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

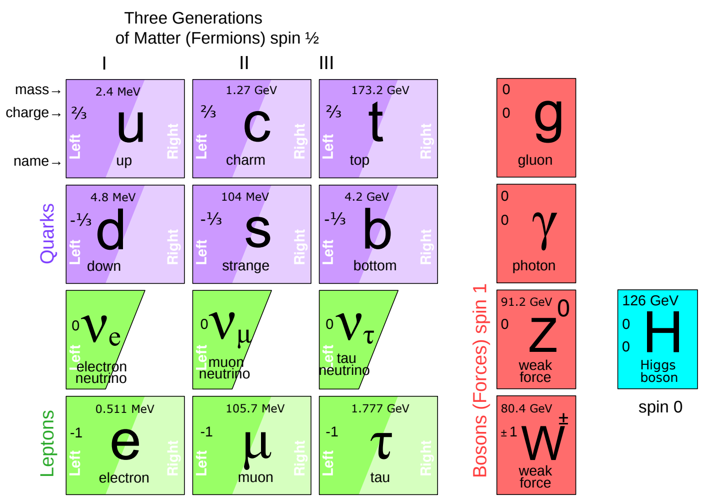
Theoretical motivation

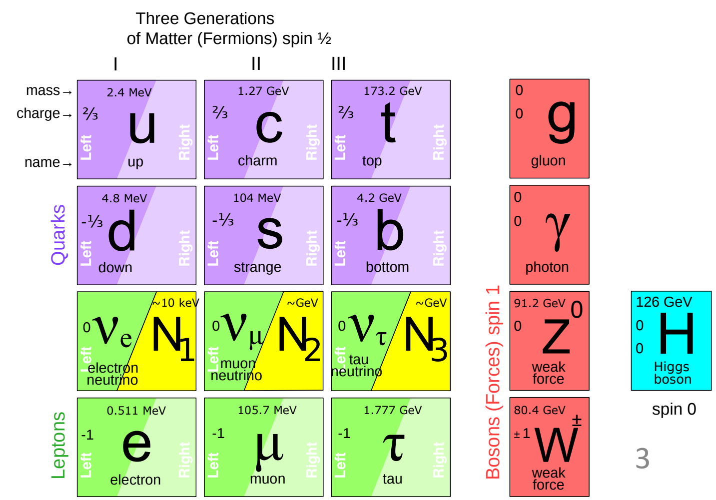
- *Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model The SM may work successfully up to Planck scale !*

- *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*

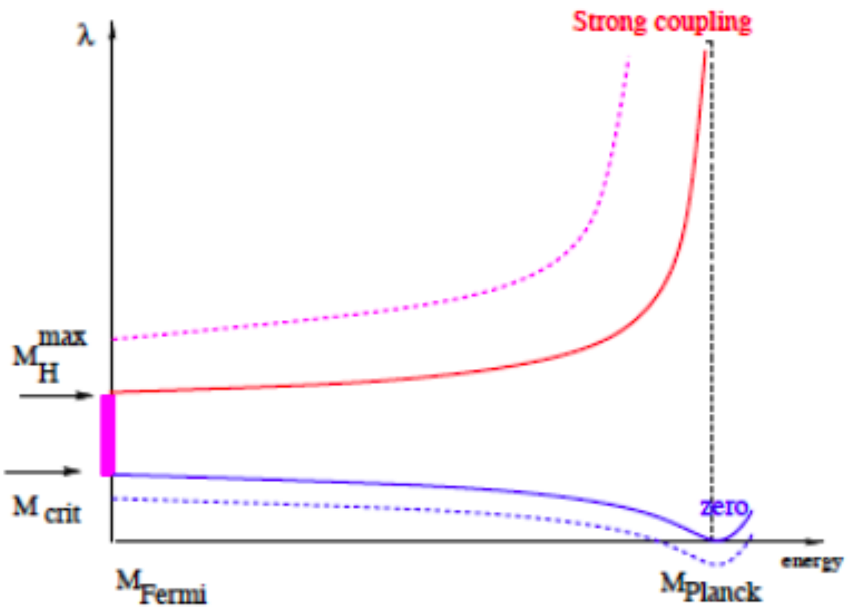




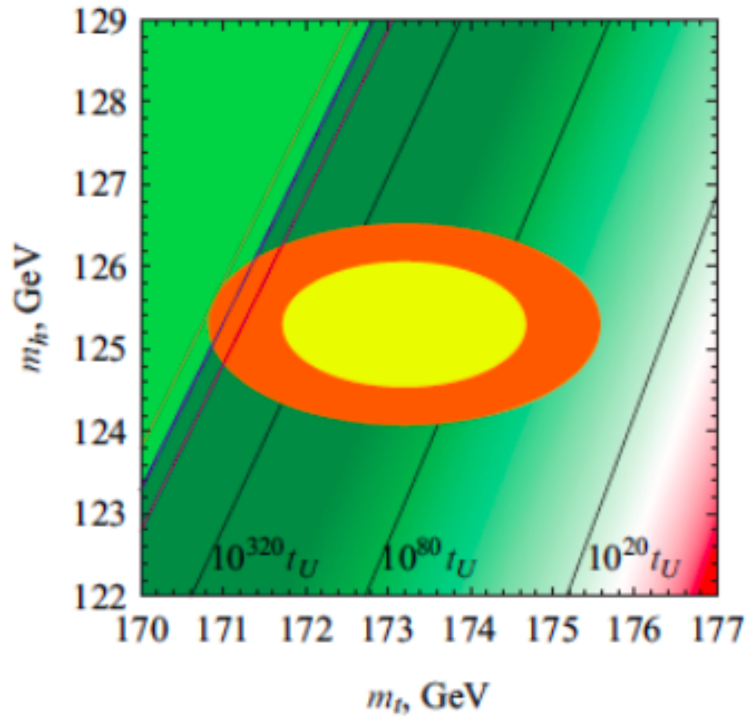
SM may well be a consistent effective theory all the way up to the Plank scale

✓ *M_H < 175 GeV → SM is a weakly coupled theory up to the Plank energies !*

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

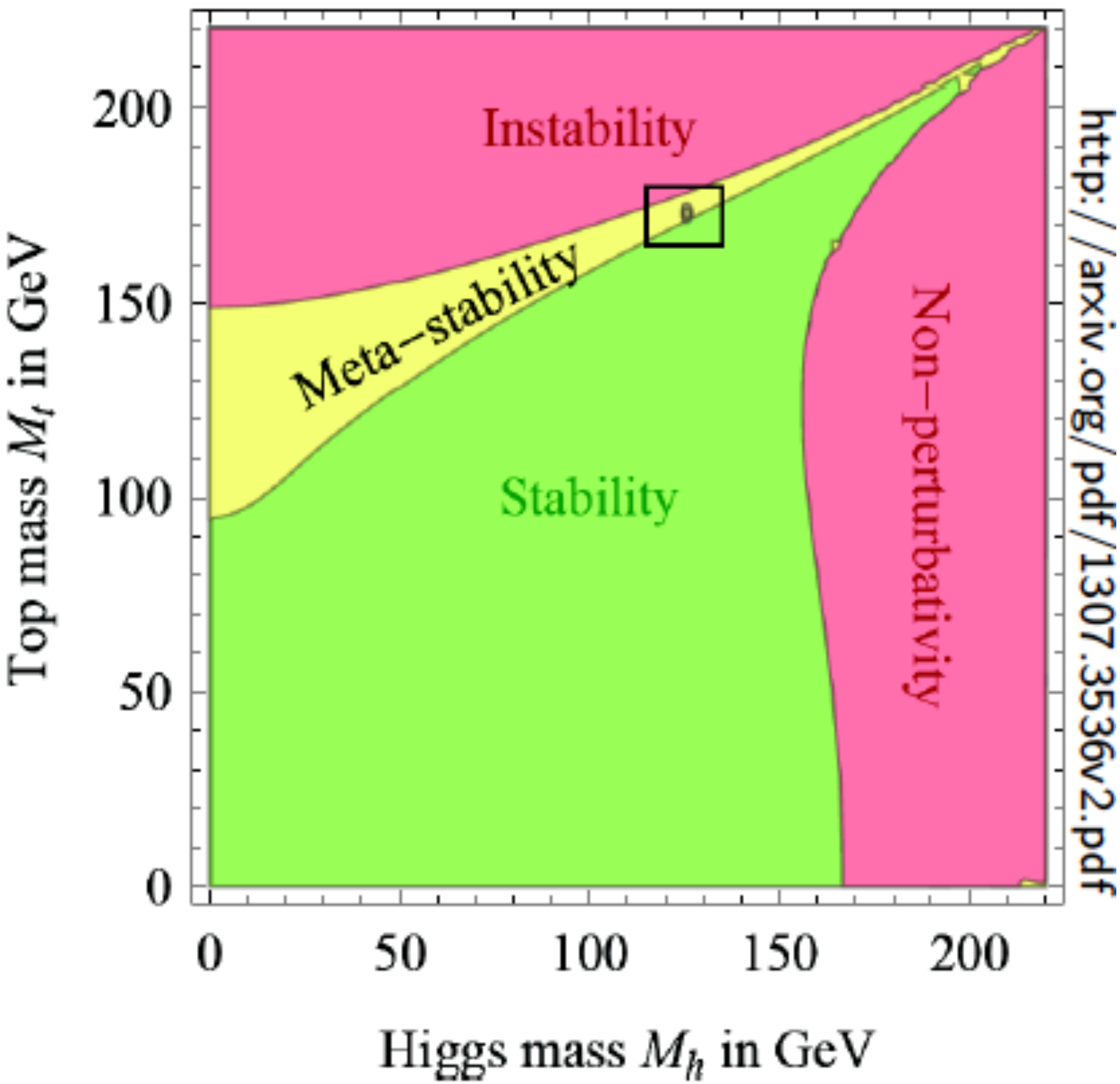


Stable vacuum is perfectly admitted by present data



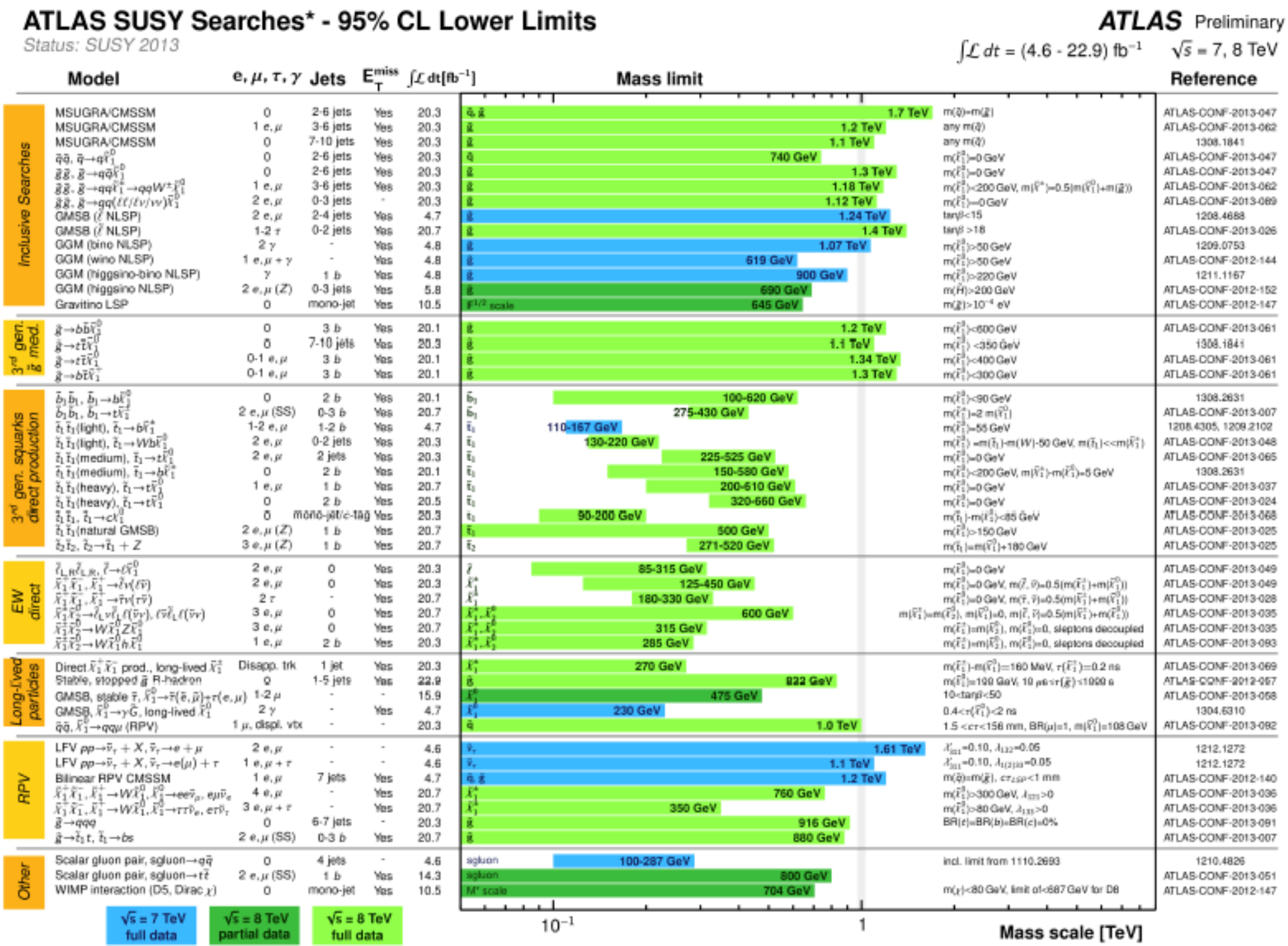
✓ *No sign of New Physics seen*

Hard to believe that this is a pure coincidence !



