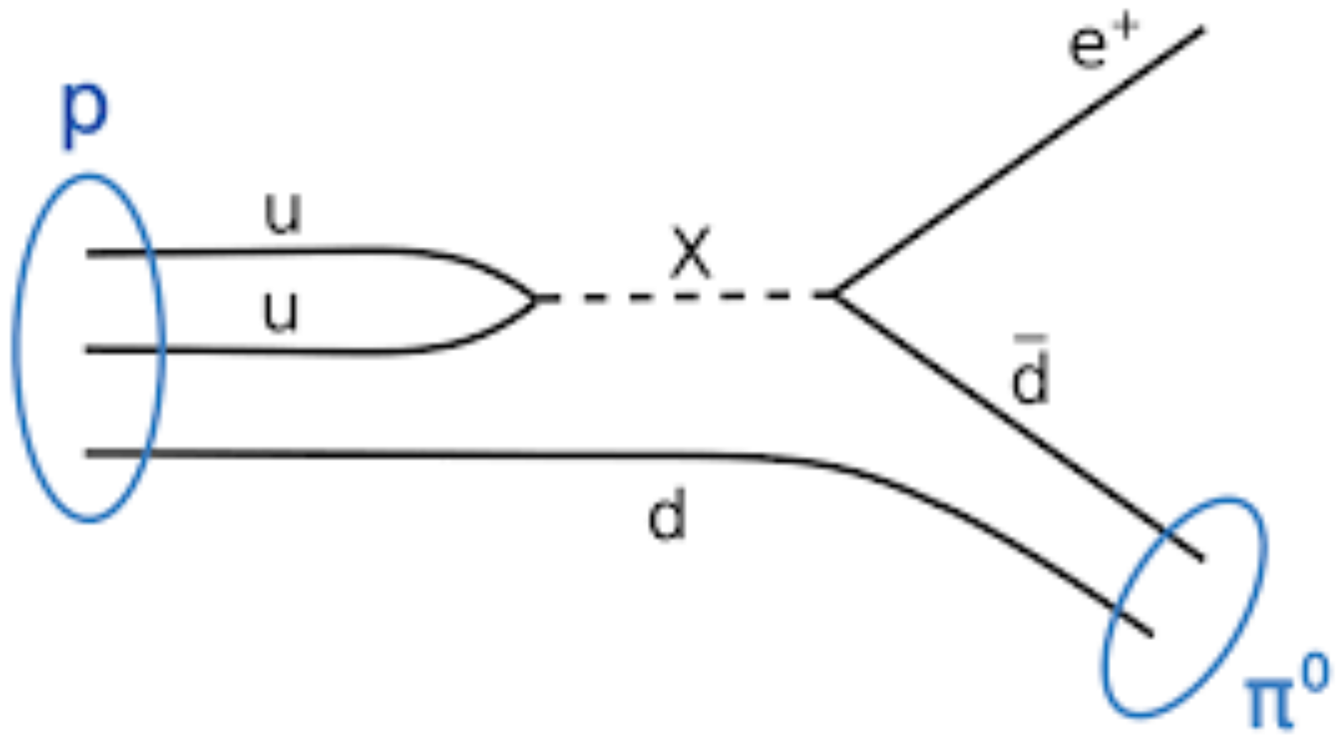
(Assisted) baryon number violation

Mathew Arun Thomas,
School of Physics, IISER TVM



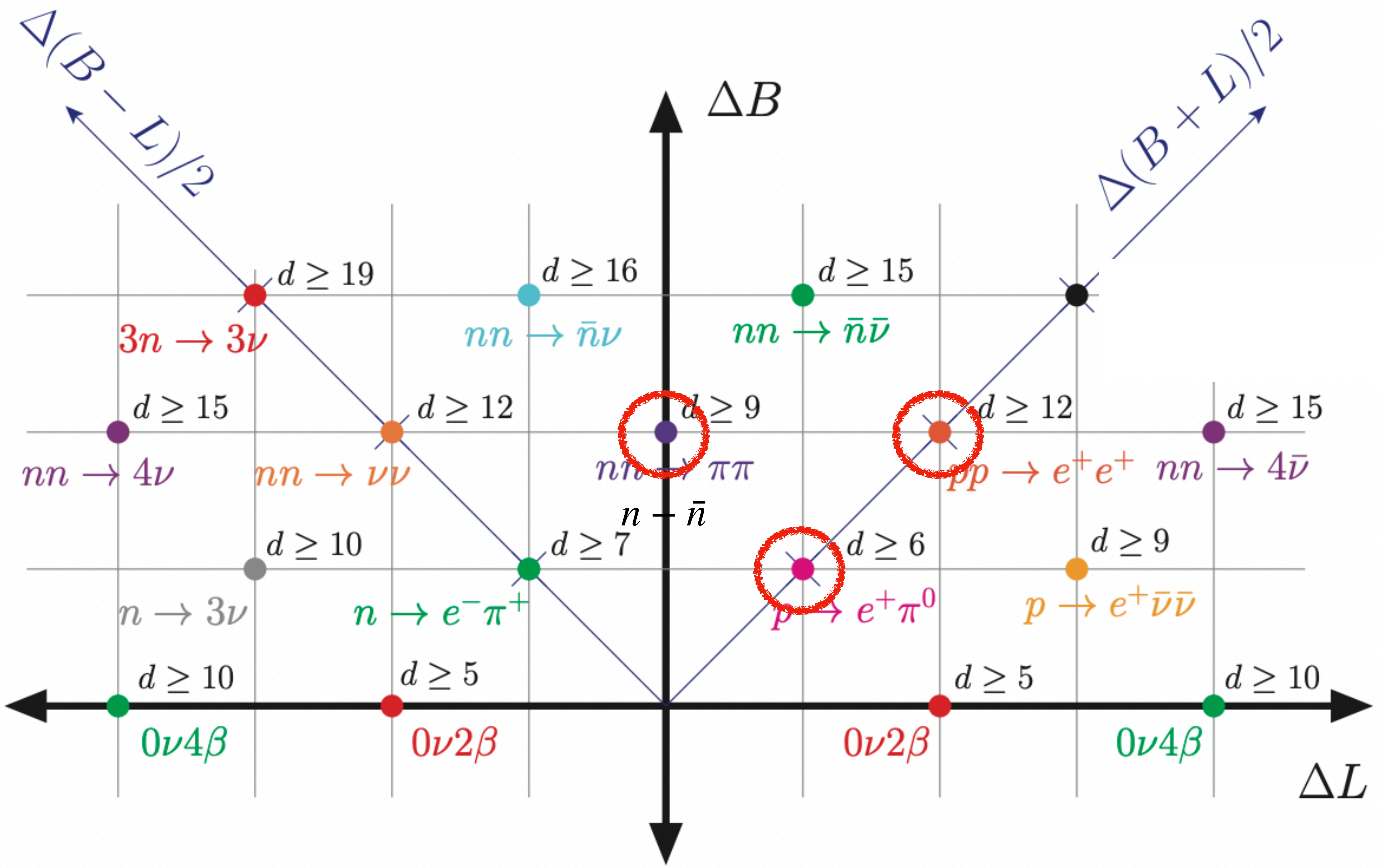
Assuming perturbative couplings to ‘X’ particle

Quark level dim-6

$$
\begin{aligned}
\mathcal{L}_{d=6} = \; & y^1_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{Q}^C_{i,c,\gamma}\epsilon_{ij}L_{j,d}) \\
& + y^2_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{Q}^C_{i,a,\alpha}\epsilon_{ij}Q_{j,b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) \\
& + y^3_{abcd}\epsilon^{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q}^C_{i,a,\alpha}Q_{j,b,\beta})(\overline{Q}^C_{k,c,\gamma}L_{l,d}) \\
& + y^4_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) + \text{h.c.}\,,
\end{aligned}
$$

$$
\Gamma(p \to e^+\pi^0) \simeq \frac{1}{2\times 10^{34}\,\text{yr}}\left|\frac{y^j_{1111}}{(3\times 10^{15}\,\text{GeV})^{-2}}\right|^2 .
$$

