ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Solving the neutrino mass and baryon asymmetry puzzles with experiments at PS and SPS

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New Opportunities in the Physics Landscape at CERN

Aim of the talk:

to argue that the SPS and PS high intensity protons beam can be used to search for physics beyond the Standard Model, namely for

new neutrino states – massive neutral leptons

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- Fix the pattern of neutrino mass hierarchy

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- Complete the Standard Model
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- Discover CP-violation in neutrino sector
- Reveal the origin of baryon asymmetry of the Universe and its sign

Outline

- Motivation
  - Neutrino masses
  - Dark matter
  - Baryon asymmetry of the Universe
- Experimental signatures
- Conclusions

Neutrino masses

Neutrinos have mass. Possible origin of this mass - existence of right-handed neutrinos (singlet fermions, sterile neutrinos...) with mass M_N and Yukawa couplings to the SM leptons and the Higgs boson. The see-saw formula,

$$m_\nu = -M_D \frac{1}{M_N} [M_D]^T, \quad M_D = Fv,$$

coming from

$$F\bar{L}NH + M_N \bar{N}^c N, \quad \langle H \rangle = v = 246 \text{ GeV}$$

tells nothing about the scale of M_N!

Popular choice: GUT see-saw

Assume that Yukawa couplings of N to the Higgs and left-handed lepton doublets is similar to those in quark or charged lepton sector (say, $F \sim 1$, as for the top quark) and find M_N from requirement that one gets correct active neutrino masses:

$$M_N \simeq \frac{F^2 v^2}{m_{atm}} \simeq 6 \times 10^{14}\ \mathrm{GeV}$$

$m_{atm} \simeq 0.05$ eV is the atmospheric neutrino mass difference.

GUT see-saw: problems

- Hierarchy problem: M_N is much larger than EW scale: one has to understand not only why $M_W \ll M_{Pl}$, but also why $M_W \ll M_N$ and why $M_N \ll M_{Pl}$. Three fine tunings instead of one.
- Stabilization of hierarchy - SUSY. SUGRA - gravitino production problem. Reheating temperature must be smaller than $T_{\rm reh} \lesssim 10^{10}$ GeV. Problem with leptogenesis. Extra scale - extra (4th) hierarchy problem! Why $M_N \ll M_{GUT}$?
- Unfortunately, no direct experimental verification is foreseen

Alternative: EW see-saw

Assume that the Majorana masses of N are smaller or of the same order as the mass of the Higgs boson and find Yukawa couplings from requirement that one gets correct active neutrino masses:

$$F \sim \frac{\sqrt{m_{atm} M_N}}{v} \sim (10^{-6} - 10^{-13}),$$

Advantages:

- No new energy scale - no new hierarchy or fine tuning problem in comparison with the Standard Model.
- Masses of new leptons are small: they can be found experimentally.

Resent theoretical result

An extension of the Standard Model by three light singlet fermions (the νMSM, neutrino minimal SM) allows to address all experimentally confirmed signals in favour of physics beyond the SM:

- Consistent description of neutrino masses and oscillations
- Can explain dark matter in the Universe
- Can explain baryon asymmetry of the Universe
- Can provide inflation (as well as the Standard Model)

the SM

There are 36 quark states: left fermionic doublets and right singlets:

$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$

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9 + 3 leptonic states

$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ and $e_R,\quad \mu_R,\quad \tau_R$

12 $SU(3) \times SU(2) \times U(1)$ gauge bosons (8+3+1)

and one Higgs doublet,

in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 0) \times 3 \times 2 = 90$ fermionic and

$(8 + 3 + 1) \times 2 + 4 = 28$ bosonic degrees of freedom

the νMSM

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$(u\ ,d)_L,\ (c\ ,s)_L,\ (t\ ,b)_L$ and $u_R\ ,\ d_R,\ c_R\ ,\ s_R,\ t_R\ ,\ b_R$

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9 + 3 leptonic states

$(\nu_e, e)_L,\ (\nu_\mu, \mu)_L,\ (\nu_\tau, \tau)_L$ and $N_e, e_R,\ N_\mu, \mu_R,\ N_\tau, \tau_R$

12 $SU(3) \times SU(2) \times U(1)$ gauge bosons (8+3+1)

and one Higgs doublet,

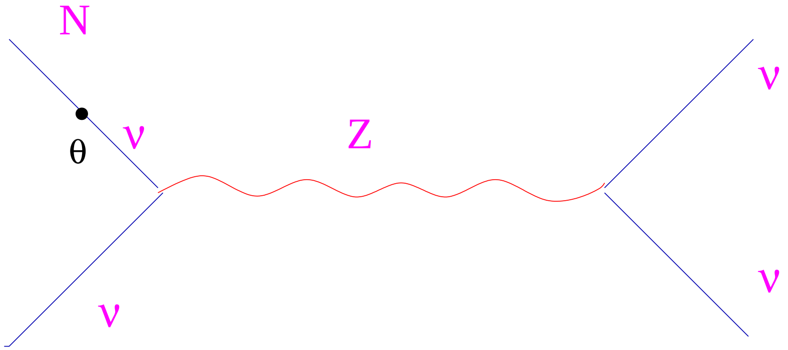
in total $(3 \times 2 + 3 \times 2 + 2 + 1 + 1) \times 3 \times 2 = 96$ fermionic and

$(8 + 3 + 1) \times 2 + 4 = 28$ bosonic degrees of freedom

$N_e = N_1$: Dark matter

Dodelson, Widrow; Shi, Fuller; Dolgov, Hansen;
Abazajian, Fuller, Patel; Asaka, Blanchet, M.S., Laine

Yukawa couplings are small $\rightarrow$ sterile N_1 can be very stable.



Main decay mode: $N_1 \longrightarrow 3\nu$.

Subdominant radiative decay channel: $N_1 \longrightarrow \nu\gamma$.

