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 2020 Symposium

May 4 - 6, 2020

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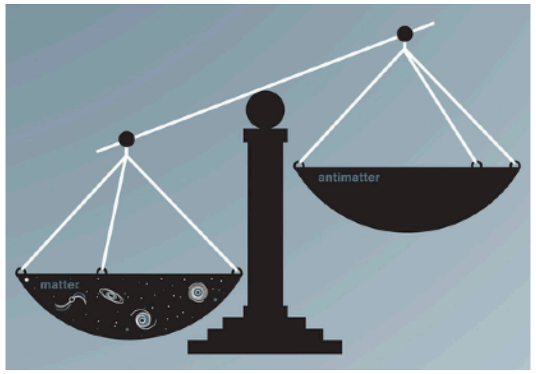
(in collaboration with Julia Harz, Michael Ramsey-Musolf, and Tianyang Shen)

New physics?

Λ (Energy)

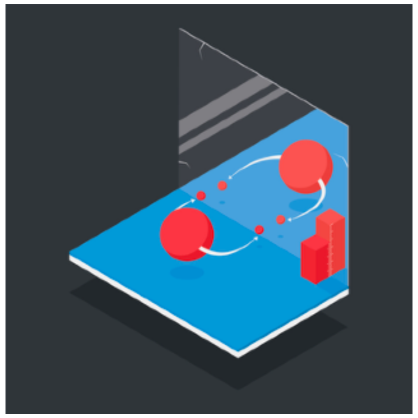


Symmetry magazine (Oct 2015)

Why is there way more matter than antimatter in the observable universe?

Symmetry magazine (Aug 2014)

Will we see BSM physics at the LHC?



CERN press release (Mar 2019)

Are neutrinos their own antiparticles?

Lepton Number Violation

$(\mathscr{L} = \#\,\text{leptons} - \#\,\overline{\text{leptons}})$

↓

TeV-scale

Deppisch, Harz & Hirsch (2013)
De Gouvêa *et al.* (2019)
Helo *et al.* (2013)

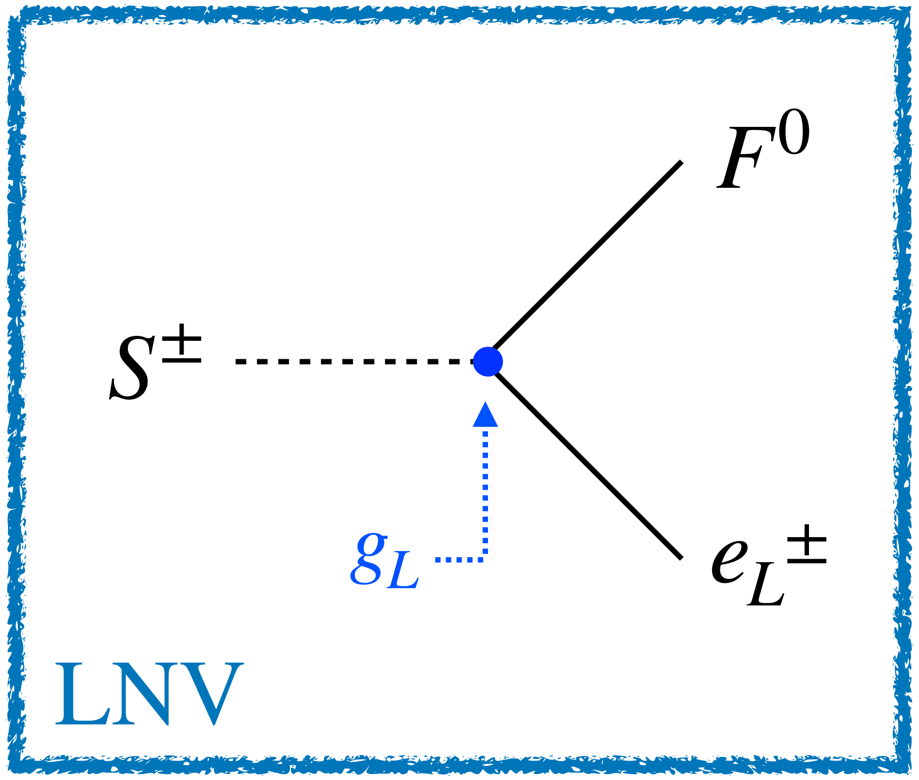
New physics? Model O2

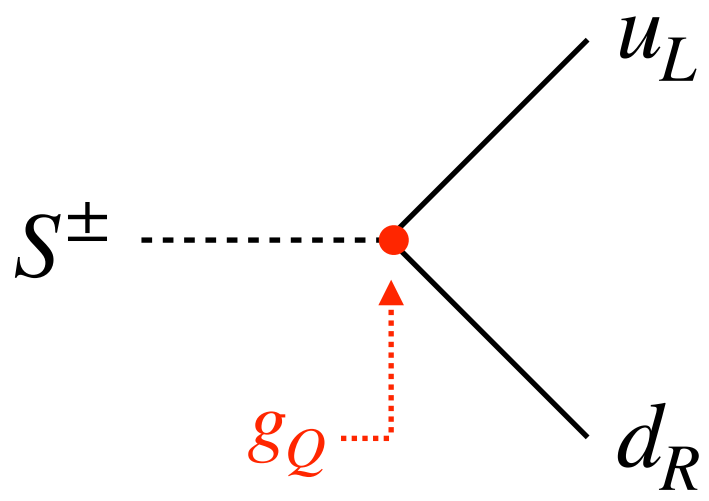
We study a simplified model: **"Model O2"** Peng, Ramsey-Musolf & Winslow (2015)

