Probing heavy neutral leptons in the νMSM

Shintaro Eijima (KEK)

Based on;
- JHEP07(2019)077 [SE, M. Shaposhnikov, I. Timiryasov]
- ArXiv:1902.04535 [I. Boiarska, K. Bondarenko, A. Boyarsky, SE, M. Ovchynnikov, O. Ruchayskiy, I. Timiryasov]

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Physics of right-handed neutrinos

Right-handed neutrinos can explain phenomena beyond the Standard Model (SM).

$$\mathscr{L} = \mathscr{L}_{SM} + i\bar{\nu}_{RI}\gamma^{\mu}\partial_{\mu}\nu_{RI} - F_{\alpha I}\bar{L}_{\alpha}\tilde{\Phi}\nu_{RI} - \frac{[M_M]_I}{2}\bar{\nu}^{c}_{RI}\nu_{RI} + h.c.$$

1. Seesaw mechanism
   → Neutrino oscillations

2. Leptogenesis
   → Baryon Asymmetry of the Universe (BAU)

3. Dark Matter (DM)
   → Sterile neutrino

4. …

Neutrino Minimal Standard Model (νMSM)

[Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05)]

Right-handed neutrinos with masses below the electroweak scale, ~ 100 GeV, can explain phenomena beyond the Standard Model (SM) and be probed experimentally.

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Heavy Neutral Leptons (HNLs) with $M = \mathcal{O}(1\text{-}10)$ GeV

Search for long-lived particles

N_2 N_3

3. Dark Matter (DM)
   → Sterile neutrino

with $M = \mathcal{O}(10)$ keV

X-ray obsearvations

N_1

Neutrino Minimal Standard Model (νMSM)

[Asaka, Shaposhnikov ('05)] [Asaka, Blanchet, Shaposhnikov ('05)]

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Goal of this work

We can probe origin of the puzzle of early Universe in laboratories!

<u>Q1. Where should we explore for the leptogenesis?</u>

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Q2. How can we probe the HNLs experimentally?

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In this talk I show a parameter space of HNLs for the successful BAU and how it will be tested in experiments.

1. Introduction
2. Seesaw mechanism
3. Leptogenesis via right-handed neutrino oscillation
4. Search for heavy neutral leptons

Seesaw mechanism for HNLs

[Minkowski ('77)][Yanagida ('79)] [Gell-Mann, Ramond, Slansky ('79)][Glashow ('79)][Mohapatra, Senjanovic ('79)]

Seesaw mechanism suggests couplings of HNLs are suppressed.

$$\mathscr{L}_M = [M_D]_{\alpha I} \bar{\nu}_{L\alpha} \nu_{RI} + \frac{[M_M]_I}{2} \bar{\nu}^c_{RI} \nu_{RI} + h.c. \qquad [M_D]_{\alpha I} \equiv \langle \Phi \rangle F_{\alpha I}$$

To mass basis under $|M_D| \ll M_M$

$$\mathscr{L}_M \simeq \frac{[m_\nu]_i}{2} \bar{\nu}_i \nu^c_i + \frac{[M_N]_I}{2} \bar{N}^c_I N_I + h.c. \qquad M_N \simeq M_M$$

$$[m_\nu]_i = -U^\dagger_{PMNS} [M_D M_M^{-1} M_D^T] U^*_{PMNS} = -\langle \Phi \rangle^2 U^\dagger_{PMNS} [F M_M^{-1} F^T] U^*_{PMNS}$$

$$\Delta m^2_{atm} \simeq 2.5 \times 10^{-3} \ \mathrm{eV}^2 \ \rightarrow m_\nu \sim 0.05 \ \mathrm{eV}$$

$$\rightarrow \quad \boxed{F \sim \sqrt{\frac{m_\nu M_N}{\langle \Phi \rangle^2}} \simeq 4 \times 10^{-8} \left(\frac{M_N}{\mathrm{GeV}} \right)^{\frac{1}{2}}}$$

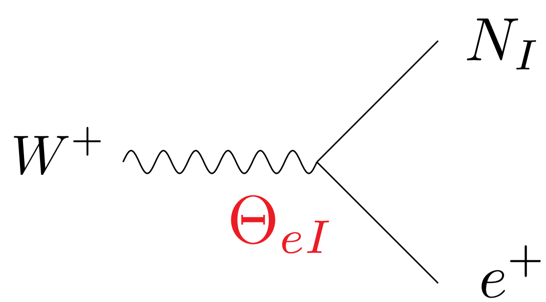
Interaction of HNLs

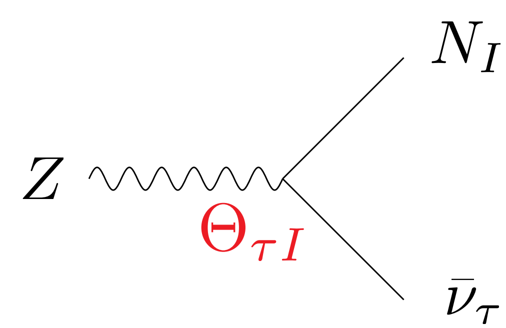
HNLs interact with SM particles as ordinary neutrinos through active-sterile mixing.

$$\nu_{L\alpha} = [U_{PMNS}]_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c$$

$$\Theta_{\alpha I} \equiv \frac{[M_D]_{\alpha I}}{M_N} = \frac{\langle\Phi\rangle F_{\alpha I}}{M_N} \sim 7\times 10^{-6}\left(\frac{\mathrm{GeV}}{M_N}\right)^{\frac{1}{2}}$$

Weak interaction with $\Theta_{\alpha I}$





Long-lived particle

$$\Gamma(N \to 3\nu) = \frac{G_F^2 M_N^5}{192\pi^3}\sum_\alpha |\Theta_\alpha|^2$$

$$\longrightarrow \quad \tau_N \sim 1 \text{ sec}\left(\frac{\mathrm{GeV}}{M_N}\right)^4$$

$$\Gamma(N \to \pi^+ e^-) \simeq \frac{G_F^2}{16\pi}|\Theta_e|^2 |V_{ud}|^2 f_\pi^2 M_N^3$$

$$\longrightarrow \quad \tau_N \sim 0.1 \text{ sec}\left(\frac{\mathrm{GeV}}{M_N}\right)^2$$

Yukawa couplings for ν oscillation measurements

Neutrino oscillation measurements determine structure of the Yukawa couplings.

$$\Delta m^2_{atm} \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2 \ and\ \Delta m^2_{sol} \simeq 7.4 \times 10^{-5} \mathrm{eV}^2 \longrightarrow \mathbf{N}_{\nu_R} \geq 2$$

$$[m_\nu]_i = -\langle\Phi\rangle^2 U^\dagger_{PMNS}[F M_M^{-1} F^T] U^*_{PMNS}$$

Δm^2, θ_{ij}, δ, η

Flavor structure;

$|F_e| : |F_\mu| : |F_\tau|$

$$F = \frac{i}{\langle\Phi\rangle} U_{PMNS}\, m_\nu^{\frac{1}{2}}\, \Omega\, M_N^{\frac{1}{2}}$$ (3x2 matrix)

[Casas, Ibarra ('01)]

$$\underset{\text{(NH)}}{\Omega} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix}$$

$\cos(i\,\mathrm{Im}\omega) = (e^{\mathrm{Im}\omega} + e^{-\mathrm{Im}\omega})/2 \quad \sin(i\,\mathrm{Im}\omega) = i(e^{\mathrm{Im}\omega} - e^{-\mathrm{Im}\omega})/2$

$(\Omega\Omega^T = 1)$ Enhancement; $F \propto e^{\mathrm{Im}\omega}$ or $e^{-\mathrm{Im}\omega}$

- Flavor components of F_α (and Θ_α) are not independent.
- Seesaw puts only the lower boundary on $|F_\alpha|$ (and $|\Theta_\alpha|$)

Yukawa couplings for ν oscillation measurements

Neutrino oscillation measurements determine structure of the Yukawa couplings.

$\Delta m^2 \simeq 2.5\times 10^{-3}$ eV^2 *and* $\Delta m^2 \simeq 7.4\times 10^{-5}$eV^2 ⟶ $N_\nu \geq 2$

The upper boundary on $|\Theta_\alpha|$ ($\propto |F_\alpha|$) is a necessary criterion for experimental searches.

Q1. Where should we explore for the leptogenesis?

⟶ How large is the upper boundary from the leptogenesis?

(NH) $\begin{pmatrix} -\sin\omega & \cos\omega \end{pmatrix}$ $(\Omega\Omega^T = 1)$ Enhancement; $F \propto e^{\mathrm{Im}\omega}$ *or* $e^{-\mathrm{Im}\omega}$

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- Seesaw puts only the lower boundary on $|F_\alpha|$ (and $|\Theta_\alpha|$)

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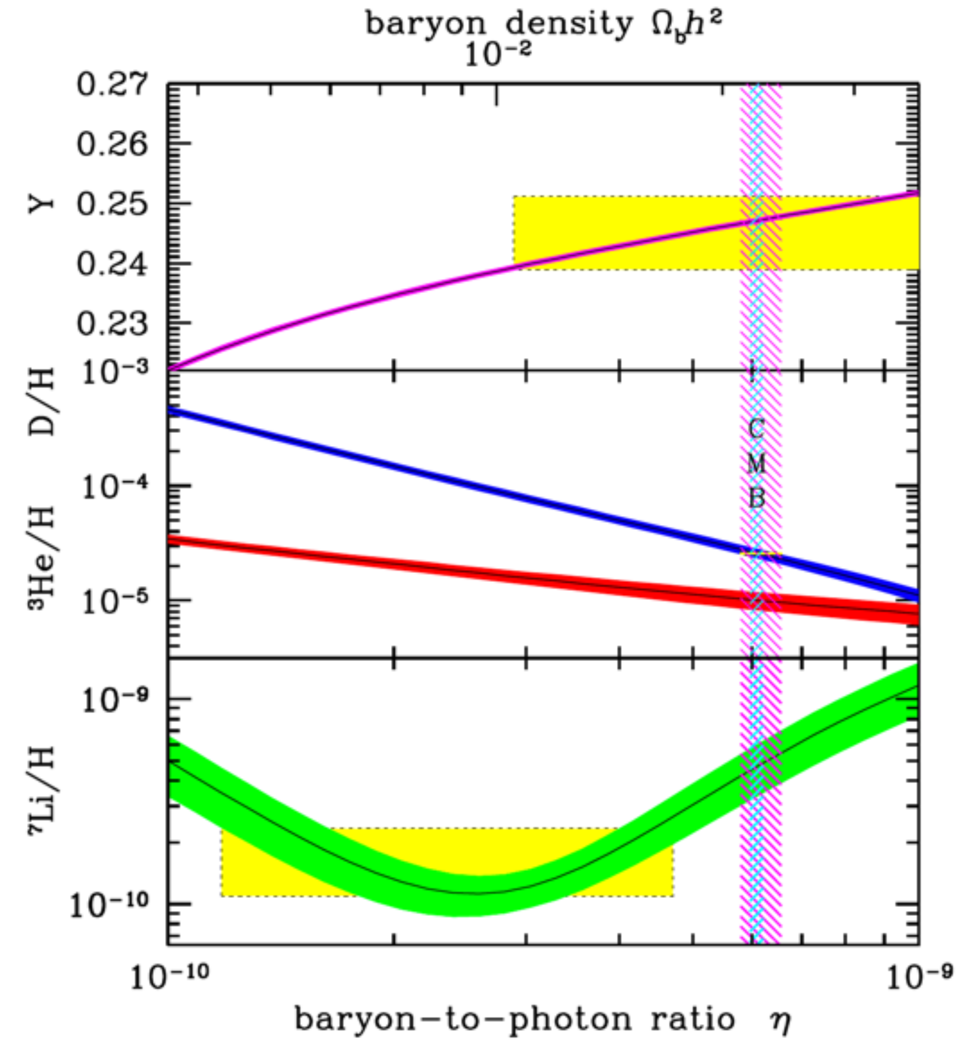
Baryogenesis with HNLs

Deviation from equilibrium can be satisfied due to the smallness of Yukawa interaction.

Observed BAU

$$Y_B^{obs} = (0.872 \pm 0.004) \times 10^{-10} \qquad Y_B \equiv \frac{n_b - n_{\bar{b}}}{s}$$

[Planck collaboration ('18)]



[PDG ('17)]

Sakharov conditions

1. B violation
   Anomalous violation (Sphaleron)

2. C and CP violation
   CP violation in neutrino Yukawa couplings

3. Deviation from equilibrium
   Decoupled due to the feeble Yukawa interaction

Leptogenesis with HNLs

Baryon asymmetry is generated by conversion from lepton asymmetry through sphaleron process.

Sphaleron process ; anomalous B violating process at high T

$$B(T_{sph}) \simeq \frac{28}{79}[B-L](T_{sph})$$

[Khlebnikov, Shaposhnikov('88)]

↑ From BSM (RHν)

Lepton asymmetry production

$T_{sph} \approx 130$ GeV ⟶ $M_N \ll T$ ⟶

- Decay is irrelevant
- Lepton number is preserved effectively

[D'Onofrio, Rummukainen, Tranberg ('14)]

⟶ Key dynamics

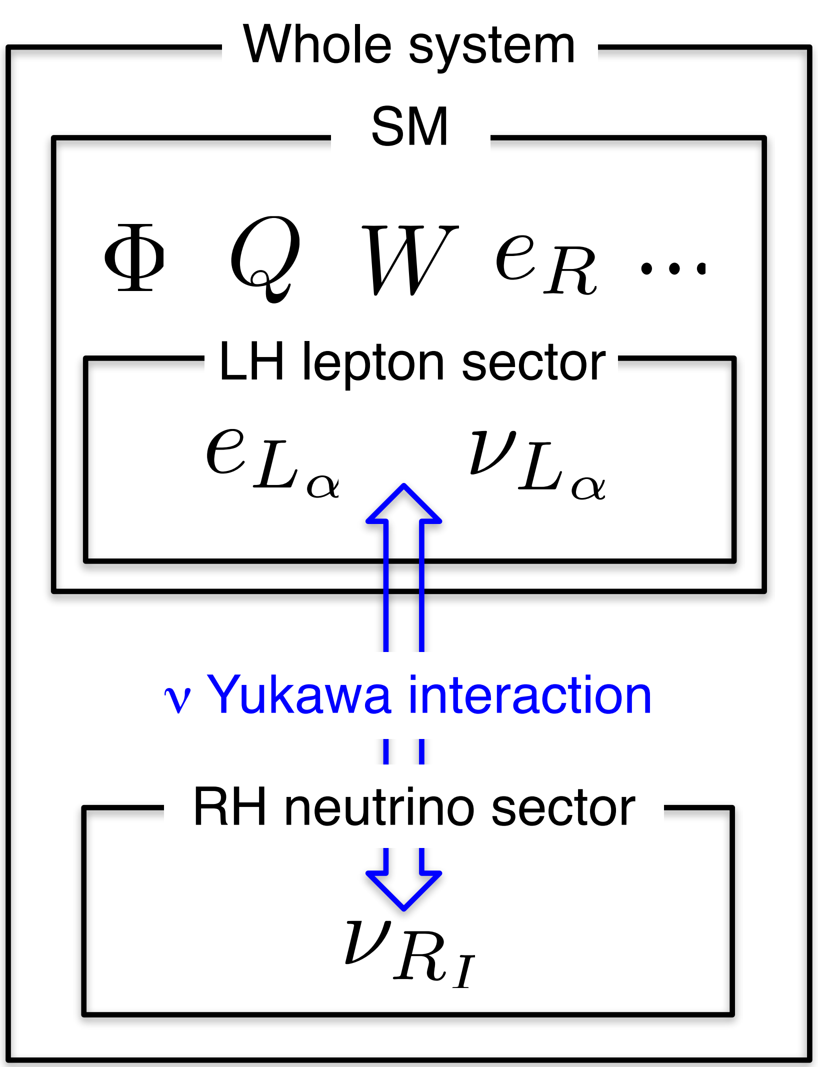
- **Right-handed neutrino oscillation**
- **Separation of lepton asymmetry**

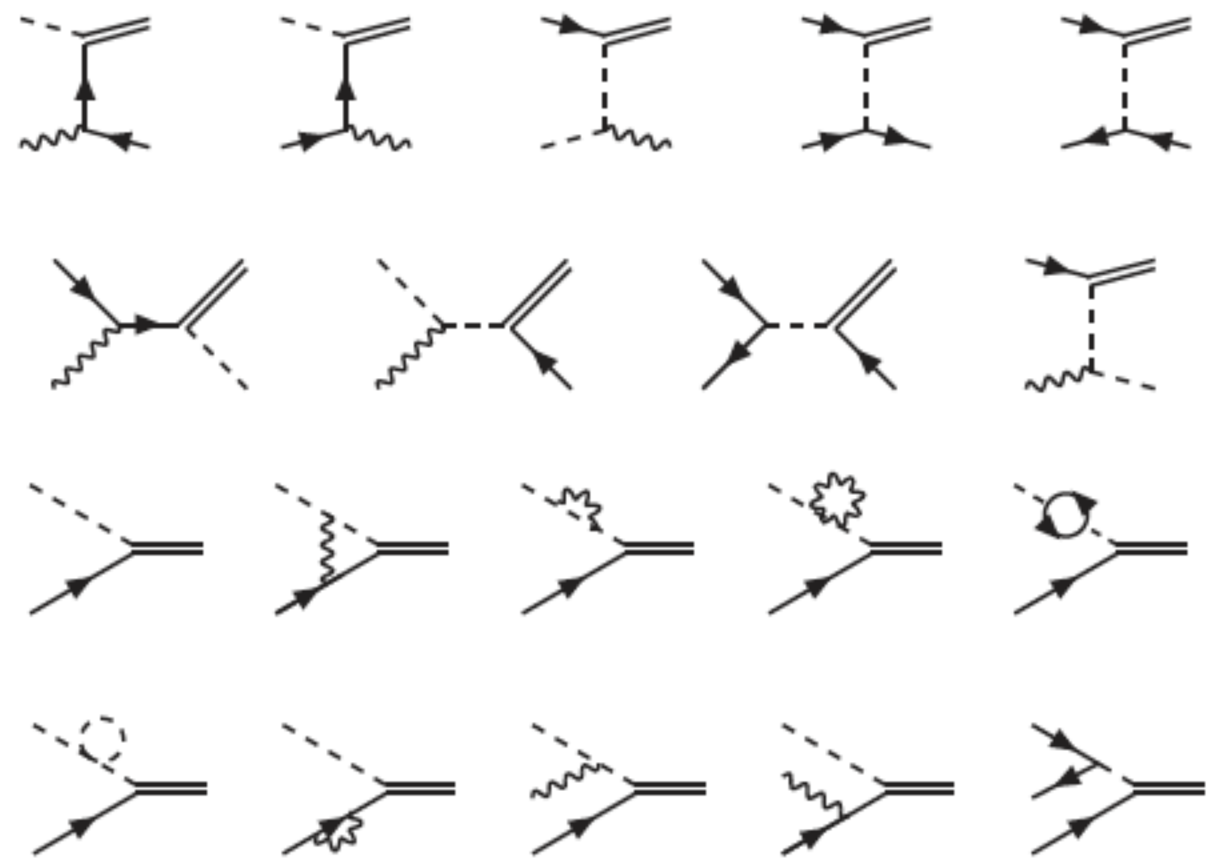
Baryogenesis via RHν oscillation [1]

[Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

RHν (anti-RHν) are produced through the Yukawa interaction

RHν production





[Ghisoiu, Laine ('14)]

$$\Gamma_N \simeq 0.01[F^\dagger F]T \quad \text{for } T > T_{EW}$$

[Ghiglieri, Laine ('17)]

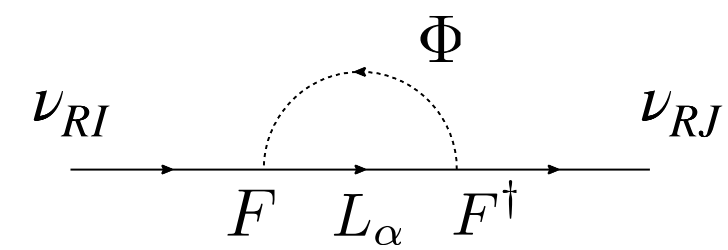
Baryogenesis via RHν oscillation [2]

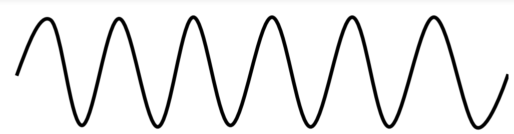
[Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

RHνs start to oscillate at "oscillation temperature", T_{osc}.

$$H_N = H_0 + H_I$$

$$H_0 \simeq \mathtt{diag}\left(\frac{M_1^2}{2p}, \frac{M_2^2}{2p}\right) \qquad H_I = [F^\dagger F]\frac{T^2}{8p}$$



ν_{RI}  ν_{RJ}

Oscillations of ν_R

$$e^{-i\left(\frac{M_I^2 - M_J^2}{2p}\right)dt}$$

Hubble param.: $\mathtt{H} = \dfrac{T^2}{M_0}$

$(\, M_0 = 7 \times 10^{17}\mathrm{GeV}\,)$

$\dfrac{M_I^2 - M_J^2}{2p} = \mathtt{H}$ gives a temperature where the oscillation gets active.

$$\longrightarrow \quad T_{osc} \simeq (\Delta M\, M\, M_0)^{\frac{1}{3}} \simeq 10^3\ \mathtt{GeV}\left(\frac{\Delta M}{10^{-8}\ \mathtt{GeV}}\right)^{\frac{1}{3}}\left(\frac{M}{1\ \mathtt{GeV}}\right)^{\frac{1}{33}}$$

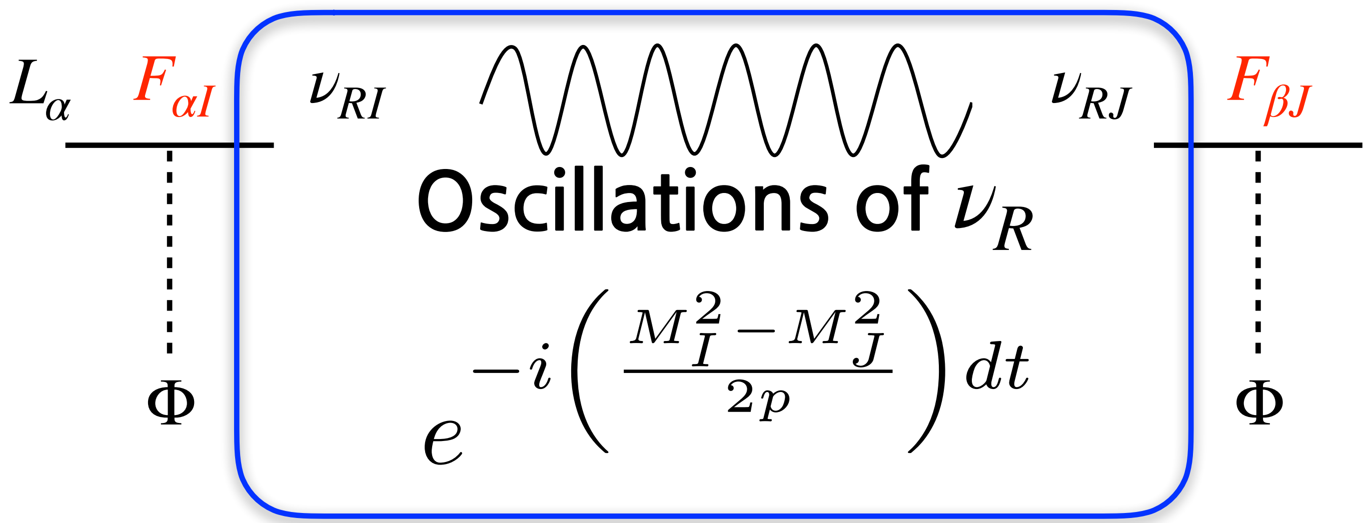
$$M = \frac{M_2 + M_1}{2} \qquad \Delta M = \frac{M_2 - M_1}{2}$$

Baryogenesis via RHν oscillation [3]

[Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

The oscillation of RHνs affects flavor transition of active neutrinos, $L_\alpha \to L_\beta$.

CP violating flavor transition of active neutrinos



$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta)$$

$\to n_{L_e} \neq 0,\ n_{L_\mu} \neq 0,\ n_{L_\tau} \neq 0$

$n_{L_e} + n_{L_\mu} + n_{L_\tau} = 0$

Asymmetric param.:

$$A^a = \mathrm{Im}[F_{\alpha 2}[F^\dagger F]_{23} F^\dagger_{\alpha 3}] \neq 0$$

$$n_{L_\alpha} \propto A^\alpha$$

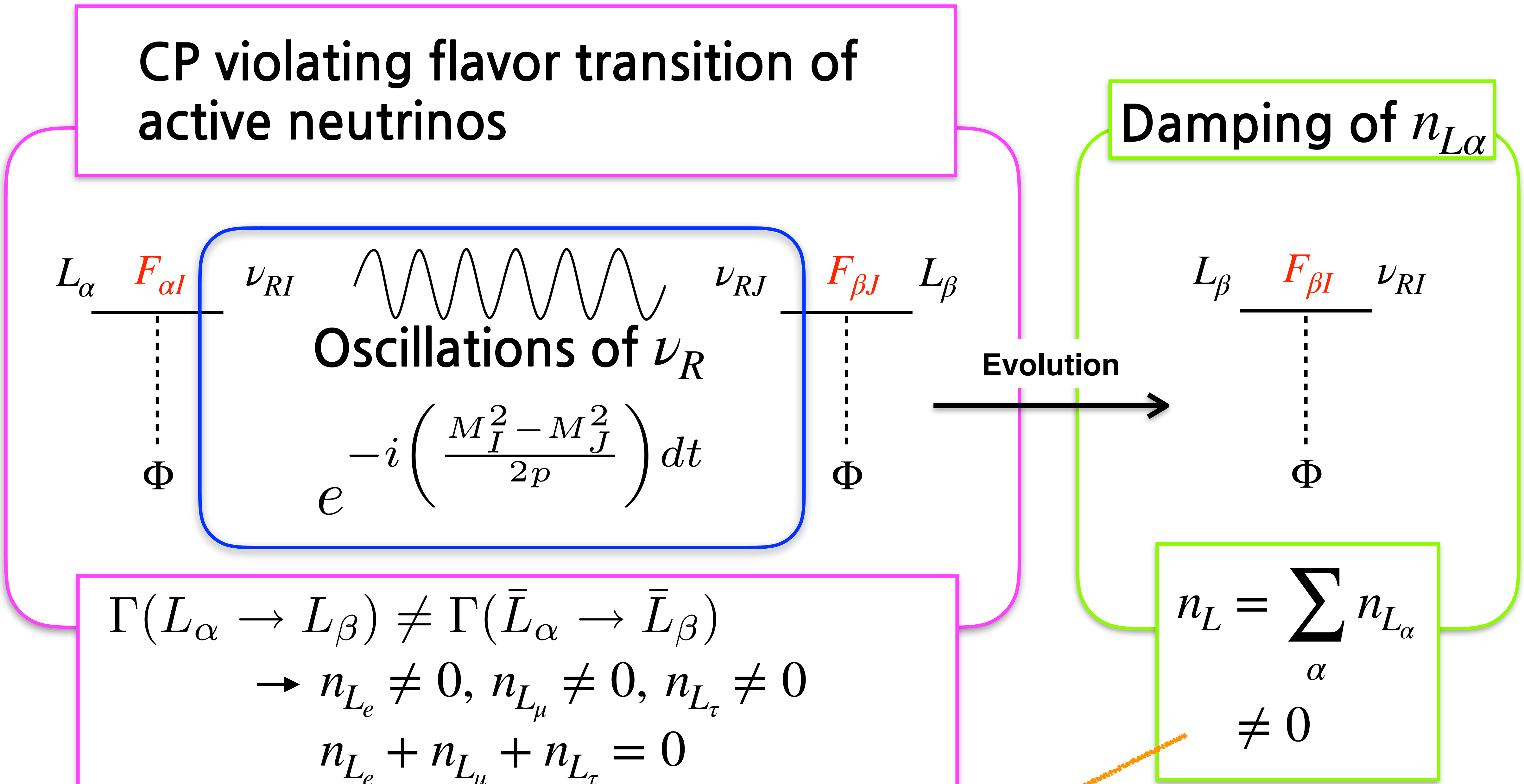
$$\sum_\alpha A^a = 0$$

cf. CP violating ν oscillations; $P_{\nu_i \to \nu_j} - P_{\bar{\nu}_i \to \bar{\nu}_j} = \sum_{I>J} 4\Im[U_{iI}U^*_{jI}U^*_{iJ}U_{jJ}] \sin\left(\frac{\Delta m^2_{IJ}}{2E}L\right)$

Baryogenesis via RHν oscillation [4]

[Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

Net lepton asymmetry is produced in evolution with flavor difference in Yukawa couplings.

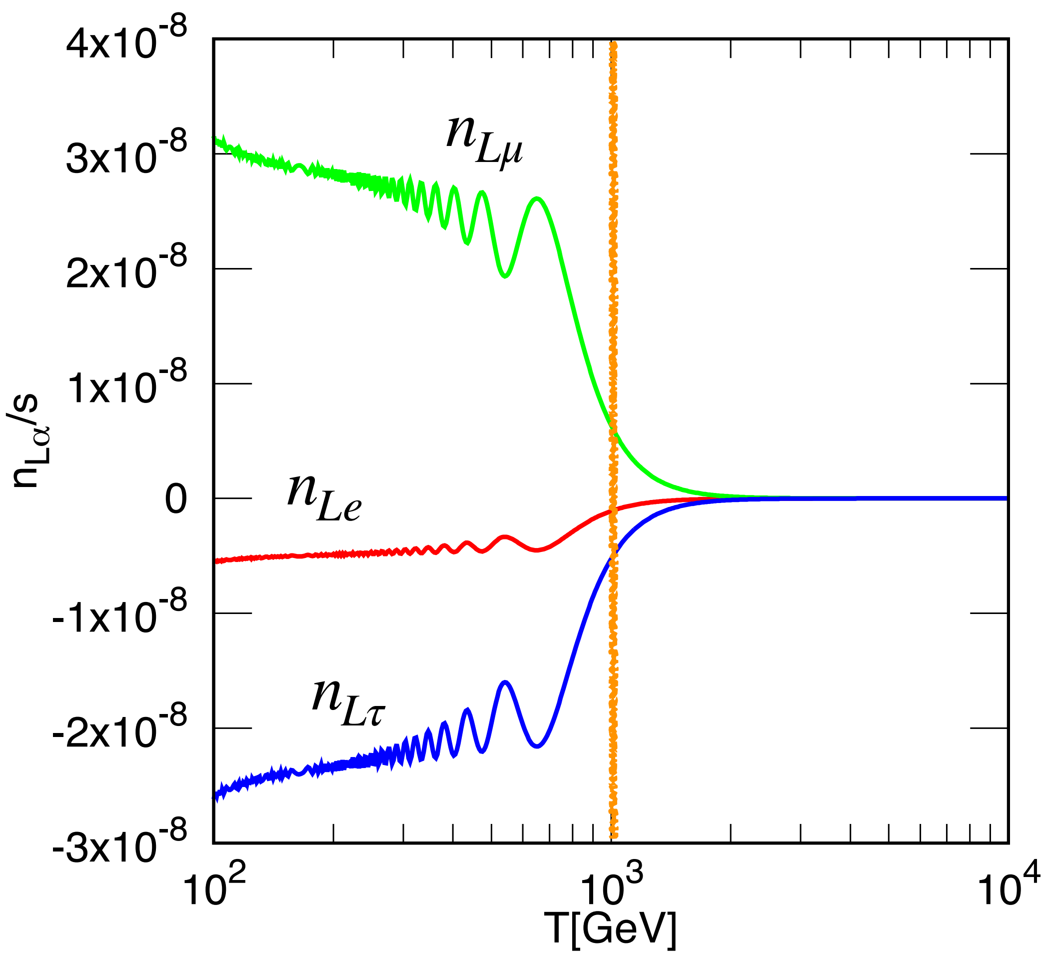


$$n_B(T_{\rm SF}) = -\frac{28}{79} n_L(T_{\rm SF}) \text{ at } T_{\rm SF} \simeq 130\,\text{GeV}$$

Evolution of asymmetries

The evolution shows the feature clearly.

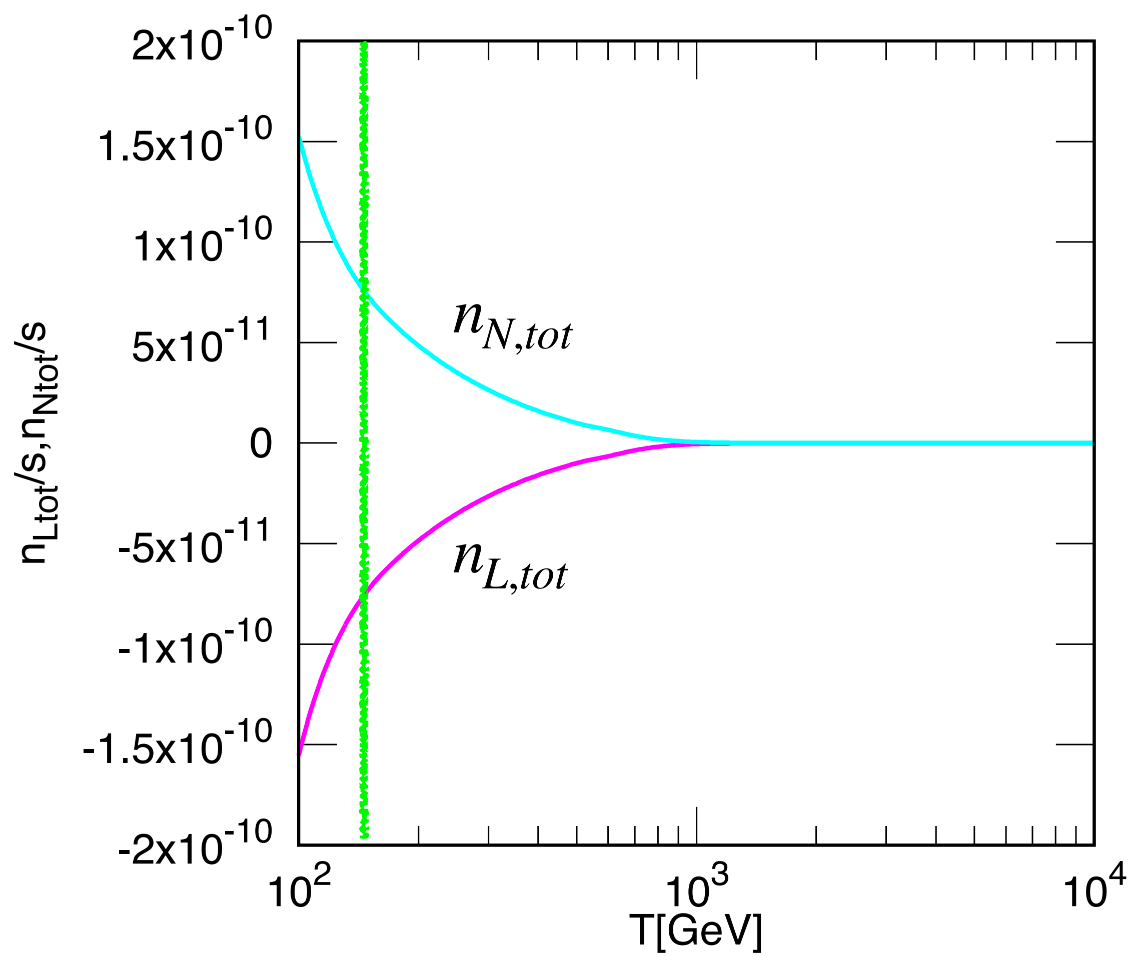
Flavor asymmetries



$T_{osc} \approx 10^3$ GeV

($M = 1$ GeV and $\Delta M = 5 \cdot 10^{-9}$ GeV)