For one flavour ($M_{N_1} < 1$ MeV):

$$\tau_{N_1} = 10^{15}\,\text{years}\left(\frac{10\text{ keV}}{M_{N_1}}\right)^5\left(\frac{10^{-9}}{\theta_1^2}\right)$$

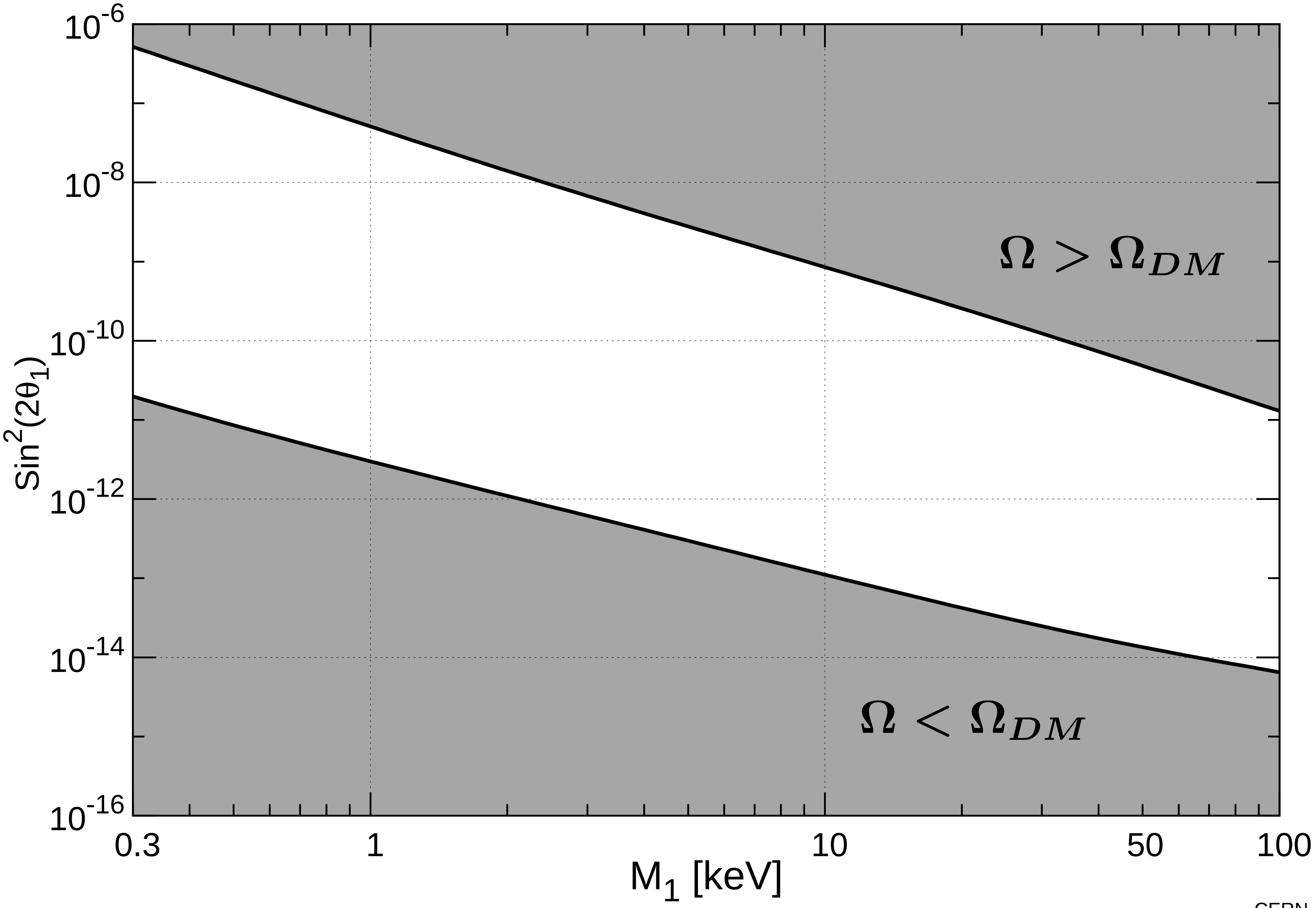
$$\theta_1 = \frac{M_D}{M_{N_1}}$$

$$\tau_{Universe} = 1.4 \times 10^{10}\,\text{years!}$$

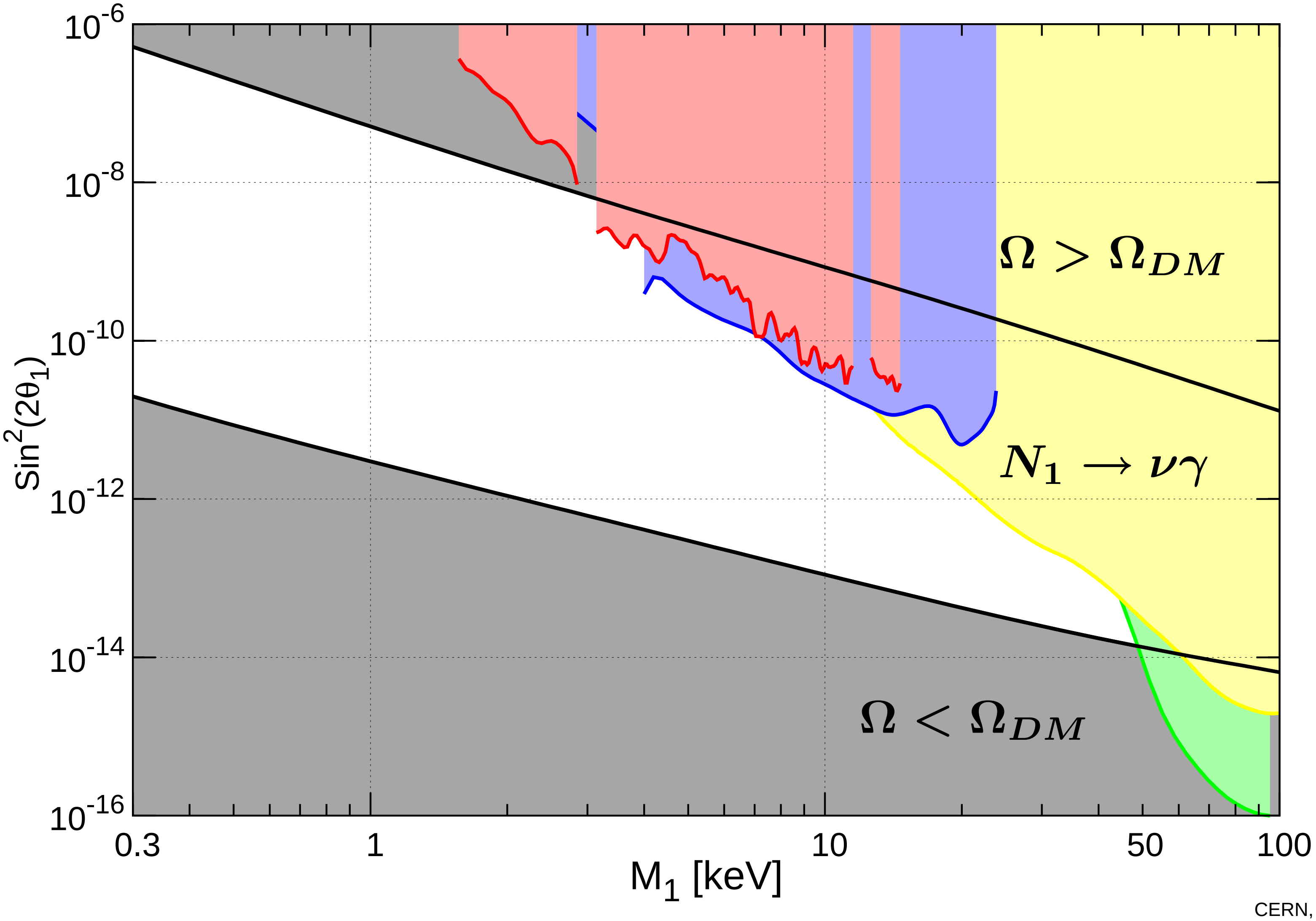
Constraints on DM sterile neutrino

- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance.
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected. Search in progress - X-ray satellites.
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. The study of Lyman-α forest spectra of distant quasars has been done; also work in progress.

