Physics of Sterile neutrinos of GeV mass scale to be tested at recently proposed new fixed-target experiment with 400 GeV proton beam of CERN SPS

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Outline

1. The main subject: a new experiment at CERN
2. Main motivation: neutrino physics
3. νMSM: 3 in 1 flask
   (neutrino oscillations, dark matter, baryon asymmetry of the Universe)
4. The experiment on direct searches at SPS
5. Status of the proposal
6. Planned activity

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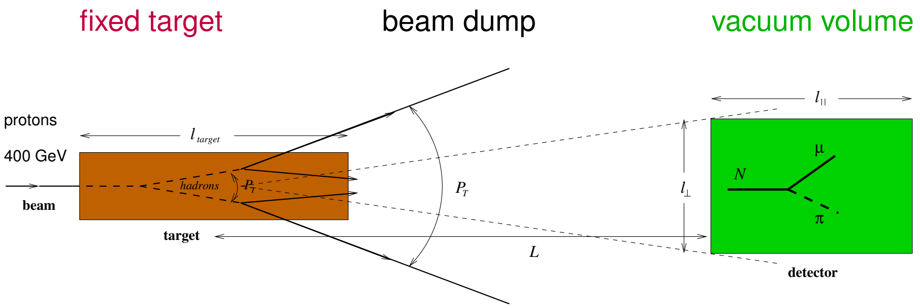
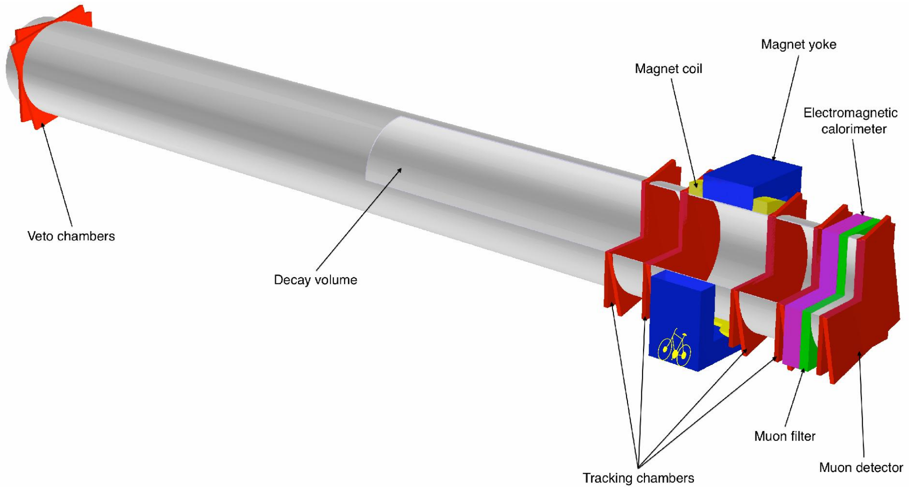
The experiment under discussion: a scheme



Searches for any BSM with

Neutral Unstable but Long Lived Particles Lighter than D-meson

The experiment under discussion: a sketch



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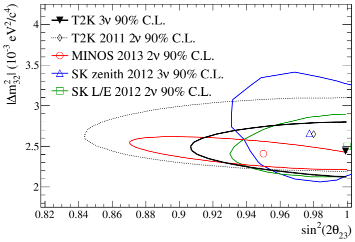
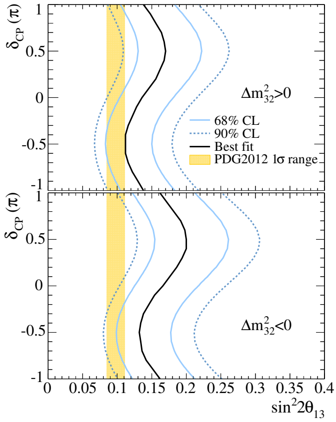
Neutrino oscillations: masses and mixing angles



"atmospheric" 2×2 sector

1308.0465



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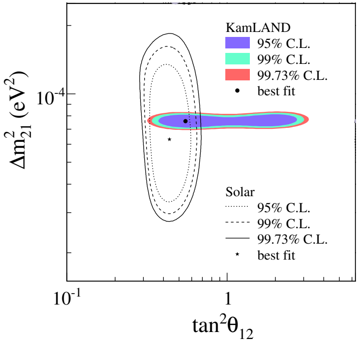


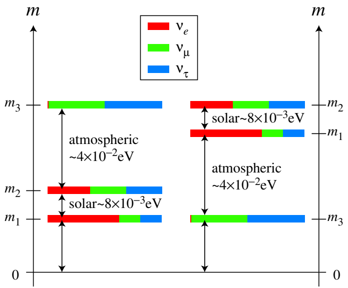
"solar" 2×2 sector

0801.4589

“Normal” and “Inverted” neutrino mass hierarchies

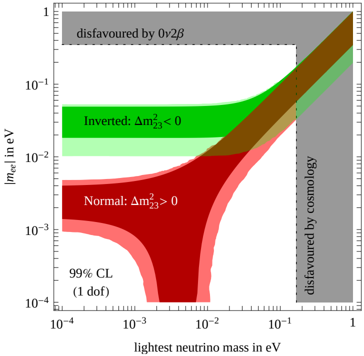
Only two squared mass differences are determined, there are options for masses...

may be, the hierarchy will be fixed by T2K & Noν ae



normal inverted
hierarchy

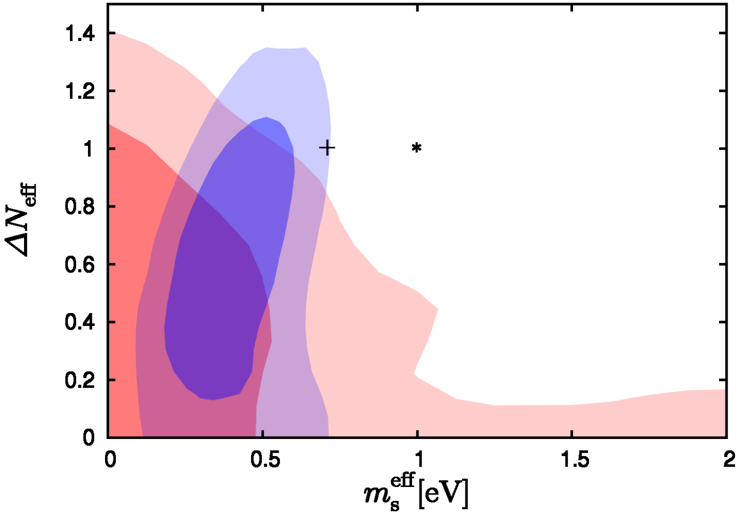
neutrinoless 2β-decay $Z->(Z+2)+2e^-$ CP ??



may be Cosmology will help...
Planck (2014)? ... EUCLID (galaxy survey)

$|m_{ee}| = \left|\sum U_{ei}^2 m_i\right|$, for Majorana masses

Planck, SZ-clusters, BAO, Hubble parameter, vs 1 eV anomalies: $+$ for LSND, $*$ for reactor and Gallium



With 3 light neutrinos $\Delta N_{\text{eff}} = 0$ Planck & BAO @ 95 CL:

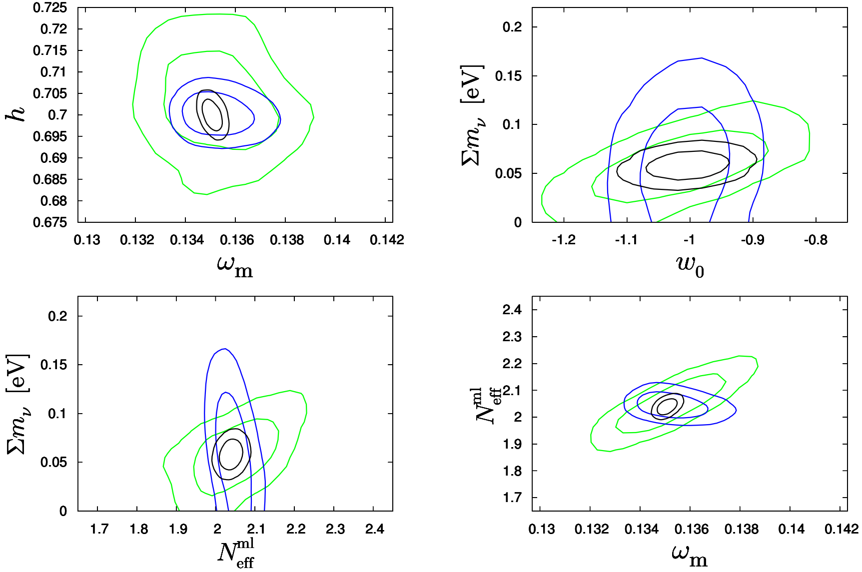
$$\sum m_\nu < 0.23\,\text{eV}$$

But with more cosmological ingredients, like 1-eV sterile neutrinos: Planck, & combined

1308.3255

Future: EUCLID-like survey of galaxies

1304.2321



Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathscr{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{v^2 F_{\alpha\beta}}{4\Lambda} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.} = m_{\alpha\beta} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

where

Λ is the scale of new dynamics

$F_{\alpha\beta}$ is the strength of new dynamics

only their ratio is fixed by the scale of active neutrino masses

Option #1 for model parameters

"Natural values for coupling constants"

$$F_{\alpha\beta} \sim 1 \qquad \Longrightarrow \qquad \Lambda \sim 3 \times 10^{14}\,\mathrm{GeV} \times \left(\frac{3\times 10^{-3}\,\mathrm{eV}^2}{\Delta m^2_{\mathrm{atm}}}\right)^{1/2}$$

The model has to be UV-completed at this scale Λ

Serious problem: contribution of new heavy particles to the Higgs boson mass

$$\delta m_h^2 \sim \Lambda^2 \gg (100\,\mathrm{GeV})^2$$

need special mechanism (SUSY ?) to cancel

LHC: no SUSY, technicolor, etc. at 1 TeV scale
flavor physics: probably no SUSY, technicolor, etc. up to 1000 TeV

Option #2 for model parameters

"Hierarchical values for coupling constants"

$F_{\alpha\beta} \ll 1$ so that $\Lambda < 100\,\text{GeV}$

The model has to be UV-completed at this scale Λ

- There is a new physics below Electroweak scale
- We haven't recognized it so far, because it is tiny coupled to SM
- And we can test it directly in a fixed target experiment !!

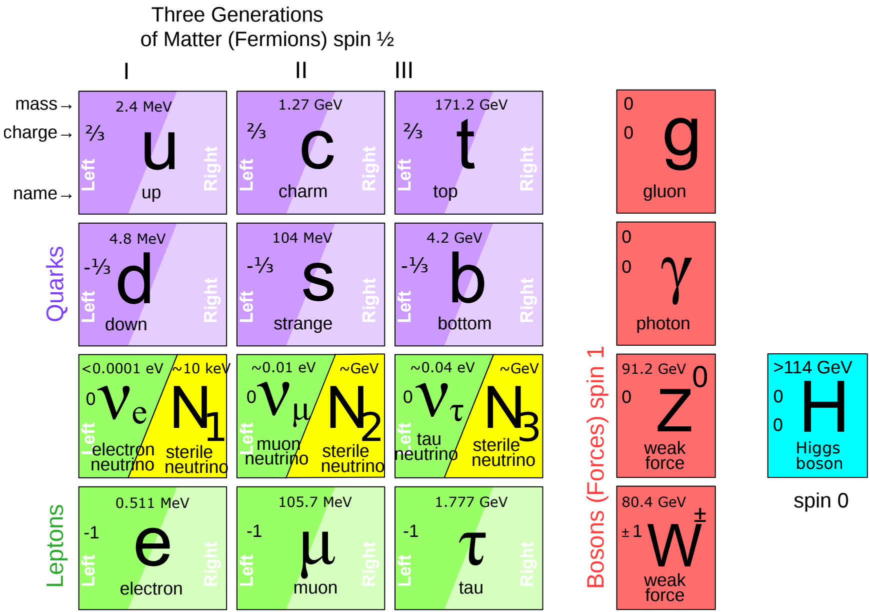
Possible new physics: Sterile neutrinos

Minimal extension of SM to explain neutrino oscillations

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- only 3 Majorana fermions (6 d.o.f.) is enough
- true renormalizable theory not worth then the SM (e.g. may work up to the Planck scale)
- baryon asymmetry via leptogenesis through redistribution of the leptonic charge between active and sterile neutrinos and transfering of the lepton asymmetry into baryon asymmetry by electoweak sphalerons
- dark matter: lightest sterile neutrino (1-50 keV)


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
Quarks
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
Leptons
<0.0001 eV
0
ν_e
electron neutrino
~10 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
Bosons (Forces) spin 1
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
Z0
weak force
80.4 GeV
±1
W±
weak force
>114 GeV
0
0
H
Higgs boson
spin 0

Seesaw type I mechanism: $M_N \gg m_{active}$

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

where $I = 1,2,3$ and $\alpha = e,\mu,\tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,,N_I\right)^{\mathrm{T}} + \text{h.c.}$$

Then for $M_N \gg \hat{M}_D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D \frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2 \frac{v^2}{M_N} \lll M_N$$

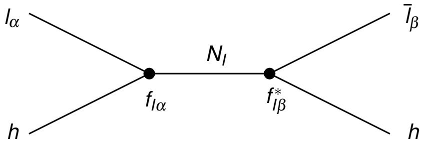
Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

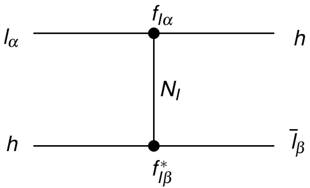
active-active mixing: (PMNS-matrix U) $\qquad U^T\hat{M}^\nu U = diag\,(m_1\,,m_2\,,m_3)$

active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

We get dim-5 operator at small momentum transfer

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$





at $|Q_N^2| \ll M_N^2$ we arrive at effective interaction (dim-5 operator)

$$\Longrightarrow \quad \mathscr{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda}\bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.} \qquad \text{where} \quad \frac{\hat{F}}{\Lambda} = \hat{f}^T \hat{M}_N^{-1} \hat{f}$$

Sterile neutrino lagrangian

Most general renormalizable with 2(3...) right-handed neutrinos N_I

$$\mathcal{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3\text{H} \to ^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H\rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total
help with leptogenesis

18: $N = 3$ sterile neutrinos:

- 3: Majorana masses M_{N_I}
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9 new parameters in total
both BAU and DM are possible

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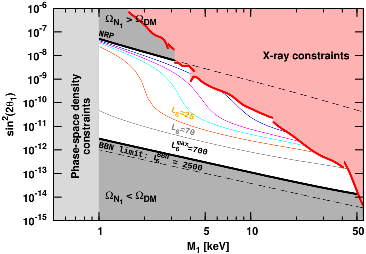
SubEW sterile neutrinos: $M_N \simeq 1$ keV-50 GeV   νMSM

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

- At $T > 100$ GeV active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_N \ll M_N$ $\longrightarrow$ baryogenesis E.Akhmedov, V.Rubakov, A.Smirnov (1998)
- Lightest sterile neutrino may comprise Dark Matter
  - production in primordial plasma due to mixing with active neutrinos is ruled out from searches at X-ray telescopes



$$\Gamma_{N\to\nu\gamma} \simeq 5.5\times10^{-22}\theta_1^2\left(\frac{M_1}{1\text{ keV}}\right)^5 \text{s}^{-1}$$

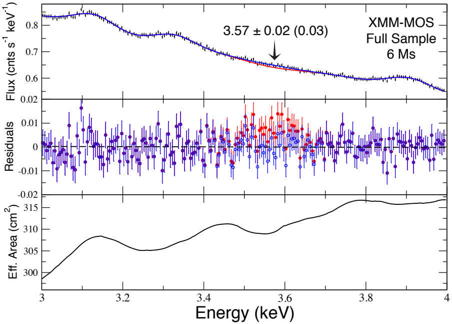
a narrow line $(\delta E_\gamma/E_\gamma \sim v \sim 10^{-3})$

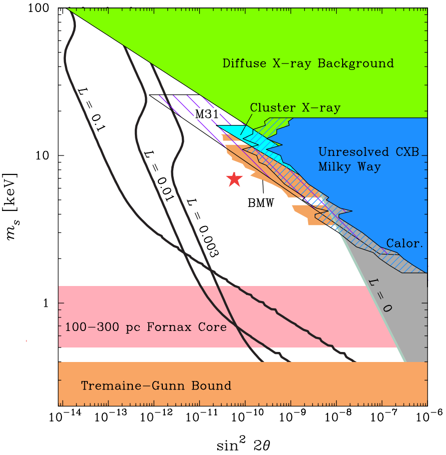
at $E_\gamma = M_N/2$

  - Possible for 1-50 keV (WDM-CDM range) either with fine-tuning in M_{N_I} ($\Delta M_N \sim 10^{-7}$ eV) to get $L \gg B$ and use the resonant production or with ANOTHER source of production, e.g. inflaton decays..

M.Shaposhnikov, I.Tkachev (2006), F.Bezrukov, D.G. (2009)

Ongoing searches for DM signal in X-rays. . .

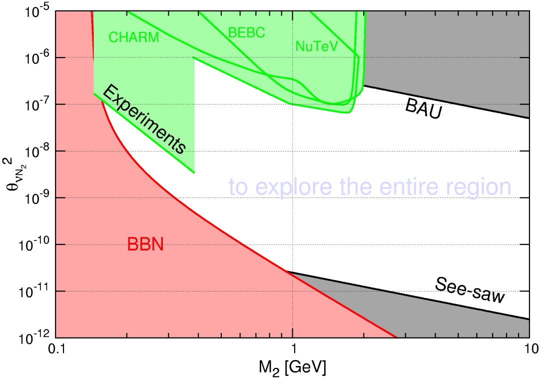




$m_s = 7.1\,\text{keV}\,, \qquad \sin^2(2\theta) \approx 7 \times 10^{-11}\,,$

1402.2301

Probing leptogenesis... waiting for SHIP



D.G, M.Shaposhnikov (2007)

lower bound at $\times 10^{-4}$

$$\mathrm{Br}(D \to lN) \lesssim 2 \cdot 10^{-8}$$
$$\mathrm{Br}(D_s \to lN) \lesssim 3 \cdot 10^{-7}$$
$$\mathrm{Br}(D \to KlN) \lesssim 2 \cdot 10^{-7}$$
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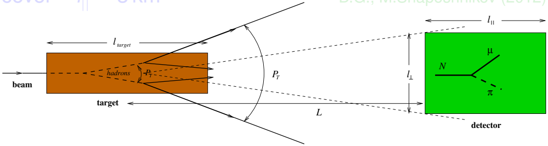
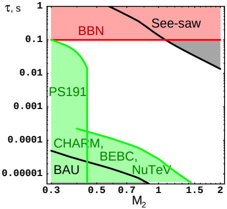
For 10^{20} PoT at 400 GeV (SPS) detectors have to cover $l_{||} \sim 3$ km

D.G., M.Shaposhnikov (2012)





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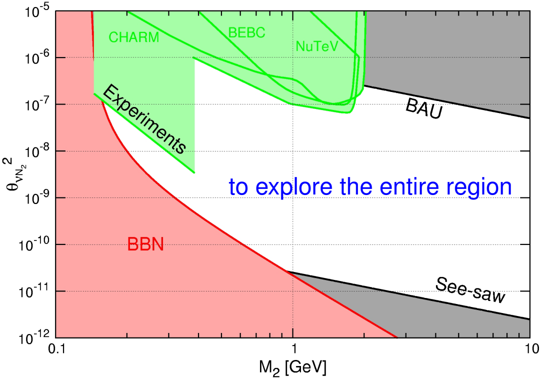

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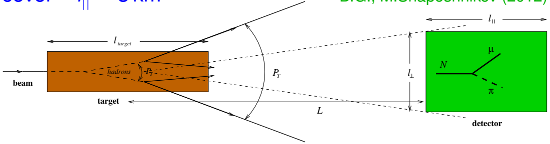
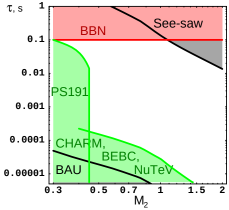
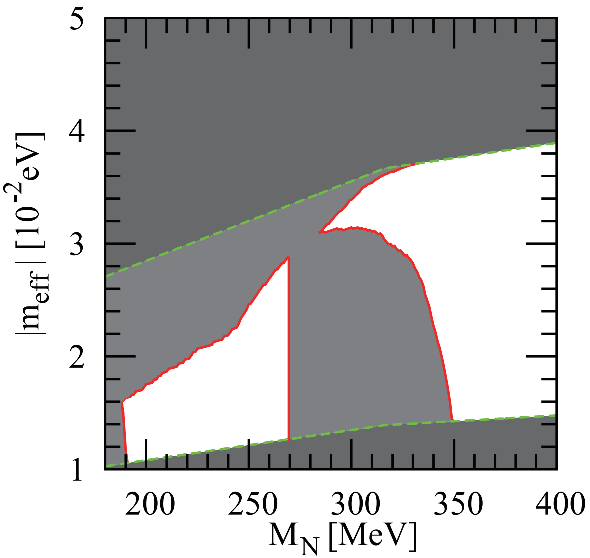




Leptogenesis in 2 + 1 scheme: $0\nu2\beta$ decay region



Inverse hierarchy 1308.3550

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Expression of Interest:
Proposal to search for Heavy Neutral Leptons at the SPS

(CERN-SPSC-2013-024 / SPSC-EOI-010)

