GENERALITAT VALENCIANA

Gen—T

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Nonstandard Nucleon Decays

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Nucleon decays:

very rich literature and history…and equally rich audience!

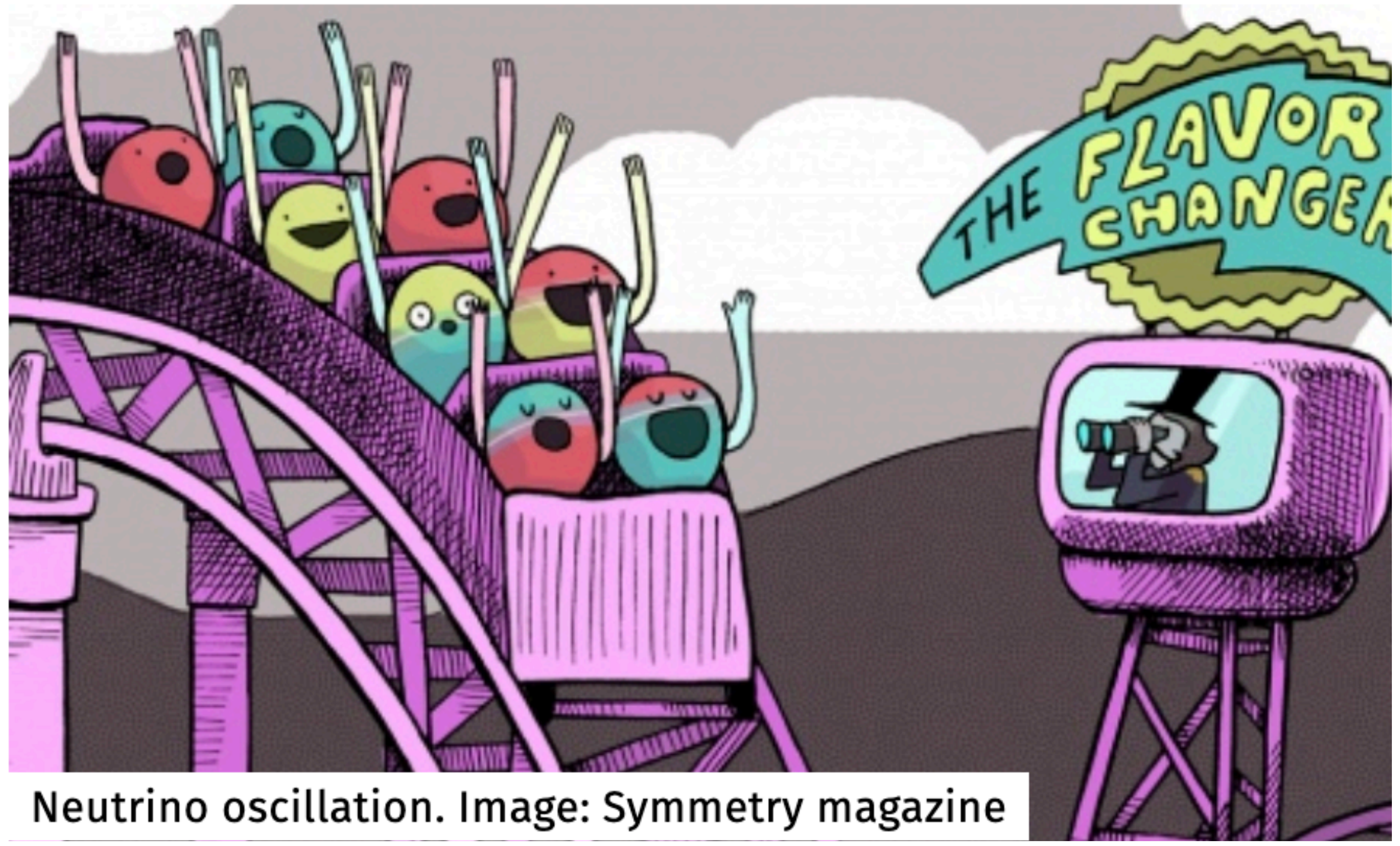
more than four decades of exploration and counting!

Very eccentric and highly biased overview in this talk!

Suggestions are very welcome.

Neutrino masses and Lepton Number Violation

The only laboratory evidence of BSM physics : **Neutrino Oscillations**

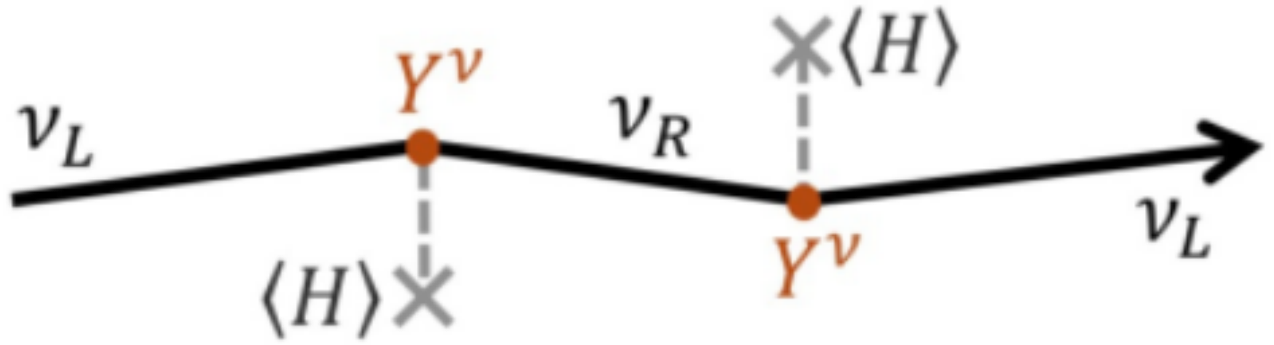


Neutrino oscillation. Image: Symmetry magazine

Purely SM:

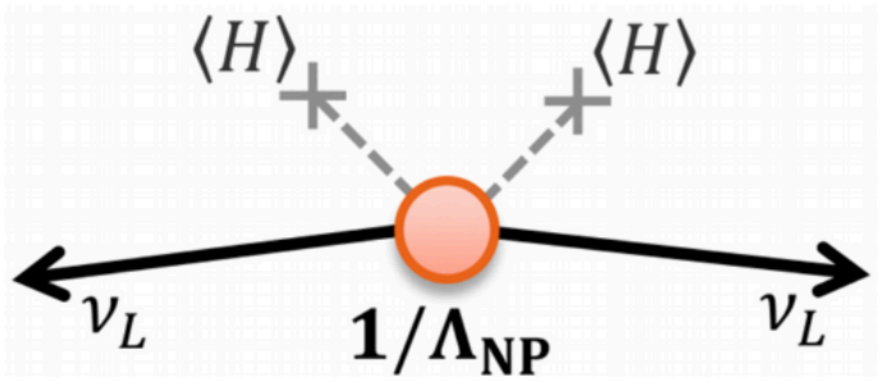
- strictly massless neutrinos
- conservation of lepton number and flavours

Two possibilities for neutrino masses:



$$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$$

VS.



$$m_M \overline{\nu}_L \nu_L^c$$

Dirac: like other fermions,

but tiny Yukawa couplings ~10^{-12}

finetuning, symmetry, ...?

Majorana: $\nu = \nu^c$: **Lepton Number Violation!**

Phenomenologically very interesting!

Connection to Leptogenesis?

LNV and Neutrinoless double beta decay

$$(A, Z) \to (A, Z+2) + 2\,e^{-} + Q_{\beta\beta}$$

Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)

Graf, Deppisch, Iachello, Kotila (2018)++

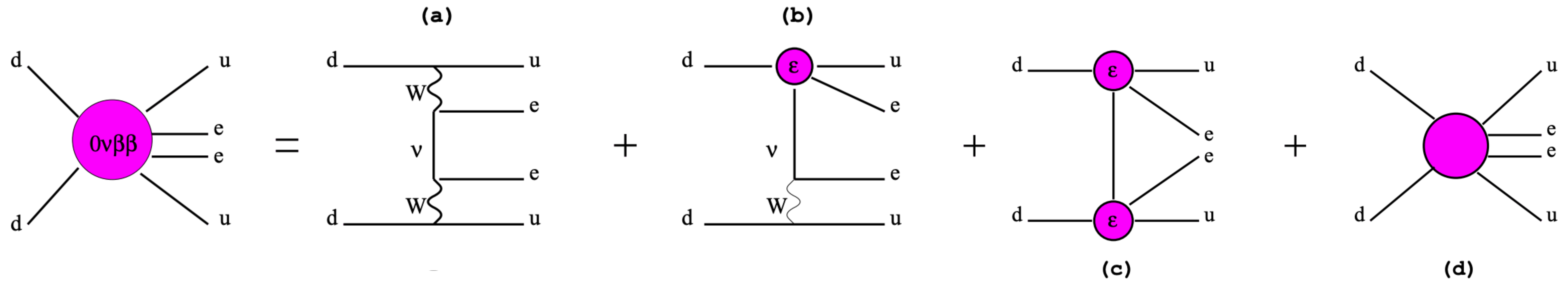
Half life $$T^{0\nu}_{1/2} = \left(G\,|\mathcal{M}|^2\,\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2\,\mathrm{y}$$

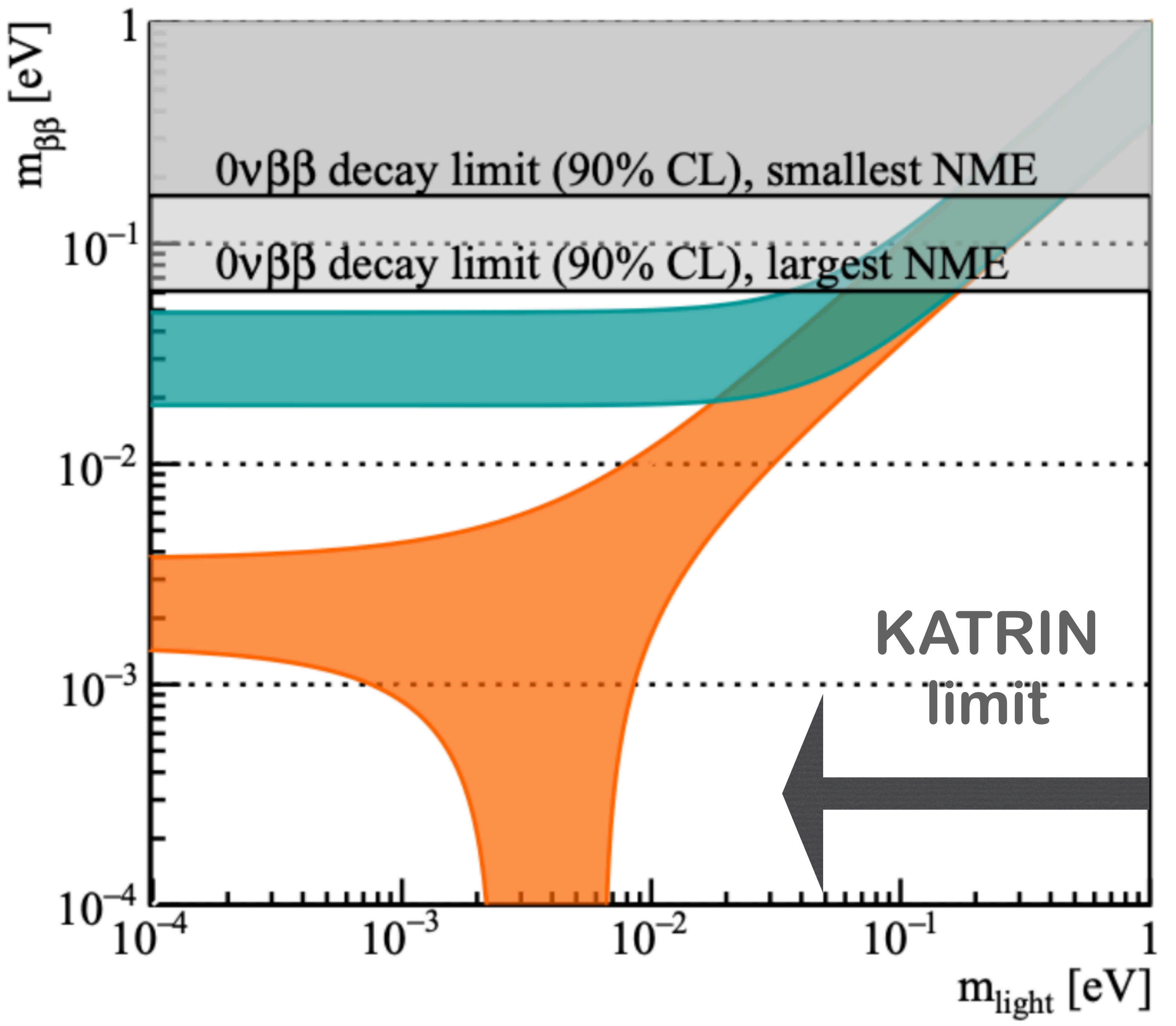
Effective mass $$\langle m_{\beta\beta}\rangle = \left|U^2_{ei}\,m_i\right|$$

Many experiments: KamLAND-Zen, LEGEND, CUORE, NEMO-3, ...

Main source of uncertainty: Nuclear Matrix elements!

- **Many body problem: isotope and operator dependent**
- **Different nuclear models**





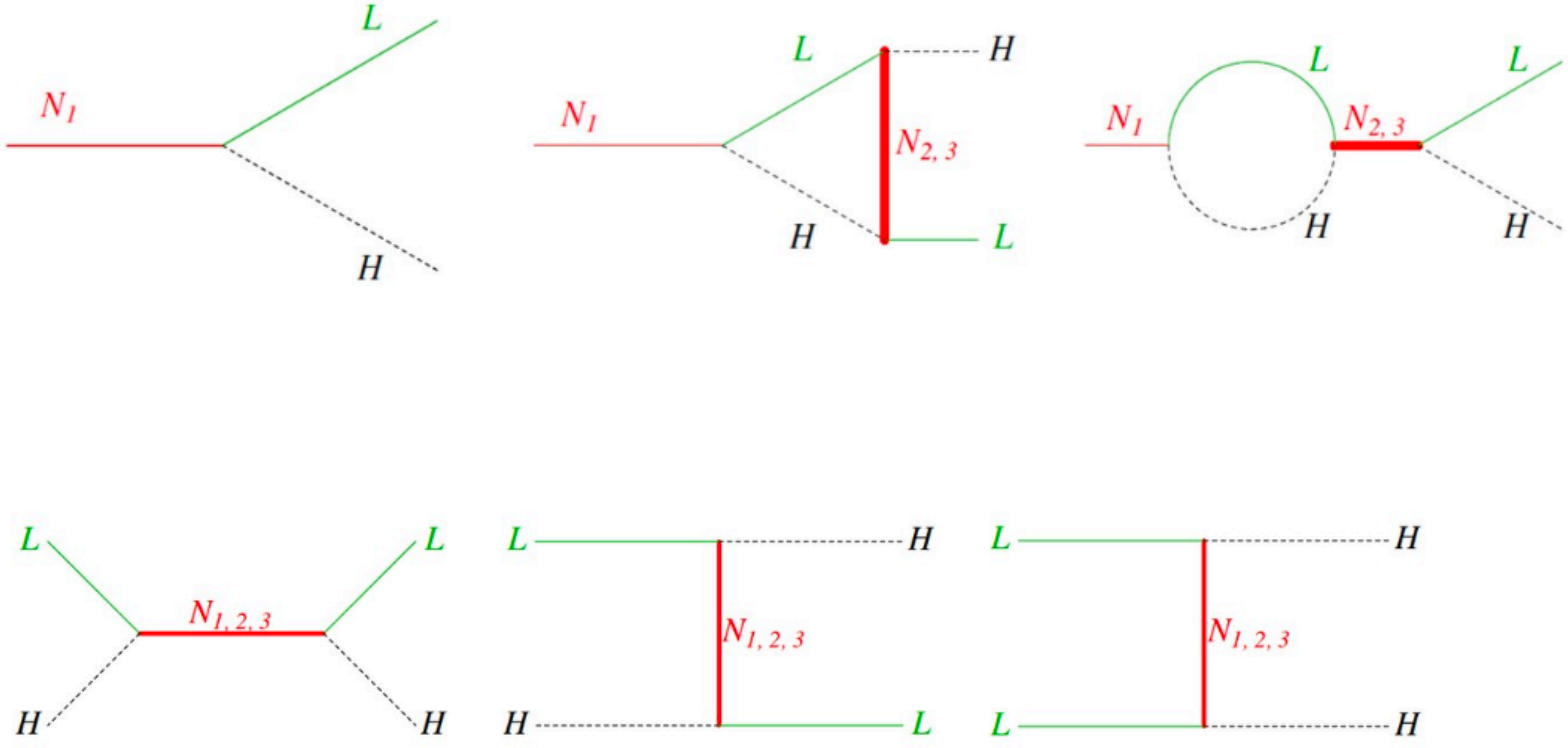
Rev. Mod. Phys. 95, 025002 (2023)

Baryogenesis/Leptogenesis

In the SM

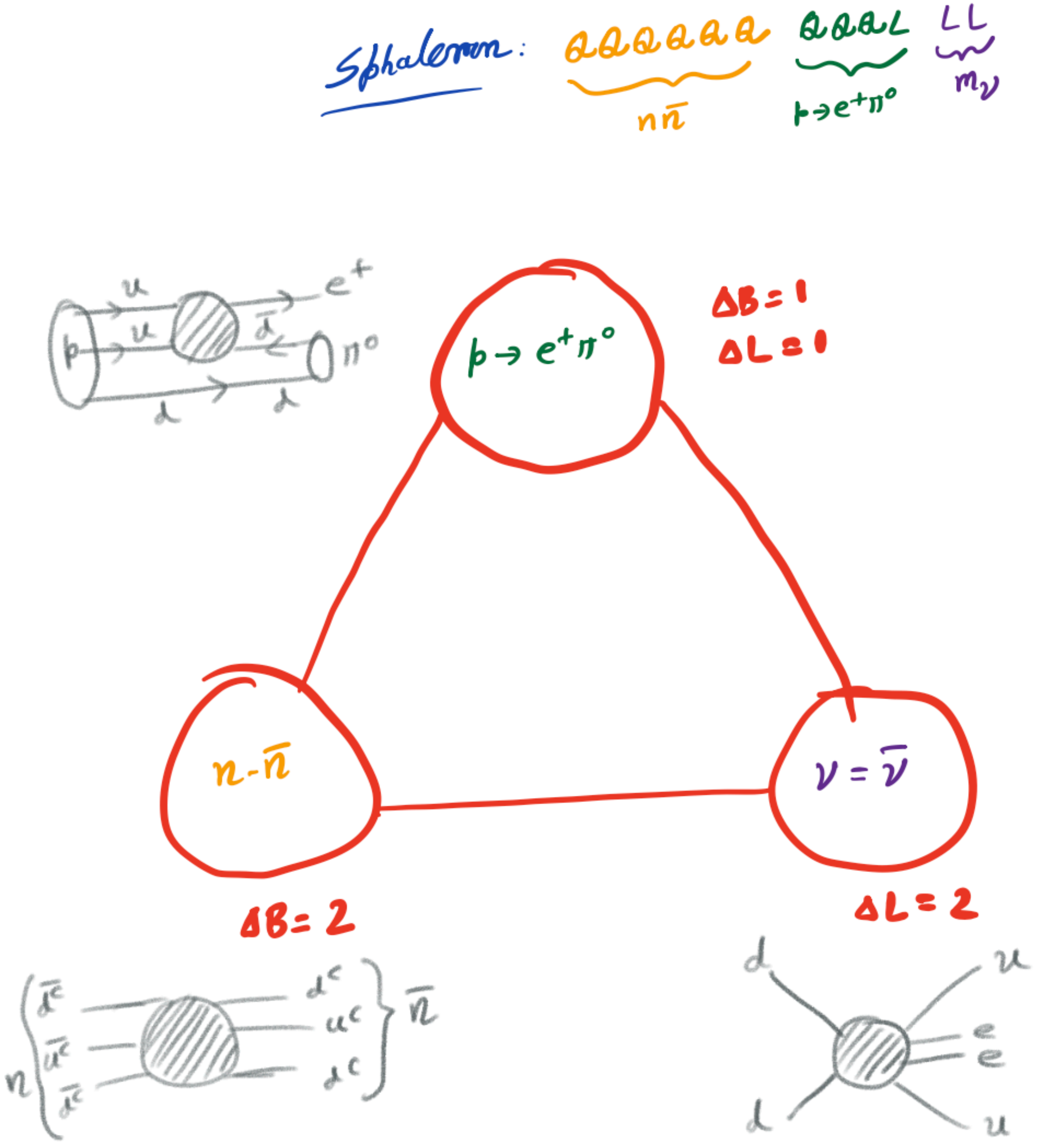
- ☑ baryon number violation
- ☒ C and CP violation
- ☒ departure from thermal equilibrium

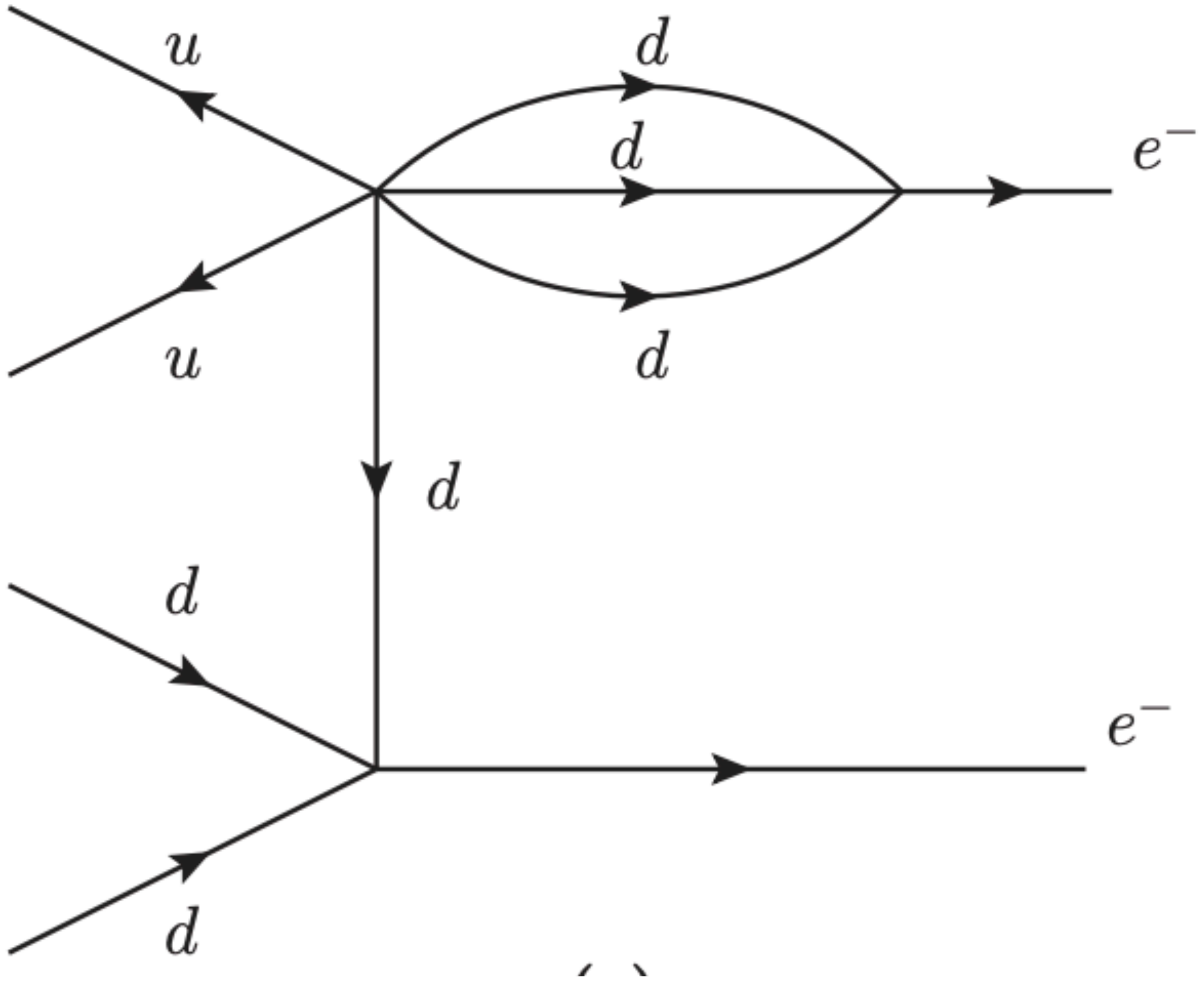
Type-I seesaw leptogenesis



Guidice et al. (2004)

The $(B - L)$ triangle





"B" and "L" violation could be intimately connected

What if a dark number "X" is in the mix?

