Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

From Zero to Hero… to Zero?

$0\nu\beta\beta$-decay, energy frontier probes, and the origin of matter

Phenomenology 2022 Symposium

May 9 - 11, 2022

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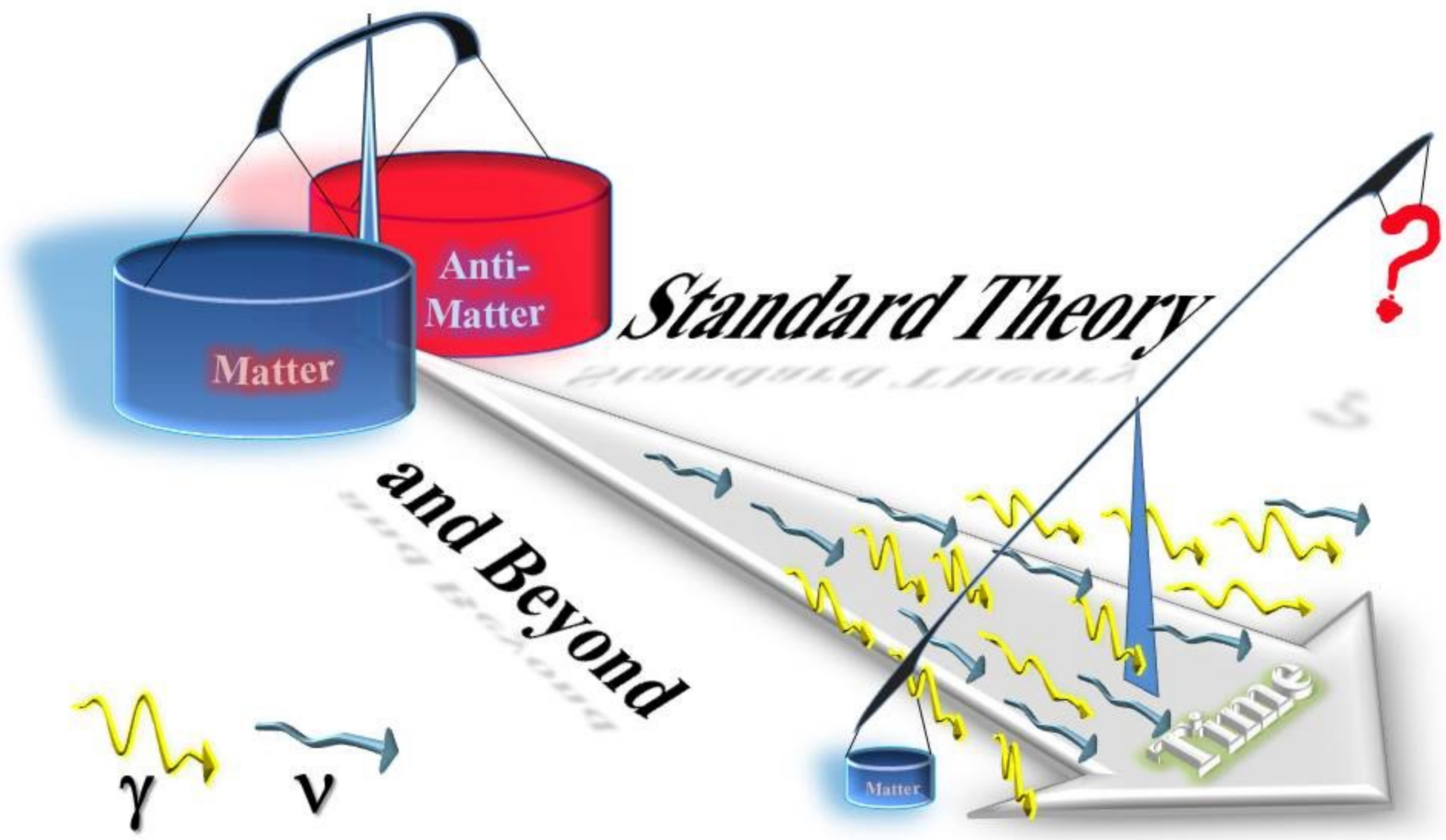
(in collaboration with Julia Harz, Michael Ramsey-Musolf, and Tianyang Shen)

I. From Zero to Hero

$$Y_B^{(obs)} = \frac{n_B - n_{\overline{B}}}{s} = (8.66 \pm 0.04) \times 10^{-11}$$

more (**B**aryonic) matter than anti-matter!



Willmann & Jungmann (2015)

How did we go from nothing to something?

Thermal leptogenesis

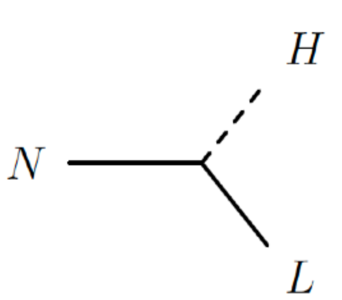
Fukugita & Yanagida (1986)

- *Simple* ingredients: **Sakharov conditions (1967)**

Non-equilibrium dynamics:

Heavy RHNs N with out-of-equilibrium, $\Delta\mathscr{L} \neq 0$ decays

$\rightsquigarrow m_{N0}\,, K$

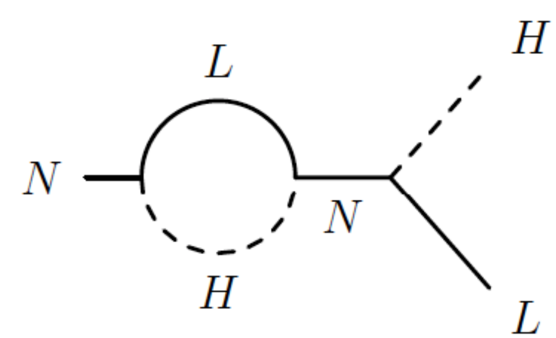


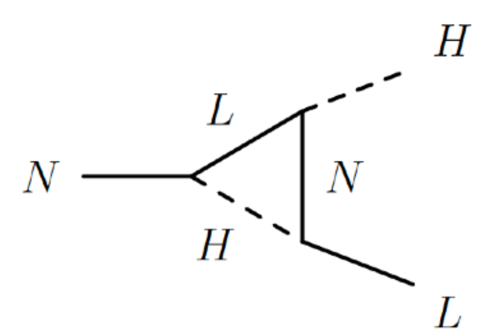
C & CP-violation:

Quantum corrections,

$\Gamma(N \to HL) \neq$

$\Gamma(N \to \overline{H}\,\overline{L}) \rightsquigarrow \epsilon$

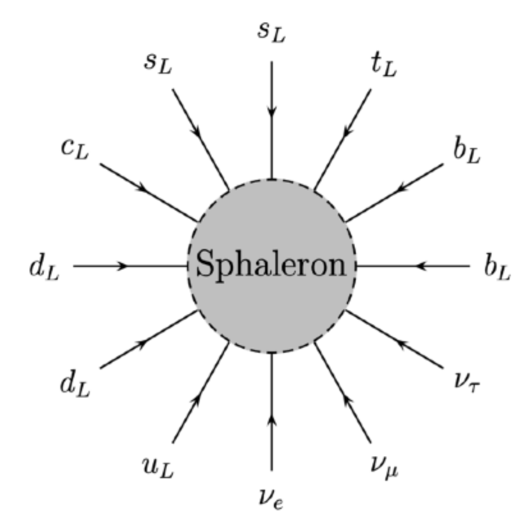




$\mathscr{B}$-violation:

EW sphaleron processes,

$\Delta\mathscr{L} \to \Delta\mathscr{B}$



Buchmüller (1998)

II. From Hero… to Zero?

- Thermal LG works, but requires $m_{N0} \gtrsim 10^9\,\mathrm{GeV}$ Davidson & Ibarra (2002)
- What if we include accessible effects? **Energy scale?**
- LNV at the **TeV-scale**: accessibility and broad impact

Helo *et al.* (2013)
Deppisch *et al.* (2014)
De Gouvêa *et al.* (2019)

Positive experimental result

hero or villain?

Simplified Model

We study a simplified model: **TeV-scale LNV** Peng *et al.* (2015)

$$\text{SM} \;+\; S : (\mathbf{1},\mathbf{2})_{1/2} \text{ and } F : (\mathbf{1},\mathbf{1})_0$$
$$m_F\,,\; m_S \sim \text{TeV}$$

Minimal interactions (*ingredients*) to address the key questions:

$$\mathscr{L}_{\text{SimpMod}} = g_Q\,\overline{Q}Sd_R + g_L\,\overline{L}\widetilde{S}F - m_S^2\,S^\dagger S - \frac{m_F}{2}\,\overline{F^c}F + \lambda_{HS}\,(S^\dagger H)^2$$

