Resonant leptogenesis

theoretical advances and experimental prospects

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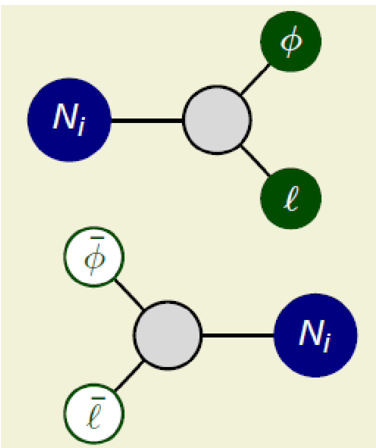
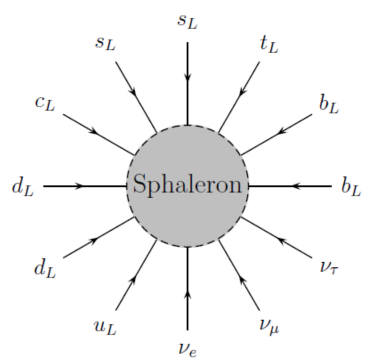
Outline

- Leptogenesis via decays
- Collider searches
- Resonant leptogenesis
- Kadanoff-Baym approach
- Leptogenesis via oscillations
- Experimental search
- Summary

