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

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

On behalf of:

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Triumph of the Standard Model

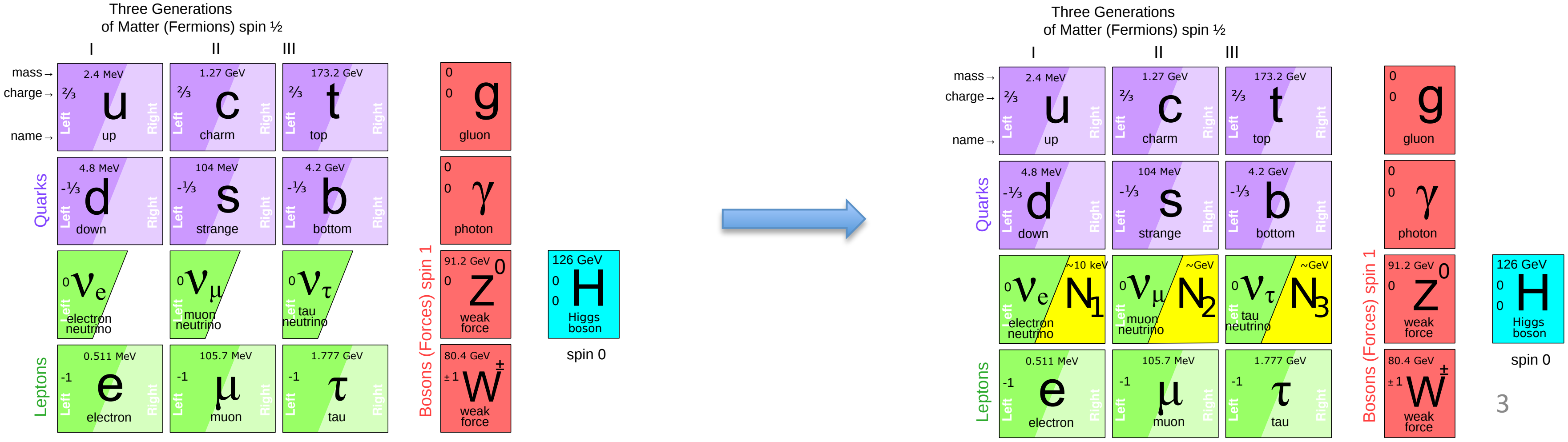
Theoretical motivation

- *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*

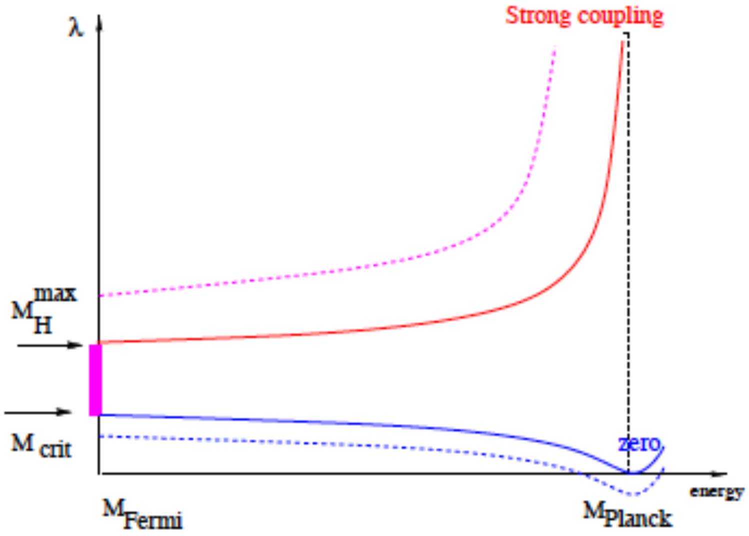


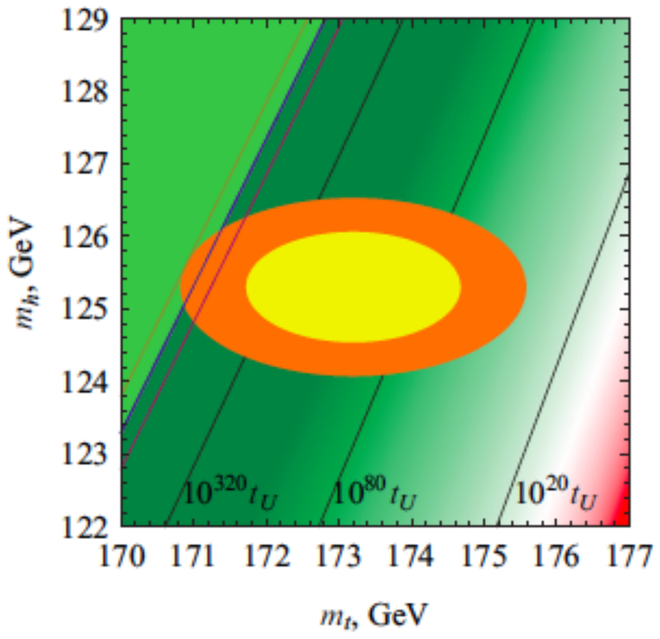
SM may well be a consistent effective theory all the way up to the Planck scale

✓ *No sign of New Physics seen beyond the SM*

✓ $\boldsymbol{M_H}$ **< 175 GeV** → *SM is a weakly coupled theory up to Planck energies !*

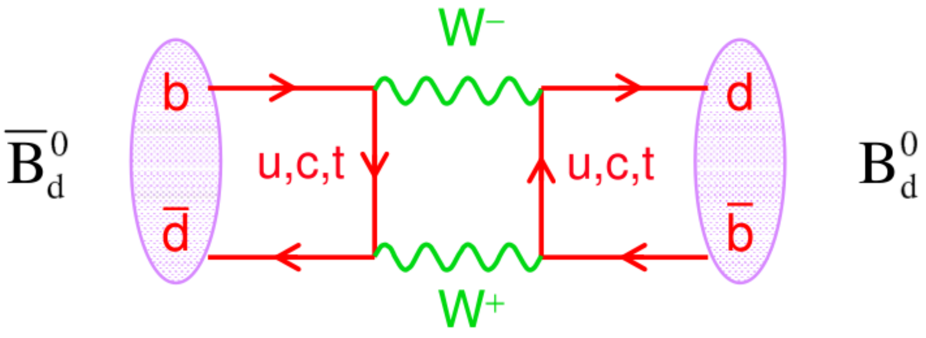
✓ $\boldsymbol{M_H}$ **> 111 GeV** → *The EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (Espinosa et al)*



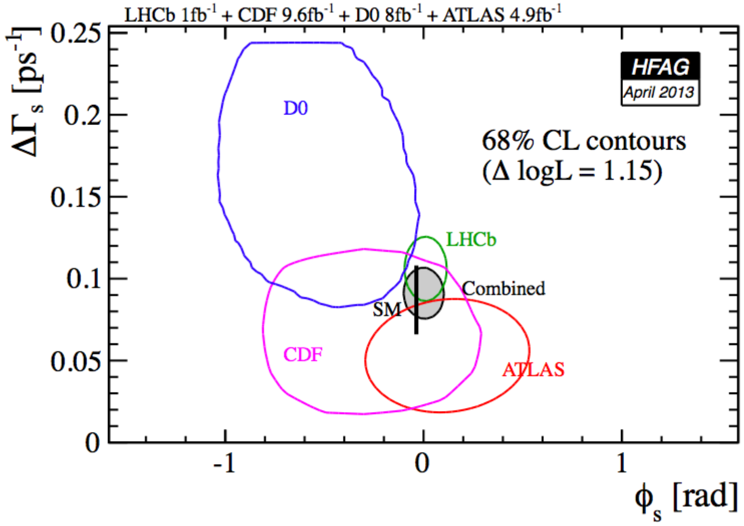


Bounds on the scale of New Physics

Most stringent limits come from observables in $B\bar{B}$ mixing



$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP}\frac{1}{\Lambda^2}$$



$$c_{NP} \to \sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4\ \text{TeV [K]}$$

$$c_{NP} \to \sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3\ \text{TeV [K]}$$

$$c_{NP} \to \sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5\ \text{TeV [K \& B]}$$

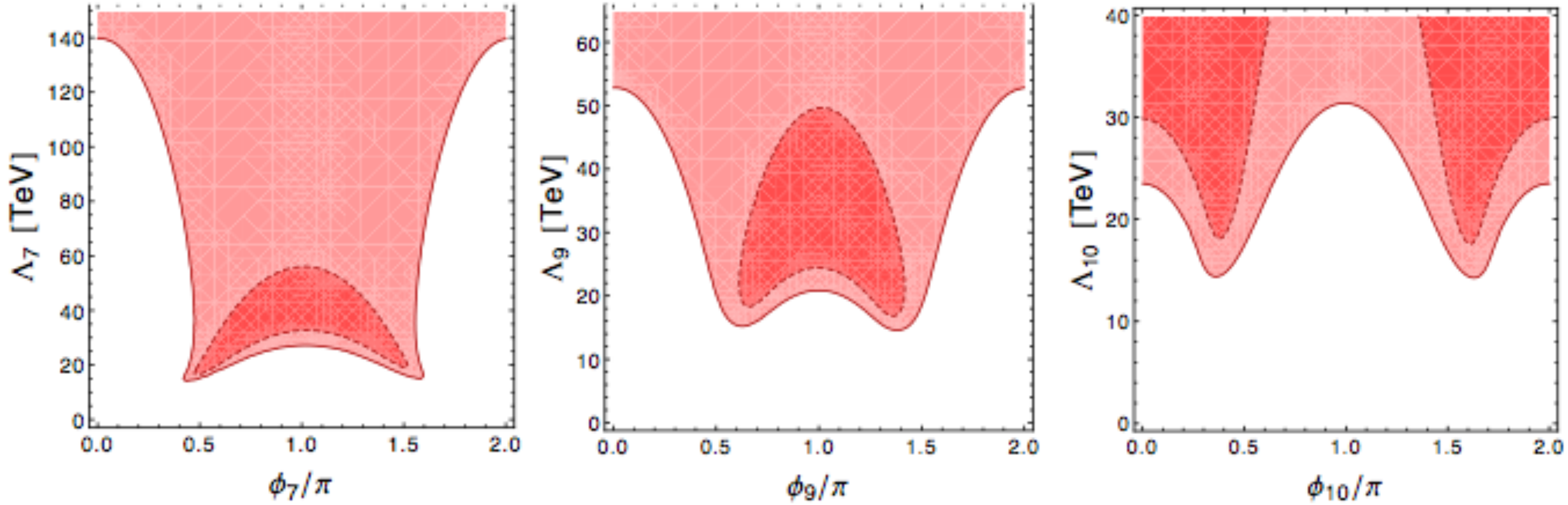
$$c_{NP} \to \sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5\ \text{TeV [K \& B]}$$

Bounds on the scale of New Physics

Limits from EW penguin processes

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2}\mathcal{O}_j$$

~tree level generic
flavour violation



Λ_{NP} > 14 - 140 TeV !!!

