Proposal to search for Heavy Neutral Leptons at the CERN SPS

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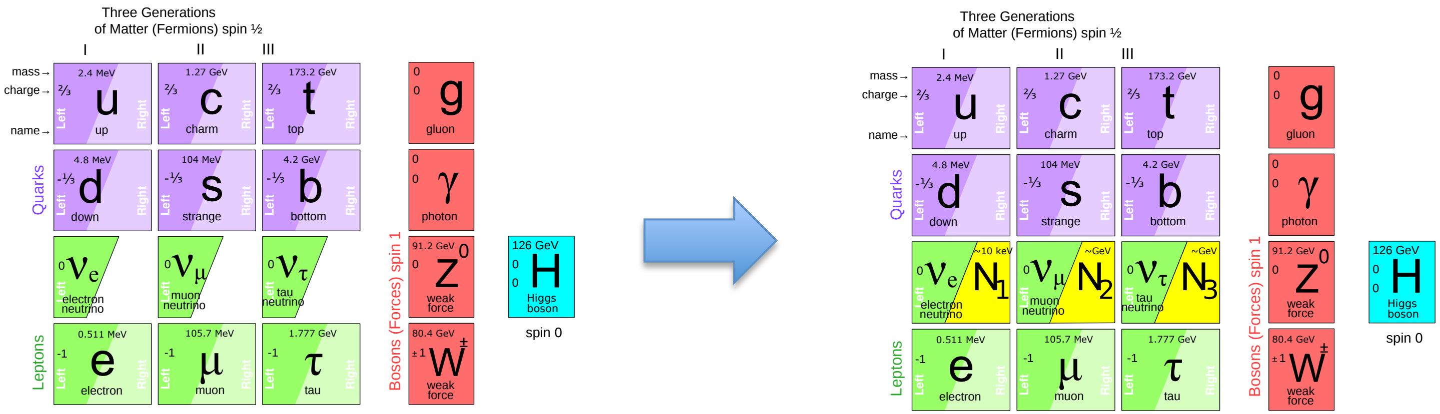
Introduction

- Discovery of a 126 GeV Higgs boson raises possibility that the SM may work successfully up to the Planck scale

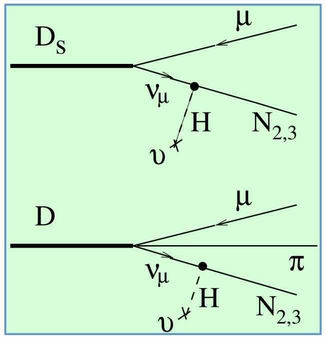
- [aside from fine-tuning problems] SM is unable to explain :
  - Neutrino masses
  - Excess of matter over antimatter in the Universe
  - The nature of non-baryonic dark matter

- The **neutrino Minimal Standard Model** (**νMSM**) [T.Asaka, M.Shaposhnikov, Phys. Lett B620 (2005) 17] aims to explain these by adding three new, neutral Majorana leptons: **N_1, N_2 and N_3**

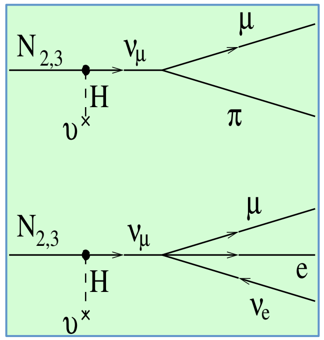


Masses and couplings of HNLs

- **Three new Heavy Neutral Leptons (HNL)** – carry no SM gauge charges – only interact via mixing of SM ν and HNL (Yukawa term)
- **N_1** can be sufficiently stable to be a DM candidate, **$M(N_1)$~10 keV**
- **$M(N_2) \approx M(N_3)$ ~ a few GeV** $\rightarrow$ can dramatically increase amount of CPV to explain Baryon Asymmetry of the Universe (**BAU**)
- **Very weak $N_{2,3}$-to-ν mixing (~ U^2)** $\rightarrow$ **$N_{2,3}$** are much longer-lived than the SM particles
  - Typical lifetimes **>10 μs** for **$(N_{2,3})$ ~ 1 GeV** $\rightarrow$ decay distance O(km)
  - too large U erases any BAU
- **$N_{2,3}$** can be produced in charm decays…



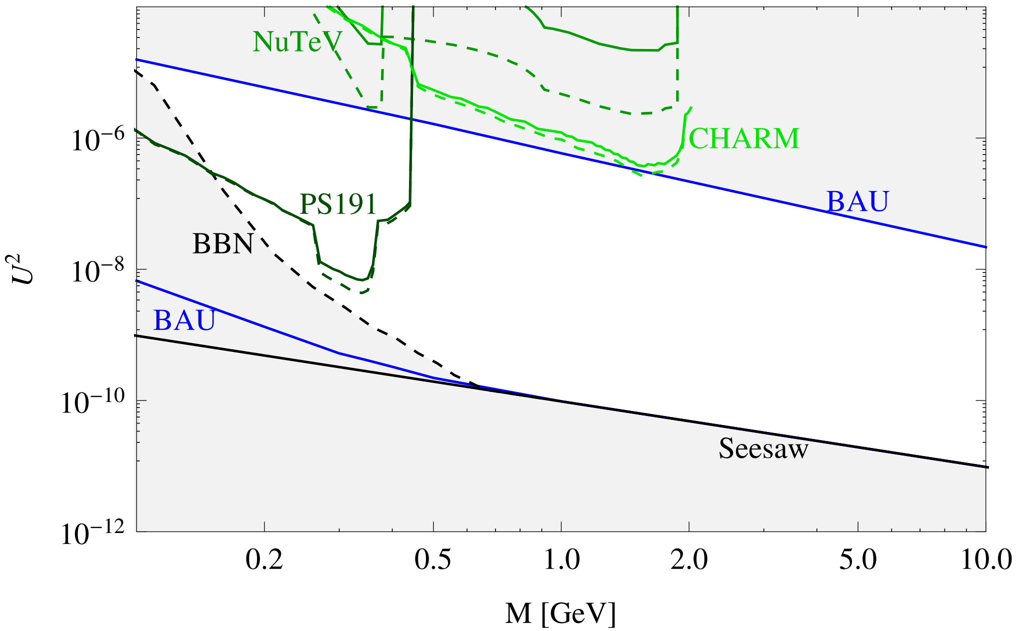
… and subsequently decay



(Focus on $\mu^-\pi^+$ decay)

