Testing sterile neutrinos with new fixed target experiment at CERN SPS

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The International Workshop on Prospects of Particle Physics: ”Neutrino Physics and Astrophysics”

Valday, Russia

Outline

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

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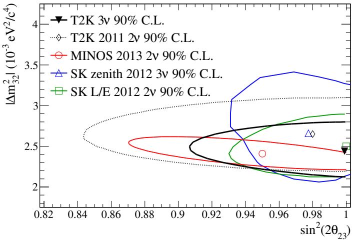
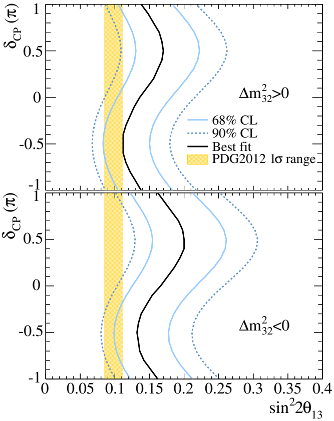
Neutrino oscillations: masses and mixing angles



“atmospheric” 2 × 2 sector

1308.0465



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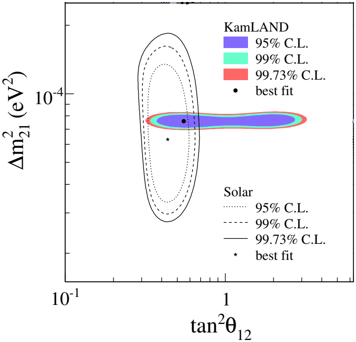

“solar” 2 × 2 sector

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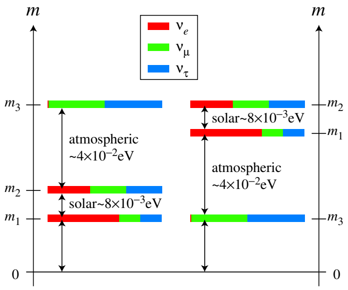
“Normal” and “Inverted” neutrino mass hierarchies

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

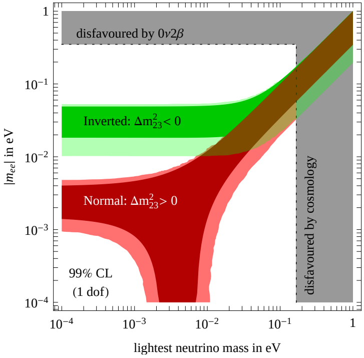
may be, the hierarchy will be fixed by T2K & Noνae



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

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"

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

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

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

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

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 $\Lambda < 100\,\mathrm{GeV}$

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

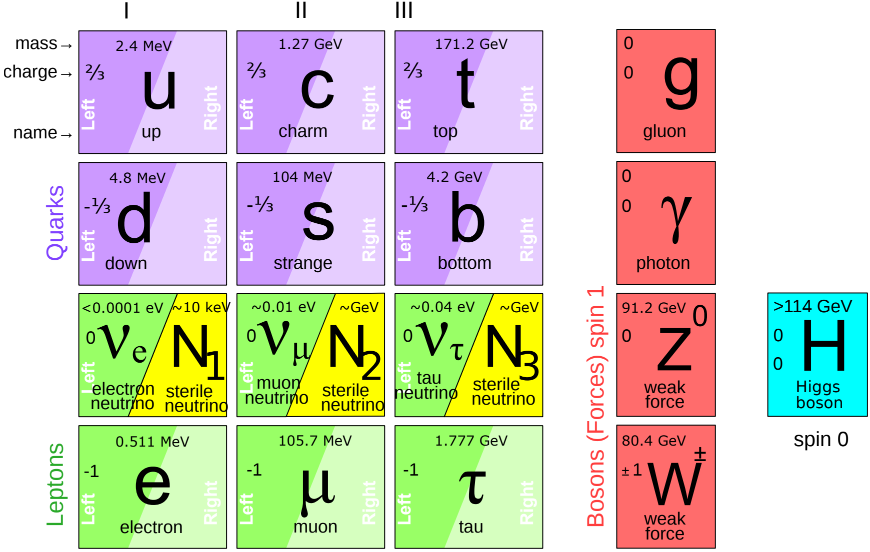
Minimal extension of SM to explain neutrino oscillations

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	Bosons (Forces) spin 1	
mass → charge → name →	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right	0 0 γ photon	
	<0.0001 eV 0 ν_e electron neutrino Left ~10 keV N_1 sterile neutrino	~0.01 eV 0 ν_μ muon neutrino Left ~GeV N_2 sterile neutrino	~0.04 eV 0 ν_τ tau neutrino Left ~GeV N_3 sterile neutrino	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^\pm$ weak force	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

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

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

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

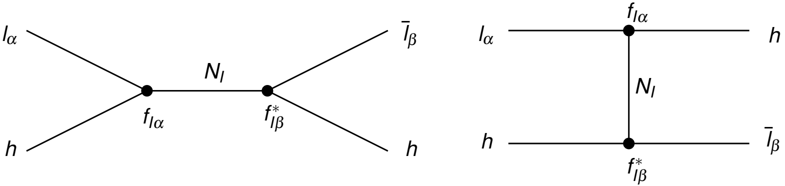
Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

