Proposal to search for Heavy Neutral Leptons at the SPS

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

Disclaimer: It is not a classical neutrino physics experiment

On behalf of:

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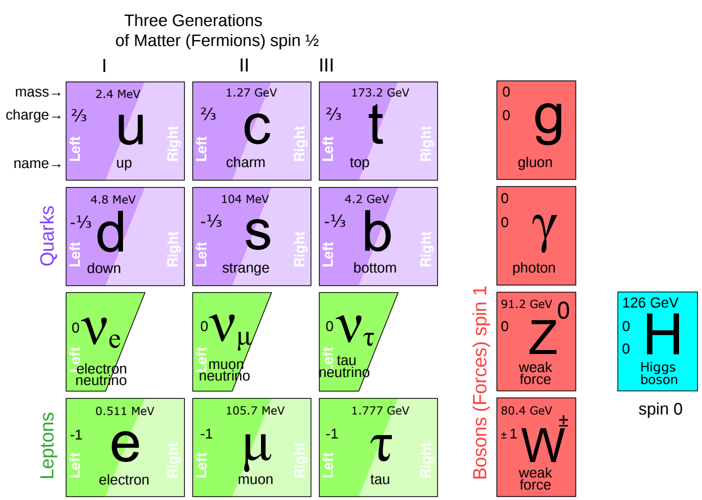
Theoretical motivation

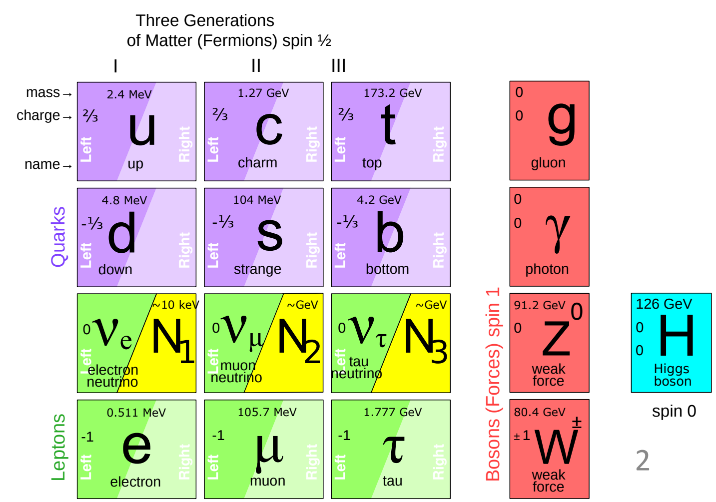
- *Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model The SM may work successfully up to Planck scale !*

- *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*

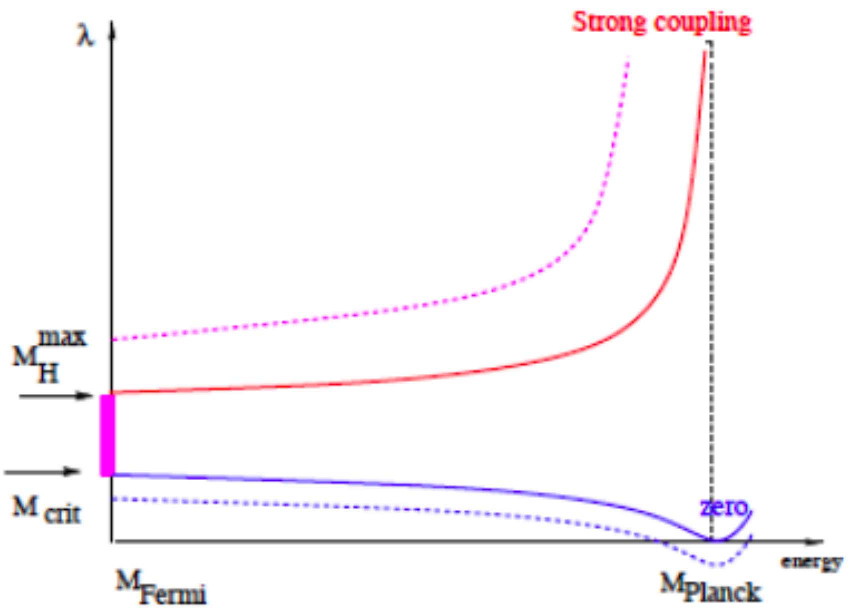
***νMSM**: T.Asaka, M.Shaposhnikov PL **B620** (2005) 17*



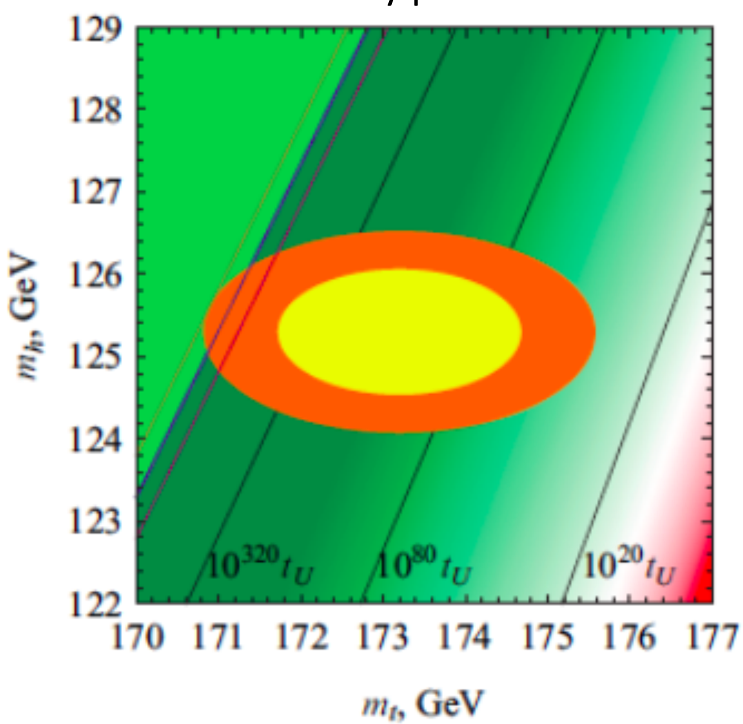


SM may well be a consistent effective theory all the way up to the Plank scale

- ✓ *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)*



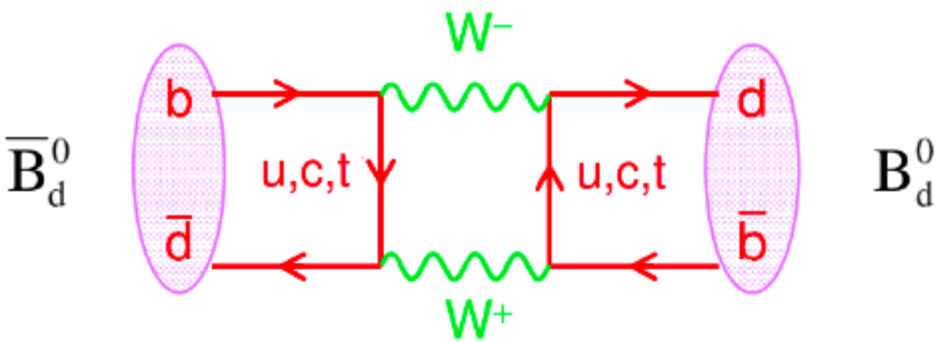
Stable vacuum is perfectly admitted by present data



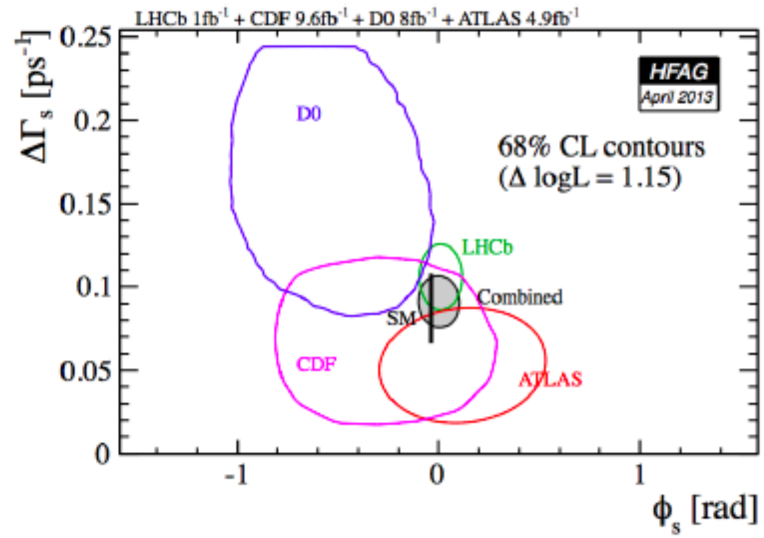
- ✓ *No sign of New Physics seen*

Bounds on the scale of New Physics

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



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



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]