On behalf of:

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2 (‡)]

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[2] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[3] *Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands*
[4] *Imperial College London, London, United Kingdom*
[5] *Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
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[7] *Physik-Institut, Universität Zürich, Zürich, Switzerland*
[(‡)] *retired*

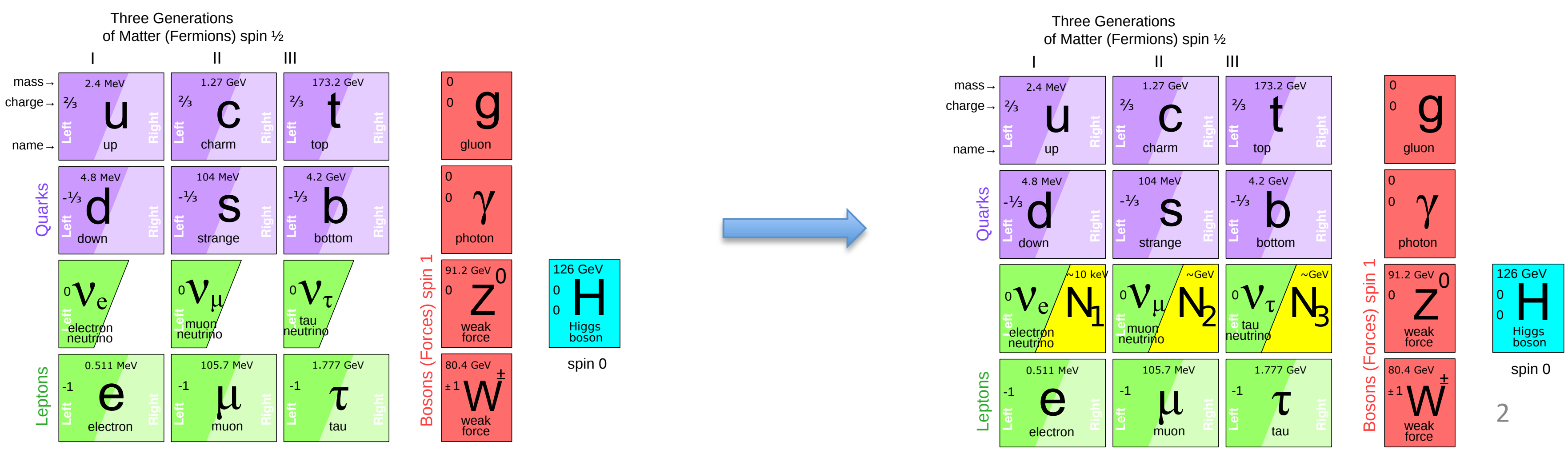
Theoretical motivation

- *Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model*
  The SM may work successfully up to Planck scale !

- *SM is unable to explain:*
  - *Neutrino masses*
  - *Excess of matter over antimatter in the Universe*
  - *The nature of non-baryonic Dark Matter*

- *All three issues can be solved by adding three new fundamental fermions, right-handed Majorana* ***H****eavy* ***N****eutral* ***L****eptons (HNL)****: N$_1$, N$_2$ and N$_3$***

νMSM*: T.Asaka, M.Shaposhnikov PL* ***B620*** *(2005) 17*



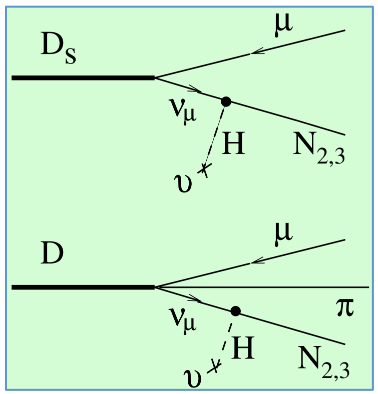
Masses and couplings of HNLs

- *N_1 can be sufficiently stable to be a DM candidate, $M(N_1)$~10keV*

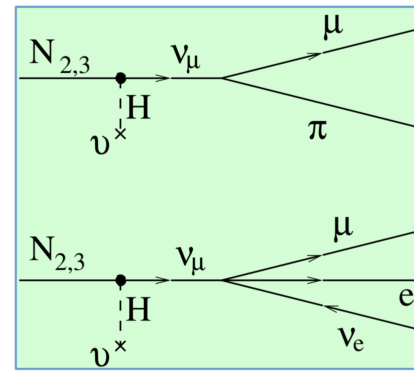
- *$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)*

Very weak $N_{2,3}$-to-ν mixing (~ U^2) → $N_{2,3}$ are much longer-lived than the SM particles

Example:
$N_{2,3}$ production in charm



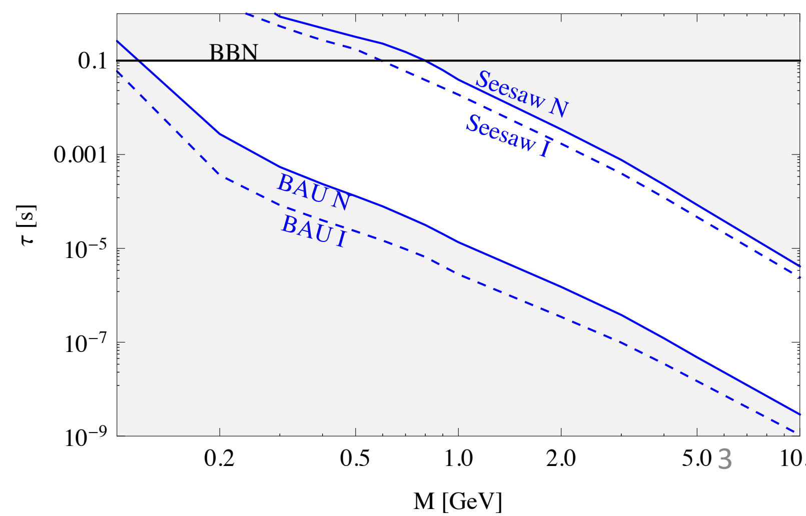
and subsequent decays



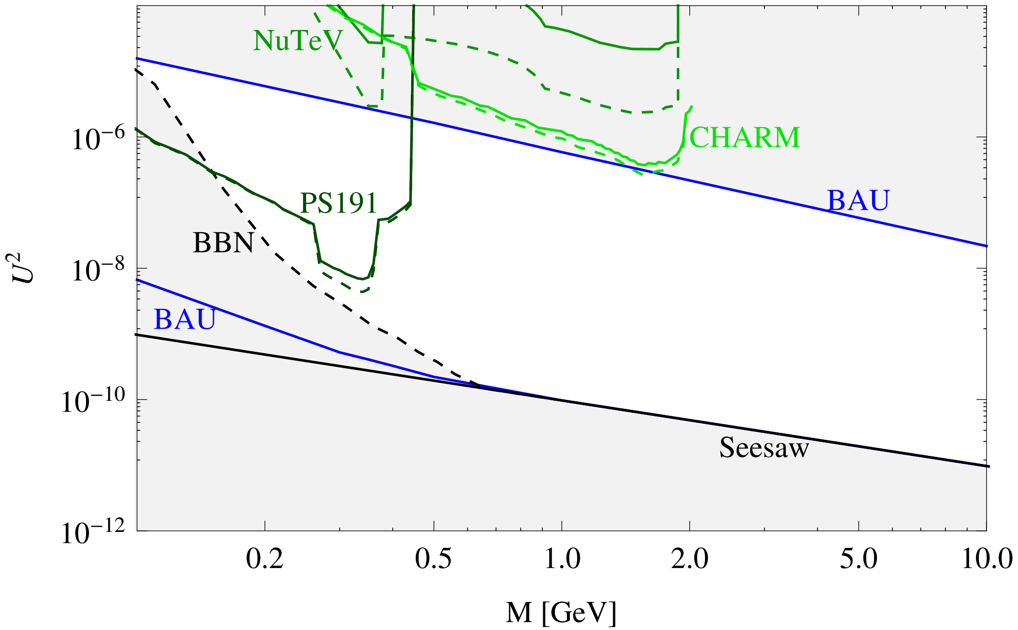
- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV Decay distance O(km)*