Experimental and cosmological constraints

- **BAU, Seesaw** and Big Bang Nucleosynthesis (**BBN)** constraints indicate that previous expts probed the interesting region only below the kaon mass :



- Mixing at both production and decay
- For D mesons, typical BF expected in allowed νMSM parameter space then,

  $\mathbf{B_{D\to N} \sim 10^{-8} - 10^{-12}}$

- τ can give further factor $\mathbf{10^{-4}}$
  → **need $\mathbf{10^{16}}$ D mesons!**

- Strong motivation to explore allowed space in region accessible with charm decays

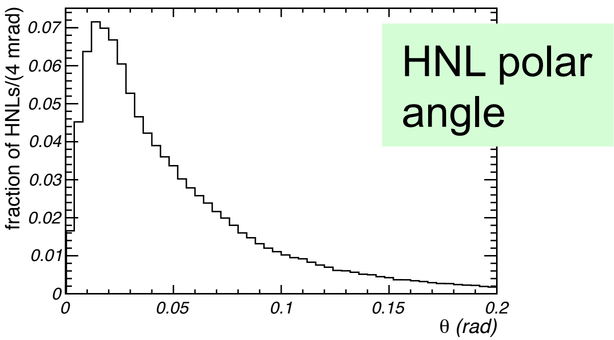
  → Propose a new beam dump experiment at CERN SPS

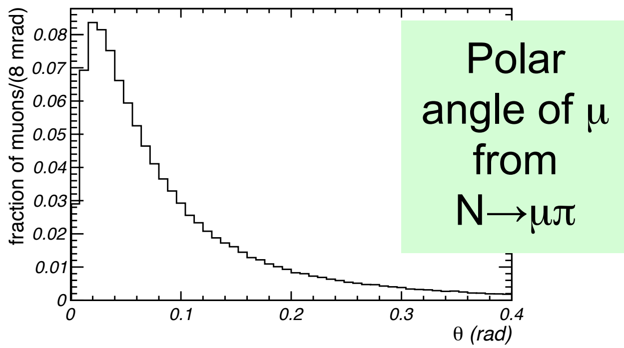
Experimental design

- Propose a beam dump experiment at the CERN SPS with at total of **~2×10^{20} protons on target** (pot)

- Crucial design parameters: **residual neutrino and muon fluxes** - can produce e.g **K^0** that decay in detector and mimic signal events
  - Short-lived resonances generate **10^{11}** muons/spill → **muon shield**
  - Neutrinos from light meson decays → **dense target/hadron absorber/ evacuate decay volume**

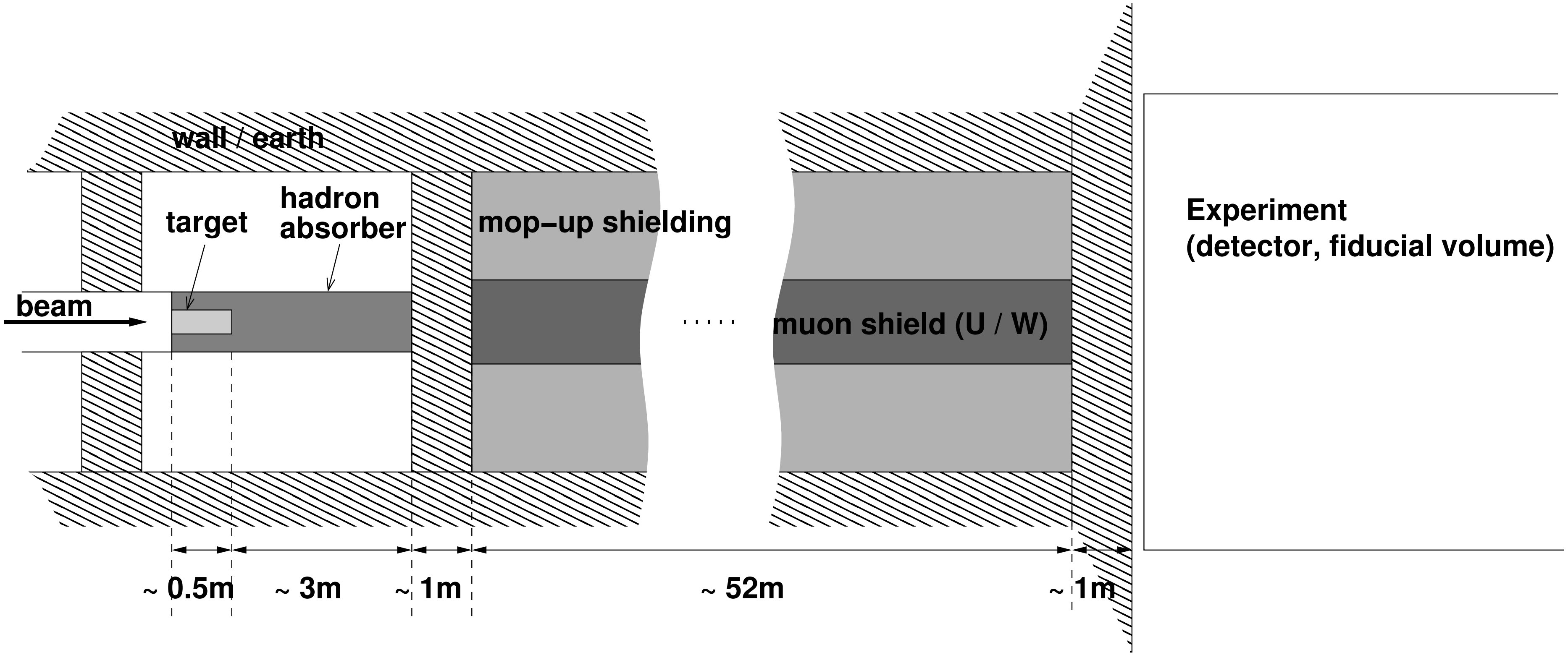
- HNLs produced in charm decays have significant **p_T** :





