Can we probe the Universe at the Fermi epoch in the lab?

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in collaboration with

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based on 1809.xxxxx

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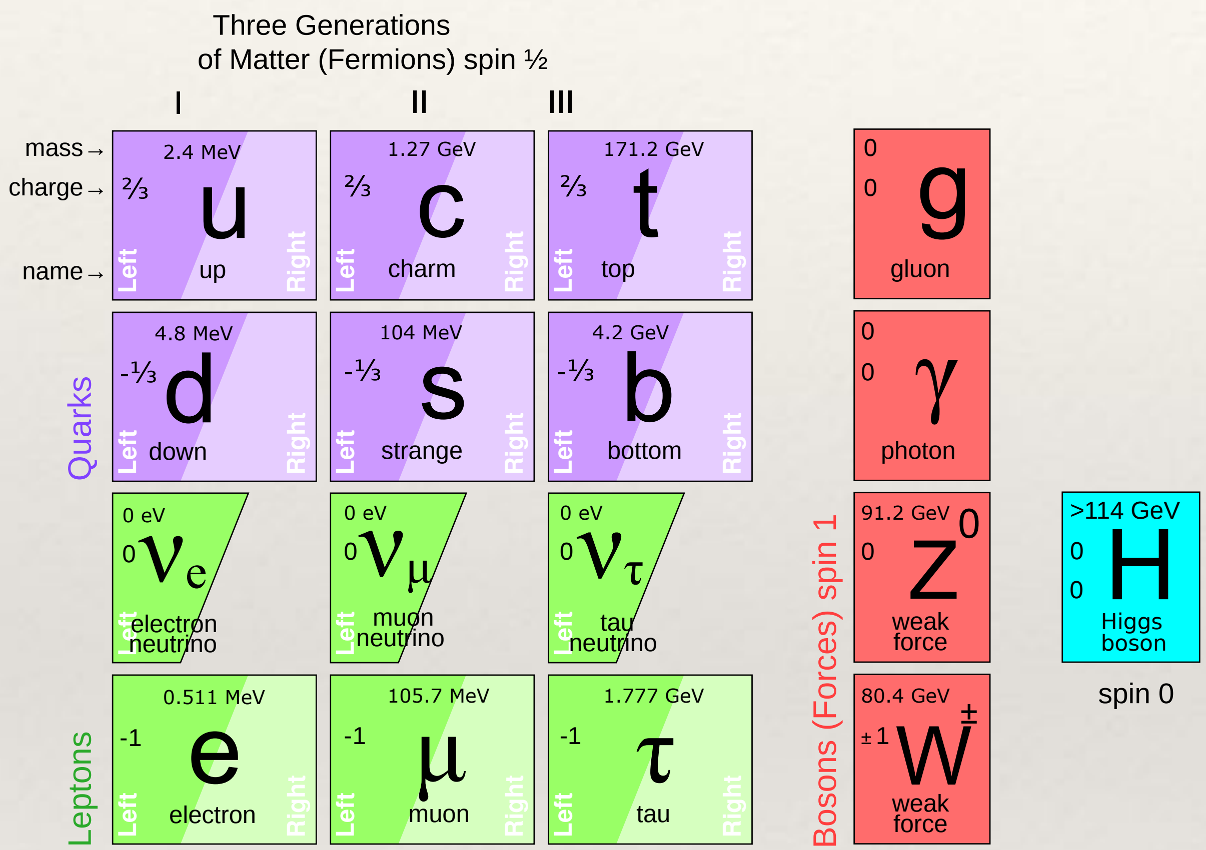
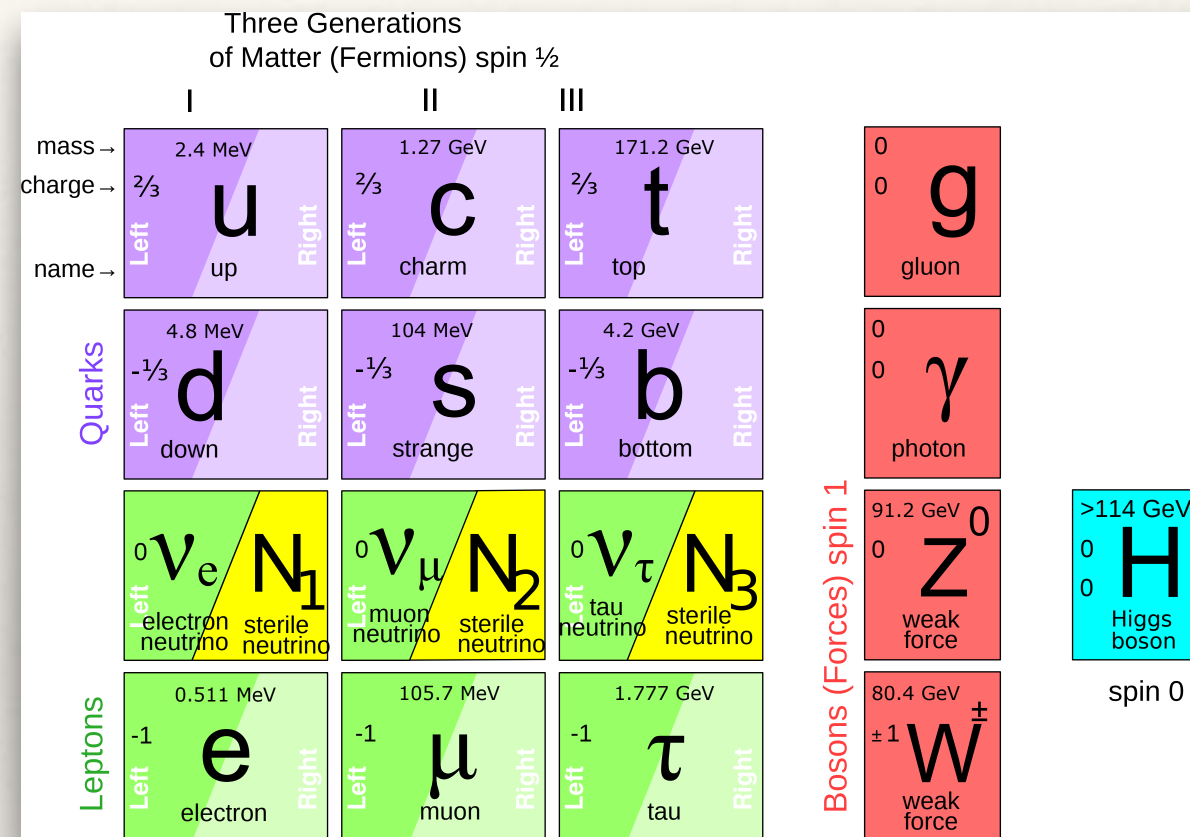
New physics below the electroweak scale

