From Neutrino Masses to Baryogenesis

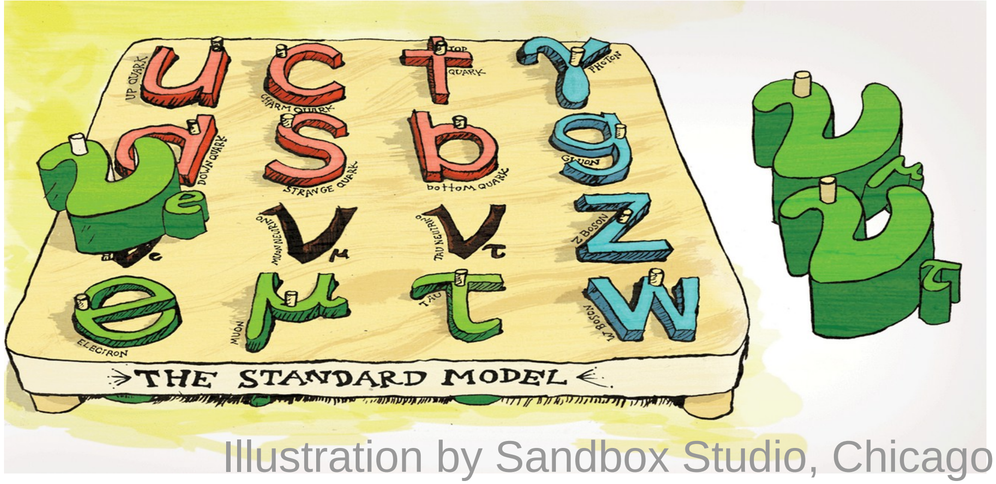


Illustration by Sandbox Studio, Chicago

December 4th 2020

Gordon Godfrey Workshop

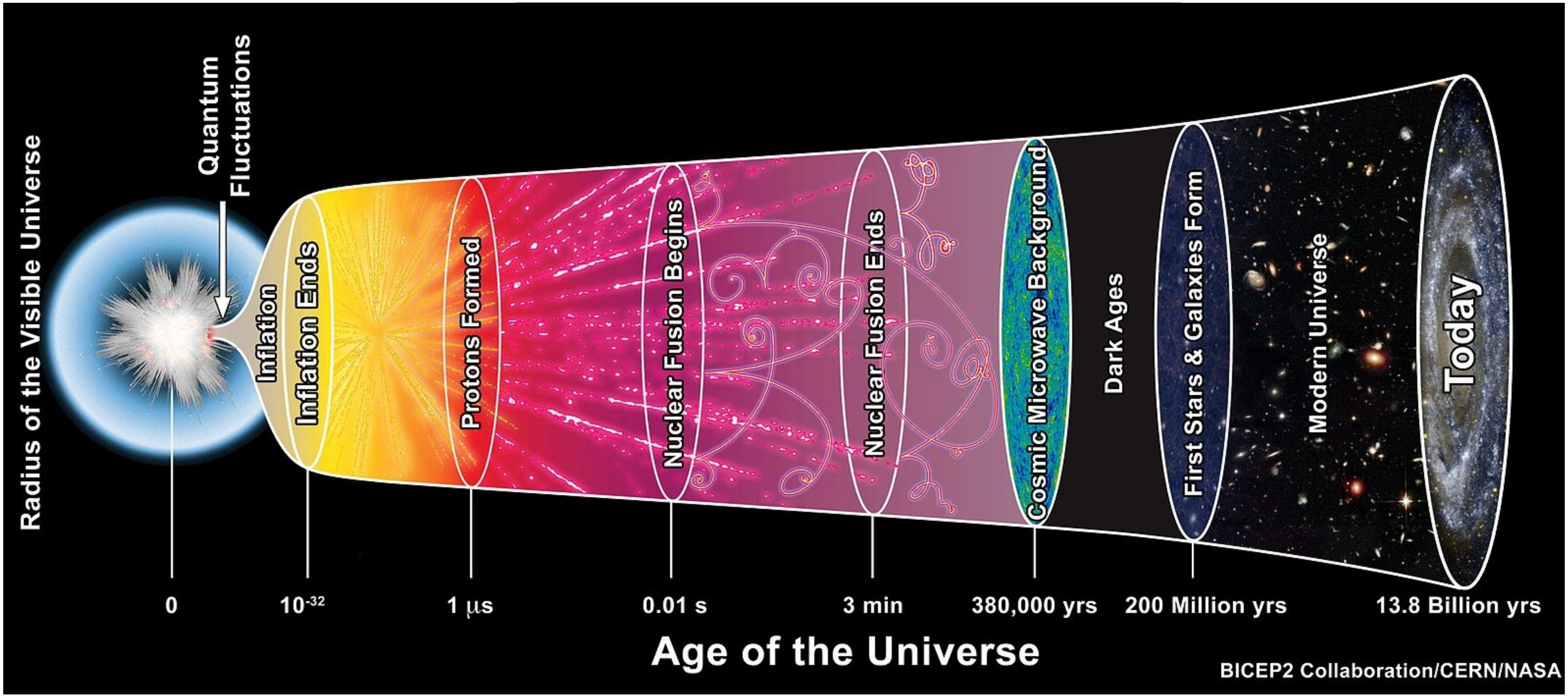
Julia Harz

Technische Universität München

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

From the Big Bang to Today…

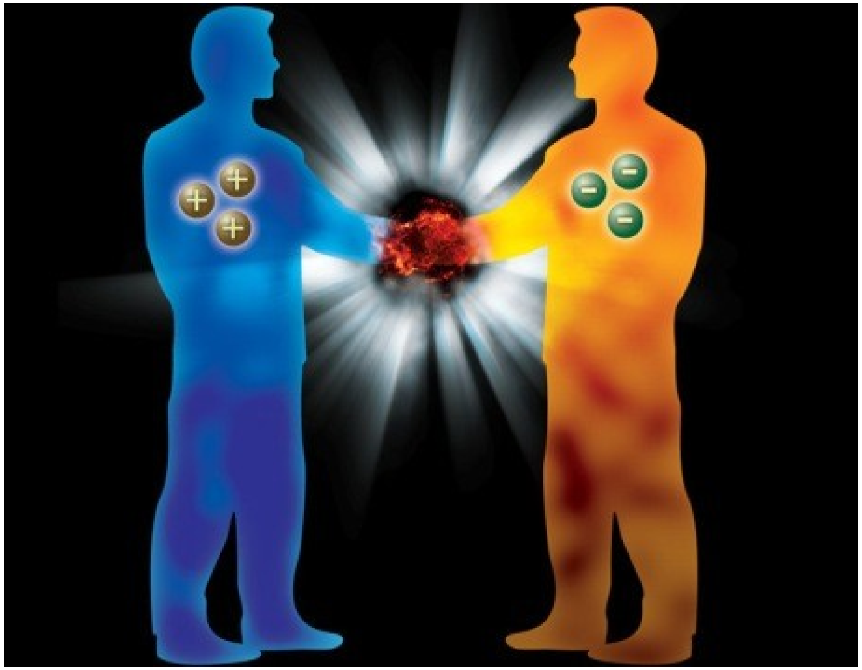


BICEP2 Collaboration/CERN/NASA

How big is the baryon asymmetry?

Our Universe consists mainly out of baryonic matter, quantified by the baryon-to-photon ratio:

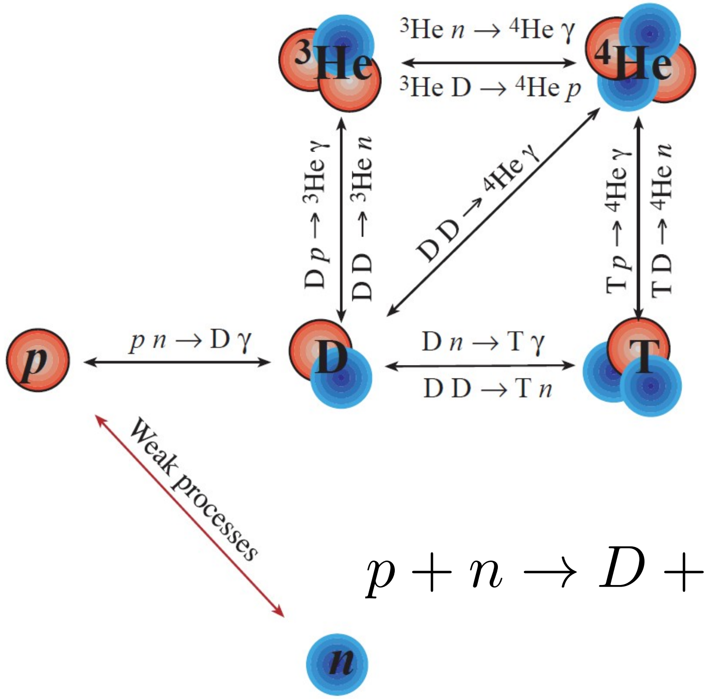
$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$



$$\boxed{\eta_B^{\text{obs}} = (6.09 \pm 0.06) \times 10^{-10}}$$

What created the asymmetry?

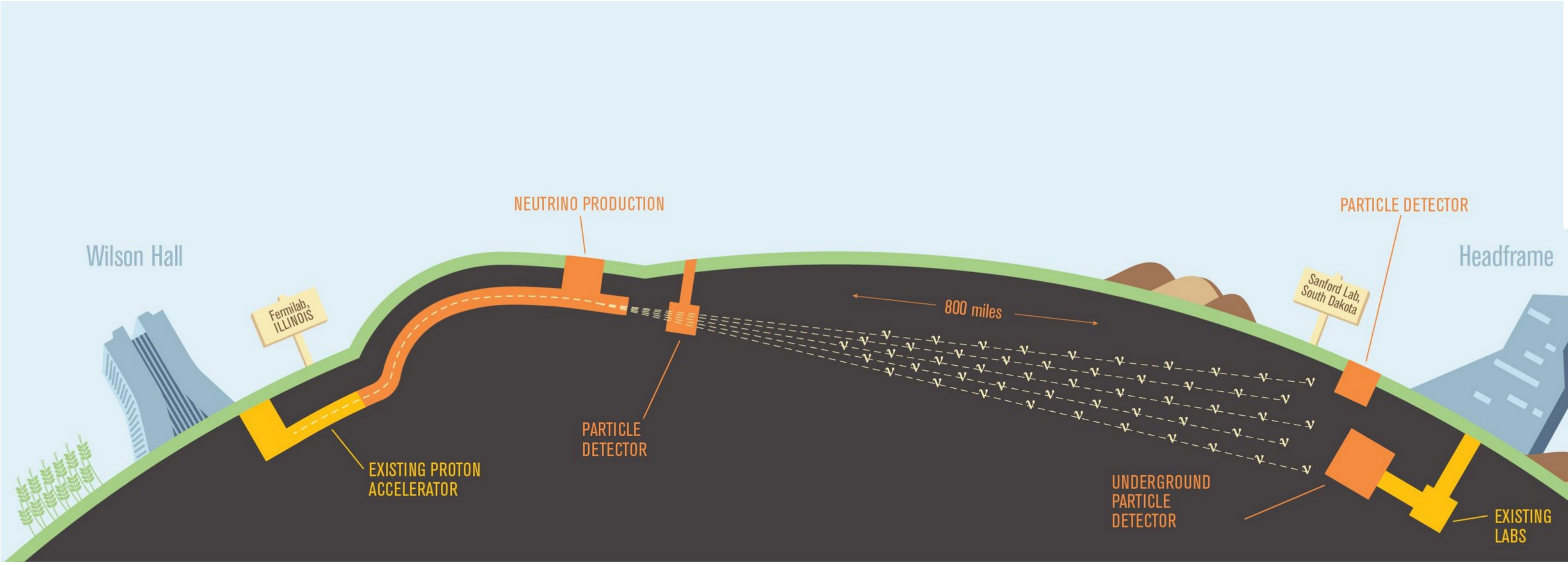
Big Bang Nucleosynthesis



$$p + n \to D + \gamma$$

$$T_{\text{nuc}}^{D} \approx \frac{B_D}{\log \eta_B^{-1}}$$

What is the nature of neutrinos?



ν_e ν_μ

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Neutrino **oscillations** require **massive** neutrinos, forbidden in the Standard Model.

How do neutrinos get their masses?

What nature do neutrinos have? Are they their own anti-particles?

Outline

Neutrinos & Lepton-number violating interactions

- Neutrinos as a window to new physics
- Why lepton-number violation?
- Lepton-number violating operators
- Testability

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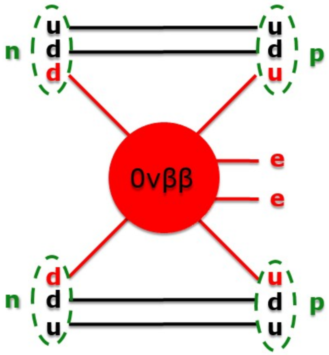
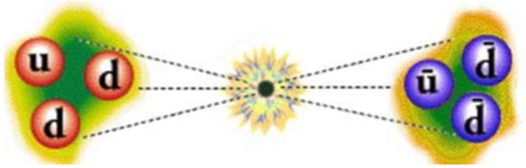
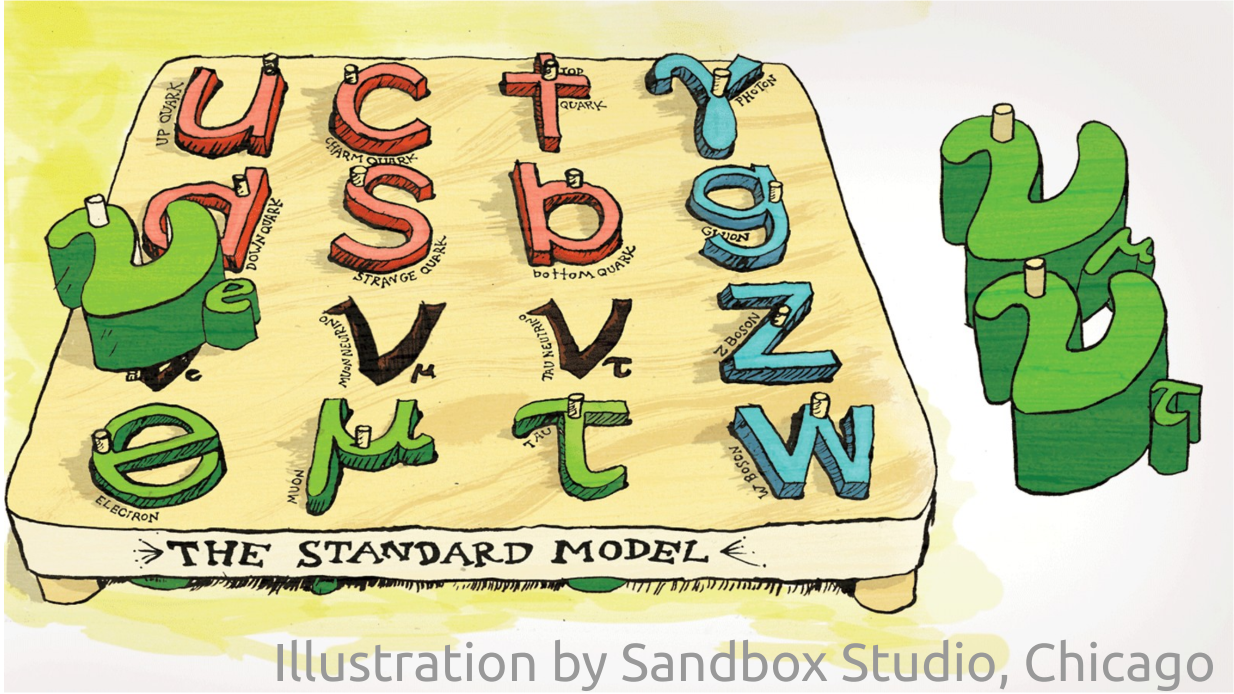
Leptogenesis & Baryogenesis

- Difficulties to probe high-scale leptogenesis
- Falsifying high-scale leptogenesis
- Low-scale leptogenesis
- High-scale baryogenesis
- Low-scale baryogenesis
- Alternative tests
- Possible links to dark matter







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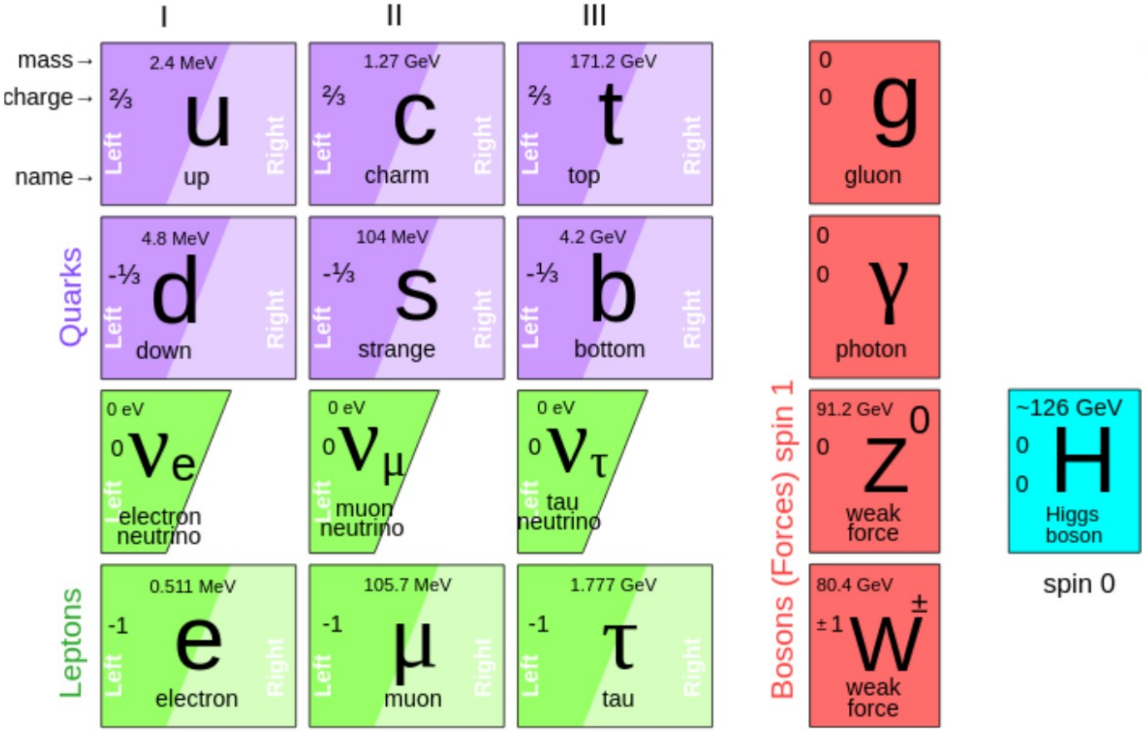
“Neutrinos, the Standard Model misfits”

Neutrinos.

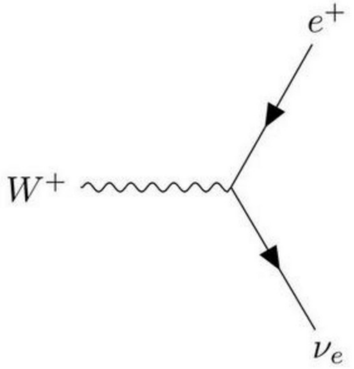
Neutrinos – what do we know?

- Standard Model (SM) contains **3 active neutrinos**



- SU(2)$_L$ **doublets**

$$L_i \rightarrow \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix}$$



- Within the SM neutrinos are **massless**

$$m_\nu = 0$$

Neutrinos – what do we know?

- Standard Model (SM) contains **3 active neutrinos**

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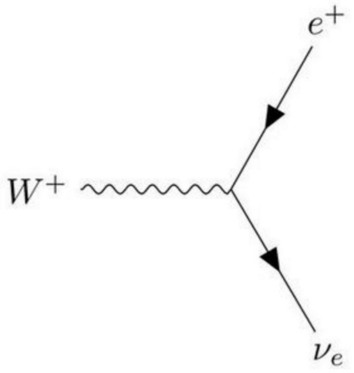
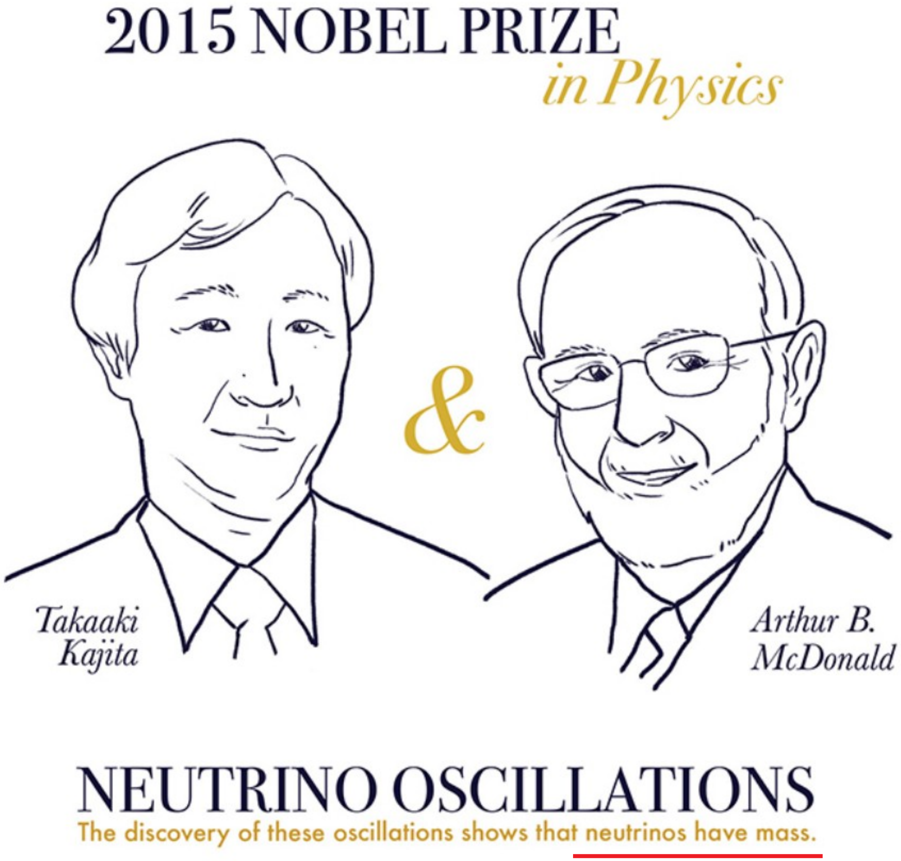




- Within the SM neutrinos are ~~**massless**~~

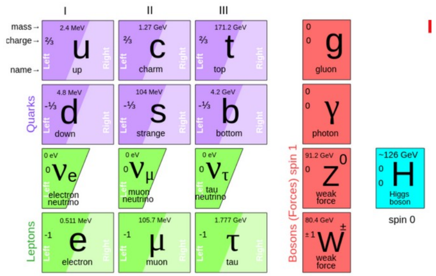
$$m_\nu \neq 0$$

How do neutrinos get their mass?

