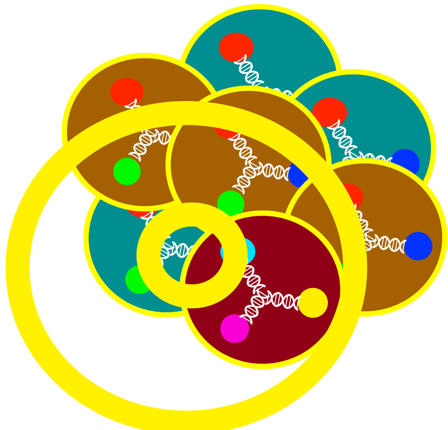
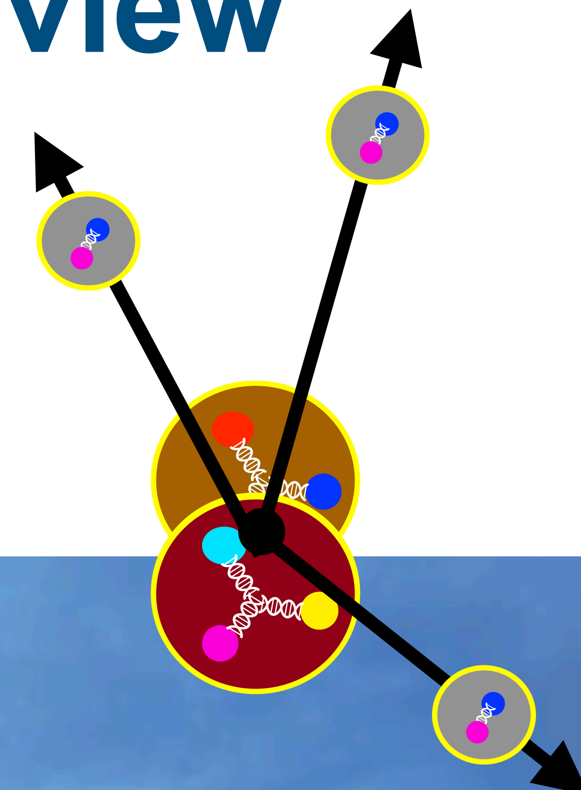
Nucleon decay:
Theory and experimental overview



Michael Wagman



NNN25

International Workshop on Next Generation
Nucleon Decay and Neutrino Detectors

October 1-3, 2025

SNOLAB sudbury

24th International Workshop on Next Generation Nucleon Decay & Neutrino Detectors (NNN25) my qualifications

Nucleon decay: Theory and experimental overview

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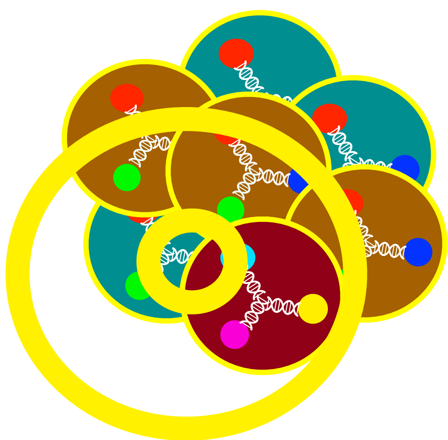

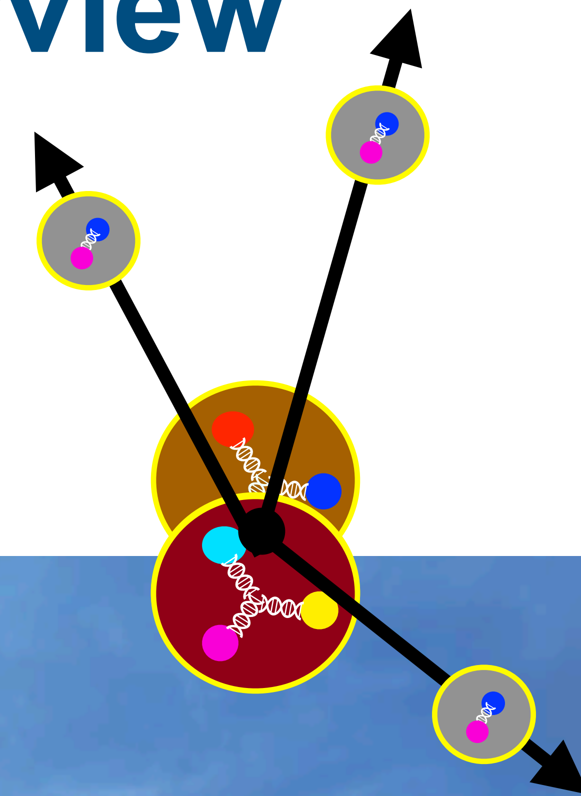

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Nucleon decay - why does it matter?

What happens to the Standard Model at very high energies?

- Theory predicts Standard Model gauge group must be embedded in a larger structure (Landau pole ~ triviality)

$$SU(3)_C \times SU(2)_L \times U(1)_Y < ???$$

- Proton decay generically predicted, but rate is model dependent

Nucleon decay - why does it matter?

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Why are there so many quarks left after the early universe?

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, Astron. Astrophys. 641, A1 (2020)

Inflationary Standard Model universe

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

Matter ↔ Antimatter

Leptogenesis

Fukugita, Yanagida, Phys. Lett. B 174 (1986)

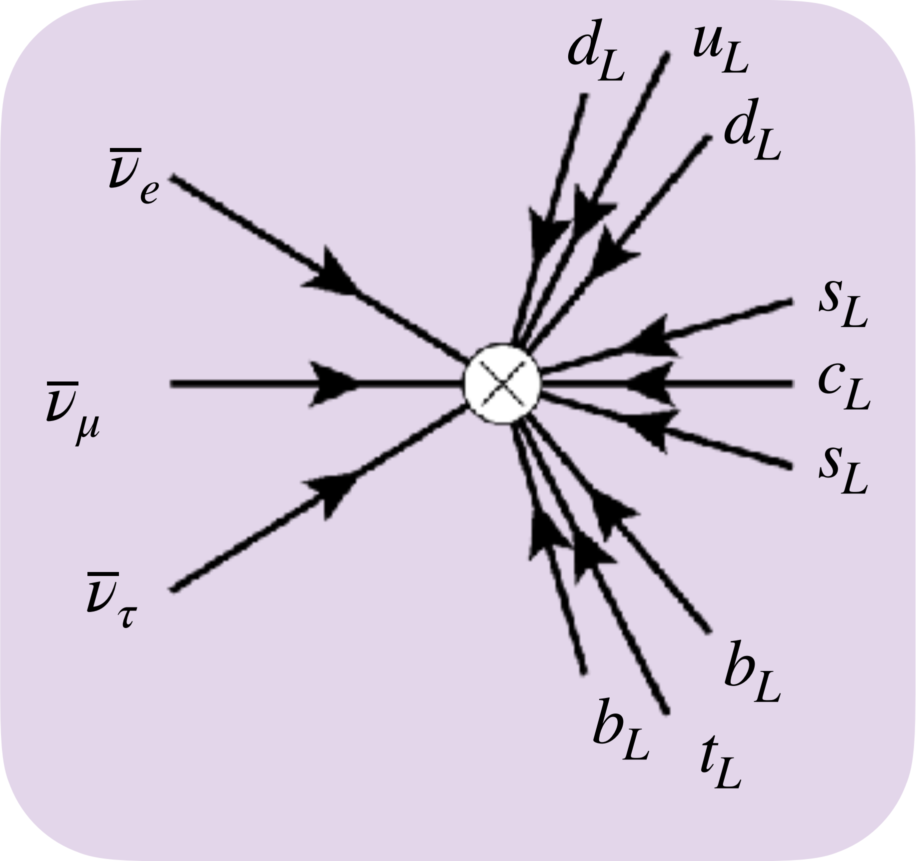
Standard Model processes can convert antileptons into quarks

't Hooft, PRL 37 (1976)

Incredibly rare at low energies, but should equilibrate in early universe

$B - L$ and CP asymmetries from Majorana neutrinos converted to B asymmetry

Electroweak sphaleron



Matter $\leftrightarrow$ Antimatter

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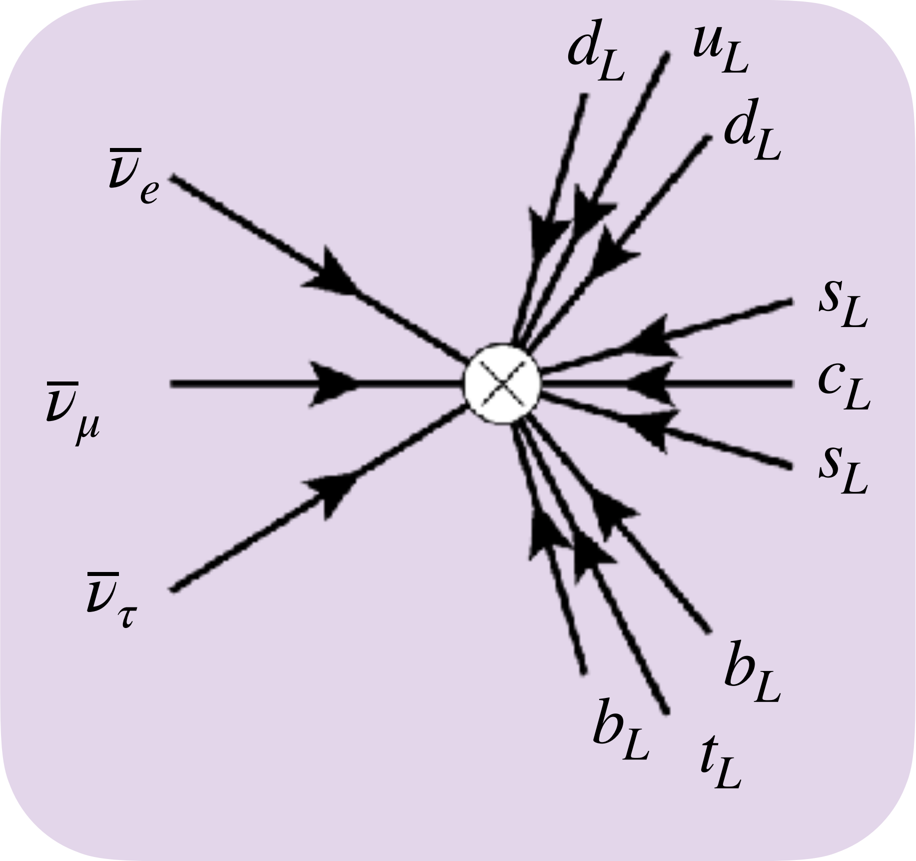
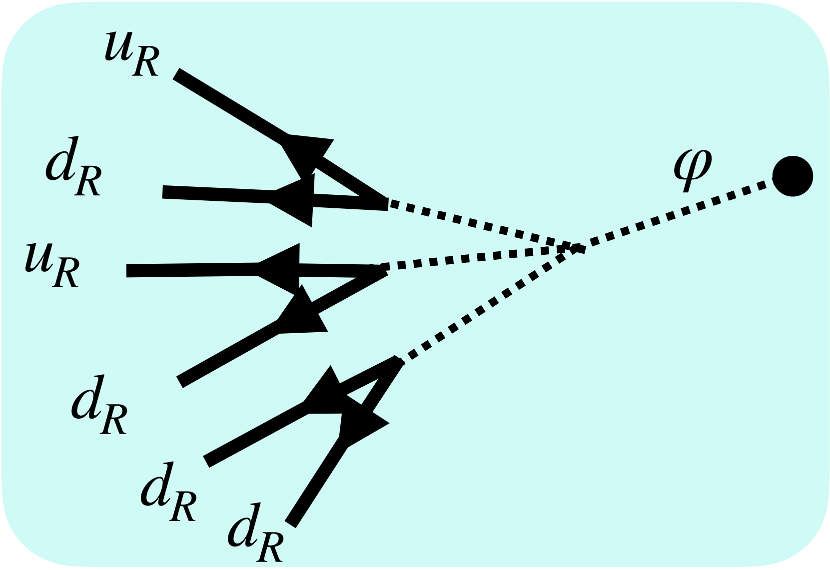


Post-sphaleron baryogenesis

Babu, Mohapatra, Nasi, PRL 97 (2006)

Mohapatra, Marshak, PRL 44 (1980), …



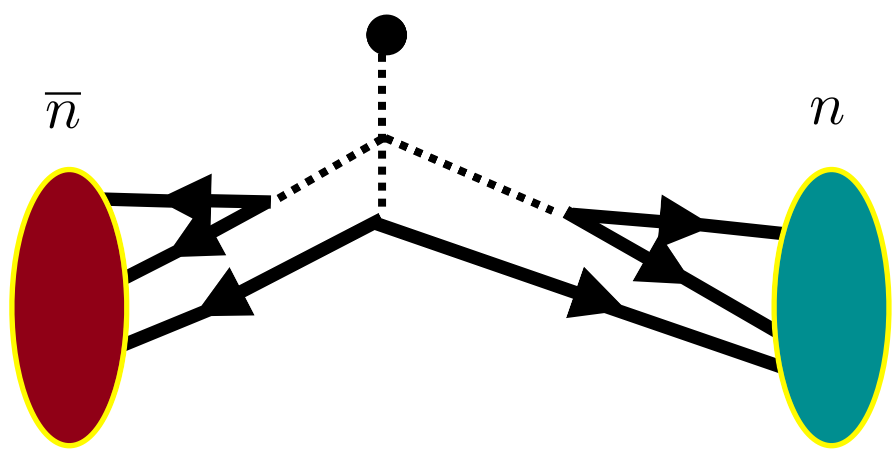
Some BSM theories include scalars coupled to diquarks, e.g. left-right symmetric models:

$$\mathcal{L} \supset y_{\alpha\beta}\,\varphi\,(q_R^{i\alpha} C q_R^{j\beta})\delta_{ij} + \ldots$$

Out-of-equilibrium scalar decays could source baryon asymmetry at relatively low energy scales

Testing post-sphaleron baryogensis?