No sign of New Physics seen

What is not found..



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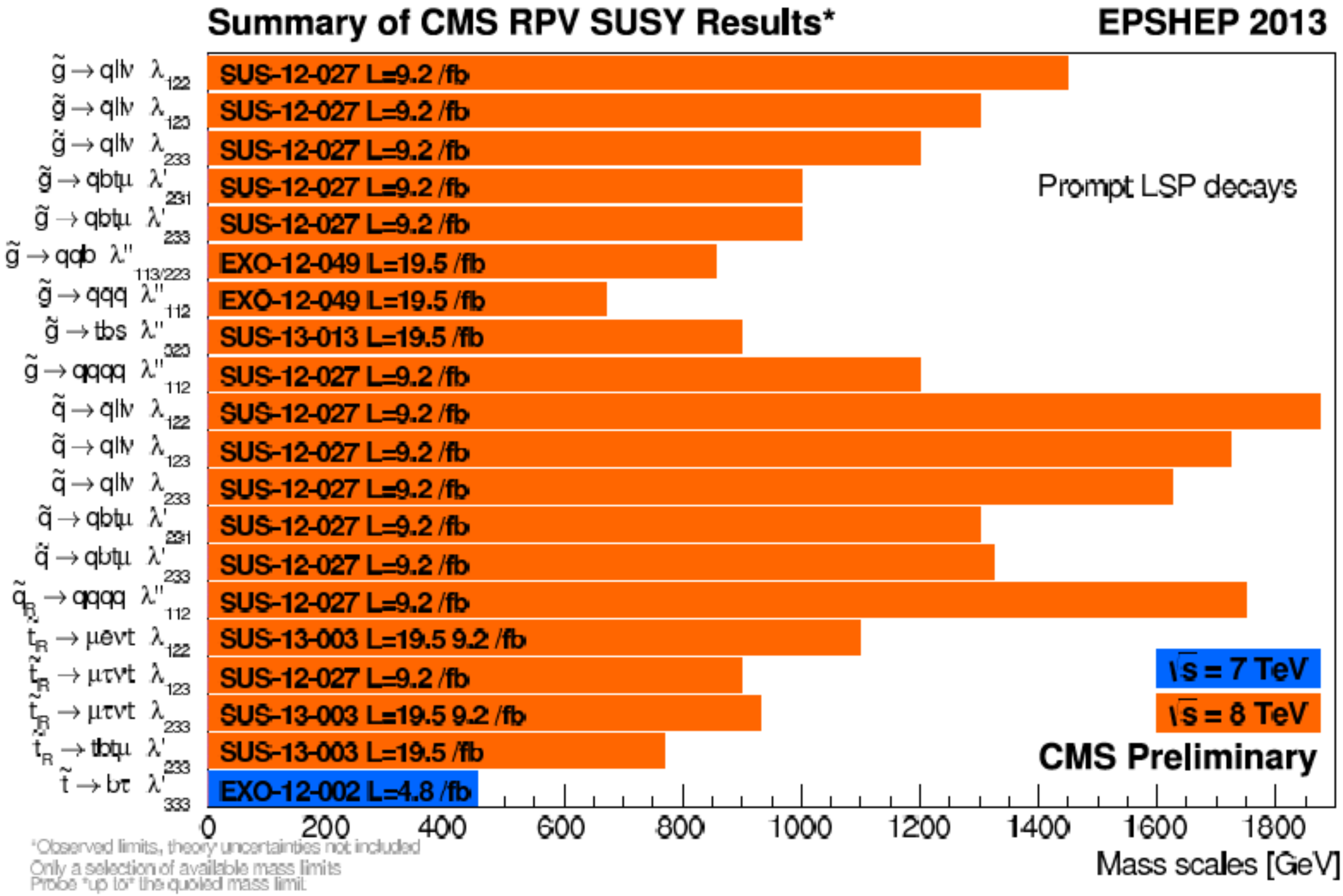
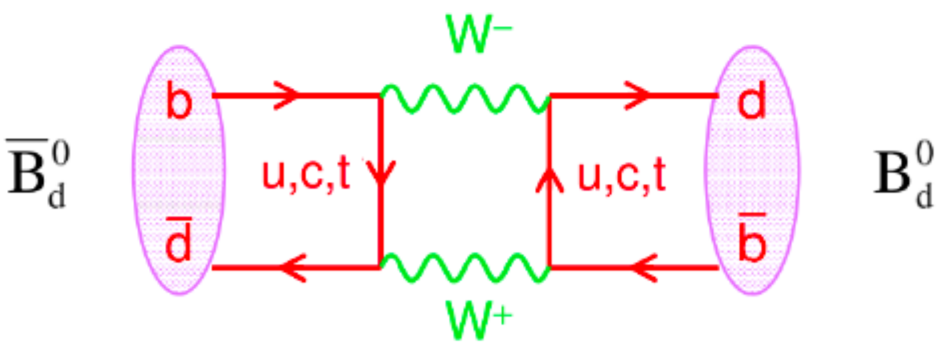
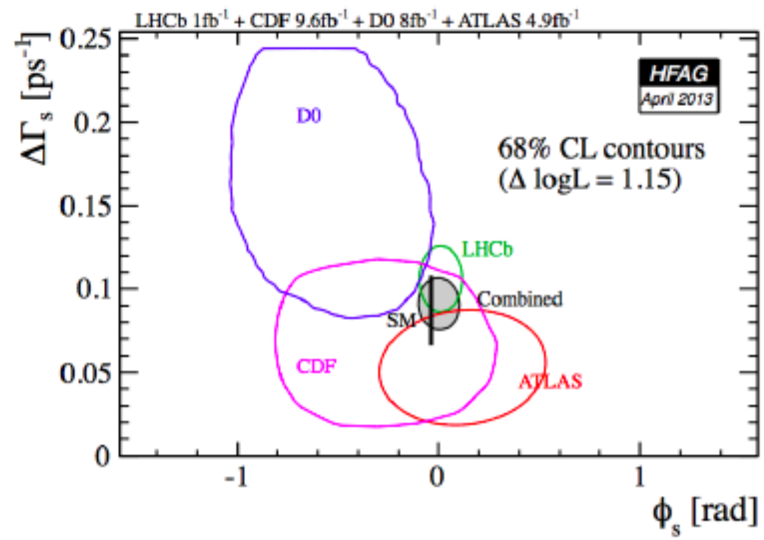


Bounds on the scale of New Physics

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}:

- ~ 1 —tree/strong + generic flavor→ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ —loop + generic flavor→ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ —tree/strong + "alignment"→ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2)$ —loop + "alignment"→ $\Lambda \gtrsim 0.5$ TeV [K & B]

Theoretical motivation

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  The SM may work successfully up to Planck scale !

- ***SM is unable to explain:***
  - Neutrino masses & oscillations
  - 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***

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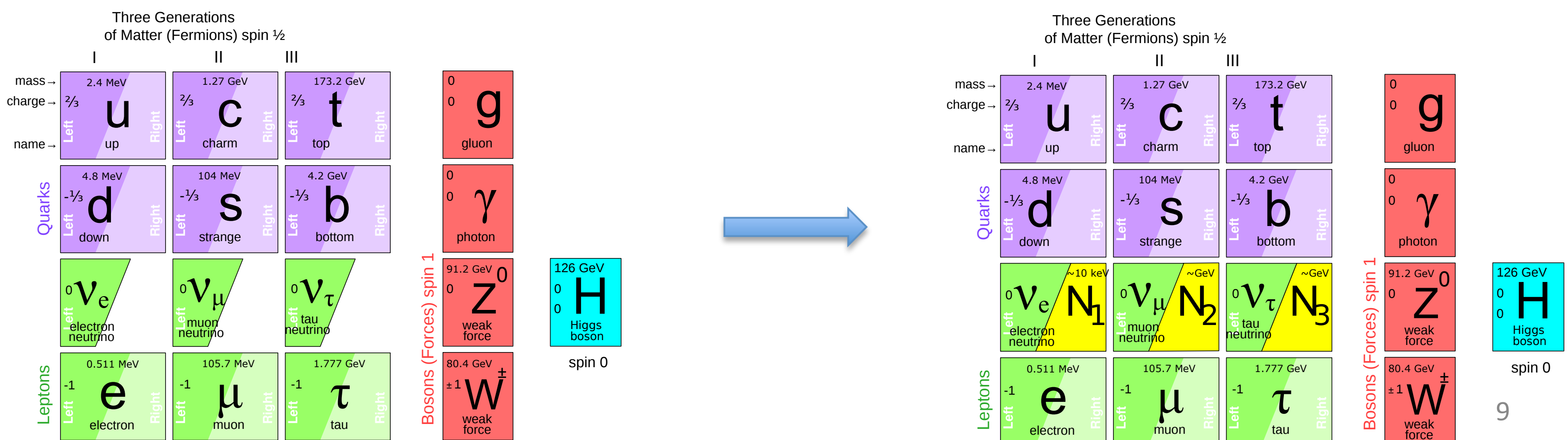


See-saw generation of neutrino masses

Most general renormalisable Lagrangian of all SM particles (+3 singlets wrt the SM gauge group):

$$L_{\rm singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha^c - M_I \bar{N}_I{}^c N_I + {\rm h.c.},$$

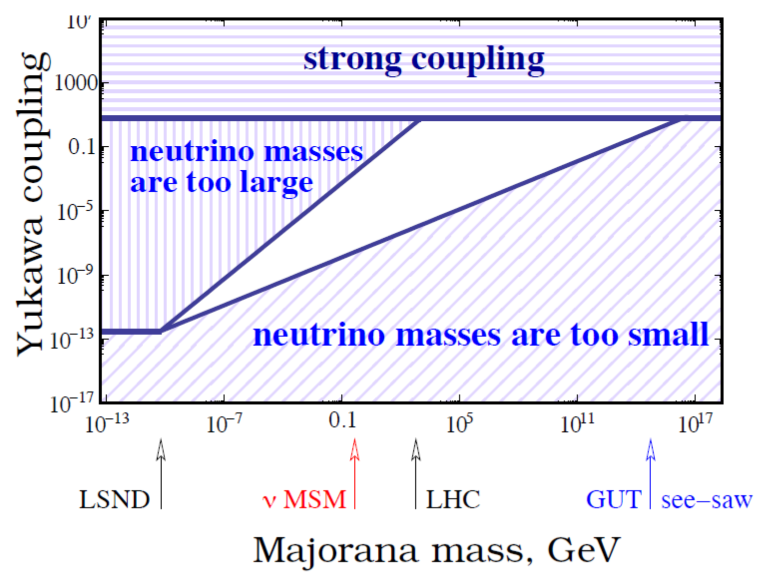
Yukawa term: mixing of N_I with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

