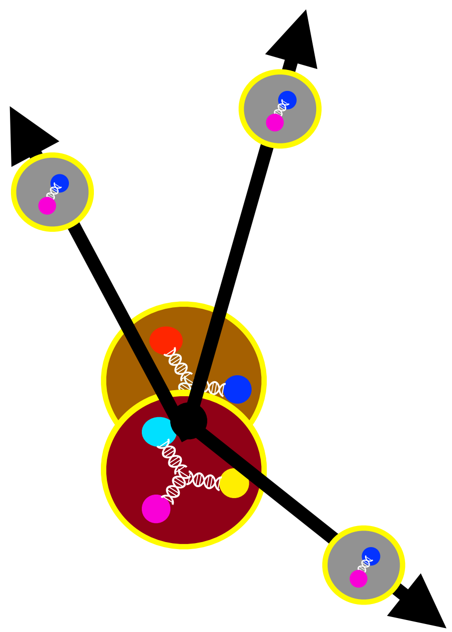
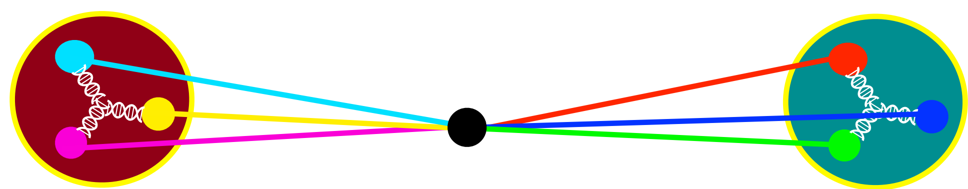
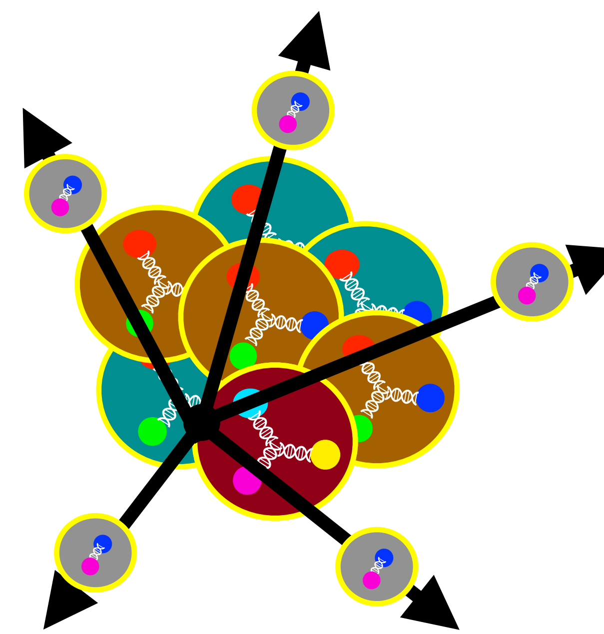
Lattice QCD results for $\Delta B = 2$ operators

Michael Wagman







Fermilab

Virtual ACFI Workshop

August 4, 2020

Why Does It Matter?

Matter-antimatter asymmetry $\eta_B = \frac{n_B}{n_\gamma}$

Inflationary Standard Model universe

$$\eta_B^{SM} \ll 10^{-20}$$

Primordial deuterium abundance

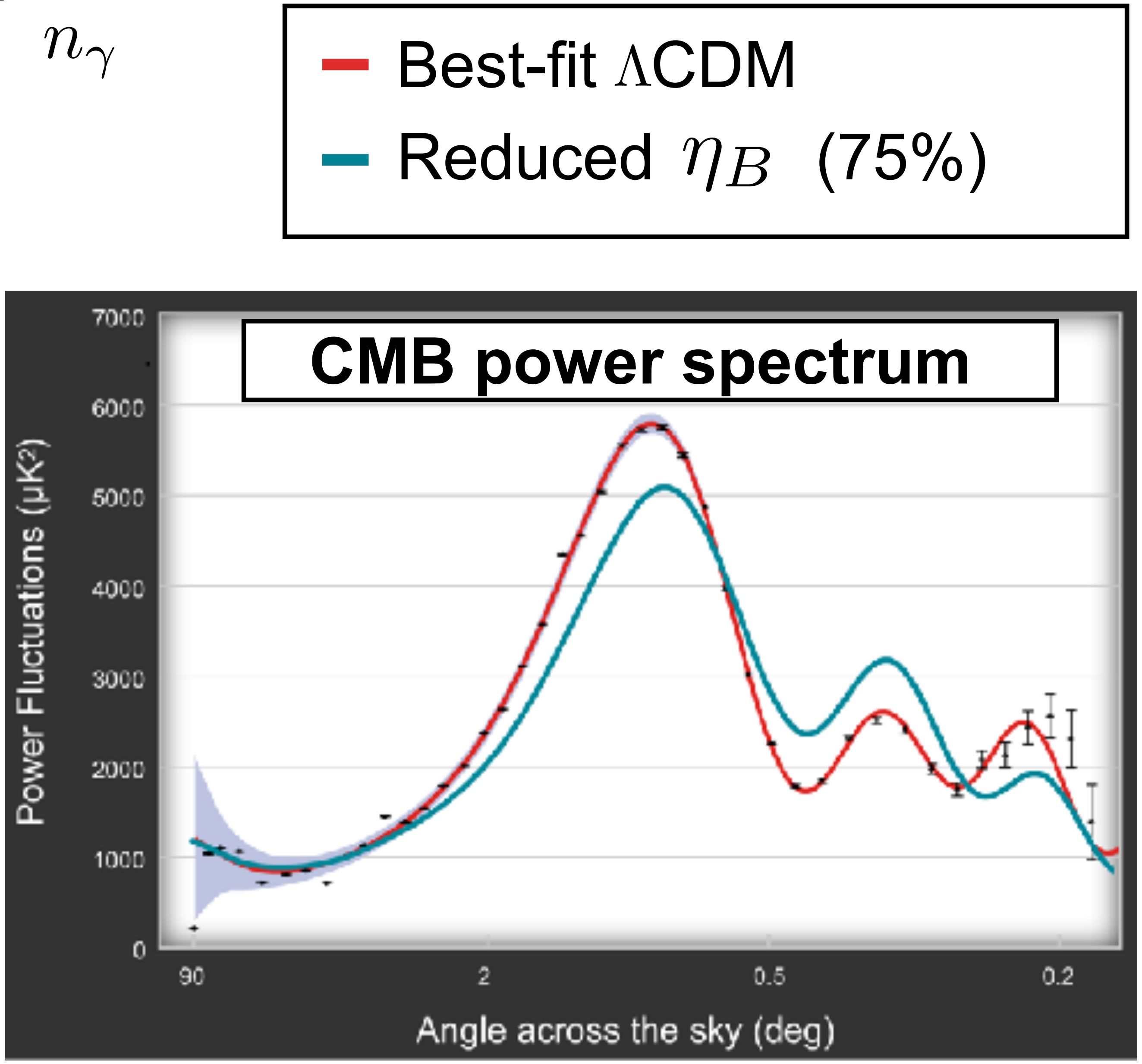
$$\eta_B^D = 6.2(4) \times 10^{-10}$$

Particle Data Group, Phys. Rev. D98 (2018)

CMB power spectrum

$$\eta_B^{CMB} = 6.14(2) \times 10^{-10}$$

Planck, arXiv 1807.06205



https://lambda.gsfc.nasa.gov/education/cmb_plotter/

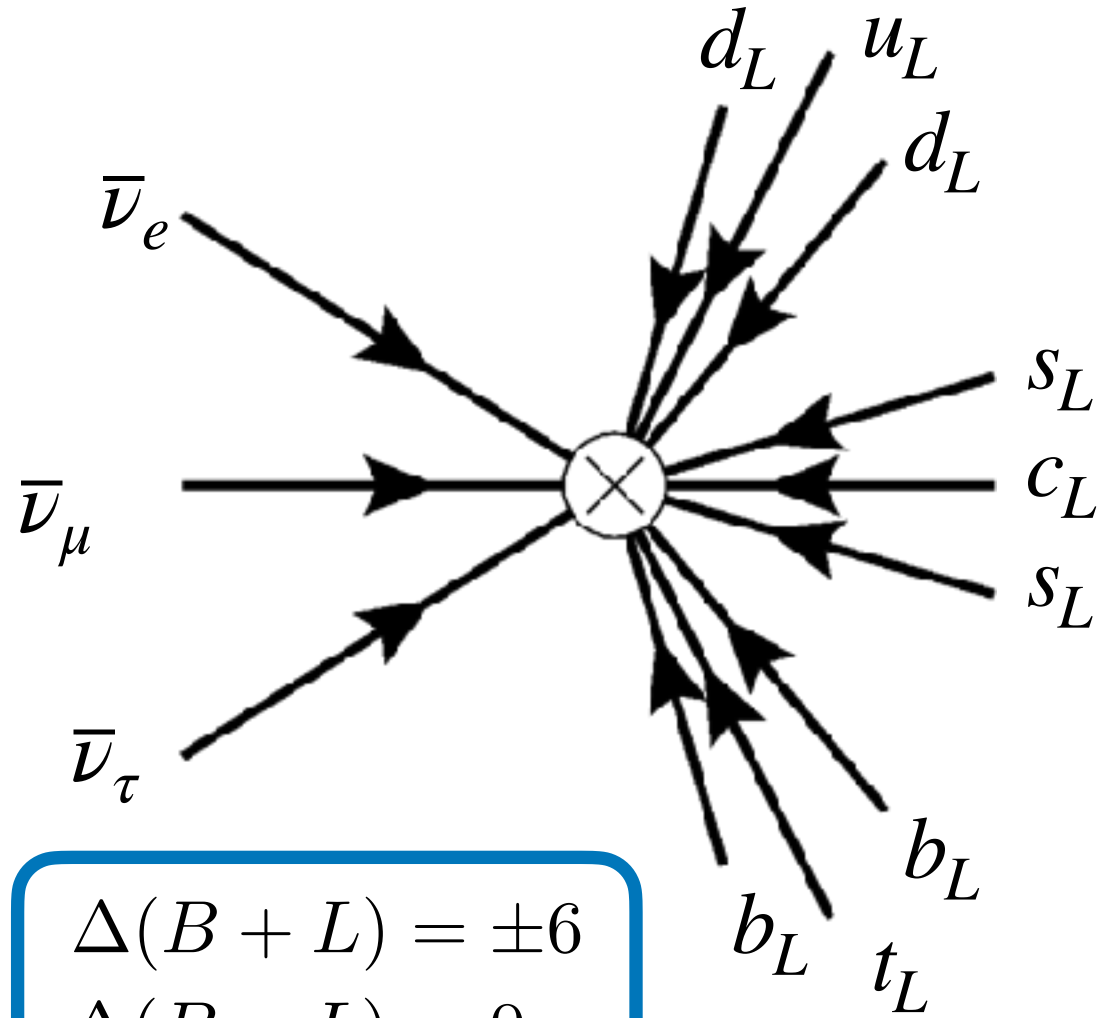
Baryogensis

Electroweak sphalerons wash out early *B+L* asymmetry, only *B-L* matters

η_B fixed by early *B-L* asymmetry or electroweak-scale *B* violation

Review: Cline, arXiv 1807.08749

Electroweak instanton/sphaleron



$$\Delta(B+L) = \pm 6$$
$$\Delta(B-L) = 0$$

Possibilities:

1) *B-L* violation before electroweak transition (leptogenesis)

2) *B* violation near/after electroweak transition (post-sphaleron baryogensis)

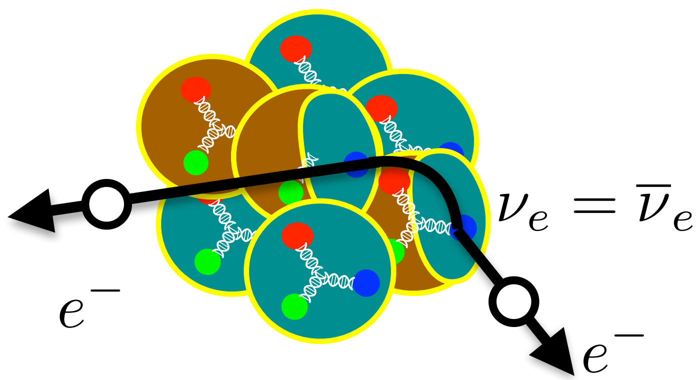
3) *B-L* asymmetry in initial conditions

B-L Violation

B-L is an "accidental" symmetry of Standard Model operators with dim ≤ 4

Dim 5: ***B-L* violating**, *L* violating
Majorana neutrino mass

$$\mathcal{L}_5 \sim \left(\frac{1}{\Lambda_{BSM}}\right)(H^T \ell^*)(\bar{\ell} H)$$



Double-β decay

$\Lambda_{BSM} \gtrsim 10^{10}$ GeV

Leptogenesis

Also dim 7, 9, … see e.g. Cirigliano et al JHEP 12 (2018)

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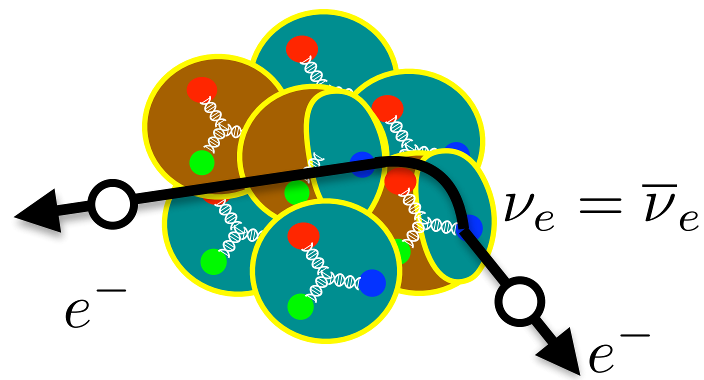