Effective operators: quark level….assuming perturbative new physics



Julian Heeck and Volodymyr Takhistov
Phys. Rev. D 101, 015005

arXiv:1910.07647

Neutron-Antineutron Oscillation Search using a 0.37 Megaton·Year Exposure of Super-Kamiokande

K. Abe *et al.* (Super-Kamiokande Collaboration)
Phys. Rev. D **103**, 012008 – Published 21 January 2021

- As a BNV process that violate both B and B-L, neutron-antineutron oscillation provides a unique probe of baryon number violation
- Most of the models predicting $n - \bar{n}$ correspond to energy scales of $10^2 - 10^3$ TeV, well above the scales that can be probed by accelerators

	Events	$T_{n-\bar{n}}$ (10^{32} yrs)	$\tau_{n\to\bar{n}}$ (10^8 s)
Expected	9.3	4.3	5.1
Observed	11	3.6	4.7

$10^{-34} GeV$

$$\mathcal{L} = i\bar{n}\gamma^\mu\partial_\mu n - \frac{m_n}{2}\left[\bar{n}n + \bar{n^c}n^c\right] - \frac{\epsilon}{2}\left[\bar{n^c}n + \bar{n}n^c\right]$$

Phys. Rev. D **87**, 075004 Jonathan M. Arnold, Bartosz Fornal and Mark B. Wise
Physics Letters B 777 (2018) 324–331 Nima Assad, Bartosz Fornal*, Benjamín Grinstein

BNV with suppressed proton decay in 4 dimensions : at high scale

The only leptoquark and diquark models with a triplet or sextet color structure that do not suffer from tree-level proton decay. The primes indicate the existence of dim 5 proton decay channels.

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$ reps.
Scalar leptoquark	$(3,2)'_{\frac{7}{6}}$
Scalar diquark	$(3,1)_{\frac{2}{3}}$, $(6,1)_{-\frac{2}{3}}$, $(6,1)_{\frac{1}{3}}$, $(6,1)_{\frac{4}{3}}$, $(6,3)_{\frac{1}{3}}$
Vector leptoquark	$(3,1)'_{\frac{2}{3}}$, $(3,1)_{\frac{5}{3}}$, $(3,3)'_{\frac{2}{3}}$
Vector diquark	$(6,2)_{-\frac{1}{6}}$, $(6,2)_{\frac{5}{6}}$

Possible interaction terms between the scalars

operator	$SU(3) \times SU(2) \times U(1)$
XQQ, Xud	$(\bar{6}, 1, -1/3)$
XQQ	$(\bar{6}, 3, -1/3)$
Xdd	$(3, 1, 2/3), (\bar{6}, 1, 2/3)$
Xuu	$(\bar{6}, 1, -4/3)$
$X\bar{Q}e$	$(3, 2, 7/6)$
$X\bar{L}u$	$(\bar{3}, 2, -7/6)$
$X\bar{L}d$	$(\bar{3}, 2, -1/6)$
XLL	$(1, 1, 1), (1, 3, 1)$
Xee	$(1, 1, 2)$

Possible vector color triplet and sextet representations.

Operator	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	p decay
$\overline{Q_L^c}\gamma^\mu u_R V_\mu$	3	2	−5/6	tree-level
	$\bar{6}$	2	−5/6	–
$\overline{Q_L^c}\gamma^\mu d_R V_\mu$	3	2	1/6	tree-level
	$\bar{6}$	2	1/6	–
$\overline{Q_L}\gamma^\mu L_L V_\mu$	3	1, 3	2/3	dim 5
$\overline{Q_L^c}\gamma^\mu e_R V_\mu^*$	3	2	−5/6	tree-level
$\overline{L_L^c}\gamma^\mu u_R V_\mu^*$	3	2	1/6	tree-level
$\overline{L_L^c}\gamma^\mu d_R V_\mu^*$	3	2	−5/6	tree-level
$\overline{u_R}\gamma^\mu e_R V_\mu$	3	1	5/3	dim 7
$\overline{d_R}\gamma^\mu e_R V_\mu$	3	1	2/3	dim 5

Physics Letters B 777 (2018) 324–331 Nima Assad, Bartosz Fornal*, Benjamín Grinstein

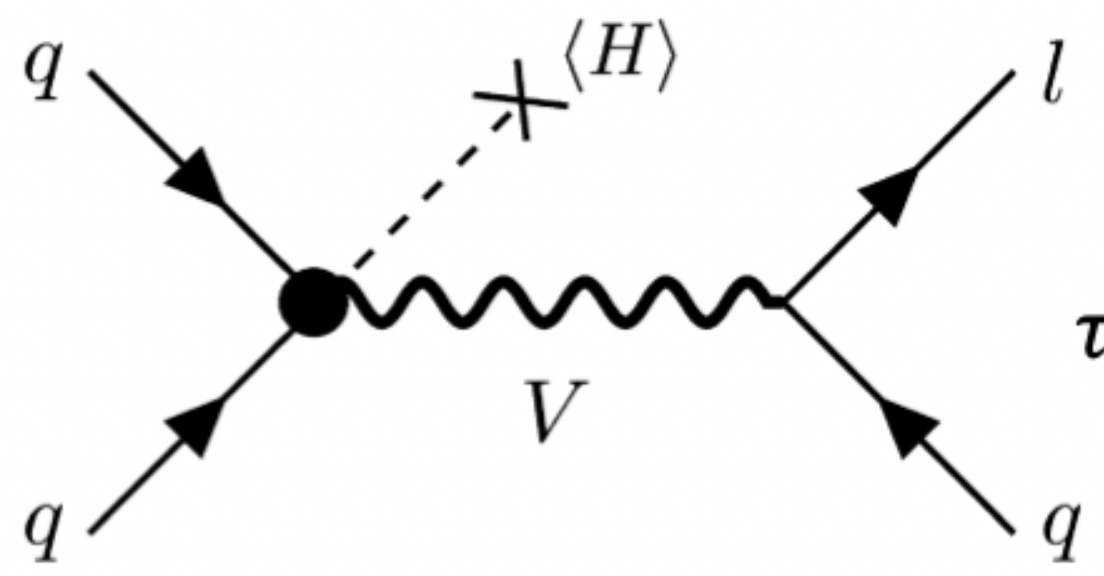
BNV with suppressed proton decay in 4 dimensions : at high scale

Vectors:

- Though tree-level proton decay is absent, there could be dim-5 operator that leads to proton-decay.

