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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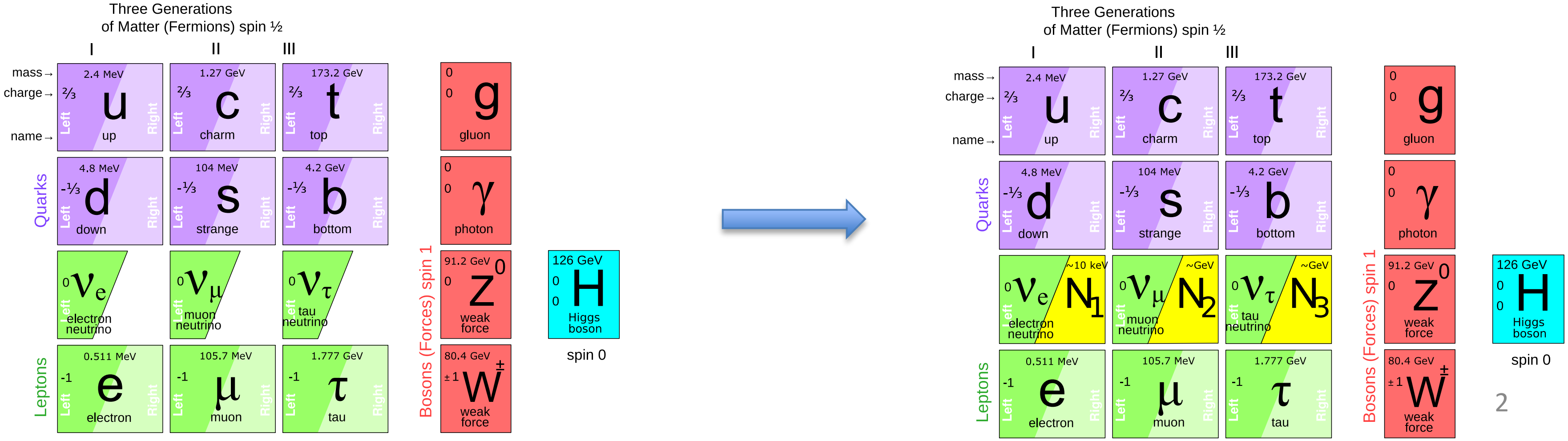
Theoretical motivation

- *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*



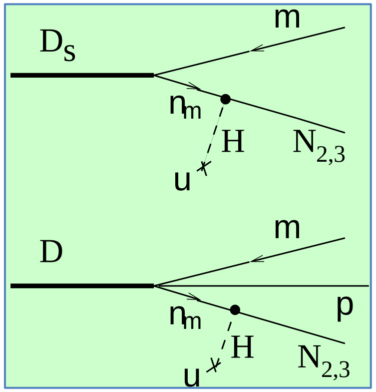
Masses and couplings of HNLs

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

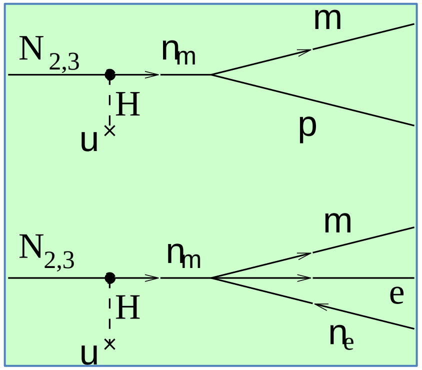
- *$M(N_2) \approx M(N_3)$ ~ a few GeV → CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)*

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

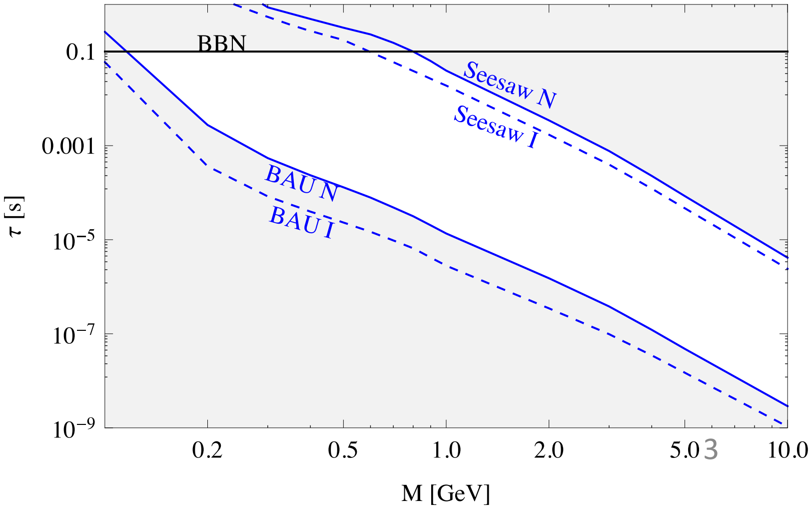


and subsequent decays



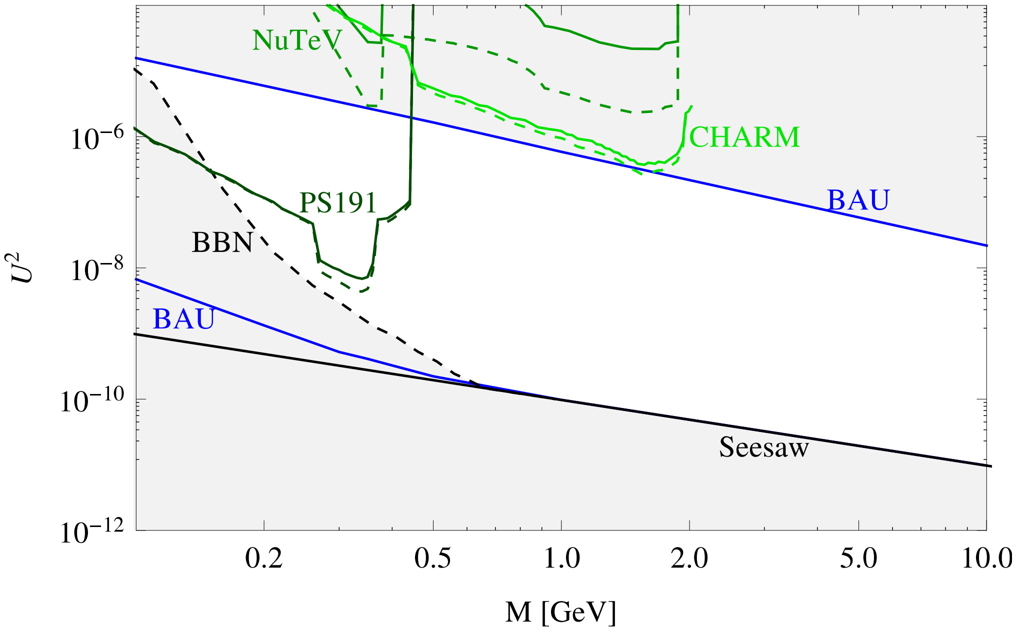
- *Typical lifetimes > 10 μs for $M(N_{2,3})$ ~ 1 GeV*
  Decay distance O(km)

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



Br(N → $\mu/e\ \pi$) ~ 0.1 – 50%
Br(N → $\mu^-/e^-\ \rho^+$) ~ 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

