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

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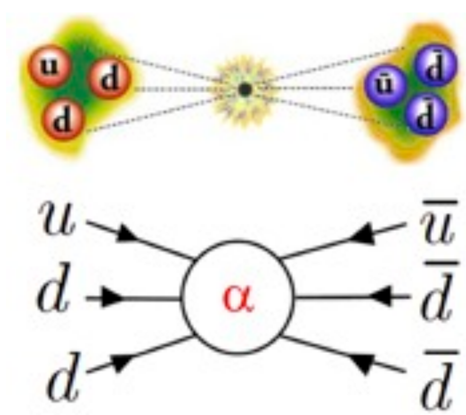

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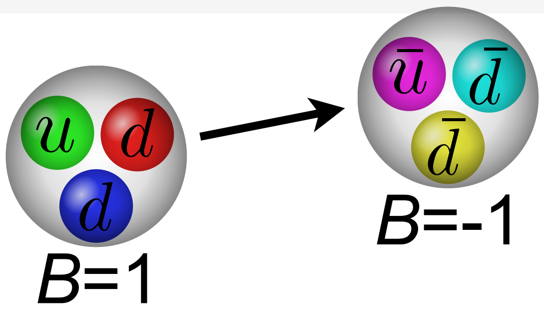
Outline

- Introduction
  - *Motivation for neutron-antineutron transition searches*
  - *Experimental status*
- Initial Lattice Results
  - *Lattice methodology for n-nbar operators*
  - *Calculations at the physical point*
- Renormalization
  - *Isospin symmetry*
- Summary & Outlook

Motivation

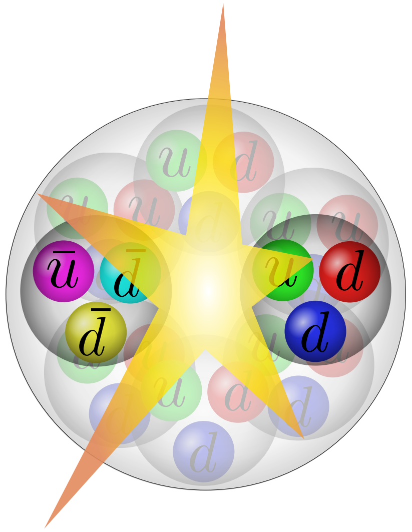
- Baryon number violation ($\Delta B=2$)

  One of Sakharov's conditions for baryogenesis



- Nuclear matter stability

  Decay of nuclei through (nn)-annihilation



- Probing BSM physics, $\Delta(B–L)$

  Connection to lepton number violation and seesaw neutrino mass mechanism?

  [R.Mohapatra, R.Marshak (1980)]

- Alternative to proton decay ($\Delta B=1$)

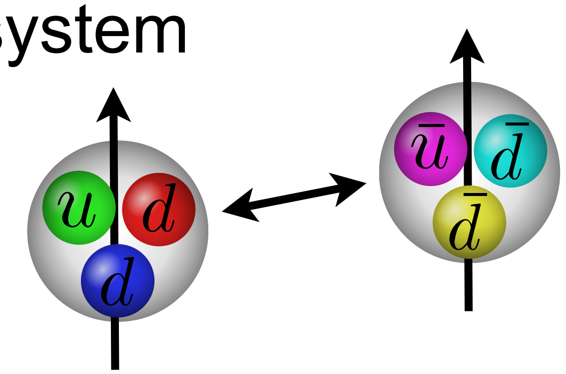
  Which one (or both?) realized in nature?

  neutron/antineutron oscillation through $\Delta B=1$ is suppressed

Basics of n ↔ $\bar{\text{n}}$ Oscillations

$\mathcal{L}_{n\bar{n}}$ is a vacuum operator and preserves spin ⇒ 2-state system

$$\mathcal{H}_{\text{osc}} = \begin{pmatrix} M_n + \frac{1}{2}\Delta M & \delta m \\ \delta m & M_n - \frac{1}{2}\Delta M \end{pmatrix}$$



where $\delta m = \langle \bar{n} | \mathcal{L}_{n\bar{n}} | n \rangle$

ΔM = induced by magnetic field or nuclear media

Oscillation probability:

$$P_{n\to\bar{n}}(t) = \left| \langle \bar{n} | e^{-i\mathcal{H}_{\text{osc}} t} | n \rangle \right|^2 = \left[\frac{(\delta m)^2}{(\Delta M/2)^2 + (\delta m)^2} \right] \sin^2 \left[\frac{1}{2} \Delta E \, t \right]$$

Current bound $\tau_{n\bar{n}} \gtrsim 10^8\, s \quad \Longleftrightarrow \quad \delta m \lesssim 6 \cdot 10^{-24}\ \text{eV}$

Earth magnetic field =0.5 Gauss: $\Delta M = 2\mu_n B_\oplus \approx 6 \cdot 10^{-12}\ \text{eV}$

$$\Delta E = \sqrt{(\Delta M)^2 + (2\delta m)^2} \approx \Delta M \gg \delta m$$

Quasifree condition (*ΔE·t <1*) for t=1sec:

$$B < (2\mu_n t)^{-1} = 5\ \text{nT} = 10^{-4} B_\oplus$$

Searches for $n \to \bar{n}$

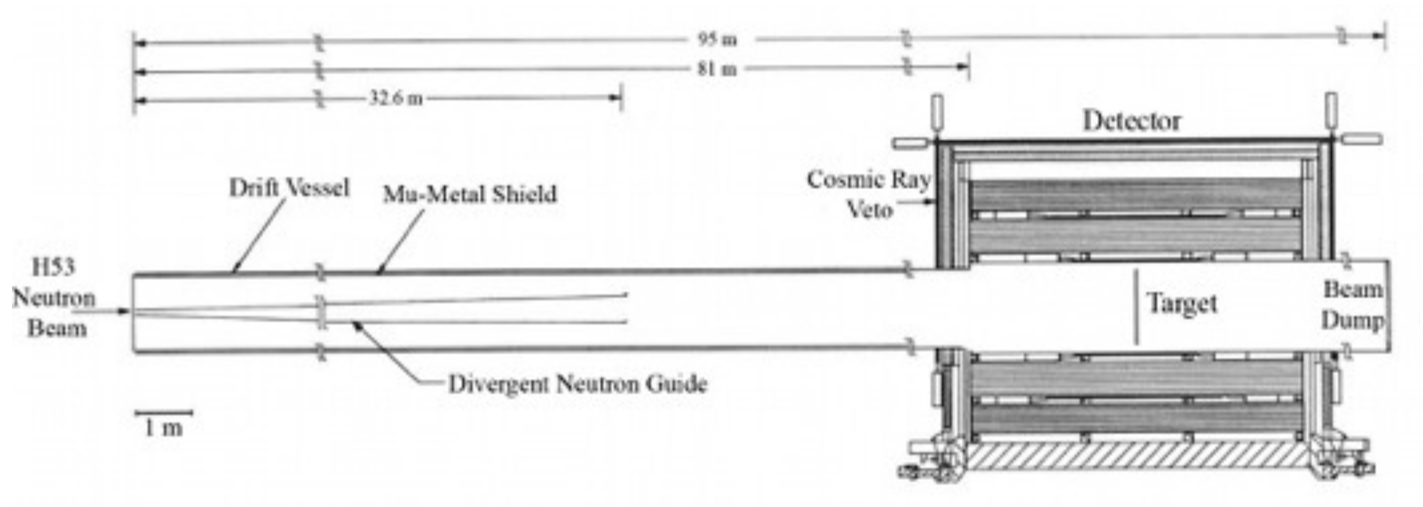
Stability of a nucleus w.r.t *(nn)* annihilation