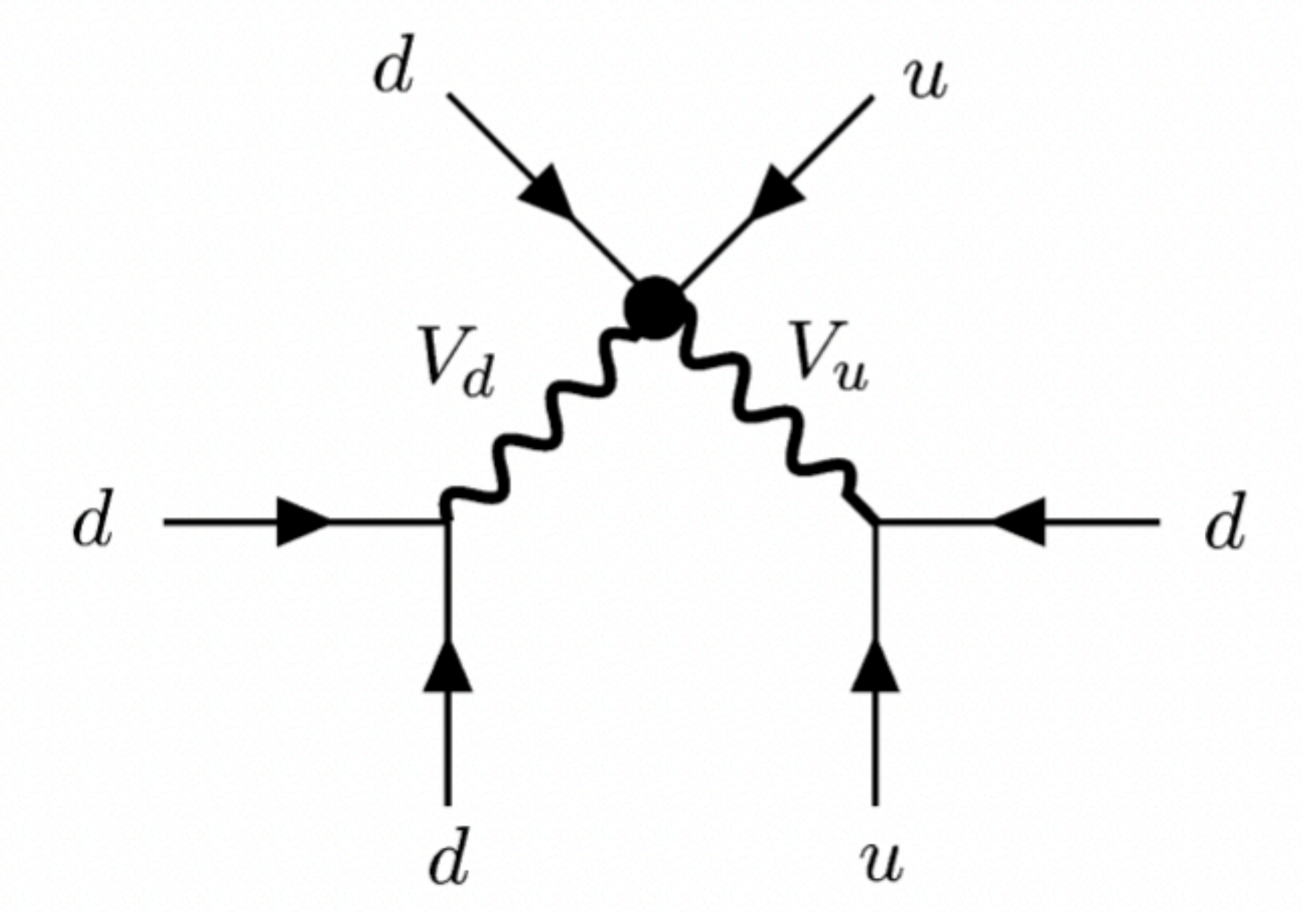
vector leptoquark representations $(3,1)_{\frac{2}{3}}$ and $(3,3)_{\frac{2}{3}}$

$$\frac{1}{\Lambda}(\overline{Q_L^c}H^\dagger)\gamma^\mu d_R V_\mu\,, \quad \frac{1}{\Lambda}(\overline{Q_L^c}\tau^A H^\dagger)\gamma^\mu d_R V_\mu^A\,,$$



Proton decay through a dimension five interaction

$$\tau_p \approx \left(2.5 \times 10^{32}\ \text{years}\right)\left(\frac{M}{10^4\ \text{TeV}}\right)^4\left(\frac{\Lambda}{M_{\text{Pl}}}\right)^2$$



Process mediating $n-\bar{n}$ oscillations via the vector diquark $(6,2)_{-\frac{1}{6}}$

- This operator does not exist if we gauge $U(1)_{B-L}$.
- In the light of null results from ΔB=1 searches, the possibility of discovering *neutron-antineutron* oscillations has recently gained increased interest

$$M \gtrsim 2.5\ \text{TeV}\left(\frac{10^8\ \text{TeV}}{\Lambda}\right)^{1/4} \gtrsim 90\ \text{TeV}$$

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	1.2×10^{35}	1.4×10^{34}
$p \to \overline{\nu}K^+$	2.8×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+\eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+\rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+\omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+\omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+\pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+\pi^-$	2.9×10^{34}	0.10×10^{34}

KEK Preprint 2016-21
(HYPER-KAMIOKANDE design report)

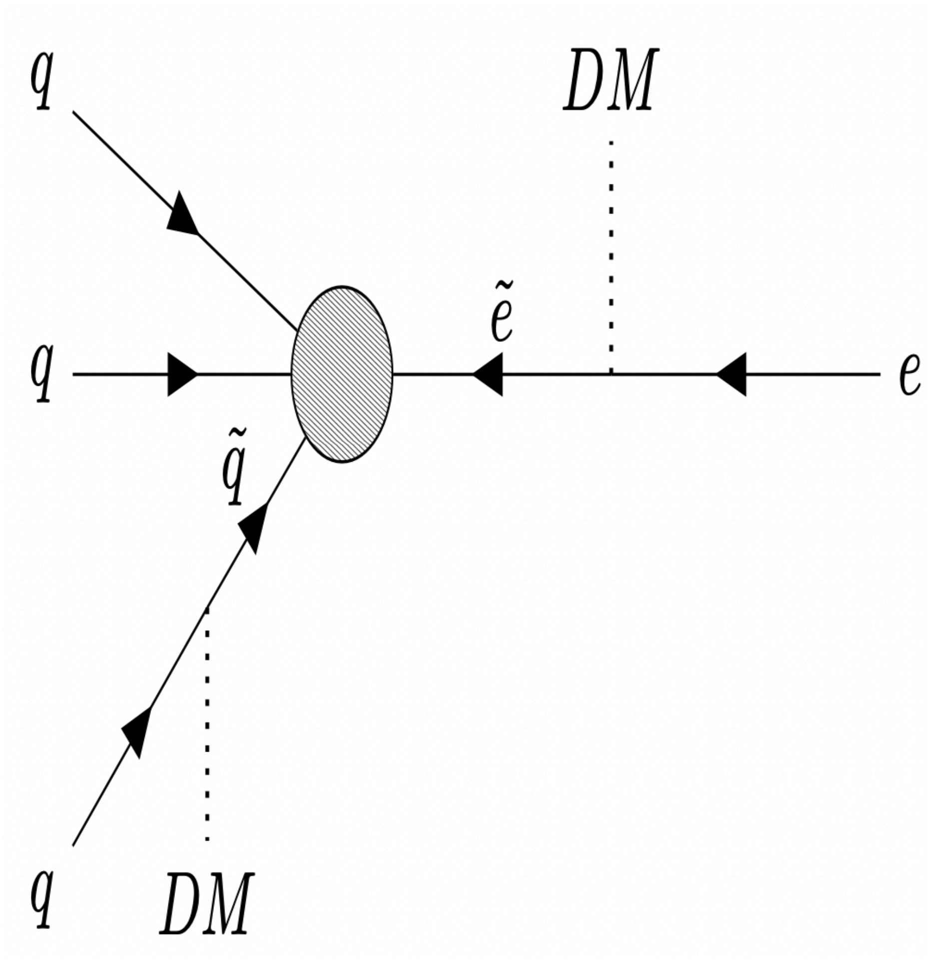
- With the next generation of experiments with higher sensitivity probing even further, the New Physics models would require further complicated structures.

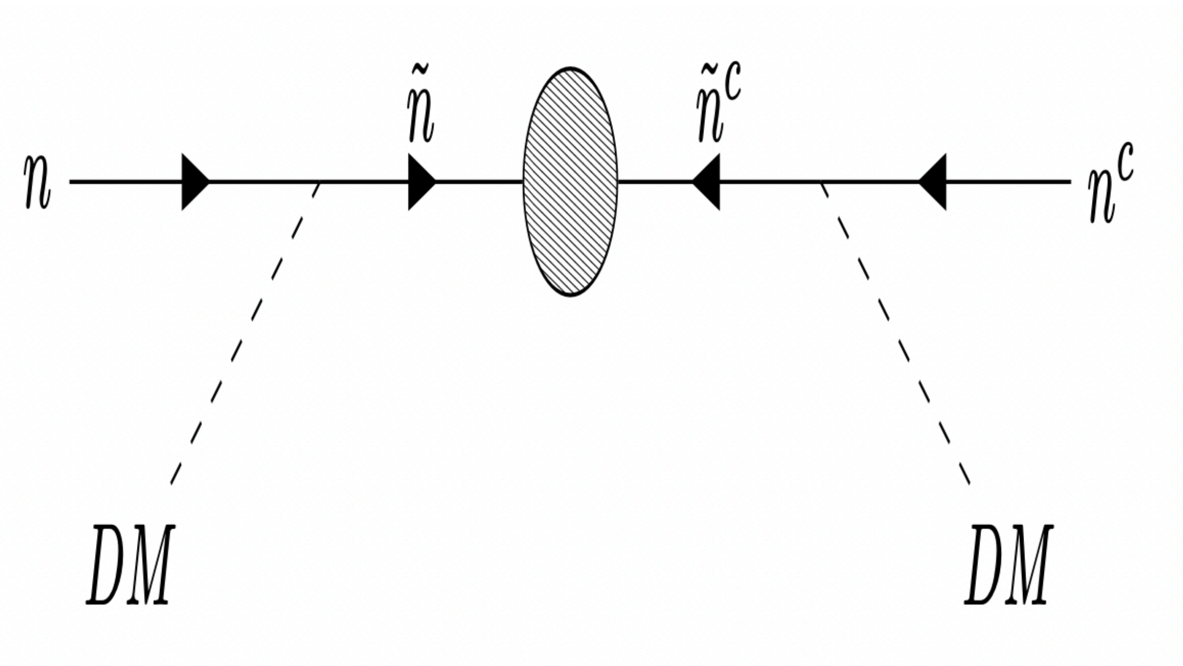
- There exists two phenomena that lack clear evidence in terrestrial experiments

    A. Baryon number violation

    B. Dark Matter

- Its curious to wonder whether both are connected. Does Dark Matter act as a catalyst for BNV ?