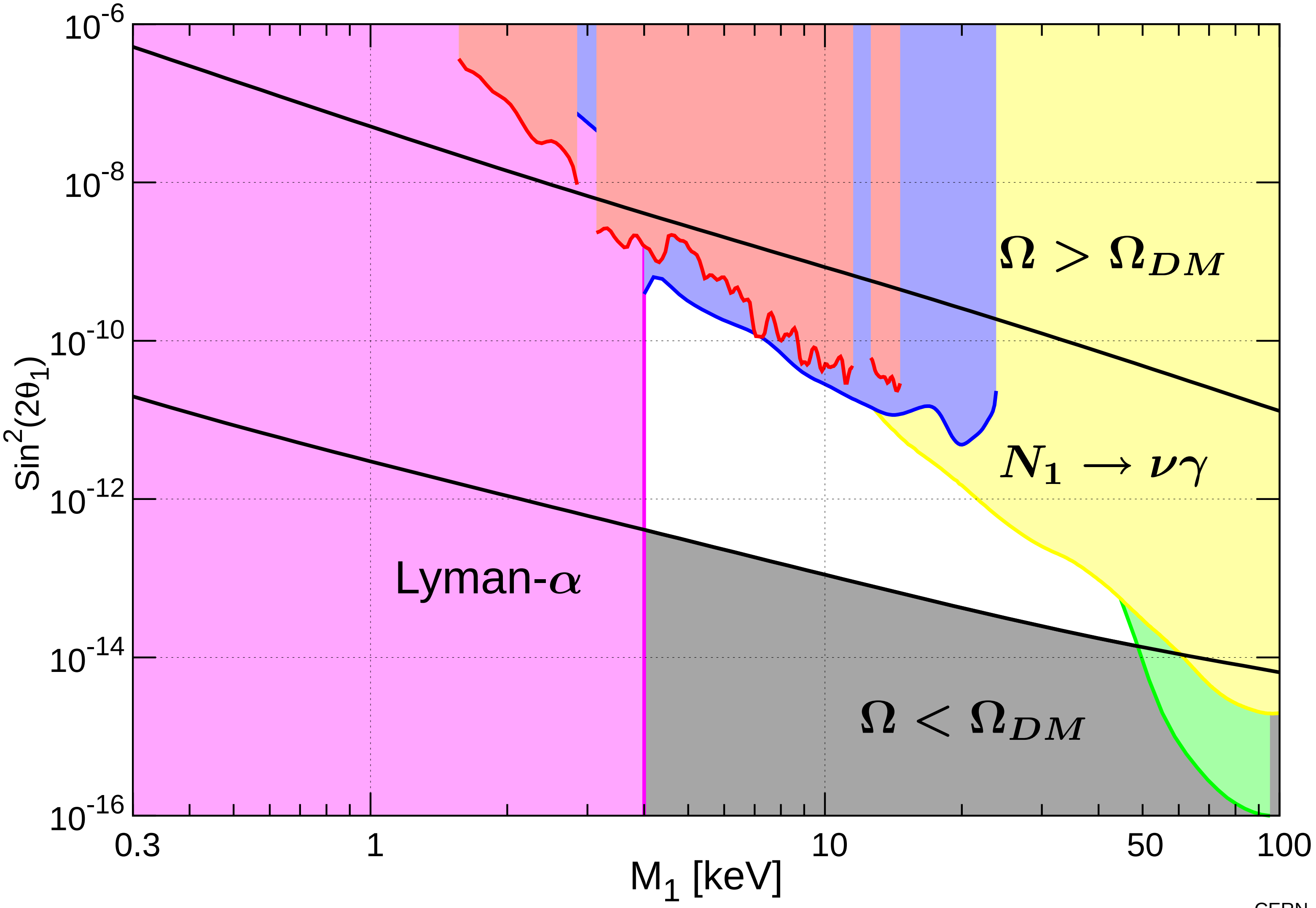
DM: production



DM: production + X-ray constraints



DM: production + X-ray constraints + Lyman-α bounds



$N_\mu = N_2,\ N_\tau = N_3$: Baryon asymmetry

Asaka, M.S; Akhmedov, Rubakov, Smirnov

- Lepton number violation: $N_{2,3} \leftrightarrow \nu$
- Baryon number violation: electroweak anomaly, sphalerons
- CP - violation: Dirac and Majorana phases in $N_{2,3} - \nu$ interactions
- Arrow of time: $N_{2,3}$ are out of thermal equilibrium for small Yukawa couplings

  Upper bound on the mass of $N_{2,3}$:

$$M_N \lesssim 10^3 \frac{v^3}{m_{\rm atm} M_{Planck}} \simeq 30\ \mathrm{GeV}$$

Value of baryon asymmetry

$$\frac{n_B}{s} \simeq 0.5 \cdot 10^{-10}\, \delta_{\mathrm{CP}} \left(\frac{10^{-5}}{\Delta M_{32}^2 / M_3^2} \right)^{\frac{2}{3}} \left(\frac{M_2}{5\ \mathrm{GeV}} \right)^{\frac{5}{3}} .$$