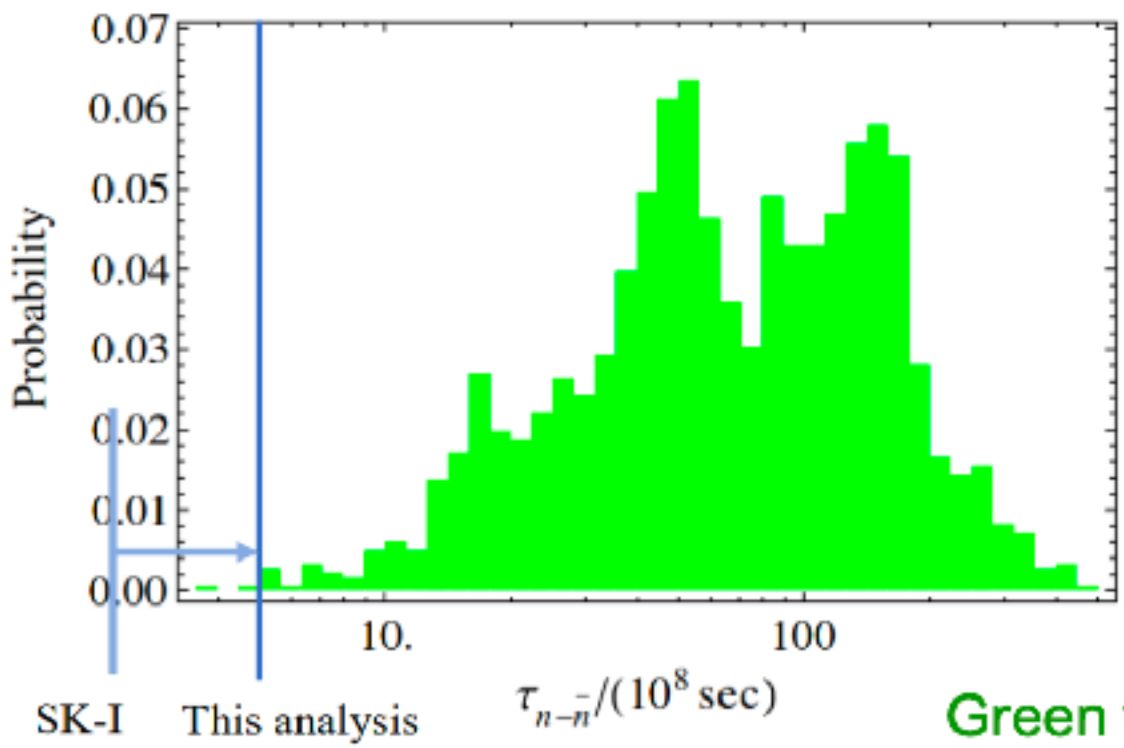
Same diagram involved in baryon asymmetry leads to neutron-antineutron oscillations



- Constraints including measured η_B lead to testable predictions for $n\overline{n}$ transition rate

Babu, Dev, Fortes, Mohapatra, PRD 87 (2013)

Experimental searches are starting to reach allowed PSB theory parameter space



Linyan Wan, INT-25-91W

Abe et al [SuperK], PRD 103 (2021)

Green from PSB model

K.S. Babu, et al, PRD 87 115019 (2013)

This result first reached the range of theoretical prediction.

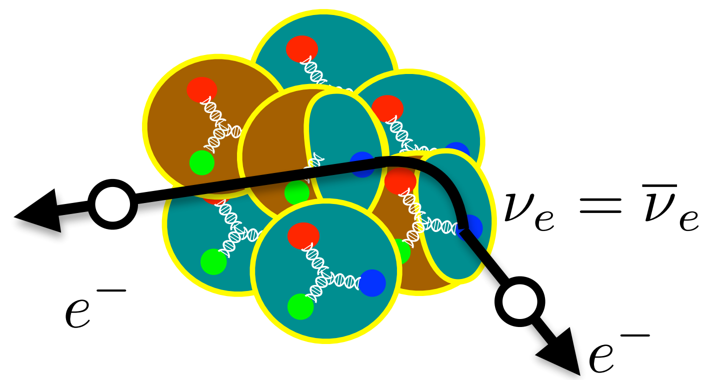
01/13/2025 NNbar Search in Large Neutrino Detectors - Linyan WAN @ INT

Predicting new physics signatures

Standard Model EFT can be used to organize generic BSM signatures

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

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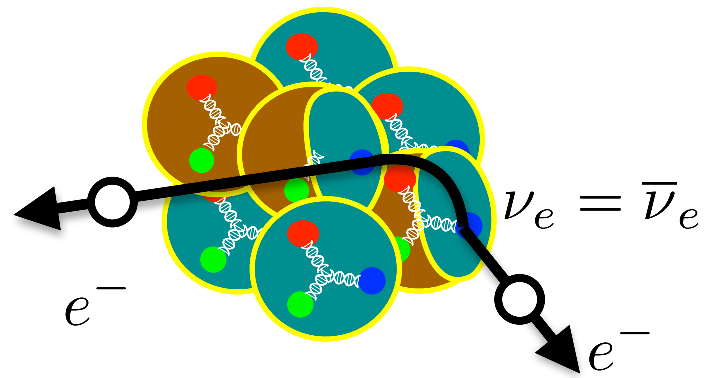


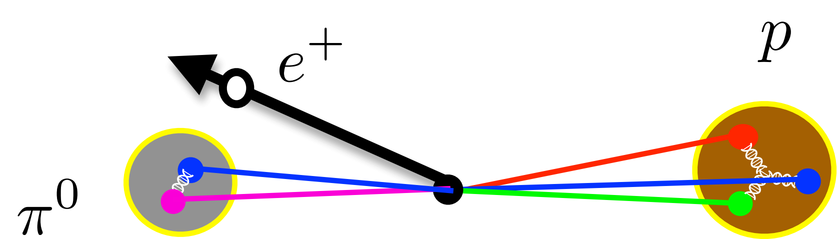
Double-β decay

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

✓ Leptogenesis

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

✗ Sphaleron washout (?)

Heeck, Takhistov, PRD 101 (2020), …

Predicting new physics signatures

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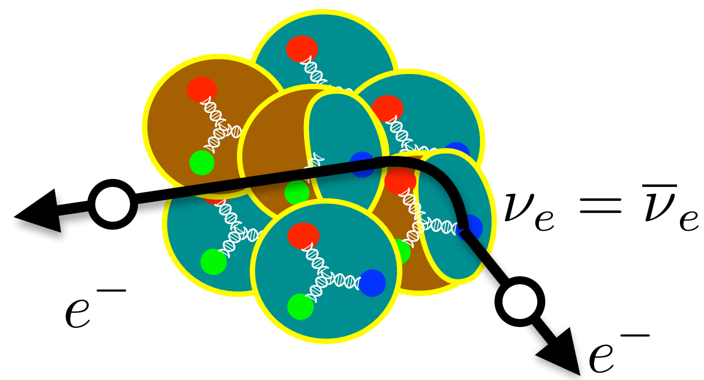


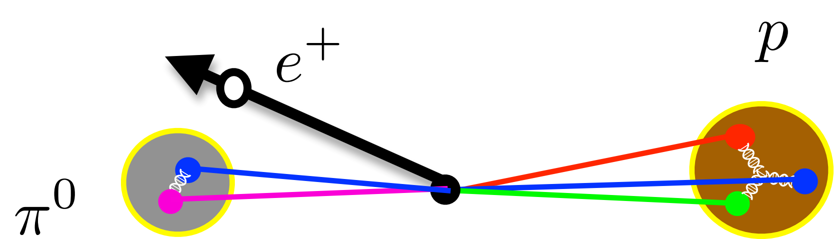
Double-β decay

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

✓ Leptogenesis

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

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



Proton decay

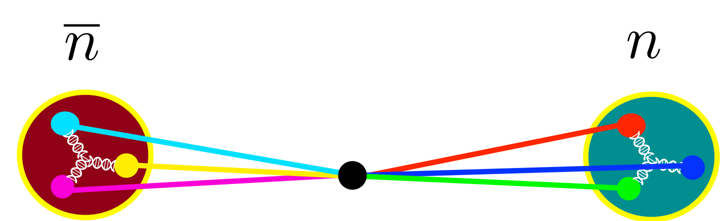
$\Lambda_{BSM} \gtrsim 10^{16}$ GeV

✗ Sphaleron washout (?)

Heeck, Takhistov, PRD 101 (2020), …

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

$$\mathcal{L}_9 \sim \left(\frac{1}{\Lambda_{BSM}^5}\right) uddudd + \ldots$$



Neutron-antineutron oscillations

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

✓ Post-sphaleron baryogengesis

Experimental constraints on $n\overline{n}$

$n\overline{n}$ transition / oscillation phenomenology similar to meson, neutrino oscillations

$$\mathcal{P}_{n\overline{n}} = \sin^2(t/\tau_{n\overline{n}})e^{-\Gamma_n t}$$

Measured $n\overline{n}$ rate + QCD theory input needed to constrain BSM physics parameters

Compute with lattice QCD

Measure $n\overline{n}$ transition rate

$$\tau_{n\overline{n}}^{-1} \sim \frac{\langle \overline{n} | uddudd | n \rangle}{\Lambda_{\text{BSM}}^5}$$

Infer scale of new physics

Experimental constraints on $n\bar{n}$

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

$$\mathcal{P}_{n\bar{n}} = \sin^2(t/\tau_{n\bar{n}})e^{-\Gamma_n t}$$

Measured $n\bar{n}$ rate + QCD theory input needed to constrain BSM physics parameters

Measure $n\bar{n}$ transition rate → $\tau_{n\bar{n}}^{-1} \sim \dfrac{\langle \bar{n} | uddudd | n \rangle}{\Lambda_{\text{BSM}}^5}$

Compute with lattice QCD (numerator)

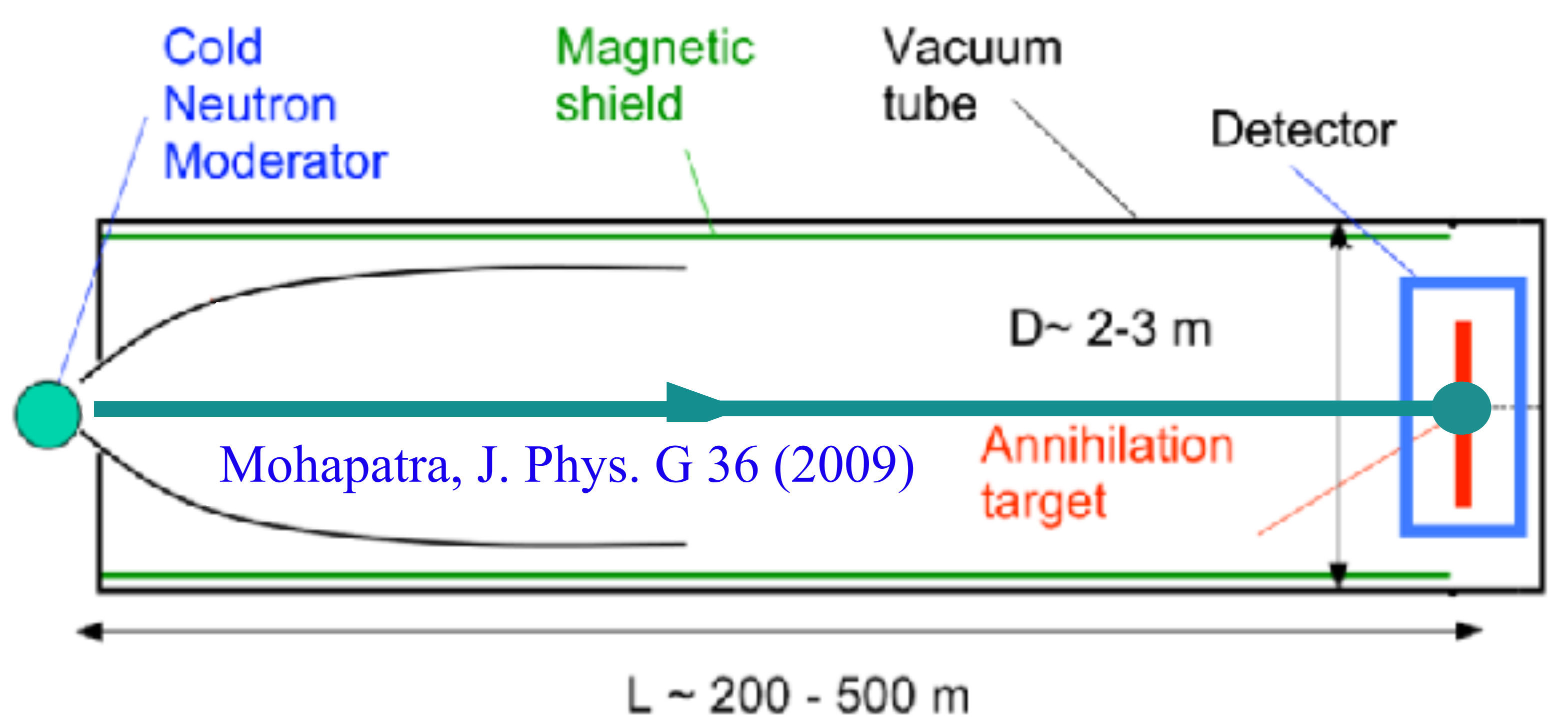
Infer scale of new physics (denominator)