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)

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

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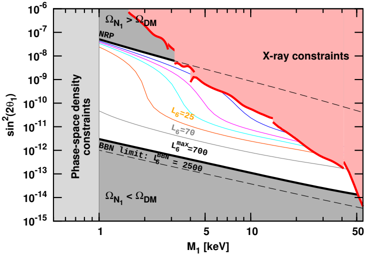
Heavy sterile neutrinos: $M_N \simeq 1\,\text{keV-}50\,\text{GeV}$ νMSM

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

- At $T > 100\,\text{GeV}$ active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_N \ll M_N$ 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



$$\Gamma_{N\to\nu\gamma} \simeq 5.5\times 10^{-22}\theta_1^2 \left(\frac{M_1}{1\ \text{keV}}\right)^5 \text{s}^{-1}$$

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} $(\Delta M_N \sim 10^{-7}\ \text{eV})$ 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)

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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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(‡) *retired*

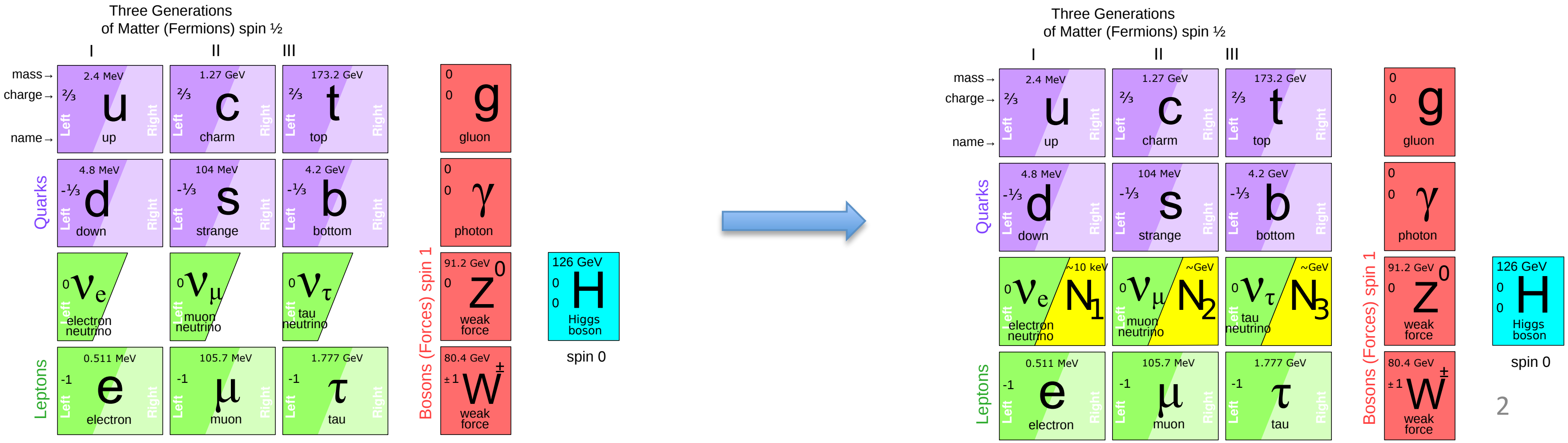
Theoretical motivation

- *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*



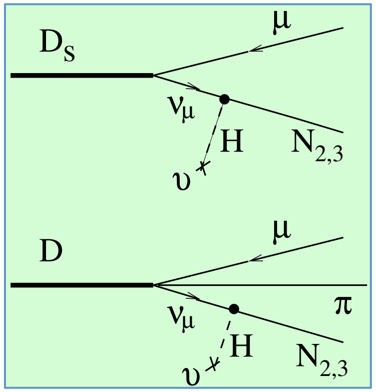
Masses and couplings of HNLs

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

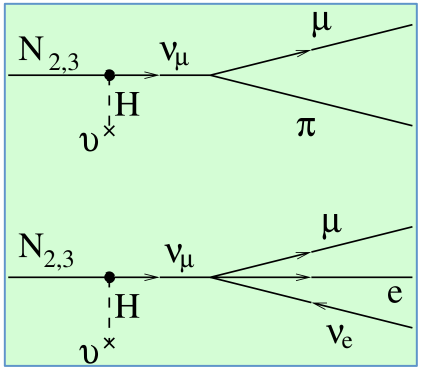
- *$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)*