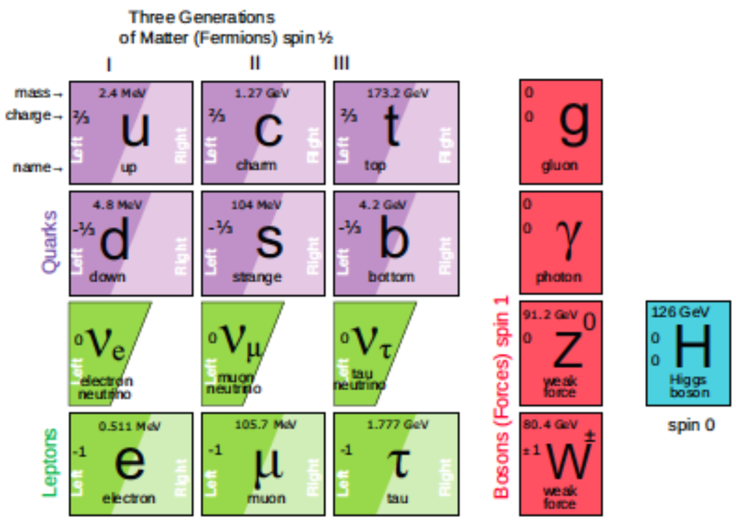
The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim \frac{m_D^2}{M}$
where $m_D \sim Y_{I\alpha} v$ *- typical value of the Dirac mass term*

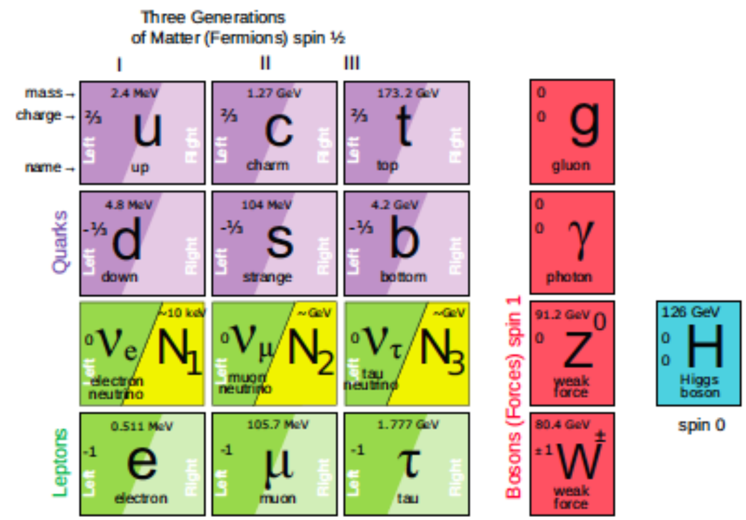
Example:

For M ~ 1 GeV and m_ν ~ 0.05 eV it results in m_D ~ 10 keV and Yukawa coupling ~ 10^{-7}



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.

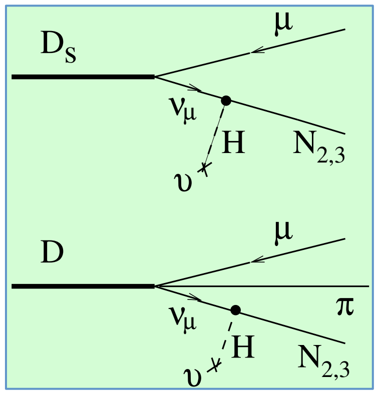
Masses and couplings of HNLs

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

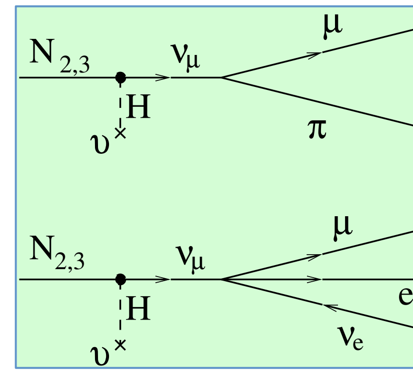
- *$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)*

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



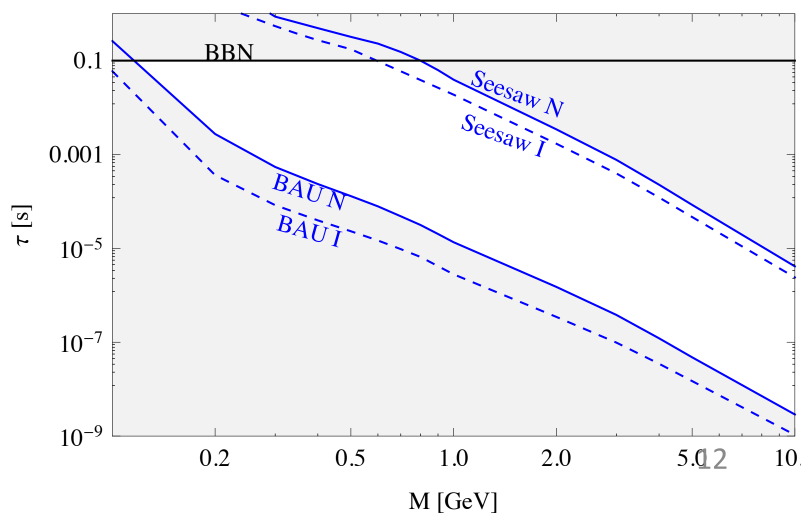
and subsequent decays



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

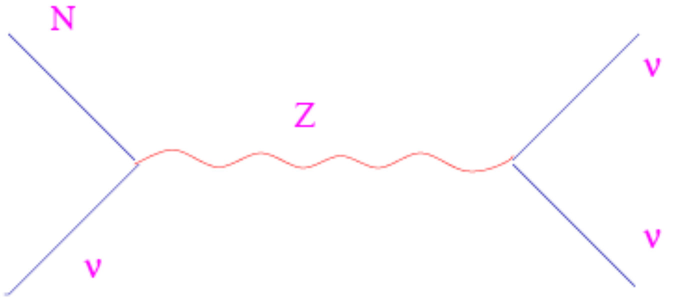
- *Typical BRs (depending on the flavour mixing):*

  $Br(N \to \mu/e\ \pi)$ ~ 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: $N \to 3\nu$.

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

For one flavour:

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

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

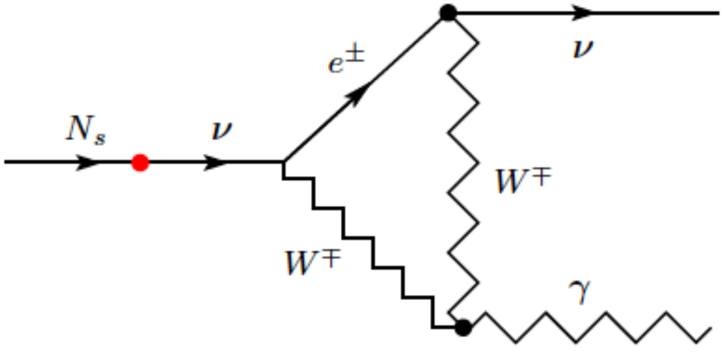
Dark Matter candidate HNL N_1

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

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

Photon energy:

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



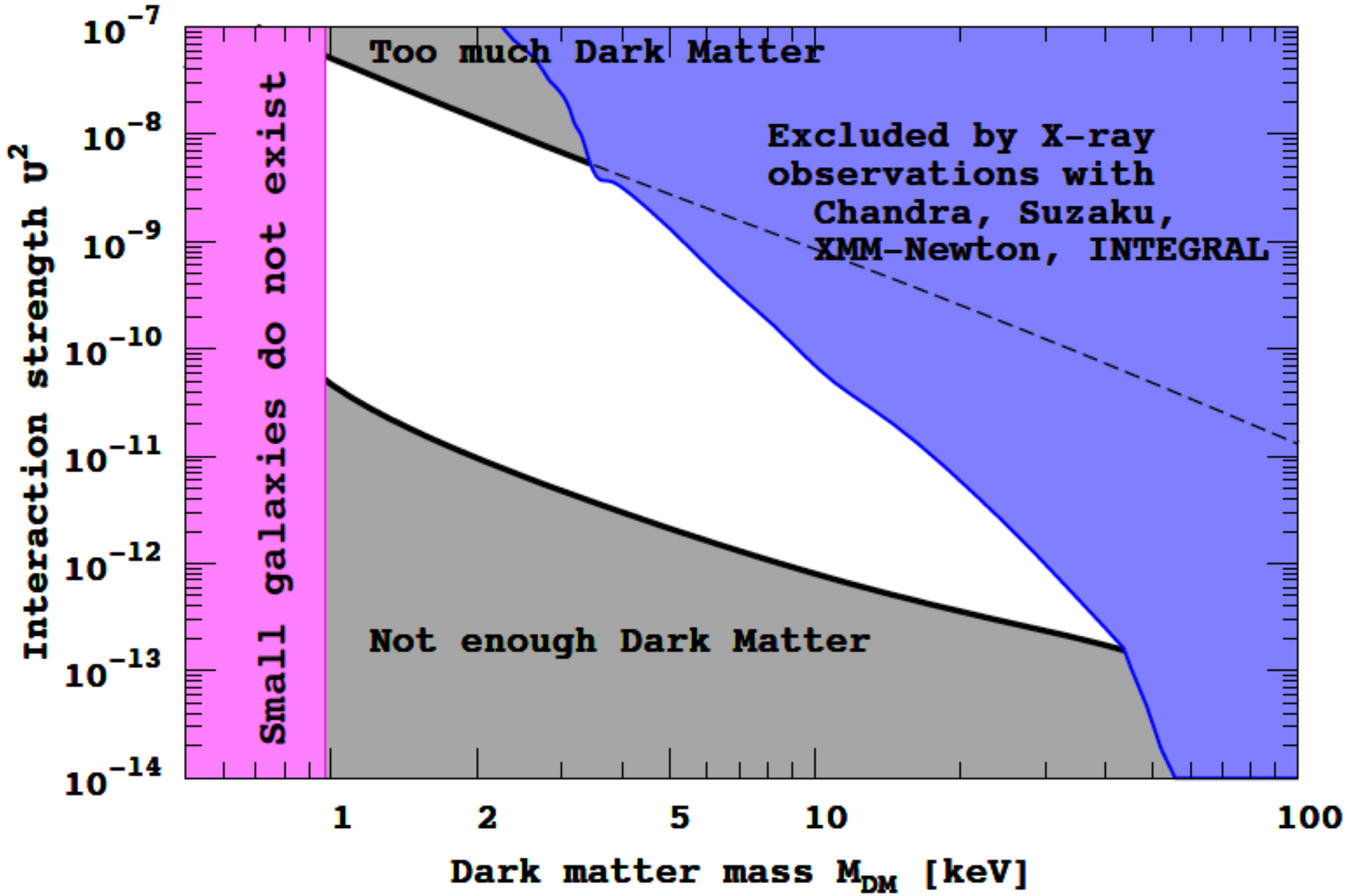
Radiative decay width:

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

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 $l\bar{l} \rightarrow \nu N_1$, $q\bar{q} \rightarrow \nu N_1$ 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*

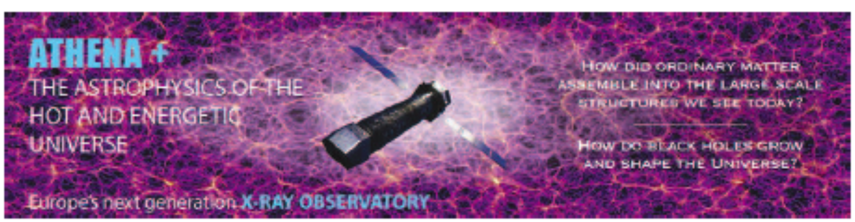
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)

- Proposed/planned X-ray missions with sufficient spectral resolution:

Astro-H

LOFT

Athena+



Origin/Xenia

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- ***$M(N_2) \approx M(N_3)$ ~ 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

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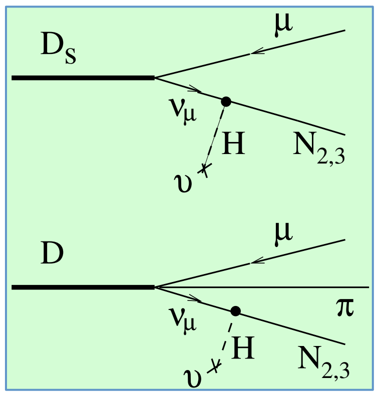