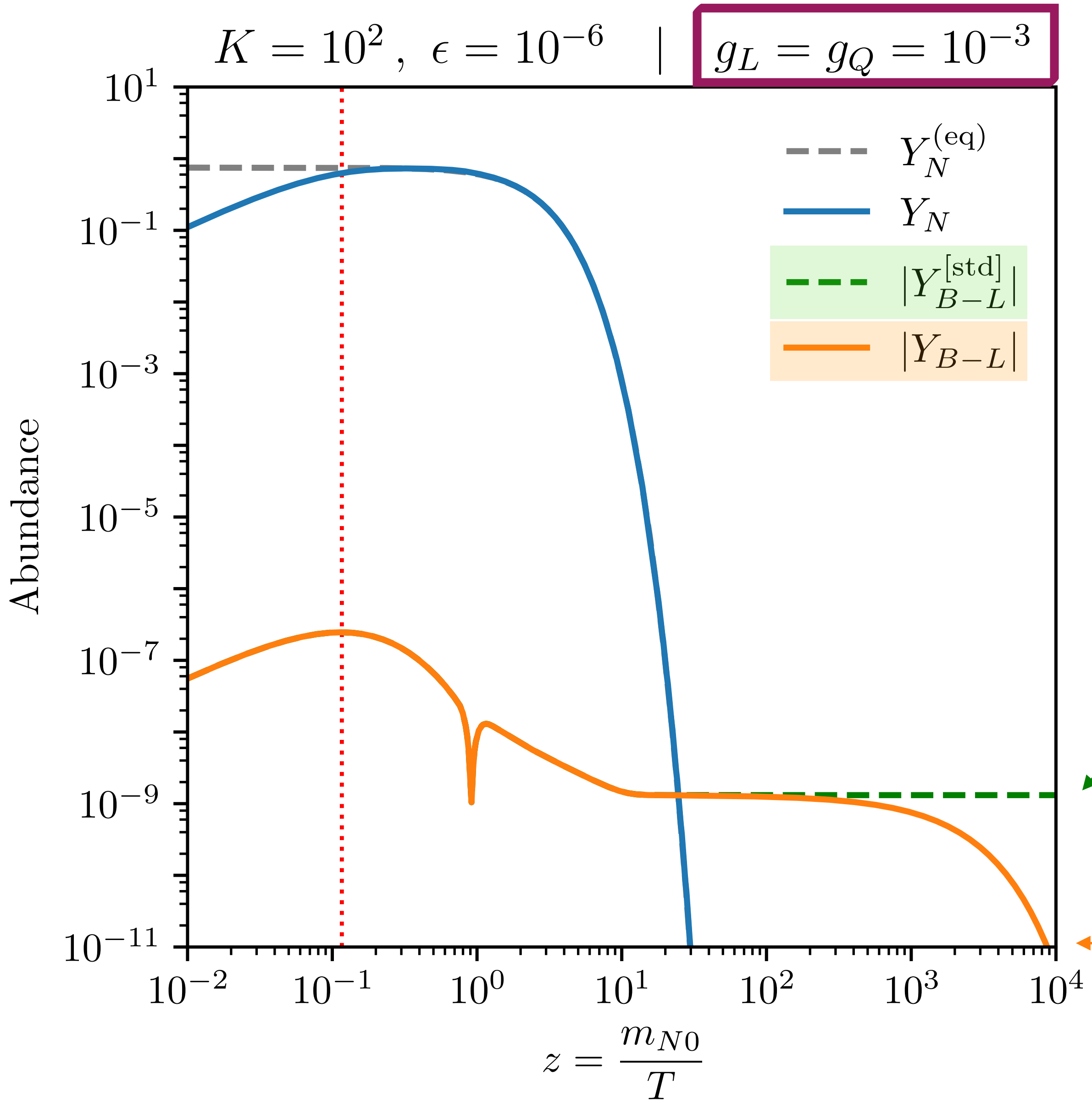
$\widetilde{X} \equiv \epsilon X^*\,, \quad \epsilon^{12} = +1$

$\left(SU(3)_C\,,\,SU(2)_L\right)_{U(1)_Y}$

TeV-scale LNV effects

- What if we include accessible TeV-scale effects? **Simplified Model**

$|Y_{B-L}| \mapsto |Y_B|$
via Sphaleron



(time)

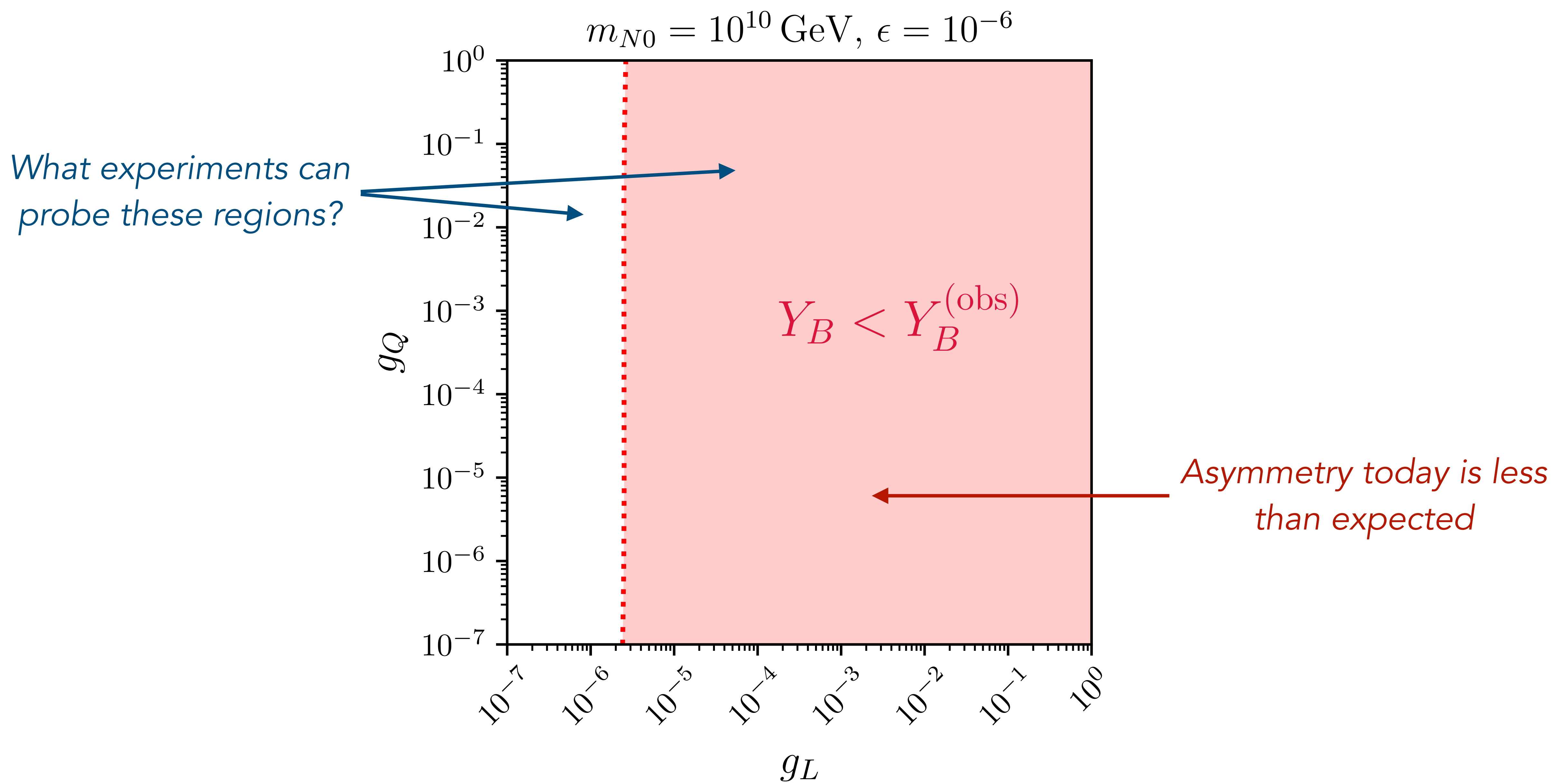
Non-zero final baryon asymmetry

Vanishing final baryon asymmetry

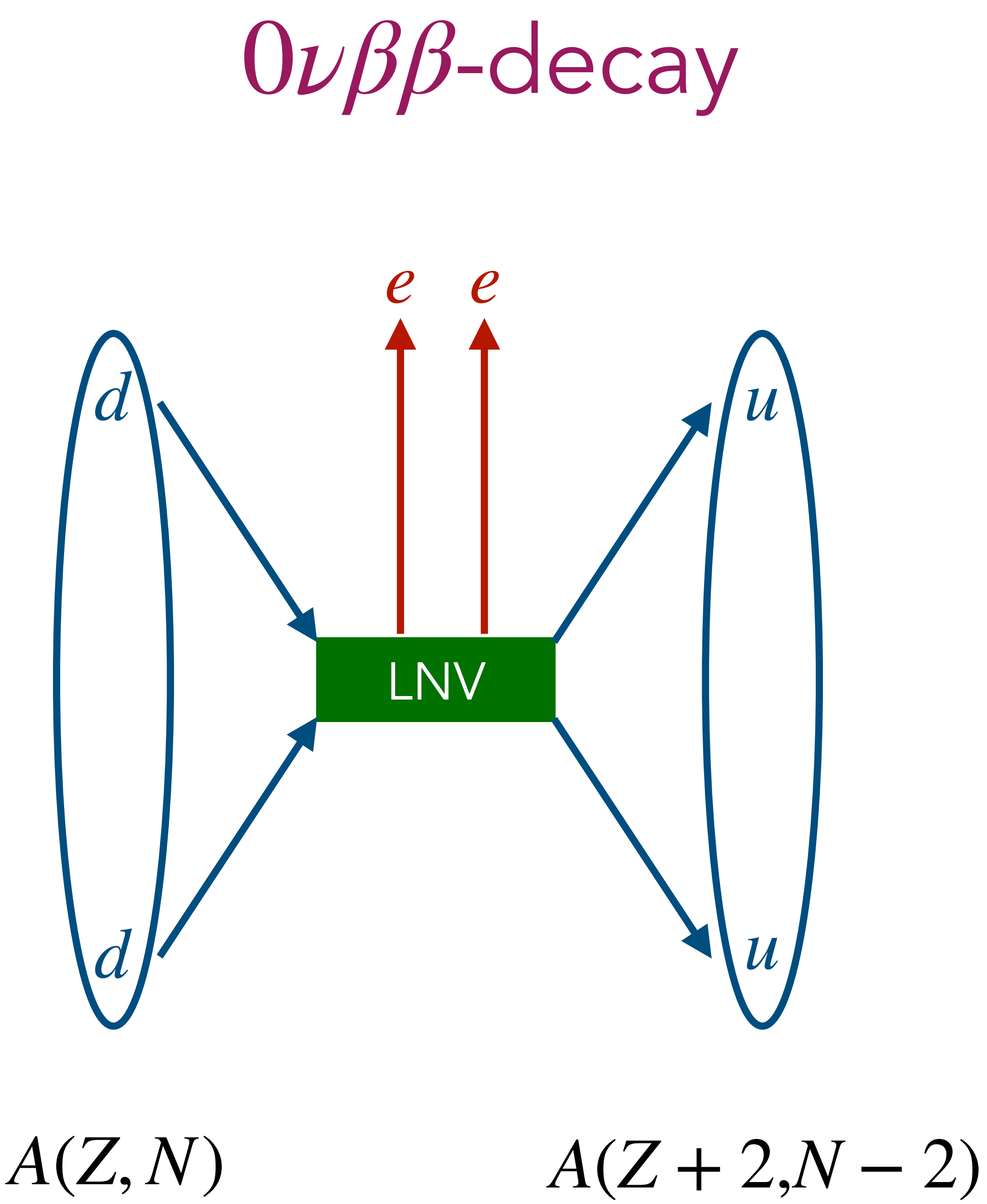
$Y_X = n_X/s$ (normalized number density)