- ^{56}Fe [Soudan 2] $T_d(^{56}Fe) > 0.72 \cdot 10^{32}$ yr $\longrightarrow$ $\tau_{n\bar{n}} > 1.4 \cdot 10^8$ s
- ^{16}O [Super-K] $T_d(^{16}O) > 1.77 \cdot 10^{32}$ yr $\longrightarrow$ $\tau_{n\bar{n}} > 3.3 \cdot 10^8$ s
- ^{2}H [SNO] $T_d(^{2}H) > 0.54 \cdot 10^{32}$ yr $\longrightarrow$ $\tau_{n\bar{n}} > 1.96 \cdot 10^8$ s

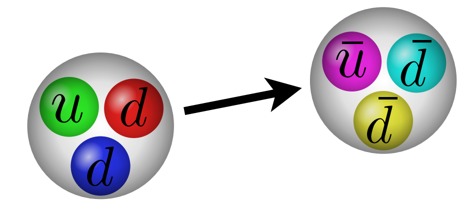
Sensitivity is limited by atmospheric neutrinos

Quasifree neutrons (*ΔEt <<1*) in vacuum:

ILL Grenoble high-flux reactor,1990 [M.Baldo-Ceolin et al, 1994)]



B < 10 nT
L/v ~ 0.1 s
T ~ 1 year



$$\tau_{n\bar{n}} > 0.86 \cdot 10^8 sec$$

Prospects to increase sensitivity to ***10^2-10^3*** *x ILL, $\tau_{n\text{-}n} \gtrsim 10^9$-$10^{10}$ s, matter stability bound $\gtrsim 10^{35}$ yr*

Neutron ↔ Antineutron Operators

Effective 6-quark operators *From Beyond (the Standard Model)* :
interaction with a massive Majorana lepton, unified theories, etc

[T.K.Kuo, S.T.Love, PRL45:93 (1980)]
[R.N.Mohapatra, R.E.Marshak, PRL44:1316 (1980)]

$$\mathcal{H}_{n\bar{n}} = \begin{pmatrix} E+V & \delta m \\ \delta m & E-V \end{pmatrix} \qquad \tau_{n\bar{n}} = (2\delta m)^{-1}$$

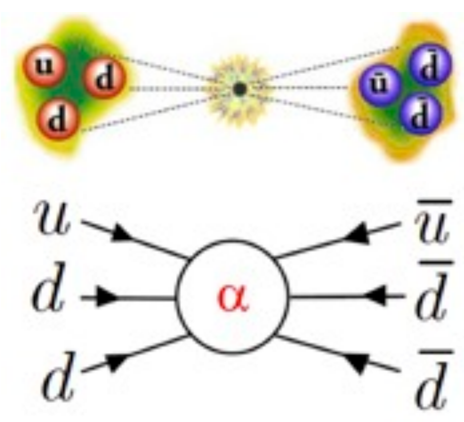
$$\mathcal{L}_{\text{eff}} = \sum_i \left[c_i \mathcal{O}_i^{6q} + \text{h.c.}\right] \qquad \delta m = -\langle\bar{n}| \int d^4x\, \mathcal{L}_{\text{eff}} |n\rangle = -\sum_i c_i \langle\bar{n}|\, \mathcal{O}_i^{6\text{q}}\, |n\rangle$$

Dimension-9 point-like operators suppressed by $(M_X)^{-5}$

What would be the scale for new physics behind n↔n̄?

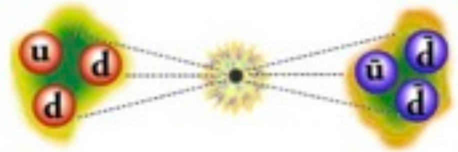
Current limit on $\tau_{n\text{-}\bar{n}}$ requires $M_X \gtrsim$ *few* · *10*^{2} TeV

Sensitivity of matter to BN-violating terms is determined by nuclear scale physics and non-perturbative QCD



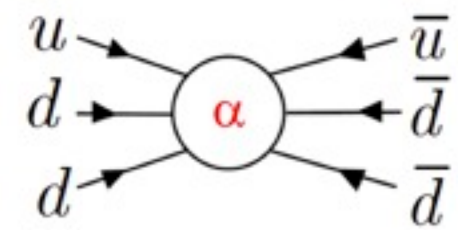
Neutron ↔ Antineutron Matrix Elements

Operators: pseudoscalar singlets w.r.t $SU(3)_c \otimes U(1)_{em} \left[\otimes SU(2)_L\right]$



$$\mathcal{O}_{1\,\chi_1\{\chi_2\chi_3\}} = T^s_{ijklmn}\left[u^{iT}_{\chi_1} C u^j_{\chi_1}\right]\left[d^{kT}_{\chi_2} C d^l_{\chi_2}\right]\left[d^{mT}_{\chi_3} C d^n_{\chi_3}\right]$$

$$\chi_{1,2,3} = R, L$$



$$\mathcal{O}_{2\,\{\chi_1\chi_2\}\chi_3} = T^s_{ijklmn}\left[u^{iT}_{\chi_1} C d^j_{\chi_1}\right]\left[u^{kT}_{\chi_2} C d^l_{\chi_2}\right]\left[d^{mT}_{\chi_3} C d^n_{\chi_3}\right]$$

Computed using MIT bag model

$$\mathcal{O}_{3\,\{\chi_1\chi_2\}\chi_3} = T^a_{ijklmn}\left[u^{iT}_{\chi_1} C d^j_{\chi_1}\right]\left[u^{kT}_{\chi_2} C d^l_{\chi_2}\right]\left[d^{mT}_{\chi_3} C d^n_{\chi_3}\right]$$

[T.Kuo, S.Love, PRL45:93 (1980)]

[S.Rao, R.Shrock, PLB116:238 (1982)]

Chiral *SU(2)$_{L,R}$* multiplet classification:

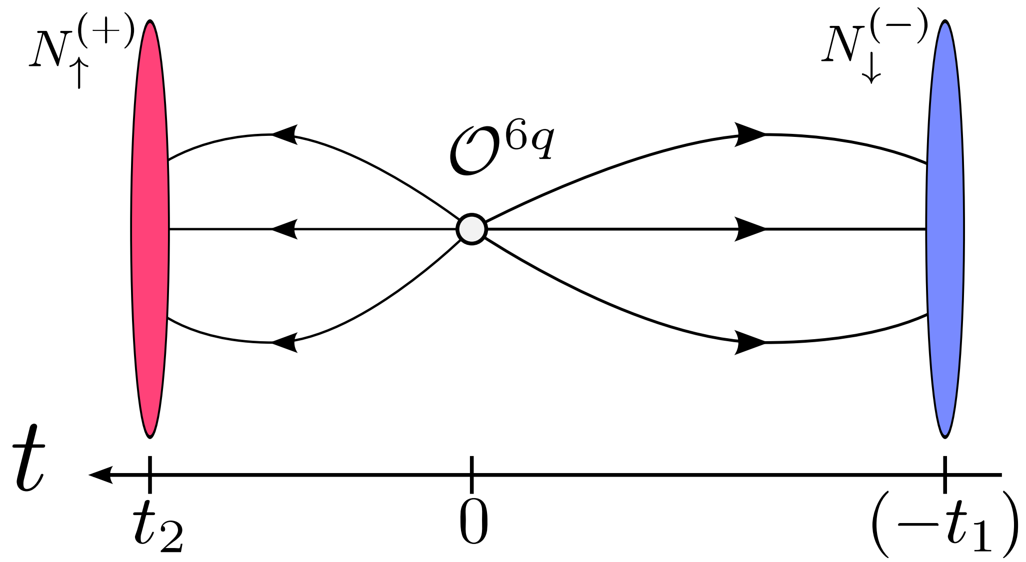
$[(RRR)_{\mathbf{3}}]$	$\mathcal{O}^1_{R(RR)} + 4\mathcal{O}^2_{(RR)R}$	$\mathbf{3}_R \otimes \mathbf{0}_L$	$(\alpha_S/4\pi)(-12)$	
$[(RRR)_{\mathbf{1}}]$	$\mathcal{O}^2_{(RR)R} - \mathcal{O}^1_{R(RR)} \equiv 3\mathcal{O}^3_{(RR)R}$	$\mathbf{1}_R \otimes \mathbf{0}_L$	$(\alpha_S/4\pi)(-2)$	*SU(2)$_L$×U(1)* -symmetric
$[R_{\mathbf{1}}(LL)_{\mathbf{2}}]$	$\mathcal{O}^2_{(LL)R} - \mathcal{O}^1_{L(LR)} \equiv 3\mathcal{O}^3_{(LL)R}$	$\mathbf{1}_R \otimes \mathbf{0}_L$	0	*SU(2)$_L$×U(1)* -symmetric
$[(RR)_{\mathbf{1}}L_{\mathbf{0}}]$	$3\mathcal{O}^3_{(LR)R}$	$\mathbf{1}_R \otimes \mathbf{0}_L$	$(\alpha_S/4\pi)(+2)$	*SU(2)$_L$×U(1)* -symmetric
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(1)}$	$\mathcal{O}^1_{L(RR)}$	$\mathbf{2}_R \otimes \mathbf{1}_L$	$(\alpha_S/4\pi)(-6)$	
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(2)}$	$\mathcal{O}^2_{(LR)R}$	$\mathbf{2}_R \otimes \mathbf{1}_L$	$(\alpha_S/4\pi)(-6)$	
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(3)}$	$\mathcal{O}^1_{R(LR)} + 2\mathcal{O}^2_{(RR)L}$	$\mathbf{2}_R \otimes \mathbf{1}_L$	$(\alpha_S/4\pi)(-6)$	

+ L⟷R counterparts

Chiral symmetry is essential for simple renormalization

Lattice Calculation

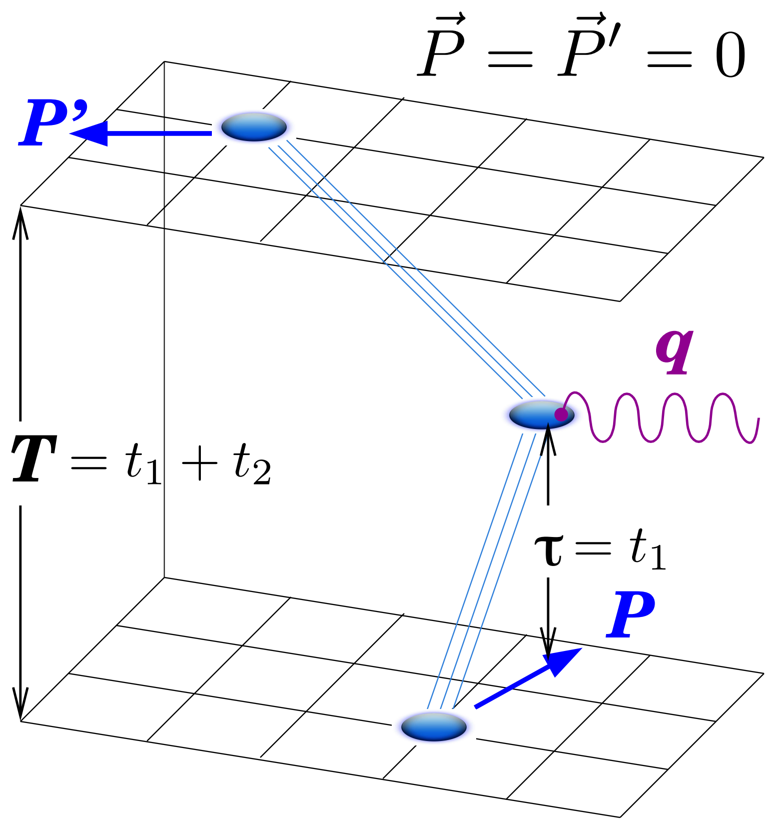
$$\langle N_\uparrow^{(+)}(t_2)\,\mathcal{O}^{6q}(0)\,N_\downarrow^{(-)}(-t_1)\rangle \underset{t_1,\,t_2,\,t_1+t_2\to\infty}{\sim} e^{-M_n(t_2+t_1)}\langle n_\uparrow|\mathcal{O}^{6q}|\overline{n}_\uparrow\rangle$$



No quark-disconnected contractions!