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

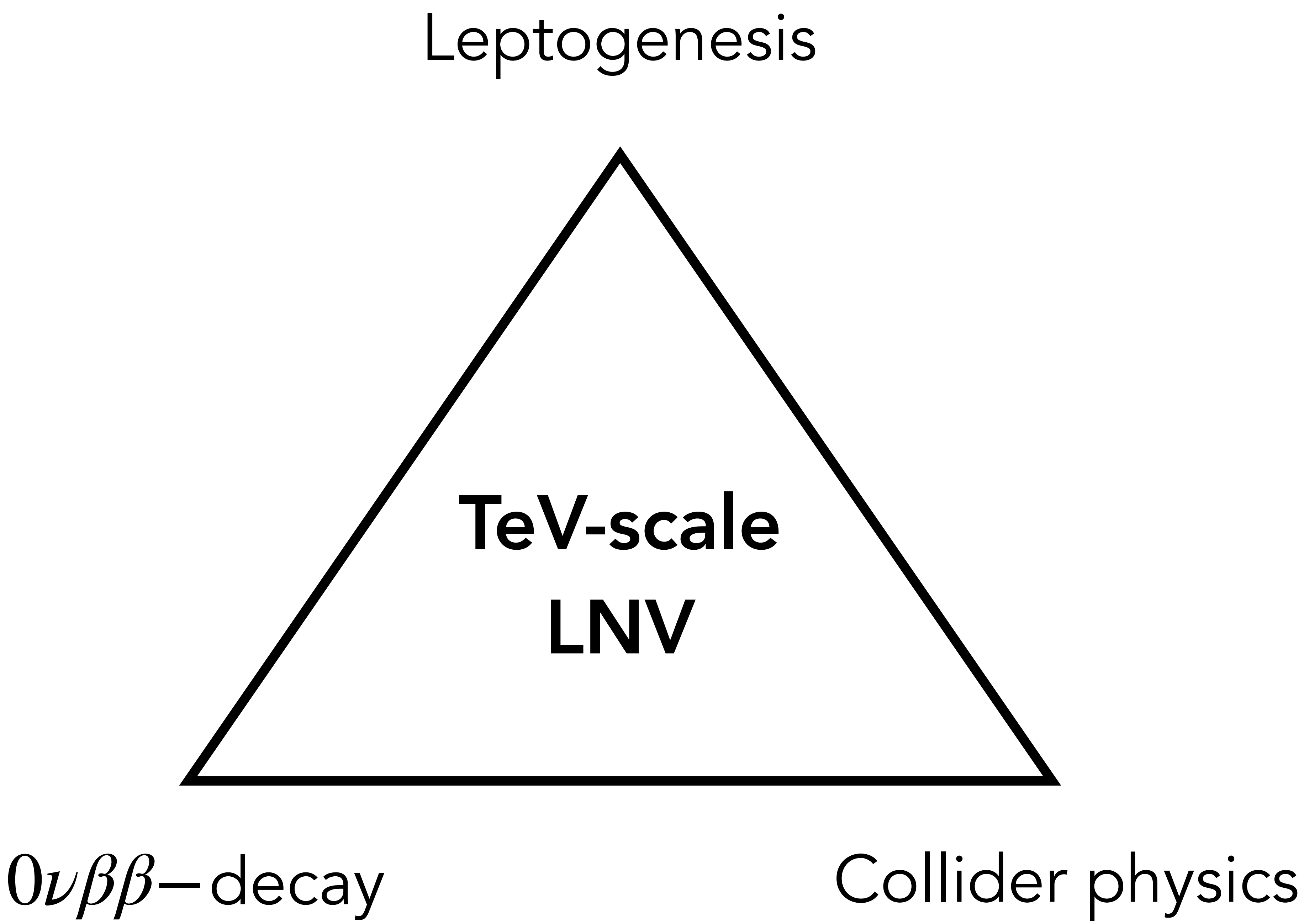
$$m_F\,,\, m_S \sim \text{TeV}$$

Minimal interactions

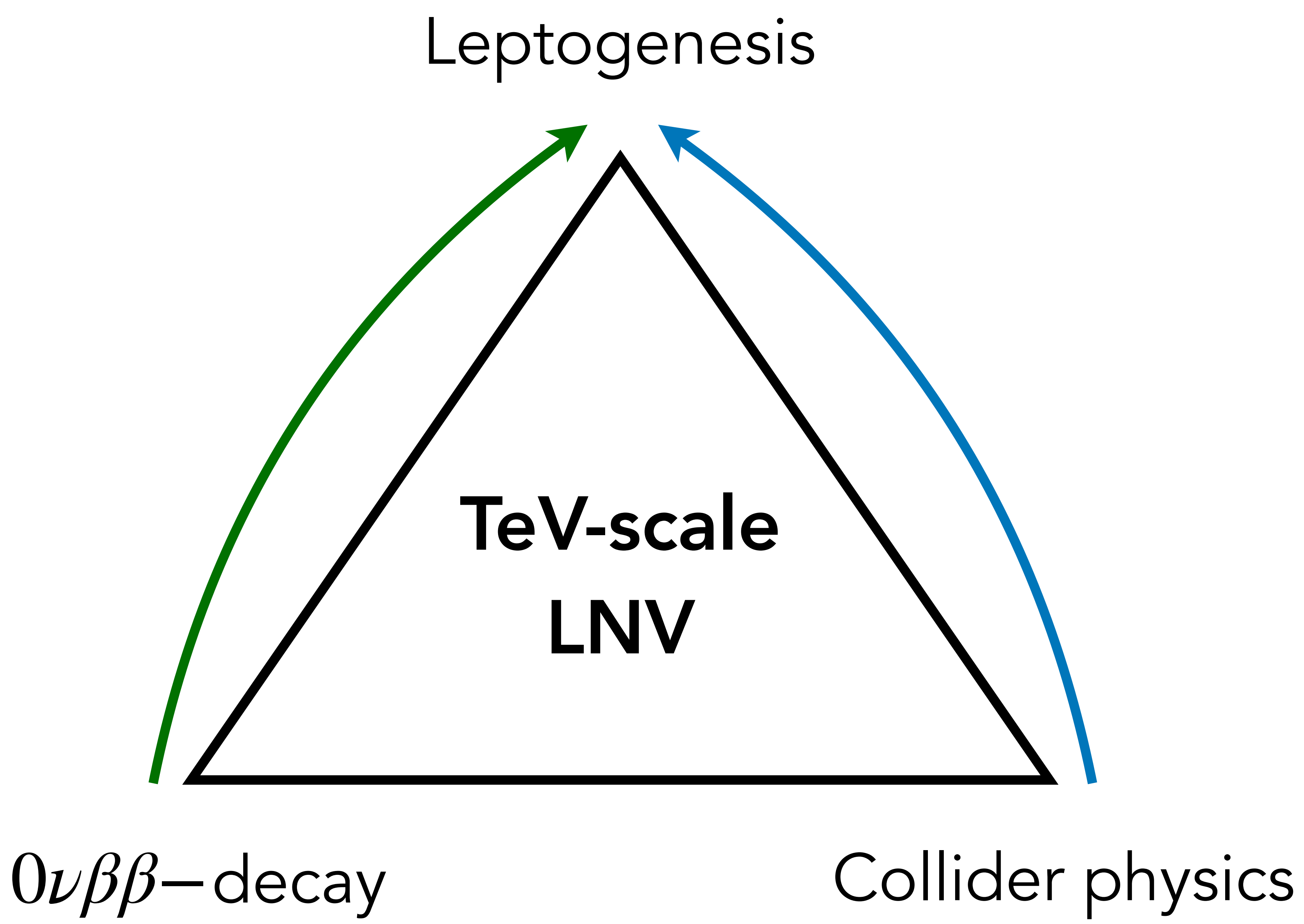




Goal of this talk



Goal of this talk



I. TeV-Scale and the Origin of matter

Leptogenesis

TeV-scale
LNV

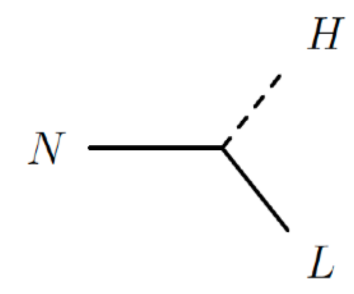
$0\nu\beta\beta-$decay

Collider physics

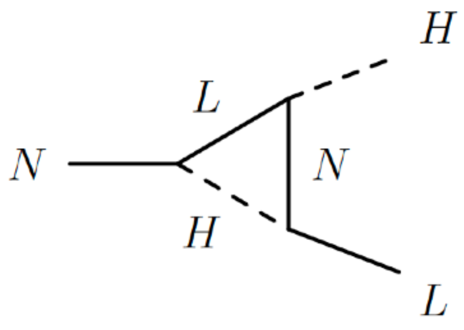
Standard leptogenesis scenario

Fukugita & Yanagida (1986)

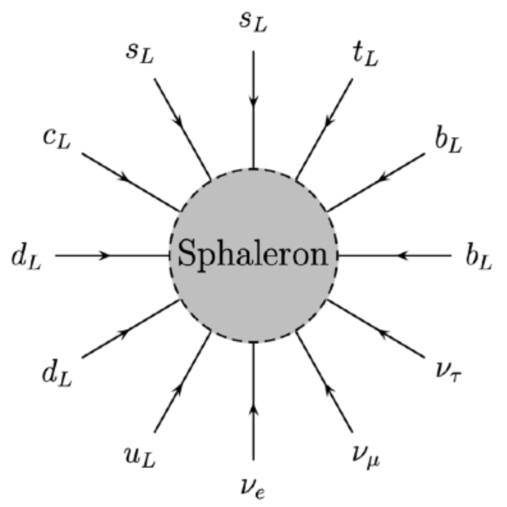
- SM + heavy right-handed, Majorana neutrino N:
  $\Delta\mathscr{L} \neq 0$



- Quantum corrections: $CP-$violation



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

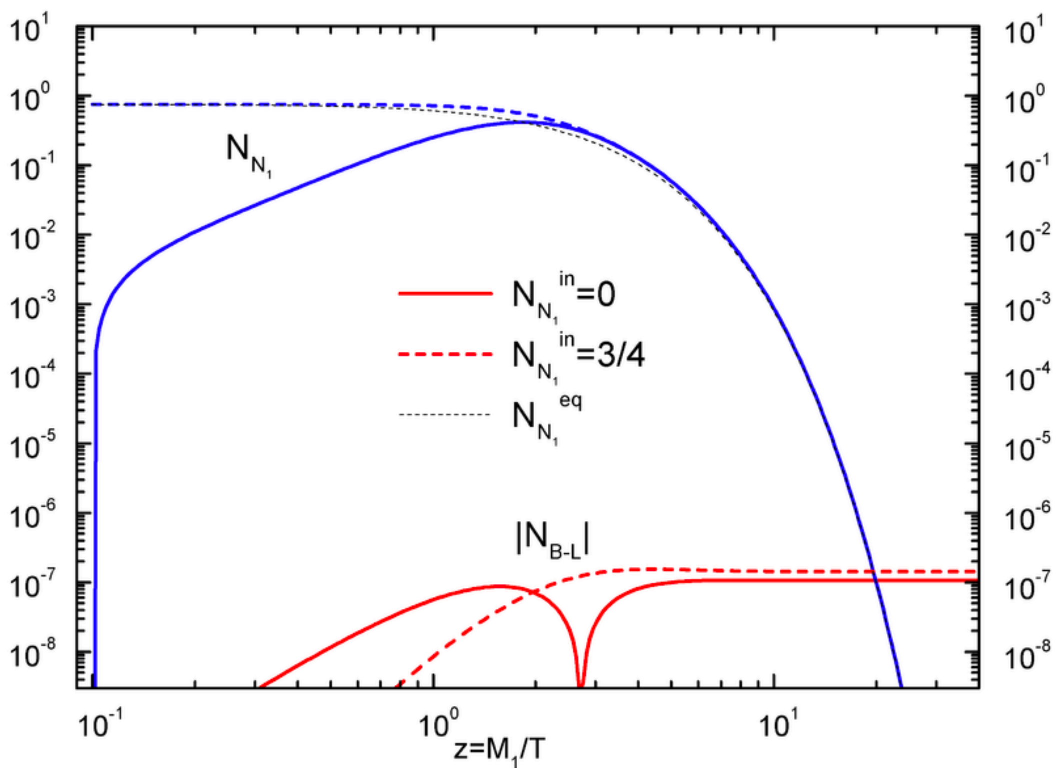


arXiv:hep-ph/9812447

Standard leptogenesis scenario

Fukugita & Yanagida (1986)

- The leptogenesis process is described by Boltzmann equations:



Buchmuller *et al.* (2015)