Can we make any concrete statements without considering a specific model?

Bottom up Effective Field Theory approach!

Babu, Mohapatra '80

Detour:

Effective Field Theory approach in a nutshell

Effective Field Theory Approach

An EFT is the set of all allowed local operators with mass dimension less than some maximum one

$$\mathcal{L} = \sum_i c_i O_i \qquad [O_i] = d_i \qquad \longrightarrow \qquad c_i \sim \frac{1}{\Lambda^{d_i - 4}}$$

We need an infinite # of operators to absorb all the divergences for d>4 => non-renormalisable

Nature decouples!

Decoupling theorem

Appelquist,Carrazzone ++

$$\mathscr{L}_{\text{full}} = \mathscr{L}_{\text{light}}(g_i) + \frac{1}{2}[(\partial_\mu \Phi_H)^2 - M^2 \Phi_H^2] + \mathscr{L}_{\Phi-\text{light}}(g_i, h_i)$$

for $|p_i| \ll M$

$$G^{(n)}(p_1, \ldots p_n) \sim C(g_i, h_i, M)\, \tilde{G}^{(n)}(p_1, \ldots . p_n)(1 + \mathcal{O}\left(\frac{1}{M}\right))$$

$$\mathscr{L}_{\text{eff}} = \tilde{\mathscr{L}}_{\text{light}}[\tilde{g}_i(g_i, h_i, M)]$$

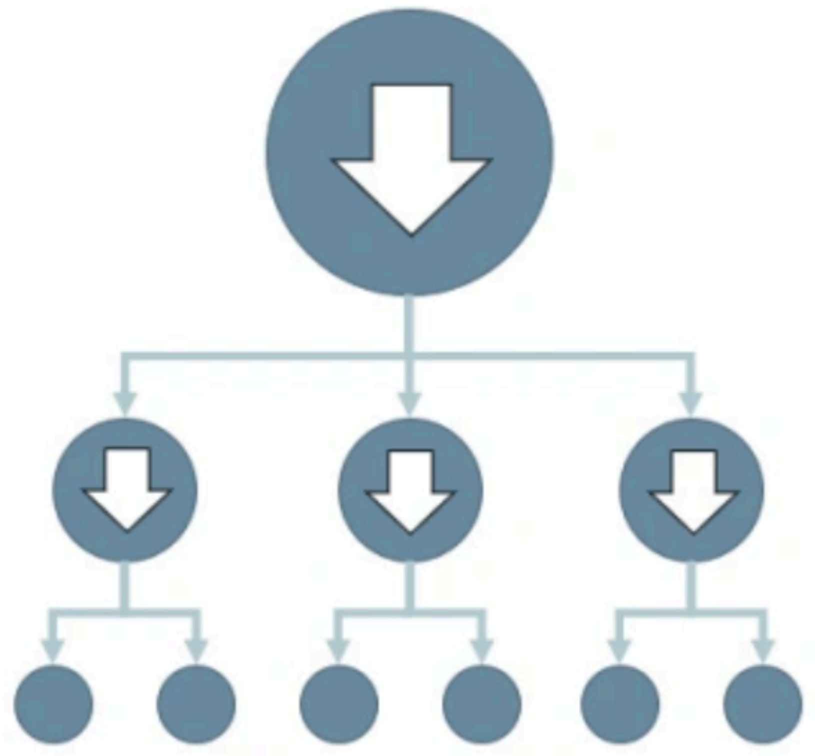
(i) there are no “+ve" powers of M, except in “$\log$”s

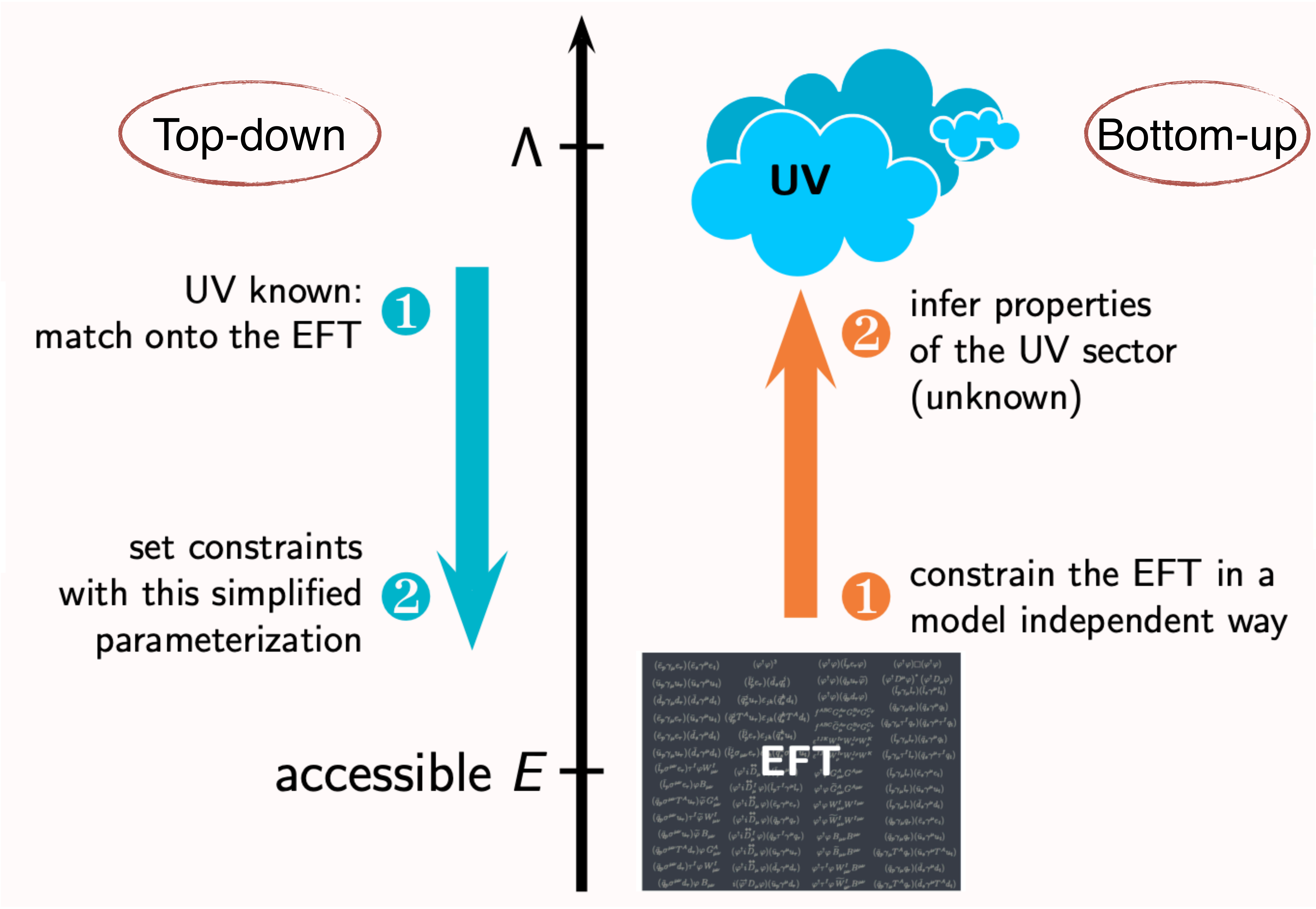
(ii) $\log M$ can be absorbed into $\tilde{g}$ and C

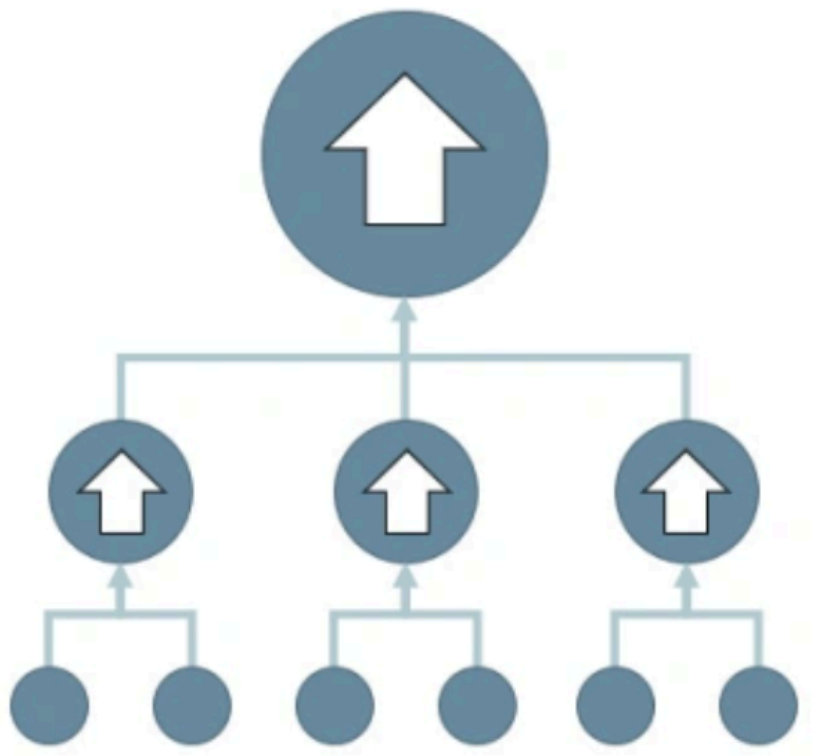
If $M = gv$ then EFT breaks down for:

v or $g \to \infty$ with $M \to \infty$

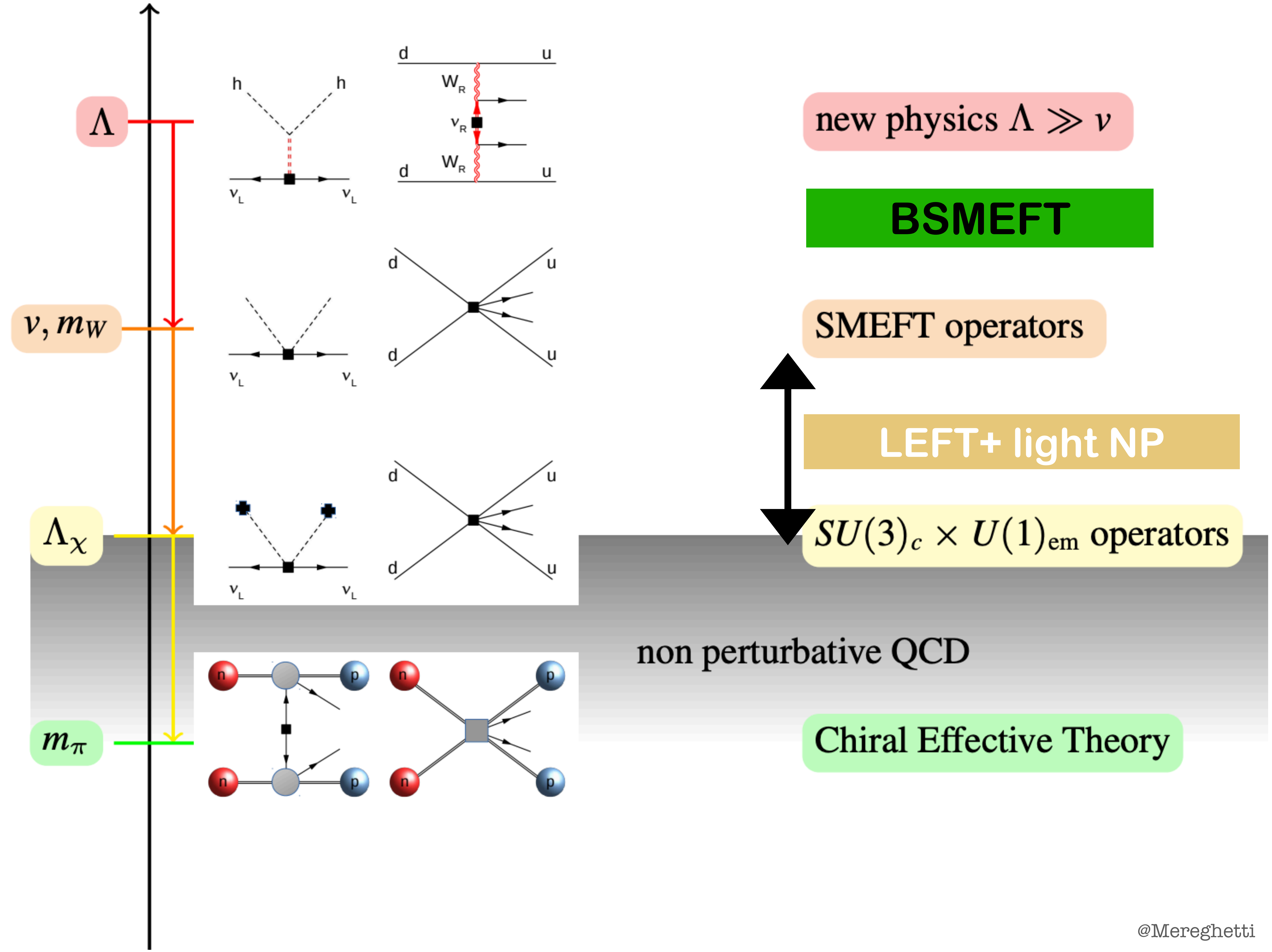
Connecting EFTs to Experiments







Some popular EFTs for BSM Phenomenology



One phenomenological application of LNV/BNV Effective Field Theory

A Simple picture of Washout in EFT Approach

Washout:

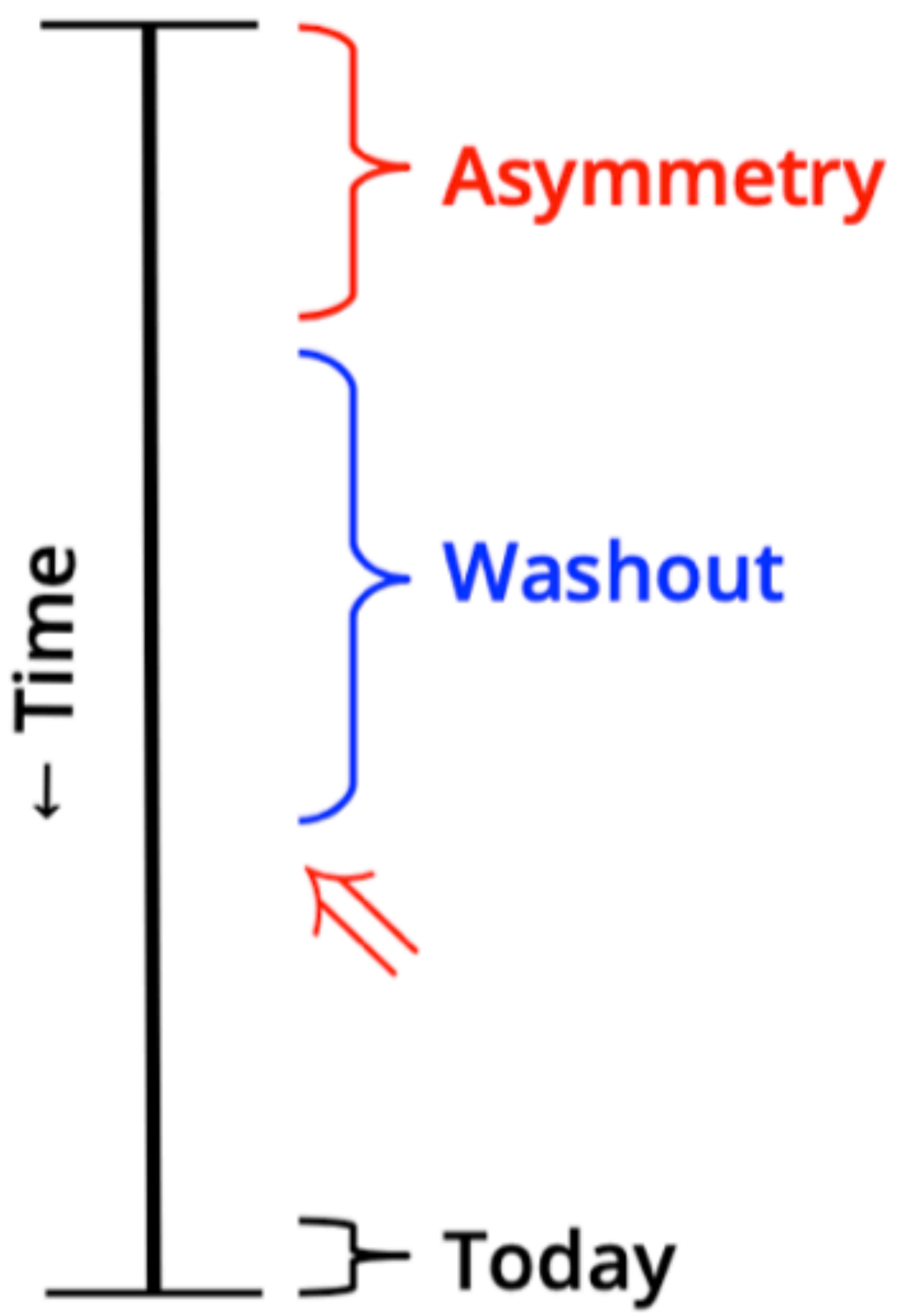
B-L violating processes that can remove (B-L) asymmetry

Generic form

$$zHn_\gamma \frac{d\eta_X}{dz} = -\sum_{a,i,j,\cdots} [Xa\cdots \leftrightarrow ij\cdots],$$

$$[Xa\cdots \leftrightarrow ij\cdots] = \frac{n_X n_a \cdots}{n_X^{eq} n_a^{eq}\cdots}\gamma^{eq}(Xa\cdots \to ij\cdots) - \frac{n_i n_j\cdots}{n_i^{eq} n_j^{eq}\cdots}\gamma^{eq}(ij\cdots \to Xa\cdots),$$

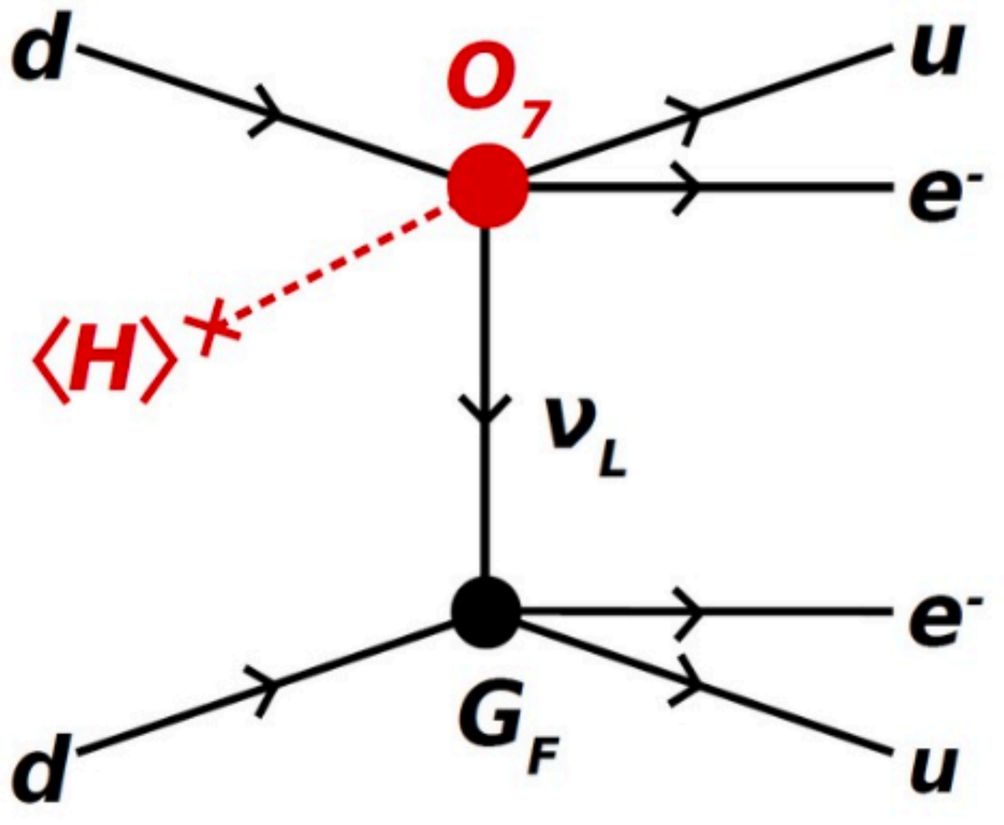
$$\gamma^{eq}(Na\cdots \to ij\cdots) = \int \frac{d^3p_N}{2E_N(2\pi)^3} e^{-\frac{E_N}{T}} \times \prod_{a=1}^{n-1}\left[\int \frac{d^3p_a}{2E_a(2\pi)^3} e^{-\frac{E_a}{T}}\right] \times \prod_{i=1}^{m}\left[\int \frac{d^3p_i}{2E_i(2\pi)^3}\right] \times (2\pi)^4\delta^4\left(p_N + \sum_{a=1}^{n-1} p_a - \sum_{i=1}^{m} p_i\right)|M|^2,$$