Single propagator $\longrightarrow \quad \forall \quad t_1,\, t_2$

Initial calculation with anisotropic Wilson in [M.Buchoff, C.Schroeder, J.Wasem, arXiv:1207.3832 (LATTICE2012)]



$$\langle n|\mathcal{O}|\bar{n}\rangle\Big|_{\mathrm{lat}} = \langle n|\mathcal{O}|\bar{n}\rangle + O\big(e^{-\Delta E_{\mathrm{exc}} t_1},\, e^{-\Delta E_{\mathrm{exc}} t_2},\, e^{-\Delta E_{\mathrm{exc}}(t_1+t_2)}\big)$$

Complete set of correlators for sophisticated exc.state analysis:

- Exponential fits
- Variational (GPoF)

Preliminary Results

- Physical pions $m_\pi = 140$ MeV

  [RBC and UKQCD collaborations, arXiv:1411.7017]

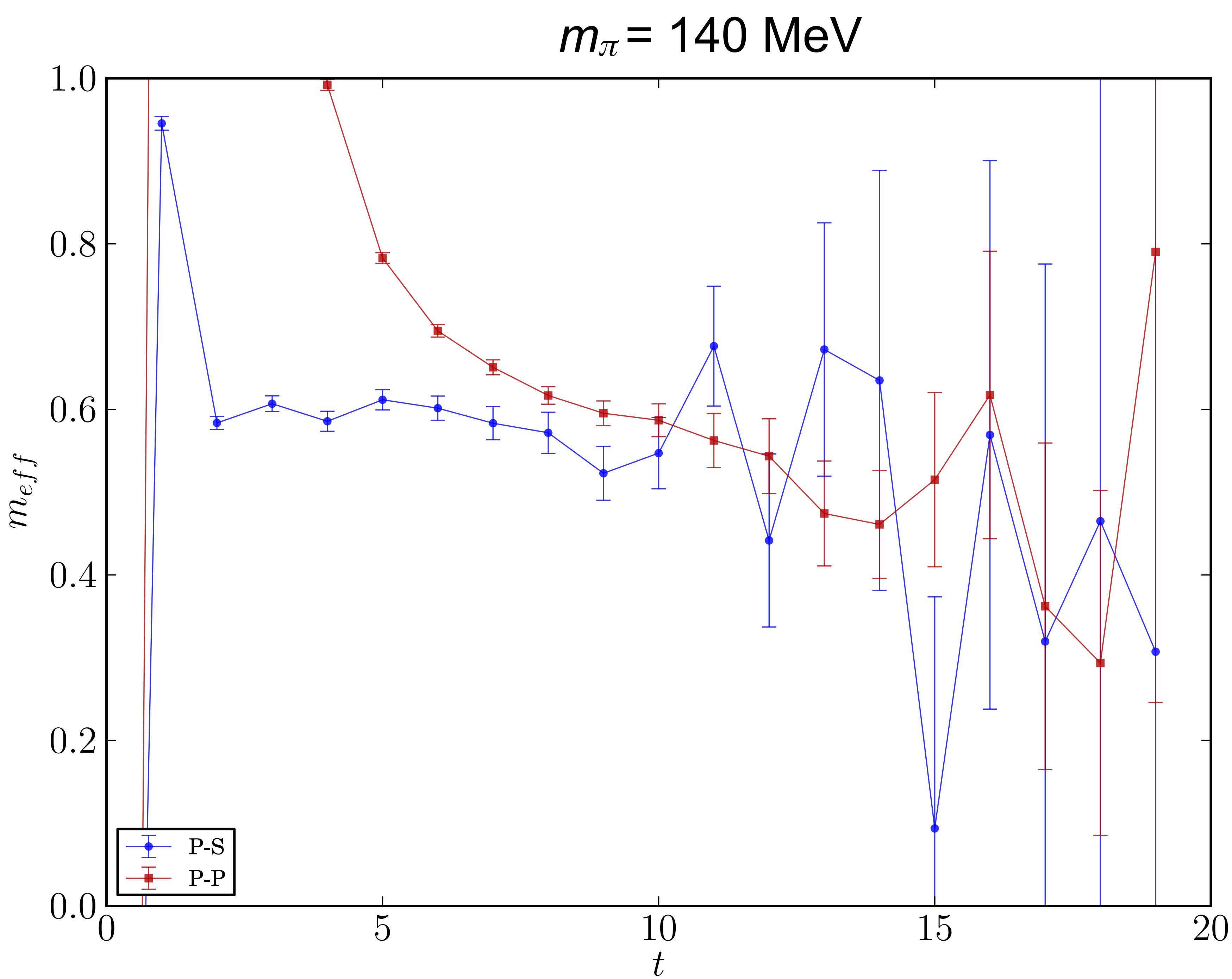
  - ✦ lattice $48^3 \times 96 = 5.5^3 \times 10.9$ fm
  - ✦ lattice spacing $a = 0.123$ fm, $a^{-1} = (1.730(4))$ GeV; $\delta(a^{-6}) \approx 1.4\%$
  - ✦ chiral (Möbius Domain Wall Fermions)
  - ✦ 28 x 81 samples (AMA)

PRELIMINARY ANALYSIS:

- ✦ simplified analysis of exc.states

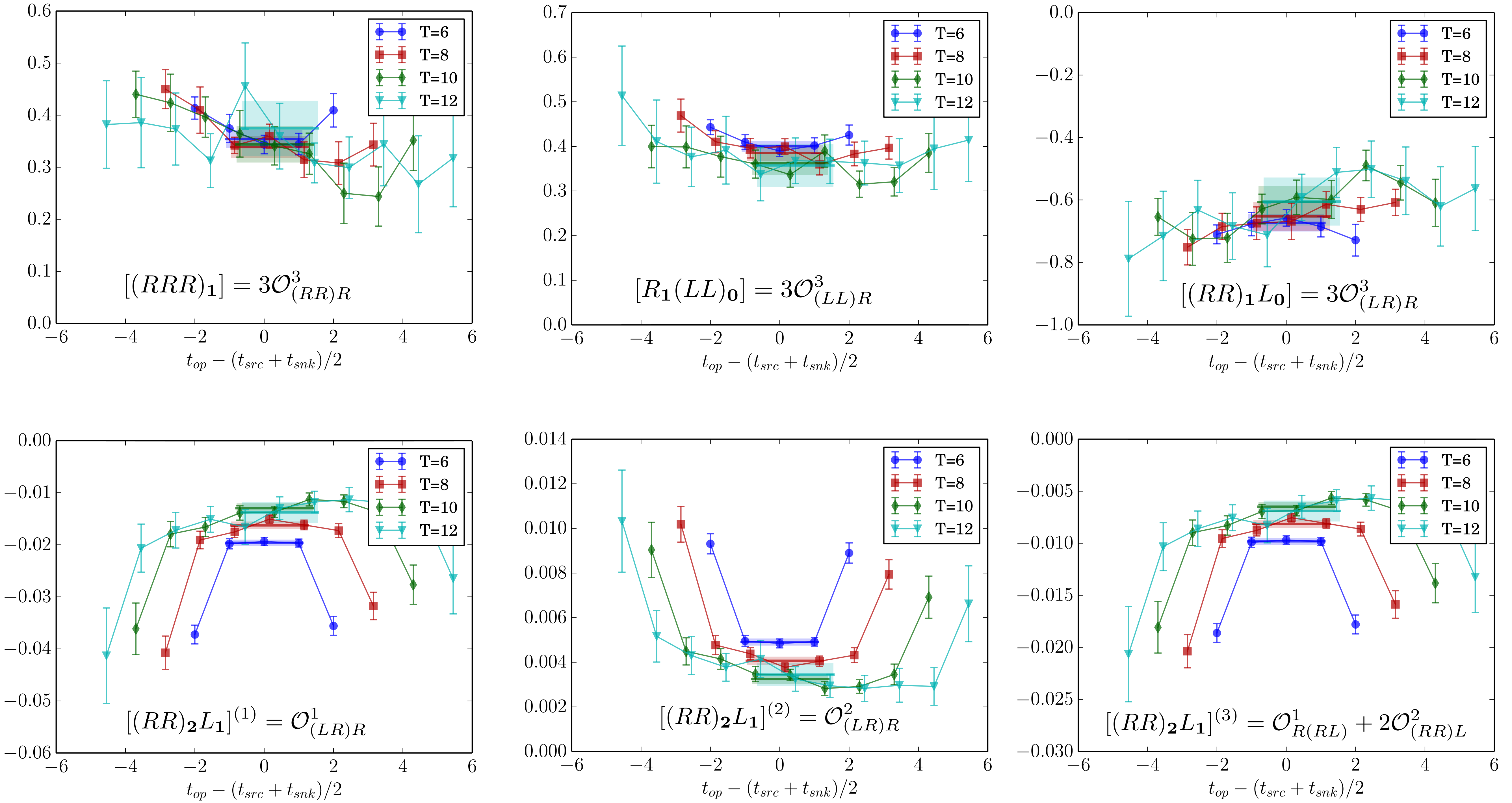
$$\langle n|\mathcal{O}|\bar{n}\rangle \sim \frac{C_{n\mathcal{O}\bar{n}}(t_2, 0, -t_1)}{\sqrt{C_{nn}(t_2, 0) C_{\bar{n}\bar{n}}(0, -t_1)}}$$