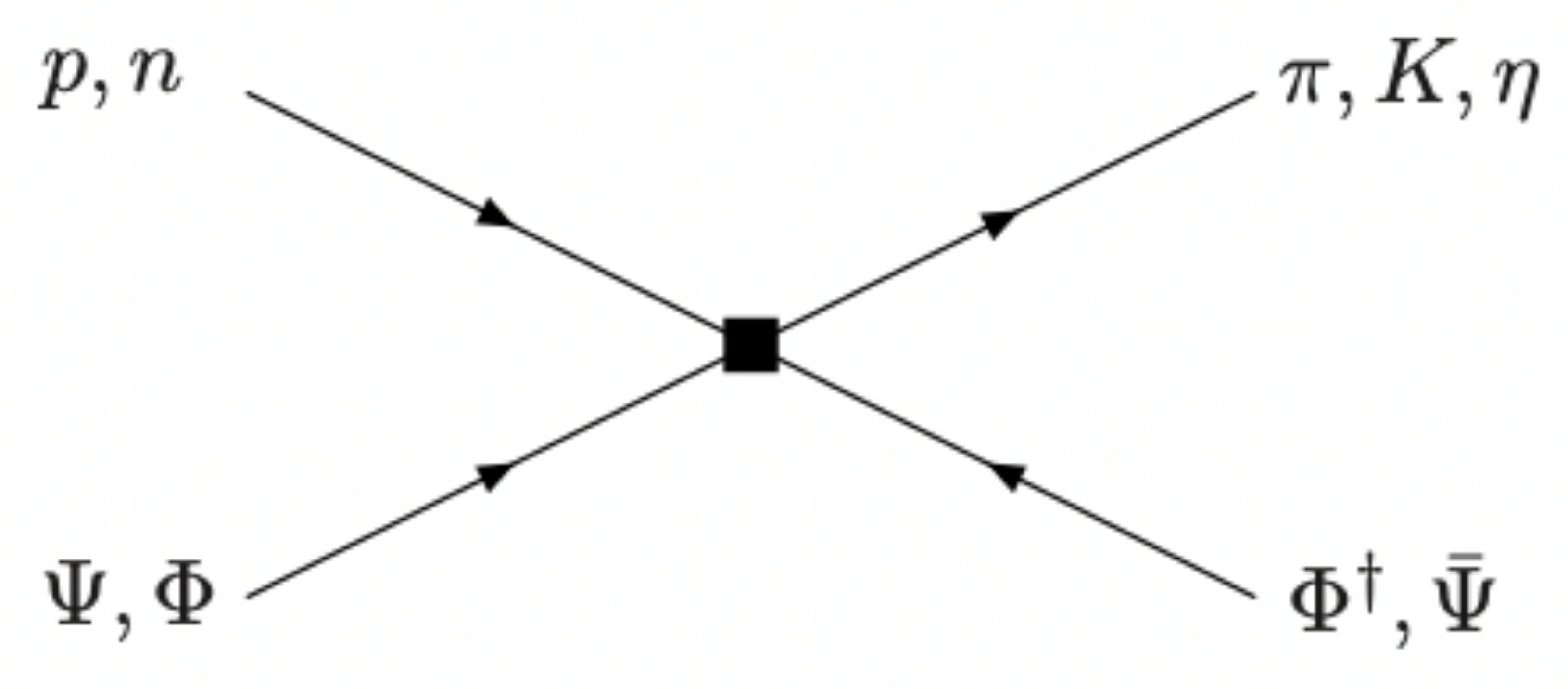
PHYSICAL REVIEW D **84,** 096008 (2011) Hooman Davoudiasl,[1,*] David E. Morrissey,[2,†] Kris Sigurdson,[3,‡] and Sean Tulin[2,§]

(Assisted/induced) baryon number violation

Asymmetric Dark Matter

- Effective induced BNV lifetime can be defined as $\tau^{-1} = n_{DM}(\sigma v)_{IND}$ where $n_{DM} = \rho_{DM}/(m_\psi + m_\phi)$

$$\mathscr{L}_{\rm eff} \sim \frac{1}{\Lambda^3} u^i_R d^j_R d^k_R \Psi_R \Phi$$



$$\tau_N^{-1} \approx (10^{32}\ \text{yrs})^{-1} \times \left(\frac{\rho_{DM}}{0.3\,\text{GeV/cm}^3}\right)\left(\frac{(\sigma v)_{IND}}{10^{-39}\,\text{cm}^3/\text{s}}\right)$$

$$(\sigma v)_{IND} \approx 10^{-39}\ \text{cm}^3/\text{s} \times \left(\frac{\Lambda_{IND}}{1\ \text{TeV}}\right)^{-6}$$

(Assisted) baryon number violation

from 4k+2 dimensions

$$\{\Gamma_M, \Gamma_N\} = 2\eta_{MN}$$

- Clifford Algebra in 4k+2 dimensions

$$\Gamma^{4k+3} = \alpha\Gamma^0\Gamma^1\Gamma^2....\Gamma^{4k+1}$$

$$P_\pm = \frac{1}{2}(1 \pm \Gamma^{4k+3}) \qquad \psi_\pm = P_\pm\psi$$

$$\psi^c = C\psi \equiv (C\Gamma^0)\psi^*$$

$$\Gamma^M = -(C\Gamma^0)\Gamma^{M*}(C\Gamma^0)^{-1} = -C(\Gamma^M)^T C^{-1} .$$

- This is unlike in 4k dimensions.

$$[C\Gamma^0, \Gamma^{4k+3}] = 0 \text{ in } 4k{+}2{-}\text{dimensions.}$$

- Thus the fermion representation and its charge conjugate must satisfy the same Weyl condition

Some properties of six dimensions

- Witten anomaly constrains the number of $SU(2)_W$ doublets to appear in multiples of 3
- Although non-vanishing reducible anomalies like $[SU(2)_W]^4$,$[SU(3)_c]^2[SU(2)_W]^2$, $[SU(2)_W]^2[U(1)_Y]^2, \ldots$ are manageable via Green-Schwarz mechanism, irreducible anomalies like $[SU(3)_c]^3[U(1)_Y]$ require the chiral assignment $Q_+, \mathscr{U}_-, \mathscr{D}_-$ for quarks and $L_\pm, \mathscr{E}_\mp, \mathscr{N}_\mp$ for leptons
- A combination of 5th and 6th component of the Hypercharge gauge boson becomes the Dark Matter candidate

Some properties of six dimensions

- On compactifying on T^2 the Lorentz generators break to $\Sigma^{MN} \to \Sigma^{\mu\nu}$ and Σ^{45} and the fermions become $\Psi_{\pm} = \psi_{\pm l} f_l + \psi_{\pm r} f_r$
- This residual Σ^{45} generates a rotational invariance $U(1)_{45}$
- Interestingly, on orbifolding, the square T^2/Z_2 would break this $U(1)_{45}$ down to a Z_4 symmetry since its invariant under $\pi/2$ rotations.
- Under this generator, the fermions $\psi_{\pm l}$ are charged $\pm 1/2$ and $\psi_{\pm r}$ are charged $\mp 1/2$
- All the operators in this geometry should keep this symmetry preserved.
- Thus, on a square T^2/Z_2 the baryon and lepton number violating operators should satisfy the selection rule $\frac{3}{2}\Delta B \pm \frac{1}{2}\Delta L = 0 \ mod \ 4$
- Other orbifolds like T^2/Z_3, makes sure that proton decay along with other $\Delta B = 2, \ \Delta L = 2$ processes are also suppressed. Except for neutron-antineutron oscillation