- Masses of the active neutrinos cannot be explained within the SM
- **BUT** right-handed neutrinos could help

Dirac mass

$$y_\nu \underset{-1/2}{L} \epsilon \overset{1/2}{H} \underset{0}{\nu_R^c} \supset m_D \nu_L \nu_R^c$$



hypercharge

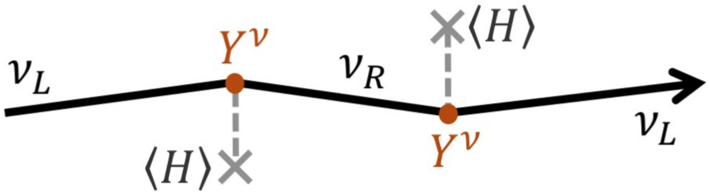
Majorana mass

$$m_M \underset{0}{\overline{\nu}_R} \underset{0}{\nu_R^c}$$

- tiny Yukawa couplings

$$m_\nu / \Lambda_{EW} \leq 10^{-12}$$

- Lepton number no accidental symmetry anymore

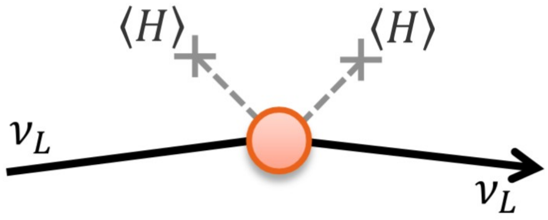


$$m_M \underset{1/2}{\overline{\nu}_L} \underset{1/2}{\nu_L^c}$$

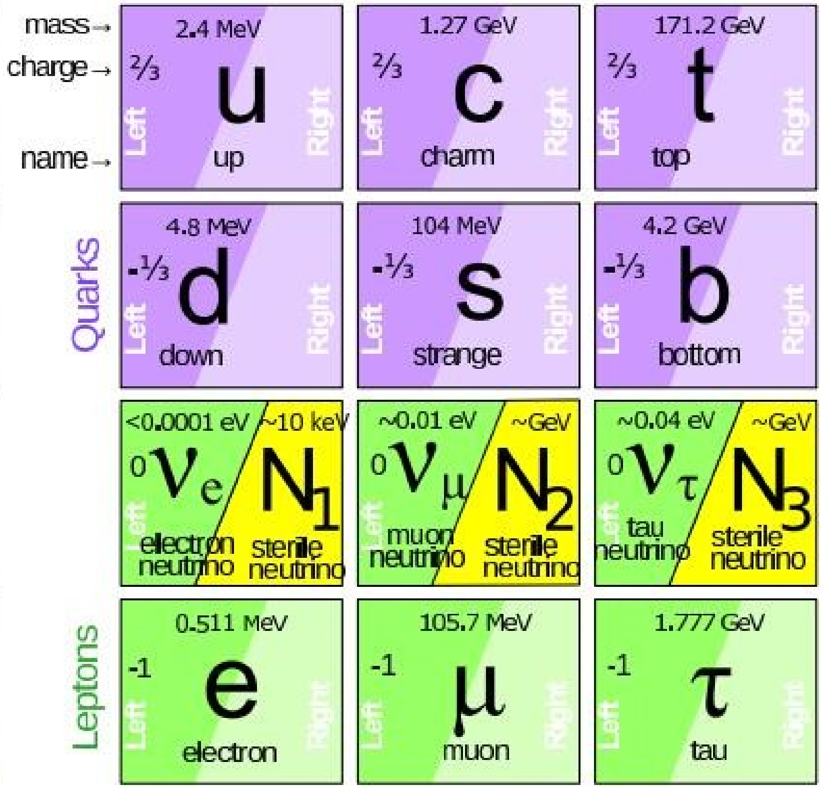
$$\underset{-1/2}{L}\overset{-1/2}{L}\underset{1/2}{H}\overset{1/2}{H}$$

not at tree-level within the SM possible

- higher dimensional operator
- Lepton number violation (**LNV**)



How do neutrinos get their mass?



mass→ charge→ name→	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right
	<0.0001 eV ~10 keV 0 ν_e N_1 electron neutrino sterile neutrino Left	~0.01 eV ~GeV 0 ν_μ N_2 muon neutrino sterile neutrino Left	~0.04 eV ~GeV 0 ν_τ N_3 tau neutrino sterile neutrino Left
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right

Dirac **Majorana**

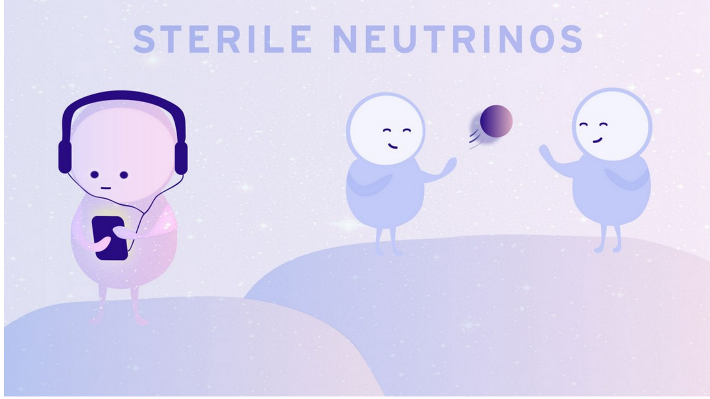
$$\mathcal{L} \supset M_D^{ij}\, \nu_{L_i} \nu^c_{R_j} + M_M^{ij}\, \bar{\nu}_{R_i} \nu^c_{R_j}$$

$$\mathcal{L} \supset M^{ij} \nu \bar{\nu} \qquad M = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}$$

Diagonalisation:

$$m_\nu = \frac{M_D^2}{M_M} \qquad \nu \approx \nu_L - \frac{M_D}{M_M} \nu_R^c$$

$$m_N = M_M \qquad N \approx \frac{M_D}{M_M} \nu_L + \nu_R^c$$

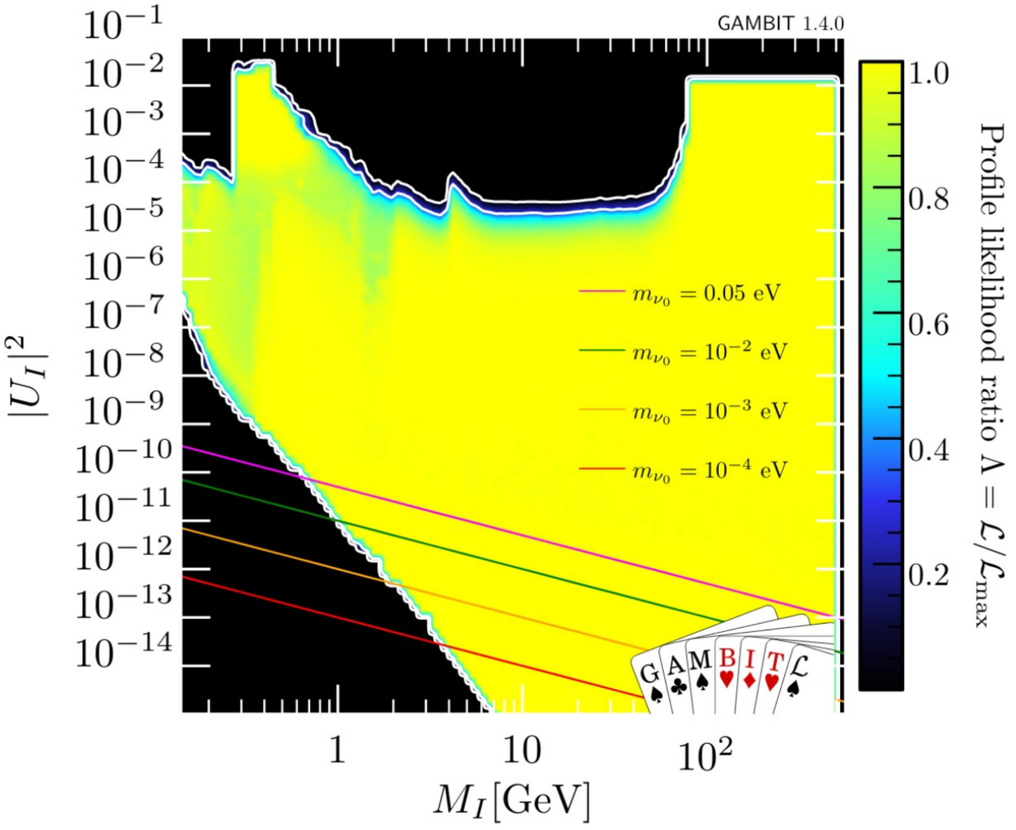


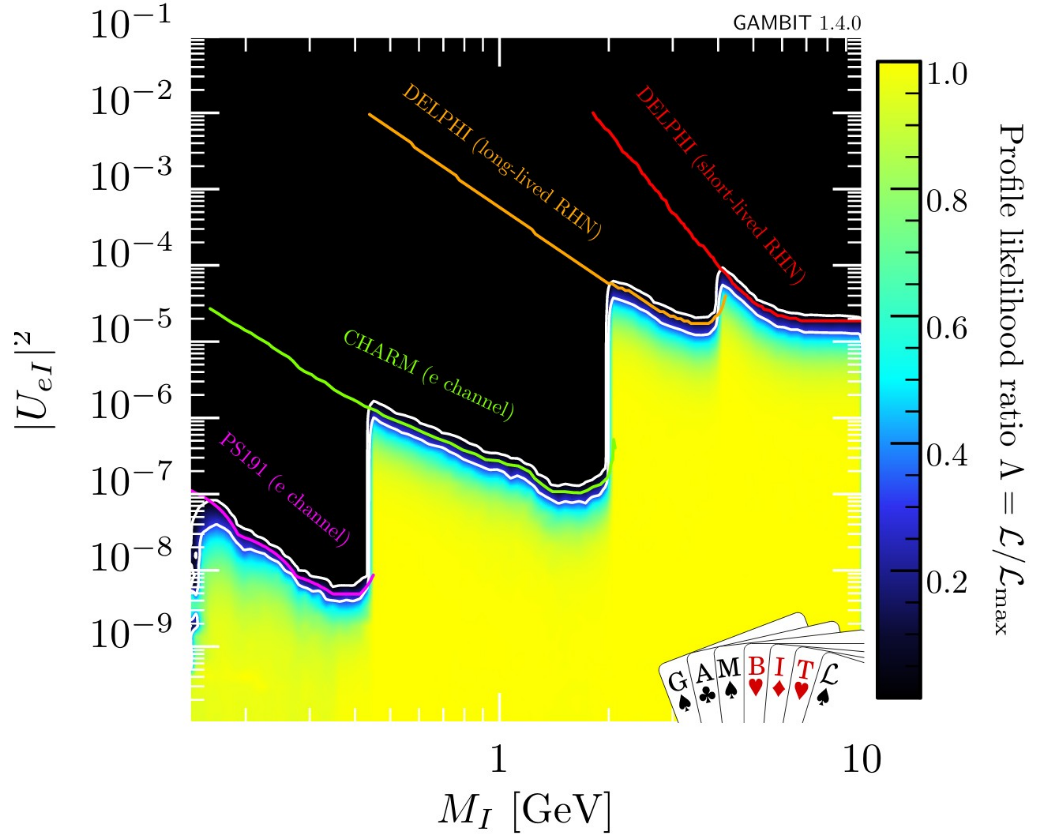
+ Sterile Neutrinos

Where are the right-handed neutrinos (not)?

GAMBIT: NeutrinoBit

M. Chrzaszcz, M. Drewes, T. Gonzalo,
JH, S. Krishnamurthy, C. Weniger (2019)





Most comprehensive analysis of see-saw I model with three right-handed neutrinos below the TeV scale

Lepton-Number Violation

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)}$$

$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

3/2 3/2 1 1

mass dimension

Lepton-Number Violation

- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

3/2 3/2 1 1

mass dimension

$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta}\epsilon_{\rho\sigma}$$

$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

$$\mathcal{O}_{8}^{(7)} = L^\alpha \bar{e}^c \bar{u}^c d^c H^\beta \epsilon_{\alpha\beta}$$

$$\mathcal{O}_{14b}^{(9)} = L^\alpha L^\beta \bar{Q}_\alpha \bar{u}^c Q^\rho d^c \epsilon_{\beta\rho}$$

$$\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}$$

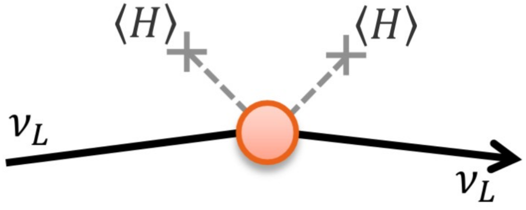
Babu, Leung (2001), de Gouvea, Jenkins (2007), Deppisch, Graf, JH, Huang (2017)

Neutrino mass generation

- LNV occurs only at odd mass dimension:

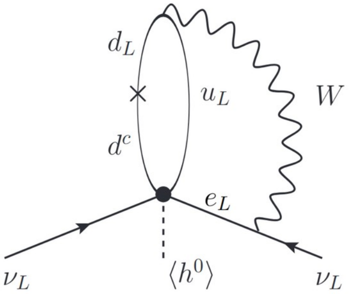
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

$$\boxed{\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}}$$

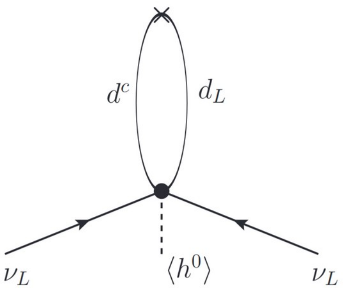


$$m_\nu \approx \frac{v^2}{\Lambda_1}$$

$$\boxed{\begin{aligned}\mathcal{O}_{3a}^{(7)} &= L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta}\epsilon_{\rho\sigma}\\ \mathcal{O}_{3b}^{(7)} &= L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}\end{aligned}}$$

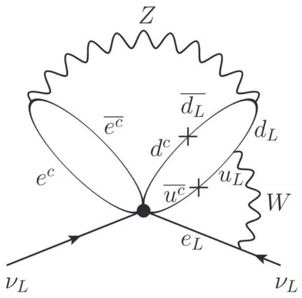


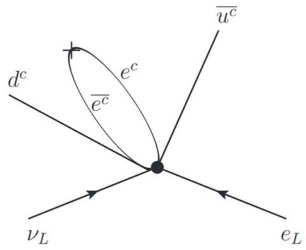
$$m_\nu \approx \frac{y_d g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda_{3a}}$$



$$m_\nu \approx \frac{y_d}{16\pi^2}\frac{v^2}{\Lambda_{3b}}$$

$$\boxed{\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}}$$





$$m_\nu \approx \frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda_{16}}$$

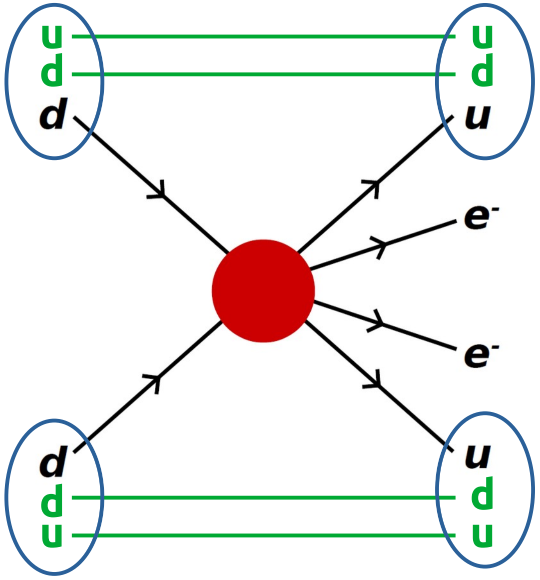
$$L^\alpha = \begin{pmatrix}\nu_L\\ e_L\end{pmatrix}^\alpha,\quad Q^\alpha = \begin{pmatrix}u_L\\ d_L\end{pmatrix}^\alpha,\quad H = \begin{pmatrix}h^+\\ h^0\end{pmatrix}$$

$$e^c_\alpha,\ u^c_\alpha,\ d^c_\alpha$$

Deppisch, Graf, JH, Huang (2017)
de Gouvea, Jenkins (2007)

Probing LNV interactions – 0νββ decay

Neutrinoless double beta decay



Most stringent limits are currently set by GERDA and Kamland-Zen:

$$T_{1/2}^{\mathrm{Ge}} \geq 0.9 \times 10^{26}\ \mathrm{y} \qquad T_{1/2}^{\mathrm{Xe}} \geq 1.07 \times 10^{26}\ \mathrm{y}$$

$$\boxed{T_{1/2}^{-1} = \mid m_{\beta\beta} \mid^2 G^{0\nu} \mid M^{0\nu} \mid^2}$$

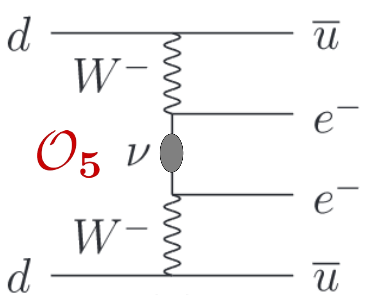
nuclear matrix element

particle physics

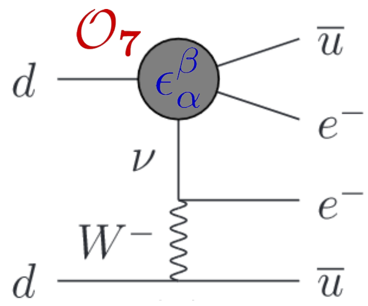
phase space factor

$\overset{?}{=}$

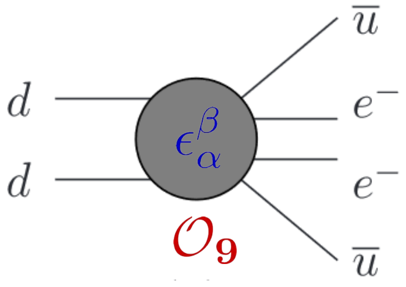
standard mass mechanism



long range contribution

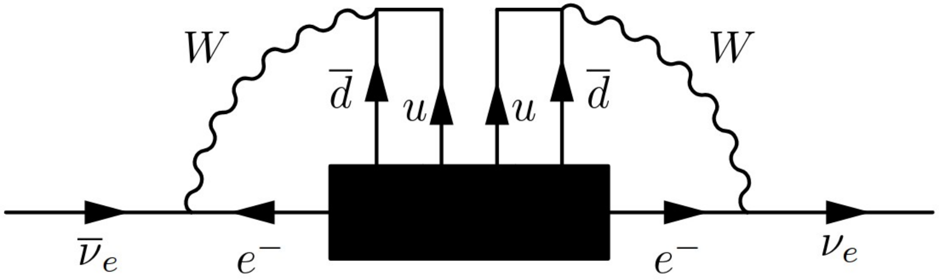


short range contribution



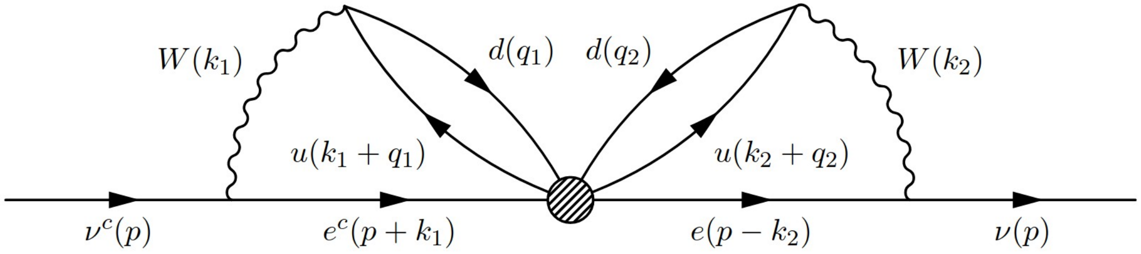
0νββ decay probes only first generation!

Does 0νββ decay directly imply Majorana neutrinos?



Schechter, Valle (1982)

Any ΔL = 2 operator that leads to 0vbb will induce a **Majorana mass contribution** via loop



Dürr, Merle, Lindner (2011)

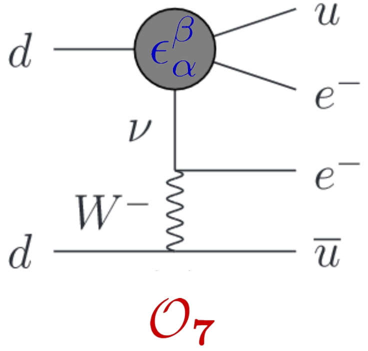
9-dim ΔL = 2 operator will lead to 0vbb but only **tiny contribution** to neutrino mass

$$\delta m_\nu = 10^{-28}\text{eV}$$

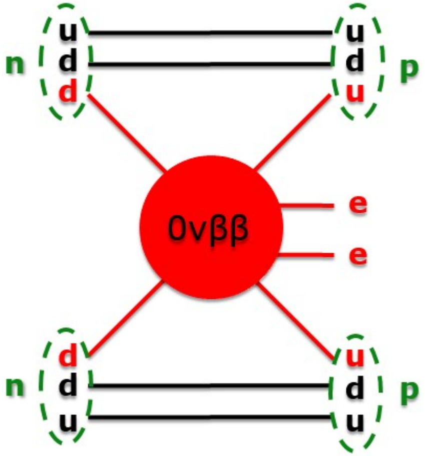
Observation of 0νββ decay does not imply that the mass mechanism is the dominant contribution.