<u>Some hints for deviation from SM with existing data:</u>

- *Violation of spectator model in B→K$\mu\mu$*
- *Angular analysis of B→K*$\mu\mu$*

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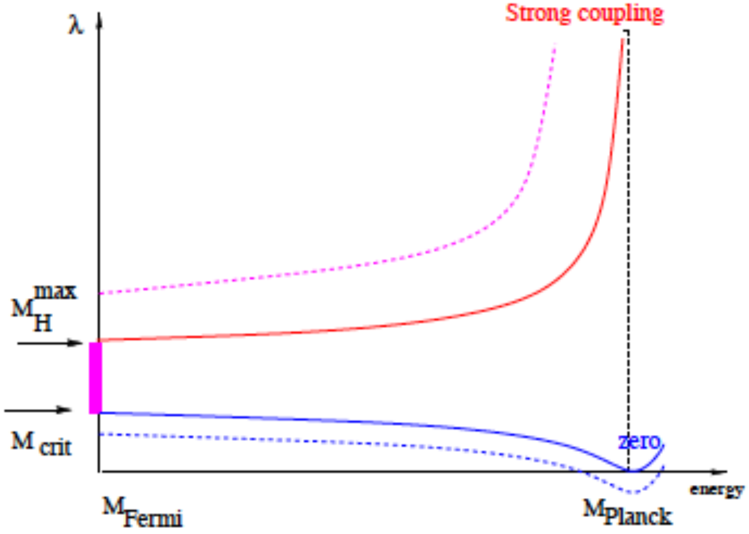
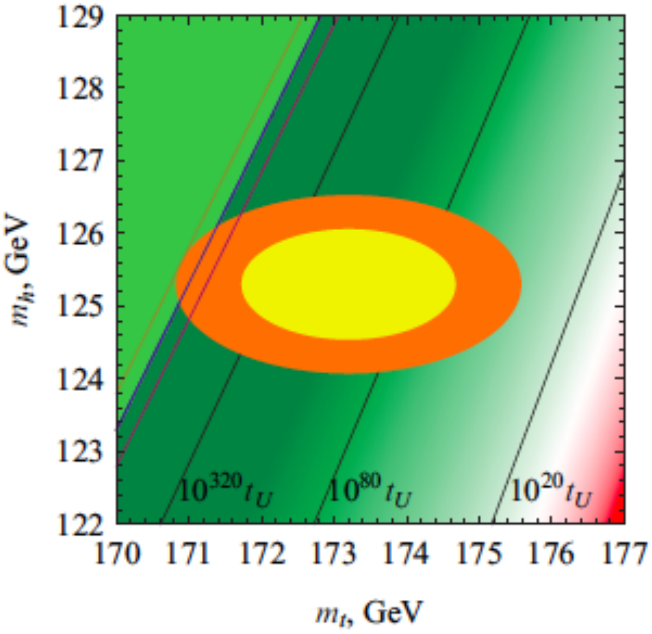




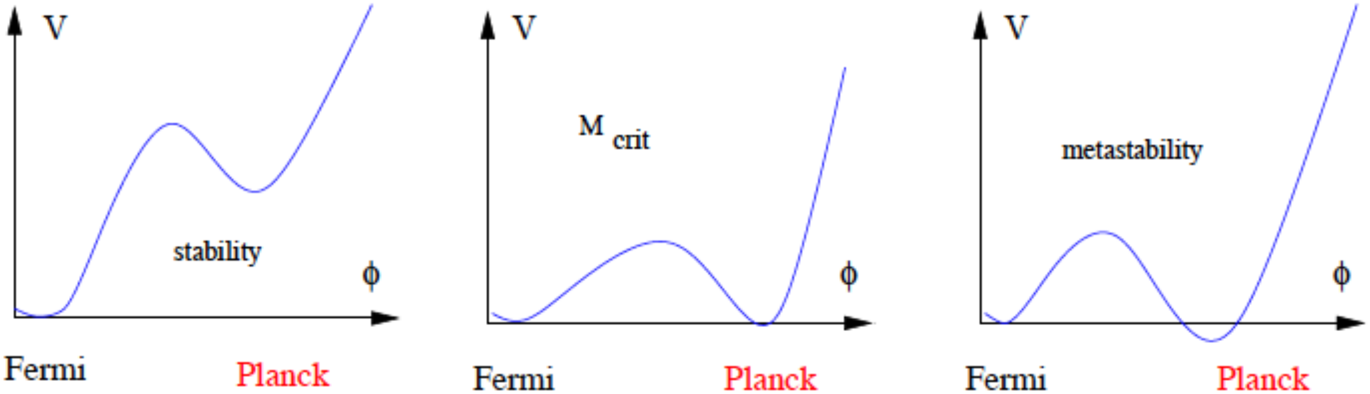
*The mass of the Higgs boson is very close to the stability bound of the Higgs mass **

$$M_{crit} = \left[129.3 + \frac{y_t(M_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5\right] \mathrm{GeV}$$

$y_t(M_t)$ - top Yukawa in $\overline{\mathrm{MS}}$ scheme

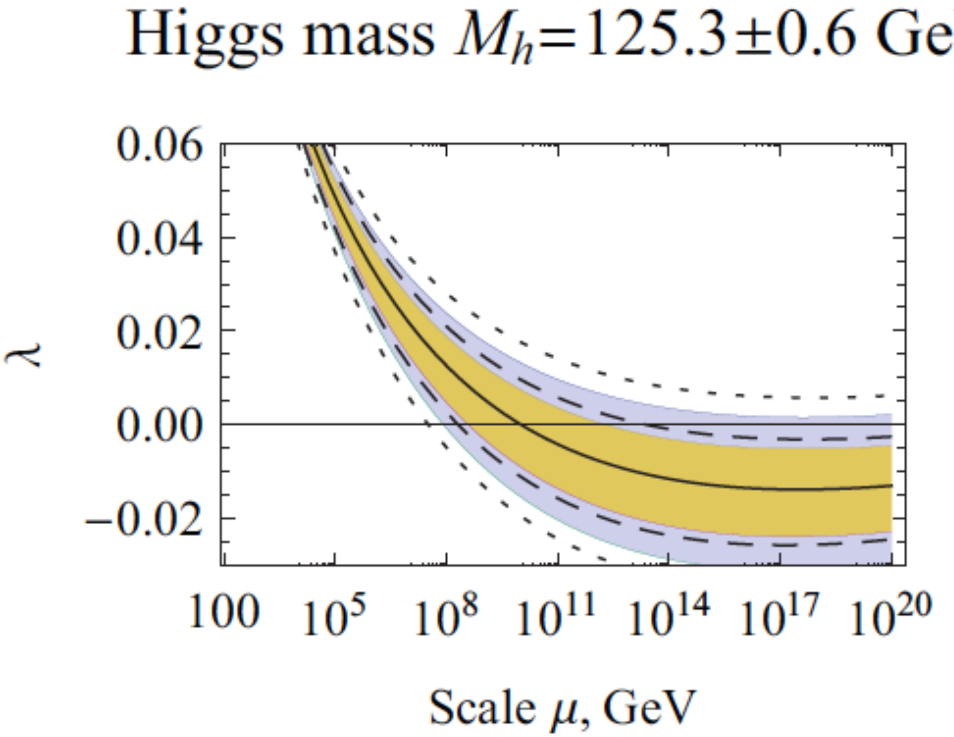
Matching at EW scale	Central value	theor. error
Bezrukov et al, $\mathcal{O}(\alpha\alpha_s)$	129.4 GeV	1.0 GeV
Degrassi et al, $\mathcal{O}(\alpha\alpha_s, y_t^2\alpha_s, \lambda^2, \lambda\alpha_s)$	129.6 GeV	0.7 GeV
Buttazzo et al, complete 2-loop	129.3 GeV	0.07 GeV

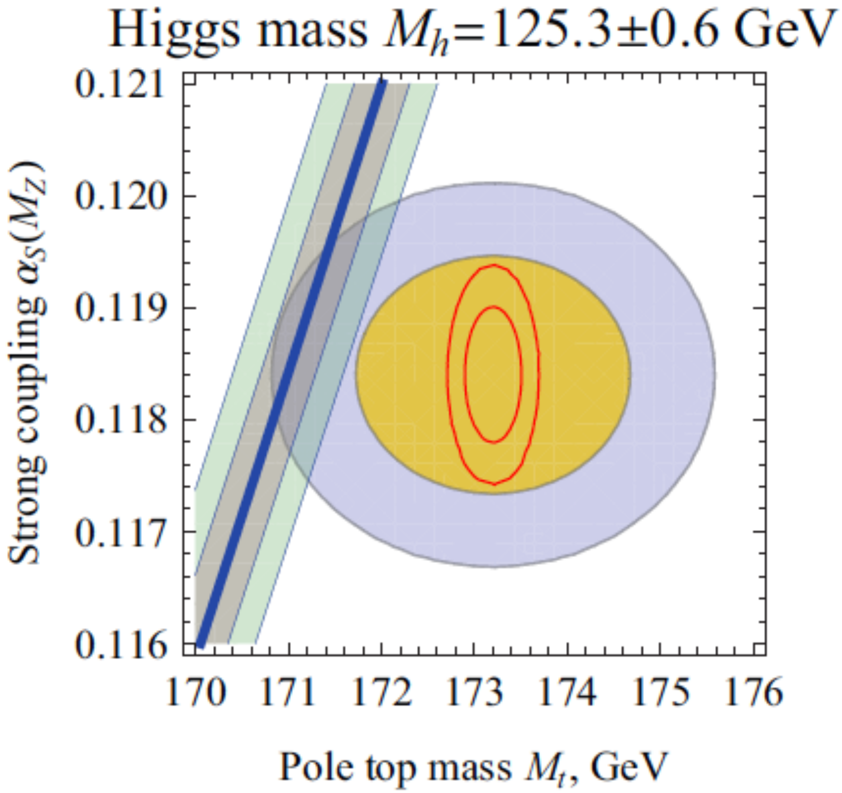
Chetyrkin et al, Mihaila et al, Bednyakov et al, 3 loop running to high energies