Leptogenesis via decays



→ ΔL →

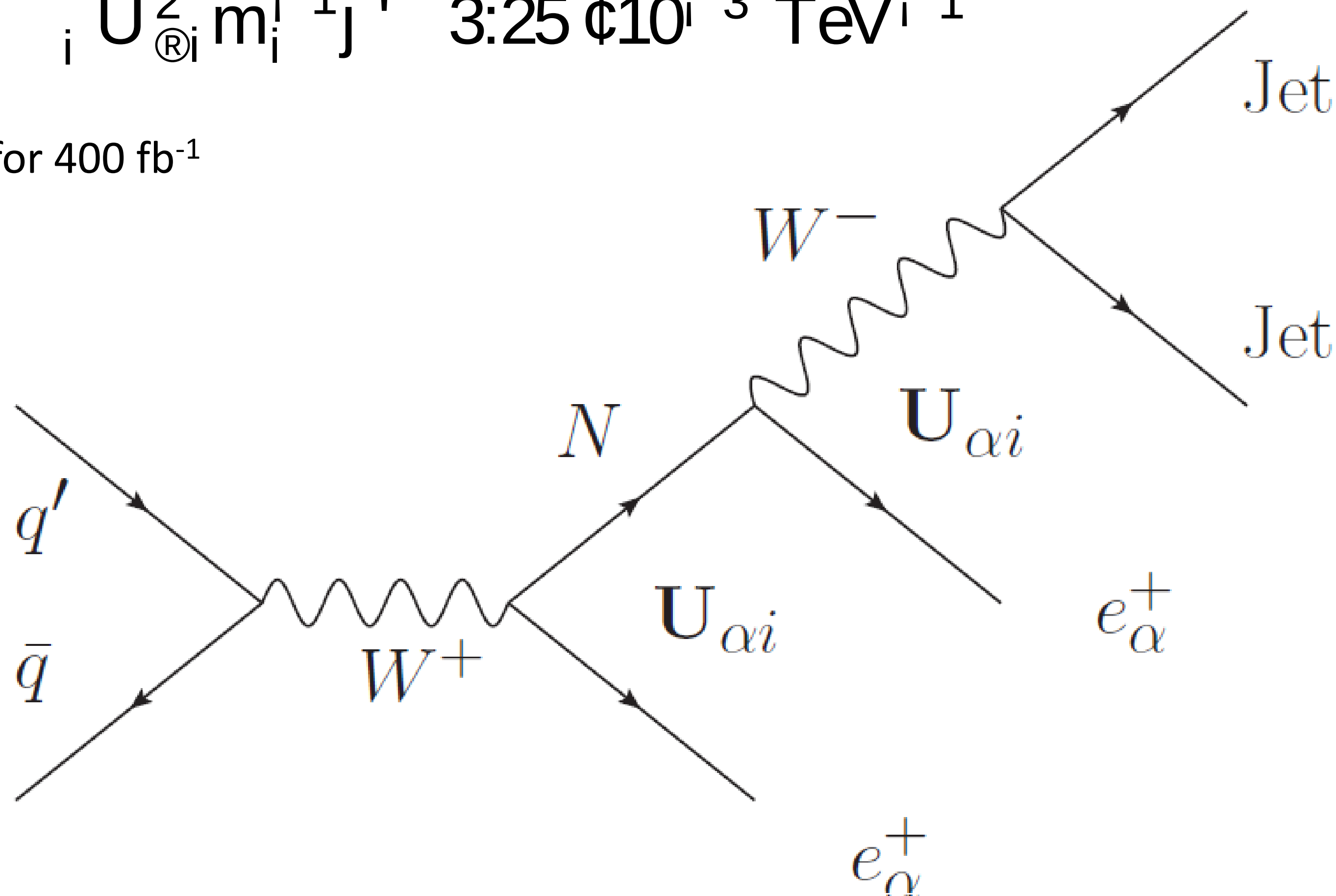


→ ΔB →

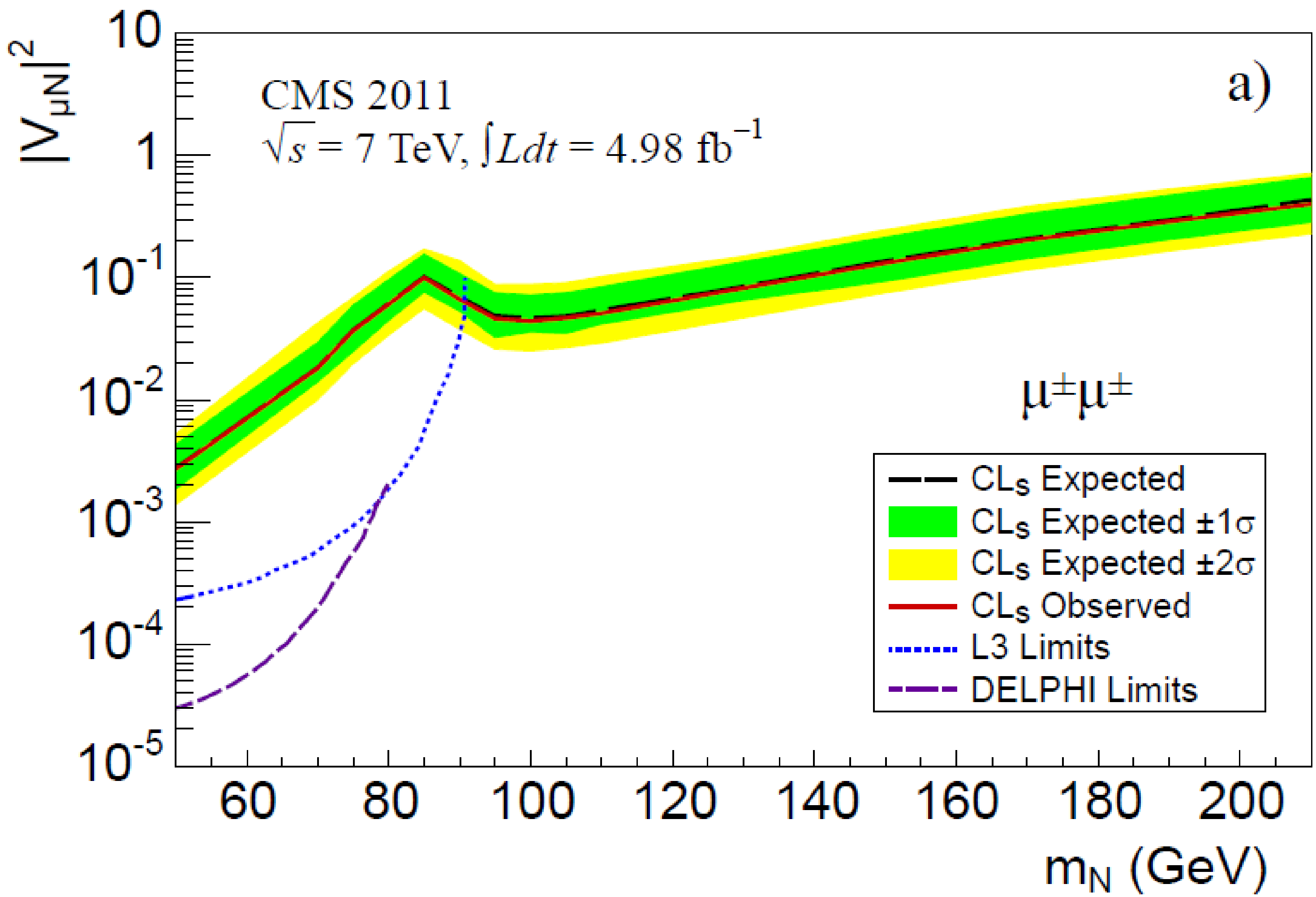
Collider signature

$$|\Gamma - U^2_{\alpha i} m_i^{-1}| \simeq 3.25 \cdot 10^{-3}\ \mathrm{TeV}^{-1}$$

for 400 fb^{-1}



CMS constraints



Successful TeV-scale leptogenesis ?

$$´ \; » \; \frac{2}{\cdot \; z_f}$$

$$\cdot \; = \; \frac{i_1}{H(M_1)} \; ´ \; \frac{\tilde{m}_1}{m_¤}$$

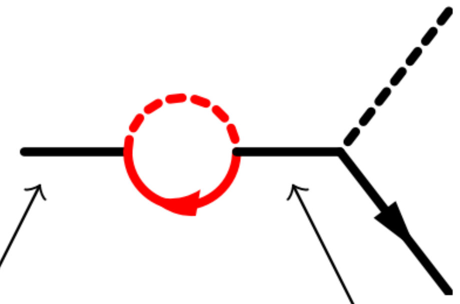
$$m_¤ \; » \; 10^{i\;3}\,eV$$

$$\tilde{m}_1 < 5 \, ¢ \, 10^{i\;3}\,eV$$

$$^2{}_1 \; \cdot \; \frac{3}{8¼} \frac{M_1 m_3}{v^2}$$

$$M_1 \; » \; 10^8\,GeV$$

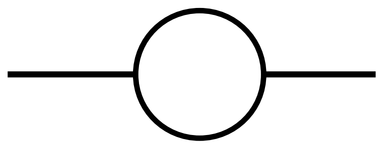
Resonant enhancement

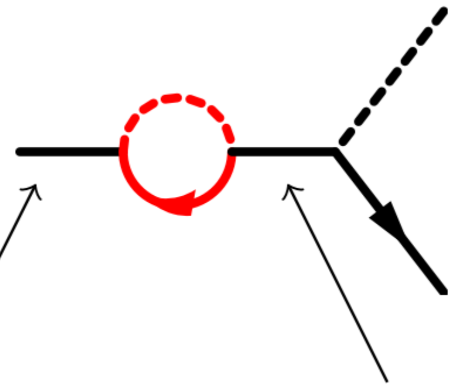


Off-shell initial N_1: $p^2 = M_1^2 + iM_1\Gamma_1$ Internal N_2: $\frac{i}{p^2 - M_2^2 - iM_2\Gamma_2}$

$$\epsilon_{N_i}^{wave} = \frac{\mathrm{Im}[(h^\dagger h)_{12}^2]}{8\pi(h^\dagger h)_{ii}} \times \frac{M_1 M_2}{M_2^2 - M_1^2}$$

Schwinger-Dyson resummation

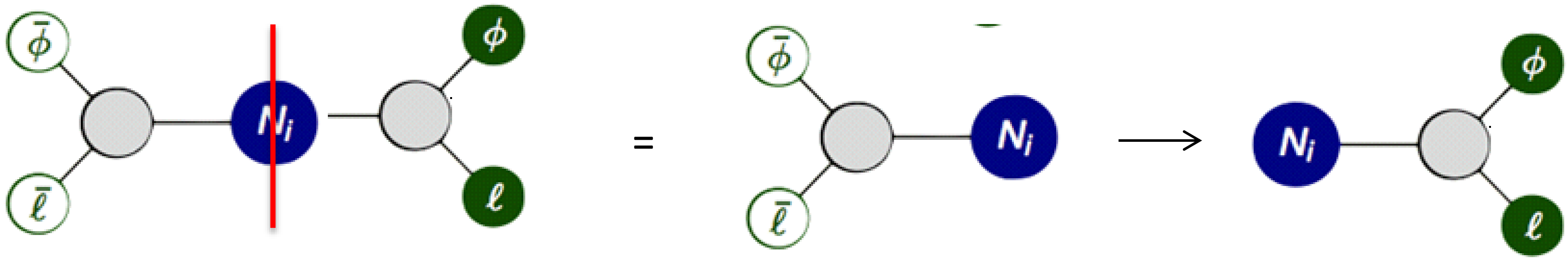


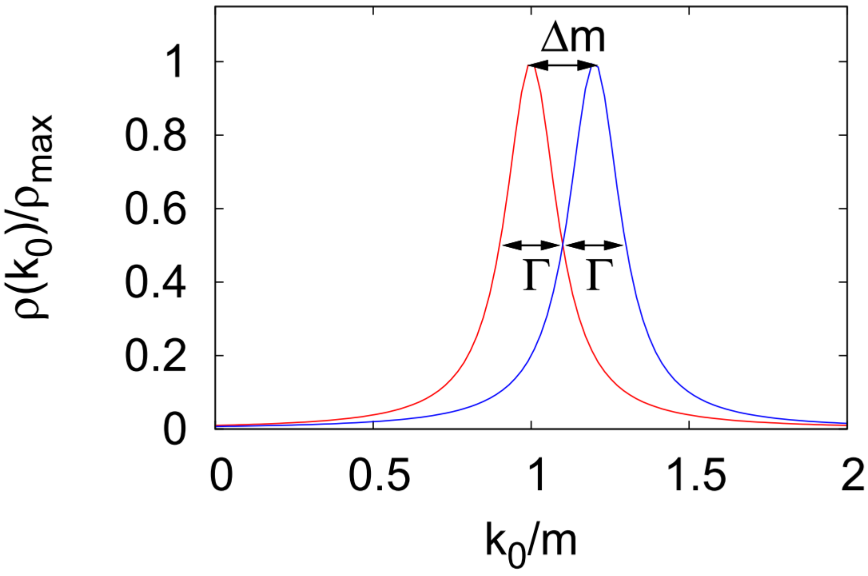


Off-shell initial N_1: $p^2 = M_1^2 + iM_1\Gamma_1$ Internal N_2: $\frac{i}{p^2 - M_2^2 - iM_2\Gamma_2}$

$$\epsilon_{N_i} = \frac{\mathrm{Im}[(h^\dagger h)_{12}^2]}{8\pi(h^\dagger h)_{ii}} \frac{M_1 M_2(M_2^2 - M_1^2)}{(M_2^2 - M_1^2 - \frac{1}{\pi}\Gamma_i M_i \ln\frac{M_2^2}{M_1^2})^2 + (M_1\Gamma_1 - M_2\Gamma_2)^2}$$

RIS subtraction ?