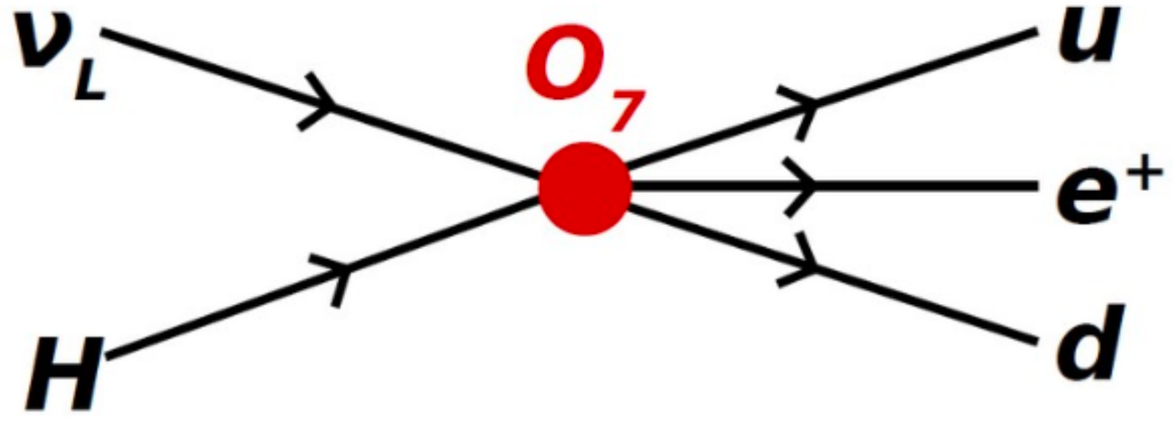
Assume: $|M|^2$ does not depend on the relative motion of particles

$$\gamma^{eq}(Na\cdots \to ij\cdots) = \frac{1}{(2\pi)^3}\int ds\,\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right) dPS^n dPS^m \times |M|^2,$$

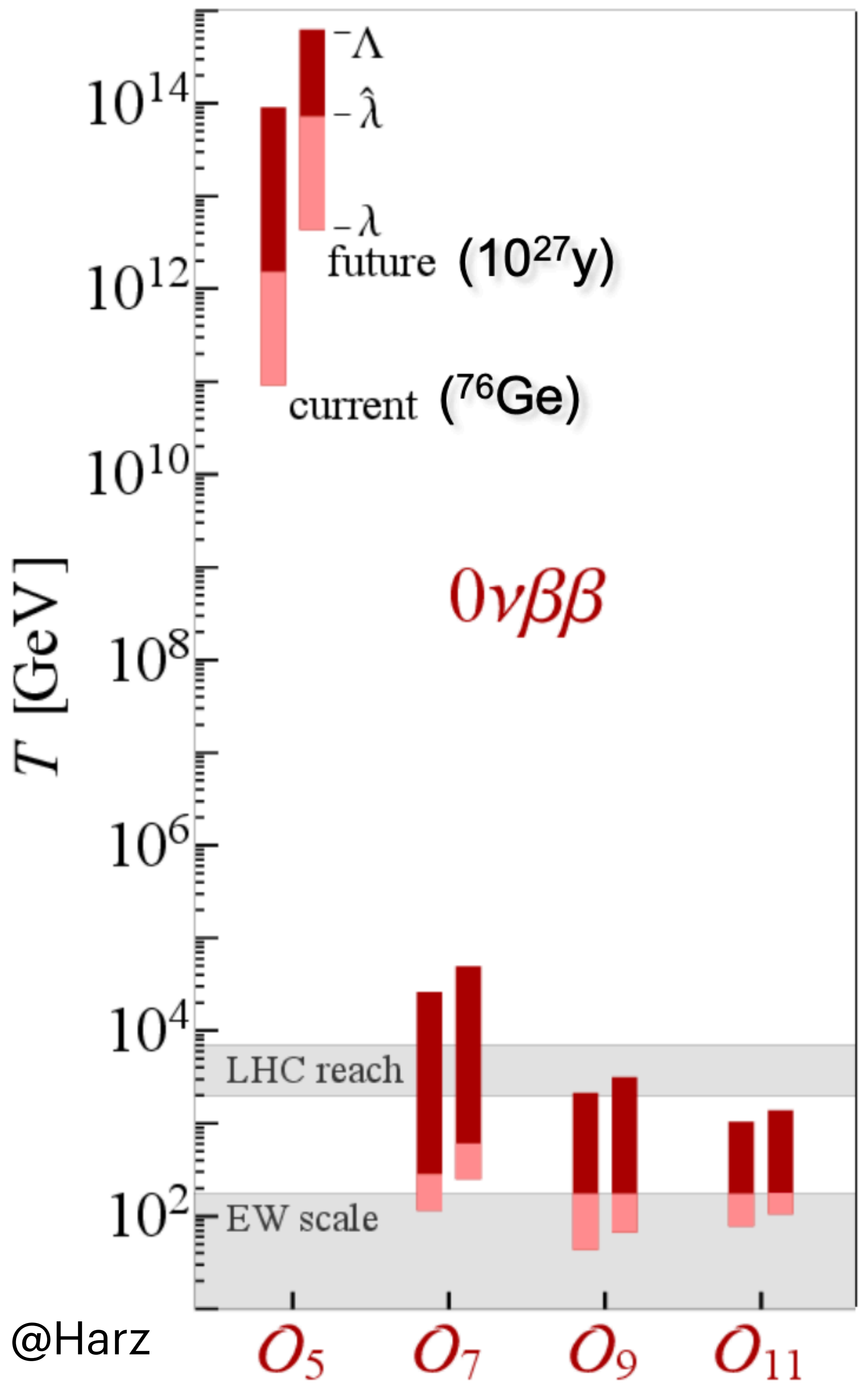
Observation of LNV and baryogensis



$\mathcal{O}$	Operator
1^{H^2}	$L^iL^jH^kH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$
4_a	$L^iL^j\overline{Q}_i\bar{u}^cH^k\epsilon_{jk}$
$4_b^\dagger$	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$



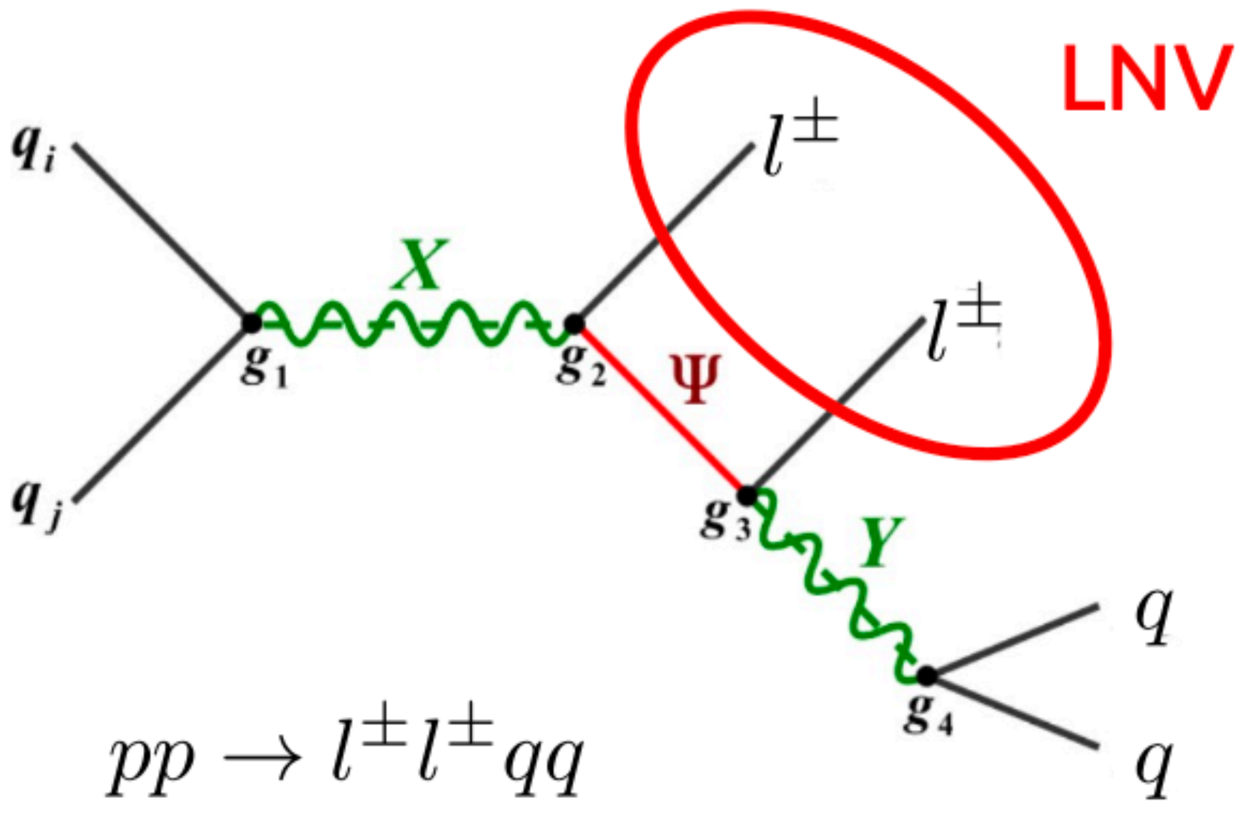
Observed rate at experiment → **New physics scale Λ** → **Washout rate**



Deppisch, Graf, Harz, Huang ’18

Deppisch, Harz, Huang, Hirsch, Päs ’15

Harz, Huang, Päs ’15

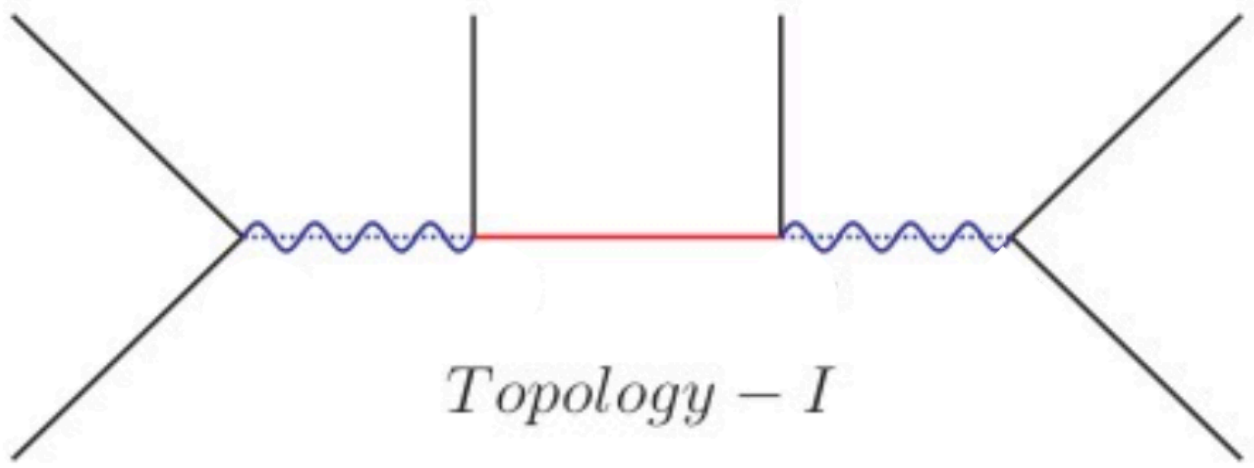


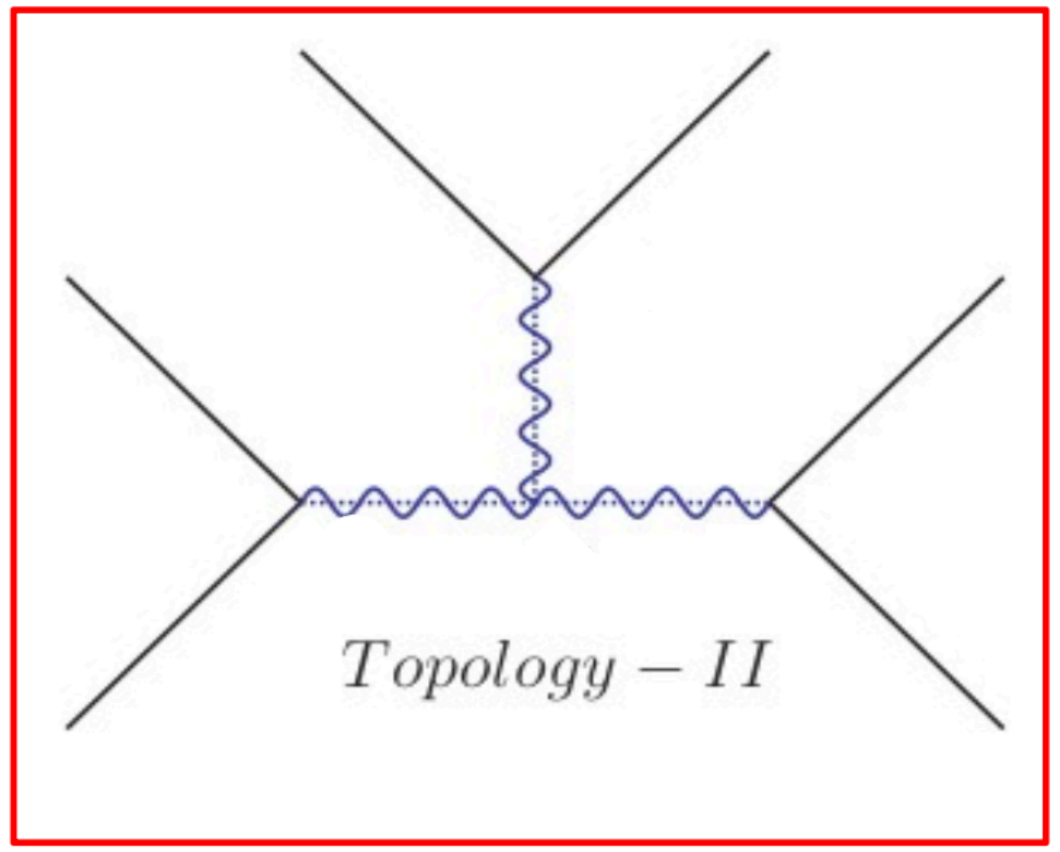
Similar approach for Colliders using resonances

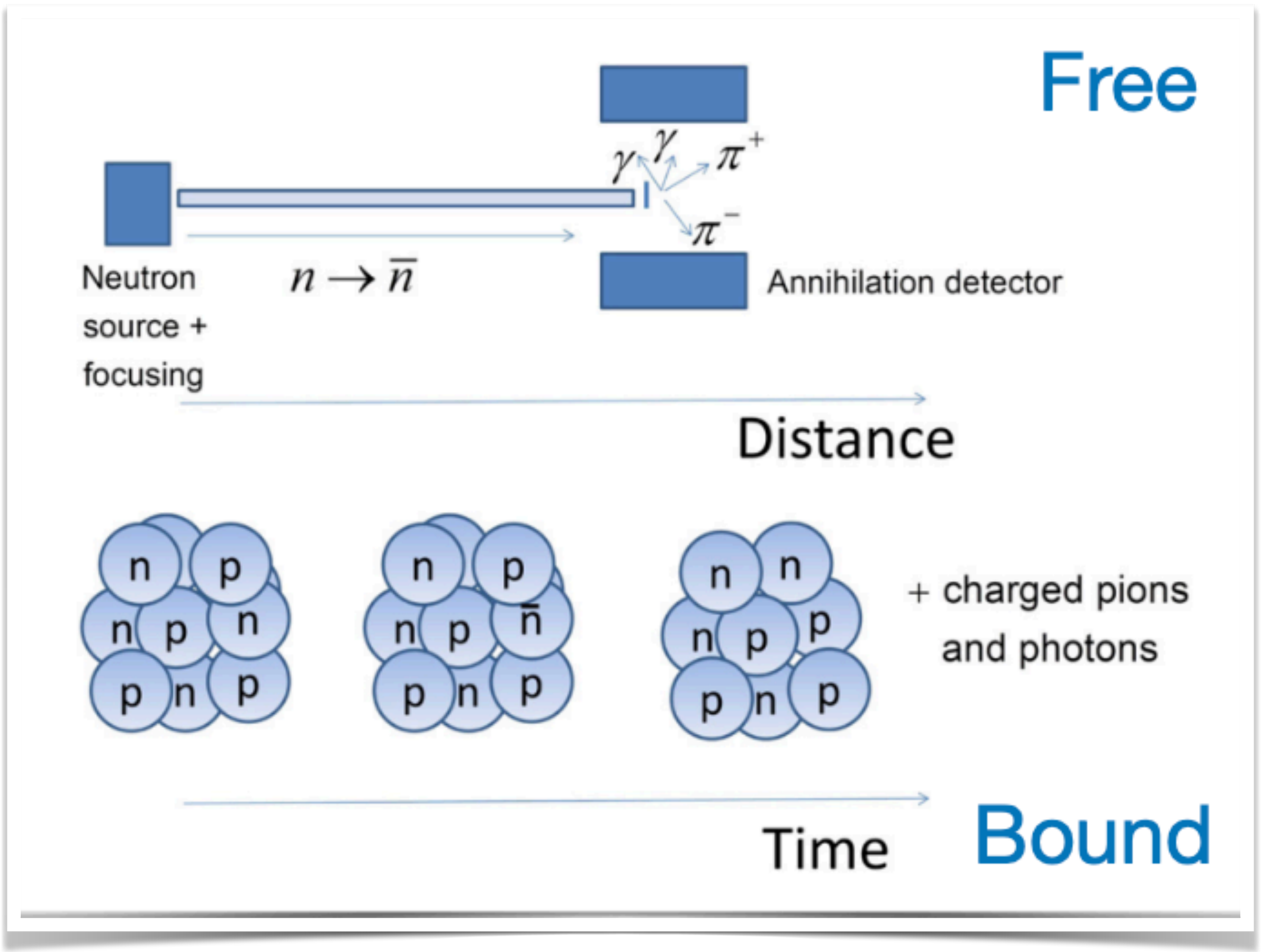
Caveats: penetration of washout in different flavor

Neutron-Antineutron oscillations

Neutron-anti-neutron oscillation can be realized at tree level by dim 9 operators







$$\mathcal{L}_{\rm WET}^{\bar{n}n} = \sum_i C_i \mathcal{O}_i + \text{h.c.}$$

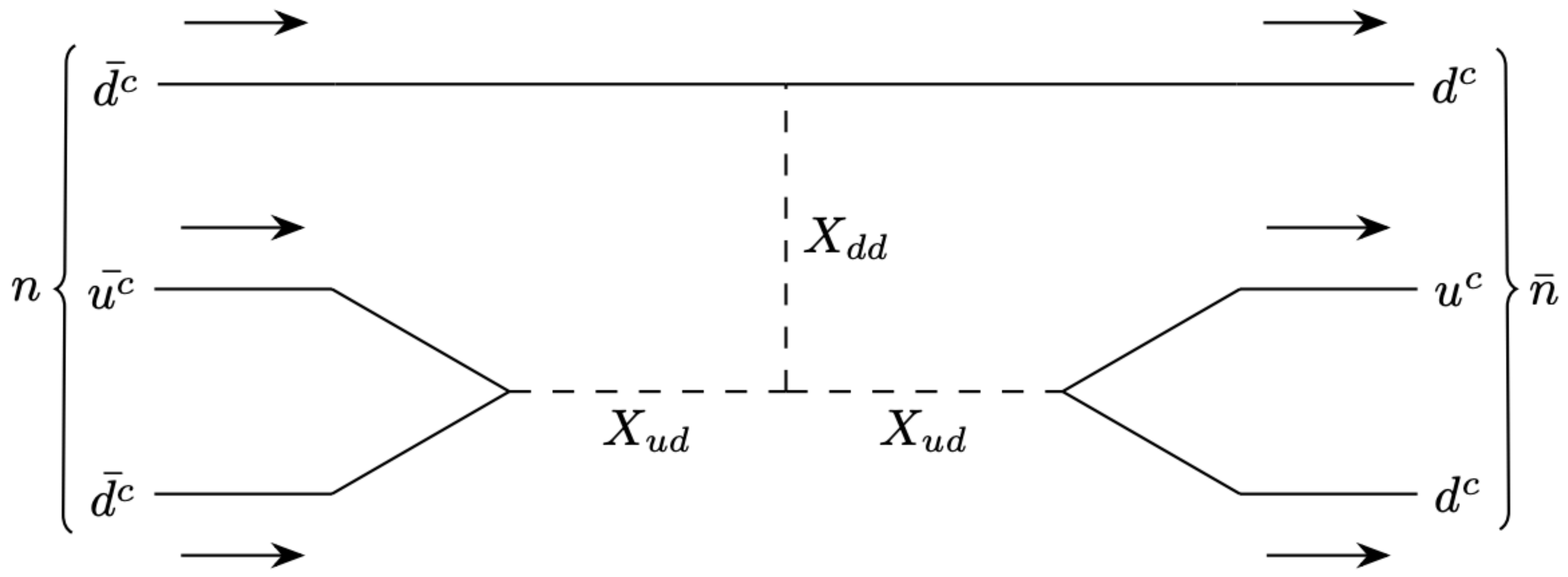
$$\mathcal{O}_1 = (\psi P_R \psi^c)(\psi P_R \psi^c)(\psi P_R \psi^c)$$

$$\tau_{n\bar{n}}^{-1} = \langle \bar{n} | \mathcal{L}_{\rm WET}^{n\bar{n}} | n \rangle = \left| C_1(\mu) \mathcal{M}_1(\mu) \right|$$

$$\mathcal{M}_i(\mu) = \langle \bar{n} | \mathcal{O}_i(\mu) | n \rangle$$

Rinaldi et al (2019)

Wilson coefficient: $C_i \propto \dfrac{1}{\Lambda^5}$ Λ = New Physics (NP) scale $\rightarrow$ encodes all the effects of heavy NP.