- No new physics found at LHC.
- There are phenomena beyond the SM:
  - Neutrino oscillations
  - Baryon asymmetry of the Universe (BAU)
  - Dark Matter
- All this problems can be addressed introducing 3 right-handed neutrinos with masses *below* the electroweak scale

νMSM
(neutrino Minimal Standard Model)

Asaka, Blanchet, Shaposhnikov 2005
Asaka, Shaposhnikov 2005





N_1 DM candidate $m \sim few \times keV$

N_2, N_3 } ν masses via see-saw, BAU, DM production $m \sim 0.1 - 10\, GeV$ almost degenerate

Akhmedov, Rubakov, Smirnov, 1998
Asaka, Shaposhnikov 2005

The νMSM: parameters

see-saw Lagrangian with 3 Majorana neutrino

Minkowski; Yanagida; Gell-Mann, Ramond, Slansky; Glashow; Mohapatra, Senjanovic

$$\mathscr{L} = \mathscr{L}_{SM} + i\bar{N}_I \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha \tilde{\Phi} N_I - \frac{M_{IJ}}{2} \bar{N}_I^c N_J + h.c.$$

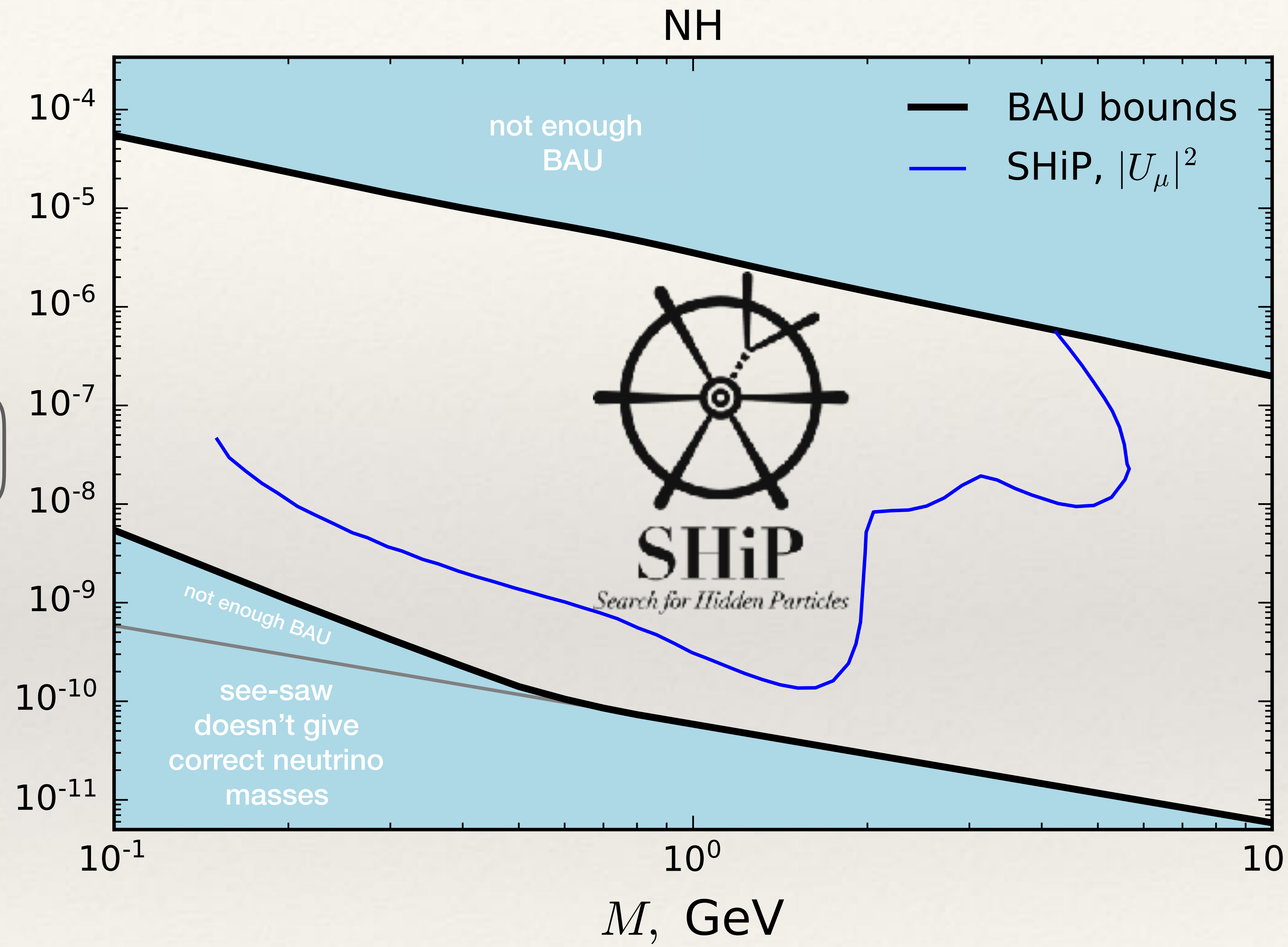
- N_1 **DM candidate — almost decoupled**
- **2 RH neutrinos (HNLs)**
- **common mass M, mass splitting ΔM**
- **4 parameters in F (compatible with oscillation data)**