Effective Mass: Gauging Excited States



$$am_{N,eff}(t) = \log \frac{\langle N(t)N(0)\rangle}{\langle N(t+1)N(0)\rangle} \xrightarrow[t\to\infty]{} am_N$$

Lattice Matrix Elements

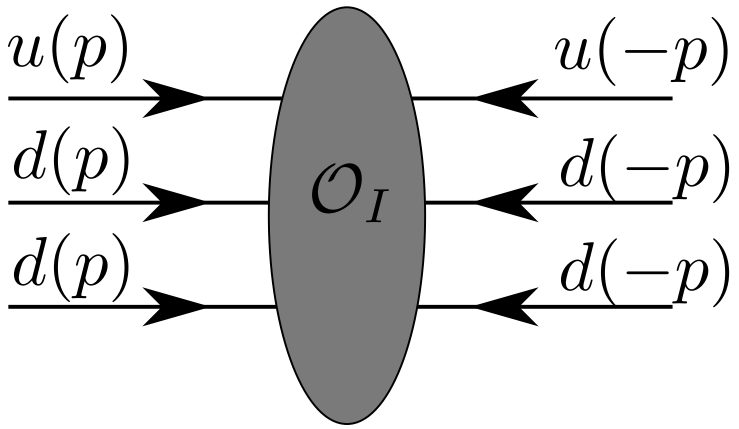


scaled x10^6, kinematics factors not divided out

Separation T=10 : ~10% stat.errorbars, consistent with T=12

Renormalization : RI-(S)MOM on a lattice

$$(G_I)^{ijklmn}_{\alpha\beta\gamma\delta\epsilon\eta}(x, p_1 \ldots p_6) = \langle \mathcal{O}_I \bar{d}^n_\eta(p_6)\bar{d}^m_\epsilon(p_5)\bar{d}^l_\delta(p_4)\bar{d}^k_\gamma(p_3)\bar{u}^j_\beta(p_2)\bar{u}^i_\alpha(p_1)\rangle$$



$$p_1 = p_3 = p_5 = p$$
$$p_2 = p_4 = p_6 = -p$$

Ext.momenta assigned to match
the 2-loop pert.QCD calculation
[M.Buchoff, M.Wagman, arXiv:1506.00647]

Contractions : loop over $(N_s N_c)^6$, for each $(N_s N_c)^6$ elements, every site (with vol.sources)

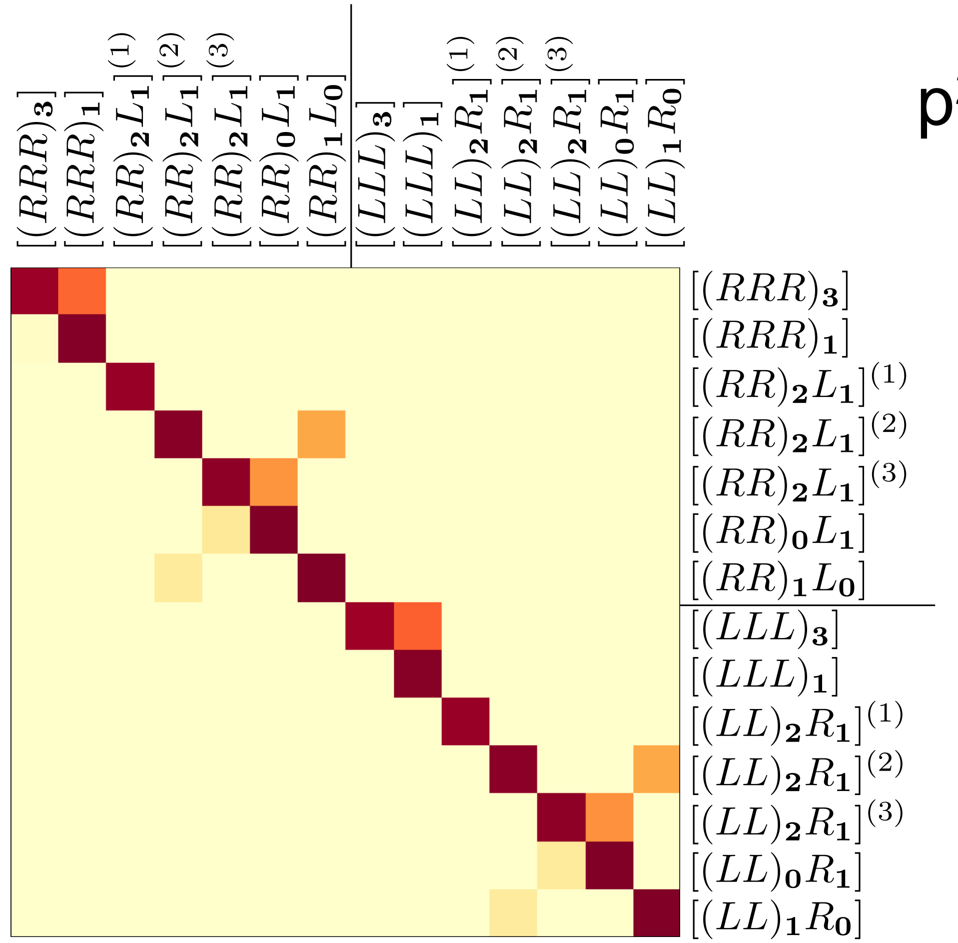
- use Fouirer-transf. propagators $x_0 \longrightarrow p_i$ for all p_i (reuse RHQBBar data, 20*81 samples)
- fermion symmetry: antisymmetrize propagators $(u_p \otimes u_{-p})$, $(d_p \otimes d_{-p})$ before contractions

