Non-official

Search for Heavy Neutral Leptons at SPS

on behalf of

W. Bonivento[1,2], A. Boyarsky[3], H. Dijkstra[2], U. Egede[4], M. Ferro-Luzzi[2], B. Goddard[2], A. Golutvin[4], D. Gorbunov[5], R. Jacobsson[2], J. Panman[2], M. Patel[4], O. Ruchayskiy[6], T. Ruf[2], N. Serra[7], M. Shaposhnikov[6], D. Treille[2] (‡)

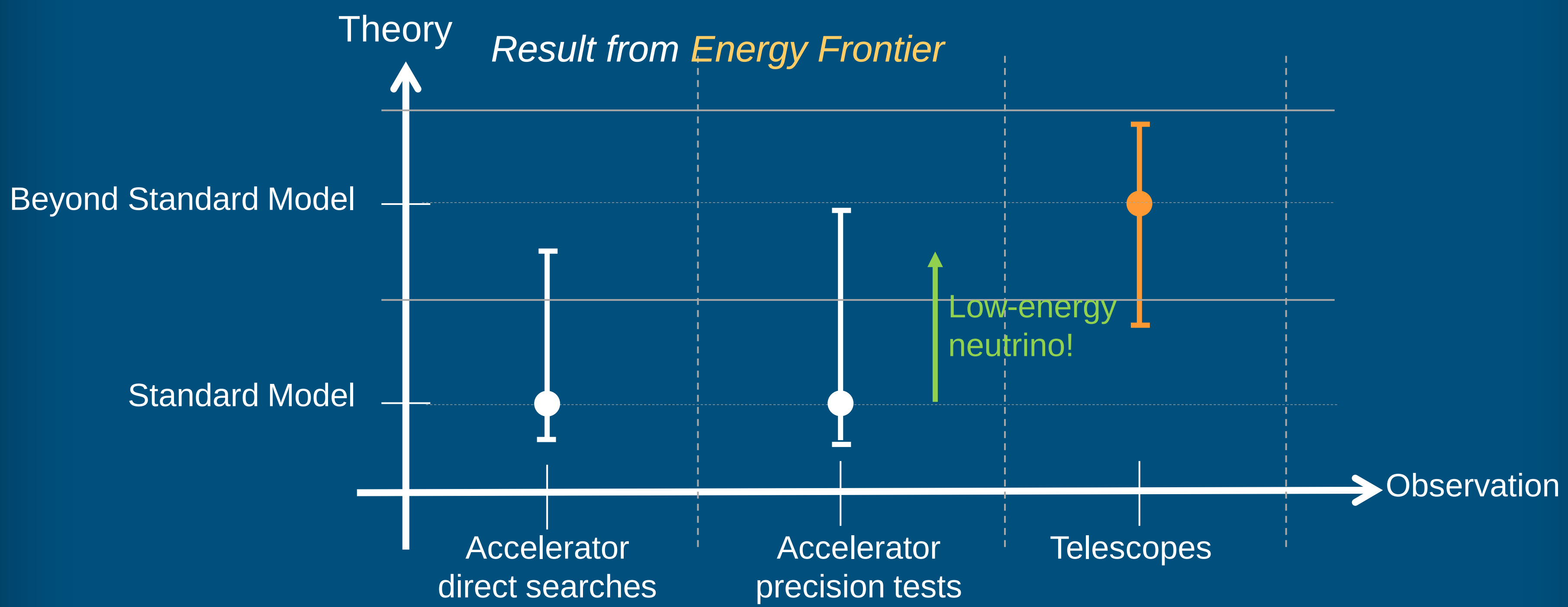
[1]Sezione INFN di Cagliari, Cagliari, Italy
[2]European Organization for Nuclear Research (CERN), Geneva, Switzerland
[3]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[4]Imperial College London, London, United Kingdom
[5]Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
[6]Ecole Polytechnique F´ed´erale de Lausanne (EPFL), Lausanne, Switzerland
[7]Physik-Institut, Universit¨at Z¨urich, Z¨urich, Switzerland
(‡)retired

➔ "Search for HIdden Particles" (SHIP) Collaboration

Expression of Interest presented at 111th Meeting of SPSC, October 22, 2013 :
CERN-SPSC-2013-024 / SPSC-EOI-010 / arXiv:1310.1762v1 [hep-ex] 7 Oct 2013

Physics Situation after LHC Run 1

Non-official

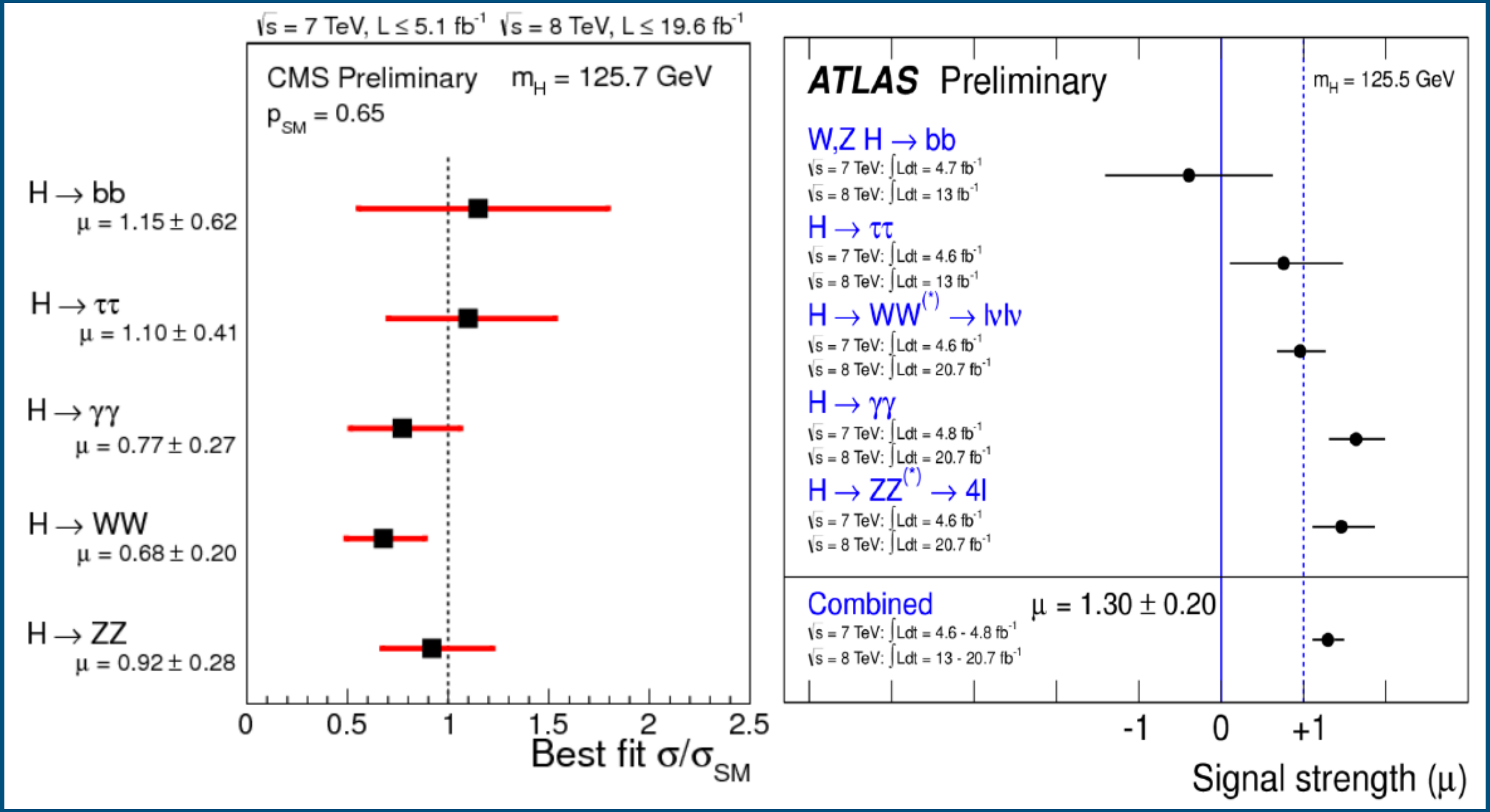


➔ Standard Model success: Higgs!

Higgs Discovery

Non-official

- It looks very much like THE Higgs boson:

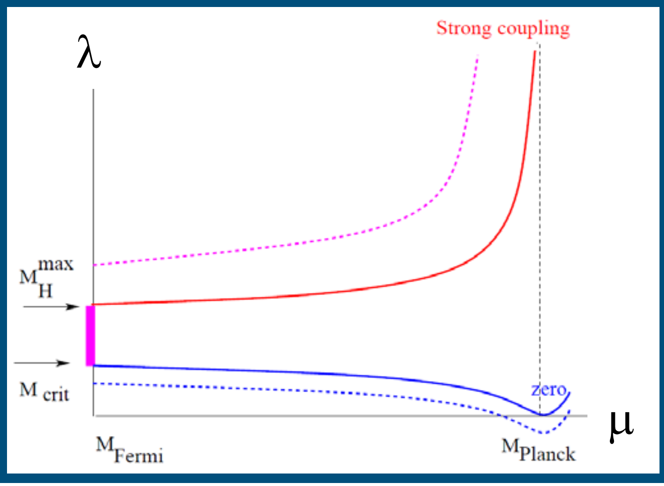


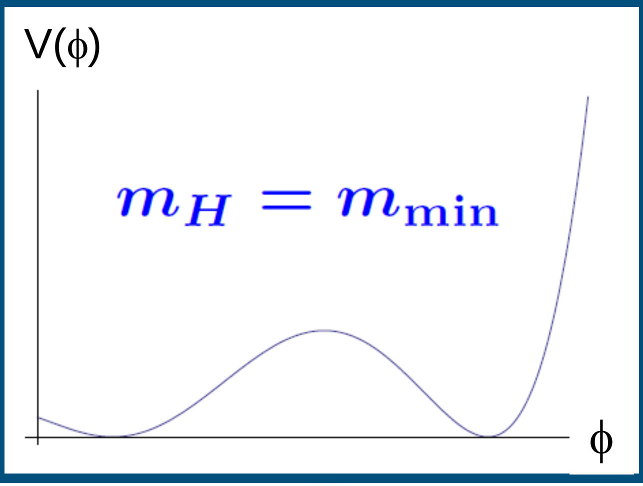
- To be done
  - Measure more precisely fermion couplings
  - Measure triple and quartic gauge couplings to reconstruct vacuum potential

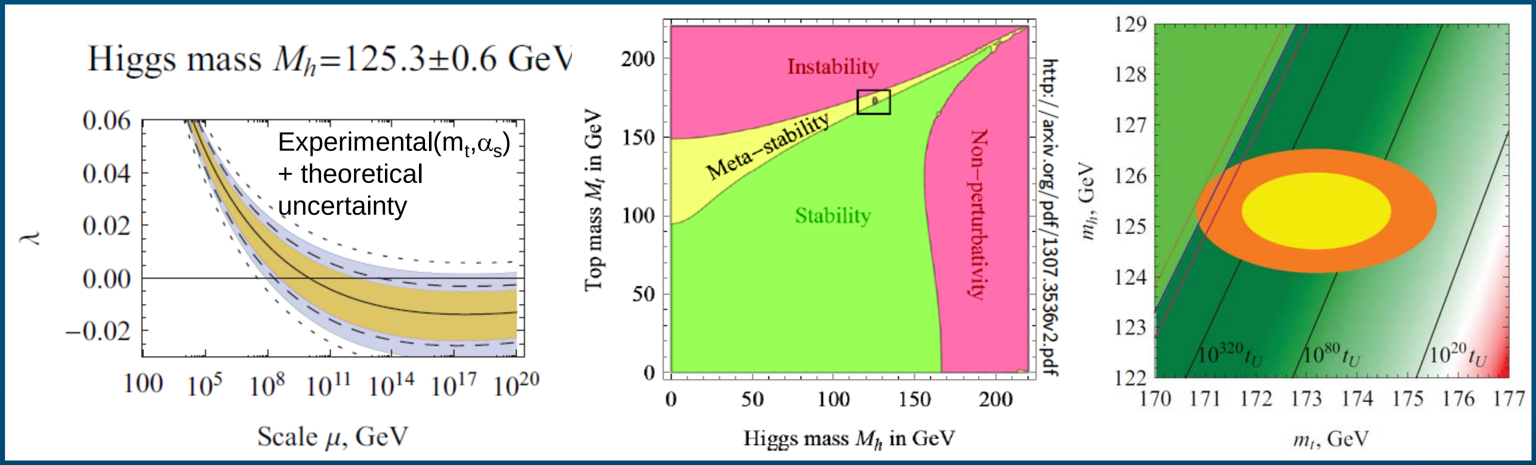
SM Validity

Non-official

- Requirement that the E.W. vacuum be the minimum of the potential up to a scale Λ, implies that $\lambda(\mu) > 0$ for any $\mu < \Lambda$.
- $M_H = 125.5 \pm 0.2_{stat} {}^{+0.5}_{-0.6}{}_{syst} GeV$ (ATLAS) / $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}\ GeV$ (CMS)
  - $m_H < 175\ GeV$: Landau pole in the self-interaction is above the quantum gravity scale M_{Pl}
  - $m_H > 111\ GeV$: Electroweak vacuum is sufficiently stable with a lifetime >>t_U