Total asymmetry



- Lepton asymmetry separation
- Only $n_{L,tot}$ converts into n_B

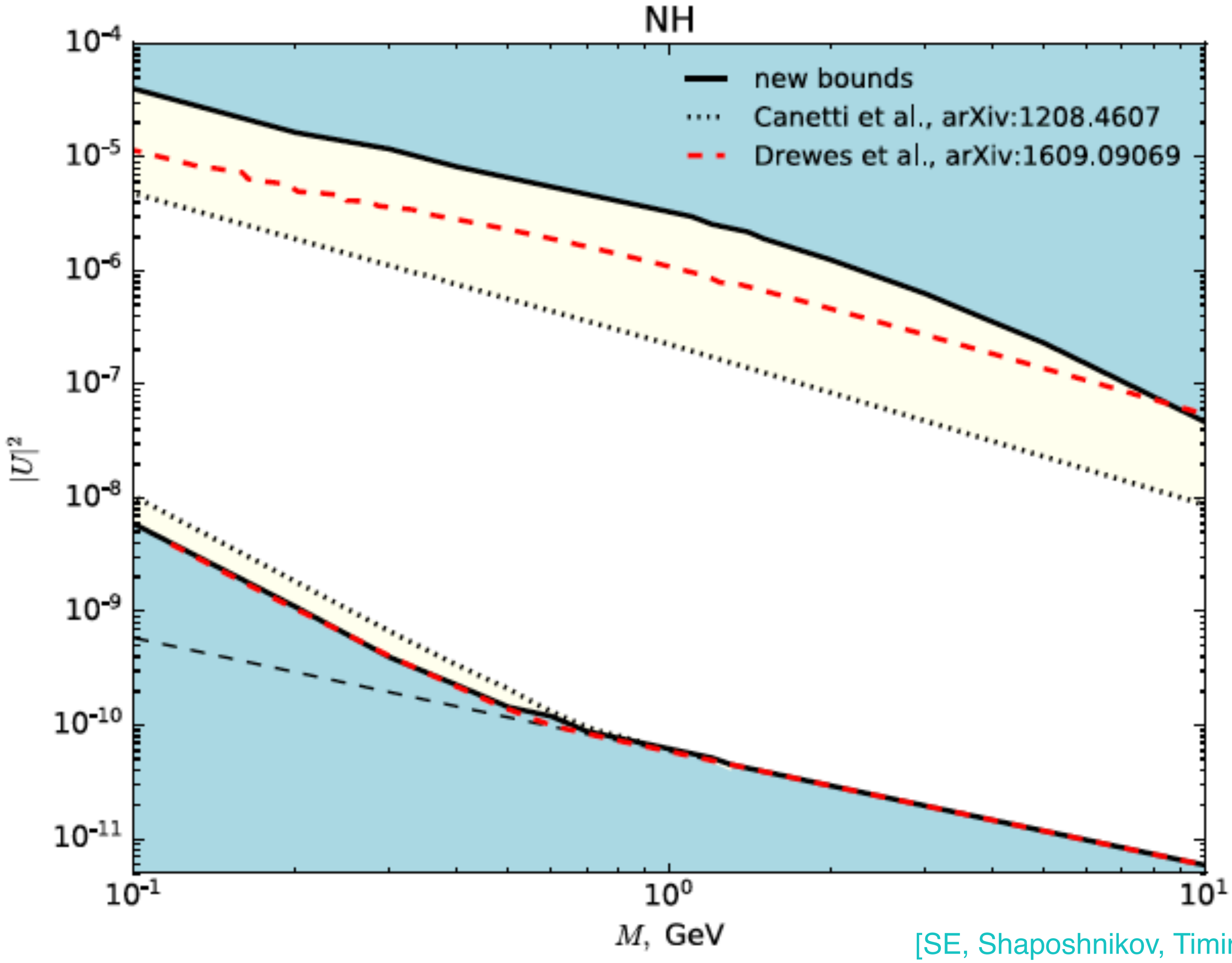
Improvements of the leptogenesis

The leptogenesis has been studied actively in recent years and the upper boundaries on HNL mixing angles have been updated.

[Asaka, SE, Ishida ('12)] [Ghiglieri, Laine ('16,'17,'18)] [Hernamdez, Kekic, Lopez-Pavon, Racker, Salvado ('16)] [Drewes, Garbrecht, Gueter, Klaric ('16)] [Hambye, Teresi ('17)] [Asaka, SE, Ishida, Minogawa, Yoshii ('17)] [Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric ('17)] [SE, Shaposhnikov ('17)] [SE, Shaposhnikov, Timiryasov ('17)]

Improvements of theoretical indication

$$U^2 \equiv \sum_{\alpha,I} |\Theta_{\alpha I}|$$



2012 →2016

$$\Gamma_N \approx 0.006 F^2 T \ \rightarrow \ \approx 0.01 F^2 T$$

2016→2018

- Lepton number violating effect
- Processes in the Higgs phase
- Plasma neutrality
- Exact treatment of sphaleron process
- …

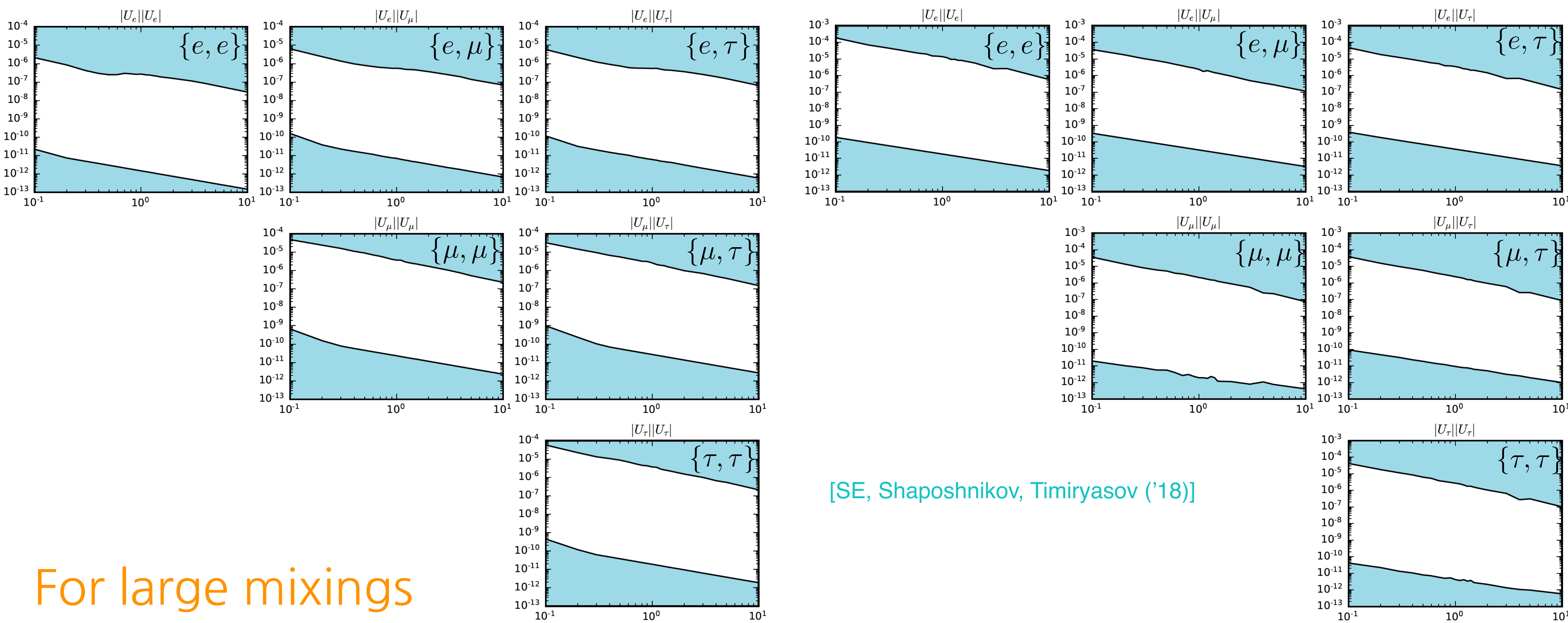
[SE, Shaposhnikov, Timiryasov ('18)]

Indication to experiments

Upper boundaries on individual mixings are evaluated from full parameter scanning.

Individual mixings $|U_\alpha||U_\beta|$ with M_N $\sum_{I,J=1,2} |\Theta_{\alpha I}|^2 |\Theta_{\beta J}|^2 = |U_\alpha|^2 |U_\beta|^2$

NH   IH



[SE, Shaposhnikov, Timiryasov ('18)]

For large mixings

$\lvert\Theta_e\rvert^2 \ll \lvert\Theta_\mu\rvert^2 \simeq \lvert\Theta_\tau\rvert^2$	and	$\delta \sim \pi,\ \eta \sim 3\pi/2,\ \mathrm{Re}\omega \sim \pi/4$	(NH)
$\lvert\Theta_e\rvert^2 \gg \lvert\Theta_\mu\rvert^2 \simeq \lvert\Theta_\tau\rvert^2$	and	$\delta \sim 0,\ \eta \sim \pi/2,\ \mathrm{Re}\omega \sim \pi/4$	(IH)

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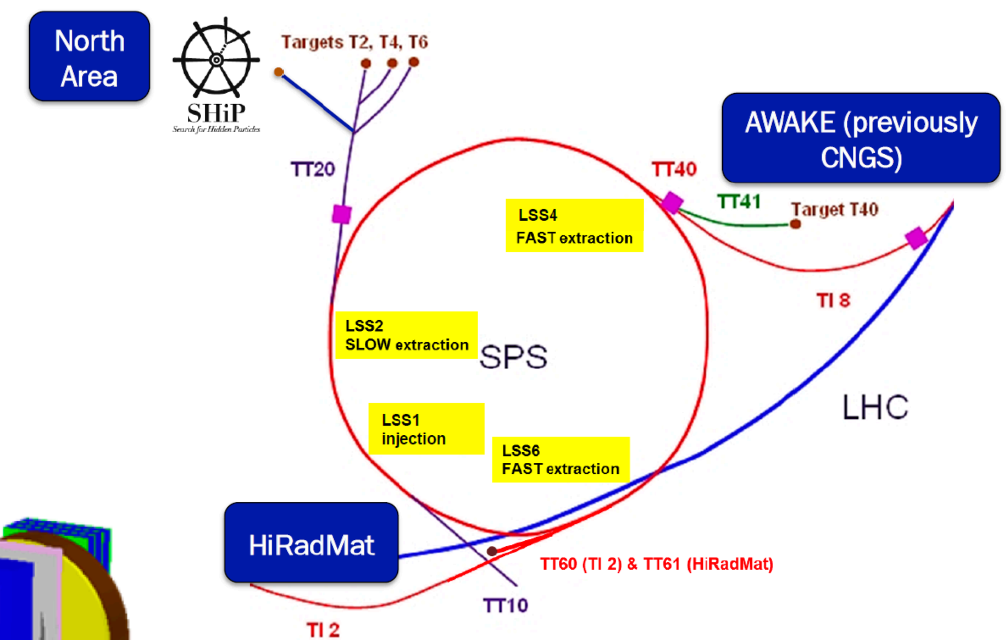
<u>**Q2. How can we probe the HNLs experimentally?**</u>

Intensity frontier experiments

There are some intensity frontier experiments in near-future, FASER, MATHUSLA, SHiP and so on.

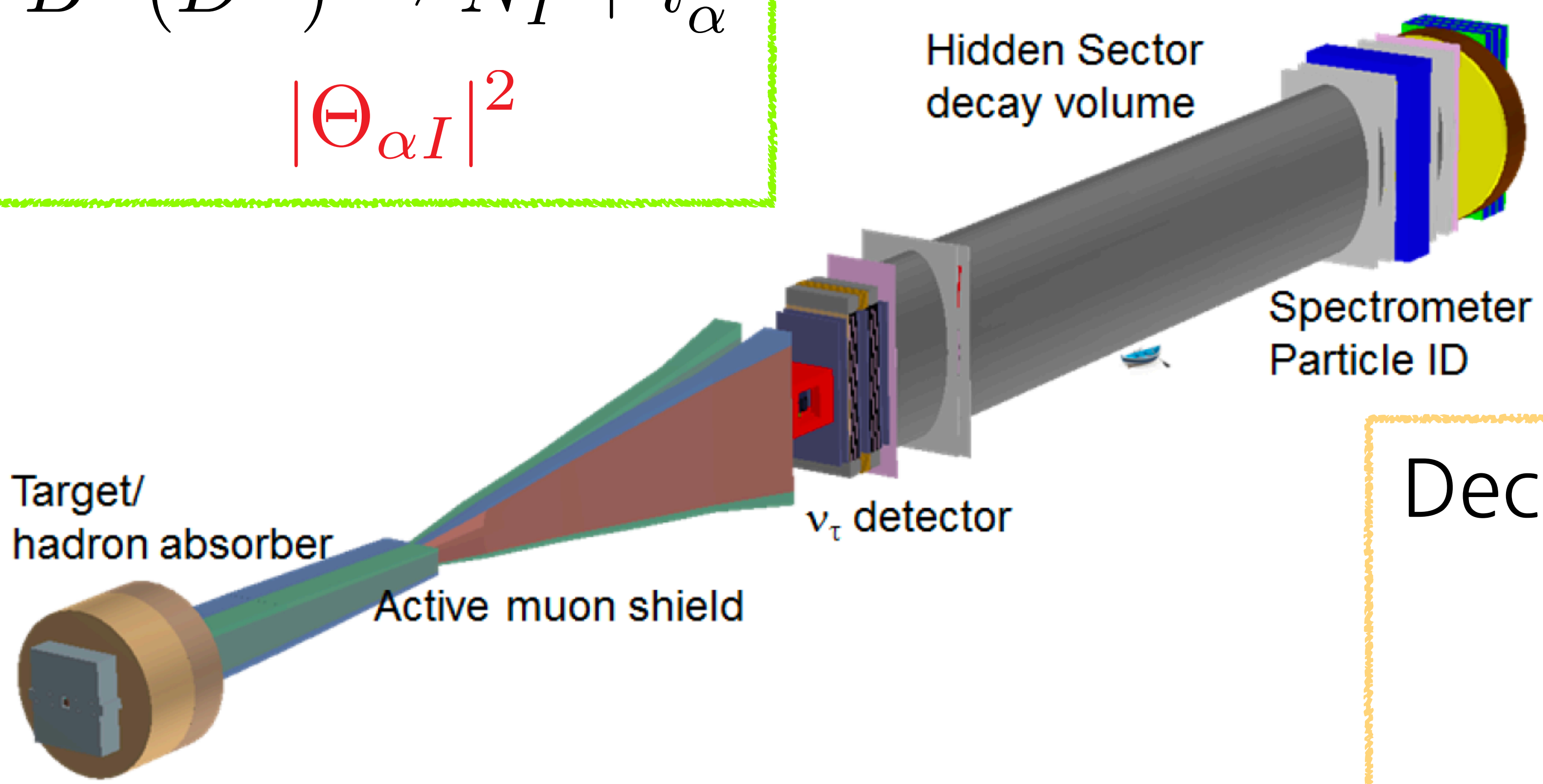


Search for Hidden Particle (SHiP)

Production of HNLs

$$B^+(D^+) \rightarrow N_I + l_\alpha^+$$

$$|\Theta_{\alpha I}|^2$$



[The SHiP collaboration ('15)]