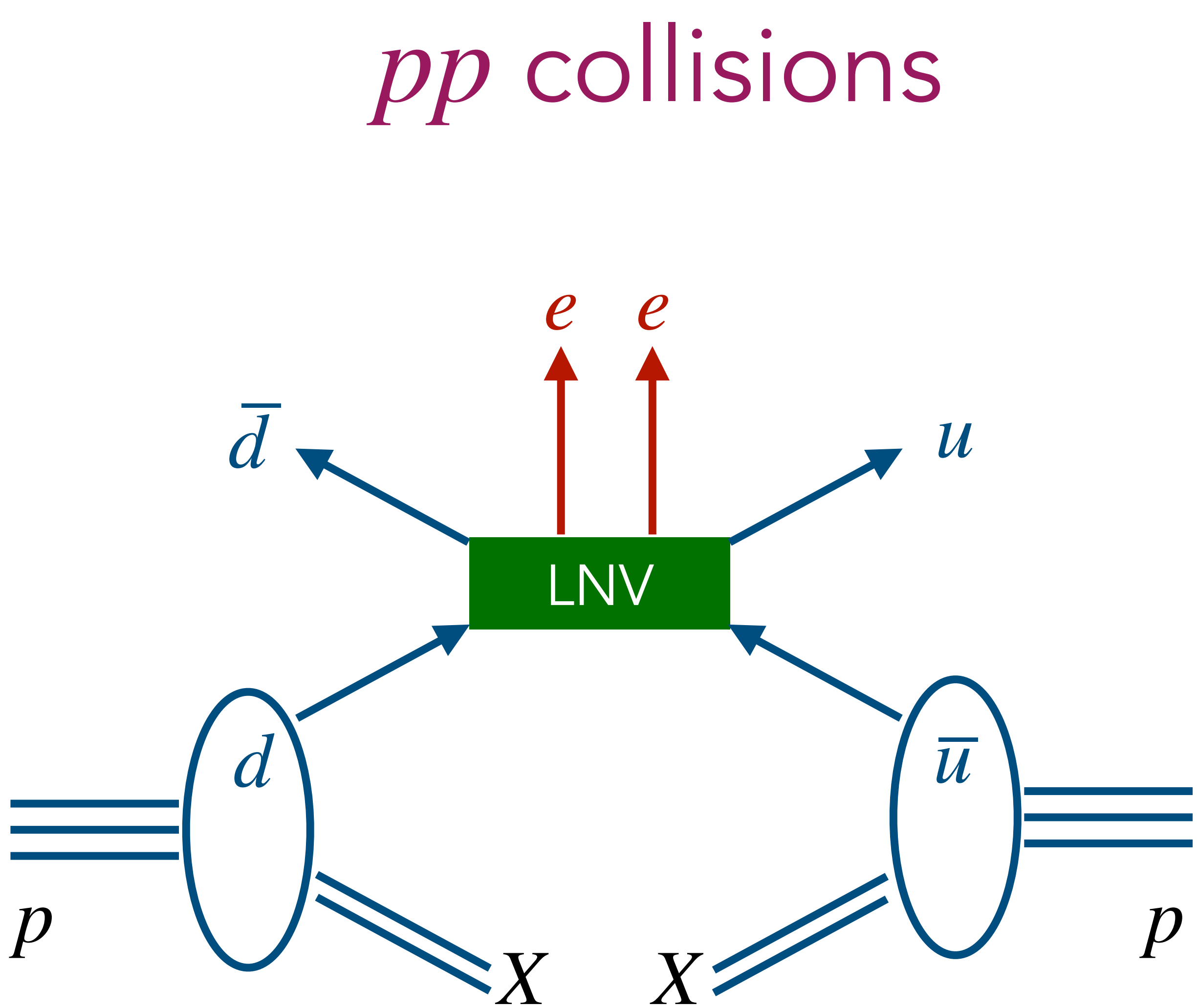
TeV-scale LNV effects

- What if we include accessible TeV-scale effects? **Simplified Model**



TeV-scale LNV: $0\nu\beta\beta$-decay & Colliders

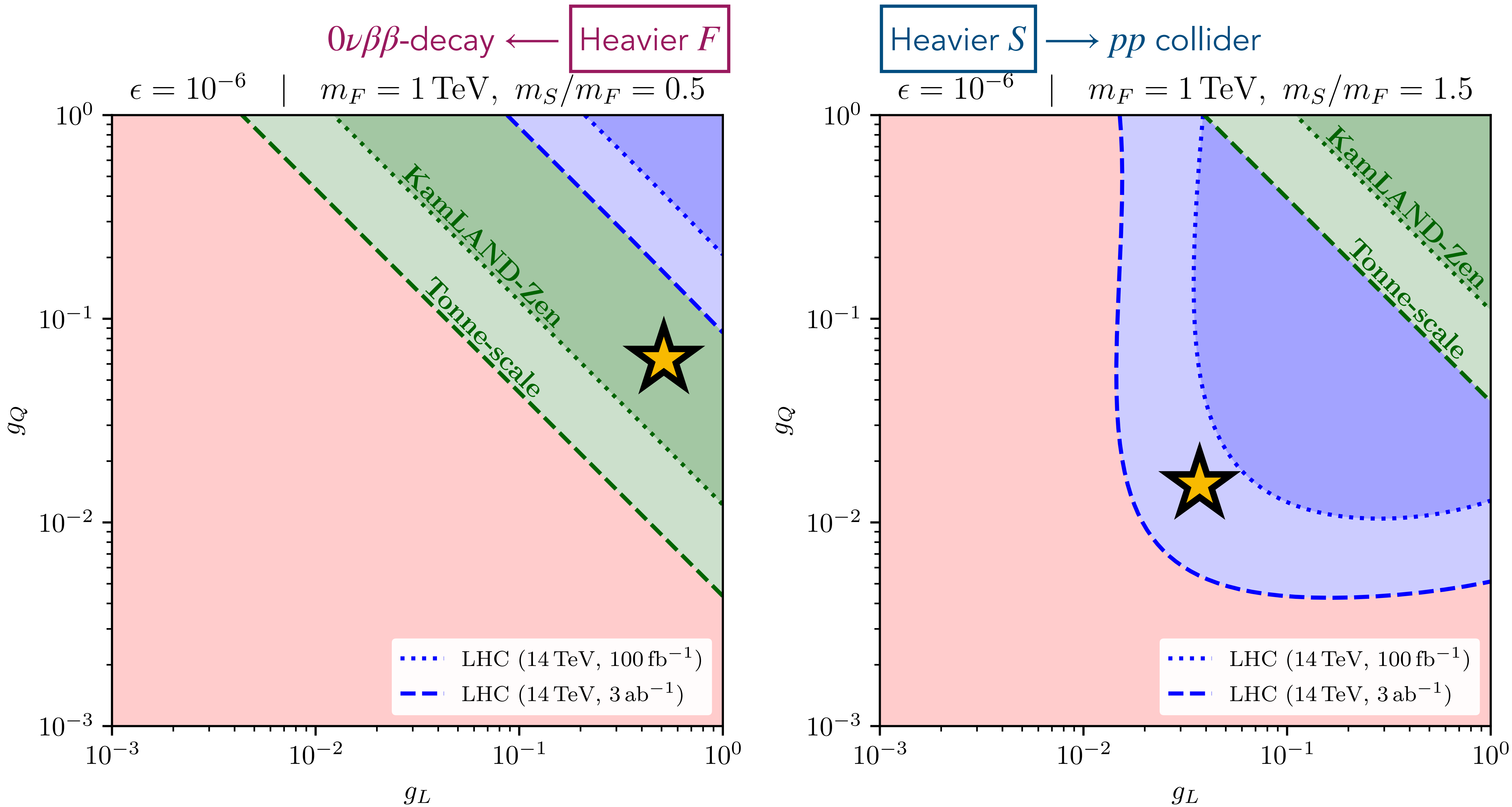




(Thanks! M. Ramsey-Musolf)

TeV-scale LNV effects: Results

- Impact of $0\nu\beta\beta$-decay **and/or** collider searches on leptogenesis
- Both searches provide complementary sensitivity!



Takeaways

- The observation of an LNV signal at the Large Hadron Collider (LHC) and/or a future 100 TeV pp collider would preclude the viability of standard thermal leptogenesis

- The observation of $0\nu\beta\beta$-decay could also rule out the standard leptogenesis paradigm, assuming the $0\nu\beta\beta$-decay amplitude is dominated by the TeV-scale LNV mechanism

- The relative reaches of $0\nu\beta\beta$-decay and collider LNV searches depends decisively on the new particle spectrum — a feature not readily seen within the previously used pure EFT approach

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Backup Slides

Baryon asymmetry: ingredients

Sakharov conditions (1967)