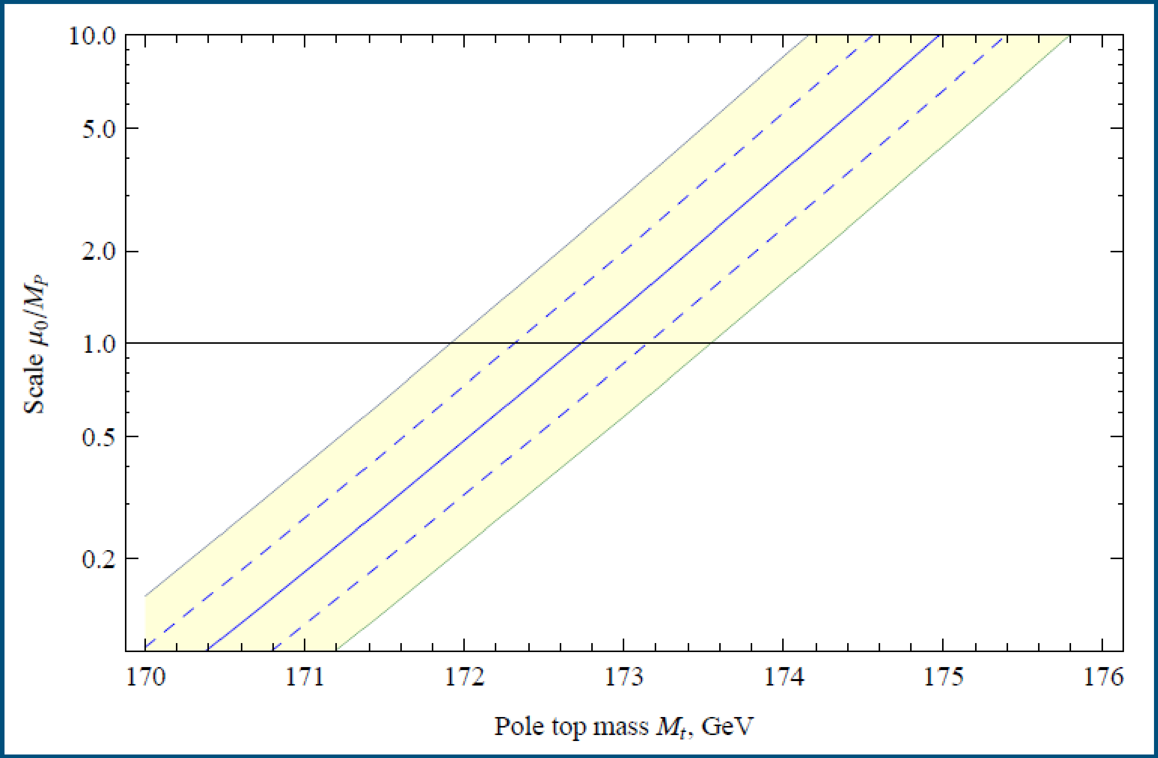




SM Validity

Non-official

- Currently used values
  - Tevatron $m_t = 173.2 \pm 0.51_{stat} \pm 0.71_{syst} GeV$
  - ATLAS and CMS: $m_t = 173.4 \pm 0.4_{stat} \pm 0.9_{syst} GeV$
  - $\alpha_s = 0.1184 \pm 0.0007$
  - Measure more precisely!

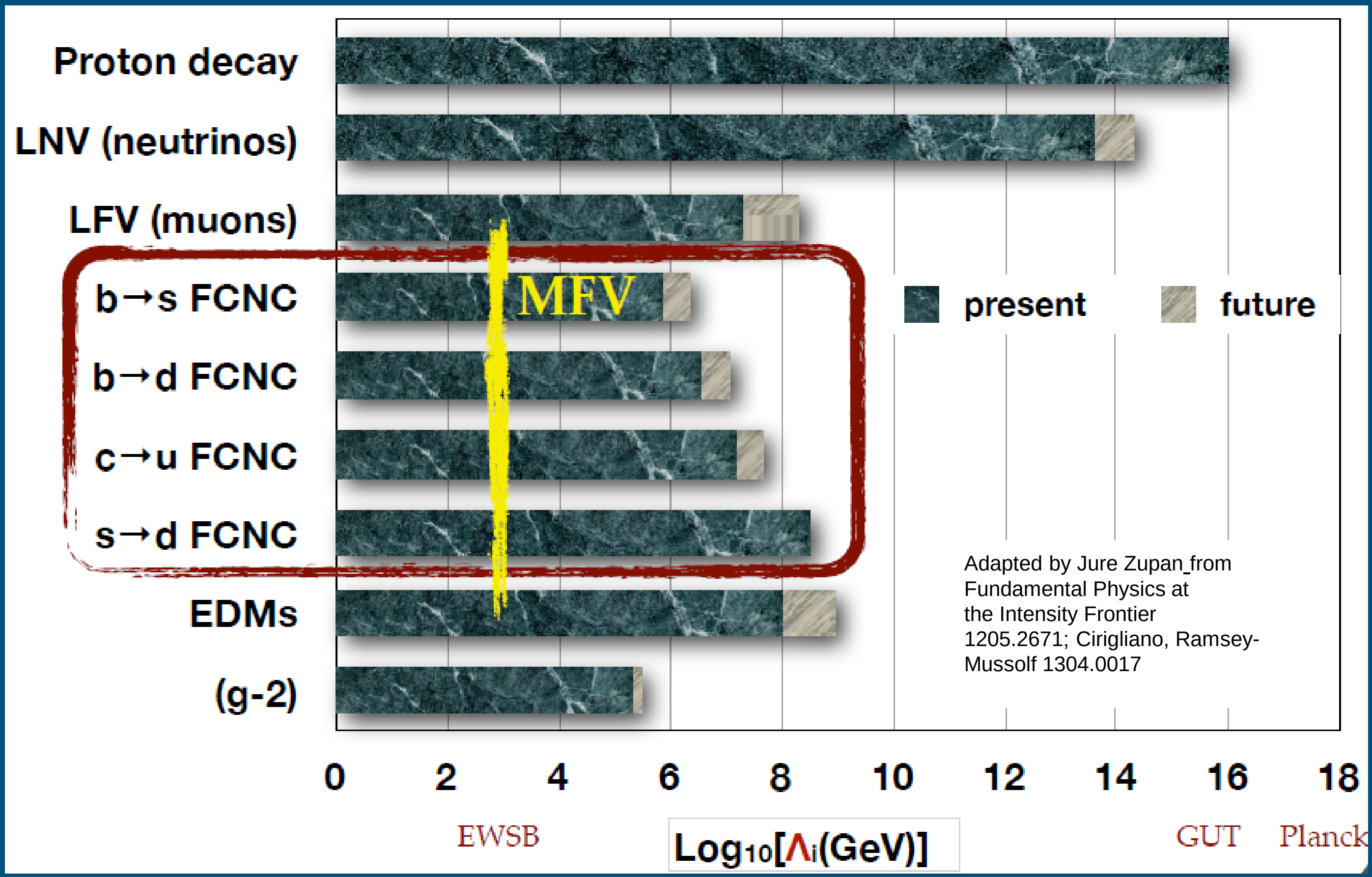


- μ_0 determined from electroweak physics gives Planck scale!

Precision Flavour Physics

Non-official

$$\sigma_{stat+sys+th} < \delta C[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}]$$



➔ Most stringent bounds on the scale of New Physics from $B\bar{B}$ mixing…

Physics Situation after LHC Run 1

Non-official

- *With a mass of the Higgs boson of 125 − 126 GeV the Standard Model is a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles*
  - ➔ No *need* for new particles *up to* Planck scale!?

<u>Outstanding questions</u>

1. Neutrino oscillations: *tiny* masses and flavour mixing
   - → Requires new degrees of freedom in comparison to SM
2. Baryon asymmetry of the Universe
   - → Measurements from BBN and CMB $\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim \left\langle \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \right\rangle_{T \gtrsim 1\ GeV} \sim 6 \times 10^{-10}$
   - → Current measured CP violation in quark sector ➔ $\eta \sim 10^{-20}$!!
3. Dark Matter from indirect gravitational observations
   - → Non-baryonic, neutral and stable or long-lived
4. Dark Energy
5. Hierarchy problem and stability of Higgs mass
6. SM flavour structure

- While we had unitarity bounds for the Higgs, no such indication on the next scale….

Physics Situation after LHC Run 1

Non-official

Very intriguing situation! Multitude of "solutions" to these questions

➔ Search for Beyond Standard Model physics at the LHC, FHC (Energy Frontier):

- Higgs and top (EW) precision physics
- Flavour precision physics
- Continued direct searches for new particles

Many extensions predict very weakly interacting long-lived objects

➔ Complementary physics program consists of searches for these

Physics Situation after LHC Run 1

Non-official

Very intriguing situation! Multitude of "solutions" to these questions

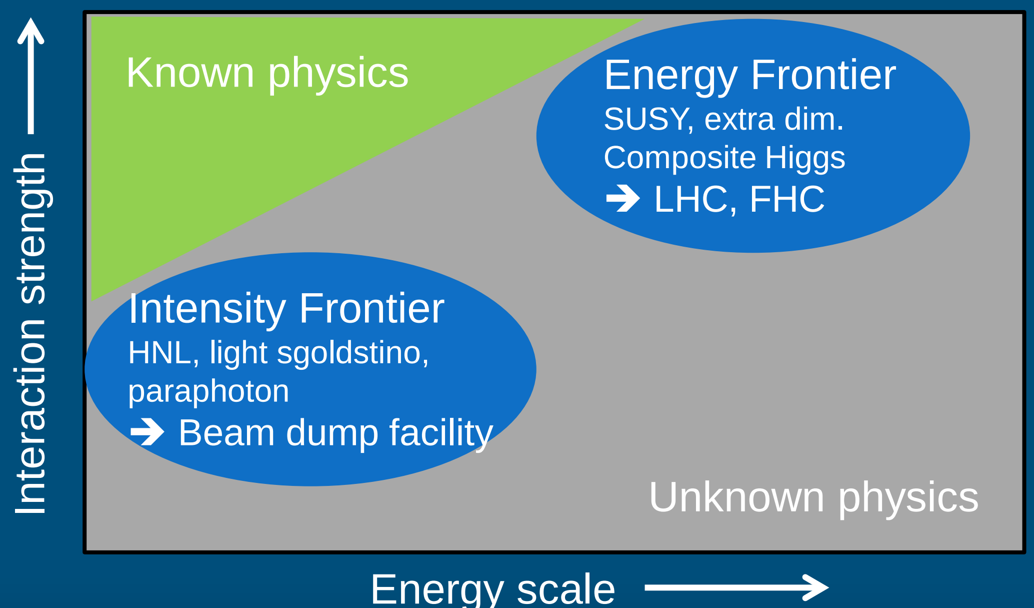
➔ Search for Beyond Standard Model physics at the LHC, FHC (Energy Frontier):

- Higgs and top (EW) precision physics
- Flavour precision physics
- Continued direct searches for new particles

Many extensions predict very weakly interacting long-lived objects

➔ Complementary physics program consists of searches for these

What about solutions to (some) these questions *below* Fermi scale and weak couplings?



Physics Situation after LHC Run 1

Non-official

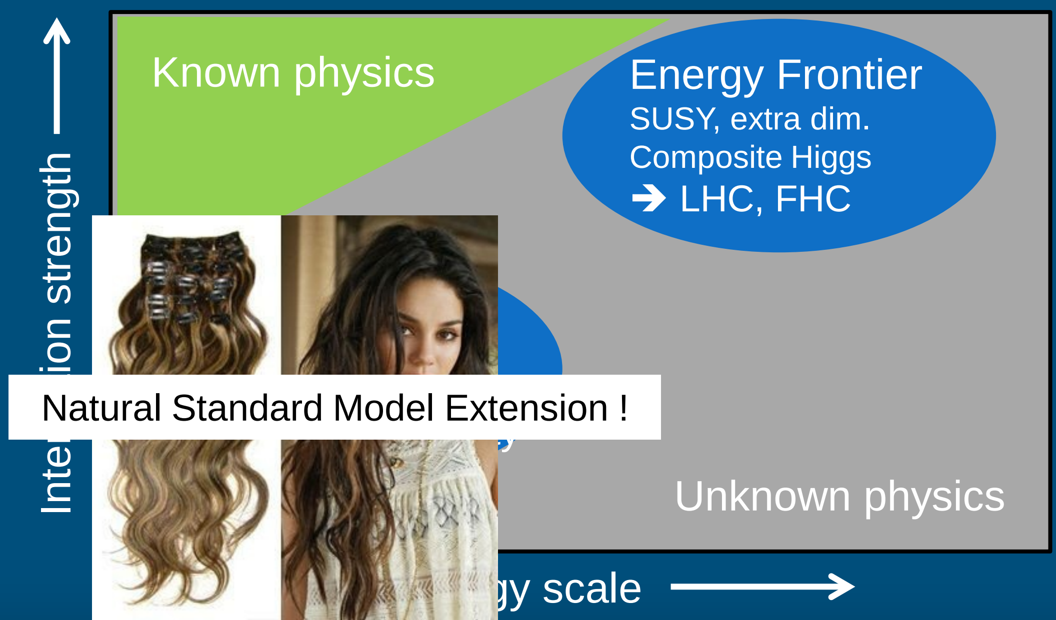
Very intriguing situation! Multitude of “solutions” to these questions

➔ Search for Beyond Standard Model physics at the LHC, FHC (Energy Frontier):
- Higgs and top (EW) precision physics
- Flavour precision physics
- Continued direct searches for new particles

Many extensions predict very weakly interacting long-lived objects

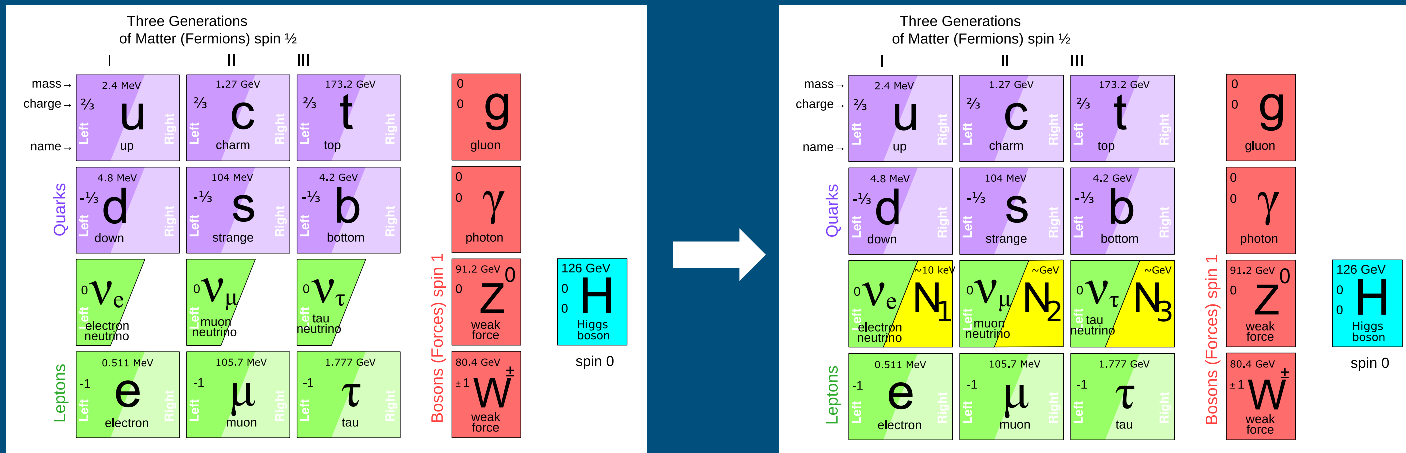
➔ Complementary physics program consists of searches for these

What about solutions to (some) these questions *below* Fermi scale and weak couplings?