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



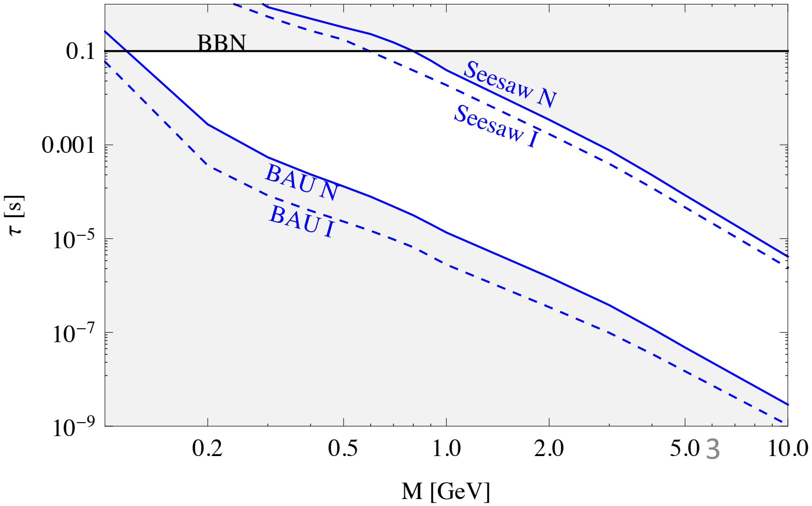
and subsequent decays



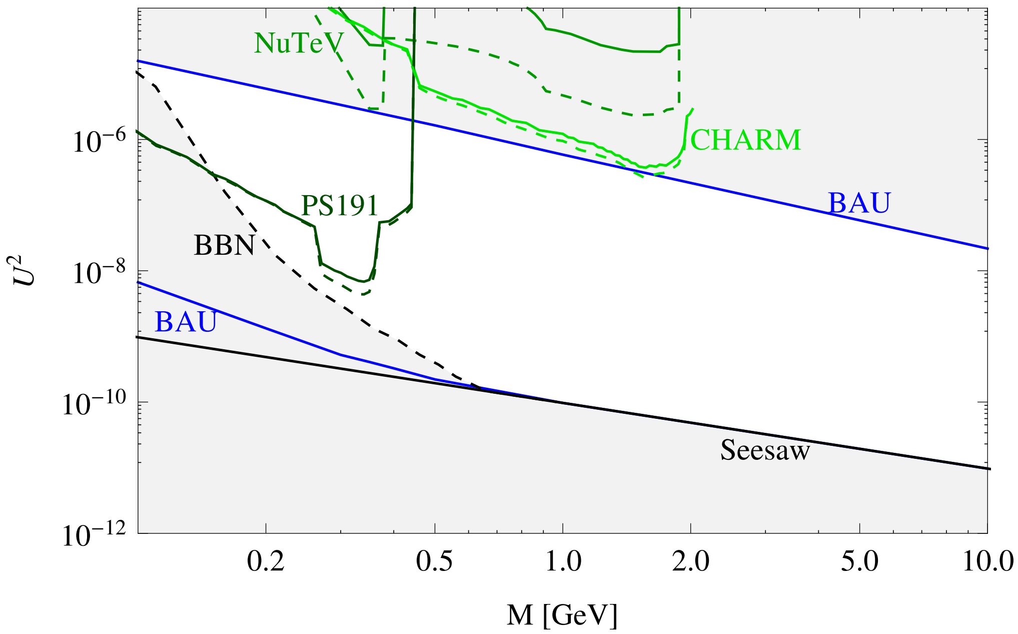
- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV Decay distance O(km)*

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

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

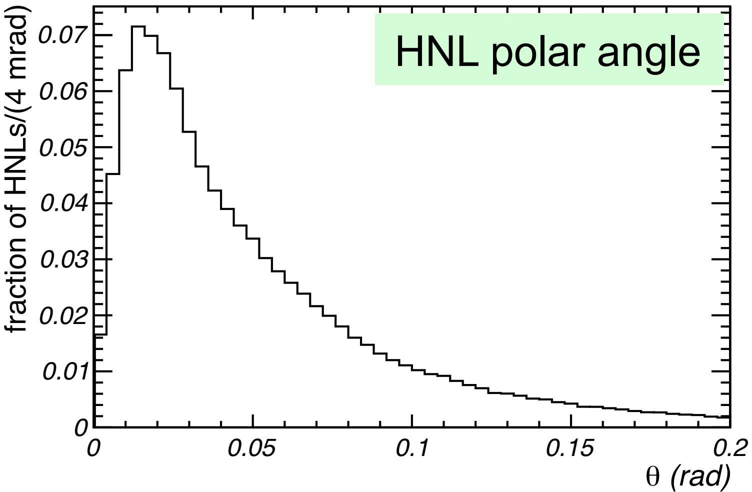
Proposal for a new experiment at the SPS to search for New Particles produced in charm decays