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✓ Leptogenesis

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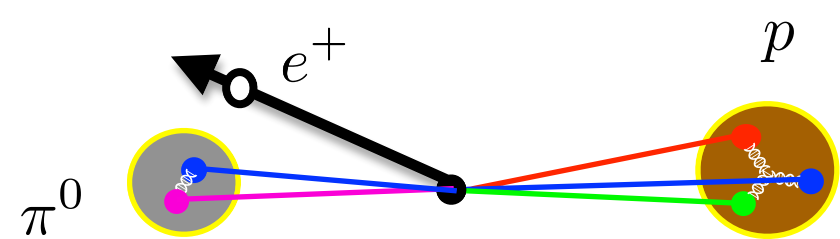
Dim 6: ***B-L* conserving**, *B* violating
proton decay operators

$$\mathcal{L}_6 \sim \left(\frac{1}{\Lambda^2_{BSM}}\right) uude + \ldots$$



Proton decay

$\Lambda_{BSM} \gtrsim 10^{16}$ GeV

✗ Washed out by sphalerons

Higher dim counter-examples: Heeck, Takhistov, PRD 101 (2020)

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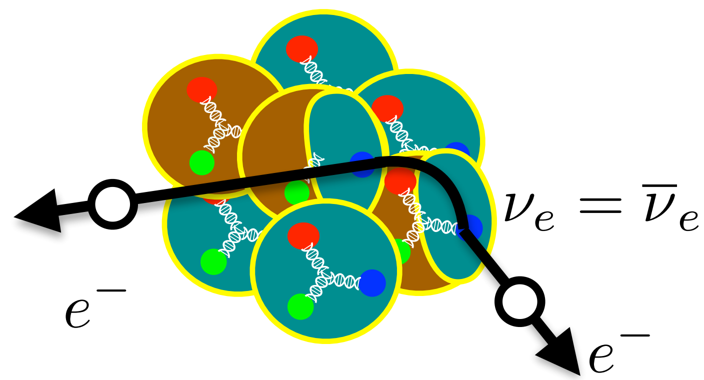

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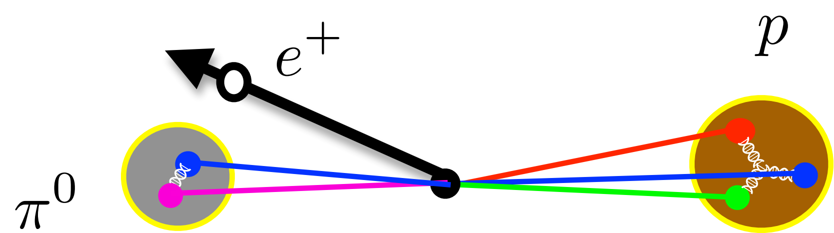

Proton decay

$\Lambda_{BSM} \gtrsim 10^{16}$ GeV

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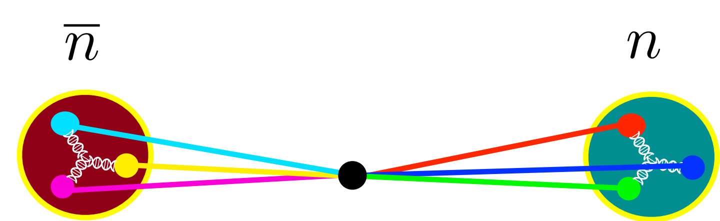
Higher dim counter-examples: Heeck, Takhistov, PRD 101 (2020)

Dim 9: ***B-L* violating**, *B* violating
Majorana neutron mass

$$\mathcal{L}_9 \sim \left(\frac{1}{\Lambda^5_{BSM}}\right) uddudd + \dots$$



Neutron-antineutron oscillations

$\Lambda_{BSM} \gtrsim 10^{5}$ GeV

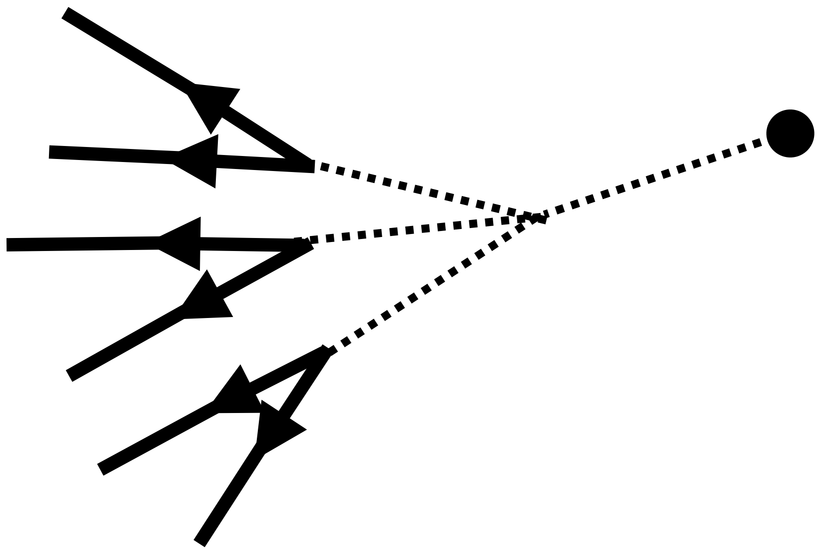
✓ Post-sphaleron baryogengesis

$n\bar{n}$ and Baryogenesis

BSM theories describe quark-level amplitudes for $|\Delta B| = 2$ processes

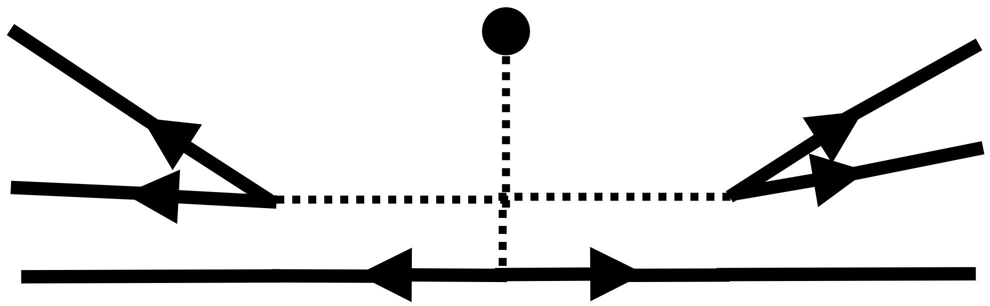
Example: Left-Right symmetric $SU(2)_L \times SU(2)_R \times SU(4)_C$ gauge theory

Baryon asymmetry from decay of BSM
Higgs boson with *B-L* violating VEV



Mohapatra, Marshak PRL 44 (1980)

Rearranging diagram gives quark-level amplitude for $n\bar{n}$ oscillations



η_B and $\tau_{n\bar{n}}^{-1}$ related, although free parameters enter for *CP*-violation

Neutron-Antineutron Oscillations

$n\bar{n}$ oscillation phenomenology similar to meson, neutrino oscillations

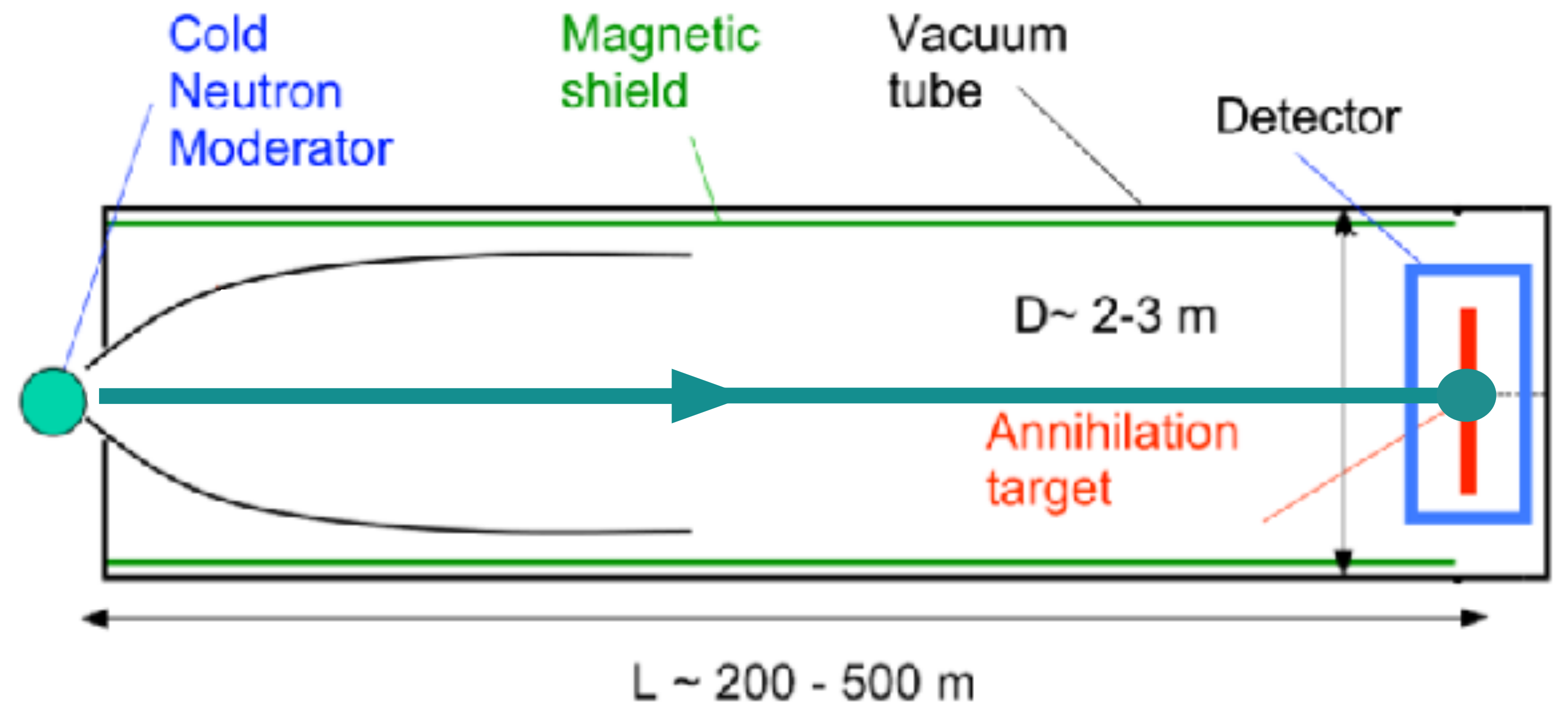
$$\mathcal{P}_{n\bar{n}} = \sin^2(t/\tau_{n\bar{n}})e^{-\Gamma_n t} \qquad \tau_{n\bar{n}}^{-1} = < \bar{n}|H_{n\bar{n}}|n >$$

In order to turn experimental constraints into BSM physics constraints, we need theory predictions of $\tau_{n\bar{n}}^{-1}$ including QCD strong interaction effects

Institut Laue-Langevin (ILL)

$$\tau_{n\bar{n}} > 0.89 \times 10^8 \text{ s}$$

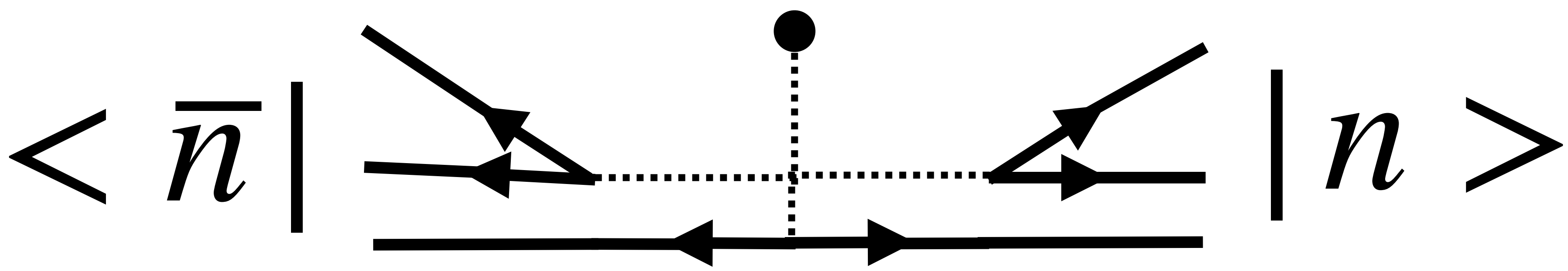
Baldo-Ceolin et al, Zeitschrift für Physik C Particles and Fields (1994)



Mohapatra, J. Phys. G 36 (2009)

QCD for $n\bar{n}$

Predicting $\tau_{n\bar{n}}^{-1}$ requires strong interaction effects in (anti)neutron states

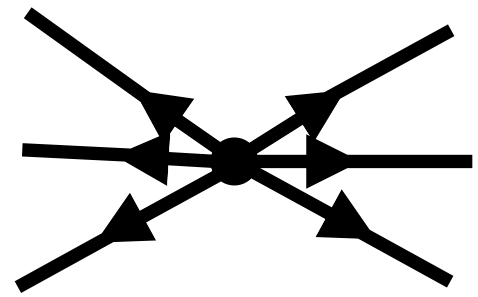


Lattice QCD — EFT for hadronic matrix elements valid below the UV cutoff a^{-1}

UV cutoff set by lattice spacing. Resource limits $a^{-1} \ll \Lambda_{BSM}$

QCD for $n\bar{n}$

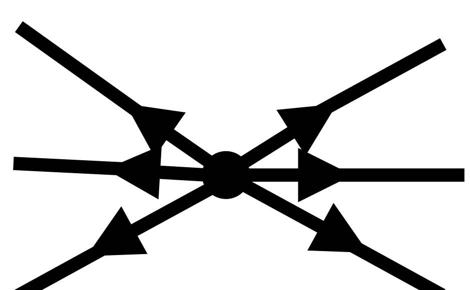
Predicting $\tau_{n\bar{n}}^{-1}$ requires strong interaction effects in (anti)neutron states