Phys.Rev.D 109 (2024) 9, 095039 Akshay and **MTA**

(Assisted) baryon number violation

6 dimensions

- Thus geometry plays a crucial role. But for generality, lets assume a simple T^2/Z_2, in which all the operators are allowed.
- The gamma matrices are

$$\Gamma^\mu = \gamma^\mu \otimes \sigma^1 \ , \ \Gamma^4 = \gamma^5 \otimes \sigma^1 \ , \Gamma^5 = \mathbb{1} \otimes \sigma^2 \qquad \Gamma^7 = \Gamma^0\Gamma^1\Gamma^2\Gamma^3\Gamma^4\Gamma^5 = \mathbb{1} \otimes \sigma^3$$

$$\begin{aligned} C &= i\Gamma^4\Gamma^2\Gamma^0 \\ &= \gamma^5\gamma^2\gamma^0 \otimes \sigma^1 \end{aligned} \qquad [C\Gamma^0, \Gamma^7] = 0$$

Phys.Rev.D 109 (2024) 9, 095039 Akshay and **MTA**

(Assisted) baryon number violation

6 dimensions

- Model independent baryon number and lepton number violating operators in six-dimensions are,

6D Lorentz symmetry	$\Delta B = 1 = \Delta L$	$\Delta B = 2 = \Delta L$
Scalar	$\frac{1}{\Lambda_6^4} C_1^S (\mathcal{Q}_+^T C \mathcal{U}_-)(\mathcal{E}_-^T C \mathcal{Q}_+)$	
Vector	$\frac{1}{\Lambda_6^4} C_1^V (\mathcal{Q}_+^T C \Gamma^M \mathcal{Q}_+)(\mathcal{Q}_+^T C \Gamma_M L_+)$	$\frac{1}{\Lambda_6^{14}} C_2^V (\mathcal{Q}_+^T C \Gamma^M \mathcal{Q}_+)^2 (\mathcal{Q}_+^T C \Gamma^N L_+)^2$
Mixed		$\frac{1}{\Lambda_6^{14}} C_2^L (\mathcal{Q}_+^T C \mathcal{U}_-)^2 (\mathcal{Q}_+^T C \Gamma^M L_+)^2$ $\frac{1}{\Lambda_6^{14}} C_2^Q (\mathcal{Q}_+^T C \mathcal{E}_-)^2 (\mathcal{Q}_+^T C \Gamma^M \mathcal{Q}_+)^2$

Phys.Rev.D 109 (2024) 9, 095039 Akshay and **MTA**

(Assisted) baryon number violation

on orbifolding to 4 dimensions

- After orbifolding, the operators with least number of KK-modes are

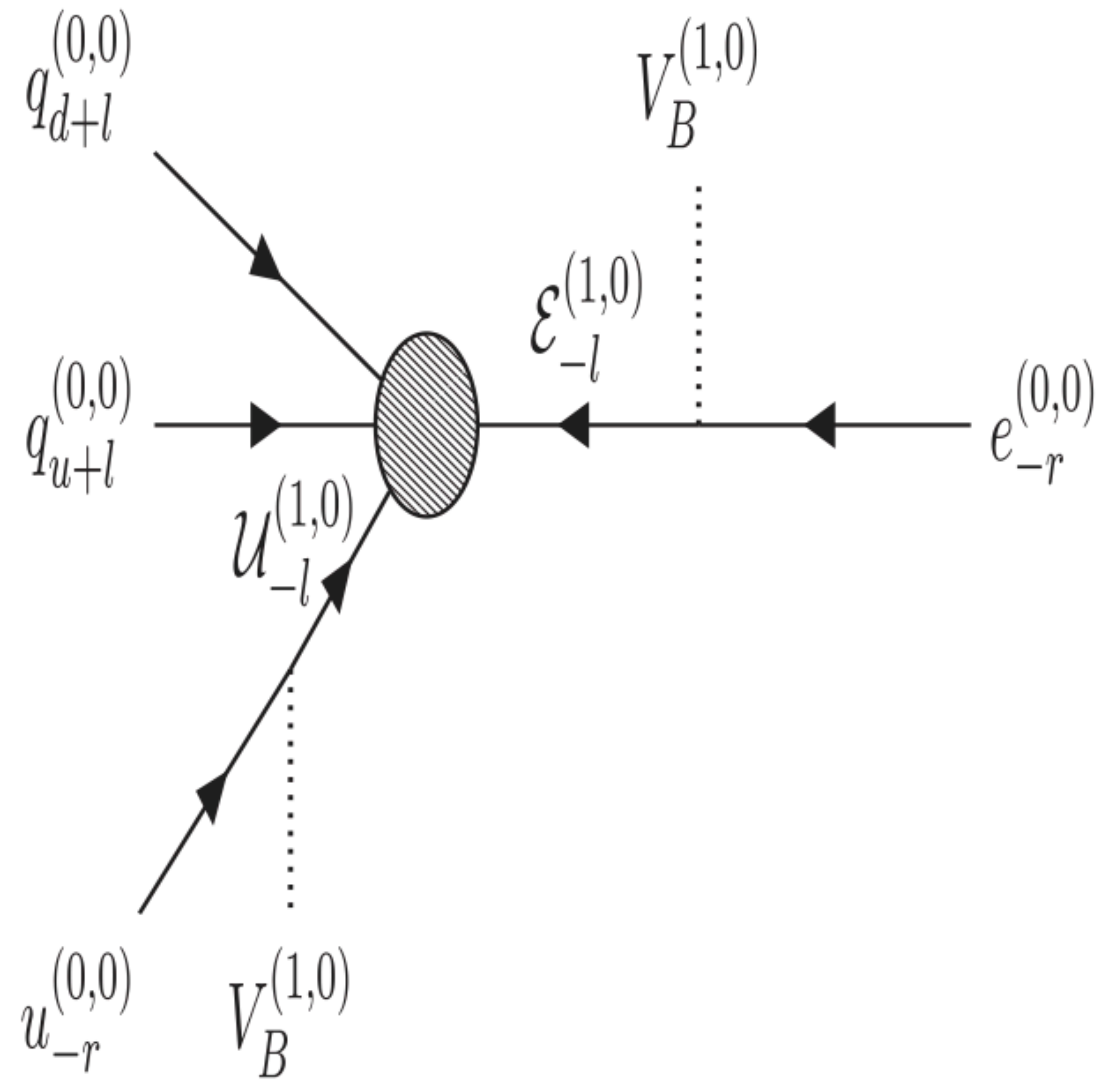
$$\Psi_\pm(x^\mu, x^4, x^5) = \frac{1}{R}\sum_{n,m}\Big(\psi^{(n,m)}_{\pm l}(x^\mu) f_{\pm l}(x_4, x_5) + \psi^{(n,m)}_{\pm r}(x^\mu) f_{\pm r}(x_4, x_5)\Big) \ ,$$

Operators	$\Delta B = 1 = \Delta L$	$\Delta B = 2 = \Delta L$
Scalar	$\frac{C^S_1}{\Lambda^2_4}(q^{(0,0)T}_{+l}\gamma^2\gamma^0\mathcal{U}^{(1,0)}_{-l})(\mathcal{E}^{T(1,0)}_{-l}\gamma^2\gamma^0 q^{(0,0)}_{+l})$	$\frac{C^S_2}{\Lambda^8_4}(q^{(0,0)T}_{+l}\gamma^2\gamma^0\mathcal{U}^{(1,0)}_{-l})^2(\mathcal{E}^{T(1,0)}_{-l}\gamma^2\gamma^0 q^{(0,0)}_{+l})^2$
Vector	$\frac{C^V_1}{\Lambda^2_4}(u^{(0,0)T}_{-r}\gamma^2\gamma^0\gamma^\mu\mathcal{D}^{(1,0)}_{-l})(u^{(0,0)T}_{-r}\gamma^2\gamma^0\gamma_\mu\mathcal{E}^{(1,0)}_{-l})$	$\frac{C^V_2}{\Lambda^8_4}(u^{(0,0)T}_{-r}\gamma^2\gamma^0\gamma^\mu\mathcal{D}^{(1,0)}_{-l})^2(u^{(0,0)T}_{-r}\gamma^2\gamma^0\gamma_\mu\mathcal{E}^{(1,0)}_{-l})^2$