Ockham's Razor

Non-official



- Introduce three neutral fermion singlets – right-handed Majorana leptons N_I with Majorana mass m_I^R ≡ "Heavy Neutral Leptons (HNL)"
  - Make the leptonic sector similar to the quark sector
  - No electric, strong or weak charges ➔ "sterile"

Minkowski 1977
Yanagida 1979
Gell-Mann, Ramond, Slansky 1979
Glashow 1979

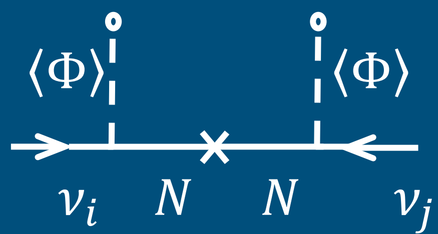
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{\substack{I=1,2,3;\\ \ell=1,2,3(e,\mu,\tau)}} i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\ell} \bar{N}_I \Phi^\dagger L_\ell - m_I^R \bar{N}_I^c N_I + h.c$$

where L_ℓ are the lepton doublets, Φ is the Higgs doublet, and $Y_{I\ell}$ are the corresponding new Yukawa couplings

- Discovery of Higgs vital for the see-saw model! ➔ Responsible for the Yukawa couplings!

Type I See-saw Trivia

- $Y_{I\ell}\overline{N}_I\Phi^\dagger L_\ell$ lepton flavour violating term results in mixing between N_I and SM active neutrinos when the Higgs SSB develops the $< VEV > = v \sim 246\ GeV$
  - ➔ Oscillations in the mass-basis and matter-anti-matter asymmetry



- Mixing between N_I and active neutrino $\mathcal{U}_{I\ell} = \frac{Y_{I\ell}v}{m_I^R} \sim \frac{m_D}{m^R}$
  - Total strength of coupling $\mathcal{U}^2 = \sum_{\substack{I=1,2,3 \\ \ell=1,2,3(e,\mu,\tau)}} \frac{v^2|Y_{\ell I}|^2}{{m_I^R}^2}$

- Type I See-saw with $m^R >> m_D (= Y_{I\ell}v)$ ➔ superposition of chiral states give
  - ➔ Active neutrino mass in mass basis $\tilde{m}_1 \sim \frac{m_D^2}{m^R} \sim m_\nu$
  - ➔ Heavy singlet fermion mass in mass basis $\tilde{m}_2 \sim m^R\left(1 + \frac{m_D^2}{{m^R}^2}\right) \sim m^R \sim M_N$

Four "popular" N mass ranges

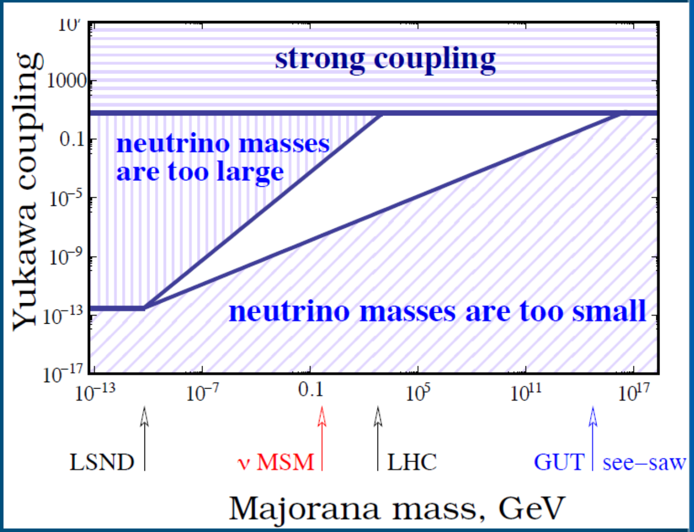
Non-official

➔ Irrespective of mass, the HNLs may explain neutrino oscillations and active neutrino mass

1. GUT see-saw ($10^9 < M_N < 10^{14}$ GeV) :
   - Motivated by GUT theories
   - BAU generated via sphalerons by CP violating decays of $N's$ to a lepton asymmetry
   - Large mass of HNLs results in fine-tuning problem for the Higgs mass

     ➔ Low energy SUSY but largely disfavoured by LHC results
   - No DM candidate and no way to probe in accelerator based experiments
2. E.W. see-saw ($M_N \sim 10^2 – 10^3$ GeV):
   - Motivated by hierarchy problem at the electroweak scale
   - BAU generated via resonant leptogenesis and sphalerons
   - No DM candidate
   - Part of parameter space may be explored in ATLAS /CMS
3. νMSM see-saw ($M_N \sim m_q/m_{l^\pm}$)
   - BAU via resonant leptogenesis and sphalerons
   - $\mathcal{O}(10)keV$ range DM candidate
4. eV see-saw ($M_N \sim$ eV)
   - Motivated by the 2-3σ anomalies observed in the short-baseline experiments
   - No BAU and no candidate for DM

arXiv:1204.5379



νMSM (Asaka, Shaposhnikov: hep-ph/0505013)

Non-official

- Assumption that N_I are $\mathcal{O}(m_q/m_{l^\pm})$
  - ➔ Consequence: Yukuawa couplings are very small
    - $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\ GeV, m_\nu = 0.05\ eV)$
    - $\mathcal{U}^2 \sim 10^{-11}$

➔ Experimental challenge ➔ Intensity Frontier

Role of N_1 with a mass of $\mathcal{O}$(keV)
➔ Dark Matter

Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU

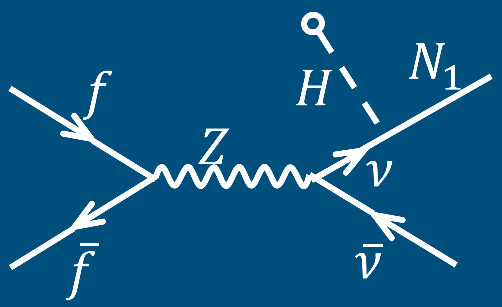
➔ No new energy scale!

νMSM N_1 = Dark Matter

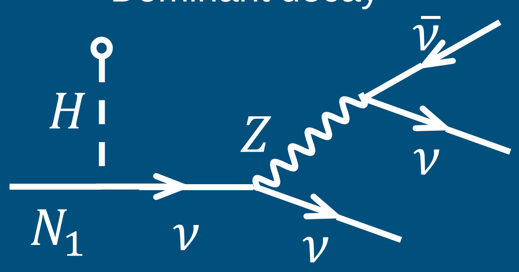
Non-official

- Assume lightest singlet fermion N_1 has a very weak mixing with the other leptons
  - Mass $M_1 \backsim \mathcal{O}(keV)$ and very small coupling
    - ➔ Sufficiently stable to act as Dark Matter candidate
    - ➔ Give the right abundance
    - ➔ Decouples from the primordial plasma very early
  - Produced relativistically out of equilibrium in the radiation dominant epoque ➔ erase density fluctuations below free-streaming horizon ➔ sterile neutrinos are redshifted to be non-relativistic before end of radiation dominance (Warm Dark Matter → CDM)
    - ➔ Temperature dependent : Production suppressed at T>100 MeV
    - ➔ Decaying Dark Matter

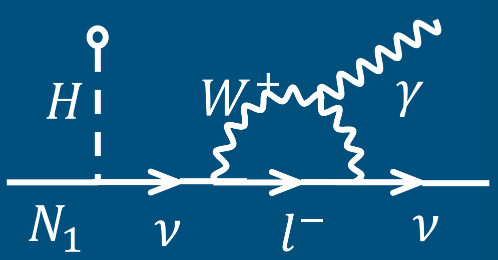
Production from υ ↔ N oscillations



Dominant decay



Subdominant radiative decay



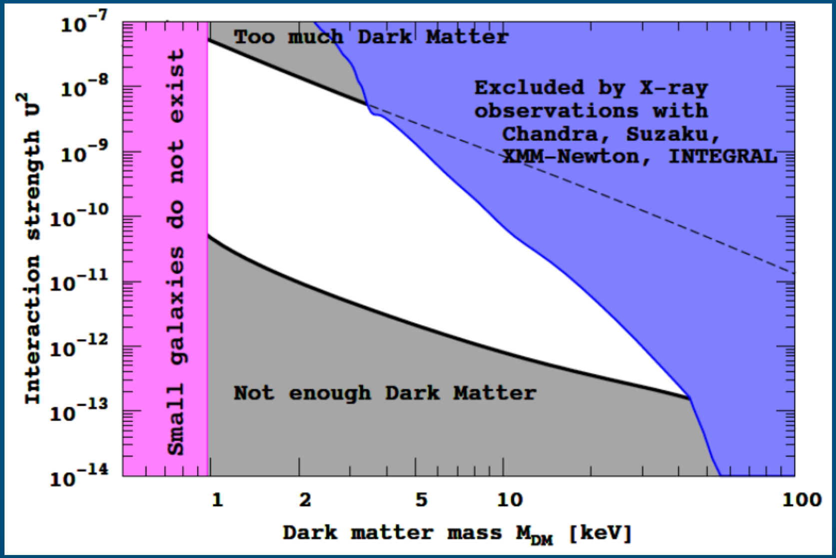
$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

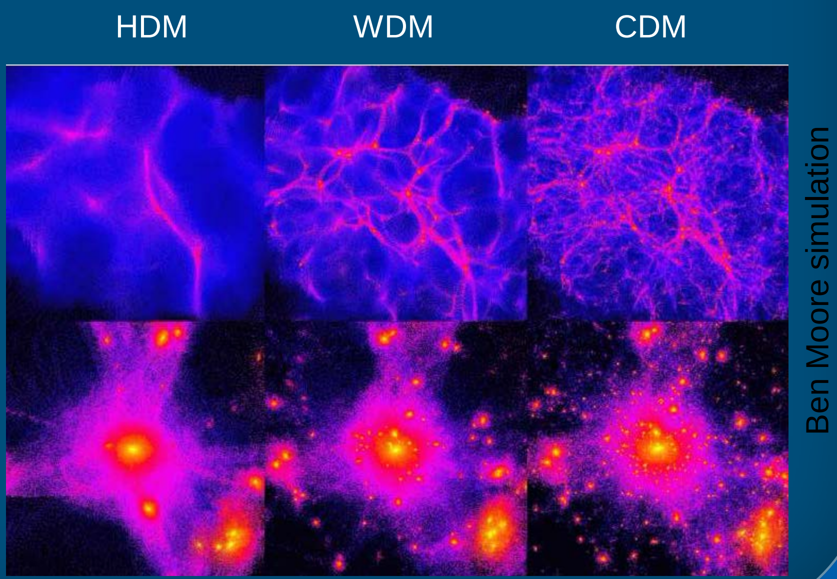
Dark Matter Constraint and Search

Non-official

1. Tremaine-Gunn bound: average phase-space density for fermionic DM particles cannot exceed density given by Pauli exclusion principle
   ➔ For smallest dark matter dominated objects such as dwarf spheroidal galaxies of the Milky Way
2. X-ray spectrometers to detect mono-line from radiative decay
   - Large field-of-view ~ ~ size of dwarf spheroidal galaxies ~ 1º
   - Resolution of $\frac{\Delta E}{E} \sim 10^{-3} - 10^{-4}$ coming from width of decay line due to Doppler broadening

   ➔ Proposed/planned X-ray missions: Astro-H, LOFT, Athena+, Origin/Xenia
3. Lyman-α forest
   - Super-light sterile neutrino creates cut-off in the power spectrum of matter density fluctuations due to sub-horizon free-streaming $d_{FS} \sim 1\,\mathrm{Gpc}\, m_{eV}^{-1}$
   - Fitted from Fourier analysis of spectra from distant quasars propagating through fluctuations in the neutral hydrogen density at redshifts 2-5