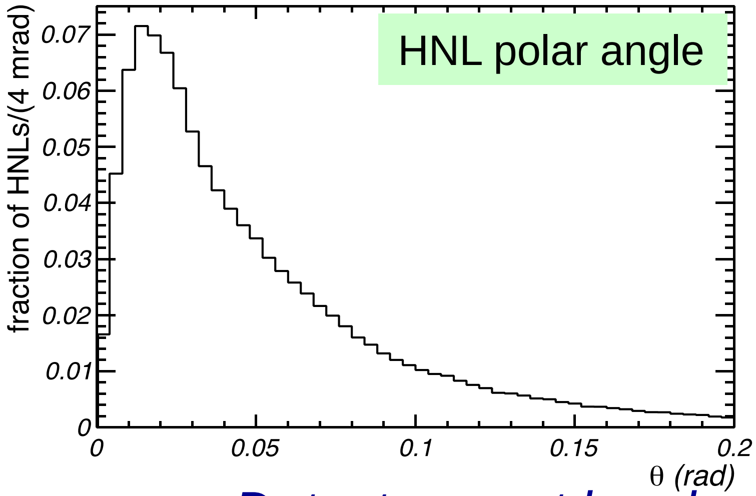
Proposal for a new experiment at the SPS to search for New Particles produced in charm decays

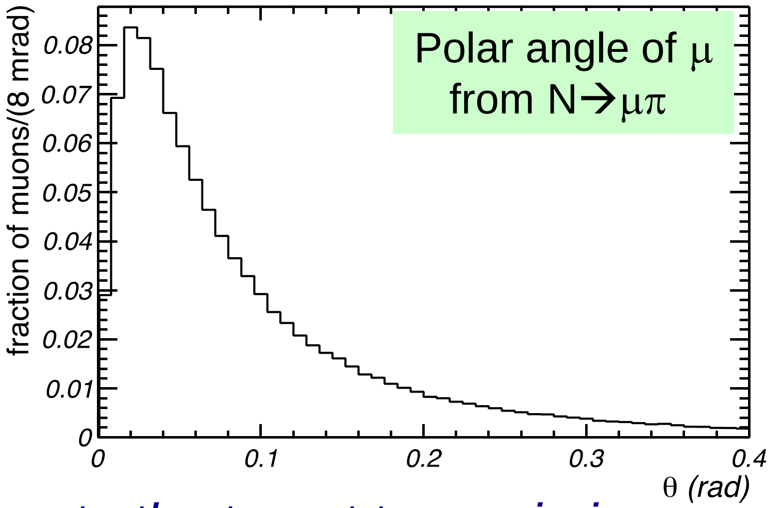
Experimental requirements

- *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*

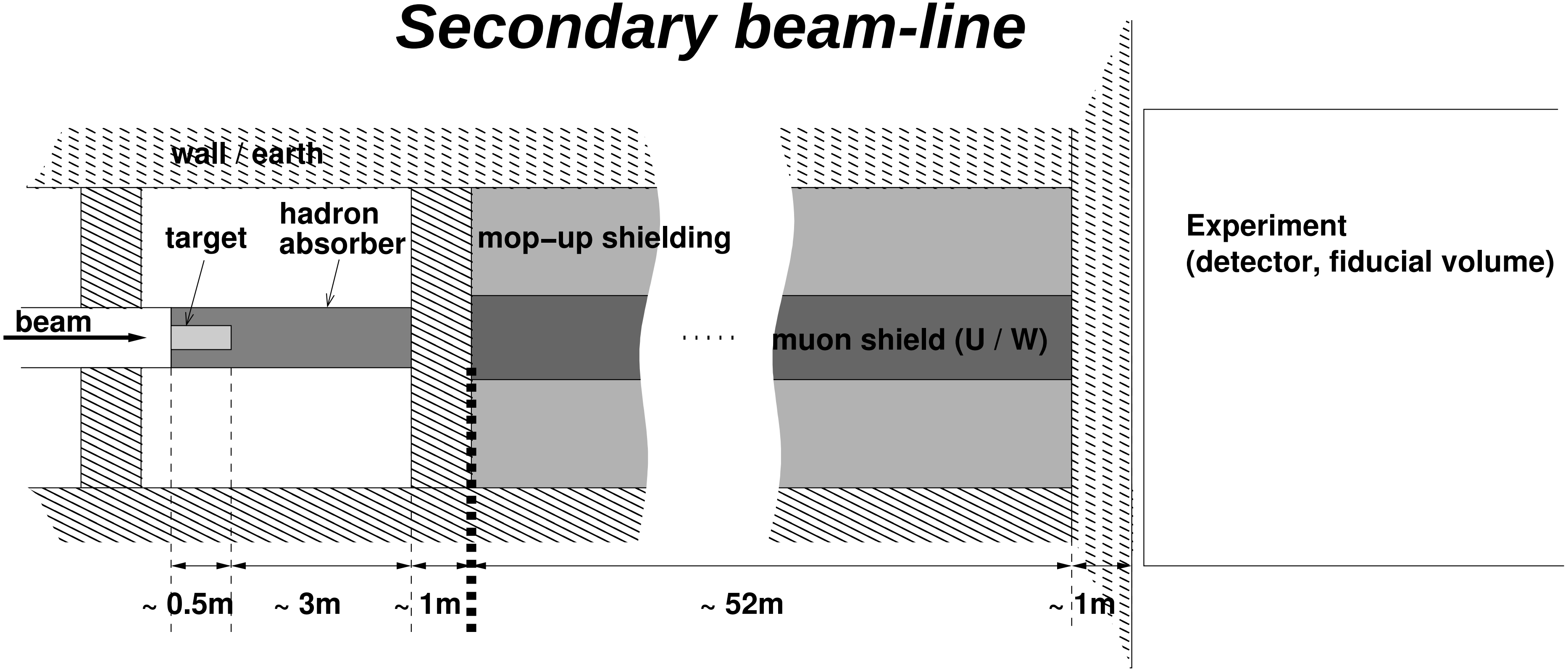




Detector must be placed close to the target to maximize geometrical acceptance

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*

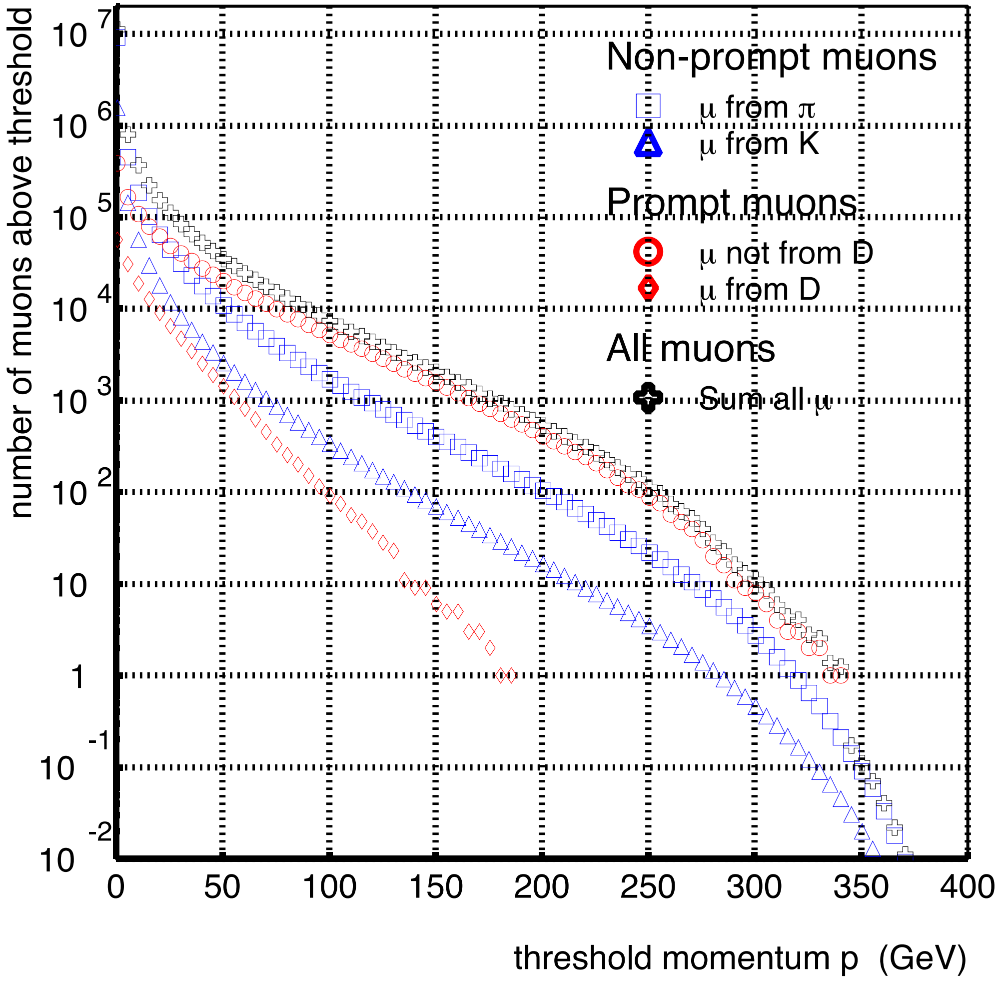
- *No requirement to have a small beam spot*