1. $\mathscr{B}$ violation

   number of $B \neq$ number of $\overline{B}$

   SM Sphalerons ✓

2. C & CP violation

   $\Gamma(A + B \to C) \neq \Gamma(\overline{A} + \overline{B} \to \overline{C})$

   SM CKM CPV ✗

3. Non-equilibrium dynamics*

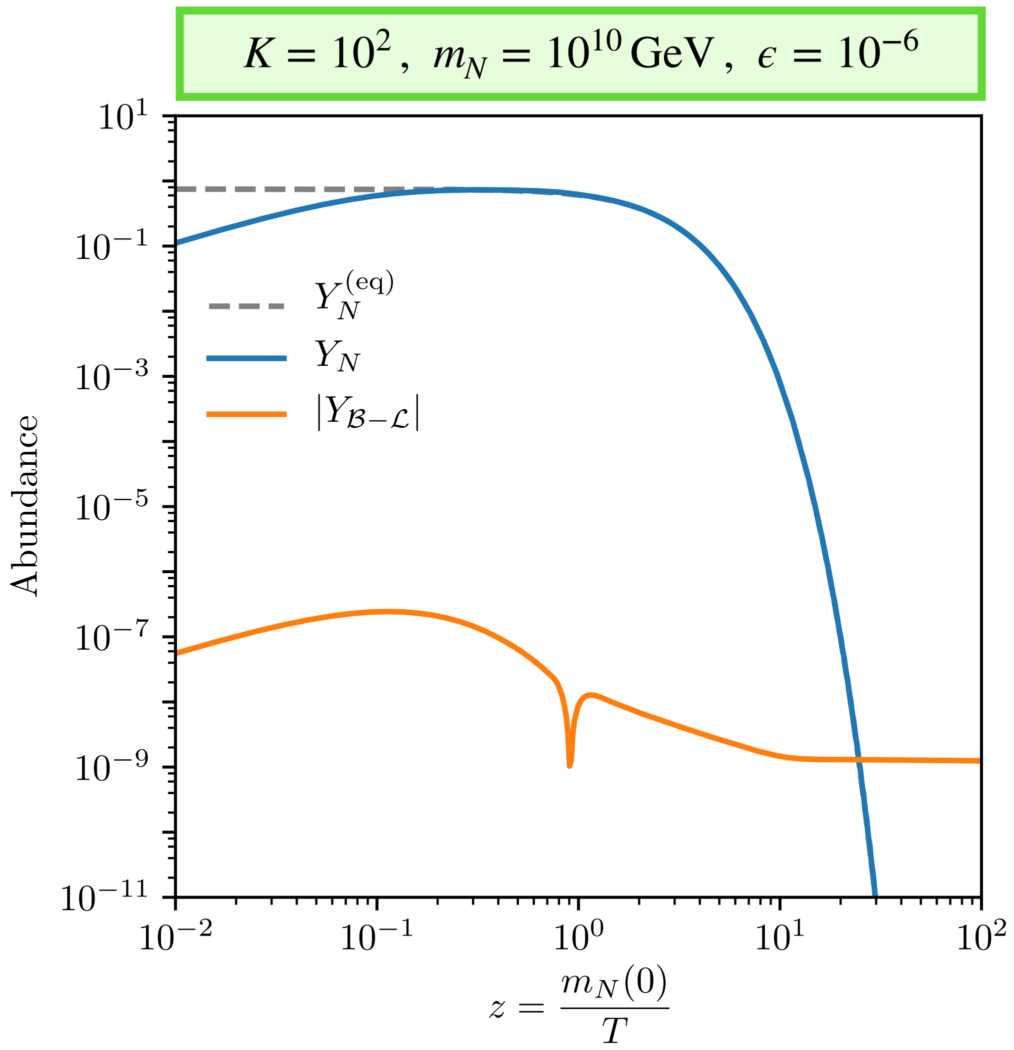
   Prevent washout by inverse processes

   SM EWPT ✗

New physics!

Boltzmann Equations

The dynamics is described by Boltzmann equations:



Scattering

Decay

$$\frac{dY_N}{dz} = -\left(D + S\right)\left(Y_N - Y_N^{(\mathrm{eq})}\right)$$

$$\frac{dY_{\mathscr{B}-\mathscr{L}}}{dz} = -\epsilon\, D \left(Y_N - Y_N^{(\mathrm{eq})}\right) - W\, Y_{\mathscr{B}-\mathscr{L}}$$

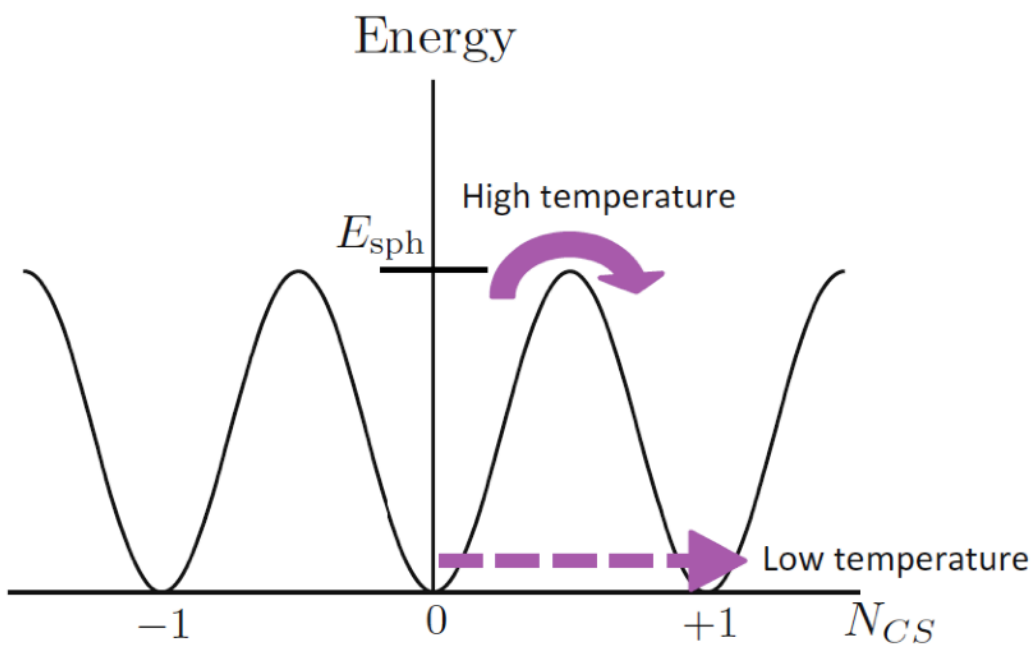
CPV source
(decay)

Washout
(inverse decay, $\Delta\mathscr{L} = 1, 2$)

$Y_X = n_X/s$ (normalized number density)

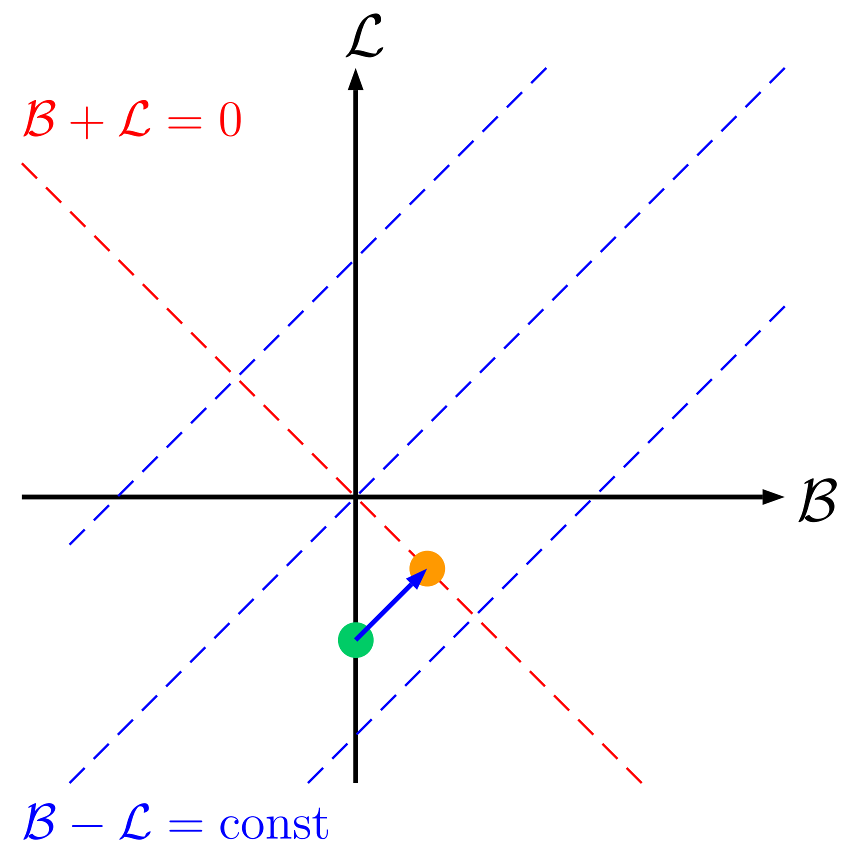
Baryon asymmetry: EW Sphalerons

- In the SM, non-perturbative effects can violate $\mathscr{B}$ and $\mathscr{L}$. This violation is such that $\mathscr{B} - \mathscr{L}$ is conserved (while $\mathscr{B} + \mathscr{L}$ is violated)



Fuyuto (Springer Theses, 2018)

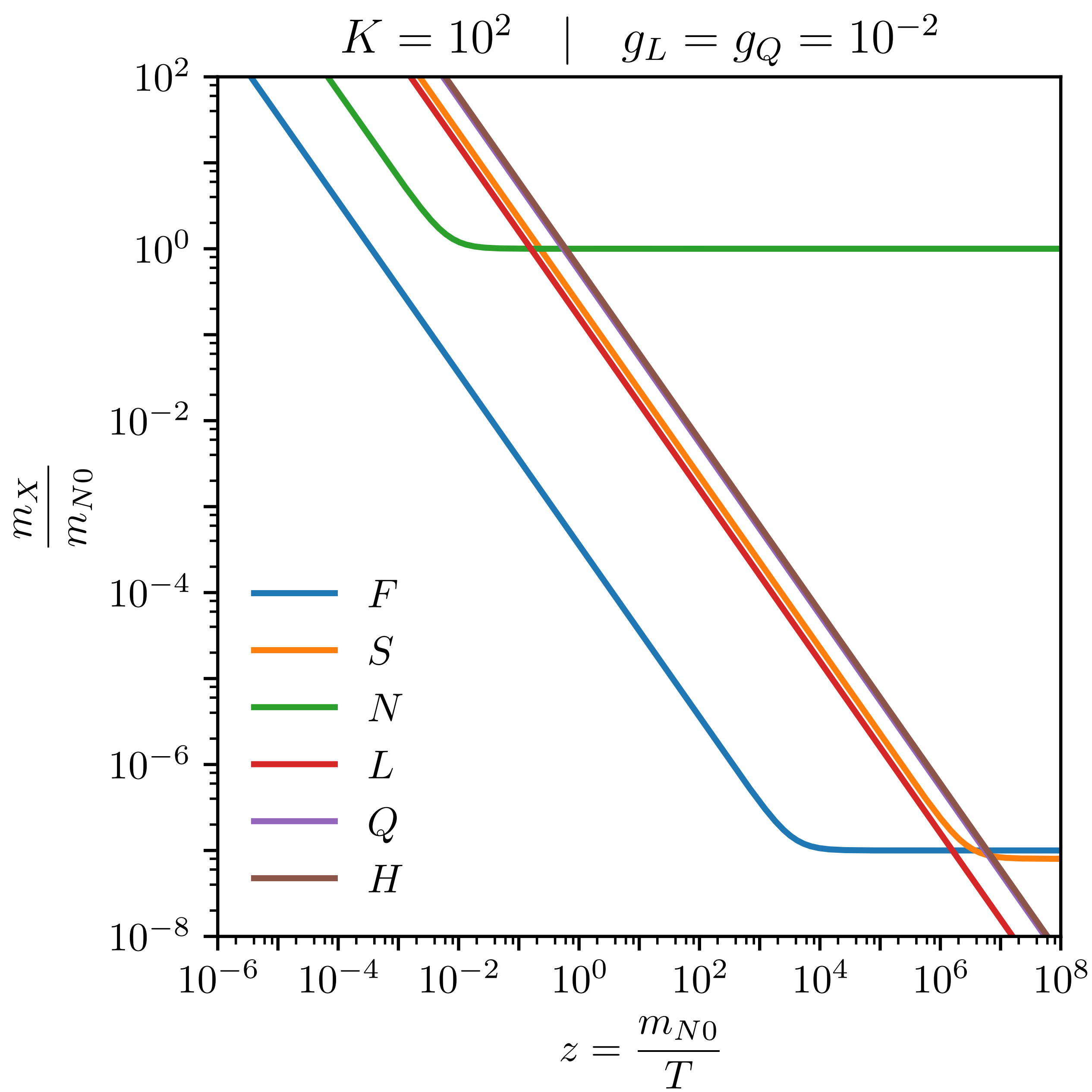
$$\Delta\mathscr{B} = \Delta\mathscr{L} = 3N_{CS}$$



