AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

TeV-scale lepton number violation: $0\nu\beta\beta-$decay, the origin of matter, and energy frontier probes

Phenomenology 2021 Symposium

May 24 - 26, 2021

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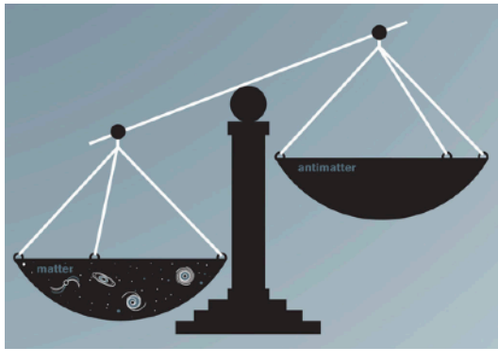
(in collaboration with Julia Harz, Michael Ramsey-Musolf, and Tianyang Shen)

New physics?

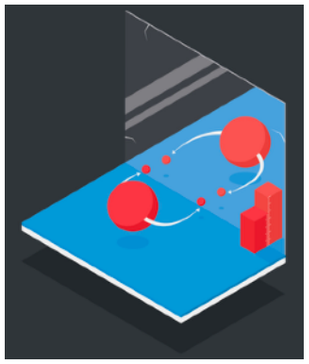


Symmetry magazine
(Oct 2015)

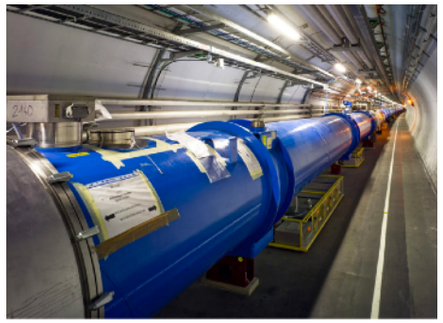
Lepton
Number
Violation

TeV-scale

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

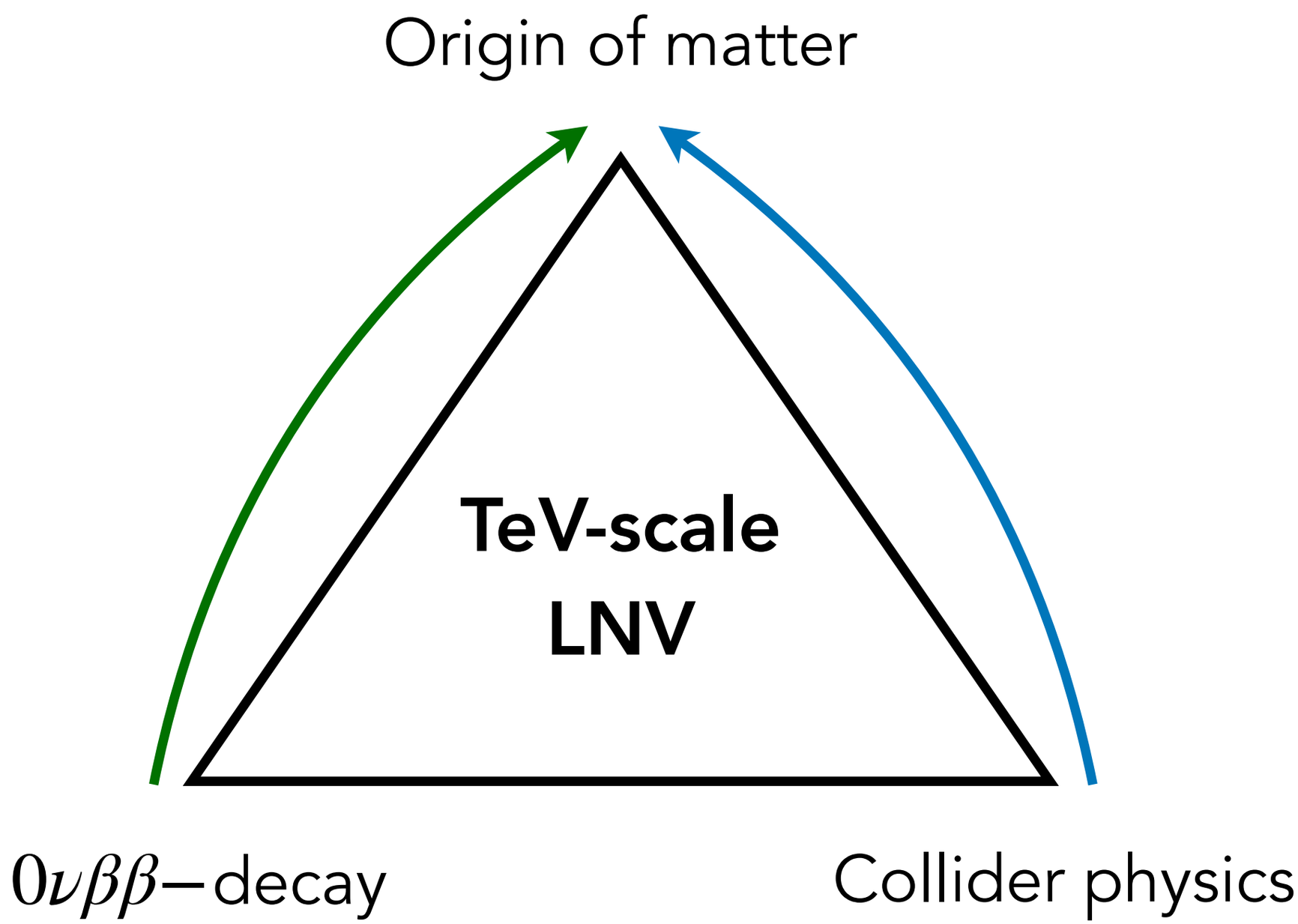


CERN press release
(Mar 2019)



Symmetry magazine
(Aug 2014)

Goal of this talk



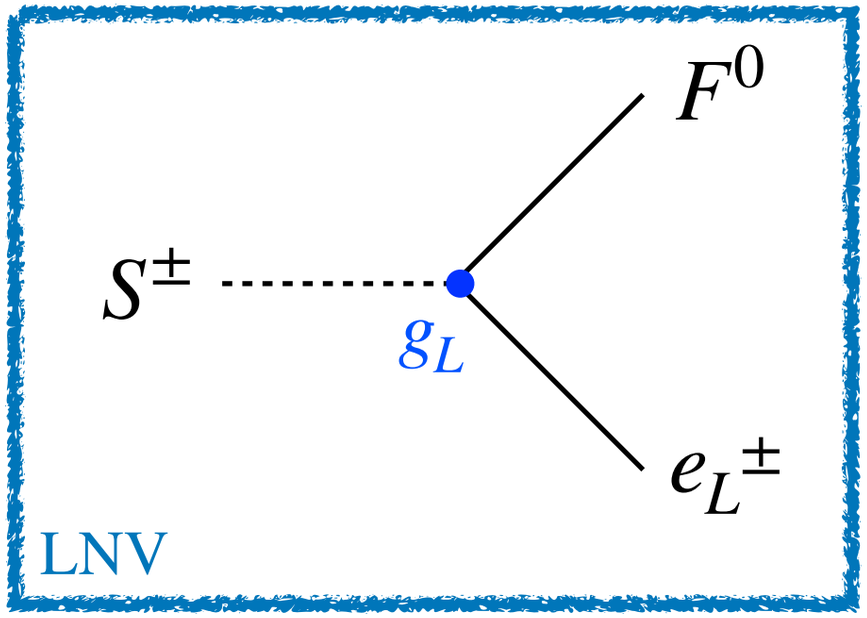
New physics? Model O2

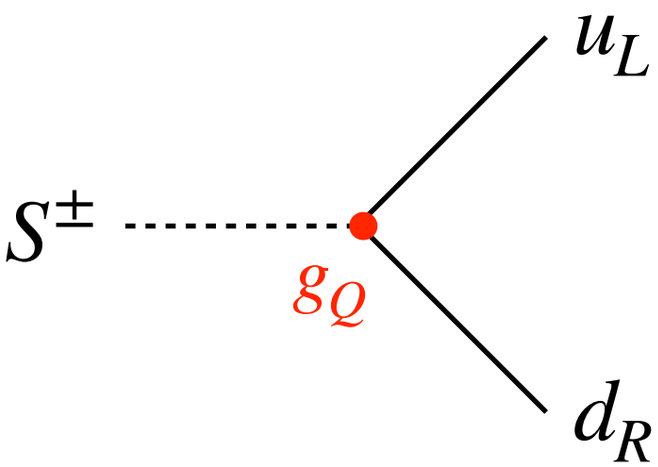
We study a simplified model: **"Model O2"** Peng *et al.* (2015)

$$\text{SM} \; + \; S : (\mathbf{1}, \mathbf{2}, 1/2) \text{ and } F : (\mathbf{1}, \mathbf{1}, 0)$$

$$m_F \, , \, m_S \sim \text{TeV}$$

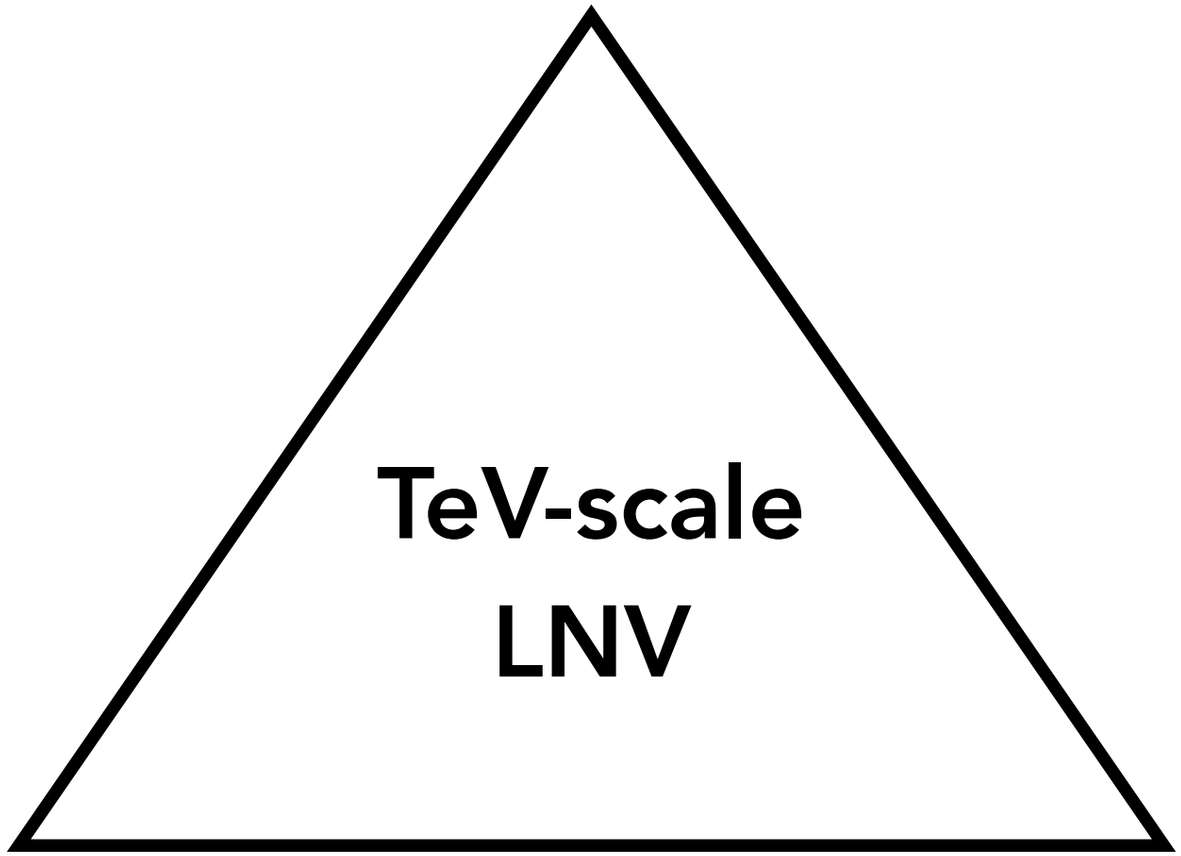
Minimal interactions to illustrate the ideas:





I. TeV-Scale and the Origin of matter

Origin of matter



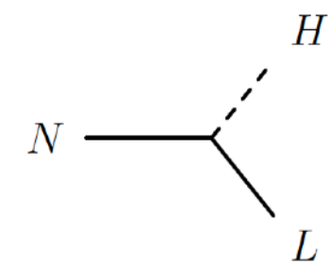
$0\nu\beta\beta-$decay

Collider physics

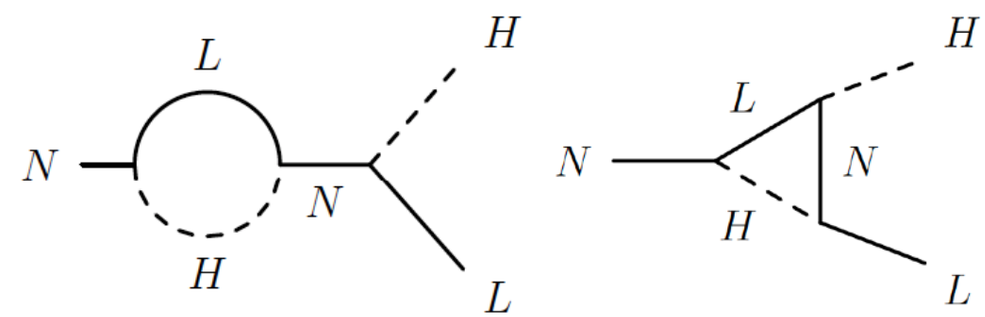
Standard leptogenesis scenario

Fukugita & Yanagida (1986)