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*



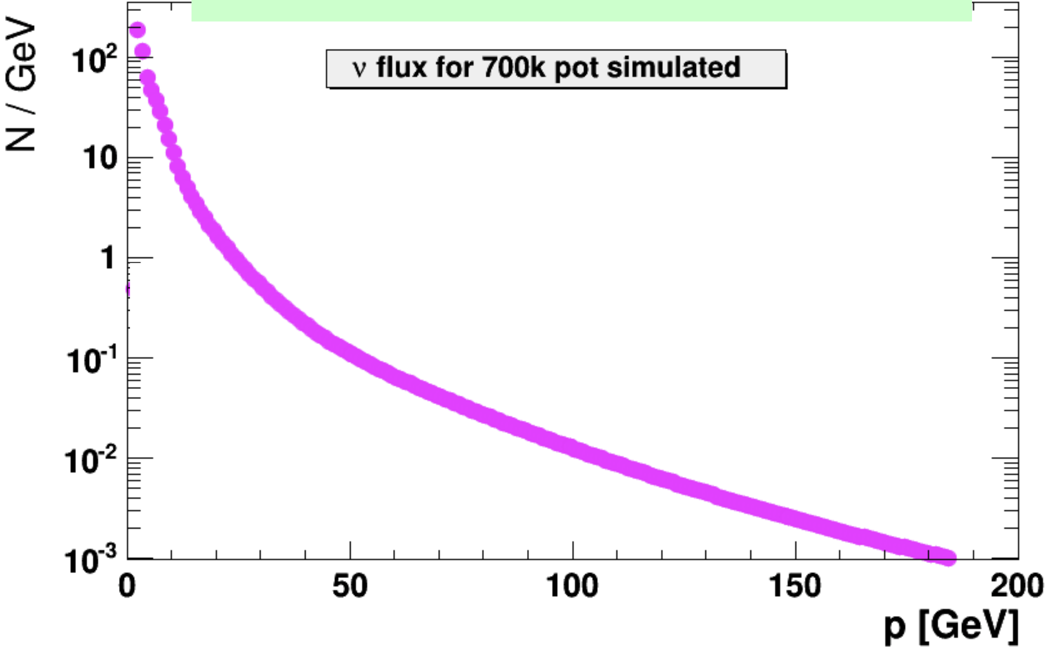
Assume that muon induced backgrounds will be reduced to negligible level with such a shield

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

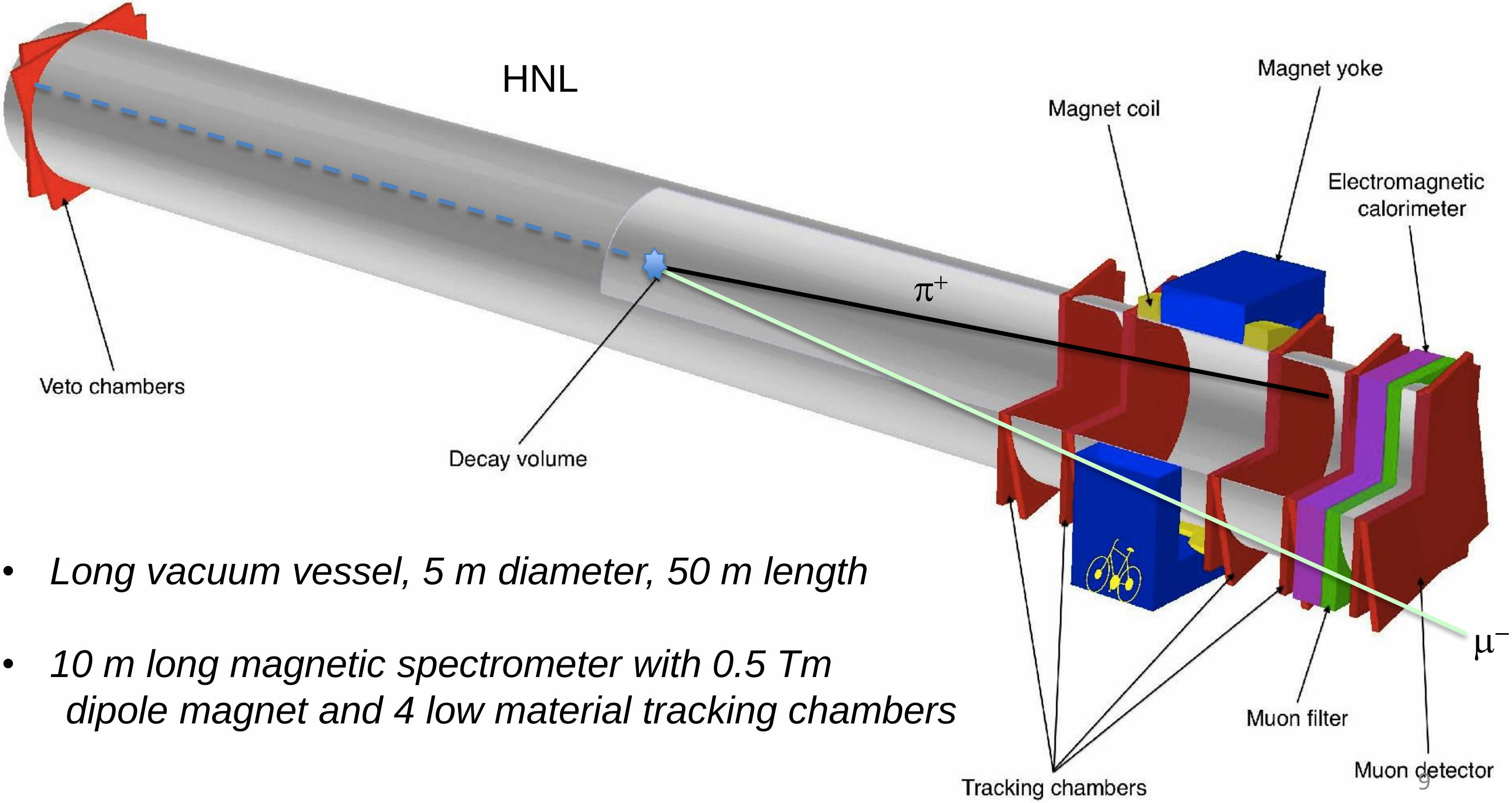


2×10^4 neutrino interactions per 2×10^{20} pot in the decay volume at atmospheric pressure → becomes negligible at 0.01 mbar