Decomposition of 126 multiplet of $SO(10)$

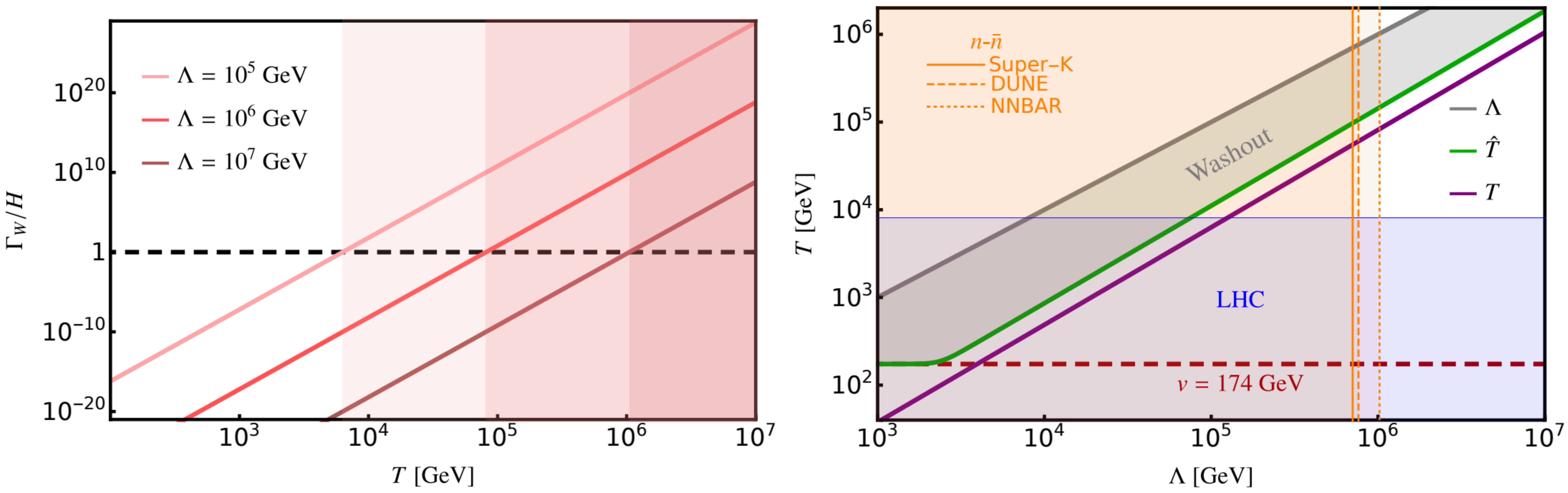
$G_{\rm PS}$	$G_{\rm LR}$	$G_{\rm SM}$
$(\mathbf{1}, \mathbf{3}, \overline{\mathbf{10}})$	$(1, 1, 3, +2)$	$(\mathbf{1}, \mathbf{1}, \mathbf{0}) \oplus (1, 1, +1) \oplus (1, 1, +2)$
	$(\bar{3}, 1, 3, +\frac{2}{3})$	$(\bar{3}, 1, -\frac{2}{3}) \oplus (\bar{3}, 1, +\frac{1}{3}) \oplus (\bar{3}, 1, +\frac{4}{3})$
	$(\bar{\mathbf{6}}, \mathbf{1}, \mathbf{3}, -\frac{\mathbf{2}}{\mathbf{3}})$	$(\bar{\mathbf{6}}, \mathbf{1}, -\frac{\mathbf{4}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}}, \mathbf{1}, -\frac{\mathbf{1}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}}, \mathbf{1}, +\frac{\mathbf{2}}{\mathbf{3}})$

Neutron-Antineutron oscillations

$n-\bar{n}$ operators correspond to washout processes $\Delta B = 2$

Out of equilibrium temperature: $\Gamma \sim H, \quad \Gamma \propto \left|C_i \mathcal{M}_i\right|^2 \propto \left|\frac{1}{\Lambda^5}\right|$

chemical potential relations=> $$zHn_\gamma \frac{d\eta_{\Delta B}}{dz} = -c\frac{T^{14}}{\Lambda^{10}}\eta_{\Delta B}$$



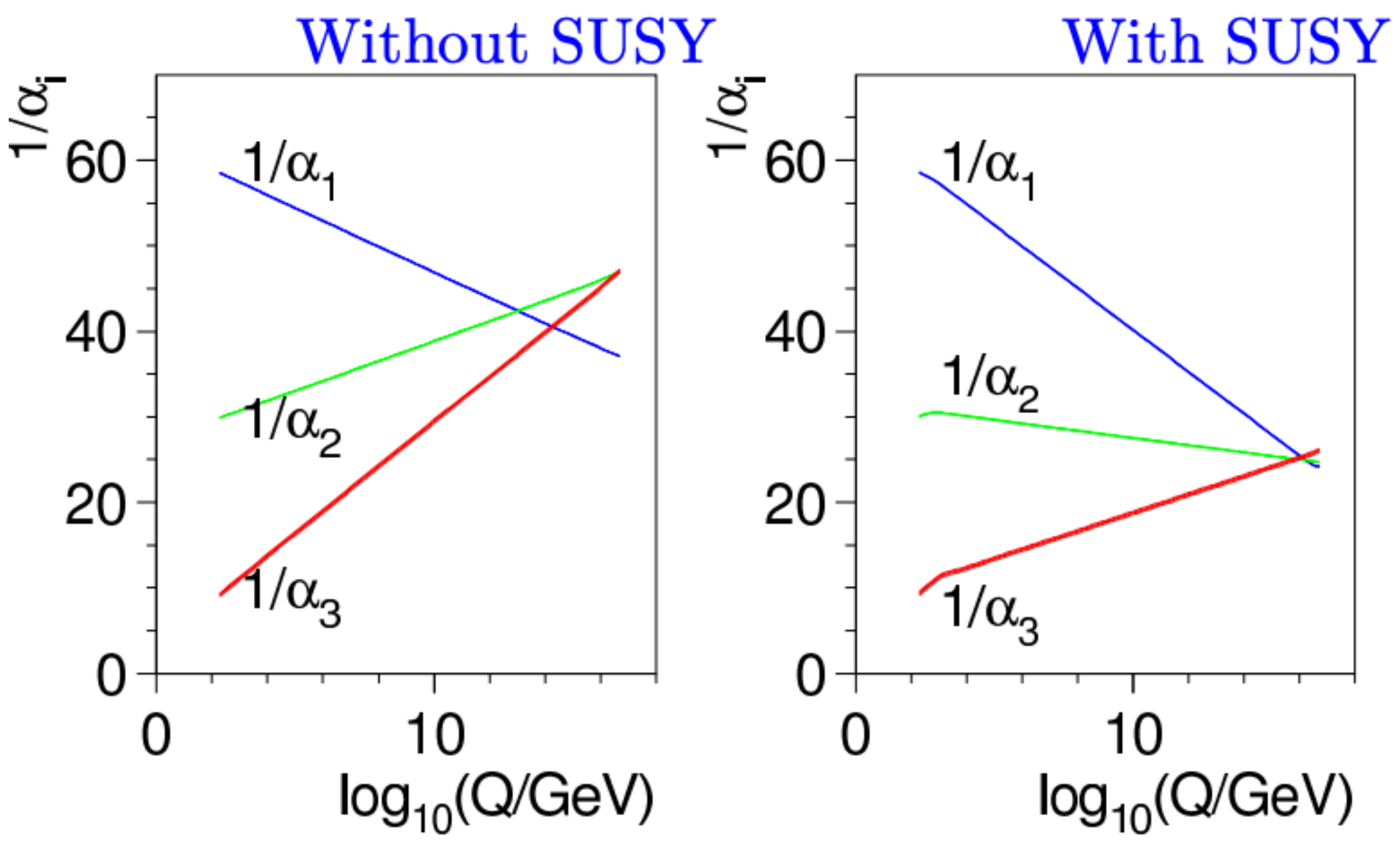
Observed NP scale Λ in $n-\bar{n}$ operator -> the OOE temperature for the washout

Caveats: validity of the EFT treatment e.g. hierarchical NP scales, CPV sources

Fridell, Harz, **CH** JHEP '21

Back to BNV and Nucleon Decays

BNV and GUTs in a flash



$$10 : \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix} \qquad \bar{5} : (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$\bar{\mathbf{5}} \equiv (\mathbf{d^c}, \ell) \qquad \mathbf{10} \equiv (\mathbf{u^c}, \mathbf{q}, \mathbf{e^c})$$

Quarks and leptons in the same multiplet

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$

12 heavy gauge boson => quarks ->leptons
+higgs color triplets

Doublet-triplet splitting problem: $\mathbf{5} \equiv (\mathbf{h_c}, \mathbf{h}) \qquad \bar{\mathbf{5}} \equiv (\bar{\mathbf{h}}_\mathbf{c}, \bar{\mathbf{h}})$

Realistic $SU(5)$ SUSY GUT lifetime $\sim 10^{34}\, yrs$ Babu, Bajc, Tavartkiladze '12

BNV @ dim-6 SMEFT

SM does not contain any fields that can mediate B-violating interactions:

Weinberg ’79
Wilczek, Zee ’79
Abbott, Wise ‘80

$$O^{(1)}_{abcd} = \left(\overline{d^C_{\alpha a R}}\, u_{\beta b R}\right)\left(\overline{q^C_{i\gamma c L}}\, \ell_{j d L}\right)\epsilon_{\alpha\beta\gamma}\,\epsilon_{ij}$$

$$O^{(2)}_{abcd} = \left(\overline{q^C_{i\alpha a L}}\, q_{j\beta b L}\right)\left(\overline{u^C_{\gamma c R}}\, \ell_{d R}\right)\epsilon_{\alpha\beta\gamma}\,\epsilon_{ij}$$

$$O^{(3)}_{abcd} = \left(\overline{q^C_{i\alpha a L}}\, q_{j\beta b L}\right)\left(\overline{q^C_{k\gamma c L}}\, \ell_{\ell d L}\right)\epsilon_{\alpha\beta\gamma}\,\epsilon_{ij}\,\epsilon_{k\ell}$$

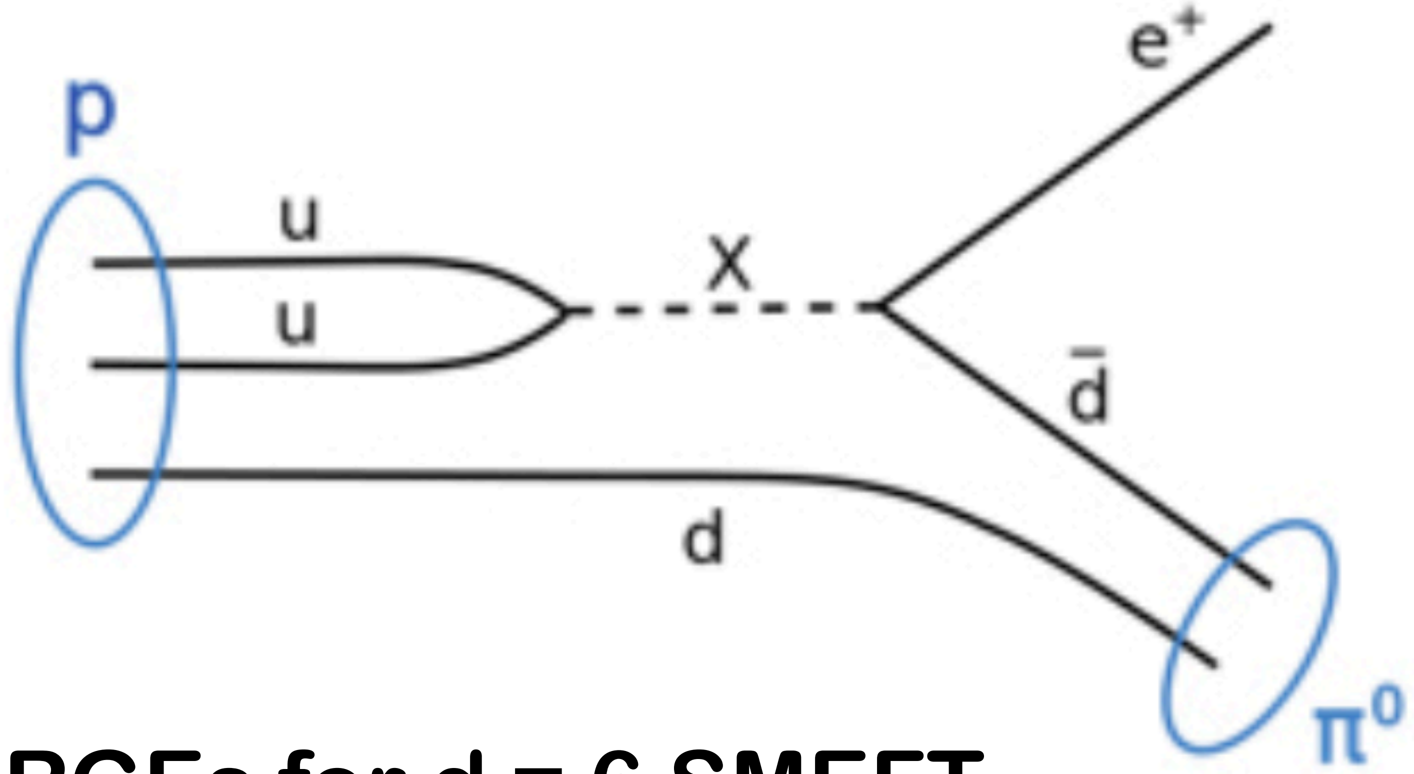
$$O^{(4)}_{abcd} = \left(\overline{q^C_{i\alpha a L}}\, q_{j\beta b L}\right)\left(\overline{q^C_{k\gamma c L}}\, \ell_{\ell d L}\right)\epsilon_{\alpha\beta\gamma}\,(\vec{\tau}\epsilon)_{ij}\cdot(\vec{\tau}\epsilon)_{k\ell}$$

$$O^{(5)}_{abcd} = \left(\overline{d^C_{\alpha a R}}\, u_{\beta b R}\right)\left(\overline{u^C_{\gamma c R}}\, \ell_{d R}\right)\epsilon_{\alpha\beta\gamma}$$

$$O^{(6)}_{abcd} = \left(\overline{u^C_{\alpha a R}}\, u_{\beta b R}\right)\left(\overline{d^C_{\gamma c R}}\, \ell_{d R}\right)\epsilon_{\alpha\beta\gamma}$$

B. Grzadkowski et al. ‘10

	B-violating
Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

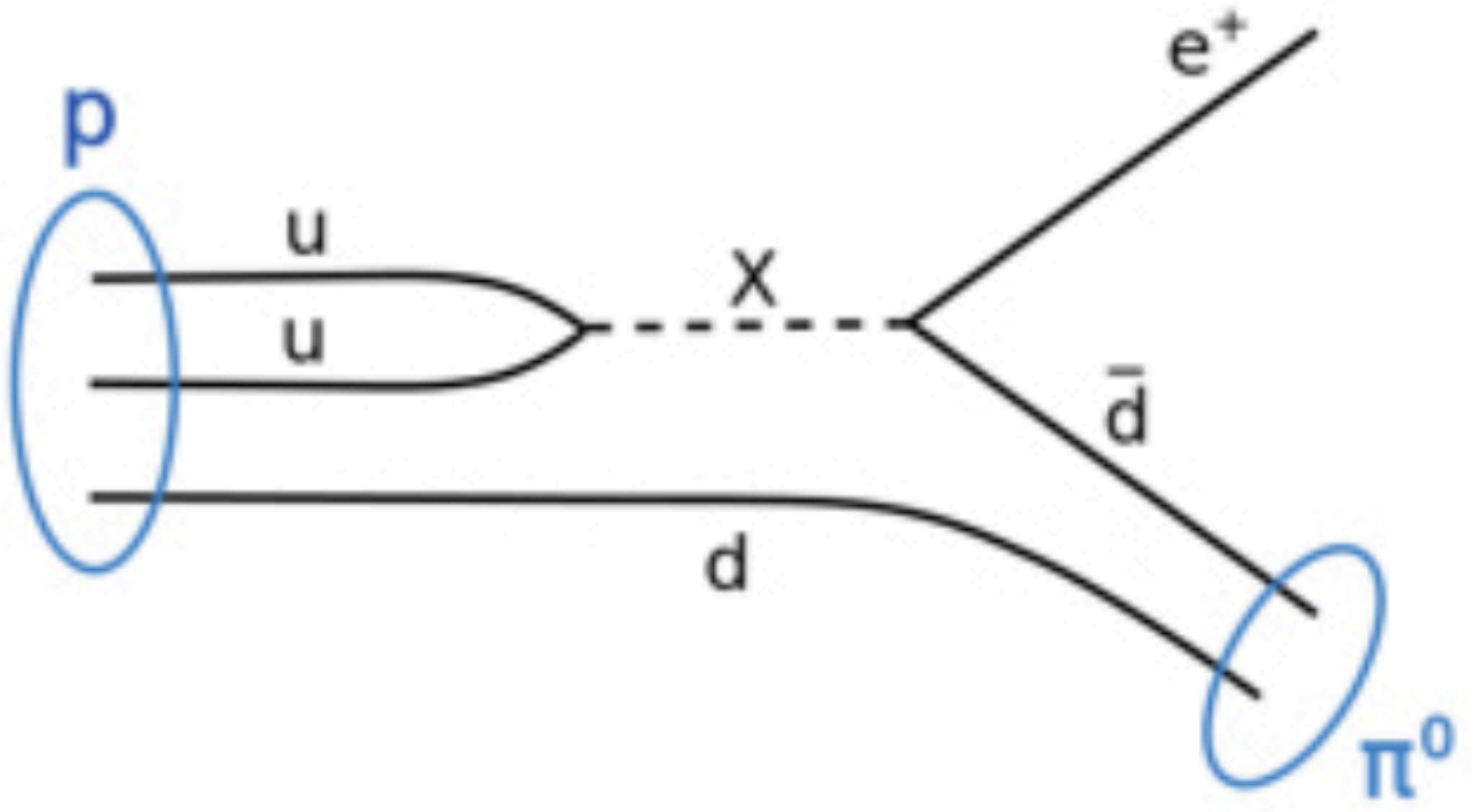


RGEs for d = 6 SMEFT

Manohar et al. ‘14

BNV @ dim-6 SMEFT

Simplest scale estimate: $\tau_p \propto \frac{M^4_{\rm GUT}}{\alpha^2_{\rm GUT} m_p^5}$



Realistic estimate:RG running, Matrix elements

$$\tau_p \lesssim 6 \times 10^{39} \frac{1}{\alpha^2_{\rm GUT}} \left(\frac{M_X}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{0.003\ {\rm GeV}^3}{\alpha_{\chi pt}}\right)^2 \quad {\rm yrs}$$

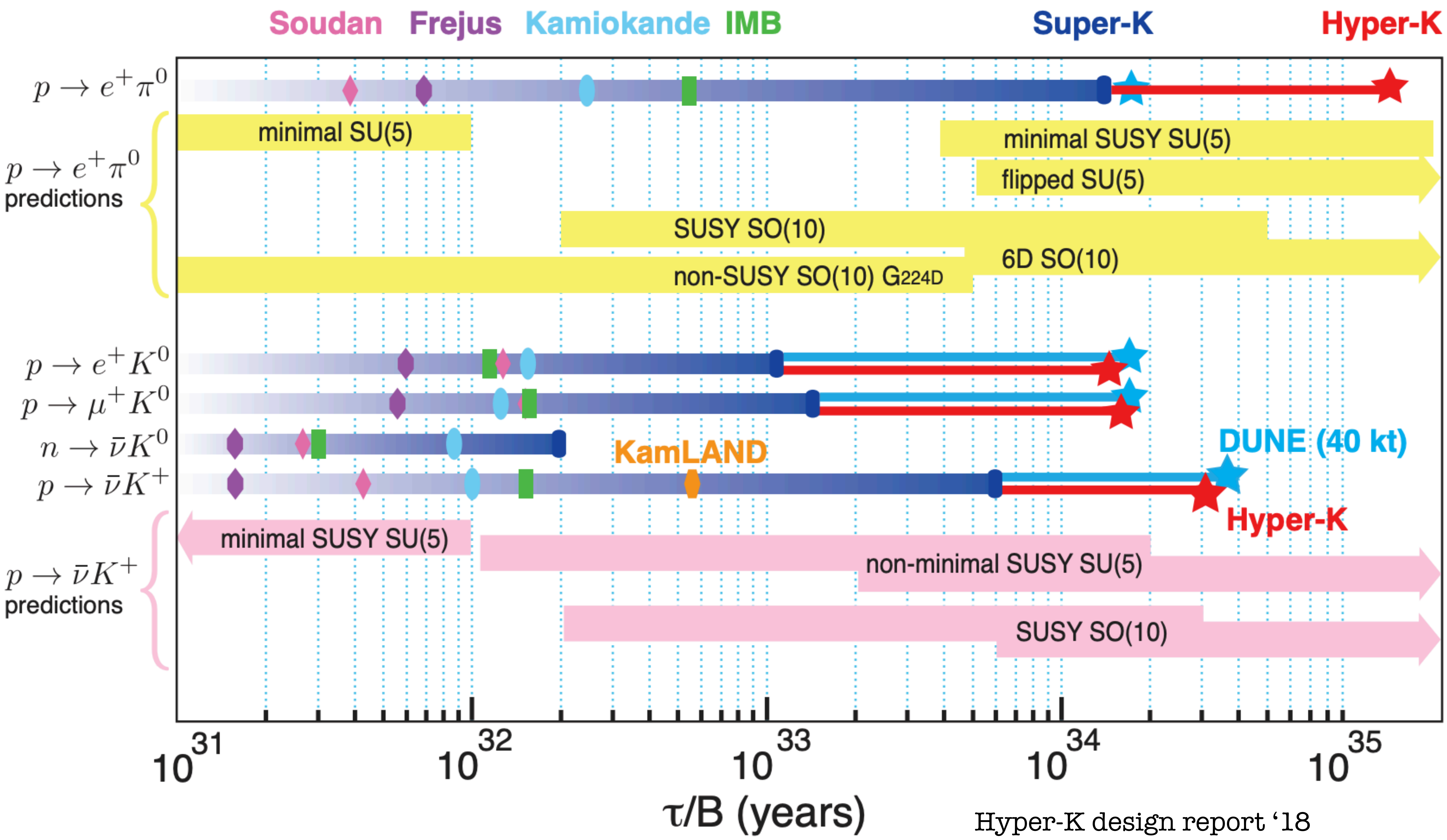
Doršner, Fileviez-Perez '05;
Nath, Fileviez-Perez '07

Assume only dim-6 operators induced by superheavy X
=> Upper bound on proton lifetime for any GUT with or without SUSY

All of the dimension-six nucleon decay operators violate both B and L but not $(B-L)$

=> No "GUT" baryogenesis!