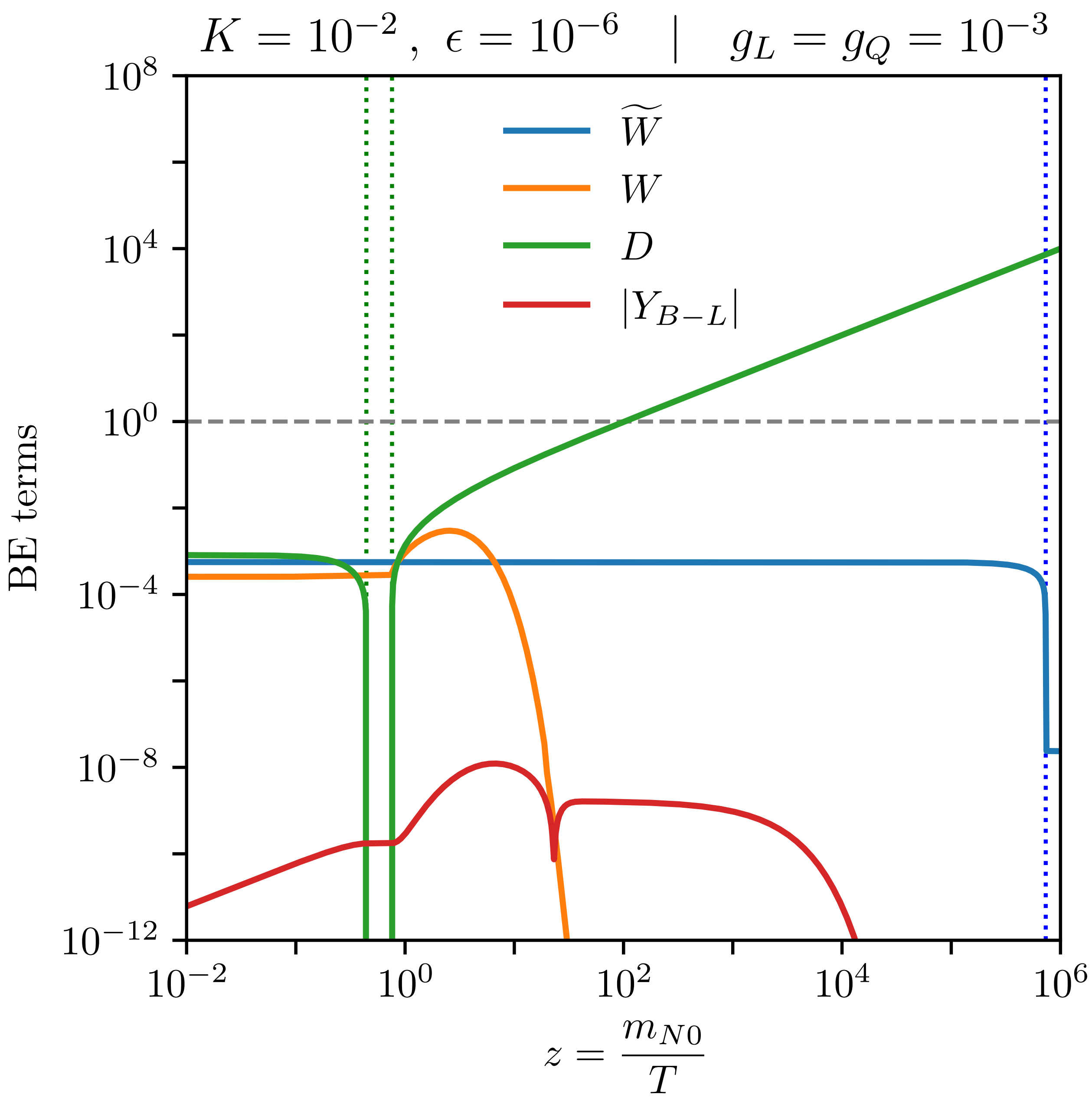
Sphaleron transitions:
- Conserve $\mathscr{B} - \mathscr{L}$
- Wash $\mathscr{B} + \mathscr{L}$ out

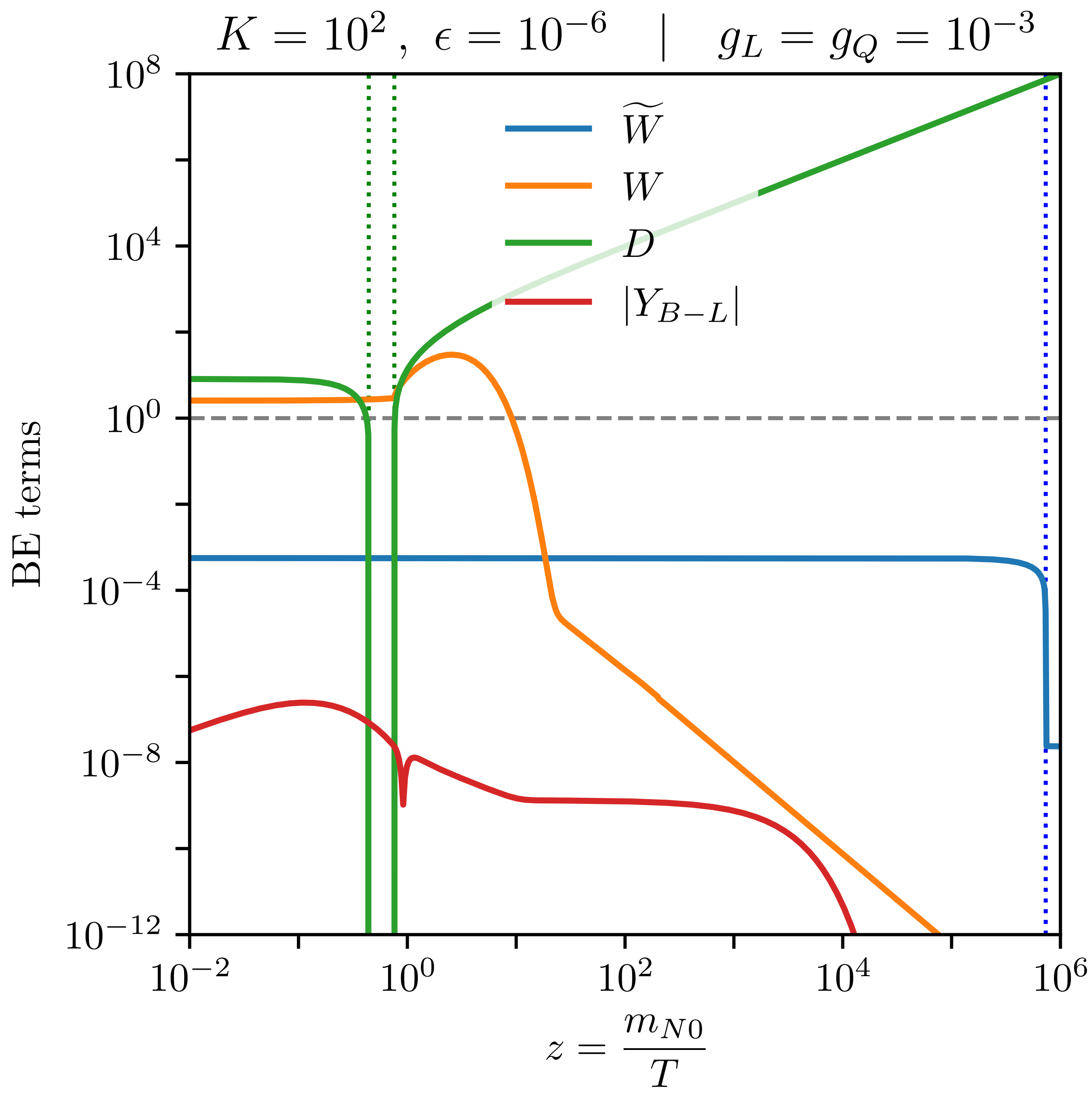
$\mathscr{L}$ asymmetry is reprocessed into $\mathscr{B}$ asymmetry