Thermal effects

$$M_{¡}(T) \;'\; M_{¡}(0) + ¡_{¡}\, ¢c(T{=}M_{¡})^2$$

$$¢M(T) \;'\; ¢M(0) + (¡_2 \;¡\; ¡_1)\, ¢c(T{=}M_1)^2$$

$$¢M \;»\; ¡_1 + ¡_2$$

$$²_{¡} \;/\; \frac{\mathrm{Im}(H^2_{12})(M_2^2 \;¡\; M_1^2)}{(M_1^2 \;¡\; M_2^2)^2 + (M_1 ¡_1 \;¡\; M_2 ¡_2)^2}$$

Kadanoff-Baym equations

$$((i\partial\!\!\!/_x - M_i)\delta^{ik} - \delta\Sigma_N(x)^{ik})S_F^{kj}(x,y) = \int_0^{x^0} dz^0 \int d^3z\, \Sigma_{N\rho}^{ik}(x,z) S_F^{kj}(z,y) - \int_0^{y^0} dz^0 \int d^3z\, \Sigma_{NF}^{ik}(x,z) S_\rho^{kj}(z,y)$$

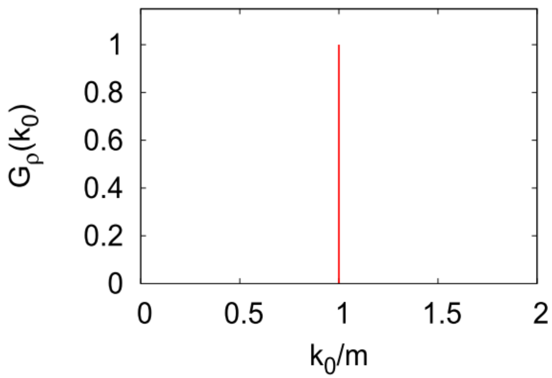
$$((i\partial\!\!\!/_x - M_i)\delta^{ik} - \delta\Sigma_N(x)^{ik})S_\rho^{kj}(x,y) = \int_{y^0}^{x^0} dz^0 \int d^3z\, \Sigma_{N\rho}^{ik}(x,z) S_\rho^{kj}(z,y)$$

see hep-ph/0409233 for a comprehensive review

Quasiparticle approximation

Boltzmann limit

- on-shell quasi-stable particles

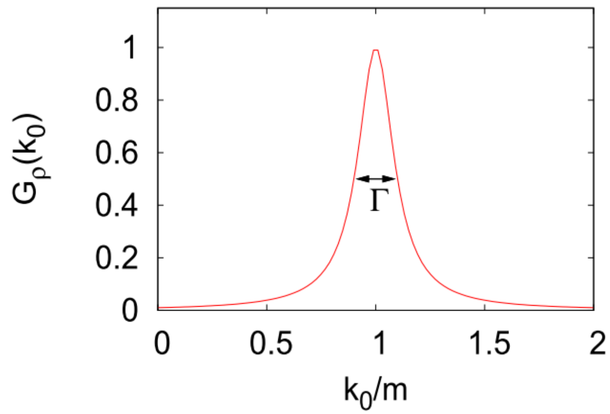


$$S_\rho^{ij}(k) \sim \delta^{ij}\delta(k^2 - m_i^2)$$

$$S_F^{ij}(t,k) = \left(\frac{1}{2} - f_k^i(t)\right) S_\rho^{ij}(k)$$

More general

- spectrum with (thermal) width



$$S_\rho^{ij}(t,k) \propto \frac{\delta^{ij} 2k_0 \Gamma_i(t)}{(k^2 - m_{th,i}^2(t))^2 + k_0^2 \Gamma_i(t)^2} + \dots$$

Advantages

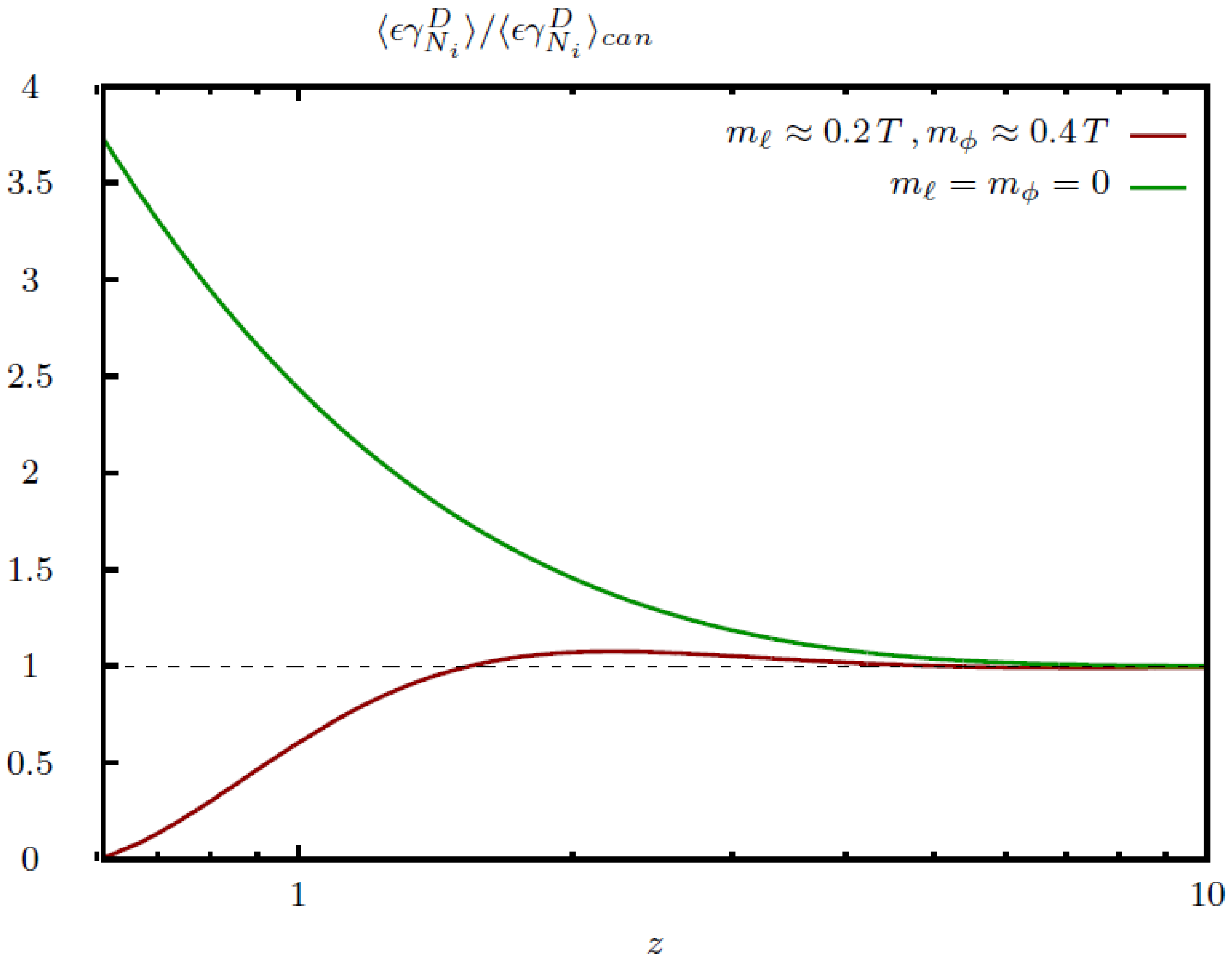
- Do not rely on quasiparticle picture
- Take medium corrections into account
- Resum series of daisy and ladder diagrams
- Take memory effects into account