Probing LNV interactions – 0νββ decay

long range contribution

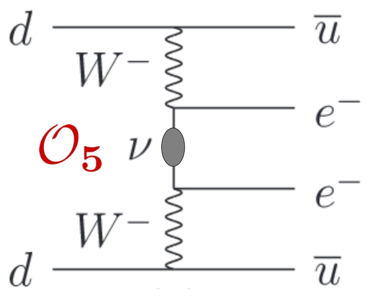


$\overset{?}{=}$



$\overset{?}{=}$

standard mass mechanism



$$\boxed{T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2}$$

$$\boxed{T_{1/2}^{-1} = G_{0\nu}\mid \mathcal{M}\mid^2\mid m_{\beta\beta}\mid^2}$$

Leptonic and hadronic current with different chirality structure:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\{j^\mu_{V-A}J^\dagger_{V-A,\mu} + \sum_{\alpha,\beta}\epsilon_\alpha^\beta j_\beta J_\alpha^\dagger\}$$

$$j_\beta = \bar{e}\mathcal{O}_\beta\nu$$

$$J_\alpha^\dagger = \bar{u}\mathcal{O}_\alpha d$$

$$\mathcal{O}_{V\pm A} = \gamma^\mu(1\pm\gamma_5)$$

$$\mathcal{O}_{S\pm P} = (1\pm\gamma_5)$$

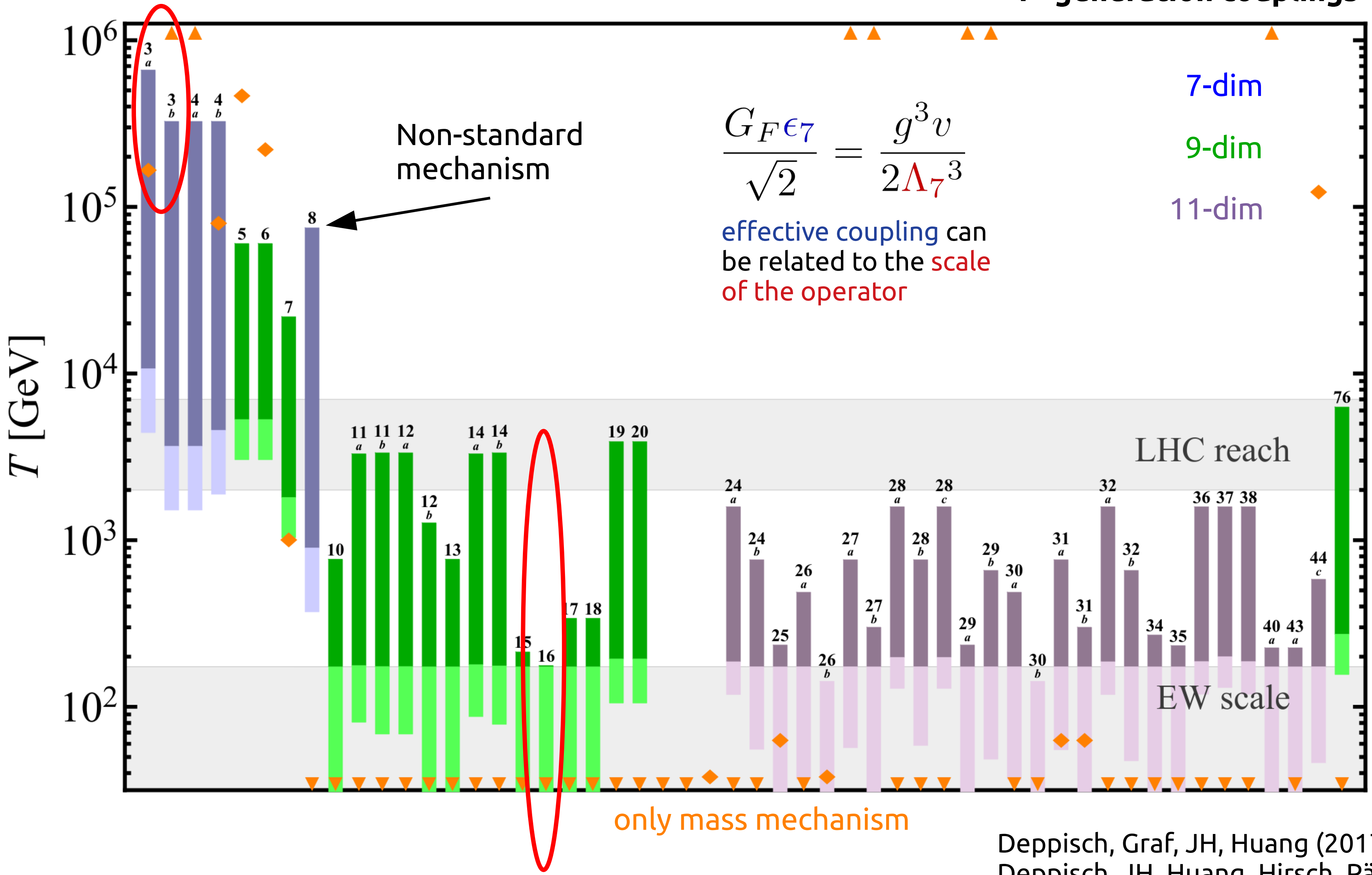
$$\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_\mu,\gamma_\nu](1\pm\gamma_5)$$

$\lvert\epsilon\rvert\times 10^8$	ϵ_ν	ϵ^{V+A}_{V-A}	ϵ^{V+A}_{V+A}	$\epsilon^{S+P}_{S\pm P}$	$\epsilon^{T_R}_{T_R}$
^{76}Ge	41	0.21	37	0.66	0.07
^{76}Xe	26	0.11	22	0.26	0.03

Deppisch, Hirsch, Päs (2012)

Scales of LNV New Physics

1^{st} generation couplings



Non-standard mechanism

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2\Lambda_7{}^3}$$

effective coupling can be related to the scale of the operator

7-dim

9-dim

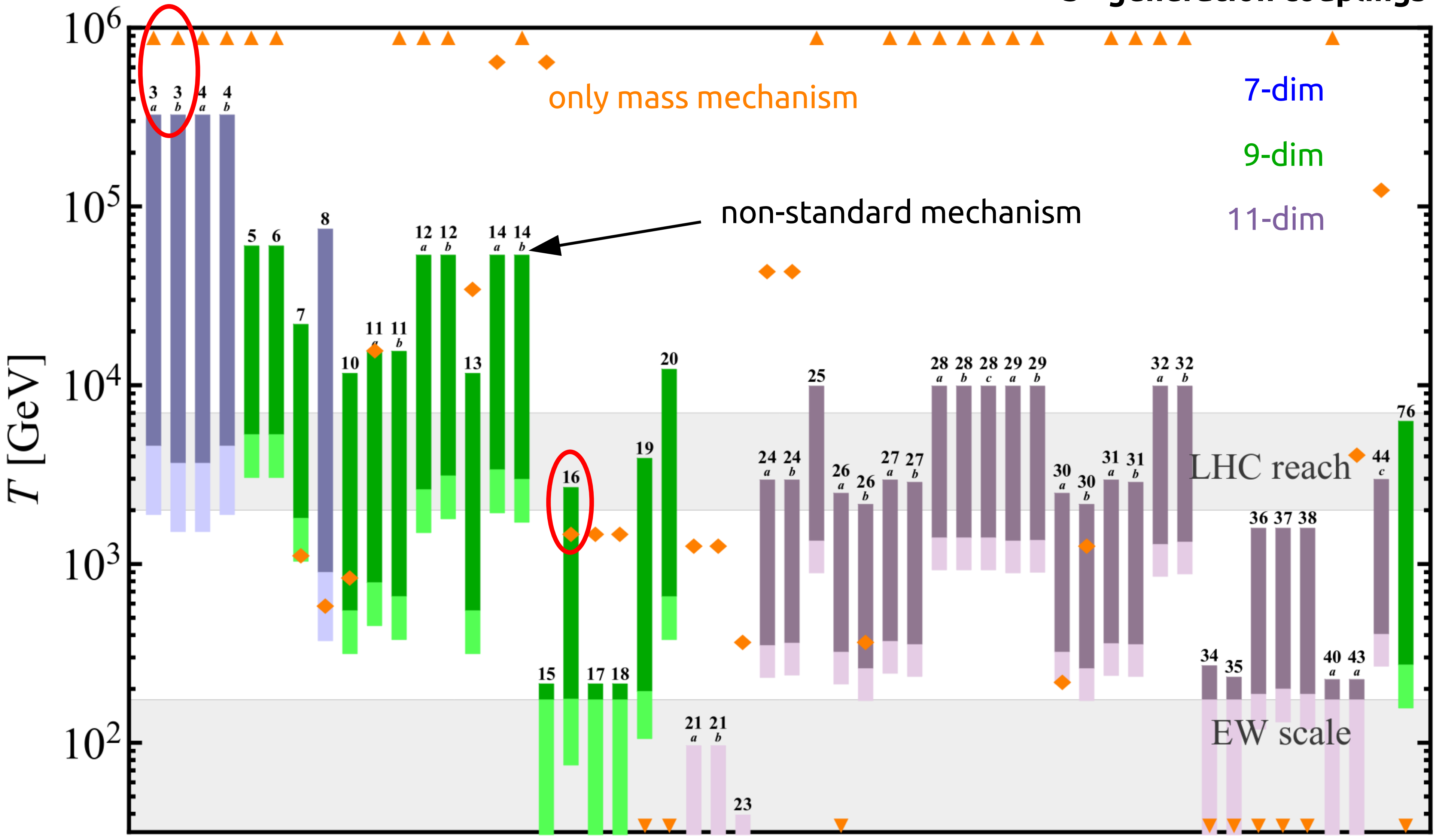
11-dim ◆

only mass mechanism

Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Scales of LNV New Physics

3rd generation couplings



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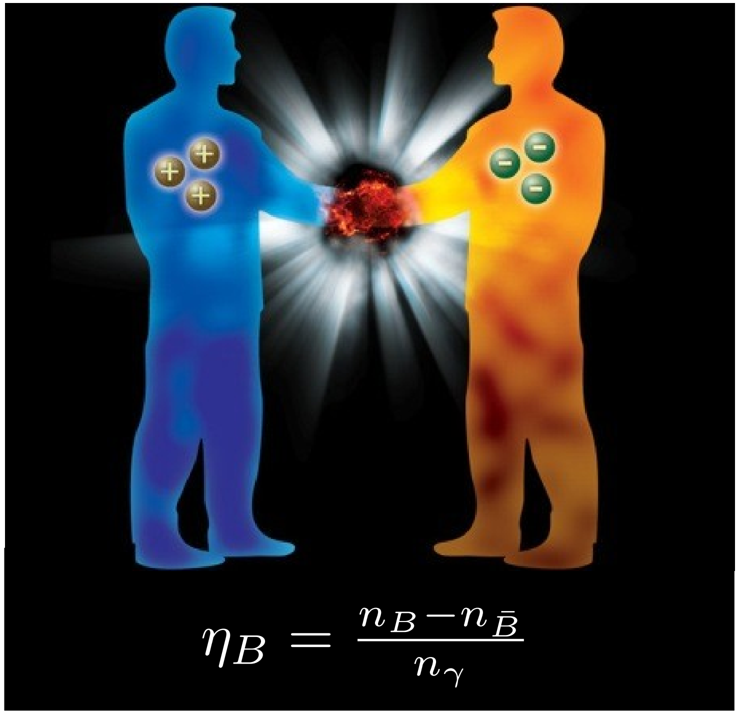
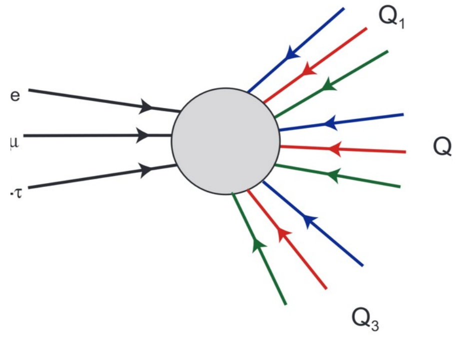


$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

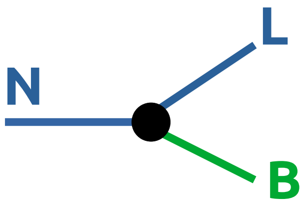
Baryon Asymmetry.

Why do we need new physics?

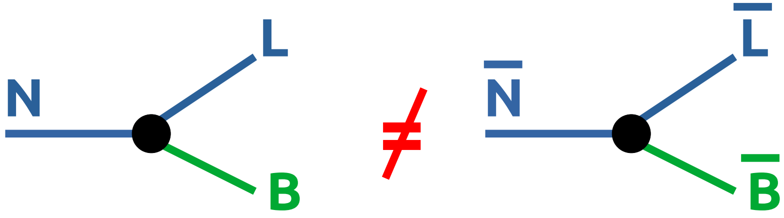
Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).



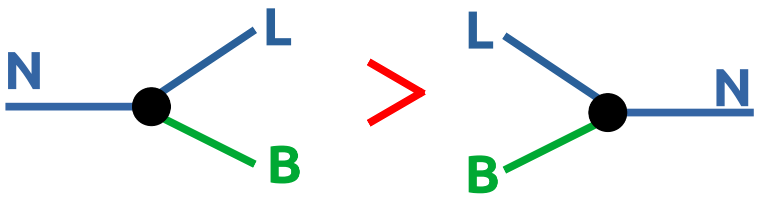
☐ baryon number violation



☐ C and CP violation



☐ departure from thermal equilibrium



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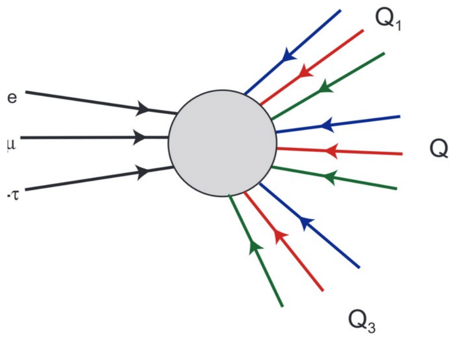
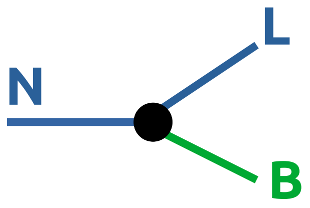


Standard Model?

☑ baryon number violation



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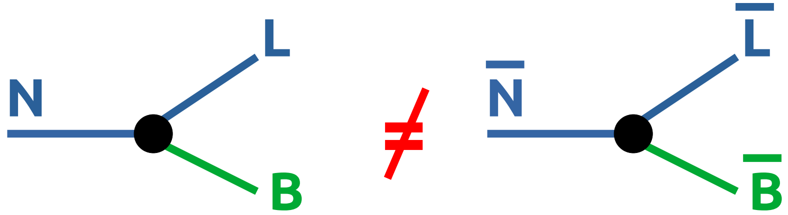
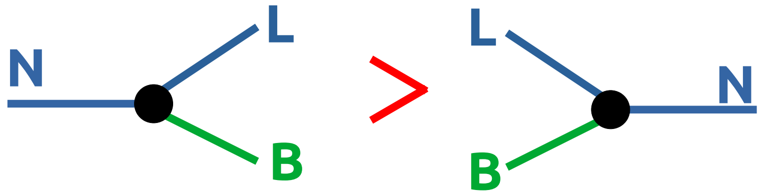


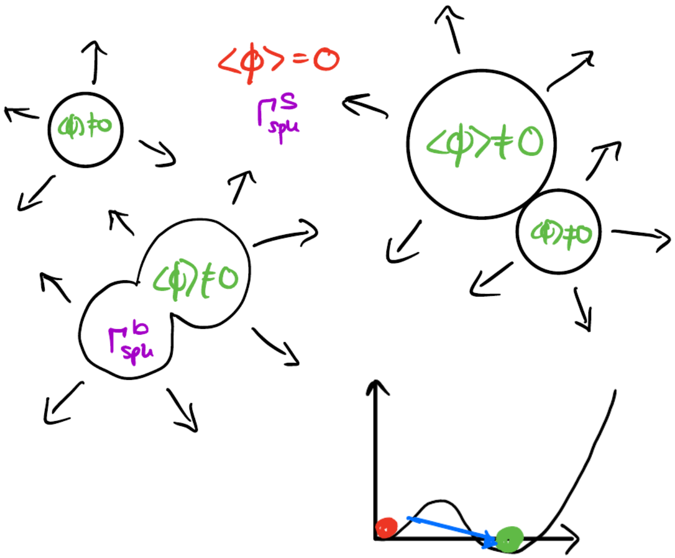
☒ departure from thermal equilibrium

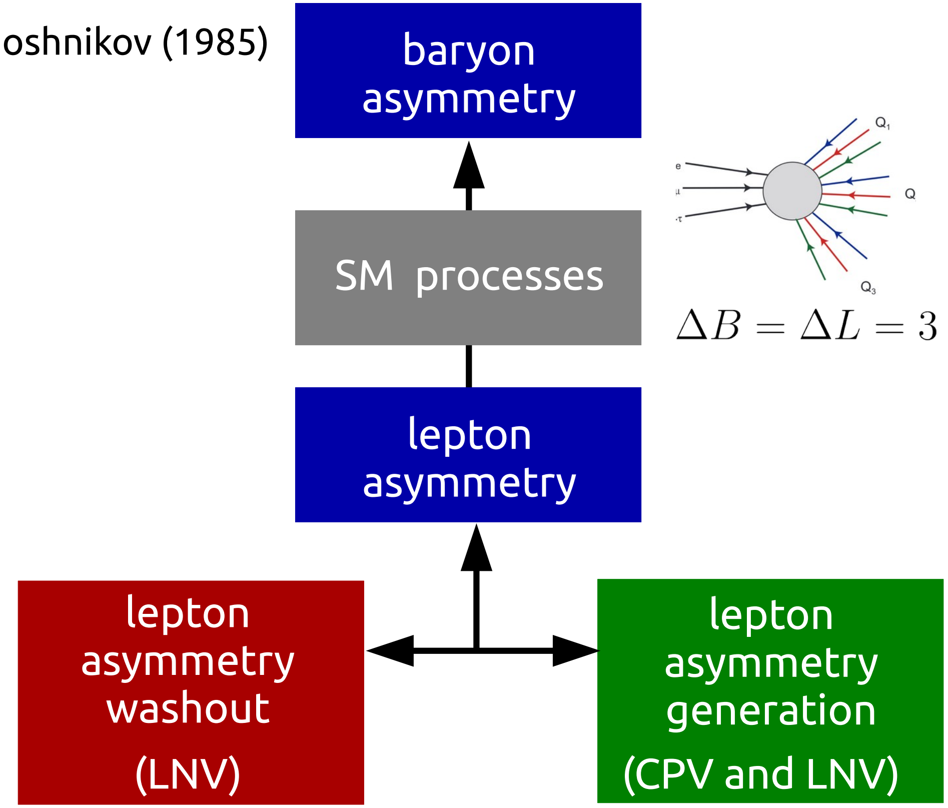


There has to be new physics in order to explain our own existence!

Many theoretical models and ideas...

- **Electroweak Baryogenesis** Kuzmin, Rubakov, Shasposhnikov (1985)
- **Affleck-Dine Baryogenesis** Affleck, Dine (1985)
- **Spontanous Baryogenesis** Kohen, Kaplan (1987)
- **GUT Baryogenesis** Youshimura (1978), Barr (1979), Toussaint et al. (1979), Dimopoulos, Susskind (1978)
- **Leptogenesis** Fukugita-Yanagida (1986)
- **and many new ones!**





baryon asymmetry

SM processes

$\Delta B = \Delta L = 3$

lepton asymmetry

lepton asymmetry washout

(LNV)

lepton asymmetry generation

(CPV and LNV)

Which mechanism is realised in nature?

Many theoretical models and ideas...

- **Electroweak Baryogenesis** Kuzmin, Rubakov, Shasposhnikov (1985)
- **Affleck-Dine Baryogenesis** Affleck, Dine (1985)
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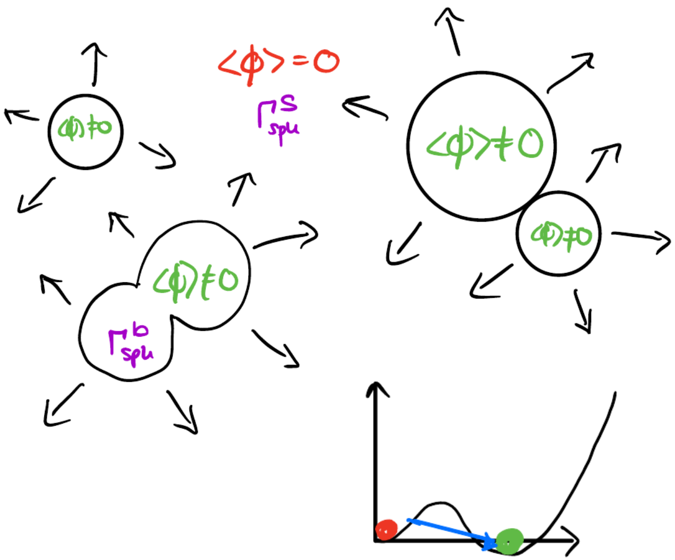

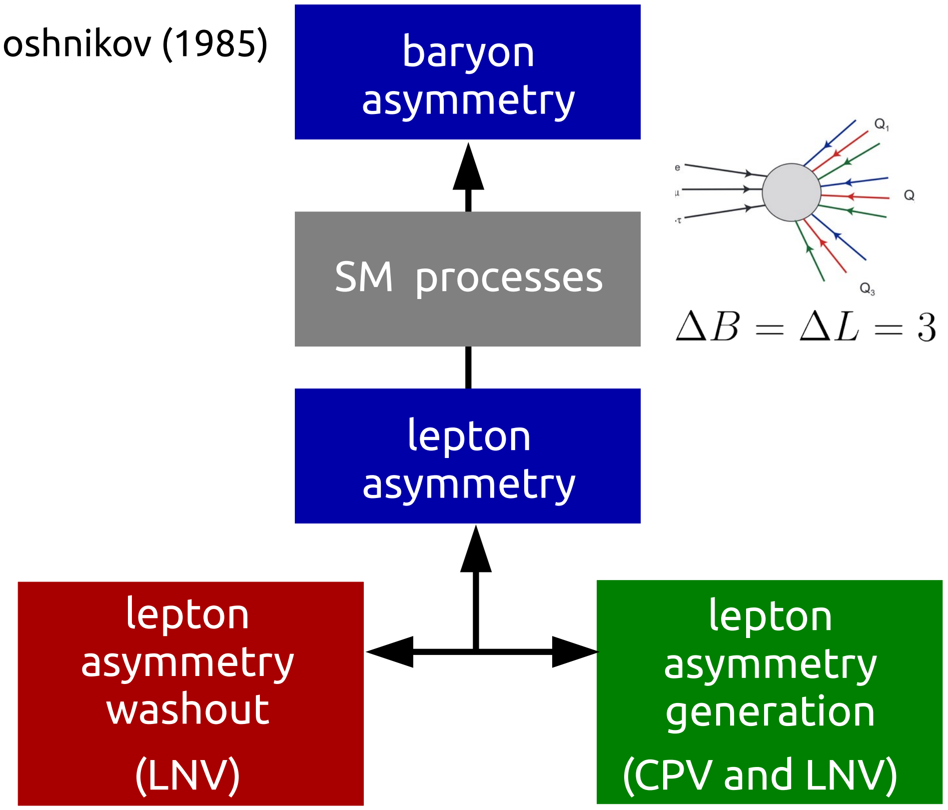
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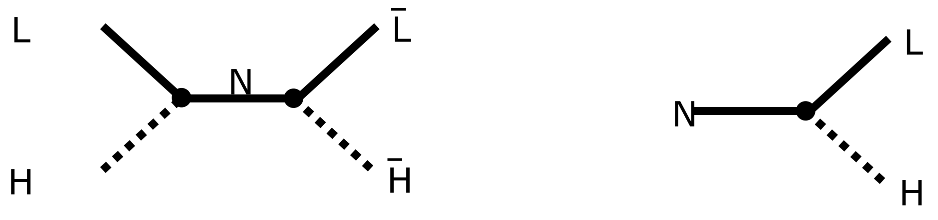


Probing Leptogenesis at the high scale

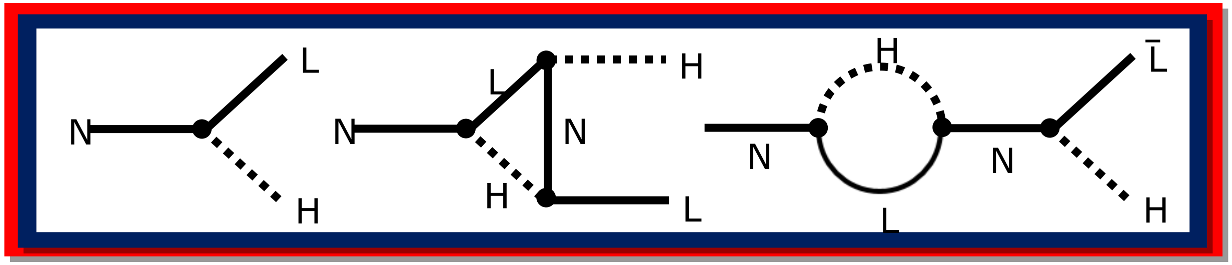
- generation of lepton asymmetry via **heavy neutrino decays**
- competition with lepton number violating (LNV) **washout processes**
- conversion to baryon asymmetry via **sphaleron processes** at

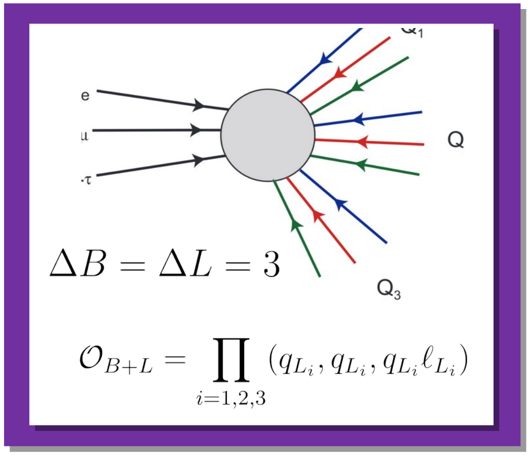
Fukugita et al. 1986

$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\mathrm{eq}})$$

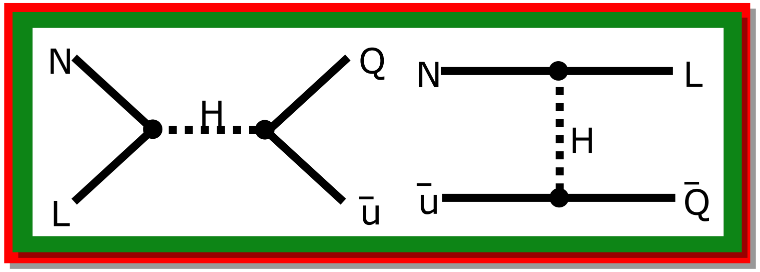
$$Hz\frac{dN_L}{dz} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{\mathrm{eq}}) - \Gamma_W N_L$$