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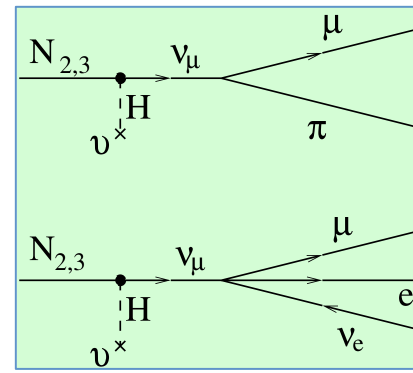

- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV Decay distance O(km)*

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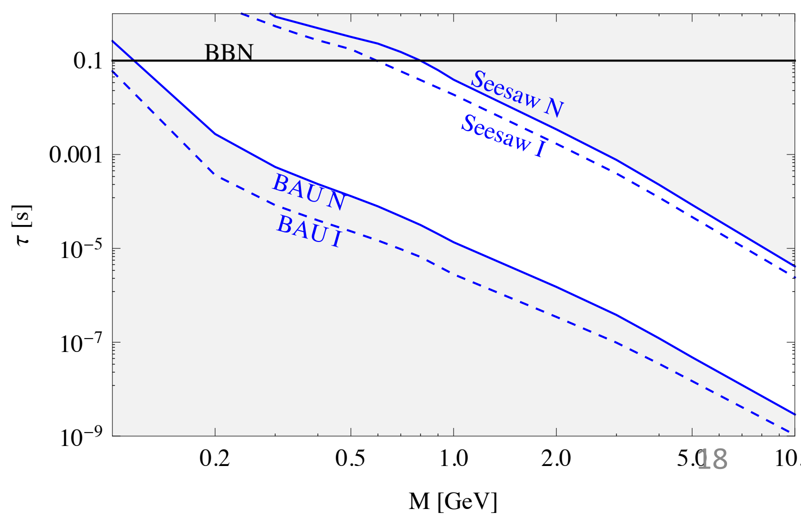

Baryon asymmetry

- *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

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) using sphaleron lepton-to-baryon number transformation*

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

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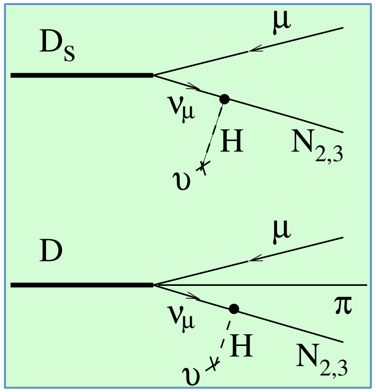

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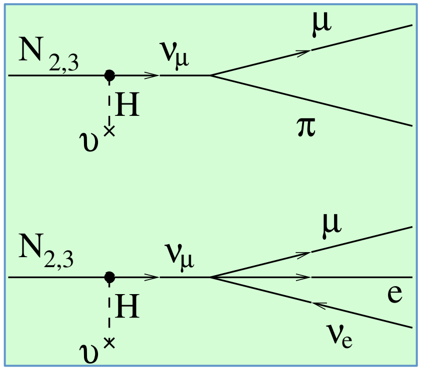

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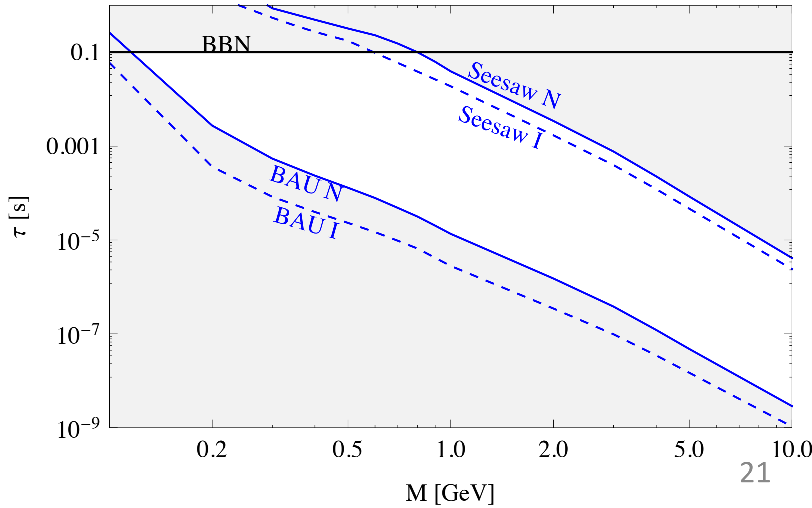
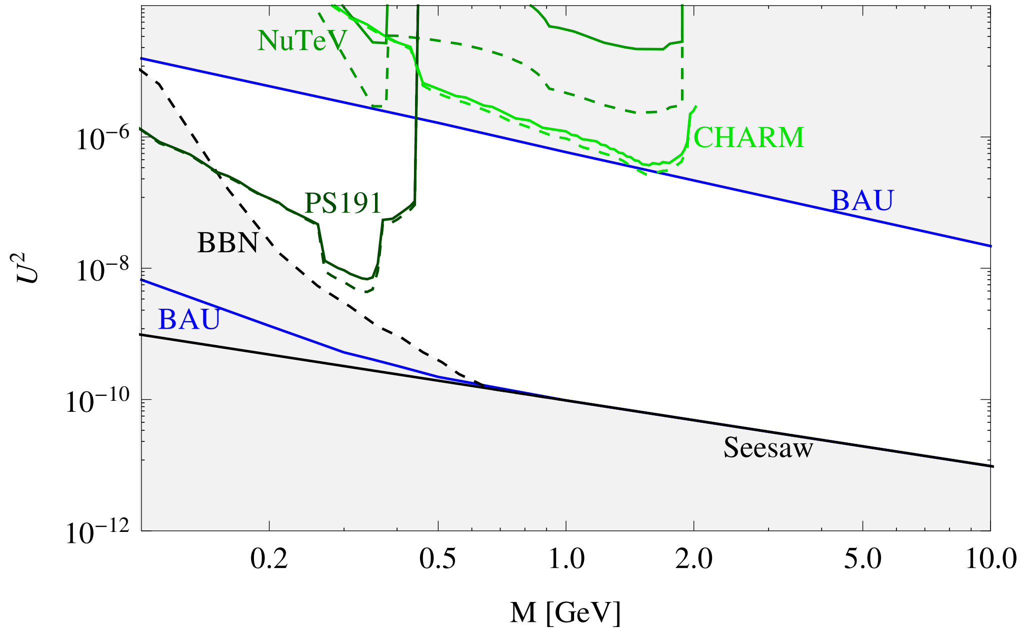


Experimental and cosmological constraints



- ***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 long-lived Particles produced in charm decays

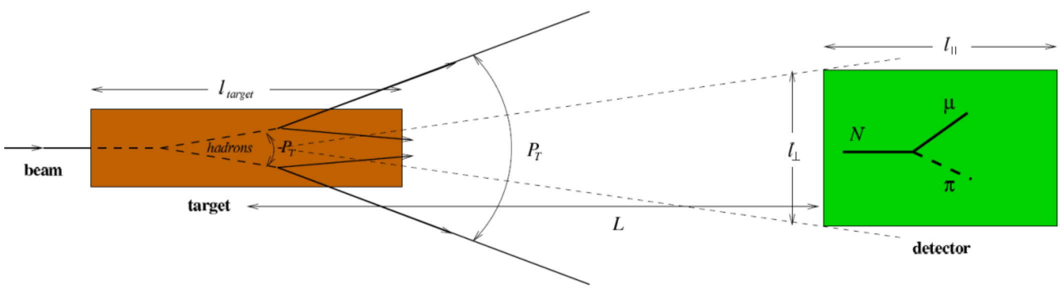
Experimentally this domain has not been very well explored !

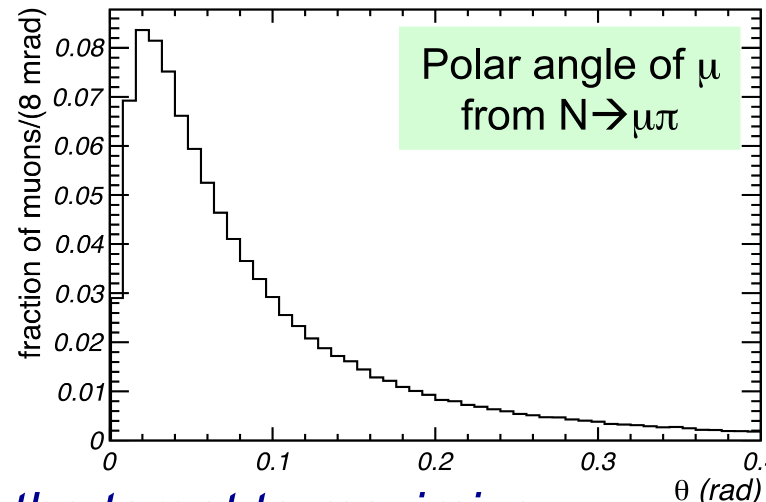
Experimental requirements

- *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

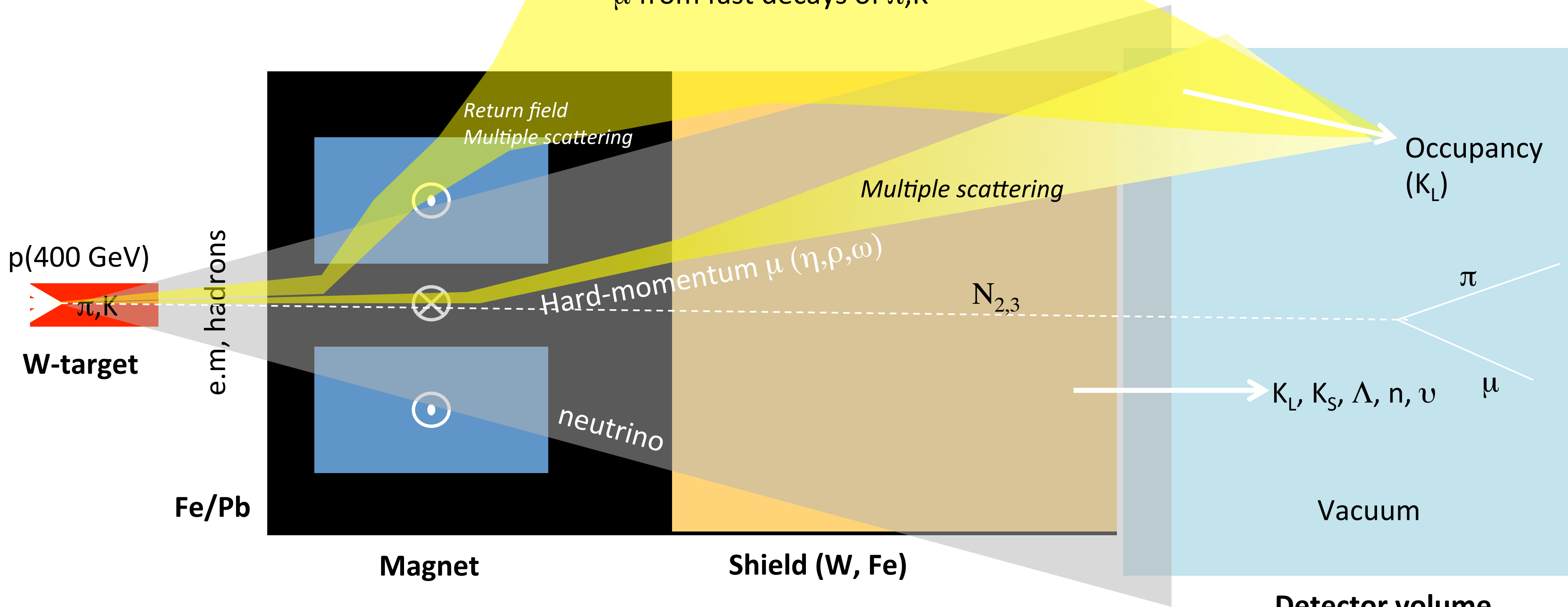
(incompatible with conventional neutrino facility)

Initial reduction of beam induced backgrounds

- *Heavy target (50 cm of W)*
- *Hadron absorber*
- *Muon shield: optimization of active and passive shields is underway*

Acceptable occupancy <1% per spill of 5×10^{13} p.o.t.

spill duration 1s → < 50×10^{6} muons
spill duration 10ms → < 50×10^{3} muons
spill duration $10\mu s$ → < 500 muons



Generic setup, not to scale!