- SM + heavy right-handed, Majorana neutrino N:
  Out-of-equilibrium decay, $\Delta\mathscr{L} \neq 0$

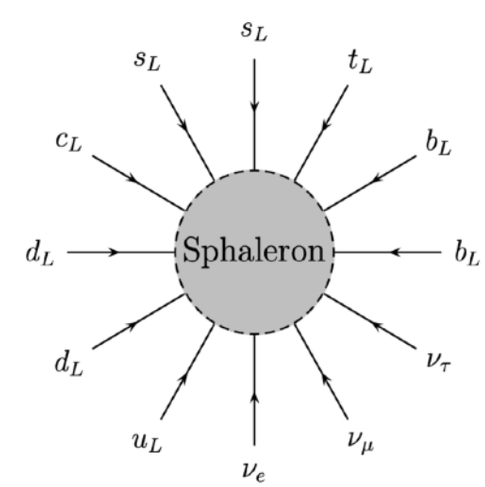


- Quantum corrections:
  $\Gamma(N \to HL) \neq \Gamma(N \to \overline{H}\,\overline{L})$
  $\Rightarrow CP-$violation



- Sphaleron processes: $\Delta\mathscr{L} \to \Delta\mathscr{B}$

Sakharov 1, 2 & 3



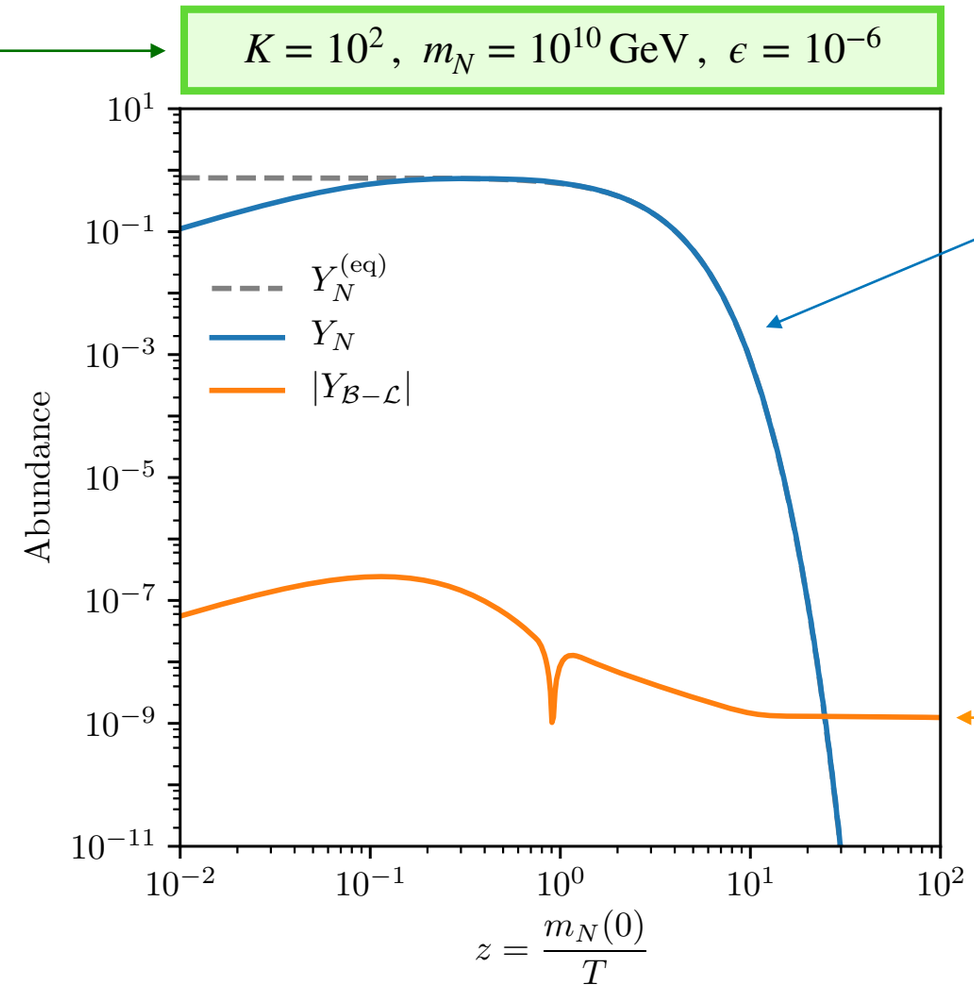
arXiv:hep-ph/9812447

Standard leptogenesis scenario

Fukugita & Yanagida (1986)

- Standard LG works, but requires $m_N \gtrsim 10^9\,\mathrm{GeV}$ Davidson & Ibarra (2002)