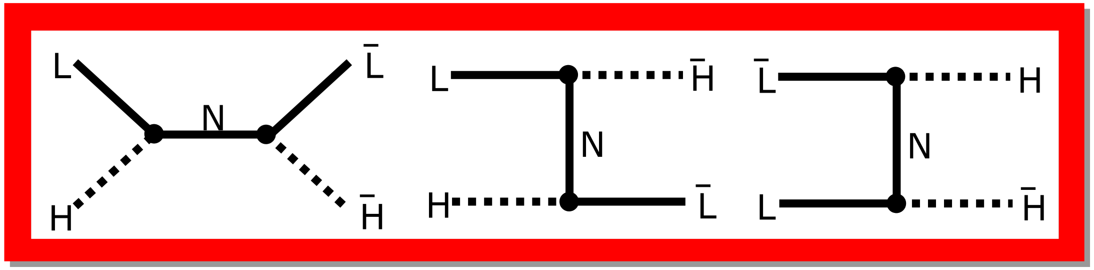
$\Delta L = 1$ **source of CP violation**





sphaleron processes





$\Delta L = 2$ **scattering processes** $\Delta L = 2$ **washout processes**

Probing Leptogenesis at the high scale

Small neutrino masses and washout pushes the right-handed neutrino to high scales.

$$M_N \gtrsim 10^8 \left(\frac{\eta_B}{5 \times 10^{-11}}\right) \left(\frac{0.06\mathrm{eV}}{m_3}\right) \mathrm{GeV}$$

Ways out: almost degenerate particles, late decays, massive decay (annihilation) products

review by Racker 2016

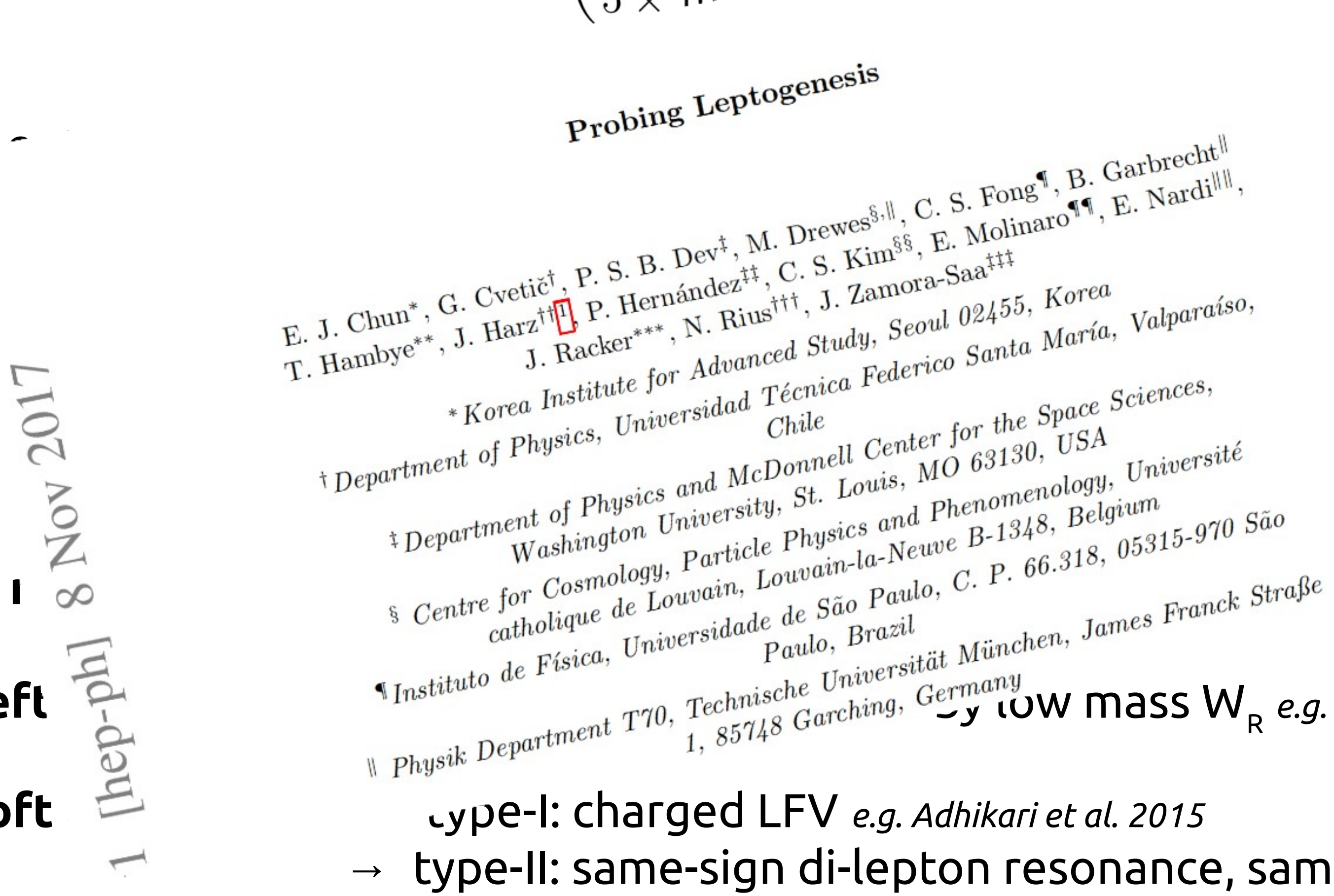
Plethora of examples:

- Extension of **seesaw type-I** by **new scalars** with same quantum numbers as SM fermions → e.g. long-lived scalars, R-hadrons, heavy sterile neutrinos *e.g. Fong et al. 2013*
- **Z' models** → same-sign di-lepton final states *e.g. Chun 2005*
- **Left-right symmetric models** → falsification by low mass W_R *e.g. Dev. et al. 2015*
- **Soft leptogenesis** → type-I: charged LFV *e.g. Adhikari et al. 2015*
  → type-II: same-sign di-lepton resonance, same-sign tetra-leptons
  e.g. Chun et al. 2006

Probing Leptogenesis at the high scale

Small neutrino masses and washout pushes the right-handed neutrino to high scales.

$$M_N \gtrsim 10^8 \left(\frac{\eta_B}{5 \times 10^{-11}}\right) \left(0.06\text{eV}\right.$$



Probing Leptogenesis

E. J. Chun[*], G. Cvetič[†], P. S. B. Dev[‡], M. Drewes[§,‖], C. S. Fong[¶], B. Garbrecht[‖]
T. Hambye[**], J. Harz[††], P. Hernández[‡‡], C. S. Kim[§§], E. Molinaro[¶¶], E. Nardi[‖‖],
J. Racker[***], N. Rius[†††], J. Zamora-Saa[‡‡‡]

[*] *Korea Institute for Advanced Study, Seoul 02455, Korea*

[†] *Department of Physics, Universidad Técnica Federico Santa María, Valparaíso, Chile*

[‡] *Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130, USA*

[§] *Centre for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, Louvain-la-Neuve B-1348, Belgium*

[¶] *Instituto de Física, Universidade de São Paulo, C. P. 66.318, 05315-970 São Paulo, Brazil*

[‖] *Physik Department T70, Technische Universität München, James Franck Straße 1, 85748 Garching, Germany*

1 [hep-ph] 8 Nov 2017

Ways … on) products

by Racker 2016

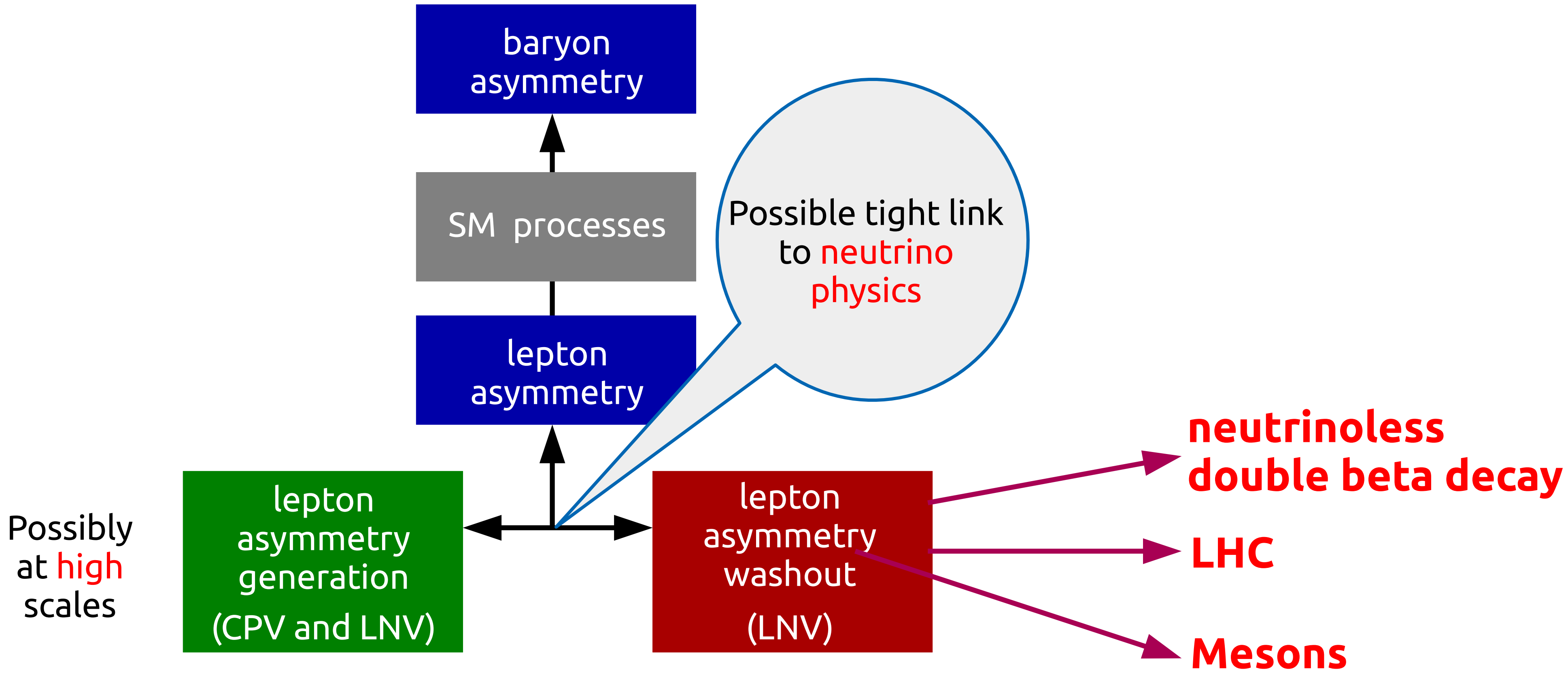
Plet

- E… fe… M *al. 2013*
- **Z'**
- **Left** … low mass W_R *e.g. Dev. et al. 2015*
- **Soft** … type-I: charged LFV *e.g. Adhikari et al. 2015*

→ type-II: same-sign di-lepton resonance, same-sign tetra-leptons *e.g. Chun et al. 2006*

LNV as a probe of baryogenesis models

The generation of a baryon asymmetry – baryogenesis – can be created by a lepton asymmetry – leptogenesis:



baryon asymmetry

SM processes

lepton asymmetry

Possible tight link to neutrino physics

Possibly at high scales

lepton asymmetry generation (CPV and LNV)

lepton asymmetry washout (LNV)

neutrinoless double beta decay

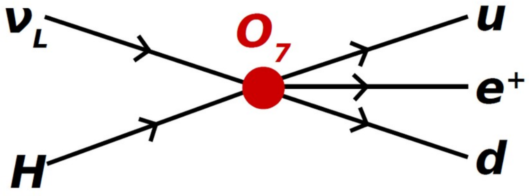
LHC

Mesons

In turn, lepton number violation (LNV) can destroy a lepton asymmetry, and thus even a baryon asymmetry!

Lepton Asymmetry Washout

- LNV operator would cause washout of **pre-existing** net lepton asymmetry in the early Universe



$$\mathcal{O}_7 = (L^i d^c)(\bar{e}^c \bar{u}^c) H^j \epsilon_{ij}$$

$$zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} = -\left(\frac{n_{L_e} n_{\bar{e}^c}}{n^{\text{eq}}_{L_e} n^{\text{eq}}_{\bar{e}^c}} - \frac{n_{u^c} n_{\bar{d}^c} n_{\bar{H}}}{n^{\text{eq}}_{u^c} n^{\text{eq}}_{\bar{d}^c} n^{\text{eq}}_{\bar{H}}}\right) \gamma^{\text{eq}}(L_e \bar{e}^c \to u^c \bar{d}^c \bar{H})$$

$$zHn_\gamma \frac{d\eta_{\Delta L_e}}{dz} = -c_D \frac{T^{2D-4}}{{\Lambda_D}^{2D-8}} \eta_{\Delta L_e}$$

$$\gamma^{eq} \propto \frac{T^{2D-4}}{{\Lambda_D}^{2D-8}}$$

c_D operator specific factor

η_L lepton density

- **washout efficient if**

$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H} \frac{T^{2D-4}}{{\Lambda_D}^{2D-8}} = c'_D \frac{\Lambda_{\text{Pl}}}{\Lambda_D} \left(\frac{T}{\Lambda_D}\right)^{2D-9} > 1$$

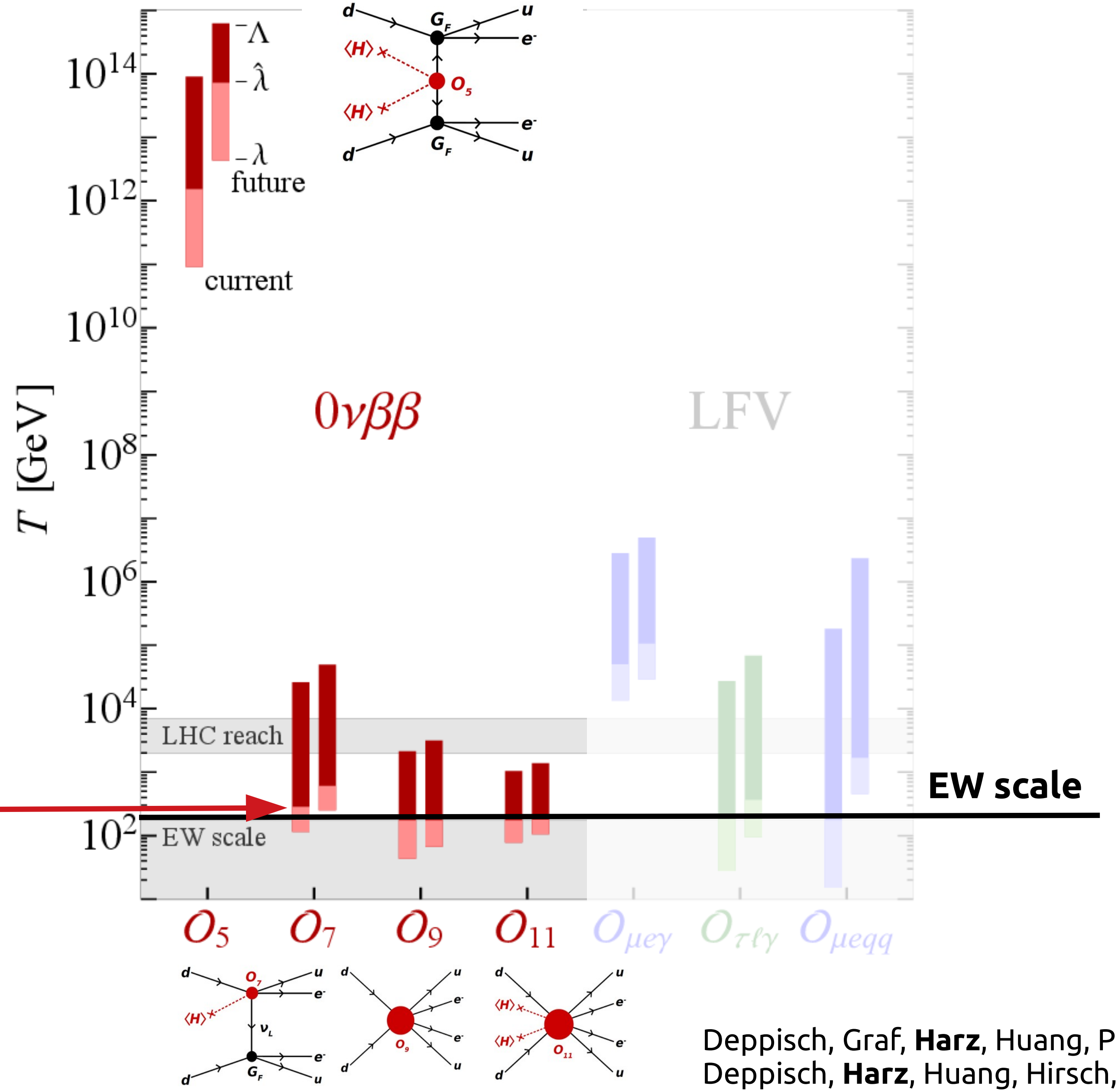
If 0νßß is observed, washout efficient in the temperature interval

$$\Lambda_D \left(\frac{\Lambda_D}{c'_D \Lambda_{\text{Pl}}}\right)^{\frac{1}{2D-9}} \equiv \lambda_D < T < \Lambda_D$$

Falsifying Baryogenesis with 0νββ

scale above which high-scale baryogenesis can be excluded

$$\frac{\Gamma_W}{H} > 1$$



Deppisch, Graf, **Harz**, Huang, Phys. Rev. D98 (2018)
Deppisch, **Harz**, Huang, Hirsch, Päs, Phys. Rev. D92 (2015)

Falsifying Baryogenesis with 0νββ

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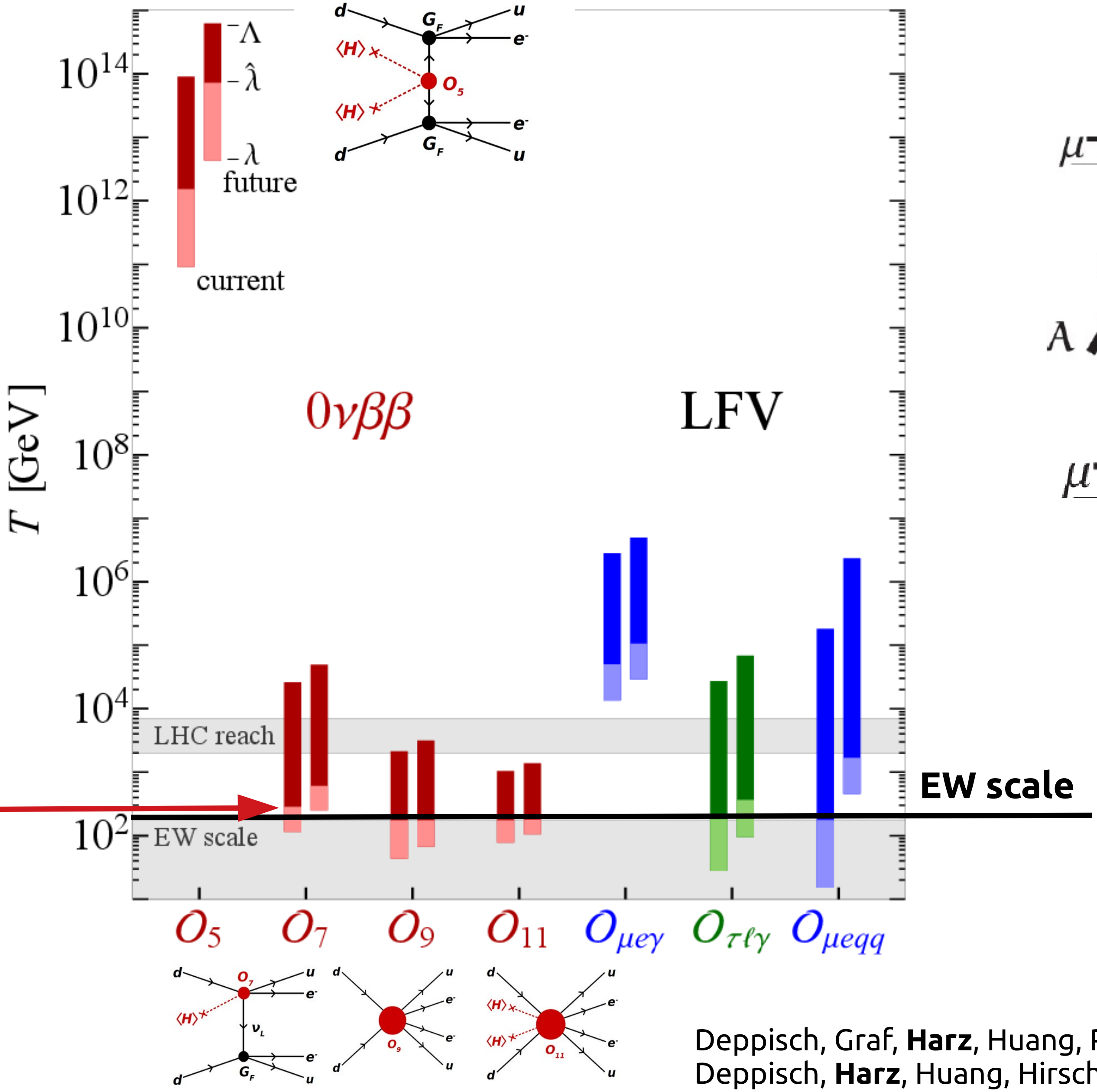
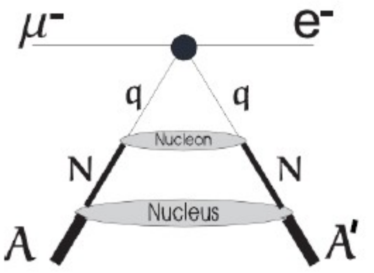
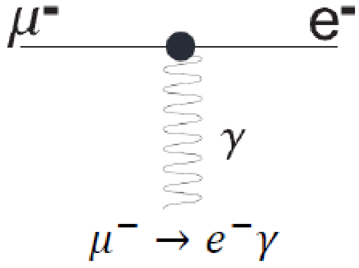