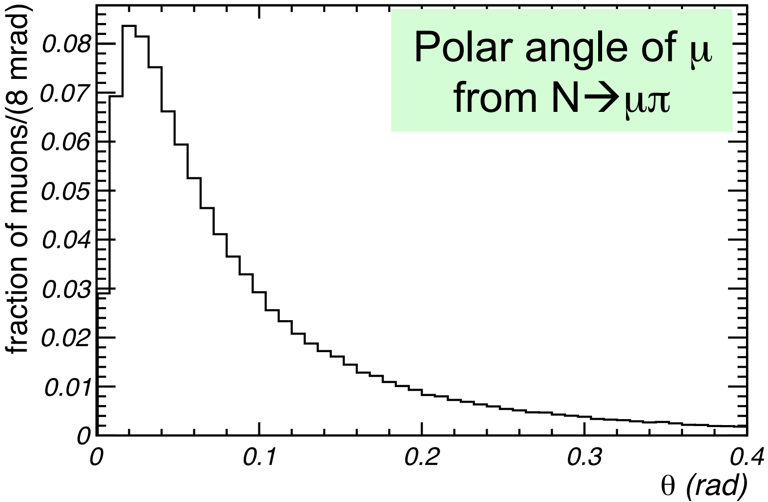
Experimental requirements

- *Search for HNL in Heavy Flavour decays*

Beam dump experiment at the SPS with a total of 2×10^{20} protons on target (pot) to produce large number of charm mesons

- *HNLs produced in charm decays have significant P_T*

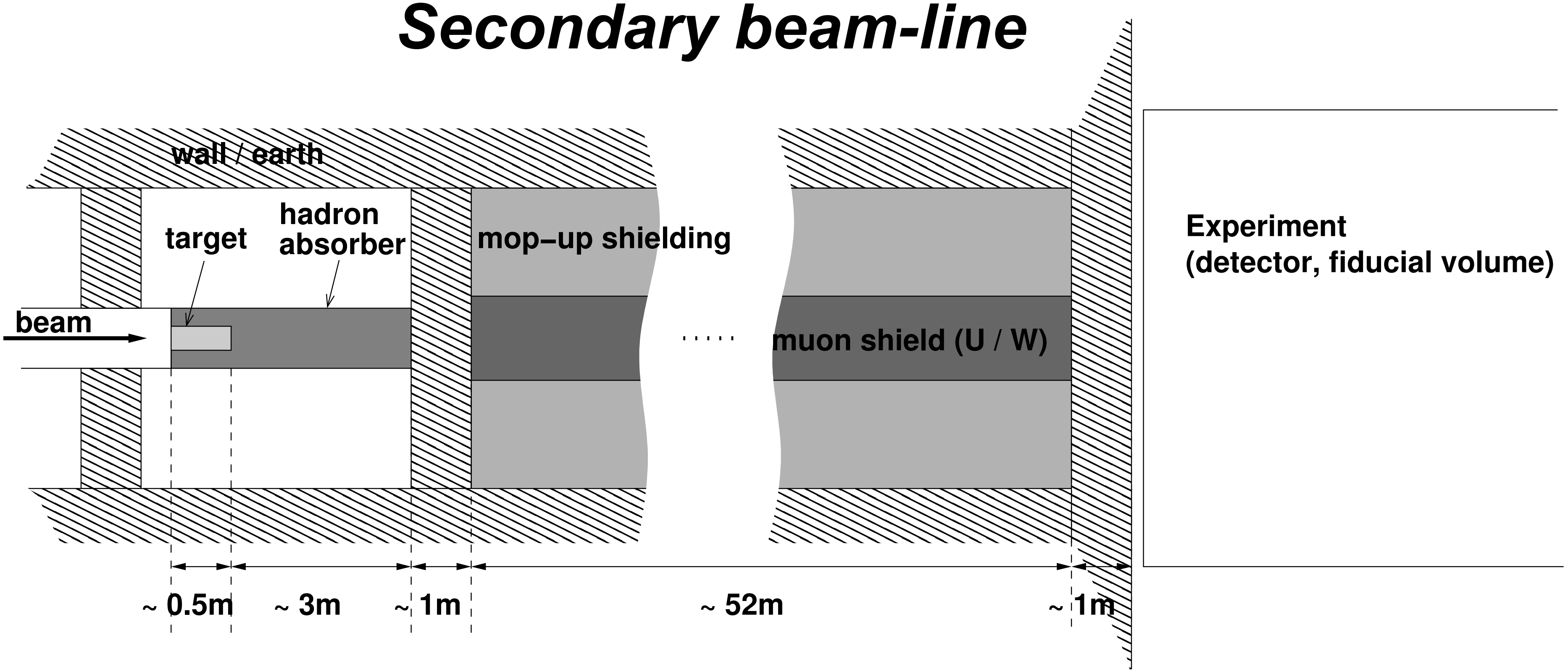




Detector must be placed close to the target to maximize geometrical acceptance

Effective (and “short”) muon shield is essential to reduce muon-induced backgrounds (mainly from short-lived resonances accompanying charm production)

Secondary beam-line



Proton target

- *Preference for relatively slow beam extraction O(s) to reduce detector occupancy*

- *Sufficiently long target made of dense material (50 cm of W) to reduce the flux of active neutrinos produced mainly in π and K decays*