Clean experimental setup using shielded beam of cold neutrons (theorist's cartoon):

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)



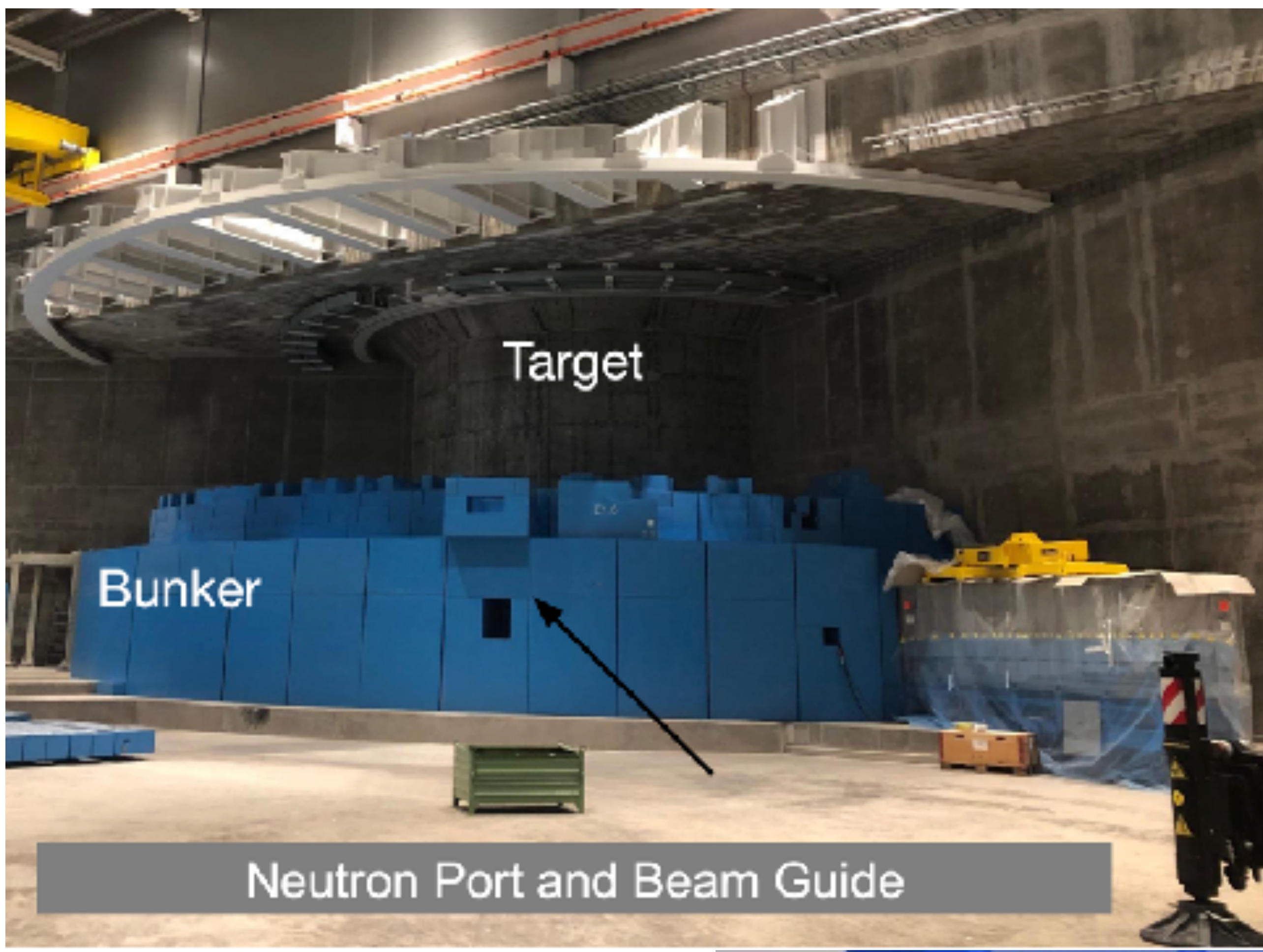
Mohapatra, J. Phys. G 36 (2009)

New constraints on $n\bar{n}$

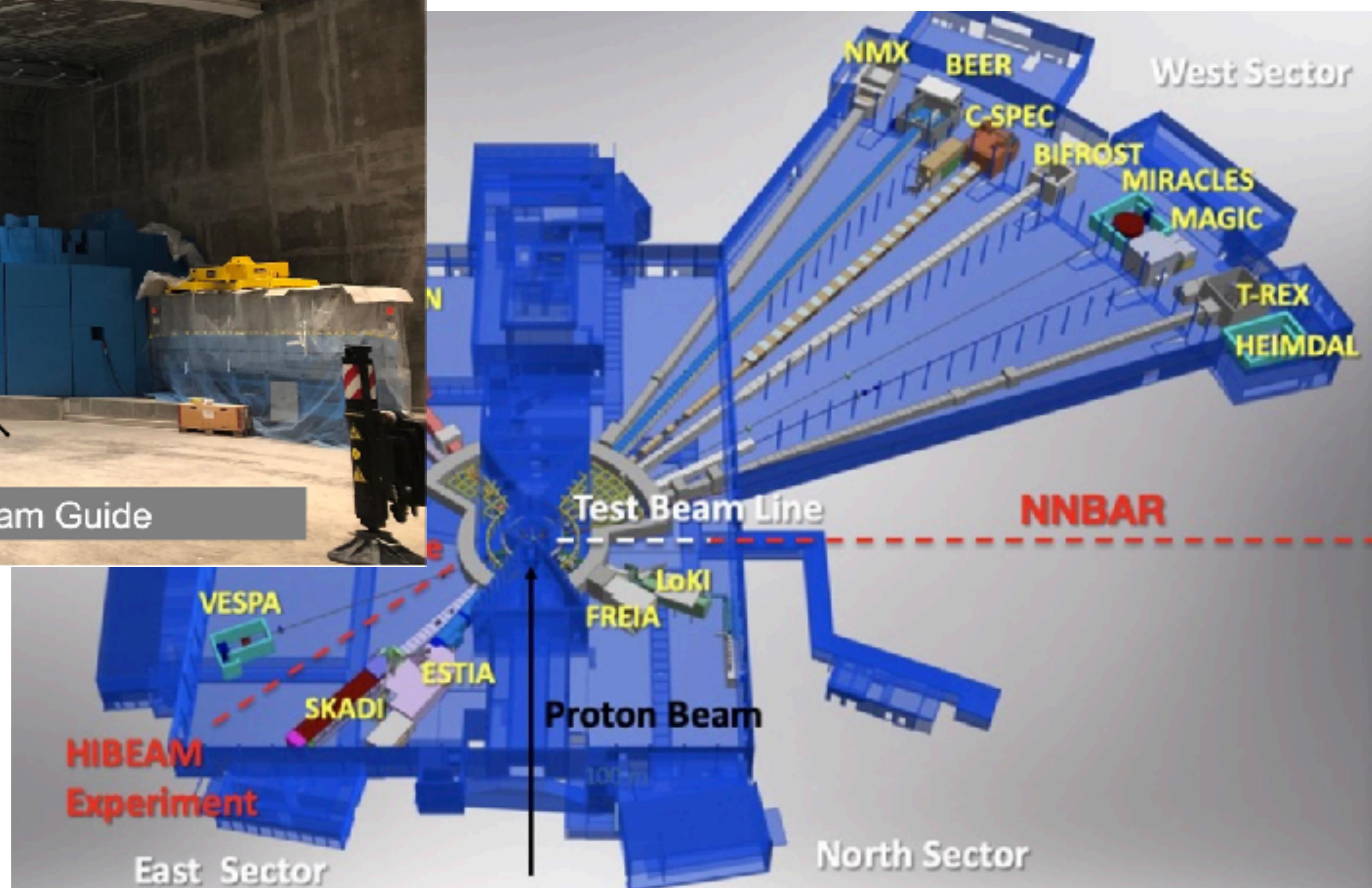
Future experiments at the European Spallation Source could increase sensitivity to $\tau_{n\bar{n}}^{-2}$ by one (HIBEAM) to three (NNBAR) orders of magnitude

Addazi et al, J. Phys. G. 48 (2021)

- Science runs starting in 2027, further upgrades needed for NNBAR



Courtesy John Womersley

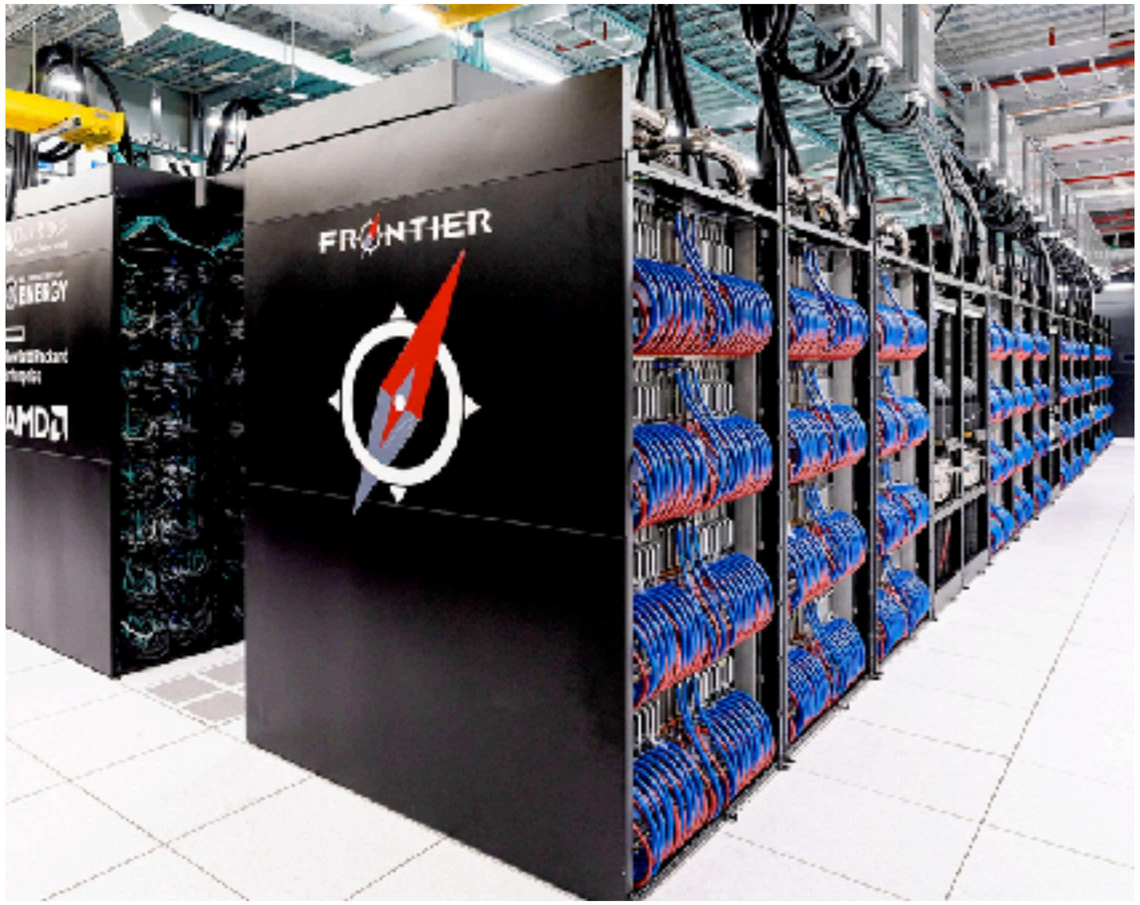


NNBAR CDR: Santoro et al, J. Neutron Res 25 (2023)

Lattice QCD in a nutshell

Lattice QCD enables nonperturabtive calculations of QCD path integrals numerically

$$\langle \mathcal{O} \rangle = \int \mathcal{D}U\mathcal{D}\overline{q}\mathcal{D}q \; e^{-S_{QCD}(U,q,\overline{q})} \; \mathcal{O}(U,q,\overline{q}) \;\approx \frac{1}{N_{\rm cfg}} \sum_{i=1}^{N_{\rm cfg}} \mathcal{O}(U_i)$$



Quark fields integrated out analytically, propagators obtained with matrix inversion

- Dirac matrix size ~ $10^9 \times 10^9$

Monte Carlo sample gluon fields with probability $\propto e^{-S_{QCD}}$

Finite volume + non-zero lattice spacing

➡ finite number of integrals to compute

$$\mathcal{D}q \equiv \prod_{\mu=1}^{4} \prod_{x_\mu=0}^{(L/a)-1} dq(x)$$

$n\overline{n}$ and LQCD

High-scale new physics can be parametrized in SM EFT:

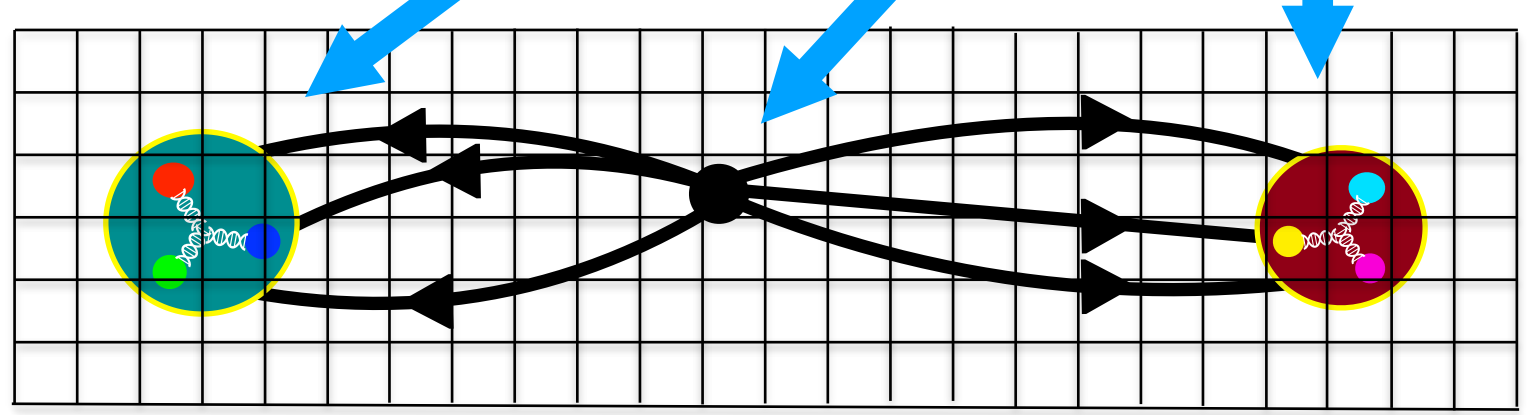
$$\mathcal{L}_9 = \frac{1}{\Lambda_{BSM}^5} \sum_I C_I^{\overline{\text{MS}}}(\Lambda_{BSM}) Q_I^{\overline{\text{MS}}}(\Lambda_{BSM})$$

Complete basis of six-quark operators

$$Q_1 \sim (u_R^i C d_R^j)(u_R^k C d_R^l)(d_R^m C d_R^n) T_{ijklmn}^{AAS}$$

Three-point correlation functions involving Q_I computable in LQCD

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



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

Ratio of $n\overline{n}$ and neutron correlation functions gives matrix elements plus excited state effects that can be studied by e.g. multi-state fits

Neutron-Antineutron Oscillations

LQCD calculations performed with

- ✓ ~physical quark masses
- ✓ nonperturbative renormalization
- ✓ 2-loop perturbative renormalization

  Buchoff, MW, PRD 93 (2016)
- ✗ 1 lattice spacing / volume

  FV ChEFT: Bijens, Kofoed, Eur Phys J C (2017)

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	$-0.23(10)$

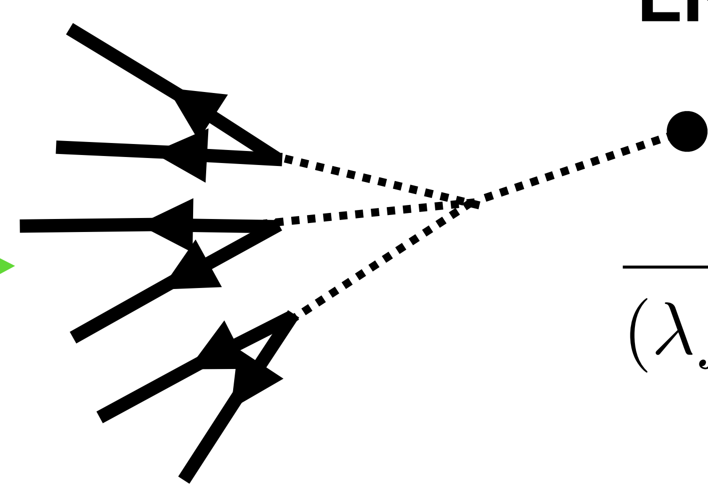
Standard Model EFT:

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

ILL:

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

LR-symmetric example:



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

Experimental Implications

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

	$\mathcal{M}_I^{\overline{\text{MS}}}(700\ \text{TeV})\ [10^{-5}\ \text{GeV}^6]$	MIT Bag $\times$ 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 $SU(2)_L \times SU(2)_R \times SU(4)_C$ example, lower bound on BSM couplings from ILL **390 TeV** instead of **290 TeV**

B violation in nuclei

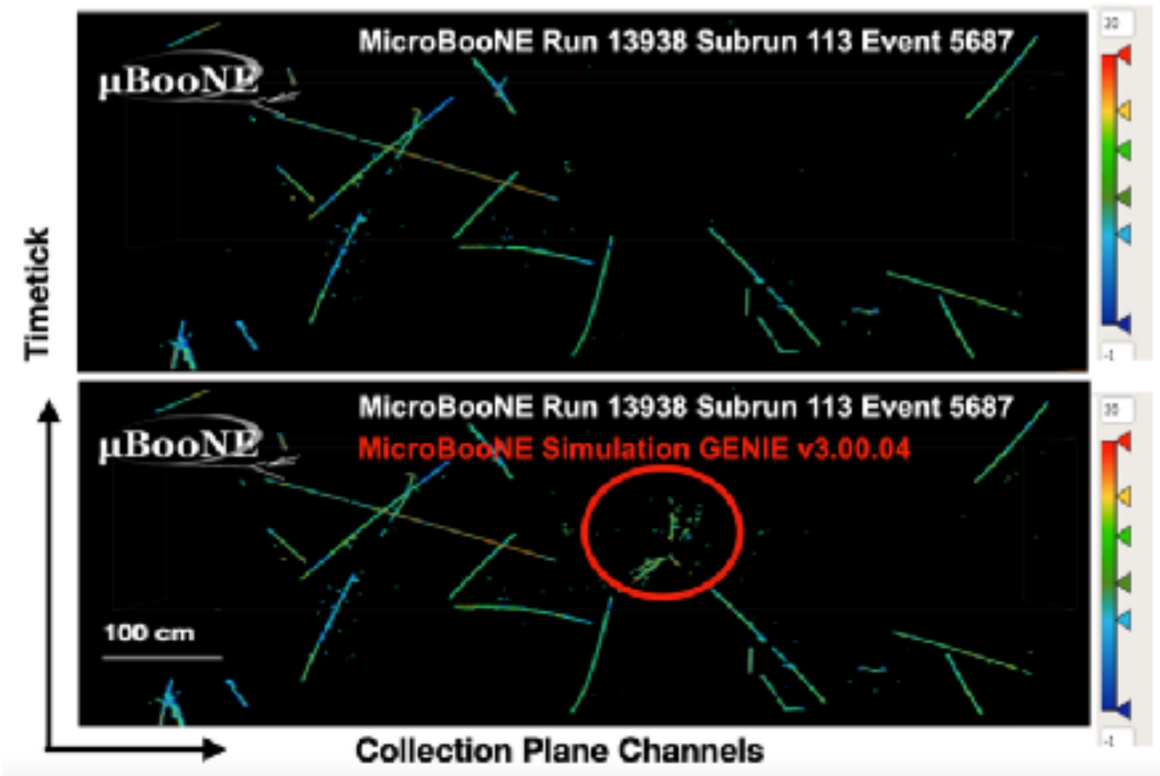
Future large-volume detectors such as DUNE and Hyper-Kamiokande will provide new discoveries or limits for intranuclear $n\bar{n}$, proton decay, …

Getting from experiments involving nuclei to constraints on BSM requires theory:

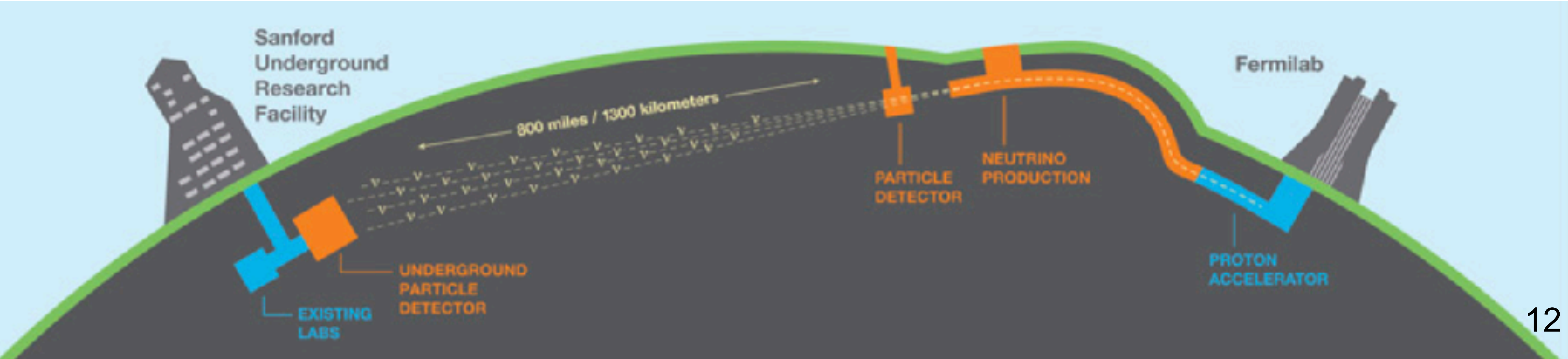
- Nuclear models (error bars?)
- Direct LQCD calculations (computation?)
- **LQCD informed hadronic and nuclear effective theories**

Intranuclear $n\bar{n}$ simulation

Abratenko et al [MicroBooNE] JINST 19 (2024)



DUNE



Proton decay

BSM theories with high-scale *B* violation, including some GUTs, predict that protons decay at ~observable rates

Long history of experimental searches for decay modes with clean signatures

$$\tau/Br(p \to e^+\pi^0) > 1.6 \times 10^{34} \text{ years}$$

Abe et al [Super K], PRD 95 (2017)

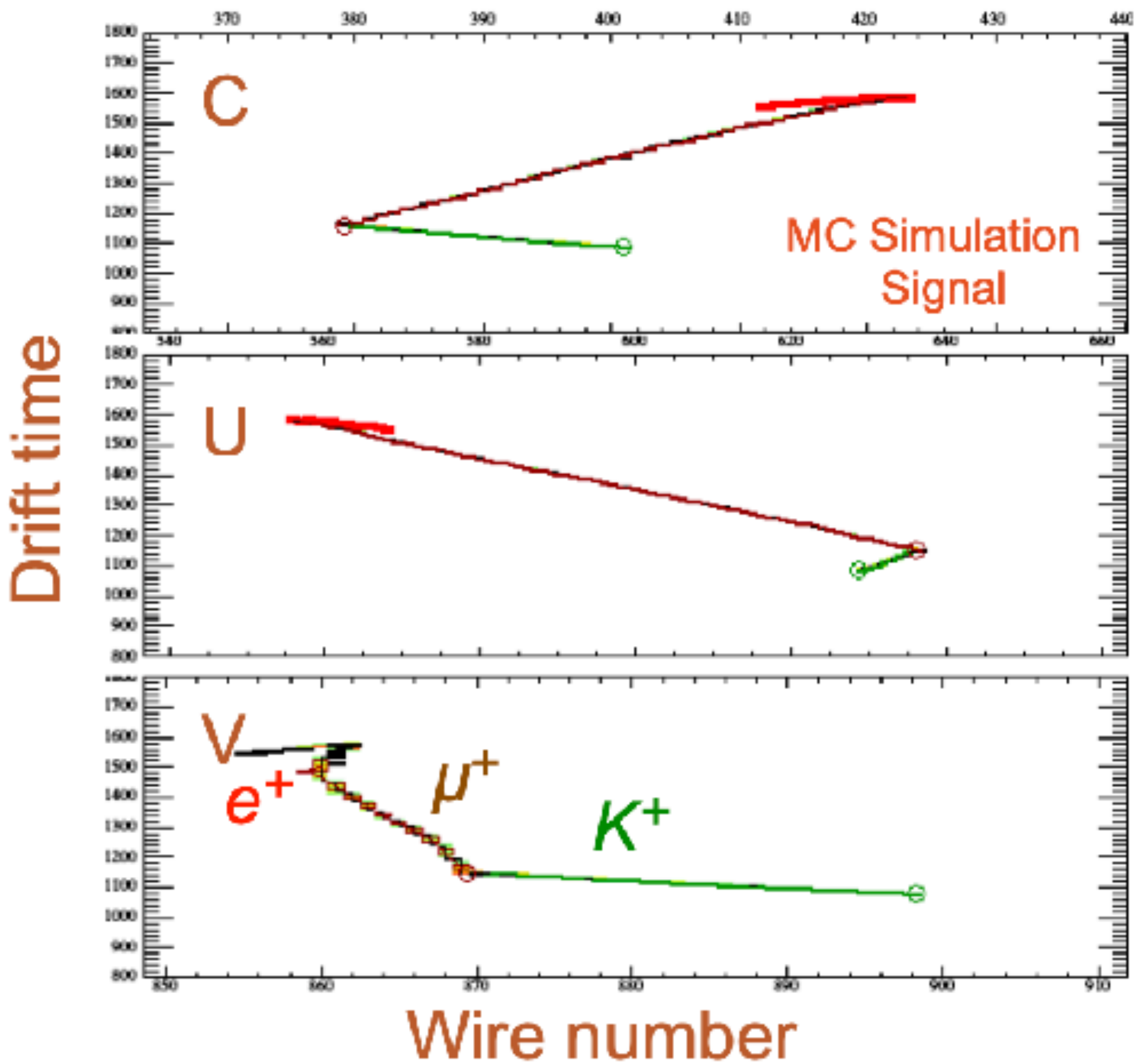
$$\tau/Br(p \to \nu K^+) > 5.9 \times 10^{33} \text{ years}$$

Abe et al [Super K], PRD 90 (2014)

Future searches at DUNE and Hyper Kamiokande could improve limits by an order of magnitude

Predictions for QCD matrix elements of dim 6 operators needed to constrain BSM models

Simulated proton decay event at DUNE



Viktor Pěč [DUNE], BLV 2019

Proton decay and LQCD

LQCD calculations relevant for proton decay pursued for 20+ years

Aoki et al [JLQCD], PRD 62 (2000)

Tensions between direct calculations and indirect calculations using χPT relations led to concern about quark mass systematics