Decay term

Scattering term

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

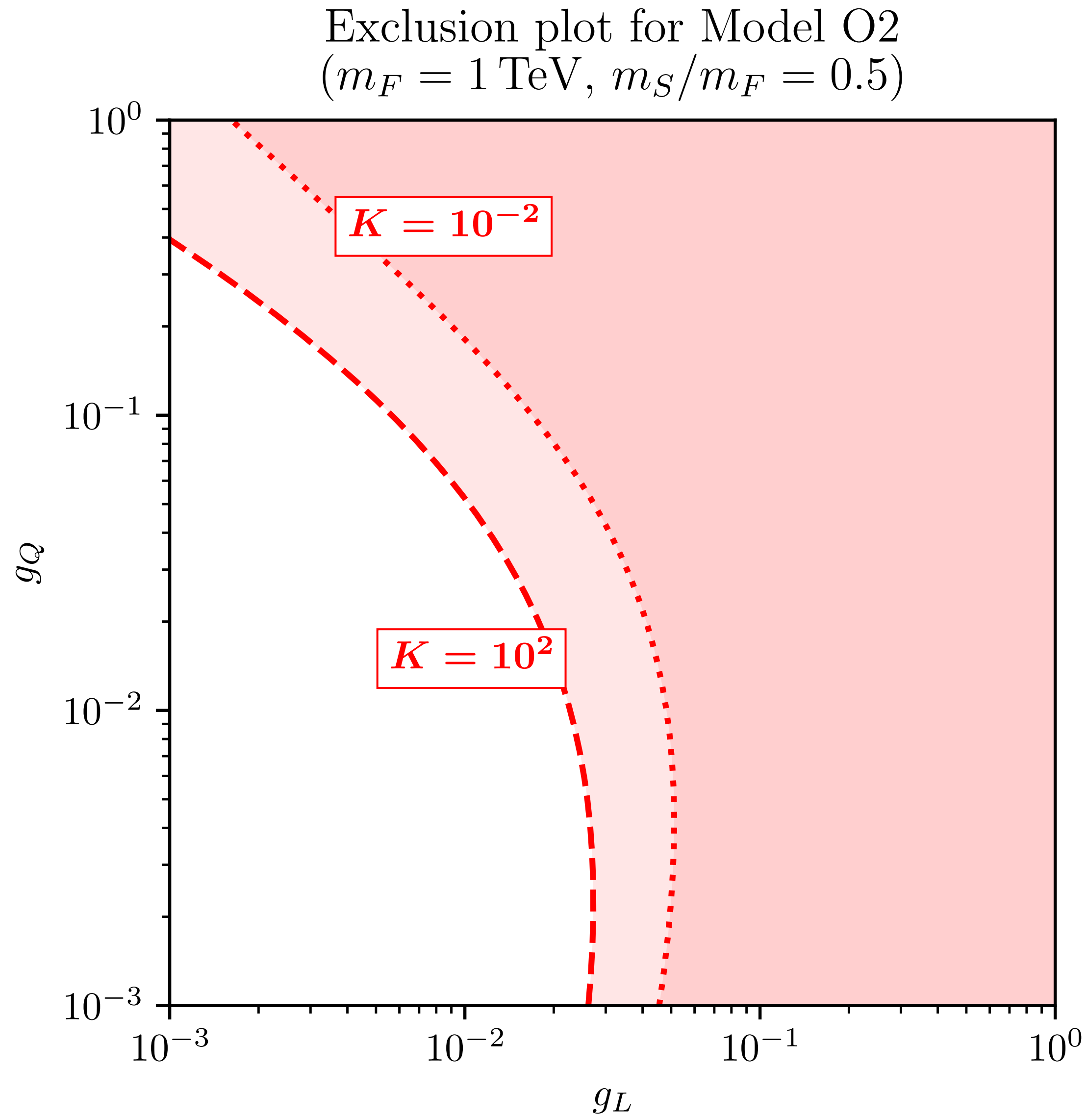
$$\frac{dY_{\mathscr{B}-\mathscr{L}}}{dz} = -\,\epsilon\, D\left(Y_N - Y_N^{(\mathrm{eq})}\right) - W\, Y_{\mathscr{B}-\mathscr{L}}$$