  - Detector must be close to target to maximise geometrical acceptance
  - Shielding for muons must be as short as possible

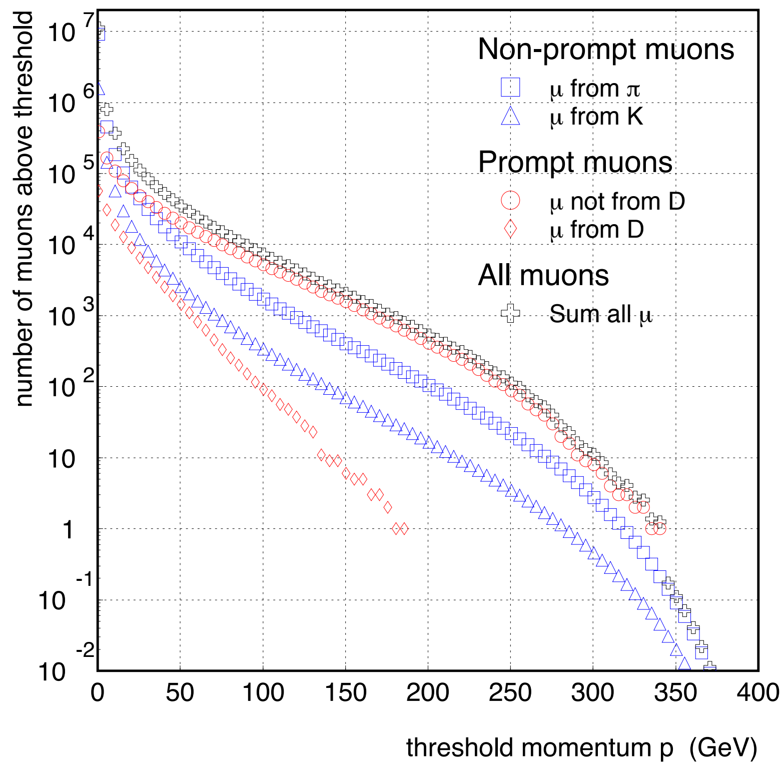
Secondary beam-line



- Proton target
  - Preference for relatively slow beam extraction O(s) to reduce detector occupancy
  - No requirement to have a small beam spot

Muon shield

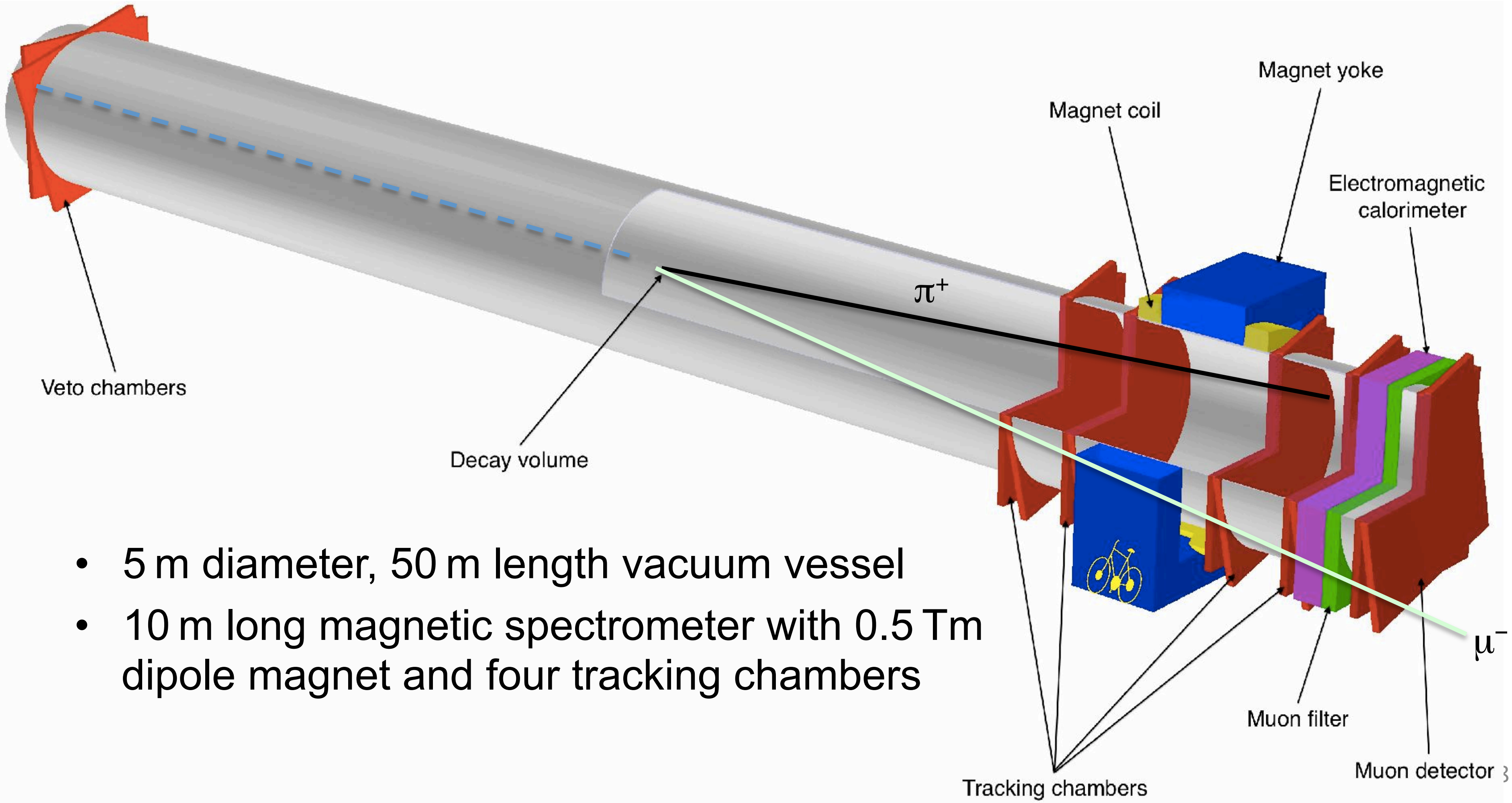
- Main sources of muons simulated using PYTHIA (10^9 p @ 400 GeV)
- Cross-checked with results from CHARM beam-dump experiment
- A muon shield made of ~55 m W(U) should stop muons with E<400 GeV
- Detailed simulations being performed to define the exact length and radial extent of the shield