Detector concept

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

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

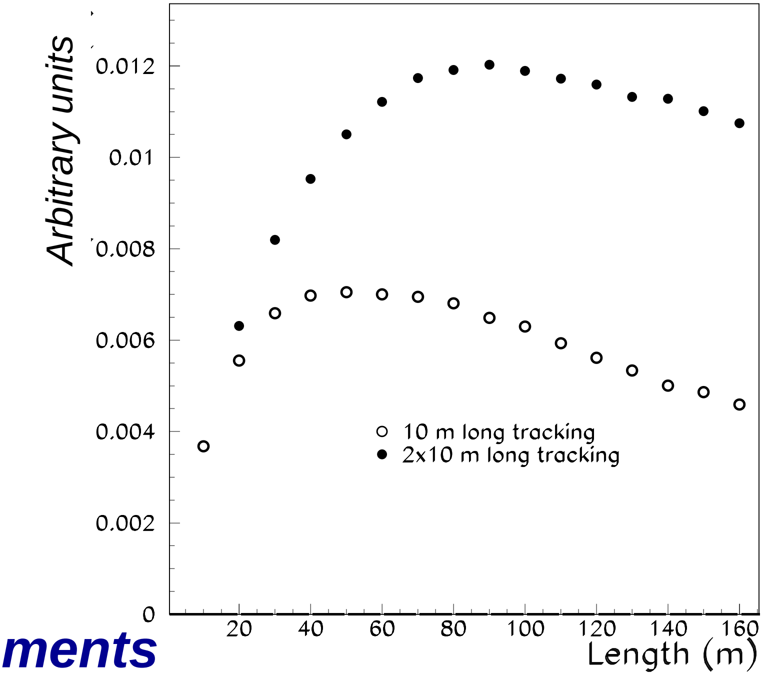


- *Long vacuum vessel, 5 m diameter, 50 m length*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

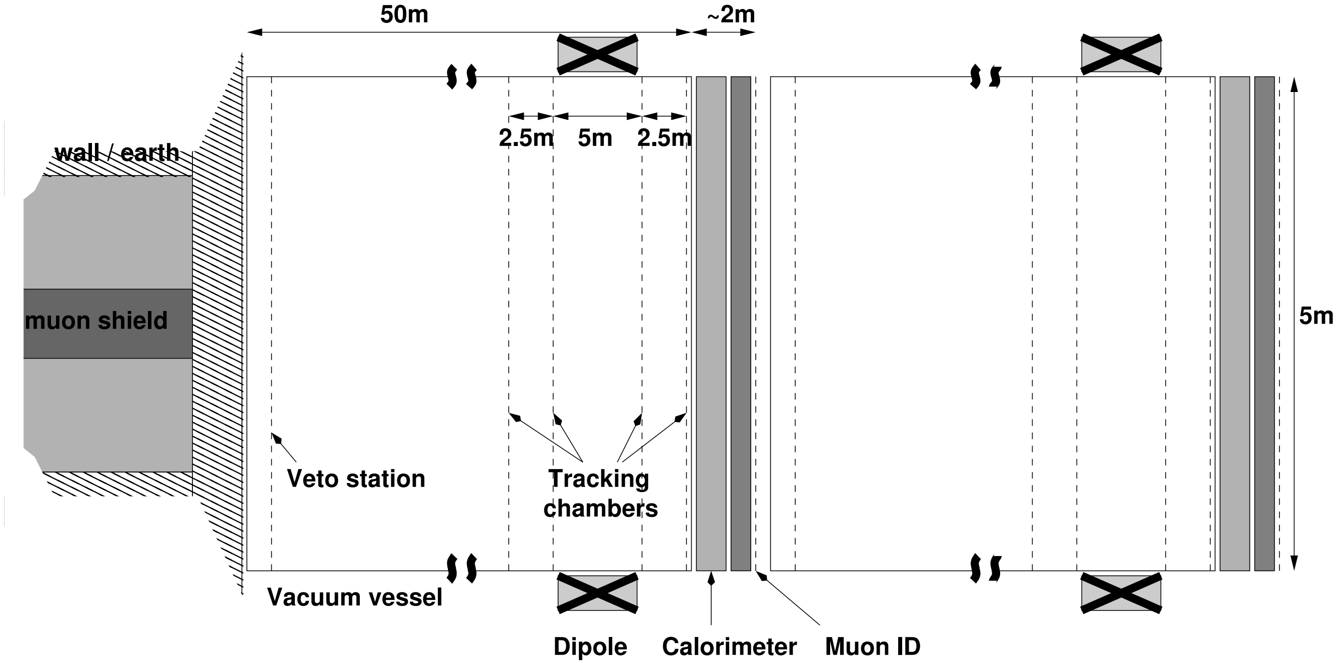
Detector concept (cont.)