Decay of HNLs

$$N_I \rightarrow \nu_\gamma l_\beta^- l_\gamma^+$$

$$N_I \rightarrow l_\beta^- M^+$$

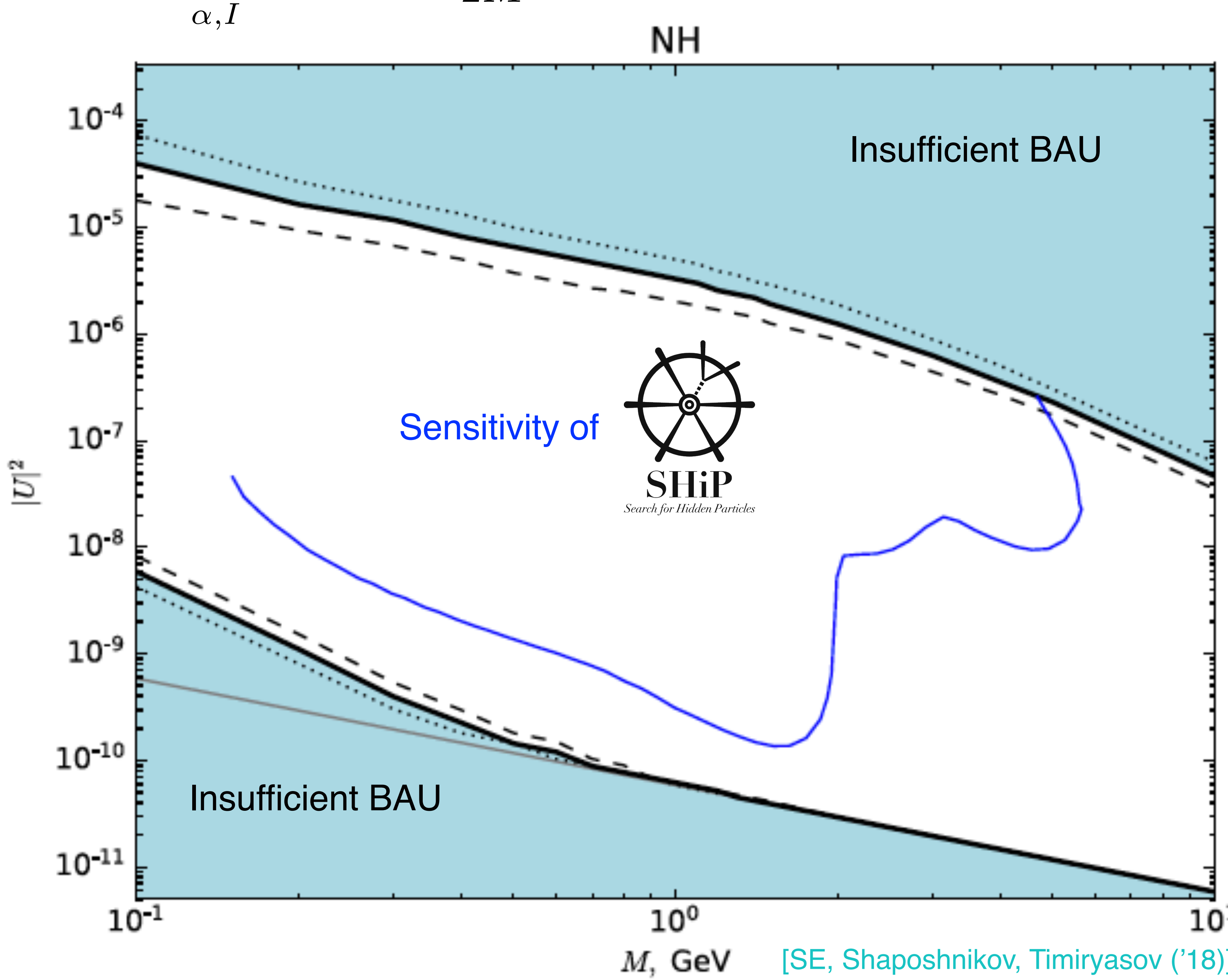
$$|\Theta_{\beta I}|^2$$

2027?~

SHiP experiments

SHiP experiment tests the wide region of parameter space for Leptogenesis for $M_N \lesssim m_B$.

$$U^2 \equiv \sum_{\alpha,I} |\Theta_{\alpha I}|^2 \simeq \frac{\sum_i m_i}{2M}(X_\omega^2 + X_\omega^{-2}) \qquad X_\omega = \exp(\mathrm{Im}\,\omega)$$



[SE, Shaposhnikov, Timiryasov ('18)]

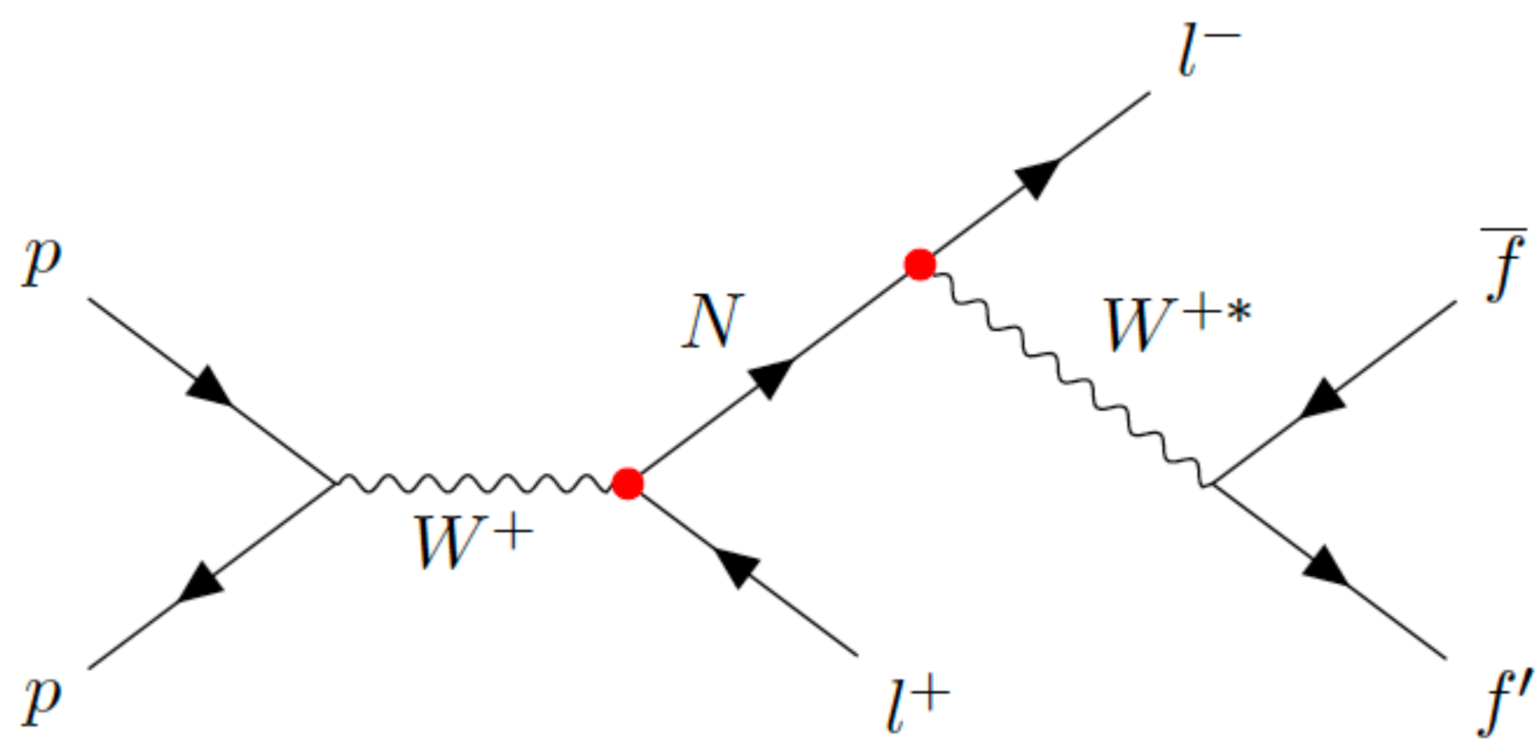
$m_{D^\pm} = 1869$ MeV

$m_{B_0} = 5279$ MeV

$m_{B_c^+} = 6274$ MeV

Displaced vertex search

Displaced vertex technique in colliders is to look for geometrical gaps of vertexes in trackers.



[Drewes, Hajer ('19)]

It has potential to address remaining parameter regions, $M_N \gtrsim m_B$.

Displaced vertex search at LHC

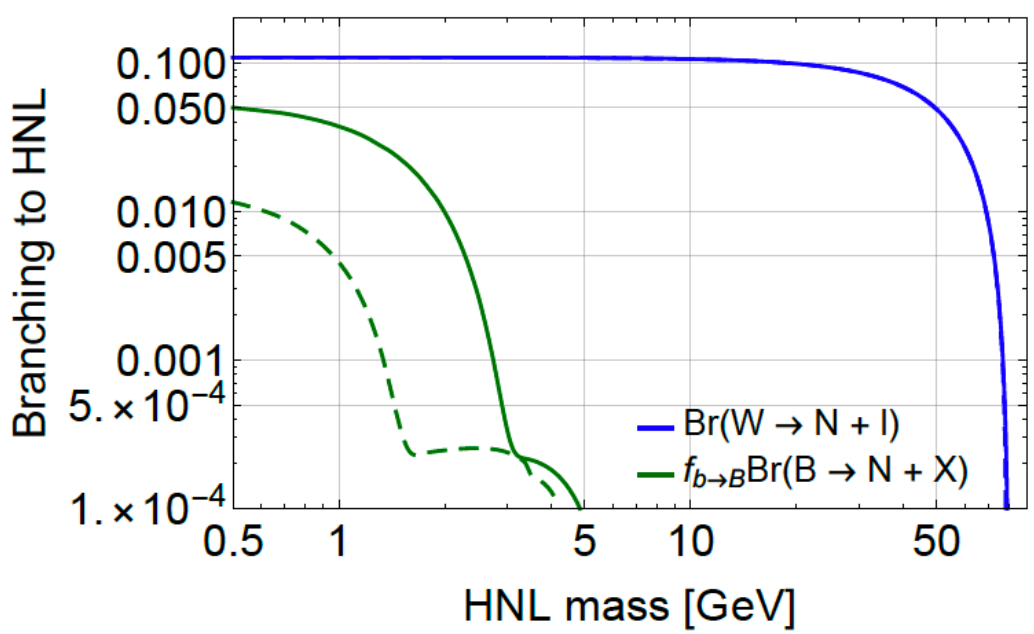
Displaced vertex search can be performed at LHC.

Sensitivity estimation

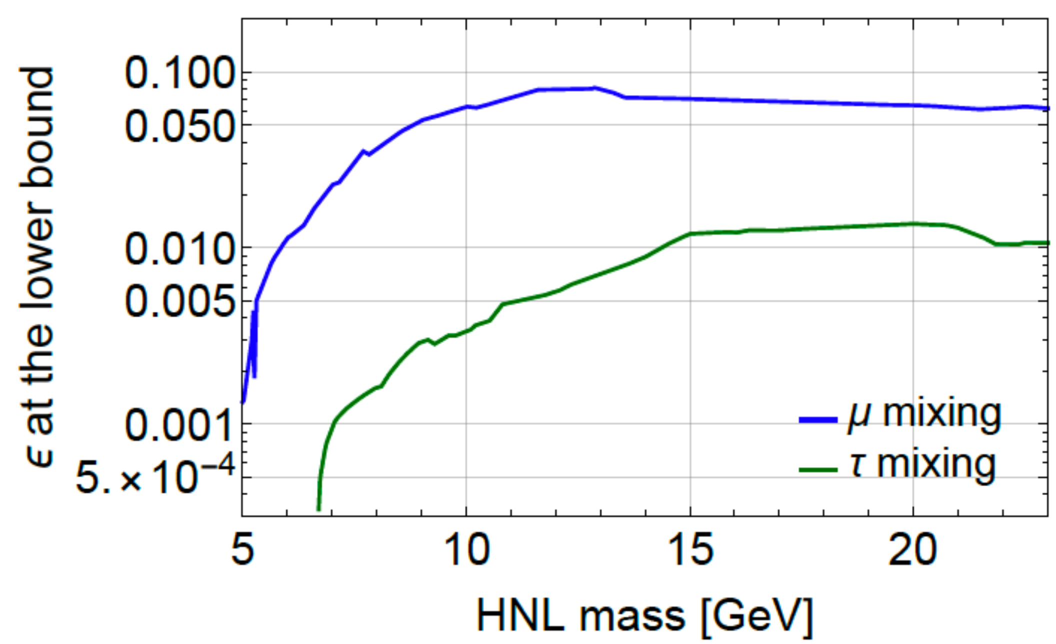
$$N_{\text{events}} = N_{\text{parent}} \cdot \text{Br} \cdot P_{\text{dec}} \cdot \epsilon$$

$$P_{\text{dec}} = e^{-l_{\min}/c\tau\langle\gamma_N\rangle} - e^{-l_{\max}/c\tau\langle\gamma_N\rangle}$$

Parent/Experiment	$l_{\min},\ l_{\max}$	Cross-section	Number	$\langle E\rangle$
W @ ATLAS/CMS, Short DV	0.4 cm, 30 cm [72]	$\sigma_W \simeq 193$ nb [87]	5×10^{11}	–
W @ CMS, Long DV	2 cm, 300 cm	$\sigma_W \simeq 193$ nb [87]	5×10^{11}	–
B @ LHCb	2 cm, 60 cm [66]	$\sigma_{b\bar{b}} \simeq 1.3 \times 10^8$ pb [88]	$4.9 \cdot 10^{13}$	84 GeV [89]



[Kling, Trojanowski ('18)] [Aaij et al. LHCb Collaboration ('11,'17)]



[Cottin, Helo, Hirsch ('18)]

Displaced vertex search at ATLAS and CMS

ATLAS/CMS can extend experimental reach of the mass.

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W @ ATLAS/CMS, Short DV	0.4 cm, 30 cm [72]	$\sigma_W \simeq 193$ nb [87]	5×10^{11}	–
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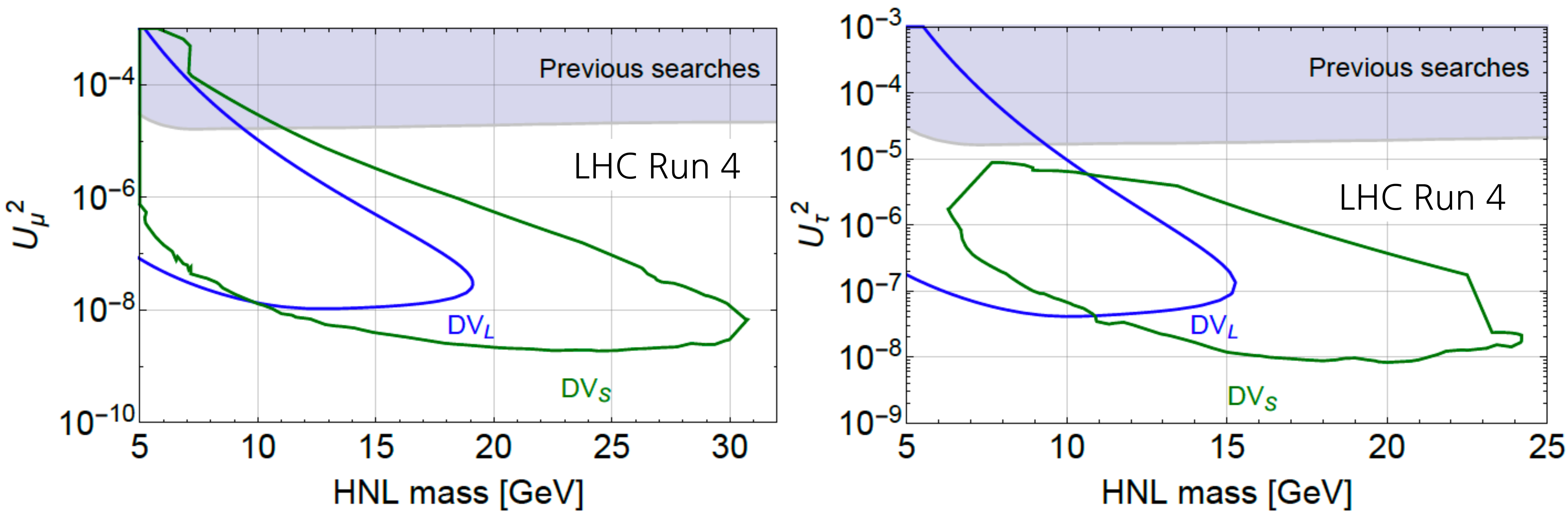

- DV_S: $W^+ \to l_\alpha^+ N \to l_\alpha^+ (l_\beta^- \bar{f} f')$ in inner tracker of ATLAS/CMS
- DV_L: $W^+ \to l_\alpha^+ N \to l_\alpha^+ (\mu^- \mu^+ \nu_\mu)$ in muon tracker of CMS

Displaced vertex search at LHCb

Decays of HNLs in LHCb can be identified as a DV event.