$< \bar{n} |$  $| n >$

Lattice QCD — EFT for hadronic matrix elements valid below the UV cutoff a^{-1}

UV cutoff set by lattice spacing. Resource limits $a^{-1} \ll \Lambda_{BSM}$

Exploit separation of QCD and BSM scales with Standard Model EFT

 $= \left(\frac{\lambda f^3 \tilde{v}_{B-L}}{\Lambda_{BSM}^5}\right)\left[(u_i C P_R d_j)(u_k C P_R d_l)(u_m C P_R d_n) T^{AAS}_{ijklmn}\right]$

Six-Quark Operators

Arbitrary BSM theory predictions possible once QCD matrix elements calculated for complete basis of dim-9 six-quark operators

$$\mathcal{L}_9 = \frac{1}{\Lambda_{BSM}^5} \sum_I C_I^{\overline{\text{MS}}}(\Lambda_{BSM}) Q_I^{\overline{\text{MS}}}(\Lambda_{BSM})$$

Basis of 18 six-quark operators

Kuo, Love, PRL 45 (1980)   Chang, Chang, Phys. Lett. B 92 (1980)

Complete basis of 14 operators (spin-color-flavor Fierz), renormalization

Caswell, Milutinovic, Phys. Lett. 122B (1983)

MIT bag model matrix element calculations

Rao, Shrock, Nucl. Phys. B 232 (1984)

14x14 renormalization matrix relates regularized and renormalized

$$Q_I^{\overline{\text{MS}}}(\mu) = \sum_J Z_{IJ}^{\overline{\text{MS}}}(\mu, a) Q_J^{\text{lattice}}(a)$$

Chiral Operators

Chiral symmetry can be used to build an operator basis with no mixing under renormalization in perturbative QCD: $Q_1, \ldots, Q_7, Q_1^P, \ldots, Q_7^P$

Buchoff, MW et al, PRD 96 (2016)

Building blocks: **Singlet diquark** **Vector diquark**

$$\mathcal{D}_{L,R} = qCP_{L,R}i\tau^2 q \qquad \mathcal{D}^a_{L,R} = qCP_{L,R}i\tau^2\tau^a q$$

---

4 $SU(2)_L$ singlet operators:

$$Q_1 = \mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^+ T^{AAS} \qquad Q_2 = \mathcal{D}_L\mathcal{D}_R\mathcal{D}_R^+ T^{AAS} \qquad Q_3 = \mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^+ T^{AAS}$$

$$Q_4 = \mathcal{D}_R^3\mathcal{D}_R^3\mathcal{D}_R^+ T^{SSS} - \text{traces}$$

---

10 $SU(2)_L$ non-singlet operators:

$$Q_5 = \mathcal{D}_R^-\mathcal{D}_L^+\mathcal{D}_L^+ T^{SSS} \qquad Q_6 = \mathcal{D}_R^3\mathcal{D}_L^3\mathcal{D}_L^+ T^{SSS} \qquad Q_7 = \mathcal{D}_R^+\mathcal{D}_L^3\mathcal{D}_L^3 T^{SSS} - \text{traces}$$

$$Q_I^P = -Q_I(L \leftrightarrow R)$$

Symmetry Constraints

$n\bar{n}$ matrix elements $\mathcal{M}_I = < \bar{n}|Q_I|n >$ further constrained by symmetry

Parity: $\mathcal{M}_I^P = -\mathcal{M}_I$ **Isospin:** $\mathcal{M}_4 = 0 \quad \mathcal{M}_5 = \mathcal{M}_6 = -\frac{3}{2}\mathcal{M}_7$

$SU(2)_L$ non-singlet operators suppressed in EFT by $v = \text{Higgs VEV}$

$$\mathcal{M}_{n-\bar{n}} = \frac{1}{\Lambda_{BSM}^5}\left[\sum_{I=1,2,3} \widetilde{C}_I \mathcal{M}_I + \frac{v^2}{\Lambda_{BSM}^2} \sum_{I=1,2,3,5} \widetilde{C}_I^P \mathcal{M}_I^P + \frac{v^4}{\Lambda_{BSM}^4} \widetilde{C}_5 \mathcal{M}_5\right]$$

Rinaldi, Sryitsyn, MW et al, PRD 99 (2019)

In isospin limit:

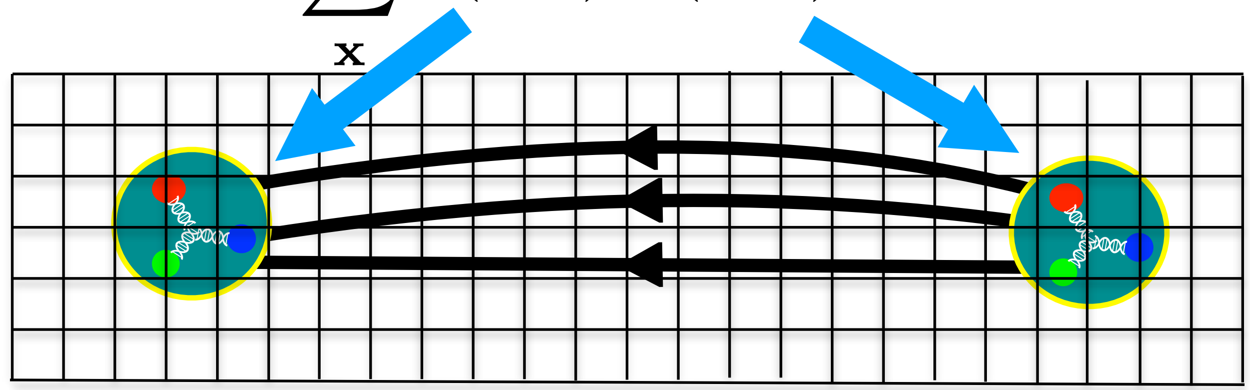
3 dominant matrix elements $\mathcal{M}_1,\ \mathcal{M}_2,\ \mathcal{M}_3$

1 subdominant matrix element $\mathcal{M}_5$

The Neutron

Neutron correlation function: path integral with neutron source/sink separated in Euclidean (imaginary) time

$$G_n(t) = \int \mathcal{D}\overline{q}\mathcal{D}q\mathcal{D}U\ e^{-S_{QCD}} \sum_{\mathbf{x}} n(\mathbf{x},t)\ \overline{n}(\mathbf{0},0)$$



Path integrals evaluated by Monte Carlo sampling field configurations

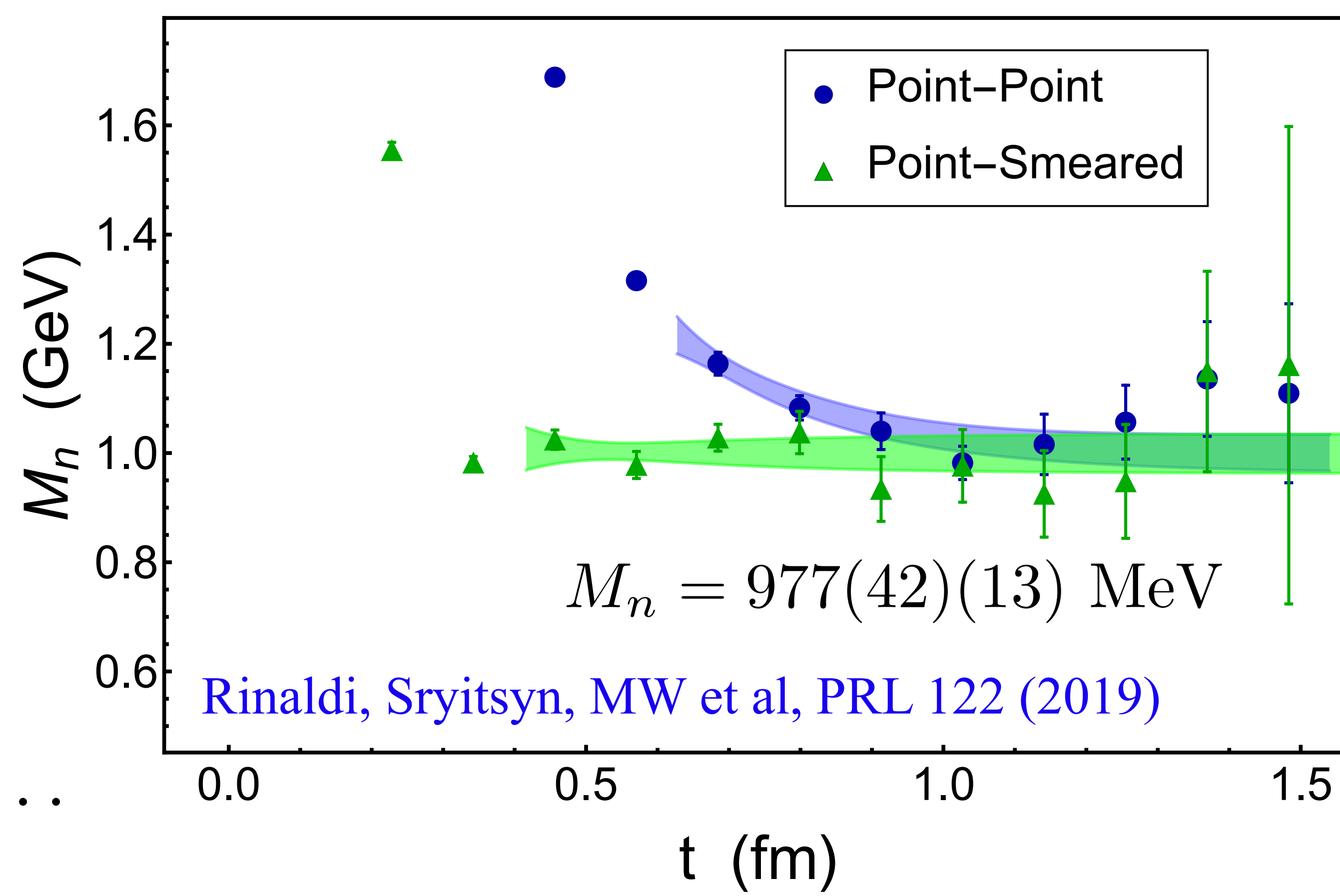
Physical quark mass configurations

Blum et al (RBC, UKQCD), PRD 93 (2016)

Neutron mass extracted by fitting to spectral representation

$$G_n(t) = Z_0 e^{-M_n t} + Z_1 e^{-(M_n+\delta_n)t} + \ldots$$

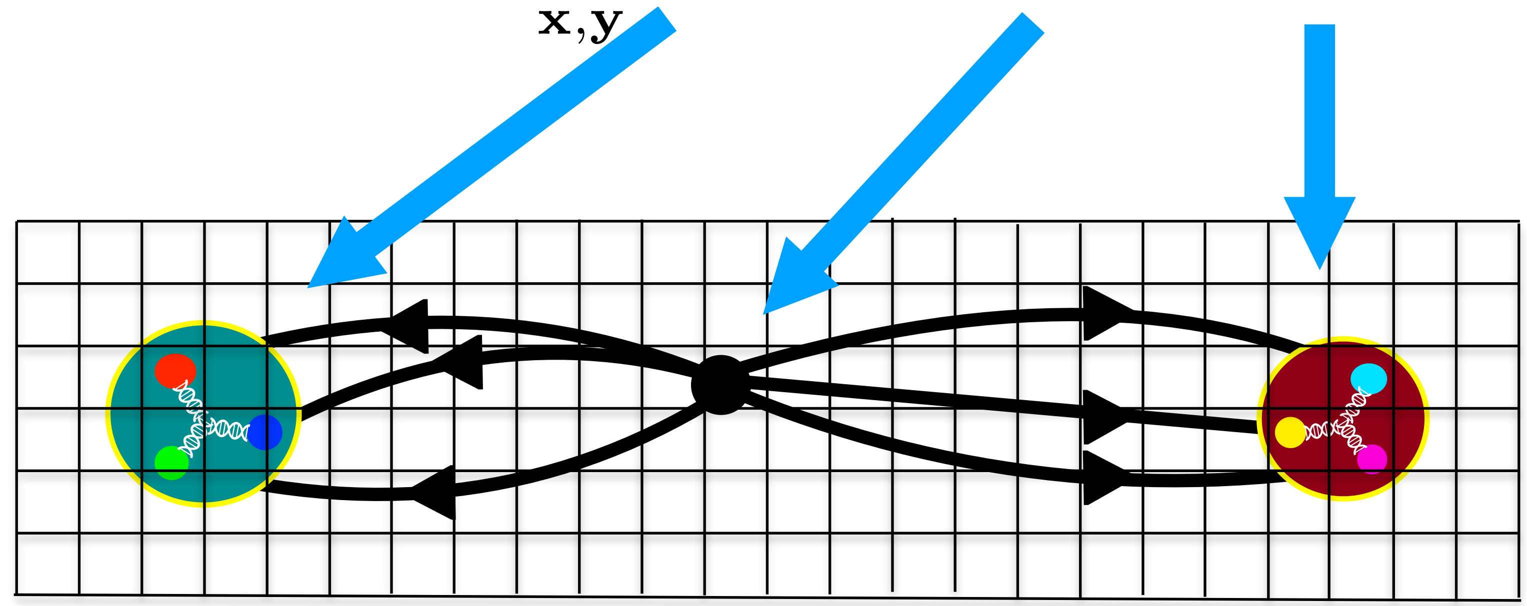
Effective mass: $M_n(t) = -\partial_t \ln G_n(t)$



$n\bar{n}$ Matrix Elements

$n\bar{n}$ correlation function includes Q_I between (anti)neutron source and sink

$$G_I^{n\bar{n}}(t,\tau) = \int \mathcal{D}\bar{q}\mathcal{D}q\mathcal{D}U e^{-S_{QCD}} \sum_{\mathbf{x},\mathbf{y}} n(\mathbf{x}, t-\tau)\ Q_I^\dagger(0)\ n(\mathbf{y}, -\tau)$$



Rinaldi, Sryitsyn, MW et al, PRL 122 (2019) Rinaldi, Sryitsyn, MW et al, PRD 99 (2019)