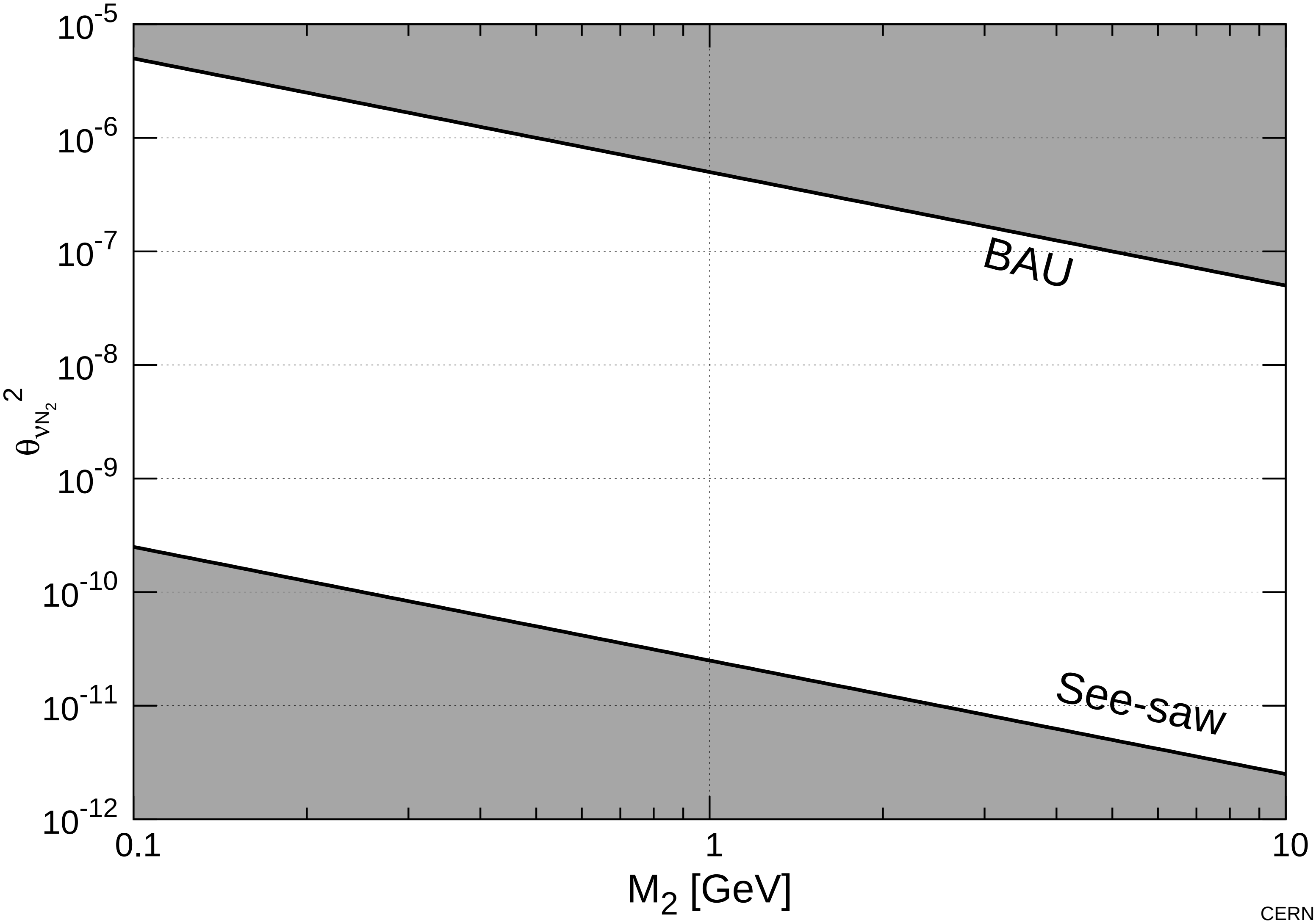
$\delta_{\mathrm{CP}} \sim 1$ is consistent with observed ν oscillations.

Non-trivial requirement: $|M_2 - M_3| \ll M_{2,3}$, i.e. heavier neutrinos must be degenerate in mass. Almost Dirac fermion!

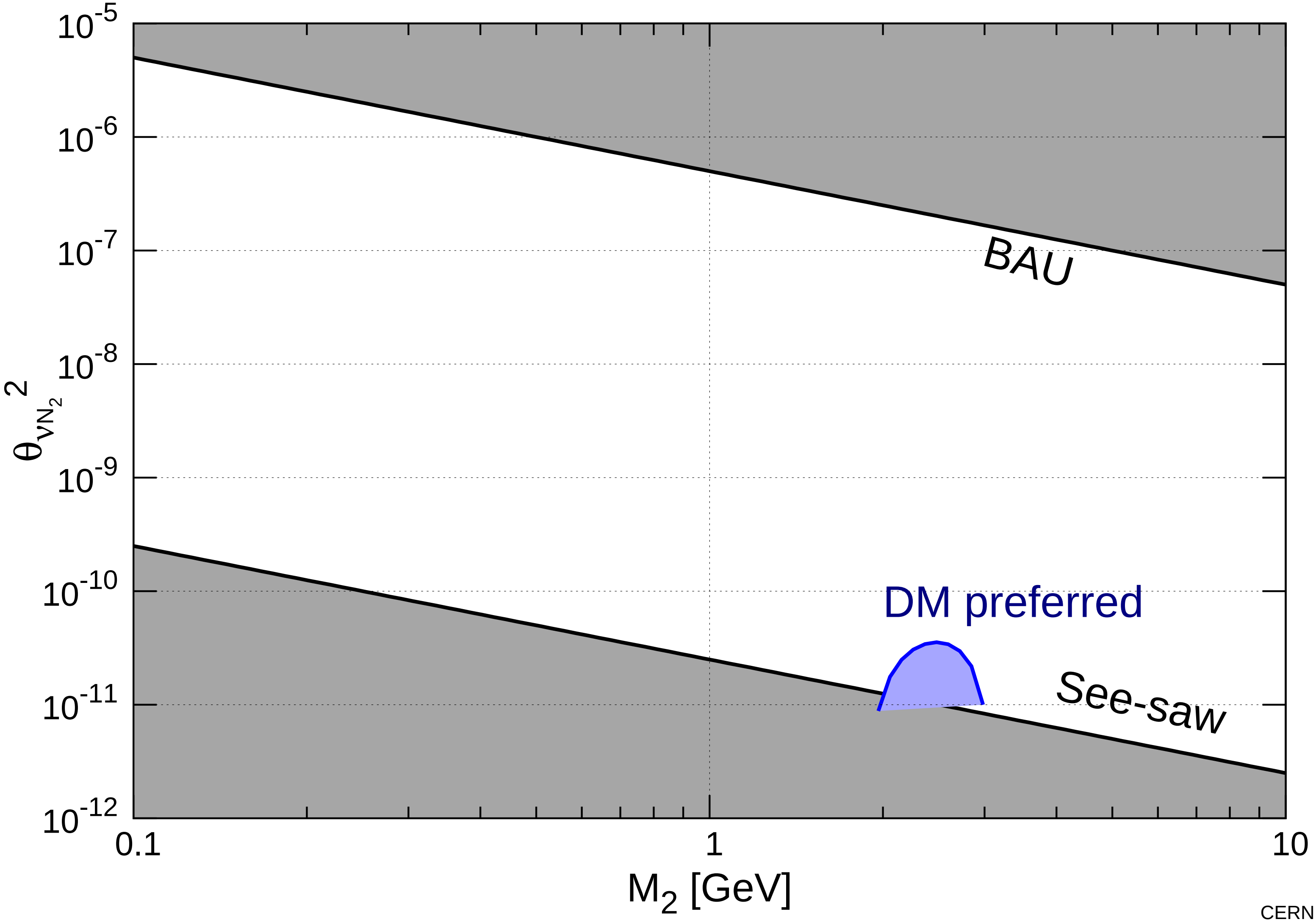
Constraints on BAU sterile neutrinos

- BAU generation requires out of equilibrium: mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $\boldsymbol{N_{2,3}}$ to active neutrinos cannot be too small (see-saw)
- Dark matter and BAU. Concentration of DM sterile neutrinos must be much larger than concentration of baryons (remember: $\boldsymbol{M_1 \sim 10}$ keV)
- BBN. Decays of $\boldsymbol{N_{2,3}}$ must not spoil Big Bang Nucleosynthesis
- Experiment. Many efforts at CERN and elsewhere. $\boldsymbol{N_{2,3}}$ have not been seen (yet).