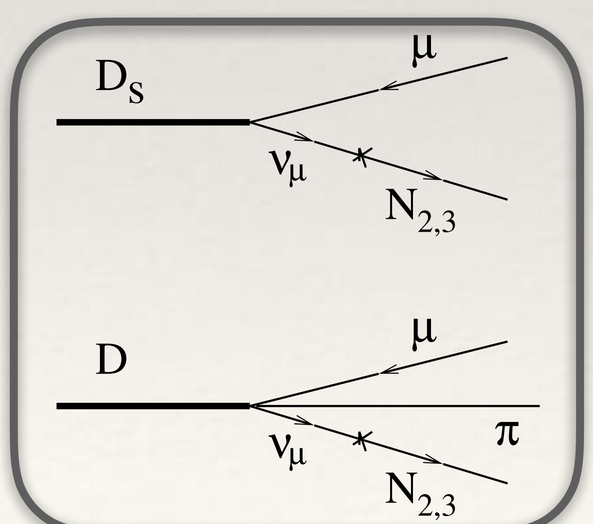
Casas, Ibarra, 2001

Baryogenesis in the νMSM: a way to probe the Universe at T > 130 GeV in accelerator experiments

NA62, SHiP, MATHUSLA

total mixing $|U|^2$



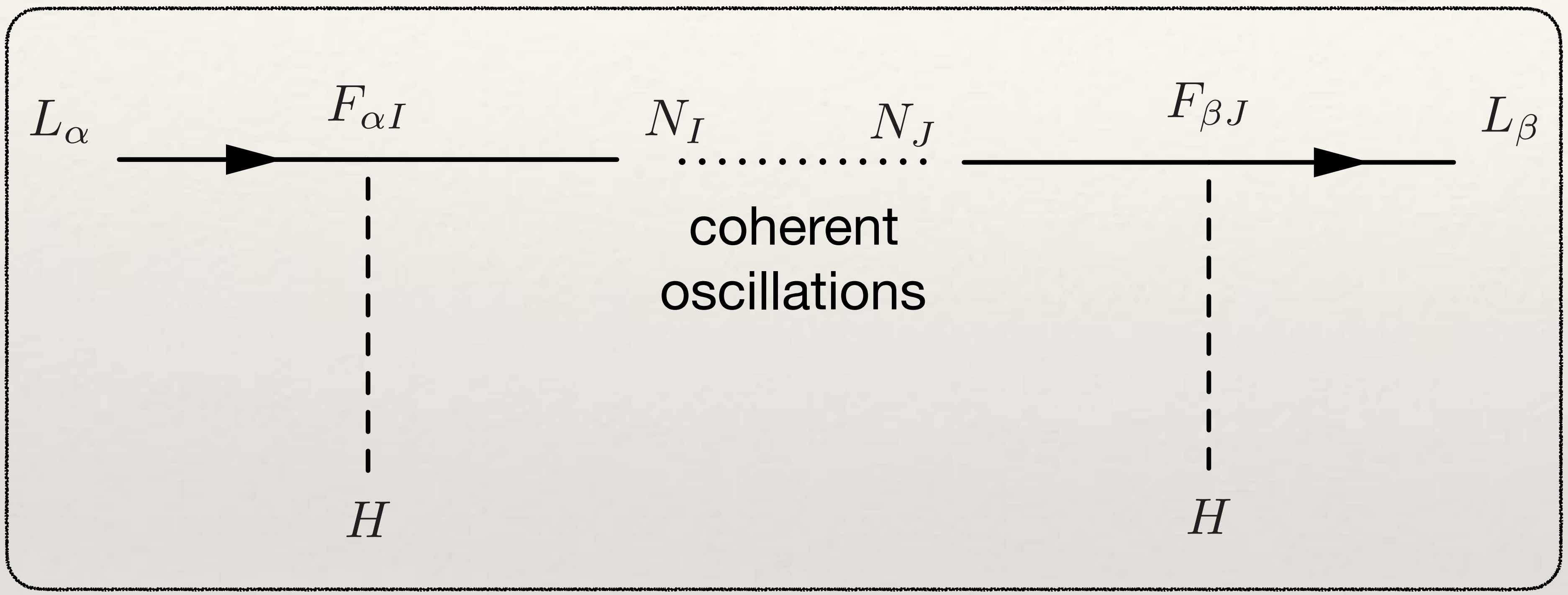


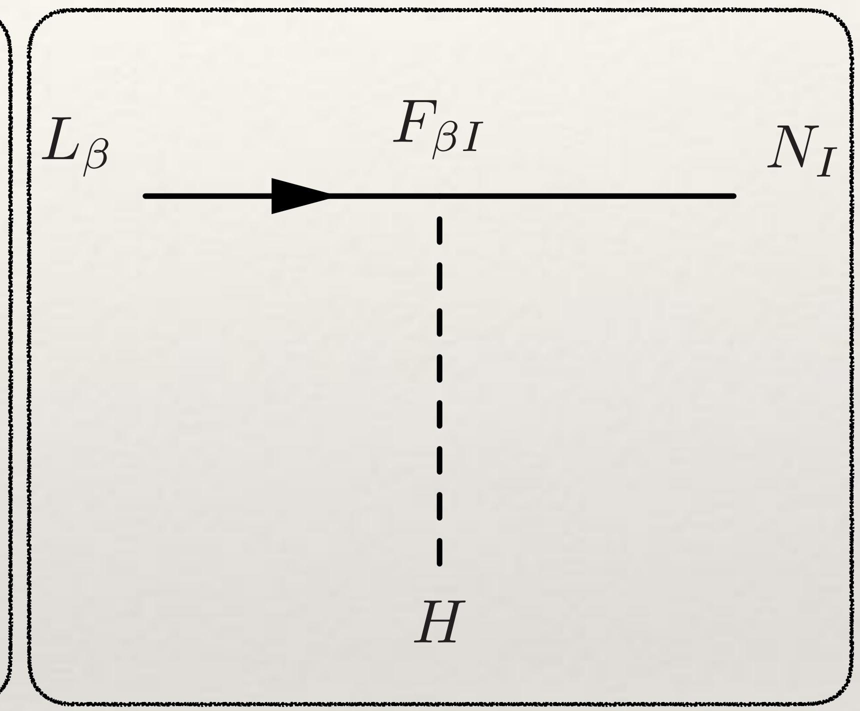
Mass of the N_2 (and N_3)

Right-handed neutrinos = heavy neutral leptons (HNLs)

Generation of asymmetry

$$\mathscr{L} = \mathscr{L}_{SM} + i\bar{N}_I\gamma^\mu\partial_\mu N_I - F_{\alpha I}\bar{L}_\alpha\tilde{\Phi}N_I - \frac{M_{IJ}}{2}\bar{N}_I^c N_J + h.c.$$





No lepton asymmetry
SM species
are in equilibrium
L-> N is out of equilibrium

Individual lepton asymmetries.