Ratio of $n\bar{n}$ and neutron correlation functions gives matrix elements plus excited state effects

$$\frac{G_I^{n\bar{n}}(t,\tau)}{G_n(t)} = \mathcal{M}_I + \mathcal{A}_I e^{-\delta_n t} + \mathcal{B}_I e^{-\delta_n \tau} + \mathcal{C}_I e^{-\delta_n (t-\tau)}$$

Non-Perturbative Renormalization

Lattice regularized operators require renormalization

RI/MOM scheme convenient for LQCD matrix elements

Martinelli et al, Nucl Phys B445 (1995)

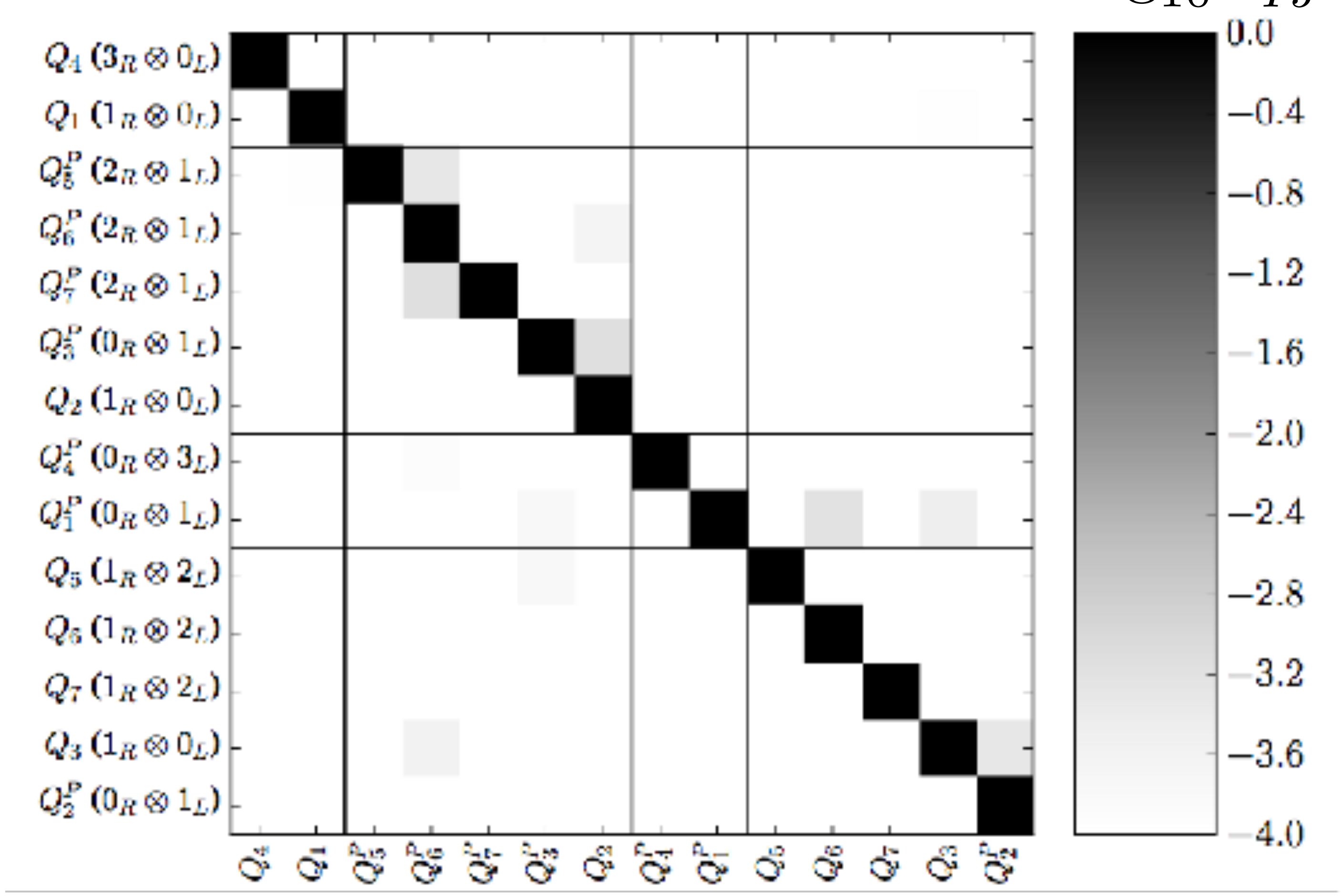
$$Z_q^{RI}(\mu)^3 Z_{IJ}^{RI}(\mu)\Lambda_J(\mu) = \Lambda_I^{tree}(\mu)$$

Quark field renormalization

Blum et al (RBC, UKQCD), PRD 93 (2016)

Vertex function

Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)



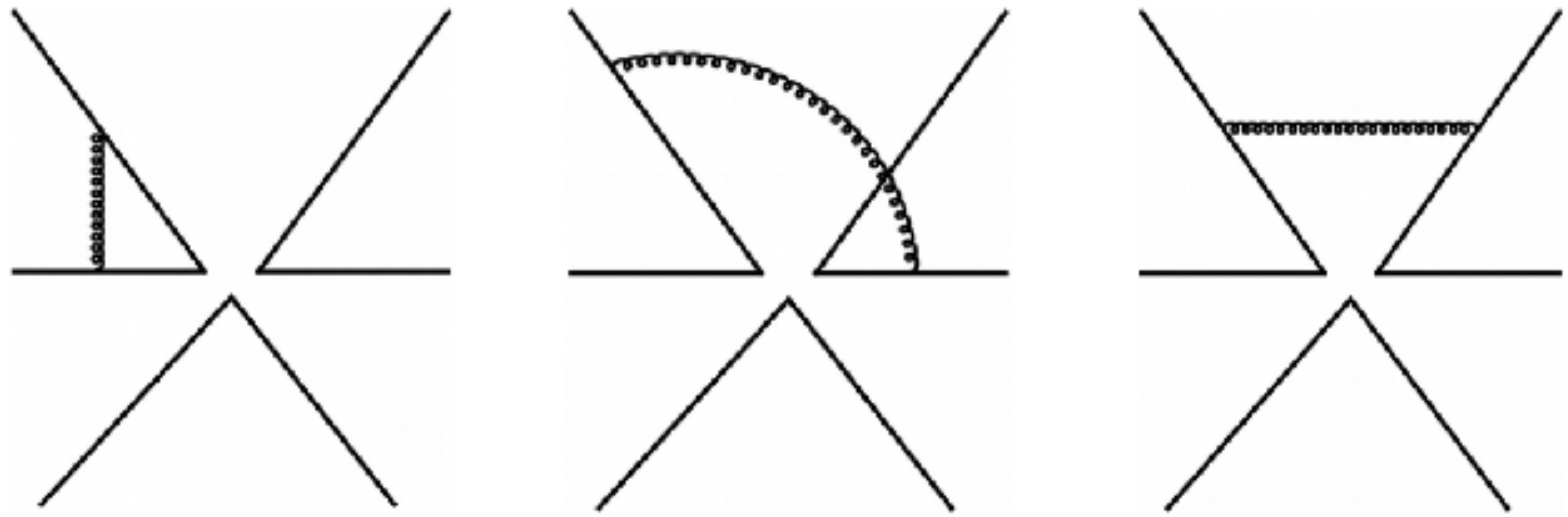
Matrix of renormalization factors diagonal up to 10^{-3}

Negligible mixing from quark mass effects, lattice artifacts, non-perturbative $U_1(A)$ violation

One-Loop Matching

One-loop running (leading log): Caswell and Milutinovic, Phys. Lett. 122B (1983)

One-loop matching (next-to-leading-log) from finite parts of computed using same RI/MOM scheme as non-perturbative renormalization



15 one-loop diagrams in 3 topologies

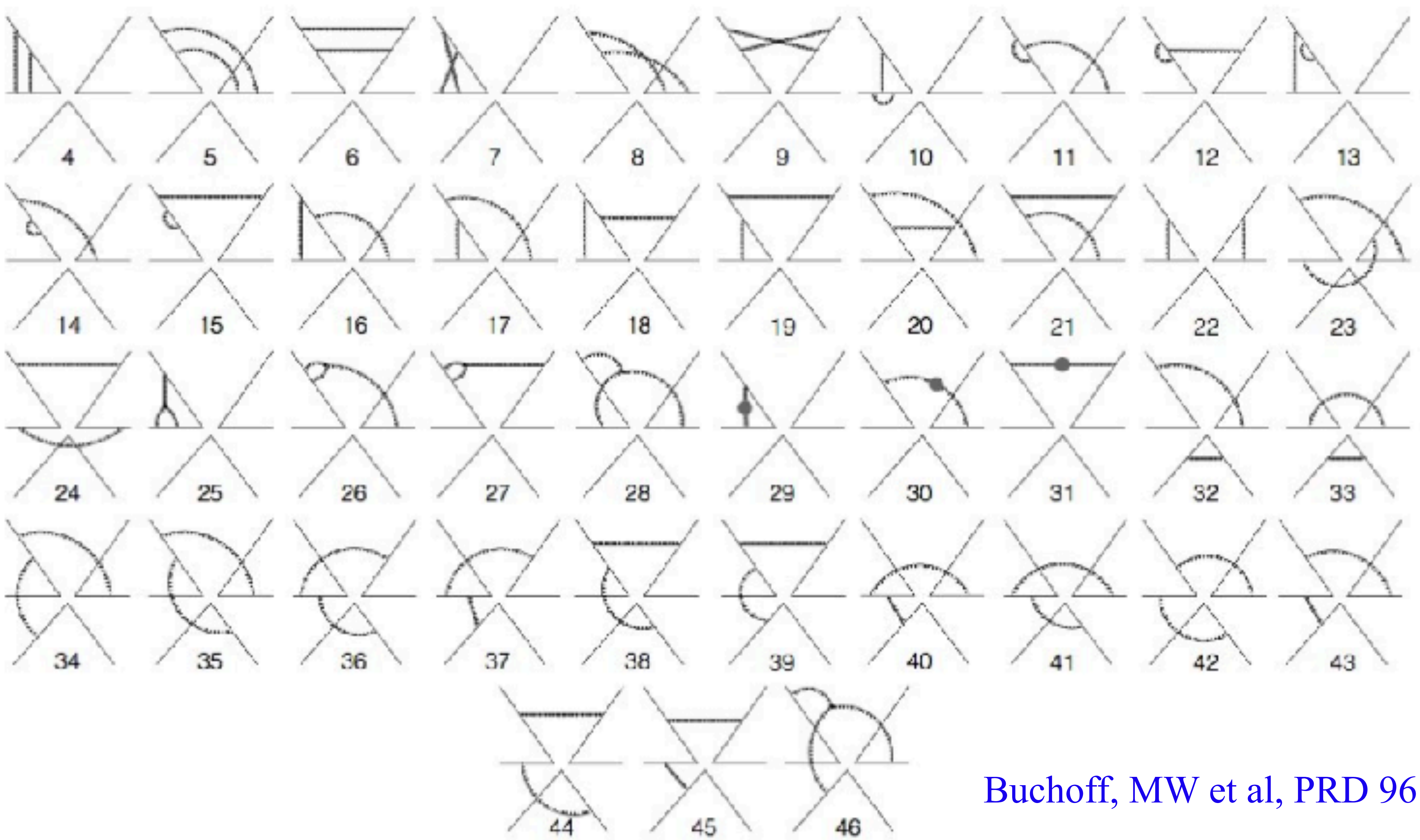
Buchoff, MW et al, PRD 96 (2016)

All topologies identical to four-quark weak matrix element diagrams with a pair of spectator quarks, integrals can be checked against literature

Two-Loop Running

Two-loop running (next-to-leading-log)

350 two-loop diagrams in 46 topologies. Several new to literature



Buchoff, MW et al, PRD 96 (2016)

Evanescent operators (zero in D=4 but present in dimensional regularization) lead to non-flavor-blind counterterms unusual in QCD

$n\bar{n}$ Error Budget (Q_1)

• Statistics Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)	• 27% uncertainty
• Excited states Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)	• 4% uncertainty
• Discretization effects	• 3% estimated uncertainty
• Finite volume Bijnens and Kofoed, Eur Phys J C 77 (2017)	• 1% estimated uncertainty
• Quark mass dependence Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)	• 1% estimated uncertainty (isospin breaking)
• Non-perturbative renormalization Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)	• 57% effect
• 1-loop RG evolution Caswell and Milutinovic, Phys. Lett. 122B (1983)	• 36% effect $\mu = 2\text{ GeV} \rightarrow \Lambda_{BSM} = 700\text{ TeV}$
• 2-loop RG evolution Buchoff, MW et al, PRD 96 (2016)	• 9% effect $\mu = 2\text{ GeV} \rightarrow \Lambda_{BSM} = 700\text{ TeV}$
• 1-loop renorm scheme matching Buchoff, MW et al, PRD 96 (2016)	• 8% effect

QCD $n\bar{n}$ Results

Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)

	$\mathcal{M}_I^{\overline{\text{MS}}}(700\text{ TeV})\ [10^{-5}\text{ GeV}^6]$
Q_1	$-26(7)$
Q_2	$144(26)$
Q_3	$-47(11)$
Q_5	$-0.23(10)$

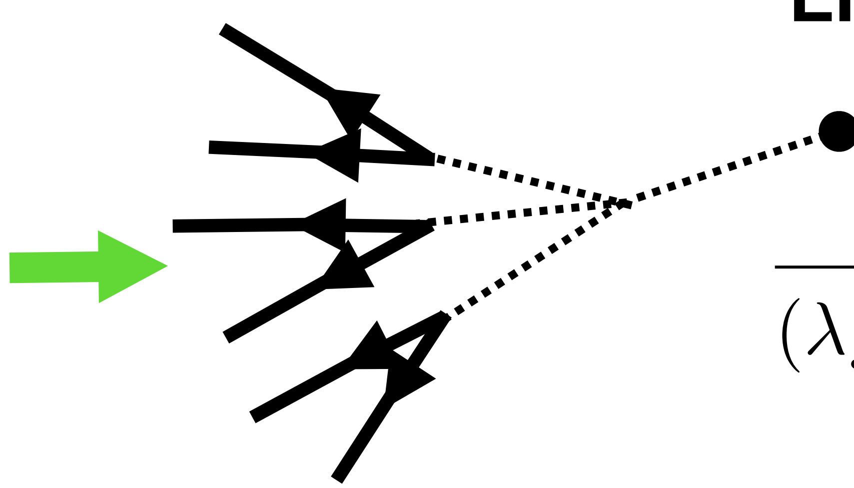
Standard Model EFT:

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

LR-symmetric example:

ILL:

$$\tau_{n\bar{n}} > 0.89 \times 10^8\text{ s}$$



$$\frac{\Lambda_{BSM}}{(\lambda f^3 \widetilde{v}_{B-L})^{1/5}} > 390 \pm 22\text{ TeV}$$

Experimental Implications

Rinaldi, Sryitsyn, MW et al, PRL 122 (2019) Rao, Shrock, Nucl. Phys. B 232 (1984)

	$\mathcal{M}_I^{\overline{\text{MS}}}(700\ \text{TeV})\ [10^{-5}\ \text{GeV}^6]$	$\text{MIT Bag} \times \text{RG}\ [10^{-5}\ \text{GeV}^6]$
Q_1	$-26(7)$	$-6.4,\ -5.2$
Q_2	$144(26)$	$16,\ 19$
Q_3	$-47(11)$	$-9.1,\ -7.6$
Q_5	$-0.23(10)$	$-0.28,\ 0.15$

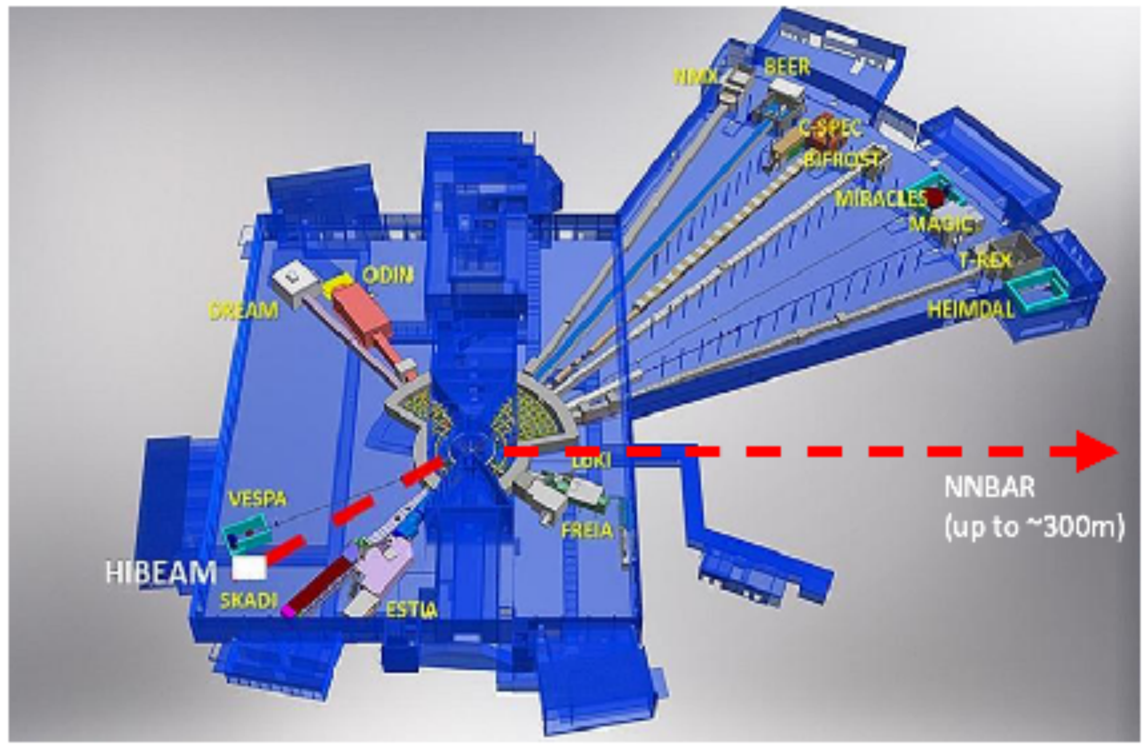
For fixed BSM parameters, QCD predicts experimental sensitivity is **25 - 64 times higher** than predicted using MIT bag model

$$N_{events} \propto \tau_{n\bar{n}}^{-2} \approx \left(\sum_{I=1}^{3} \widehat{C}_I^{\overline{\text{MS}}}(\Lambda_{BSM}) \mathcal{M}_I^{\overline{\text{MS}}}(\Lambda_{BSM}) \right)^2$$

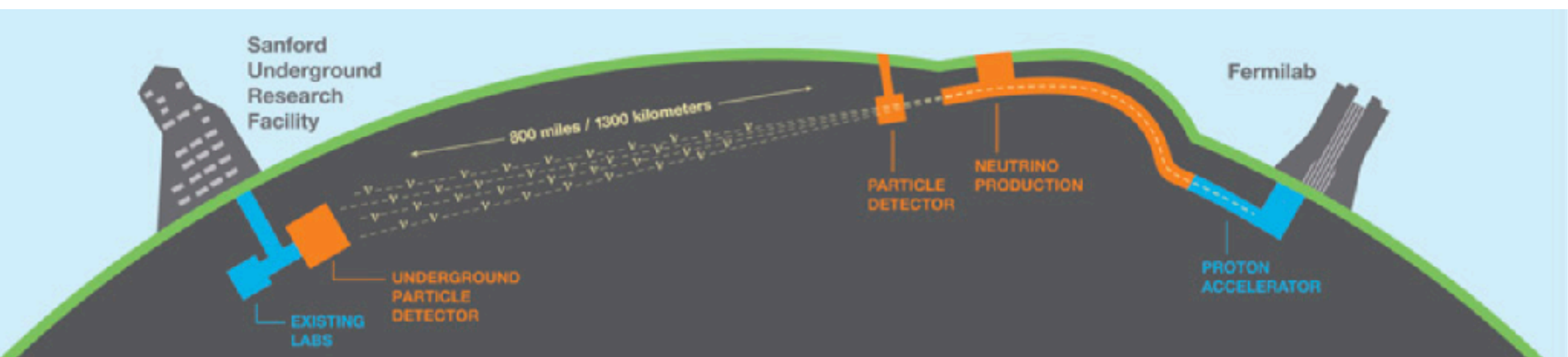
For $SU(2)_L \times SU(2)_R \times SU(4)_C$ BSM Higgs mass/coupling lower bound from ILL **390 TeV** instead of **290 TeV**

Experimental Outlook

Future experiments at ESS will significantly improve direct bounds on $\tau_{n\bar{n}}$



DUNE and Hyper-K will improve bounds on *B*-*L* violation in nuclei



$n\bar{n}$ in EFT

At the hadronic level, $|\Delta B| = 2$ interactions lead to a Majorana mass term for the neutron

$$\mathcal{L}^{(2)}_{|\Delta B|=2} = -\delta m \; n^{c\dagger} n + \text{h.c.} + \ldots$$

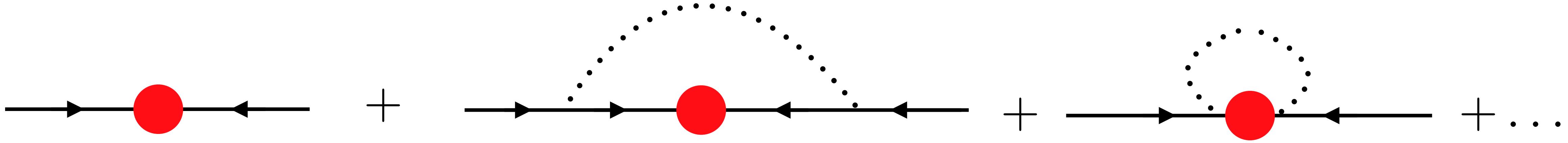
$n\bar{n}$ oscillation rate can be identified with Majorana mass

$$\tau^{-1}_{n\bar{n}} = < \bar{n} | H_{n\bar{n}} | n > = \delta m + \ldots$$

$\mathcal{O}(m_\pi^2/\Lambda_\chi^2)$ corrections arise from pion loops, including couplings to (non-chiral-singlet) operator insertions

Bijnens and Kofoed, Eur Phys J C 77 (2017)

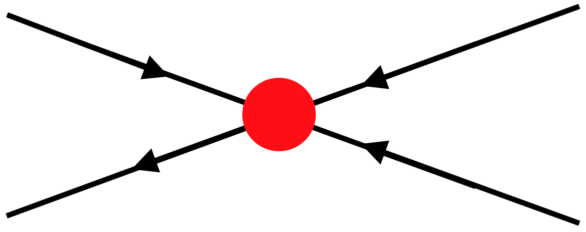
Single-nucleon EFT used to determine finite-volume effects on $\mathcal{M}_I$



Intranuclear $n\bar{n}$ in EFT

In the two-nucleon sector, *B-L* violating interactions lead to additional contact operator

$$\mathcal{L}^{(4)}_{|\Delta B|=2} = i\widetilde{B}_0 \left[(N^T P_i N)^\dagger (N^{cT} \tau^2 Y_i^- N) - \mathrm{h.c.} \right] + \ldots$$



Oosterhof, Long, de Vries, Timmermans, van Kolck, PRL 122 (2019)

Deuteron decay rate calculated through optical theorem

$$\Gamma_d = -(\delta m)^2 \frac{m_N}{\kappa} \mathrm{Im}[a_{\overline{n}p}] \left(1 + 0.47 - \frac{(\kappa - \mu)\mathrm{Im}[\widetilde{B}_0]}{\sqrt{2}\pi\delta m \ \mathrm{Im}[a_{\overline{n}p}]} \right)$$

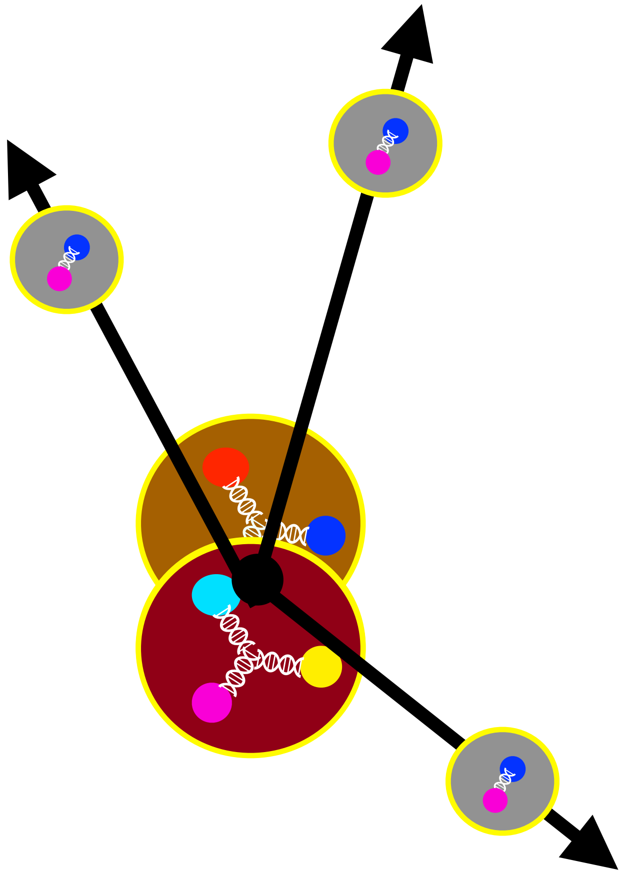
$$\approx -(\delta m)^2 \frac{m_N}{\kappa} \mathrm{Im}[a_{\overline{n}p}] \, (1.47 \pm 0.4)$$

Deuteron decay

EFT result determines nuclear suppression factor

$$R_d \equiv \Gamma_d^{-1}/\tau_{n\bar{n}}^2 \;\; = (1.1 \pm 0.3) \times 10^{22} s^{-1}$$

Oosterhof, Long, de Vries, Timmermans, van Kolck, PRL 122 (2019)



Result ~2x smaller than previous optical potential models

Dover, Gal, Richard PRD 27 (1983)

Combining with LQCD result,

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

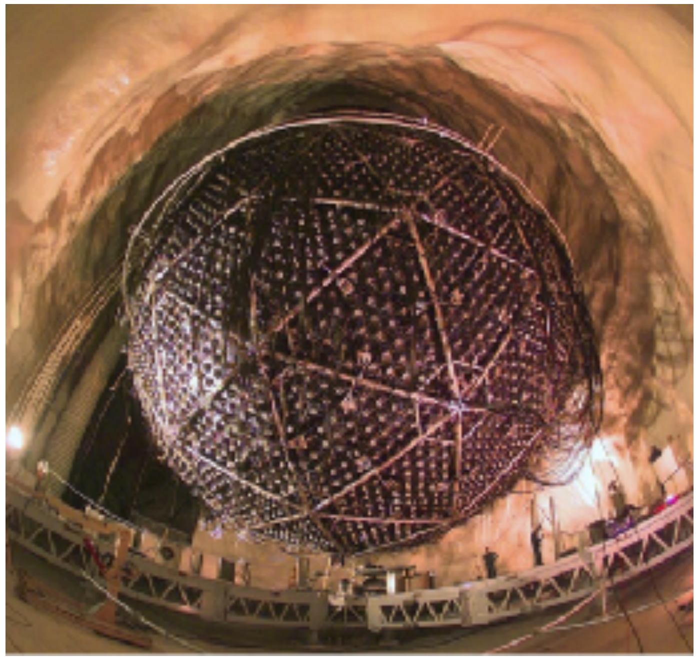
Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)

experimental constraints on deuteron lifetime can be used to constrain parameters of BSM theories of *B-L* violation