- Expect that muon-induced backgrounds will be reduced to negligible level with such a shield
- After shield expect **2×10^4** neutrino interactions in the decay volume per **2×10^{20} pot** at atmospheric pressure → **negligible at 0.01 mbar**

Detector Concept

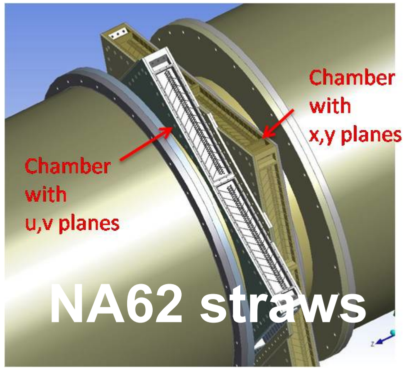
- Aim to reconstruct HNL decays into the final states: **$\mu^-\pi^+$, $\mu^-\rho^+$, $e^-\rho^+$**
- Require long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter



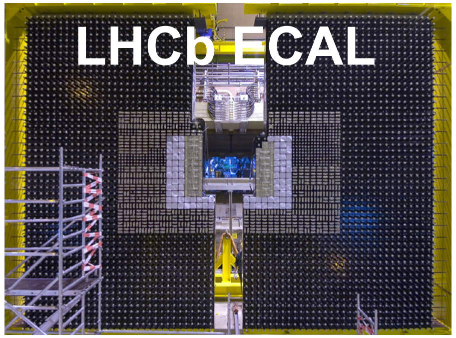
- 5 m diameter, 50 m length vacuum vessel
- 10 m long magnetic spectrometer with 0.5 Tm dipole magnet and four tracking chambers

Detector Technologies

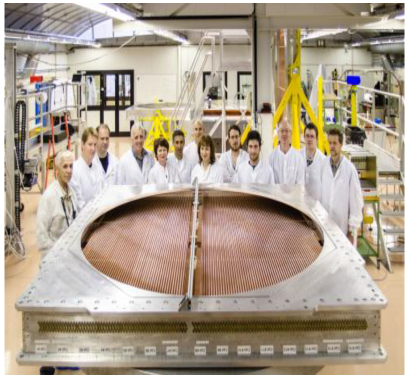
- **Dipole magnet**
  - Magnet similar to LHCb design required, but with ~40% less iron and 3× less power dissipated
  - Free aperture of ~16 m^2 and field integral ~ 0.5Tm over 5 m length



- **Vaccum tank and straw tracker**
  - NA62 has 10^{-5} mbar pressure cf. 10^{-2} mbar required here
  - Have demonstrated gas tightness of straw tubes with **120 μm spatial resolution** and **0.5% X_0/X** material budget in long term tests