* Froggatt, Nielsen

Our vacuum may be absolutely stable as perfectly compatible with current measurements of M_t , M_H and α_s





errors in y_t: theory + experiment

Tevatron: $M_t = 173.2 \pm 0.51 \pm 0.71$ GeV

ATLAS and CMS: $M_t = 173.4 \pm 0.4 \pm 0.9$ GeV

$\alpha_s = 0.1184 \pm 0.0007$

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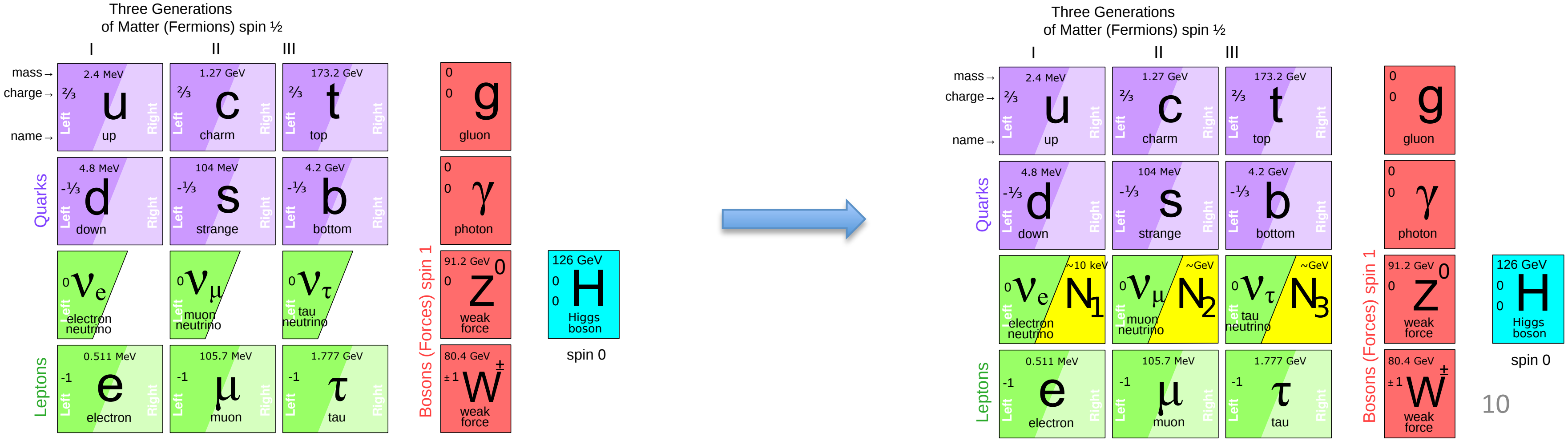
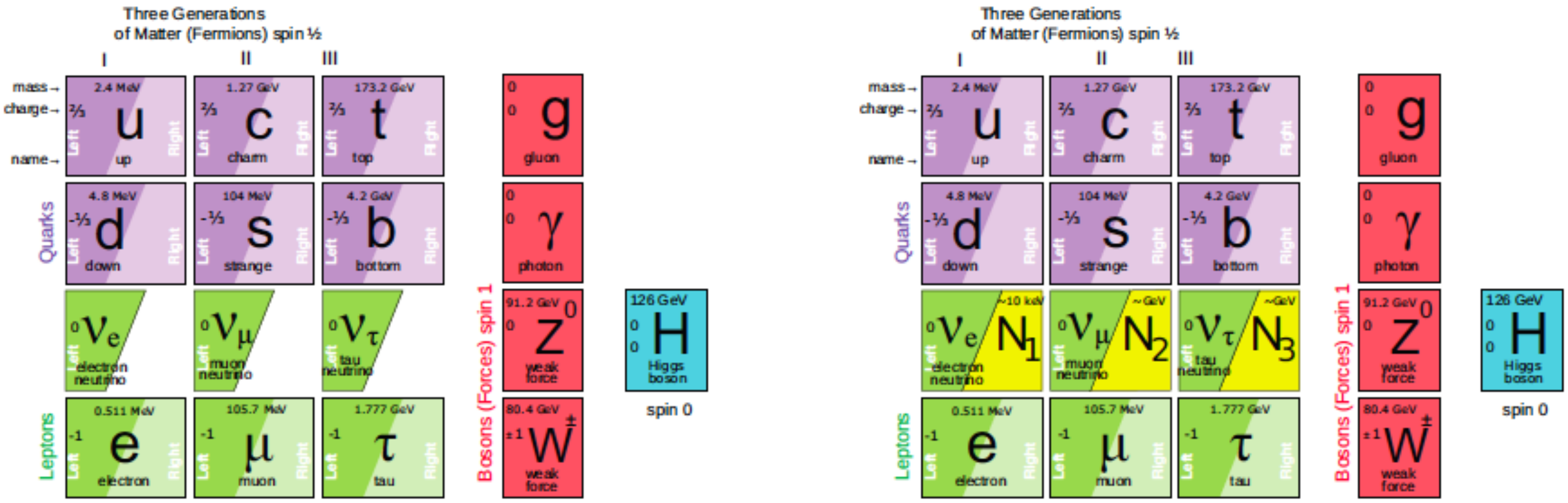


The νMSM model



N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

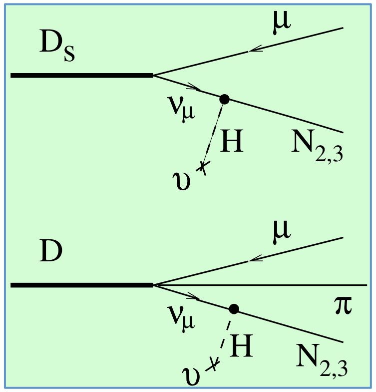
Masses and couplings of HNLs

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

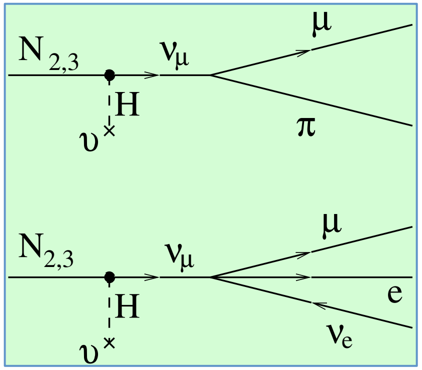
- $M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)

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



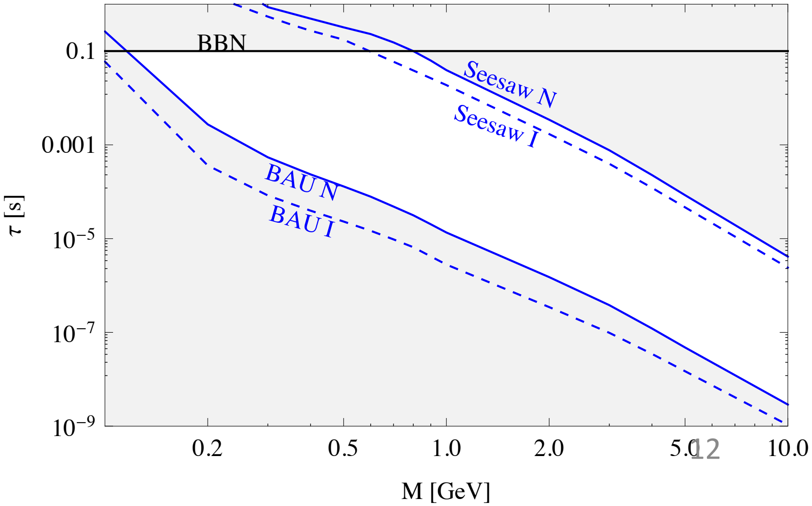
and subsequent decays



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

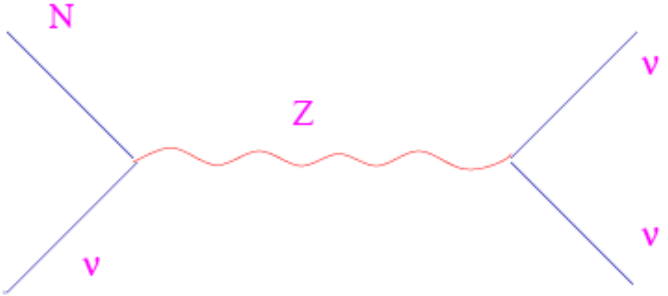
- Typical BRs (depending on the flavour mixing):

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



Dark Matter candidate HNL N_1

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



Main decay mode: $N \rightarrow 3\nu$.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

For one flavour:

$$\tau_{N_1} = 10^{14}\,\text{years} \left(\frac{10\ \text{keV}}{M_N}\right)^5 \left(\frac{10^{-8}}{\theta_1^2}\right)$$

$$\theta_1 = \frac{m_D}{M_N}$$

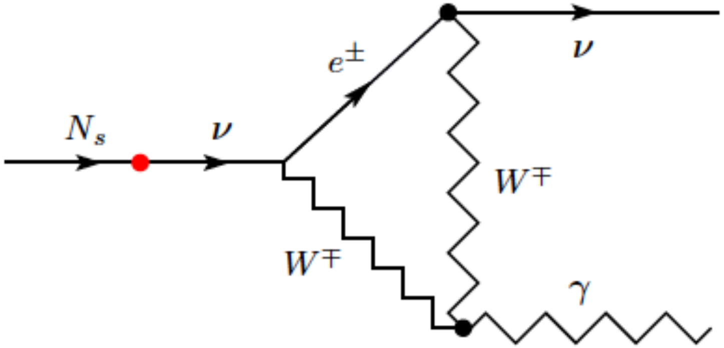
Dark Matter candidate HNL N_1

DM particle is not stable. Main decay mode $N_1 \to 3\nu$ is not observable.