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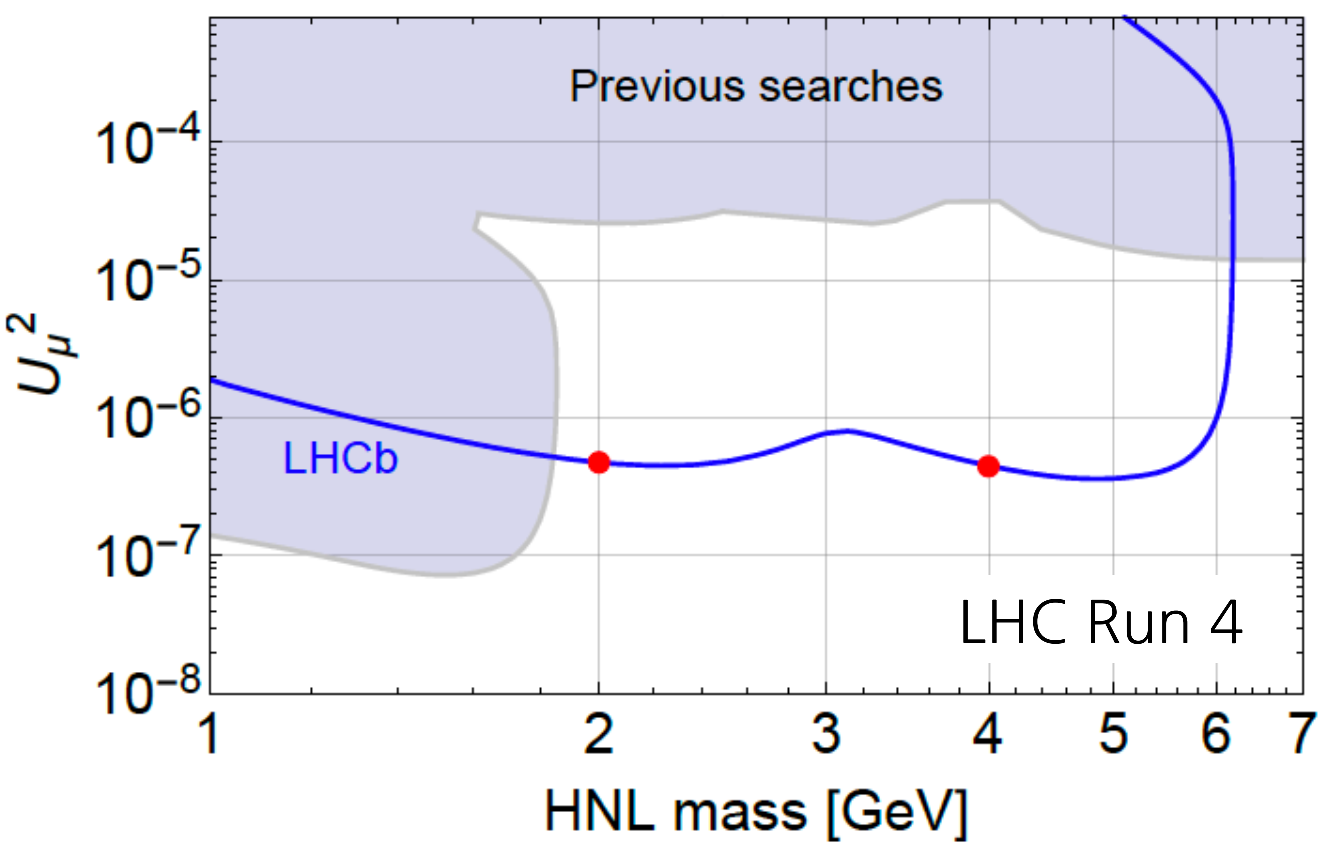
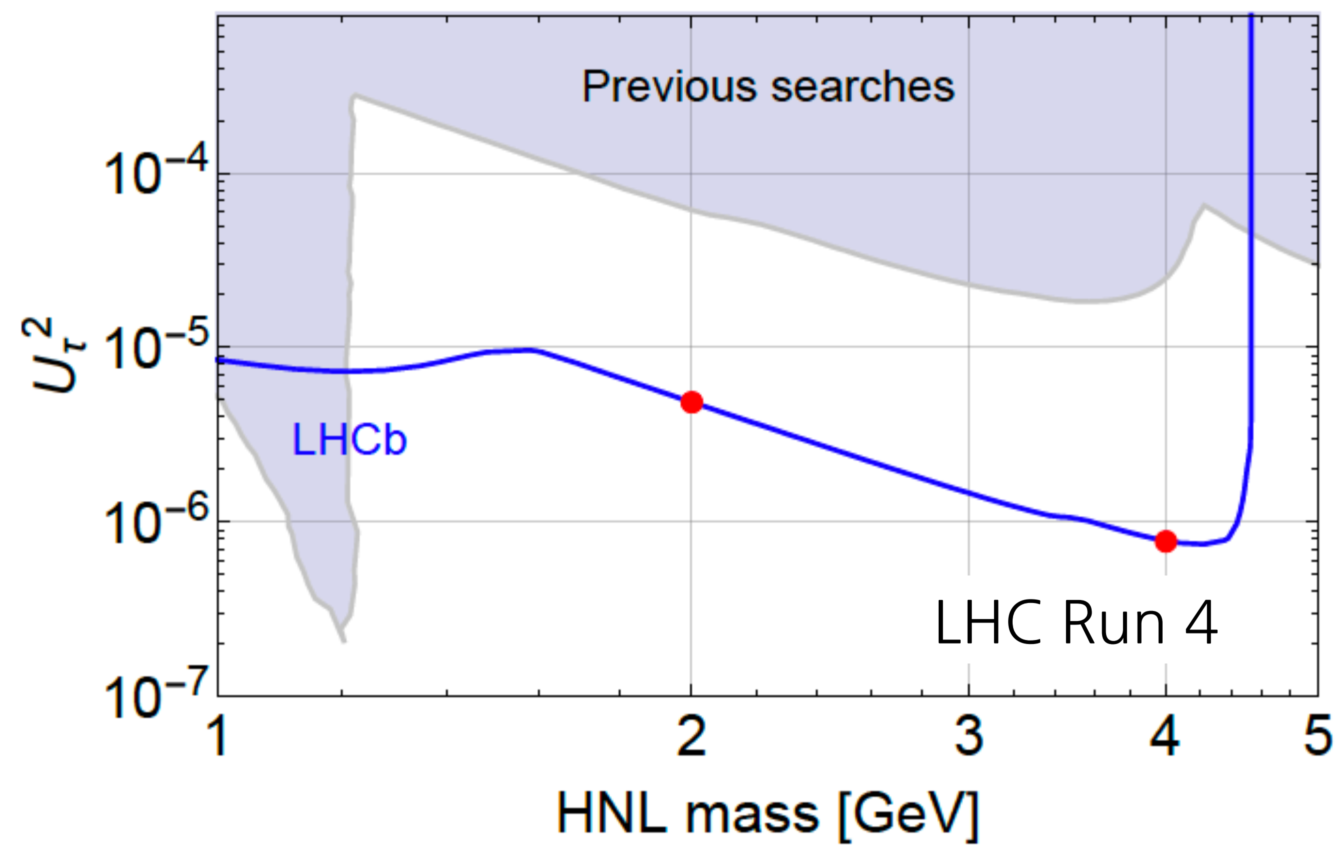




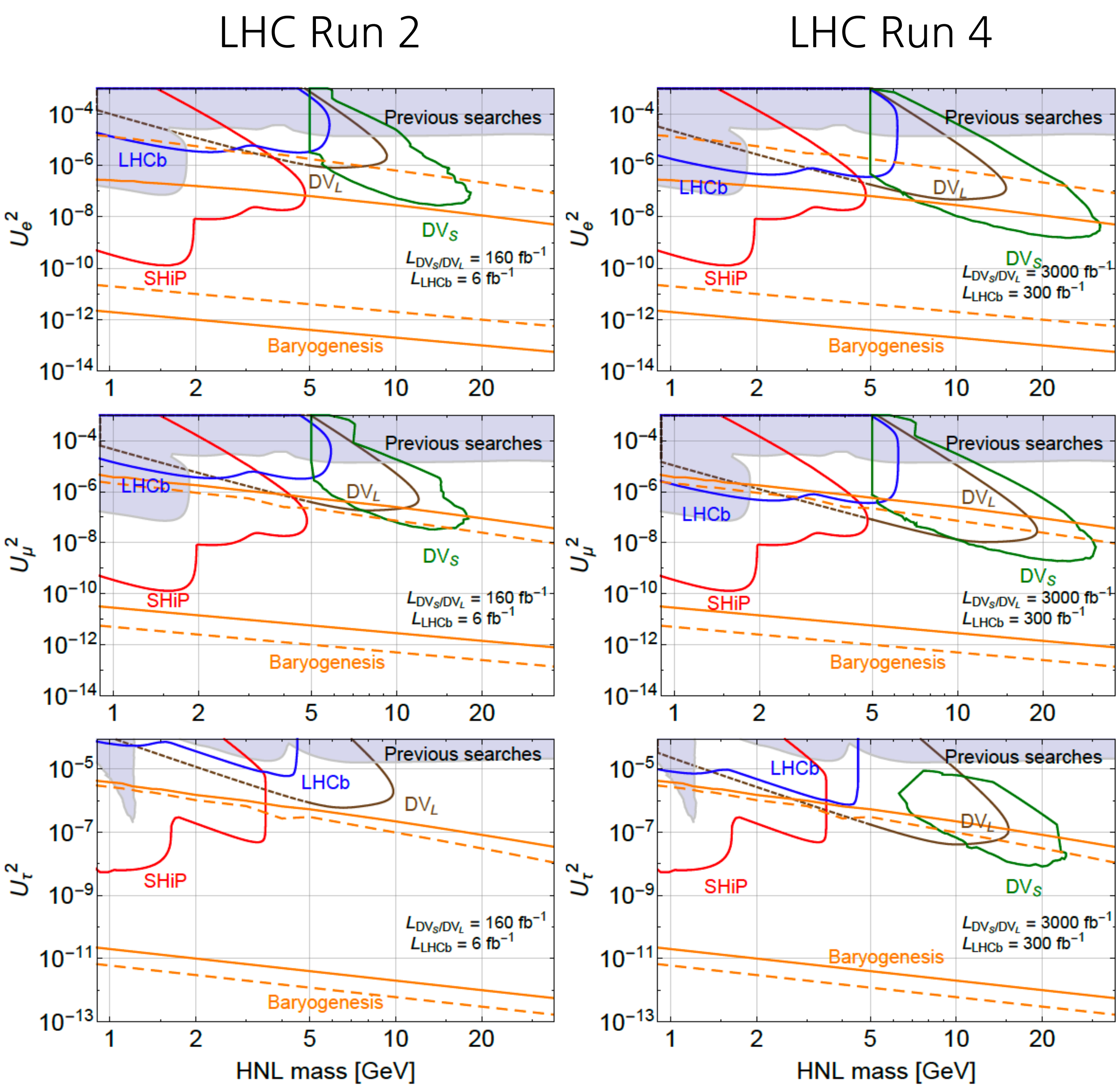
$$M^+ \to l_\alpha^+ N \to l_\alpha^+ (l_\beta^- + \cdots)$$

$$\epsilon \sim 10^{-2}$$

[Aaij et al. LHCb Collaboration ('14)]

Summary plots

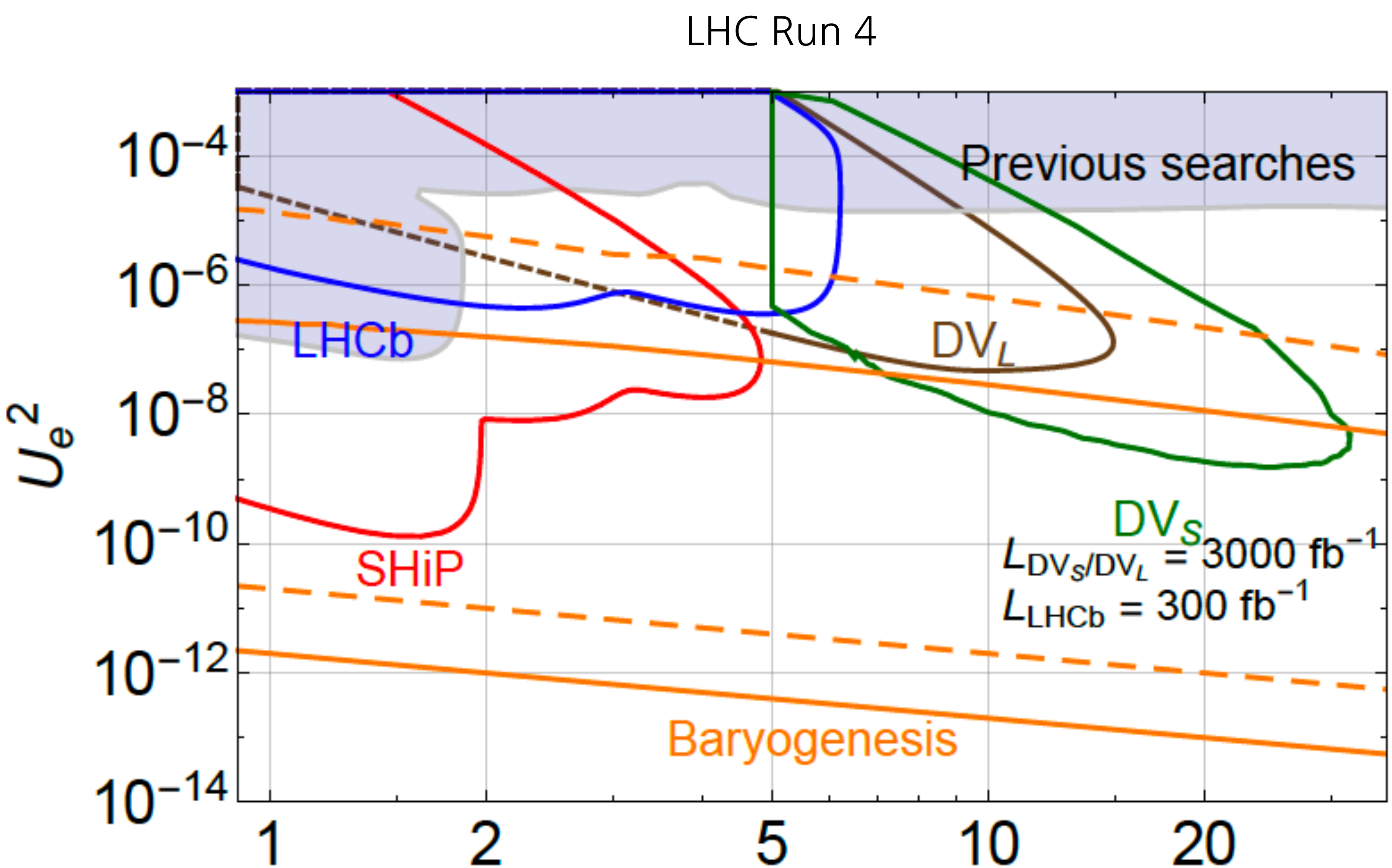
DV searches at LHC and SHiP complete each other.



[Boiarska, Bondarenko, Boyarsky, SE, Ovchynnikov, Ruchayskiy, Timiryasov ('19)]

Summary plots

DV searches at LHC and SHiP complete each other.



[Boiarska, Bondarenko, Boyarsky, SE, Ovchynnikov, Ruchayskiy, Timiryasov ('19)]

Summary

We have a chance to prove the matter-antimatter asymmetry of the Universe through exploring heavy neutral leptons.

Baryogenesis via right-handed neutrino oscillations has been studied actively and the theoretical prediction to parameter space has been updated.

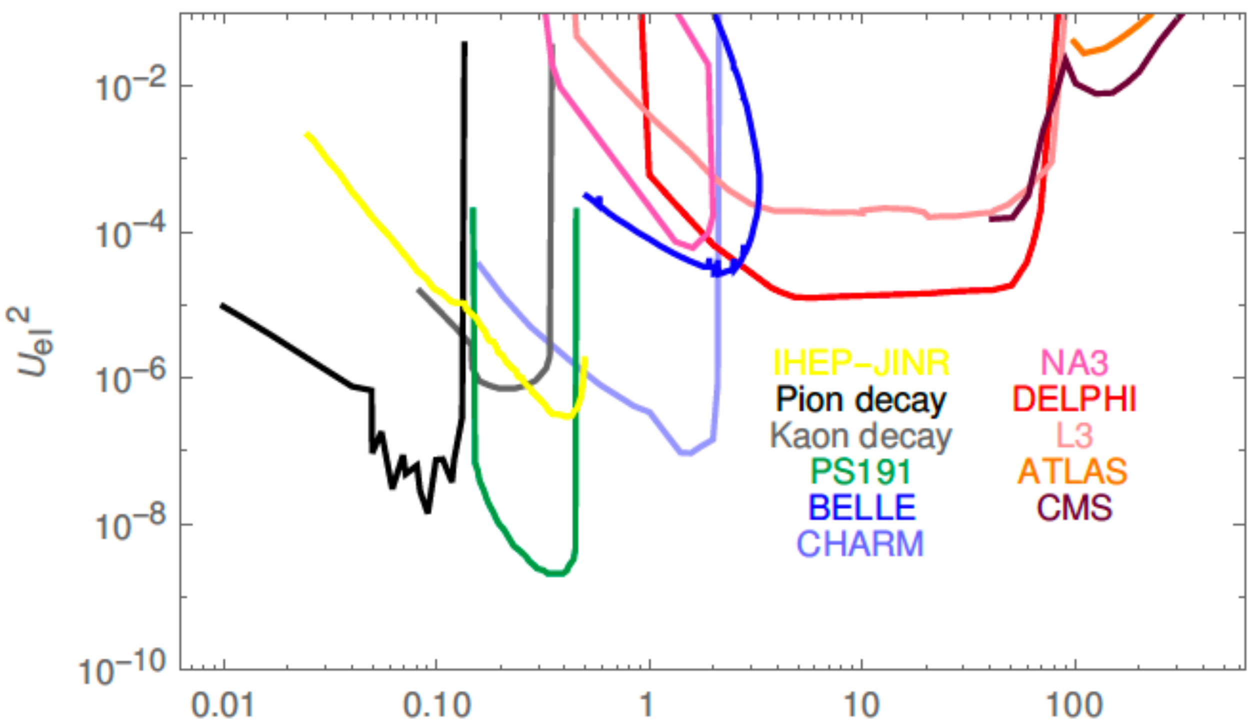
In the test displaced vertex searches at LHC and intensity frontier experiments in near future complete each other.