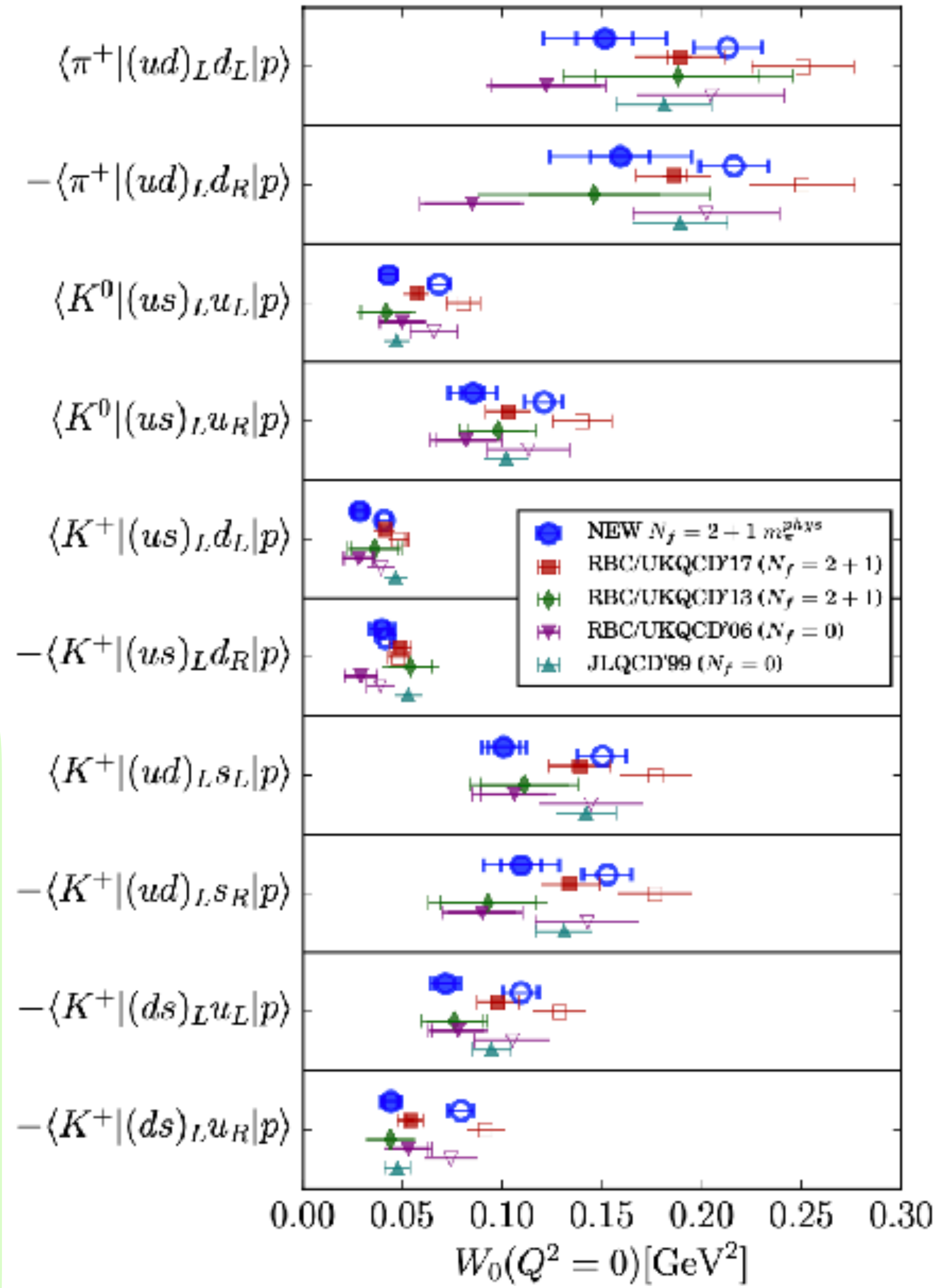
Martin and Staving, PRD 85 (2012)

Addressed by recent LQCD calculations:

Yoo et al, PRD 105 (2022)

- ~physical quark masses
- nonperturbative renormalization
- 2 lattice spacings
- Direct and indirect methods

10-20% precision achieved, quark mass effects found to be modest

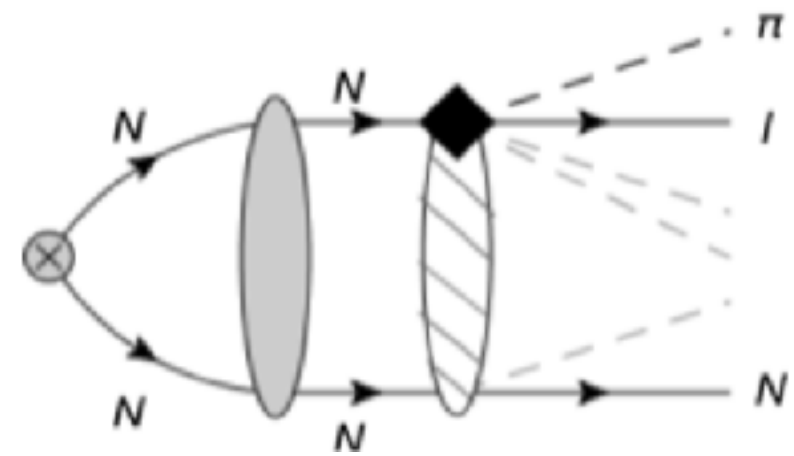


Yoo, Aoki, Boyle, Izubuchi, Soni, and Syritsyn, PRD 105 (2022)

Proton decay in nuclei

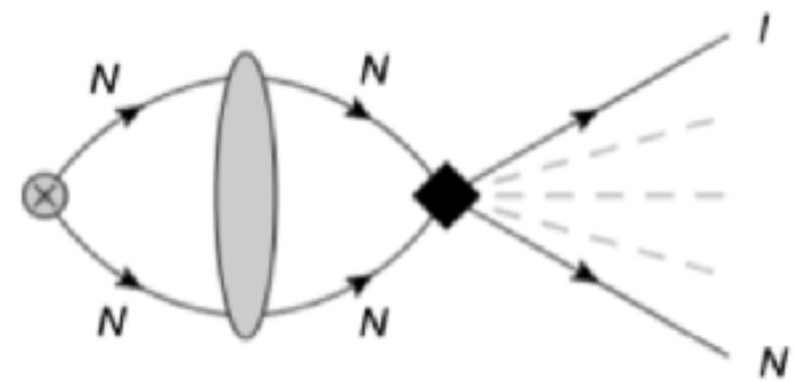
Nuclear effective theories can describe intranuclear proton decay as single-nucleon operator insertions plus corrections from correlations

Most effects of local three-quark operators captured by single-nucleon $\Delta B = 1$ vertex



Oosterhof, de Vries, Timmermans, van Kolck, PLB 820 (2021)

Effects of nucleon-nucleon correlations on e.g. deuteron lifetime computed in EFT



$$\Gamma_d = \Gamma_p + \Gamma_n + \Delta\Gamma$$

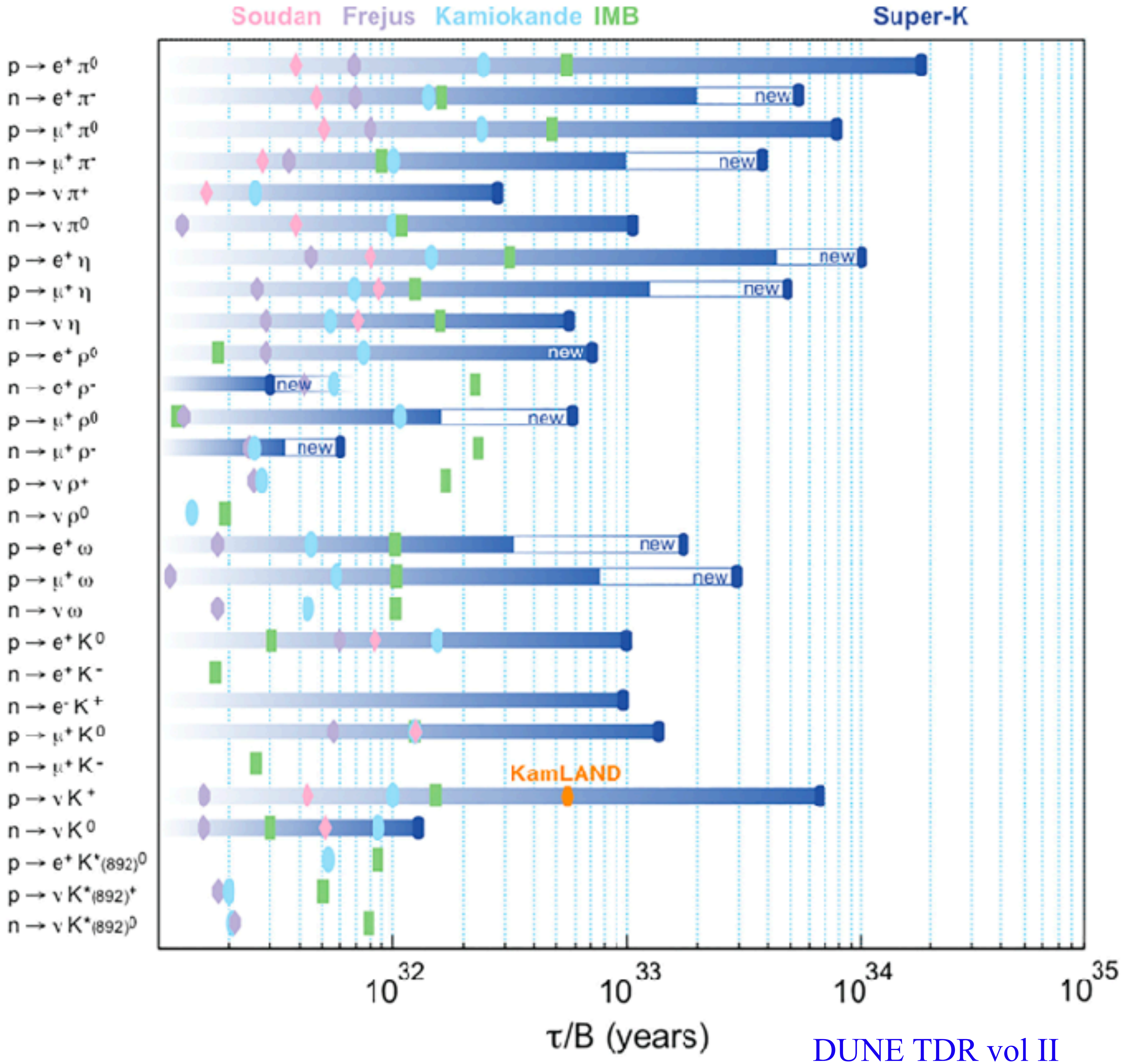
Chiral EFT results consistent with power counting arguments