Leptogenesis with Simplified Model - I



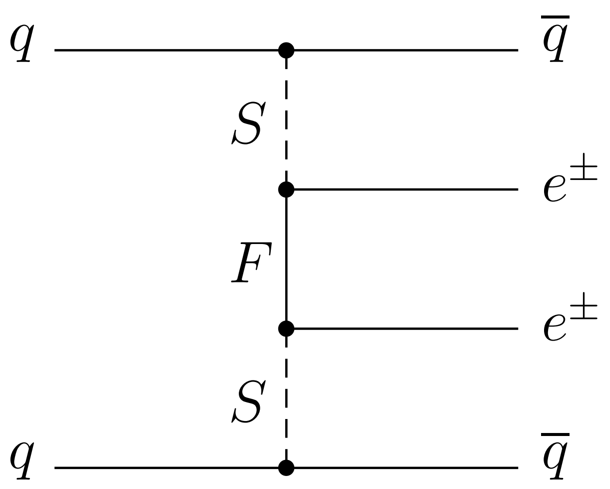
Leptogenesis with Simplified Model - II



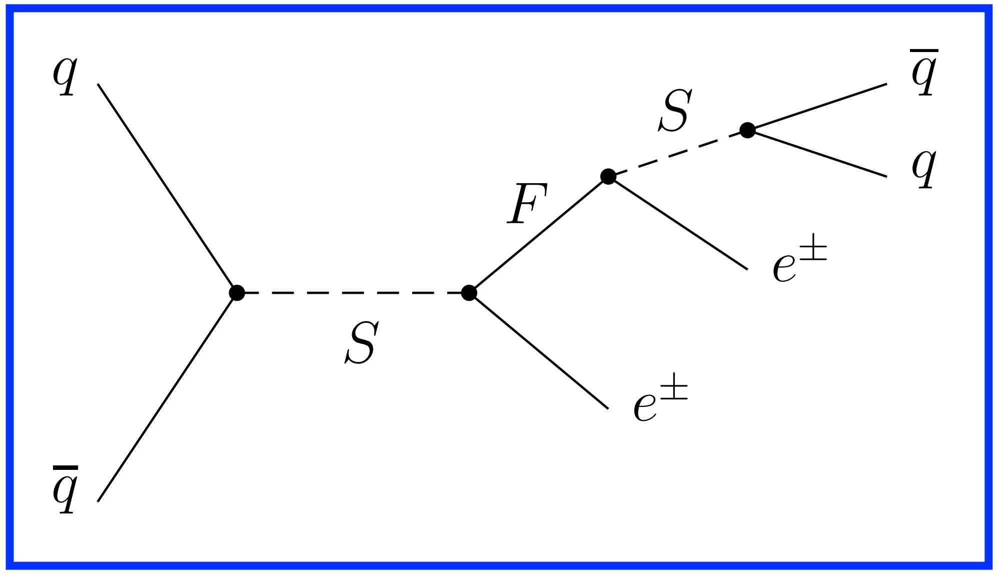


LNV searches at colliders

- **Signal:** two same-sign electrons and two jets, $pp \to jje^{\pm}e^{\pm}$



(a) $t-$channel



Dominant contribution

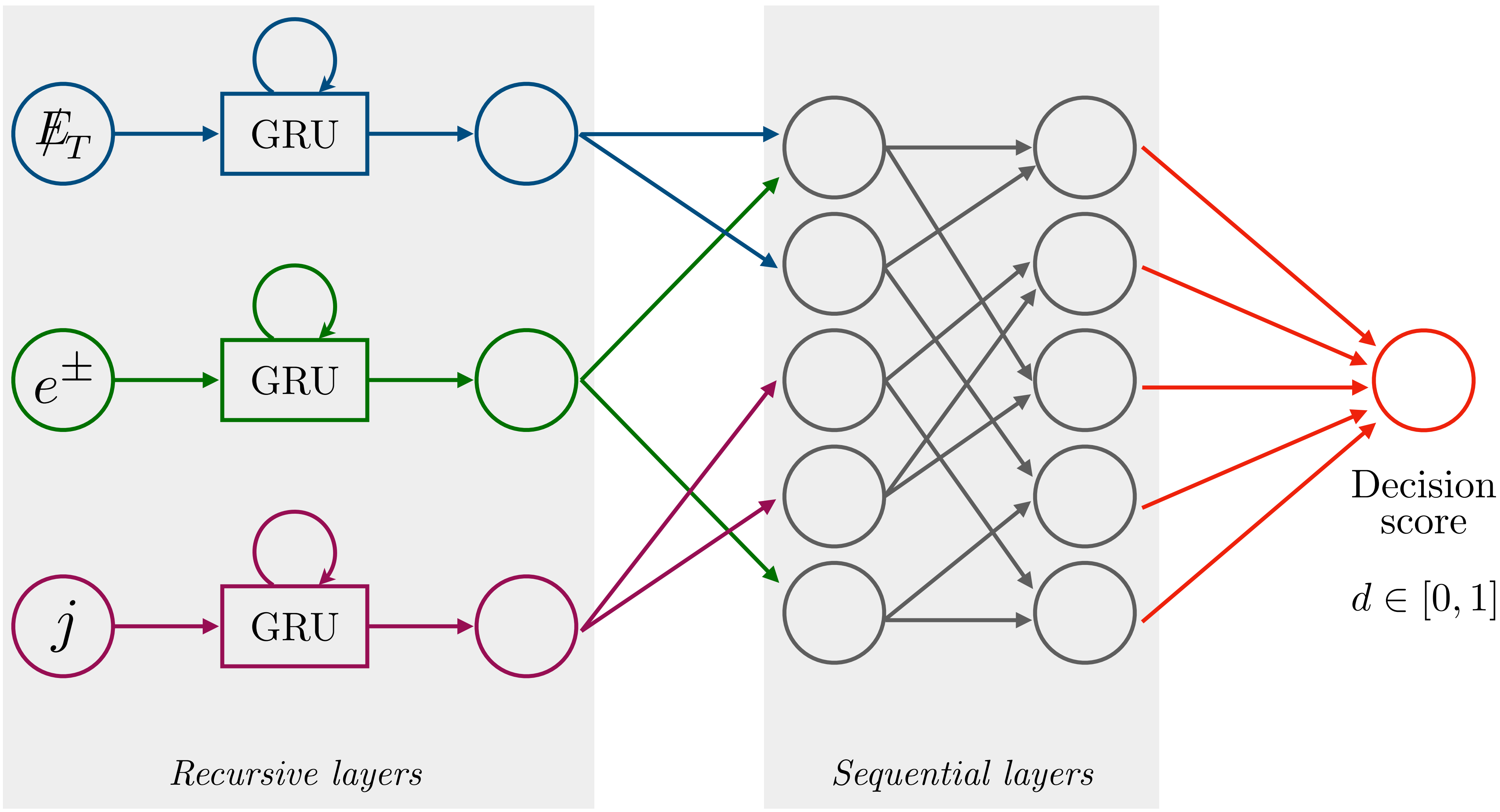
(b) $s-$channel

- **Background:**
  - SM processes with 2SS leptons (e.g., $jjWW, t\bar{t}W, t\bar{t}Z$)
  - Charge misidentification (e.g., $t\bar{t}, Z/\gamma*$)
  - Jet-fakes (e.g., $t\bar{t}, W+3j$)

Dominant contributions

RNN for signal/background discrimination

- Madgraph + Pythia 8 + Delphes for MC simulation
- Neural Networks for signal/background discrimination



Effective operators - I

Prézeau, Ramsey-Musolf, Vogel (2003)

$d = 9$ effective operators ($\mathscr{O}_i \propto \bar{u}\bar{u}dd\bar{e}\bar{e}^c$) contributing to $0\nu\beta\beta-$decay:

$$\mathscr{L}_{0\nu\beta\beta} = \frac{1}{\Lambda^5}\left\{\left(o_1\mathcal{O}_{1+}^{++} + o_2\mathcal{O}_{2+}^{++} + o_3\mathcal{O}_{2-}^{++} + o_4\mathcal{O}_{3+}^{++} + o_5\mathcal{O}_{3-}^{++}\right)\bar{e}e^c + \left(o_6\mathcal{O}_{1+}^{++} + o_7\mathcal{O}_{2+}^{++} + o_8\mathcal{O}_{2-}^{++} + o_9\mathcal{O}_{3+}^{++} + o_{10}\mathcal{O}_{3-}^{++}\right)\bar{e}\gamma_5 e^c + \left(o_{11}\mathcal{O}_{4+}^{++,\mu} + o_{12}\mathcal{O}_{4-}^{++,\mu} + o_{13}\mathcal{O}_{5+}^{++,\mu} + o_{14}\mathcal{O}_{5-}^{++,\mu}\right)\bar{e}\gamma_\mu\gamma_5 e^c + \text{h.c.}\right\}$$

$$\mathcal{O}_{1+}^{ab} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_R\tau^b\gamma_\mu q_R)\ ,$$

$$\mathcal{O}_{2\pm}^{ab} = (\bar{q}_R\tau^a q_L)(\bar{q}_R\tau^b q_L) \pm (\bar{q}_L\tau^a q_R)(\bar{q}_L\tau^b q_R)\ ,$$

$$\mathcal{O}_{3\pm}^{ab} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_L\tau^b\gamma_\mu q_L) \pm (\bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_R\tau^b\gamma_\mu q_R)\ ,$$

$$\mathcal{O}_{4\pm}^{ab,\mu} = (\bar{q}_L\tau^a\gamma^\mu q_L \mp \bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_L\tau^b q_R - \bar{q}_R\tau^b q_L)\ ,$$