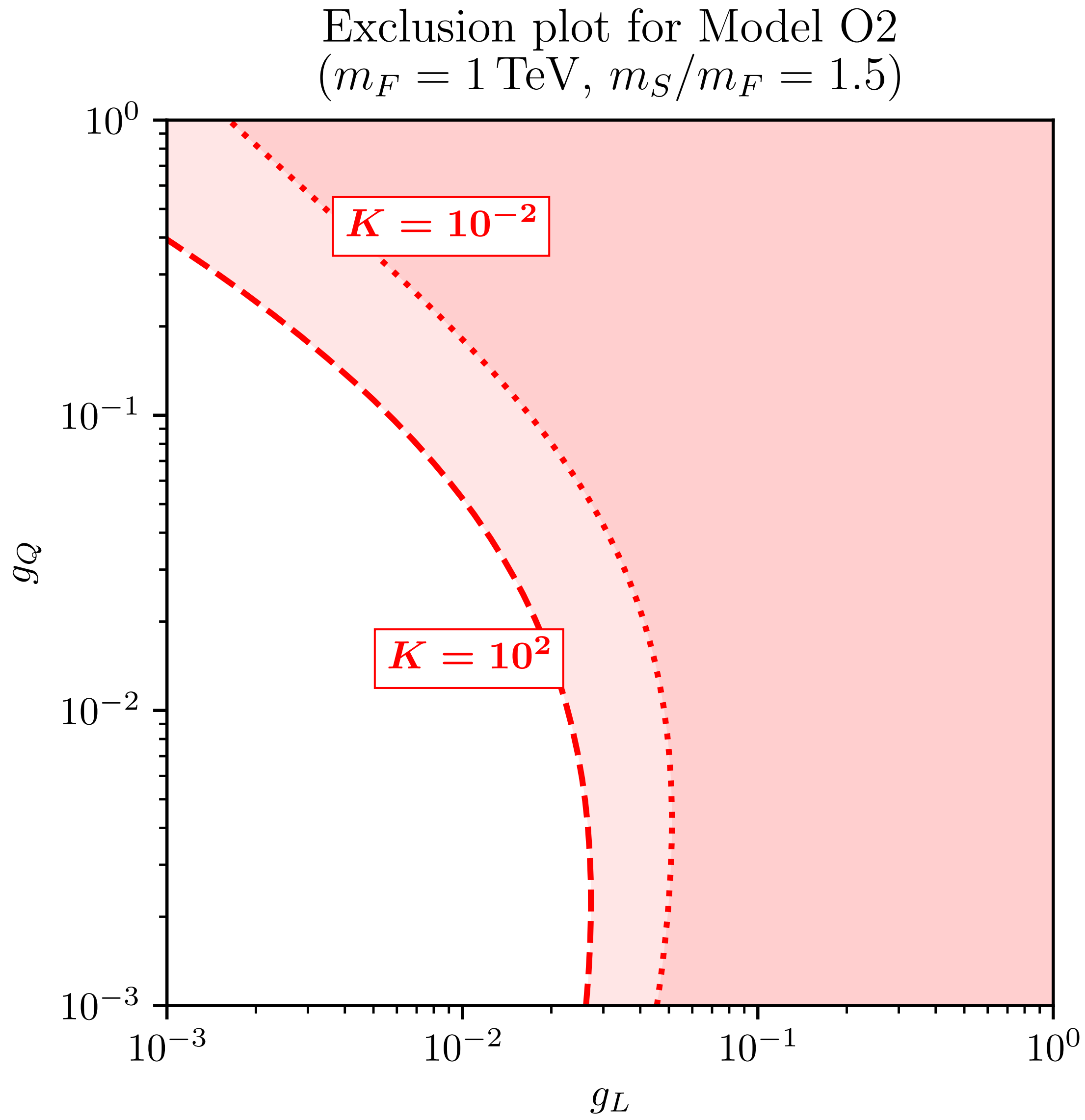
Washout term

Y_X (N_X) : normalized number density

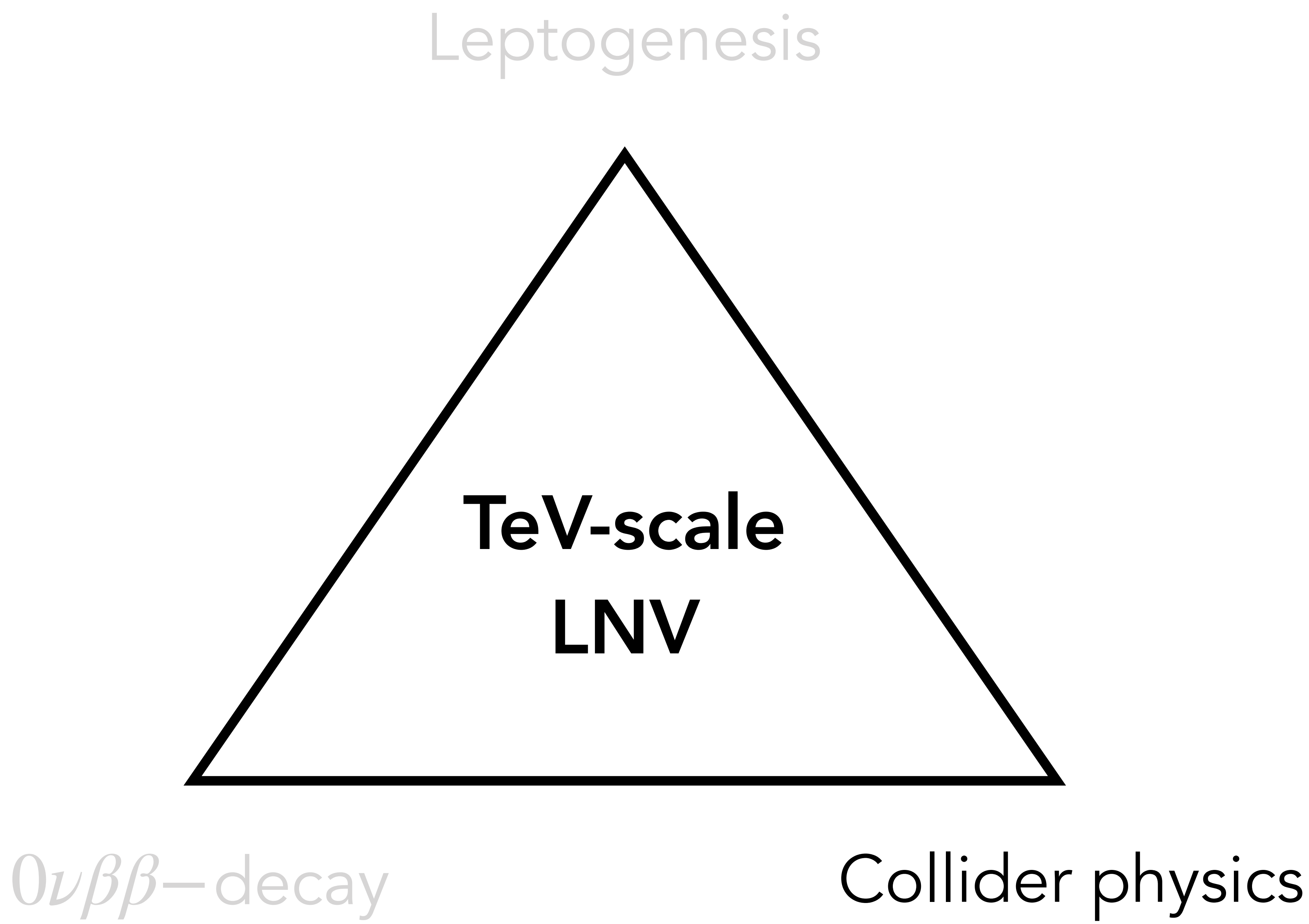
TeV-scale LNV effects

- Standard LG works, but requires $m_N \gtrsim 10^9\,\mathrm{GeV}$ Davidson & Ibarra (2002)
- What if we include accessible TeV-scale effects? **Model O2**

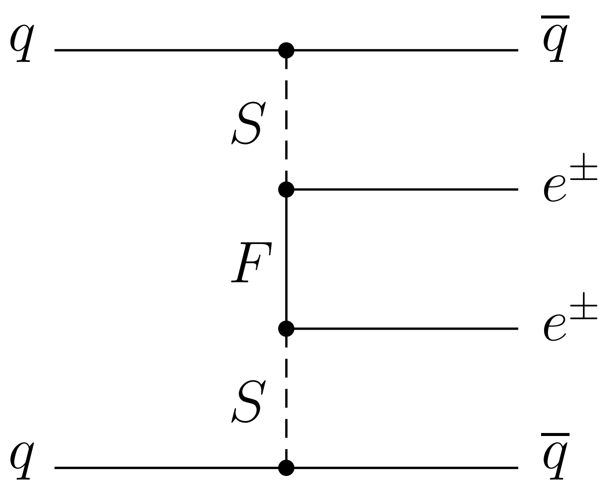




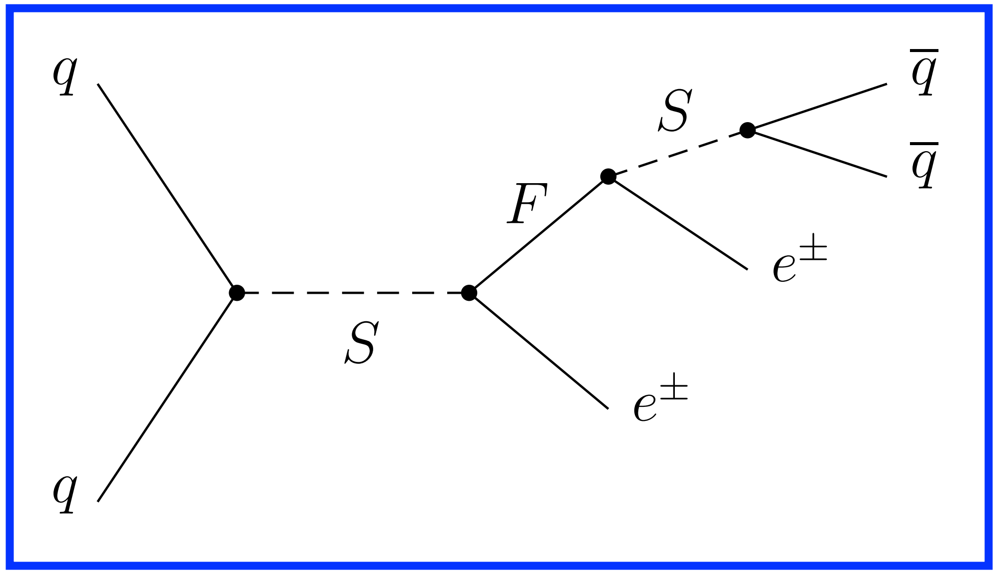
II. TeV-Scale and Energy frontier probes



- **Signal:** two same-sign leptons and two jets, $pp \to jj\ell^{\pm}\ell^{\pm}$



(a)



(b)

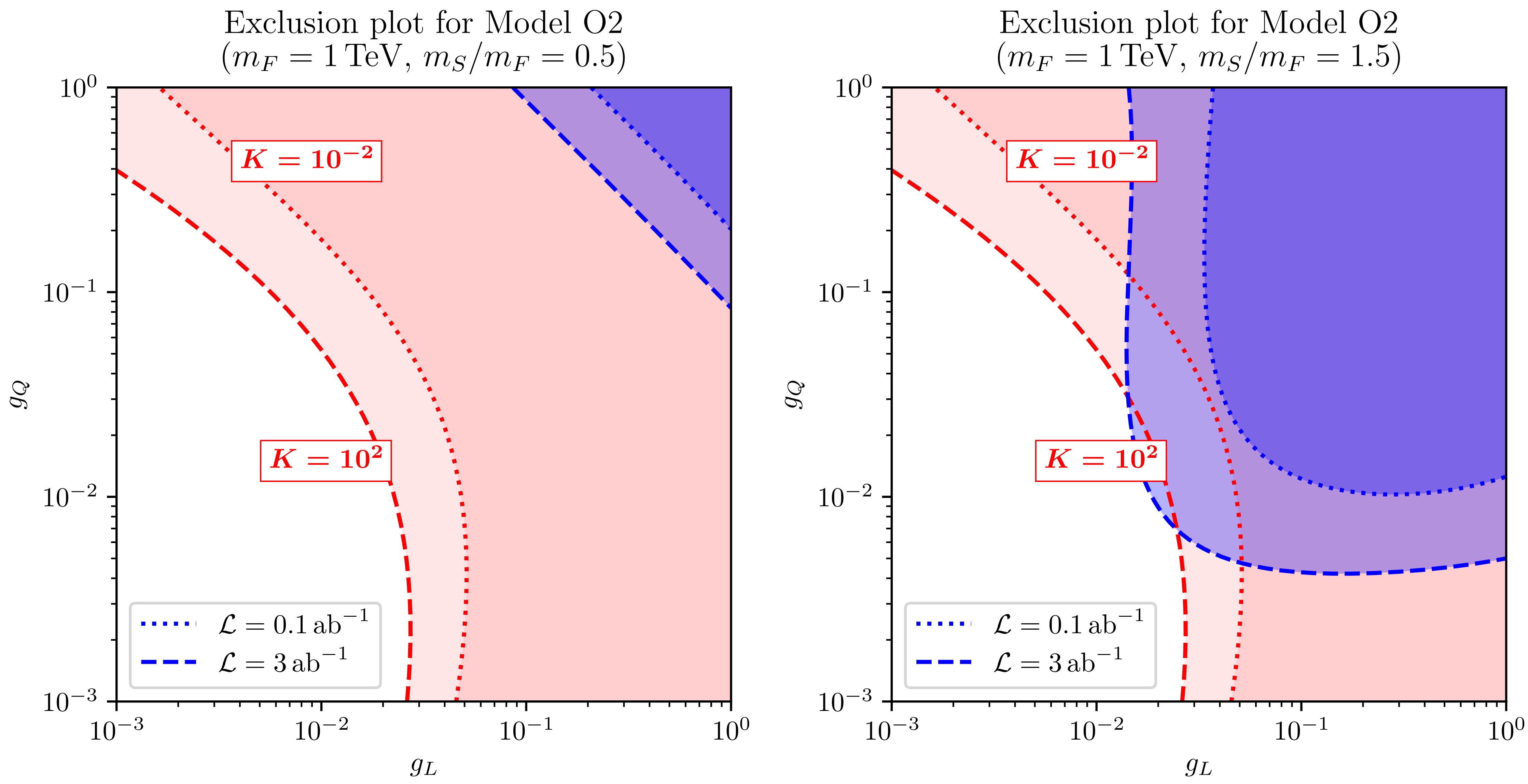
- **Background:**

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.*, $t\bar{t}, W+3j$)