Third Sakharov condition

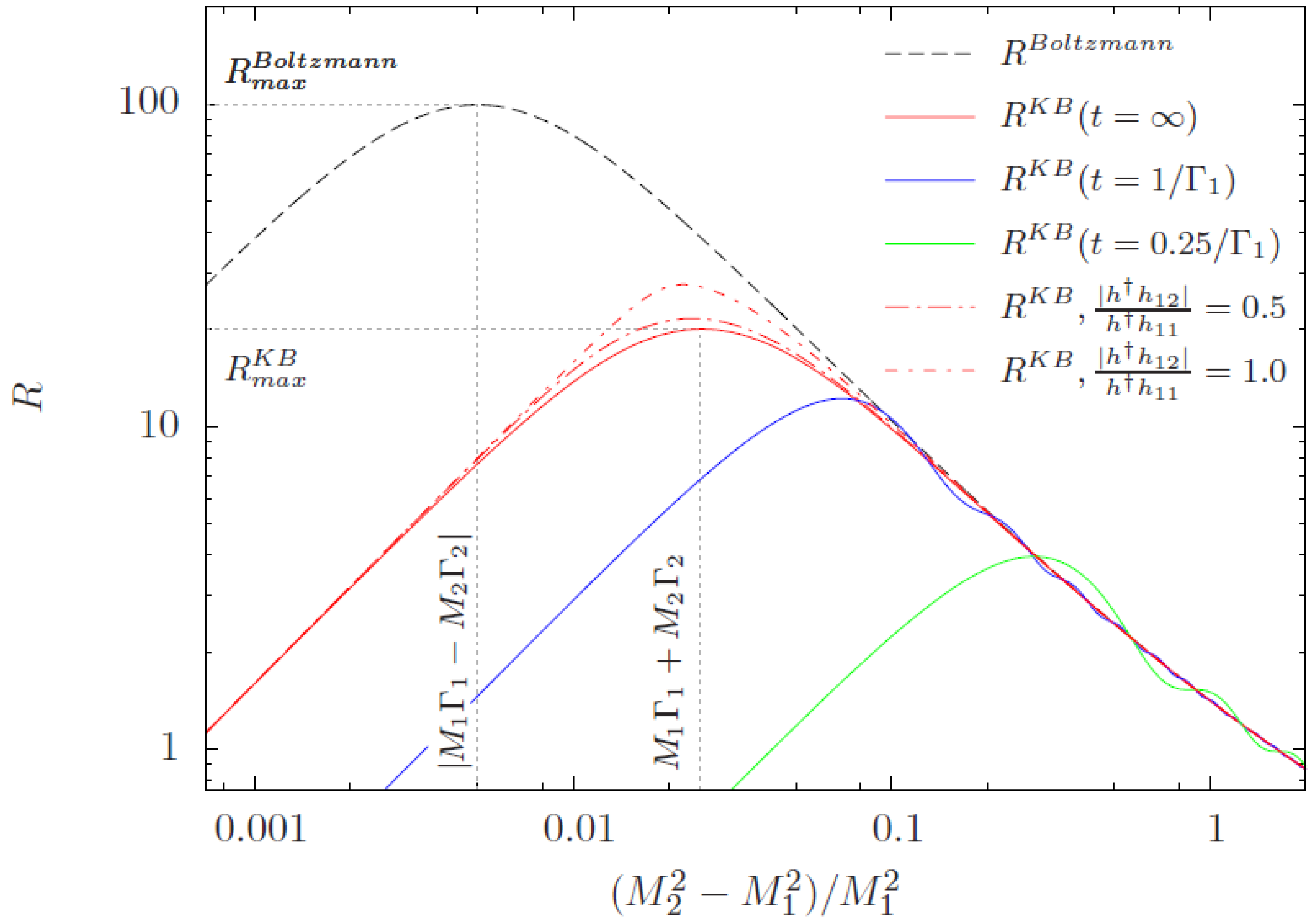
$$
\begin{aligned}
\frac{s\mathcal{H}}{z}\frac{dY_L}{dz} = & \sum_i \int d\Pi^{pkq}_{\ell\phi N_i} \mathcal{F}^{pk;q}_{\ell\phi\leftrightarrow N_i} \Xi_{\ell\phi\leftrightarrow N_i} \\
& - \sum_i \int d\Pi^{pkq}_{\bar{\ell}\bar{\phi} N_i} \mathcal{F}^{pk;q}_{\bar{\ell}\bar{\phi}\leftrightarrow N_i} \Xi_{\bar{\ell}\bar{\phi}\leftrightarrow N_i} \\
& - 2 \int d\Pi^{p_1 k_1 p_2 k_2}_{\ell\phi\bar{\ell}\bar{\phi}} \mathcal{F}^{p_2 k_2;p_1 k_1}_{\bar{\ell}\bar{\phi}\leftrightarrow \ell\phi} \Xi_{\bar{\ell}\bar{\phi}\leftrightarrow \ell\phi} \\
& - \int d\Pi^{p_1 p_2 k_1 k_2}_{\ell\ell\bar{\phi}\bar{\phi}} \mathcal{F}^{k_1 k_2;p_1 p_2}_{\bar{\phi}\bar{\phi}\leftrightarrow \ell\ell} \Xi_{\bar{\phi}\bar{\phi}\leftrightarrow \ell\ell} \\
& - \int d\Pi^{p_1 p_2 k_1 k_2}_{\bar{\ell}\bar{\ell}\phi\phi} \mathcal{F}^{p_1 p_2;k_1 k_2}_{\bar{\ell}\bar{\ell}\leftrightarrow \phi\phi} \Xi_{\bar{\ell}\bar{\ell}\leftrightarrow \phi\phi} \,.
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{F}^{p_a p_b ..;p_i p_j ..}_{ab..\leftrightarrow ij..} \equiv & (2\pi)^4 \delta(p_a + p_b + .. - p_i - p_j - ..) \\
& \times \left[f_i f_j ..(1-\xi^a f_a)(1-\xi^b f_b).. \right. \\
& \left. - f_a f_b ..(1-\xi^i f_i)(1-\xi^j f_j)..\right] ,
\end{aligned}
$$