Deuteron decay searches

Experimental constraints on deuteron lifetime obtained from SNO

SNO



$$\Gamma_d^{-1} > 1.18 \times 10^{31} \text{ years}$$

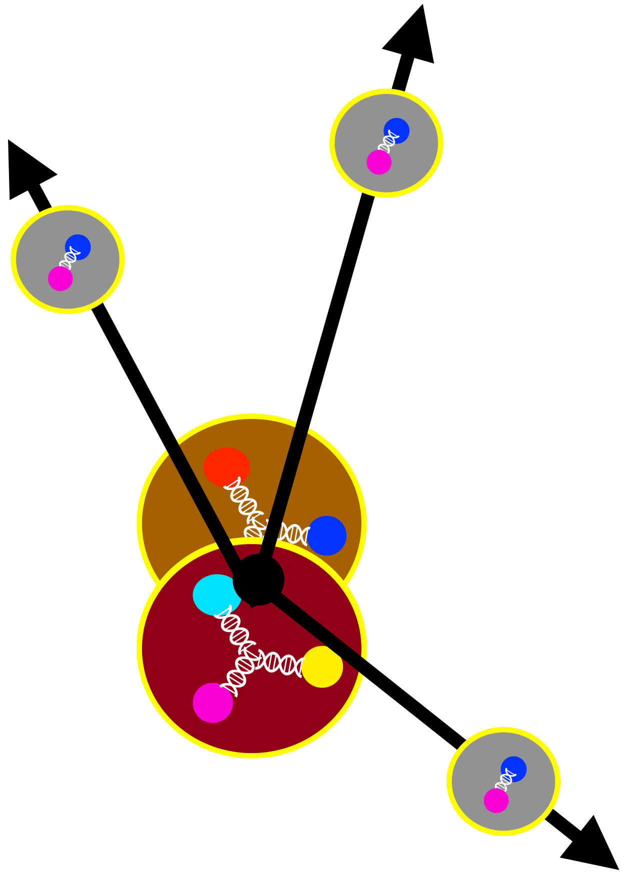
Aharmin et al (SNO), PRD 96 (2017)

SNO + EFT: $\tau_{n\bar{n}} > 1.6 \times 10^8$ s

Oosterhof, Long, de Vries, Timmermans, van Kolck, PRL 122 (2019)

*However, see Haidenbauer, Ulf-G. Meißner, Chinese Physics C 44 (2020)

SNO + EFT + LQCD: $$\frac{\Lambda_{BSM}}{(\lambda f^3 \widetilde{v}_{B-L})^{1/5}} > 439 \text{ TeV}$$

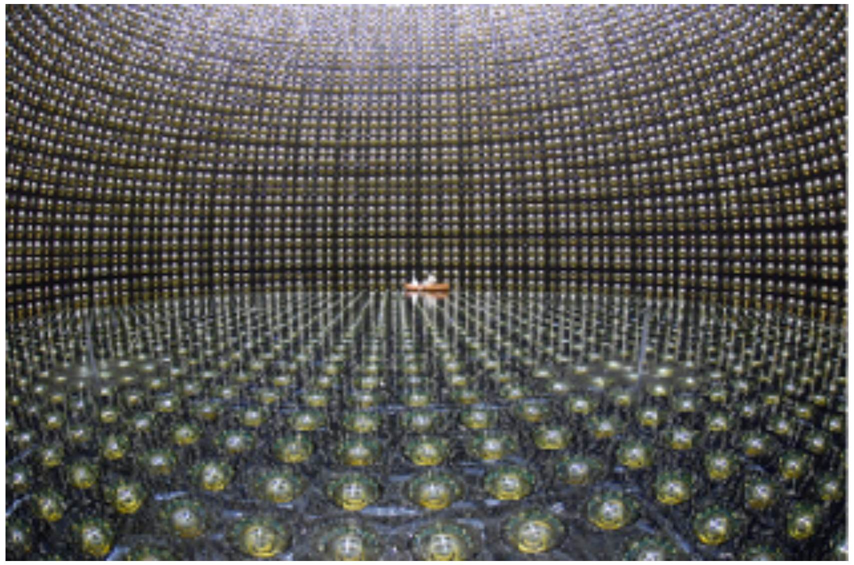


Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)

Oxygen decay searches

Super K extracts stronger but more theoretically uncertain bounds from oxygen decay

Super K



Nuclear optical potential model

$$R_O \approx 5.17 \times 10^{22}\ \mathrm{s}^{-1}$$

Friedman, Gal, PRD 78 (2008)

Super K constraint $\Gamma^{-1}_{O^{16}} > 19 \times 10^{31}$ years

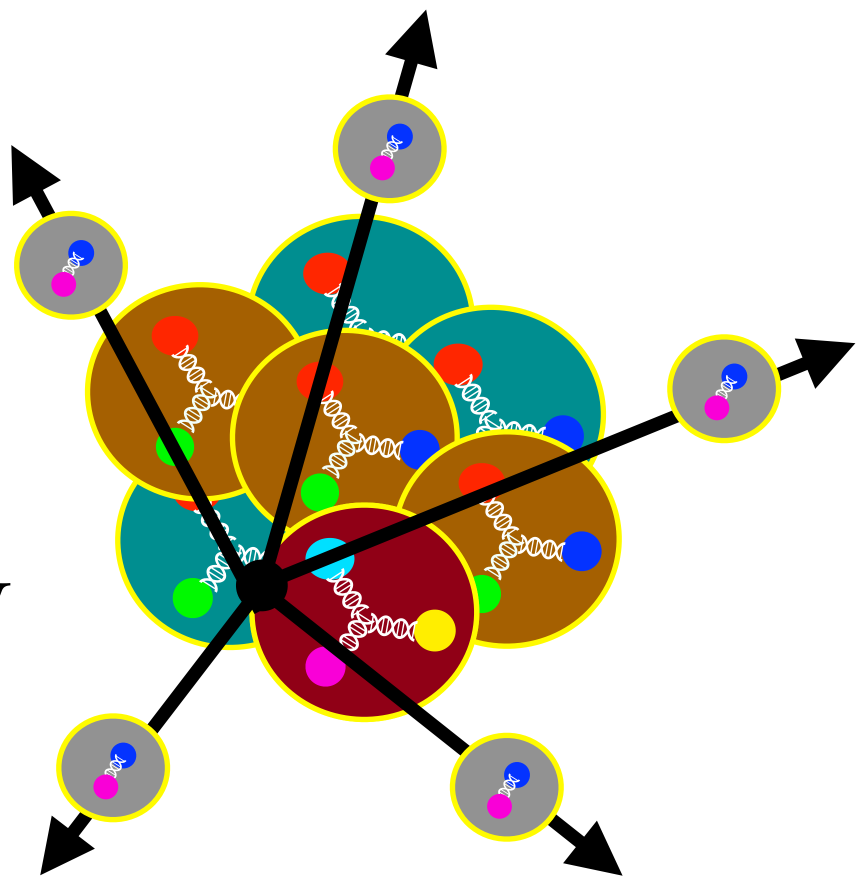
Abe et al (Super K), PRD 91 (2015)

Super K + optical potential $\tau_{n\bar{n}} \gtrsim 2.7 \times 10^{8}\ \mathrm{s}$

Super K + optical potential + LQCD:

$$\frac{\Lambda_{BSM}}{(\lambda f^3 \widetilde{v}_{B-L})^{1/5}} \gtrsim 480\ \mathrm{TeV}$$

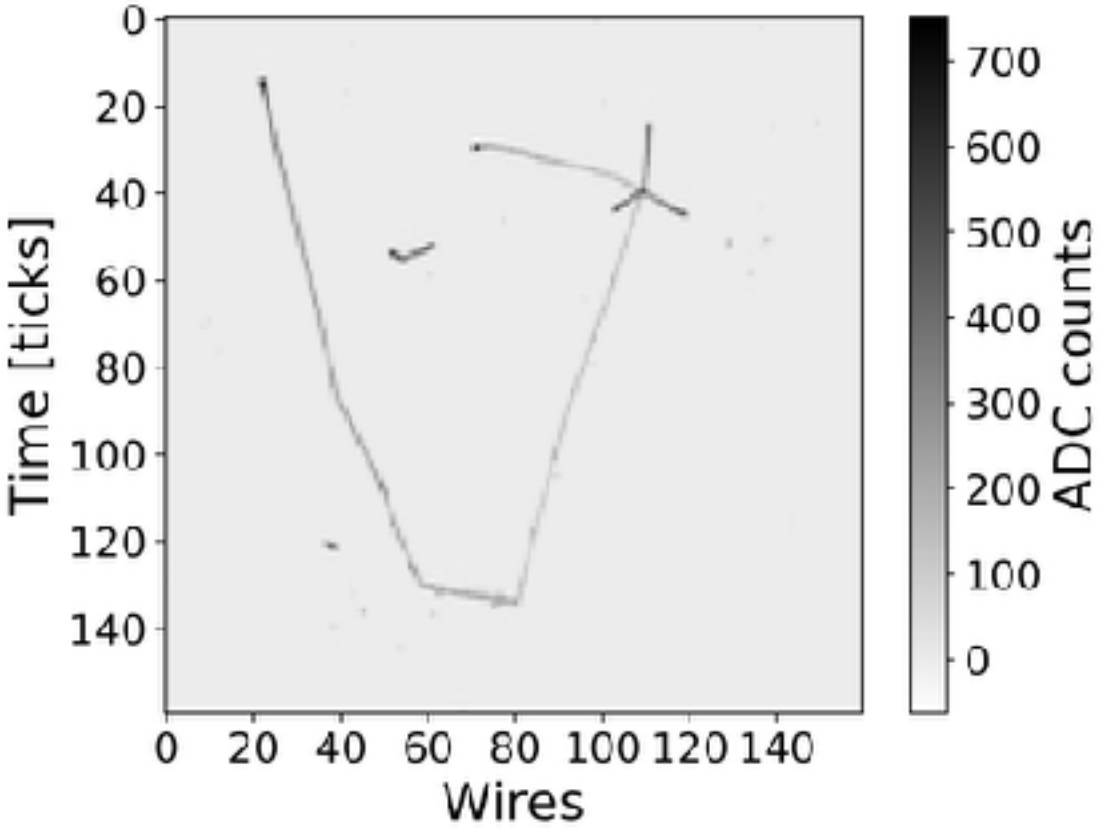
Rinaldi, Sryitsyn, MW et al, PRL 122 (2019)



Argon decay searches

DUNE and Hyper-K will probe *B-L* violation in nuclei at even higher scales

Dominant $|\Delta B| = 2$ decays have clear multi-pion signatures at DUNE



J. Hewes, PhD Thesis (2017)

Argon nuclear suppression factor computed in optical potential model

$$R_{Ar} \sim 5.6 \times 10^{22}\ \mathrm{s}^{-1}$$

Barrow, Golubeva, Paryev, Richard, PRD 101 (2020)

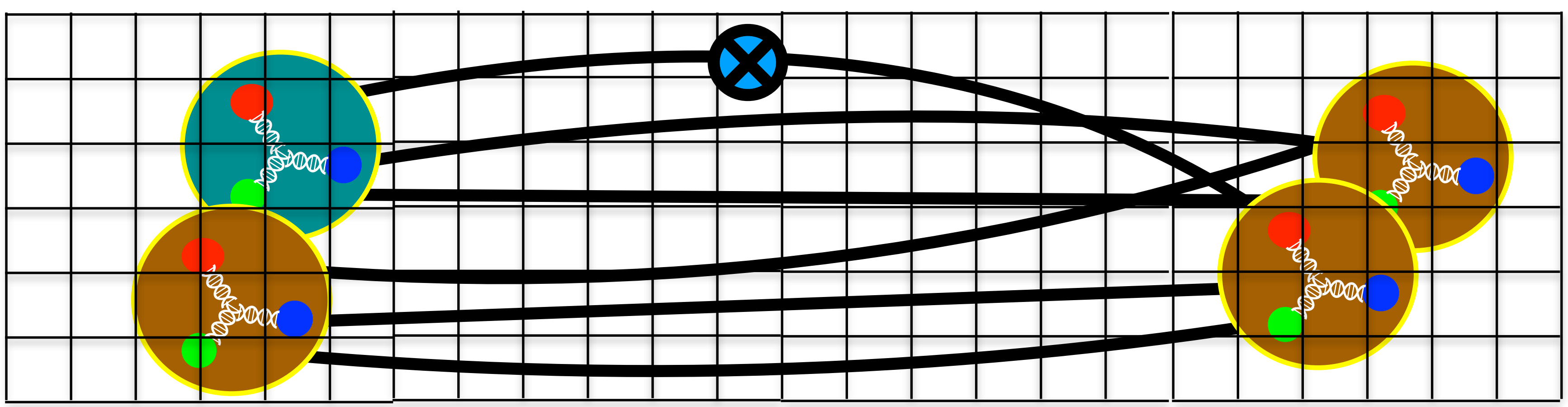
Understanding nuclear effects on in-medium $n\bar{n}$ oscillations essential for reliably interpreting future searches for *B-L* violation in nuclei

Nuclear matrix elements in LQCD

Nuclear effects governed by QCD matrix elements of same operator basis with appropriate initial / final nuclear states

$$\mathcal{M}_{I,\alpha}(N,Z) = \langle N-2, Z, \alpha | \, Q_I \, | N, Z \rangle$$