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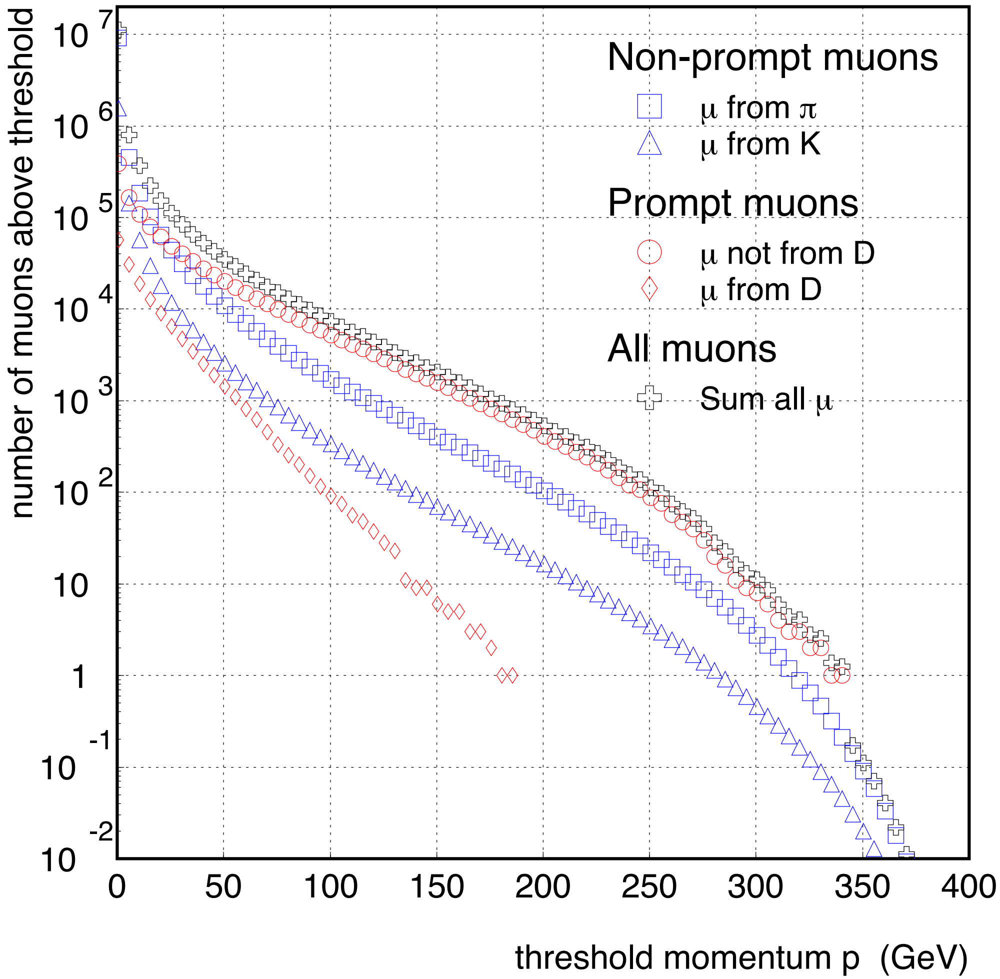
Secondary beam-line (cont.)

Muon shield

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

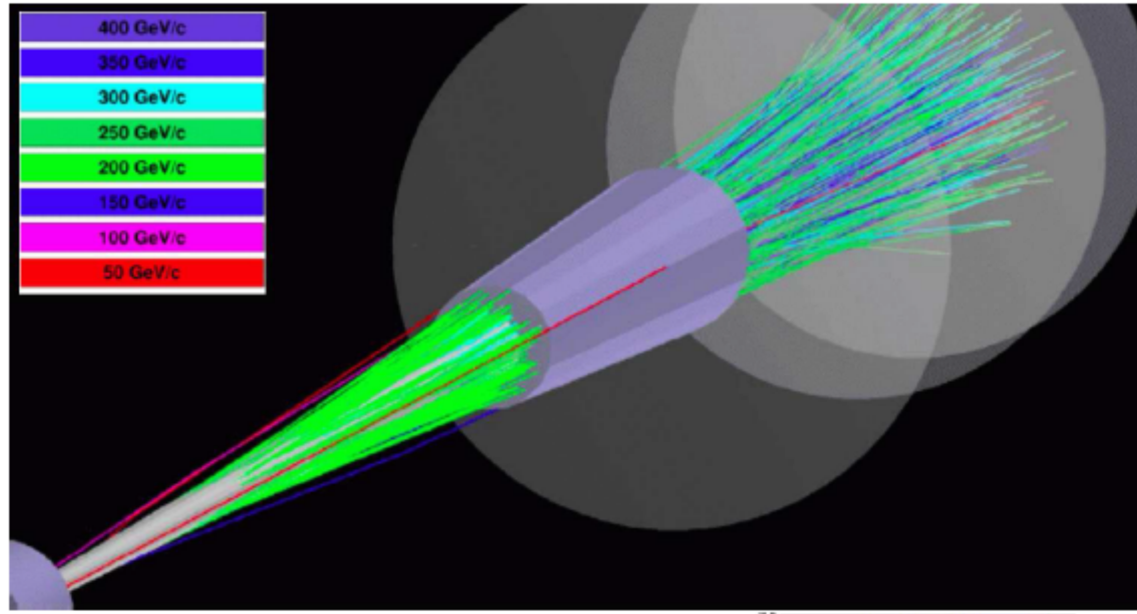
- *A muon shield made of ~55 m W(U) should stop muons with energies up to 400 GeV*
- *Cross-checked with results from CHARM beam-dump experiment*
- *Detailed simulations will define the exact length and radial extent of the shield*

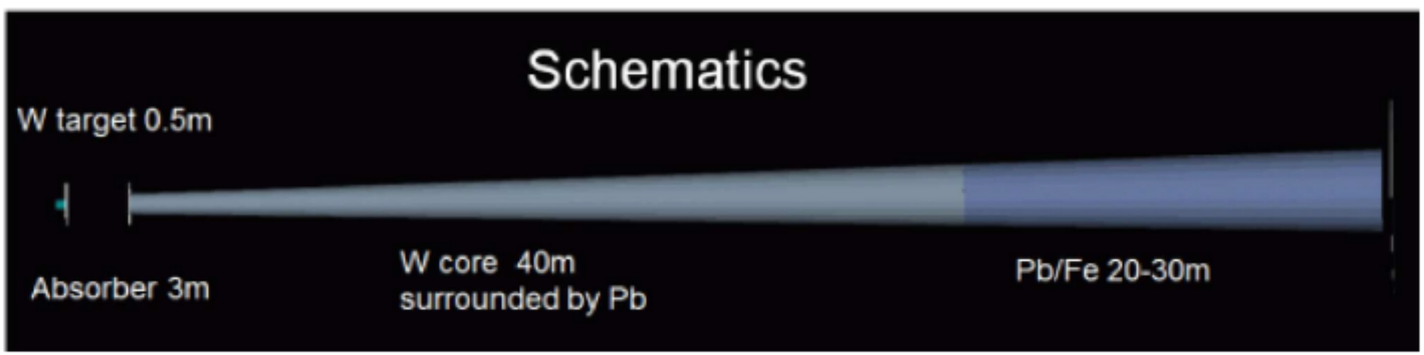


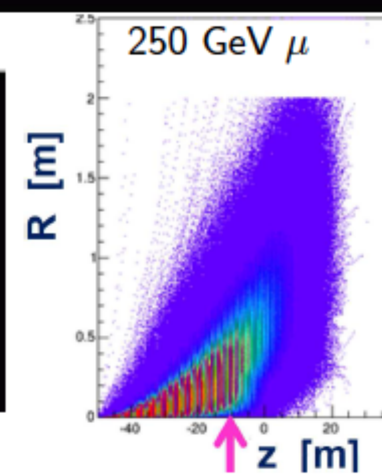
Muon shield optimization

Passive μ-filter

- Geant studies to estimate flux.
- MS and €: limit W-length to 40 m.
- High-p at small θ: W⌀12-50 cm
- +20-30 m of Pb/Fe :
- reduction of 10^7 possible
- Robust/easy to operate





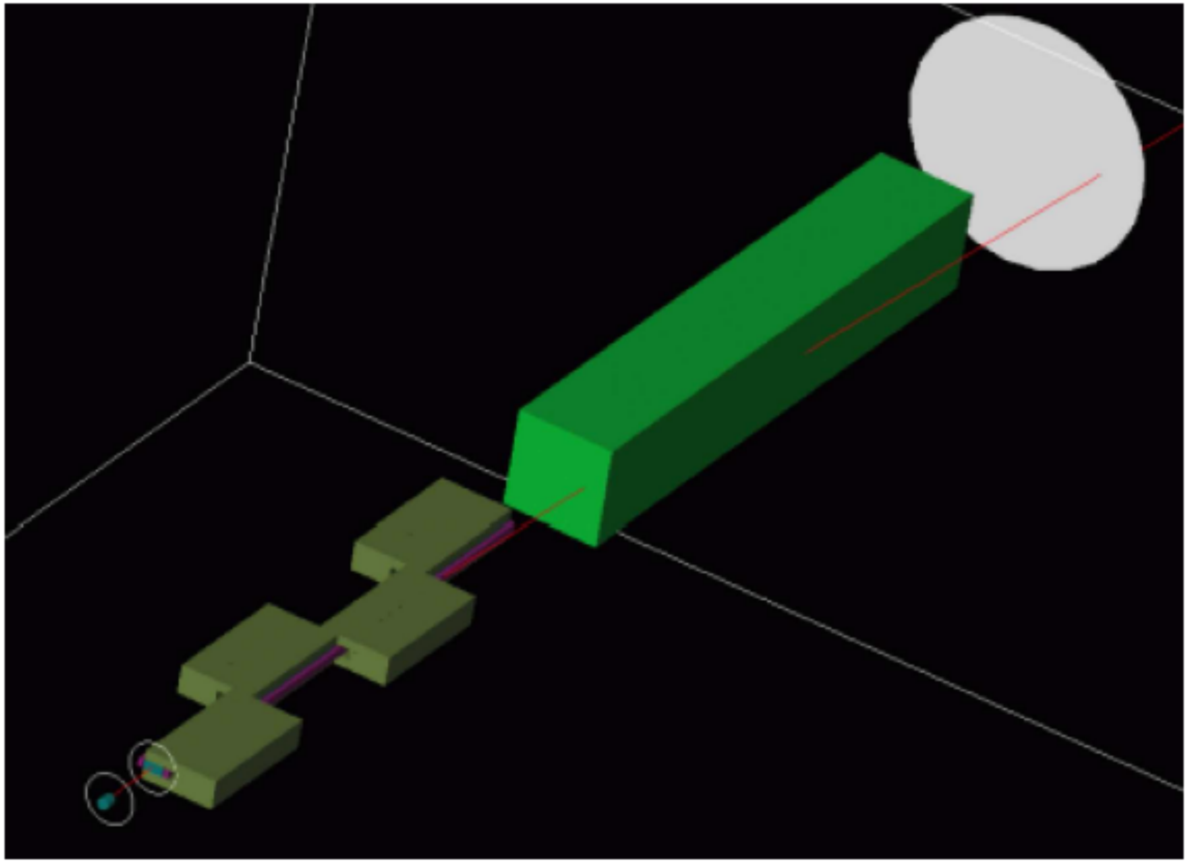


Muon shield optimization

Alternative: Active (+passive) μ-filter

- Use 6 m long C-shaped magnets.
- Produces 40 Tm total field with 4 magnets: high-p swept out.
- Problem: return-B of low-p μ:
  - alternate return-B left/right
  - Add passive Fe-shield