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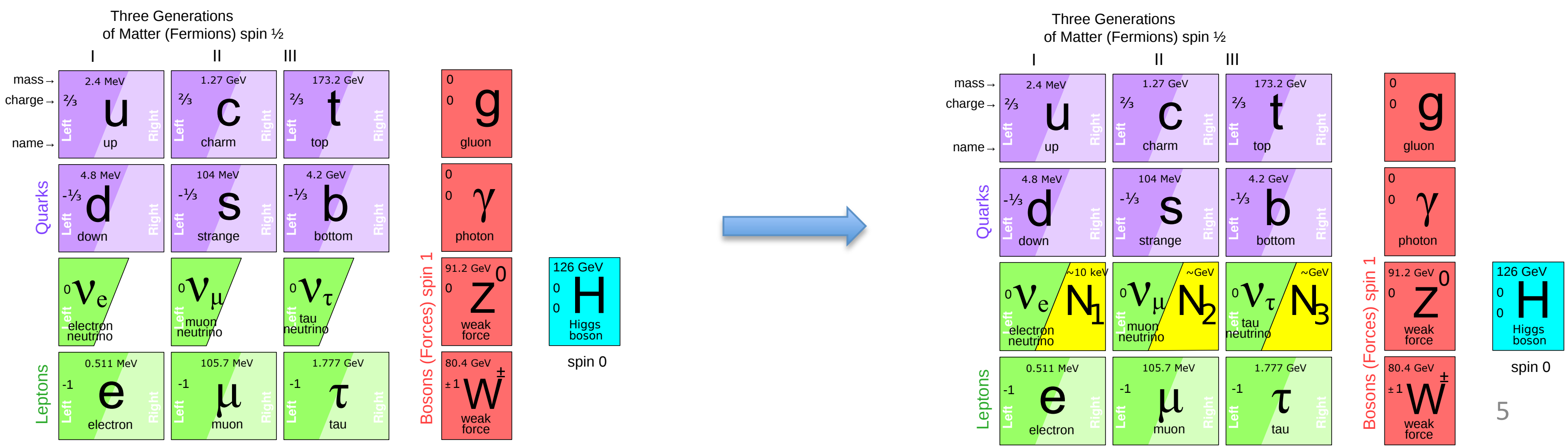
νMSM: *T.Asaka, M.Shaposhnikov PL **B620** (2005) 17*

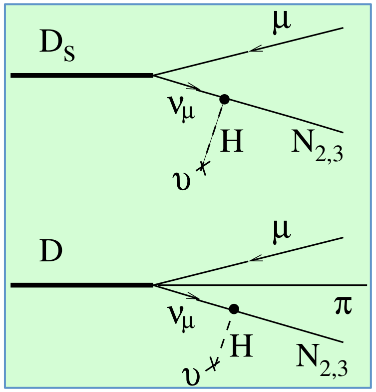


Masses and couplings of HNLs

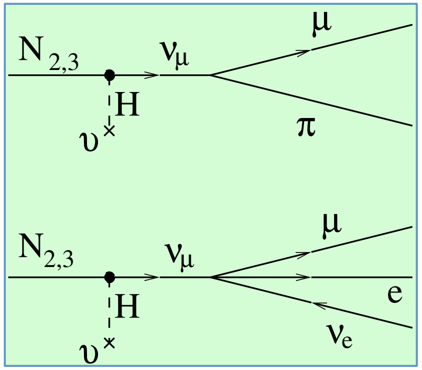
- *N_1 can be sufficiently stable to be a DM candidate, $M(N_1)$~10keV*
- *$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU) using sphaleron lepton-to-baryon number transformation*

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

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

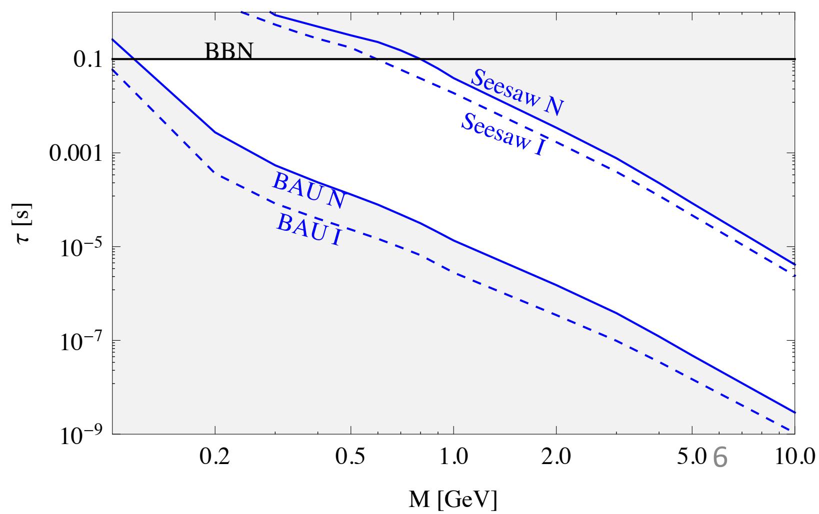


and subsequent decays

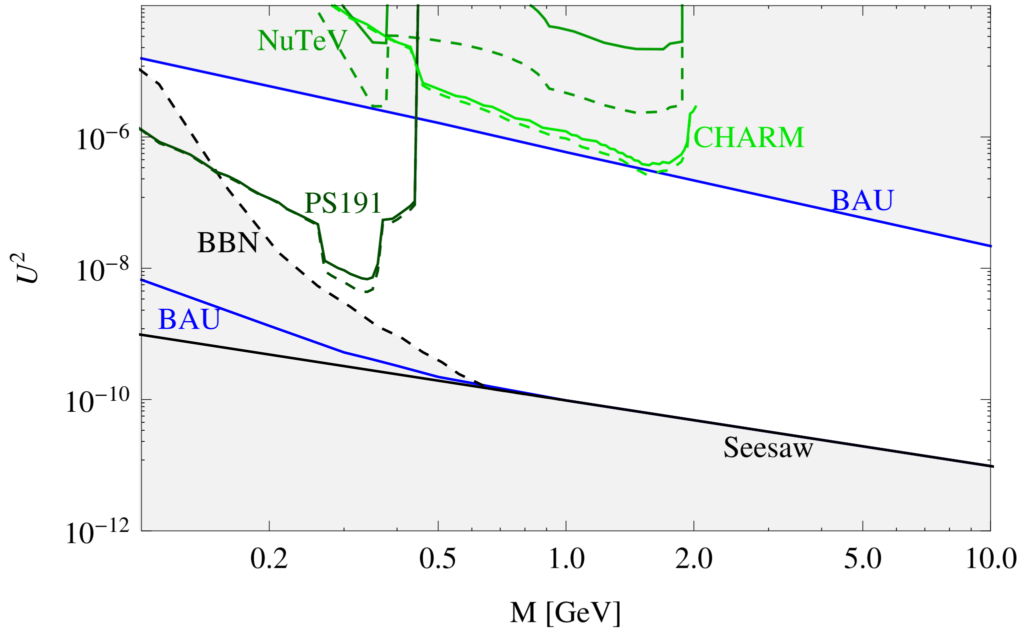


- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV*
  Decay distance O(km)
- *Typical BRs (depending on the flavour mixing):*

Br(N → μ/e π) ~ 0.1 – 50%
Br(N → μ^-/e$^-$ ρ^+) ~ 0.5 – 20%
Br(N → $\nu\mu$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*

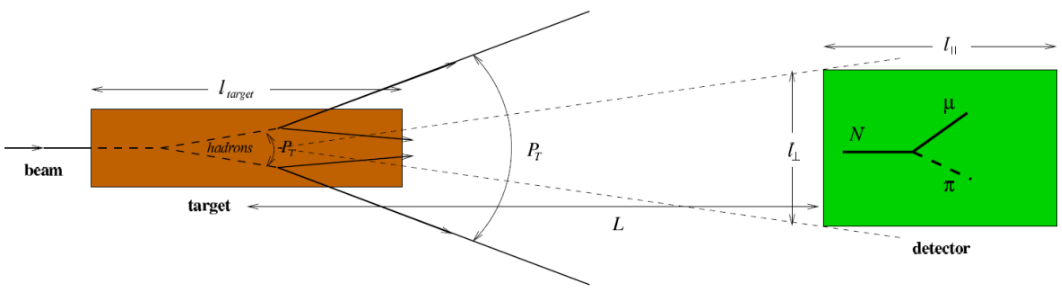
Proposal for a new experiment at the SPS to search for New long-lived Particles produced in charm decays
Experimentally this domain has not been very well explored !