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

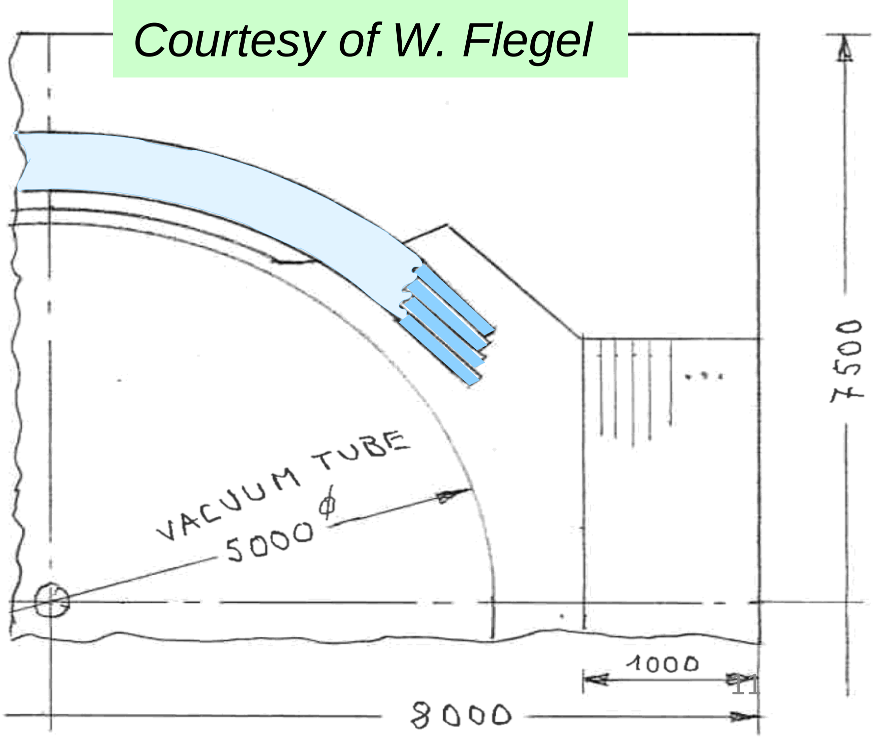
based on existing technologies

- *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

LHCb diplole magnet



Courtesy of W. Flegel

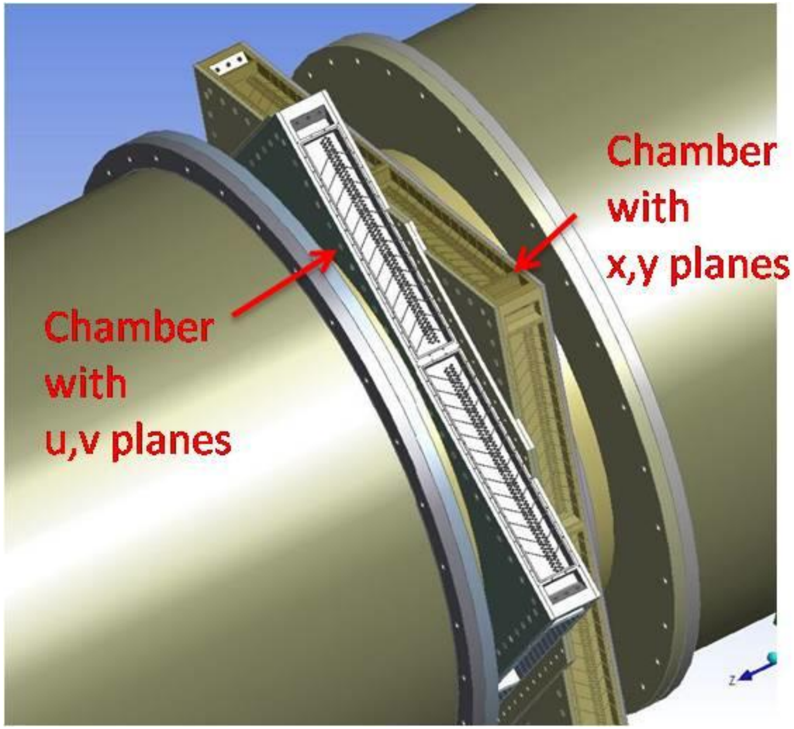
Detector apparatus (cont.)

based on existing technologies

NA62 vacuum tank and straw tracker

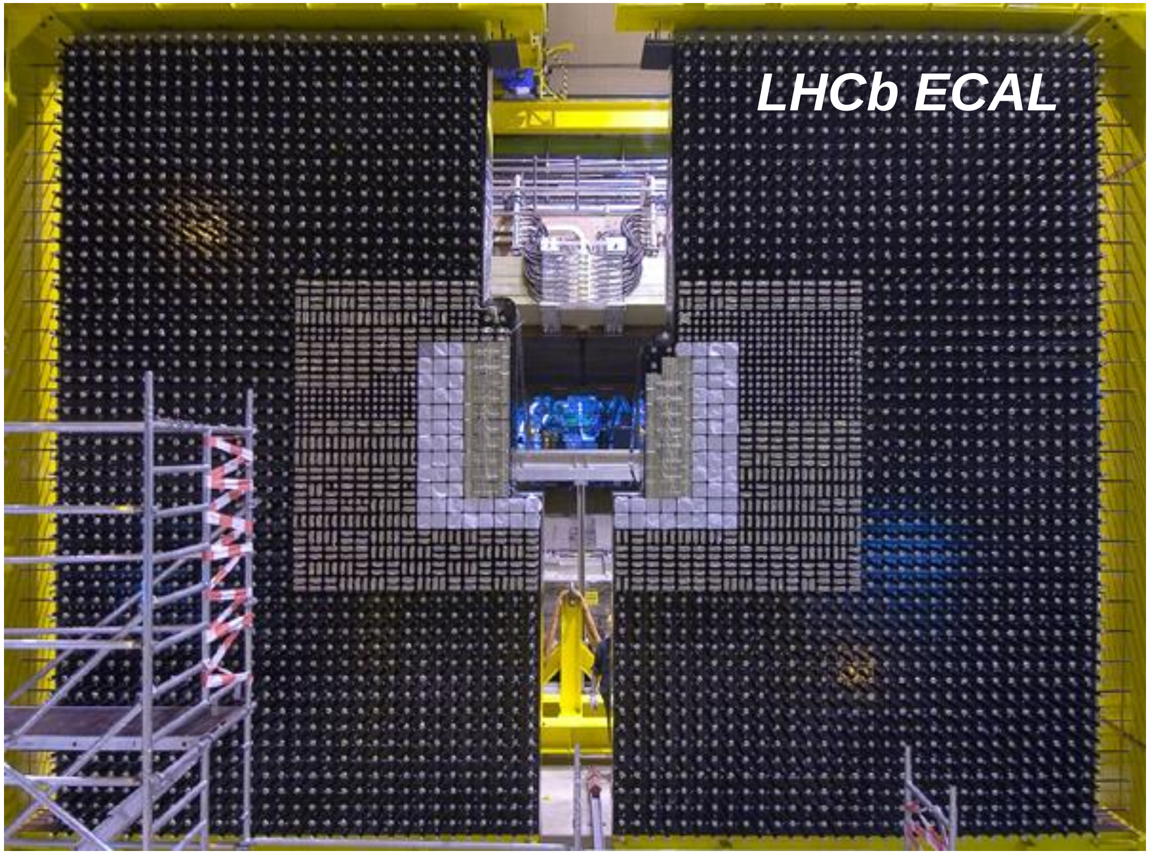
- *< 10^{-5} mbar pressure in NA62 tank*

- *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

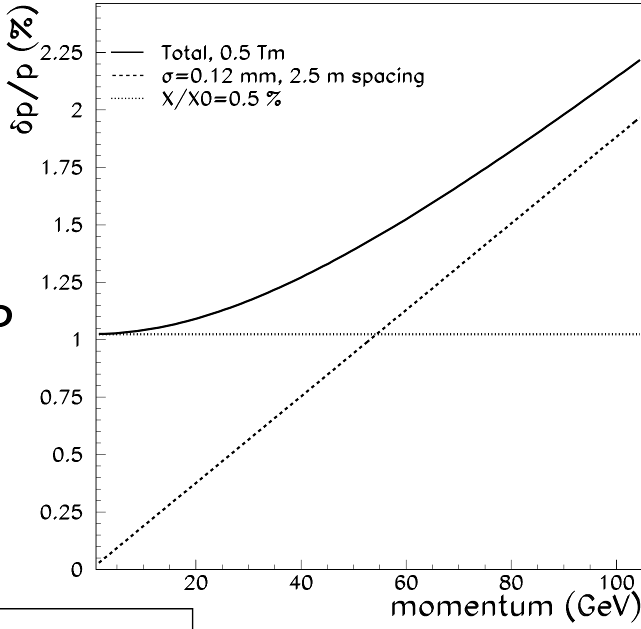
- *~10% of neutrino interactions in the muon shield just upstream of the decay volume produce Λ or K^0 (as follows from GEANT+GENIE and NOMAD measurement)*