Backup

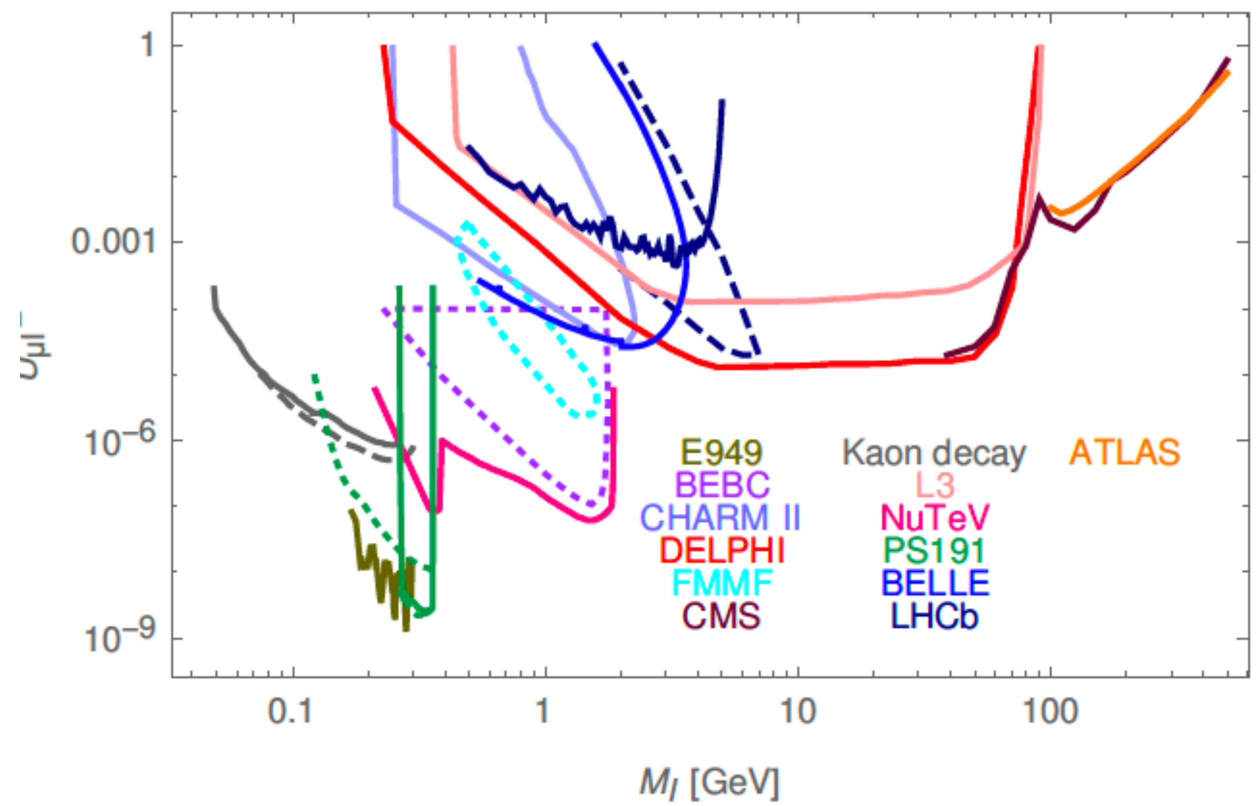
Experimental bounds

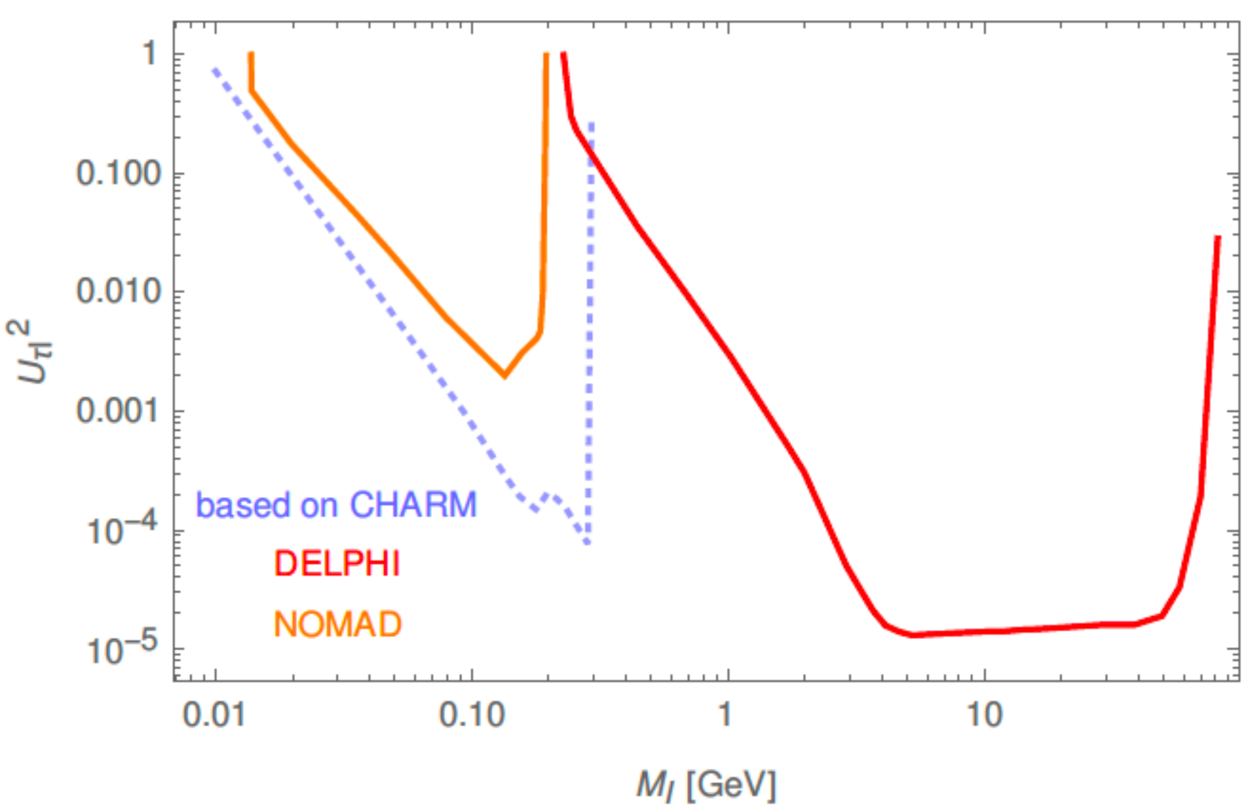
Negative results in past experiments have put upper bounds on the mixings.

Mixing with e



Mixing with μ





Mixing with τ

[Drewes, Garbrecht ('17)]

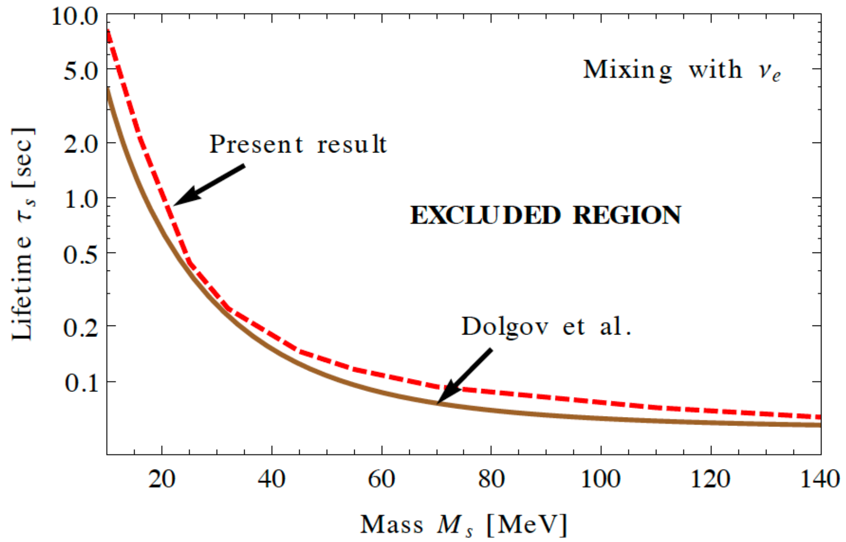
Cosmological bounds

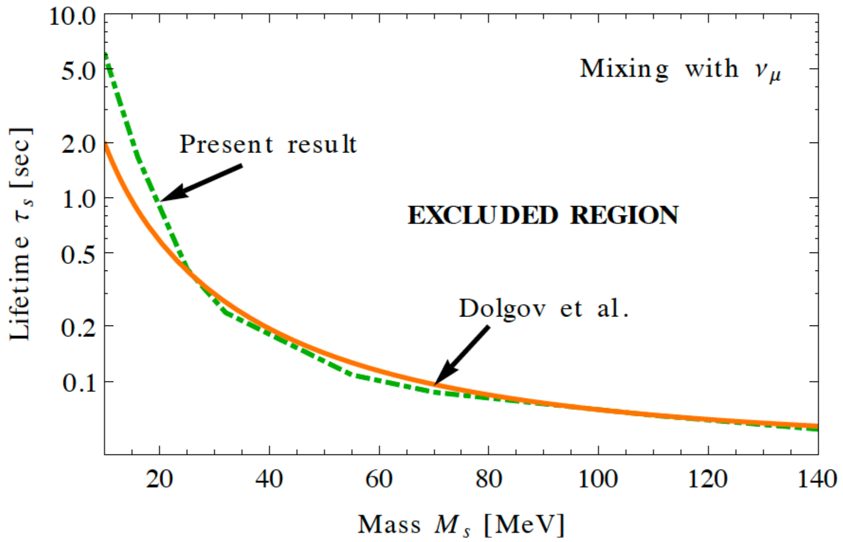
Long-live HNLs may spoil the success of Big-Bang Nucleosynthesis.

Upper bound on lifetime

For $M_N < m_\pi$

[Ruchayskiy, Ivashko ('12)]





For $M_N \geq m_\pi$

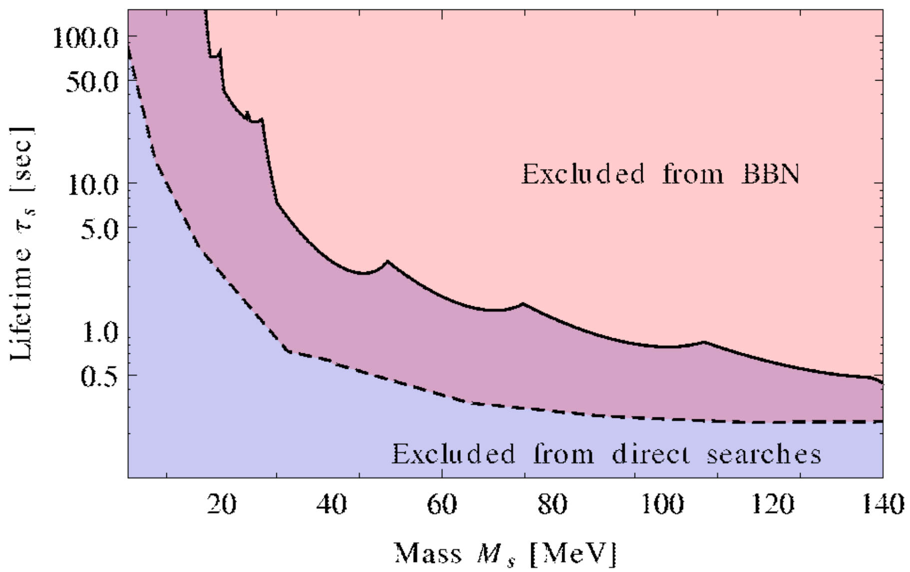
$$\tau_N \leq 0.1\,\mathrm{sec}$$

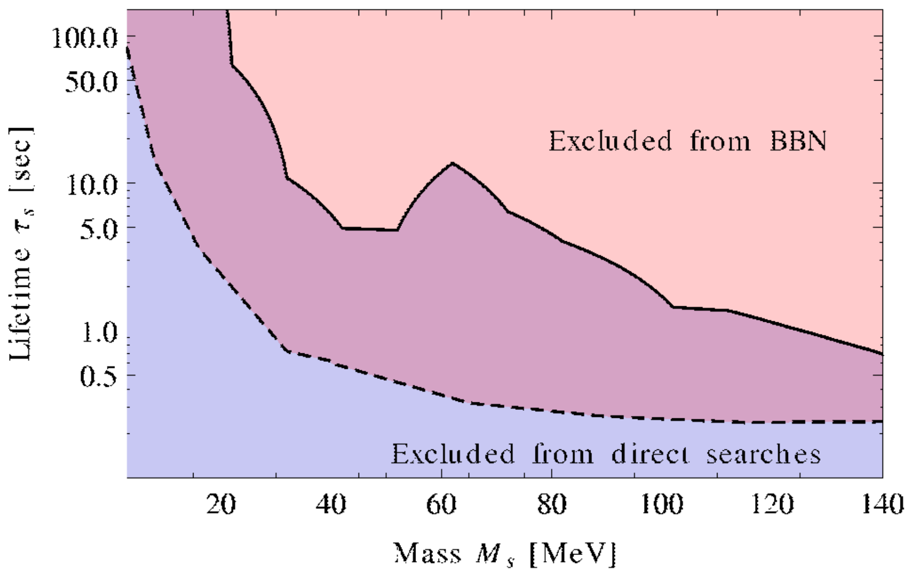
[Dolgov, Hansen, Raffelt, Semikoz ('00)]

Lower bound of mixings

$$\tau_N = \Gamma_N^{-1} \propto (\Theta^2)^{-1}$$

$M_N \lesssim m_\pi$ is excluded.





Kinetic equations

The mechanism is described by kinetic equations of density matrix.

Density matrix: $\rho = \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix}$

ρ_{II} : occupation numbers
ρ_{IJ}: correlations

For ν_R and anti-ν_R (2x2 matrix)

$$\frac{d\rho_N}{dt} = -i\left[H_N, \rho_N\right] - \frac{1}{2}\left\{\Gamma_N, \rho_N - \rho_N^{\rm eq}\right\} - \frac{1}{2}\sum_\alpha \left[\tilde{\Gamma}_N^\alpha \Delta\rho_{\nu_\alpha}\right]$$

Oscillation Production and Destruction Communication (back-reaction)

$$\frac{d\rho_{\bar{N}}}{dt} = -i\left[H_N^*, \rho_{\bar{N}}\right] - \frac{1}{2}\left\{\Gamma_N^*, \rho_{\bar{N}} - \rho_N^{\rm eq}\right\} + \frac{1}{2}\sum_\alpha \left[\left(\tilde{\Gamma}_N^\alpha\right)^* \Delta\rho_{\nu_\alpha}\right]$$

For lepton asymmetries $\Delta\rho_{\nu_\alpha}\ (\alpha = e, \nu, \tau)$

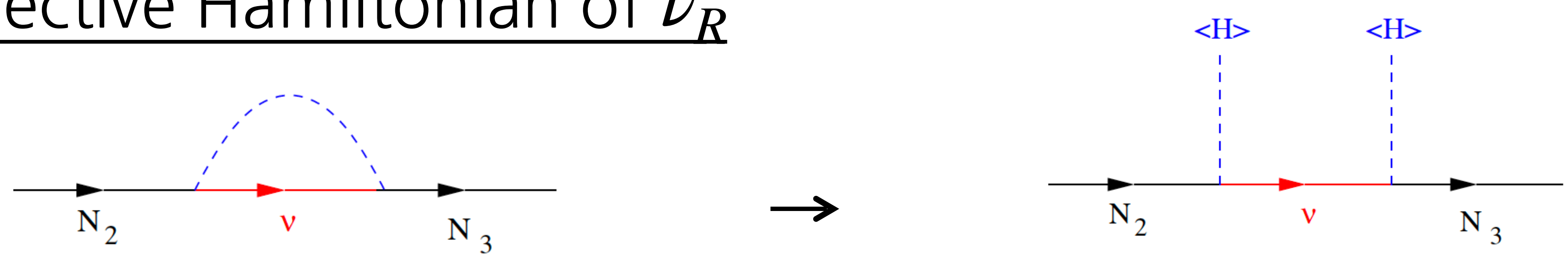
$$\frac{d\Delta\rho_{\nu_\alpha}}{dt} = -\Gamma_{\nu_\alpha}\Delta\rho_{\nu_\alpha} + \mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}\rho_{\bar{N}}] - \mathrm{Tr}[\tilde{\Gamma}_{\nu_\alpha}^*\rho_N]$$

Damping Communication (back-reaction)

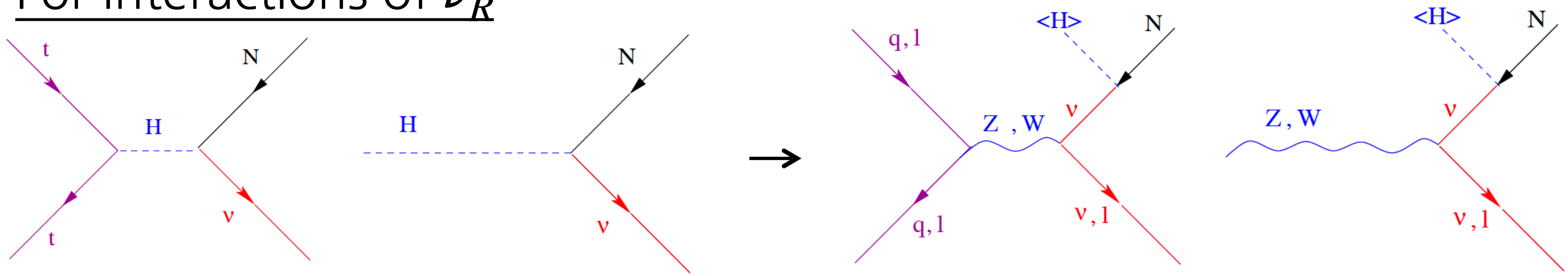
Kinetic equations in the Higgs phase

Gauge interaction with neutrino mixing gets dominant instead of Yukawa interaction.