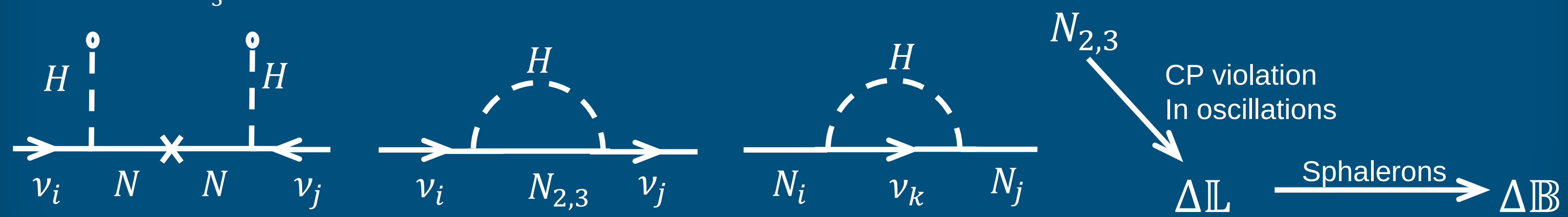


νMSM N_2 and N_3

Non-official

- N_1 as DM ($M_{N_1} \ll M_{N_2} \approx M_{N_3}$) gives no contribution to active neutrino masses
  - ➔ Neglect for the rest
  - ➔ Reduces number of effective parameters for Lagrangian with $N_{2,3}$
    - 18 parameters ➔ 11 new parameters:
      - 2 Majorana masses
      - 2 diagonal Yukawa couplings as Dirac masses
      - 4 mixing angles
      - 3 CP violating phases (only one in SM in quark sector)
      - ➔ Two mixing angles related to active neutrinos and mass difference measured in low-energy neutrino experiment

- Generation of BAU with N_2 and N_3 (Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov)
  1. Leptogenesis from coherent resonant oscillations with interference between CP violating amplitudes
     ➔ Two fermion singlets should be quasi-degenerate
  2. Sterile neutrinos out of equilibrium ($\Gamma_{N_{2,3}}$ < Hubble rate of expansion) at the E.W. scale above the sphaleron freeze-out
  3. Lepton number of active left-handed neutrinos transferred to baryon number by sphaleron processes
     - $\mathbb{L}_\ell - \frac{\mathbb{B}}{3}$ remain conserved while $\mathbb{L}_\ell$ and $\mathbb{B}$ are violated individually



Thermal History in νMSM

Non-official

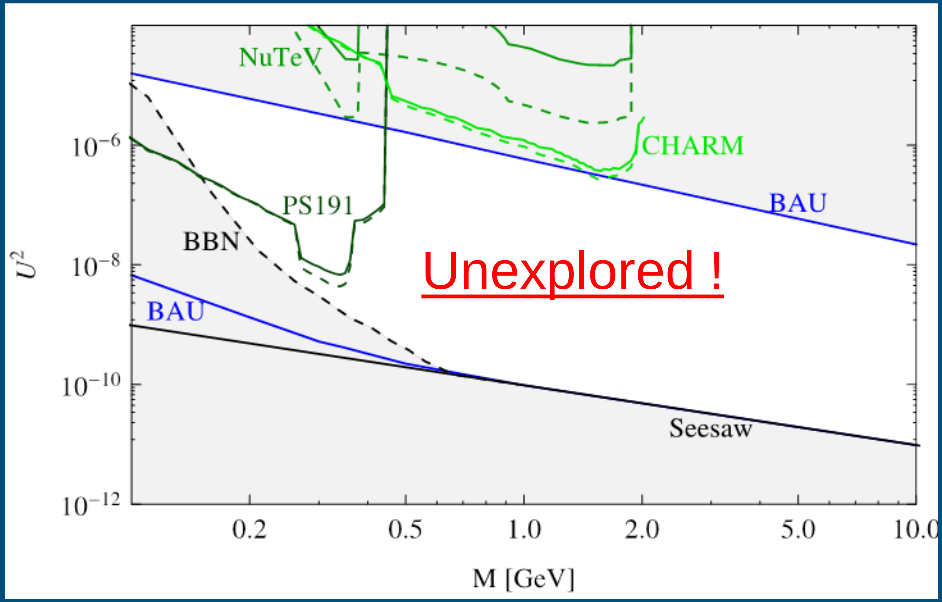
(arXiv:1208.4607)

	T	zero abundance of N_I
		thermal production of N_2, N_3 → lepton asymmetry generated
200 GeV	T_{EW}	**Electroweak Symmetry Breaking** → lepton Asymmetry converted to baryon asymmetry
	T_+	N_2, N_3 reach equilibrium → lepton asymmetry washed out
few GeV	T_-	N_2, N_3 freeze out → lepton asymmetry generated
	T_d	N_2, N_3 decay → lepton asymmetry generated
100 MeV	T_{DM}	**resonant N_1 Dark Matter production**
		t

N_2 and N_3 Constraints in νMSM

Non-official

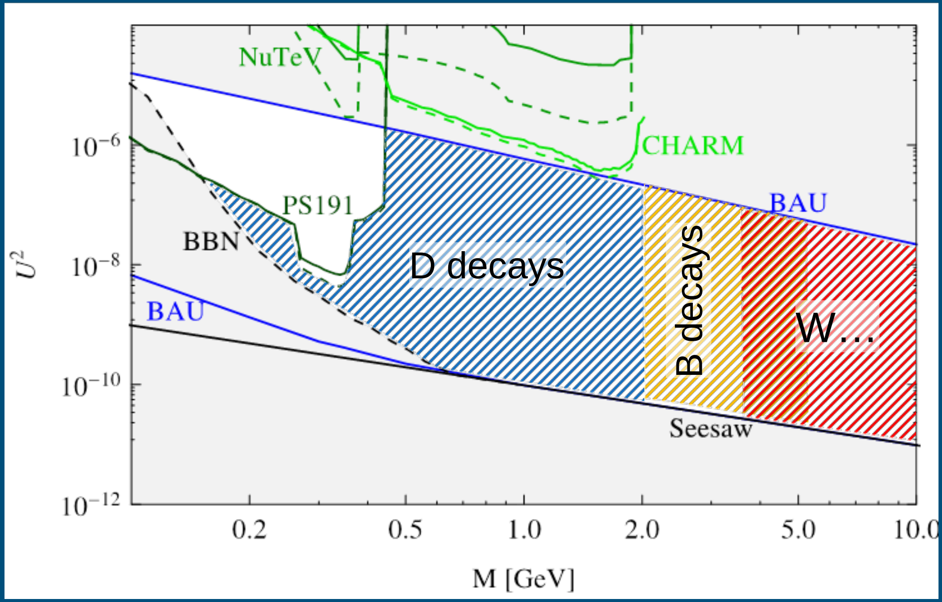
1. See-saw: Lower limit on mixing with active neutrinos to produce oscillations and masses
2. BAU: Upper limit on mixing to guarantee out-of-equilibrium oscillations ($\Gamma_{N_{2,3}} < H$)
3. BBN: Decays of N_2 and N_3 must respect current abundances of light nuclei
   ➔ Limit on lifetime $\tau_{N_{2,3}} < 0.1s \ (T > 3\ MeV)$
4. Experimental: No observation so far…
   ➔ Constraints 1-3 now indicate that previous searches were largely outside interesting parameter space



N_2 and N_3 Constraints in νMSM

Non-official

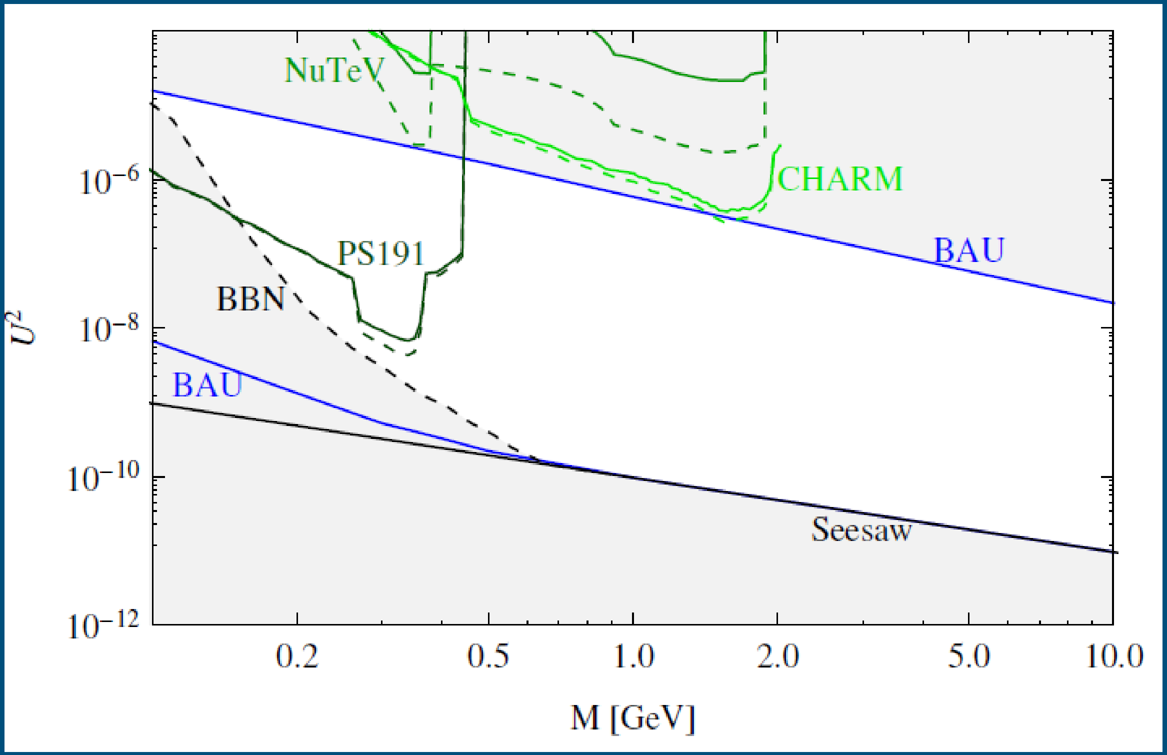
1. See-saw: Lower limit on mixing with active neutrinos to produce oscillations and masses
2. BAU: Upper limit on mixing to guarantee out-of-equilibrium oscillations ($\Gamma_{N_{2,3}} < H$)
3. BBN: Decays of N_2 and N_3 must respect current abundances of light nuclei
   ➔ Limit on lifetime $\tau_{N_{2,3}} < 0.1s \;\; (T > 3\;MeV)$
4. Experimental: No observation so far…
   ➔ Constraints 1-3 now indicate that previous searches were largely outside interesting parameter space

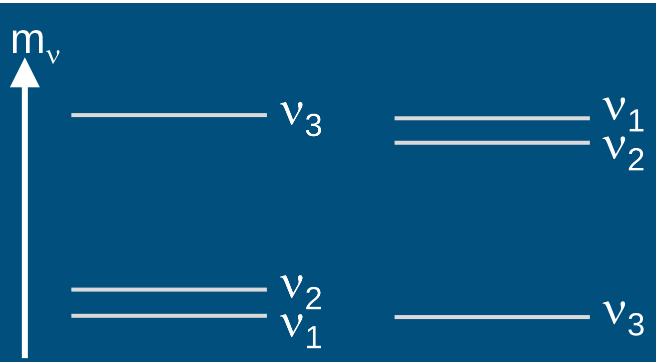


- Large fraction of interesting parameter space can be explored in accelerator based search
  - $m_\pi < M_N < 2$ GeV
  - $M_N > 2$ GeV is not reachable at any operating facility

Constraints - Inverted Hierarchy

Non-official





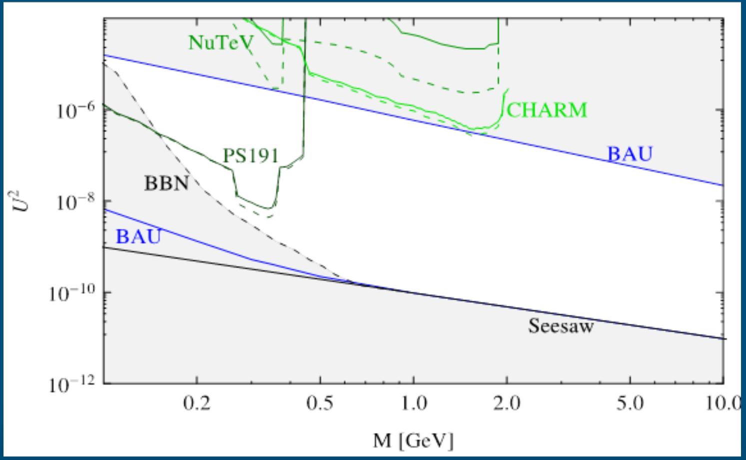
Conventional hierachy   Inverted hierachy

Constraints in Variants of νMSM (references at end)

Non-official

1. νMSM: HNLs are required to explain neutrino masses, BAU, and DM
   - $\mathcal{U}^2$ is the most constrained
2. HNLs are required to explain neutrino masses and BAU
   - N_1 , N_2 and N_3 are available to produce neutrino oscillations/masses and BAU
3. HNLs are required to explain neutrino masses
   - Only experimental constraints remain
4. HNLs are required to explain Dark Matter
5. HNLs are helpful in cosmology and astrophysics
   - E.g. HNL may influence primordial abundance of light elements
   - E.g. HNL with masses below 250 MeV can facilitate the explosions of the supernovae

- HNLs are not required to explain anything - just so
  - Contributions of the HNL to the rare lepton number violating processes μ → e, μ → eee