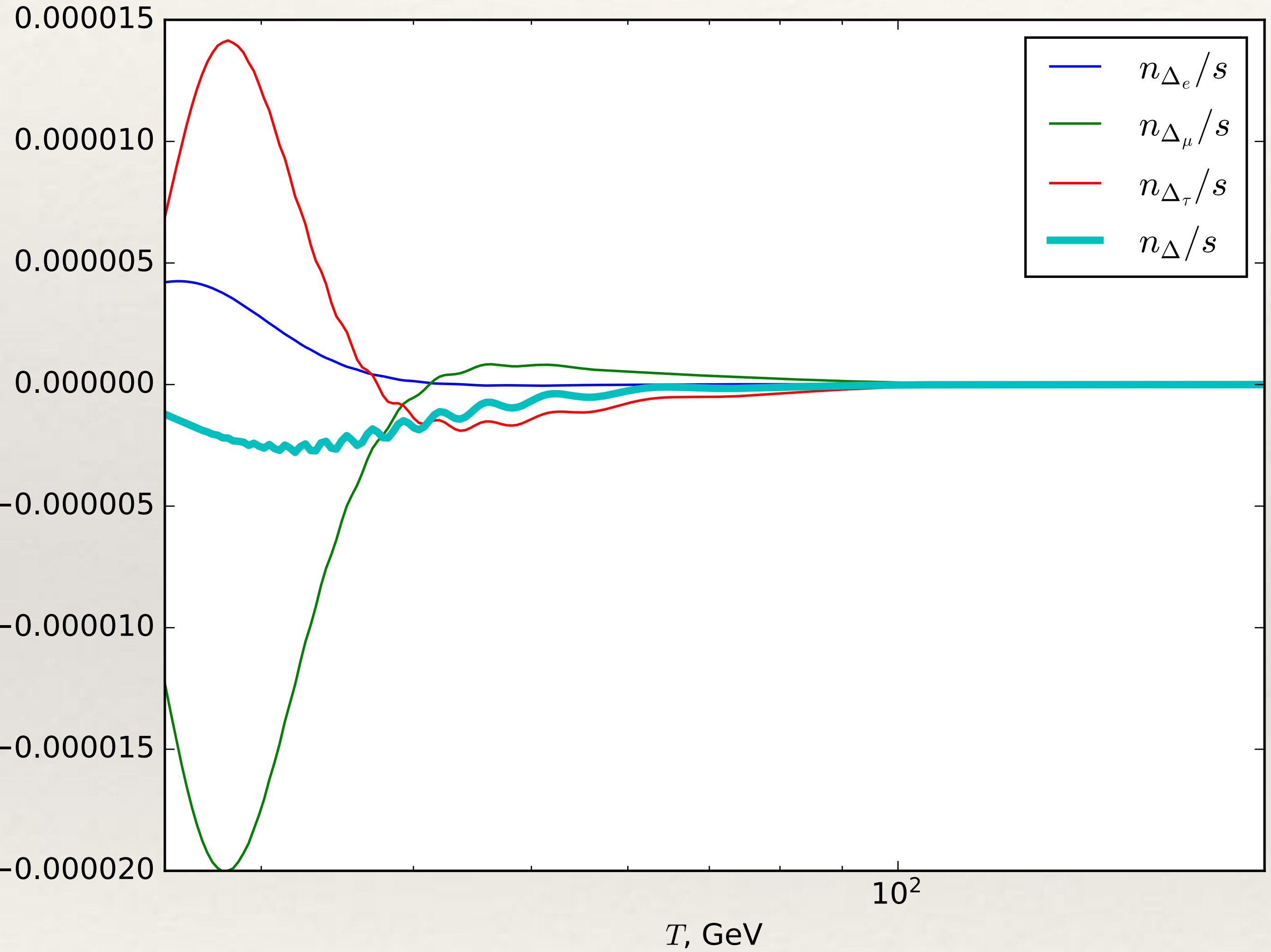
$$n_{L_\alpha} \neq n_{\overline{L_\alpha}}$$