- *Typical BRs (depending on the flavour mixing):*

$Br(N \to \mu/e\ \pi)$ ~ 0.1 – 50%
$Br(N \to \mu^-/e^-\ \rho^+)$ ~ 0.5 – 20%
$Br(N \to \nu\mu e)$ ~ 1 – 10%



Experimental and cosmological constraints



- ***Recent progress in cosmology***

  - *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*

→ *Strong motivation to explore cosmologically allowed parameter space*

Proposal for a new experiment at the SPS to search for New Particles produced in charm decays

Expected event yield

- *Integral mixing angle* U^2 *is given by* $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$
- *A conservative estimate of the sensitivity is obtained by considering only the decay* $N_{2,3} \rightarrow \mu^- \pi^+$ *with production mechanism* $D \rightarrow \mu^+ NX$, *which probes* U_μ^2
- $U^2 \leftrightarrow U_\mu^2$ *depends on flavour mixing*
- *Expected number of signal events:*

$$N_{signal} = n_{pot} \times 2\chi_{cc} \times BR(U_\mu^2) \times \varepsilon_{det}(U_\mu^2)$$

$n_{pot} = 2 \times 10^{20}$

$\chi_{cc} = 0.45 \times 10^{-3}$

$BR(U_\mu^2) = BR(D \rightarrow N_{2,3}X) \times BR(N_{2,3} \rightarrow \mu\pi)$

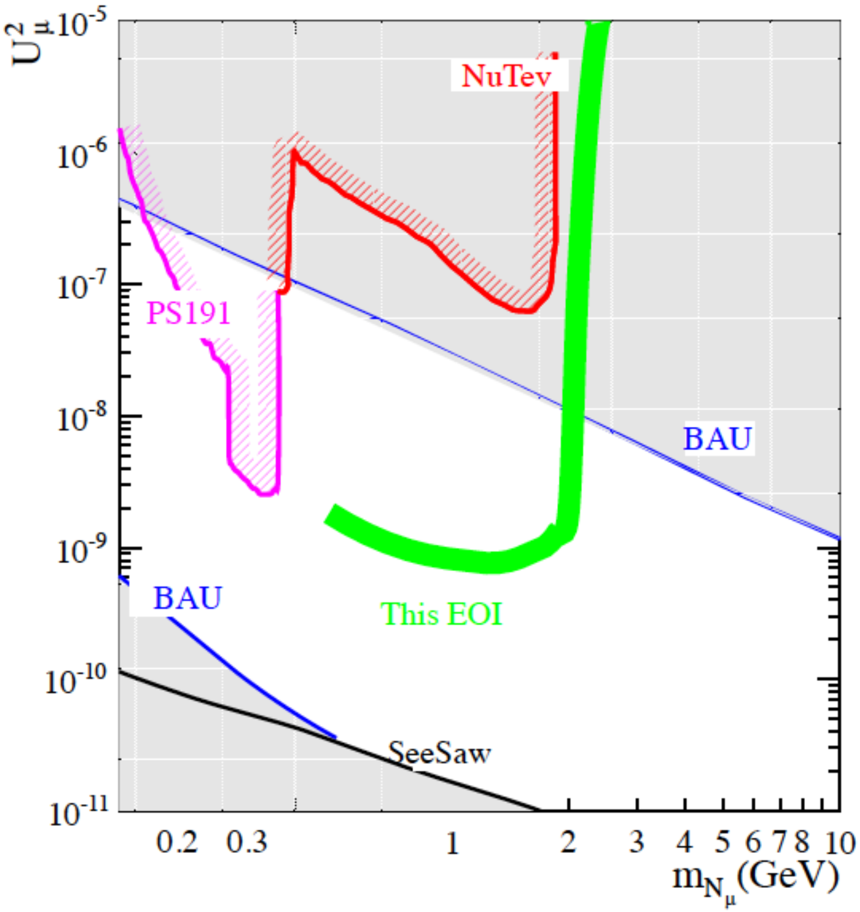
$BR(N_{2,3} \rightarrow \mu^- \pi^+)$ *is assumed to be 20%*

$\varepsilon_{det}(U_\mu^2)$ *is the probability of the* $N_{2,3}$ *to decay in the fiducial volume and* μ, π *are reconstructed in the spectrometer*

Expected event yield (cont.)

Assuming $U_\mu^2 = 10^{-7}$ (corresponding to the strongest experimental limit currently for $M_N \sim 1$ GeV) and $\tau_N = 1.8\times10^{-5}$ s

~12k fully reconstructed $N \rightarrow \mu^-\pi^+$ events are expected for $M_N = 1$ GeV



120 events for cosmologically favoured region: $U_\mu^2 = 10^{-8}$ & $\tau_N = 1.8\times10^{-4}$s

Conclusion

- *The proposed experiment will search for NP in the largely unexplored domain of new, very weakly interacting particles with masses below the Fermi scale*

- *Detector is based on existing technologies*
  Ongoing discussions of the beam lines with experts

- ***The impact of HNL discovery on particle physics is difficult to overestimate !***

  It could solve the most important shortcomings of the SM:
  - *The origin of the baryon asymmetry of the Universe*
  - *The origin of neutrino mass*
  - *The results of this experiment, together with cosmological and astrophysical data, could be crucial to determine the nature of Dark Matter*

- ***The proposed experiment perfectly complements the searches for NP at the LHC***

Outline

1. The main subject: a new experiment at CERN
2. Main motivation: neutrino physics
3. νMSM: 3 in 1 flask
   (neutrino oscillations, dark matter, baryon asymmetry of the Universe)
4. The experiment on direct searches at SPS
5. Status of the proposal
6. Planned activity

Towards the proposal

- νMSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005), see also review A. Boyarsky, O. Ruchayskiy, M.Shaposhnikov (2009)
- direct tests of νMSM: D.G., M.Shaposhnikov (2007)
- searches for dark matter A. Boyarsky, O. Ruchayskiy, M.Shaposhnikov, I.Tkachev, etc...
- proposal for direct searches submitted to European Strategy Group, 2012 D.G., M.Shaposhnikov
- sketch of realistic experiment S.Gninenko, D.G., and M.Shaposhnikov (2013)
- Expression Of Interests: Proposal to Search for Heavy Neutral Leptons at the SPS W. Bonivento et al, 1310.1762

Sterile
Neutrinos
Out
Of
Proton beam
Y

http://snoopy.web.cern.ch/snoopy/

Evaluation of the proposal by SPSC

Outcome of the 112th SPSC:

"The Committee **received with interest** the response of the proponents to the questions raised in its review of EOI010. The SPSC **recognises** the interesting physics potential of searching for heavy neutral leptons and investigating the properties of neutrinos. Considering the large cost and complexity of the required beam infrastructure as well as the significant associated beam intensity, such a project should be designed as a general purpose beam dump facility with the broadest possible physics programme, including maximum reach in the investigation of the hidden sector. To further review the project the Committee **would need an extended proposal** with further developed physics goals, a more detailed technical design and a stronger collaboration. . . We will also provide some more detailed comments on some of the items which a future proposal should address. We will collate these and hopefully send them to you within the next week."