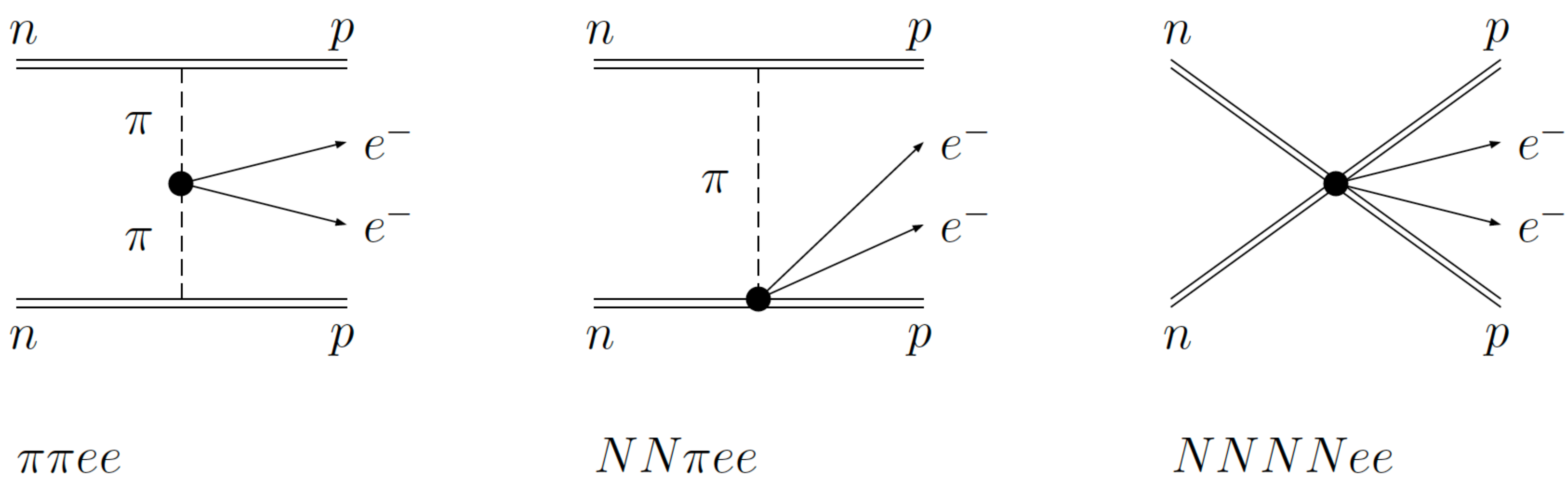
$$\mathcal{O}_{5\pm}^{ab,\mu} = (\bar{q}_L\tau^a\gamma^\mu q_L \pm \bar{q}_R\tau^a\gamma^\mu q_R)(\bar{q}_L\tau^b q_R + \bar{q}_R\tau^b q_L)\ .$$

Different combinations of 4 quarks and 2 electrons

Operators $\longleftrightarrow$ Models

Effective operators - II

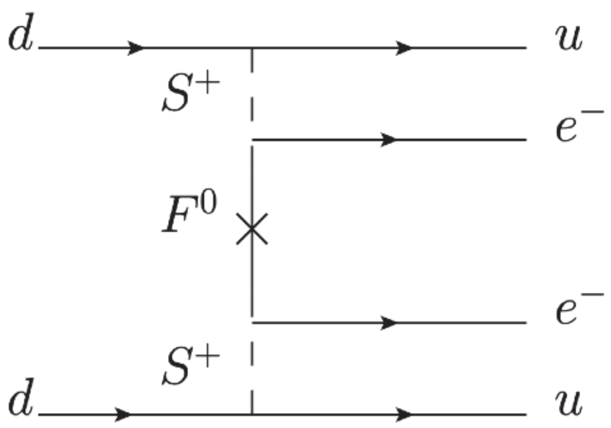
Prézeau, Ramsey-Musolf, Vogel (2003)

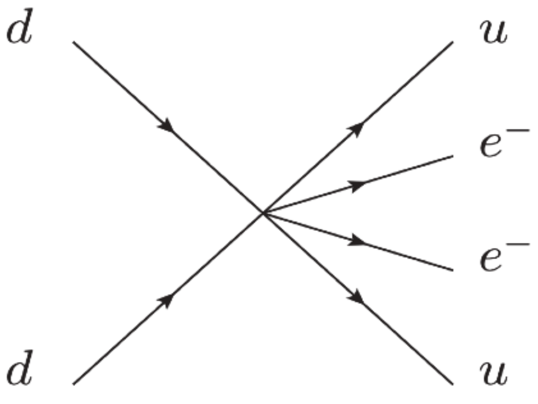


Operator	$\mathcal{O}_{1+}^{\pm\pm}$	$\mathcal{O}_{2+}^{\pm\pm}$	$\mathcal{O}_{2-}^{\pm\pm}$	$\mathcal{O}_{3+}^{\pm\pm}$	$\mathcal{O}_{3-}^{\pm\pm}$	$\mathcal{O}_{4+}^{\pm\pm,\mu}$	$\mathcal{O}_{4-}^{\pm\pm,\mu}$	$\mathcal{O}_{5+}^{\pm\pm,\mu}$	$\mathcal{O}_{5-}^{\pm\pm,\mu}$
$\pi\pi ee$ LO	✓	✓	✗	✗	✗	✗	✗	✗	✗
$\pi\pi ee$ NNLO	✓	✓	✗	✓	✗	✗	✗	✗	✗
$NN\pi ee$ LO	✗	✗	✓	✗	✗	✓	✓	✓	✓
$NN\pi ee$ NLO	✗	✓	✗	✓	✗	✓	✓	✓	✓
$NNNNee$ LO	✓	✓	✗	✓	✗	✓	✓	✓	✓

Simplified models ↦ Effective operators - I

1. Obtain the $0\nu\beta\beta-$decay operator after integrating out heavy d.o.f:
   $\mathcal{O} \propto \bar{u}d\bar{u}d\bar{e}e^c$





$\mathcal{O}_{\text{SimpMod}}$

$$\mathscr{L}(q,e) = \frac{{G_F}^2}{\Lambda_{\beta\beta}} \sum_i C_i \mathcal{O}_i \,\bar{e}\Gamma_i e^c + \text{h.c.}$$

C_i: Wilson coefficients

$\mathcal{O}_i$: $dim-9$ LNV effective operators

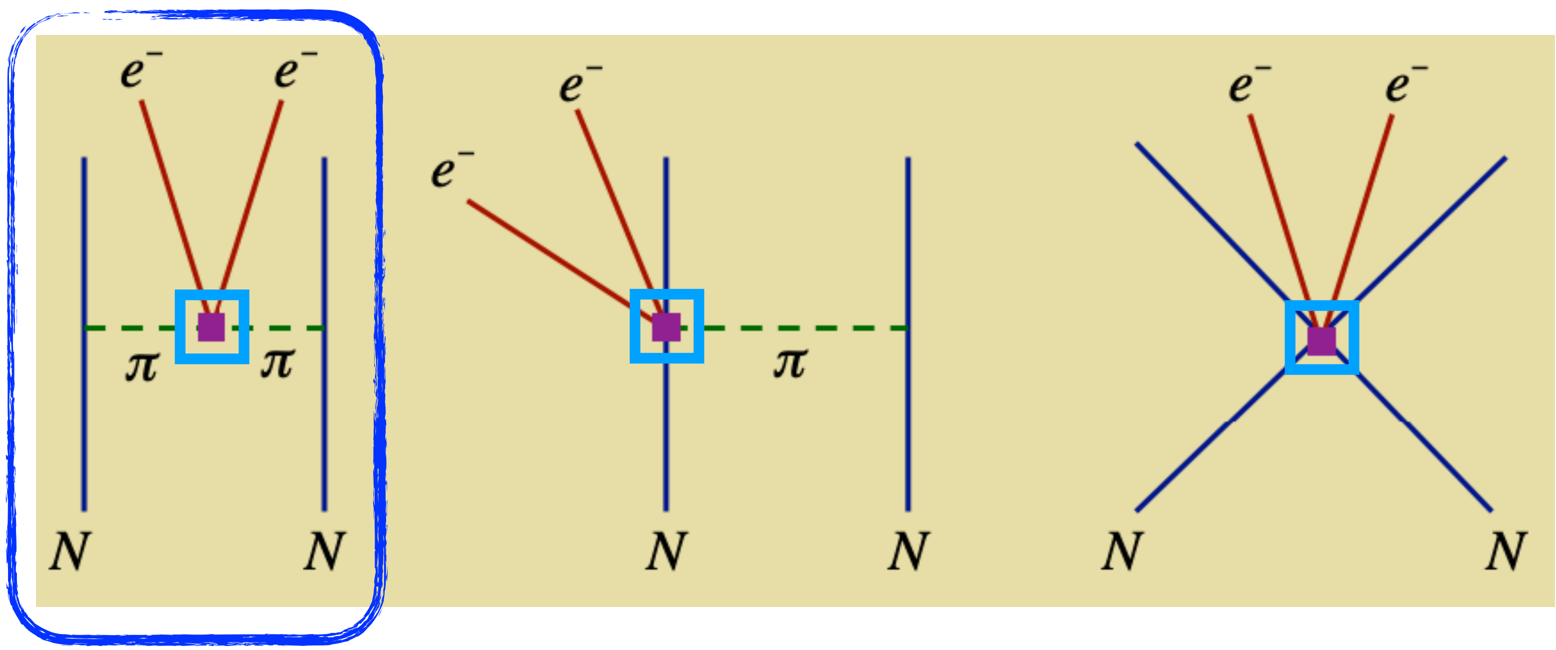
Prezeau *et al.* (2003)
Graesser (2016)
Cirigliano *et al.* (2017, 2018)

Simplified models ↦ Effective operators - II

2. Match quark-electron operators onto two-nucleon operators

$$\mathscr{L}(q,e) = \frac{{G_F}^2}{\Lambda_{\beta\beta}} \sum_i C_i \mathcal{O}_i \, \overline{e}\Gamma_i e^c + \text{h.c.}$$