Phys.Rev.D 109 (2024) 9, 095039 Akshay and **MTA**

(Assisted) $\Delta B = 1,\ \Delta L = 1$ process

$$\mathcal{O}_1 = \frac{C_1^S}{\Lambda_4^2}(q_{+l}^{(0,0)T}\gamma^2\gamma^0\mathcal{U}_{-l}^{(1,0)})(\mathcal{E}_{-l}^{T(1,0)}\gamma^2\gamma^0 q_{+l}^{(0,0)}) + \frac{C_1^V}{\Lambda_4^2}(u_{-r}^{(0,0)T}\gamma^2\gamma^0\gamma^\mu\mathcal{D}_{-l}^{(1,0)})(u_{-r}^{(0,0)T}\gamma^2\gamma^0\gamma_\mu\mathcal{E}_{-l}^{(1,0)})$$



$$C_{\text{AND}}\mathcal{O}_{\text{AND}} = y_u y_e g_Y^2 \frac{C_1^S}{\Lambda_4^2}\frac{1}{M_{KK}^2}(q_{+l}^{T(0,0)}\gamma^2\gamma^0 u_{-r}^{(0,0)}) \times (e_{-r}^{T(0,0)}\gamma^2\gamma^0 q_{+l}^{(0,0)})V_B^{(1,0)}V_B^{(1,0)},$$

$$C_{p\to e} = y_u y_e g_Y^2 \frac{C_1^S}{16\pi^2\Lambda_4^2}\left(\frac{M_s}{M_{KK}}\right)^4$$

$$\Gamma_{p\to e} = \frac{1}{2\times 10^{34}}\left|\frac{C_{p\to e}}{(3\times 10^{15}\ \text{GeV})^{-2}}\right|^2$$

Phys.Rev.D 109 (2024) 9, 095039 Akshay and **MTA**

(Assisted) $\Delta B = 2,\ \Delta L = 2$ process

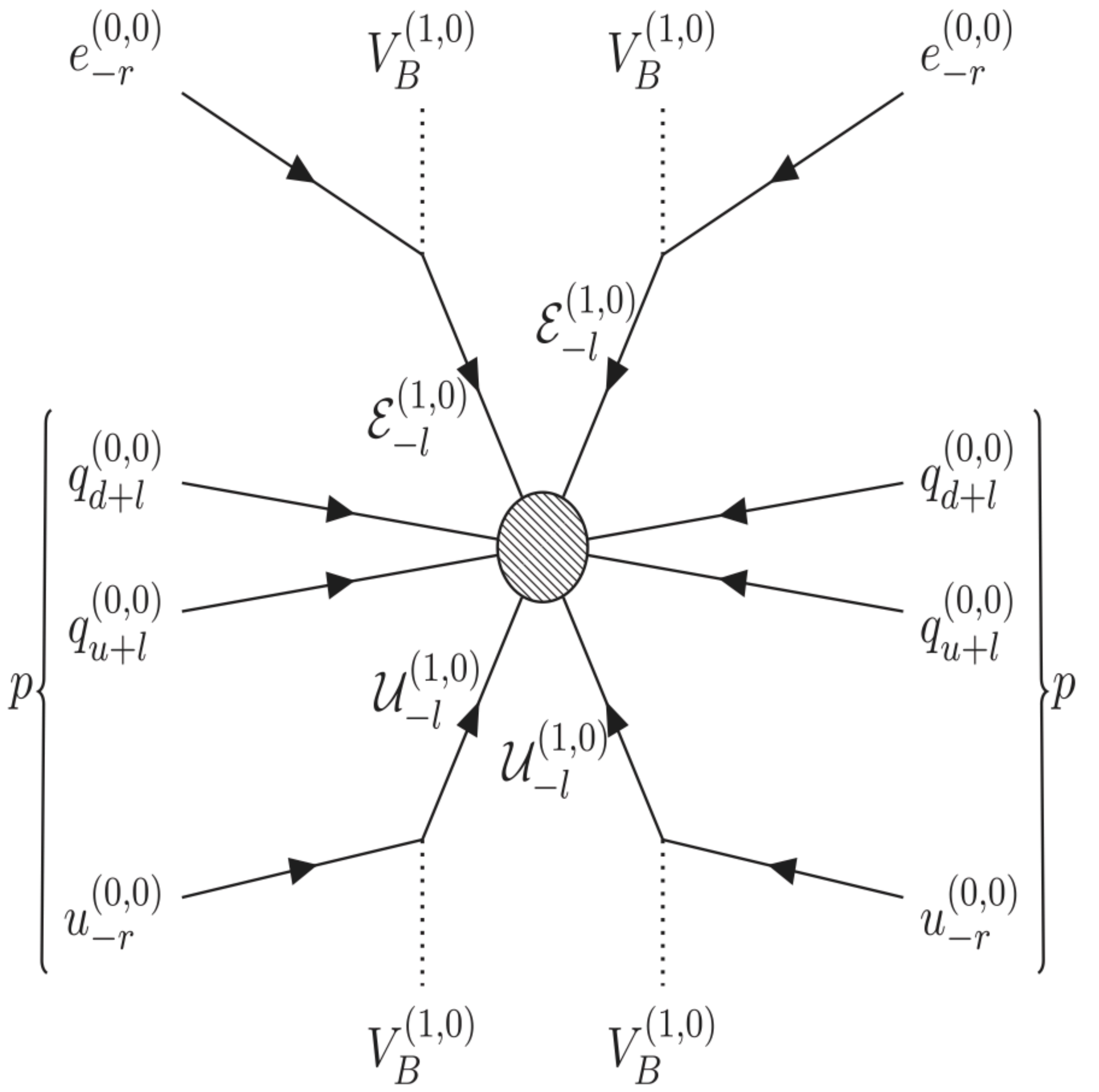
$$\mathcal{O}_2 = \frac{C_2^S}{\Lambda_4^8}(q_{+l}^{(0,0)T}\gamma^2\gamma^0\mathcal{U}_{-l}^{(1,0)})^2(\mathcal{E}_{-l}^{T(1,0)}\gamma^2\gamma^0 q_{+l}^{(0,0)})^2 + \frac{C_2^V}{\Lambda_4^8}(u_{-r}^{(0,0)T}\gamma^2\gamma^0\gamma^\mu\mathcal{D}_{-l}^{(1,0)})^2(u_{-r}^{(0,0)T}\gamma^2\gamma^0\gamma_\mu\mathcal{E}_{-l}^{(1,0)})^2$$

$$C_{\text{ANNA}}\mathcal{O}_{\text{ANNA}} = y_u^2 y_e^2 g_Y^4\frac{C_2^S}{\Lambda_4^8 M_{KK}^4}(q_{+l}^{(0,0)T}\gamma^2\gamma^0 u_{-r}^{(0,0)})^2 \times (e_{-r}^{T(0,0)}\gamma^2\gamma^0 q_{+l}^{(0,0)})^2 V_B^{(1,0)}V_B^{(1,0)}V_B^{(1,0)}V_B^{(1,0)}$$

$$\boldsymbol{DM + p \to DM + \bar{p} + e^+ + e^+}$$

$$\mathcal{O}_{VVppee} = \frac{1}{(\Lambda_{VVppee})^4}(\bar{p}^c p)(\bar{e}^c e)V_B^{(1,0)}V_B^{(1,0)}$$

$$\tau_{\text{ANNA}} = 5\times 10^{33}\text{years}\left(\frac{\Lambda_{VVppee}}{300\text{ GeV}}\right)^8$$



Summary:

- Dark Matter being a catalyst to baryon number violation can be the reason for the rarity of events
- Other places in the galaxy with higher Dark Matter density would be efficient regions to generate the required baryon number violation
- Interesting signatures would be positron fluxes from DM spikes

Thank you

Dinucleon and Nucleon Decay to Two-Body Final States with no Hadrons in Super-Kamiokande

Super-Kamiokande Collaboration arXiv:1811.12430

The Super-Kamiokande (SK) water Cherenkov detector, with a fiducial volume of 22.5 kilotons, contains 1.2×10^{34} nucleons. SK lies one kilometer under Mt. Ikenoyama in Japan's Kamioka Observatory. The detector is cylindrical with a diameter of 39.3 meters and a height of 41.4 meters, optically separated into an inner and an outer region. Eight-inch photomultiplier tubes (PMTs) line the outer detector facing outwards and serve primarily as a veto for cosmic ray muons, and 20-inch PMTs face inwards to measure Cherenkov light in the inner detector [12].