So we have changed the name. . . to SHIP

- νMSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005), see also review A. Boyarsky, O. Ruchayskiy, M.Shaposhnikov (2009)
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Search for HIdden Particles

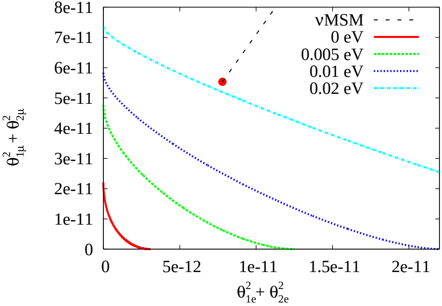
To Host Rats from the SUSY ship. . .

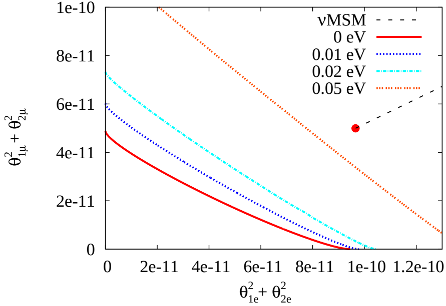
The proposed fixed-target for non-νMSM physics

- General type-I sterile neutrinos (no νMSM constraints)
- Physics of weak interactions (neutrino beam scatterings off matter)
- Other BSM physics: light, (very) weakly coupled to SM, relatively long-lived new particles

Required sensitivity to exclude seesaw type-I

D.G., A.Panin (2013)





say, another production mechanism of dark matter neutrinos or not a dark matter (axion instead), so that $M_1 > M_2 = M_3 = 1$ GeV

scales as $\propto 1/M_{max}$ for nondegenerate case

Physics within the SM: physics of ν_τ ?

- Most intensive beam of ν_τ we ever had
- θ_W from neutrino scatterings:
  for isoscalar target (e.g. ^{40}Ca)
  plugged inside the detector fiducial volume
  one expects (upto very moderate corrections)

$$\frac{\sigma_\nu^{\rm NC} - \sigma_{\bar\nu}^{\rm NC}}{\sigma_\nu^{\rm CC} - \sigma_{\bar\nu}^{\rm CC}} = \frac{1}{2} - \sin^2\theta_W$$

done at TeVatron by NuTeV for ^{56}Fe

- measurement of $\sigma_{\nu A}$ for various materials,
  e.g. required to improve sensitivity (background, etc)
  of neutrino oscillation experiments, geoneutrino detectors, . . .

Other BSM physics to be tested

- light, very weakly interacting, yet unstable particles:
  produced (in)directly on target, then decaying in the detector fiducial volume
  - light sgoldstinos (superpartners of goldstino in SUSY models)
    e.g., D.S. Gorbunov (2001) — e.g. $D \to \pi X$, then $X \to l^+ l^-$
  - R-parity violating neutralinos in SUSY models
    e.g., A. Dedes, H.K. Dreiner, P. Richardson (2001) — e.g. $D \to l \tilde{\chi}$, then $\tilde{\chi} \to l^+ l^- \nu$
  - massive paraphotons (in secluded dark matter models)
    e.g., M. Pospelov, A. Ritz, M.B. Voloshin (2008) — e.g. $\Sigma \to p V$, then $V \to l^+ l^-$
- light, fairly weakly interacting, unstable particles:
  produced in beam dump (rock), right in front of detector, then decaying in the detector fiducial volume
  - sterile neutrinos with transition dipole moments
    e.g., S.N. Gninenko (2009,2010) — $\nu A \to N A$, then $N \to \nu \gamma$

as compared to CHARM
longer lifetimes and smaller couplings will be accessible

Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

Phenomenological motivation: light particles are hidden if couplings are tiny, so no GUT-like gauge interactions between SM and hidden sector

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta H^\dagger H S^\dagger S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Light sgoldstinos in SUSY models

SUSY is spontaneously broken (no scalar electron with mass of 510 keV !!)

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons couple to all massive fields
(Goldberger–Treiman formula like for pion)

$$\mathcal{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

Higgs mechanism: three modes of H are eaten giving masses to Z, $W^{\pm}$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino

$$\mathcal{L}_\psi \propto \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi$$

Super-Higgs mechanism: goldstino is eaten giving mass to gravitino

ψ — goldstino $\overset{SUGRA}{\longrightarrow}$ longitudinal gravitino

Physics of Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

~~SUSY~~ $\longleftrightarrow$ $F \equiv \langle F_\varphi \rangle \neq 0$ $\qquad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$ $\qquad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$ — scalar

sgoldstino: $\mathcal{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\qquad F \sim$ (~~SUSY~~ scale)^2 $\qquad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$ — pseudoscalar

M_{soft}: MSSM soft terms
superpartner masses and trilinear couplings,

massless at tree level
naturally may be light...

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u q_i u_j, \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

Light sgoldstinos at the new fixed-target

Why is it interesting?

- allows to probe the scale of SUSY breaking
- R-even, hence single production and decay into SM particles
- may be responsible for HyperCP anomaly in $\Sigma \to p\mu^+\mu^-$: $m_P = 214.3$ MeV

hep-ph/0509147

Phenomenology is defined by MSSM soft terms and scale of SUSY breaking

sgoldstinos produced in heavy meson decays	hep-ph/0610066 :	tested at Belle (1005.1450)
	1112.5230:	tested at LHCb (1303.1092)

At the beam-dump experiment

Sgoldstino production and lifetime are naturally dominated by gluons

$$\tau_X = 10^{-6}\,\text{s} \times \left(\frac{\sqrt{F}}{1000\,\text{TeV}}\right)^4 \left(\frac{3\,\text{TeV}}{M_{\lambda_g}}\right)^2 \left(\frac{1\,\text{GeV}}{m_{S,P}}\right)^3$$

produced in D-meson decays fly for several kilometers and then decay into

$$X \to \gamma\gamma,\ \ \mu^+\mu^-,\ \ \pi^+\pi^-,\ \ \pi^0\pi^0,\ \ e^+e^-$$

For 2×10^{20} POTs we expect for number of signal $\pi^+\pi^-$ pairs in $L \simeq 100$ m detector

$$N_{\pi^+\pi^-} \simeq 2 \times \left(\frac{1000\,\text{TeV}}{\sqrt{F}}\right)^8 \left(\frac{M_{\lambda_g}}{3\,\text{TeV}}\right)^4 \left(\frac{m_{S,P}}{1\,\text{GeV}}\right)^2$$

R-parity violating neutralinos in SUSY models

Superpotential (SUSY-invariant part) gives Yukawa-like couplings for SM fermions

$$W_{\not R} = \lambda_{ijk} L_i^a \varepsilon_{ab} L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a \varepsilon_{ab} Q_j^b \bar{D}_k + \lambda''_{ijk} \bar{U}_i^\alpha \varepsilon_{\alpha\beta\gamma} \bar{D}_j^\beta \bar{D}_k^\gamma$$

Yet the proton is stable if $\lambda'' = 0$ (baryon parity), or $\lambda, \lambda' = 0$ (lepton parity) and proton is lighter than LSP: $R_p = (-1)^{(3B+L+2S)}$

But LSP is unstable in these models, so no problems with overproduction (but we need another candidate to be dark matter. . .)