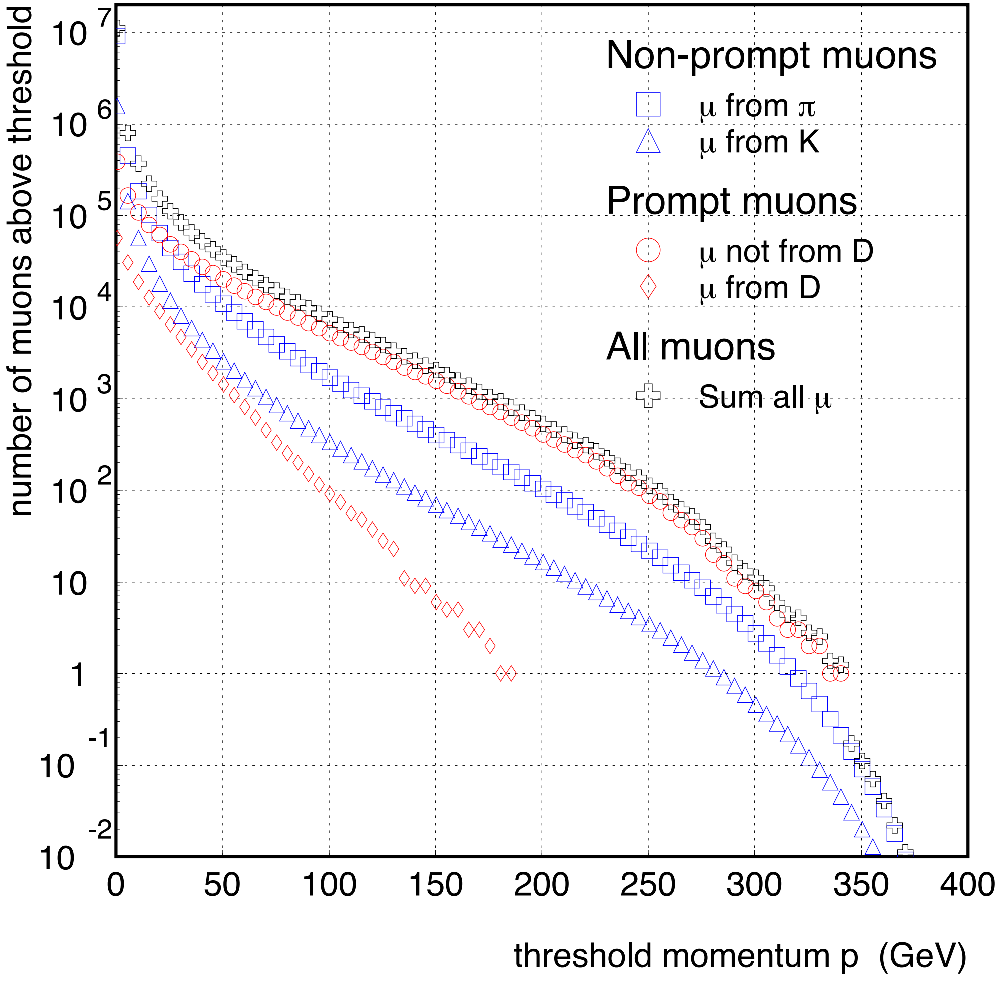
- *No requirement to have a small beam spot*

Secondary beam-line (cont.)

Muon shield

Main sources of the muon flux (estimated using PYTHIA with 10^9 protons of 400 GeV energy)

- *A muon shield made of ~55 m W(U) should stop muons with energies up to 400 GeV*
- *Cross-checked with results from CHARM beam-dump experiment*
- *Detailed simulations will define the exact length and radial extent of the shield*



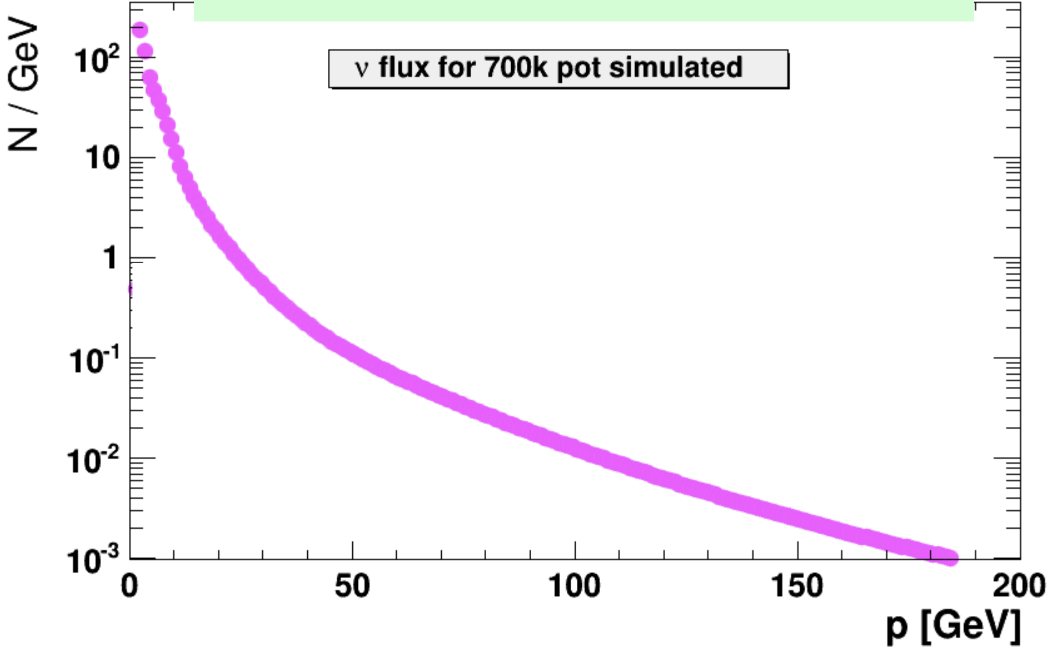
Assume that muon induced backgrounds will be reduced to negligible level with such a shield