$$\Delta\Gamma \sim O(\kappa^2/\Lambda_\chi^2) \sim 10^{-2}$$

Binding momentum ~ 45 MeV ~ 1 GeV

Nuclear effects on intranuclear proton decay rates expected to be few percent

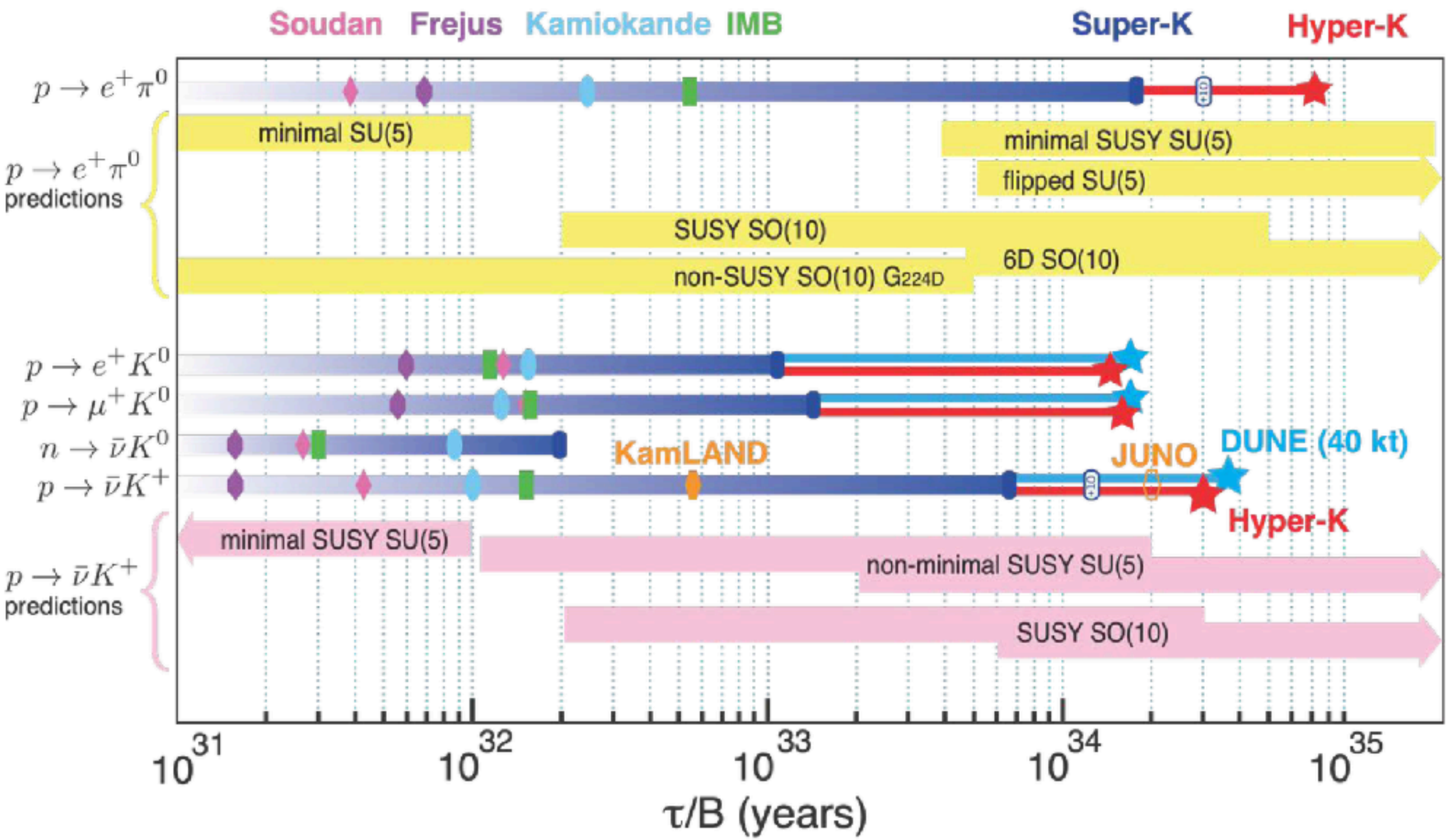
Current proton decay limits



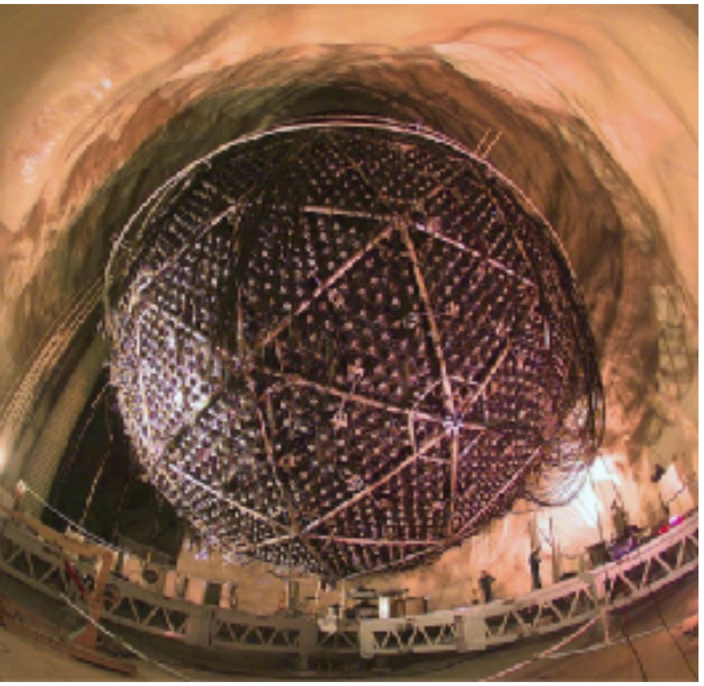
DUNE TDR vol II

Future proton decay searches

Ed Kearns, BLV 2020



$n\bar{n}$ in nuclei



SNO constraint:

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

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

KSW

$$\tau_{n\bar{n}} > 1.6 \times 10^{8} \text{ s}$$

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

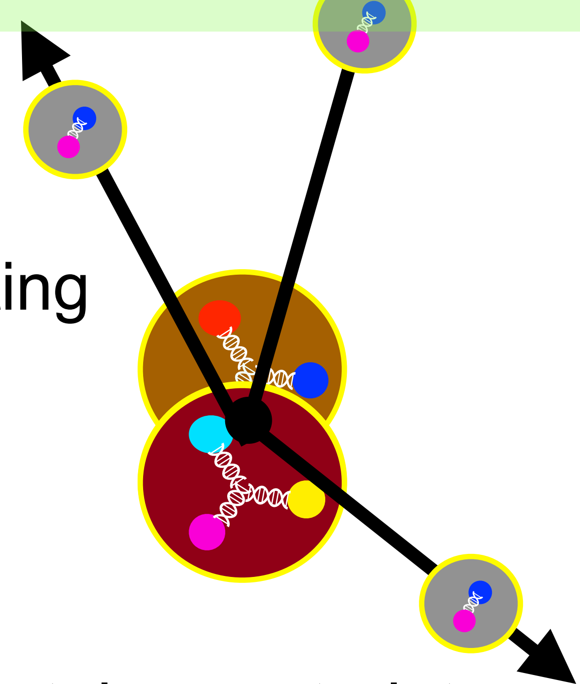
Weinberg

$$\tau_{n\bar{n}} > 2.6 \times 10^{8} \text{ s}$$

Haidenbauer and Meißner, Chinese Physics C 44 (2020)

Deuteron lifetime related to $\tau_{n\bar{n}}$ in chiral EFT

….but results sensitive to choice of power counting



Oxygen lifetime provides stronger but more uncertain constraints

Super K constraint

$$\Gamma_{O^{16}}^{-1} > 3.6 \times 10^{32} \text{ years}$$

Abe et al [Super K], PRD 103 (2021)

$$\tau_{n\bar{n}} \gtrsim 4.7 \times 10^{8} \text{ s}$$

State-of-the-art optical potentials:

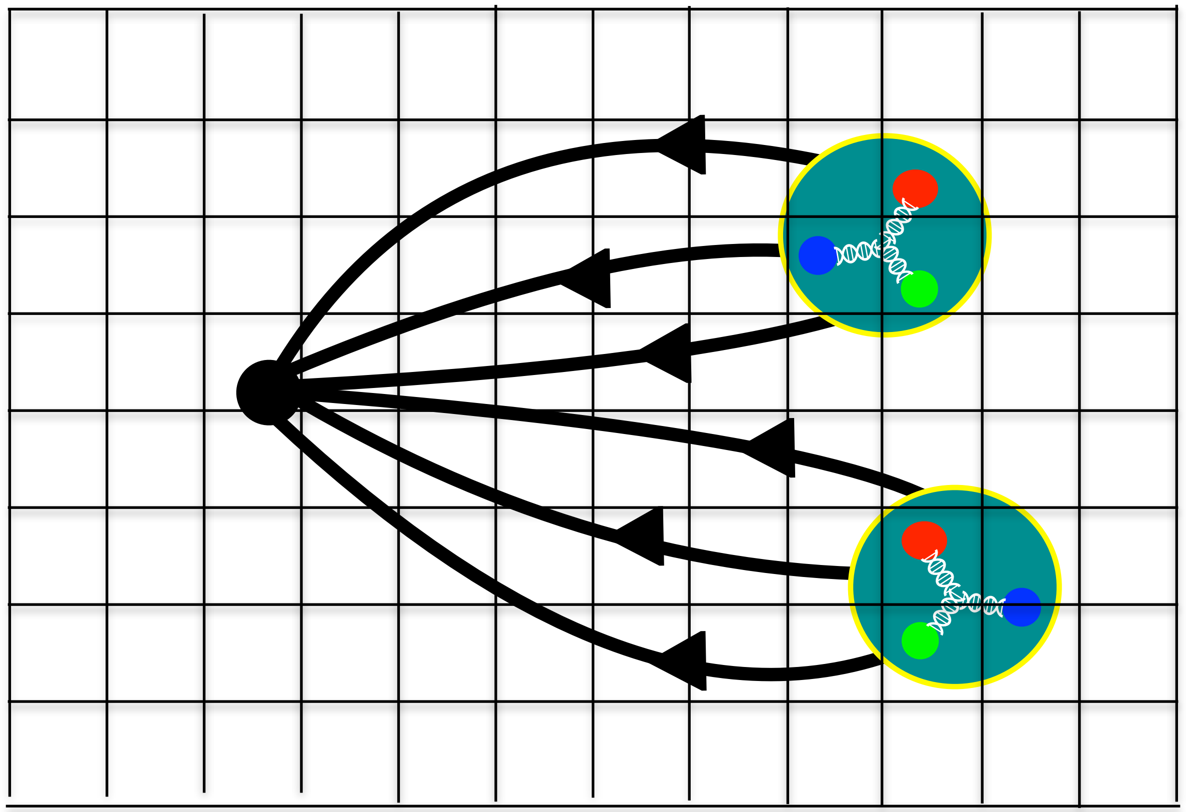
Friedman, Gal, PRD 78 (2008)

Dineutron decay with LQCD

Can lattice QCD help constrain nuclear effects in intranuclear $n\bar{n}$ searches?

Simplest possible LQCD calculation of $n\bar{n}$ in multi-nucleon system:

$$\langle Q_I(t) n n^\dagger(0) \rangle \quad =$$



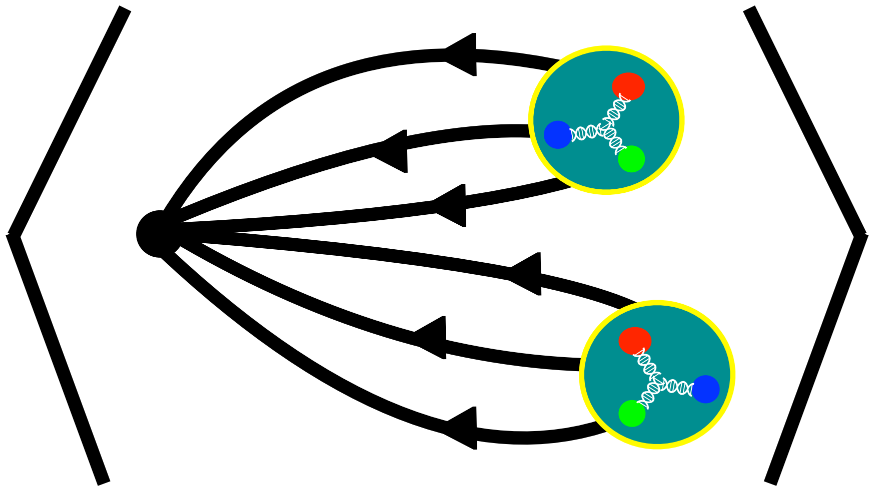
Dineutron decay matrix element can be extracted from LQCD two-point function

$$\langle Q_I(t) n n^\dagger(0) \rangle \sim \sum_J \langle 0 | Q_J | nn \rangle Z_{JI} + \ldots$$

Nonperturbative QCD matrix element contains info to constrain unknown NLO+ EFT couplings that may have sizable impact even on deuterium

Oosterhof et al, PRL 122 (2019) Haidenbauer and Meißner, Chinese Physics C 44 (2020)

Towards $n\bar{n}$ in nuclei



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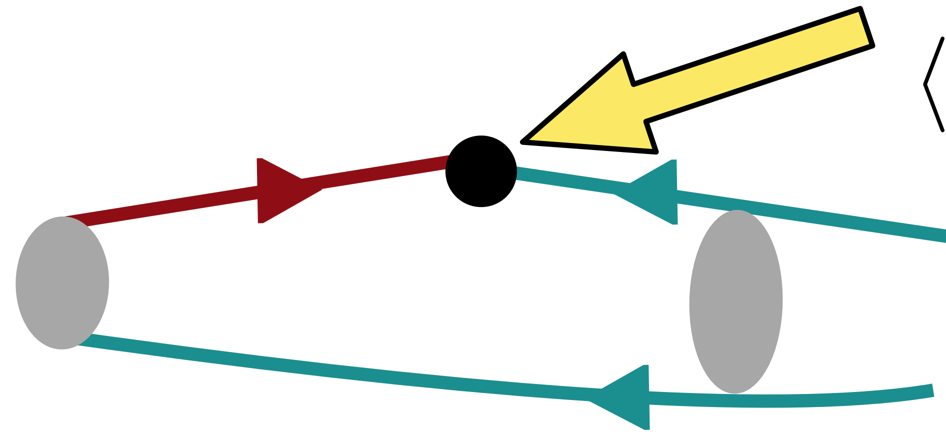
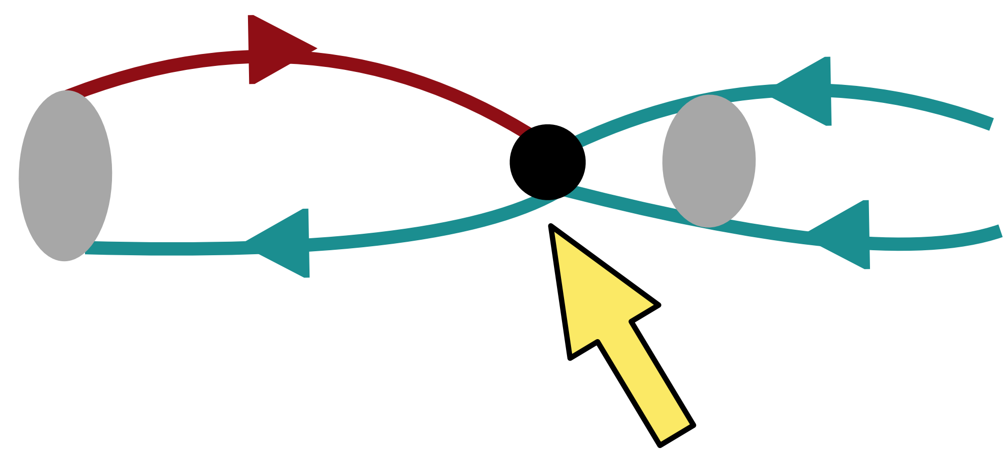


"Known"
EFT input
$\langle \overline{n} | Q_I | n \rangle$

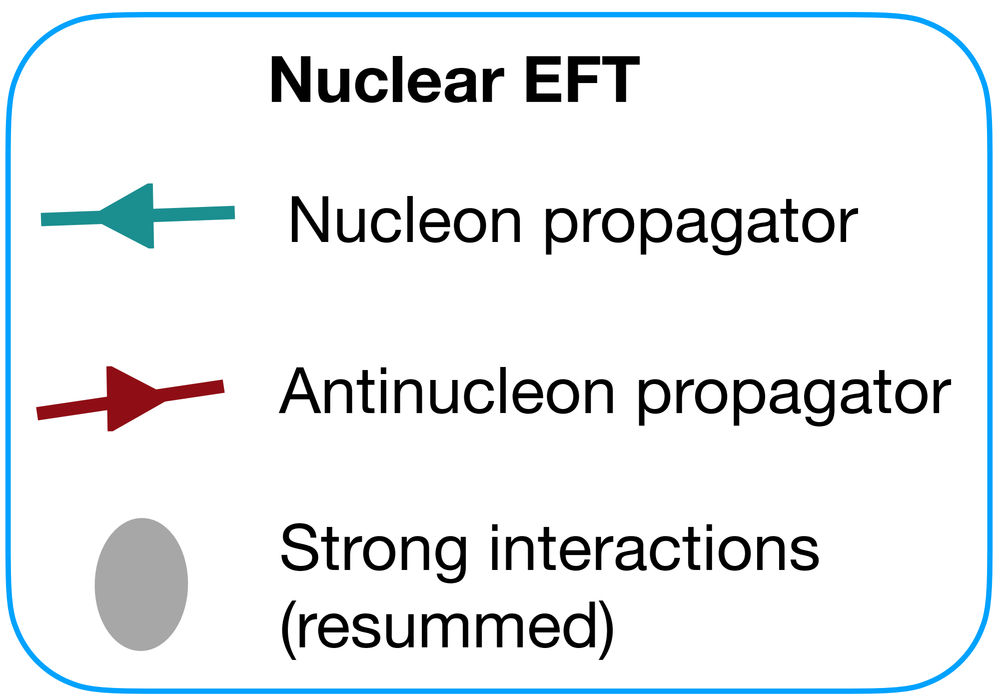
Dineutron decay matrix elements can be matched to nuclear EFTs to constrain higher-order LECs

+



Unknown EFT input
$\langle n\overline{n} | Q_I | nn \rangle$

+ . . .