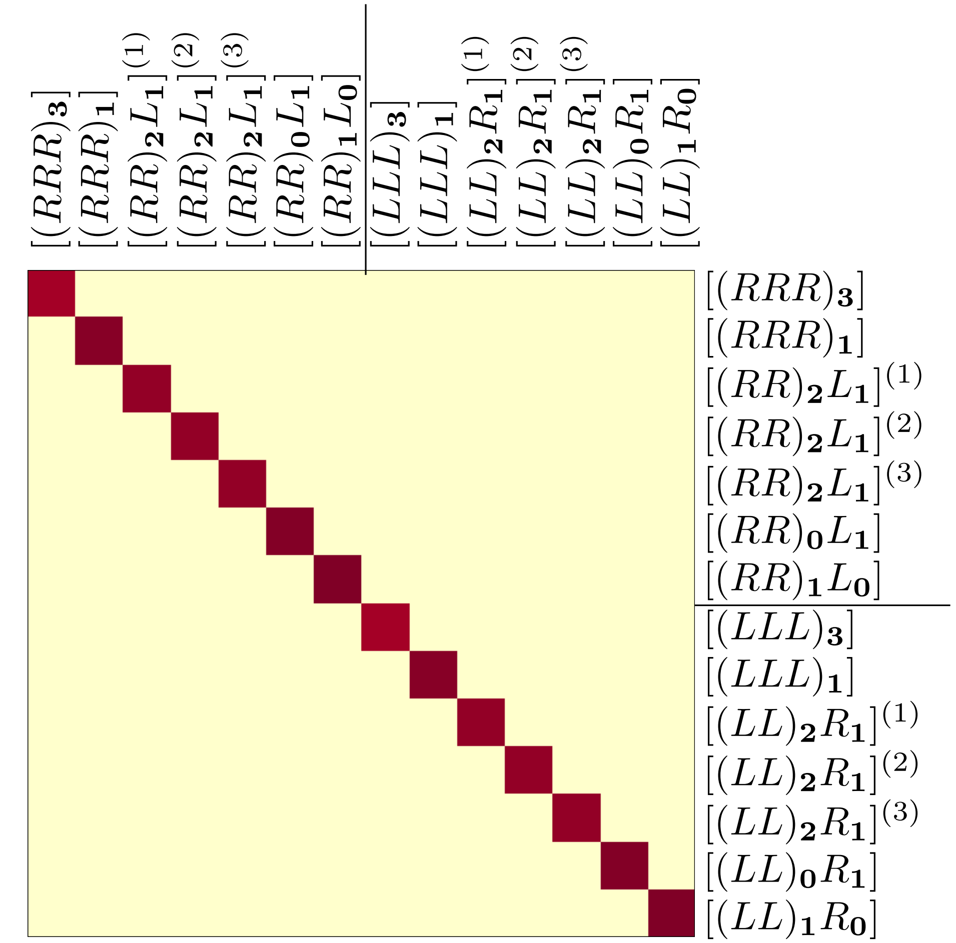
Use 4d diagonal $p = (k, k, k, k)$, $(a{\cdot}k) < \pi/2$ to
minimize discretization errors at higher scale

Restoring Chiral Isomultiplets

Problem: $\begin{pmatrix} u(p) \\ d(-p) \end{pmatrix}$ is not an *SU(2)* doublet: mix $3_R \leftrightarrow 1_R$, etc

$p^2 \approx (5.6\ \mathrm{GeV})^2$



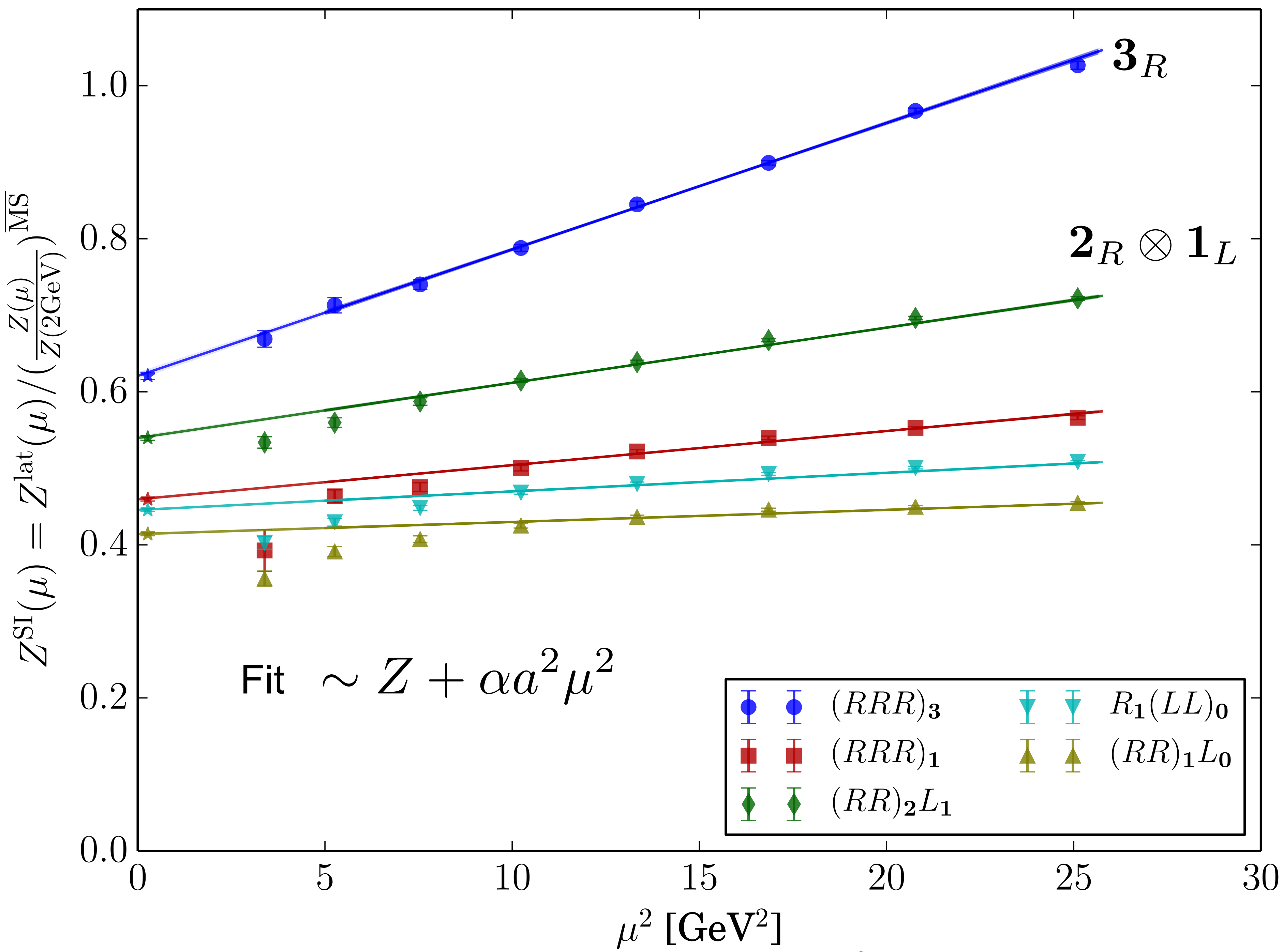


Trick: symmetrize over ext.momenta permutations to restore *SU(2)* symmetry

$$\frac{1}{5}\langle\mathcal{O}^{6q}\,\bar{u}(+p)\bar{u}(+p)\bar{d}(+p)\bar{d}(-p)\bar{d}(-p)\bar{d}(-p)\rangle + \frac{3}{5}\langle\mathcal{O}^{6q}\,\bar{u}(+p)\bar{u}(-p)\bar{d}(+p)\bar{d}(+p)\bar{d}(-p)\bar{d}(-p)\rangle + \frac{1}{5}\langle\mathcal{O}^{6q}\,\bar{u}(-p)\bar{u}(-p)\bar{d}(+p)\bar{d}(+p)\bar{d}(+p)\bar{d}(-p)\rangle$$