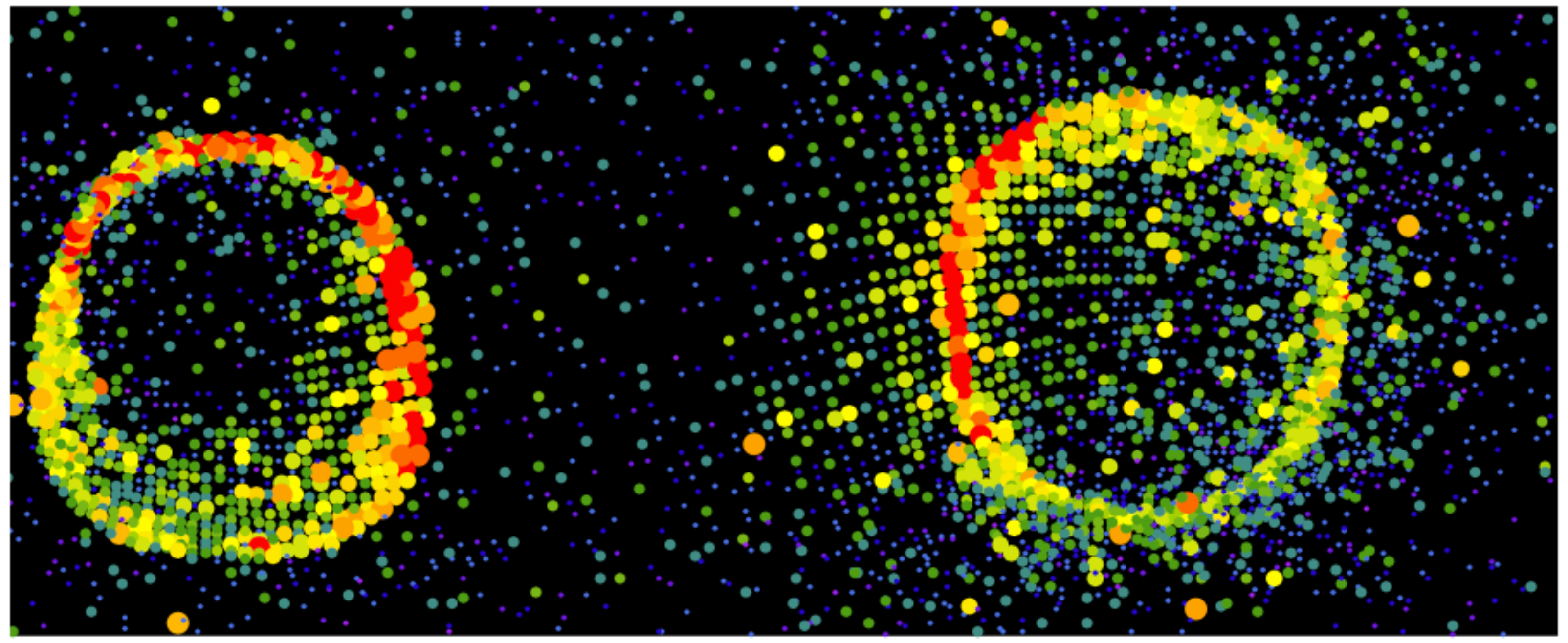
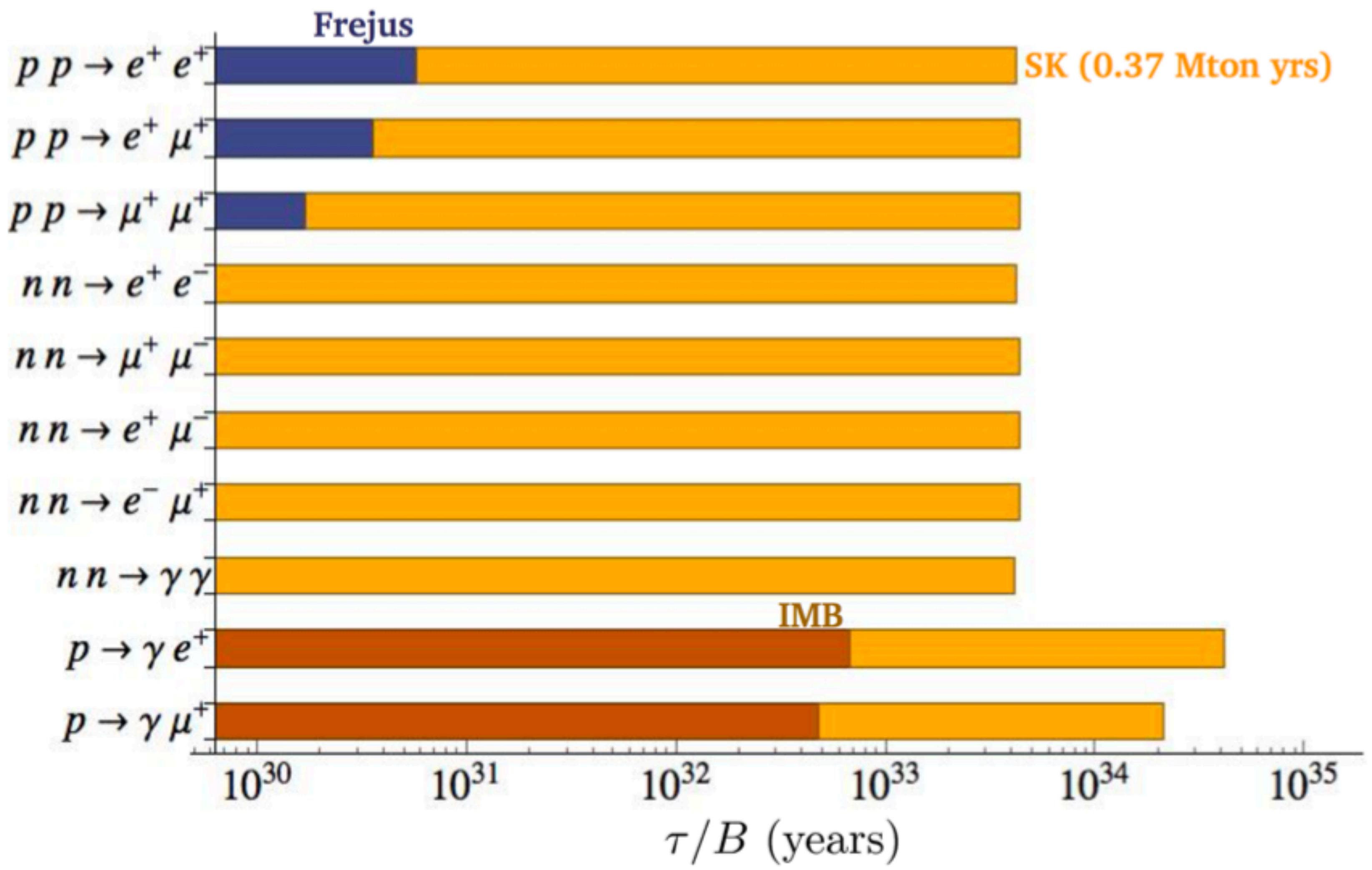


FIG. 1. (color online) An SK event display of a typical $pp \to e^+\mu^+$ event shown in θ-ϕ view. The non-showering ring (from the μ^+) is on the left and the showering ring (from the e^+) is on the right. The energy of each ring is approximately 900 MeV.