$N_{2,3}$: BAU


10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$\theta_{\nu N_2}^{\ 2}$
BAU
See-saw
0.1
1
10
M_2 [GeV]

$N_{2,3}$: BAU + DM



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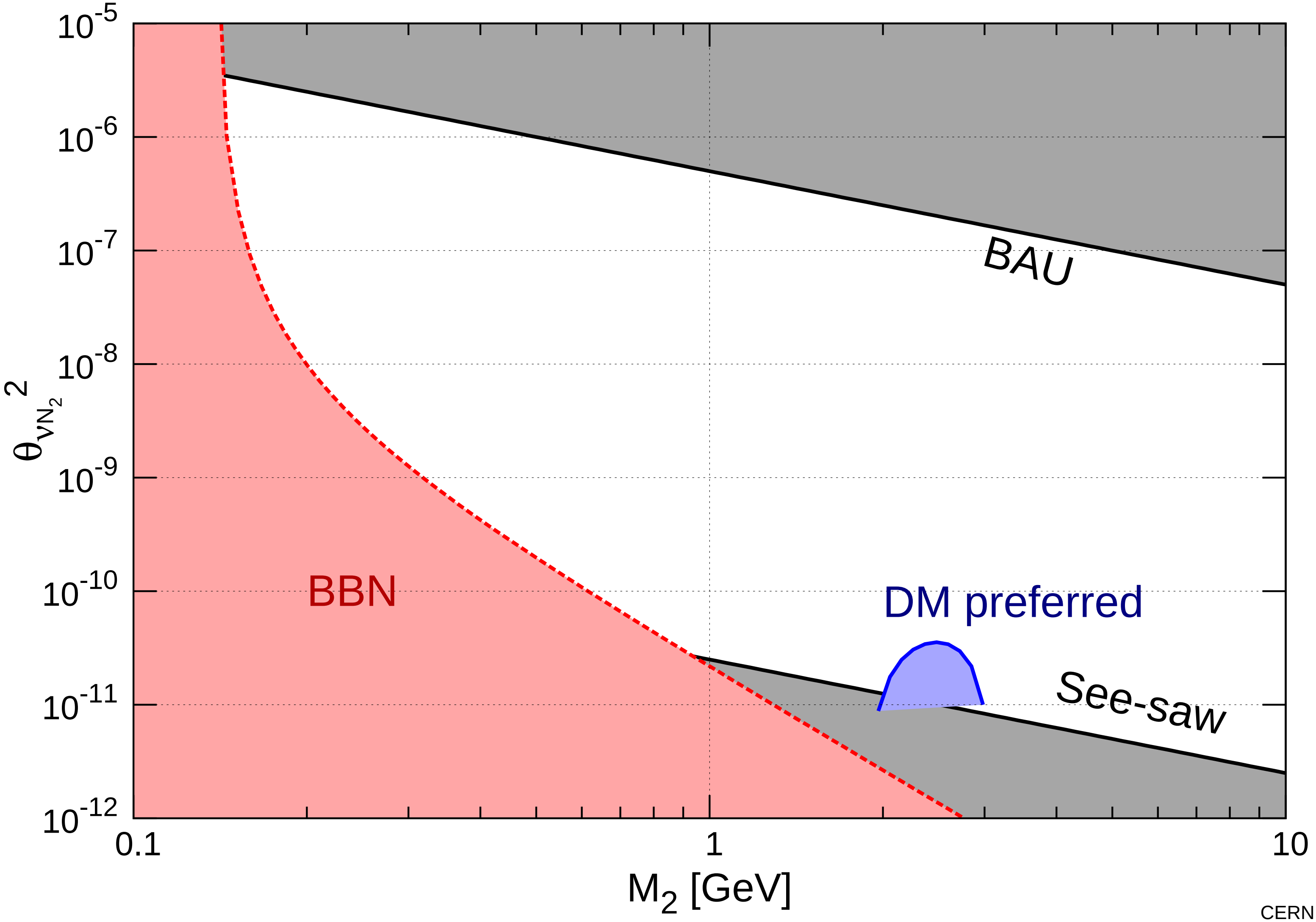
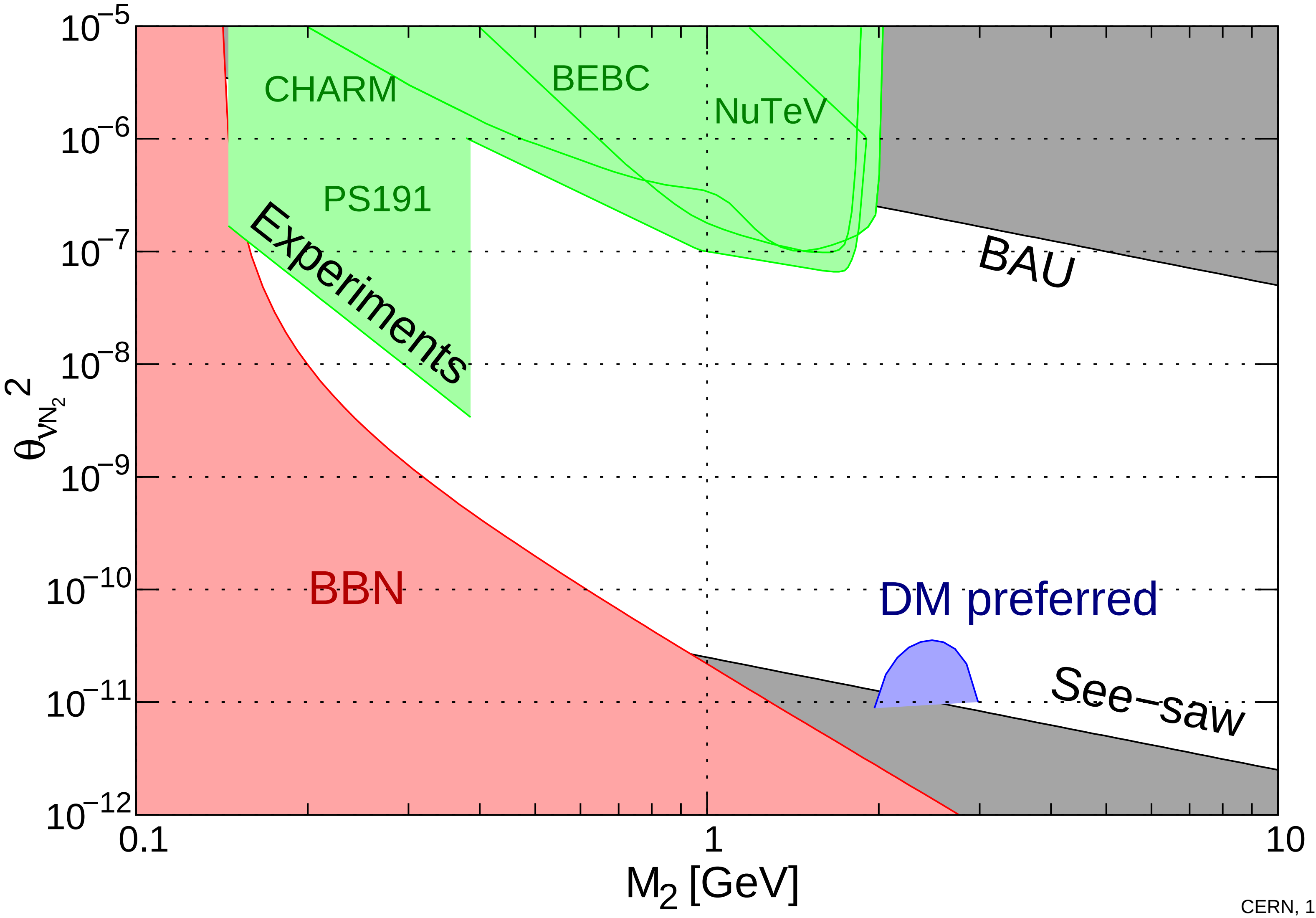
$\theta_{\nu N_2}{}^2$
BAU
DM preferred
See-saw
0.1
1
10
M_2 [GeV]