(already symmetric in $\{p_1, p_2\},\ \{p_3, p_4, p_5, p_6\}$)

“Scale-independent” Ren.factors



Perturbative 1-loop running from
W.Caswell *et al* PLB122:373 (1983)]

Take variances between 2–4 GeV and 4–6 GeV fits as estimates of syst.errors

Preliminary Results in MSbar(2GeV)

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	$Z(\text{lat} \to \overline{MS})$	$\mathcal{O}^{\overline{MS}(2\text{ GeV})}$	Bag "A"	$\frac{\text{LQCD}}{\text{Bag "A"}}$	Bag "B"	$\frac{\text{LQCD}}{\text{Bag "B"}}$
$[(RRR)_{\mathbf{3}}]$	0.62(12)	0	0	–	0	–
$[(RRR)_{\mathbf{1}}]$	0.454(33)	45.4(5.6)	8.190	5.5	6.660	6.8
$[R_{\mathbf{1}}(LL)_{\mathbf{0}}]$	0.435(26)	44.0(4.1)	7.230	6.1	6.090	7.2
$[(RR)_{\mathbf{1}}L_{\mathbf{0}}]$	0.396(31)	-66.6(7.7)	-9.540	7.0	-8.160	8.1
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]^{(1)}$	0.537(52)	-2.12(26)	1.260	-1.7	-0.666	3.2
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]^{(2)}$	0.537(52)	0.531(64)	-0.314	-1.7	0.167	3.2
$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]^{(3)}$	0.537(52)	-1.06(13)	0.630	-1.7	-0.330	3.2

- matrix elements : T=10 plateau average
- renormalization: only syst.errors, estimated from variation over entire range
- MIT Bag model results from [S.Rao, R.Shrock, PLB116:238 (1982)]

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Summary & Outlook

- Clear lattice signal for non-zero $\langle n|\mathcal{O}^{6q}|\bar{n}\rangle$ even with modest statistics

  Physical m_π = 140 MeV *pion mass lattices with chiral symmetry*

- Comparison with the MIT Bag Model

- Current stat&sys. errors already not exceed ~15%

  Reduction of model dependence of n-nbar oscillations phenomenology

Outlook

- Study and improve control of syst.errors in renormalization

  Alternative momentum arrangement?

  Step-scaling?

  Two-loop perturbative running and matching?

- Improve analysis to extract ground state M.E.

  Easy to analyze excited state effects with chosen scheme

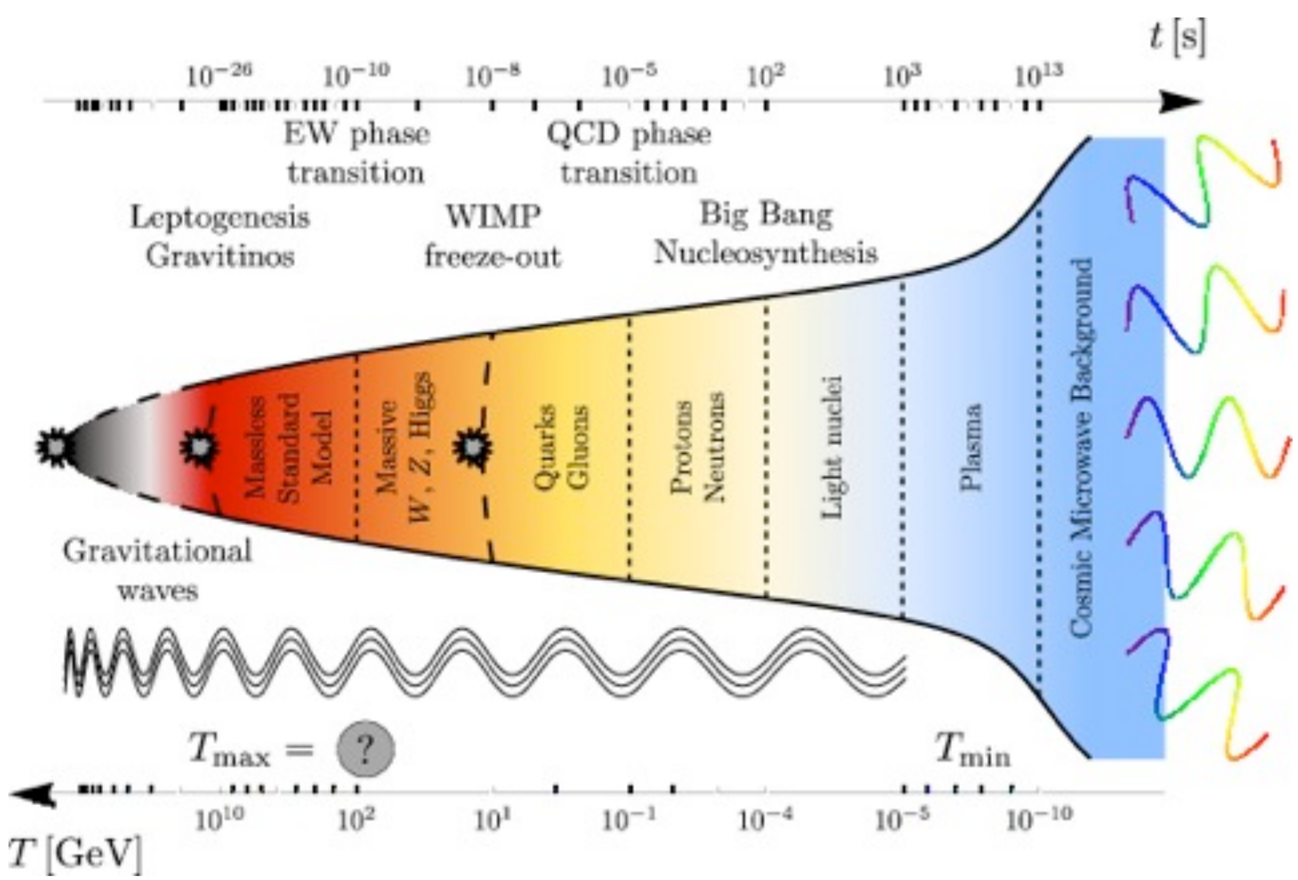
- Study discretization effects with another (finer) lattice spacing