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$



Radiative decay width:

$$\Gamma_{\rm rad} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256\cdot 4\pi^4}\,\sin^2(2\theta)\,M_N^5$$

Constraints on DM HNL N_1

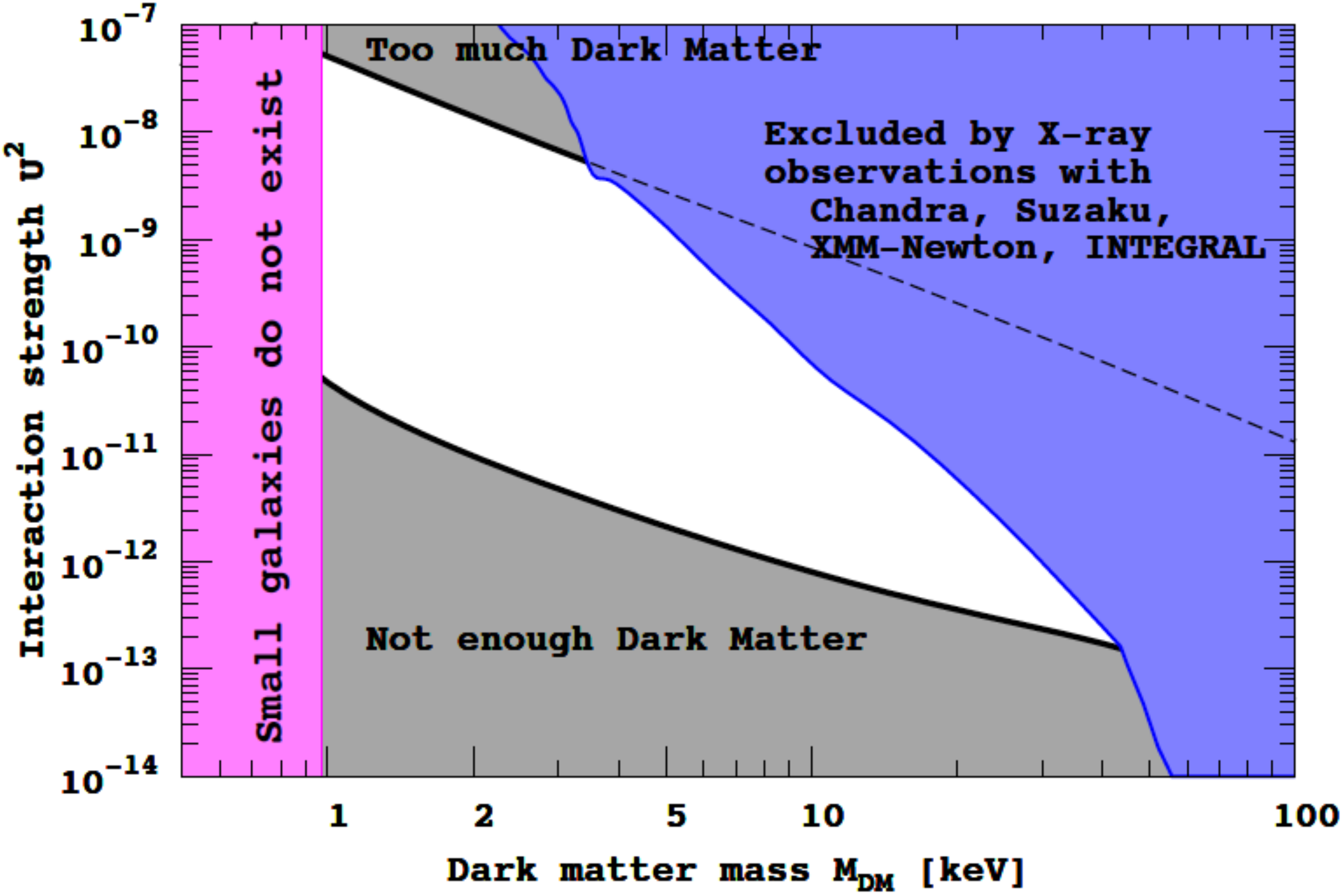
- ✓ ***Stability*** → *N_1 must have a lifetime larger than that of the Universe*

- ✓ ***Production*** → *N_1 are created in the early Universe in reactions $\bar{l}l \rightarrow \nu N_1$, $q\bar{q} \rightarrow \nu N_1$ etc. Need to provide correct DM abundance*

- ✓ ***Structure formation*** → *N_1 should be heavy enough ! Otherwise its free streaming length would erase structure non-uniformities at small scales (Lyman-α forest spectra of distant quasars and structure of dwarf galaxies)*

- ✓ ***X-ray spectra*** → *Radiative decays $N_1 \rightarrow \gamma\nu$ produce a mono-line in photon galaxies spectrum. This line has not yet been seen by X-ray telescopes (such as Chandra or XMM-Newton)*

Allowed parameter space for DM HNL N_1

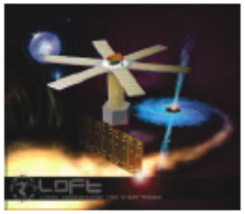


Searches for DM HNL N_1 in space

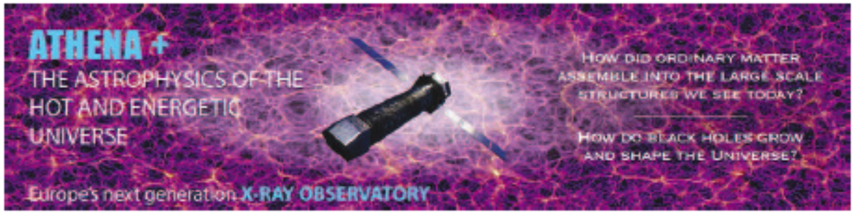
- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)
- Proposed/planned X-ray missions with sufficient spectral resolution:

Astro-H

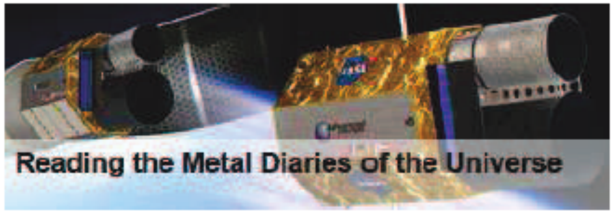
LOFT



Athena+



Origin/Xenia



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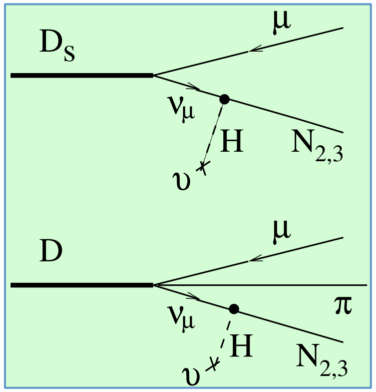

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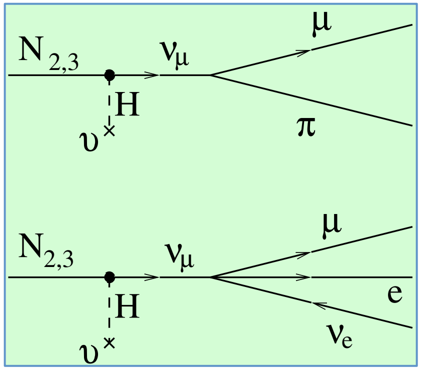

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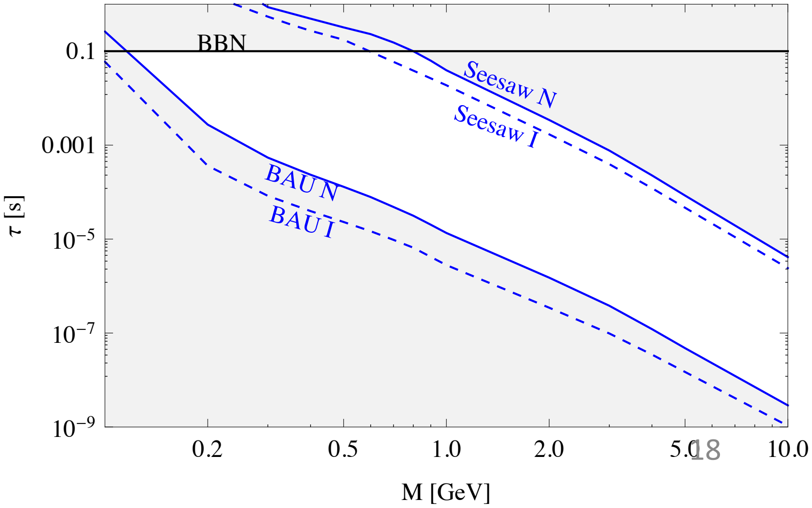

Baryon asymmetry

- *CP is not conserved in νMSM*

  6 CPV phases in the lepton sector and 1 CKM phase in the quark sector (to be compared with only one CKM phase in the SM)

- *Deviations from thermal equilibrium*

⬇

- ✓ ***HNL are created in the early Universe***
- ✓ ***CPV in the interference of HNL mixing and decay***
- ✓ ***Lepton number goes from HNL to active neutrinos***
- ✓ ***Then lepton number transfers to baryons in the equilibrium sphaleron processes***

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry is generated by CPV in HNL mixing and decays + sphalerons

- ✓ *BAU generation requires out of equilibrium → mixing angle of $N_{2,3}$ can not be large*
- ✓ *To generate correct order of the active neutrino masses the mixing angle of $N_{2,3}$ to active neutrino can not be too small*
- ✓ *Decays of $N_{2,3}$ should keep BBN scenario working*
- ✓ *Experimental constraints*

PS *Explanation of DM with N_1 reduces a number of free parameters*
→ Degeneracy of $N_{2,3}$ masses is required to ensure sufficient CPV

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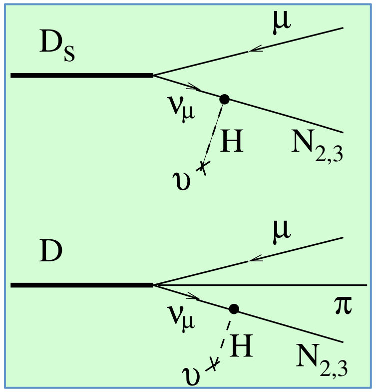

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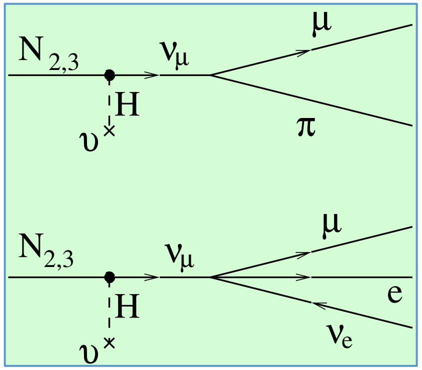