Experimental requirements (cont.)

- *Minimize background from interactions of active neutrinos in the detector decay volume*

Requires evacuation of the detector volume

Momentum spectrum of the neutrino flux after the muon shield

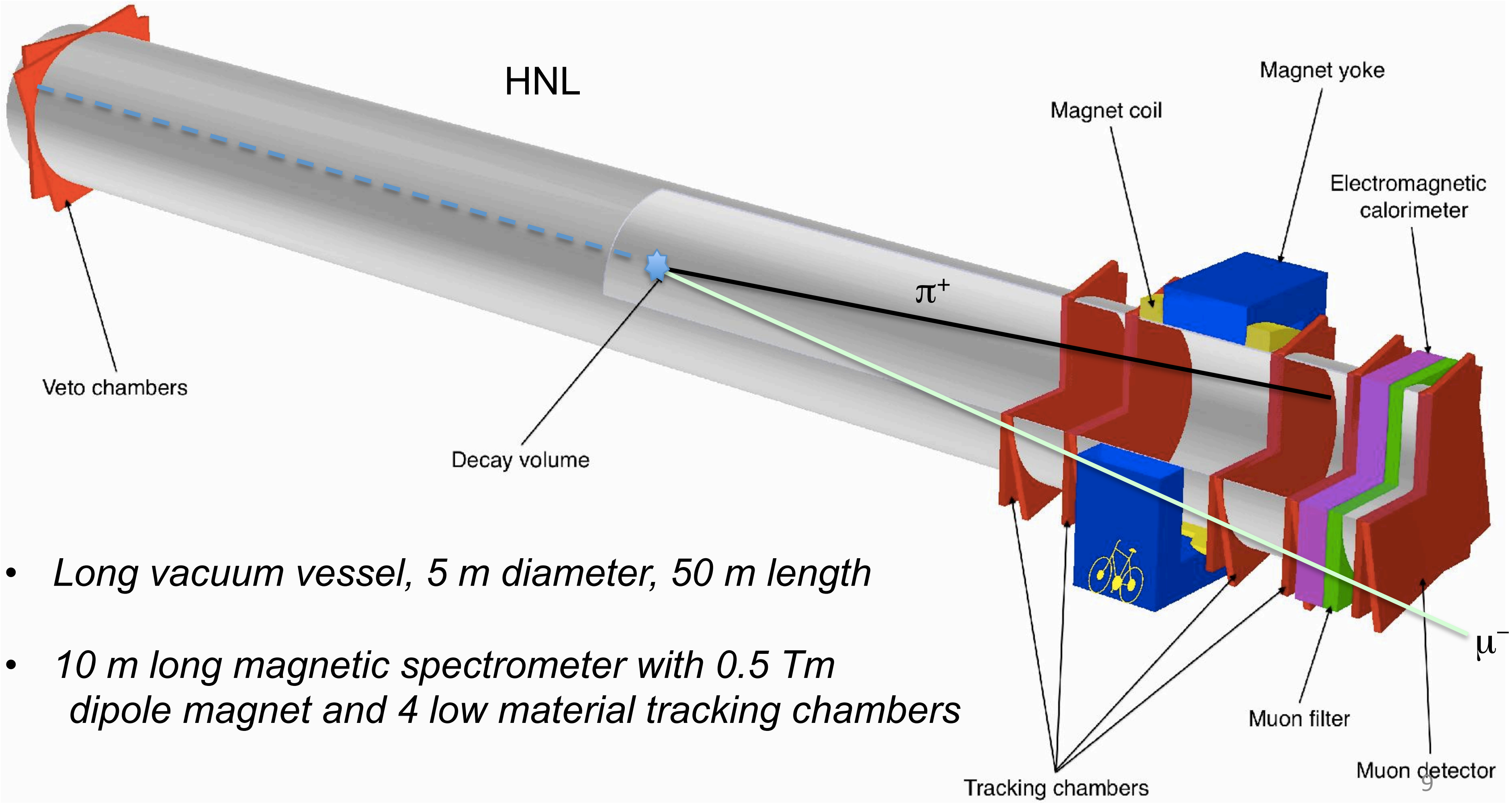


2×10^4 neutrino interactions per 2×10^{20} pot in the decay volume at atmospheric pressure → becomes negligible at 0.01 mbar