- *Majority of decays occur in the first 5 m of the decay volume*

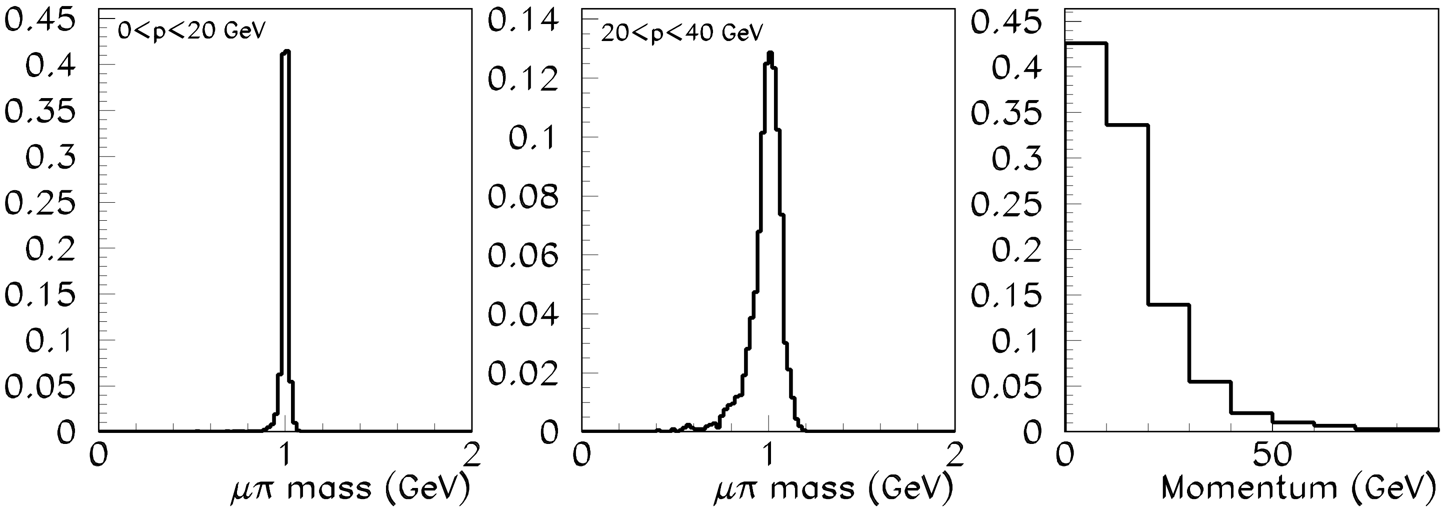
- *Requiring μ–id. for one of the two decay products*
  → ***150 two-prong vertices in 2×10^{20} pot***

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*

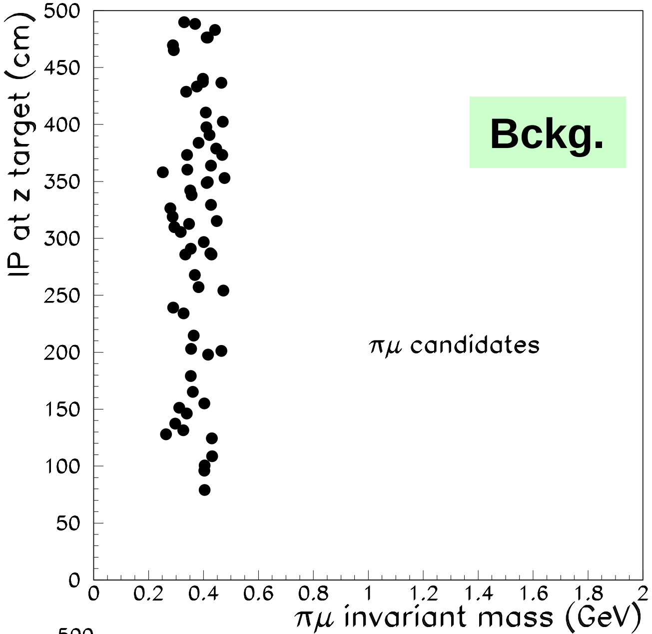
Detector concept (cont.)

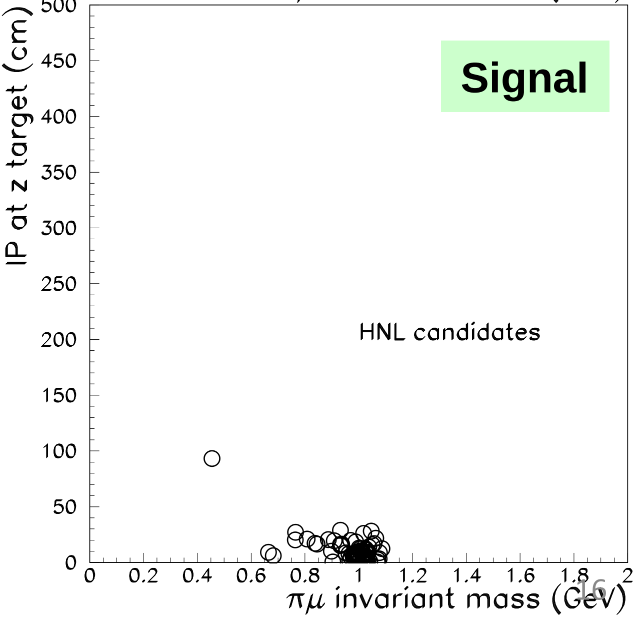
Impact Parameter resolution

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 $D \rightarrow \mu^+ N X$, which probes U_μ^2
- $U^2 \longleftrightarrow U_\mu^2$ depends on flavour mixing
- Expected number of signal events:

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

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

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

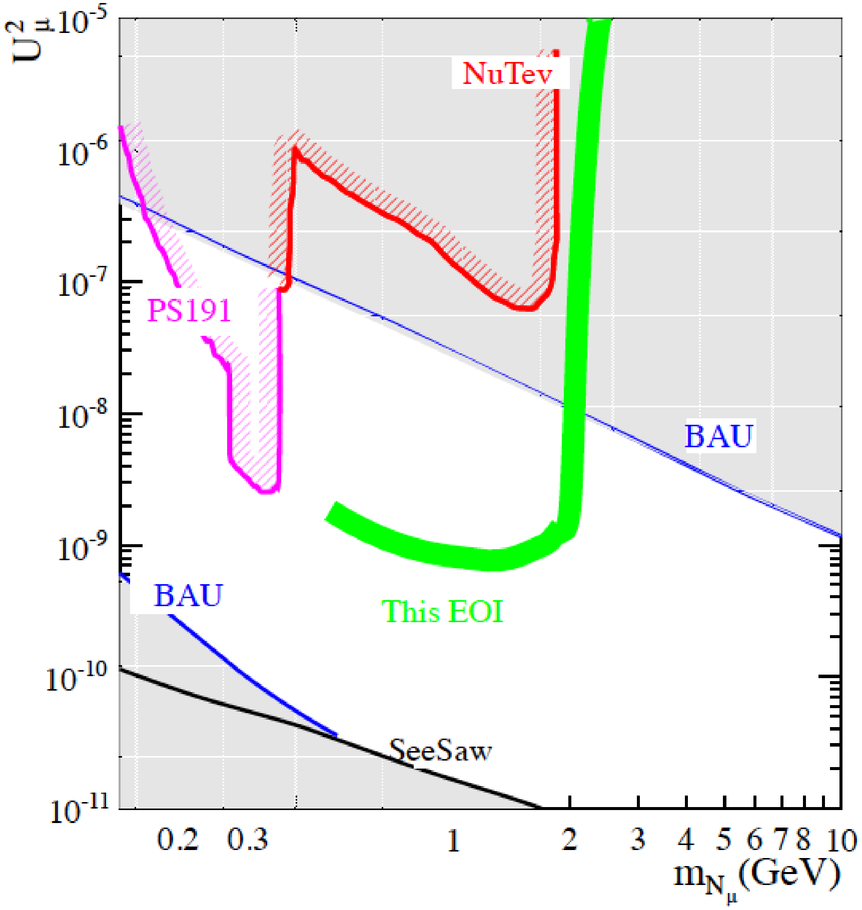
$BR(U_\mu^2) = BR(D \rightarrow N_{2,3} X) \times BR(N_{2,3} \rightarrow \mu\pi)$
$BR(N_{2,3} \rightarrow \mu^- \pi^+)$ is assumed to be 20%

$\varepsilon_{det}(U_\mu^2)$ 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 → $\mu^-\rho^+$ with ρ^+ → $\pi^+\pi^0$, doubling the signal yield
- Study of decay channels with electrons such as N → eπ 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