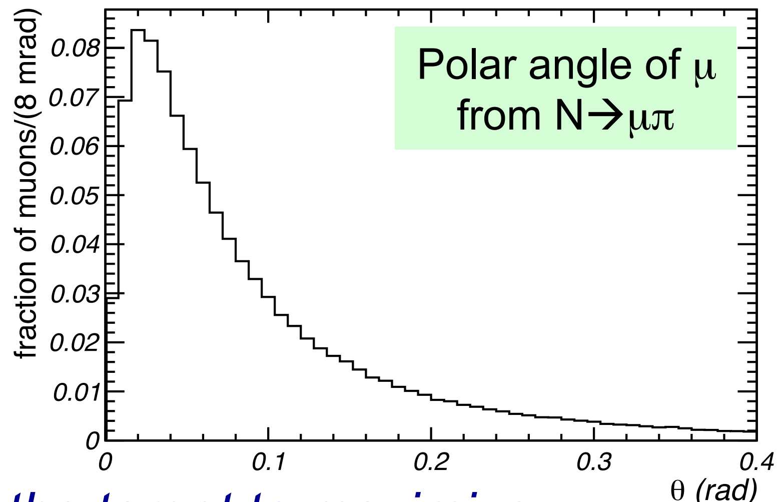
Experimental requirements

- *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

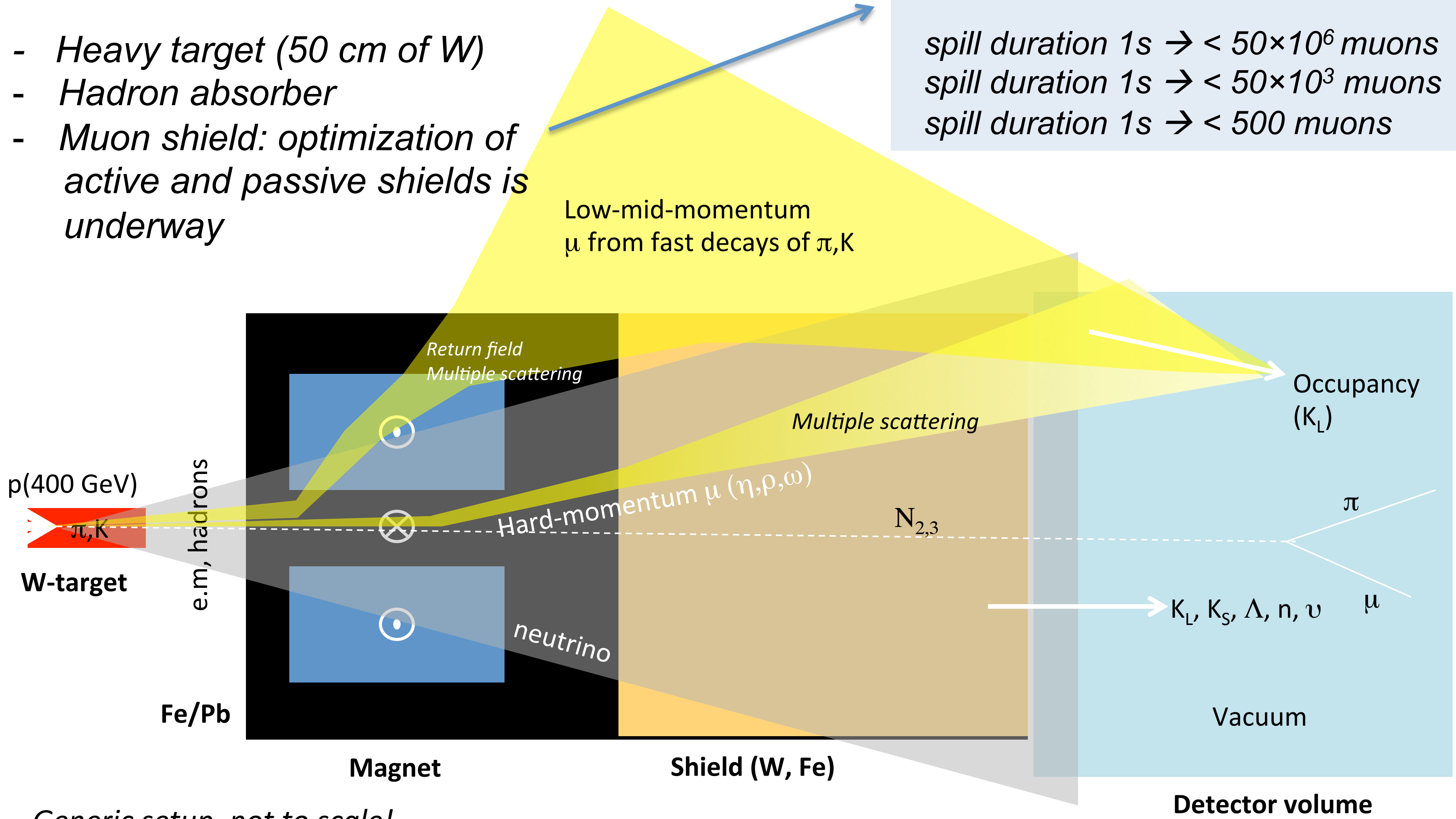
(incompatible with conventional neutrino facility)

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 1s → < 50×10^{3} muons
spill duration 1s → < 500 muons