EW scale



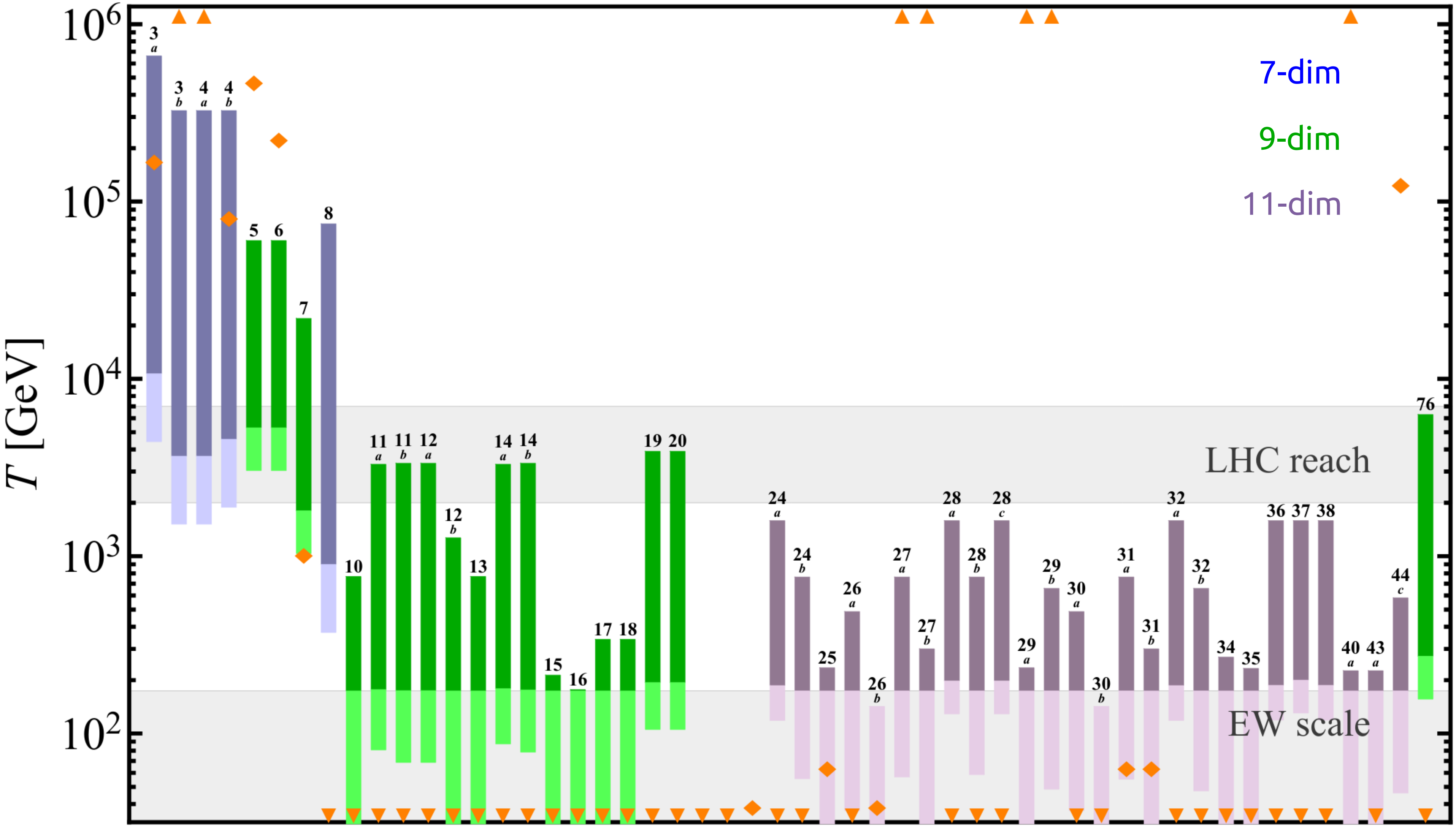


$\mu^- \rightarrow e^-\gamma$

Deppisch, Graf, **Harz**, Huang, Phys. Rev. D98 (2018)
Deppisch, **Harz**, Huang, Hirsch, Päs, Phys. Rev. D92 (2015)

Lepton asymmetry washout

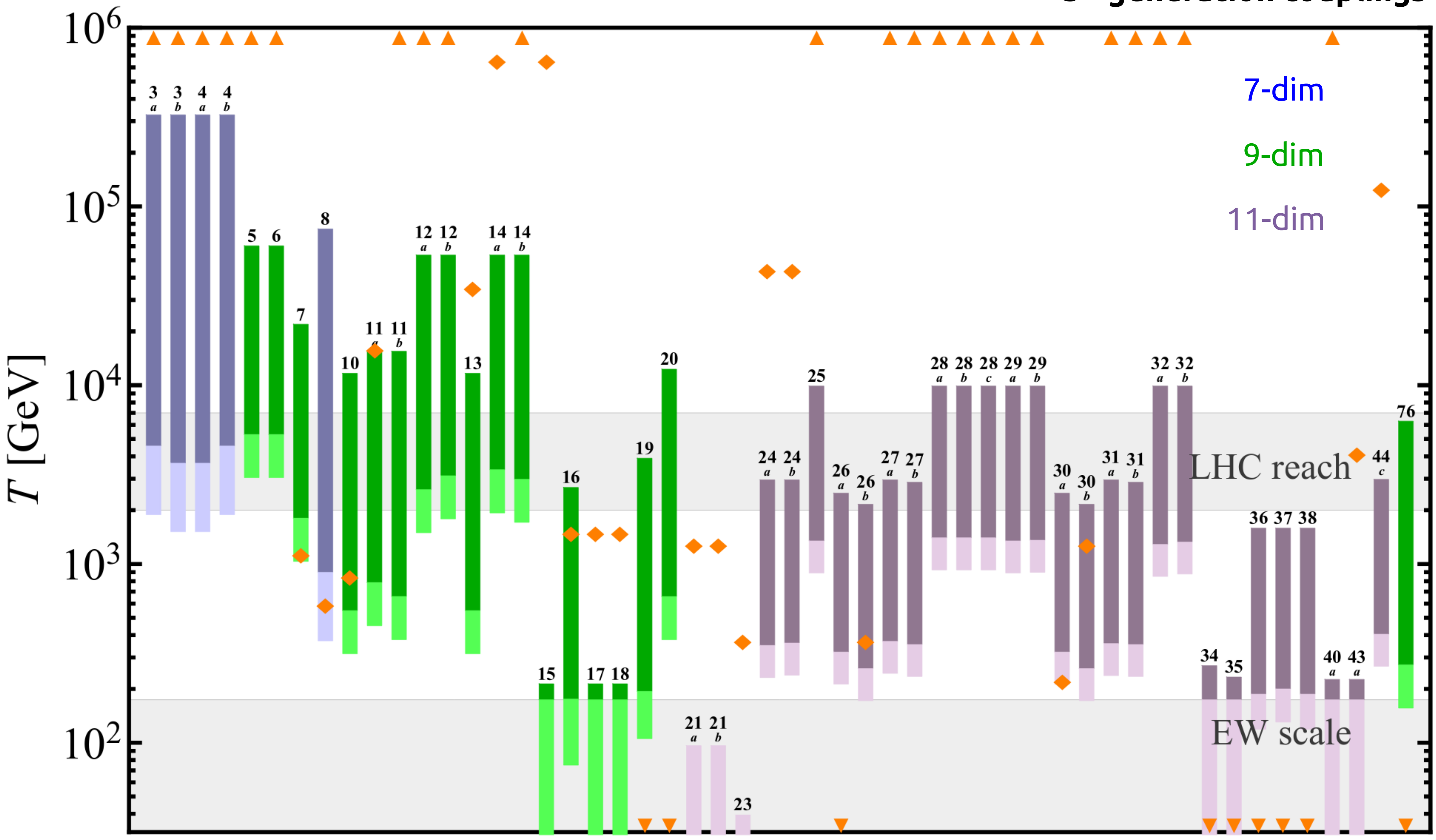
1st generation couplings



Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Lepton asymmetry washout

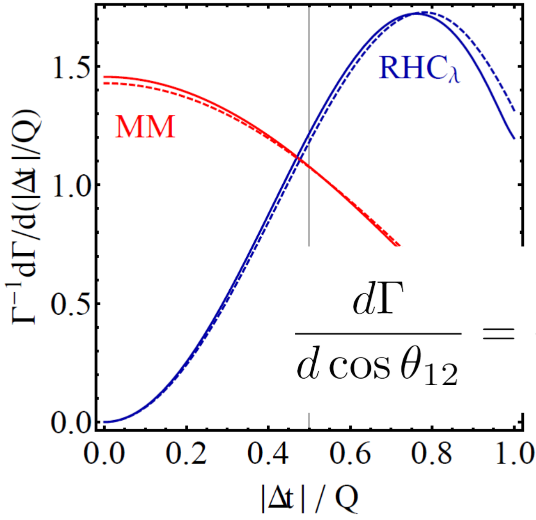
3rd generation couplings



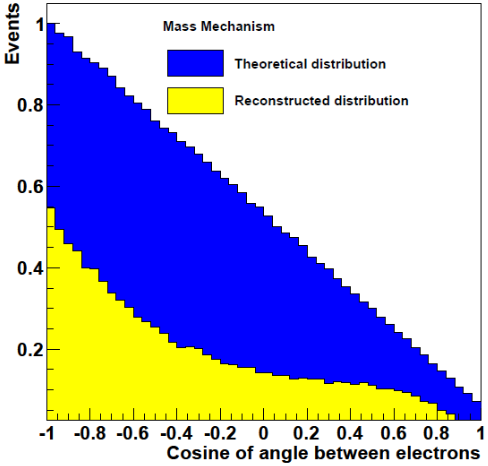
Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

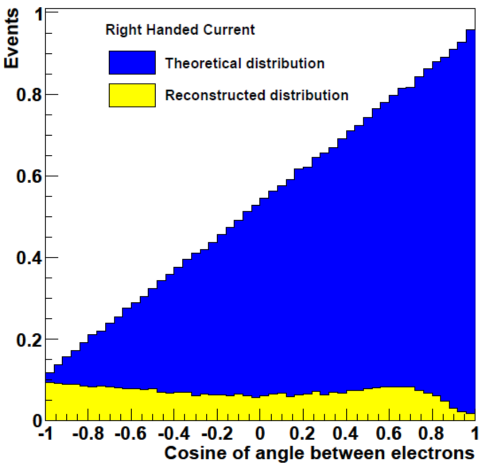
Distinguishing between different operators

- **SuperNEMO** will be able to discriminate O_7 from others, due to e^-_R and e^+_L in the final state



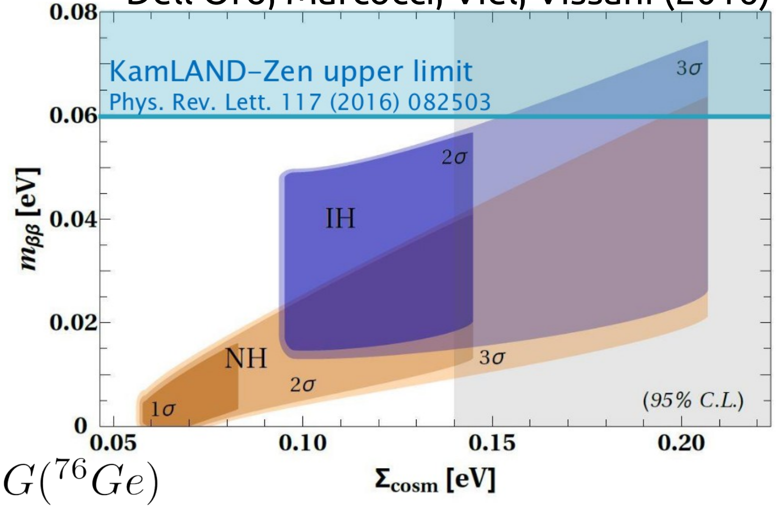
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$



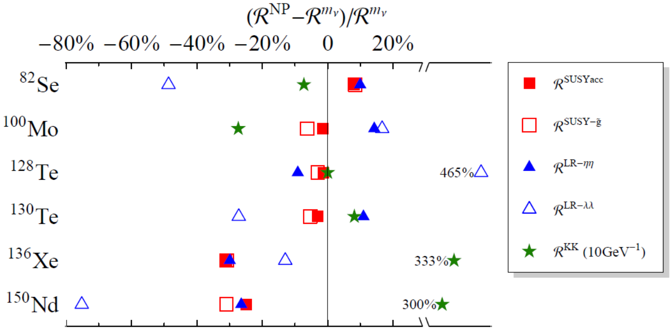


- **discrepancy between sum of neutrino masses from cosmology and 0vbb half live measurements** could indicate non-standard mechanism

Dell’Oro, Marcocci, Viel, Vissani (2016)



- distinguishing between different mechanisms via measurements in **different isotopes**

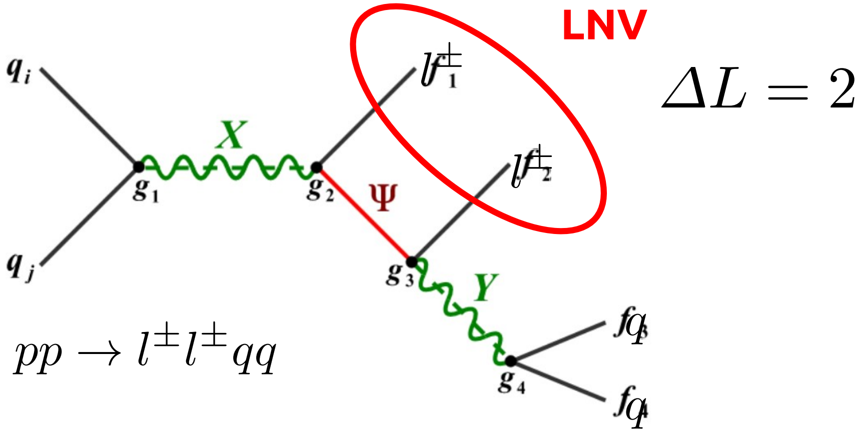


$$\frac{T_{1/2}(^AX)}{T_{1/2}(^AX)}) = \frac{|\mathcal{M}(^{76}Ge)|^2 G(^{76}Ge)}{|\mathcal{M}(^AX)|^2 G(^AX)}$$

- observation of $0\nu\beta\beta$ via O_9 and O_{11} will imply observation of **LNV at LHC**

Falsifying Baryogenesis with the LHC

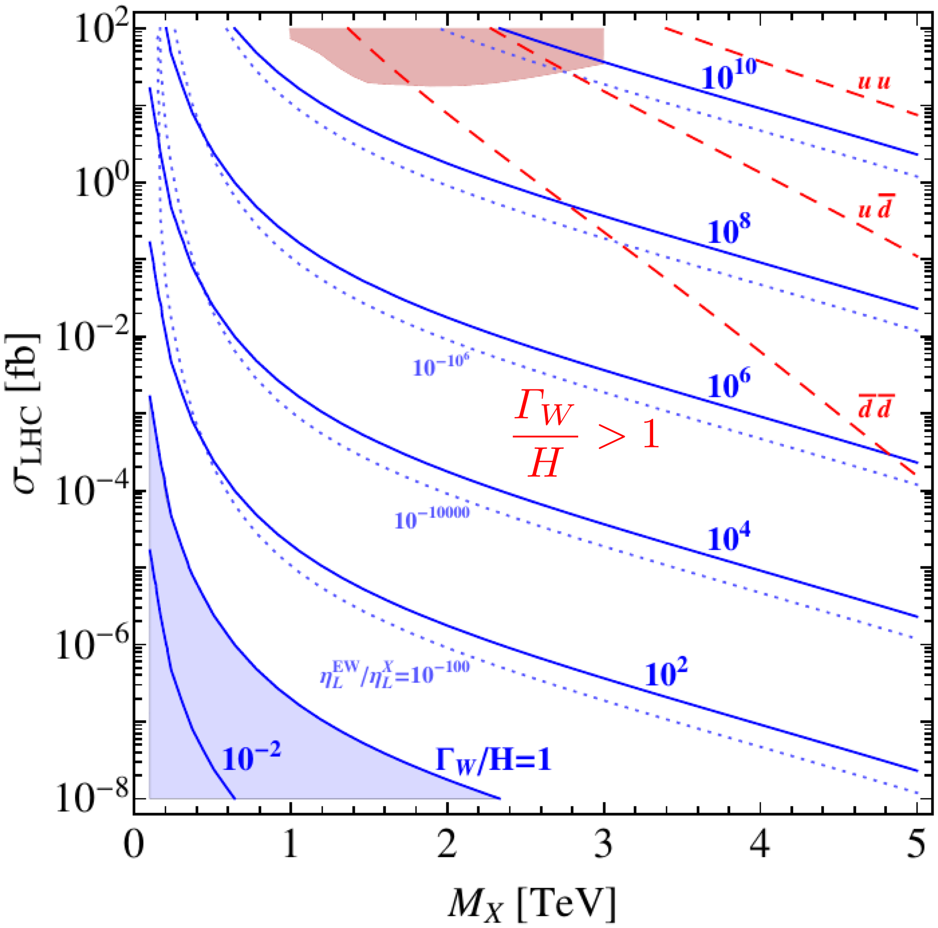
Washout processes could be observable at the LHC



$pp \to l^\pm l^\pm qq$

Large washout, if $\frac{\Gamma_W}{H} > 1$.

$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\text{LHC}}}{\text{fb}}$$

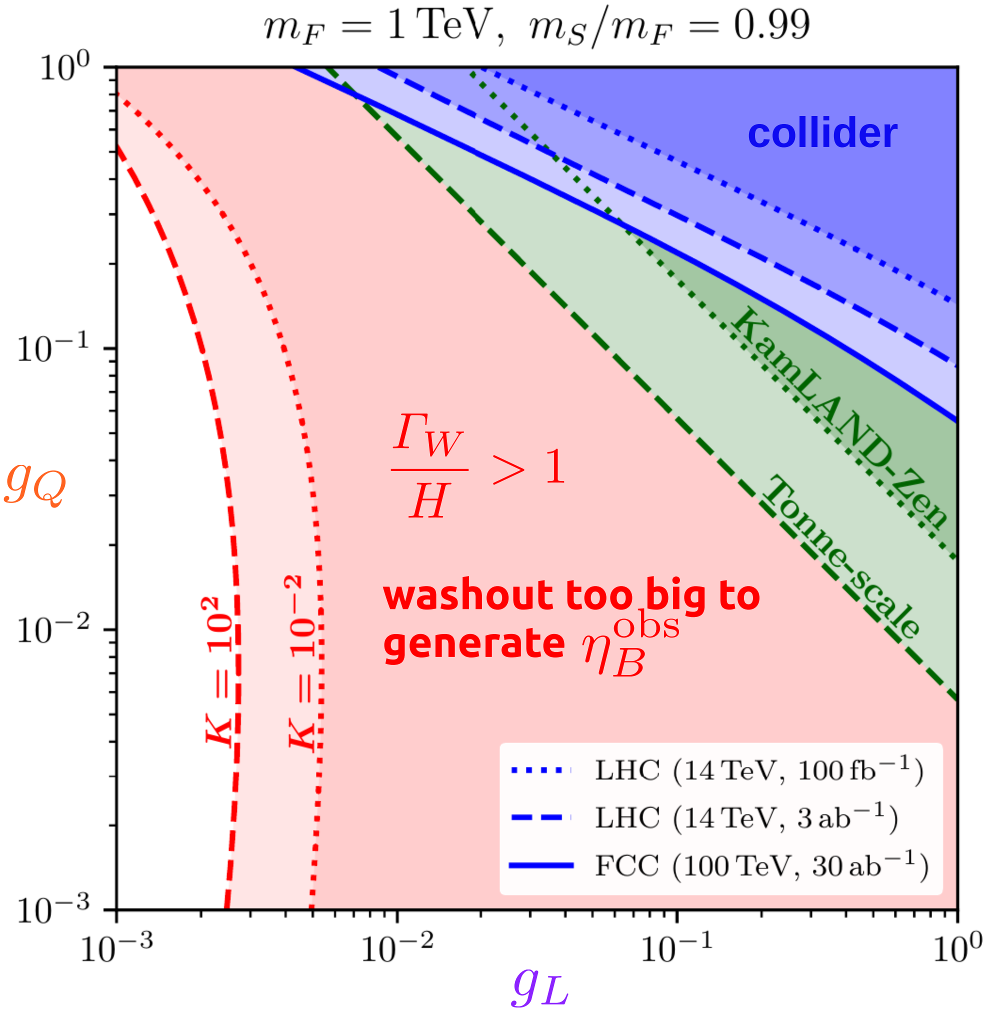


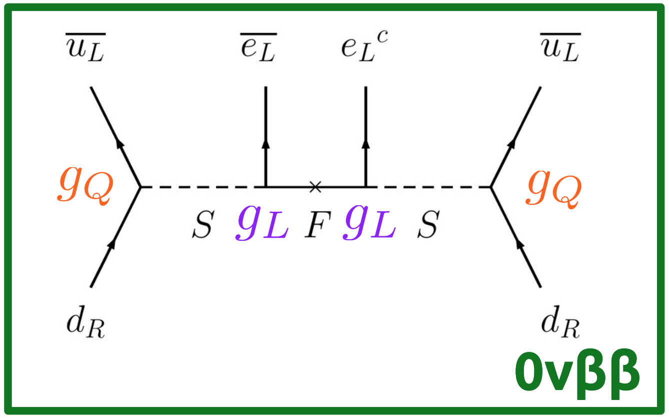
Observation of any washout process at the LHC would falsify high scale baryogenesis!

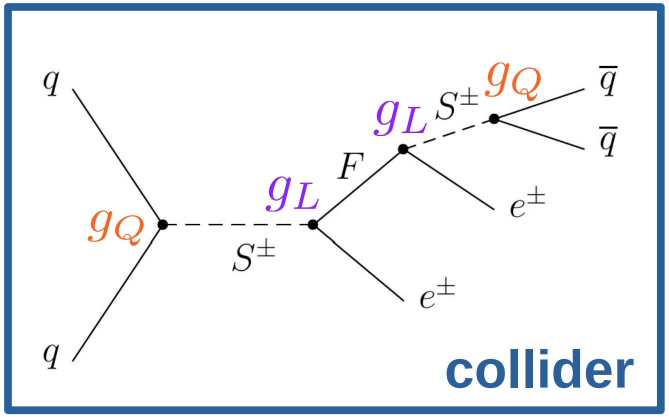
Deppisch, **Harz**, Hirsch, Phys. Rev. Lett. (2014)
Deppisch, **Harz**, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

Combining LHC & 0νββ

$$\mathcal{L} = g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2}\overline{F^c}F + g_S (S^\dagger S)^2 + \lambda_{HS}(S^\dagger H)^2 + \text{h.c.}$$



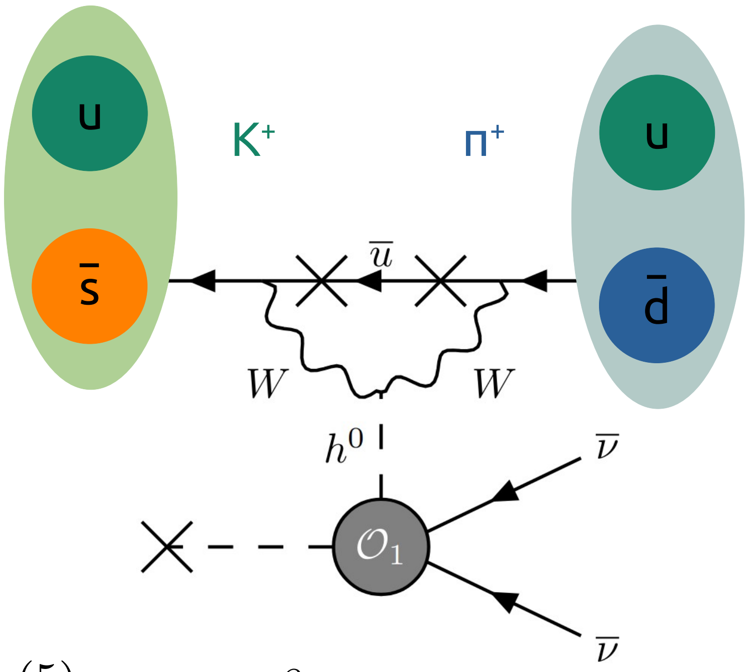




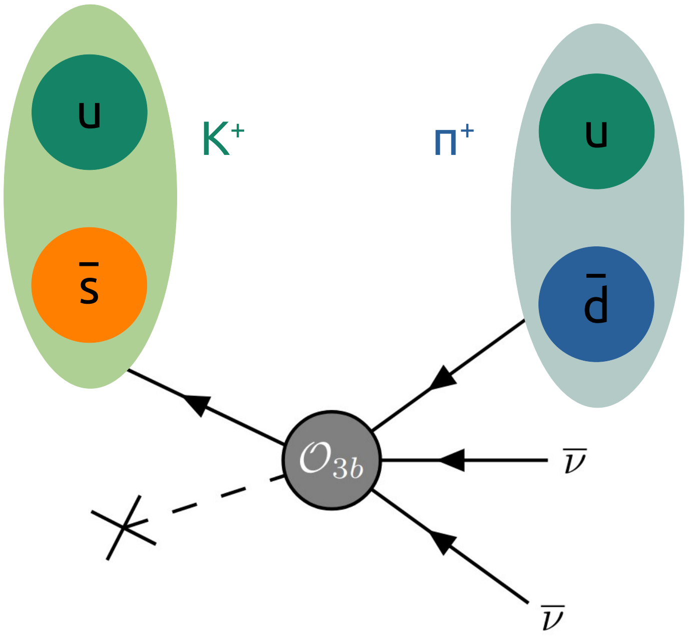
Comprehensive analysis confirms EFT results and shows interesting interplay between collider and 0νββ reach.