Experimental Status



Hyper-K design report '18

BNV @ dim-6 SMEFT: Many popular GUT models

Model class	Lifetime [years]	Ruled out?
Minimal SU(5) [Georgi & Glashow (1974)]	$10^{30} - 10^{31}$	yes
Minimal SUSY SU(5) [Dimopoulos & Georgi; Sakai & Yanagida]	$10^{28} - 10^{34}$	yes
SUGRA SU(5) [Nath, Chamseddine & Arnowitt (1985)]	$10^{32} - 10^{34}$	yes
SUSY (MSSM/ESSM) SO(10)/$G(224)$ [Babu, Pati & Wilczek]	$2 \cdot 10^{34}$	yes
SUSY (MSSM/ESSM, $d = 5$) SO(10) [Lucas & Raby; Pati]	$10^{32} - 10^{35}$	partially
SUSY SO(10) + $\mathrm{U(1)}_{\mathrm{fl}}$ [Shafi & Tavartkiladze (2000)]	$10^{32} - 10^{35}$	partially
SUSY ($d = 5$) SU(5) – option I [Hebecker & March-Russell (2002)]	$10^{34} - 10^{35}$	partially
SUSY (MSSM, $d = 6$) SU(5) or SO(10) [Pati (2003)]	$\sim 10^{34.9\pm1}$	partially
Minimal non-SUSY SU(5) [Doršner & Fileviez-Pérez (2005)]	$10^{31} - 10^{38}$	partially
Minimal non-SUSY SO(10)	???	no
SUSY (CMSSM) Flipped SU(5) [Ellis, Nanopoulos & Walker (2002)]	$10^{35} - 10^{36}$	no
GUT-like models from string theory [Klebanov & Witten (2003)]	$\sim 10^{36}$	no
Split SUSY SU(5) [Arkani-Hamed *et al.* (2005)]	$10^{35} - 10^{37}$	no
SUSY ($d = 5$) SU(5) – option II [Alciati *et al.* (2005)]	$10^{36} - 10^{39}$	no

Lee, Mohapatra, Parida, Rani '95;

Minimal non-SUSY SO(10) $\longrightarrow \mathcal{G} \longrightarrow \mathcal{G}_{\mathrm{SM}}$, $\tau_p = \tau(p \to e^+\pi^0)$

Model A ($\mathcal{G} = G_{422D}$):	$\tau_p = 1.44 \cdot 10^{32.1\pm0.7}$ years	ruled out
Model B ($\mathcal{G} = G_{422}$):	$\tau_p = 1.44 \cdot 10^{37.4\pm0.7}$ years	allowed
Model C ($\mathcal{G} = G_{3221D}$):	$\tau_p = 1.44 \cdot 10^{34.2\pm0.7}$ years	partially
Model D ($\mathcal{G} = G_{3221}$):	$\tau_p = 1.44 \cdot 10^{37.7\pm0.7}$ years	allowed

Intermediate symmetries
=> different GUT scales and proton decay rates

Cancellation of proton decay

Dorsner, Fileviez Perez '05
Fornal, Grinstein '17

BNV @ dim-7 SMEFT

Weinberg '80; Weldon, Zee '80

$$\mathcal{O}_1 = (Q_i Q_j)(d^c L_k)^* H_l^* \epsilon_{ij}\epsilon_{kl}, \mathcal{O}_2 = (Q_i Q_j)(d^c L_j)^* H_i^*,$$

$$\mathcal{O}_3 = (d^c d^c)^* (Q_i e^c) H_i^*, \qquad \mathcal{O}_4 = (d^c d^c)^* (u^c L_i)^* H_j^* \epsilon_{ij}$$

$$\mathcal{O}_5 = (d^c u^c)^* (d^c L_i)^* H_j^* \epsilon_{ij}, \quad \mathcal{O}_6 = (d^c d^c)^* (d^c L_i)^* H_i,$$

$$\mathcal{O}_7 = (d^c D_\mu d^c)^* (\overline{L}_i \gamma^\mu Q_i), \quad \mathcal{O}_8 = (d^c D_\mu L_i)^* (\overline{d^c} \gamma^\mu Q_i),$$

$$\mathcal{O}_9 = (d^c D_\mu d^c)^* (\overline{d^c} \gamma^\mu e^c) \ ,$$

Pati-Salam GUT: Pati, Salam, Sarkar '83

$SO(10)$ **GUT:** Babu, Mohapatra '12

Lehman '14
Liao et al. '16

$$\mathcal{O}^{prst}_{\bar{L}dud\tilde{H}} = \varepsilon_{\alpha\beta\sigma}\varepsilon_{ij}(\bar{L}_{ip} d_{\alpha r})(u_{\beta s} C d_{\sigma t}) H_j^*,$$

$$\mathcal{O}^{prst}_{\bar{L}dddH} = \varepsilon_{\alpha\beta\sigma}\delta_{ij}(\bar{L}_{ip} d_{\alpha r})(d_{\beta s} C d_{\sigma t}) H_j,$$

$$\mathcal{O}^{prst}_{\bar{e}Qdd\tilde{H}} = -\varepsilon_{\alpha\beta\sigma}\delta_{ij}(\bar{e}_p Q_{i\alpha r})(d_{\beta s} C d_{\sigma t}) H_j^*,$$

$$\mathcal{O}^{prst}_{\bar{L}dQQ\tilde{H}} = -\varepsilon_{\alpha\beta\sigma}\delta_{kl}\delta_{ij}(\bar{L}_{kp} d_{\alpha r})(Q_{l\beta s} C Q_{i\sigma t}) H_j^*,$$

$$\mathcal{O}^{prst}_{\bar{L}QddD} = \varepsilon_{\alpha\beta\sigma}\delta_{ij}(\bar{L}_{ip}\gamma_\mu Q_{j\alpha r})(d_{\beta s} C i D^\mu_{\sigma\rho} d_{\rho t}),$$

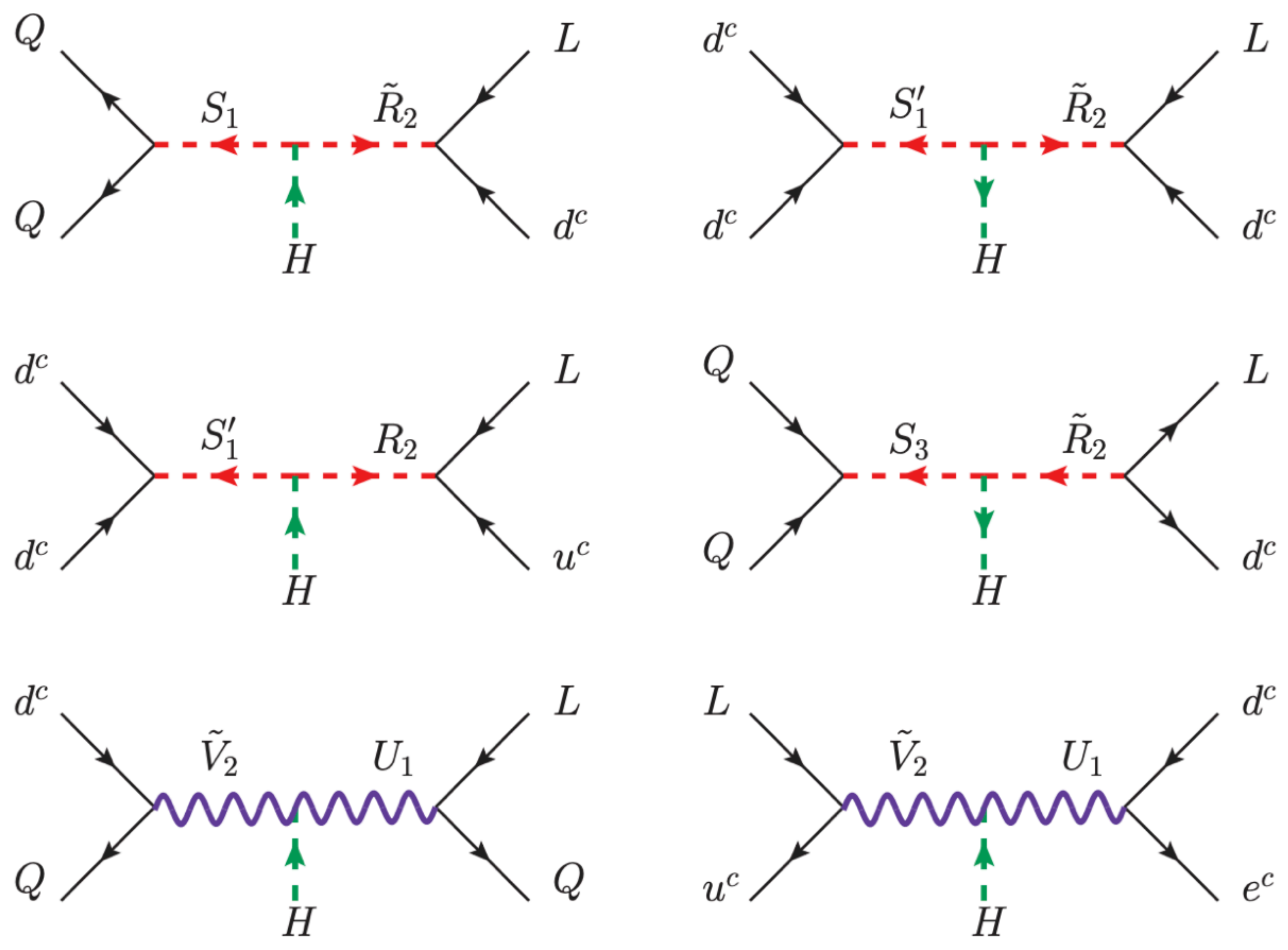
$$\mathcal{O}^{prst}_{\bar{e}dddD} = \varepsilon_{\alpha\beta\sigma}(\bar{e}_p \gamma_\mu d_{\alpha r})(d_{\beta s} C i D^\mu_{\sigma\rho} d_{\rho t}).$$

All of the dim-7 nucleon decay operators violate $(B-L)$: $\Delta B = -\Delta L = 1$

=> potential connection to baryogenesis!

BNV @ dim-7 SMEFT

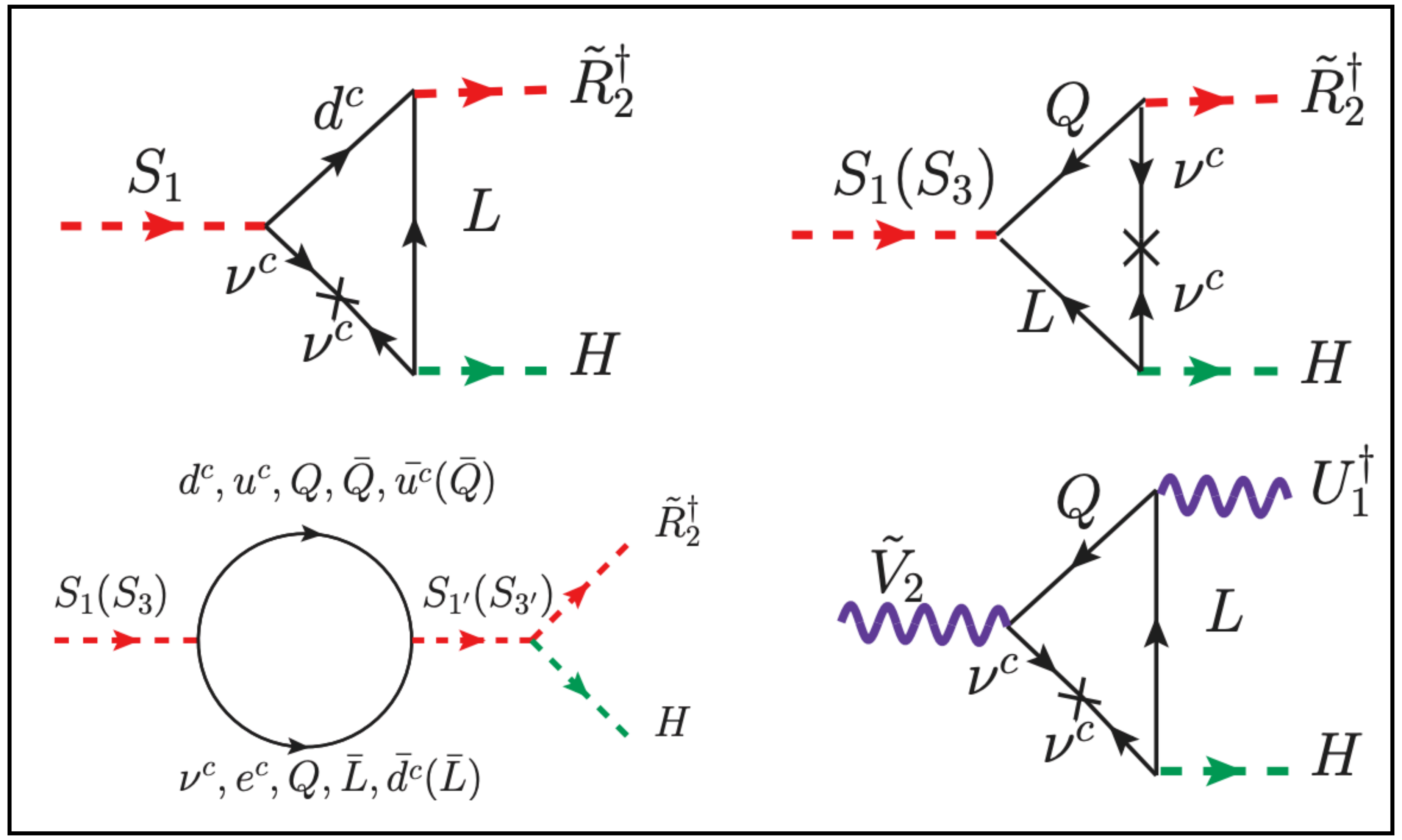
LQ	$G_{\rm SM}$	$SU(5)$	$G_{\text{Pati-Salam}}$	$SO(10)$
S_1	$(\bar{3},1,1/3)$	$\bar{5}$, $\overline{45}$, $\overline{50}$	(1,1,6), $(1,3,\overline{10})$	10, 120, $\overline{126}$
S_1'	$(\bar{3},1,-2/3)$	10	$(1,3,6)$	120 $\overline{126}$
$\tilde{S}_1$	$(\bar{3},1,4/3)$	45	$(1,3,6)$	120 $\overline{126}$
$\tilde{R}_2$	$(3,2,1/6)$	10, 15	$(2,2,15)$	120, $\overline{126}$
R_2	$(3,2,7/6)$	$\overline{45}$, $\overline{50}$	$(2,2,15)$	120, $\overline{126}$
S_3	$(\bar{3},3,1/3)$	$\overline{45}$	$(3,1,6)$	120, $\overline{126}$

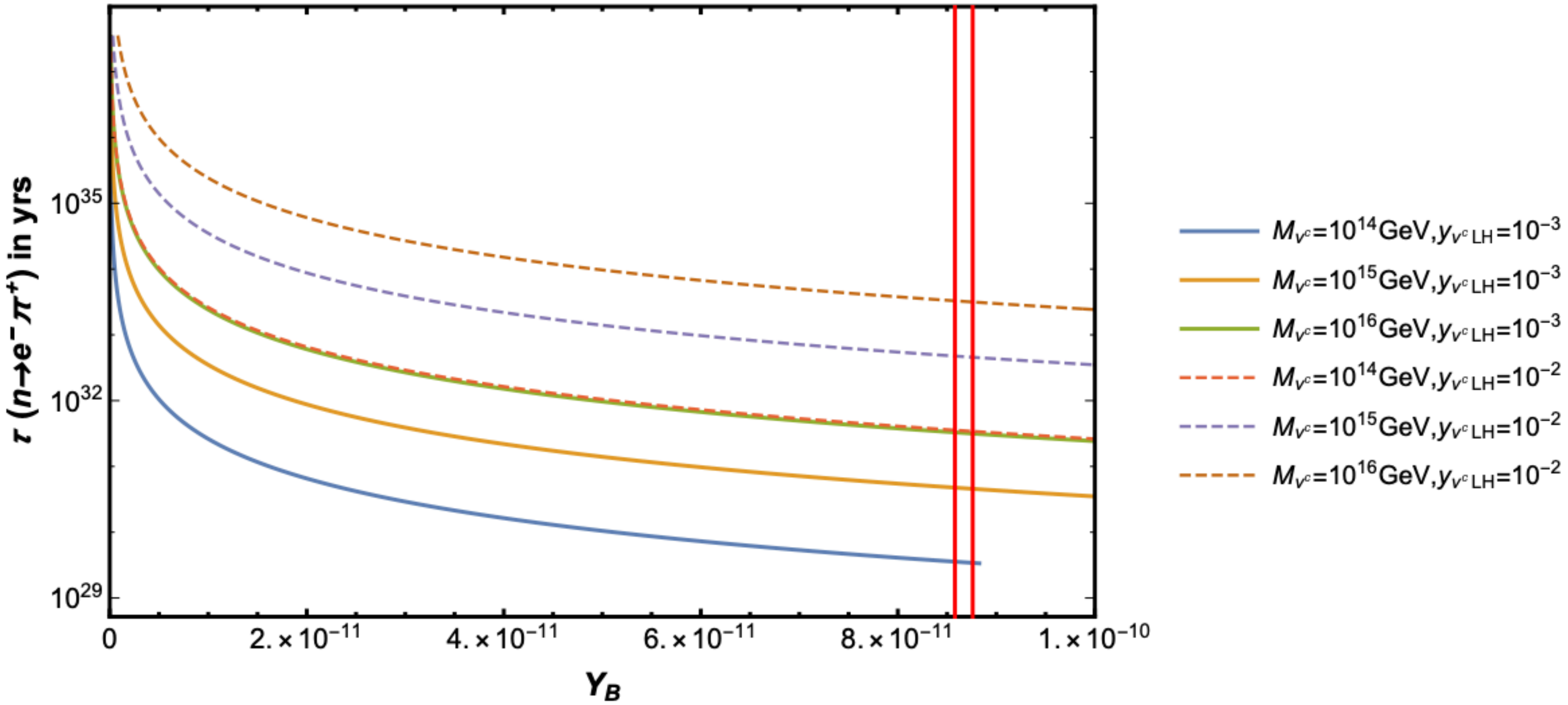


Phenomenology: Doršner, Fajfer, Greljo, Kamenik, Košnik '16

Babu, Mohapatra '12; **CH**, Sarkar '18

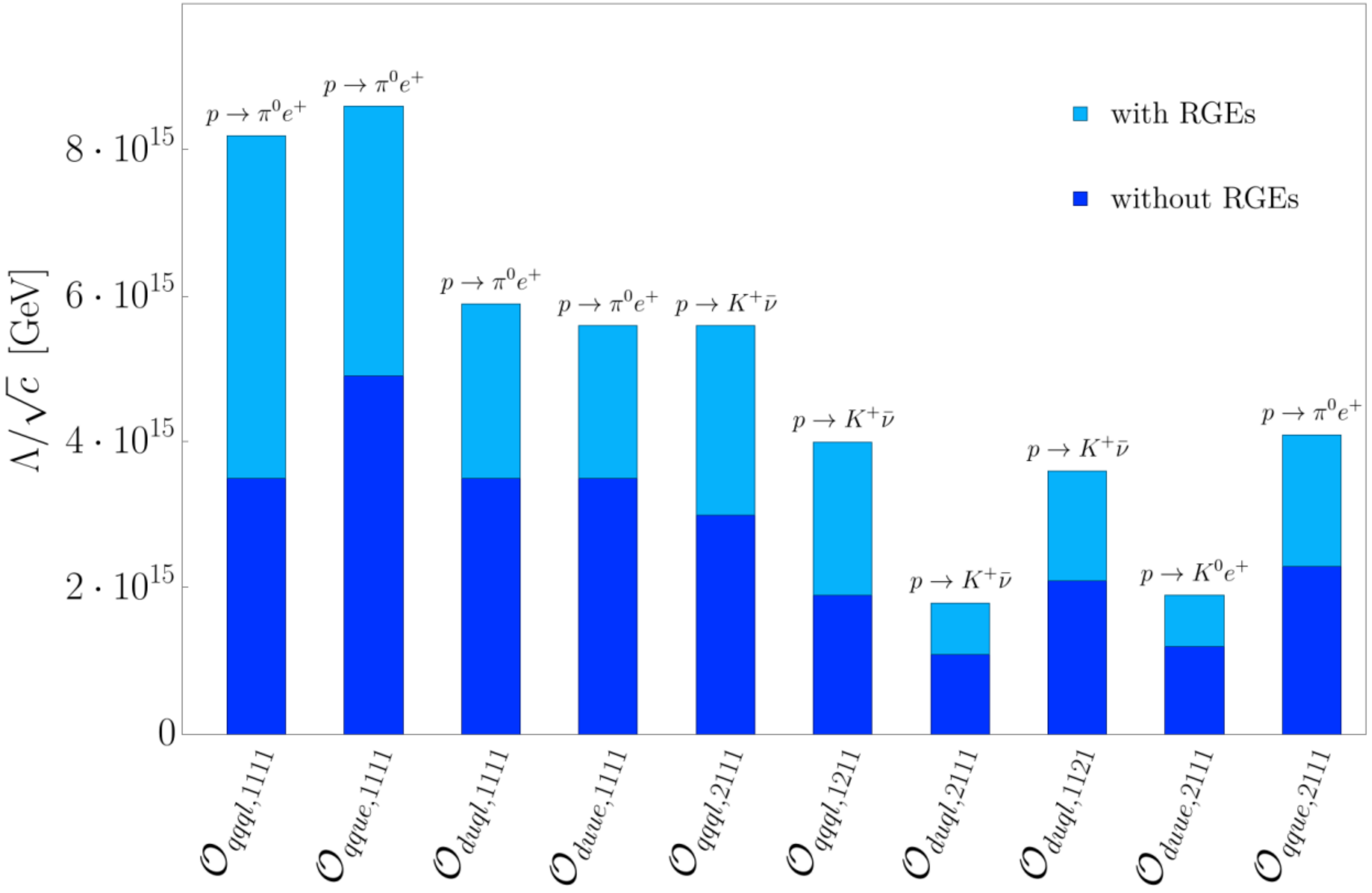
correlation between baryogenesis and proton decay rates