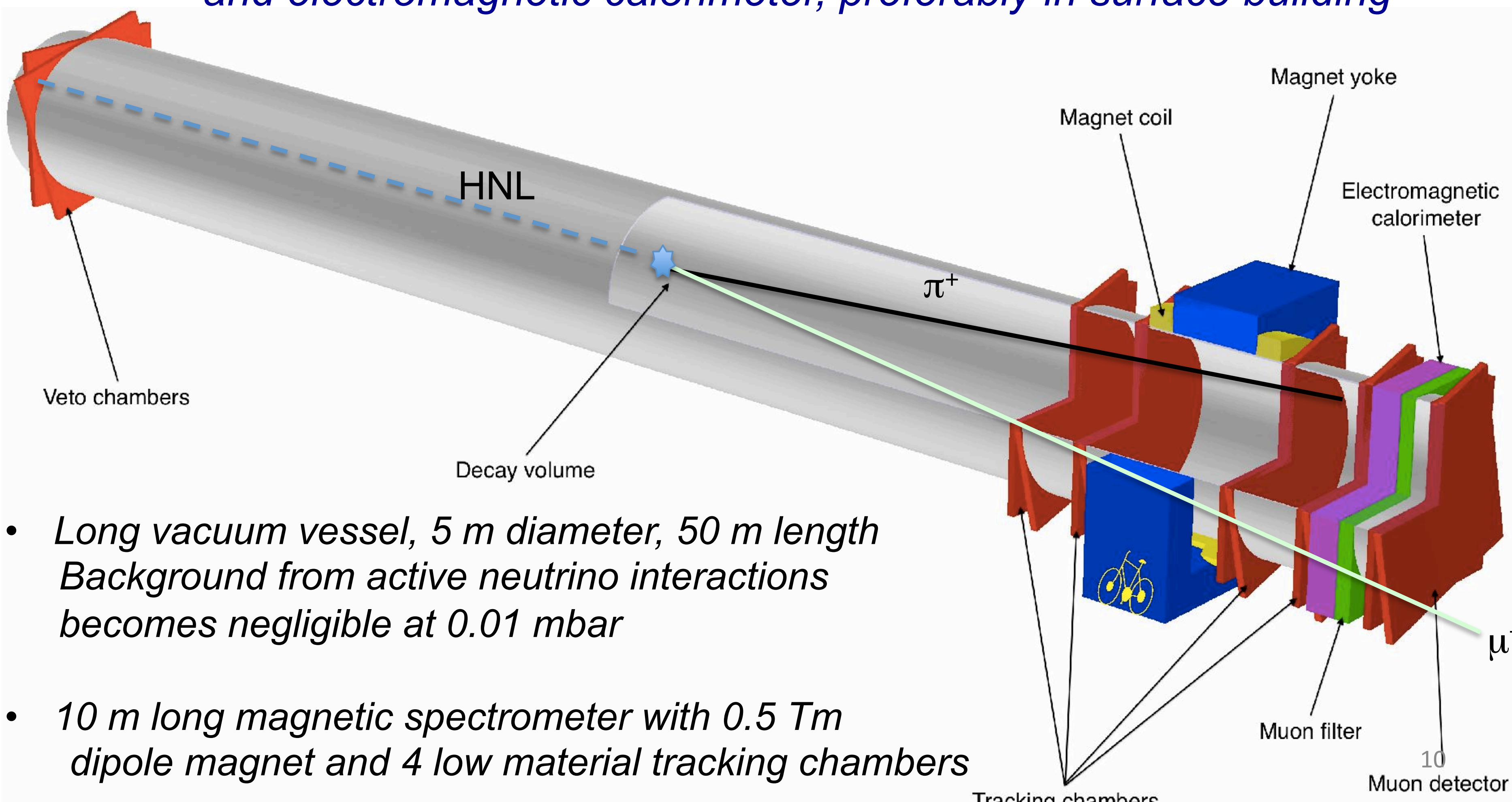


Generic setup, not to scale!

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*



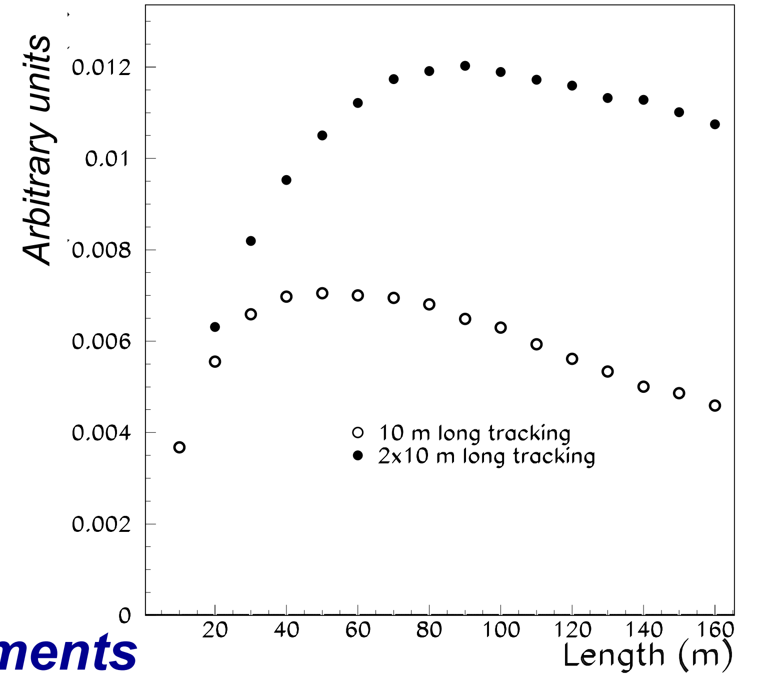
- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*

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

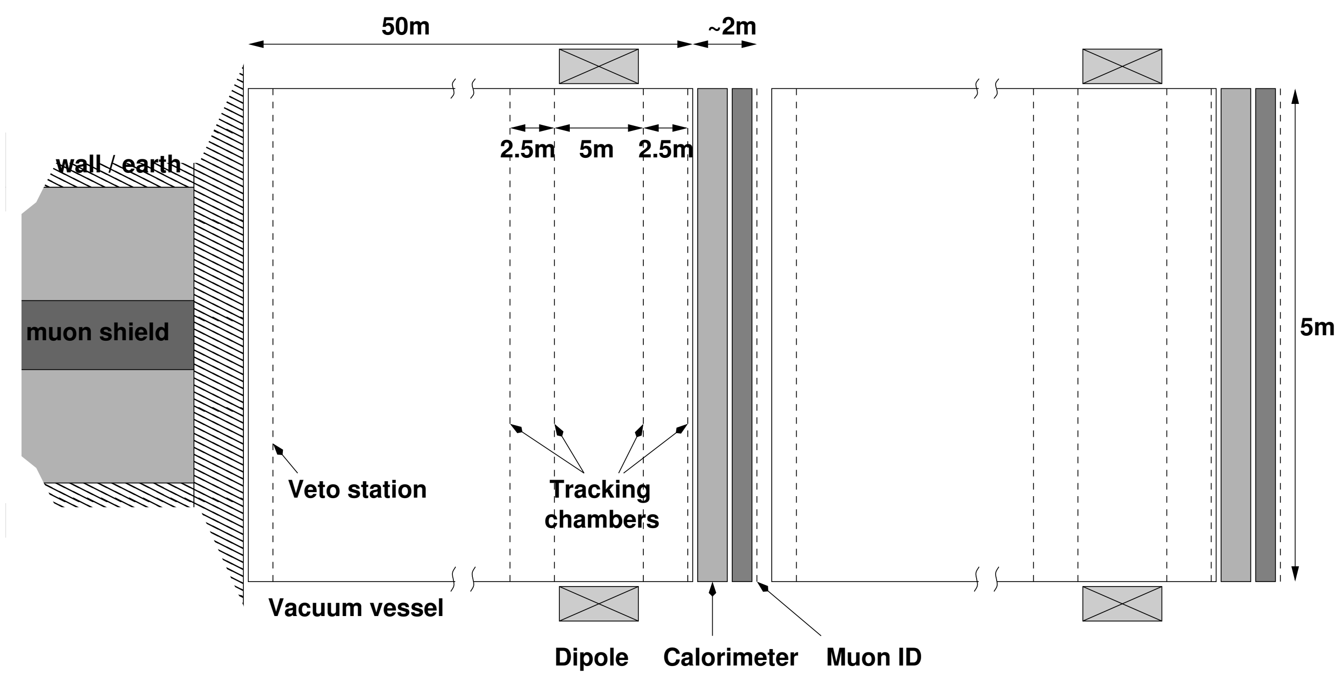
Detector concept (cont.)

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



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)

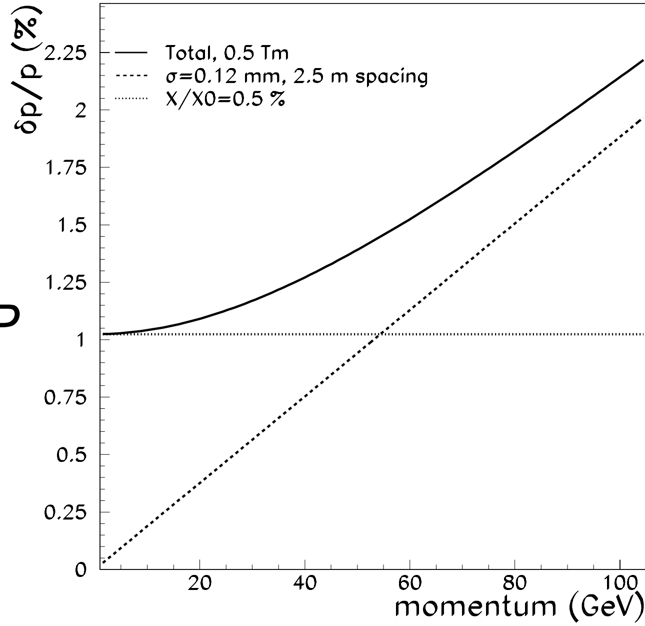
→ *yields CC(NC) rate of ~6(2)×10^5 per int. length per 2×10^{20} pot*