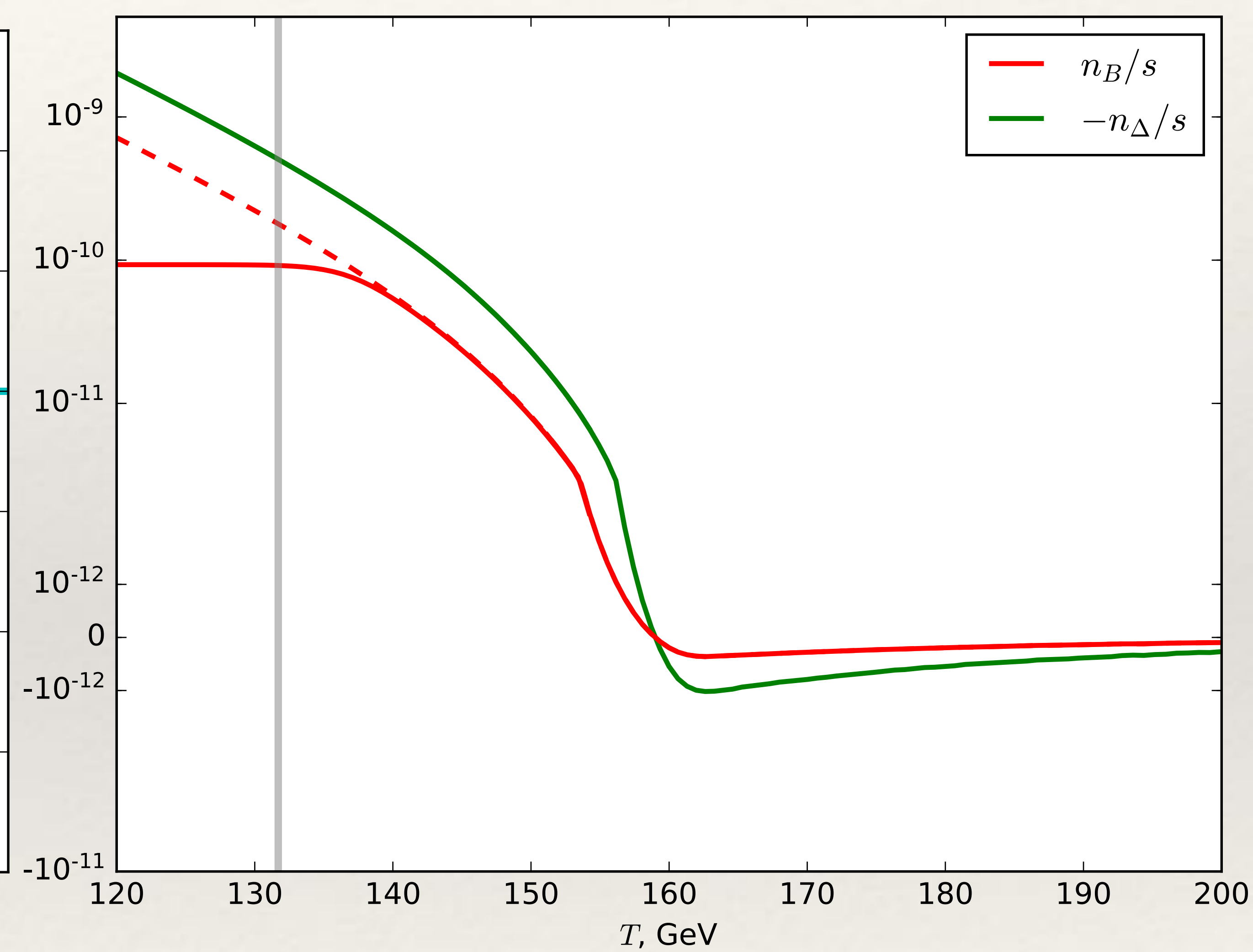
Total lepton asymmetry

$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\overline{L_\alpha} \to \overline{L_\beta})$$