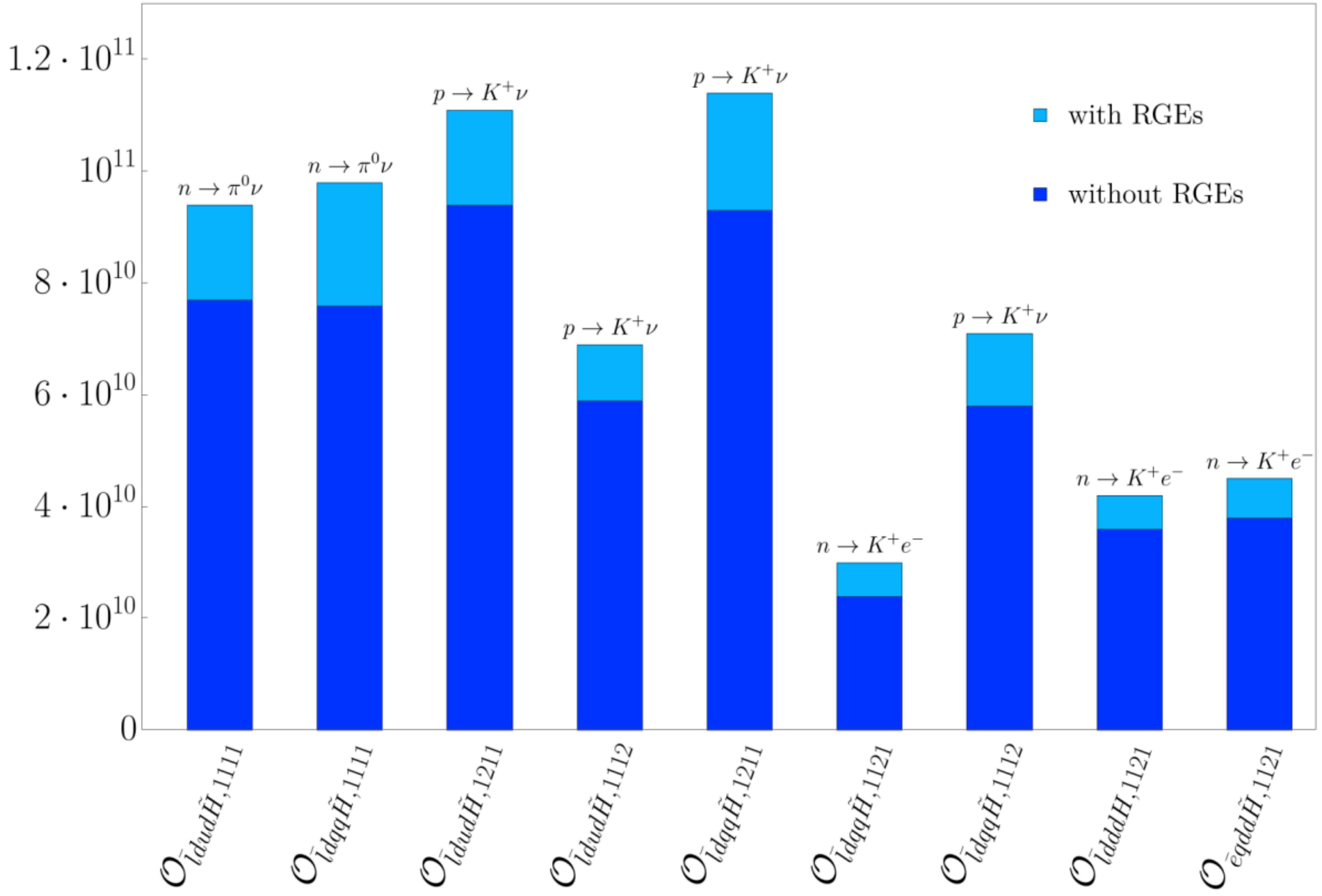


BNV limits on NP scales @ dim-6 &-7 SMEFT

Dim-6 SMEFT



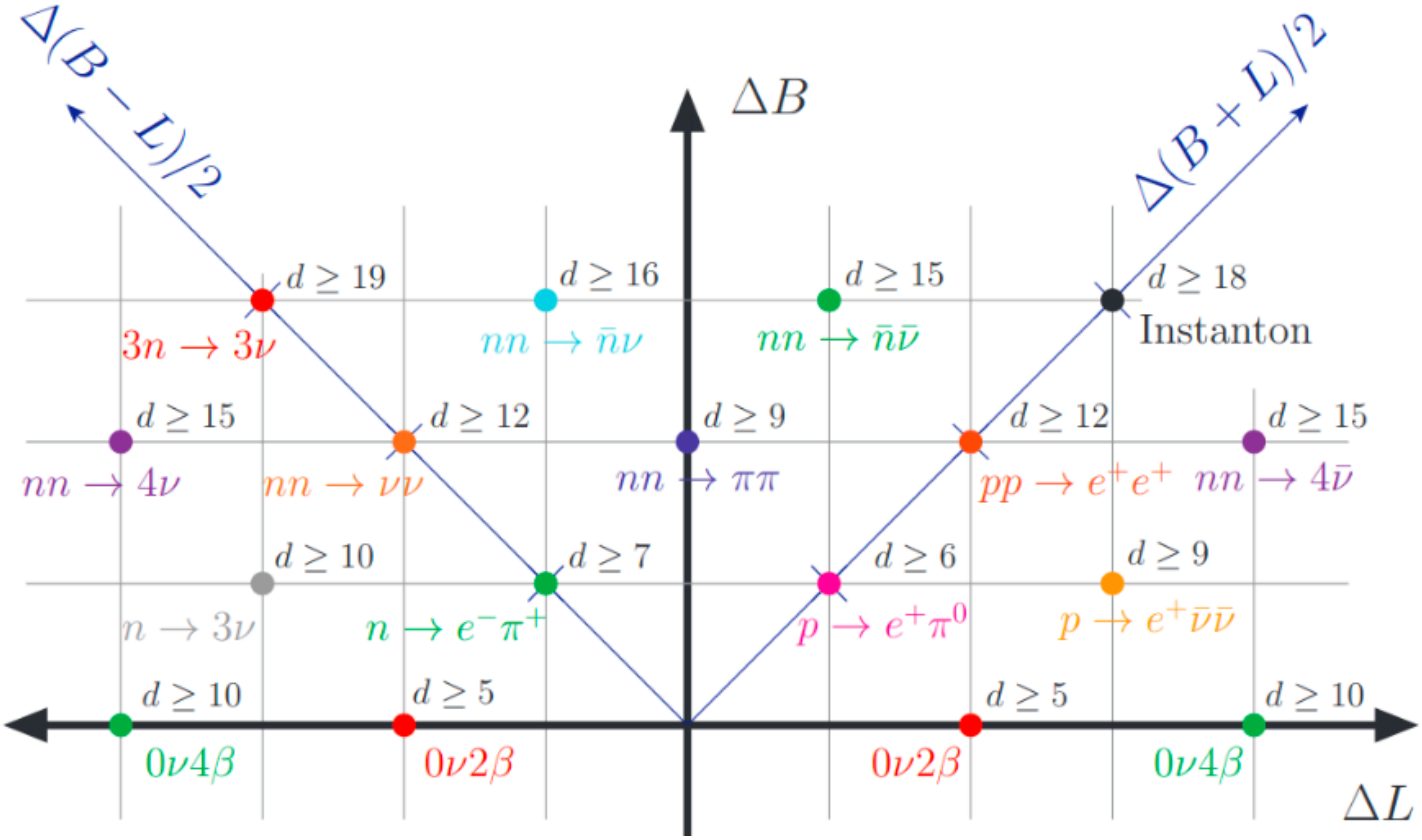
Dim-7 SMEFT



Gargalionis, Herrero-García, Schmidt, Santamaria ‘24

Standard L/BNV: global view

Heeck,Takhistiov ’20



Beyond standard Nucleon decays and Sterile neutrinos

d=6 SMEFT

$$\mathcal{O}_1 = [\overline{d_R{}^c} u_R][\overline{Q^c} L],$$
$$\mathcal{O}_2 = [\overline{Q^c} Q][\overline{u_R{}^c} e_R],$$
$$\mathcal{O}_3 = [\overline{Q^c} Q]_1 [\overline{Q^c} L]_1,$$
$$\mathcal{O}_4 = [\overline{Q^c} Q]_3 [\overline{Q^c} L]_3,$$
$$\mathcal{O}_5 = [\overline{d_R{}^c} u_R][\overline{u_R{}^c} e_R],$$

d=6 N_R-SMEFT

$$\mathcal{O}_{N1} = [\overline{Q^c} Q][\overline{d_R{}^c} N],$$
$$\mathcal{O}_{N2} = [\overline{u_R{}^c} d_R][\overline{d_R{}^c} N].$$

Modes (p)	$\pi^+ + \not{E}$	$\pi^0 e^+$	$K^+ + \not{E}$
Current [yrs]	$3.9 \cdot 10^{32}$ [8]	$1.6 \cdot 10^{34}$ [9]	$5.9 \cdot 10^{33}$ [10]
Future [yrs]		$1.2 \cdot 10^{35}$ [48]	$> 3 \cdot 10^{34}$ [49]
$\mathcal{O}_1$	✓	✓	✓
$\mathcal{O}_2$	—	✓	—
$\mathcal{O}_3$	✓	✓	✓
$\mathcal{O}_4$	—	—	✓
$\mathcal{O}_5$	—	✓	—
$\mathcal{O}_{N1}$	✓	—	✓
$\mathcal{O}_{N2}$	✓	—	✓

Helo, Hirsch, Ota '18

$$\mathcal{O}_1, \mathcal{O}_3: \quad \Gamma(p \xrightarrow{\mathcal{O}_{1,3}} \pi^+ \bar{\nu}_e) = 2\Gamma(p \xrightarrow{\mathcal{O}_{1,3}} \pi^0 e^+)$$

Distinguishability: charged pion mode without the neutral one

Nonstandard nucleon decay: many Light BSM-EFT physics cases

$\mathcal{O}$	Operator	$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$\mathcal{O}_{d^2uN}$	$\epsilon^{abc}\,(\bar{d}_a^c N)\,(\bar{d}_b^c u_c)$	$(1,1)$	6	$p(n)\to\pi^{+(0)}\bar{N}$	sterile neutrino
$\mathcal{O}_{Dd^2u\bar{N}}$	$\epsilon^{abc}\,(\bar{N}\gamma_\mu d_a)\,(\bar{d}_b^c D^\mu u_c)$	$(1,-1)$	7	$n\to N\gamma$ $p(n)\to\pi^{+(0)}N\gamma$	sterile neutrino
$\mathcal{O}_{du^2e\phi}$	$\epsilon^{abc}\,(\bar{d}_a^c u_b)\,(\bar{e}^c u_c)\,\phi^\dagger$	$(1,1)$	7	$p\to e^+\phi$ $p(n)\to e^+\pi^{0(-)}\phi$	dark scalar, majoron
$\mathcal{O}_{d^2Q\bar{L}X}$	$\epsilon^{abc}\,(\bar{Q}_a^{c\,i}\gamma_\mu d_b)\,(\bar{L}_i d_c)X^\mu$	$(1,-1)$	7	$n\to\nu X$ / $e^-\pi^+X$ $p(n)\to\nu\pi^{+(0)}X$	dark photon
$\mathcal{O}_{dQ^2\bar{L}\bar{H}\phi}$	$\epsilon^{abc}\,(\bar{Q}_a^{c\,i}Q_b^j)\,(\bar{L}_i d_c)\,H_j^\dagger\phi^\dagger$	$(1,-1)$	8	$n\to\nu\phi$ / $e^-\pi^+\phi$	dark scalar, majoron
$\mathcal{O}_{Dd^2QLa}$	$\epsilon^{abc}(\partial_\mu a)\,(\bar{Q}_a^{c\,i}\gamma^\mu d_b)\,(\bar{L}_i d_c)$	$(1,-1)$	8	$n\to\nu a$ / $e^-\pi^+a$	axion-like particles
$\mathcal{O}_{Dd^2u\bar{N}a}$	$\epsilon^{abc}(\partial_\mu a)\,(\bar{N}\gamma^\mu d_a)\,(\bar{d}_b^c u_c)$	$(1,-1)$	8	$n\to Na$ $p(n)\to\pi^{+(0)}Na$	axion-like particle with sterile neutrino
$\mathcal{O}_{duQe\bar{L}\bar{N}}$	$\epsilon^{abc}\,(\bar{e}^c u_a)\,(\bar{Q}_b^{c\,i}\gamma_\mu d_c)\,(\bar{L}_i\gamma^\mu N^c)$	$(1,-1)$	9	$p\to e^+\nu N$ $n\to e^+e^-N$	sterile neutrino
$\mathcal{O}_{du^2eN^2}$	$\epsilon^{abc}\,(\bar{d}_a^c u_b)\,(\bar{e}^c u_c)\,(\bar{N}^c N)$	$(1,3)$	9	$p\to e^+\bar{N}\bar{N}$	sterile neutrino

Fridell, **CH**, Takhistiov arXiv: 2312.13740

Super-K searches for BNV: spreading of the momentum peak

For 2-body decays: the final state momenta are determined by the masses

$$\Gamma_{\psi\to ij} = \frac{1}{16\pi}\frac{\lambda^{1/2}(m_\psi, m_i, m_j)}{m_\psi^3}|\sum_I C_I \mathcal{M}_I^{\psi\to ij}|^2 \qquad |\vec{p}_i| = \frac{\lambda^{1/2}(m_\psi^2, m_i^2, m_j^2)}{2m_\psi}$$

In the ideal scenario this leads to a sharp peak at the given momentum

This peak is spread due to effects from:

Fermi motion

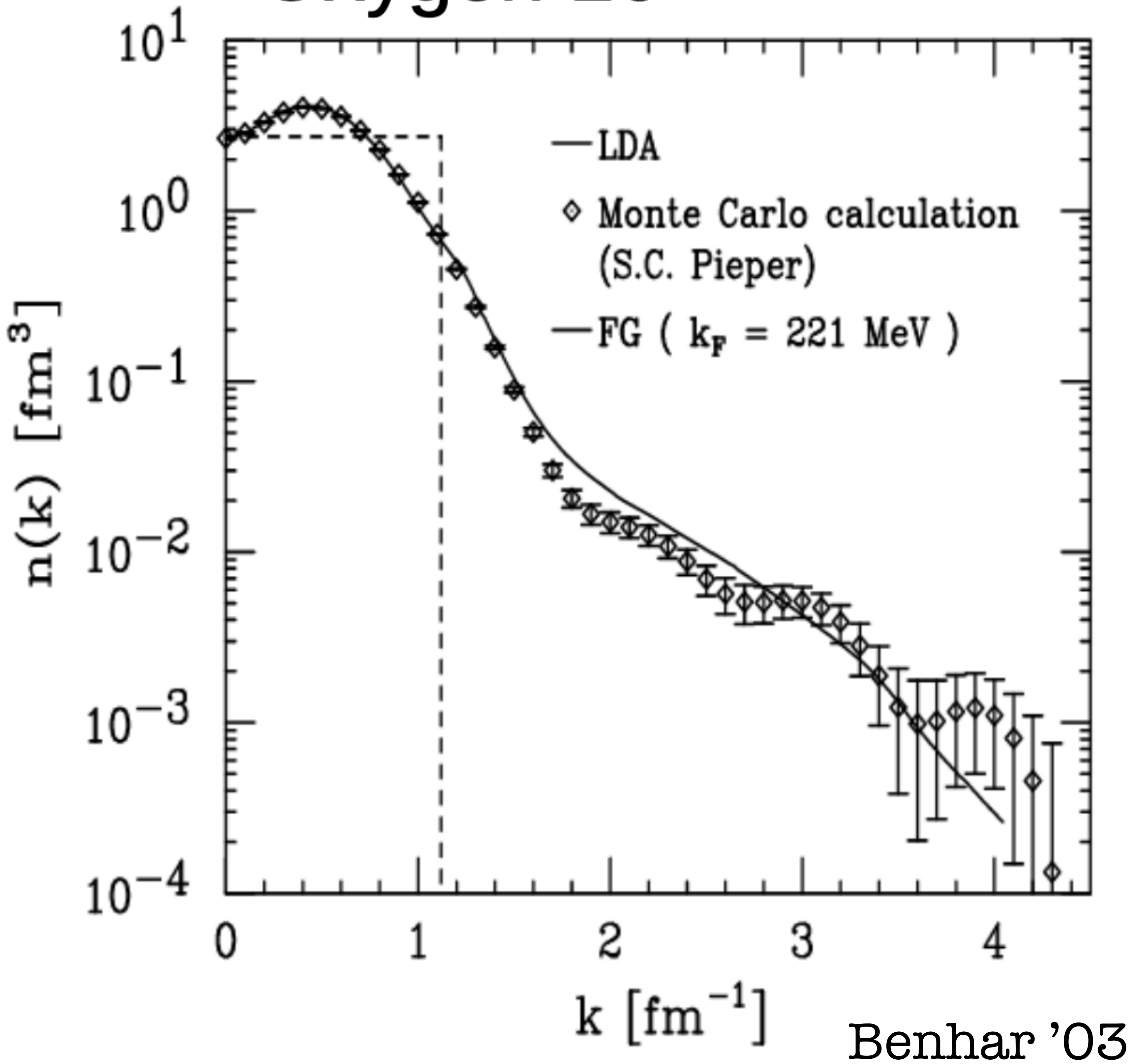
nuclear binding energies

Nucleon-nucleon correlation in decays

Benhar '03 nucl-th/0307061

Super-K and Hyper-K are both made up of water:
oxygen has most of the protons

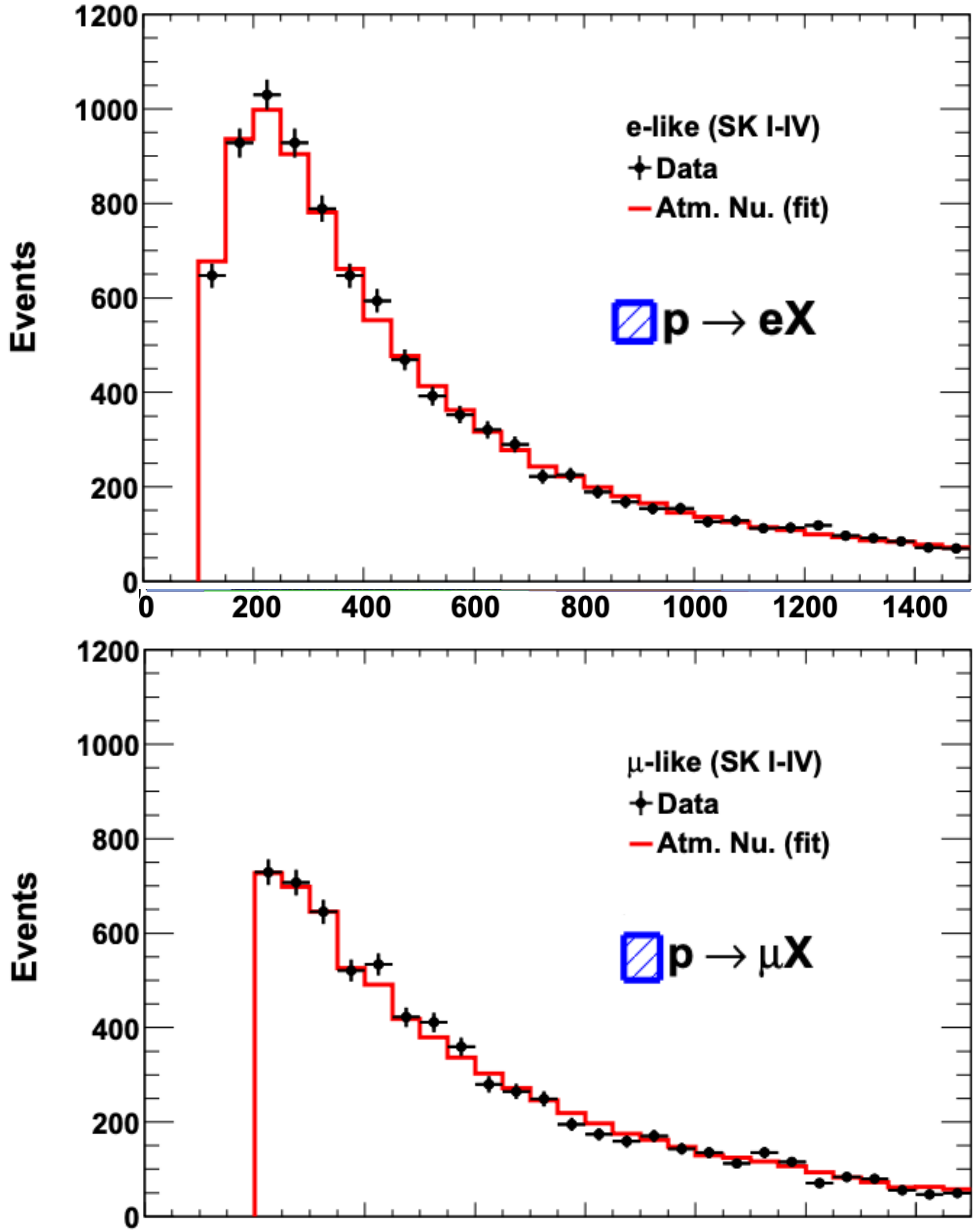
Oxygen 16



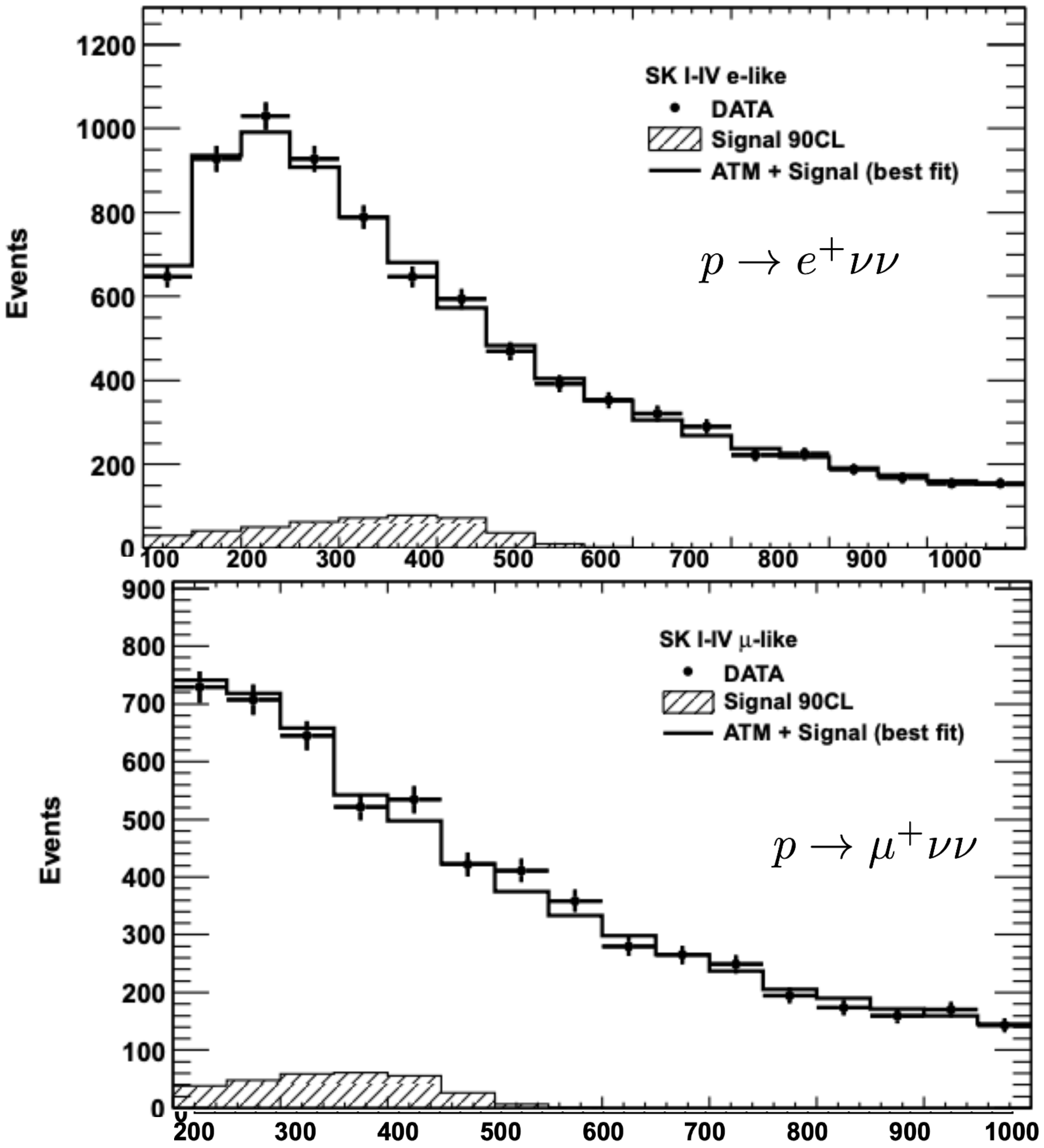
Benhar '03

Super-K searches for BNV

Rich GUT model building history: mostly light neutrino final states are explored in the literature



Super-K: Takhistov et. al PRL ‘15



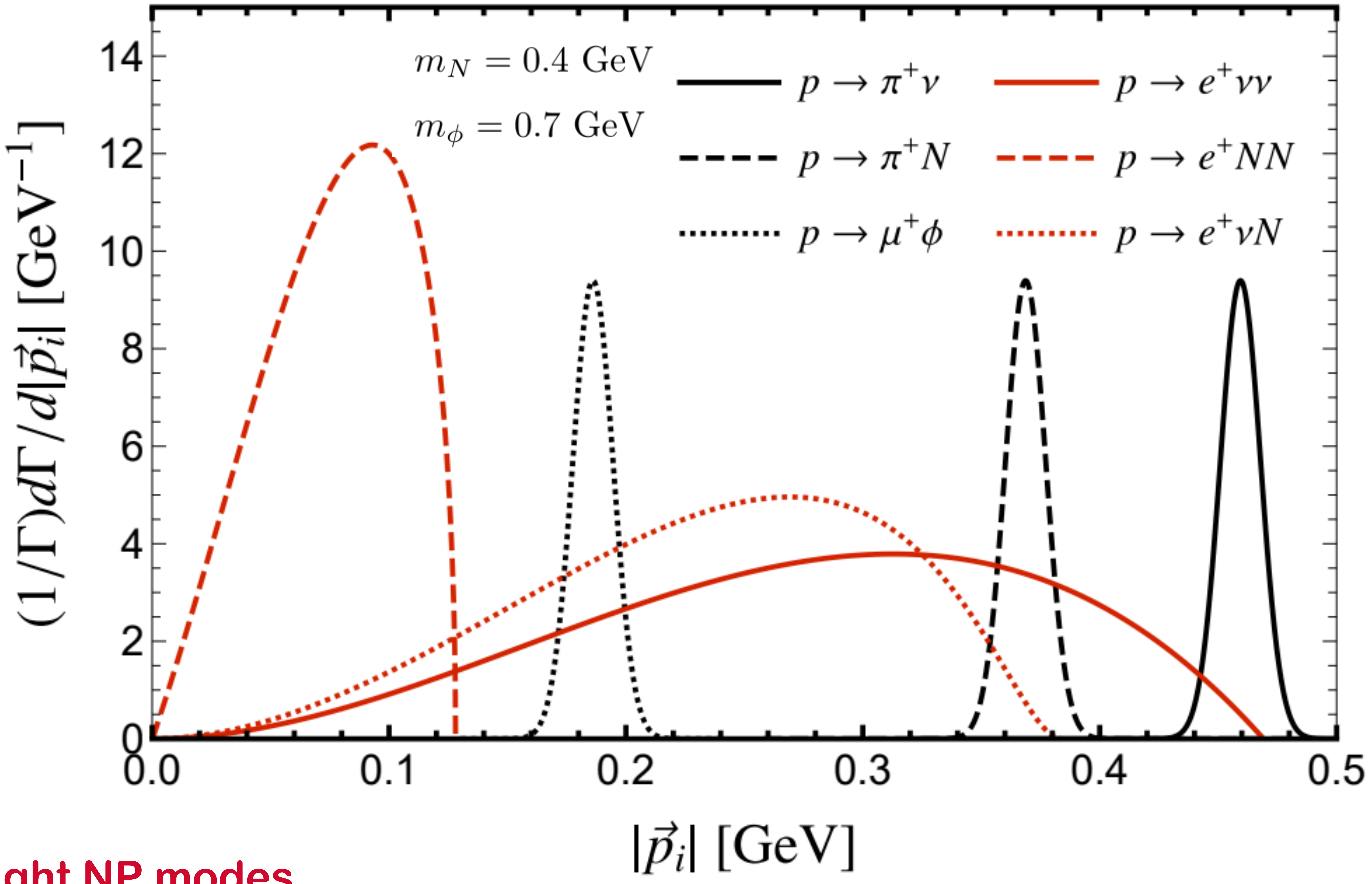
Super-K: Takhistov et. al PRL ‘14

What if there is light new physics below proton mass?