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***

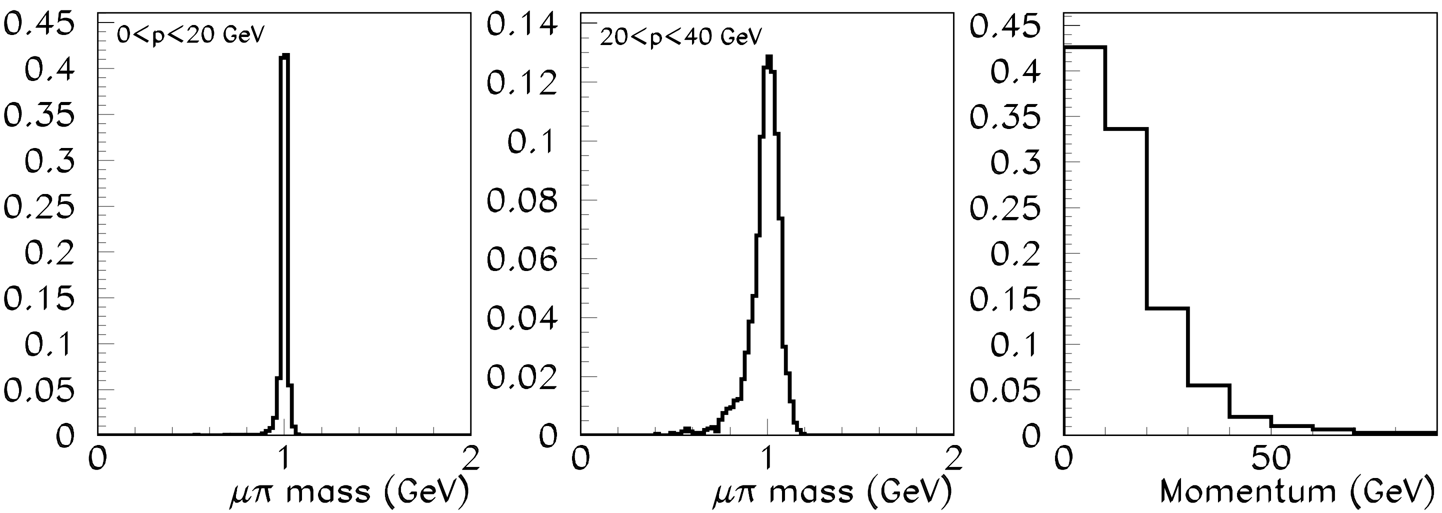
Detector concept (cont.)

Magnetic field and momentum resolution



- *Multiple scattering and spatial resolution of straw tubes give similar contribution to the overall δP / P*
- *For $M(N_{2,3})$ = 1 GeV 75% of μ π decay products have both tracks with P < 20 GeV*

Reconstruction of HNL with 1 GeV mass



- *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*

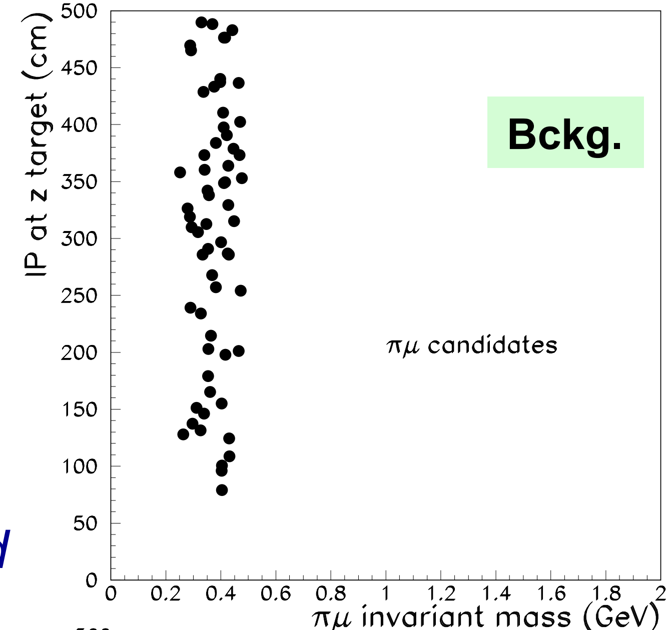
Detector concept (cont.)

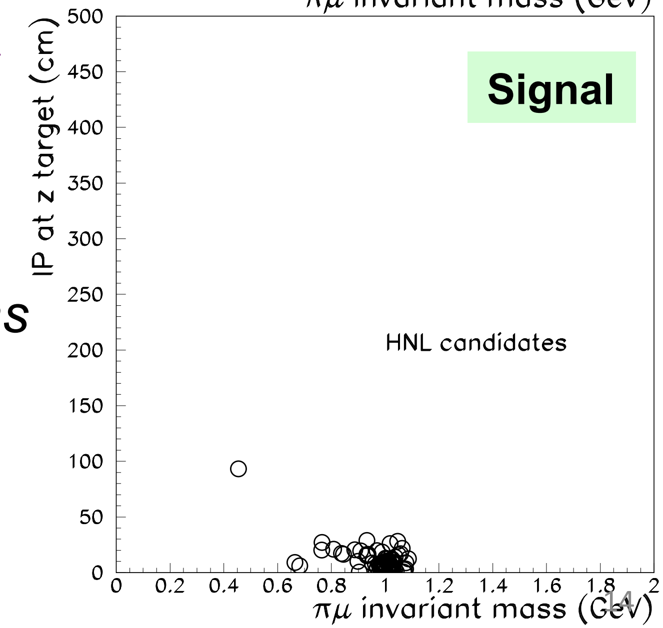
Impact Parameter resolution

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

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

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

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

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

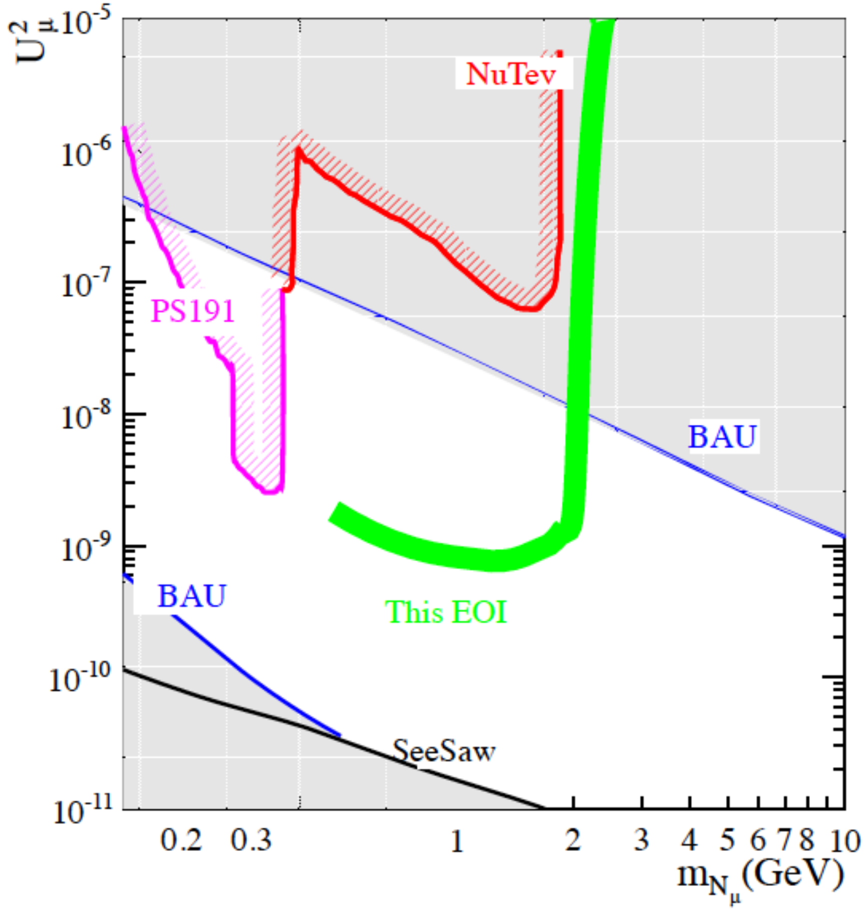
$BR(N_{2,3} \rightarrow \mu^- \pi^+)$ is assumed to be 20%

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

Expected event yield (cont.)