BACKUP

Neutron Oscillations and Baryogenesis

- Baryosynthesis requires $B-$ or $L-$ violation :
  - leptotenesis: ΔL above T_{EW} , transformed to ΔB by sphalerons
  - (if exist) $n\text{-}\bar{n}$ oscillations can wash away ΔB during EW transition
  - then, $n\leftrightarrow\bar{n}$ must explain post-sphaleron baryogenesis below T_{EW}
    upper limit on $\tau_{n\text{-}\bar{n}} < 5\cdot 10^{10}$ *sec* (proton-decay already excluded)

Interplay of T_{EW} and ΔB scales



Neutron Oscillation and Neutrino See-Saw

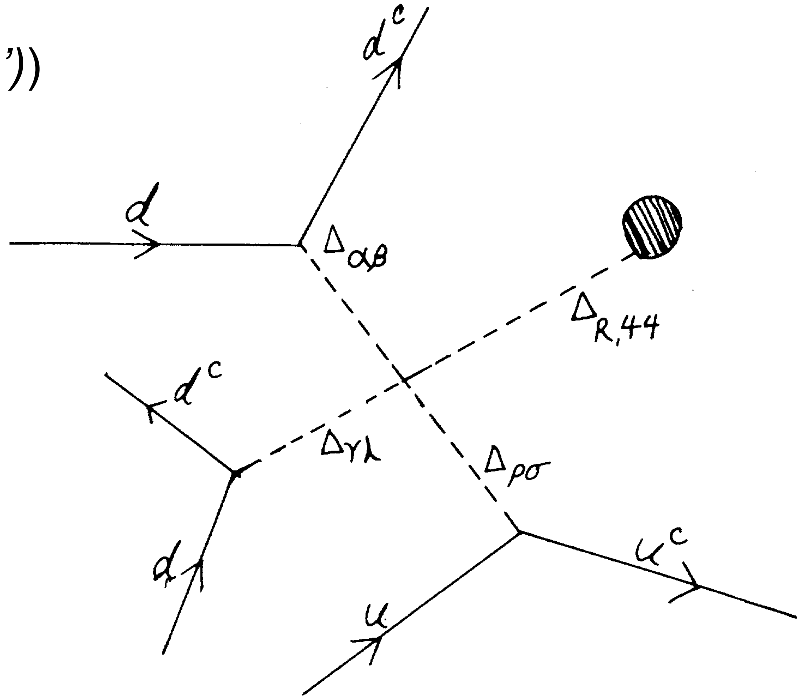
- *n*-$\bar{n}$ oscillation $\Delta B = 2$ breaks $(B–L)$: beyond-SM physics
- Similarly, $\Delta L = 2$ *from* Majorana neutrino masses in the see-saw mechanism:

is there connection between the two?

[Mohapatra, Marshak, PRL44:1316 (1980)]
Quark-lepton unification theory

$$SU(2)_R \otimes SU(2)_L \otimes [U(1)_{(B-L)} \otimes SU(3)_c]_{\text{(remnants of } SU(4'))}$$

with Majorana ν_R predicts



$$\Delta L = 2$$
$$\Delta B = 2$$

Spontaneous breaking
$SU(2)_R \otimes U(1)_{(B-L)} \rightarrow U(1)_Y$
with Higgs field

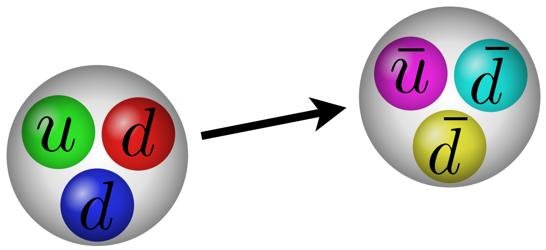
$$\langle \Delta_{R,44} \rangle = v \neq 0$$

Searches for $n \to \bar{n}$: Proposed Improvements

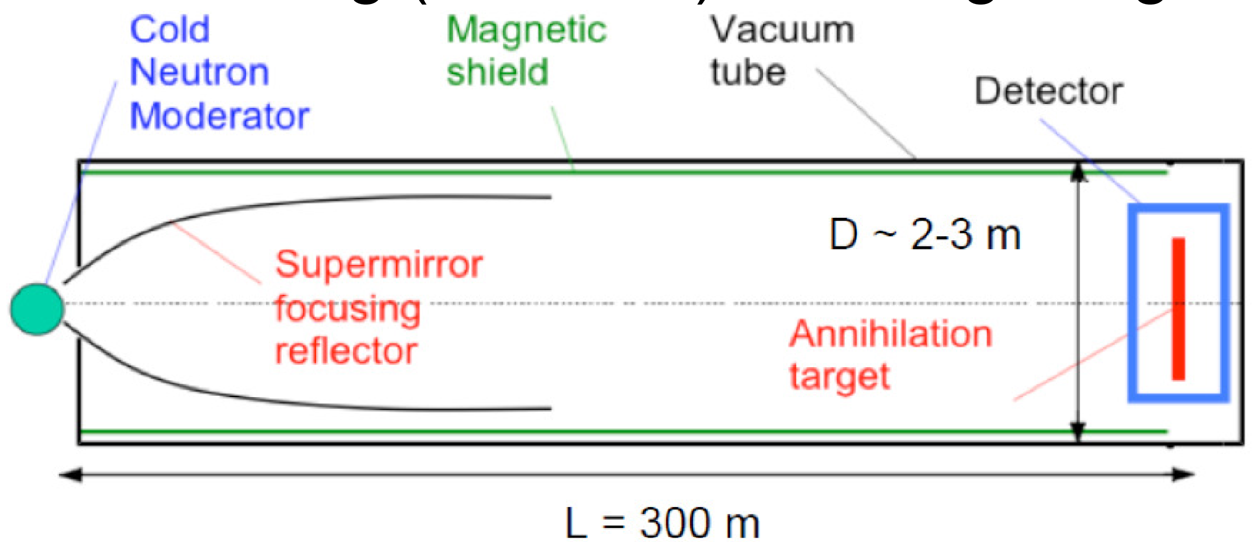
[Phillips et al, arXiv:1410.1100]

- Free-neutron oscillation (similar to ILL):

  Maximize *Prob* ~ N_n * $(t_{free})^2$



- ✦ Neutrons from spallation sources:
  e.g. European Spallation source: x12 neutron flux
- ✦ Elliptic mirror for slow neutrons (reflect ~70% of $v_\perp \lesssim$40m/s neutrons)
- ✦ Better mag.field screening (B < 1 nT) and longer flight time



*Expected to increase sens. x**10^2-10^3** ILL, $\tau_{n\text{-}n} \gtrsim 10^9$-$10^{10}$ s, matter stability bound $\gtrsim 10^{35}$ yr*

- Other proposed experiments:
  - stored ultra-cold neutrons (4-5m/s)
  - vertical cold neutron beams