Light BSM-EFT: momentum distributions

Distribution shifts:

lower momenta for higher NP masses



Fridell, **CH** ,Takhistiov '23

GUT motivated cuts might have missed light NP modes

Many new limits from the existing searches!

Cut optimization at Hyper-K: to target motivated physics cases

Light BSM-EFT: momentum distributions

3-body decays the distribution is more spread out

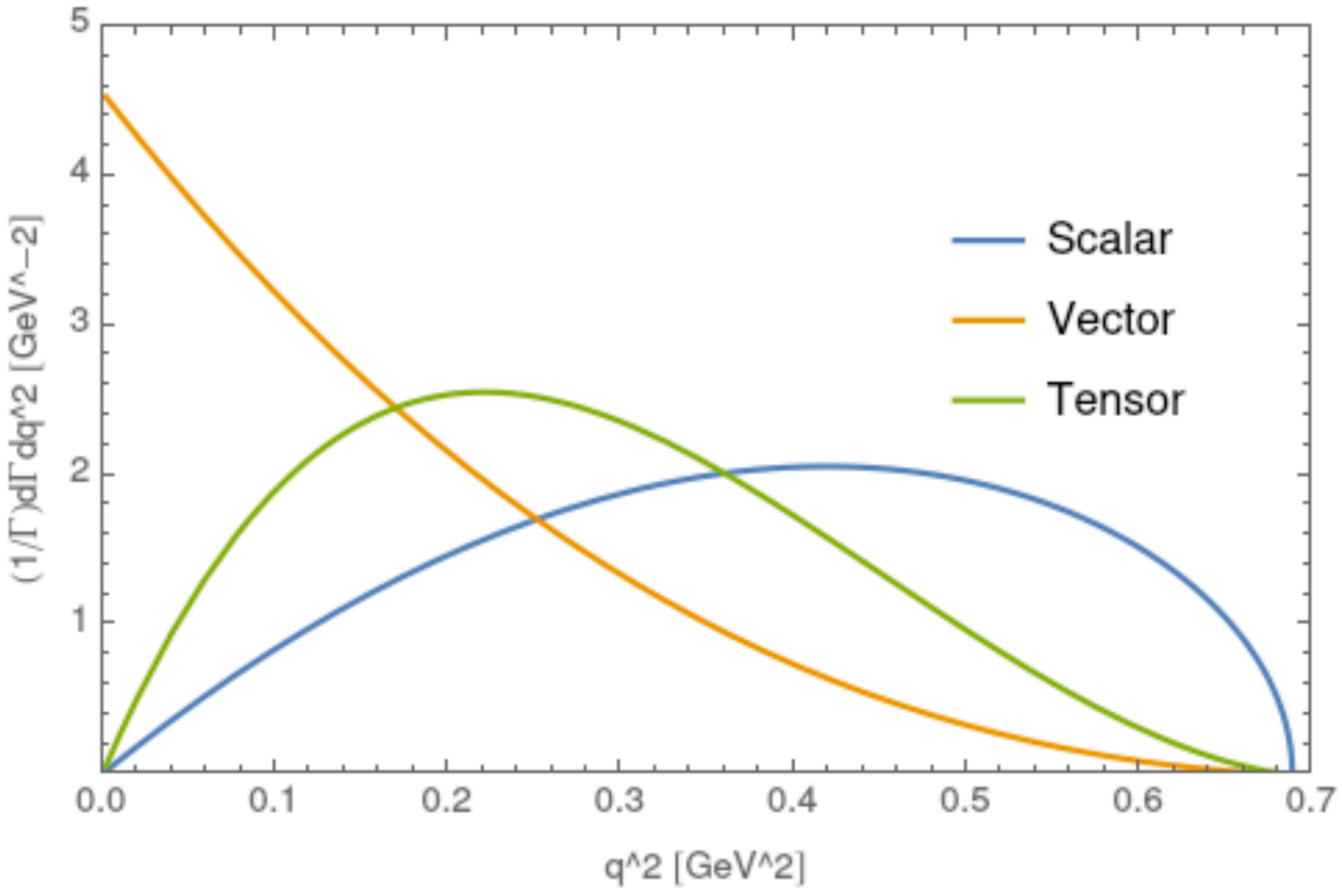
$$\frac{d\Gamma_{\psi\to ijk}}{d|\vec{p}_i|} = \frac{1}{(2\pi)^3}\frac{1}{32m_\psi^3}\frac{2m_\psi|\vec{p}_i|}{\sqrt{m_i^2+|\vec{p}_i|^2}}\int_{t^-}^{t^+} dt|\mathcal{M}_{\psi\to ijk}|^2$$

Possibility to distinguish different interactions:

Scalar: $(\psi_1\psi_2)(\psi_3\psi_4)$

Vector: $(\psi_1\gamma_\mu\psi_2)(\psi_3\gamma^\mu\psi_4)$

Tensor: $(\psi_1\sigma_{\mu\nu}\psi_2)(\psi_3\sigma^{\mu\nu}\psi_4)$



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For two NP particles in the final state we also have double the mass d.o.f.s

Nonstandard Nucleon Decay: A GUT UV example

LRSM: Chang, Mohapatra, Parida ‘84
Deppisch et al ’14

$\Omega_R(1,3,0,1)$ $\Delta_R(1,3,-2,1)$

PS: $(1,1,1)$ $(1,1,15)$ $(1,3,15)$ $(\mathbf{1},\mathbf{3},\overline{\mathbf{10}})$

$$SO(10) \xrightarrow{M_U} \mathcal{G}_{224D} \xrightarrow{M_P} \mathcal{G}_{224} \xrightarrow{M_C} \mathcal{G}_{2213} \xrightarrow{M_\Omega} \mathcal{G}_{2113} \xrightarrow{M_{B-L}} \mathcal{G}_{SM}$$

$SO(10)$ $\{54\}_H$ $\{210\}_H$ $\{210\}_H$ $\{210\}_H$ 126_H

$$\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \equiv (3,1,-2), \qquad \Delta_R = \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \equiv (1,3,-2),$$

$$\Omega_L = \begin{pmatrix} \omega_L^0 & \omega_L^+/\sqrt{2} \\ \omega_L^-/\sqrt{2} & -\omega_L^0 \end{pmatrix} \equiv (3,1,0), \qquad \Omega_R = \begin{pmatrix} \omega_R^0 & \omega_R^+/\sqrt{2} \\ \omega_R^-/\sqrt{2} & -\omega_R^0 \end{pmatrix} \equiv (1,3,0),$$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \equiv (2,2,0), \qquad \sigma \equiv (1,1,0).$$

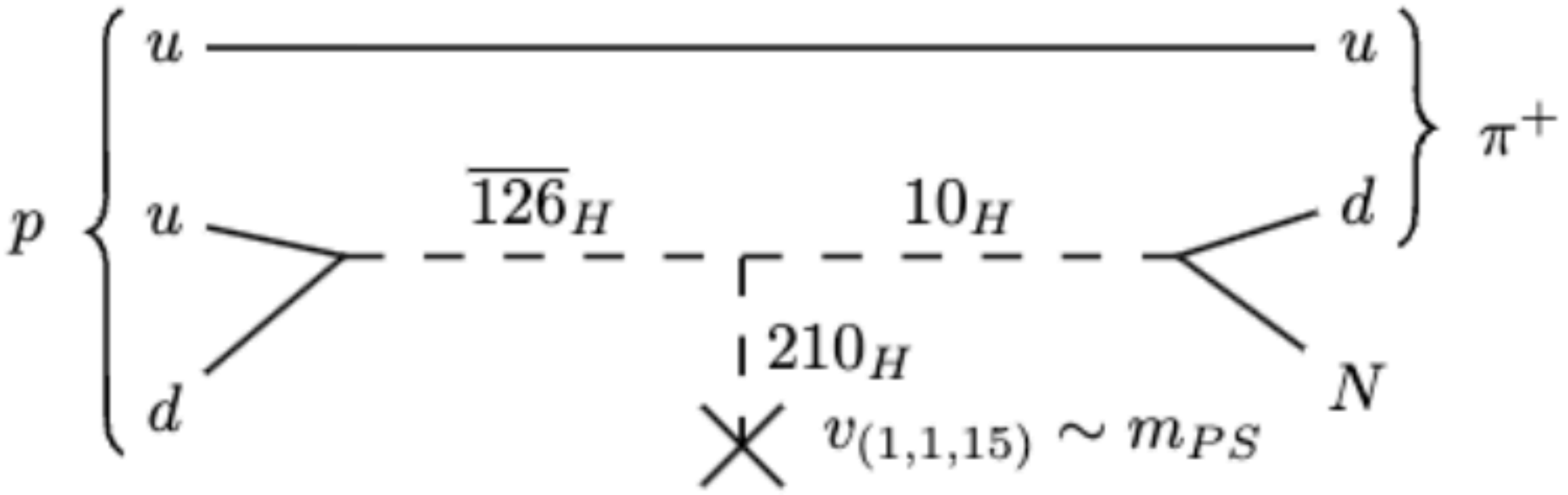
$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix}, \quad \langle\Delta_L\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix}, \quad \langle\Delta_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

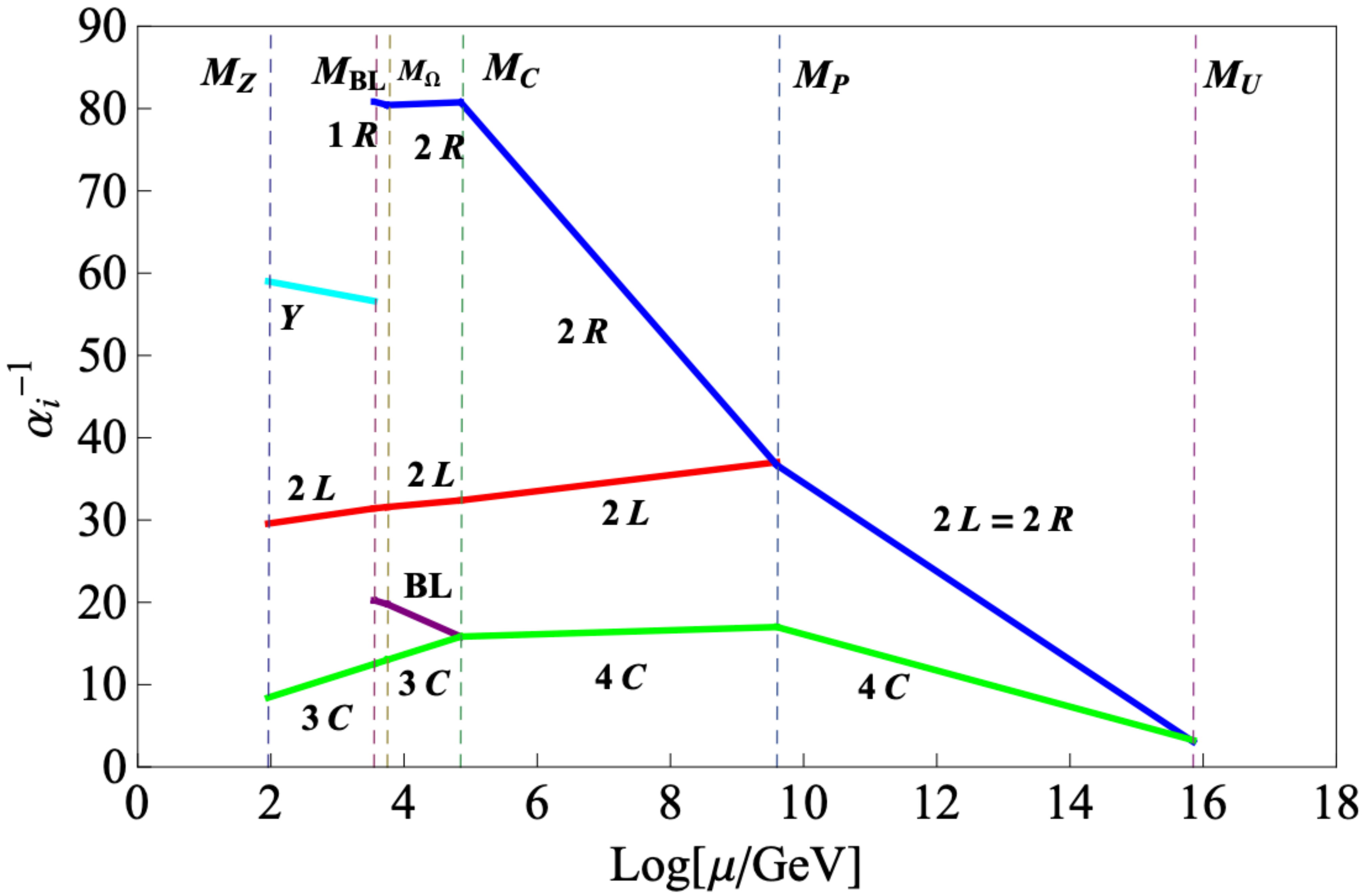
$$\langle\Omega_L\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \omega_L & 0 \\ 0 & \omega_L \end{pmatrix}, \quad \langle\Omega_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \omega_R & 0 \\ 0 & \omega_R \end{pmatrix}, \quad \langle\sigma\rangle = M_P.$$

$$v_L \approx \frac{\beta v^2 v_R}{M\langle\sigma\rangle}$$

$$m_\nu \approx M_L = f v_L = \frac{v_L}{v_R} M_R = \frac{\beta v^2}{M\langle\sigma\rangle} M_R$$

Fridell, **CH**, Takhistiov ’23





LRSM with light N_R pheno: Mikulenko ’24
Vries et.al ‘24

Nonstandard Nucleon decays and ALPs

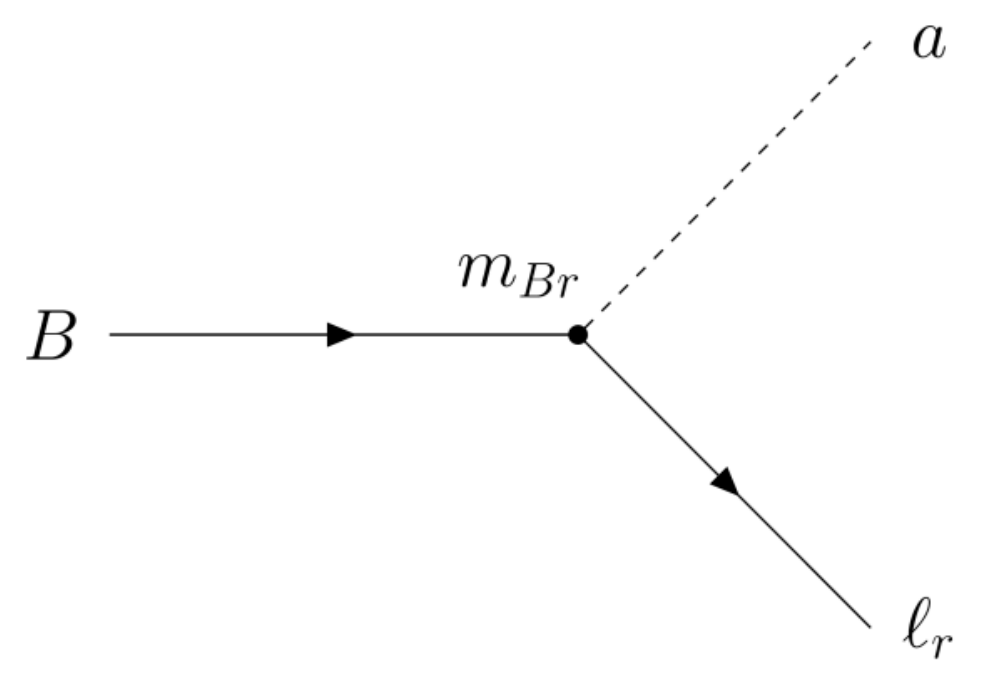
A recent study: Li, Schmidt, Yao '24

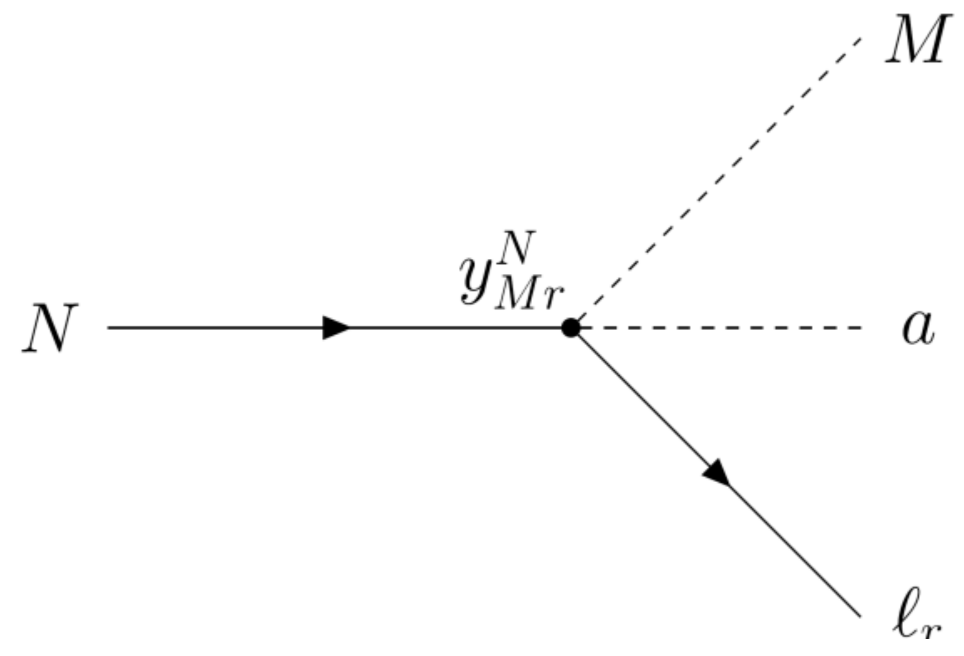
$$\mathcal{O}_{\partial aLQd} = \epsilon^{\alpha\beta\gamma}\partial_\mu a(\bar{L}d_\alpha)(\bar{Q}^c_\beta\gamma^\mu d_\gamma)\ , \quad \mathcal{O}_{\partial aed} = \epsilon^{\alpha\beta\gamma}\partial_\mu a(\bar{d}^c_\alpha d_\beta)(\bar{e}\gamma^\mu d_\gamma)$$

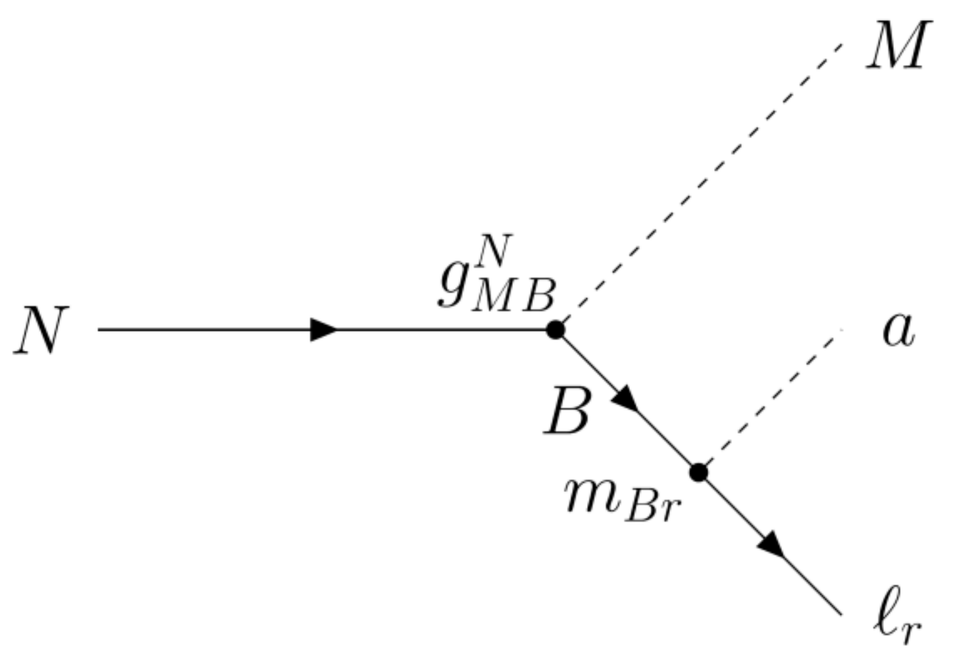
Process
$n \to \nu a$
$\Lambda^0 \to \nu a$
$\Sigma^0 \to \nu a$
$\Xi^0 \to \nu a$
$\Sigma^- \to \ell^- a$
$\Xi^- \to \ell^- a$