Nevertheless cosmology and astrophysics exclude

BBN: $0.1\,\text{s} < \tau_{\text{LSP}}$ cosmic γ-rays (FERMI): $\tau_{\text{LSP}} < 10^{18}\,\text{yr}$

hence, the allowed range:

$$3 \times 10^{-23} < (\lambda, \lambda', \lambda'') < 3 \times 10^{-10}$$

Direct searches at LHC (and TeVatron) probe:

$$(\lambda, \lambda', \lambda'') > 10^{-6}$$

otherwise LSP decays outside ATLAS and CMS

R-parity violating neutralinos at the fixed-target

The range remains to be directly tested:

$$3 \times 10^{-10} < (\lambda, \lambda', \lambda'') < 10^{-6}$$

hep-ph/0106199: “Fixed-target experiments with remote detectors can probe significantly longer lifetimes than collider experiments and are thus an ideal environment for closing this gap in sensitivity”

production in meson decays: 0905.2051 — probed by BaBar, Belle

$B^{\pm} \to l^{\pm}\tilde{\chi}_0$, $B^0 \to \nu\tilde{\chi}_0$ — R-violating

neutralinos decay into SM particles, e.g.

$\tilde{\chi}_0 \to \mu^+\mu^-\nu$ — R-violating

$\lambda \neq 0$ was discussed after NuTeV dimuon events — hep-ex/0104037, hep-ph/0007195

Number of events at the proposed experiment with N_D D-mesons and detector length $L \simeq 100$ m

R-conserving (double neutralino production)

$$N \simeq 10 \times \left(\frac{m_{\tilde{\chi}_0}}{1\,\mathrm{GeV}}\right)^6 \left(\frac{\lambda}{3 \times 10^{-8}}\right)^2 \left(\frac{N_D \cdot \mathrm{Br}\,(D \to \tilde{\chi}_0 + \ldots)}{10^6}\right)$$

Massive vectors (paraphotons)

Vector portal to a secluded sector: e.g. with Dark matter Ψ

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector: mixing with $U(1)_Y$ is naturally expected and unsuppressed by high energy scale 0711.4866

$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

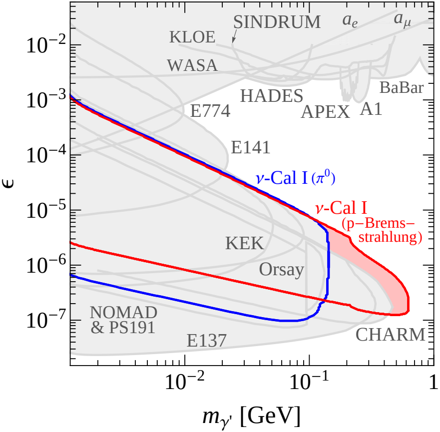
Cosmology:

- Limits from BBN:

$$\tau_V < 1\,\text{s}\,, \implies \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

- For DM particles to be in thermal equilibrium in primordial plasma:

$$\varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-11} \times \left(\frac{m_\Psi}{500\,\text{GeV}}\right)^2$$



1311.5104

Production by virtual photon $\sigma \propto \varepsilon^2$

Decay through virtual photon, $\Gamma \propto \varepsilon^2$

$V \to e^+e^-,\ \mu^+\mu^-$, etc

Paraphotons: improvement of CHARM

$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

Constraints on mixing ε

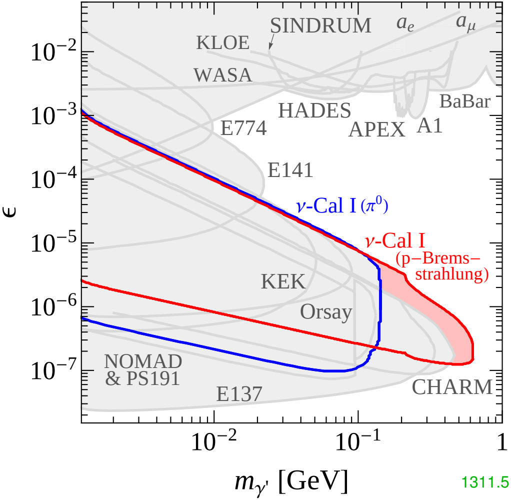
- Limits from above:
  decays before reaching CHARM

  $$L_{\text{CHARM}} = 400\,\text{m} > l_{\text{decay}} \propto \frac{1}{\varepsilon^2 m^2_{\gamma'}}$$

  $L = 50\,\text{m}$, hence
  a factor of 3 improvement
- Limits from below:
  too few events in CHARM

  $$\sigma_{\text{production}} \propto \varepsilon^2\,, \quad \Gamma_{\text{decay}} \propto \varepsilon^2$$

  Luminosity, geometry,...
  2 orders of magnitude improvement



1311.5104

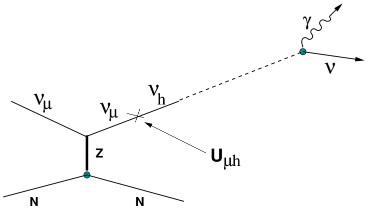
Sterile neutrinos with transition dipole moments

Pure phenomenological approach:
electric d and magnetic μ transition (two different neutrinos, active or sterile, involved) dipole moments

$$d_{IJ}\bar{N}_I\gamma^\mu\gamma^\nu\gamma^5 N_J F_{\mu\nu}\,,\quad \mu_{IJ}\bar{N}_I\gamma^\mu\gamma^\nu N_J F_{\mu\nu}\,,\quad d_{I\alpha}\bar{N}_I\gamma^\mu\gamma^\nu\gamma^5\nu_\alpha F_{\mu\nu}\,,\quad \mu_{I\alpha}\bar{N}_I\gamma^\mu\gamma^\nu\nu_\alpha F_{\mu\nu}$$

Renewed interest after 0902.3802, 0907.4666 explaining MiniBooNE anomaly and after 1009.5536, 1101.4004, 1107.0279, 1210.1519 explaining MiniBooNE and LSND anomalies

present limits:
1201.5194 and 1303.4587 give limits for ν_μ and $\bar{\nu}_\mu$ from NOMAD and MiniBooNE data at the level of $d\,,\mu \lesssim 10^{-8}\mu_B$



production: transition $\nu_\tau \to N$ on heavy nuclei ($\sigma \propto Z^2$) in detector or right before vacuum

then radiative decay inside the detector (can we recognize a single energetic photon ?)