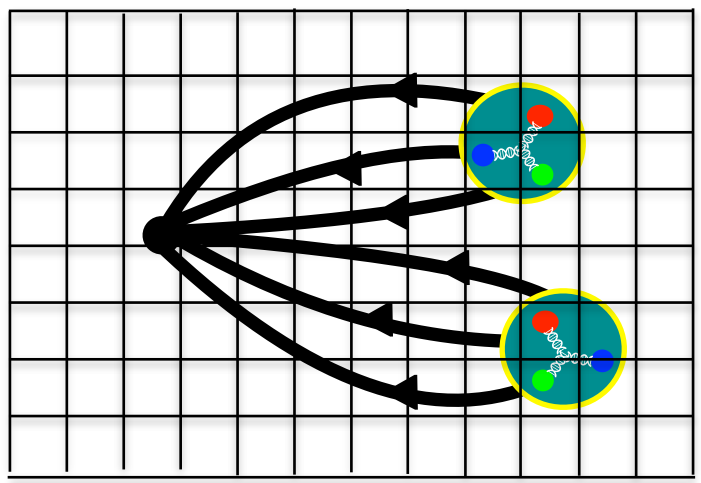


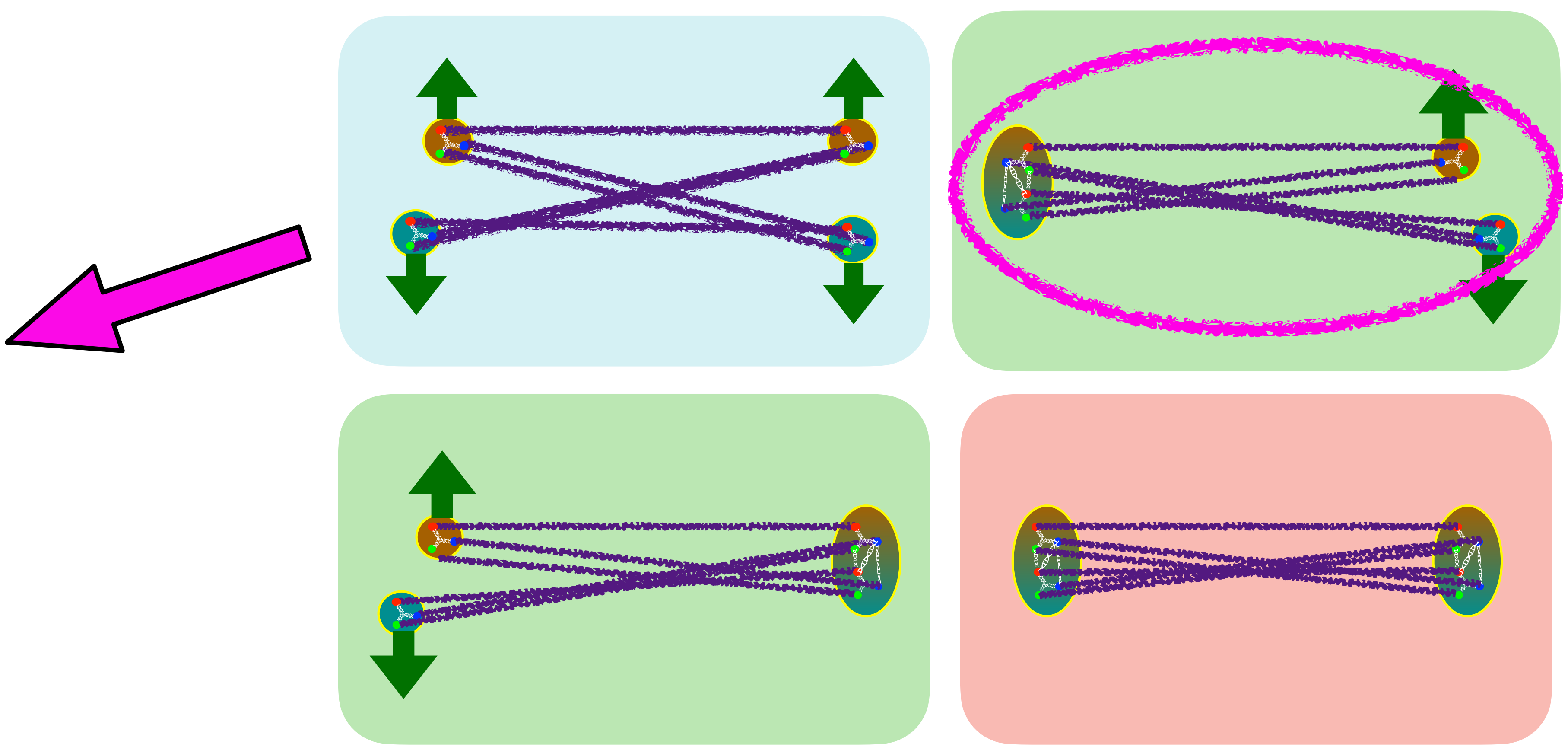
~ NLO input discussed in

Oosterhof et al, PRL 122 (2019)

LQCD and $n\bar{n}$ in nuclei

LQCD calculations can use the same codes (and some data) as NN spectroscopy calculations using correlator matrices





Correlator topology corresponds to "hexaquark" - "dibaryon" off-diagonal element of correlator matrix

Amarasinghe, MW et al [NPLQCD], PRD 107 (2023)

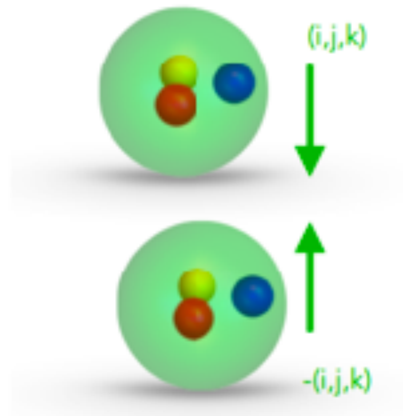
Detmold, MW et al [NPLQCD], PRD 111 (2025)

Bulava et al [BaSc], arXiv:2505.05547

Six quarks on a lattice

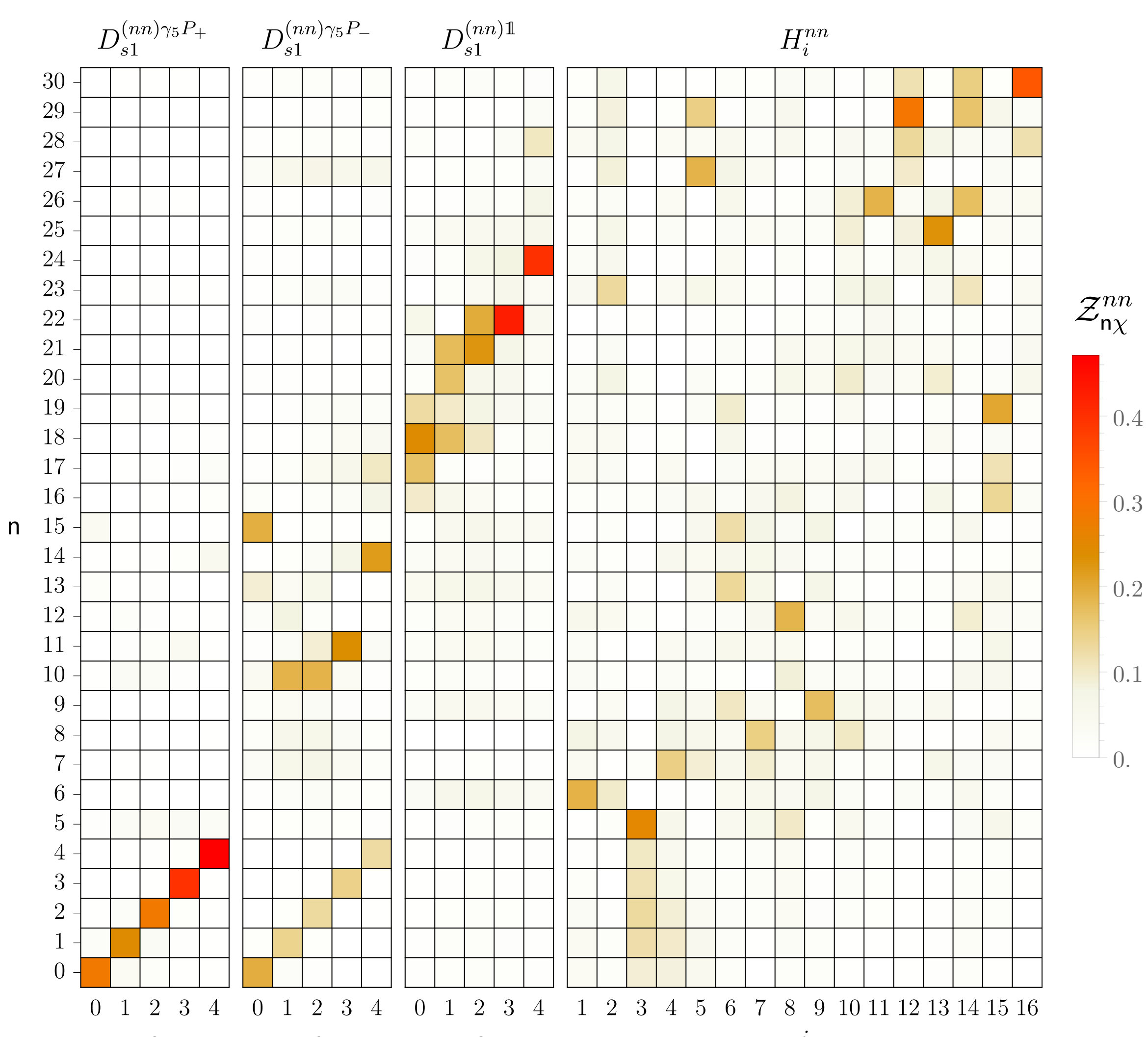
Hexaquark

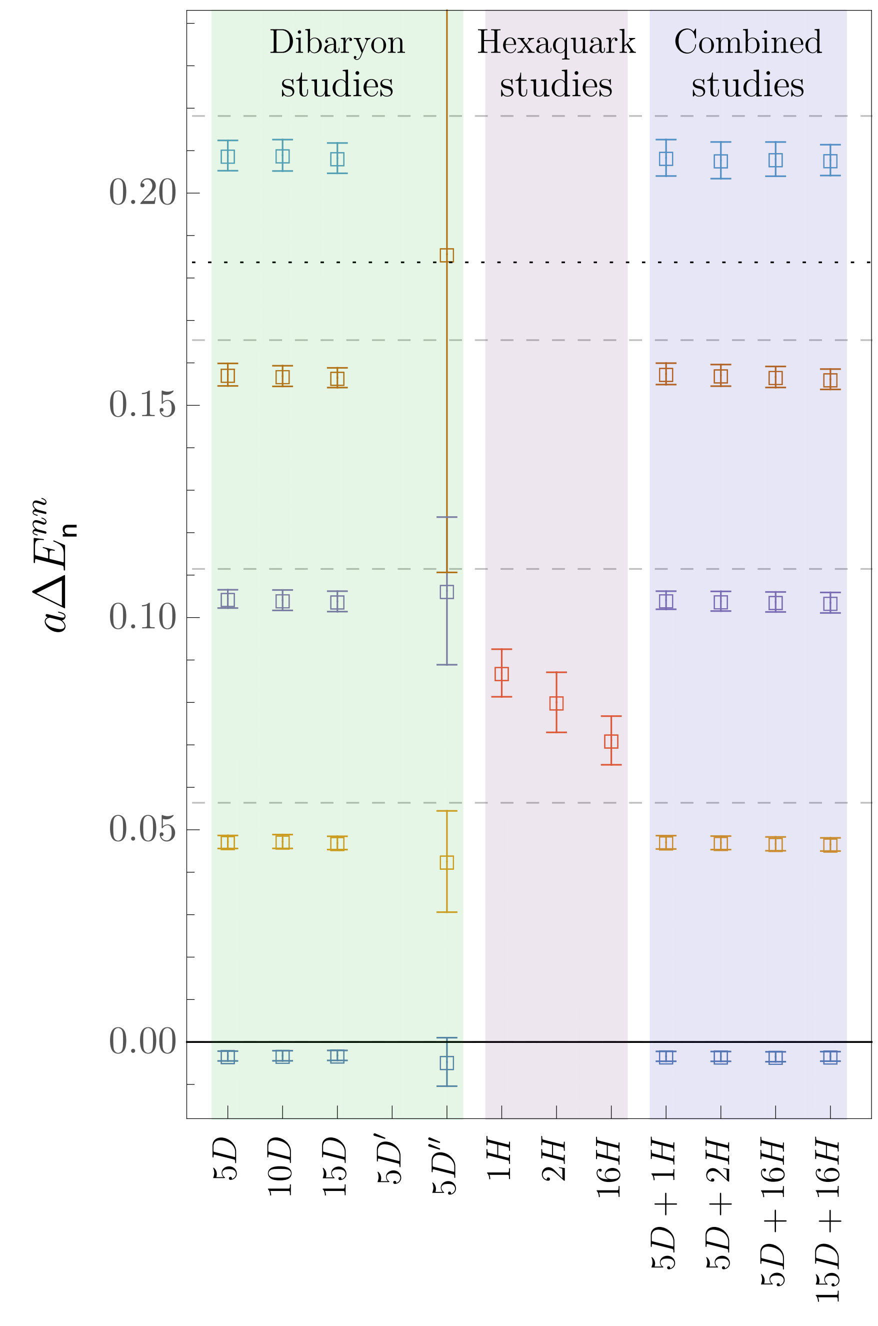
Dibaryon



Energies and overlaps computed for a wide range of interpolating operators including a complete basis of local 6-quark operators