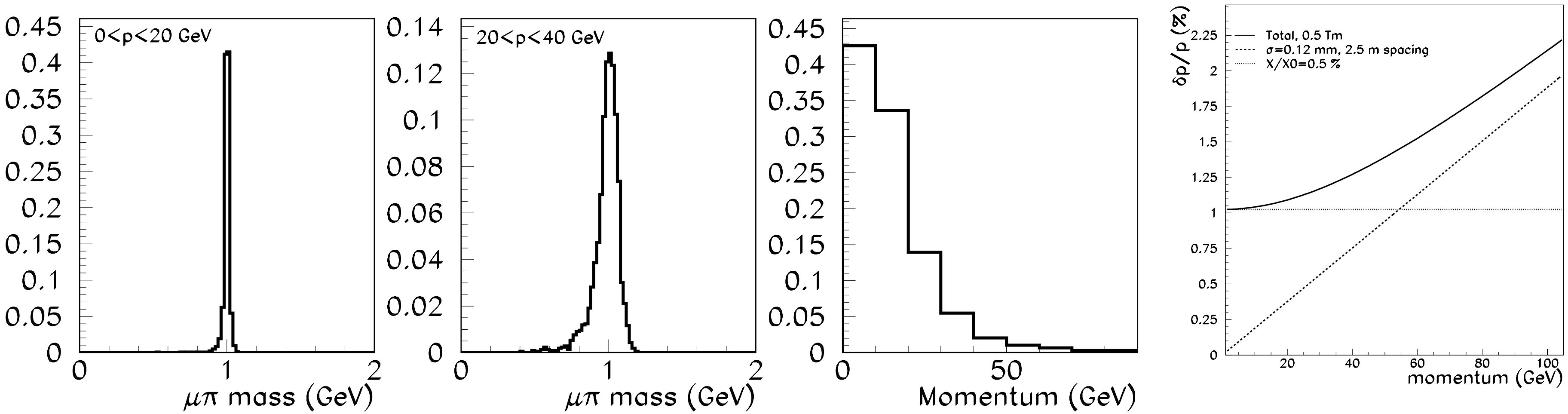


- **Electromagnetic calorimeter**
  - Shashlik technology used in LHCb would provide economical solution with good energy and time resolution



Spectrometer resolution

- Arrange spectrometer such that multiple scattering and spatial resolution of straw tubes give similar contribution to the overall **$\delta p/p$**
- For **$m(N_{2,3})$ = 1 GeV,** 75% of $\mu^-\pi^+$ decay products have p < 20 GeV



- For 0.5 Tm field integral **σ_{mass} ~ 40 MeV** for p < 20 GeV
- → Ample discrimination between high mass tail from small number of residual $K_L \to \pi^+\mu^-\nu$ and 1 GeV HNL

Residual Backgrounds I

- Use a combination of GEANT and GENIE to simulate the Charged Current and Neutral Current neutrino interactions in the final part of the muon shield (again cross-checked with CHARM measurements)
  → **CC(NC) rate of ~6(2)×10^5 per int. length per 2×10^{20} pot**
- Instrumentation of the last part of the muon shield would allow the rate of CC + NC to be measured and neutrino interactions to be tagged
- ~10% of neutrino interactions in the muon shield just upstream of the decay volume produce Λ or $\mathbf{K^0}$ (similar fraction from NOMAD measurements)
- Majority of decays occur in the first 5 m of the decay volume
- Requiring μ−id. for one of the two decay products
  → **150 two-prong vertices in 2×10^{20} pot**

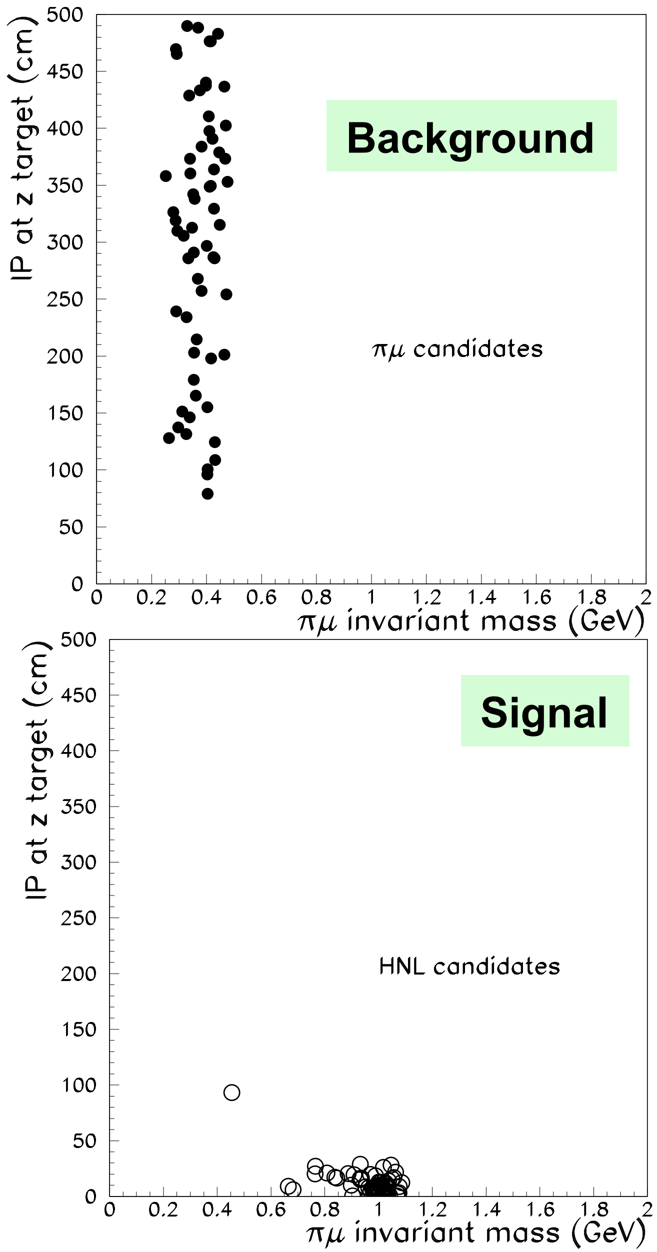
Residual Backgrounds II

- **K_L** produced in the final part of the muon shield have very different pointing to the target cf signal events

  → Use Impact Parameter (IP) to further suppress K_L background

- IP < 1 m is 100% efficient for signal and leaves only a handful of background events

- The IP cut will also be used to reject backgrounds induced in neutrino interactions in the material surrounding the detector