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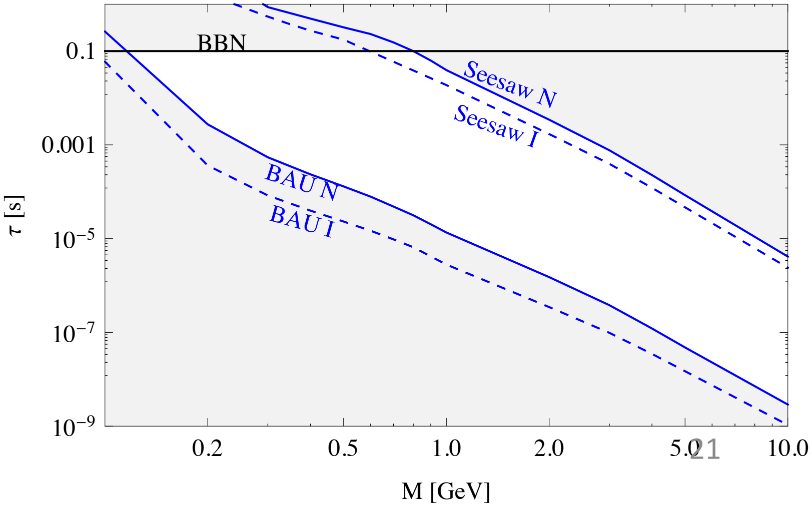
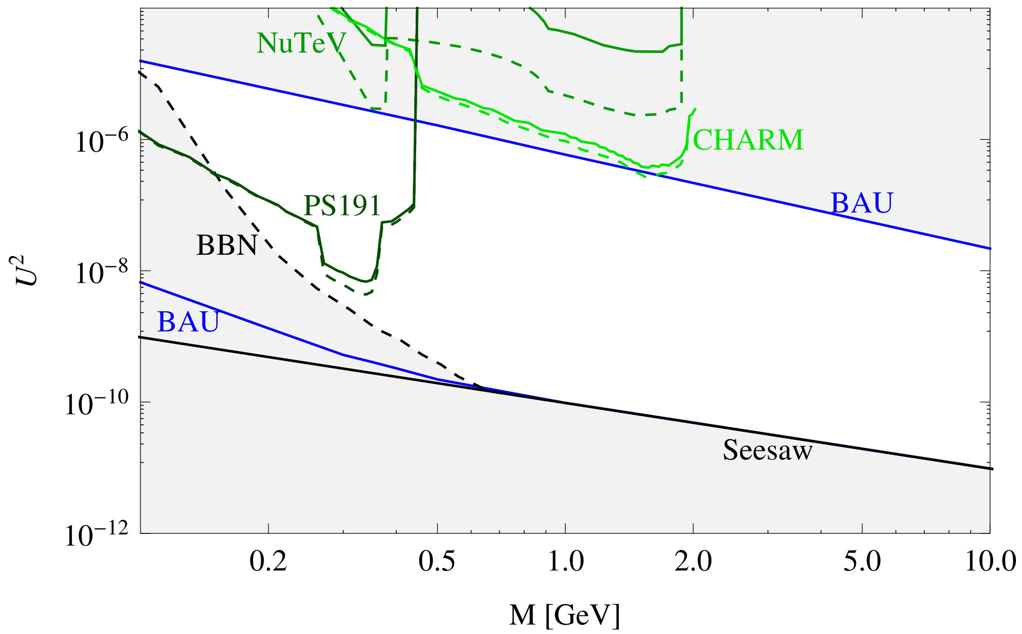


Experimental and cosmological constraints



- ***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*

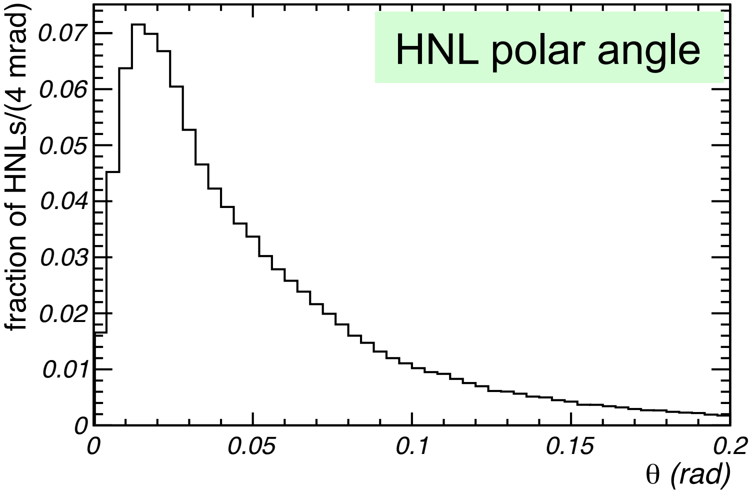
Proposal for a new experiment at the SPS to search for New Particles produced in charm decays

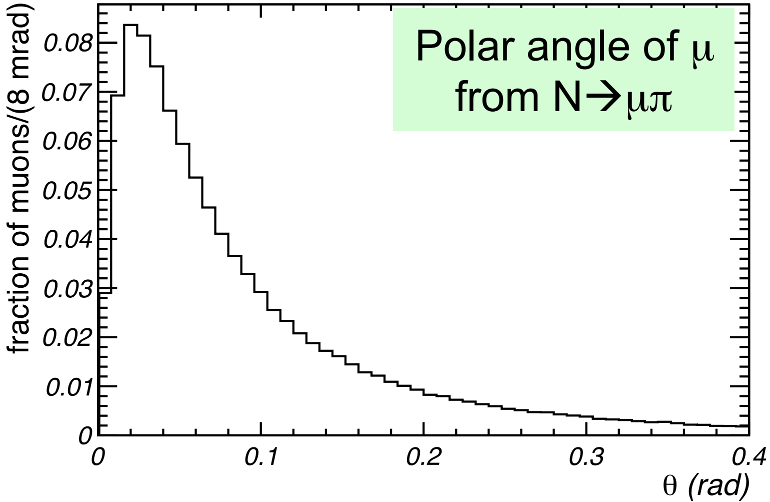
Experimental requirements

- *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*

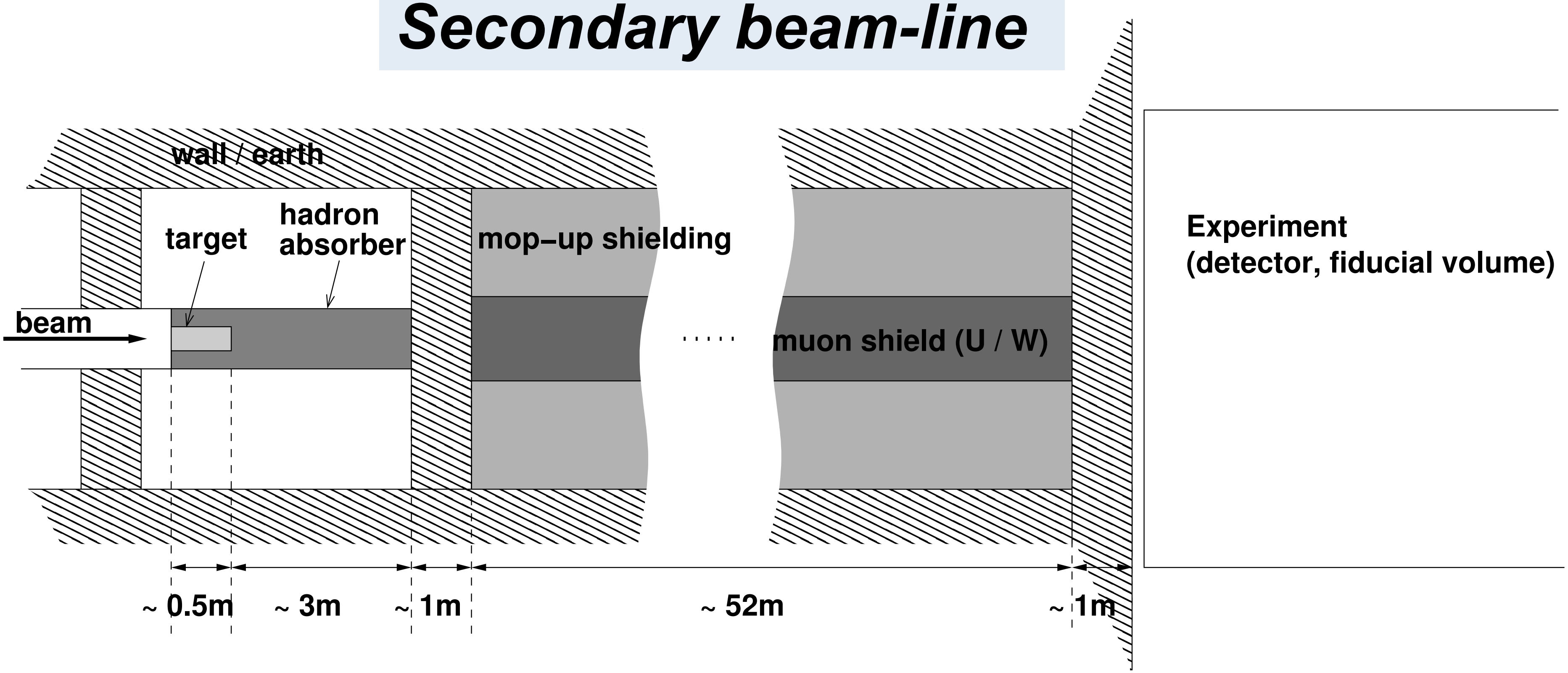

HNL polar angle


Polar angle of μ from N→μπ

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.)