- reduction of 10^7 possible



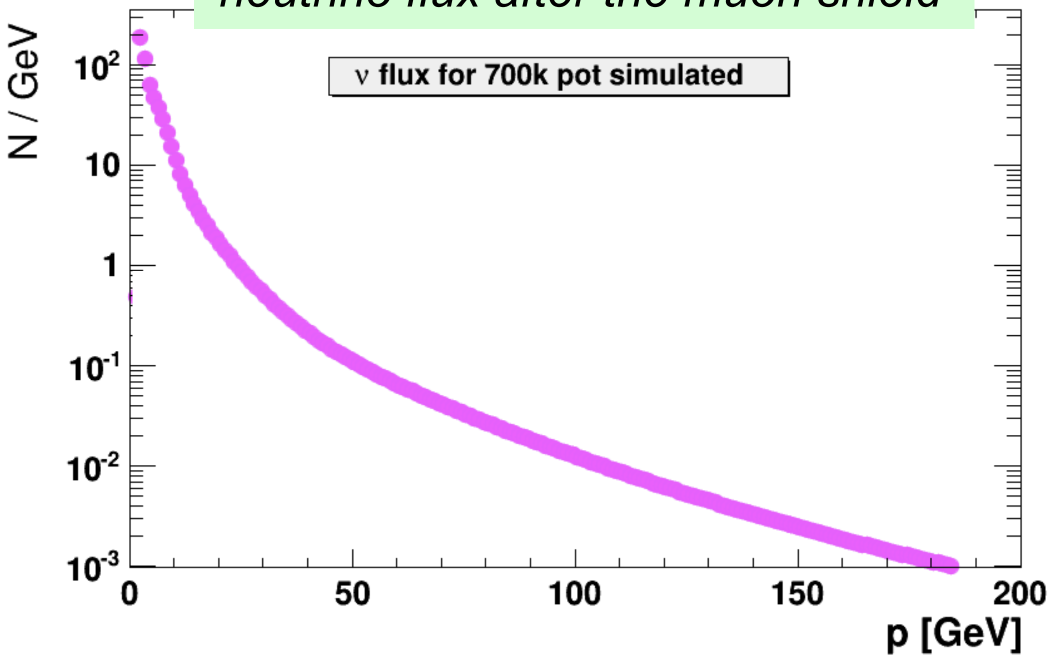
Work in progress, need to optimize together with SPS-spill length, and induced background.

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



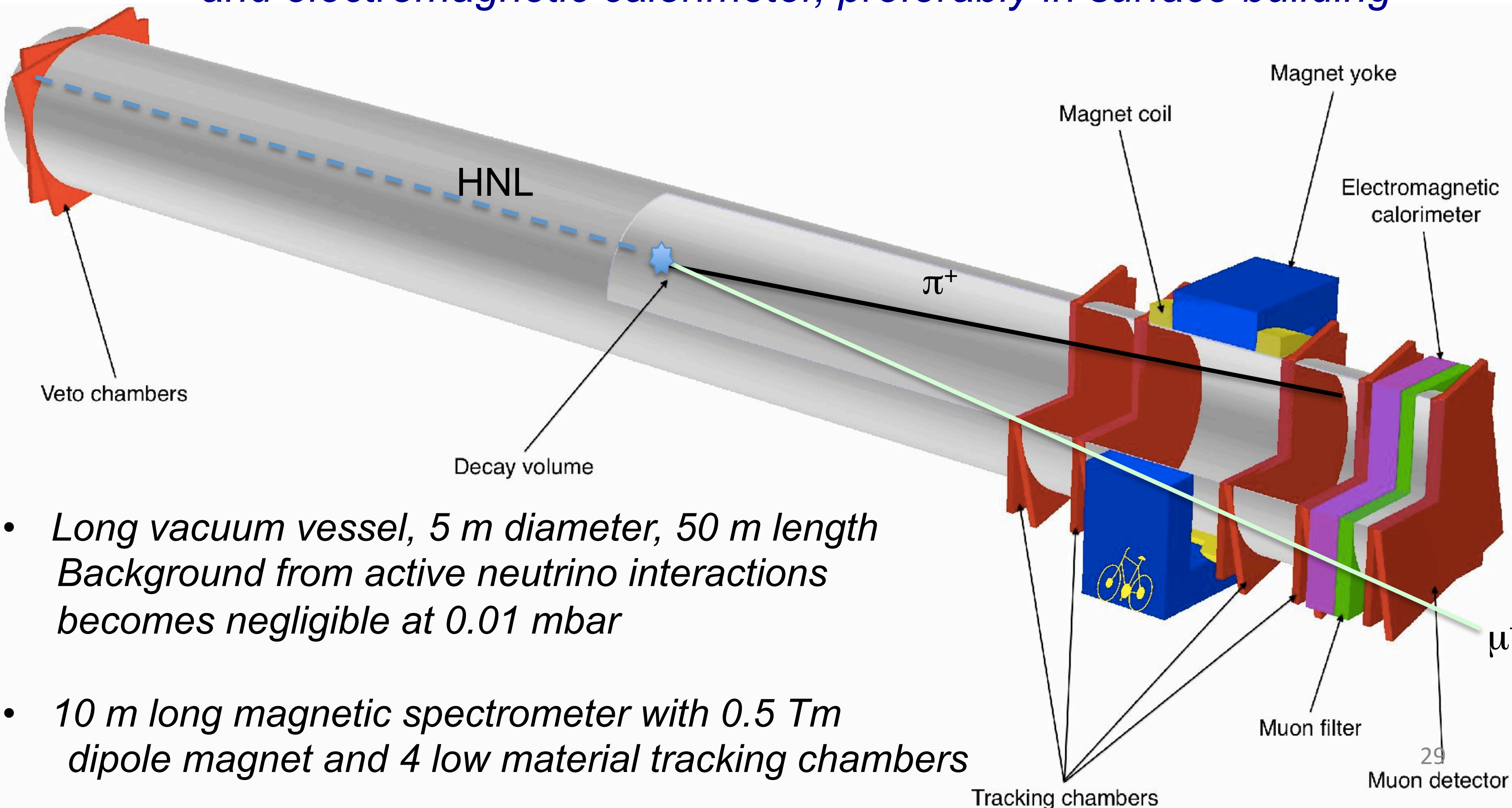
2×10^4 neutrino interactions per 2×10^{20} pot in the decay volume at atmospheric pressure → becomes negligible at 0.01 mbar

Detector concept

(based on existing technologies)

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

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



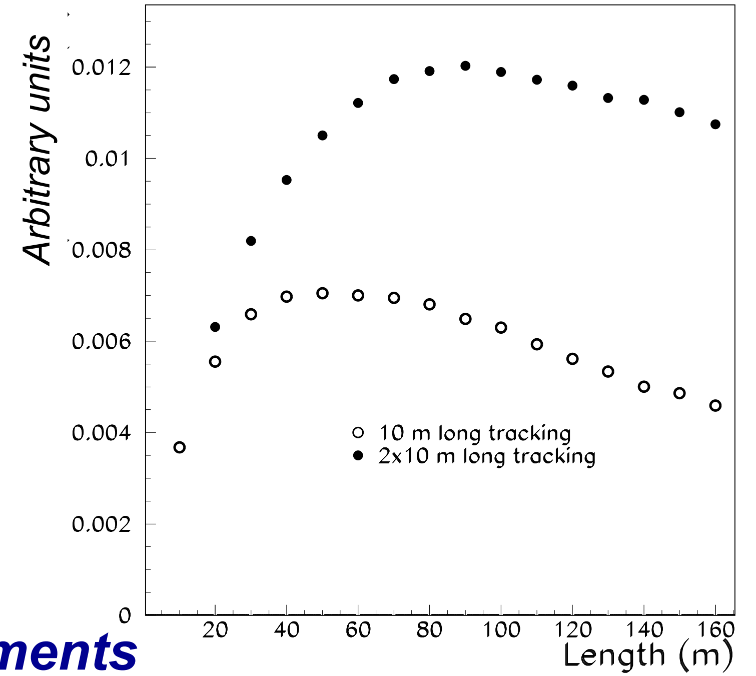
- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*

- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

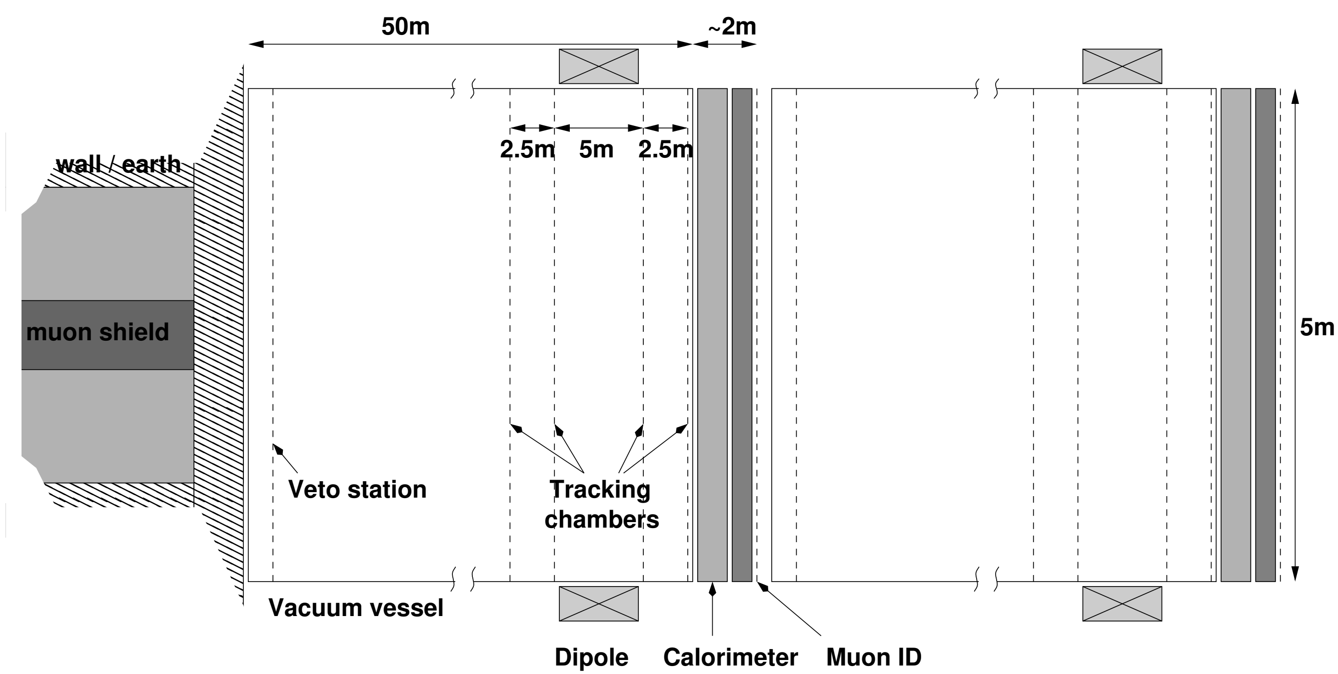
Detector concept (cont.)