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

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



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

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 $\times 10^{-9}$

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*

- ✓ ***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 and in neutrino physics***

BACK - UP

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 → $\mu\ \tilde{\chi}_0$ with $\tilde{\chi}_0 \to \mu^+\mu^-\nu$

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

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

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)

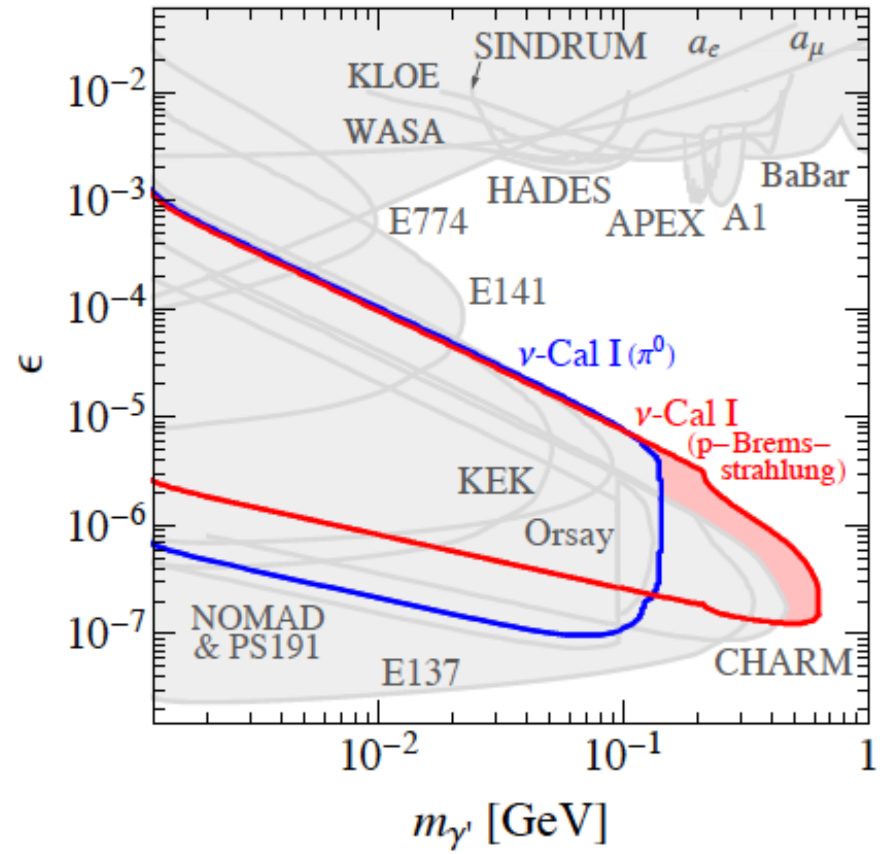
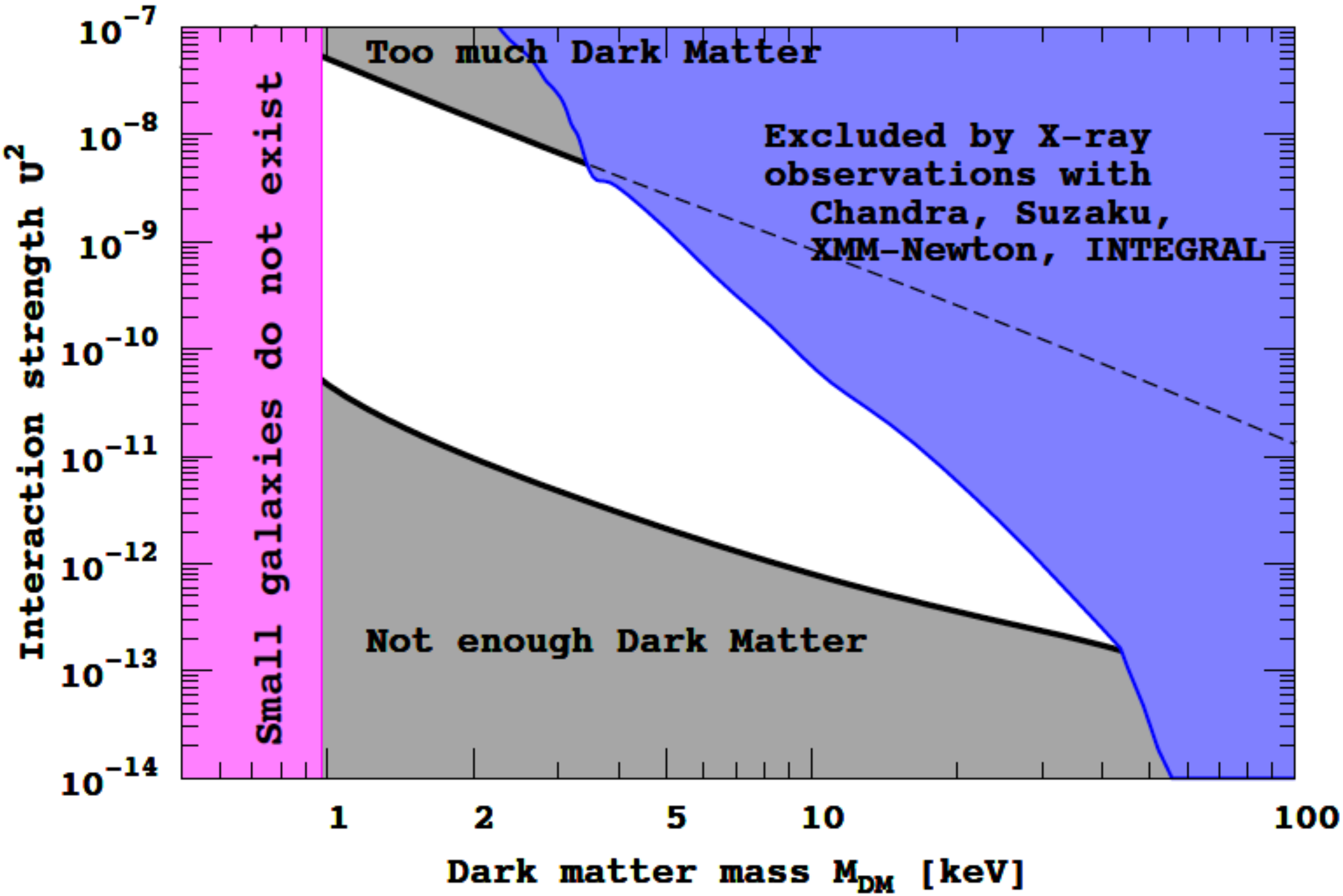


Figure 1: Present direct limits on the model parameter space (ϵ,$m_{\gamma'}$), for details and original references see [36].

Two orders of magnitude better sensitivity than in the CHARM experiment

Parameter space of HNL dark matter



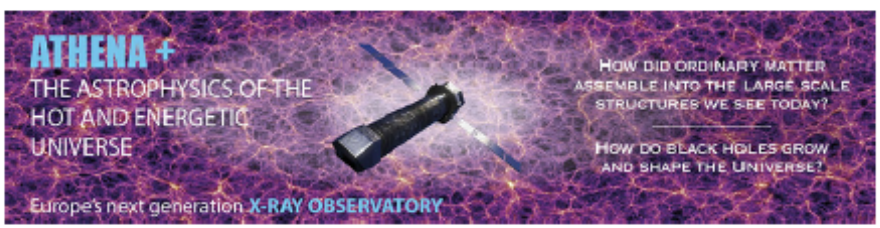
Searches for HNL in space

- 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

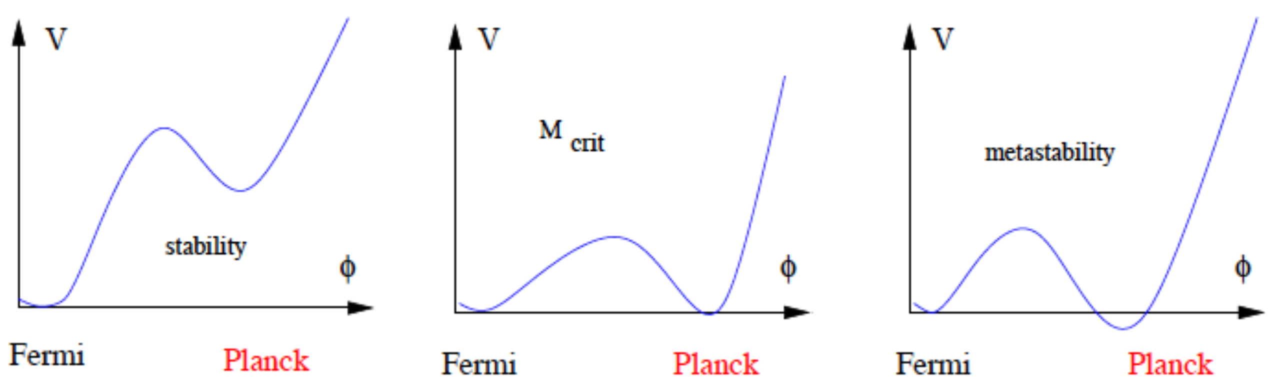
The mass of the Higgs boson is very close to the stability bound on the Higgs mass* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety value for M_H*** (09'):