Expected event yield

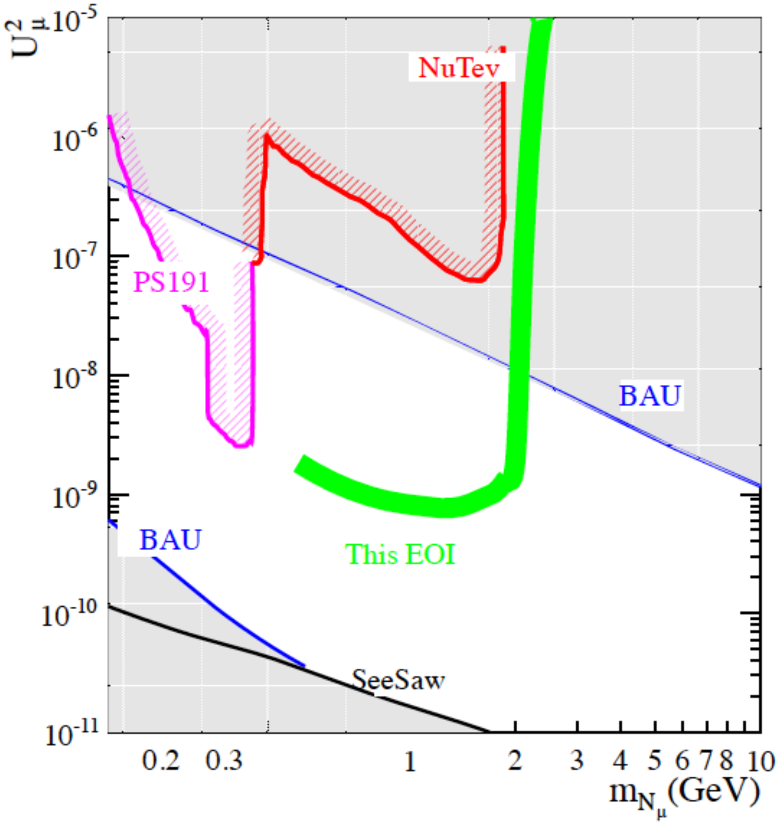
- Integral mixing angle U^2 is given by $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$
- Make a conservative estimate of the sensitivity by only considering the decay $N_{2,3} \rightarrow \mu^- \pi^+$ – probes U_μ^2
- Expected number of signal events then,

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

$N_{pot} = 2 \times 10^{20}$
$\chi_{cc} = 0.45 \times 10^{-3}$
$BR(U_\mu^2) = BR(D \rightarrow N_{2,3}X) \times BR(N_{2,3} \rightarrow \mu\pi)$
$\varepsilon_{det}(U_\mu^2)$ = prob. for $N_{2,3}$ to decay in detector and μ, π to be reconstructed

- Strongest experimental limit for $\mathbf{M_N}$ **~1 GeV** at $\mathbf{U_\mu^2 = 10^{-7}}$
  - Would then expect $\boldsymbol{\tau_N = 1.8 \times 10^{-5}}$**s** and **~12k** fully reconstructed $\mathbf{N \rightarrow \mu^- \pi^+}$
- For cosmologically favoured region $\mathbf{U_\mu^2 = 10^{-8}}$ ($\boldsymbol{\tau_N = 1.8 \times 10^{-4}}$**s**)
  - Would expect **120** fully reconstructed events

Expected sensitivity



- ECAL will allow reconstruction of modes with a π^0 e.g. $\mathbf{N\rightarrow\mu^-\rho^+}$ where $\rho^+\rightarrow\pi^+\pi^0$
- Study of decay channels with electrons would allow to further increase the signal yield (and constrain $\mathbf{U_e^2}$)

- **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}**

Conclusions

- 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 discussion of the beam line with CERN experts

- **The discovery of a HNL would have enormous impact – could solve several of the significant problems 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