The following selection criteria are applied to signal MC, atmospheric ν MC, and data:

(A1) Events must be fully contained in the inner detector with the event vertex within the fiducial volume (two meters inward from the detector walls),

(A2) There must be two Cherenkov rings,

(A3) Both rings must be showering for the $pp \to e^+e^+$, $nn \to e^+e^-$, $nn \to \gamma\gamma$ and $p \to e^+\gamma$ modes; one ring must be showering and one ring must be non-showering for the $pp \to e^+\mu^+$, $nn \to e^+\mu^-$, $nn \to e^-\mu^+$ and $p \to \mu^+\gamma$ modes; both rings must be non-showering for the $pp \to \mu^+\mu^+$, $nn \to \mu^+\mu^-$ modes (see note in [19]),

(A4) There must be zero Michel electrons for the $pp \to e^+e^+$, $nn \to e^+e^-$, $nn \to \gamma\gamma$ and $p \to e^+\gamma$ modes; there must be less than or equal to one Michel electron for the $pp \to e^+\mu^+$, $nn \to e^+\mu^-$, $nn \to e^-\mu^+$ and $p \to \mu^+\gamma$ modes; there is no Michel electron cut for the $pp \to \mu^+\mu^+$, $nn \to \mu^+\mu^-$ modes (see note in [20]),

(A5) The reconstructed total mass, M_{tot}, should be $1600 \leq M_{tot} \leq 2050$ MeV/c^2 for the dinucleon decay modes; the reconstructed total mass should be $800 \leq M_{tot} \leq 1050$ MeV/c^2 for the nucleon decay modes,

(A6) The reconstructed total momentum, P_{tot}, should be $0 \leq P_{tot} \leq 550$ MeV/c for the dinucleon decay modes; for the nucleon decay modes, it should be $100 \leq P_{tot} \leq 250$ MeV/c for the event to be in the "High $P_{\rm tot}$" signal box and $0 \leq P_{tot} \leq 100$ MeV/c for the event to be in the "Low $P_{\rm tot}$" signal box,

(A7) [SK-IV nucleon decay searches only] There must be zero tagged neutrons.

Decay mode	Lifetime limit per oxygen nucleus ($\times 10^{33}$ years)	Lifetime limit per nucleon ($\times 10^{34}$ years)
$pp \to e^+ e^+$	4.2	—
$nn \to e^+ e^-$	4.2	—
$nn \to \gamma\gamma$	4.1	—
$pp \to e^+ \mu^+$	4.4	—
$nn \to e^+ \mu^-$	4.4	—
$nn \to e^- \mu^+$	4.4	—
$pp \to \mu^+ \mu^+$	4.4	—
$nn \to \mu^+ \mu^-$	4.4	—
$p \to e^+ \gamma$	—	4.1
$p \to \mu^+ \gamma$	—	2.1

arXiv:1811.12430 (Dinucleon and Nucleon Decay to Two-Body Final States with no Hadrons in Super-Kamiokande)

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+ \pi^0$	1.2×10^{35}	1.4×10^{34}
$p \to \bar{\nu} K^+$	2.8×10^{34}	0.7×10^{34}
$p \to \mu^+ \pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+ \eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+ \eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+ \rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+ \rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+ \omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+ \omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+ \pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+ \pi^-$	2.9×10^{34}	0.10×10^{34}

KEK Preprint 2016-21
(HYPER-KAMIOKANDE design report)

Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+ \nu\nu$	10.2×10^{32}	1.7×10^{32}
$p \to \mu^+ \nu\nu$	10.7×10^{32}	2.2×10^{32}
$p \to e{+}X$	31.1×10^{32}	7.9×10^{32}
$p \to \mu^+ X$	33.8×10^{32}	4.1×10^{32}
$n \to \nu\gamma$	23.4×10^{32}	5.5×10^{32}
$np \to e^+ \nu$	6.2×10^{32}	2.6×10^{32}
$np \to \mu^+ \nu$	4.2×10^{32}	2.0×10^{32}
$np \to \tau^+ \nu$	6.0×10^{32}	3.0×10^{32}

TABLE IV. Parameters of past (KAM [114, 115]), running (SK [116, 117]), and future (HK-3TankLD and HK-1TankHD) water Cherenkov detectors. The KAM and SK have undergone several configuration changes and parameters for KAM-II and SK-IV are referred in the table. The single-photon detection efficiencies are products of the quantum efficiency at peak (~ 400 nm), photo-electron collection efficiency, and threshold efficiency. Most right column (HK-1TankHD) shows another design under study which consist of one tank instrumented with high density PMTs.

	KAM	SK	HK-3TankLD	HK-1TankHD
Depth	1,000 m	1,000 m	650 m	650 m
Dimensions of water tank				
diameter	15.6 m ϕ	39 m ϕ	74 m ϕ	74 m ϕ
height	16 m	42 m	60 m	60 m
Total volume	4.5 kton	50 kton	774 kton	258 kton
Fiducial volume	0.68 kton	22.5 kton	560 kton	187 kton
Outer detector thickness	$\sim$ 1.5 m	$\sim$ 2 m	1 $\sim$ 2 m	1 $\sim$ 2 m
Number of PMTs				
inner detector (ID)	948 (50 cm ϕ)	11,129 (50 cm ϕ)	40,000 (50 cm ϕ)	40,000 (50 cm ϕ)
outer detector (OD)	123 (50 cm ϕ)	1,885 (20 cm ϕ)	20,000 (20 cm ϕ)	6,700 (20 cm ϕ)
Photo-sensitive coverage	20%	40%	13%	40%
Single-photon detection efficiency of ID PMT	unknown	12%	24%	24%
Single-photon timing resolution of ID PMT	$\sim$ 4 nsec	2-3 nsec	1 nsec	1 nsec

KEK Preprint 2016-21
ICRR-Report-701-2016-1

Scalar LeptoQuark and Scalar Diquark

The Lagrangian for the singlet LeptoQuark S_2 $(\bar{3}, 2, \frac{5}{3})$ and singlet Diquark $DQ_2(\bar{3}, 2, -\frac{5}{3})$ interactions with the fermions given by,

$$\mathcal{L}_S = y^{(+-)}\bar{\mathcal{Q}^C}_+ S_2 \mathcal{E}_- + z^{(-+)}\bar{\mathcal{U}^C}_-(DQ_2)\mathcal{Q}_+ + h.c., \tag{38}$$

where $y^{(+-)}$ and $z^{(-+)}$ are complex 3×3 Yukawa coupling matrices.

Vector LeptoQuark and Scalar Diquark

The interaction of the vector LeptoQuark and scalar Diquark with the fermions given as,

$$\mathcal{L}_{SV} = z^{(-+)}\bar{\mathcal{U}^C}_-(DQ_2)\mathcal{Q}_+ + w^{(++)}\bar{\mathcal{Q}^C}_+ \Gamma^M V_{3M} L_+ + h.c., \tag{39}$$

where the V_{3M} is the vector triplet LeptoQuark and the DQ_2 is the scalar Diquark doublet.

Scalar LeptoQuark and Vector Diquark

The coupling of the scalar LeptoQuark and vector Diquark with the fermions is:

$$\mathcal{L}_{VS} = y^{(+-)}\bar{\mathcal{Q}^C}_+ S_2 \mathcal{E}_- + x^{(++)}\bar{\mathcal{Q}^C}^a_+ \Gamma^M \epsilon^{ab} DQ_{3M}\mathcal{Q}^b_+ + h.c., \tag{40}$$

Vector LeptoQuark and Vector Diquark

The interaction becomes,

$$\mathcal{L}_{VV} = x^{(++)}\bar{\mathcal{Q}^C}^a_+ \Gamma^M \epsilon^{ab} DQ_{3M}\mathcal{Q}^b_+ + w^{(++)}\bar{\mathcal{Q}^C}_+ \Gamma^M V_{3M} L_+ + h.c., \tag{41}$$

where the V_{3M},DQ_{3M} are the triplet vector Leptoquark and Diquark.