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***



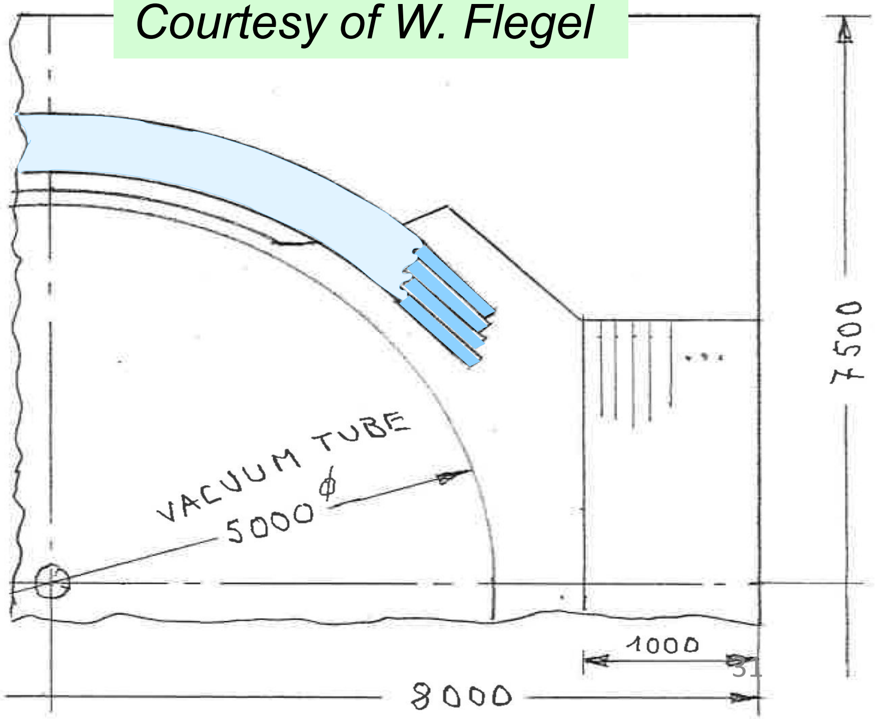
Detector apparatus

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



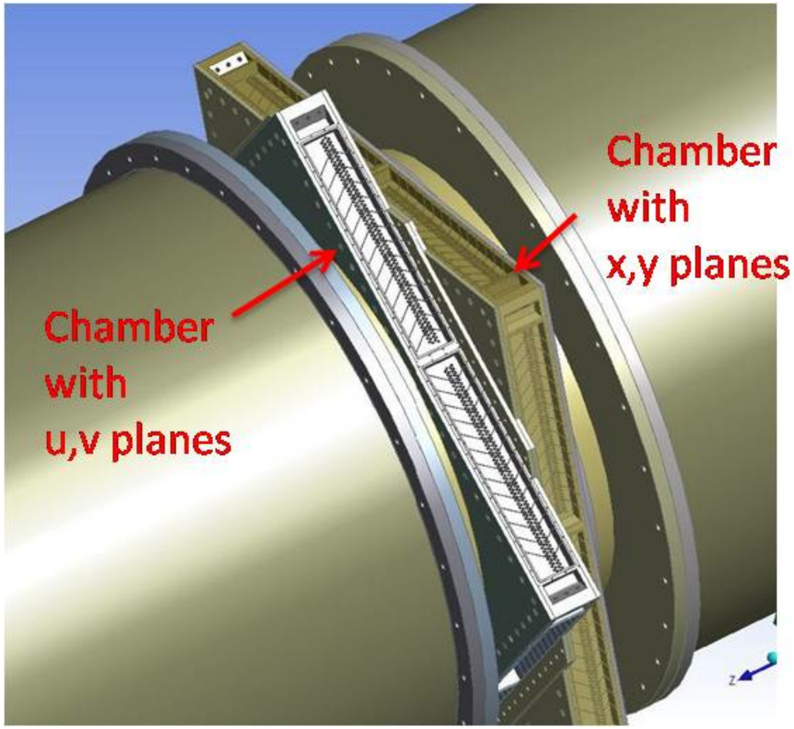
Courtesy of W. Flegel

Detector apparatus (cont.)
based on existing technologies

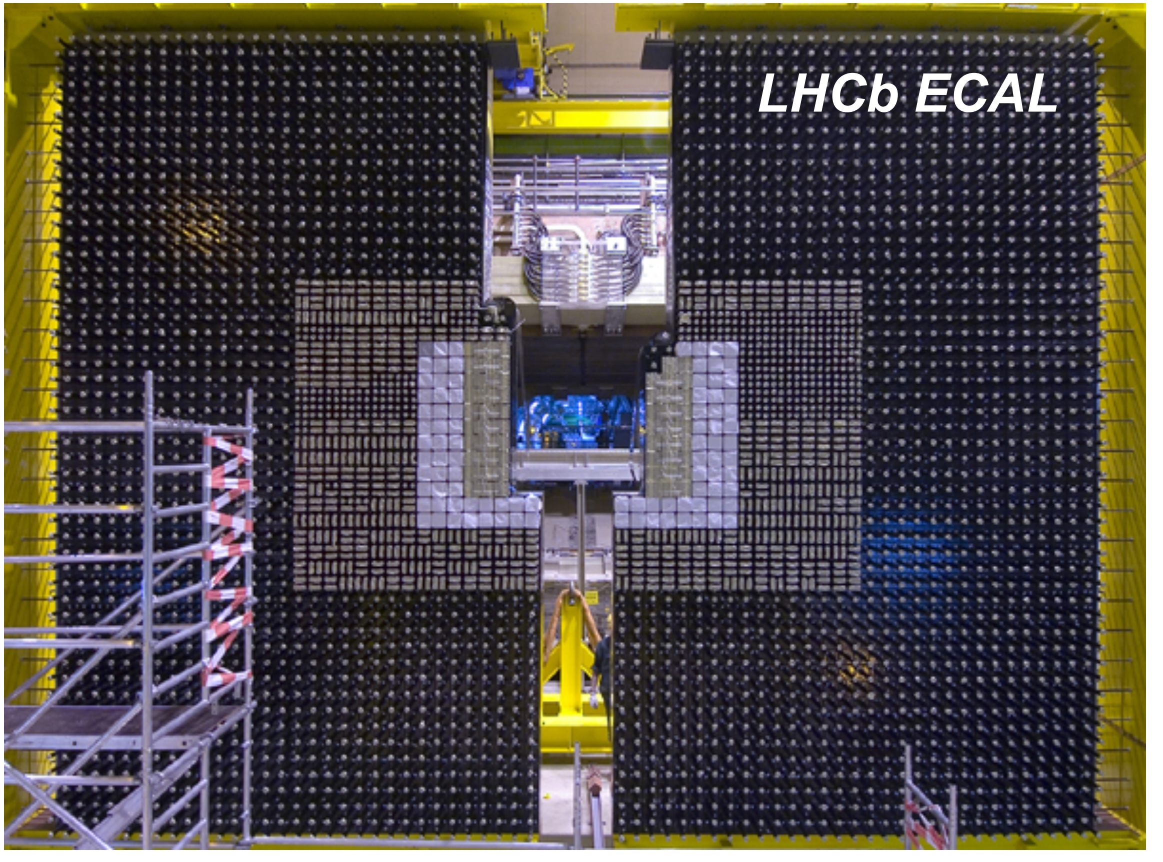
NA62 vacuum tank and straw tracker

- *< 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)×10^5 per int. length per 2×10^{20} pot*

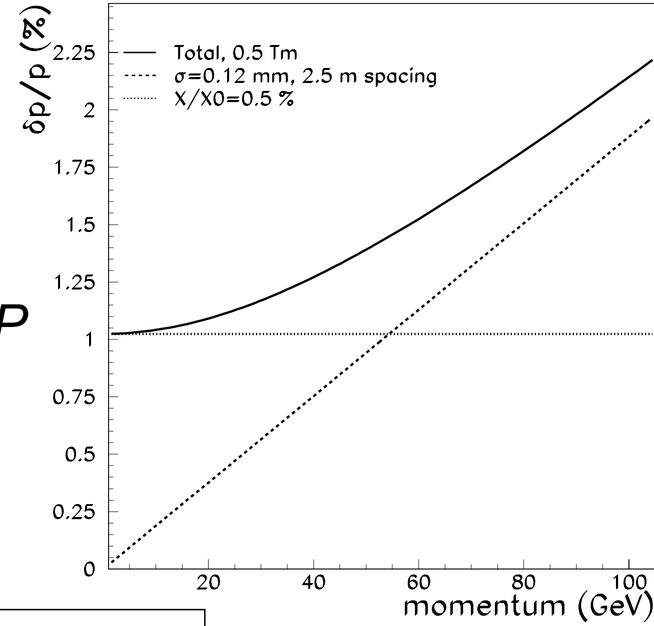
Instrumentation of the end-part of the muon shield would allow the rate of CC + NC to be measured and neutrino interactions to be tagged

- *~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***

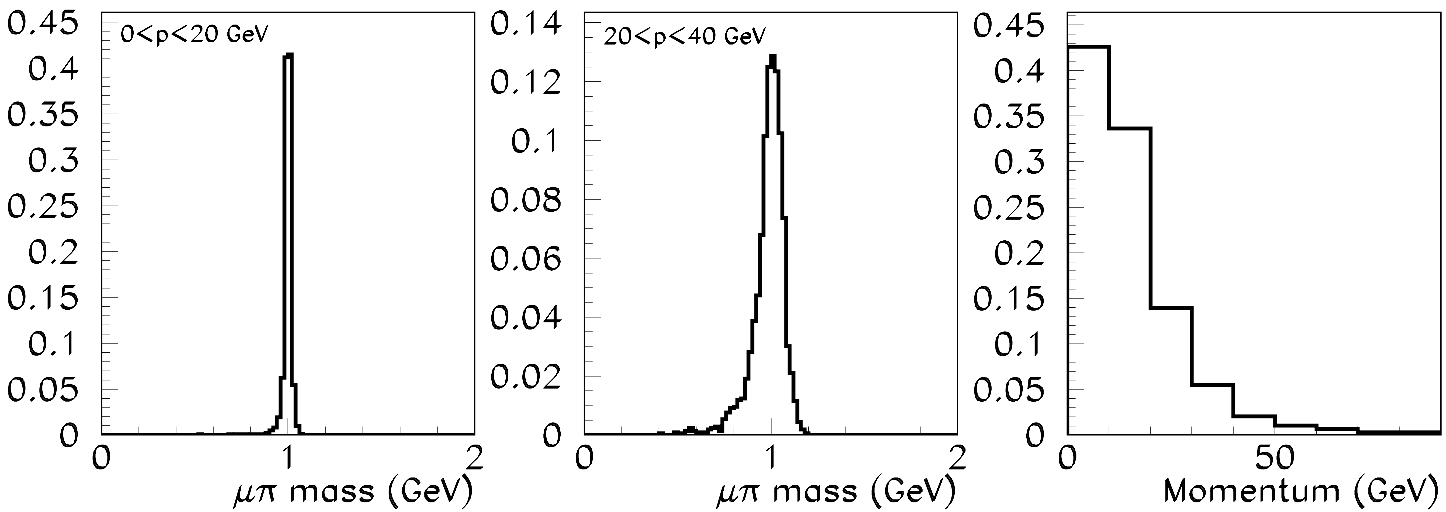
Detector concept (cont.)

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

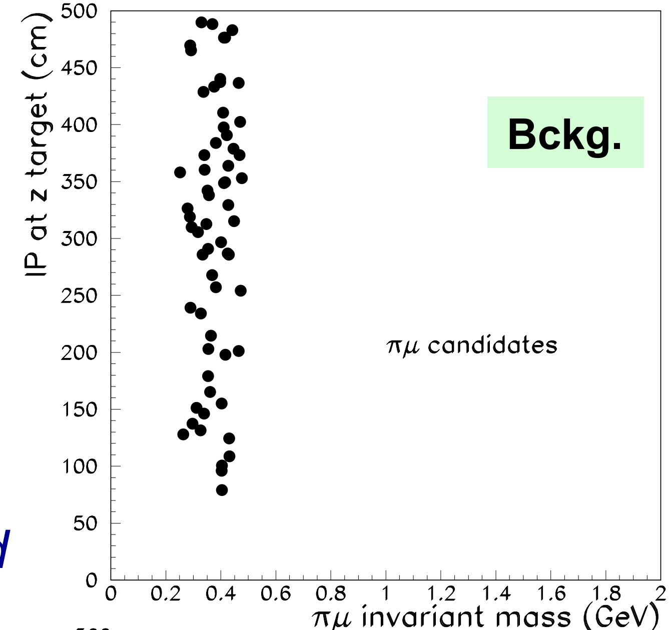
Detector concept (cont.)