For effective Hamiltonian of ν_R



For interactions of ν_R



Lepton number conserving and violating contributions

$$\Gamma = \Gamma_+ + \Gamma_- \qquad \Gamma_+, H_+ \propto T$$

; Lepton # conserving

$$H = H_+ + H_- \qquad \Gamma_-, H_- \propto (M/T)^2 T$$

; Lepton # violating

H and Γ in the Higgs phase

Effective Hamiltonian

$$H_N = H_0 + H_I,$$

$$H_0 = -\frac{\Delta M M}{E_N}\sigma_1$$

$$H_I = h_+ \sum_\alpha Y^N_{+,\alpha} + h_- \sum_\alpha Y^N_{-,\alpha},$$

Production and back-reaction rates

$$\Gamma_N = \gamma_+ \sum_\alpha Y^N_{+,\alpha} + \gamma_- \sum_\alpha Y^N_{-,\alpha} \qquad \Gamma_{\nu_\alpha} = (\gamma_+ + \gamma_-) \sum_I h_{\alpha I} h^*_{\alpha I}$$

$$\tilde{\Gamma}^\alpha_N = -\gamma_+ Y^N_{+,\alpha} + \gamma_- Y^N_{-,\alpha} \qquad \tilde{\Gamma}_{\nu_\alpha} = -\gamma_+ Y^\nu_{+,\alpha} + \gamma_- Y^\nu_{-,\alpha}$$

Coefficients

$$h_+ = \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)(E_N + E_\nu)}{k E_N (4(E_N + E_\nu)^2 + \gamma_\nu^2)},$$

$$h_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)(E_N - E_\nu)}{k E_N (4(E_N - E_\nu)^2 + \gamma_\nu^2)},$$

$$\gamma_+ = \frac{2\langle\Phi\rangle^2 E_\nu (E_N + k)\gamma_\nu}{k E_N (4(E_N + E_\nu)^2 + \gamma_\nu^2)},$$

$$\gamma_- = \frac{2\langle\Phi\rangle^2 E_\nu (E_N - k)\gamma_\nu}{k E_N (4(E_N - E_\nu)^2 + \gamma_\nu^2)},$$

$$E_N = \sqrt{k^2 + M^2} \qquad E_\nu = k - b_L$$

Yukawa couplings

$$Y^N_{+,\alpha} = \begin{pmatrix} h_{\alpha 3} h^*_{\alpha 3} & -h_{\alpha 3} h^*_{\alpha 2} \\ -h_{\alpha 2} h^*_{\alpha 3} & h_{\alpha 2} h^*_{\alpha 2} \end{pmatrix},$$

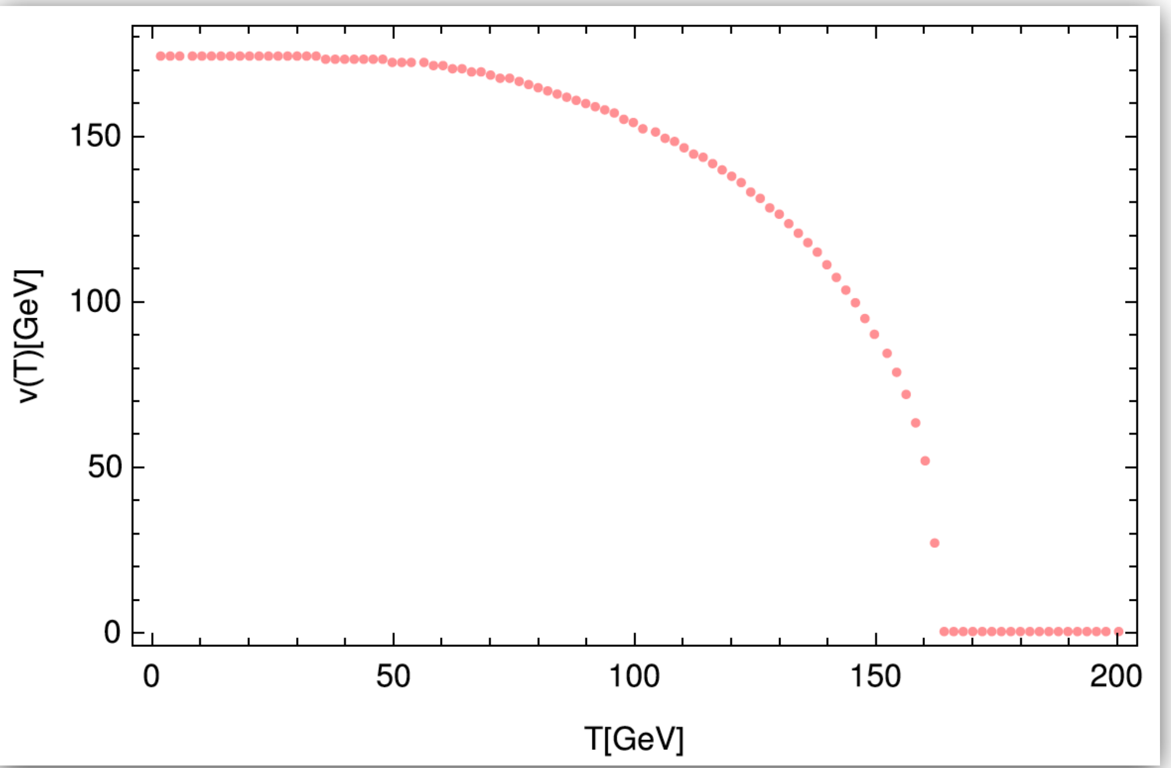
$$Y^N_{-,\alpha} = \begin{pmatrix} h_{\alpha 2} h^*_{\alpha 2} & -h_{\alpha 3} h^*_{\alpha 2} \\ -h_{\alpha 2} h^*_{\alpha 3} & h_{\alpha 3} h^*_{\alpha 3} \end{pmatrix},$$

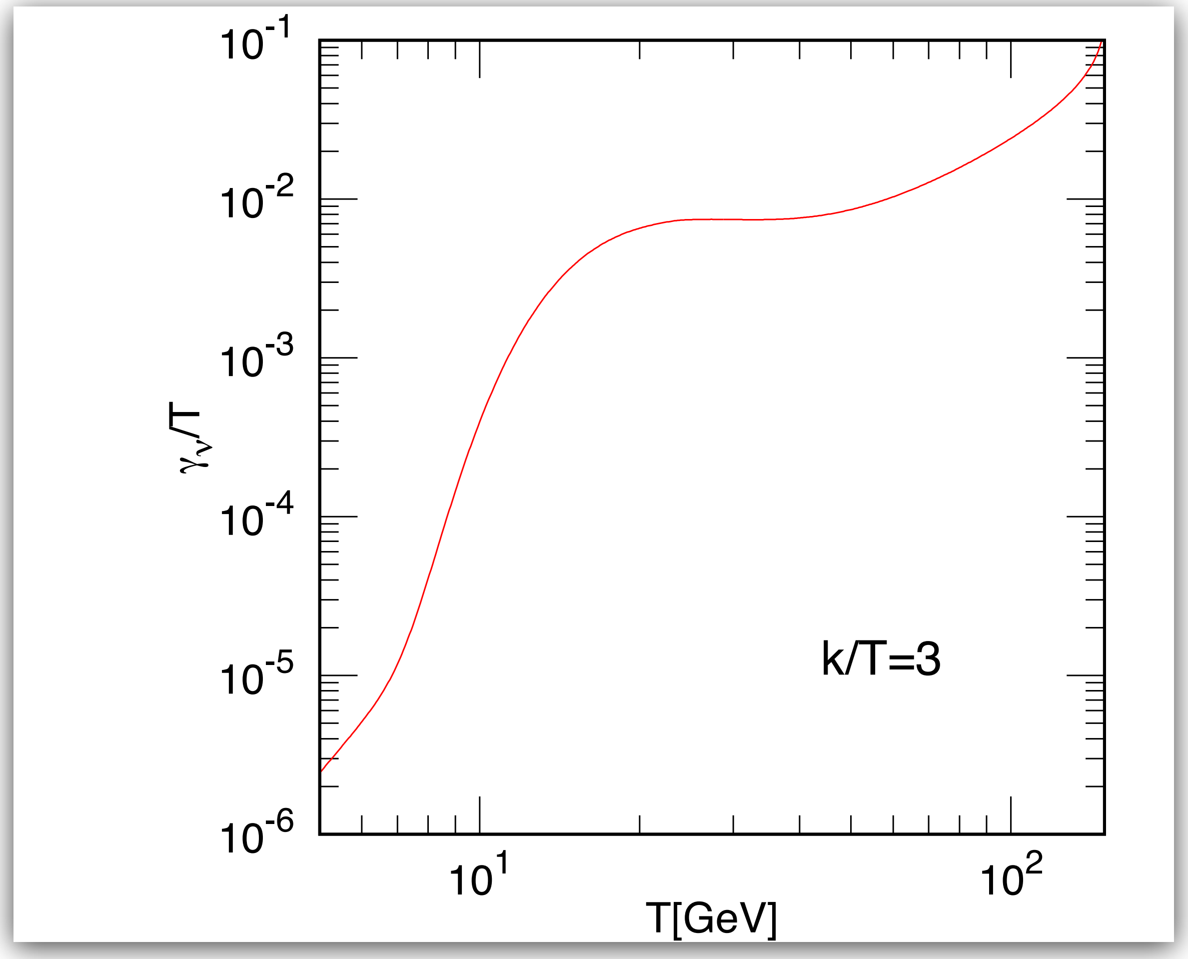
$$Y^\nu_{+,\alpha} = \begin{pmatrix} h_{\alpha 3} h^*_{\alpha 3} & -h_{\alpha 2} h^*_{\alpha 3} \\ -h_{\alpha 3} h^*_{\alpha 2} & h_{\alpha 2} h^*_{\alpha 2} \end{pmatrix},$$

$$Y^\nu_{-,\alpha} = \begin{pmatrix} h_{\alpha 2} h^*_{\alpha 2} & -h_{\alpha 2} h^*_{\alpha 3} \\ -h_{\alpha 3} h^*_{\alpha 2} & h_{\alpha 3} h^*_{\alpha 3} \end{pmatrix},$$

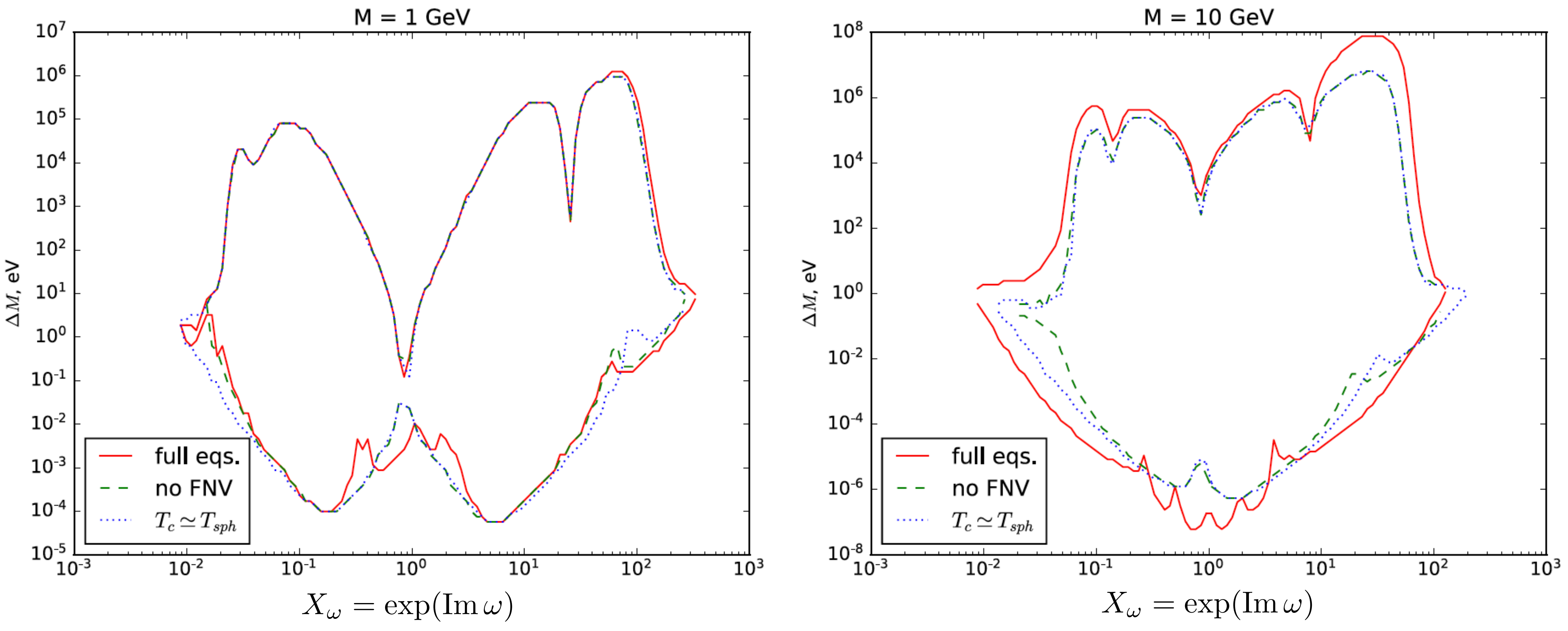
Leptogenesis in the Higgs phase can be performed exactly

T-depending parameters





Effects of LNV and in the Higgs phase



Plasma neutrality

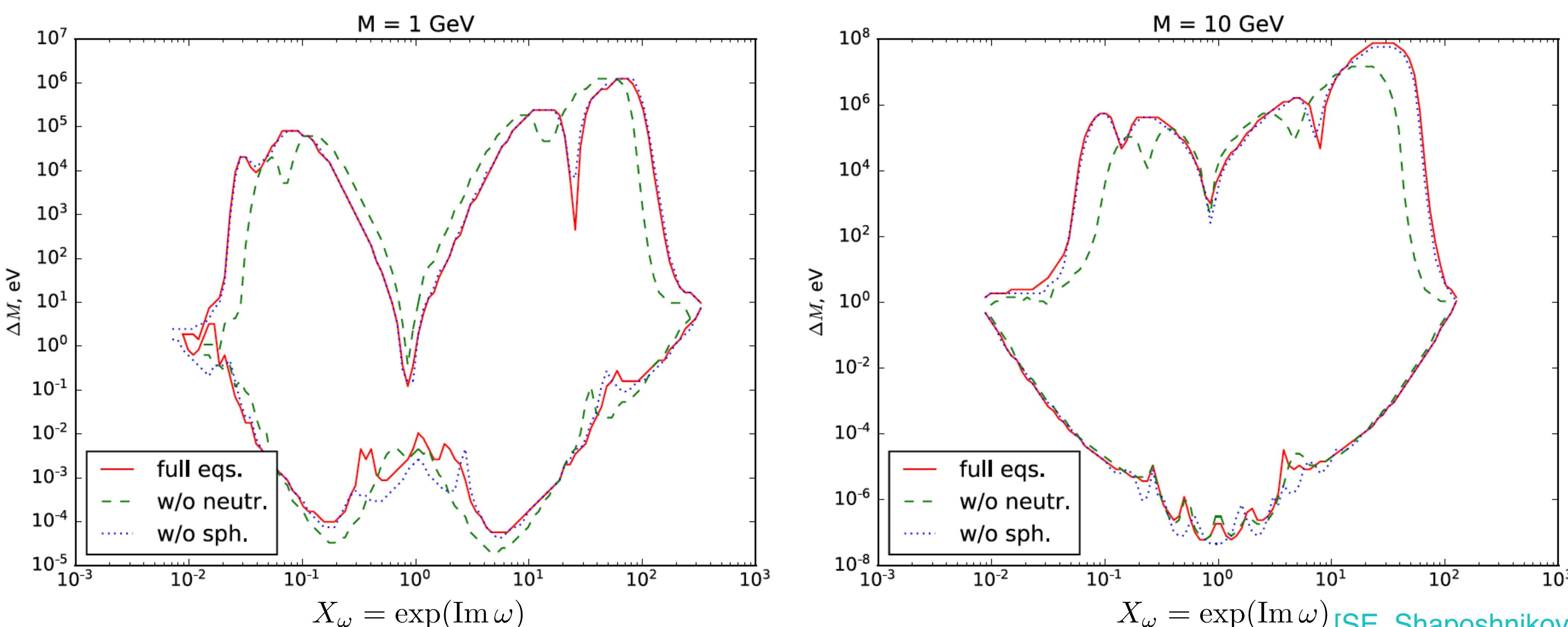
Generated lepton asymmetries have to be distributed into other SM particles in plasma immediately.

Replacing as follows in the right-handed side of kinetic equations.

$$\mu_\alpha = \omega_{\alpha\beta}(T) n_{\Delta_\beta} + \omega_B(T) n_B,$$

$$\omega(T) = \frac{1}{T^2}\begin{pmatrix} a & b & b \\ b & a & b \\ b & b & a \end{pmatrix}, \quad a = \frac{22\left(15x^2+44\right)}{9\left(17x^2+44\right)}, \quad b = \frac{8\left(3x^2+22\right)}{9\left(17x^2+44\right)},$$

$$\omega_B(T) = \frac{1}{T^2}\frac{4\left(27x^2+77\right)}{9\left(17x^2+44\right)} \qquad x = \langle\Phi(T)\rangle/T$$



[SE, Shaposhnikov, Timiryasov ('18)]

Exact treatment of sphaleron process

Usual approach is instant freeze-out of sphaleron process.