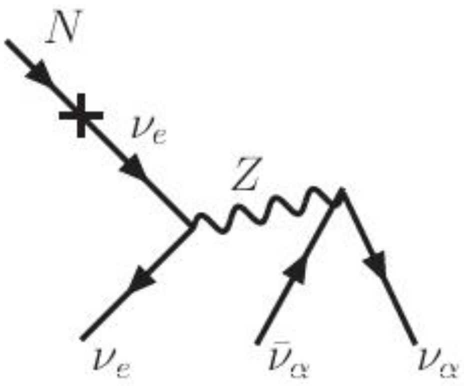
Switzerland: Ecole Polytechnique Federale de Lausanne (EPFL),
University of Zurich,
University of Geneva

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

BACK - UP

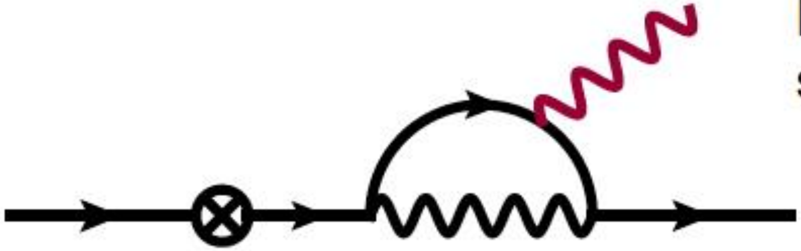
Dark matter

- For small Yukawa couplings HNL can live long and be **dark matter**



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

- Characteristic signature: can have **radiative decay**

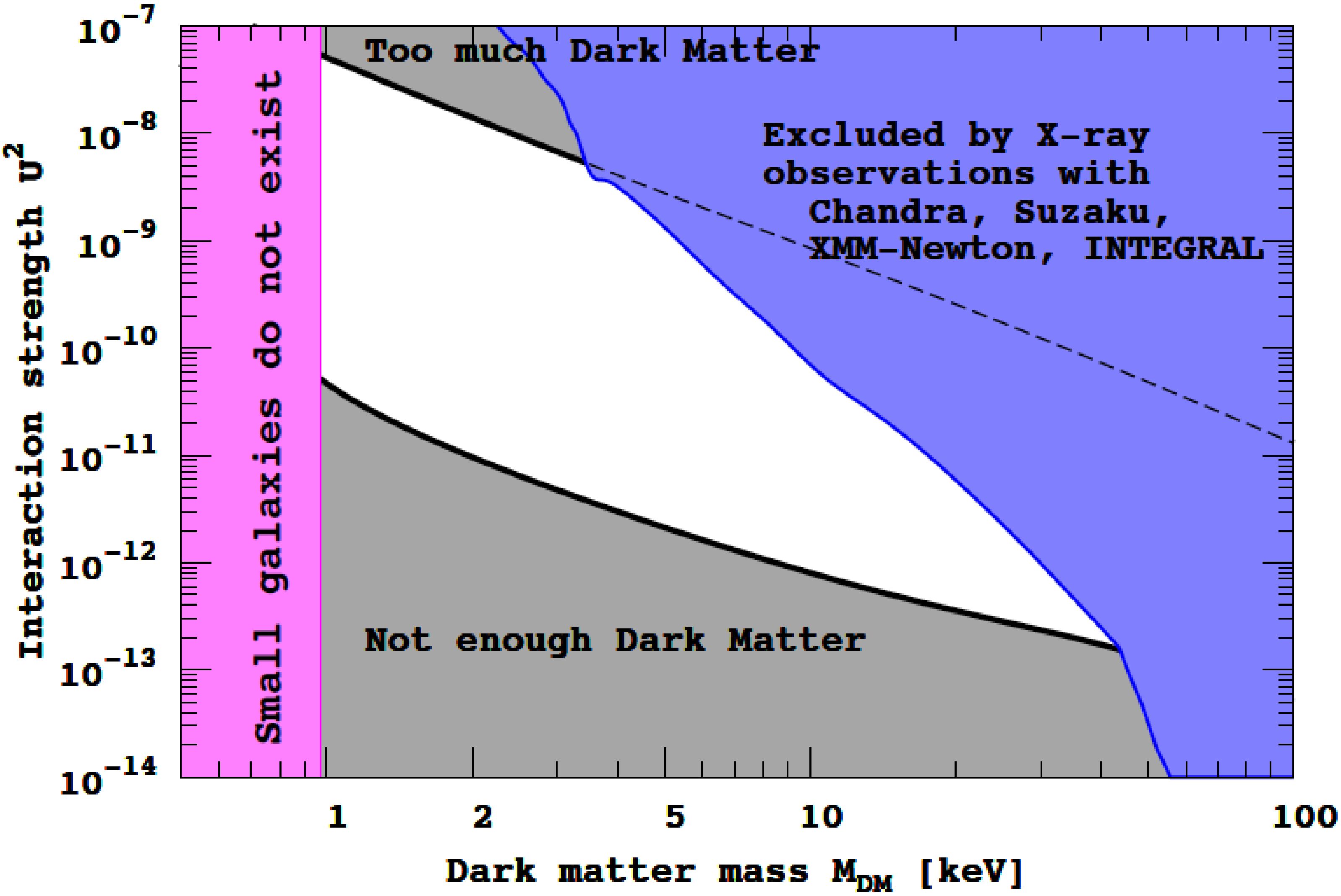


Monochromatic decay line in the spectra of galaxies

$$E_\gamma = \frac{1}{2} M c^2$$

- Decaying dark matter candidate

Parameter space of HNL dark matter



Searches for HNL in space

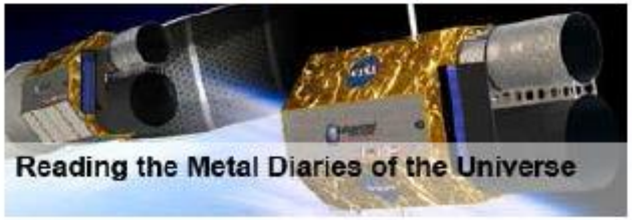
- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)
- Proposed/planned X-ray missions with sufficient spectral resolution:

Astro-H

LOFT

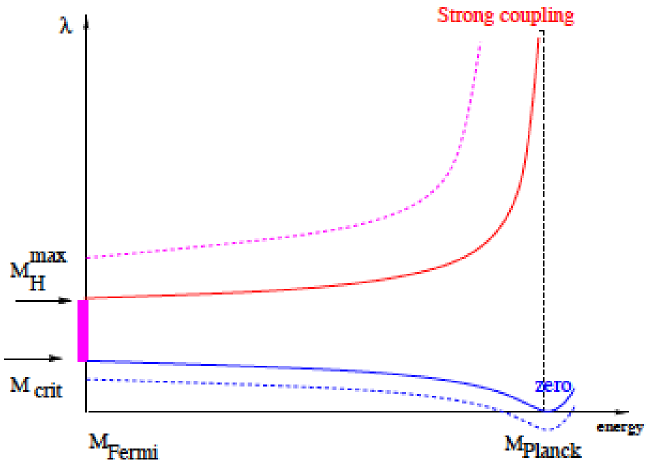
Athena+

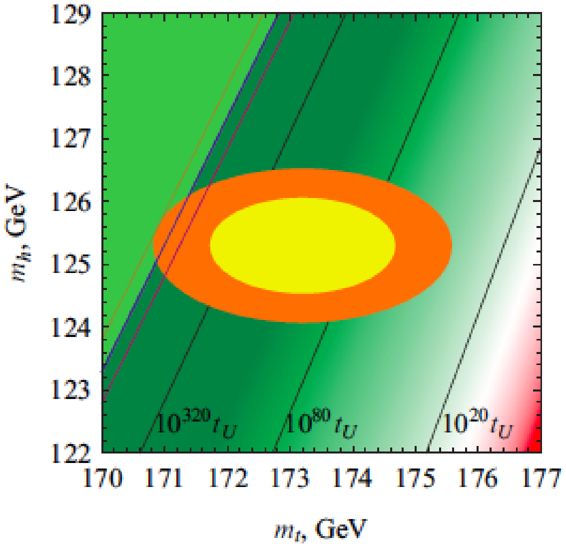
Origin/Xenia



The main LHC result: SM is a consistent effective theory all the way up to the Planck scale