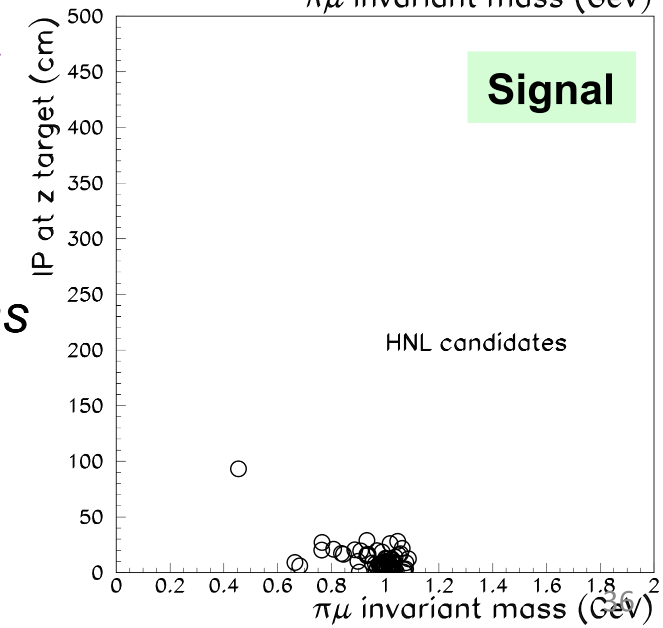
Impact Parameter resolution

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:*

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

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

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

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

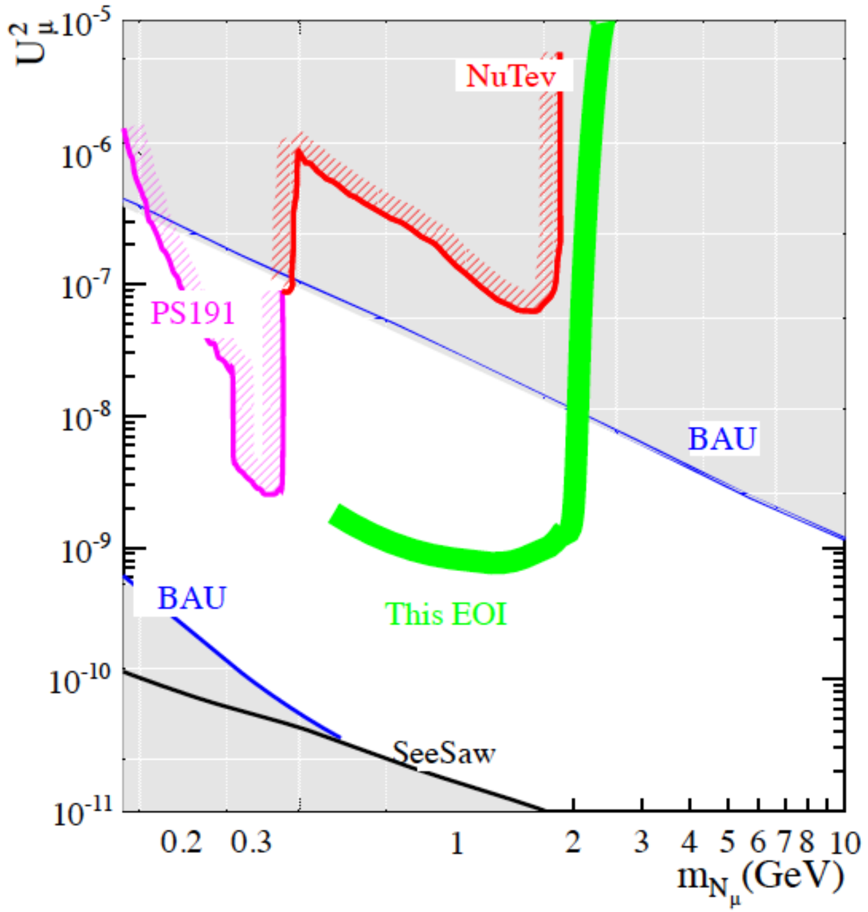
$BR(N_{2,3} \rightarrow \mu^- \pi^+)$ *is assumed to be 20%*

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

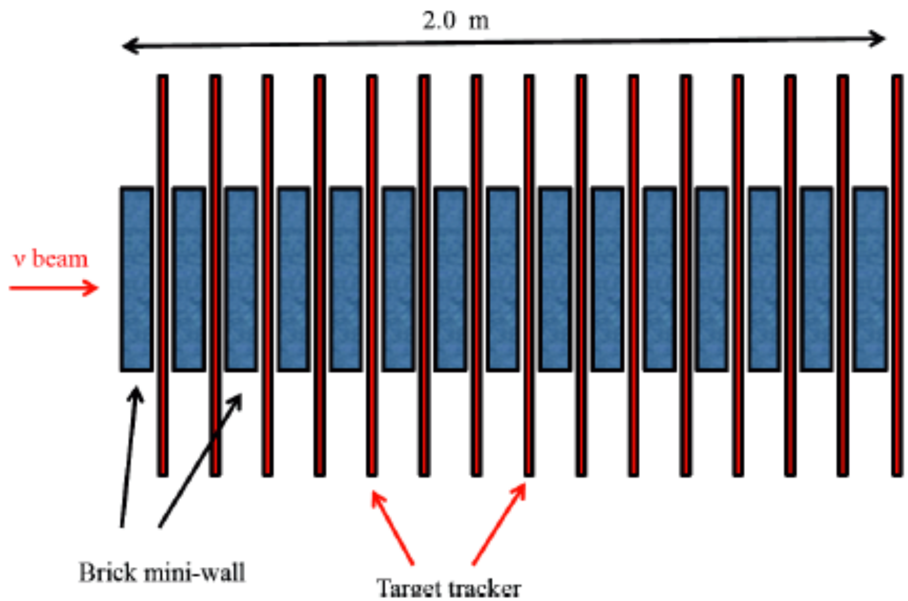
- *ECAL will allow the reconstruction of decay modes with π^0 such as $N \rightarrow \mu^- \rho^+$ with $\rho^+ \rightarrow \pi^+ \pi^0$, doubling the signal yield*
- *Study of decay channels with electrons such as $N \rightarrow e\pi$ would further increase the signal yield and constrain U_e^2*

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 $\times 10^{-9}$

SM physics

ν_τ Physics with 2×10^{20} pot

- Scaling from DONUT: 20 times more CC with same ν-target mass.
- But can increase ν-target mass "easily", lets say to 3 % of OPERA emulsion surface:



- Only requires limited space along beam-line, hence "no" loss for HNL acceptance.
- HNL spectrometer is forward spectrometer of ν-physics program.
- ν-target allows to tag K_L which coincide with ν-interactions.
- Expect 1500-2000 CC ν_τ interactions.
- In addition: $5\times$ ν_μ CC charm production than CHORUS (2k).

Status of the SPSC review

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010. - 2013
- SPSC assigned 4 referees, who came with a list of questions.
- 3/1/2014: answers to questions: snoopy.web.cern.ch/snoopy/EOI/SPSC-EOI-010_ResponseToReferees.pdf
- 15/1/2014: SPSC discussed our proposal.

17/1/2014: The official feedback from the Committee is as follows :

"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."
Cheers,
Gavin, Lau, Matthew and Thierry
(for the SPS Committee).

Conclusion and Next steps

- *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 !***

- ***The proposed experiment perfectly complements the searches for NP at the LHC and in neutrino physics***

A collaboration is currently being setup with aim for the first collaboration meeting in June. Let us know if you are interested to join !

BACK - UP

Other BSM physics

Search for light, very weakly interacting, yet unstable New Particles

Massive paraphotons, p (in secluded Dark Matter models),
e.g. $\Sigma \rightarrow pV$ with $V \rightarrow \mu\mu$

M. Pospelov, A. Ritz,
M.B. Voloshin (2008)

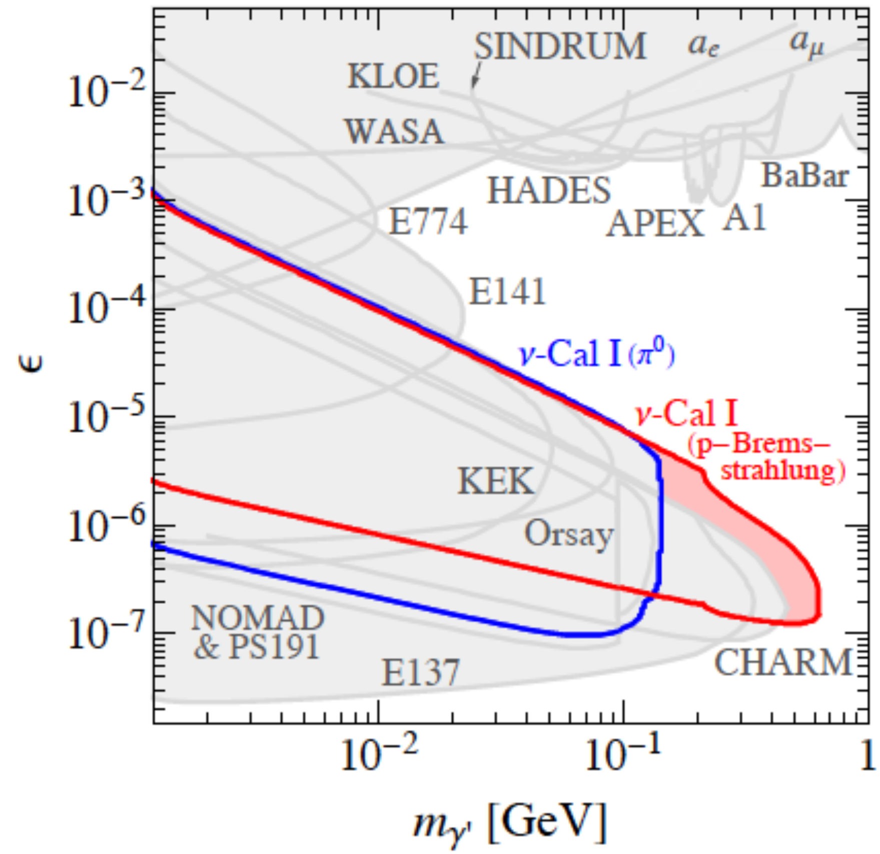


Figure 1: Present direct limits on the model parameter space (ϵ,$m_{\gamma'}$), for details and original references see [36].

Two orders of magnitude better sensitivity than in the CHARM experiment

Other BSM physics

Search for light, very weakly interacting, yet unstable New Particles

Light s-goldstinos (super-partners of SUSY goldstinos),
e.g. D → πX with X → $\mu\mu$

D.S. Gorbunov (2001)

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

R-parity violating neutralinos in SUSY goldstinos,
e.g. D → $\mu\,\bar{\chi}_0$ with $\bar{\chi}_0 \to \mu^+\mu^-\nu$

A. Dedes, H.K. Dreiner,
P. Richardson (2001)

$$N \simeq 20 \times \left(\frac{m_{\chi_0}}{1\,\mathrm{GeV}}\right)^6 \left(\frac{\lambda}{10^{-8}}\right)^2 \left(\frac{\mathrm{Br}\,(D \to \chi_0 + \ldots)}{10^{-10}}\right)$$

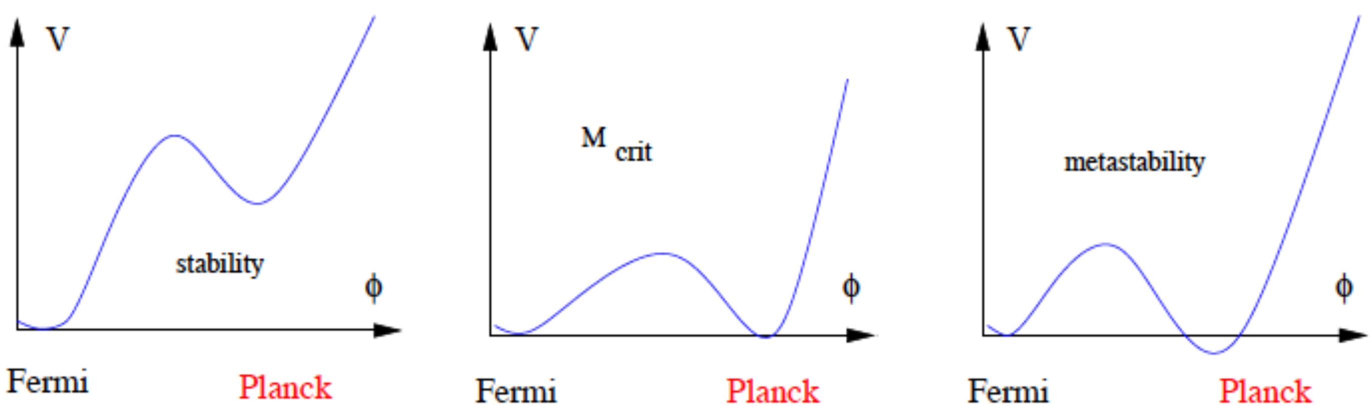
*The mass of the Higgs boson is very close to the stability bound of the Higgs mass **

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

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