Parameters



RHN abundance

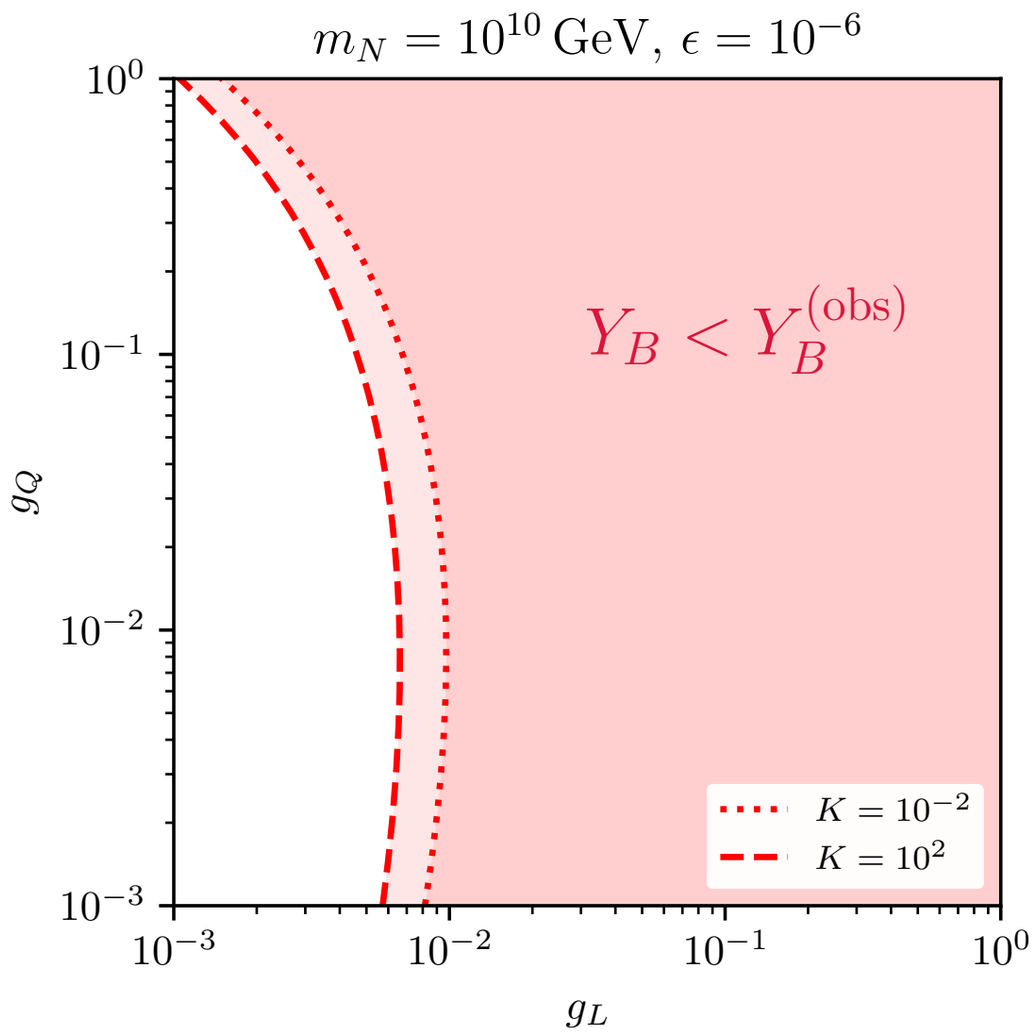
Non-zero final baryonic asymmetry

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

- What if we include accessible TeV-scale effects? **Model O2**

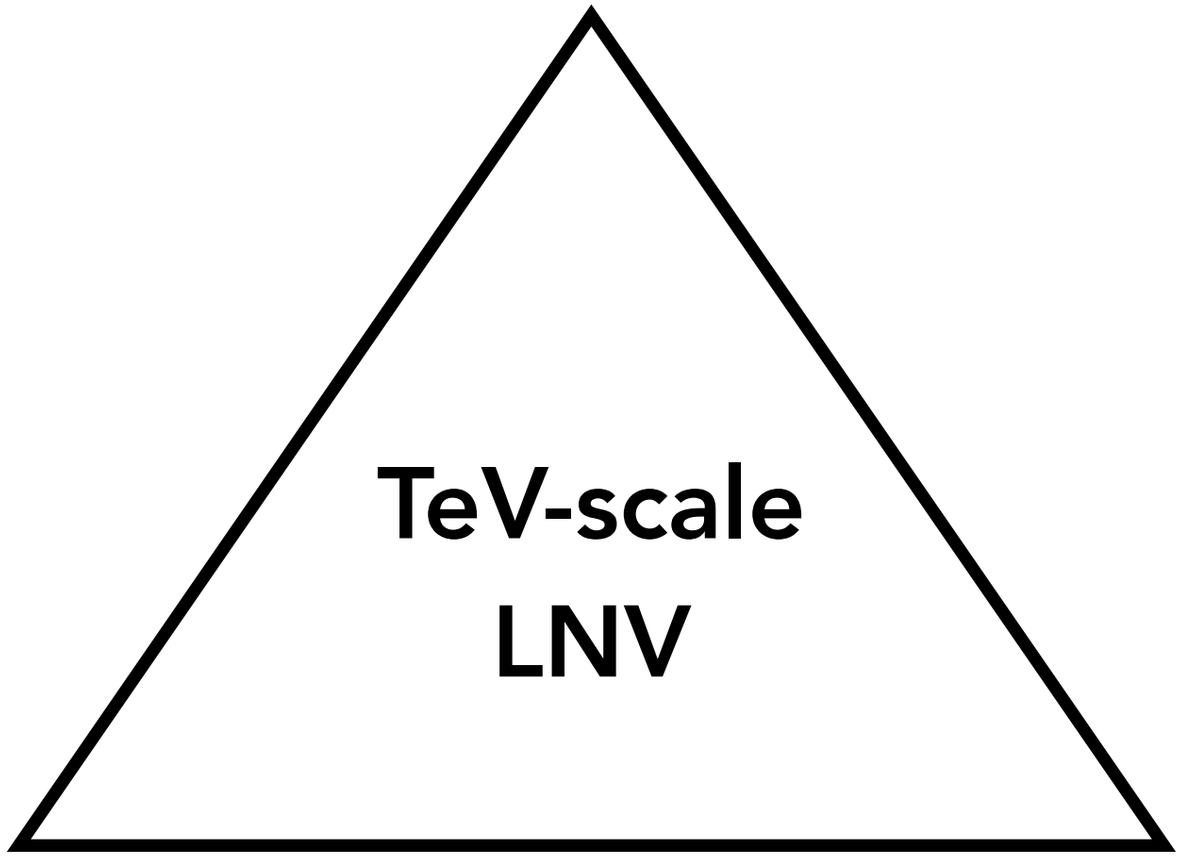
TeV-scale LNV effects

- What if we include accessible TeV-scale effects? **Model O2**



II. TeV-Scale and Energy frontier probes

Origin of matter

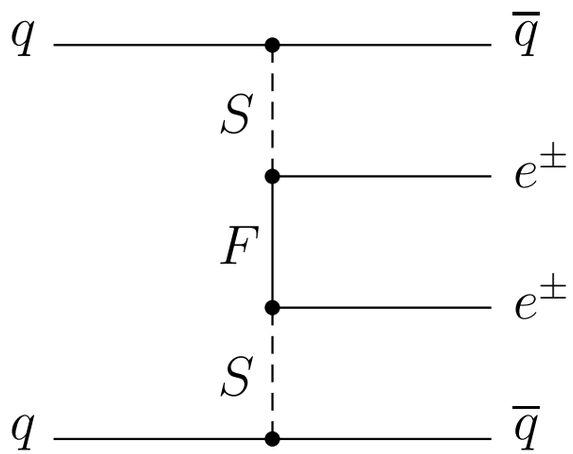


$0\nu\beta\beta-$decay

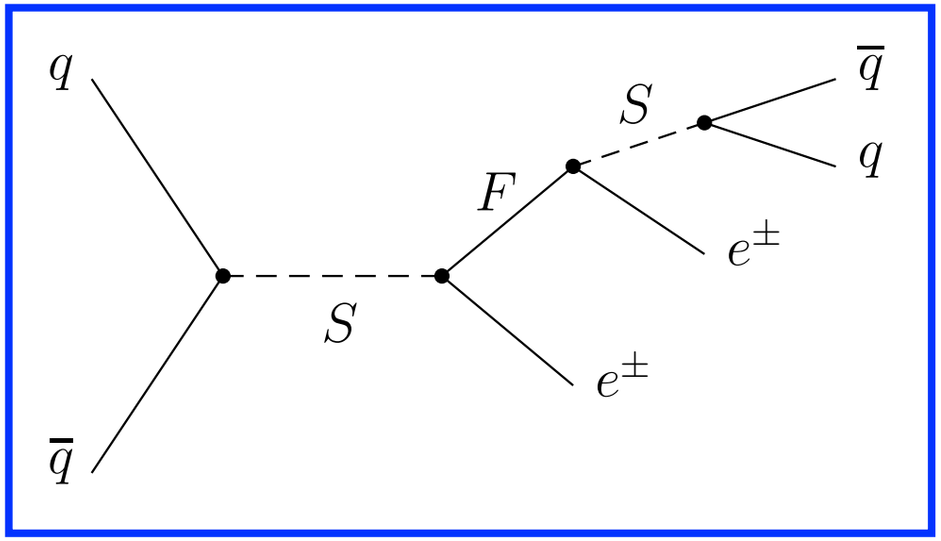
Collider physics

LNV searches at colliders

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



(a) $t-$channel



Dominant contribution

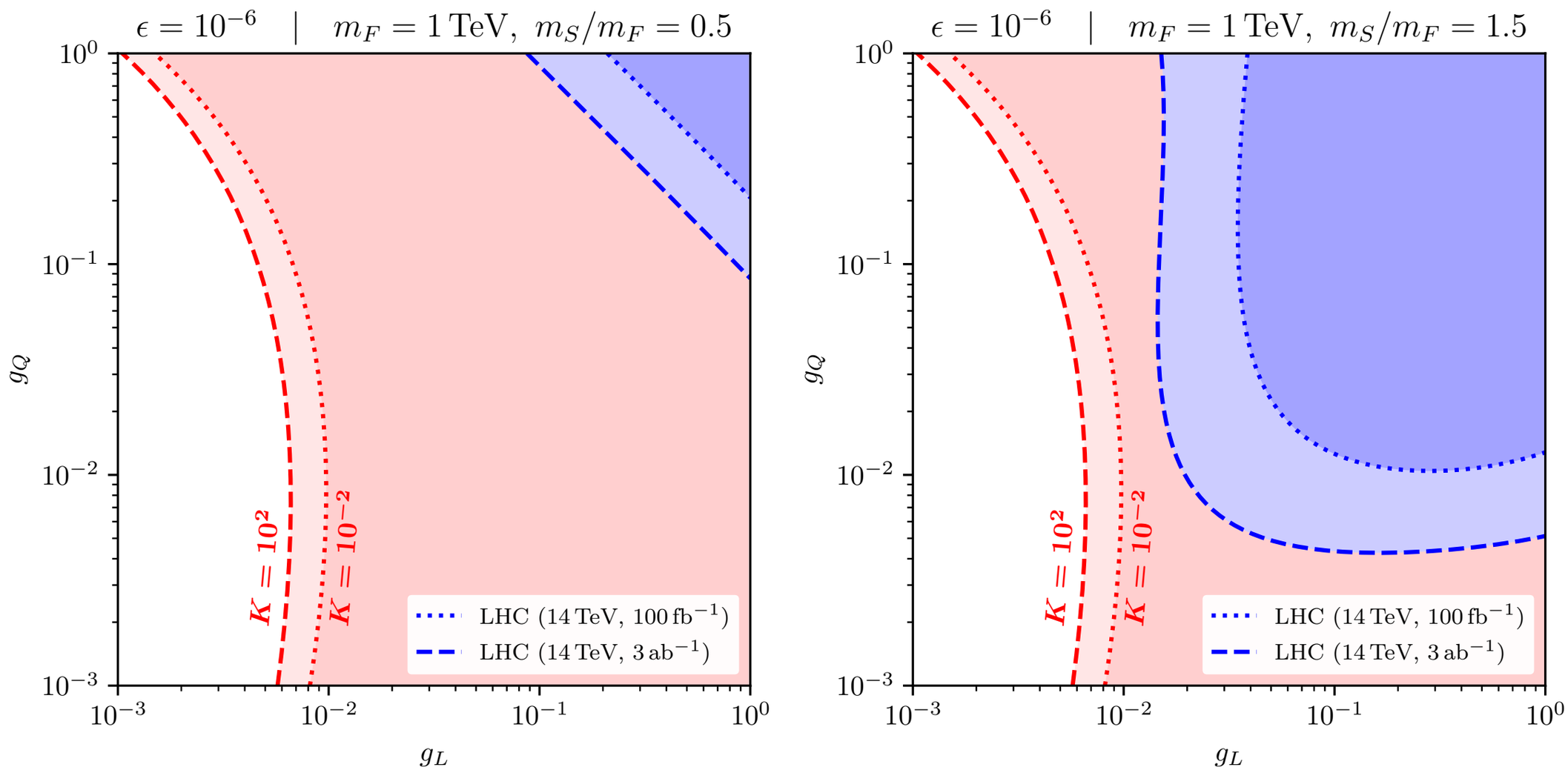
(b) $s-$channel

- **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

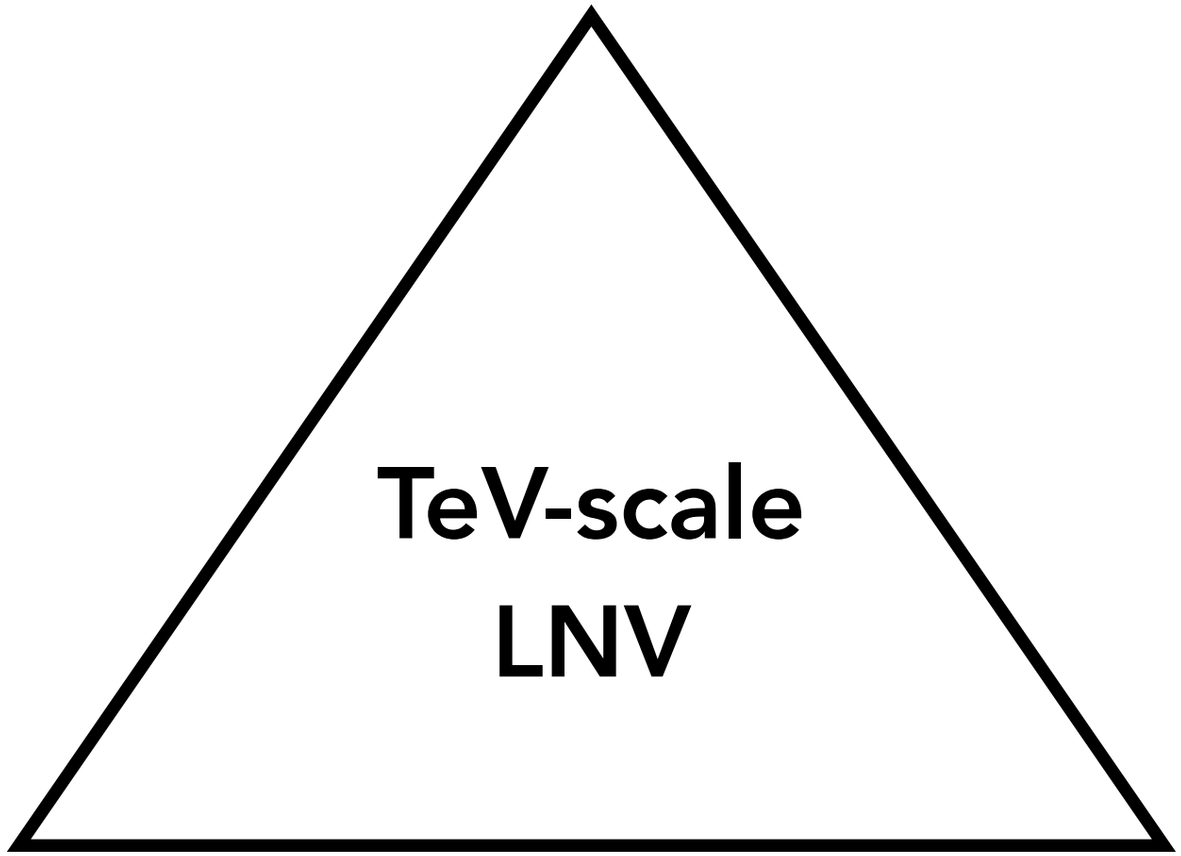
TeV-scale LNV effects

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



III. TeV-Scale and $0\nu\beta\beta-$decay

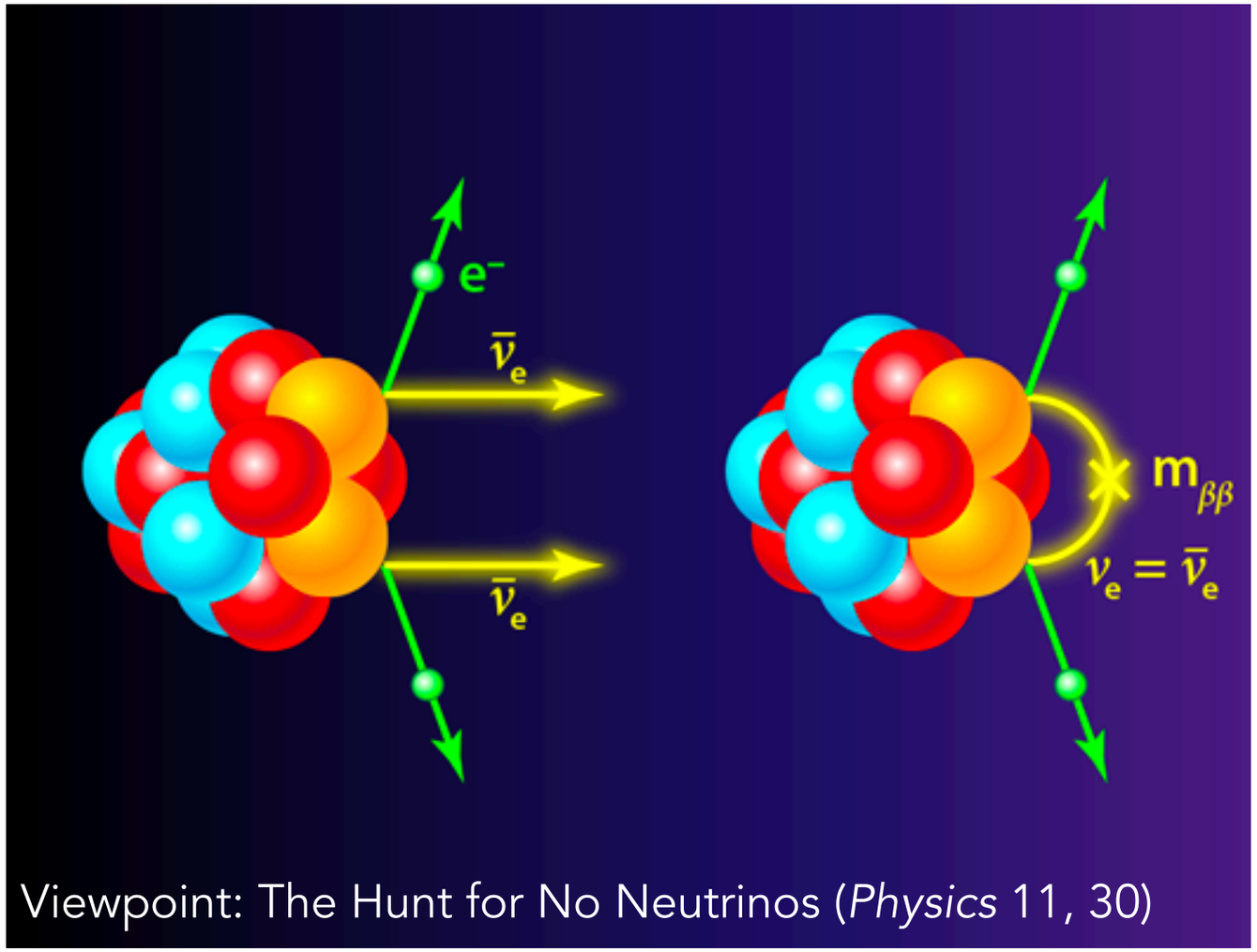
Origin of matter



$0\nu\beta\beta-$decay

Collider physics

$\beta-$decays



Viewpoint: The Hunt for No Neutrinos (*Physics* 11, 30)