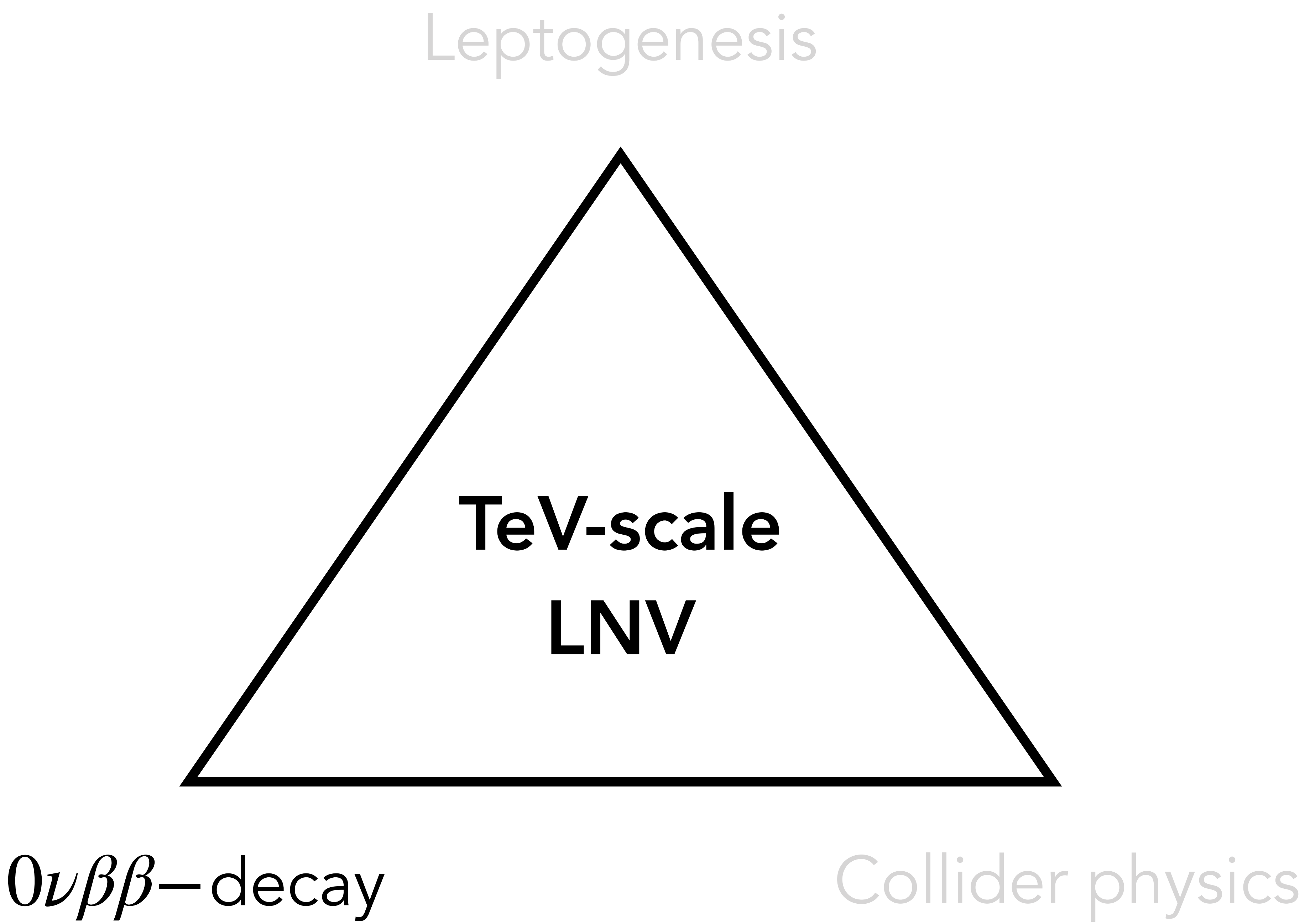
* Dominant contributions

TeV-scale LNV effects

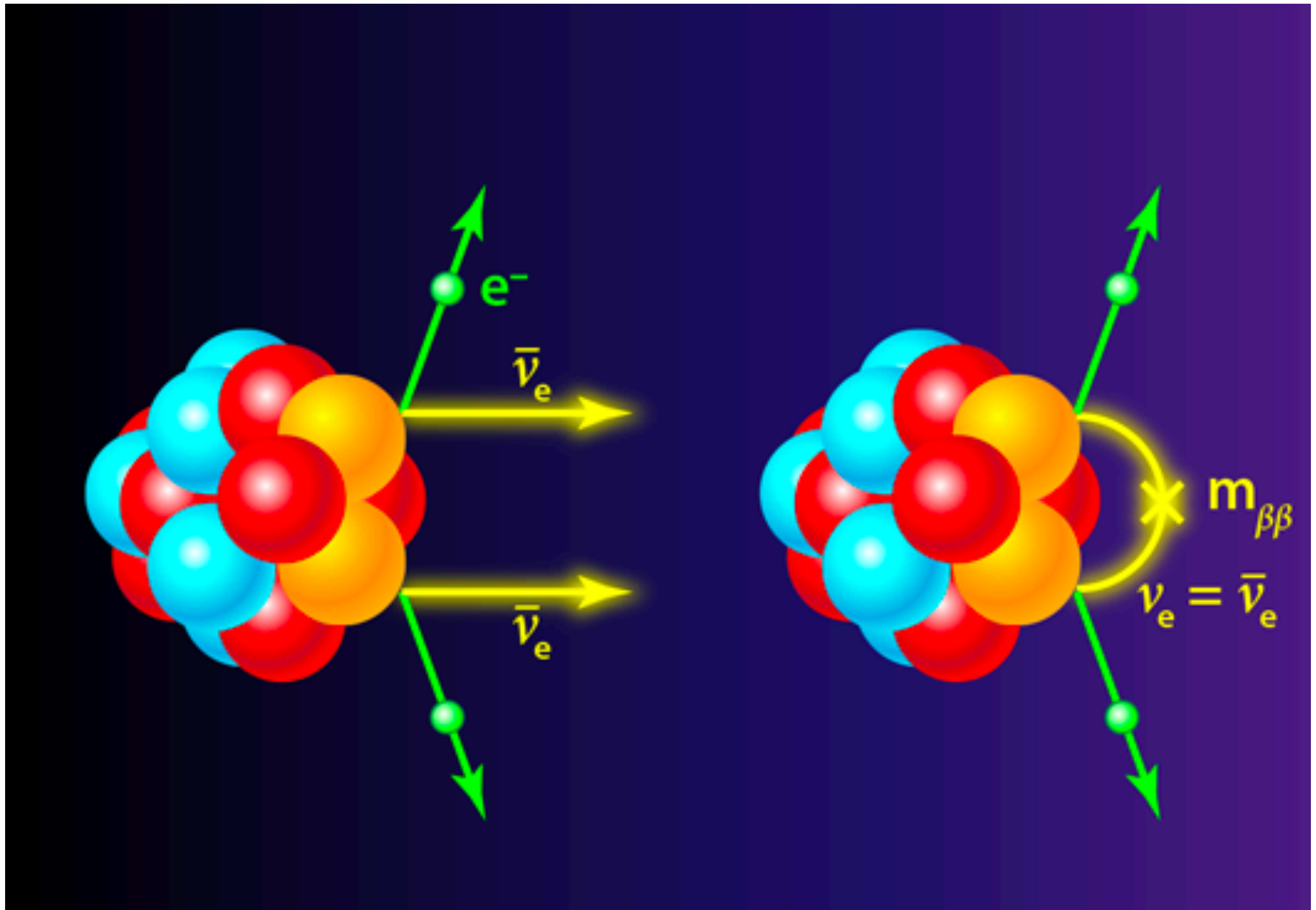
- Madgraph + Pythia 8 + Delphes for MC simulation
- Use of Neural Networks for signal/background discrimination



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



$\beta-$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

$\Delta\mathscr{L} = 2$

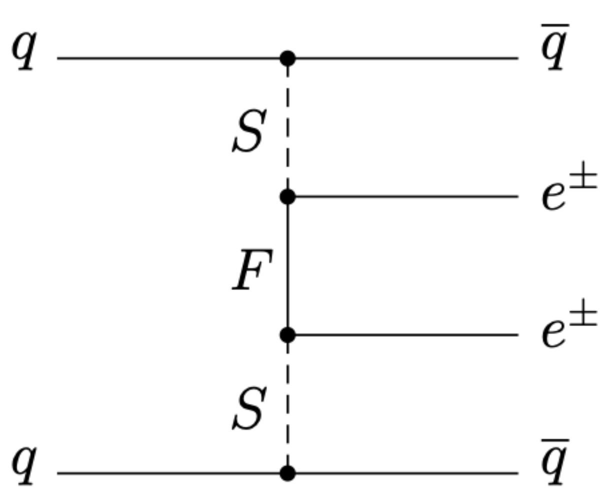
From simplified models to effective operators

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

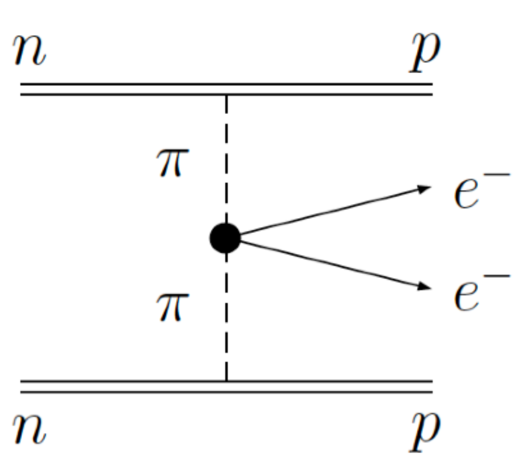
2. Match quark-electron operators onto two-nucleon operators

3. Using nuclear physics, calculate the half-life

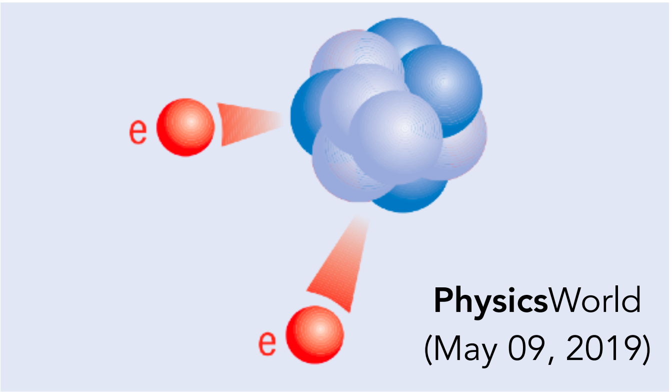
$$\mathcal{O}_{\text{Model O2}} \longrightarrow \pi\pi ee \longrightarrow T_{1/2}^{0\nu}(g_L, g_Q, m_F, m_S)$$