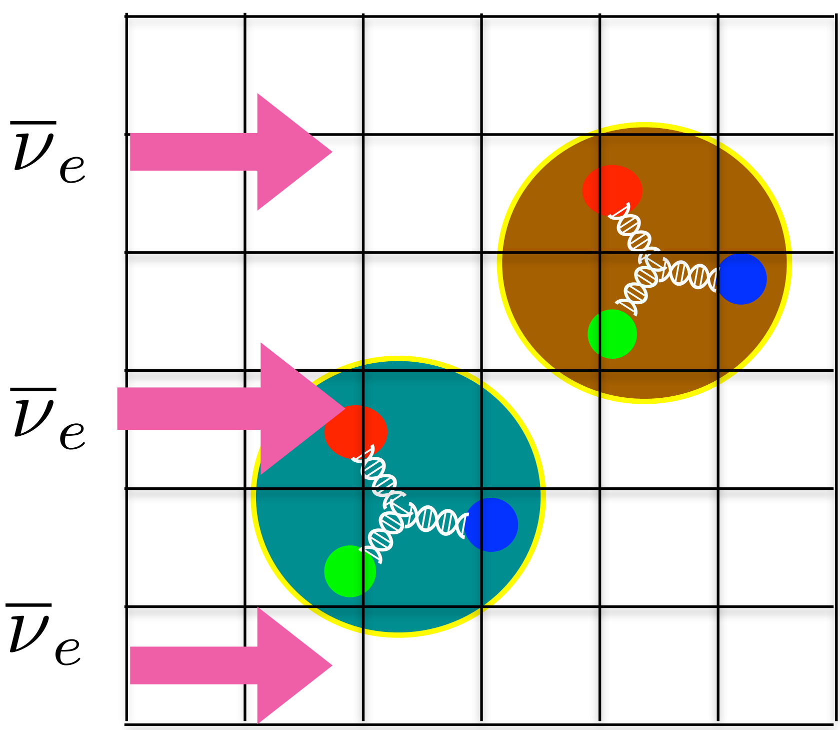
In principle, LQCD calculations of nuclear matrix elements can be performed similarly to nucleon matrix elements



Practical challenges — computational complexity of Wick contractions, low-lying excited states, signal-to-noise problem, …

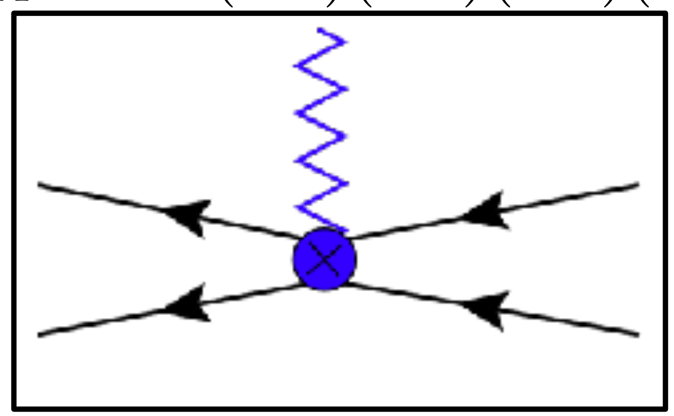
pp fusion in LQCD

1) Simulate finite-volume nuclear response to external current in LQCD



Savage et al [NPLQCD]
PRL 119 (2017)

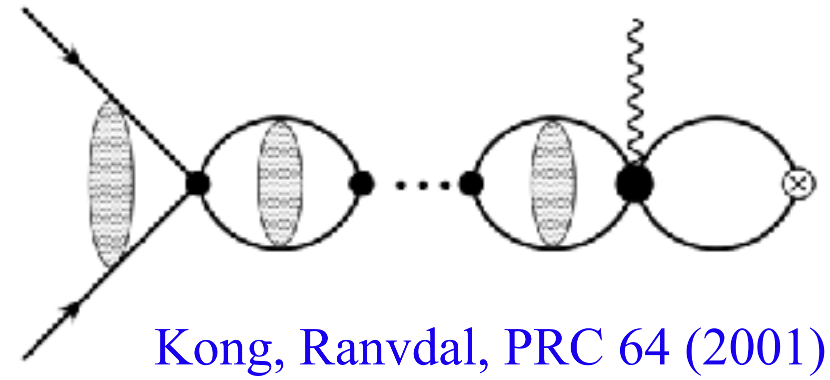
$$L_{1A} = 3.9(0.2)(1.0)(0.4)(0.9)$$



2) Calculate the same finite-volume response in EFT

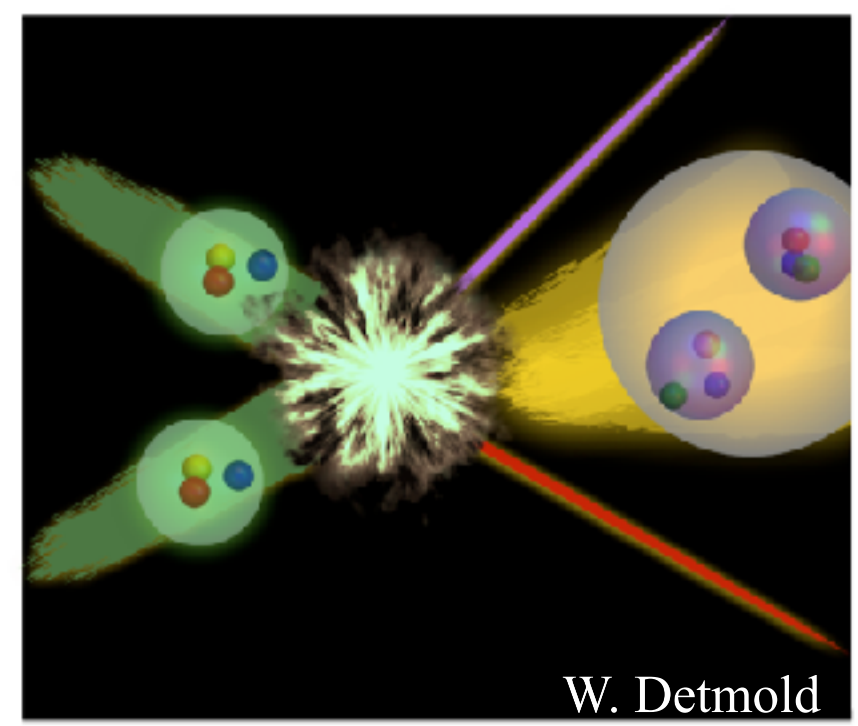
3) Fix EFT input parameters by demanding that EFT results match LQCD results

4) Compute physical reaction in EFT



Kong, Ranvdal, PRC 64 (2001)

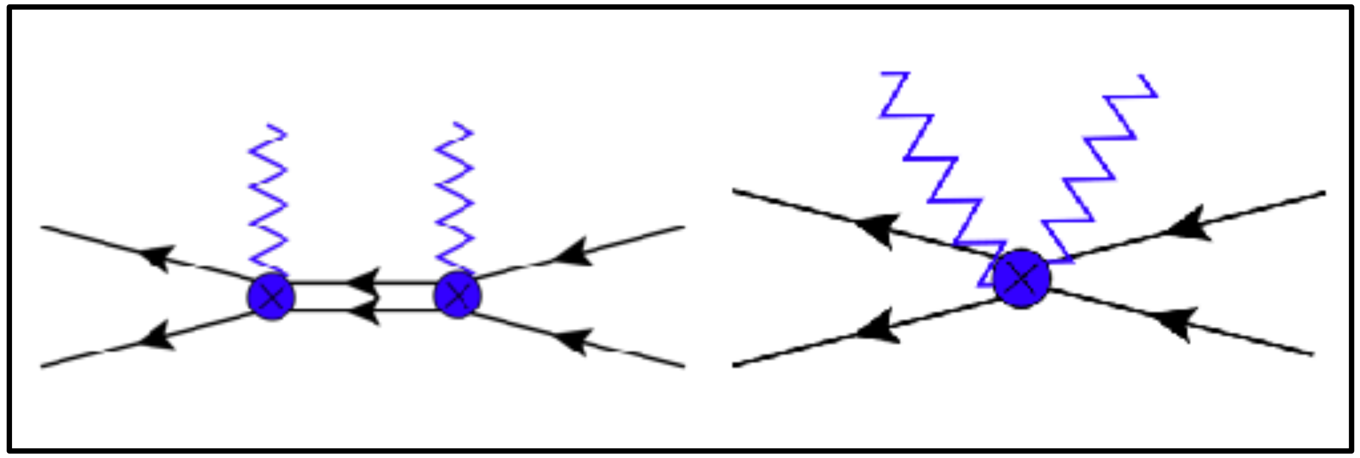
Butler, Chen, PLB 520 (2001)



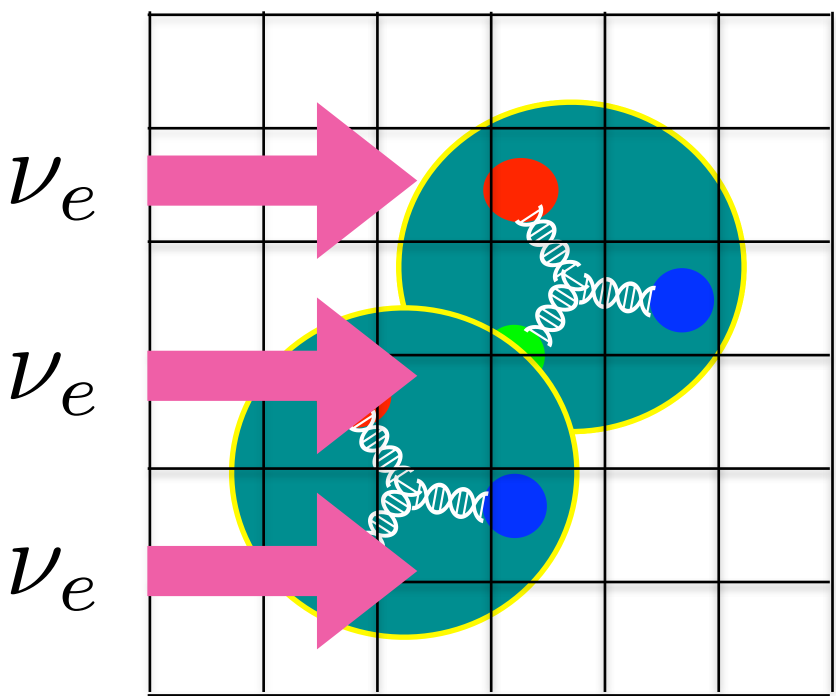
$2\nu\beta\beta$ in LQCD

See talk by Z. Davoudi tomorrow

1) Simulate finite-volume nuclear response to two external currents in LQCD



$H_{2S} = 4.7(1.3)(1.8)$ fm



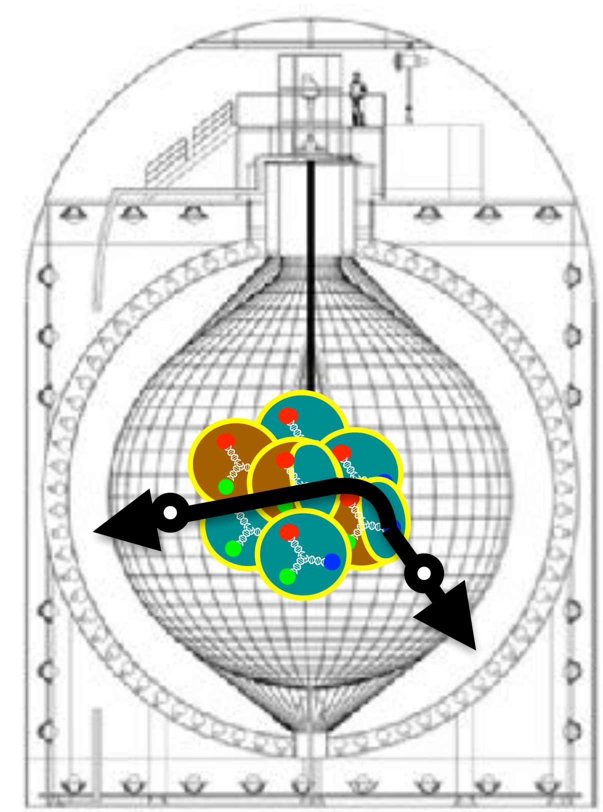
Shanahan et al [NPLQCD] PRL 119 (2017)

Tiburzi et al [NPLQCD] PRD 96 (2017)

2) Calculate finite-volume response in EFT

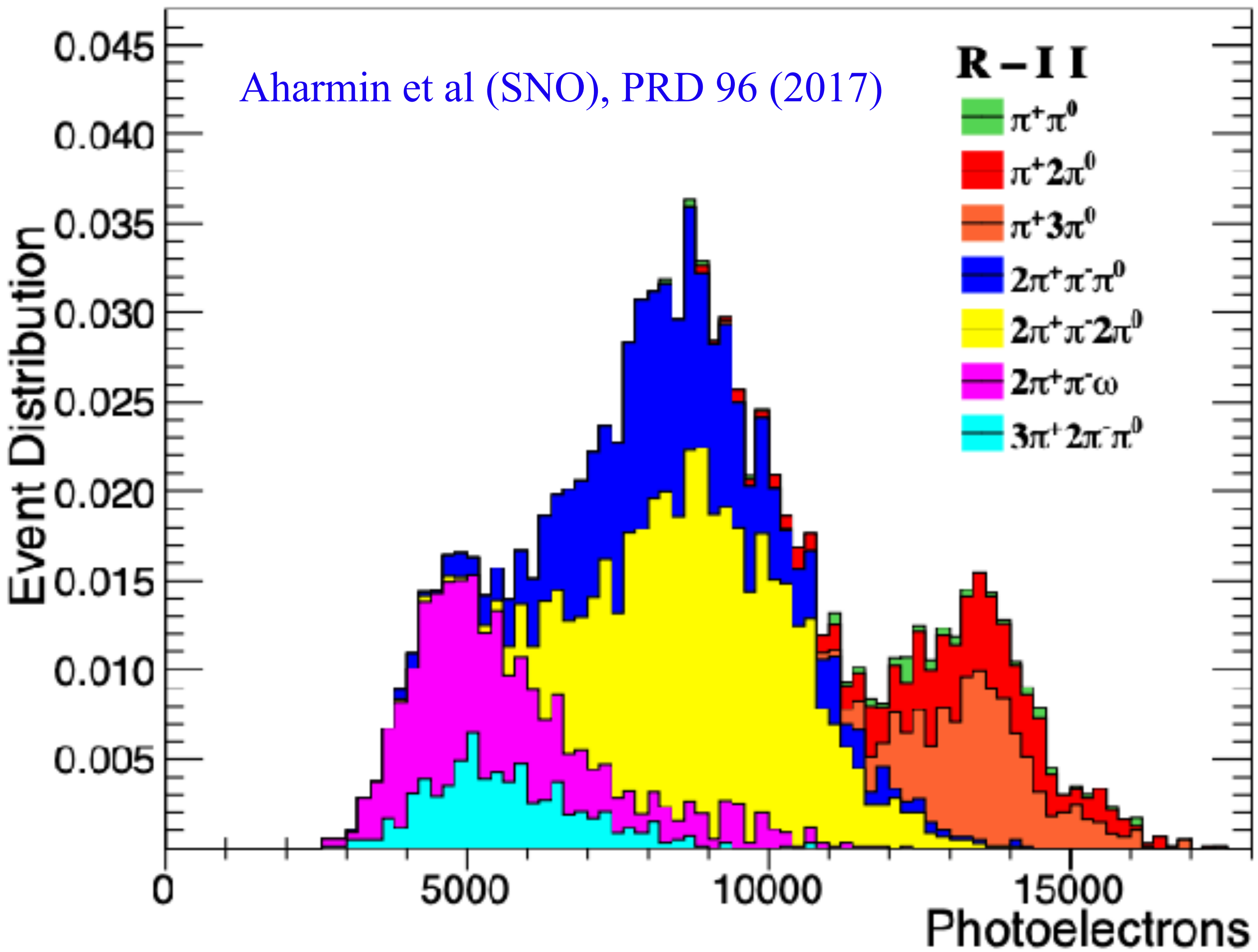
3) Fix EFT input parameters by demanding that EFT results match LQCD results