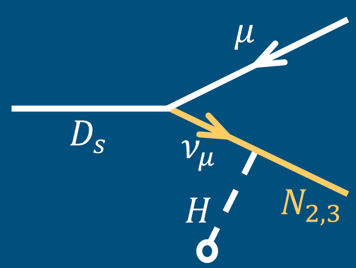


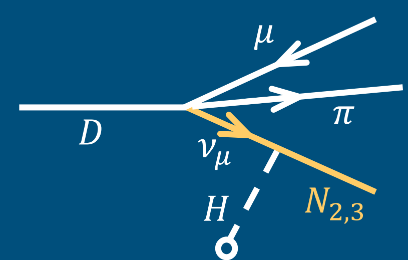
$N_{2,3}$ Production

Non-official

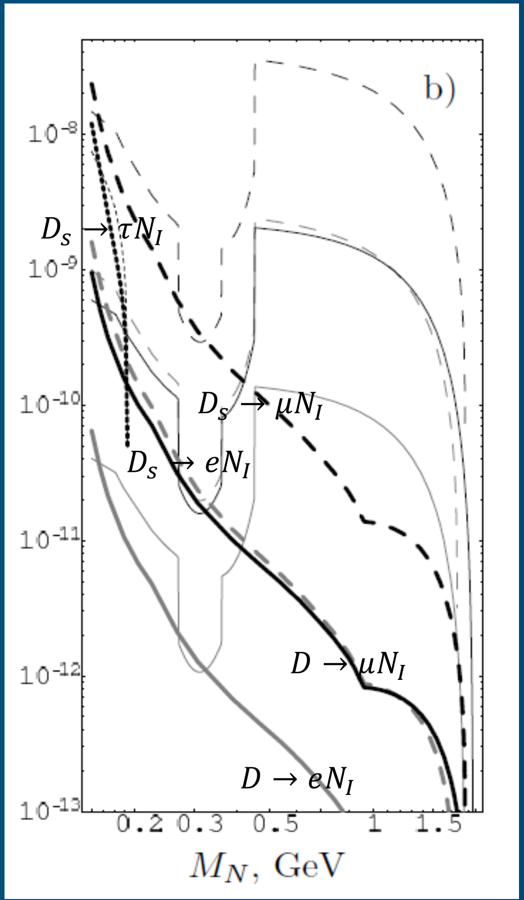
- Production in mixing with active neutrino from leptonic/semi-leptonic weak decays of charm mesons
  - Total production depend on $\mathcal{U}^2 = \sum_{\substack{I=1,2 \\ \ell=e,\mu,\tau}} |\mathcal{U}_{\ell I}|^2$
  - Relation between $\mathcal{U}_e{}^2, \mathcal{U}_\mu{}^2$ and $\mathcal{U}_\tau{}^2$ depends on exact flavour mixing
  - Ratio of Yukawa couplings can be expressed through the elements of the active neutrino mixing matrix (arXiv:0605047)

  ➔ For the sake of determining a search strategy, assume scenario with a predominant coupling to the muon flavour





Benchmark model II: muon flavour dominance



arXiv:0705.1729

- Production mechanism probes $\mathcal{U}_\mu{}^2 = \sum_{I=2,3} \frac{v^2 |Y_{\mu I}|^2}{m_I^{R\,2}}$

  ➔ Br$(D \to NX) \sim 10^{-8} - 10^{-12}$

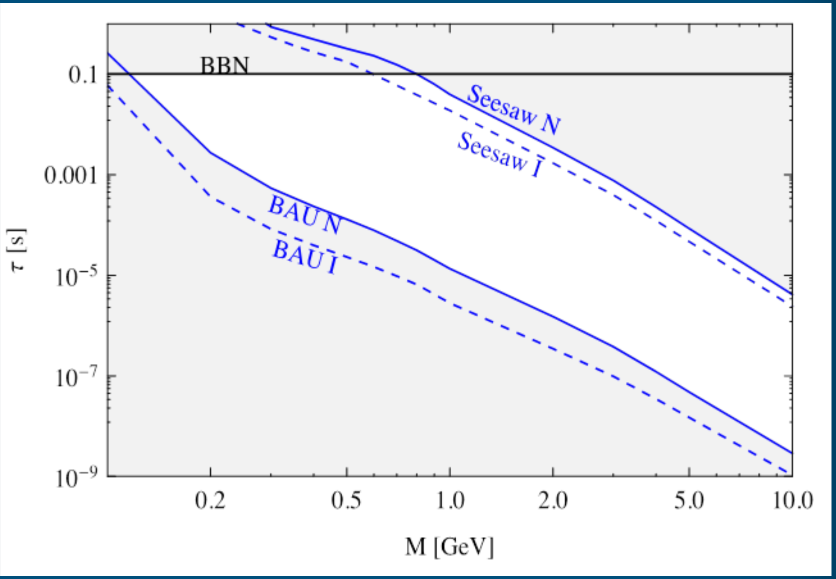
$N_{2,3}$ Decay

Non-official

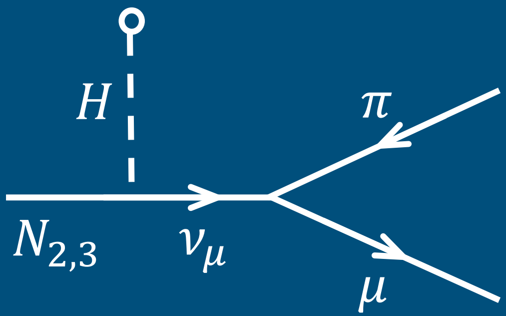
- Very weak HNL-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles
  - → Typical lifetimes > 10 μs for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$

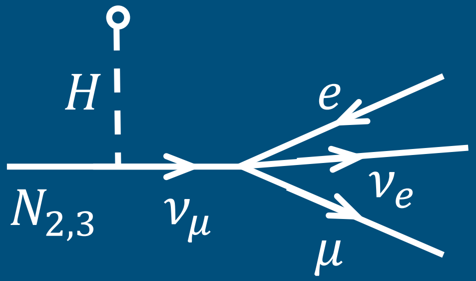
- Decay modes:
  - $N \rightarrow \mu e \nu, \pi^0 \nu, \pi e, \mu\mu\nu, \pi\mu, Ke, K\mu, \eta\nu, \eta'\nu, \rho\nu, \rho e, \rho\mu, \ldots$
  - Branching ratios depend on flavour mixing (again)
  - Typical:

Decay mode	Branching ratio
$N_{2,3} \rightarrow \mu/e + \pi$	0.1 - 50 %
$N_{2,3} \rightarrow \mu^-/e^- + \rho^+$	0.5 - 20 %
$N_{2,3} \rightarrow \nu + \mu + e$	1 - 10 %



E.g.





- Probability that $N_{2,3}$ decays in the fiducial volume $\propto \mathcal{U}_\mu^2$

Experimental Requirements/Challenges

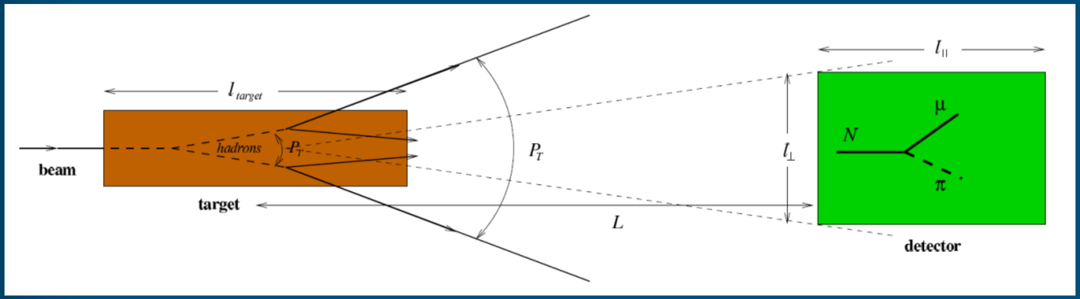
Non-official

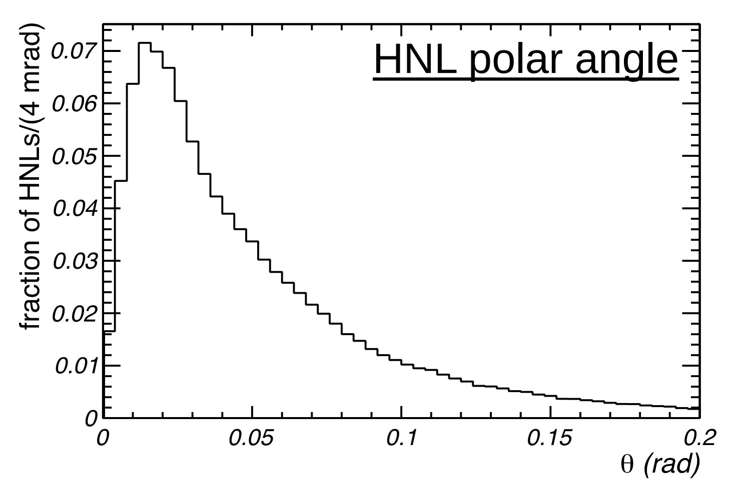
Proposal: *beam dump experiment at the SPS*

1. Sensitivity ∝ $\mathcal{U}^4$ → Number of protons on target (p.o.t.)
   ➔ SPS: 4-5x10^{13} / 6-7s @ 400 GeV = 500 kW → 2x10^{20} in 4-5 years (similar to CNGS)
2. Preference for relatively slow beam extraction $\mathcal{O}(ms - 1s)$ to reduce detector occupancy
3. Heavy material target to stop π, K before decay to reduce flux of active neutrinos
   ➔ Blow up beam to dilute beam energy on target
4. Long muon shield to range out flux of muons
5. Away from tunnel walls to reduce neutrino interactions in proximity of detector
6. Vacuum in detector volume to reduce neutrino interactions in detector
7. Detector acceptance compromise between lifetime and $N_{2,3}$ production angle
   - …and length of shield to filter out muon flux