$2\nu\beta\beta-$decay

Consistent with SM

Very rare but experimentally tested

$\Delta\mathscr{L} = 0$

$0\nu\beta\beta-$decay

Not allowed in SM

Experimentally unseen

$\Delta\mathscr{L} = 2$

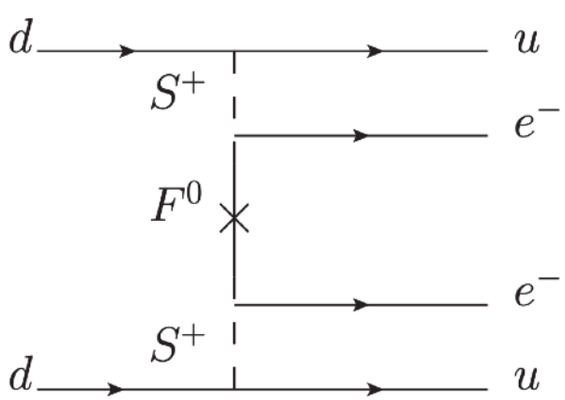
From simplified models to effective operators

0. Find the $0\nu\beta\beta-$decay diagram

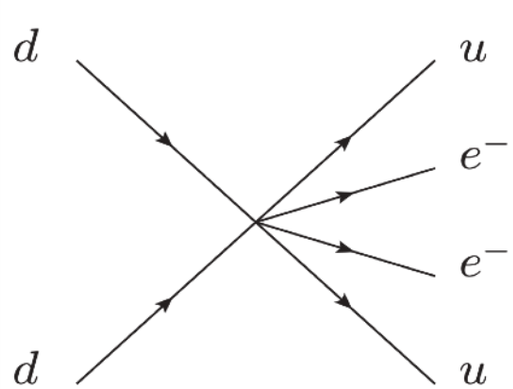
1. Obtain the quark-electron operator after integrating out heavy d.o.f: $\mathcal{O} \propto \bar{u}d\bar{u}d\bar{e}e^c$

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

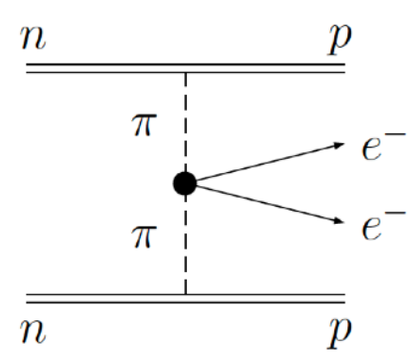
3. Using nuclear physics, calculate the half-life



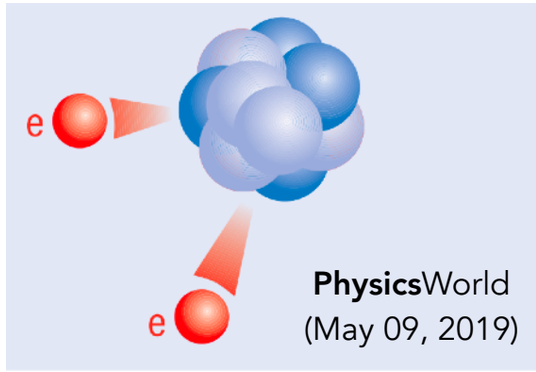
$0\nu\beta\beta$



$\mathcal{O}_{\text{Model O2}}$

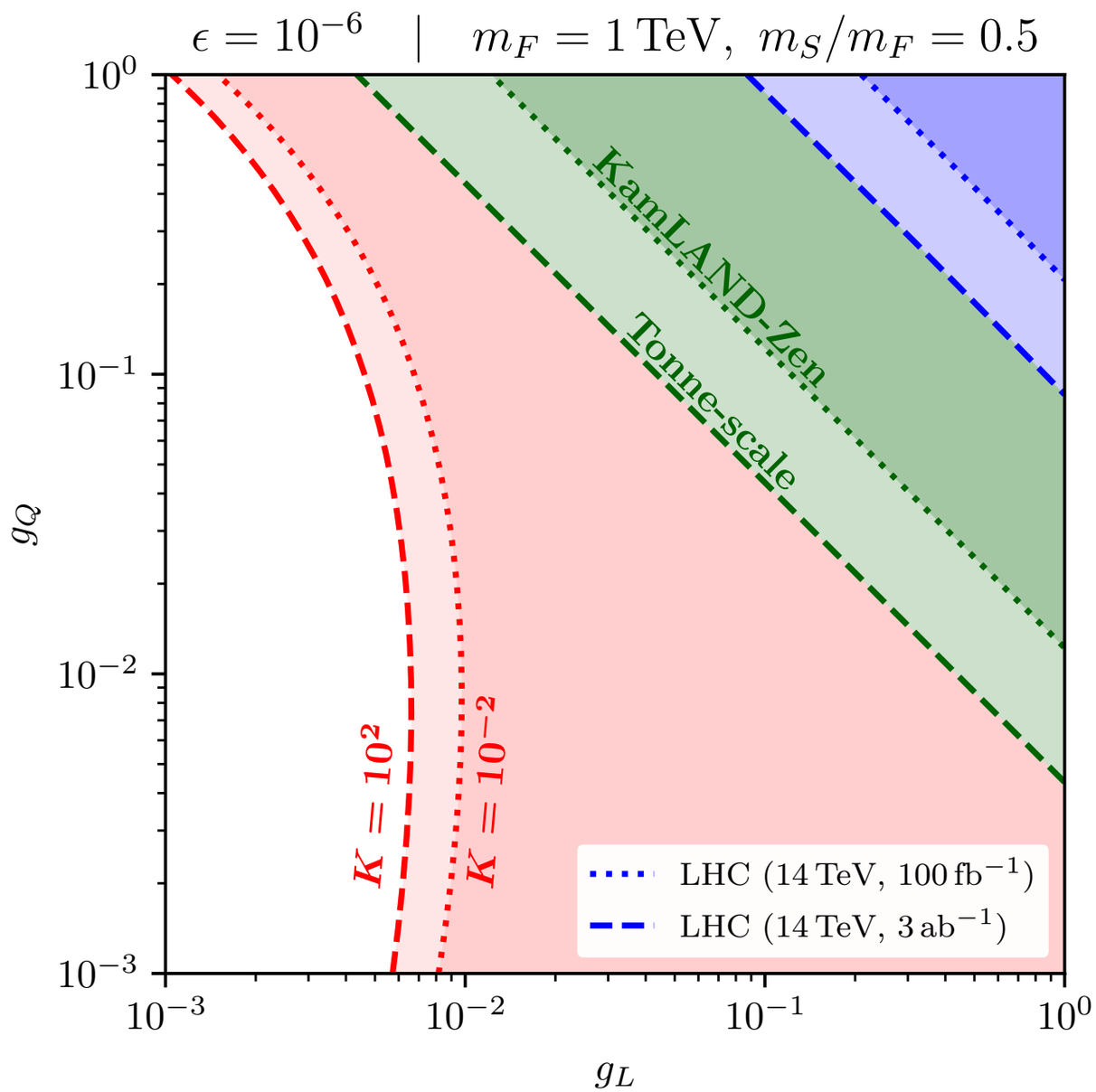


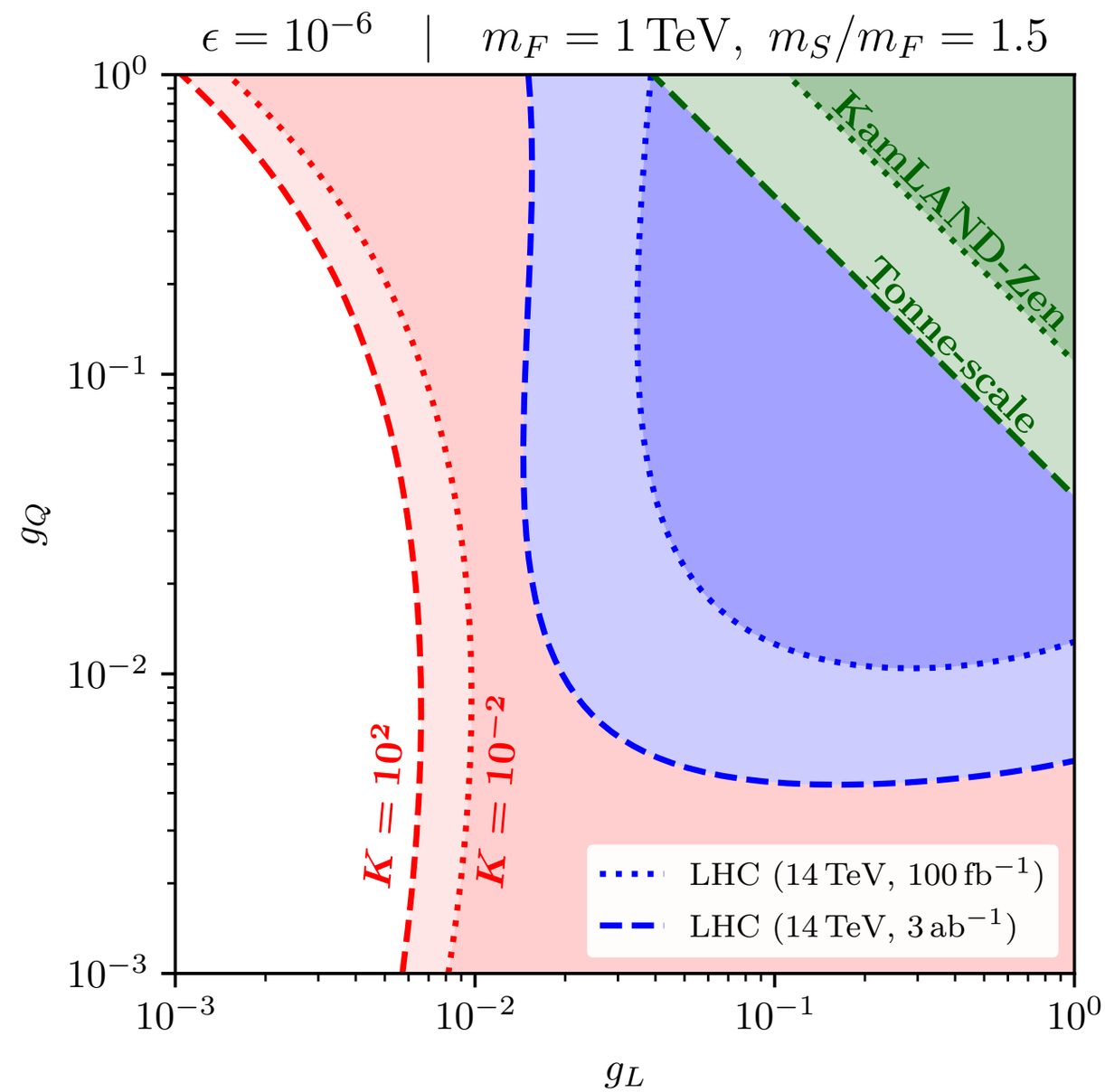
$\pi\pi ee$



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

TeV-scale LNV effects





IV. Conclusions

- Observation of TeV-scale LNV effects gives a promising option to falsify one of the standard mechanisms to explain the baryon asymmetry

- Collider and $0\nu\beta\beta-$decay searches provide complementary sensitivity (*e.g.*, mass spectrum): discovery could occur in one or the other or both

- Next step: ***flavor effects***
  - → Different collider signatures $(\mu\mu, \mu e, \tau\tau, \ldots)$
    searches (prompt, displaced vertices)
  - → Different low-energy observables $(\mu \to e\gamma, \mu \to 3e, a_\mu, \ldots)$
  - → Flavored leptogenesis (Schwinger-Keldish formalism)
  - → Interplay with neutrino physics (Casas-Ibarra parametrization)

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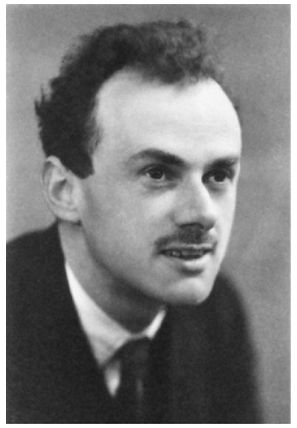
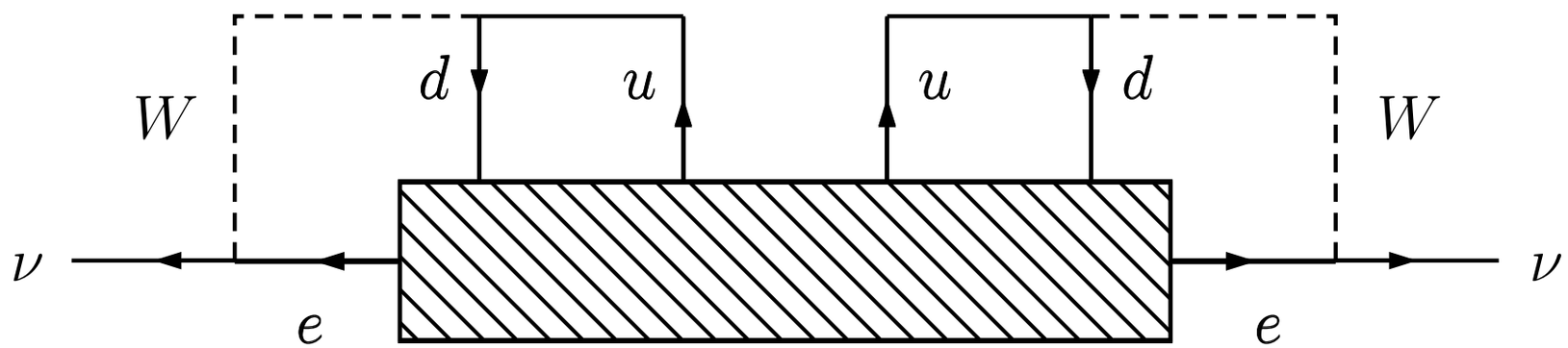
Backup slides: Dirac and Majorana masses