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

$y_t(M_t)$ - 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

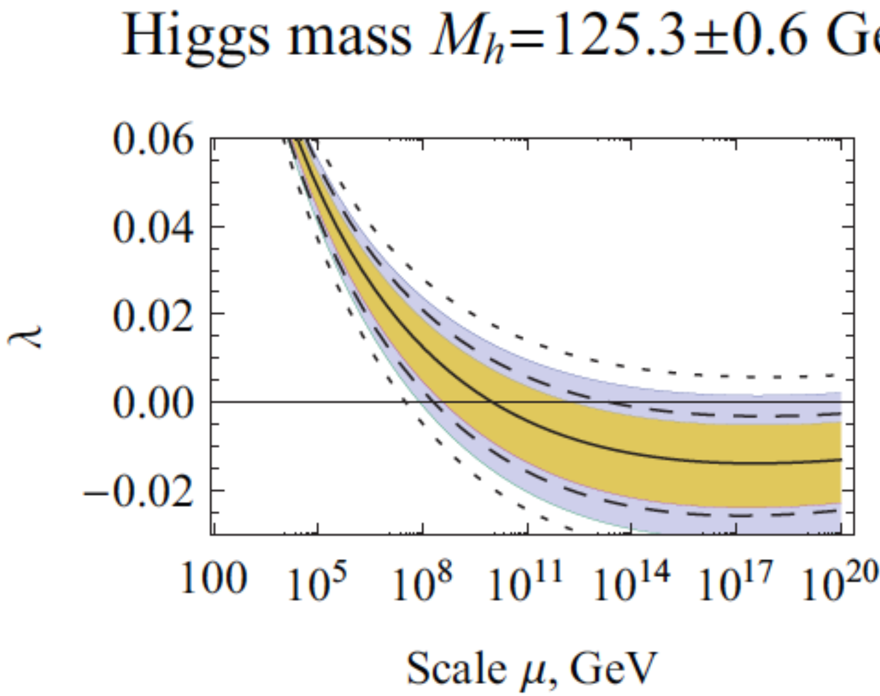


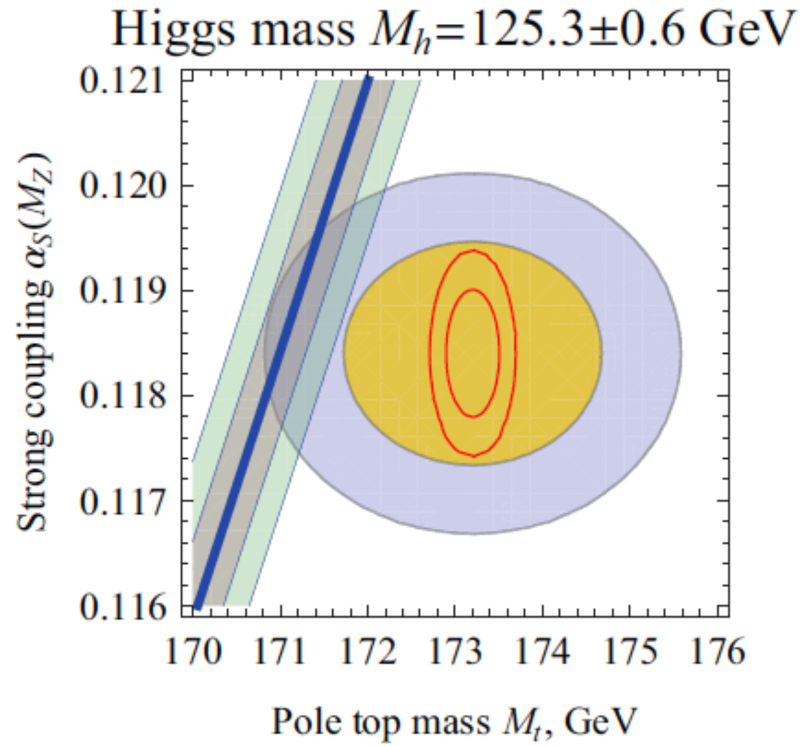
* Froggatt, Nielsen

** Bezrukov et al, De Simone et al

*** Wetterich, MS

Our vacuum may be absolutely stable - this is perfectly admitted by the present data:





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

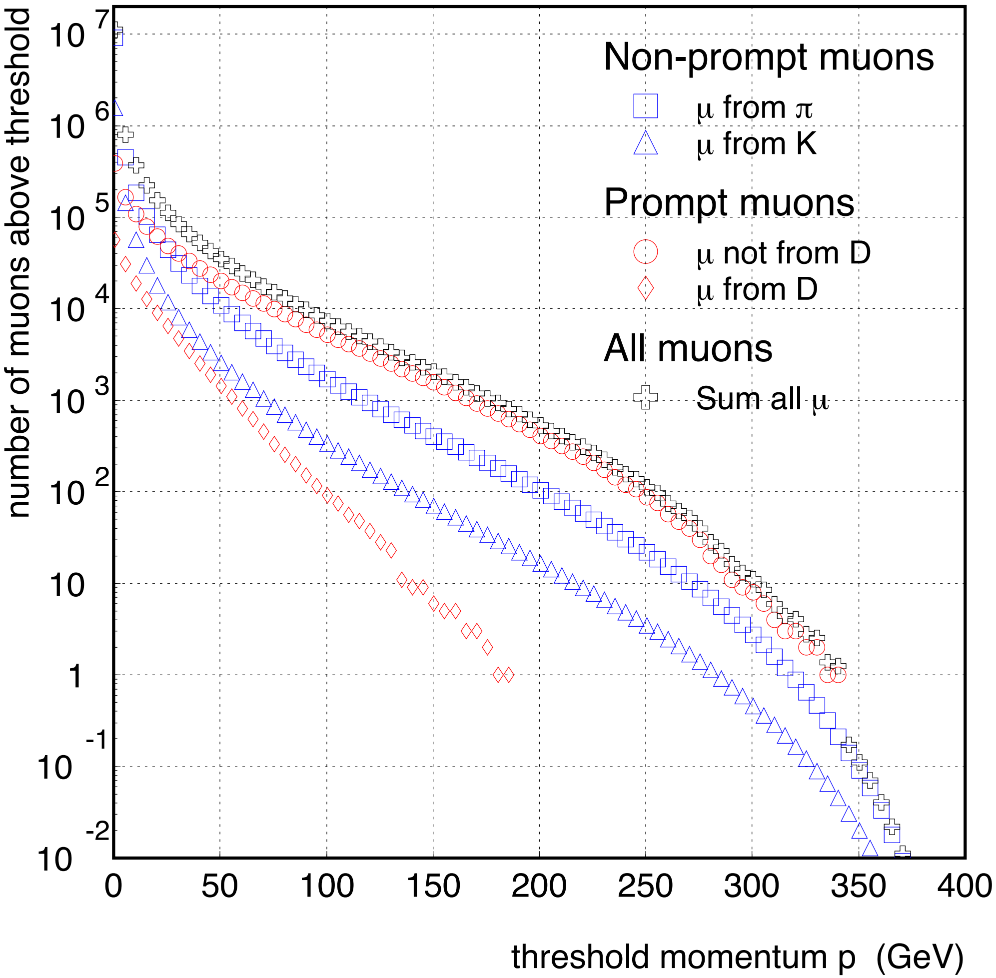
$\alpha_s = 0.1184 \pm 0.0007$

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*



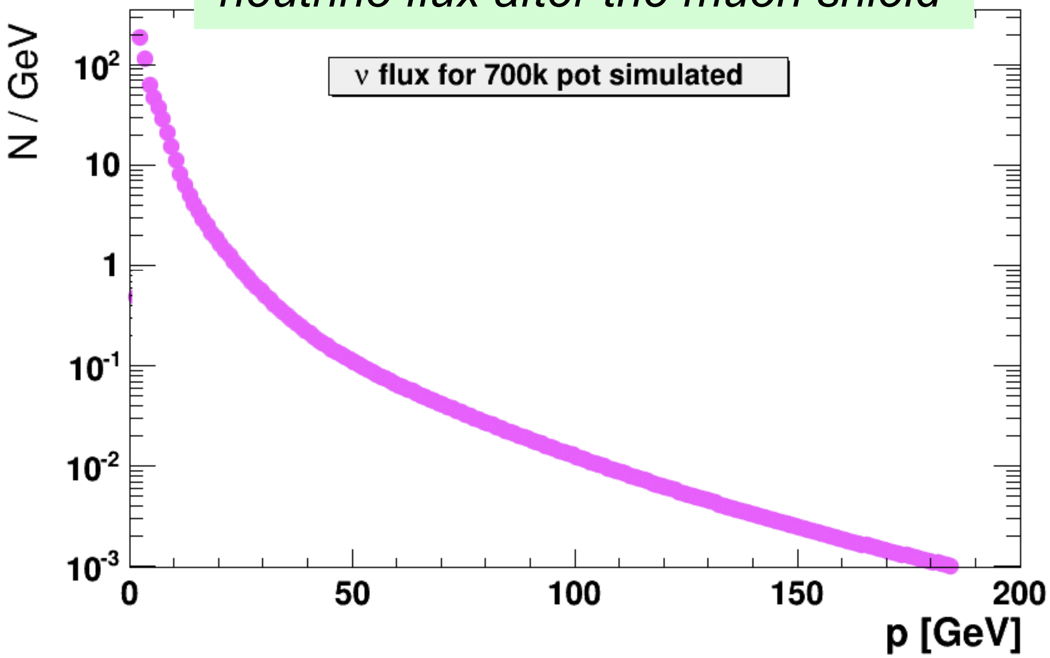
Assume that muon induced backgrounds will be reduced to negligible level with such a shield