JH, Ramsey-Musolf, Shen, Urrutia, in preparation

Constraining LNV interactions with rare kaon decays



$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$



$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

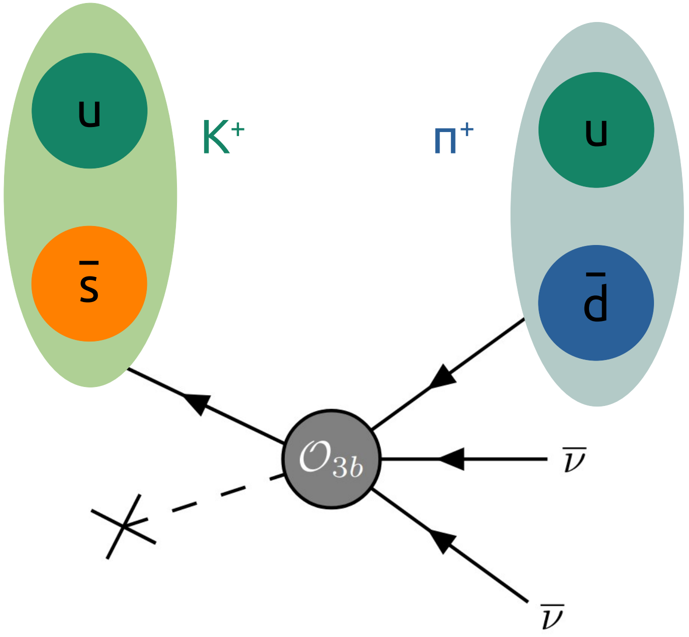
- GIM suppressed

Not explicit LNV!

- No GIM suppression
- Includes first and second generation

How are higher dimensional operators constraint by rare kaon decays?

Calculating LNV Branching Ratio



$$\boxed{\mathcal{O}_{3b}^{(7)} = L_i^\alpha L_j^\beta Q_a^\rho d_b^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}}$$

$$h^0 d_a^c d_{L_b} \nu_{L_i} \nu_{L_j}$$

$$c_1^{ijab} h^0 \left(d_a^c d_{L_b}\right)\left(\nu_{L_i}\nu_{L_j}\right) + c_2^{ijab} h^0 \left(d_a^c \nu_{L_i}\right)\left(\nu_{L_j} d_{L_b}\right)$$

$$c_1^{ijab} - \frac{c_2^{ijab}}{2} h^0 \left(d_a^c d_{L_b}\right)\left(\nu_{L_i}\nu_{L_j}\right) - \frac{c_2^{ijab}}{2} h^0 \left(d_a^c \sigma^{\mu\nu} d_{L_b}\right)\left(\nu_{L_j}\sigma_{\mu\nu}\nu_{L_i}\right) + h.c.$$

vanishes due to pseudoscalar nature of kaons and pions

$$\boxed{i\mathcal{M} = \frac{v}{\Lambda^3_{ijsd}} \underbrace{\langle \pi(p') |\, \bar{d} s \,| K(p) \rangle}_{\frac{m_K^2 - m_\pi^2}{m_s - m_d} f_0^K(s)} \nu_i(k) \nu_j(k')}$$

$$\boxed{\frac{\Gamma\left(K \to \pi \nu_i \nu_j\right)}{ds\, dt} = \frac{1}{1+\delta_{ij}} \frac{1}{(2\pi)^3} \frac{1}{32 m_K^3} |\overline{\mathcal{M}}|^2}$$

- Usage of **known hadronic matrix elements / form factors**
- **Alternative approach:** SMEFT matched on chiral perturbation theory

Li, Ma, Schmidt (2019)

Constraining power at E949

- **SM**, lepton number **conserving** **vector** current

$$\mathcal{L}_{\rm SM}^{K\to\pi\nu\bar{\nu}} = \frac{1}{\Lambda_{\rm SM}^2}\left(\bar{\nu}_i\gamma^\mu\nu_i\right)\left(\bar{d}\gamma_\mu s\right)$$

- **BSM**, lepton number **violating** **scalar** current

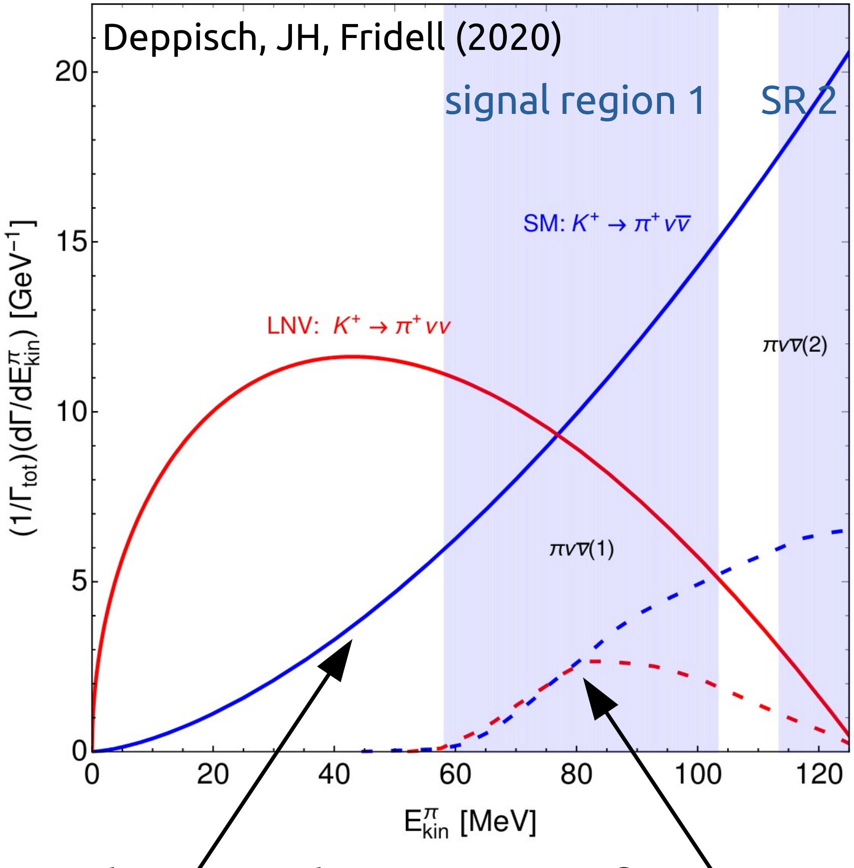
$$\mathcal{L}_{\rm BSM}^{K\to\pi\nu\nu} = \frac{v}{\Lambda_{\rm BSM}^2}\left(\nu_i\nu_j\right)\left(\bar{d}s\right)$$

→ **different phase space distribution**

- **different acceptance:**

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})_{\rm E949}^{\rm vector} < 3.35\times10^{-10} \quad \text{at } 90\%\ \text{CL}$$

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})_{\rm E949}^{\rm scalar} < 21\times10^{-10} \quad \text{at } 90\%\ \text{CL}$$

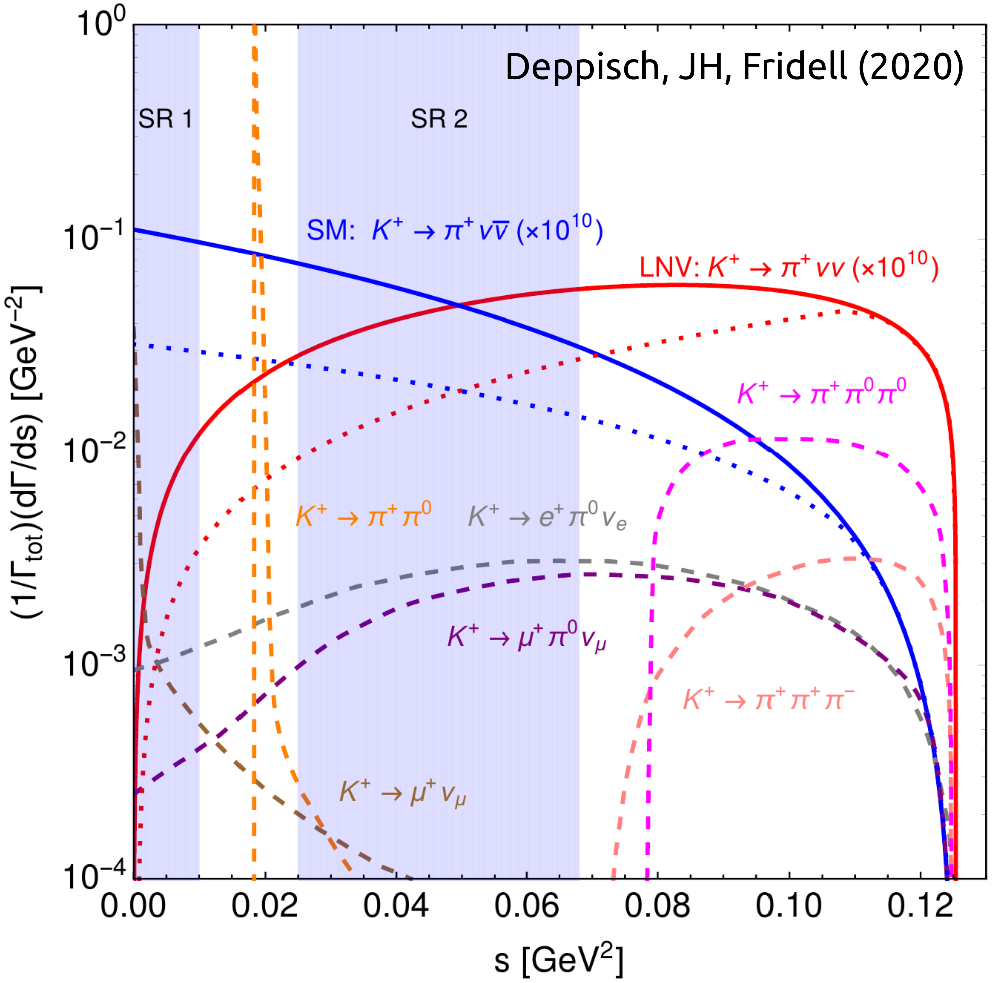


Deppisch, JH, Fridell (2020)

theoretical distribution

after experimental acceptance

Constraining power at NA62



$$s = (E_K - E_\pi)^2$$

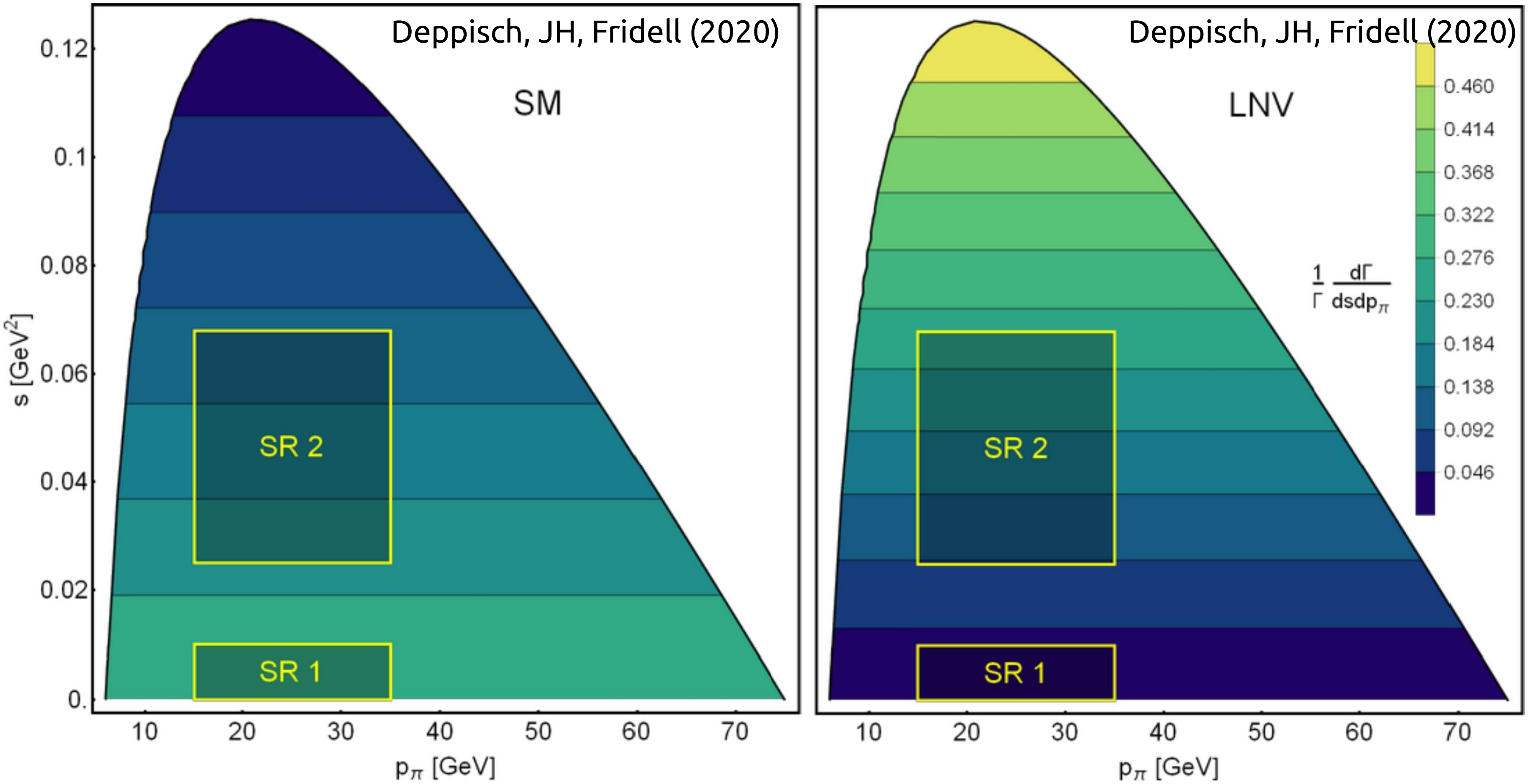
Summary of sensitivity to scalar current (based on kinematics only):

Experiment	SM (vector)	LNV (scalar)
NA62 SR 1	6%	0.3%
NA62 SR 2	17%	15%
E949 $\pi\nu\bar{\nu}(1)$	29%	2%
E949 $\pi\nu\bar{\nu}(2)$	45%	38%
KOTO	64%	30%

Experiments are generally more sensitive to vector currents

Possibility to disentangle a possible signal by improving on experimental sensitivity and strategy?

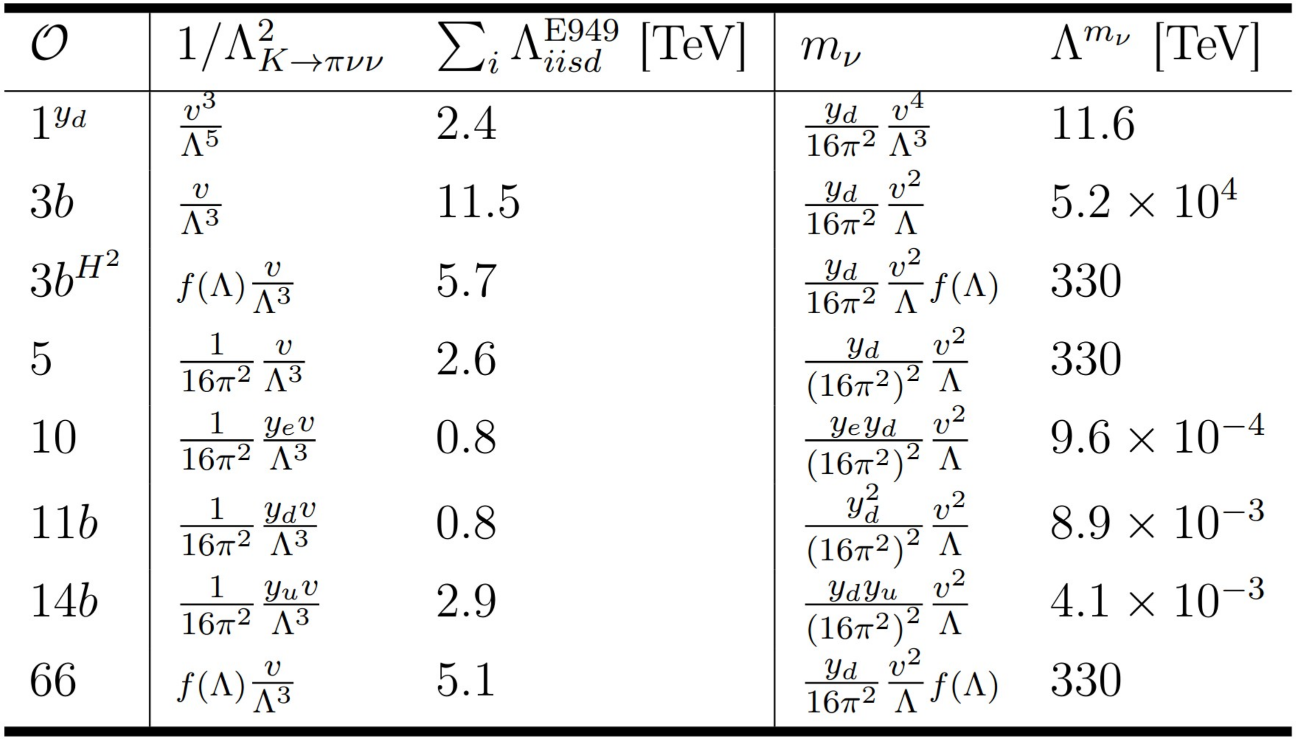
Constraining power at NA62



For **LNV** more events in **SR1** expected.
for **LNC** more events in **SR2** expected.

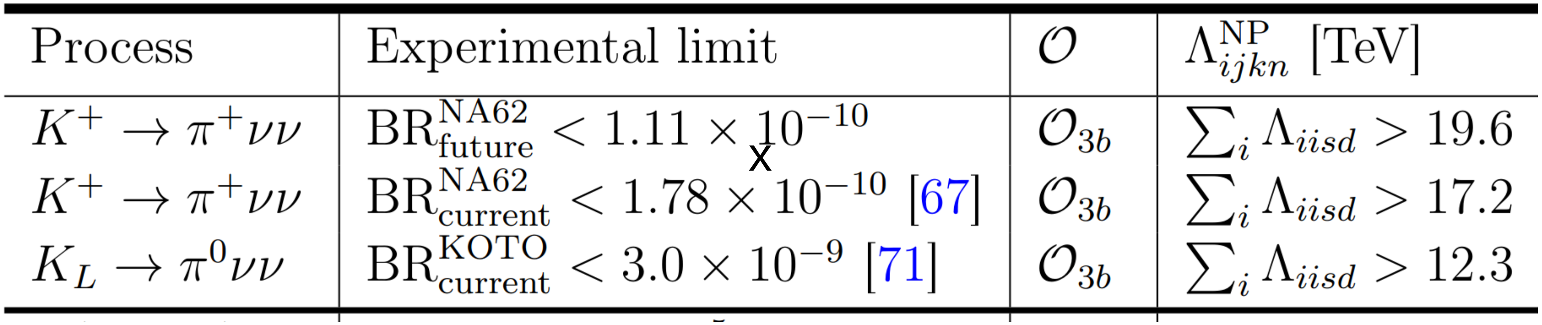
Putting pieces together

1st generation couplings



$\mathcal{O}$	$1/\Lambda^2_{K\to\pi\nu\nu}$	$\sum_i \Lambda^{\text{E949}}_{iisd}$ [TeV]	m_ν	Λ^{m_ν} [TeV]
1^{y_d}	$\frac{v^3}{\Lambda^5}$	2.4	$\frac{y_d}{16\pi^2}\frac{v^4}{\Lambda^3}$	11.6
$3b$	$\frac{v}{\Lambda^3}$	11.5	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}$	5.2×10^4
$3b^{H^2}$	$f(\Lambda)\frac{v}{\Lambda^3}$	5.7	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	330
5	$\frac{1}{16\pi^2}\frac{v}{\Lambda^3}$	2.6	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	330
10	$\frac{1}{16\pi^2}\frac{y_e v}{\Lambda^3}$	0.8	$\frac{y_e y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	9.6×10^{-4}
$11b$	$\frac{1}{16\pi^2}\frac{y_d v}{\Lambda^3}$	0.8	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	8.9×10^{-3}
$14b$	$\frac{1}{16\pi^2}\frac{y_u v}{\Lambda^3}$	2.9	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	4.1×10^{-3}
66	$f(\Lambda)\frac{v}{\Lambda^3}$	5.1	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	330

Sensitivity to different flavors than most constraining 0vββ !



Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\text{NP}}_{ijkn}$ [TeV]
$K^+ \to \pi^+\nu\nu$	$\text{BR}^{\text{NA62}}_{\text{future}} < 1.11 \times 10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 19.6$
$K^+ \to \pi^+\nu\nu$	$\text{BR}^{\text{NA62}}_{\text{current}} < 1.78 \times 10^{-10}$ [67]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 17.2$
$K_L \to \pi^0\nu\nu$	$\text{BR}^{\text{KOTO}}_{\text{current}} < 3.0 \times 10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$

Putting pieces together

1^{st} generation couplings

$\mathcal{O}$	$1/\Lambda^2_{K\to\pi\nu\nu}$	$\sum_i \Lambda^{\text{E949}}_{iisd}$ [TeV]	m_ν	Λ^{m_ν} [TeV]
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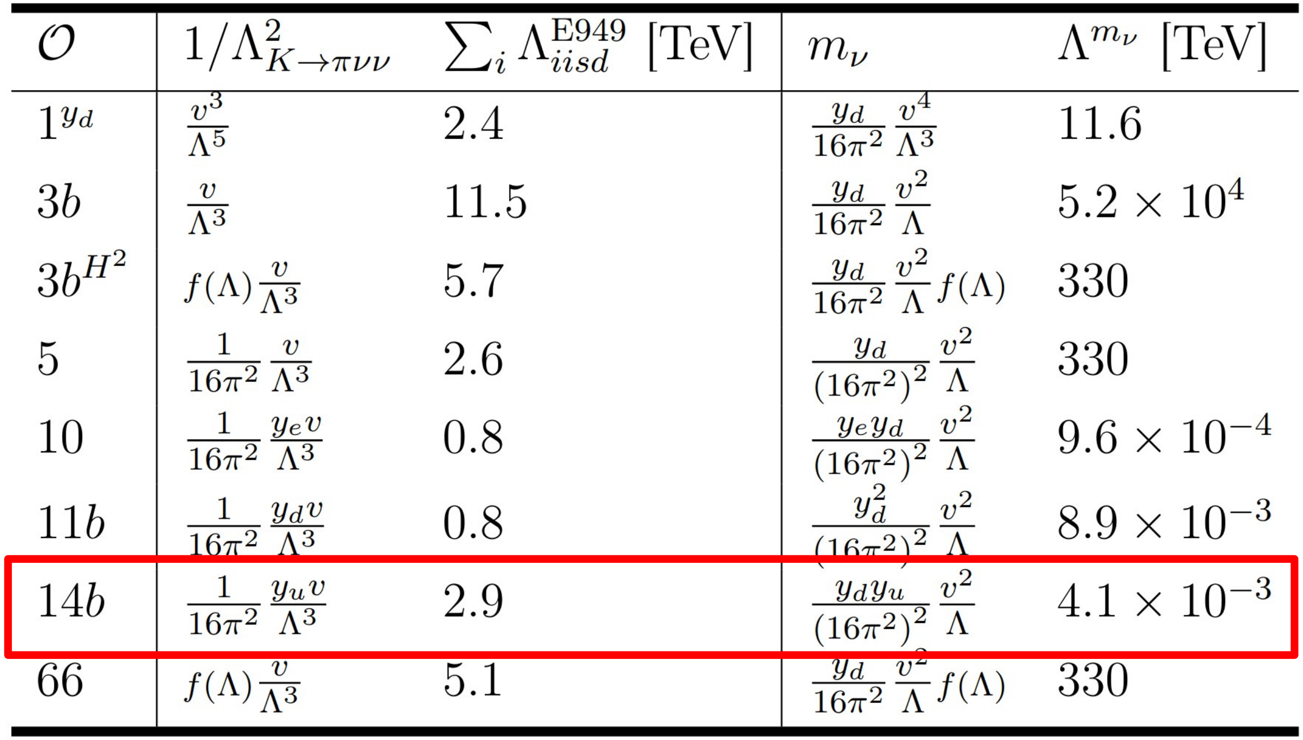
Putting pieces together

1^{st} generation couplings



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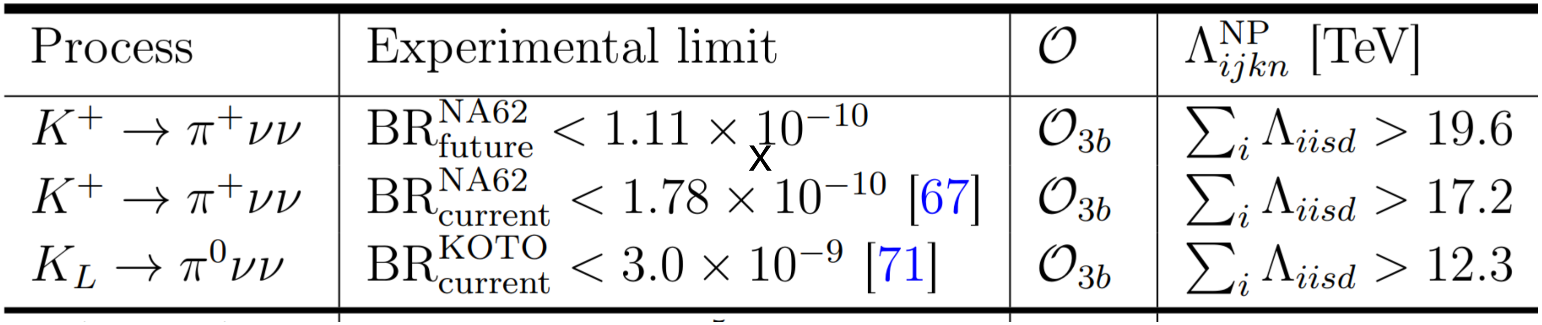

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$K_L \to \pi^0\nu\nu$	$BR^{KOTO}_{current} < 3.0 \times 10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$

Summary

Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\mathrm{NP}}_{ijkn}$ [TeV]	$\hat{\lambda}$ [TeV]
$K^+ \to \pi^+ \nu\nu$	$\mathrm{BR}^{\mathrm{NA62}}_{\mathrm{future}} < 1.11 \times 10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 19.6$	0.213
$K^+ \to \pi^+ \nu\nu$	$\mathrm{BR}^{\mathrm{NA62}}_{\mathrm{current}} < 1.78 \times 10^{-10}$ [67]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 17.2$	0.196
$K_L \to \pi^0 \nu\nu$	$\mathrm{BR}^{\mathrm{KOTO}}_{\mathrm{current}} < 3.0 \times 10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$	0.178
$B^+ \to \pi^+ \nu\nu$	$\mathrm{BR} < 1.4 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibd} > 1.4$	0.174
$B^+ \to K^+ \nu\nu$	$\mathrm{BR} < 1.6 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibs} > 1.4$	0.174
$B^0 \to \pi^0 \nu\nu$	$\mathrm{BR} < 9 \times 10^{-6}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibd} > 1.5$	0.174
$B^0 \to K^0 \nu\nu$	$\mathrm{BR} < 2.6 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibs} > 1.3$	0.174
$K^+ \to \mu^+ \bar{\nu}_e$	$\mathrm{BR} < 3.3 \times 10^{-3}$ [32]	$\mathcal{O}_{3a}$	$\Lambda_{\mu esu} > 2.4$	0.174
$\pi^+ \to \mu^+ \bar{\nu}_e$	$\mathrm{BR} < 1.5 \times 10^{-3}$ [32]	$\mathcal{O}_{3a}$	$\Lambda_{\mu eud} > 1.9$	0.174
$\pi^0 \to \nu\nu$	$\mathrm{BR} < 2.9 \times 10^{-13}$ [78]	$\mathcal{O}_{3b}$	$\Lambda_{\nu\nu ud} > 3.4$	0.174
$0\nu\beta\beta$	$T^{^{136}\mathrm{Xe}}_{1/2} \geq 1.07 \times 10^{26}$ yrs [79]	$\mathcal{O}_{3b}$	$\Lambda_{eeud} > 330$	3.5
$\mu^- \to e^+$	$R^{\mathrm{Ti}}_{\mu^- e^+} < 1.7 \times 10^{-12}$ [80]	$\mathcal{O}_{14b}$	$\Lambda_{\mu eud} > 0.01$	0.174

Bright future perspective – B-meson constraints still in LHC reach. Could imply strong lepton asymmetry washout*).

***) If LNV interaction is confirmed.**

UV complete example: Leptoquarks I

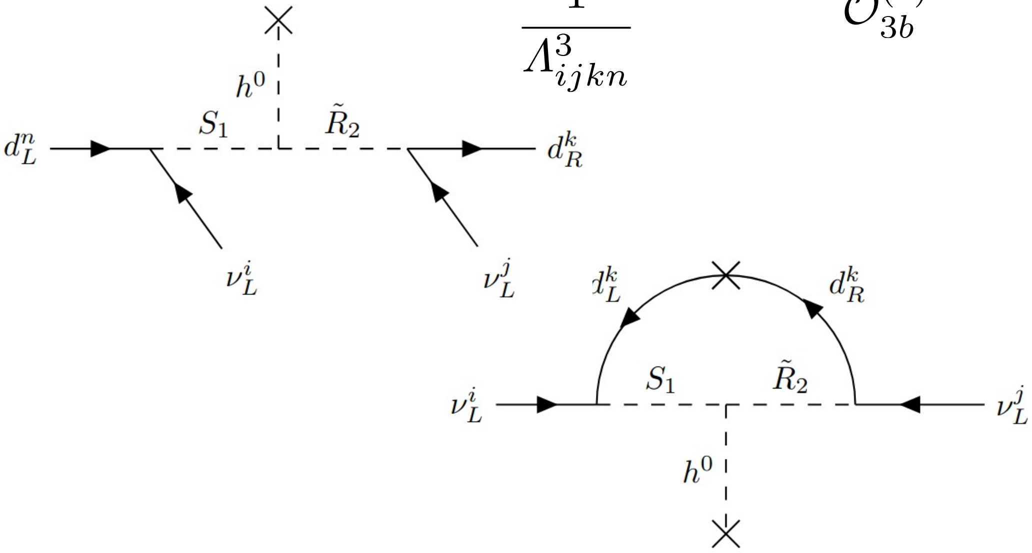
$$\boxed{\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mu S_1 H^{\dagger\alpha} \tilde{R}_{2\alpha} - g_1^{ik} \bar{L}_{i\alpha} i\sigma_2^{\alpha\beta} \tilde{R}^*_{2\beta} \overline{d}_k^c - g_2^{jn} Q_n^\alpha L_j^\beta \epsilon_{\alpha\beta} S_1 - g_3^{jn} \bar{u}_n^c e_j S_1 + \text{h.c.}}$$

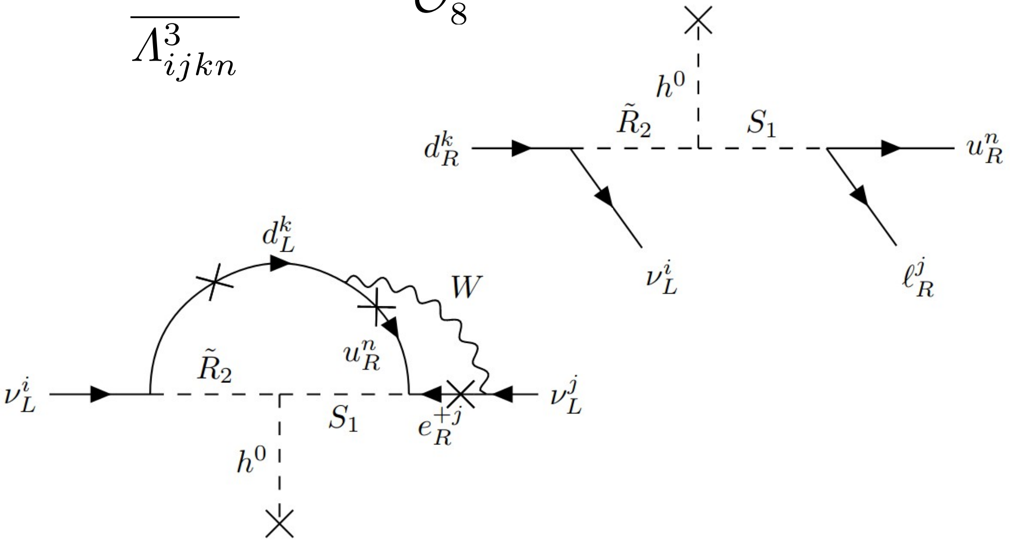
Cata, Mannel (2019)

$$\tilde{R}_2 \in 3,\ 2,\ 1/6,$$
$$S_1 \in \bar{3},\ 1,\ 1/3$$

	L	B
$\tilde{R}_2$	-1	$+\frac{1}{3}$
S_1	-1	$-\frac{1}{3}$

$$\mathcal{L}_{7D} = \underbrace{\frac{\mu g_1^{ik} g_2^{jn}}{m^2_{\tilde{R}_2} m^2_{S_1}}}_{\frac{1}{\Lambda^3_{ijkn}}} \underbrace{L_i^\alpha H^\beta d_k^c Q_n^\mu L_j^\nu \epsilon_{\alpha\beta}\epsilon_{\mu\nu}}_{\mathcal{O}_{3b}^{(7)}} + \underbrace{\frac{\mu g_1^{ik} g_3^{jn}}{m^2_{\tilde{R}_2} m^2_{S_1}}}_{\frac{1}{\Lambda^3_{ijkn}}} \underbrace{L_i^\alpha H^\beta d_k^c u_n^c e_j^c \epsilon_{\alpha\beta}}_{\mathcal{O}_8^{(7)}}$$



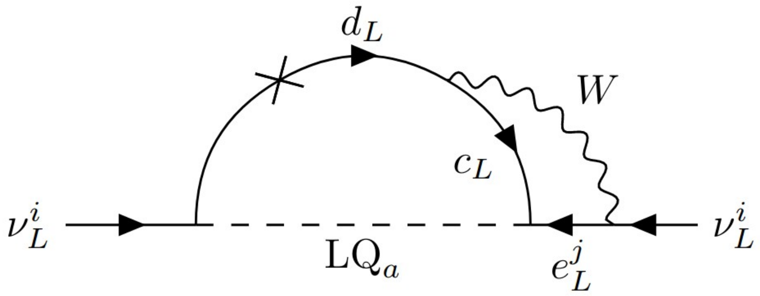


UV complete example: Leptoquarks II

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \mu S_1 H^{\dagger\alpha} \tilde{R}_{2\alpha} - g_1^{ik} \bar{L}_{i\alpha} i\sigma_2^{\alpha\beta} \tilde{R}^*_{2\beta} \overline{d}^c_k - g_2^{jn} Q^\alpha_n L^\beta_j \epsilon_{\alpha\beta} S_1 - g_3^{jn} \bar{u}^c_n e_j S_1 + \mathrm{h.c.}$$

Cata, Mannel (2019)

$$(m_\nu)_i = \sum_j \frac{3\sin(2\theta) g^2 V_{cd} \tilde{g}_1^{id} \tilde{g}_2^{jc} U_{ji}}{512\pi^4} m_d I(m^2_{\mathrm{LQ}_1}, m^2_{\mathrm{LQ}_2}, m^2_W)$$



1. gen / 2. gen / 3. gen

$$\tilde{g}_1 \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

1. gen / 2. gen / 3. gen

$$\tilde{g}_2 \sim \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$(m_\nu)_i \approx 0.08 eV$$

A contribution of leptoquarks to rare kaon decays would imply a non-trivial flavour pattern to explain smallness of neutrino masses.

Probing Leptogenesis at the GeV Scale

Leptogenesis via the **Akhmedov-Rubakov-Smirnov (ARS)** mechanism

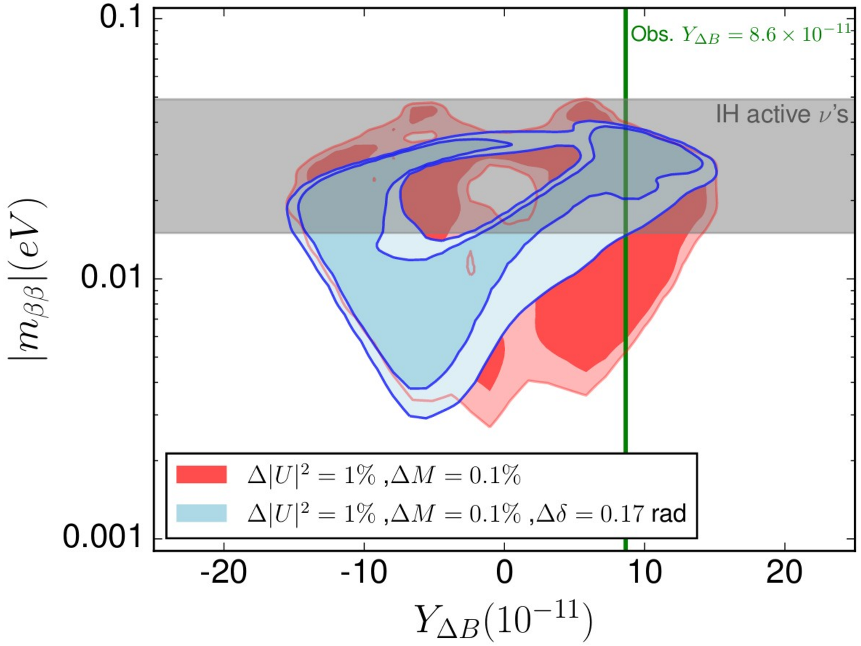
- Yukawa couplings yield small values with a certain hierarchy (equilibrium vs. non-eq.)
- $\not{CP}$ due to mixing, oscillations distribute individual lepton number unevenly
- the one in equilibrium translates its L number via sphalerons to the active sector → baryon asymmetry

Akhmedov et al. 1998

For **N=2** it was shown that the **baryon asymmetry is predictable by combination of different experimental measurements**:

- Neutrino oscillation experiments
- Neutrinoless double beta decay experiments
- Direct searches for heavy neutral leptons

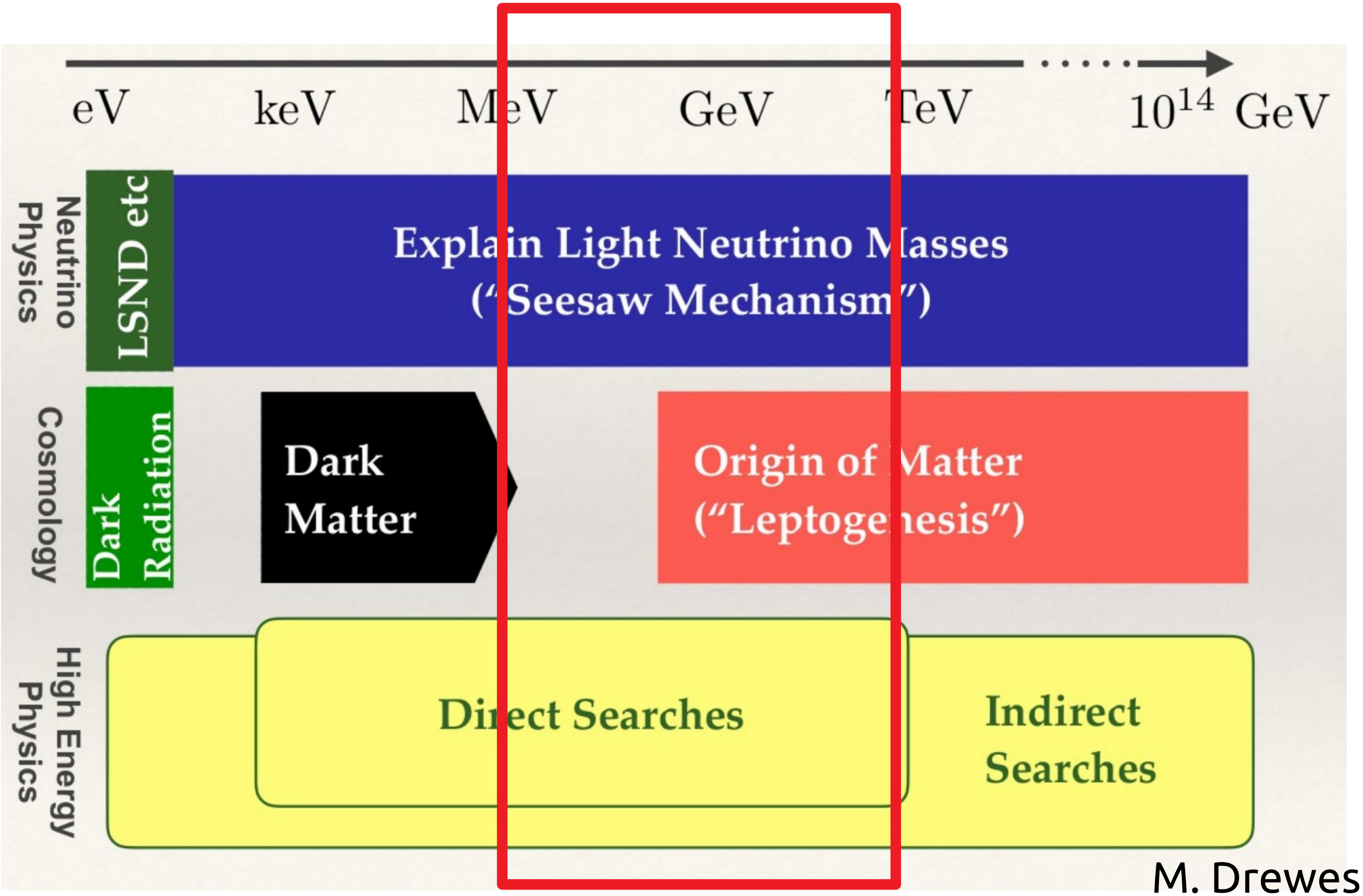
Hernandez et al. 2015, Abada et al. 2015, Drewes et al. 2016



Update to **N=3**

Abada et al. 2018

Leptogenesis & Sterile Neutrinos



M. Drewes

Leptogenesis & Gravitational waves?

NanoGrav: Sign of cosmic strings?

If particle production dominates, stochastic gravitational wave spectrum depends on

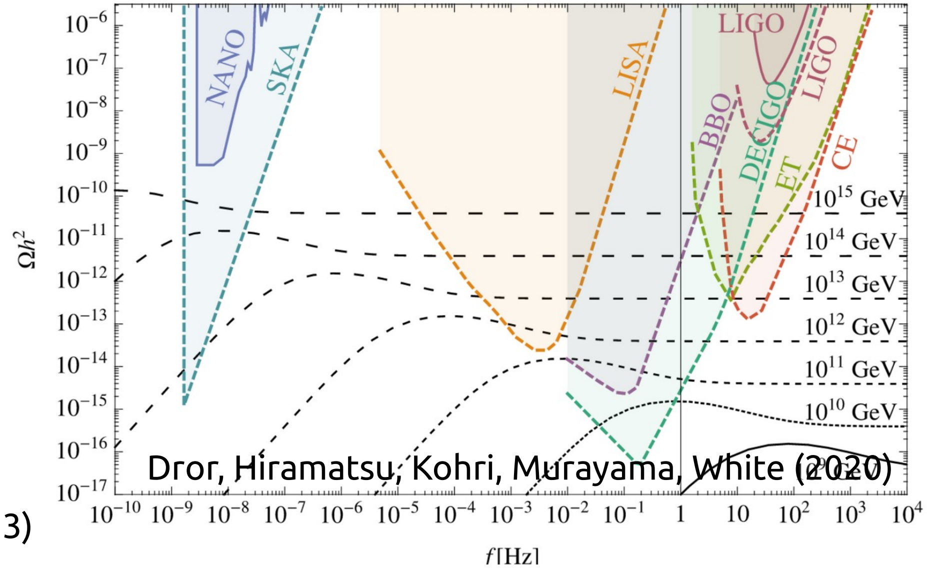
$$\Omega_{\mathrm{GW}} h^2 \propto G\mu^2$$

$$\mu \sim v^2$$

cosmic string tension

breaking scale

Hindmarsh (2011)
Buchmueller, Domcke, Kamada, Schmitz (2013)

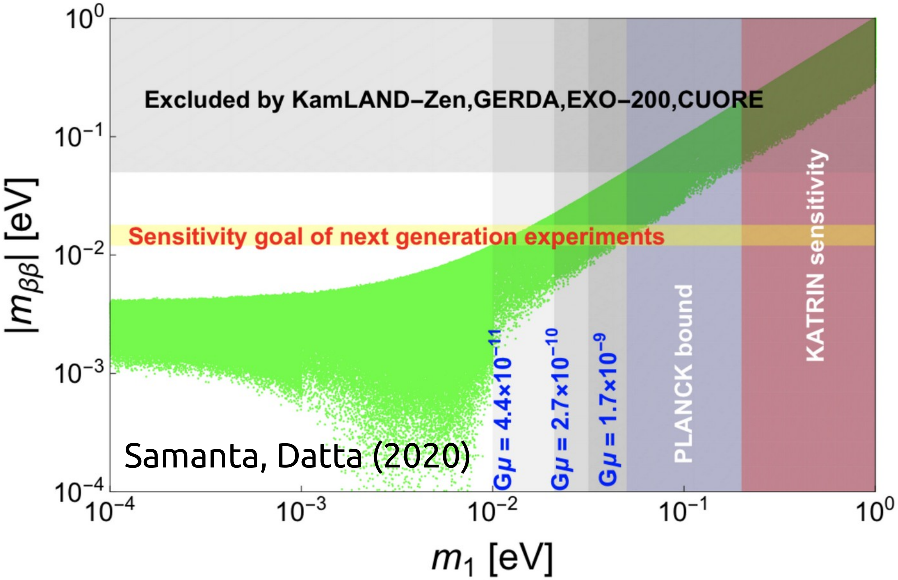


Dror, Hiramatsu, Kohri, Murayama, White (2020)

Direct and indirect links:

- cosmic string network is a generic prediction of the seesaw mechanism when B-L is broken spontaneously
- RH neutrino induced gravitational leptogenesis mechanism (RIGL)

McDonald, Shore (2015)

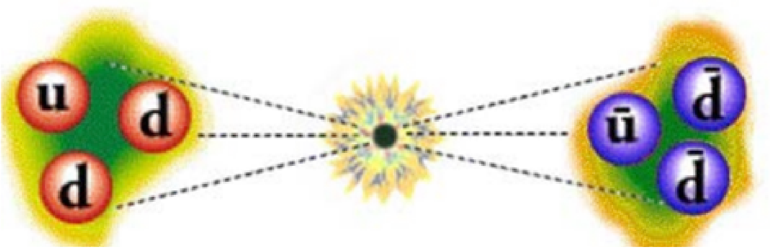


Samanta, Datta (2020)