➔ Incompatible with conventional neutrino facility

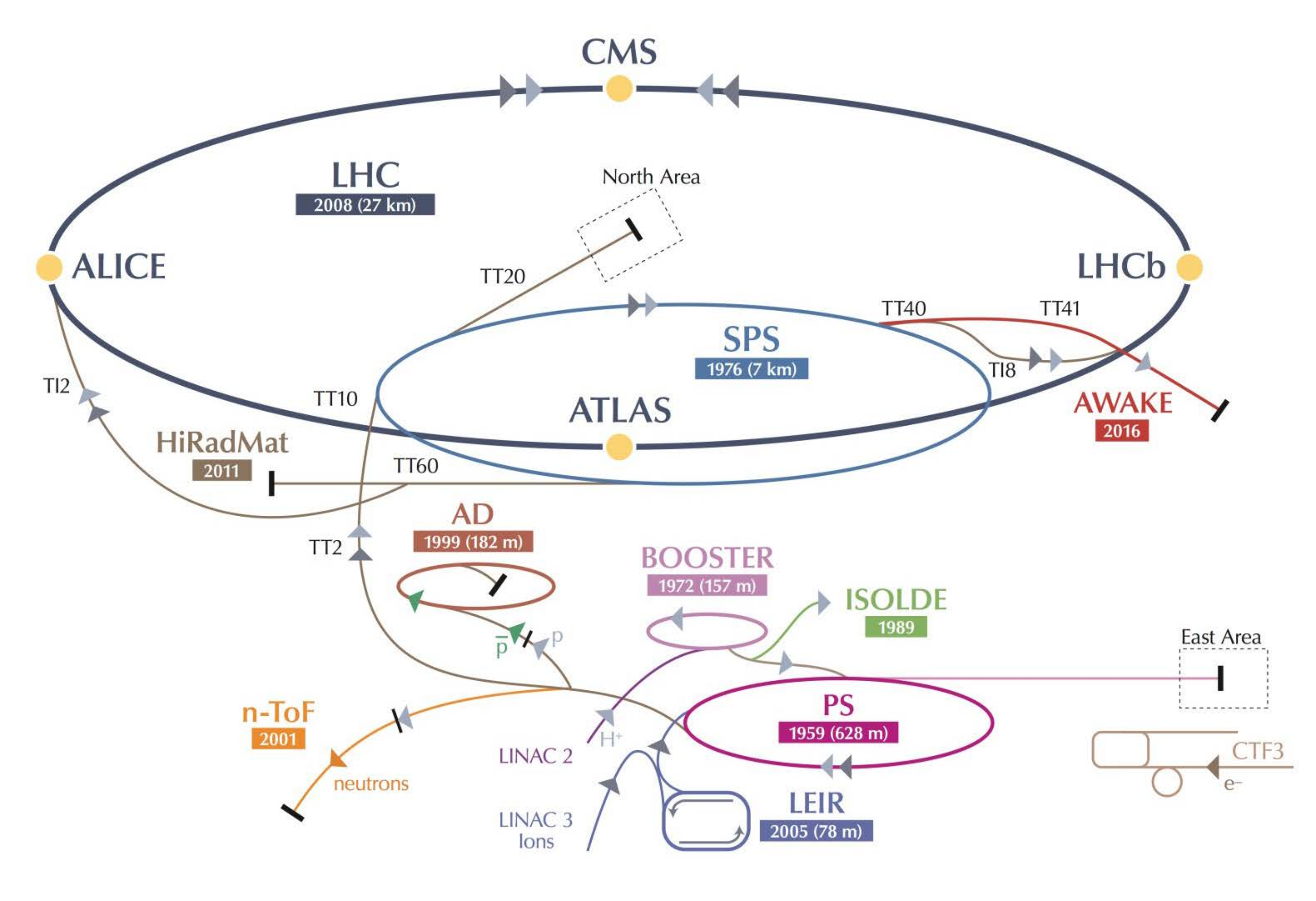
Gorbunov, Shaposhnikov





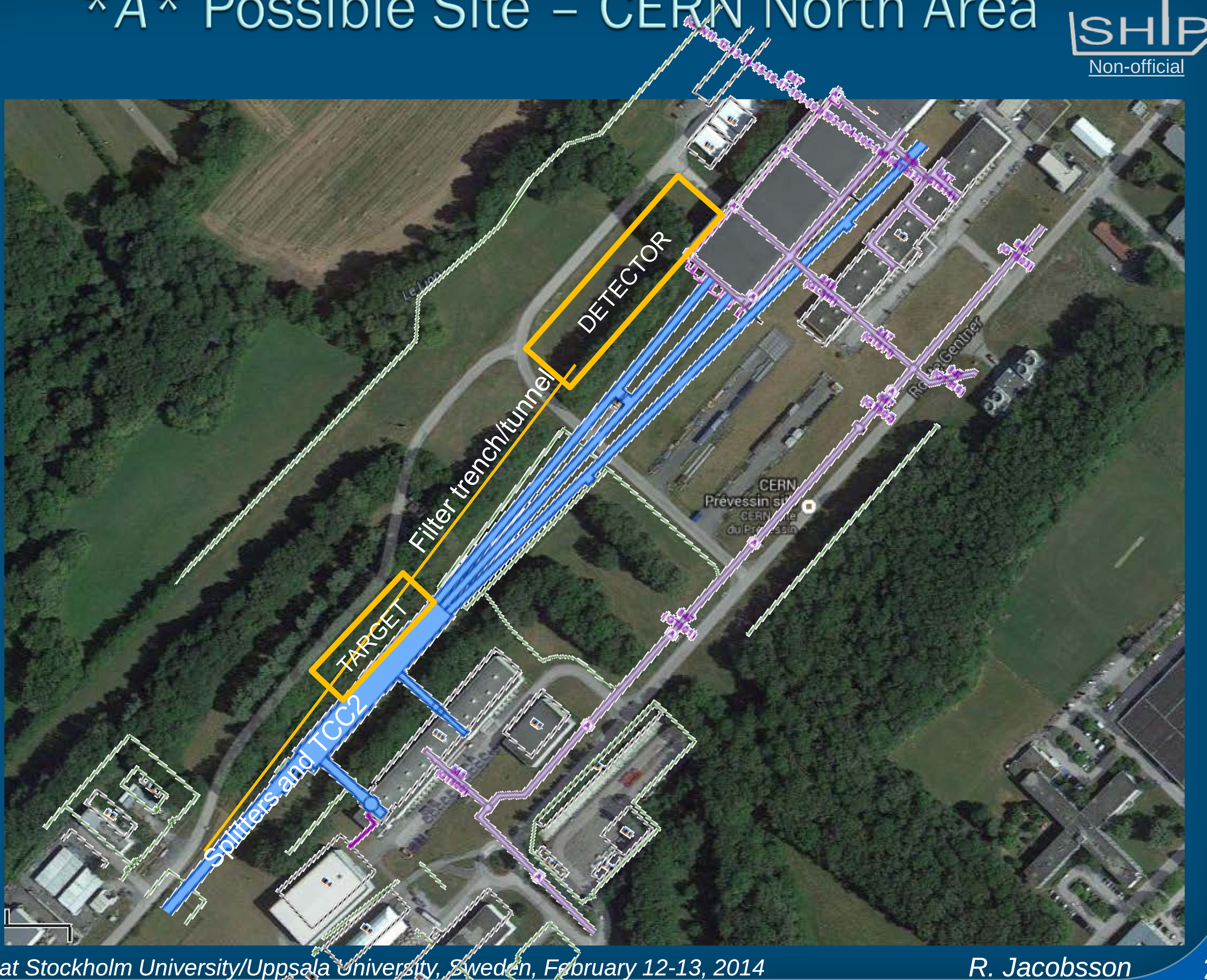
CERN Accelerator Complex

Non-official



A Possible Site – CERN North Area

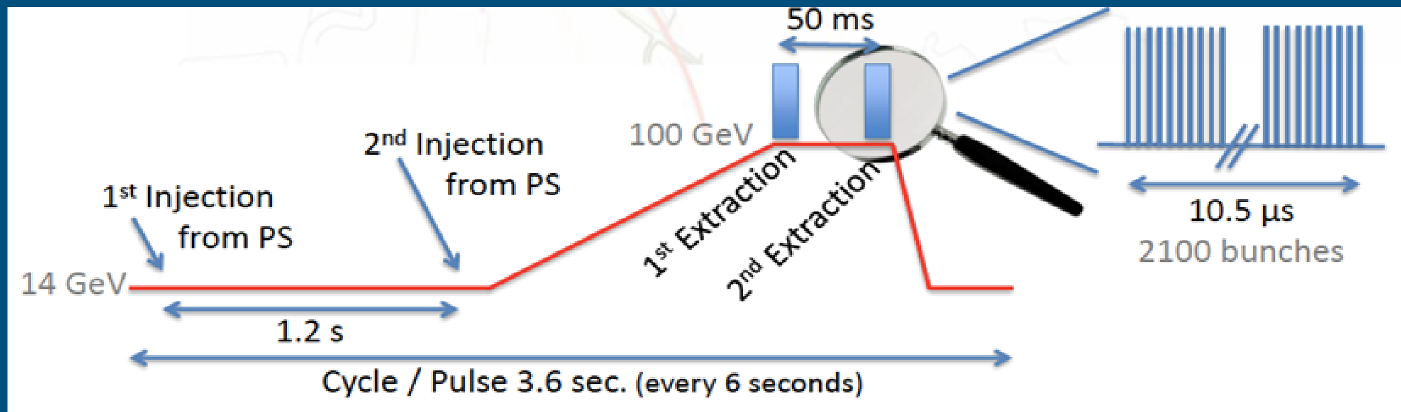
Non-official

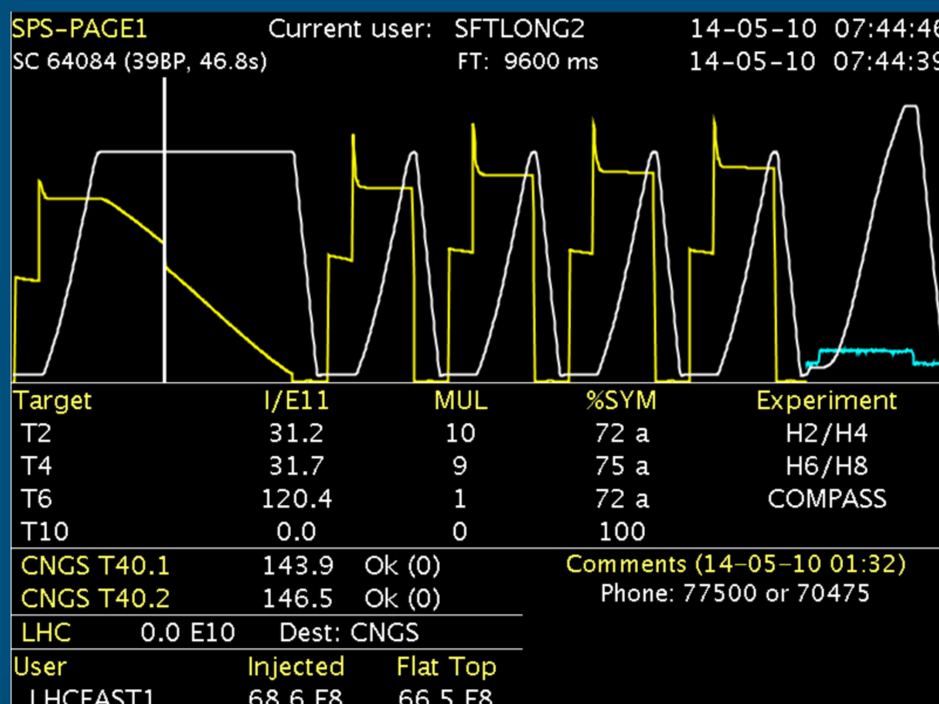


Beam Extraction 400 GeV

Non-official

- Ex. CNGS: 4-4.5x10^{13} / 6s → 4.5x10^{19} p.o.t / year → 500 kW



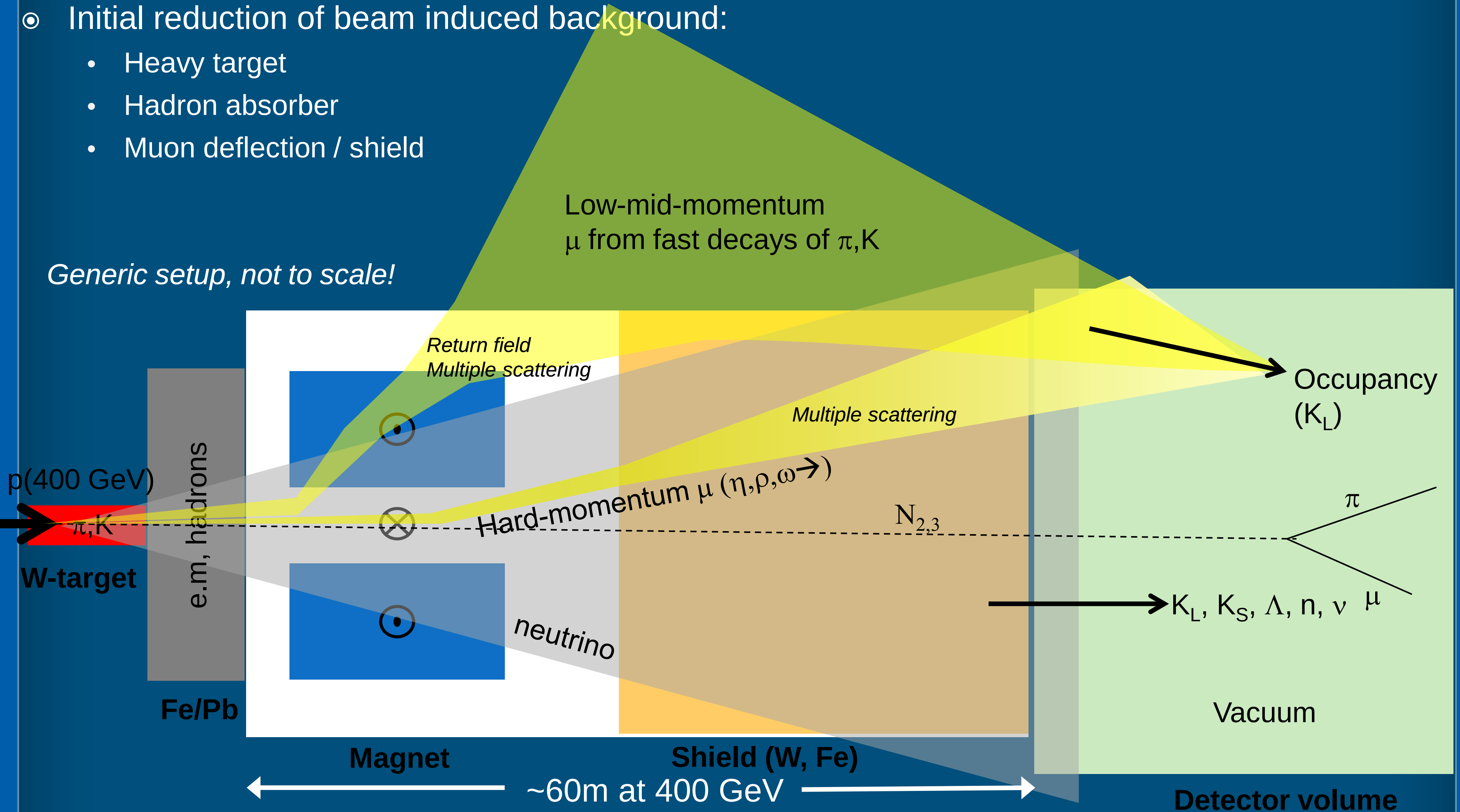


Schematic Principle of Experimental Setup

SHiP Non-official

- Initial reduction of beam induced background:
  - Heavy target
  - Hadron absorber
  - Muon deflection / shield

Generic setup, not to scale!