Detmold, MW et al [NPLQCD], PRD 111 (2025)





LQCD nn decay results

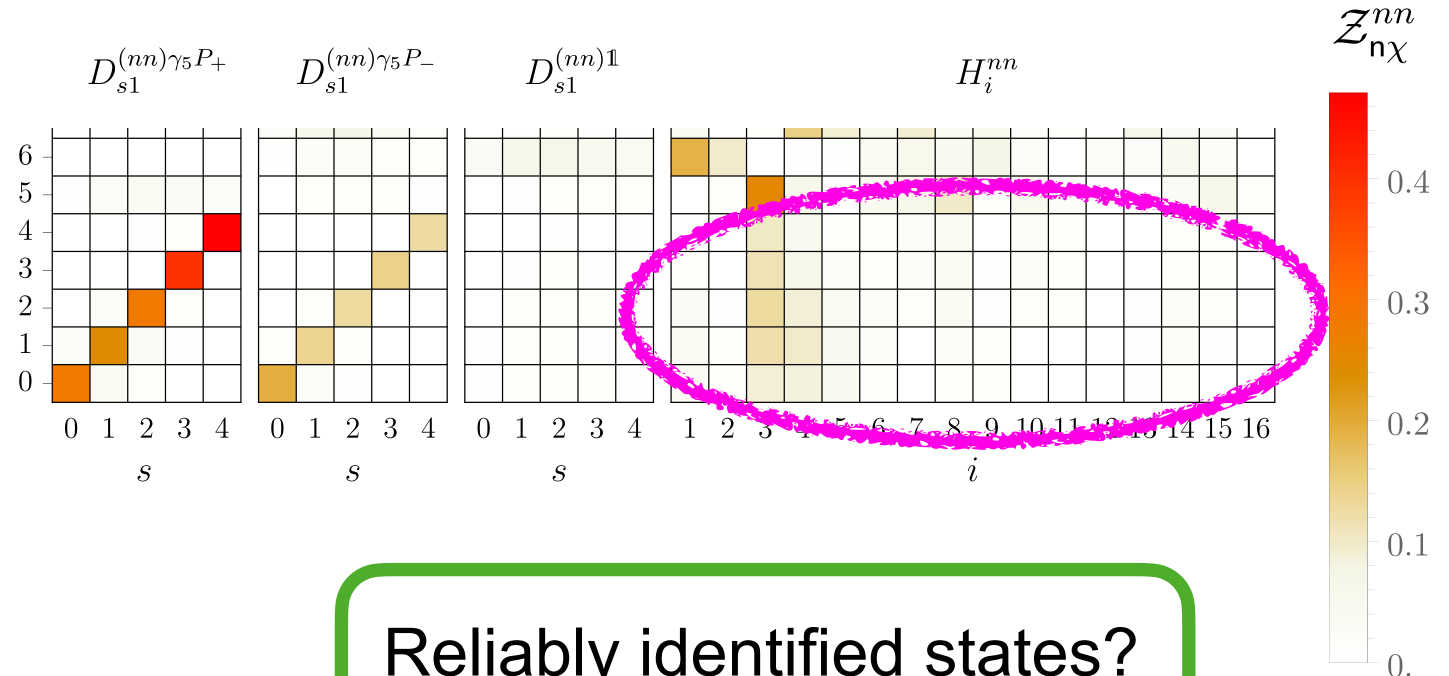
Overlap factors encode ground- and excited-state dineutron decay matrix elements of interest

$$\mathcal{Z}_{\mathsf{n}H_i^{nn}} = \langle 0 | H_i^{nn} | nn, \mathsf{n} \rangle$$

$$= \sum_J \langle 0 | Q_J | nn, \mathsf{n} \rangle \, C_{Ji}$$

Known change-of-basis matrix

Detmold, MW et al [NPLQCD], PRD 111 (2025)



Reliably identified states?

Qualitative lessons

- Strong energy (i.e. state n) dependence of $\langle 0 | H_i^{nn} | nn, \mathsf{n} \rangle$ suggests nuclear matrix elements sensitive to neutron (pair) distribution inside nucleus

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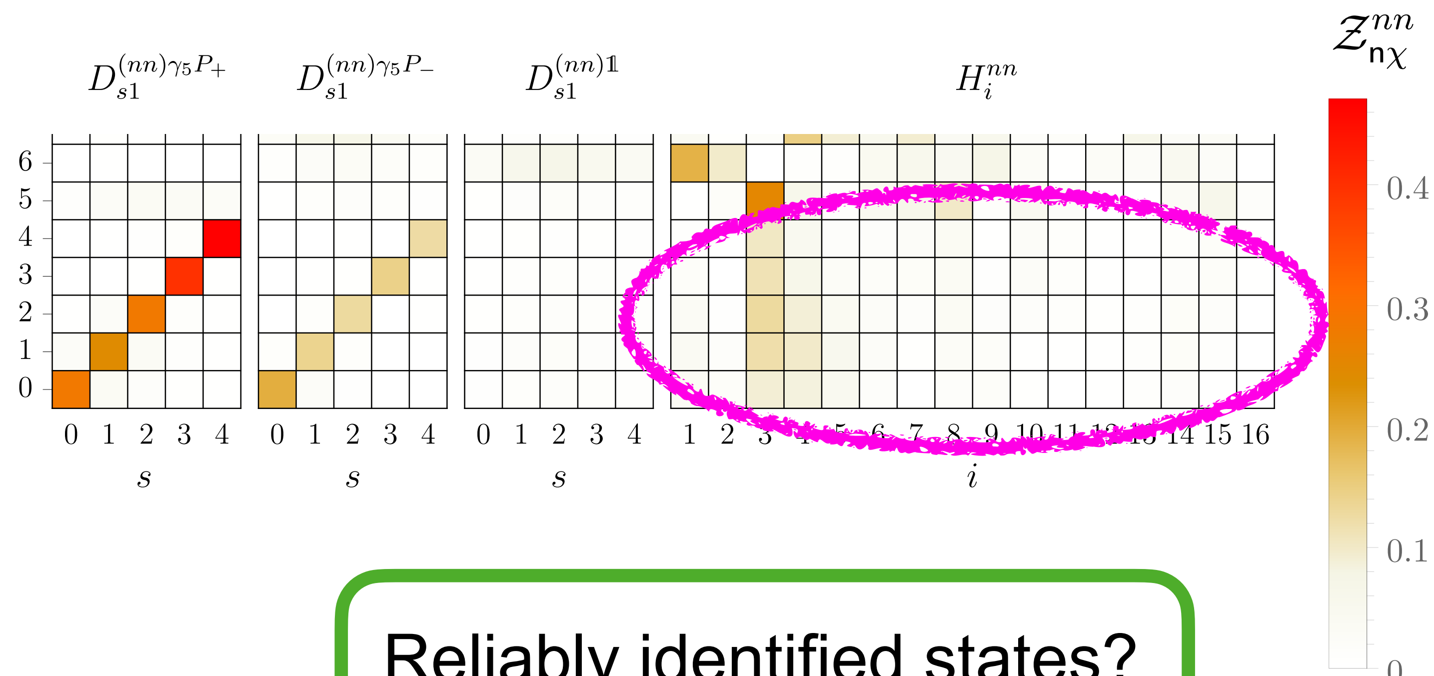

Reliably identified states?

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Quantitative challenges remain

- Quark mass effects, renormalization, and other known unknowns
- Quantifying *NN* excited-state effects: new tools from reinterpreting data analysis as eigenvalue finding

MW, PRL 134 (2025)

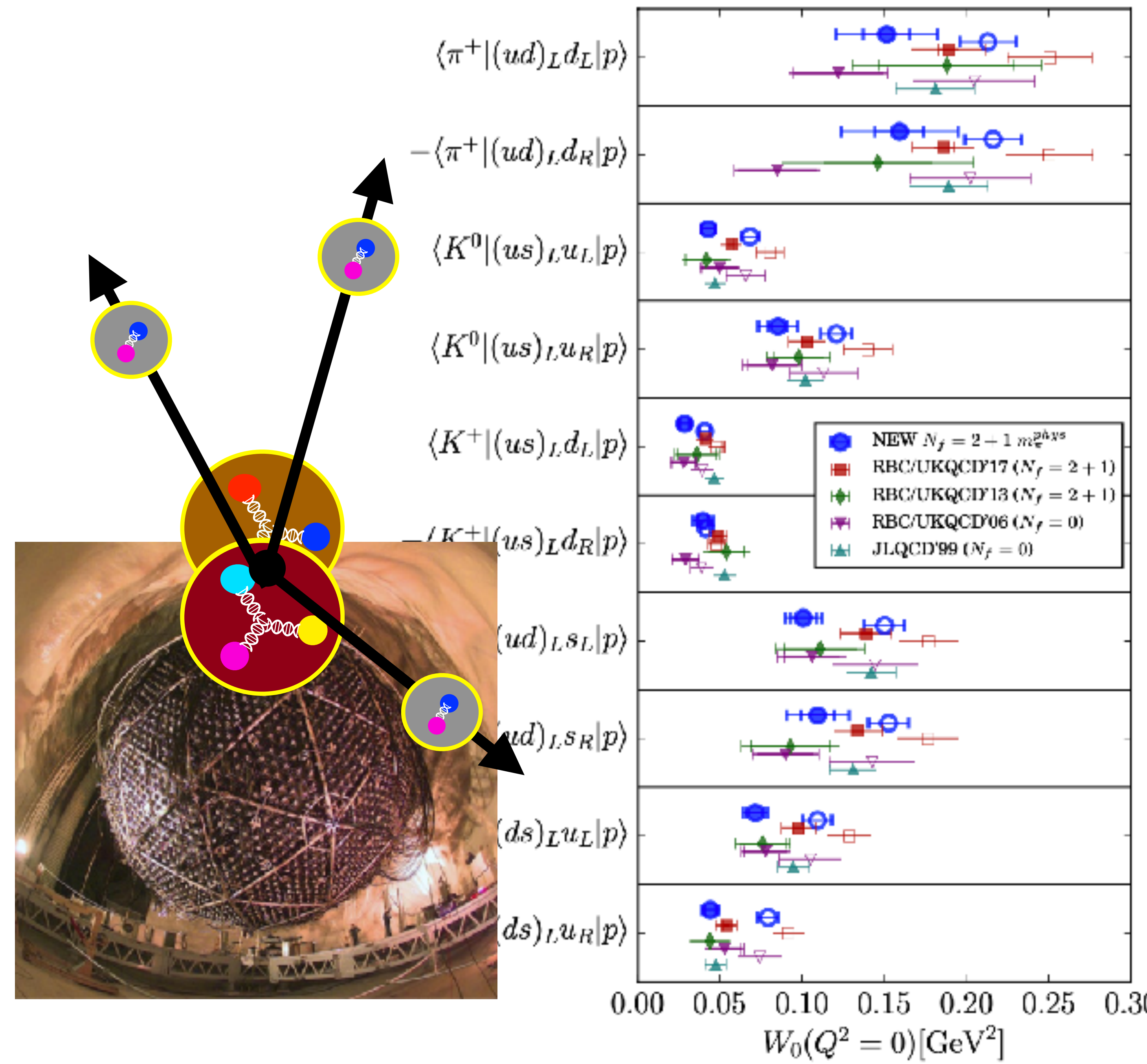
Abbott, Fleming, Hackett, Pefkou, MW, arXiv:2503.17357

Outlook

New searches for intranuclear proton decay and $n\bar{n}$ at Hyper-Kamiokande, JUNO, DUNE, …

New free neutron searches at ESS

- Lifetimes 10x longer than current limits will be probed in several channels



Lattice QCD can robustly predict matrix elements relating BSM theory and experimental data

- Free nucleon results available for proton decay and $n\bar{n}$
- Nuclear effects studied with EFT, more work needed for intranuclear $n\bar{n}$