Detector concept

- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\rho^+$*

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*



- *Long vacuum vessel, 5 m diameter, 50 m length*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

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
- $U^2 \longleftrightarrow U_\mu^2$ depends on flavour mixing
- Expected number of signal events:

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

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

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

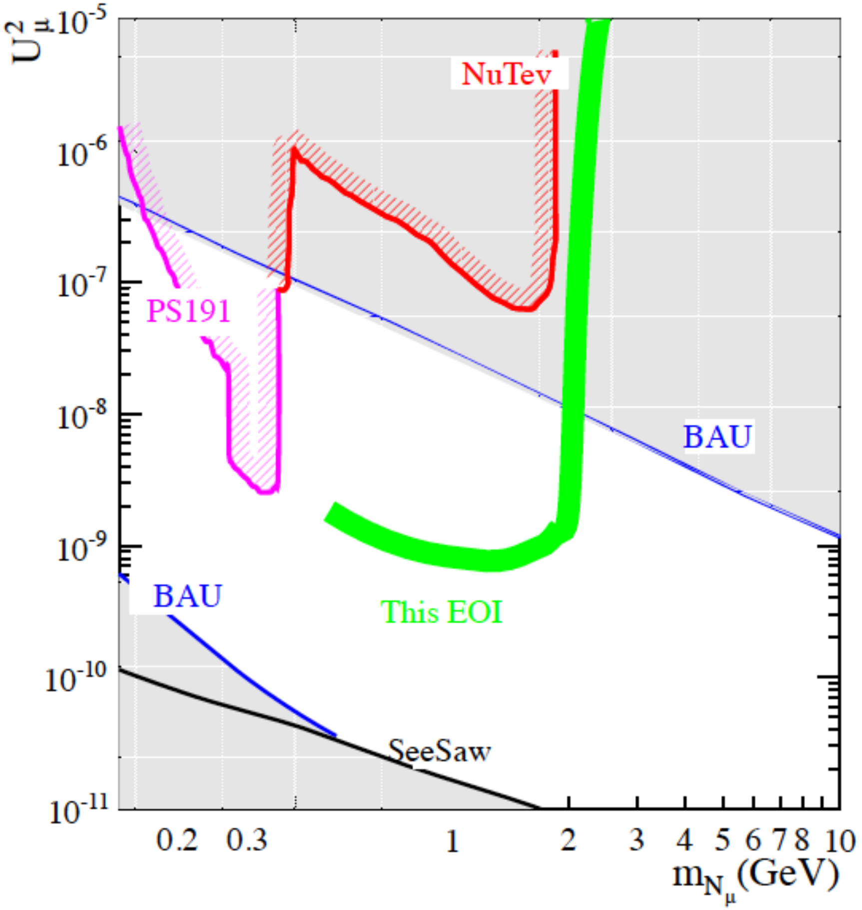
$BR(U_\mu^2) = BR(D \rightarrow N_{2,3}X) \times BR(N_{2,3} \rightarrow \mu\pi)$
$BR(N_{2,3} \rightarrow \mu^- \pi^+)$ is assumed to be 20%

$\varepsilon_{det}(U_\mu^2)$ 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

Expected event yield (cont.)

- *ECAL will allow the reconstruction of decay modes with π^0 such as $N \rightarrow \mu^- \rho^+$ with $\rho^+ \rightarrow \pi^+ \pi^0$, doubling the signal yield*
- *Study of decay channels with electrons such as $N \rightarrow e\pi$ would further increase the signal yield and constrain U_e^2*

In summary, for $M_N < 2$ GeV the proposed experiment has discovery potential for the cosmologically favoured region with $10^{-7} < U_\mu^2 <$ a few × 10^{-9}

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***

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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:

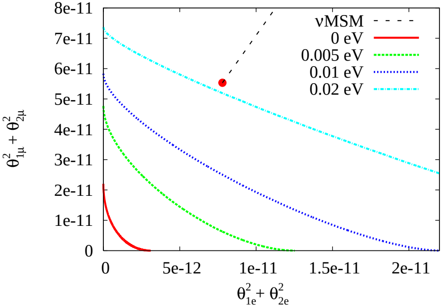
”The Committee **received with interest** the response of the proponents to the questions raised in its review of EOI010. The SPSC **recognises** the interesting physics potential of searching for heavy neutral leptons and investigating the properties of neutrinos. Considering the large cost and complexity 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.