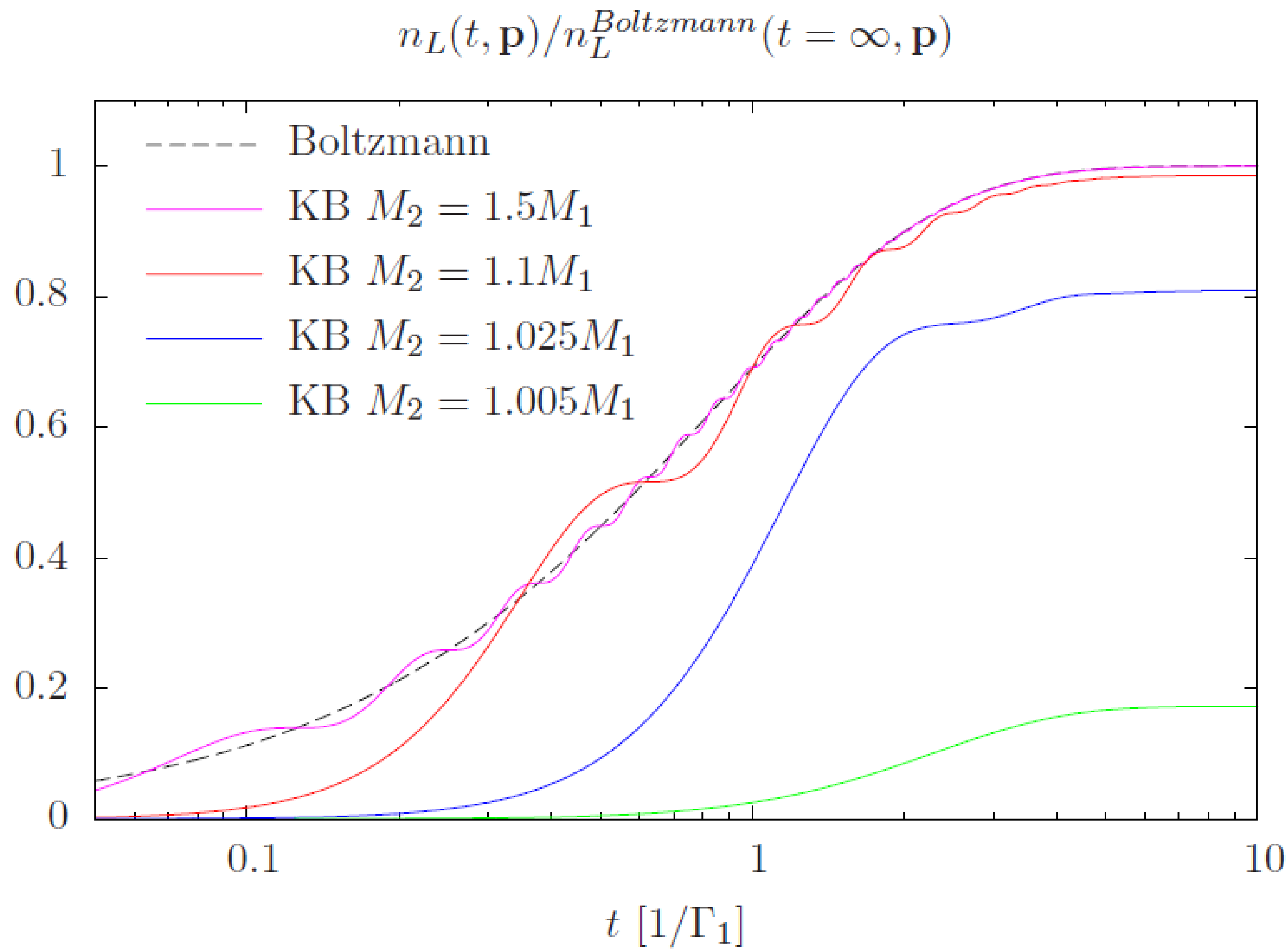
Medium enhancement of ε



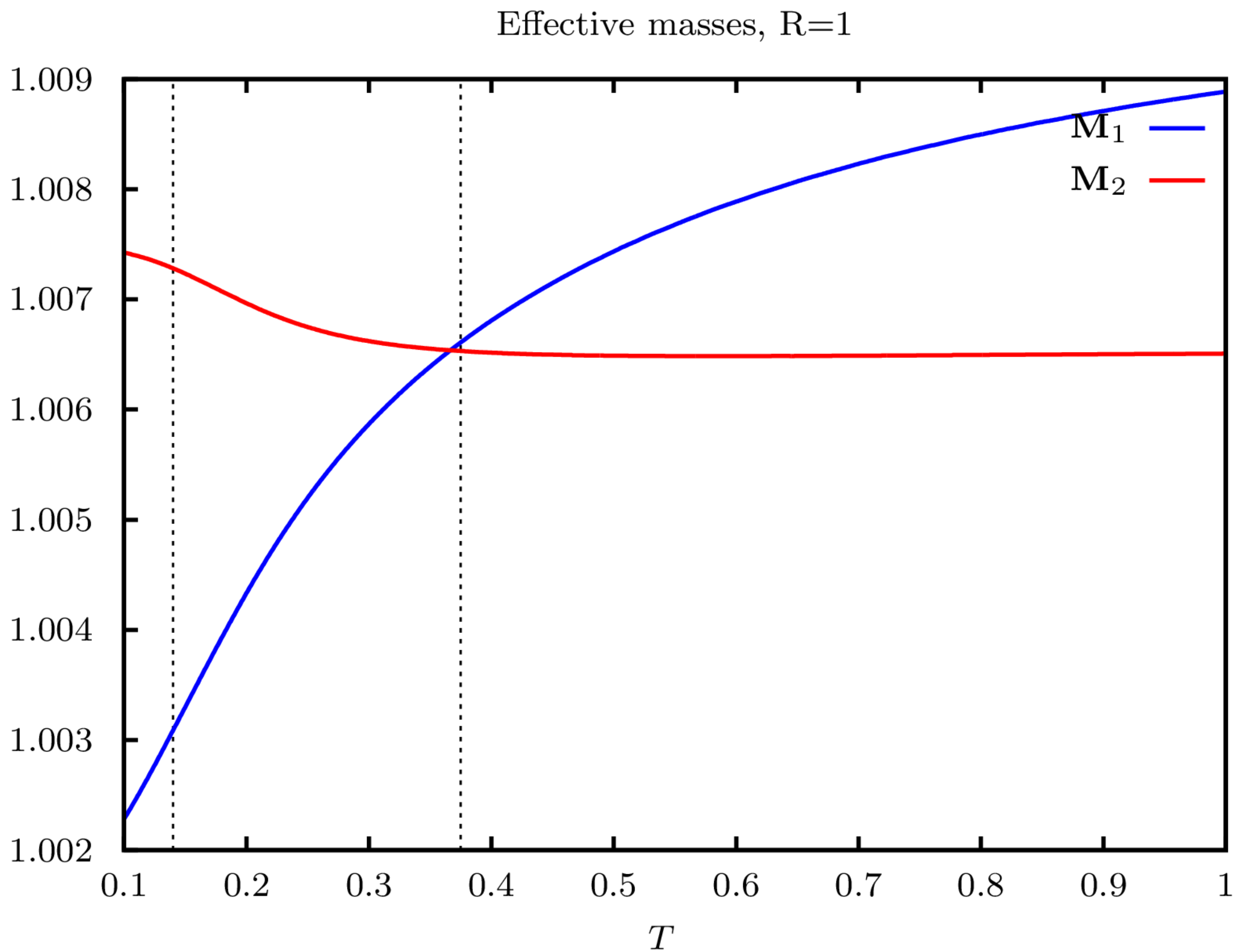
Resonant enhancement of ε



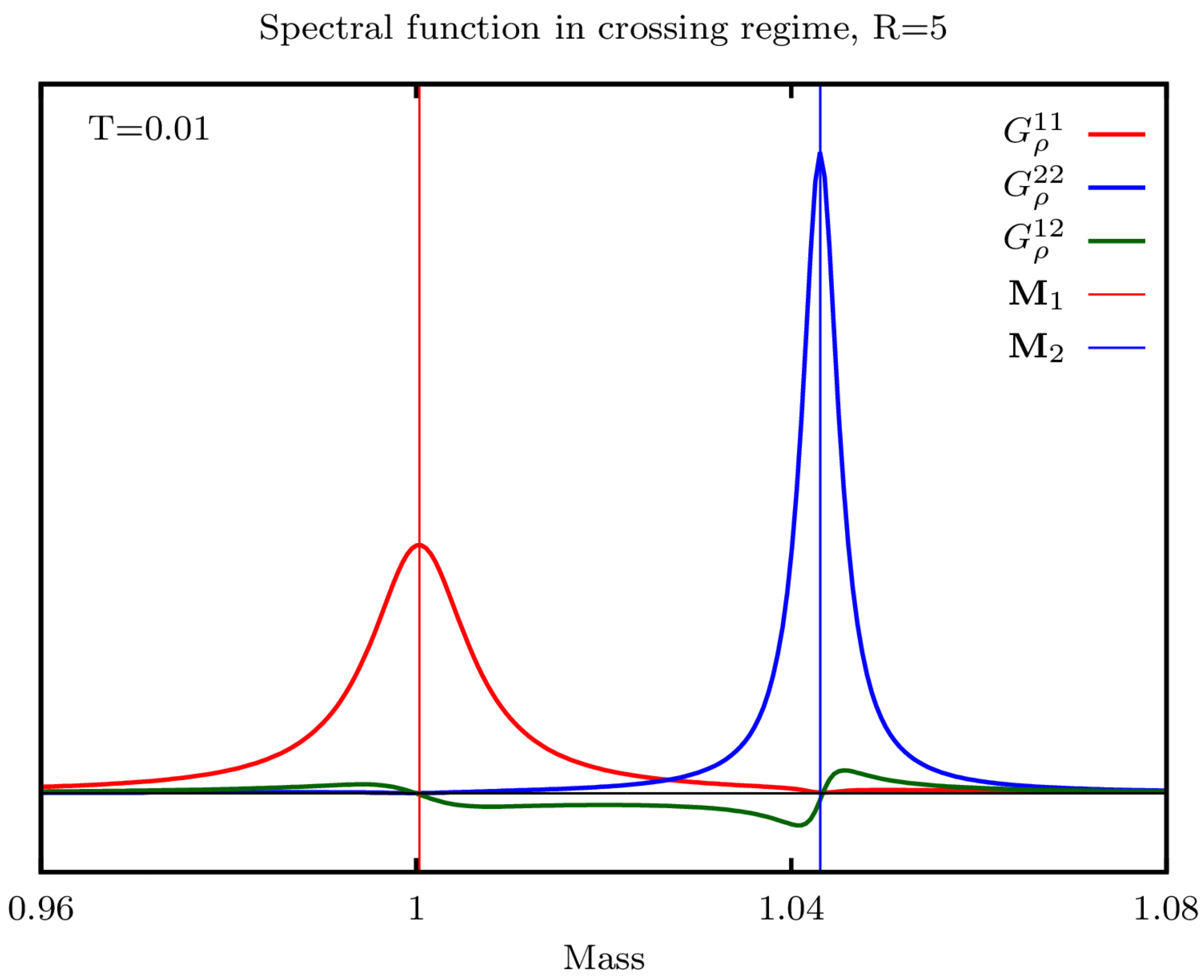