Dirac mass term: $m_D \overline{\Psi}\Psi$

Majorana mass term: $m_M \overline{\Psi^c}\Psi$

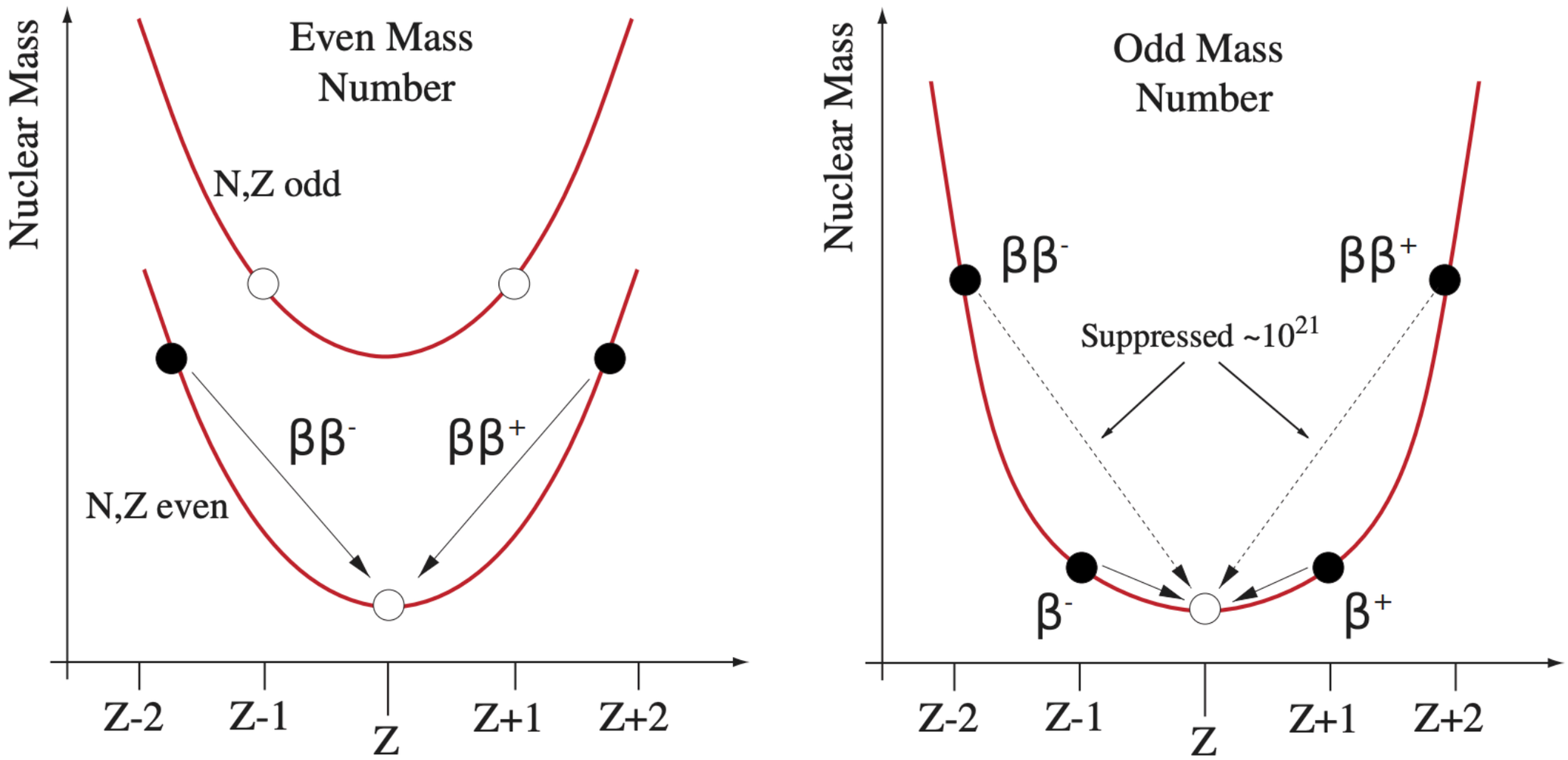


$\nu = \overline{\nu}$?



Schechter-Valle theorem (1982)

Backup slides: Nuclear shell structure

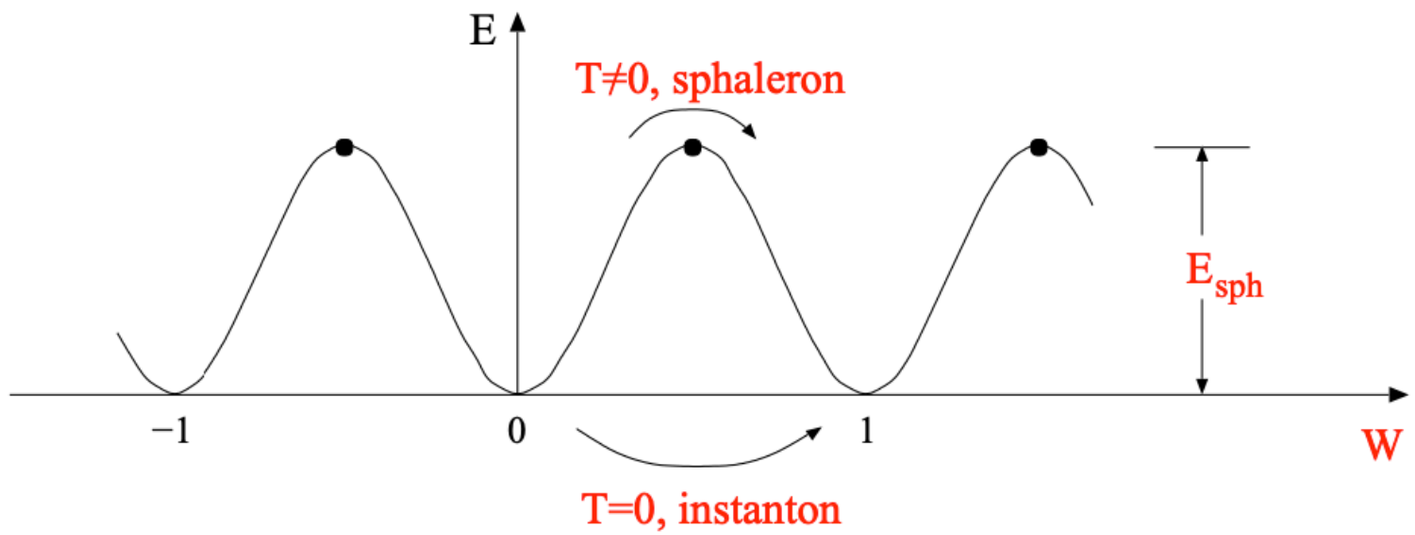


arXiv:1601.07512

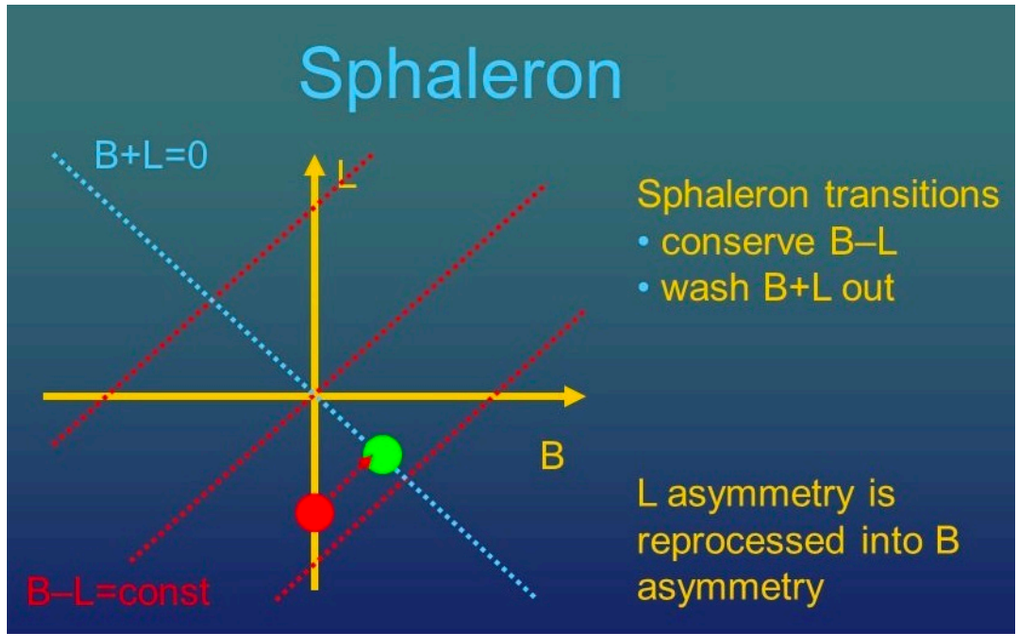
"Candidate isotopes for detecting the $0\nu\beta\beta$ are even-even nuclei that, due to the nuclear pairing force, are lighter than the odd-odd $(A, Z+1)$ nucleus, making single beta decay kinematically forbidden"

Backup slides: 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)

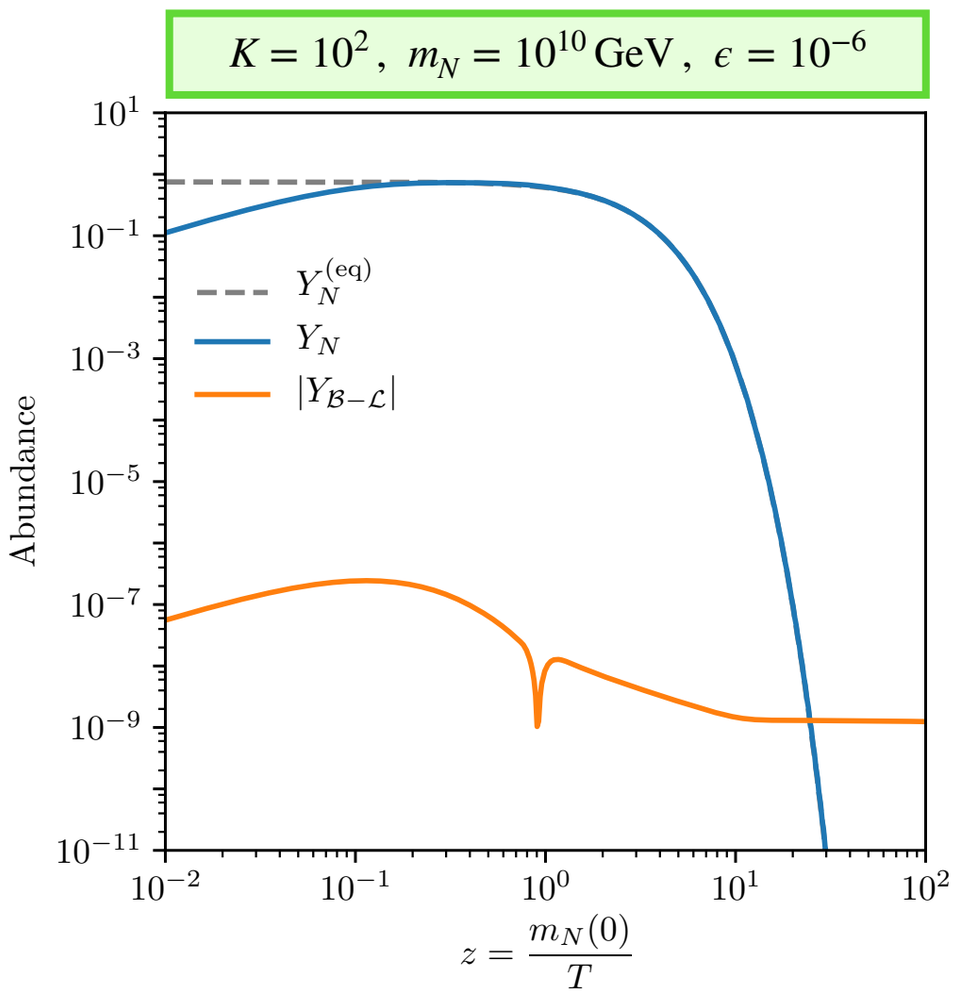


$$\Delta\mathscr{B} = \Delta\mathscr{L} = 3N_{CS}$$



Backup slides: Boltzmann Equations

The dynamics is described by Boltzmann equations:



Scattering

Decay

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

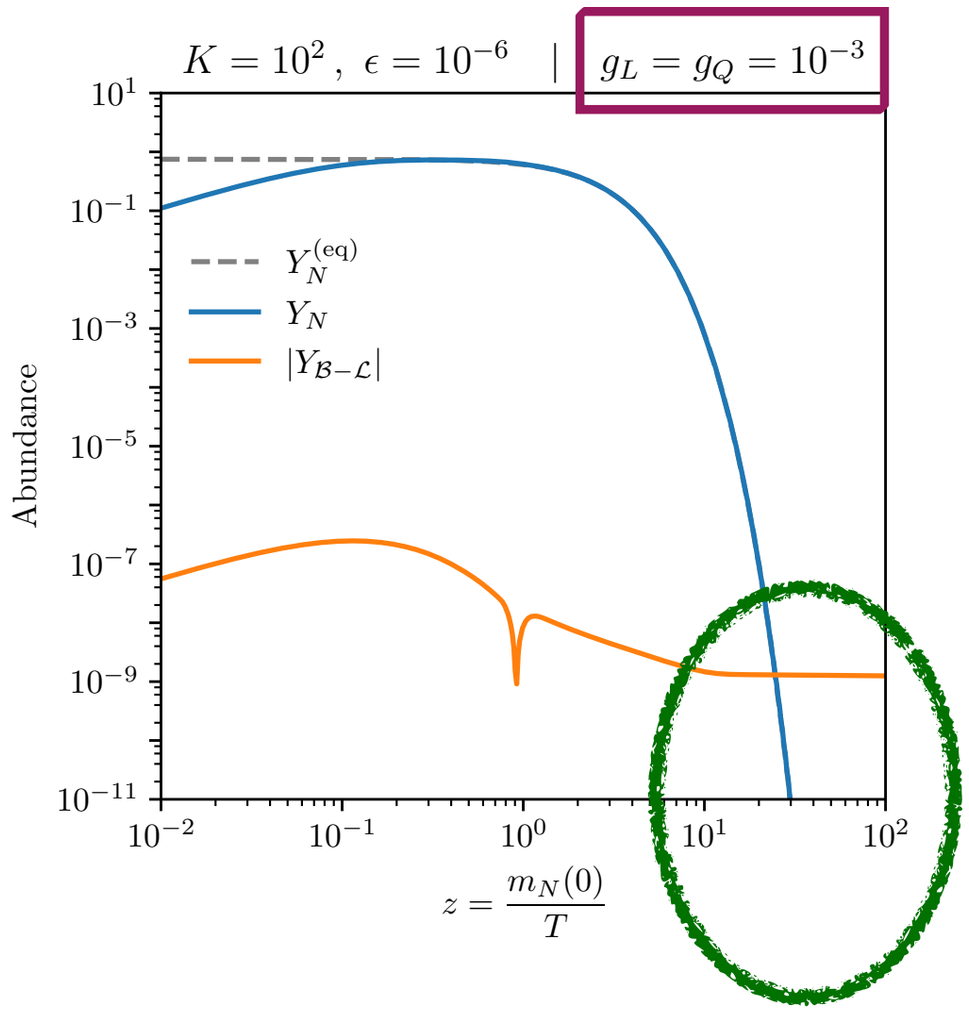
$$\frac{dY_{\mathscr{B}-\mathscr{L}}}{dz} = -\epsilon D\left(Y_N - Y_N^{(\mathrm{eq})}\right) - W\, Y_{\mathscr{B}-\mathscr{L}}$$

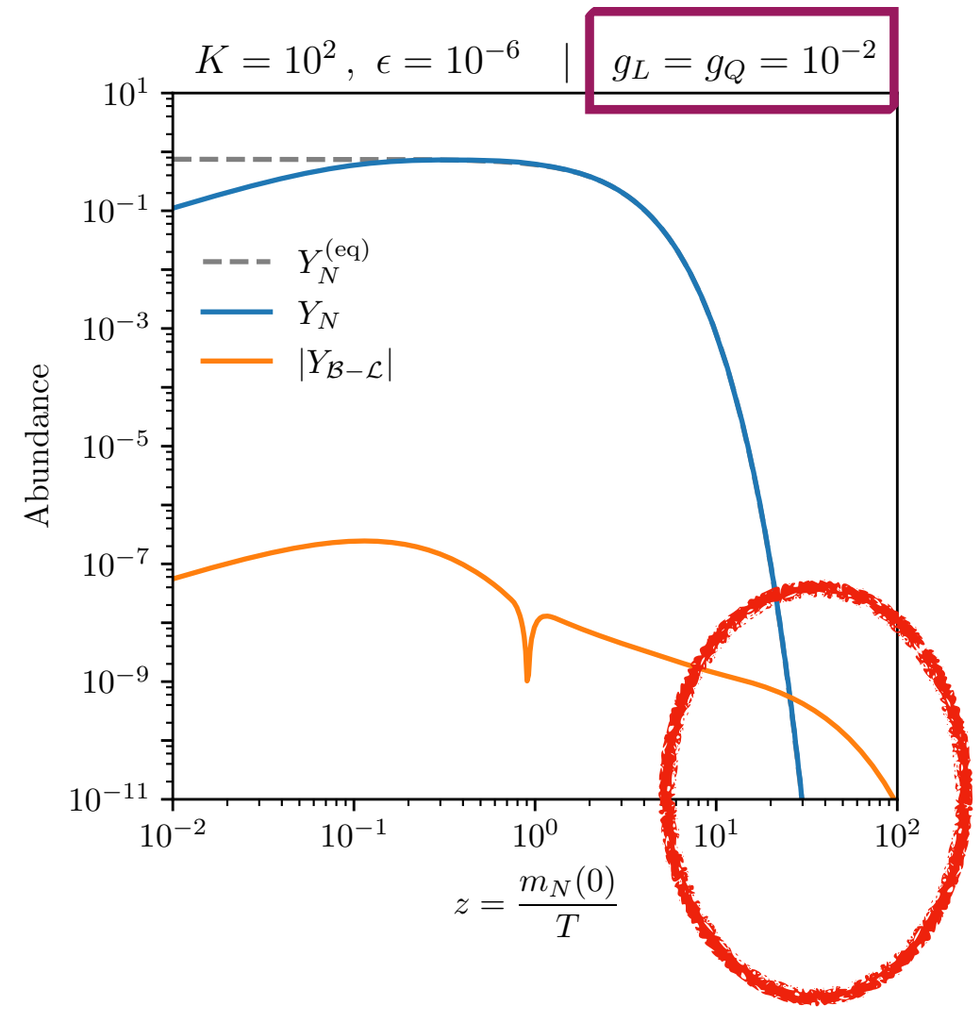
CPV source
(decay)

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

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

Backup slides: TeV-scale LNV effects





Backup slides: Effective operators - I

arXiv:hep-ph/0303205

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

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

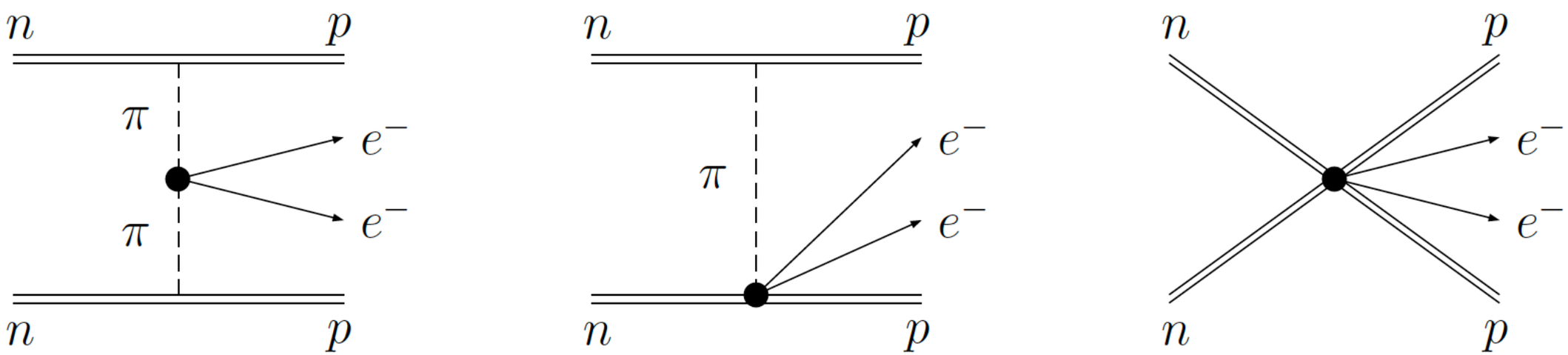
$$\mathcal{O}^{ab}_{1+} = (\overline{q}_L\tau^a\gamma^\mu q_L)(\overline{q}_R\tau^b\gamma_\mu q_R)\ ,$$
$$\mathcal{O}^{ab}_{2\pm} = (\overline{q}_R\tau^a q_L)(\overline{q}_R\tau^b q_L) \pm (\overline{q}_L\tau^a q_R)(\overline{q}_L\tau^b q_R)\ ,$$
$$\mathcal{O}^{ab}_{3\pm} = (\overline{q}_L\tau^a\gamma^\mu q_L)(\overline{q}_L\tau^b\gamma_\mu q_L) \pm (\overline{q}_R\tau^a\gamma^\mu q_R)(\overline{q}_R\tau^b\gamma_\mu q_R)\ ,$$
$$\mathcal{O}^{ab,\mu}_{4\pm} = (\overline{q}_L\tau^a\gamma^\mu q_L \mp \overline{q}_R\tau^a\gamma^\mu q_R)(\overline{q}_L\tau^b q_R - \overline{q}_R\tau^b q_L)\ ,$$
$$\mathcal{O}^{ab,\mu}_{5\pm} = (\overline{q}_L\tau^a\gamma^\mu q_L \pm \overline{q}_R\tau^a\gamma^\mu q_R)(\overline{q}_L\tau^b q_R + \overline{q}_R\tau^b q_L)\ .$$

Different combinations of 4 quarks and 2 electrons

Operators $\longleftrightarrow$ Models

Backup slides: Effective operators - II

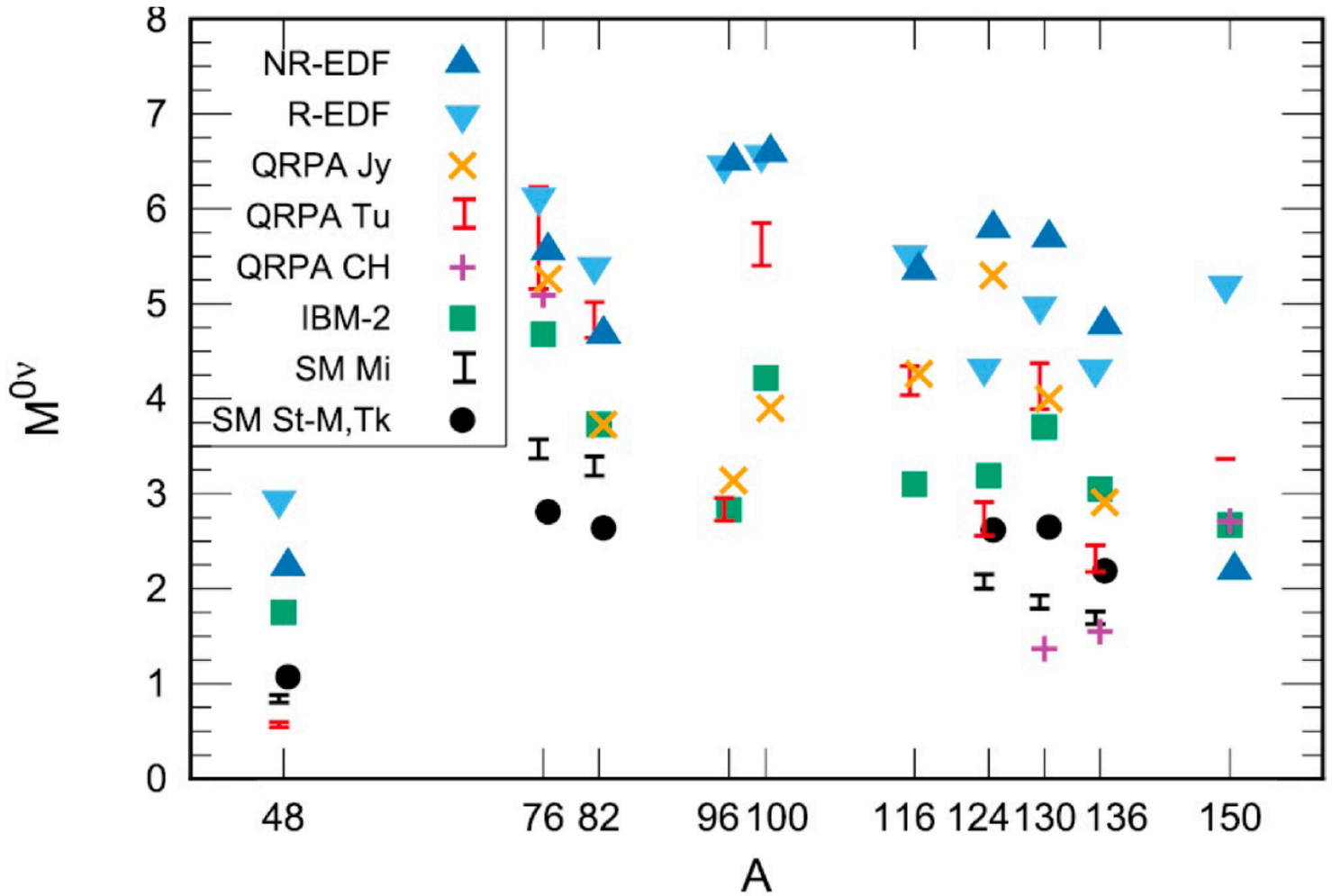
arXiv:hep-ph/0303205



$\pi\pi ee$ $\qquad$ $NN\pi ee$ $\qquad$ $NNNNee$

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

Backup slides: Nuclear Matrix Elements



Computing methods:

EDF: energy-density functional

QRPA: quasi-particle random phase approximation

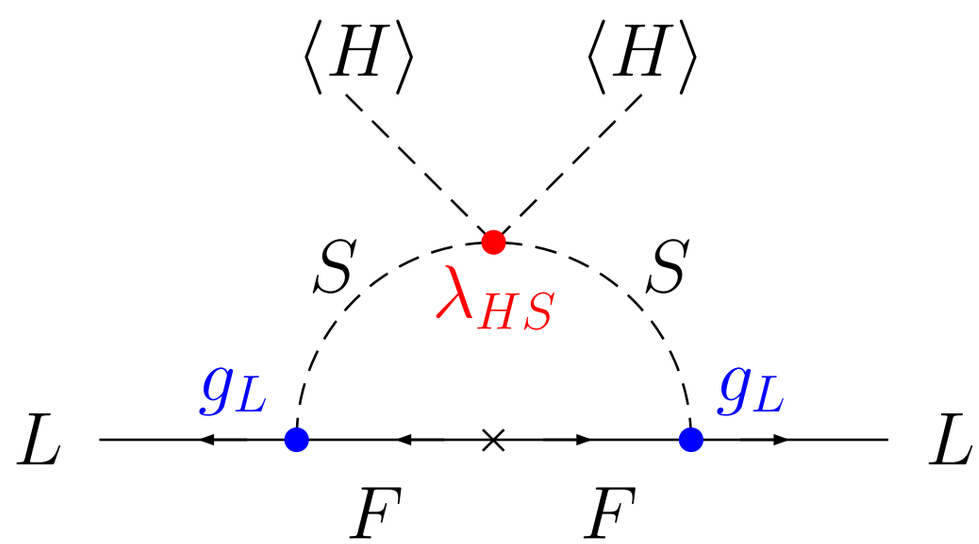
SM: shell model

IBM: interacting boson model

arXiv:1902.04097

Backup slides: Lagrangian for Model O2

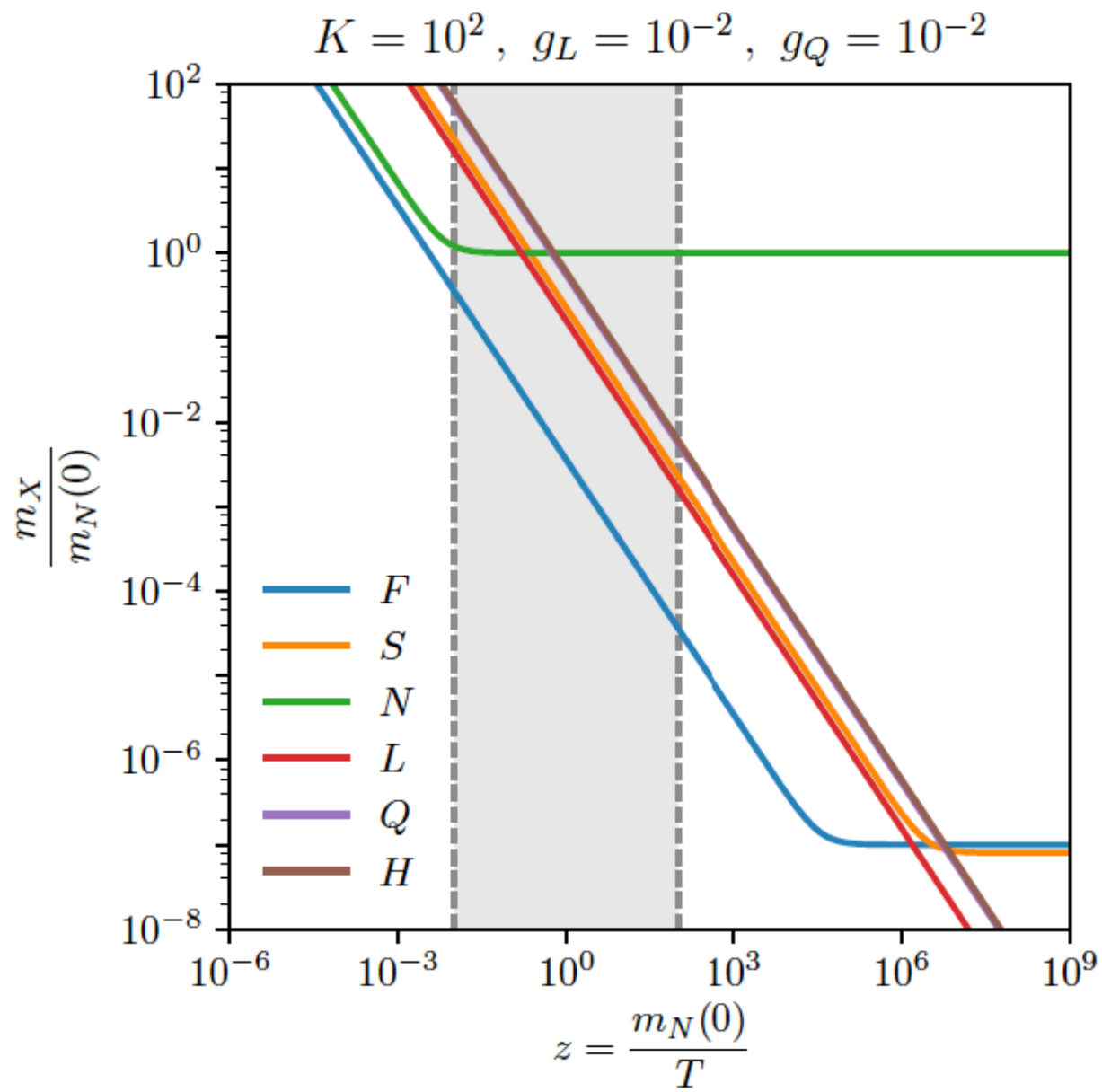
$$\mathscr{L}_{\mathrm{O2}} = g_Q \overline{Q} S d_R + g_L \overline{L} \widetilde{S} F - m_S{}^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS} (S^\dagger H)^2 + \ldots$$



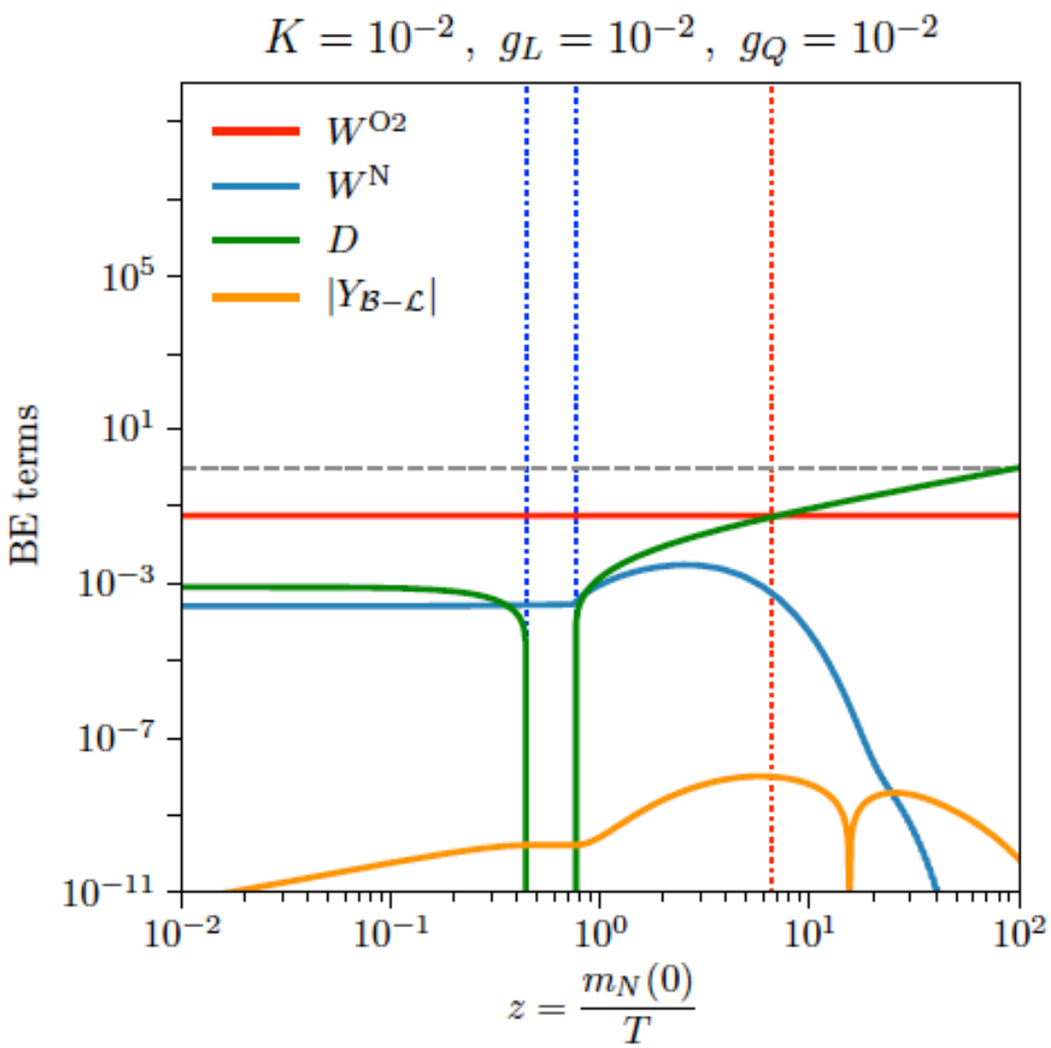
$$\widetilde{X} \equiv \epsilon X^* , \quad \epsilon^{12} = +1$$