(1)

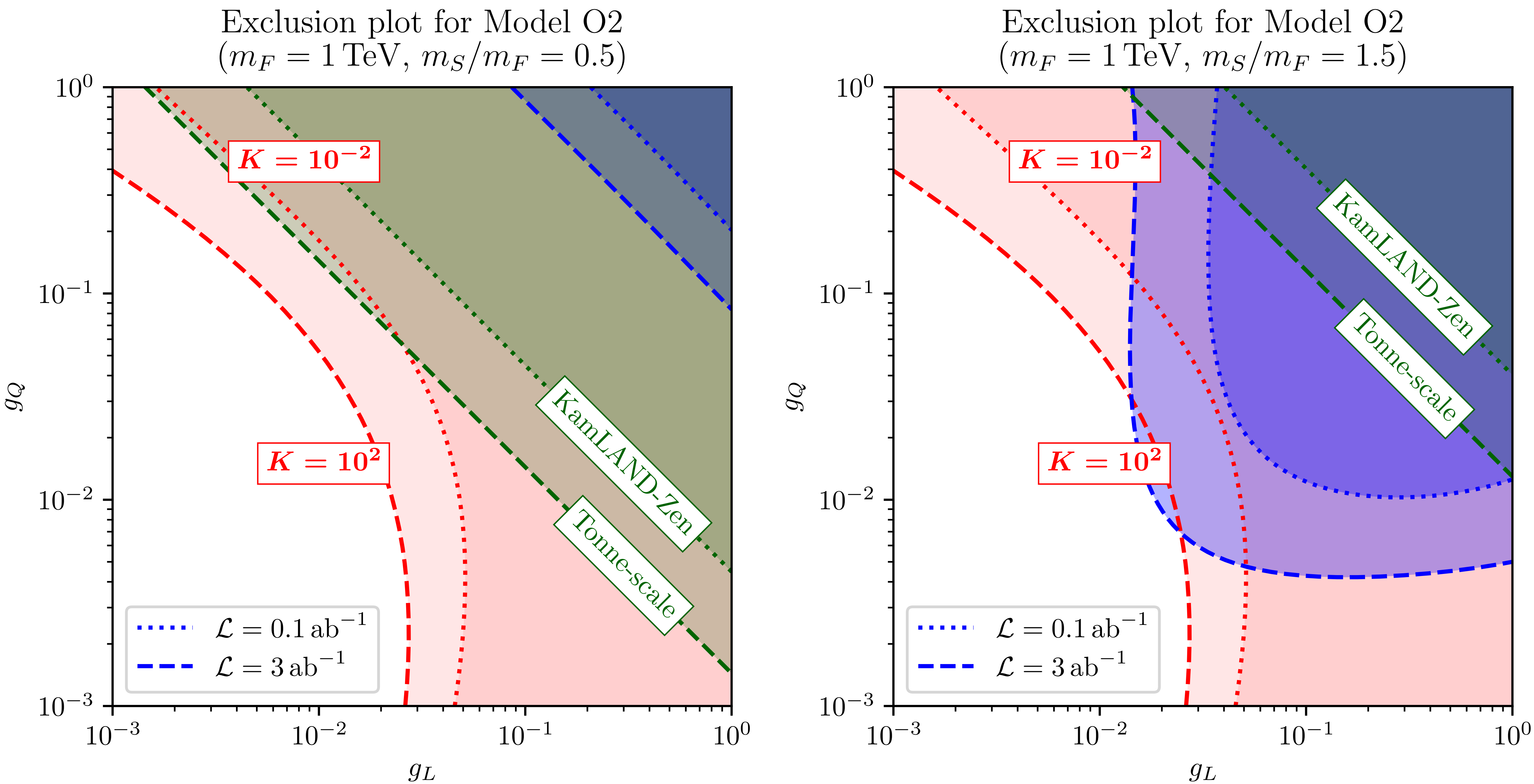


(2)



(3)

TeV-scale LNV effects



IV. Conclusions

- We have a well-motivated framework to perform different studies
- Rich phenomenology connecting different energy scales:
  A. Nuclear physics
  B. Collider physics
  C. Cosmology
- Complementarity between these different but related scenarios
- Promising options to falsify one of the standard mechanisms to explain the baryon asymmetry

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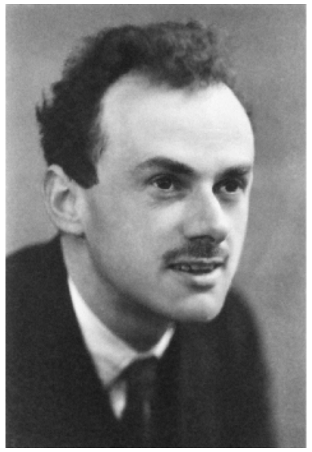
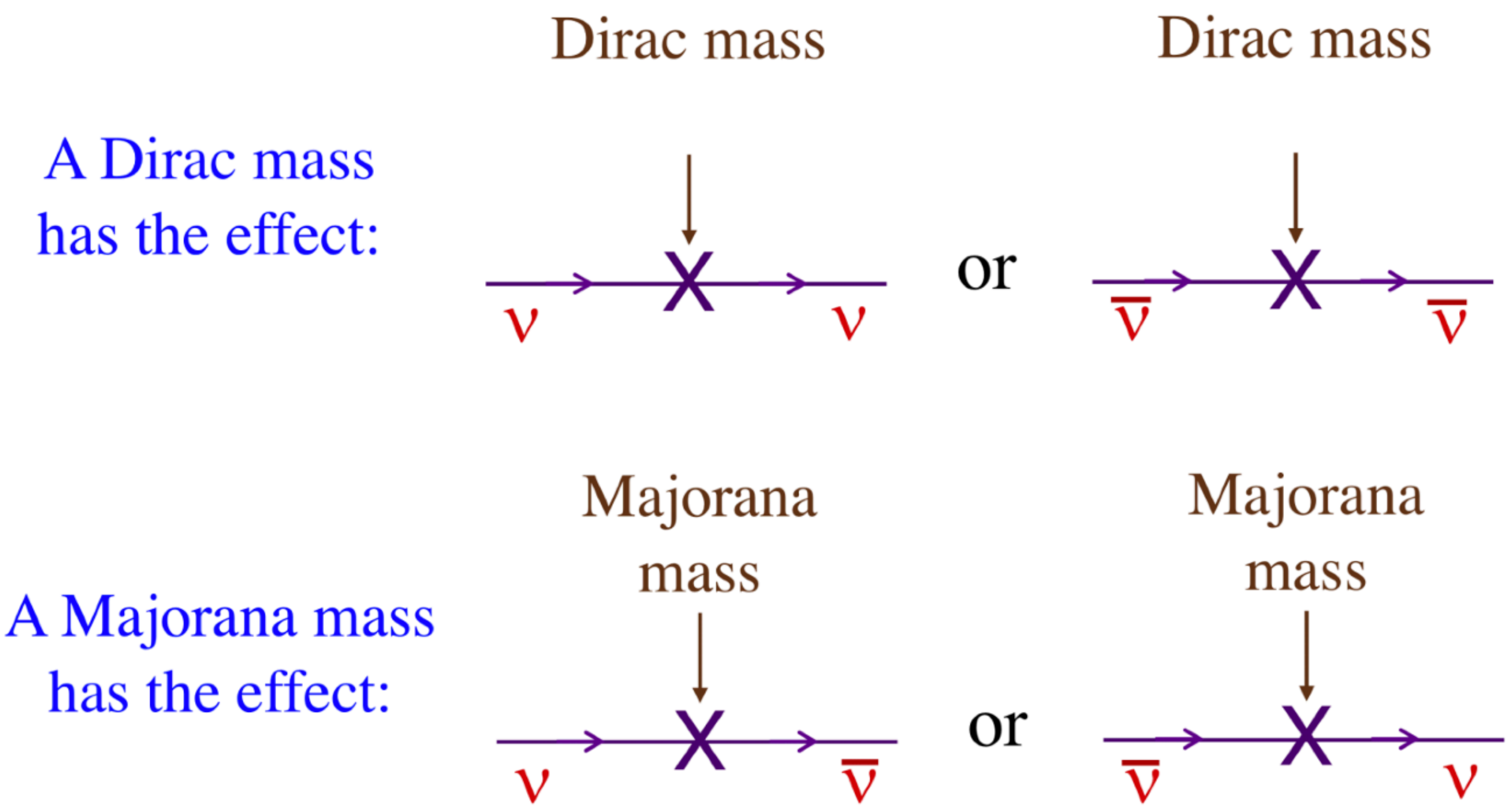
Backup slides: Dirac and Majorana masses