$N_{2,3}$: BAU + DM + BBN



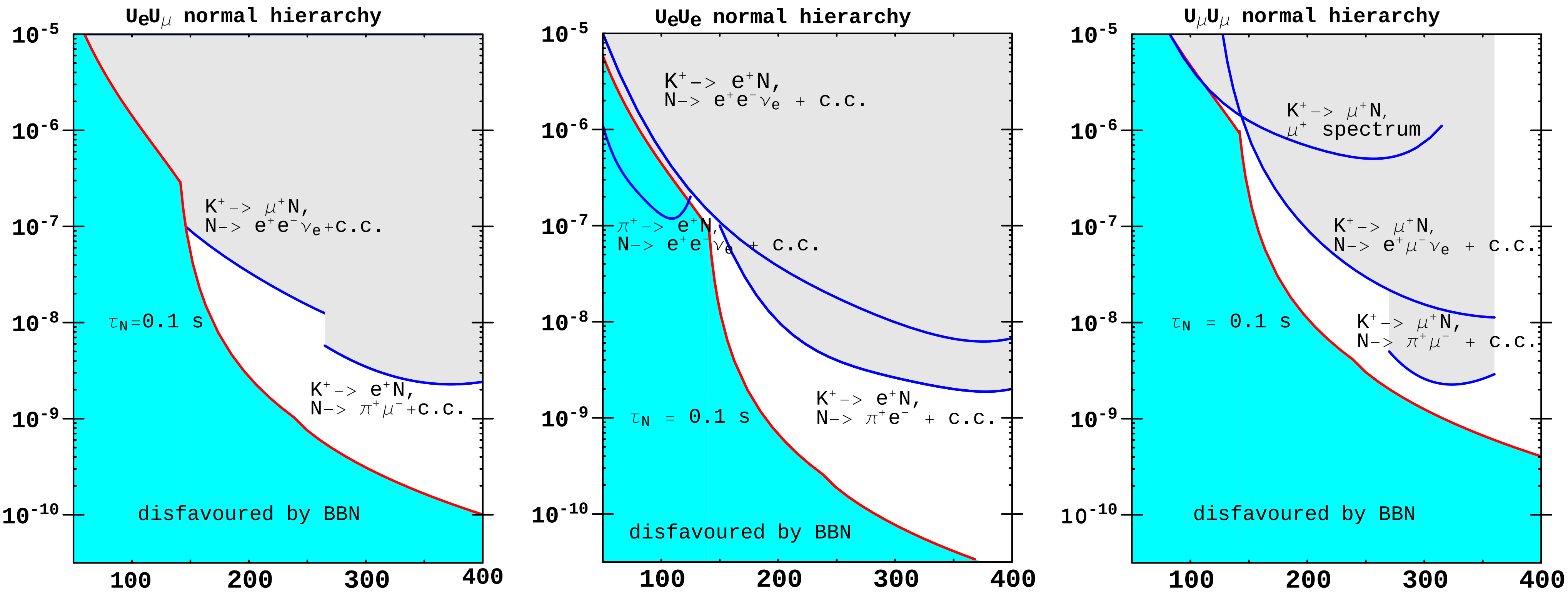
$N_{2,3}$: BAU + DM + BBN + Experiment



Previous searches at CERN

- A. M. Cooper-Sarkar *et al.* [WA66 Collaboration] “Search For Heavy Neutrino Decays In The Bebc Beam Dump Experiment”, 1985
- J. Dorenbosch *et al.* [CHARM Collaboration] “A search for decays of heavy neutrinos in the mass range 0.5-GeV to 2.8-GeV”, 1985
- G. Bernardi *et al.* [PS191 Collaboration], “Search For Neutrino Decay”, 1986;
  “Further Limits On Heavy Neutrino Couplings”, 1988
- P. Astier *et al.* [NOMAD Collaboration], “Search for heavy neutrinos mixing with tau neutrinos”, 2001
- P. Achard *et al.* [L3 Collaboration], “Search for heavy neutral and charged leptons in e^+e^- annihilation at LEP”, 2001

CERN PS191 experiment, 1988



Conclusion: $M_{2,3} > 140$ MeV

Experimental signatures 1

Challenge - from baryon asymmetry: $\theta^2 \lesssim 5 \times 10^{-7} \left(\frac{\text{GeV}}{M}\right)$

- Peak from 2-body decay and missing energy signal from 3-body decays of K, D and B mesons (sensitivity θ^2)

  Example:

  $$K^+ \to \mu^+ N, \quad M_N^2 = (p_K - p_\mu)^2 \neq 0$$

  Similar for charm and beauty.