Kinetic equation of baryon asymmetry

$$\dot{n}_B = -\Gamma_B (n_B - n_{B^{\rm eq}}),$$

$$\Gamma_B = 3^2 \cdot \frac{869 + 333(\langle\Phi\rangle/T)^2}{792 + 306(\langle\Phi\rangle/T)^2} \cdot \frac{\Gamma_{diff}(T)}{T^3},$$

$$n_{B^{\rm eq}} = -\chi(T) \sum_\alpha n_{\Delta_\alpha}, \quad \chi(T) = \frac{4\left(27(\langle\Phi\rangle/T)^2 + 77\right)}{333(\langle\Phi\rangle/T)^2 + 869}$$

$$\Gamma_{diff} \simeq \begin{cases} T^4 \cdot \exp\left(-147.7 + 0.83 T/\mathrm{GeV}\right), & \text{in the Higgs phase,} \\ T^4 \cdot 18\, \alpha_W^5, & \text{in the symmetric phase.} \end{cases}$$

[SE, Shaposhnikov, Timiryasov ('17)]

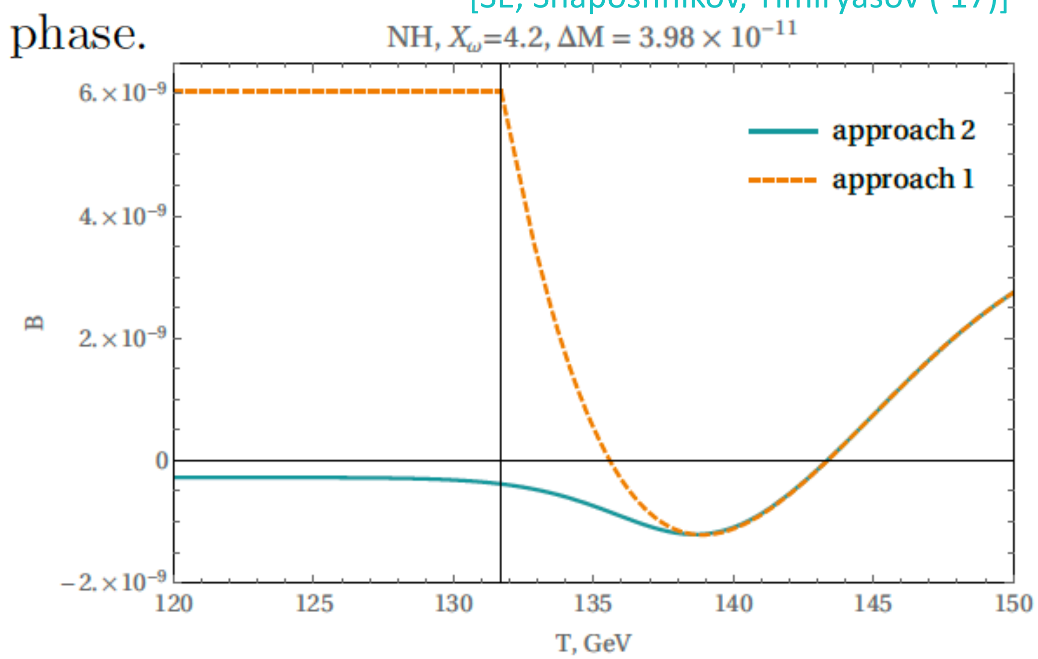
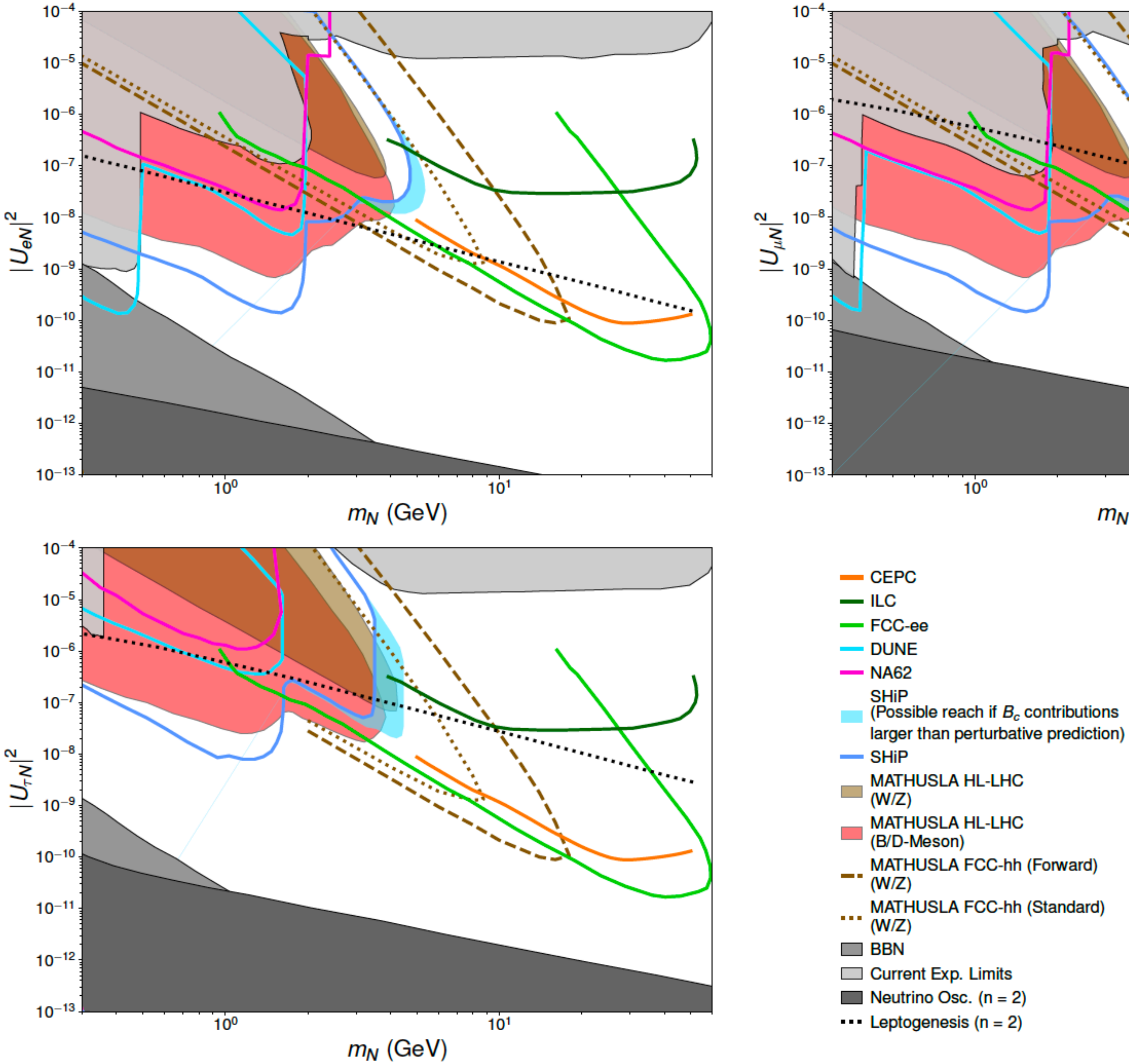


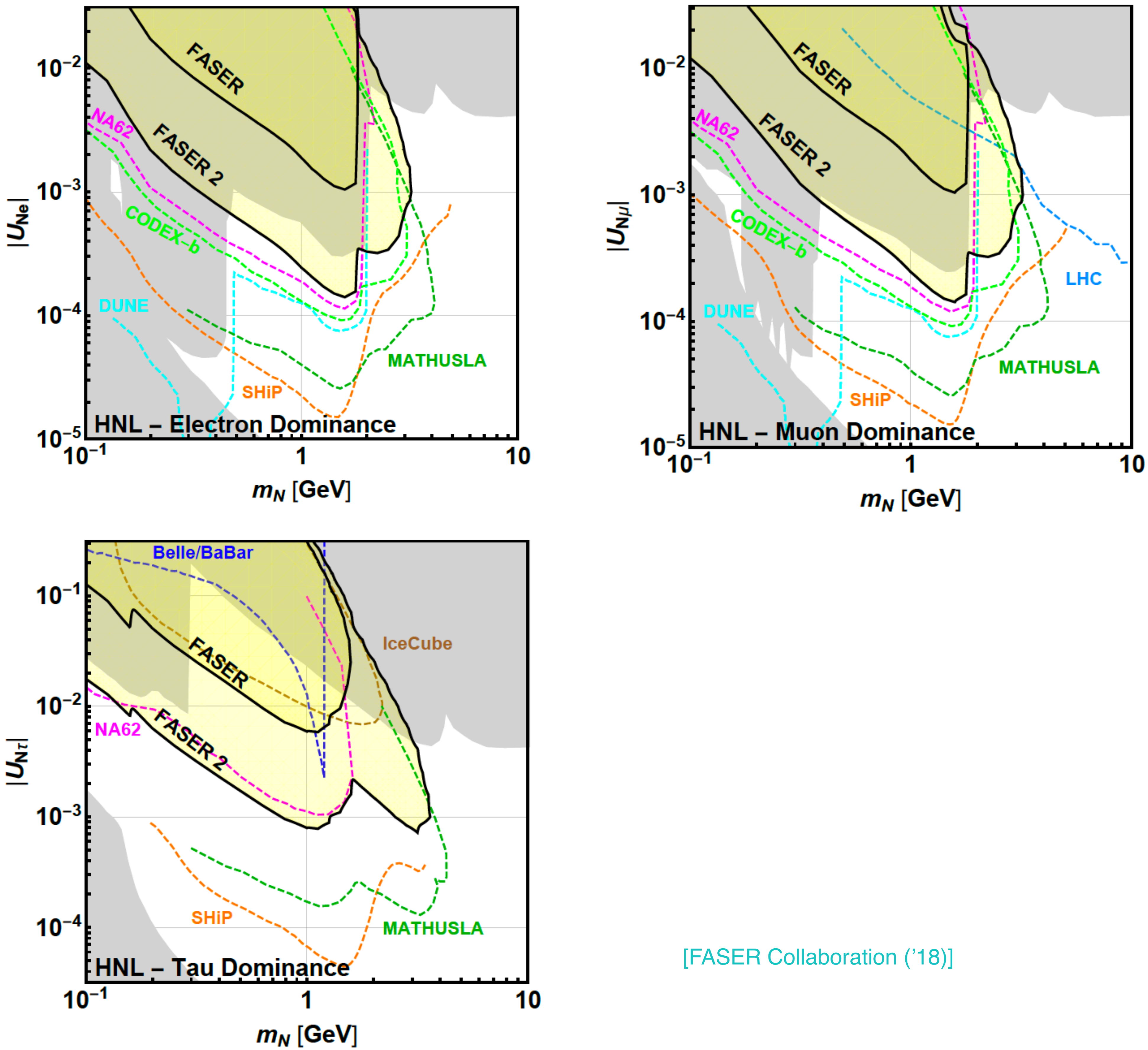
Figure 3. An example of a large deviation. $B^{\rm appr.1}/B^{\rm appr.2} \simeq -21.9$. Upper panel, $\Delta(T)$ as function of temperature in the approach with instant freeze-out (dotted orange line) and in the approach with the separate equation for B (blue line). Lower panel, $B(T)$ as function of temperature. The black vertical line shows the sphaleron freeze out temperature $T_{\rm sph} = 131.7\,\mathrm{GeV}$. To illustrate a situation when lepton asymmetry is generated right before the sphaleron freeze-out we utilize the following values of the parameters: the common mass of HNLs is $M = 1\,\mathrm{GeV}$, $\Delta M = 3.98 \cdot 10^{-11}\,\mathrm{GeV}$, $X_\omega = 4.2$, $\delta = 3\pi/2$, $\eta = 19\pi/16$, $\mathrm{Re}\,\omega = \pi/4$. See also the discussion in the main text.

MATHUSLA



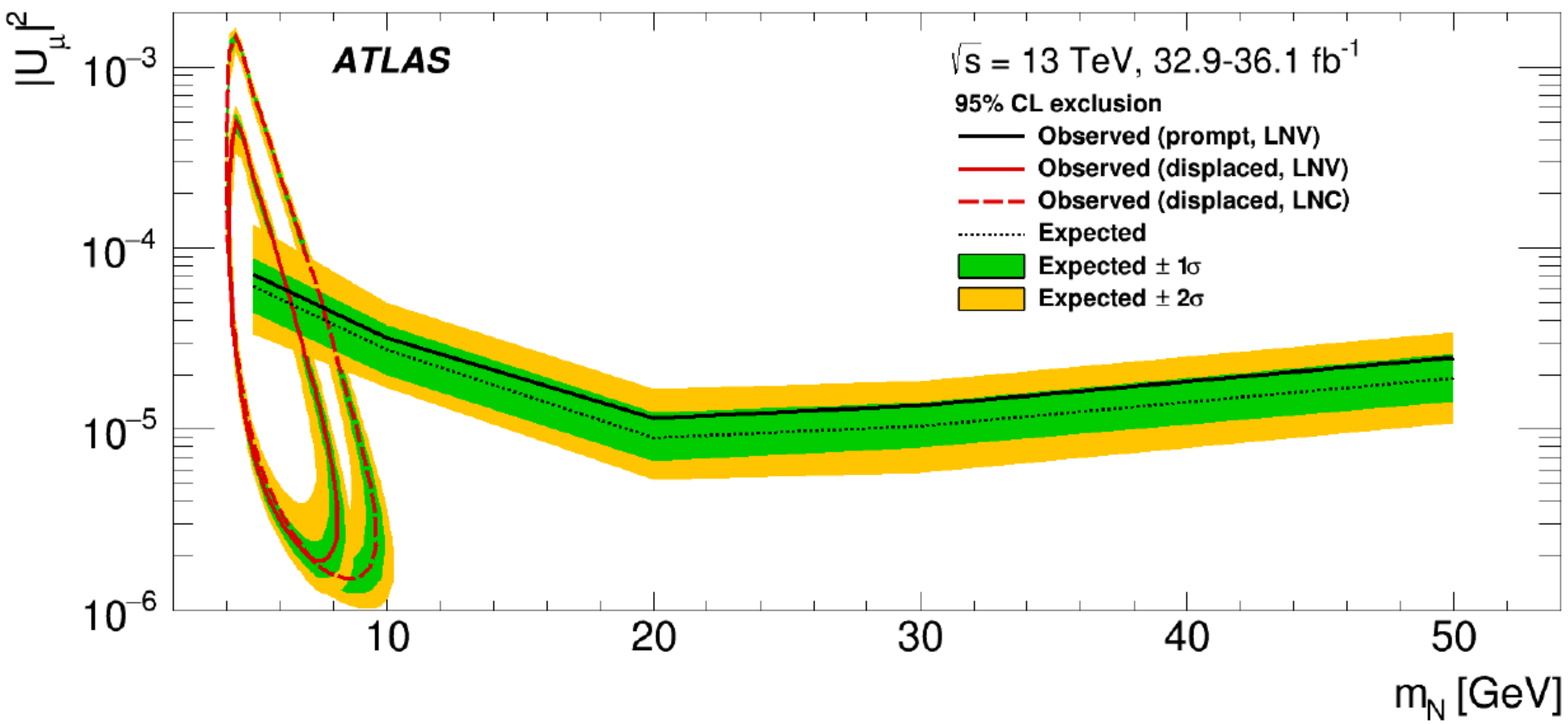
[Currin, Drewes, McCullough, Meade, Mohapatra, Shelton, Shuve, et al. ('18)]

FASER

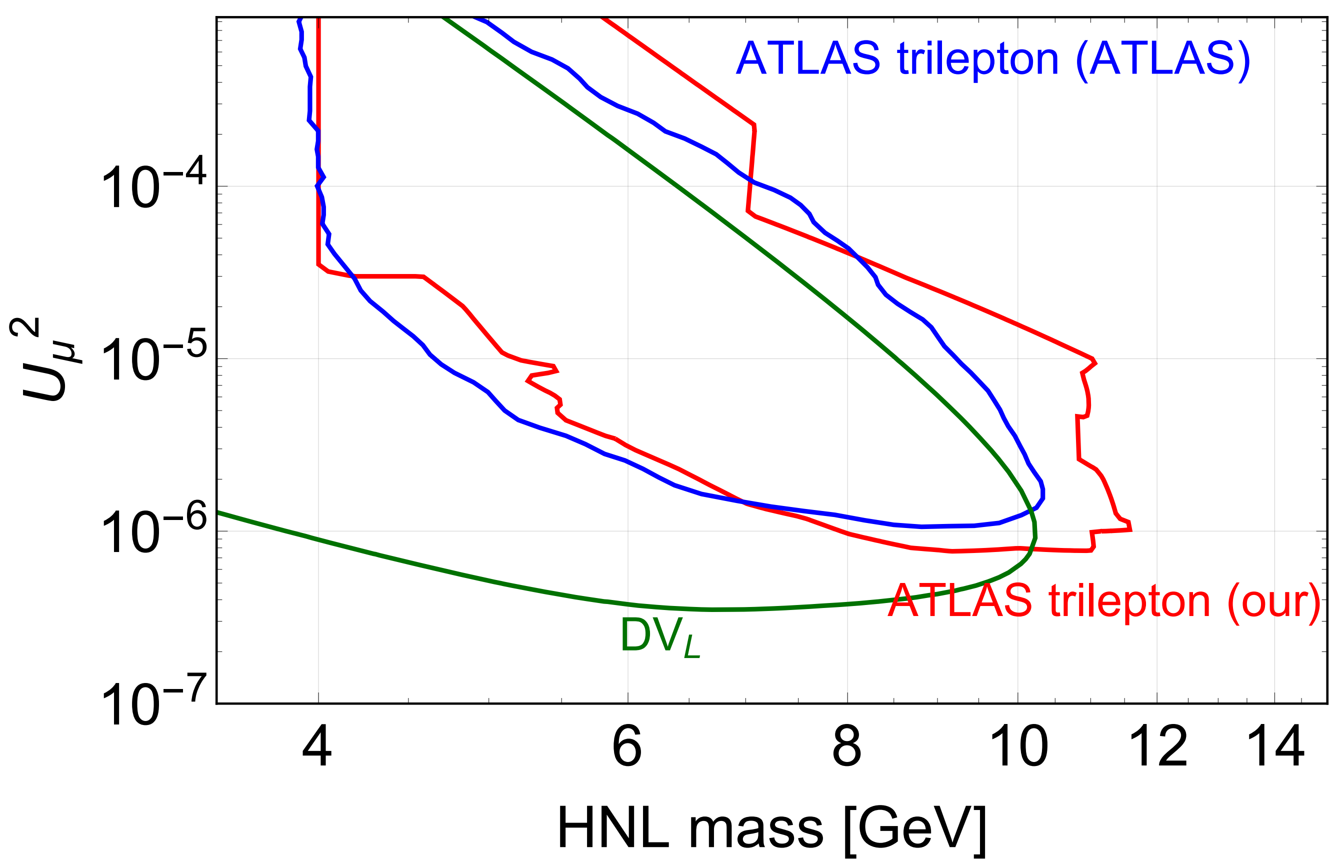


[FASER Collaboration ('18)]

Bounds from DV in ATLAS



[ATLAS Collaboration ('19)]



$$W^+ \to \mu^+ N$$
$$\to \mu^+(\mu^- \ \mu^+/e^+ \ \nu_\mu/\nu_e)$$

[Boiarska, Bondarenko, Boyarsky, SE, Ovchynnikov, Ruchayskiy, Timiryasov ('19)]