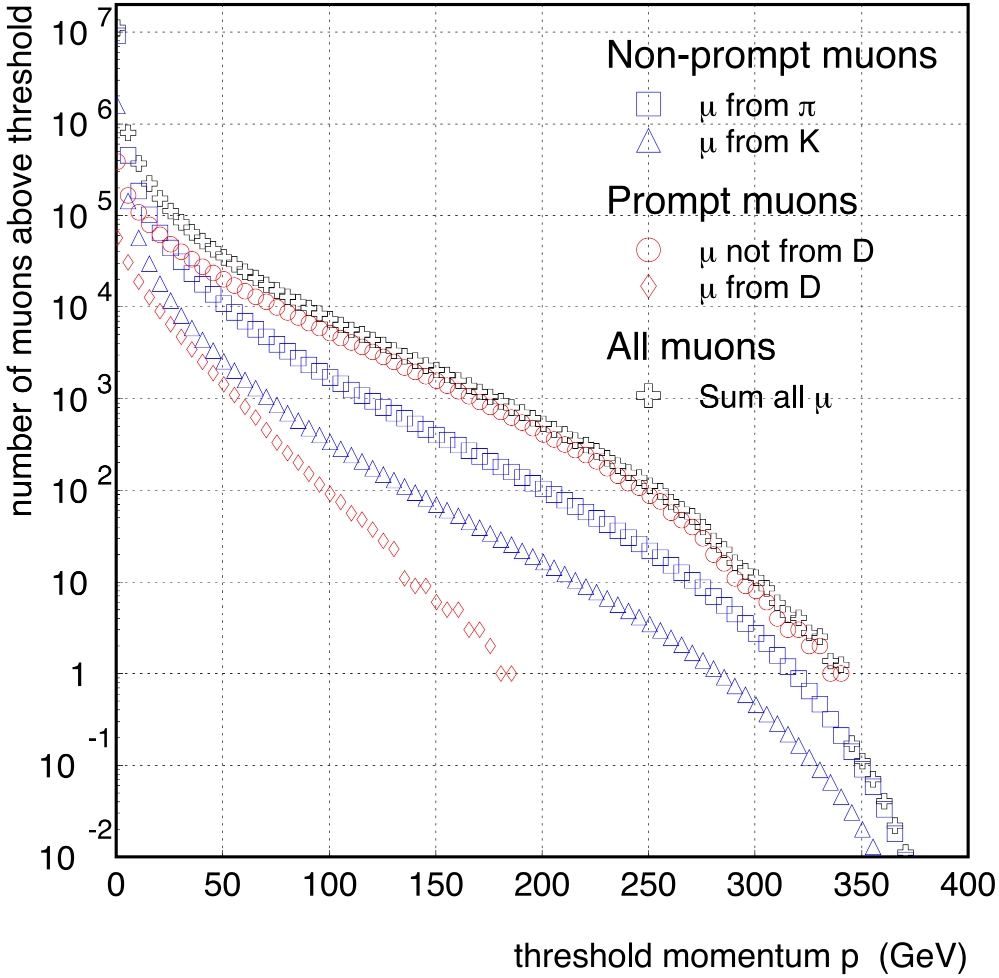
Muon shield

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*



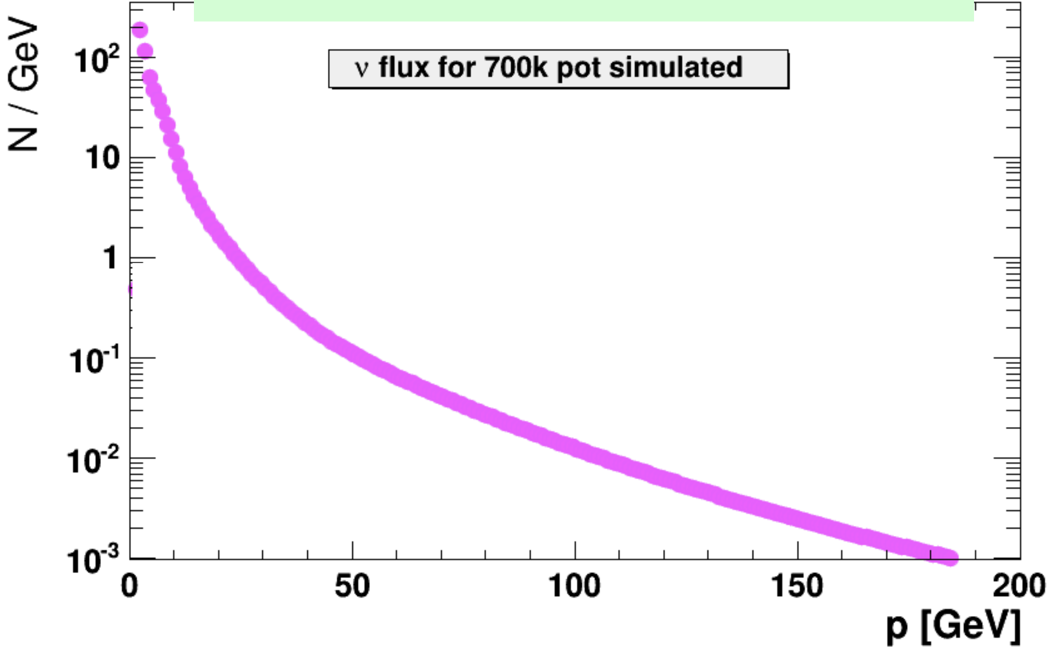
Assume that muon induced backgrounds will be reduced to negligible level with such a shield

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

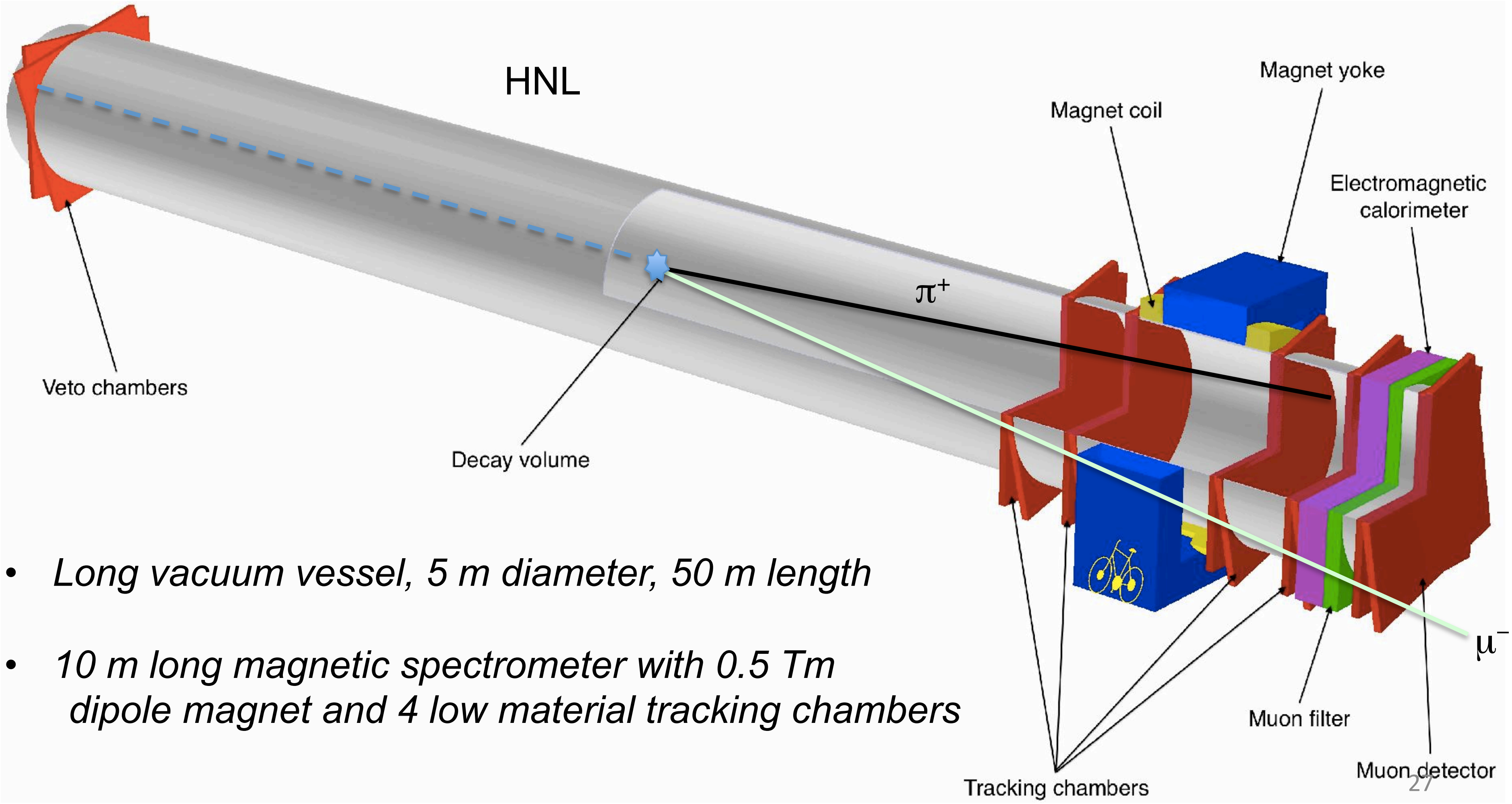


2×10^{4} neutrino interactions per 2×10^{20} pot in the decay volume at atmospheric pressure → becomes negligible at 0.01 mbar

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

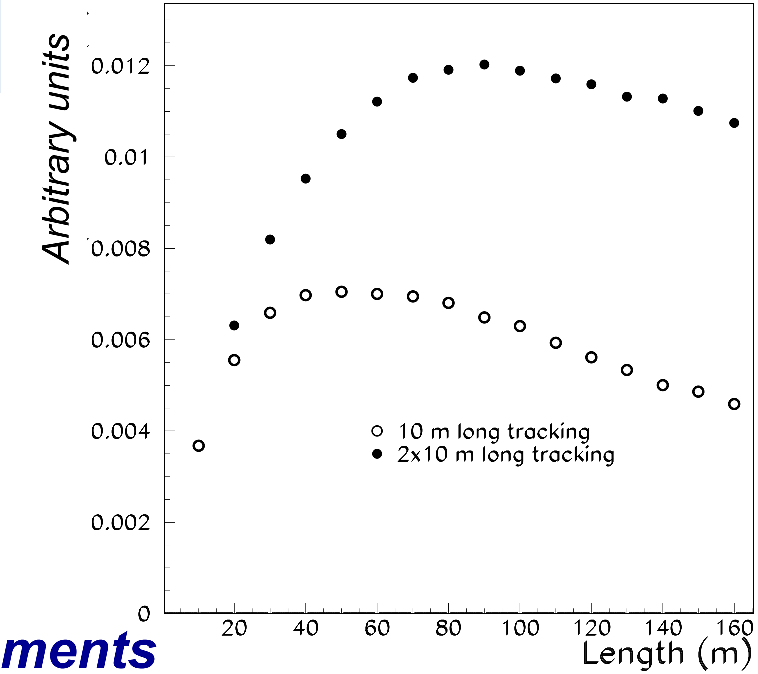


- *Long vacuum vessel, 5 m diameter, 50 m length*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