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

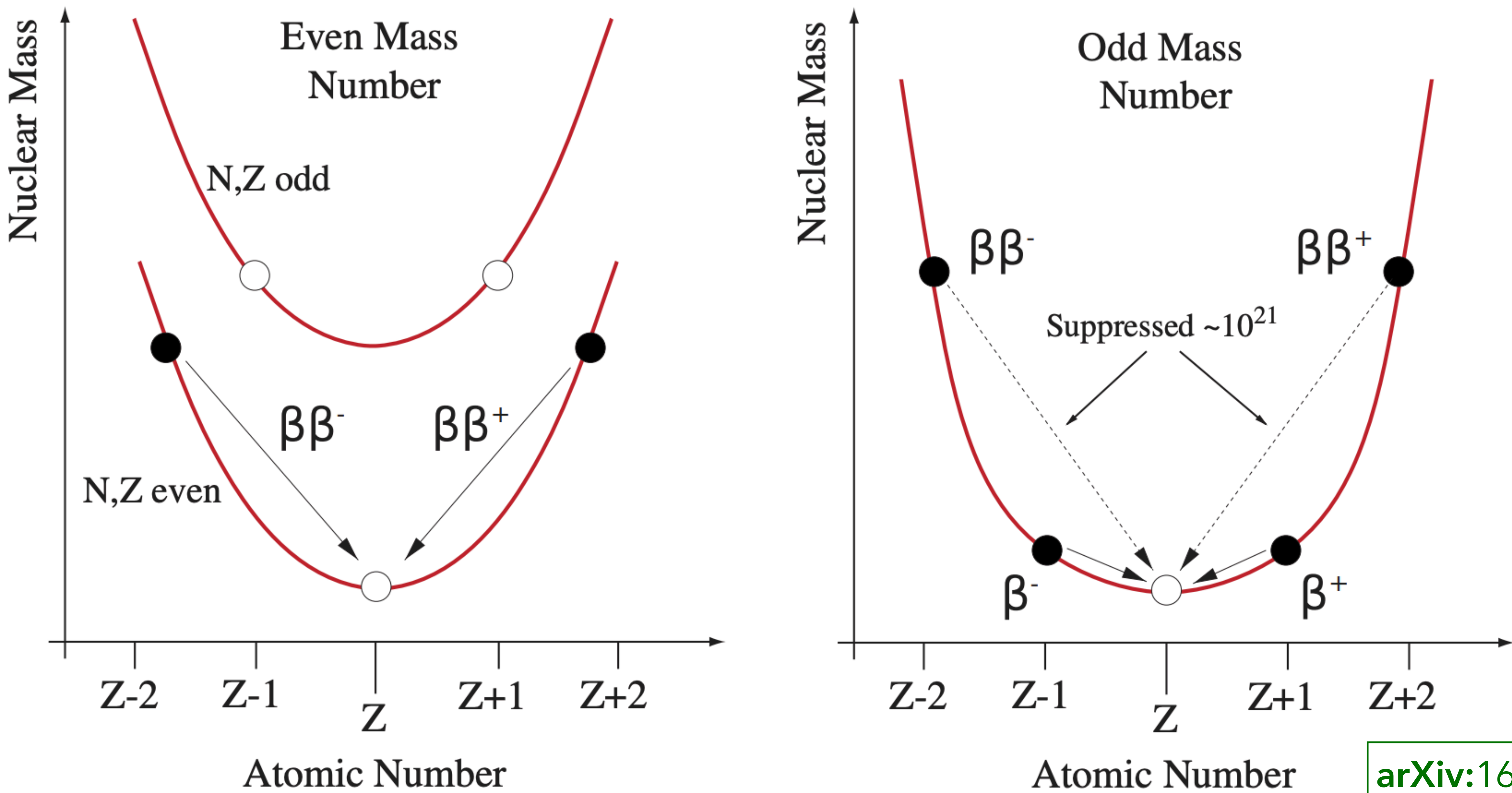
Majorana mass term: $m_M \overline{\Psi^c}\Psi$





arXiv:1805.00922

Backup slides: Nuclear shell structure



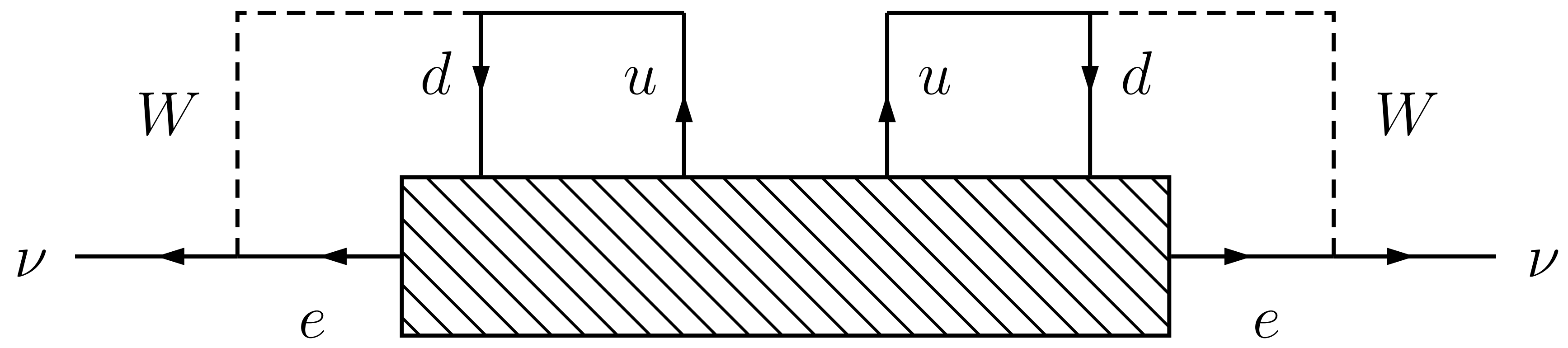
arXiv:1601.07512

"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: Neutrinoless double beta decay

- Two e^- and no $\bar{\nu}_e$ are emitted: $(A,Z) \rightarrow (A,Z+2)+2e^- + Q_{\beta\beta}$
- Not allowed in the SM: $\Delta\mathscr{L} \neq 0$
- Experimentally unseen