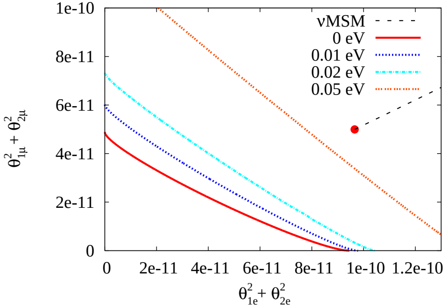
The proposed fixed-target for non-νMSM physics

- 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 mixing in 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 $M_1 > M_2 = M_3$

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)

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

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

Being discussed with:

European Organization for Nuclear Research (CERN)

France: CEA Saclay, APC/LPNHE Universite Paris-Diderot

Italy: Instituto Nazionale di Fisica Nucleare (INFN)

Netherlands: National Institute for Subatomic Physics (NIKHEF, Amsterdam)

Poland: Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences (Kracow)

Russia: Institute for Nuclear Research of Russian Academy of Science (INR, Moscow),
Institute for Theoretical and Experimental Physics ((ITEP, Moscow),
Joint Institute for Nuclear Research (JINR, Dubna)

Sweden: Stockholm University,
Uppsala University

Switzerland: Ecole Polytechnique Federale de Lausanne (EPFL),
University of Zurich,
University of Geneva

UK: University of Oxford,
University of Liverpool,
Imperial College London,
University of Warwick

Outline

Conclusion: events this year

- Estimate the sensitivity of the experiment to various BSM physics
- Choose between dump and dump+magnetic field options
- Establish a Collaboration
- Submit a detailed project (LoI/TDR) to SPS by the end of this year

This year (June?) we plan to

- Organize a Workshop on physics at SPS beam-dump (in Lausanne?)
- And the first Collaboration meeting right after that

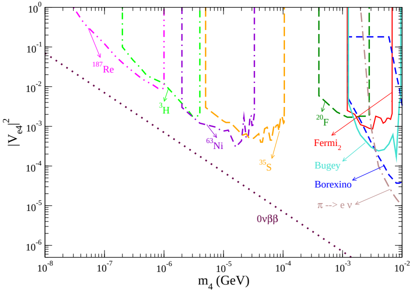
All of you and your institutes are welcome
to attend the meeting
and enter the Collaboration

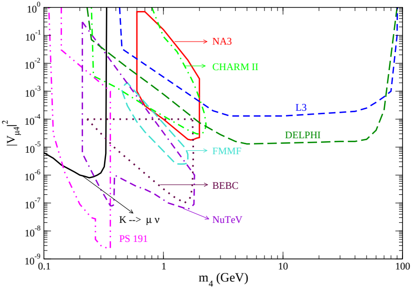
http://snoopy.web.cern.ch/snoopy/

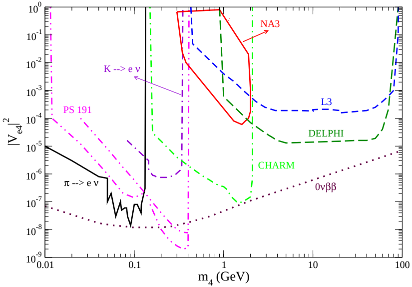
Backup slides

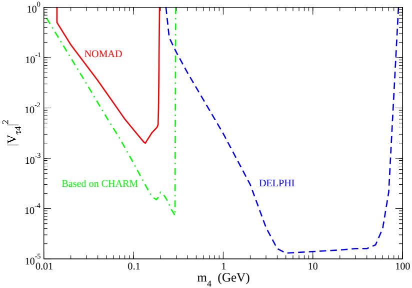
Present limits

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









Sterile neutrino lagrangian

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

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

Parameters to be determined from experiments

9(7): active neutrino sector

2 Δm^2_{ij}: 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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both BAU and DM are possible

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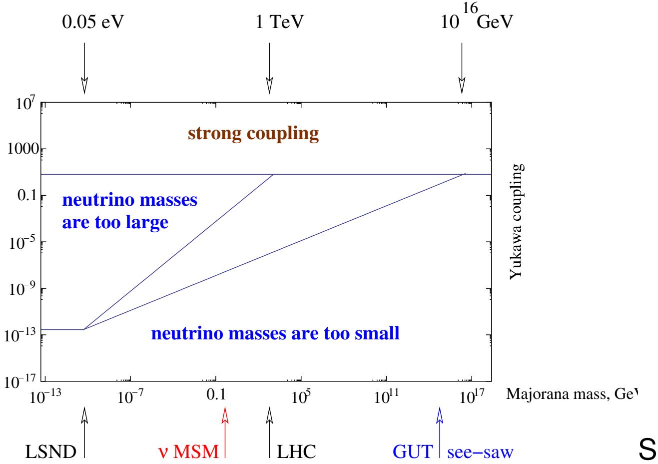
Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^\dagger \hat{M}_N^{-1} \hat{f}$

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



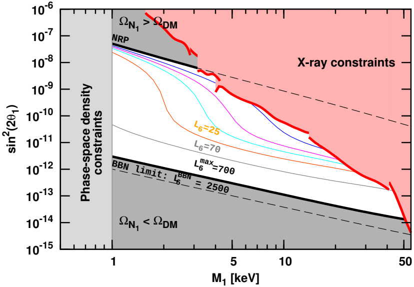
Seesaw diagram

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



Not seesaw neutrino!

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

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)

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