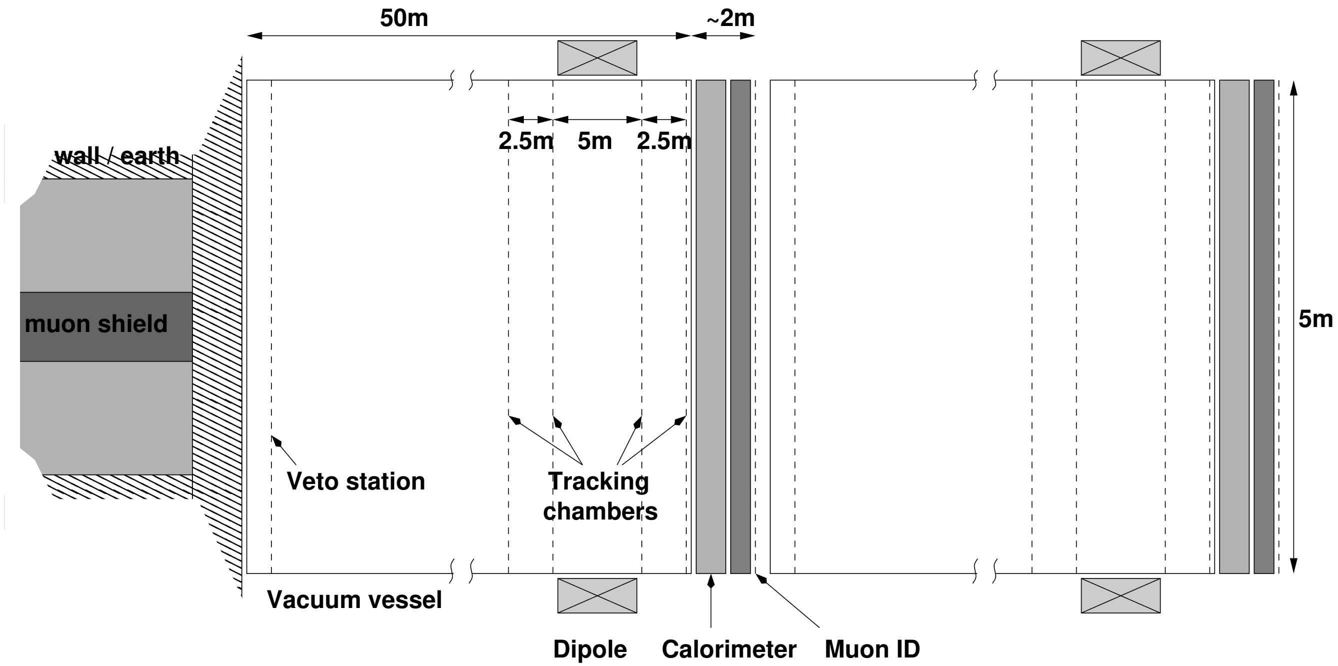
Detector concept (cont.)

Geometrical acceptance

- *Saturates for a given HNL lifetime as a function of detector length*
- *The use of two magnetic spectrometers increases the acceptance by 70%*



↳ ***Detector has two almost identical elements***



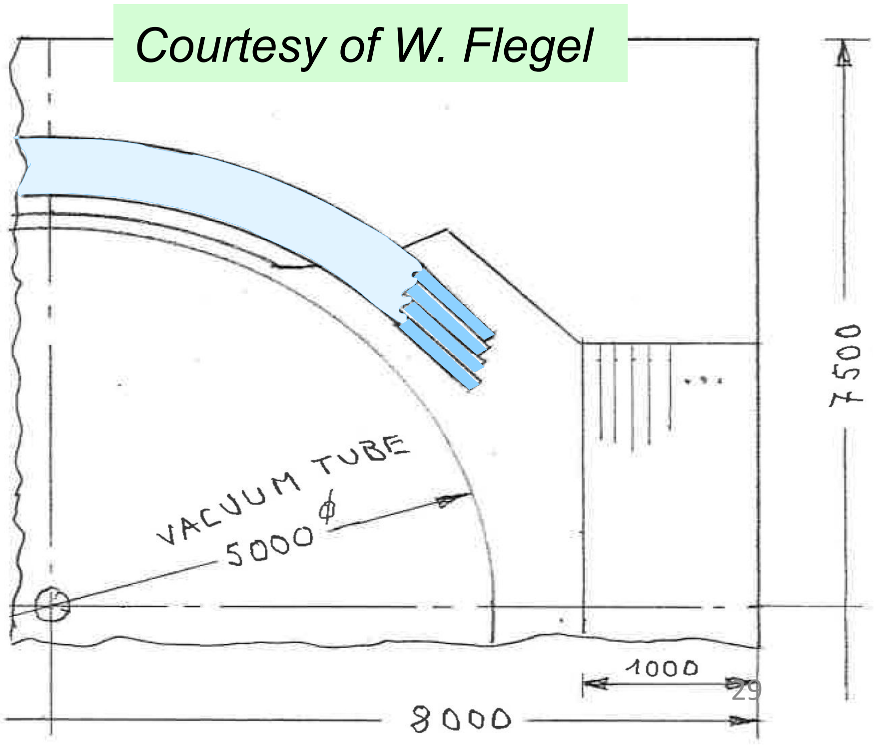
Detector apparatus

based on existing technologies

- *Experiment requires a dipole magnet similar to LHCb design, but with ~40% less iron and three times less dissipated power*

- *Free aperture of ~ 16 m^2 and field integral of ~ 0.5 Tm*

- Yoke outer dimension: 8.0×7.5×2.5 m^3
- Two Al-99.7 coils
- Peak field ~ 0.2 T
- Field integral ~ 0.5 Tm over 5 m length

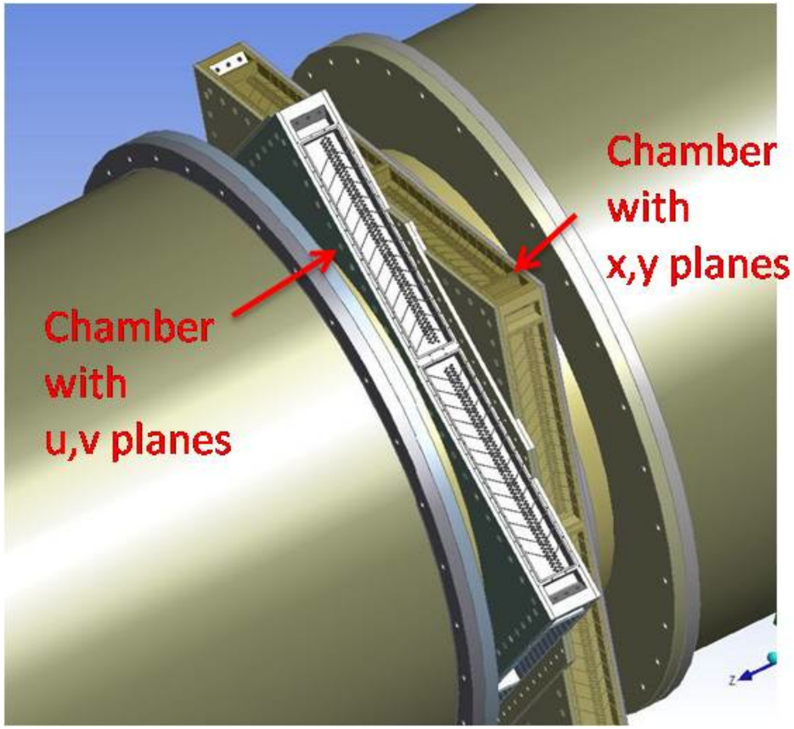

Courtesy of W. Flegel

Detector apparatus (cont.)

based on existing technologies

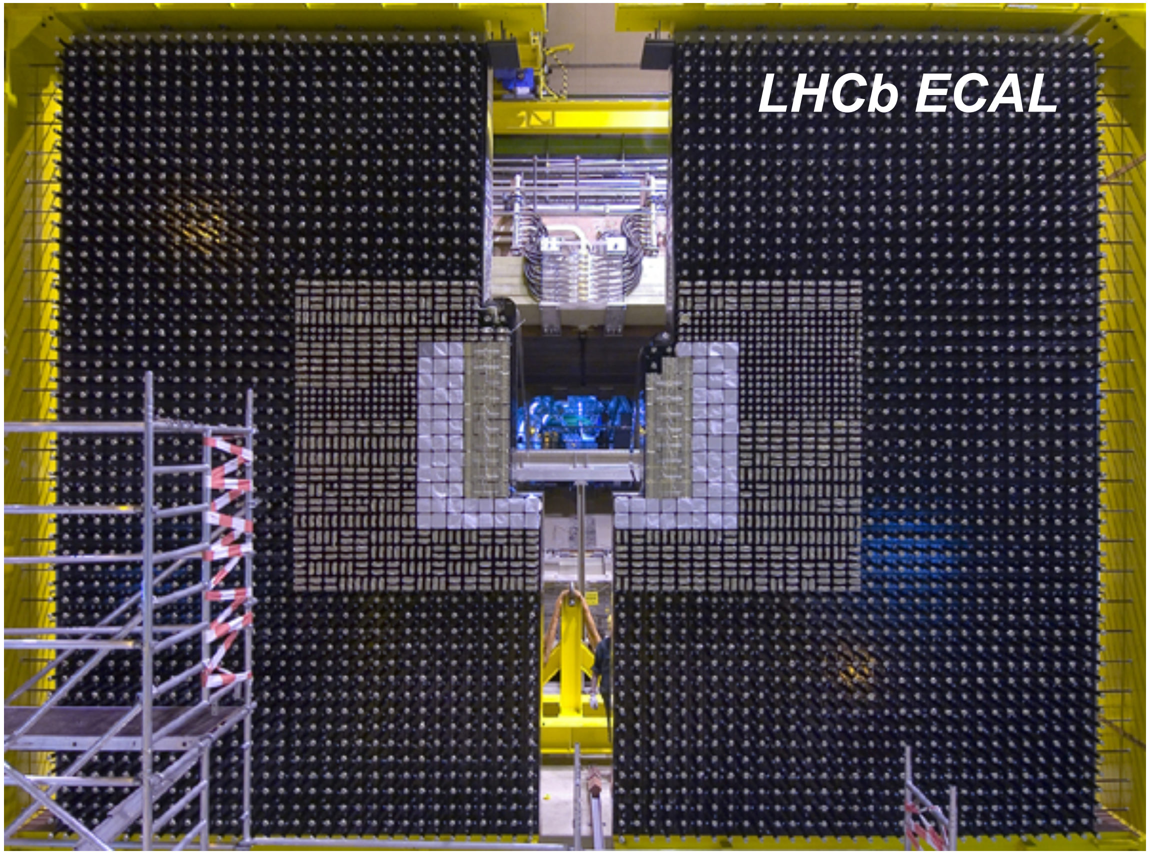
NA62 vacuum tank and straw tracker

- $< 10^{-5}$ mbar pressure in NA62 tank
- Straw tubes with 120 μm spatial resolution and 0.5% X_0/X material budget
  Gas tightness of NA62 straw tubes demonstrated in long term tests