Chiral symmetry: $\mathscr{O}_i \mapsto \mathscr{L}(\pi, N)$

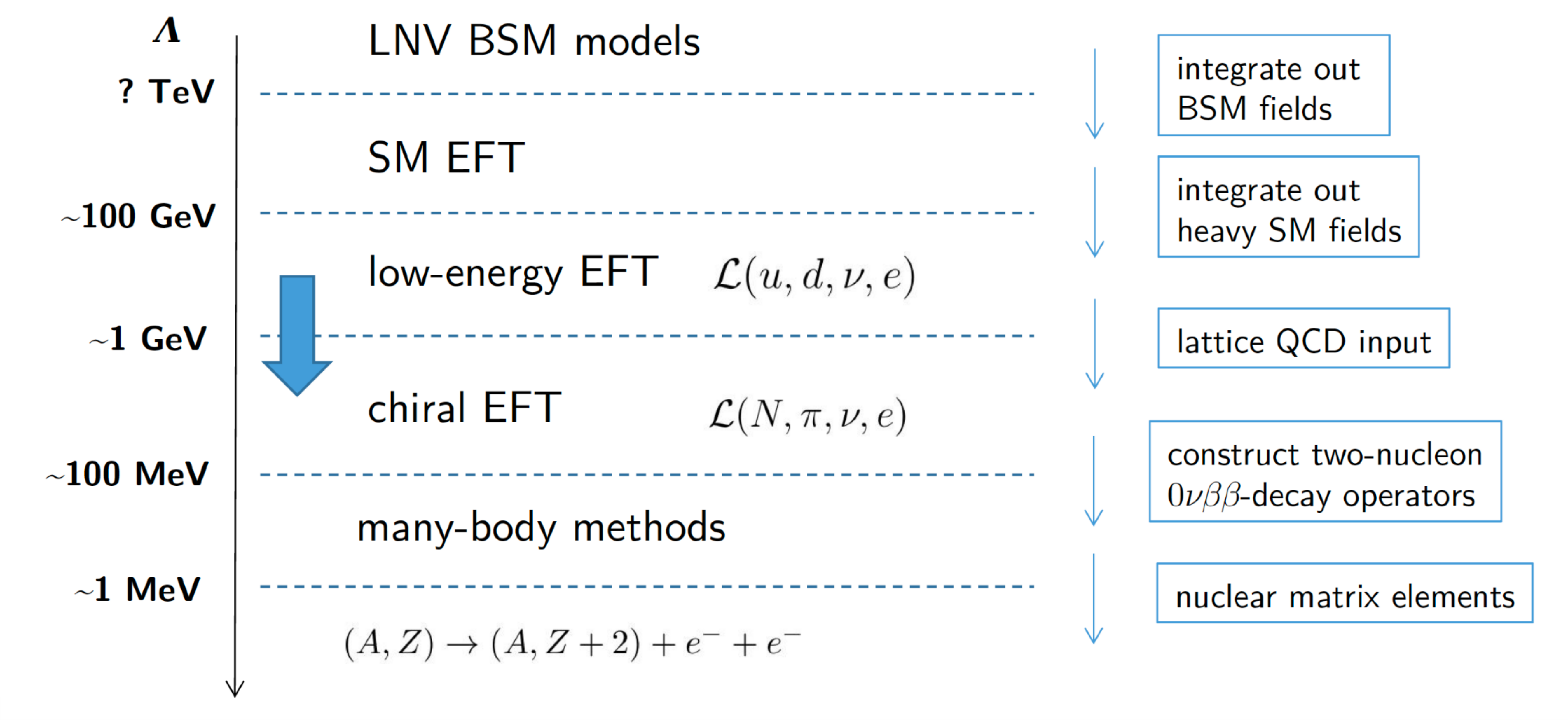


TeV LNV

Model O2: LO + counterterm Cirigliano *et al.* (2018)

(Thanks! M. Ramsey-Musolf)

Simplified models ↦ Effective operators - III

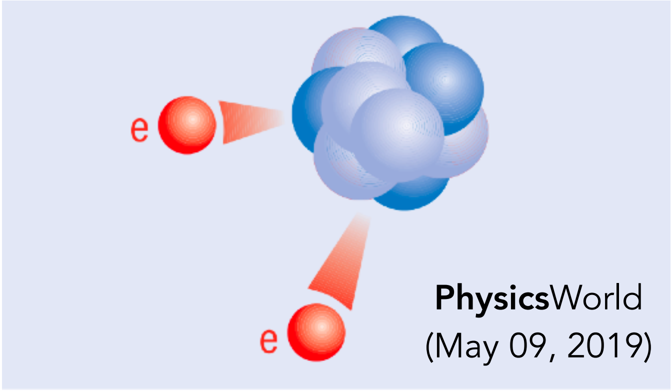


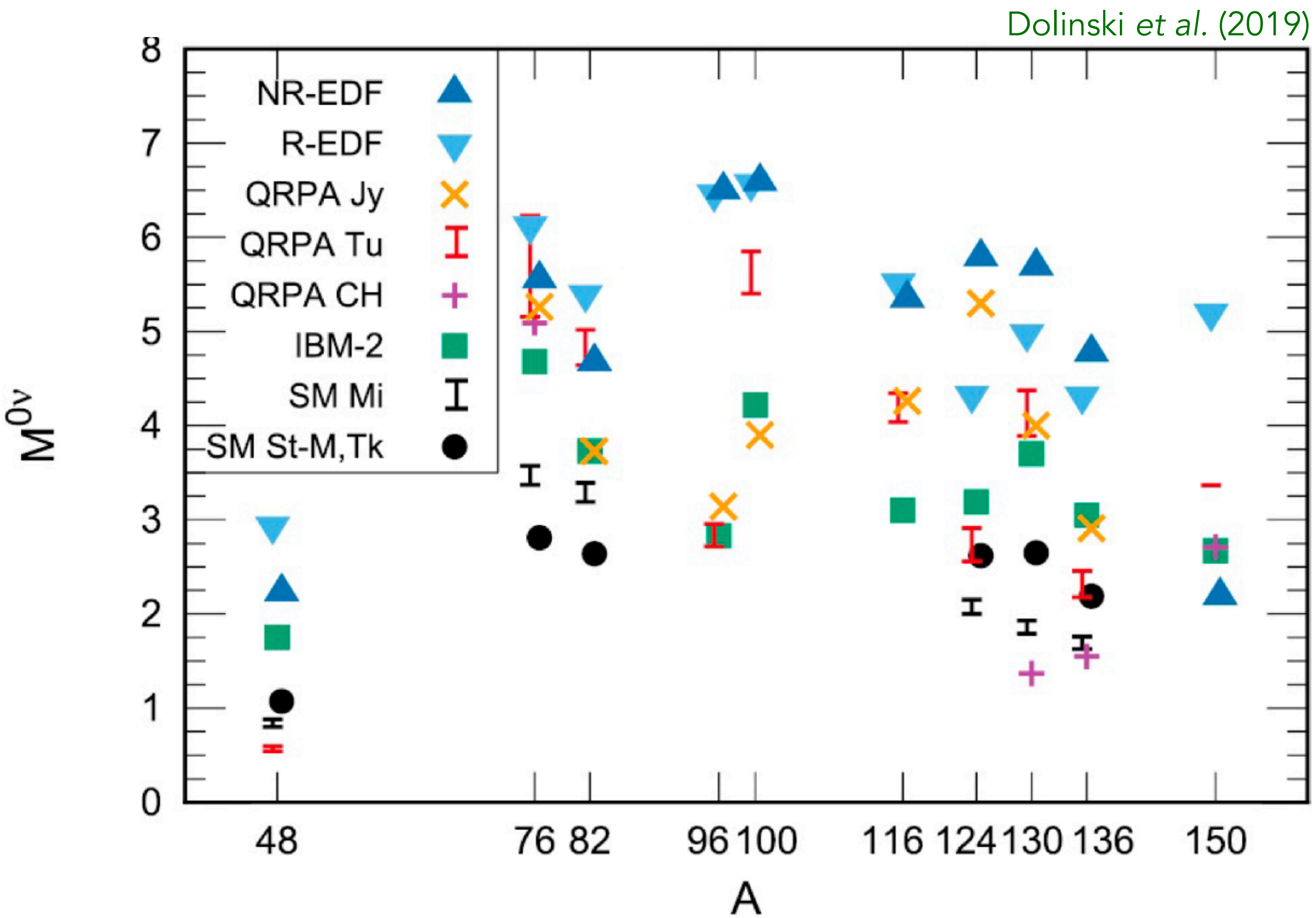
(Thanks! G. Li)

Simplified models ↦ Effective operators - III

3. Using nuclear physics, calculate the half-life

$$T^{0\nu}_{1/2}(g_L, g_Q, m_F, m_S)$$

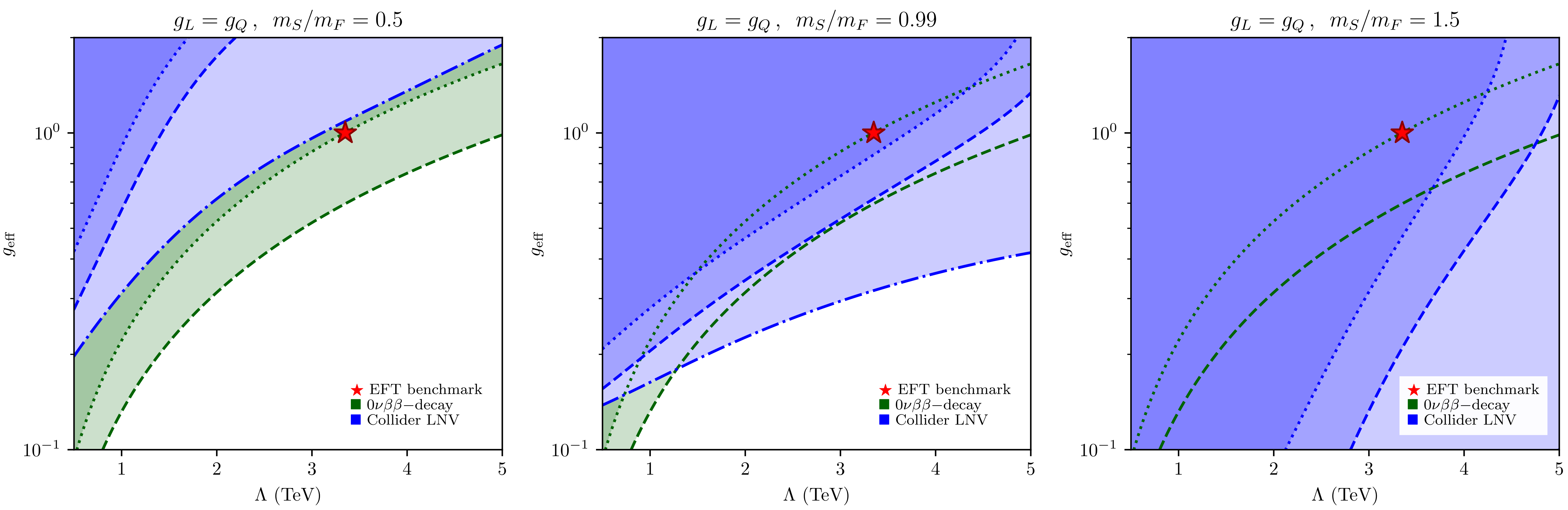




Computing methods:

- EDF: energy-density functional
- QRPA: quasi-particle random phase approximation
- SM: shell model
- IBM: interacting boson model

Comparison with EFT framework



$$\Lambda = (m_S^4\, m_F)^{1/5}\ , \quad g_{\rm eff} = g_L = g_Q$$