Negative interference



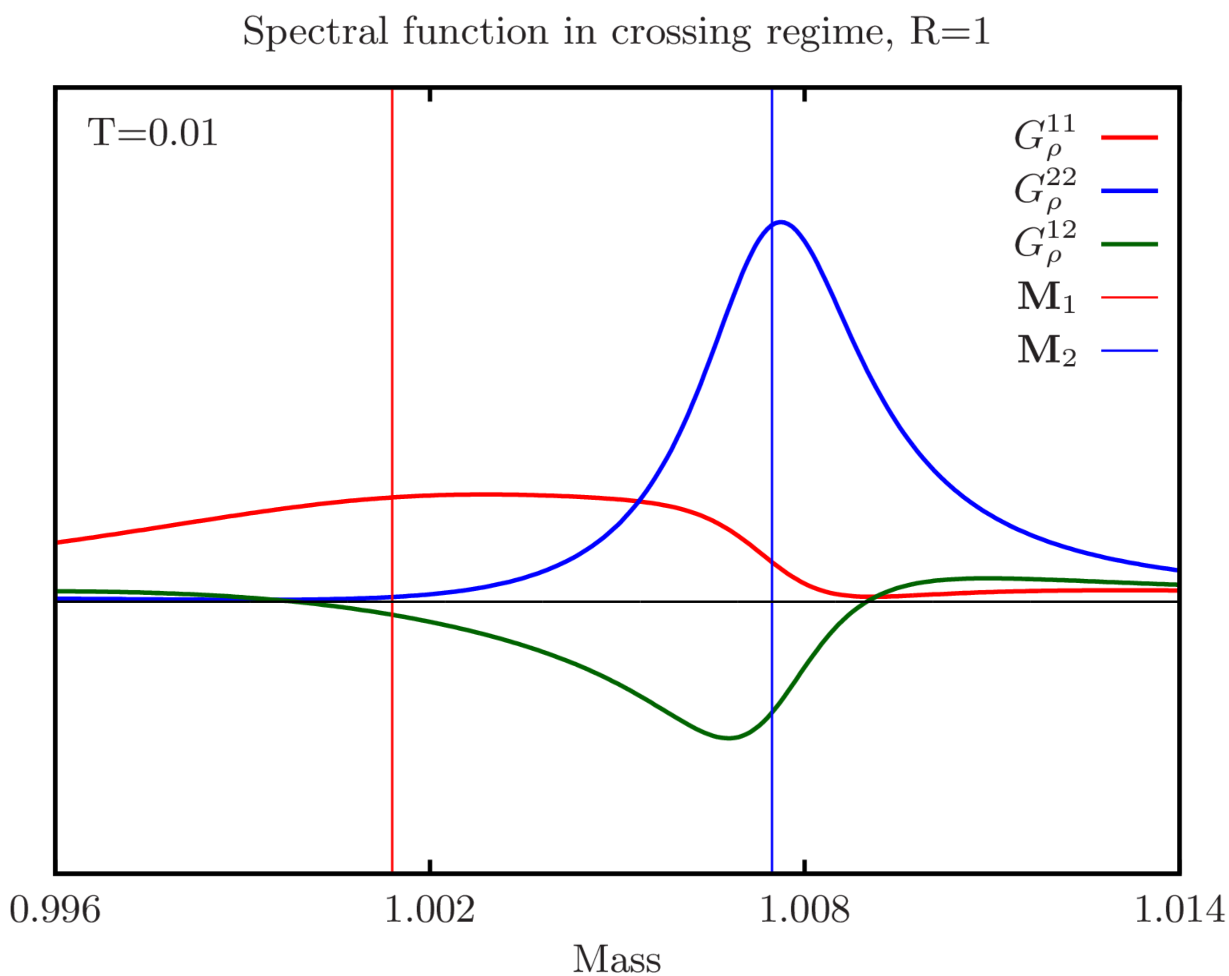
Crossing effective masses



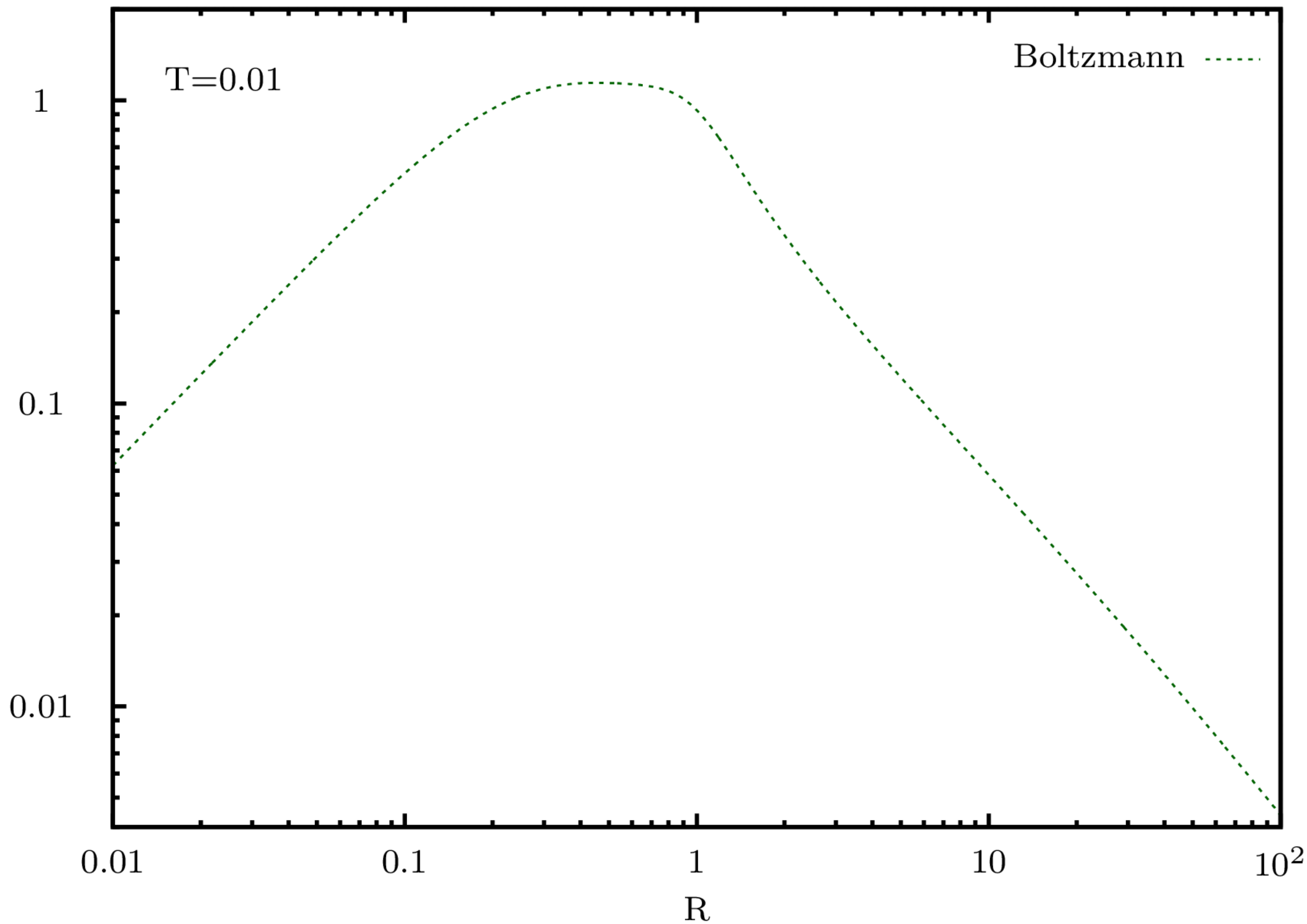
Spectral function (hierarchical)