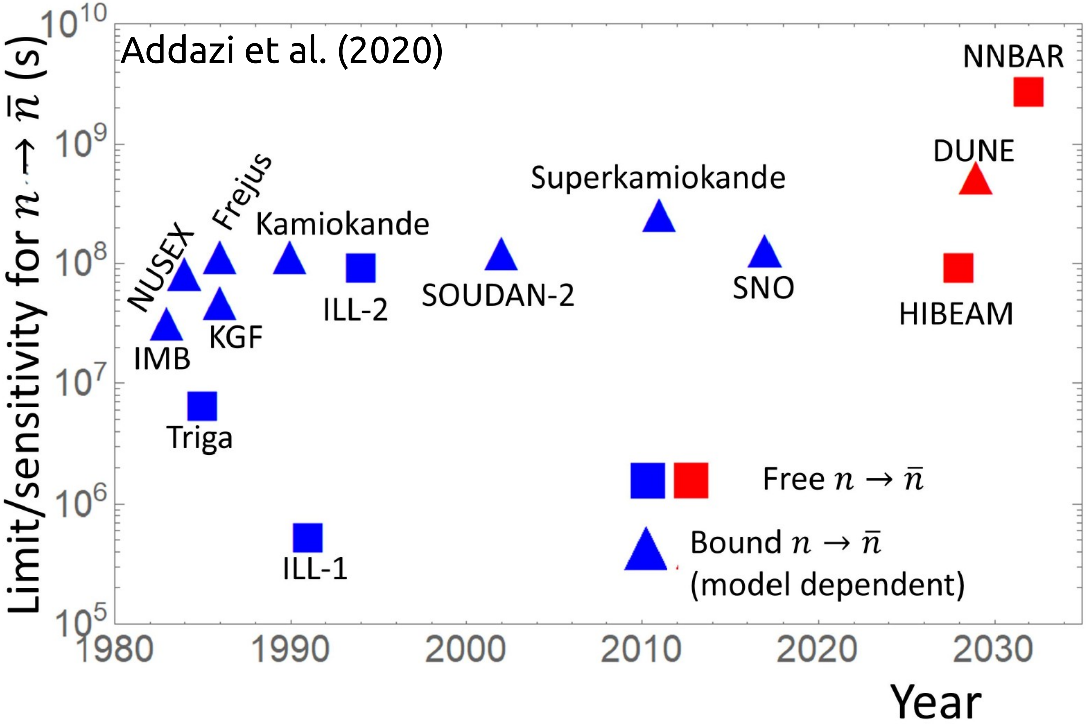
High scale baryogenesis

Testable B violation scenarios:

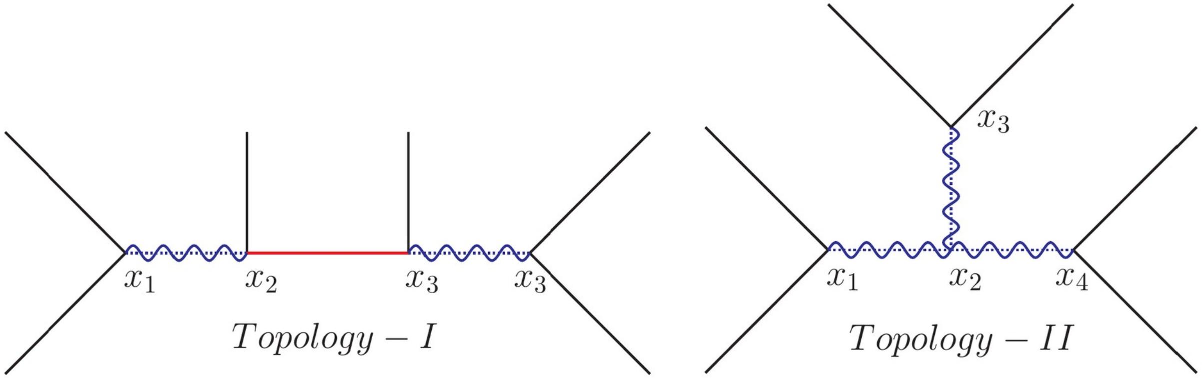
- Δ B = 1: proton decay
- Δ B = 2: n-nbar oscillations



Future sensitivity at ESS: $\tau_{n\bar{n}} \geq 10^{10} s$



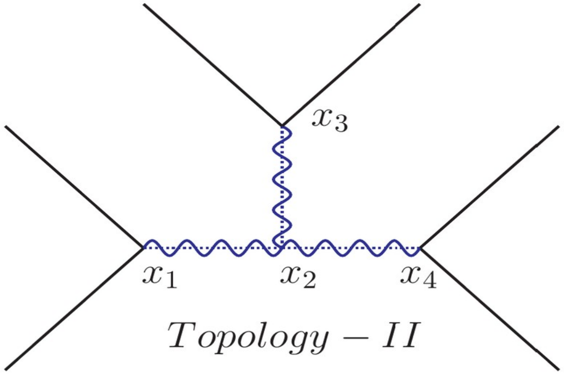
New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source, Addazi et al. (2020)



Grojean et al. (2019)

Mohapatra, Marshak (1980)
Babu, Mohapatra (2012)

High scale baryogenesis



Simplified model:

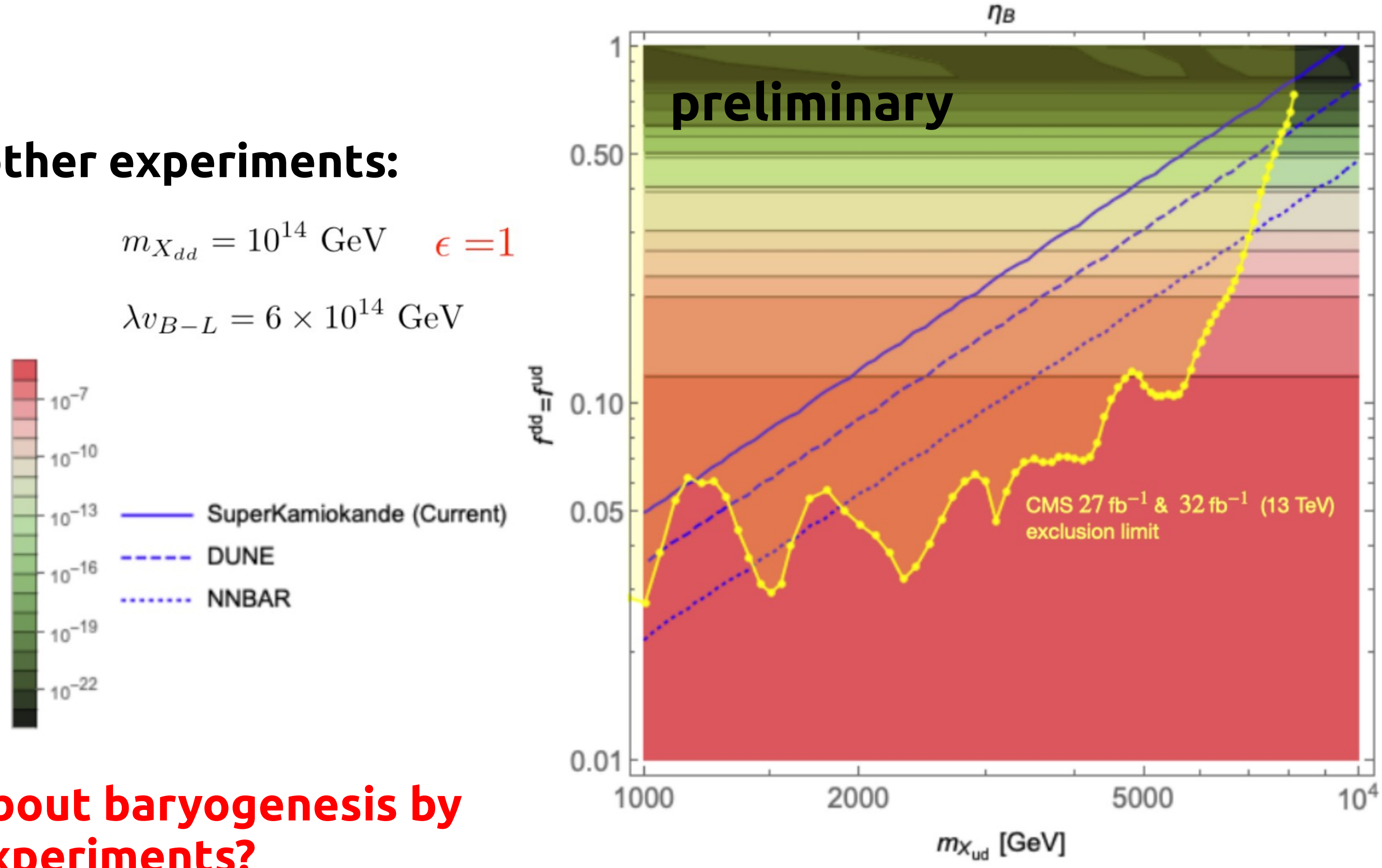
$$\mathcal{L}_{II} = f_{ij}^{dd} X_{dd} d_{iR} d_{jR} + \frac{f_{ij}^{ud}}{\sqrt{2}} X_{ud} (u_{iR} d_{jR} + u_{jR} d_{iR})$$
$$+ \lambda \xi X_{dd} X_{ud} X_{ud} + \text{h.c.}$$

Interesting interplay with other experiments:

- N-nbar oscillations
- Di-nucleon decay
- LHC
- meson oscillations

$m_{X_{dd}} = 10^{14}$ GeV $\epsilon = 1$

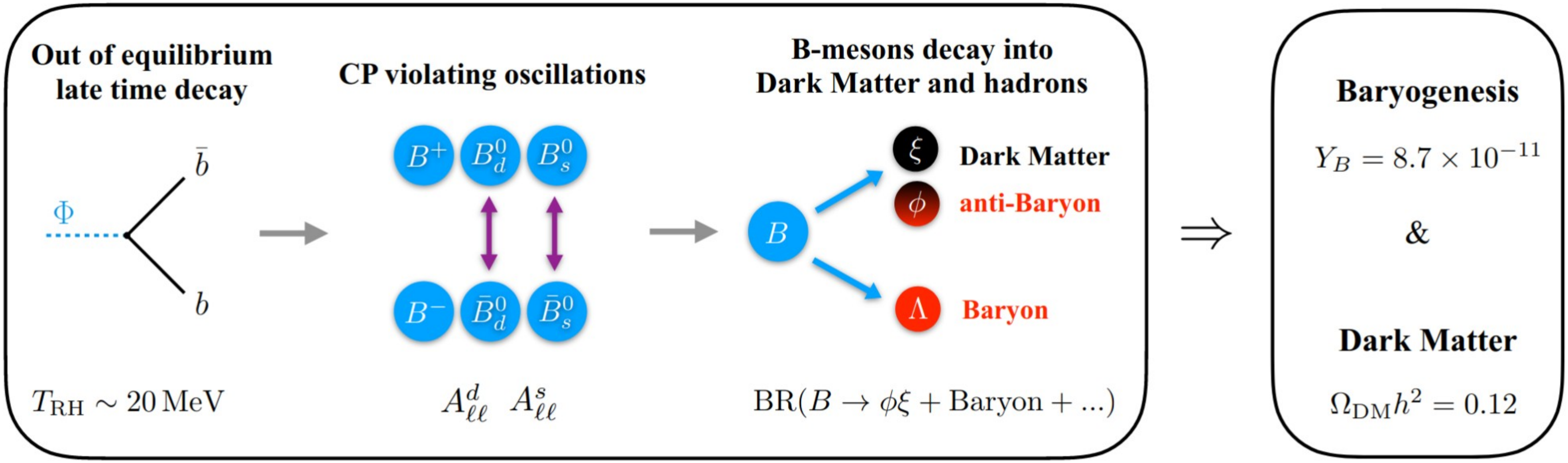
$\lambda v_{B-L} = 6 \times 10^{14}$ GeV



Fridell, JH, Hati, in preparation

Can we learn something about baryogenesis by the complementarity of experiments?

Low scale baryogenesis



Out of equilibrium late time decay

$T_{\mathrm{RH}} \sim 20\,\mathrm{MeV}$

CP violating oscillations

$A^d_{\ell\ell} \quad A^s_{\ell\ell}$

B-mesons decay into Dark Matter and hadrons

Dark Matter

anti-Baryon

Baryon

$\mathrm{BR}(B \to \phi\xi + \mathrm{Baryon} + \ldots)$

Baryogenesis

$Y_B = 8.7 \times 10^{-11}$

&

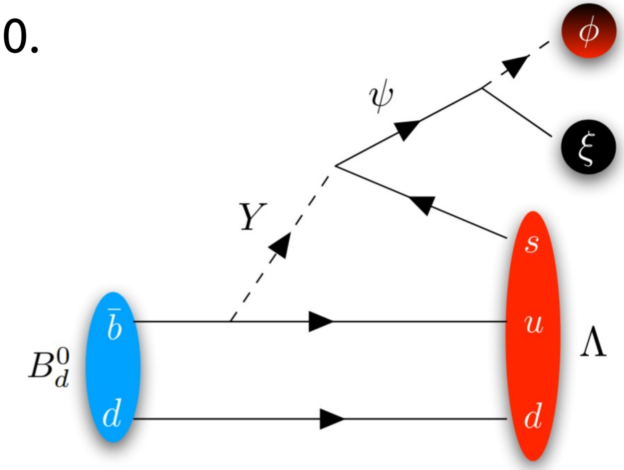
Dark Matter

$\Omega_{\mathrm{DM}} h^2 = 0.12$

Globally, Δ B = 0.

$$Y_B \propto \sum_{q=s,d} A^q_{\ell\ell} \times \mathrm{Br}(B^0_q \to \phi\,\xi + \mathrm{Baryon} + X)$$

Testable scenario at Belle, Belle-II and BarBar!



A Supersymmetric Theory of Baryogenesis and Sterile Sneutrino Dark Matter from B Mesons, Alonso-Alvarez, Elor, Nelson, Xiao (2019)
Baryogenesis and Dark Matter from B Mesons, Elor, Escudero, Nelson (2019)

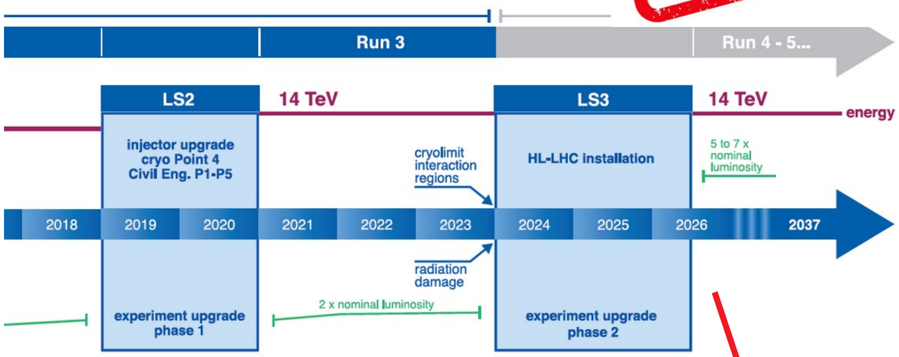
Many other possibilities…

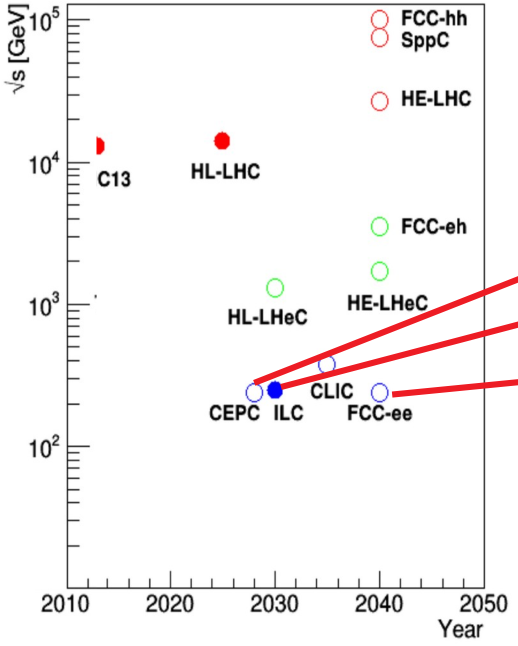
electroweak baryogenesis

MISSING

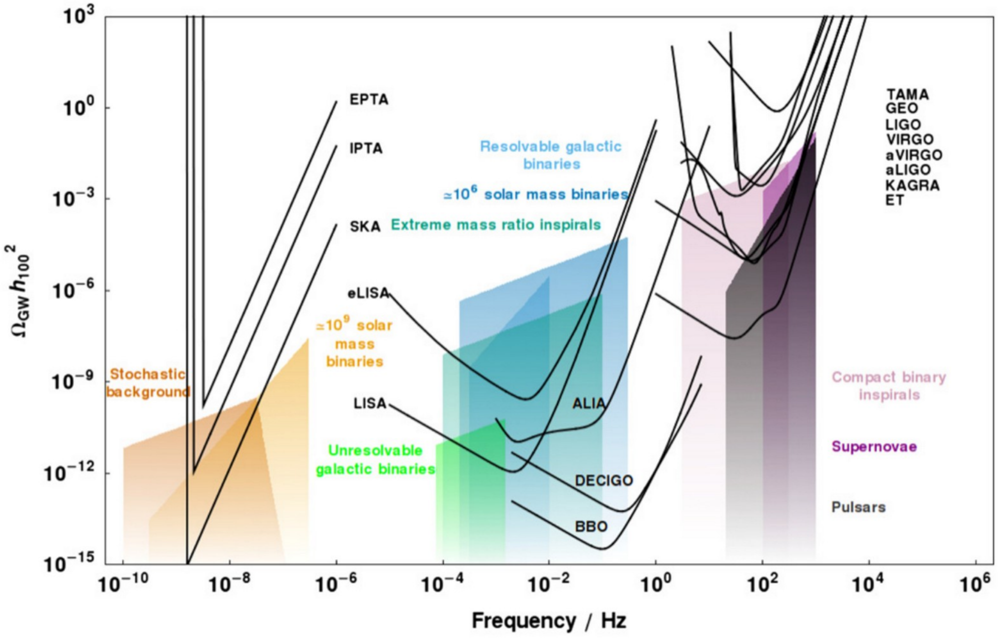
CP violation

1st order phase transition





Higgs factories

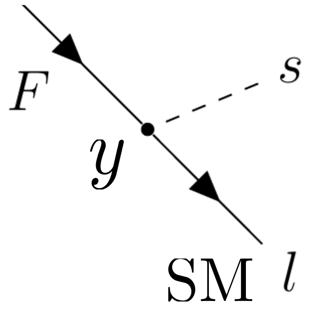


Stochastic gravitational wave background

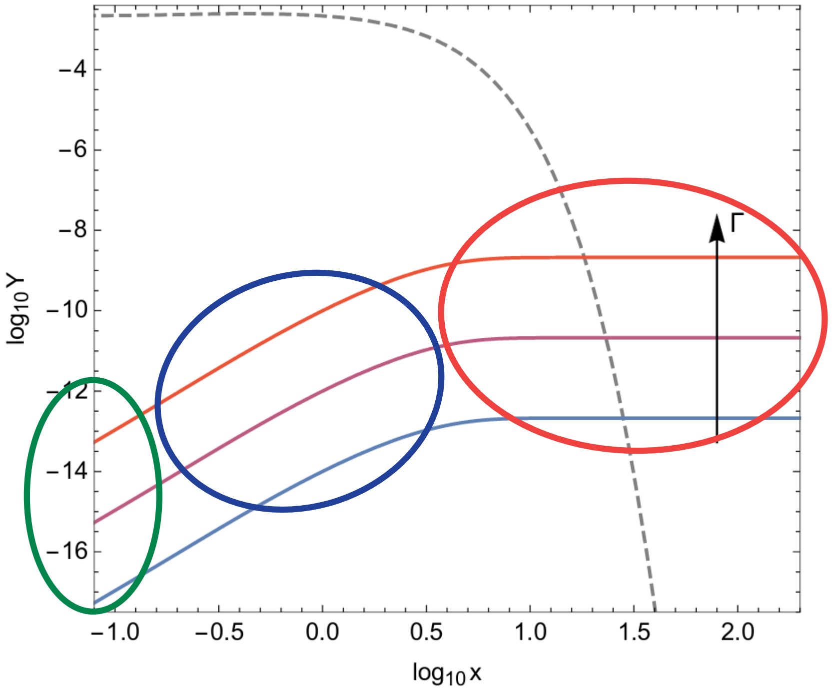
Probing freeze-in dark matter and baryogenesis

$$y_\chi Y_F X_{SM} \chi_s$$

$$y \sim \mathcal{O}(10^{-7})$$



Review Article: **The Dawn of FIMP Dark Matter: A Review of Models and Constraints**,
Bernal, Heikinheimo, Tenkanen, Tuominen, Vaskonen (2017)



$x = m_Y/T$

cooling down →

(1) Thermal equilibrium regime (T >> m)

DM is feebly interacting with the SM bath; abundance negligible

(2) DM production

DM gets produced via decay of a heavier particle Y that is in equilibrium with the SM bath

$$Y \to \mathrm{SM}\ \chi$$

(3) Freeze-in

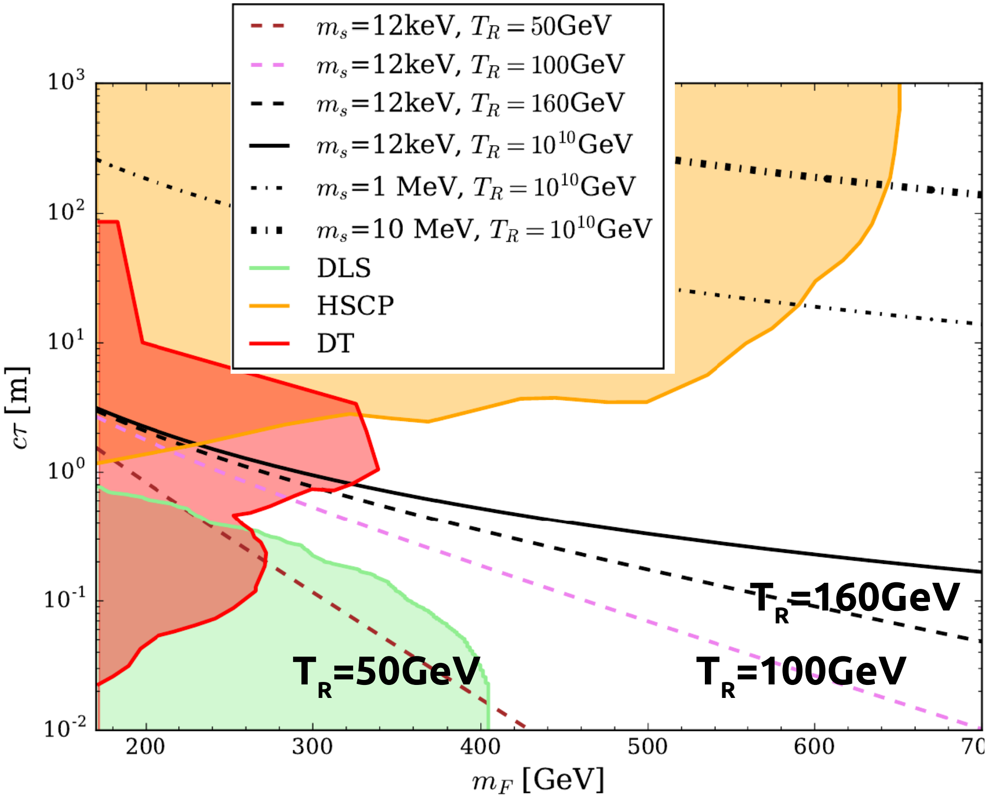
when T falls below mass of parent particle Y, production gets Boltzmann suppressed

$$n_Y \approx \exp(-m_Y/T)$$

Probing freeze-in dark matter and baryogenesis

Assuming that DM is mostly generated by decays of the parent F, we can relate the **relic abundance** with the parent particle life time

$$c\tau \approx 4.5\ \text{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\text{keV}}\right)\left(\frac{200\text{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$



- m_s=12keV is the **smallest possible mass** from Lyman-α constraints
  m_s > 12 keV would imply even smaller T_R

- If s made up **not all of the DM**, a smaller T_R would be implied

  → **most conservative choice**

Possibility to falsify baryogenesis / leptogenesis models that rely on effective sphaleron interactions.

Belanger, JH et al. (2018)

Conclusions

?

Conclusions

We live in a world full of interesting mysteries!

Astroparticle physics might guide us to new physics.

Thank you for your attention!