Generation of asymmetry

$\Delta_\alpha = L_\alpha - B/3$ preserved by sphalerons



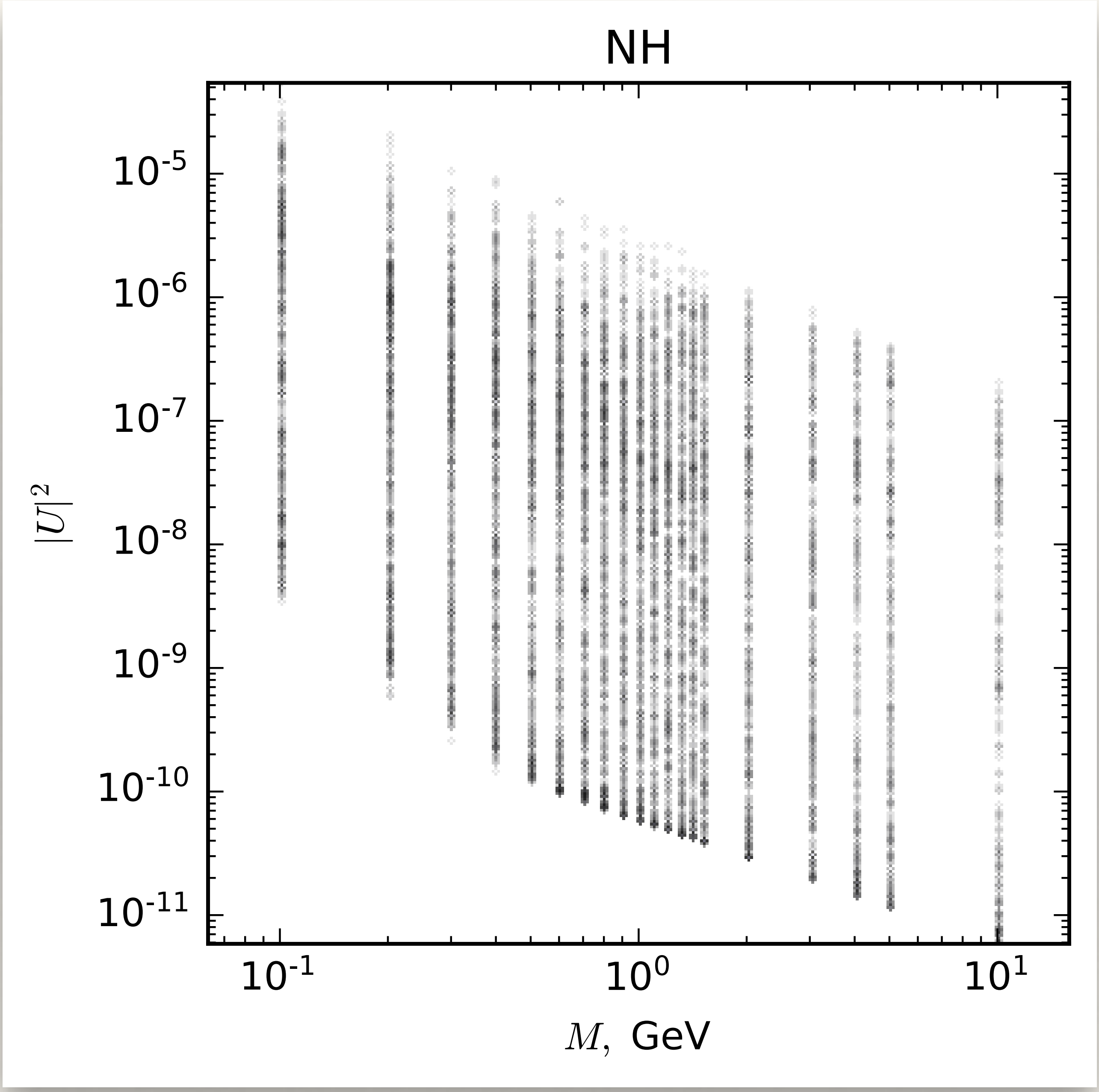


Recent improvements

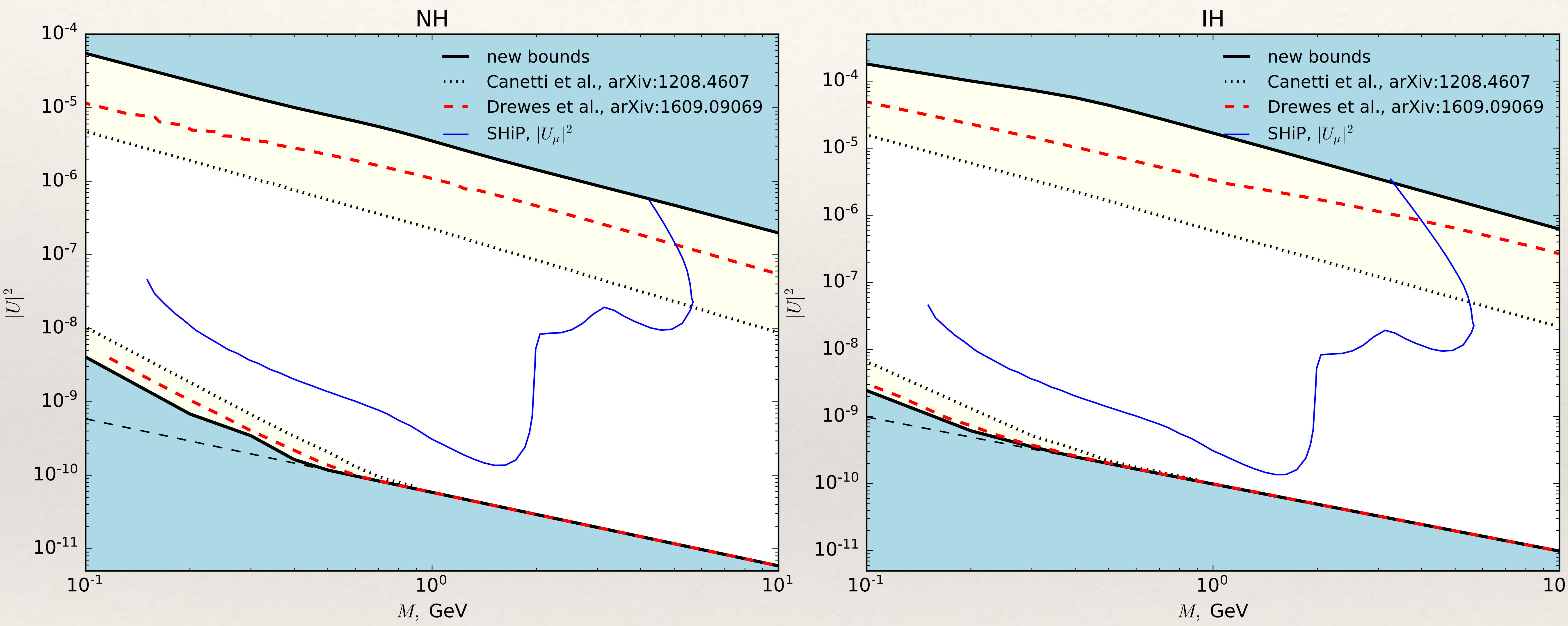
- Generation of asymmetry is described by a system of kinetic equations: (3 + 4 + 4) differential equations
- Recent improvements
  - Accurate computation of rates
    1012.3784, 1202.1288, 1403.2755, 1605.07720
  - Fermion number violating processes
    1703.06085, 1703.06087
  - Neutrality of plasma
    1401.2459, 1605.07720, 1709.07834
  - Gradual freeze-out of sphalerons
    1709.07834, 1711.08469
- Studies of the parameter space
  1208.4607, 1606.06690,1606.06719, 1609.09069, 1710.03744

A scan of the parameter space

- The model is described by 6 parameters:
  - common mass of HNLs
  - mass splitting of HNLs
  - phases of the Yukawas
- We are not aware of any priors in the space of theories
- We sample the whole parameter space directly
- Select $Y_B^{obs}/2 < Y_B < 2 \cdot Y_B^{obs}$