Outline

1 The main subject: a new experiment at CERN

2 Main motivation: neutrino physics

3 νMSM: 3 in 1 flask
(neutrino oscillations, dark matter, baryon asymmetry of the Universe)

4 The experiment on direct searches at SPS

5 Status of the proposal

6 Planned activity

Conclusion: events this year

- Estimate the sensitivity of the experiment to various BSM physics
- Choose between "dump" and "dump+magnetic field" options and more. . .
- Establish a Collaboration SHIP
- Submit a detailed project (LoI/TDR) to SPS by March 2015

On 10-12 of June we plan to organize (in Zurich?) a Workshop

- two half-days on physics case at SPS beam-dump
- and then two half-days on detector and discussion of formal collaboration

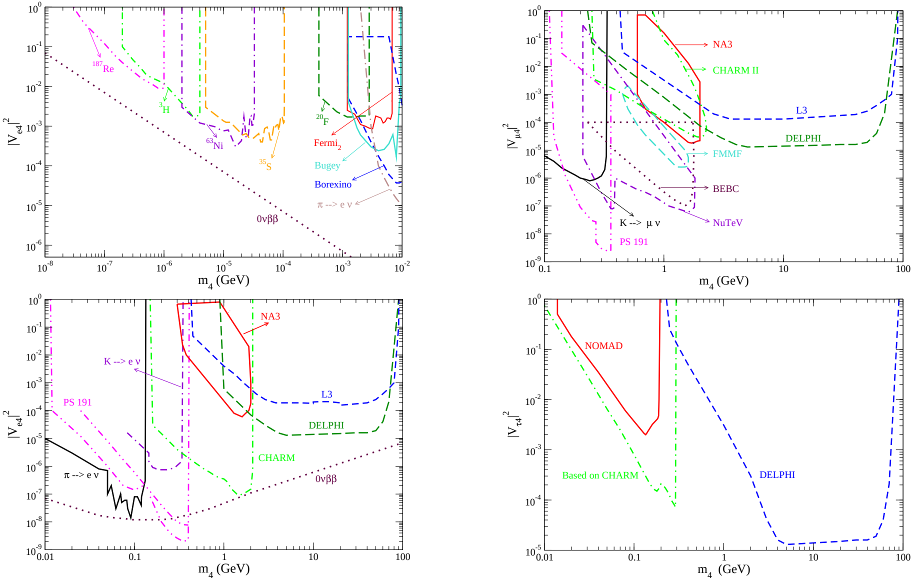
All of you and your laboratories are welcome
to attend the meeting
and enter the Collaboration

http://ship.web.cern.ch/ship/

Backup slides

Present limits

0901.3589: 1) $0\nu\beta\beta$-bound is stronger by 10, 1205.3867 2) limits from LHCb and CMS

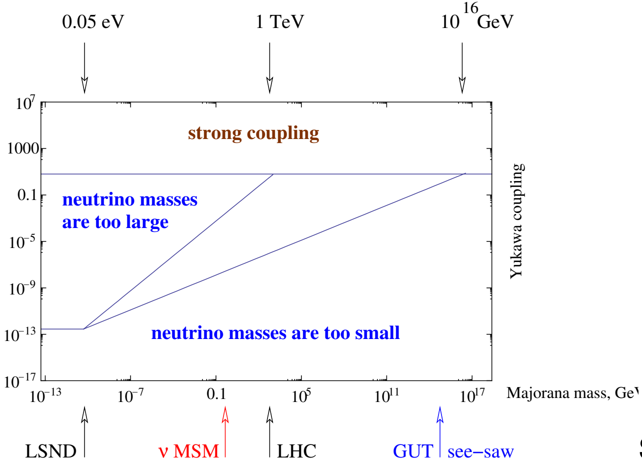


Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



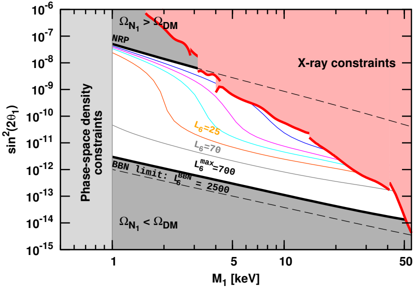
Seesaw diagram

Lightest sterile neutrino N_1 as Dark Matter

Non-resonant production (active-sterile mixing) is ruled out

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008



Dark Matter production from inflaton decays in plasma at $T \sim m_\chi$

Not seesaw neutrino!

M.Shaposhnikov, I.Tkachev (2006)

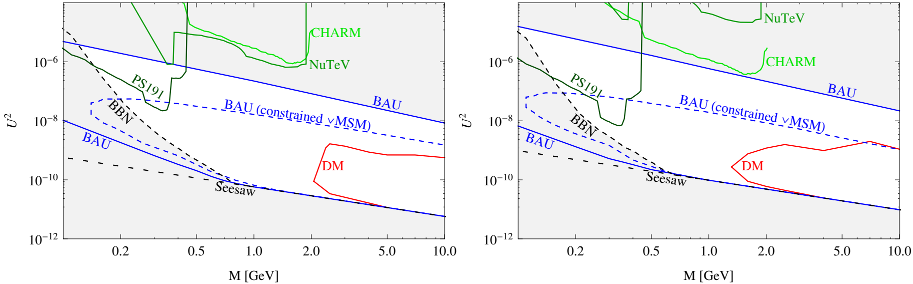
$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm ($250\,\text{MeV} < m_\chi < 1.8\,\text{GeV}$)

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\text{ MeV}}\right) \text{keV}$$

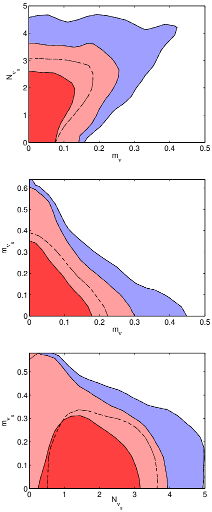
νMSM parameter space with resonant DM



L.Canetti, M.Drewes, M.Shaposhnikov 1204.3902

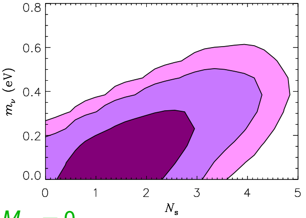
Combined analysis for sterile and active neutrinos

WMAP7+LRG+HST

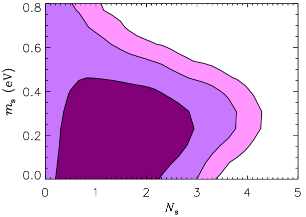


flat ΛCDM 1102.4774

CMB+SDSS+HST

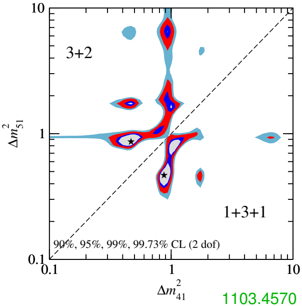


$M_{\nu s} = 0$



$m_\nu = 0$
flat ΛCDM 1006.5276

LSND+MiniBooNE



1103.4570

"3+1" :
$\Delta m^2_{41} = 1.76\,\text{eV}^2$, $|U_{e4}| = 0.151$
"3+2" :
$\Delta m^2_{41} = 0.46\,\text{eV}^2$, $|U_{e4}| = 0.108$
$\Delta m^2_{51} = 0.89\,\text{eV}^2$, $|U_{e5}| = 0.124$

BBN rules out "3+2"

For "3+1" to allow $M_N \gtrsim 1$ eV for CMB and LSS we need a new ingredient

talk by A.Starobinsky