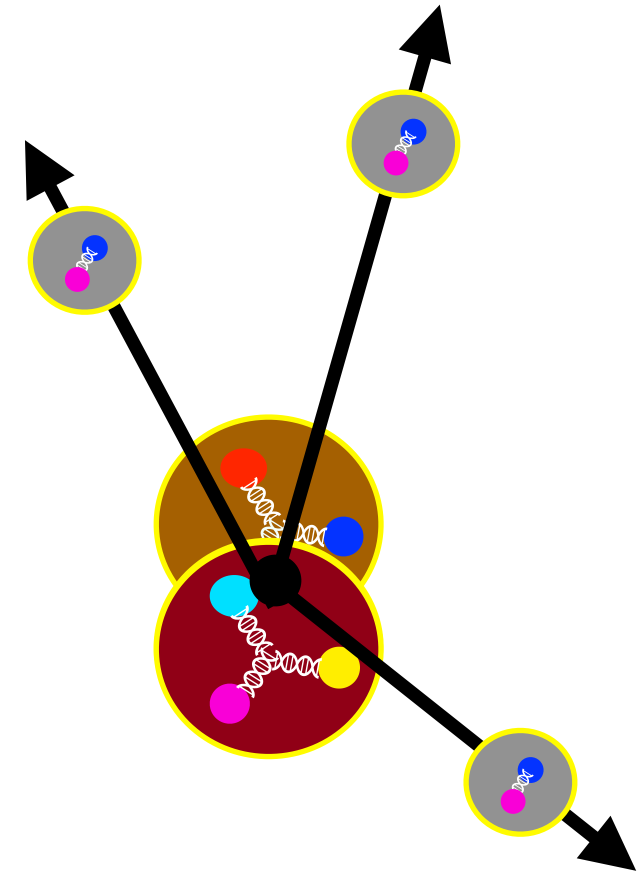
4) Compute physical reaction in EFT



Intranuclear $n\bar{n}$ in LQCD

Challenge: relevant decay modes involve multi-pion final states, even for deuteron

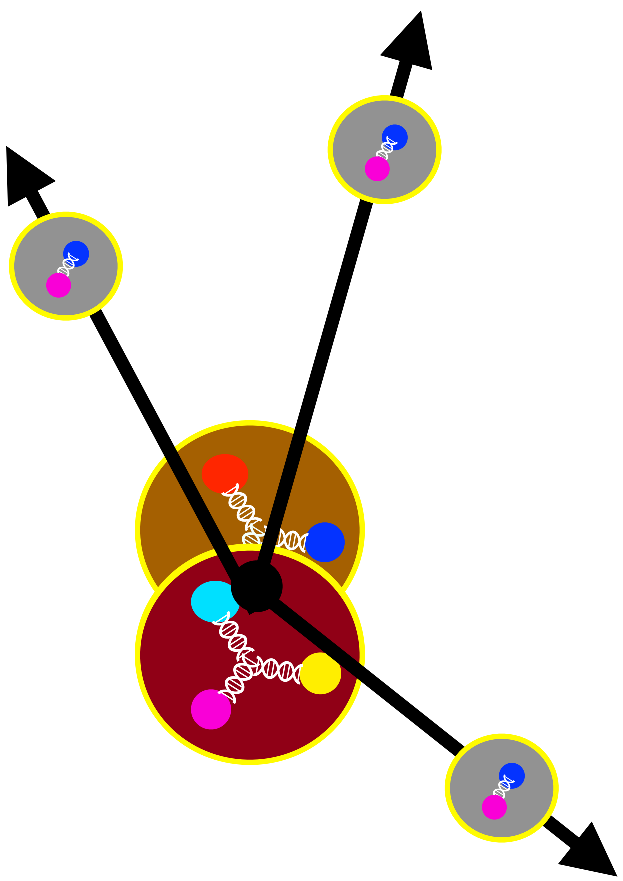




Intranuclear $n\bar{n}$ in LQCD

Challenge: relevant decay modes involve multi-pion final states, even for deuteron

Aharmin et al (SNO), PRD 96 (2017)



$$\mathcal{M}_{I,\pi^+\pi^0\pi^0}(1,1) = \langle \pi^+\pi^0\pi^0 | \, Q_I \, | d \rangle$$

Finite-volume effects for multi-hadron scattering states complicated

Lellouch Lüscher, Commun. Math. Phys. 219 (2001) … Briceño, Hansen, PRD 94 (2016) …

Finite-volume formalism for 3π scattering states recently developed, extensions to matrix elements and $\geq 4\pi$ states active research

Review: Hansen, Sharpe, Ann. Rev. Nucl. Part. Sci. 69 (2019)

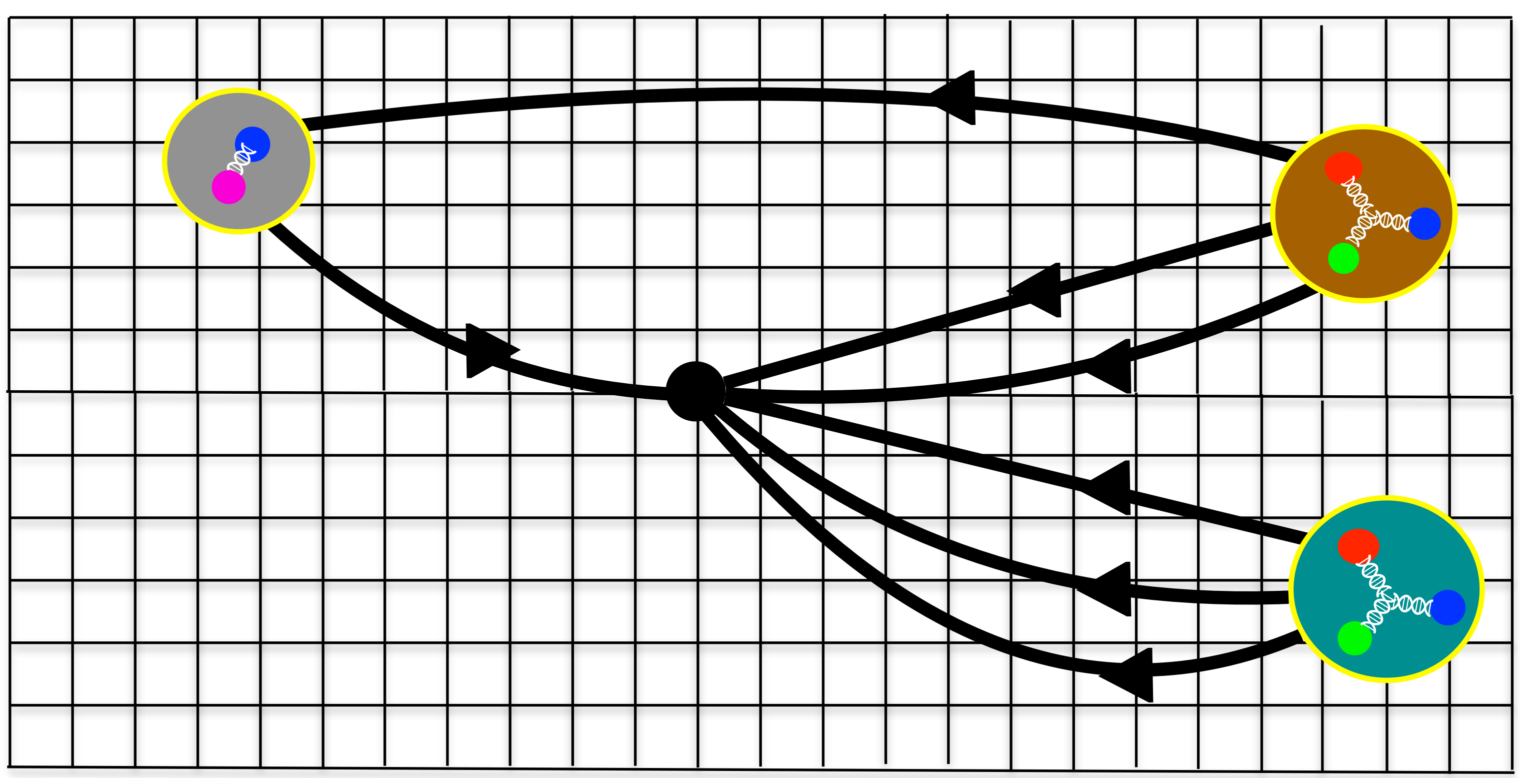
B-L violation from QCD to nuclei

Experimentally irrelevant matrix elements can still be matched between LQCD and EFT / nuclear many-body in order to constrain LECs

e.g. Shanahan et al [NPLQCD], PRL 119 (2017)

Can this be done for *B-L* violating deuteron matrix elements? e.g.

$$\mathcal{M}_{I,\pi^+}(1,1) = \langle \pi^+ | \, Q_I \, | d \rangle$$

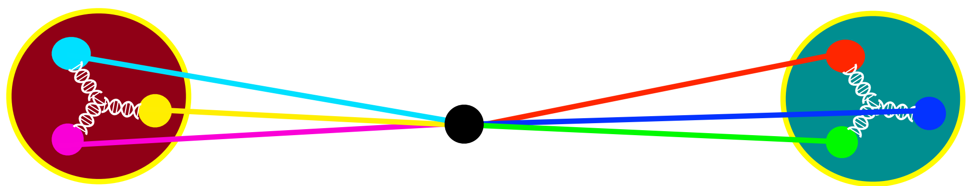


LQCD calculation challenging, but formalism exists

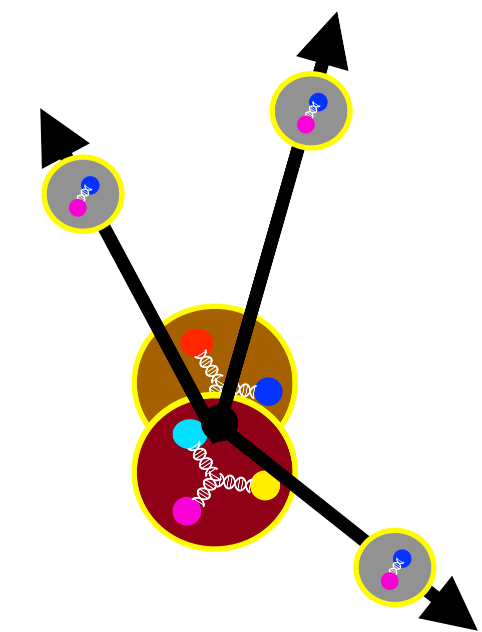
Can LQCD constrain $\widetilde{B}_0$ or nuclear many-body models of *B-L* violation?

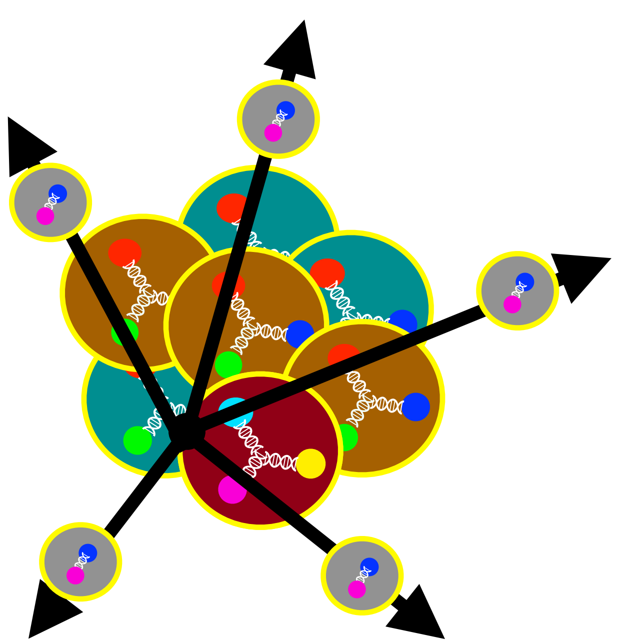
Conclusions

LQCD + SMEFT relate the $n\bar{n}$ oscillation time to fundamental parameters of *B-L* violating new physics theories with quantified uncertainties



Nuclear EFT + LQCD + SMEFT relate the deuteron decay rate to fundamental parameters of *B-L* violating new physics





Future nuclear EFT + LQCD studies could improve uncertainty quantification in *B-L* violating decays of larger nuclei