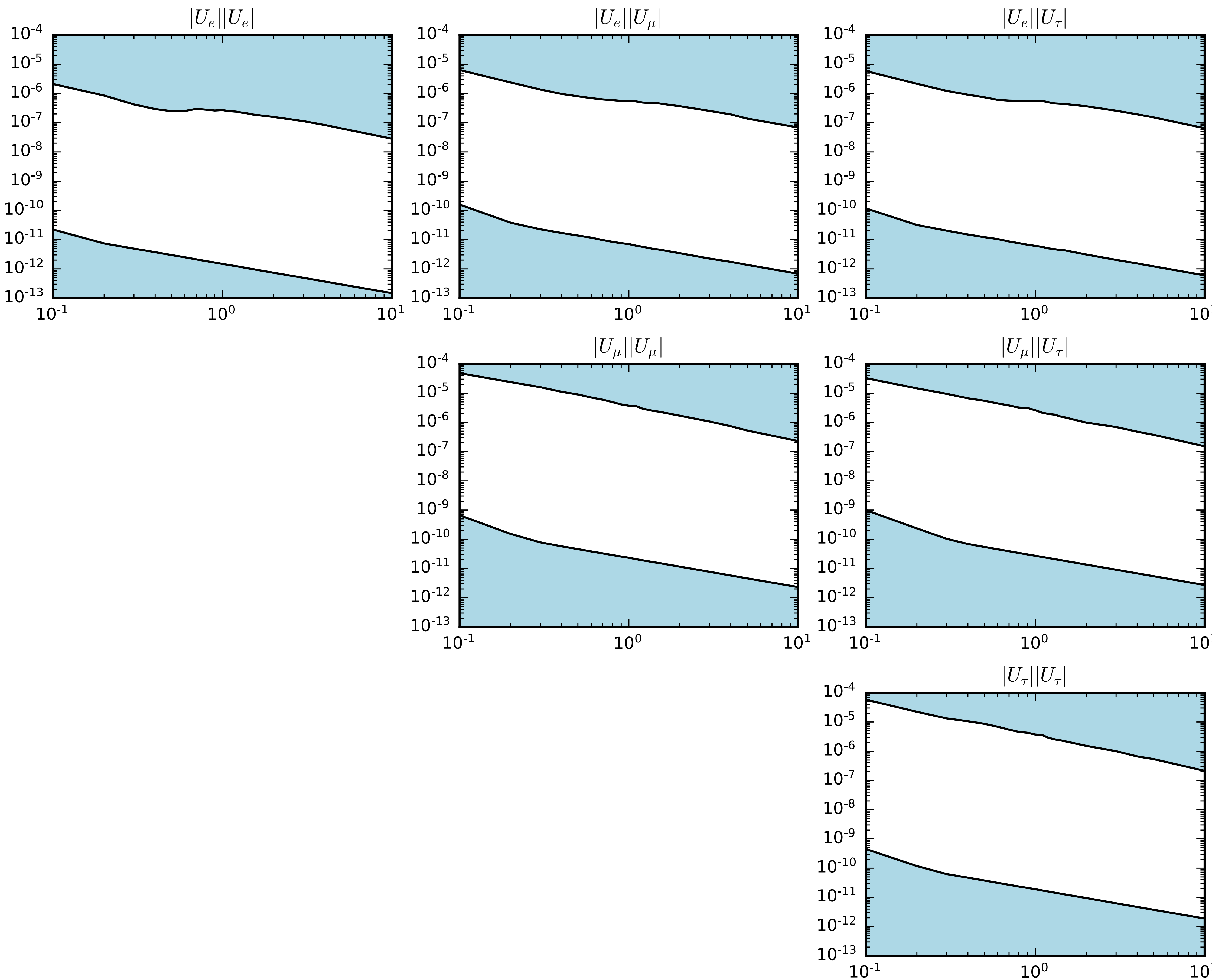


Allowed region of the parameter space



Conclusions

- Baryogenesis in the νMSM: a way to probe the Universe at $T > 130$ GeV in accelerator experiments
- We have performed a comprehensive analysis of the parameter space of the model.
- We found that the region of parameters leading to the successful baryogenesis is notably larger than it was previously obtained.


$|U_e||U_e|$
$|U_e||U_\mu|$
$|U_e||U_\tau|$
$|U_\mu||U_\mu|$
$|U_\mu||U_\tau|$
$|U_\tau||U_\tau|$
10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
10^{-1} 10^{0} 10^{1}

Kinetic equations

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int \frac{d^3k}{(2\pi)^3}\Gamma_{\nu_\alpha} f_\nu(1-f_\nu) + i\int \frac{d^3k}{(2\pi)^3}\Big(\mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}\,\rho_{\bar{N}}] - \mathrm{Tr}[\tilde{\Gamma}^*_{\nu_\alpha}\,\rho_N]\Big)\,,$$

$$i\,\frac{d\rho_N}{dt} = [H_N, \rho_N] - \frac{i}{2}\,\{\Gamma_N, \rho_N - \rho_N^{eq}\} - \frac{i}{2}\sum_\alpha \tilde{\Gamma}^\alpha_N\,\Big[2\frac{\mu_\alpha}{T} f_\nu(1-f_\nu)\Big]\,,$$

$$i\,\frac{d\rho_{\bar{N}}}{dt} = [H_N^*, \rho_{\bar{N}}] - \frac{i}{2}\,\{\Gamma_N^*, \rho_{\bar{N}} - \rho_N^{eq}\} + \frac{i}{2}\sum_\alpha (\tilde{\Gamma}^\alpha_N)^*\,\Big[2\frac{\mu_\alpha}{T} f_\nu(1-f_\nu)\Big]\,,$$