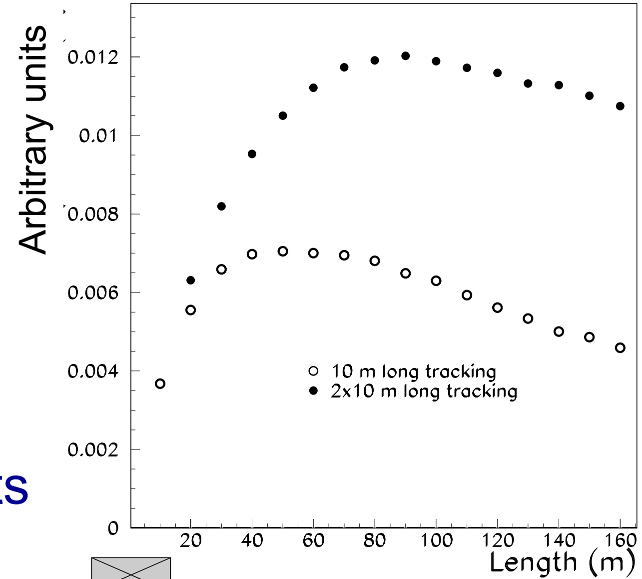
Backup

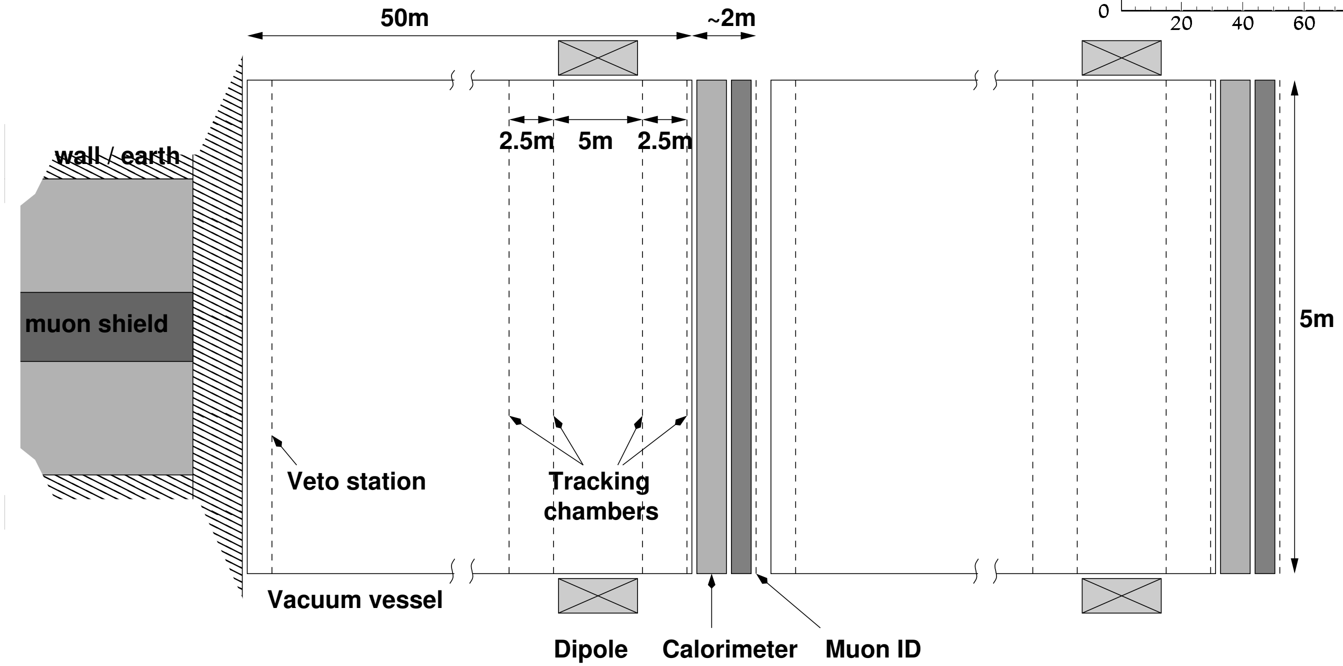
Detector Concept II

- Geometric acceptance saturates for a given HNL lifetime as a function of the detector length

- Use of two magnetic spectrometers increases acceptance by 70%

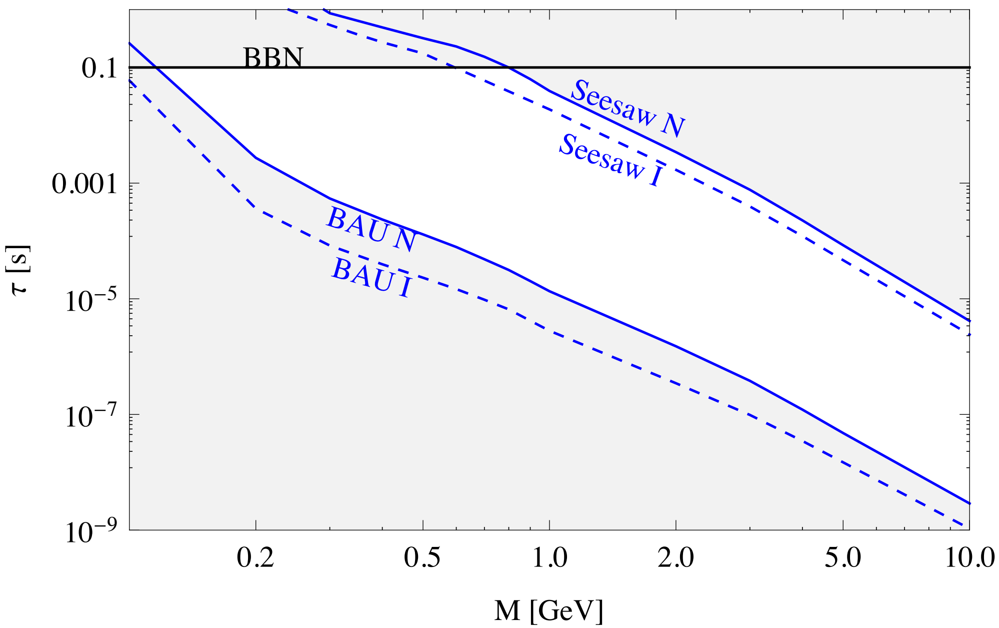
  → detector with two almost identical elements





Masses and couplings of HNLs II

- Constraints from **BAU**, **Seesaw** and Big Bang Nucleosynthesis (**BBN**) :



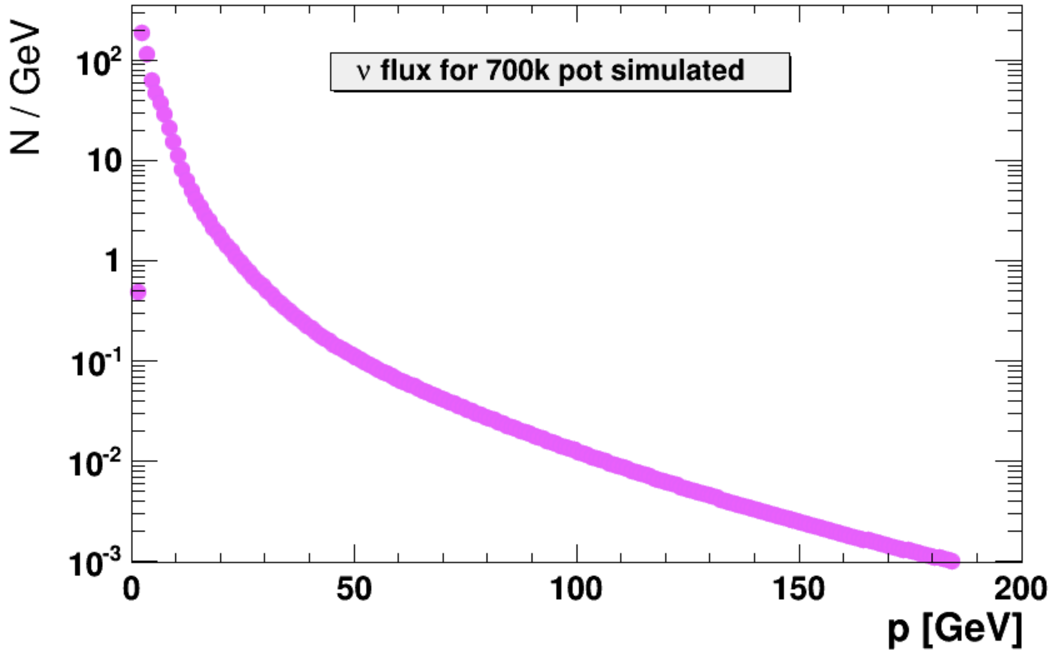
Typical lifetimes **>10 μs** for **($N_{2,3}$) ~ 1 GeV**
→ decay distance O(km)