Process
$p \to \ell^+ a$
$\Sigma^+ \to \ell^+ a$
$n \to \bar{\nu} a$
$\Lambda^0 \to \bar{\nu} a$
$\Sigma^0 \to \bar{\nu} a$
$\Xi^0 \to \bar{\nu} a$

Process
$p \to K^+ \nu a$
$n \to \pi^0 \nu a$
$p \to \pi^+ \nu a$
$n \to \eta^0 \nu a$
$n \to K^+ \ell^- a$
$n \to K^0 \nu a$
$n \to \pi^+ \ell^- a$
$n \to \bar{K}^0 \nu a$

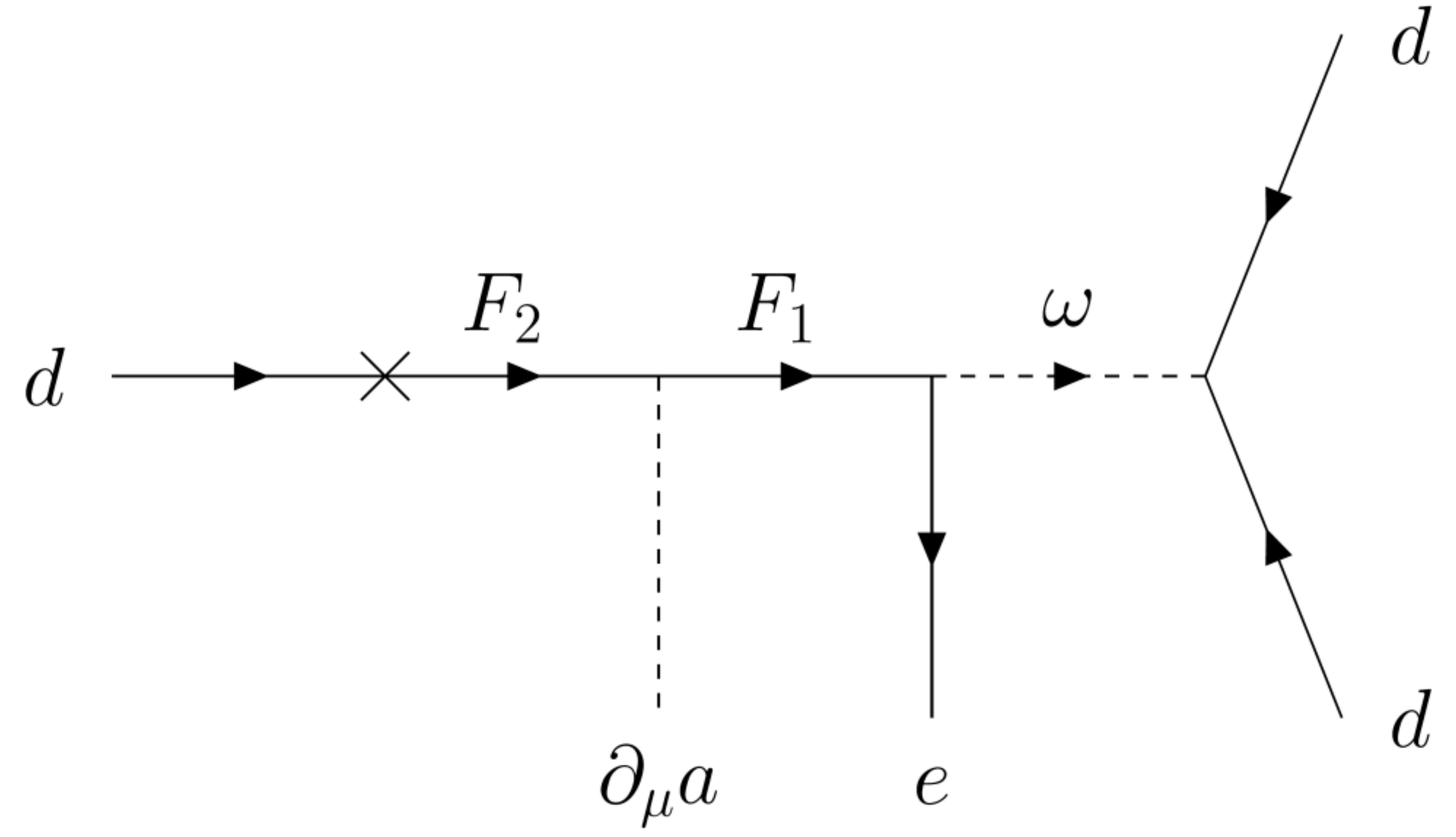






UV realisation:

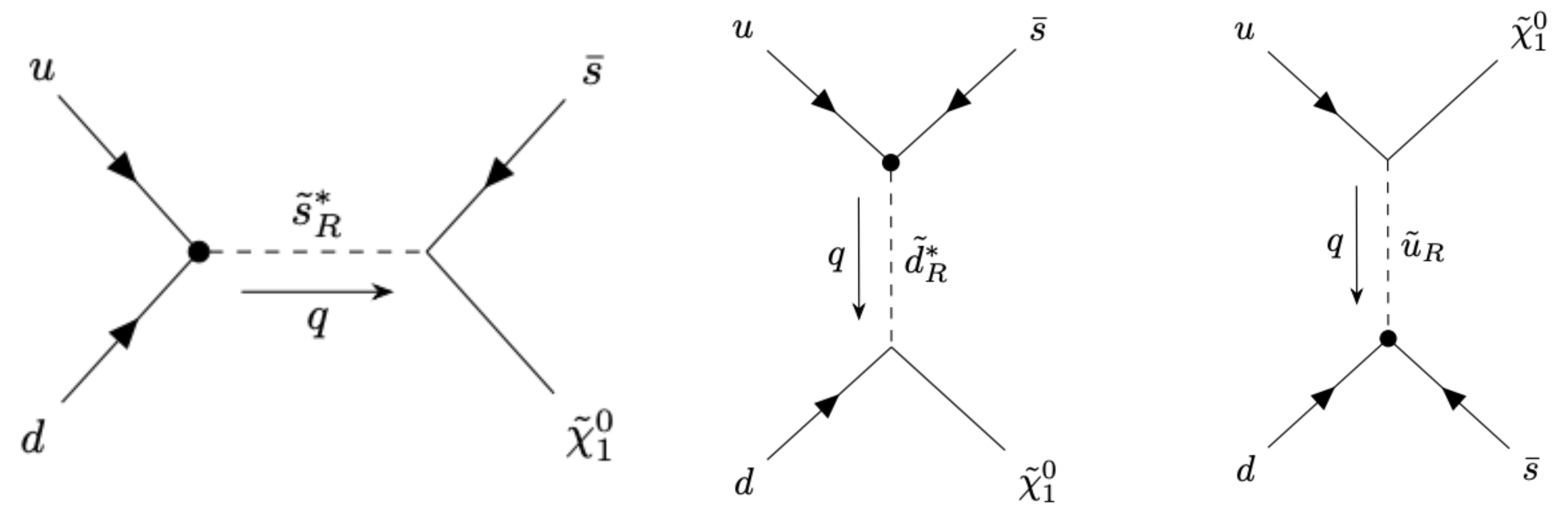
$$F_i \ = \ F_{iL} + F_{iR} \sim (3, 1, -1/3) \ \ + \ \ \omega \sim (3, 1, 2/3)$$



Nonstandard Nucleon decays and light Neutralino

Another recent study:
Domingo, Dreiner, Köhler, Nangia, Shah '24

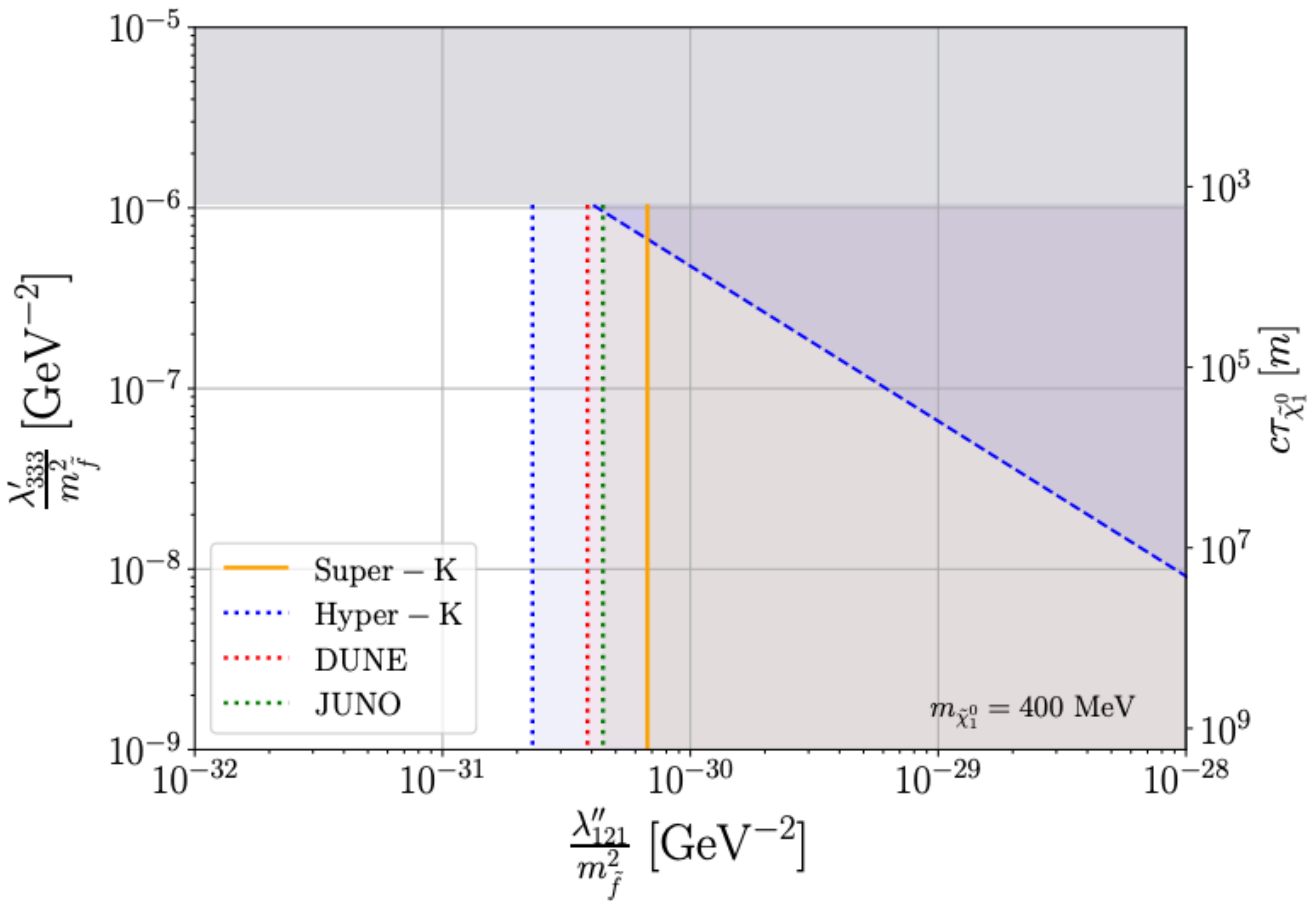
$$p \to K^+ \tilde{\chi}_1^0$$



RPV-MSSM with light neutrino: $m_{\tilde{\chi}_1^0} \leq m_p - m_{K^+} \approx 445\,\text{MeV}$

$$W_{\text{LNV}} = \epsilon_{ab}\left(\frac{1}{2}\lambda_{ijk}L^{ai}L^{bj}\bar{E}^k + \lambda'_{ijk}L^{ai}Q^{bj}\bar{D}^k\right)$$

$$W_{\text{BNV}} = \frac{1}{2}\varepsilon_{\alpha\beta\gamma}\lambda''_{ijk}\bar{U}^{\alpha i}\bar{D}^{\beta j}\bar{D}^{\gamma k}\,,$$

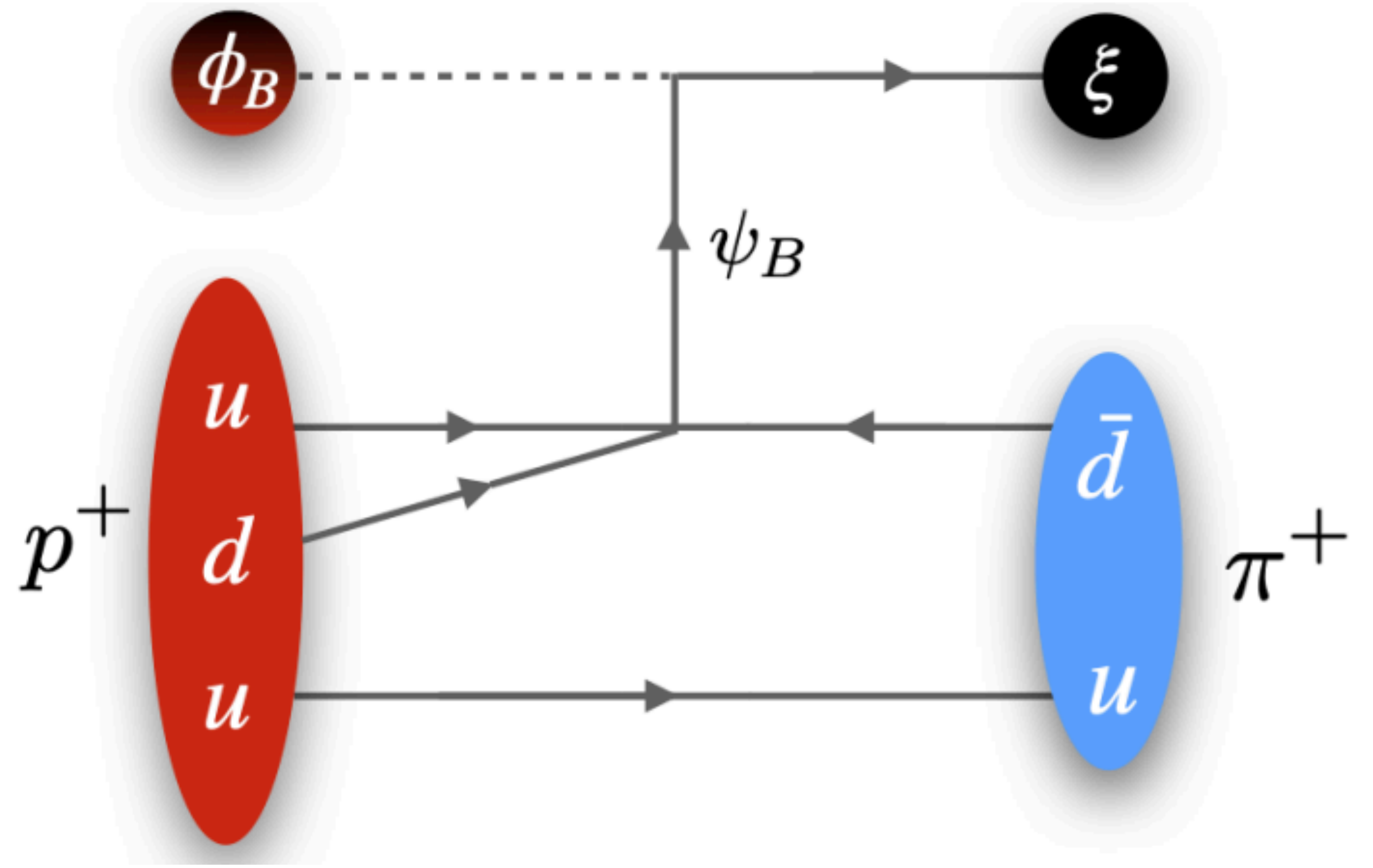


Sensitivity to new parameter space!

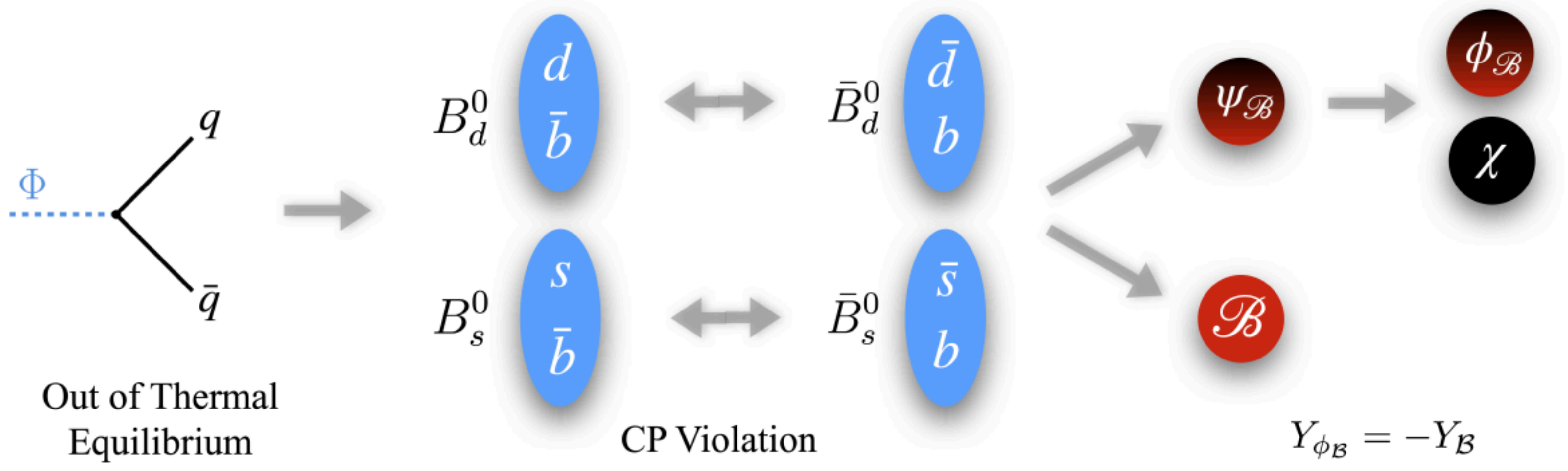
Nonstandard Nucleon conversion and "Dark"-genesis

$$\mathcal{O}_{ab,c} = C_{ab,c}\epsilon_{ijk}\left(u_a^i d_b^j\right)\left(\psi_{\mathcal{B}}\, d_c^k\right)$$

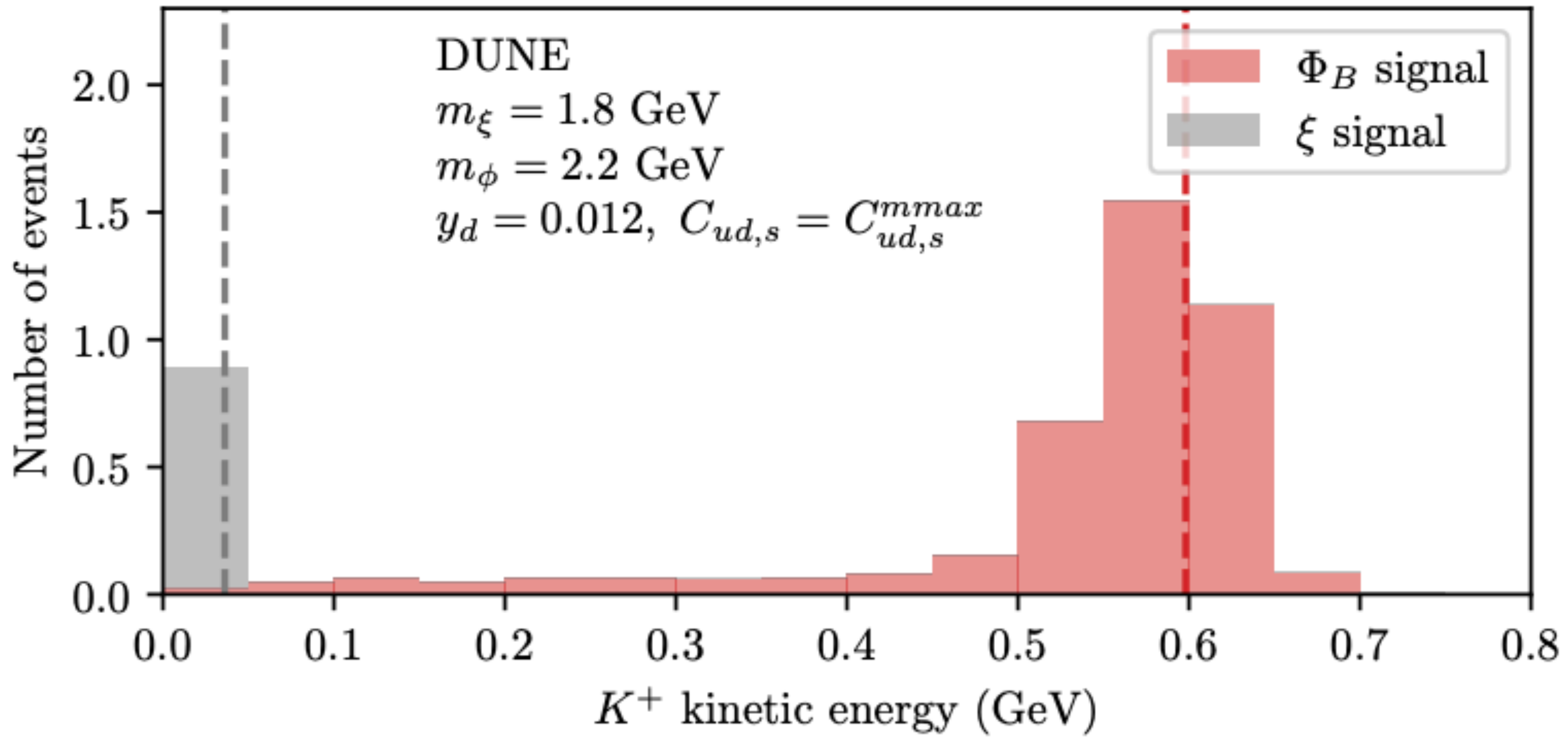
Berger, Elor '24



$$\phi_{\mathcal{B}}\, N \to \mathcal{M}\,\xi \quad \text{if} \quad m_{\phi_{\mathcal{B}}} + m_N > m_{\mathcal{M}} + m_\xi$$
$$\xi\, N \to \mathcal{M}\,\phi_{\mathcal{B}}^\star \quad \text{if} \quad m_\xi + m_N > m_{\mathcal{M}} + m_{\phi_{\mathcal{B}}}$$



Elor, Escudero, Nelson '19



Conclusions

Operators with light NP fields can lead to nonstandard nucleon decay

Existent searches can be recast into limits for many light NP EFT

Sensitivity to new parameter space in many interesting models with light NP in upcoming experiments

Possibility to generalize for conversions and other flavors

Potential to probe many existent baryogenesis mechanisms