Black Box Theorem

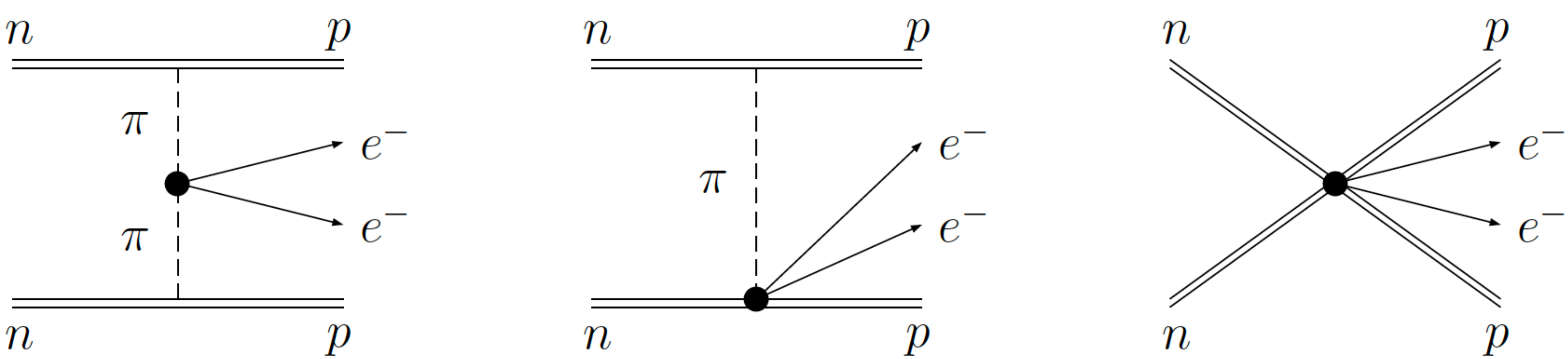


Majorana mass term: $\Delta\mathscr{L} = 2$

Phys.Rev.D 25 (1982) 2951

Backup slides: Effective operators

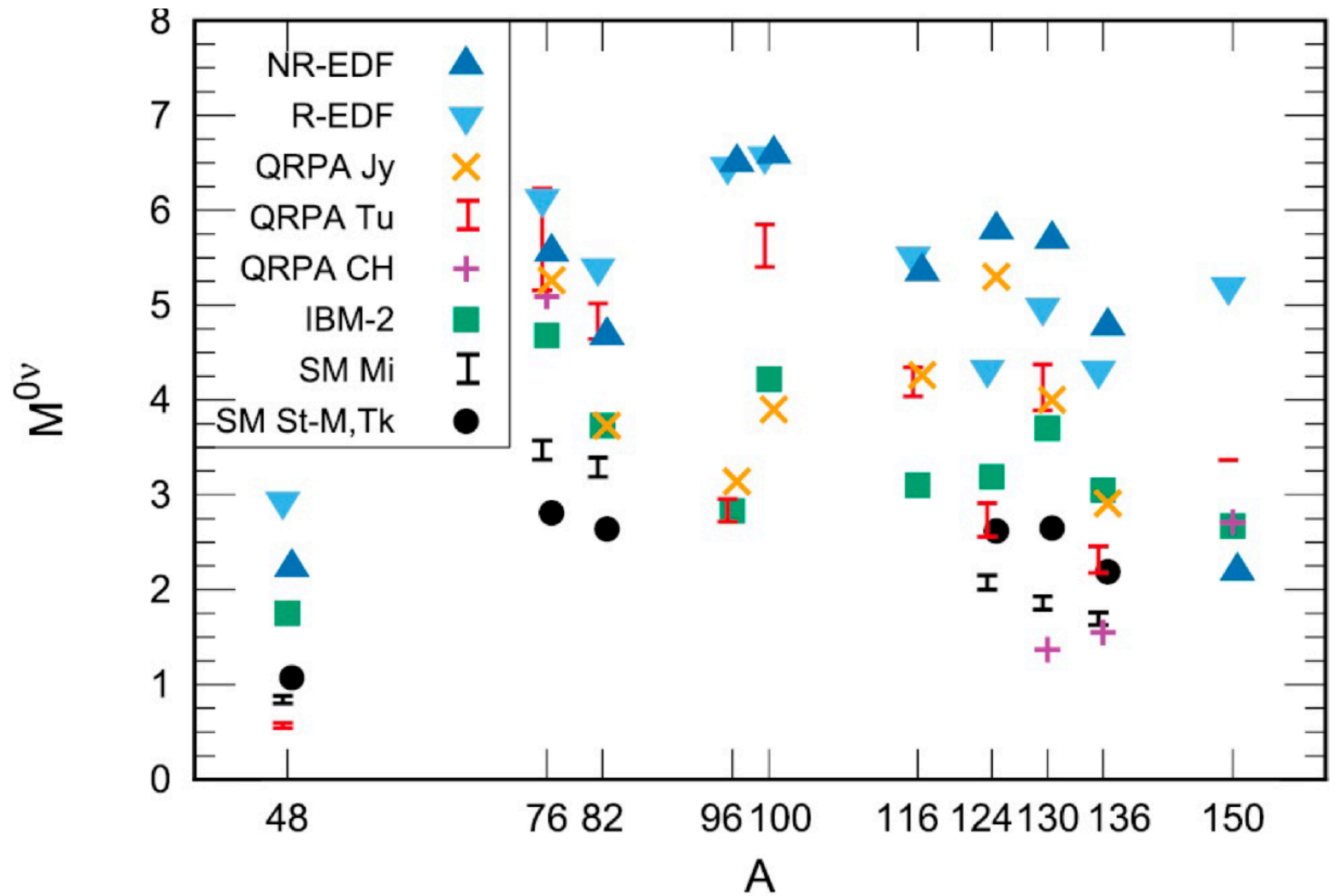
arXiv:hep-ph/0303205



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

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	✓	✓	✗	✓	✗	✓	✓	✓	✓

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

$$\mathscr{L}_{\mathrm{O2}} = g_Q \overline{Q} S d_R + g_L \overline{L} \widetilde{S} F - m_S{}^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \mathrm{h.c.}$$

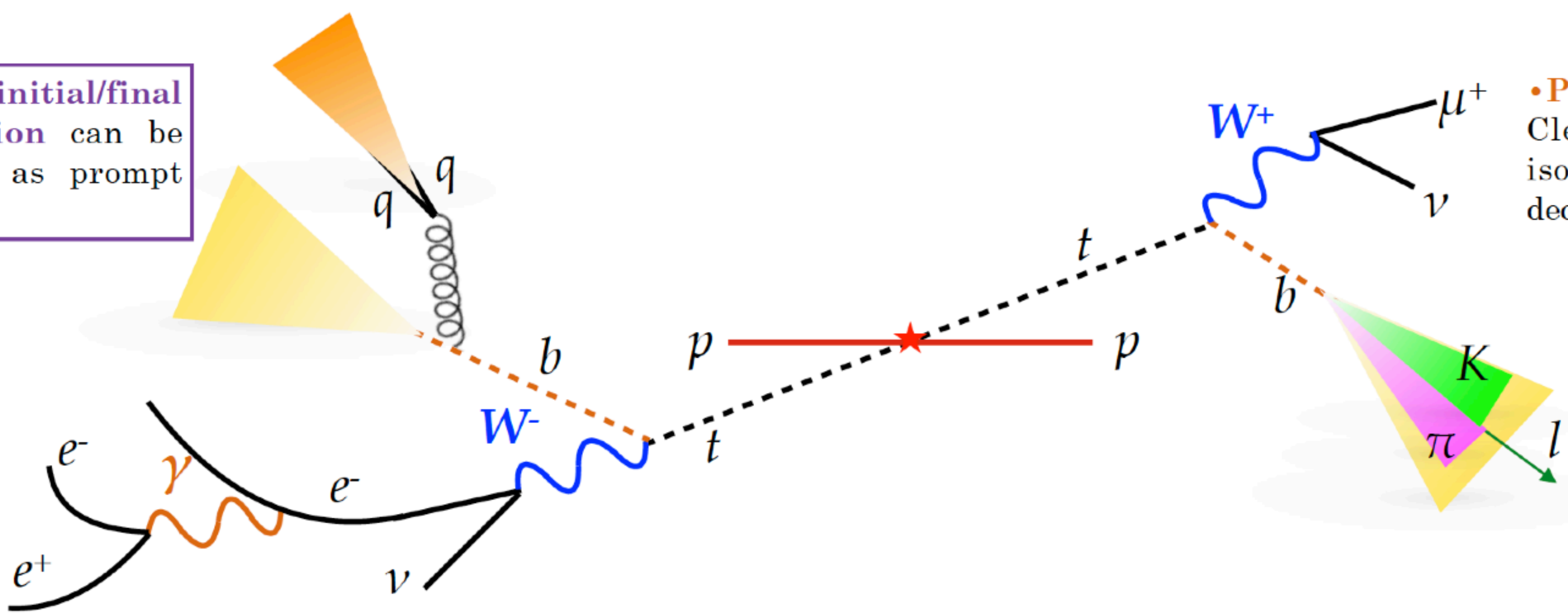
$$\widetilde{X} \equiv \epsilon X^* , \quad \epsilon^{12} = +1$$

arXiv:1508.04444

Backup slides: Background types

•Jets from initial/final state radiation can be misidentified as prompt leptons.

•Trident event:
$e^- \to e^- \gamma \to e^- e^+ e^-$
Electromagnetic cluster can be matched to wrong electron track in ID.

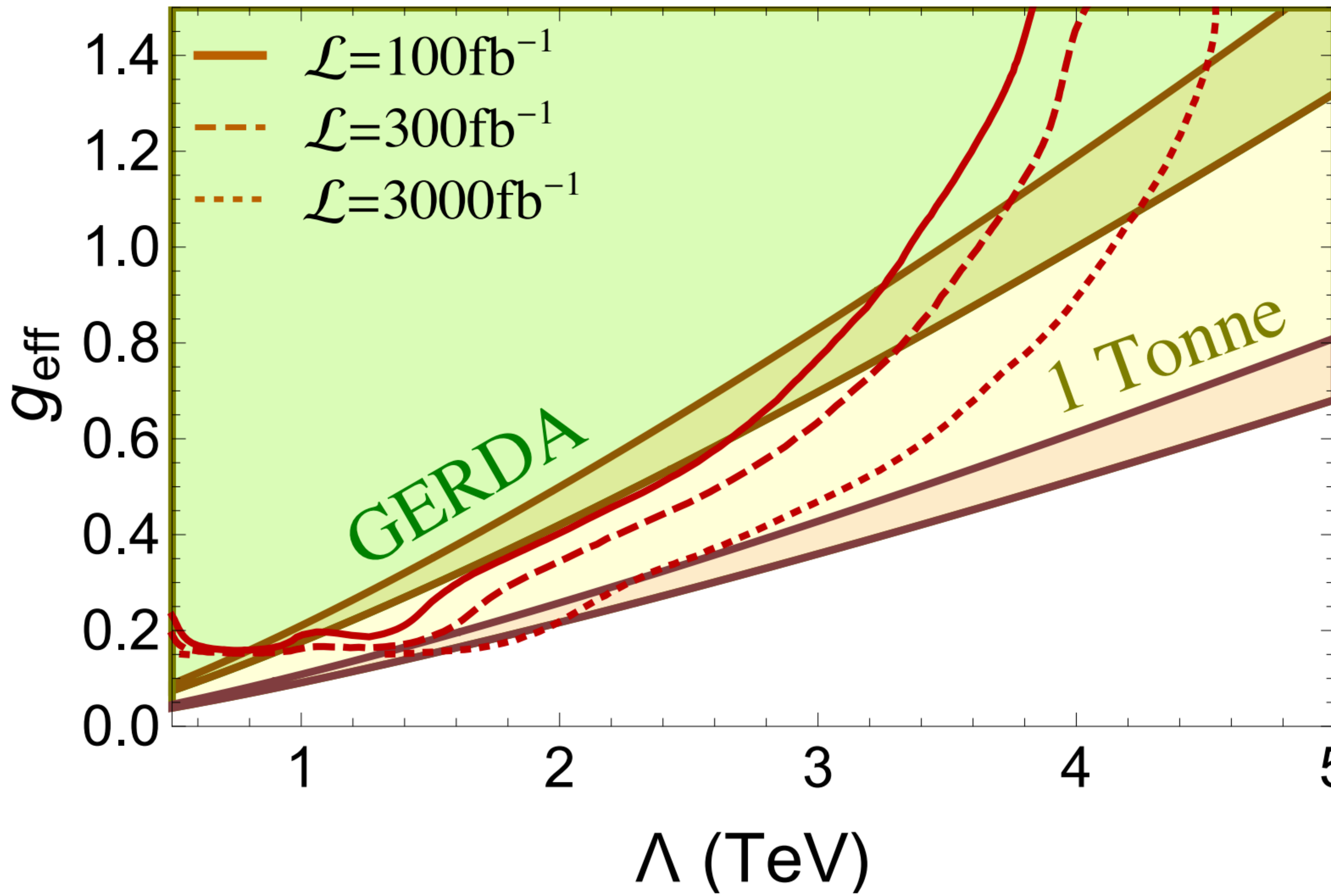


•Prompt muon from W^+ decay. Clean signature, high-p_T and isolated. Leptons from Z, W, H decays estimated with simulation.

•Non-prompt lepton from a B-hadron secondary decay, which are associated with hadron activities such as K and π. Less isolated object and larger impact parameter.

ATL-PHYS-SLIDE-2018-856

Backup slides: Previous study of Model O2



arXiv:1508.04444