Detector apparatus (cont.)

based on existing technologies



LHCb electromagnetic calorimeter

- *Shashlik technology provides economical solution with good energy and time resolution*

Residual backgrounds

Use a combination of GEANT and GENIE to simulate the Charged Current and Neutral Current neutrino interaction in the final part of the muon shield (cross-checked with CHARM measurement)

yields CC(NC) rate of ~$6(2)\times10^{5}$ per int. length per 2×10^{20} pot

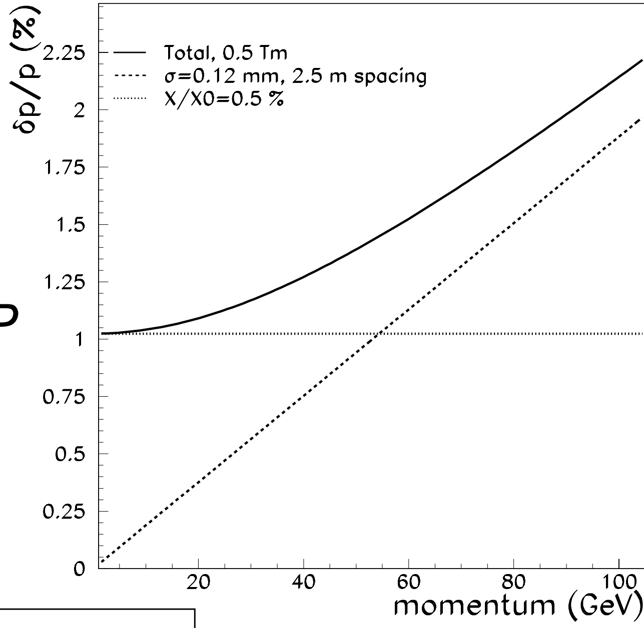
Instrumentation of the end-part of the muon shield would allow the rate of CC + NC to be measured and neutrino interactions to be tagged

- *~10% of neutrino interactions in the muon shield just upstream of the decay volume produce Λ or K^0 (as follows from GEANT+GENIE and NOMAD measurement)*
- *Majority of decays occur in the first 5 m of the decay volume*
- *Requiring μ–id. for one of the two decay products*

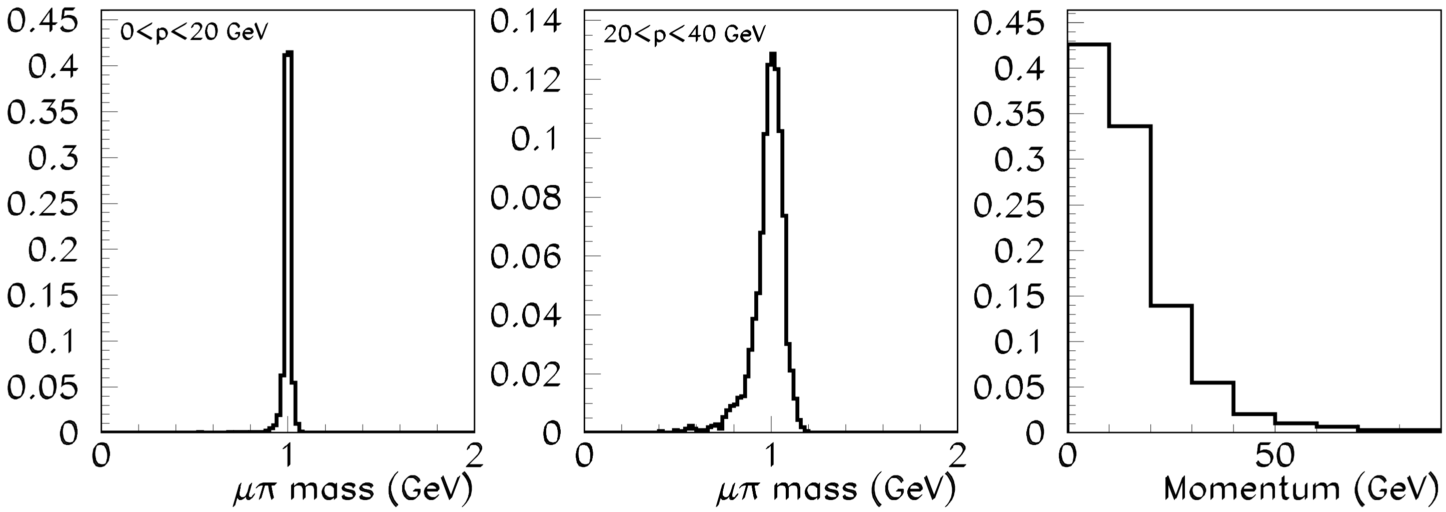
  → ***150 two-prong vertices in 2×10^{20} pot***

Detector concept (cont.)

Magnetic field and momentum resolution



- *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 both tracks with $P < 20$ 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 $K_L \rightarrow \pi^+\mu^-\nu$ and 1 GeV HNL

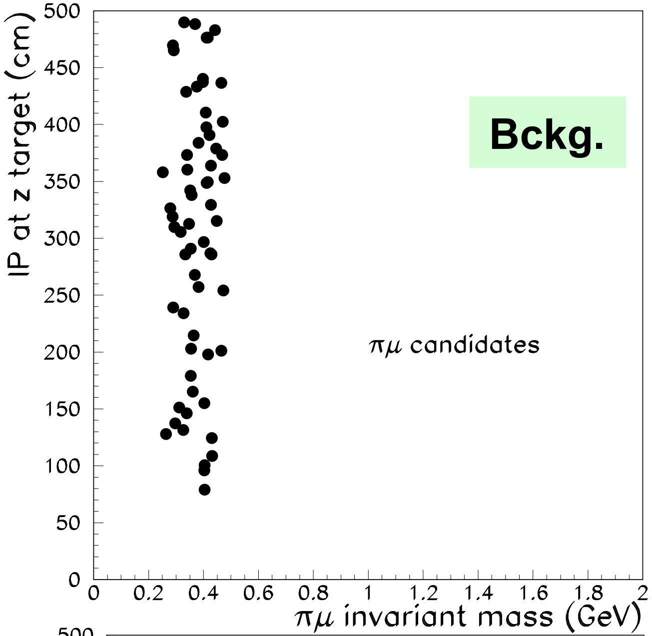
Detector concept (cont.)

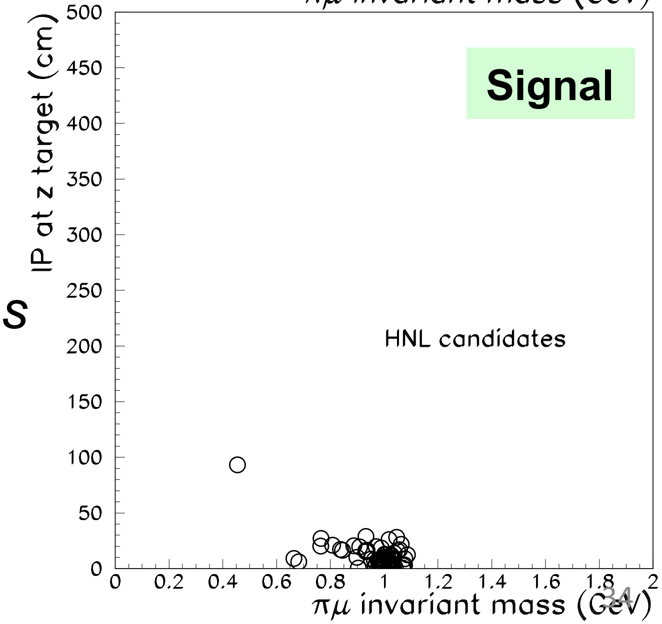
Impact Parameter resolution

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

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

- ***IP < 1 m is 100% eff. 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 $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$*
- *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:*

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

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

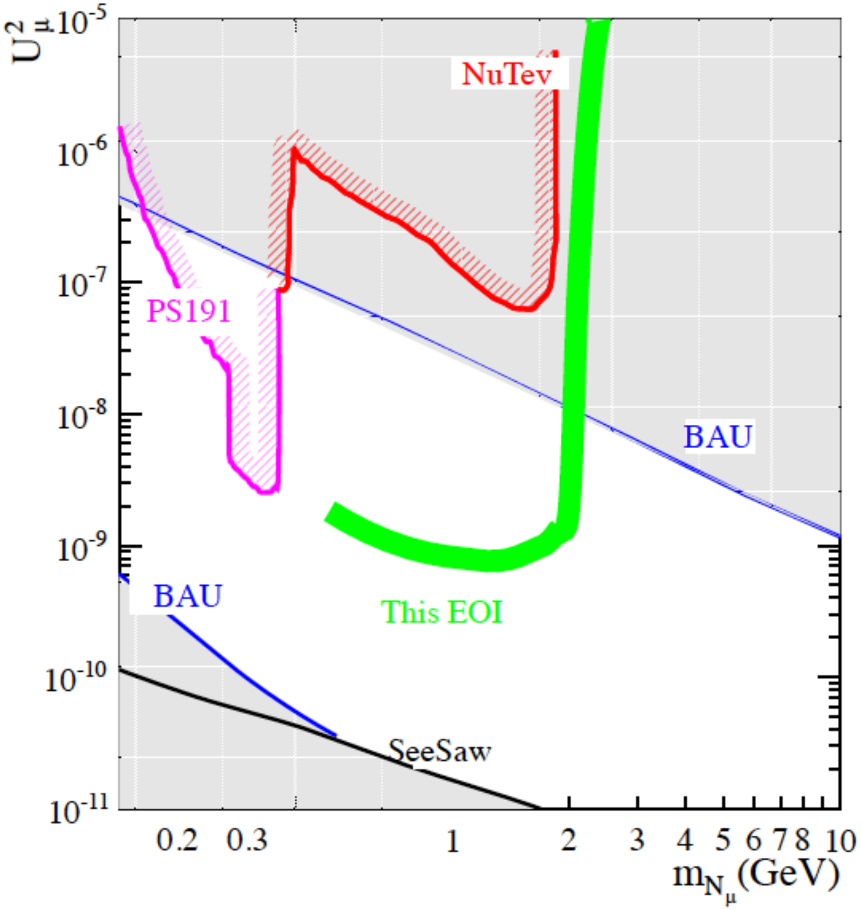
$\chi_{cc} = 0.45 \times 10^{-3}$

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

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

BACK - UP

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 $V \to l^+ l^-$