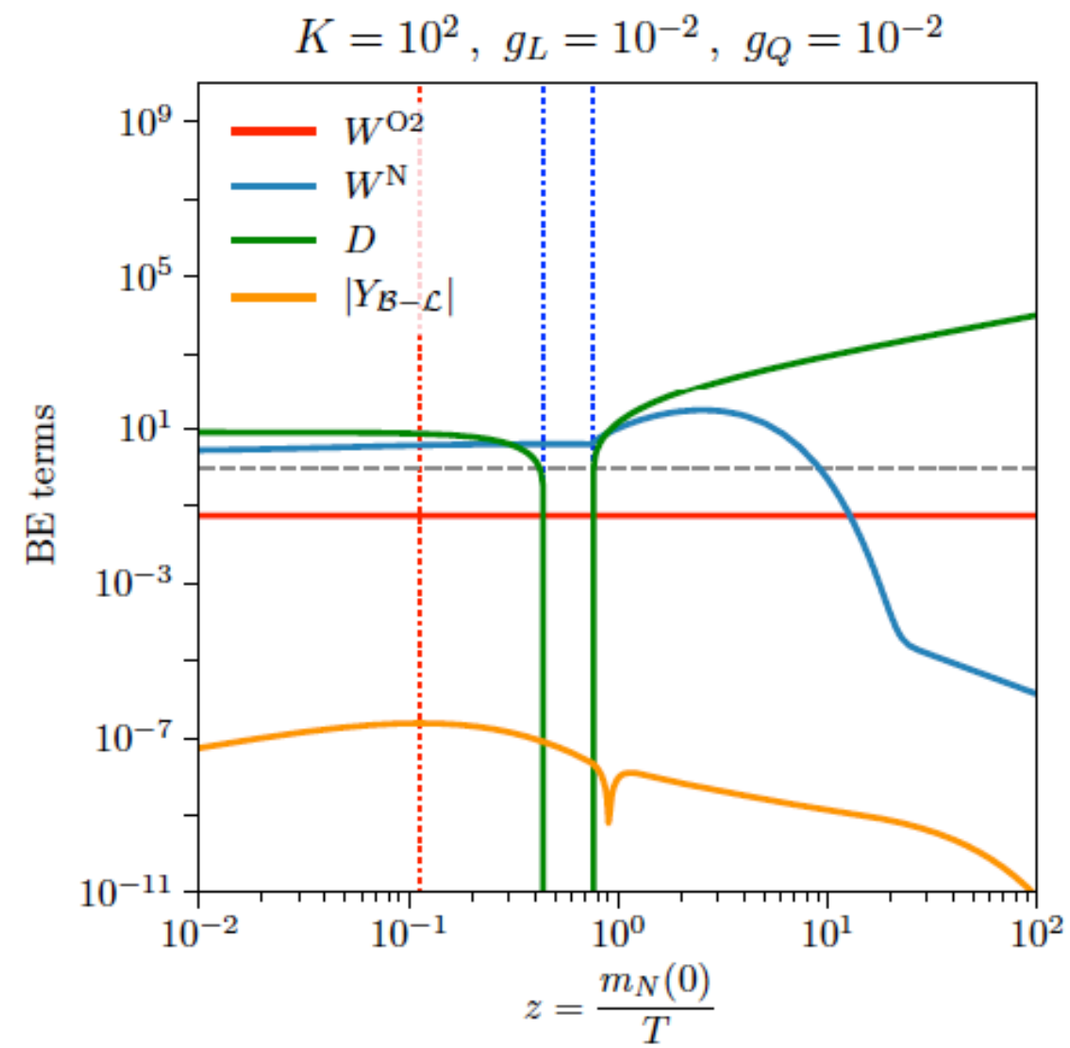
arXiv:1508.04444

Backup slides: Leptogenesis with Model O2 - I

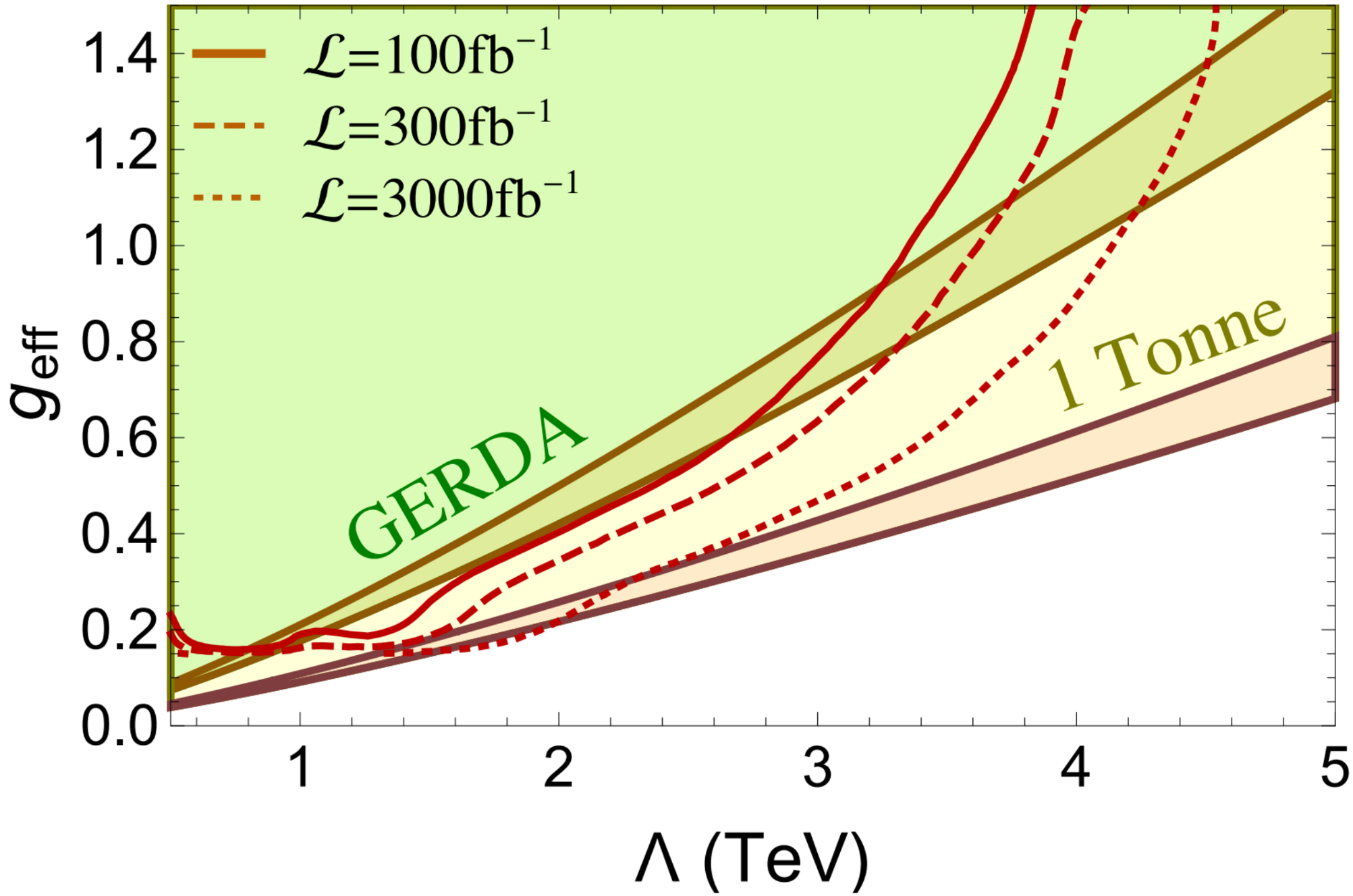


Backup slides: Leptogenesis with Model O2 - II





Backup slides: Previous study of Model O2



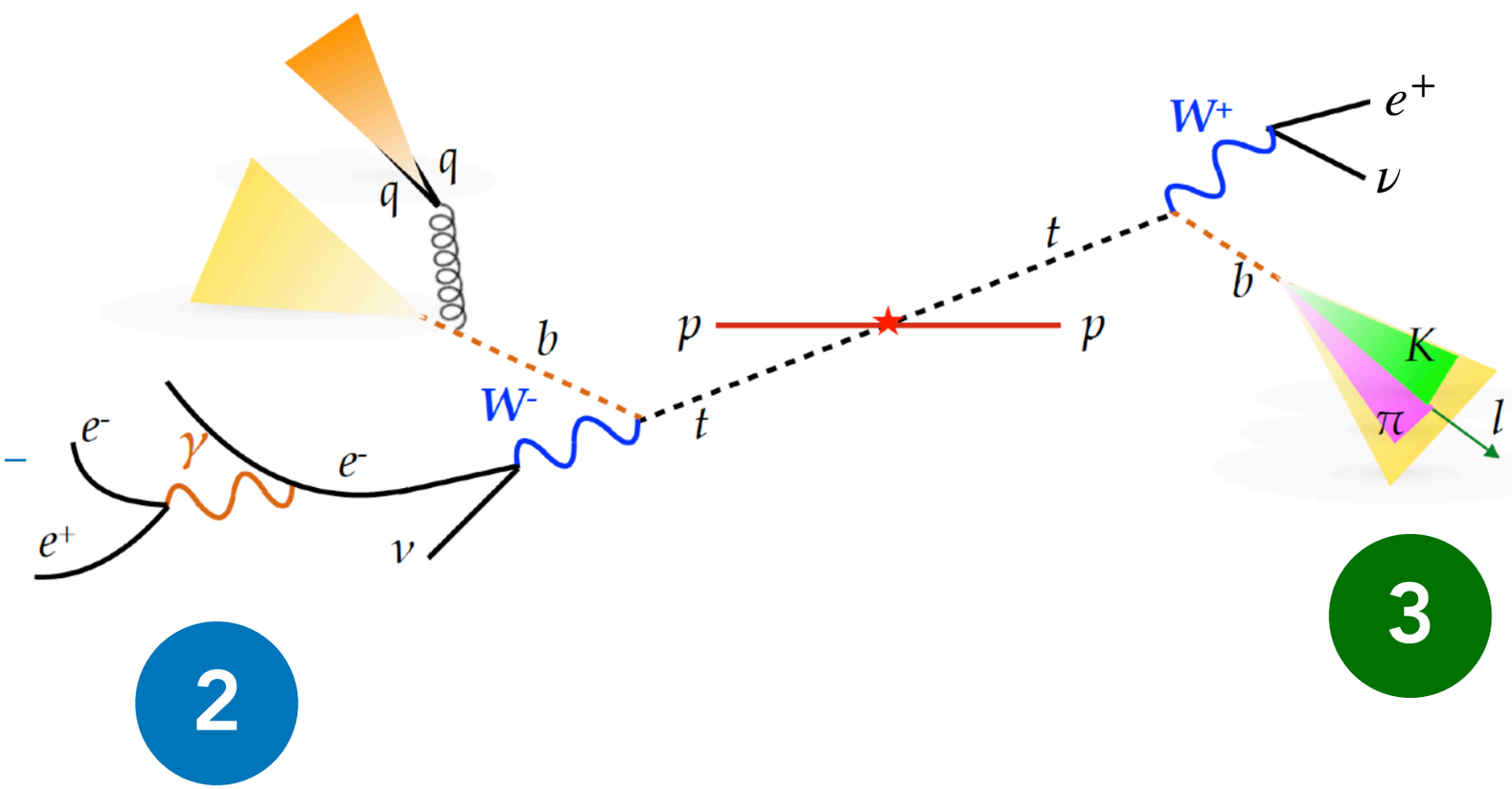
arXiv:1508.04444

Backup slides: Collider searches - I

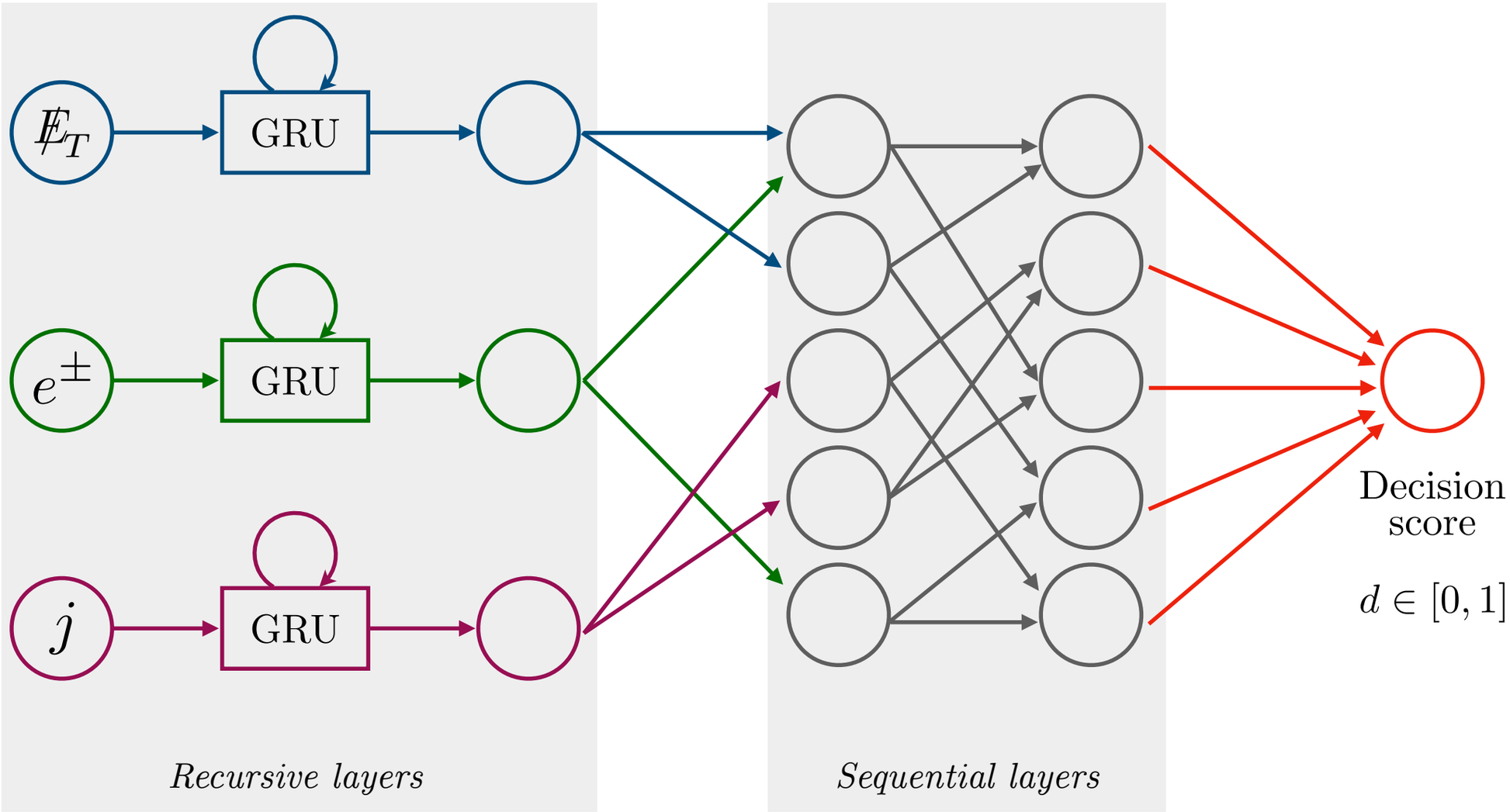
- **Background:**
  1. SM processes with 2SS leptons (*e.g.*, $jjWW, t\bar{t}W, t\bar{t}Z$)
  2. Charge misidentification (*e.g.*, $t\bar{t}, Z/\gamma^*$)
  3. Jet-fakes (*e.g.*, $t\bar{t}, W+3j$)

Dominant contributions

Trident event:
$e^- \to e^-\gamma \to e^-e^+e^-$



Non-prompt lepton from a hadron

ATL-PHYS-SLIDE-2018-856

Backup slides: Collider searches - II