  - $M_N < M_K$: KLOE, NA62, E787 (Ceccucci presentation)
  - $M_K < M_N < M_D$: charm and τ factories, CLEO
  - $M_N < M_B$: B-factories (planned luminosity is not enough to get into cosmologically interesting region)

Experimental signatures 2

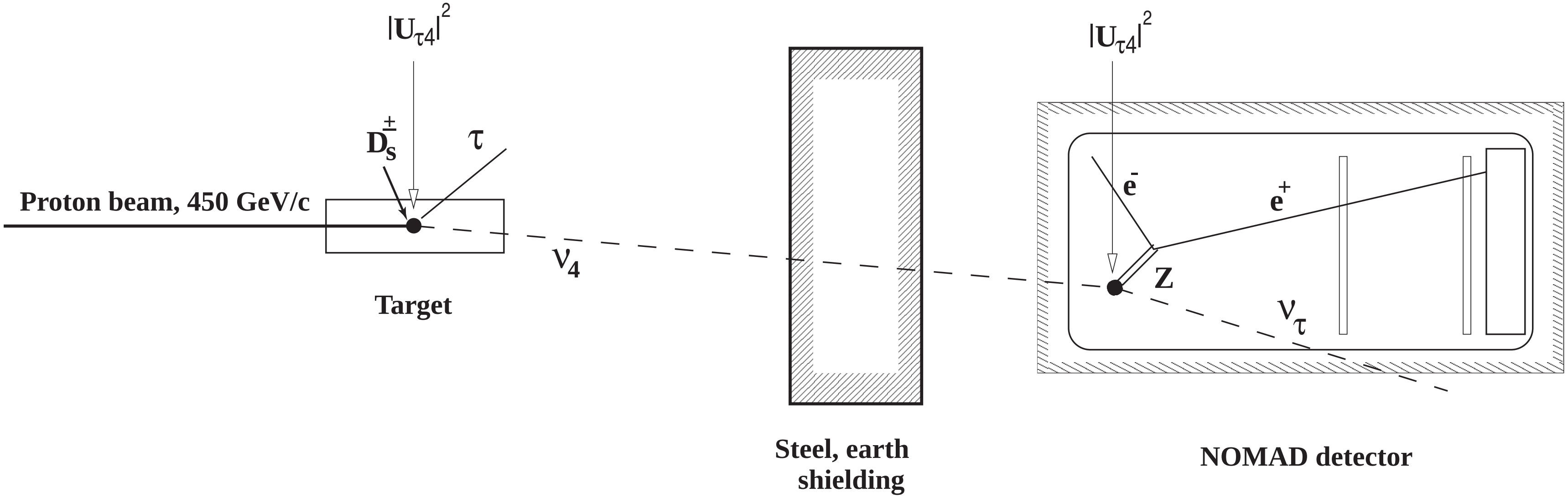
- Two charged tracks from a common vertex, decay processes $N \rightarrow \mu^+\mu^-\nu$, etc. (sensitivity $\theta^4 = \theta^2 \times \theta^2$)

  First step: proton beam dump, creation of N in decays of $K,\ D$ or B mesons: θ^2

  Second step: search for decays of N in a near detector, to collect all Ns: θ^2

  - $M_N < M_K$: Any intense source of K-mesons (e.g. from proton targets of PS. Probably, well matched to proposals by C. Rubbia and by F. Vannucci)
  - $M_N < M_D$: SPS or PS2 beam + near detector
  - $M_N < M_B$: Project X (?) + near detector
  - $M_N > M_B$: extremely difficult

$N_{2,3}$ production and decays



Type on neutrino mass hierarchy - from branching ratios of $N_{2,3}$ decays to $e,\ \mu, \tau$.

CP asymmetry can be as large as 1% - from BAU and DM

Conclusions

- New physics, responsible for neutrino masses and mixings, for dark matter, and for baryon asymmetry of the Universe may hide itself below the EW scale

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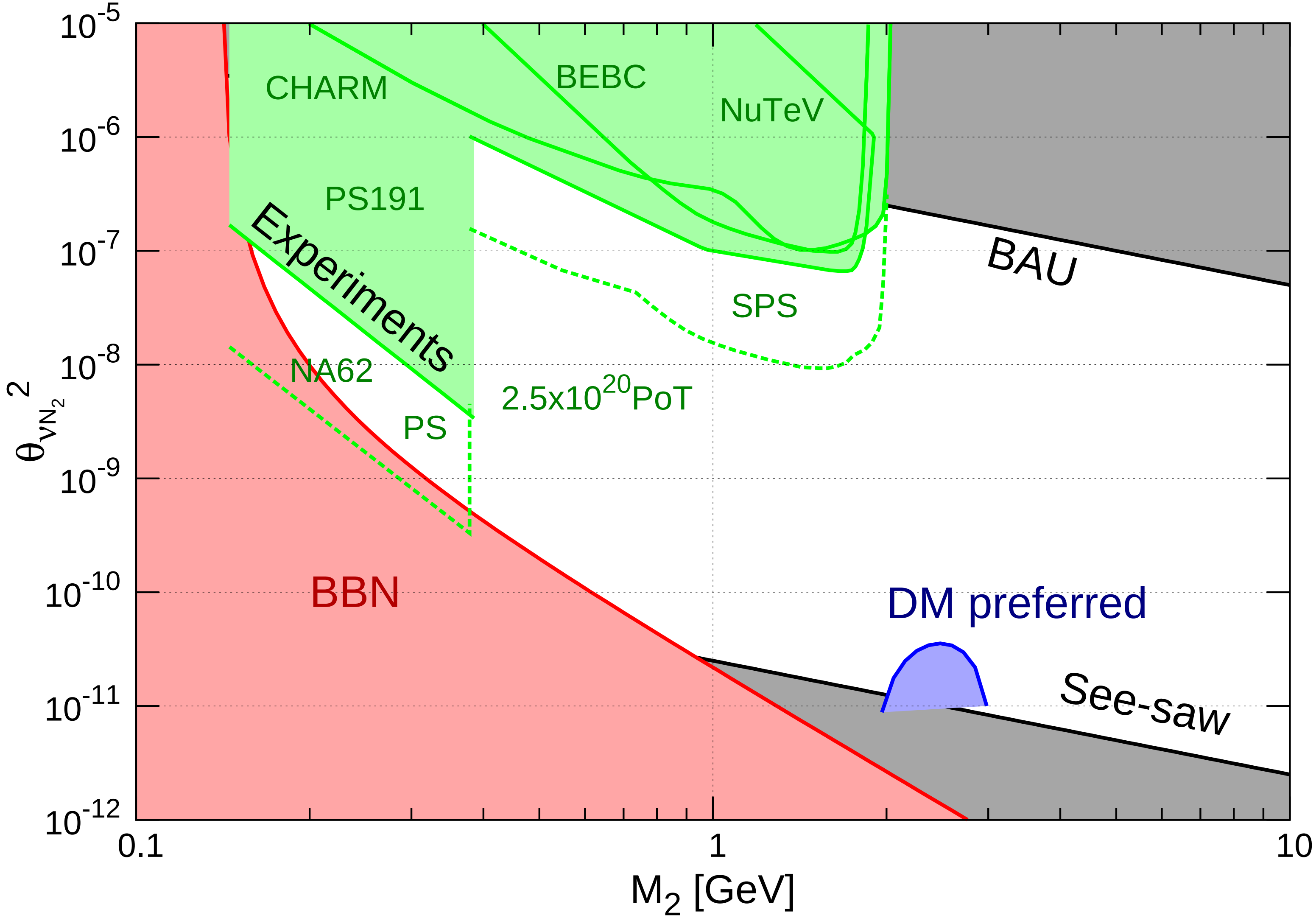
- New physics, responsible for neutrino masses and mixings, for dark matter, and for baryon asymmetry of the Universe may hide itself below the EW scale
- The estimates based on PS191, BEBC and CHARM results show that the experiments with a sensitivity in mixing strength θ^2 improved by a factor more than 10 are feasible. The coverage of significant amount of parameter space would require from CERN a delivery of more than 10^{20} POTs