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

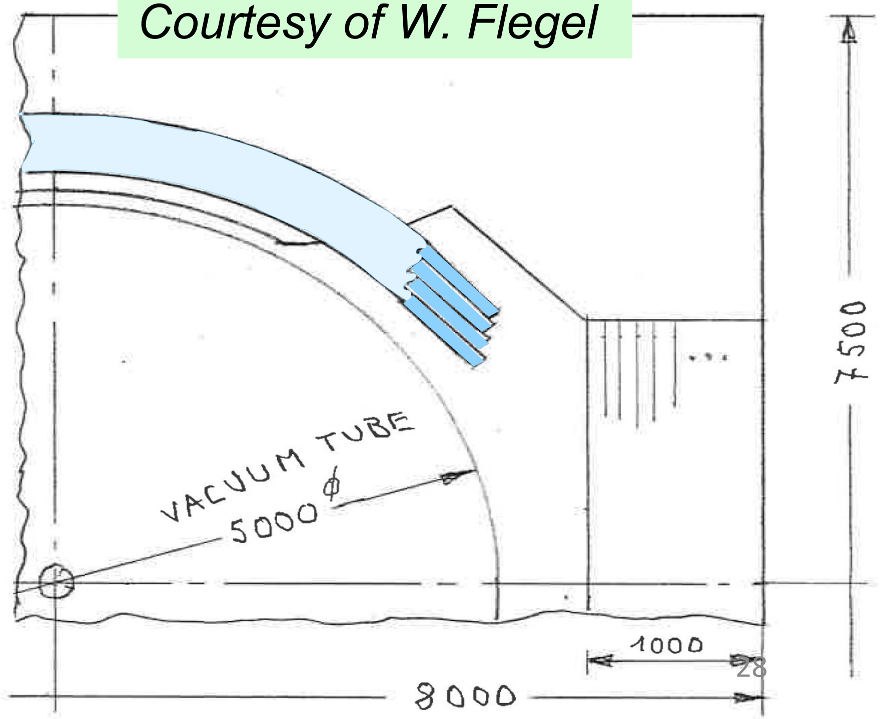
Detector apparatus

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



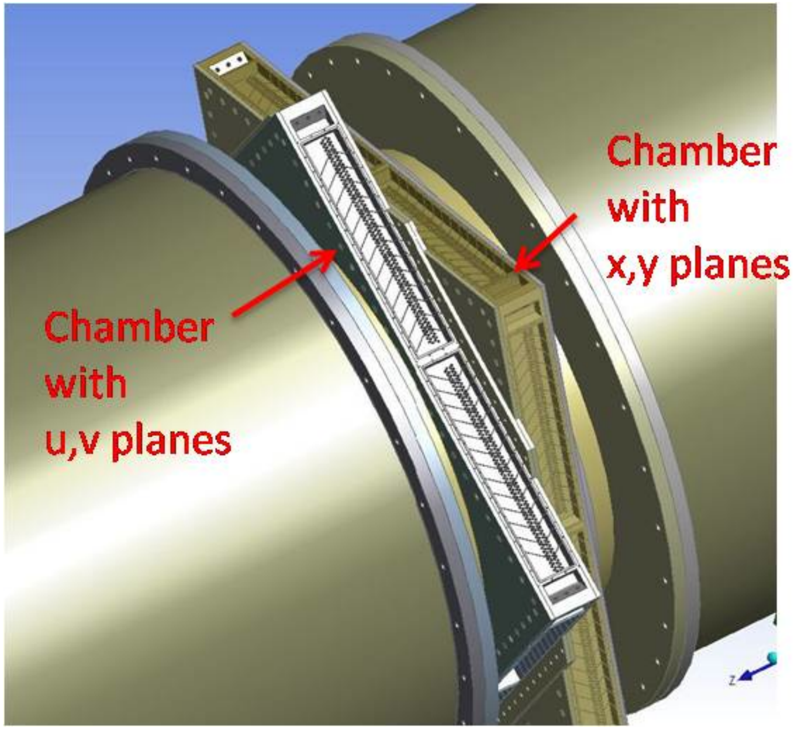
Courtesy of W. Flegel

Detector apparatus (cont.)

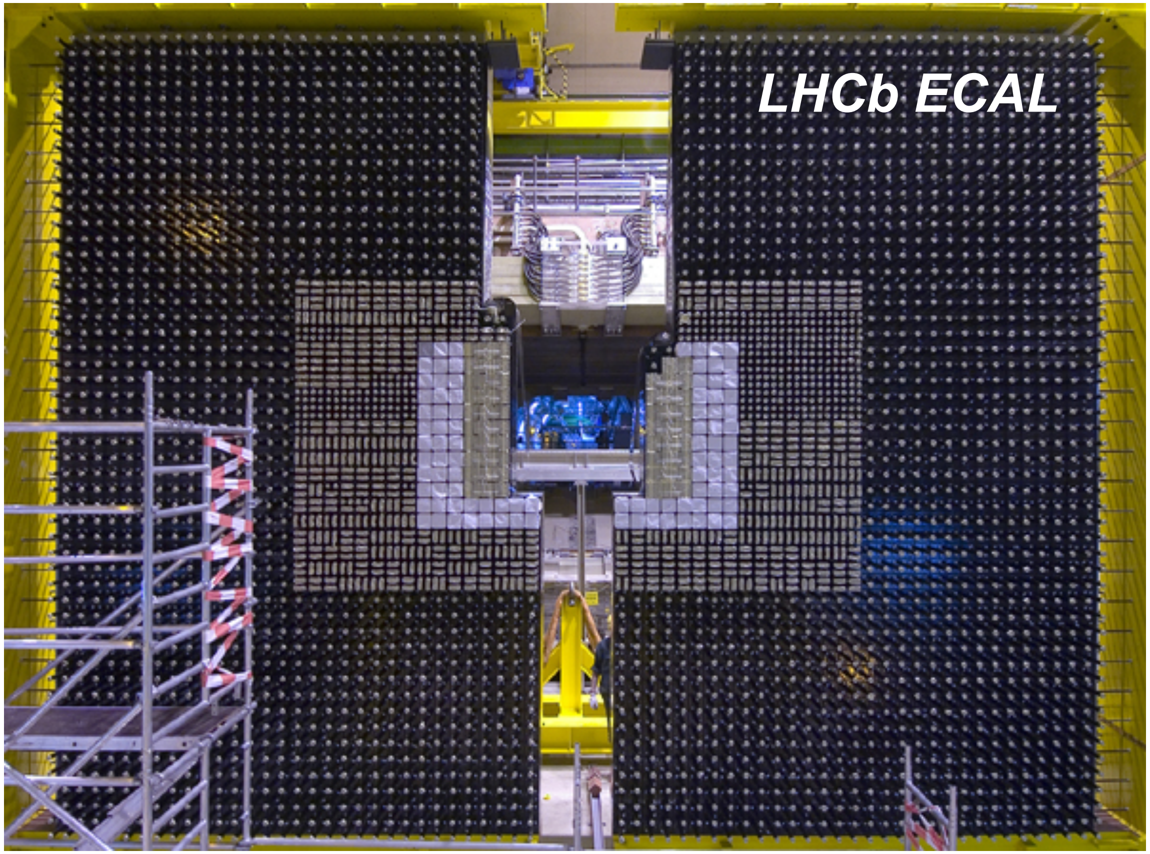
based on existing technologies

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*