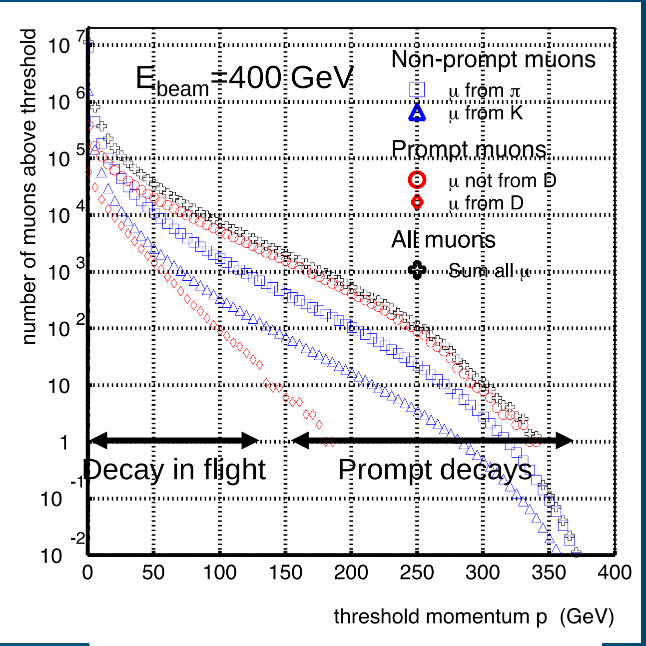


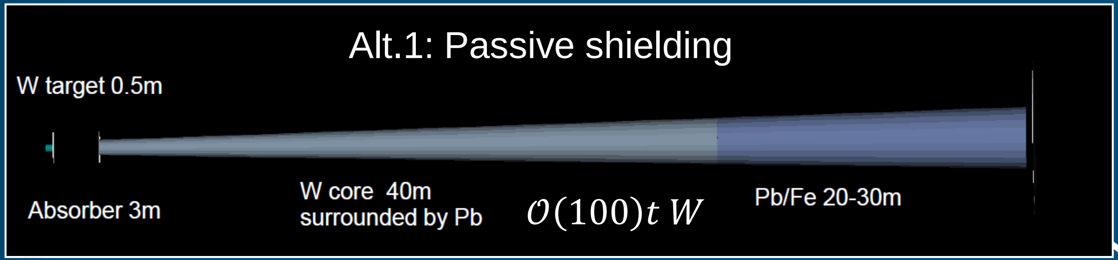
➔ Multi-dimensional optimization: Beam energy is compromise between σ_{charm}, beam intensity, background conditions, acceptance, detector resolution

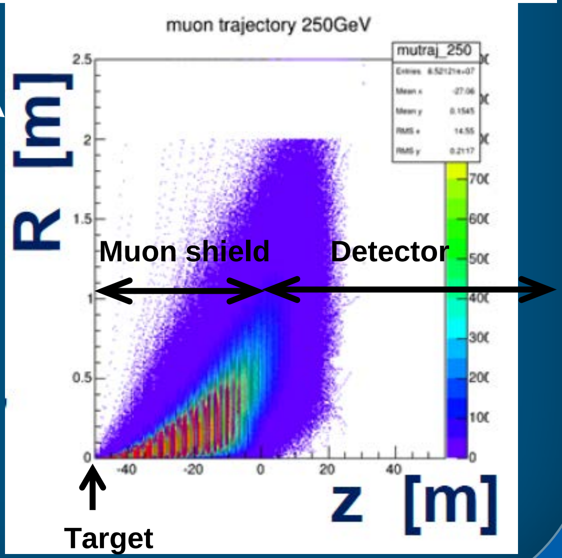
Muon Shield Optimization

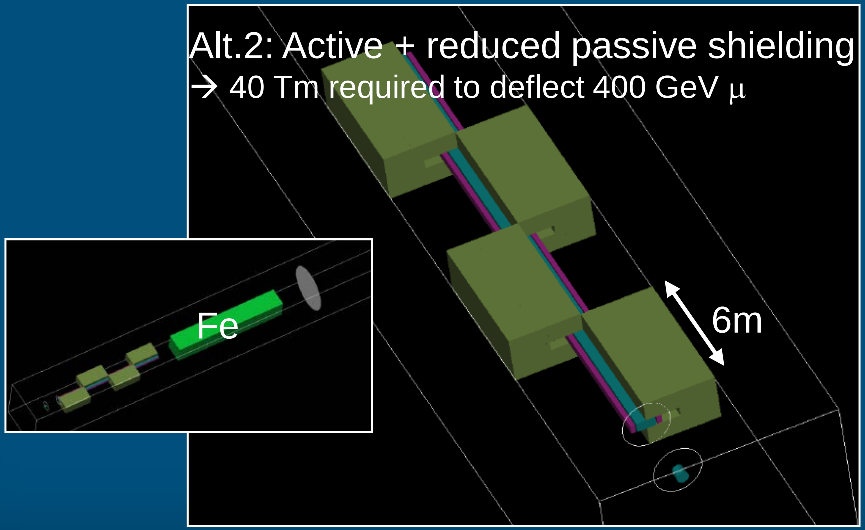
- No shield: Rate at detector 5×10^{9} muons / 5×10^{13} p.o.t.
  - Acceptable occupancy (<1%) per spill of 5×10^{13} p.o.t
  - → Spill duration ~1s: <50×10^{6} muons
  - → Spill duration ~1ms: < 50×10^{3} muons
  - → Spill duration ~10μs : <500 muons
- Simulations with passive and active/passive shield
  - Stopping power of tungsten: 54m @ E_{μ}=400 GeV

Main sources of the muon flux (Pythia)







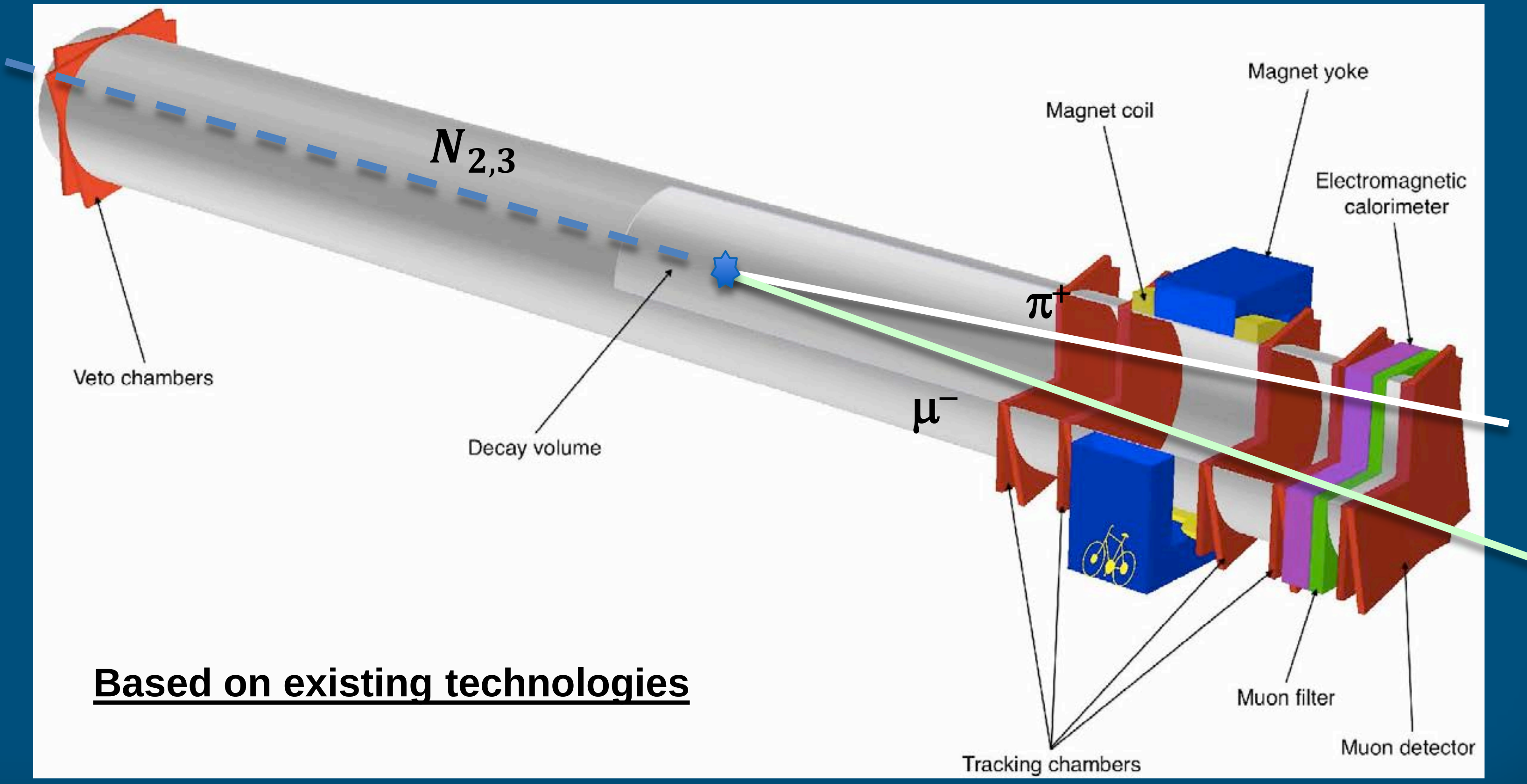


Detector Concept

Non-official

- 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

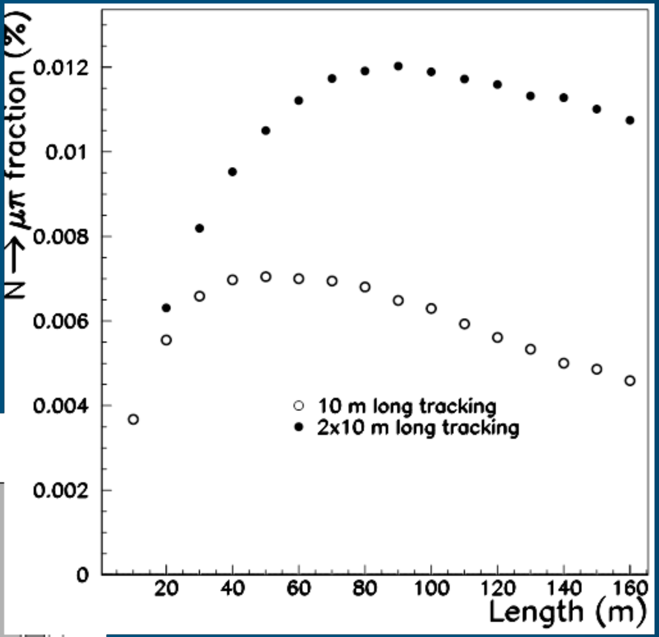


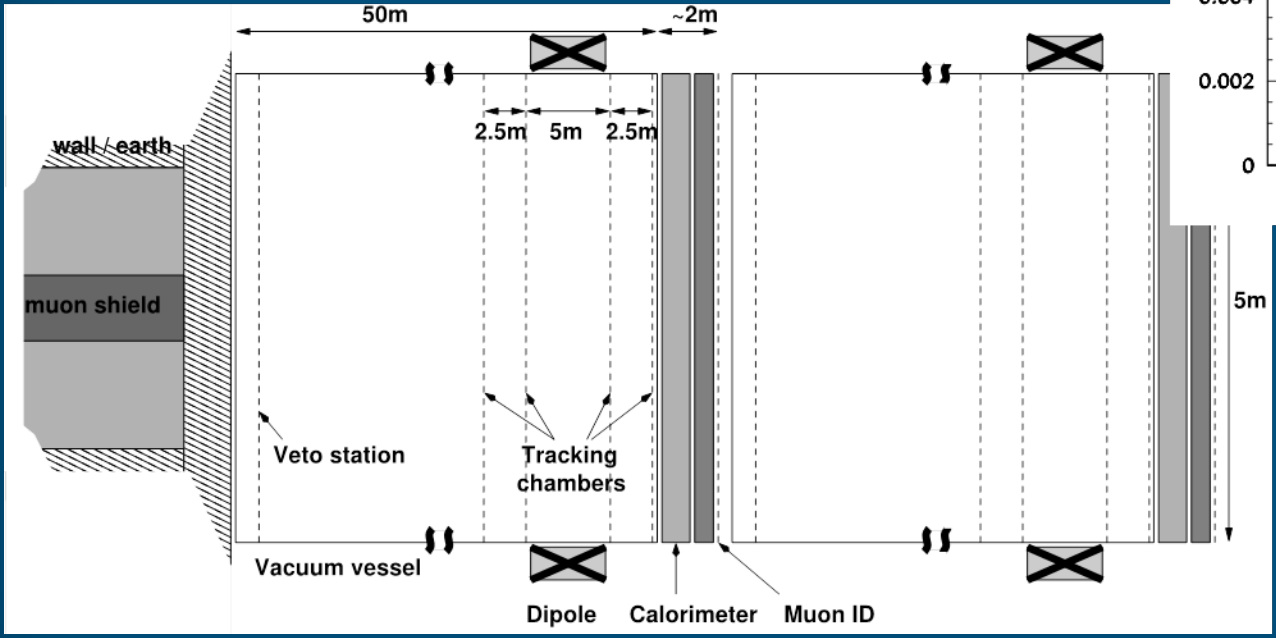
<u>Based on existing technologies</u>

Detector Concept

Non-official

- Geometric acceptance
  - Saturates for a given $N_{2,3}$ lifetime as a function of the detector length
  - The use of two magnetic spectrometers increases the acceptance by 70%
  - Detector has two almost identical elements