Spectral function (resonant)



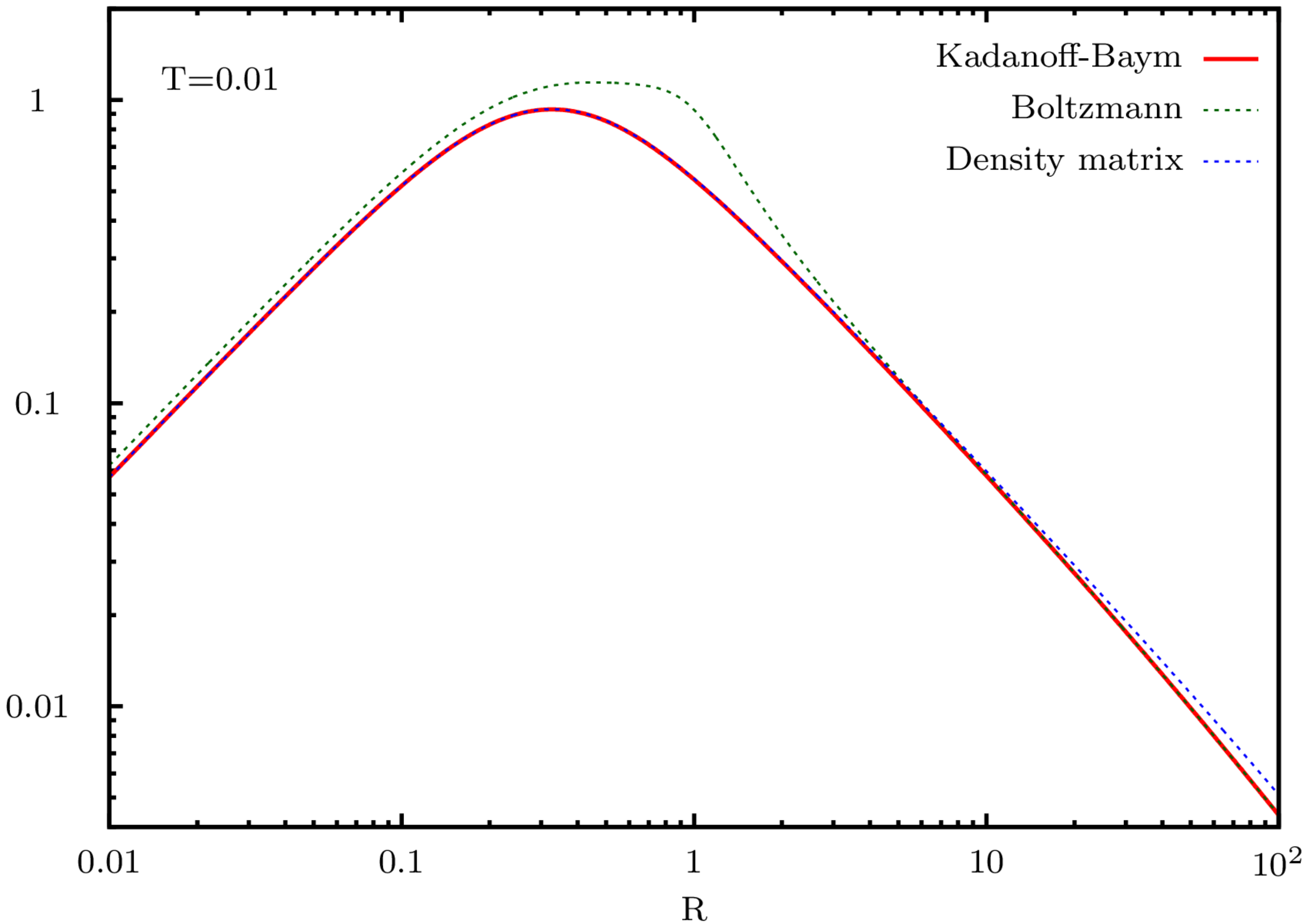
Boltzmann approximation



CP-violating parameter

$$\varepsilon_i \propto \frac{\mathrm{Im}(H_{12}^2)(M_2^2 - M_1^2)}{(M_1^2 - M_2^2)^2 + (\omega_1 \Gamma_1 - \omega_2 \Gamma_2)^2}$$

Kadanoff-Baym result



Baryogenesis via neutrino oscillations

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(March 5, 1998)

We propose a new mechanism of leptogenesis in which the asymmetries in lepton numbers are produced through the CP-violating oscillations of "sterile" (electroweak singlet) neutrinos. The asymmetry is communicated from singlet neutrinos to ordinary leptons through their Yukawa couplings. The lepton asymmetry is then reprocessed into baryon asymmetry by electroweak sphalerons. We show that the observed value of baryon asymmetry can be generated in this way, and the masses of ordinary neutrinos induced by the seesaw mechanism are in the astrophysically and cosmologically interesting range. Except for singlet neutrinos, no physics beyond the Standard Model is required.

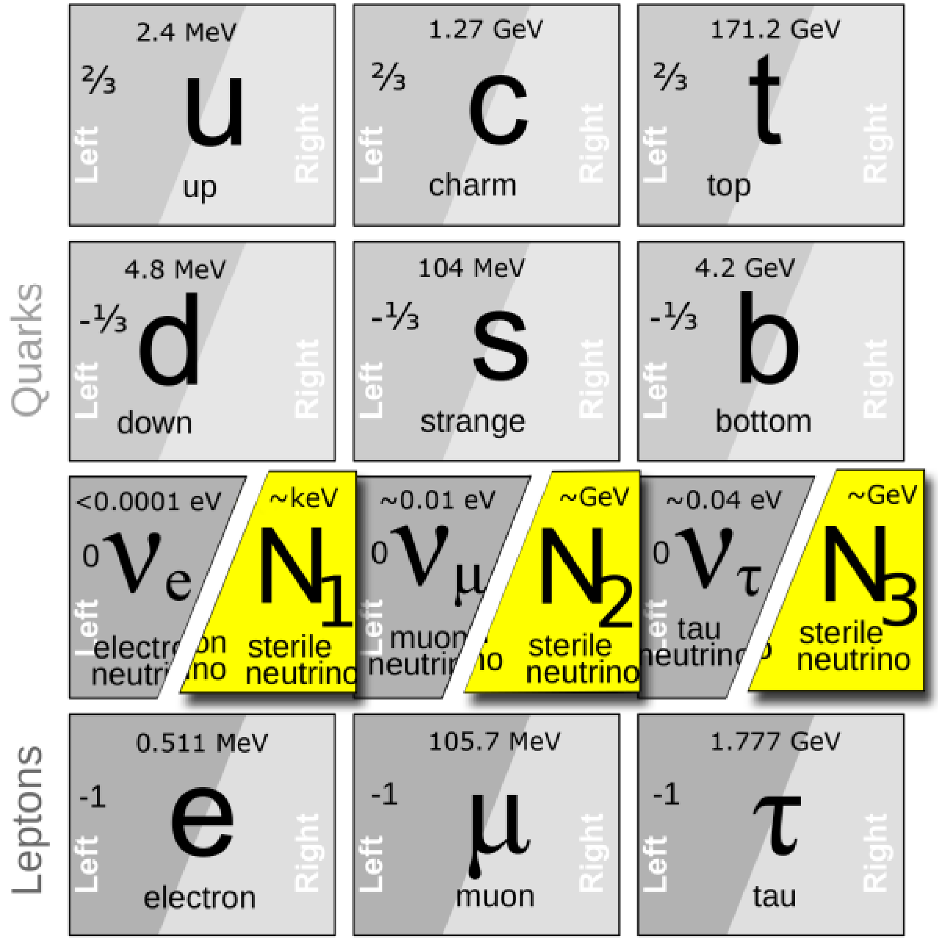
PACS: 98.80.Cq, 14.60.St IC/98/22, INR-98-14T hep-ph/9803255

1. The origin of the excess of baryons over anti-baryons in the Universe remains one of the fascinating problems of particle physics and cosmology. A number of mechanisms have been proposed to date to explain this asymmetry (for recent reviews see, *e.g.*, [1]). One of the simplest possibilities, suggested by Fukugita and Yanagida [2], is that the baryon asymmetry has originated from physics in the leptonic sector. Namely, it was assumed that at temperatures well above the electroweak scale, lepton asymmetry was produced, which was then reprocessed into the baryon asymmetry by non-perturbative electroweak effects [3] – sphalerons [4]. According to ref. [2] the lepton neutrinos are very different from those of ref. [2].