CHARM
BEBC
NuTeV
PS191
Experiments
SPS
BAU
NA62
PS
2.5x10^20PoT
BBN
DM preferred
See-saw
10^{-5}
10^{-6}
10^{-7}
10^{-8}
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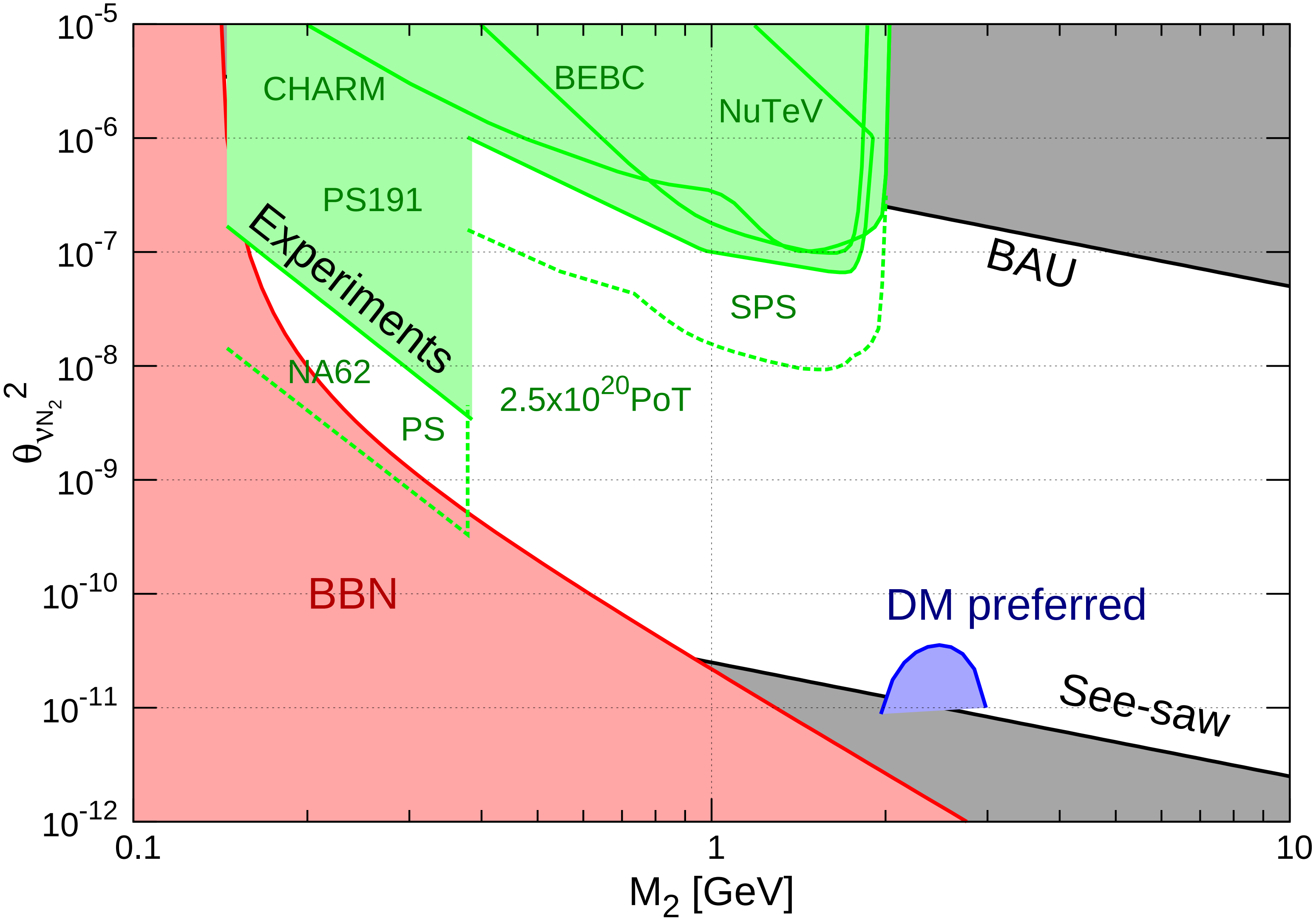
10^{-10}
10^{-11}
10^{-12}
0.1
1
10
$\theta_{\nu N_2}^2$
M_2 [GeV]



The efforts for performing the dedicated experiments, pioneered by CERN almost 25 year ago, are well justified, and, hopefully, may lead these searches to the happy end.

νMSM prediction for LHC

Hierarchy problem and cosmological inflation from the Higgs of the Standard Model:

Nothing but the Higgs in the mass interval $M_H \in [m_{min}, m_{max}]$

$$m_{\min} = [126.1 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 0.6]\ \text{GeV}\ ,$$

$$m_{\max} = [193.9 + \frac{m_t - 171.2}{2.1} \times 0.6 - \frac{\alpha_s - 0.1176}{0.002} \times 0.1]\ \text{GeV}\ .$$

Theoretical uncertainty ± 1.3 GeV.

What new particles of the νMSM cannot explain

- origin of high energy cosmic rays
- existence of 0.511 MeV annihilation line in the direction of the Galaxy center
- pulsar-kick velocities
- discrepancy between experiment and the theory prediction of anomalous magnetic moment of muon
- LSND anomaly
- MiniBooNE anomaly
- Heidelberg neutrino-less double β decays
- DAMA annual modulations
- Egret gamma-ray excess
- Pamela positron excess