- Branching fractions depend on the level of mixing, typically,
  - $B(N \to \mu^-/e^- \pi^+)$ ~ 0.1 – 50%
  - $B(N \to \mu^-/e^- \rho^+)$ ~ 0.5 – 20%
  - $B(N \to \nu\mu e)$ ~ 1 – 10%

- Focus on $\mu^-\pi^+$ signature, below
- $\mu^-\rho^+$ and $e^-\pi^+$ final states could extend the sensitivity

Residual neutrino flux

- Momentum spectrum of the neutrino flux after the muon shield



- At atmospheric pressure expect **$2{\times}10^4$** neutrino interactions in the decay volume per **$2{\times}10^{20}$ pot**

  → becomes negligible at 0.01 mbar

Other BSM physics

- Can make searches for other light, very weakly interacting new particles :
  - Light superpartners of goldstino in SUSY models e.g. **$D \to \pi X$, $X \to l^+l^-$**
    [Gorbunov (2001)]
  - R-parity violating neutralinos in SUSY models e.g. **$D \to lX$, $X \to l^+l^-\nu$**
    [A.Dedes, H.K Dreiner, P Richardson (2001)]
  - Massive paraphotons (in secluded dark matter models) e.g. **$\Sigma \to lX$, $X \to l^+l^-$**
    [M.Pospelov, A. Ritz, M.B. Voloshin (2008)]

Other facilities

- Have considered if could perform experiment elsewhere

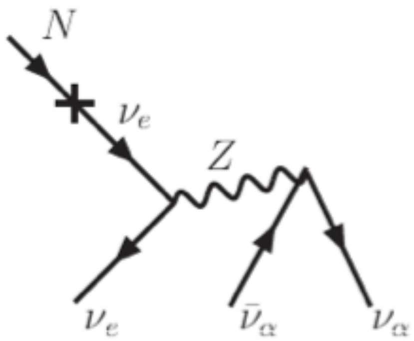
- Fermilab
  - 120 GeV proton beam, 4×10^{19} POT
    - factor ten lower event yield than in the proposed SPS experiment
  - 800 GeV proton beam, 1×10^{19} POT
    - Lower POT would be approximately compensated by higher charm cross-section
    - Would require much longer muon shield → loss of acceptance

- KEK
  - 30 GeV proton beam, 1×10^{21} POT
    - large uncertainty due to the poor knowledge of the charm cross-section at low energy
    - Estimate factor 1.5-2 lower signal yields

- Colliding beam experiment at LHC, 1000 fb^{-1}, 14 TeV
  - Assuming experiment located 60m away from the interaction region and 50 mrad off-axis to avoid LHC beams – factor 200 worse than proposal

N_1 as Dark Matter

- For small Yukawa couplings, HNL can be long-lived and therefore a dark matter candidate



$$\text{Lifetime} = \frac{192\pi^3}{G_F^2 M^5 U^2} \approx 10^{27}\,\mathrm{sec}\left(\frac{\mathrm{keV}}{M}\right)^5\left(\frac{10^{-8}}{U^2}\right)$$

- Characteristic signature: can have radiative decay which will give a monochromatic decay line in the spectra of galaxies

Searches for N_1

- N_1 has been searched or by the XMM-Newton, Chandra, Suzaku and Integral experiments

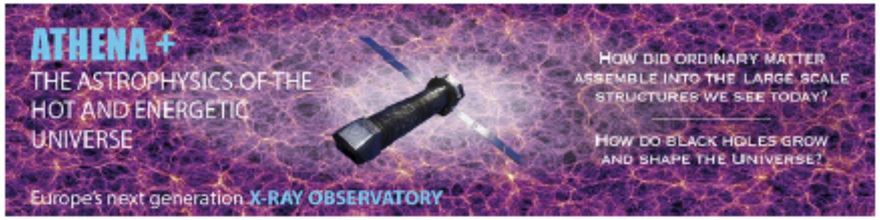
- Spectral resolution is insufficient (require **$\Delta E/E \sim 10^{-3}$**)

- Several proposed/planned x-ray missions which will have sufficient resolution:

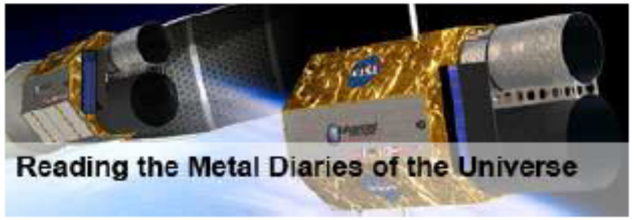
Astro-H

LOFT

Athena+



Origin/Xenia



Parameter space for N_1