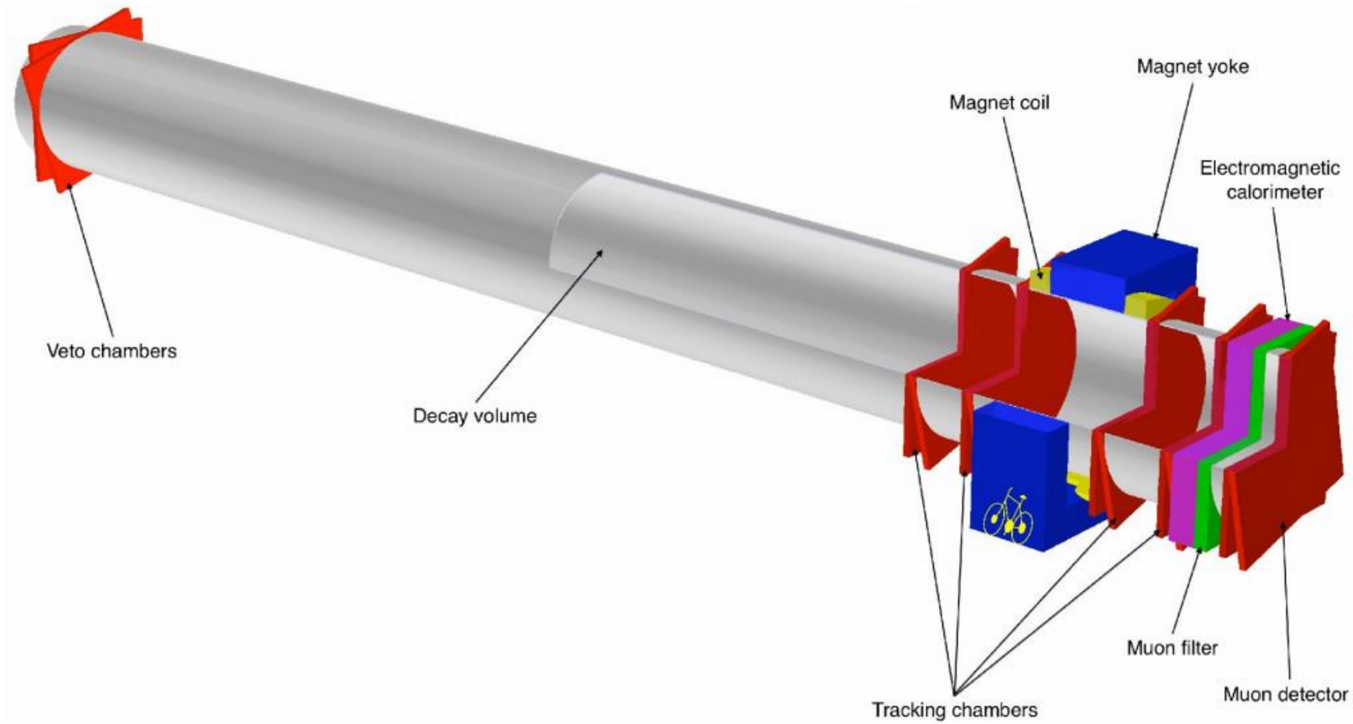
2. Let us consider the Standard Model extended by adding three types of Majorana neutrinos N_a, $a = A, B, C$ which interact with other particles only through their Yukawa couplings [6]. The corresponding Lagrangian can be written in the "Yukawa basis" (where the matrix of Yukawa coupling constants has been diagonalized) as follows,

$$\mathcal{L} = \bar{N}_{Ra} i\partial\!\!\!/ N_{Ra} + h_a \bar{l}_a N_{Ra} \Phi + \frac{M_{ab}}{2} N_{Ra}^T C N_{Rb} + h.c. \ .$$

νMSM


Quarks
Leptons
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
<0.0001 eV
0
ν_e
electron neutrino
~keV
N_1
sterile neutrino
~0.01 eV
0
ν_μ
muon neutrino
~GeV
N_2
sterile neutrino
~0.04 eV
0
ν_τ
tau neutrino
~GeV
N_3
sterile neutrino
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right

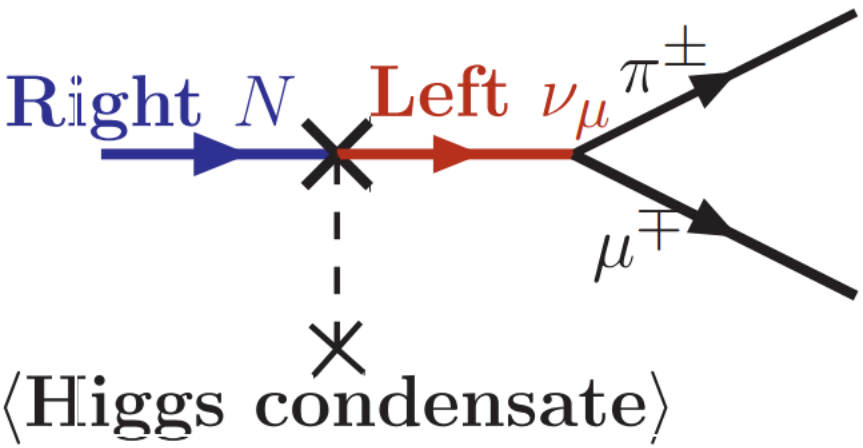
SHIP


Magnet yoke
Magnet coil
Electromagnetic calorimeter
Veto chambers
Decay volume
Muon filter
Muon detector
Tracking chambers

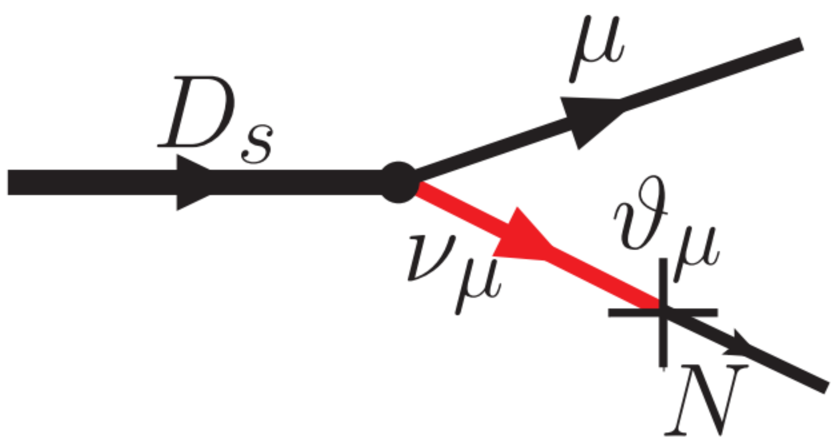
Summary

- Majorana neutrinos solve two problems
- TeV-scale Majoranas are searched for at LHC
- GeV-scale Majoranas are searched for at SHIP
- In both cases need resonant leptogenesis

Idea of SHIP



Right N
Left ν_μ
$\pi^\pm$
$\mu^\mp$
⟨Higgs condensate⟩



D_s
μ
ν_μ
ϑ_μ
N