- No signs of new physics beyond the SM are seen
- $M_H < 175$ GeV : SM is a weakly coupled theory up to Planck energies
- $M_H > 111$ GeV: Our EW vacuum is stable or metastable with a lifetime greatly exceeding the Universe age. Espinosa et al





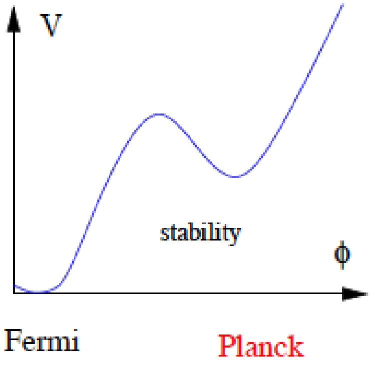
The mass of the Higgs boson is very close to the stability bound on the Higgs mass* (95’), to the Higgs inflation bound** (08’), and to asymptotic safety value for M_H*** (09’):

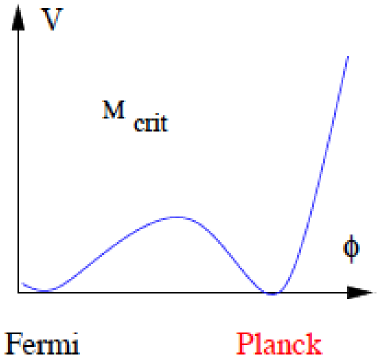
$$M_{crit} = [129.3 + \frac{y_t(M_t) - 0.9361}{0.0058} \times 2.0 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.5]\ \mathrm{GeV}$$

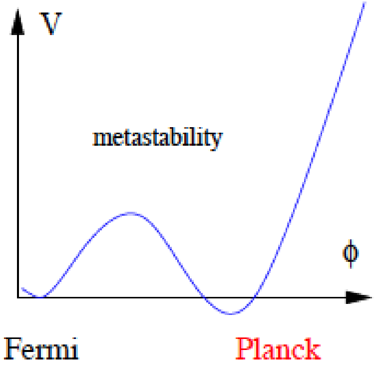
$y_t(M_t)$ - top Yukawa in $\overline{\mathrm{MS}}$ scheme

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





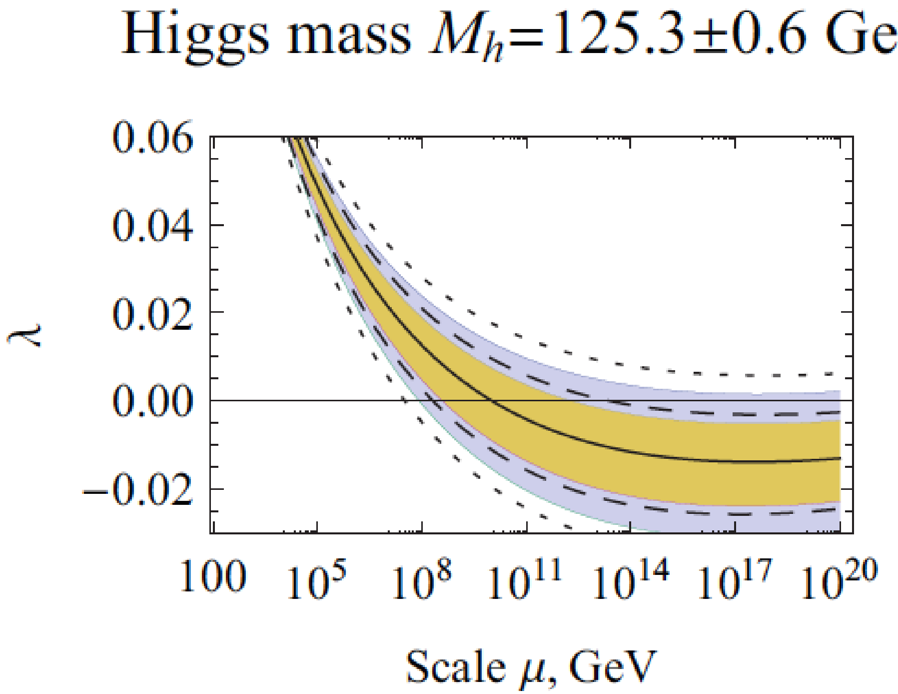


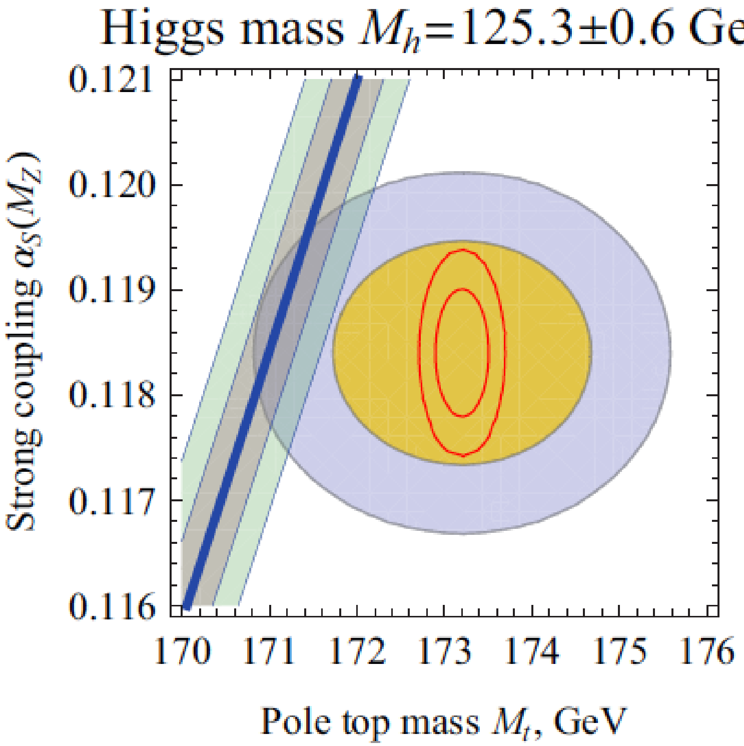
* Froggatt, Nielsen

** 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

$\alpha_s = 0.1184 \pm 0.0007$

Main uncertainty - top Yukawa coupling.

- 1 GeV experimental error in M_t leads to 2 GeV error in M_{crit}.
- Perturbation theory, $\mathcal{O}(\alpha_s^4)$. Estimate of Kataev and Kim: $\delta y_t/y_t \simeq -750(\alpha_s/\pi)^4 \simeq -0.0015$, $\delta M_{crit} \simeq -0.5$ GeV
- Non-perturbative QCD effects, $\delta M_t \simeq \pm\Lambda_{QCD} \simeq \pm 300$ MeV, $\delta M_{crit} \simeq \pm 0.6$ GeV
- Alekhin et al. Theoretically clean is the extraction of y_t from $t\bar{t}$ cross-section. However, the experimental errors in $p\bar{p} \to t\bar{t} + X$ are quite large, leading to $\delta M_t \simeq \pm 2.8$ GeV, $\delta M_{crit} \simeq \pm 5.6$ GeV.

Precision measurements of m_H, y_t and α_s are needed.

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 $V \to l^+ l^-$