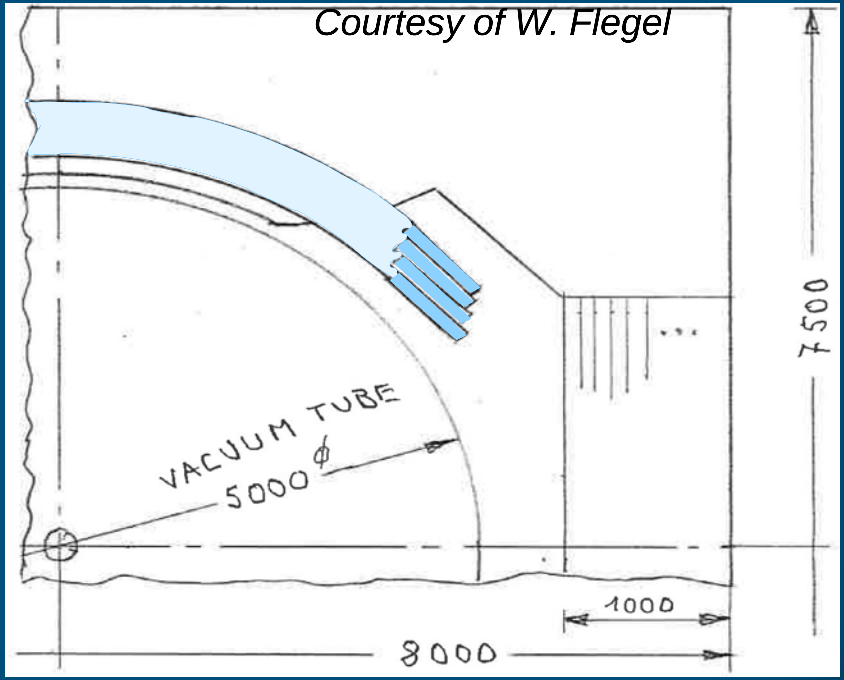




Detector Technologies

Non-official

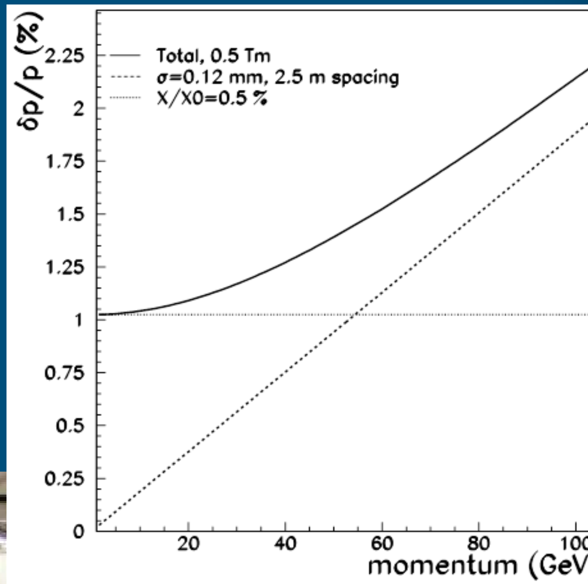
- Experiment requires a dipole magnet similar to LHCb design, but with ~40% less iron and three times less dissipated power
- Free aperture of ~ 16 m^2 and field integral of ~ 0.5 Tm
  - Yoke outer dimension: 8.0×7.5×2.5 m^3
  - Two Al-99.7 coils
  - Peak field ~ 0.2 T
  - Field integral ~ 0.5 Tm over 5 m length

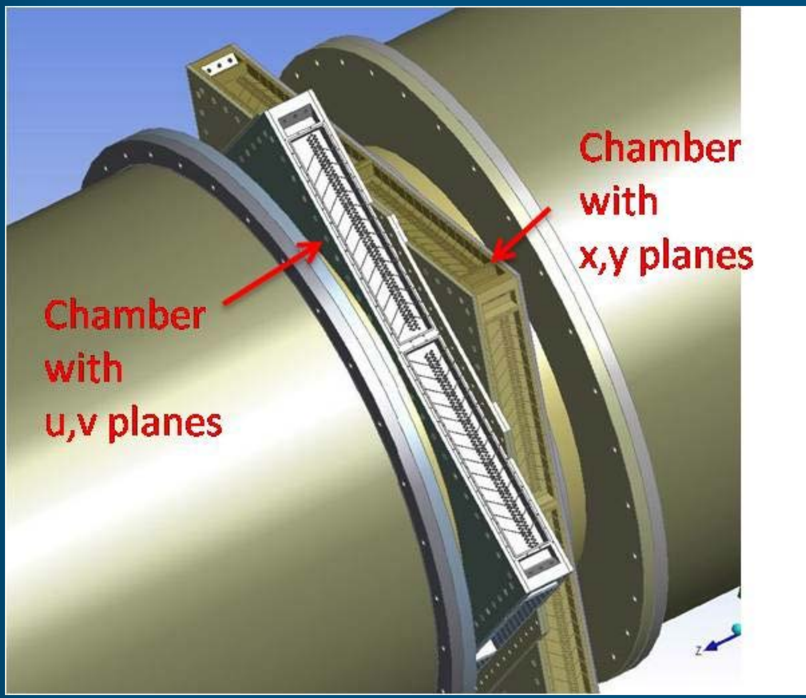


Detector Technologies

Non-official

- NA62 vacuum tank and straw tracker
  - < 10^{-5} mbar pressure in NA62 tank (cmp. 10^{-2} mbar)
  - Straw tubes with 120 μm resolution and 0.5% $\frac{X_0}{X}$ of material budget
  - Gas tightness of straw tubes demonstrated in long term tests
- Multiple scattering and spatial resolution of straw tubes give similar contribution to the overall $\frac{dP}{P}$



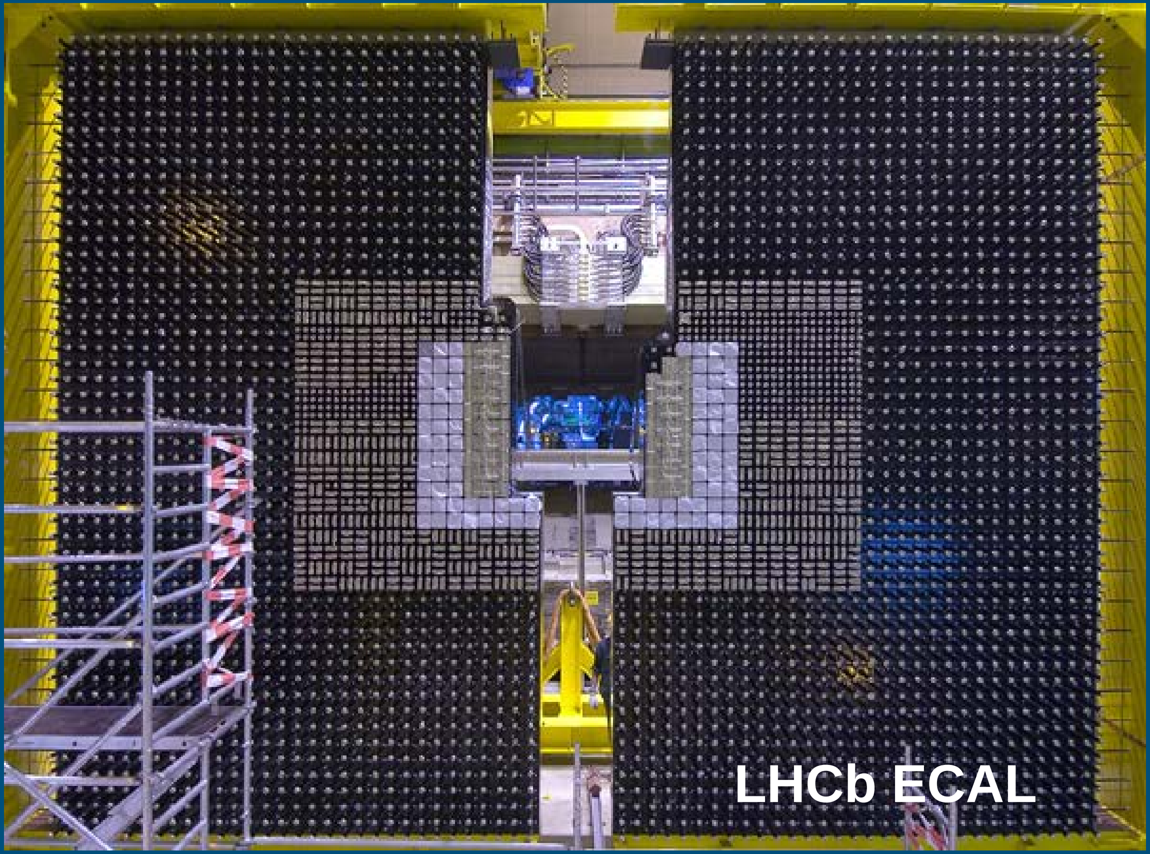


Detector Technologies

Non-official

- LHCb electromagnetic calorimeter

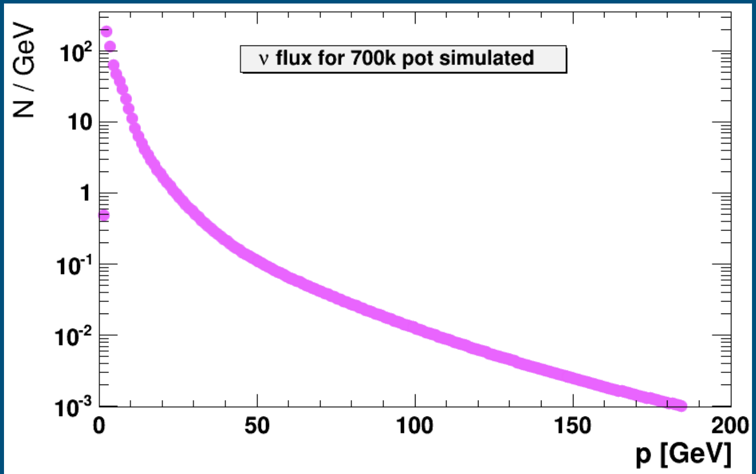
→ Shashlik technology provides economical solution with good energy and time resolution



Residual Backgrounds

Non-official

- Momentum spectrum of the neutrino flux after the muon shield



➔ 2×10^{4} neutrino interactions per 2×10^{20} protons on target in the decay volume at atmospheric pressure

➔ Becomes negligible at 0.01 mbar

- Charged Current and Neutral Current neutrino interaction in the final part of the muon shield
  - Simulated with GEANT and GENIE, and cross-checked with CHARM measurement
  - ➔ Yields CC(NC) rate of $\sim 6(2)\times10^{5}$ / λ_{inter} / 2×10^{20} p.o.t.
  - ➔ ~10% of neutrino interactions produce Λ or K^0 in acceptance
  - ➔ Majority of decays occur in the first 5 m of the decay volume
  - ➔ Requiring μ-identification for one of the two decay products: 150 two-prong vertices in 2×10^{20} p.o.t.
  - Instrumentation of the end-part of the muon shield allows the rate of CC + NC to be measured and neutrino interactions to be tagged

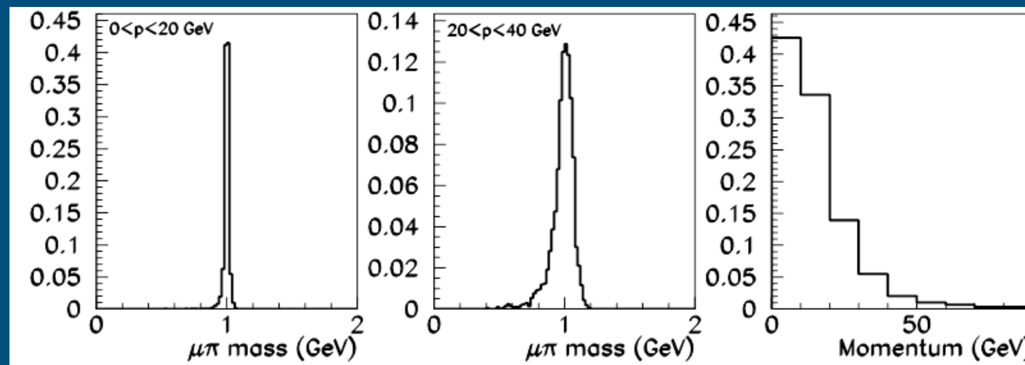
Residual Background

Non-official

Background reduction by mass

- For 0.5 Tm field integral σ_{mass} ~ 40 MeV for p < 20 GeV
- 75% of μ π decay products have both tracks with p < 20 GeV

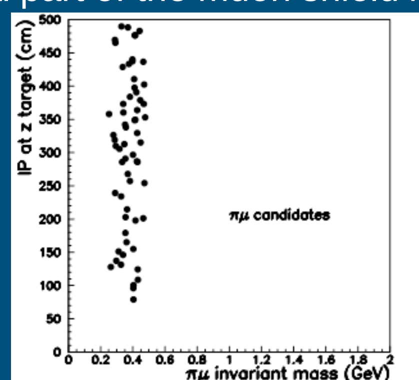
Reconstruction of $N_{2,3}$ with mass of 1 GeV

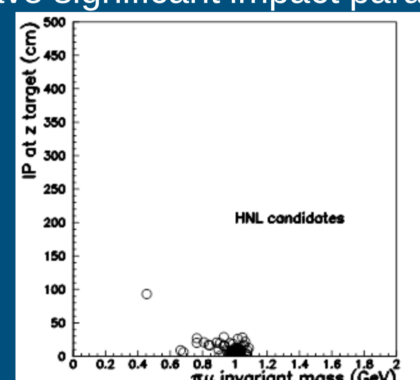


➔ Ample discrimination between high mass tail from small number of residual $K_L \rightarrow \pi\mu\nu$ and $N_{2,3}$ @ 1 GeV

Background reduction by impact parameter

- K_L produced in the final part of the muon shield have significant impact parameter





- IP < 1 m is 100% eff. for signal and leaves only a handful of background events (no mass cut)
- The IP cut will also be used to reject backgrounds induced in neutrino interactions in the material surrounding the detector, cosmics etc

Expected Event Yield $N_{2,3} \to \mu\pi$

Non-official

- Integral mixing angle $\mathcal{U}^2 = \mathcal{U}_e^2 + \mathcal{U}_\mu^2 + \mathcal{U}_\tau^2$
- A conservative estimate of the sensitivity is obtained by considering only the decay $N_{2,3} \to \mu\pi$ with production mechanism $D \to \mu N_{2,3} X$, which probes $\mathcal{U}_\mu^4$
  - Benchmark model II with predominant muon flavour coupling (arXiv:0605047)
- Expected number of signal events

$$N_{signal} = n_{pot} \times 2\chi_{cc} \times Br(\mathcal{U}_\mu^2) \times \varepsilon_{det}(\mathcal{U}_\mu^2)$$

$n_{pot} = 2 \times 10^{20}$
$\chi_{cc} = 0.45 \times 10^{-3}$

- $Br(\mathcal{U}_\mu^2) = \mathrm{Br}(D \to \mu N_{2,3} X) \times Br(N_{2,3} \to \mu\pi)$ is assumed to be 20%
- $\varepsilon_{det}(\mathcal{U}_\mu^2)$ is the probability that $N_{2,3}$ decays in the fiducial volume, and μ and π are reconstructed

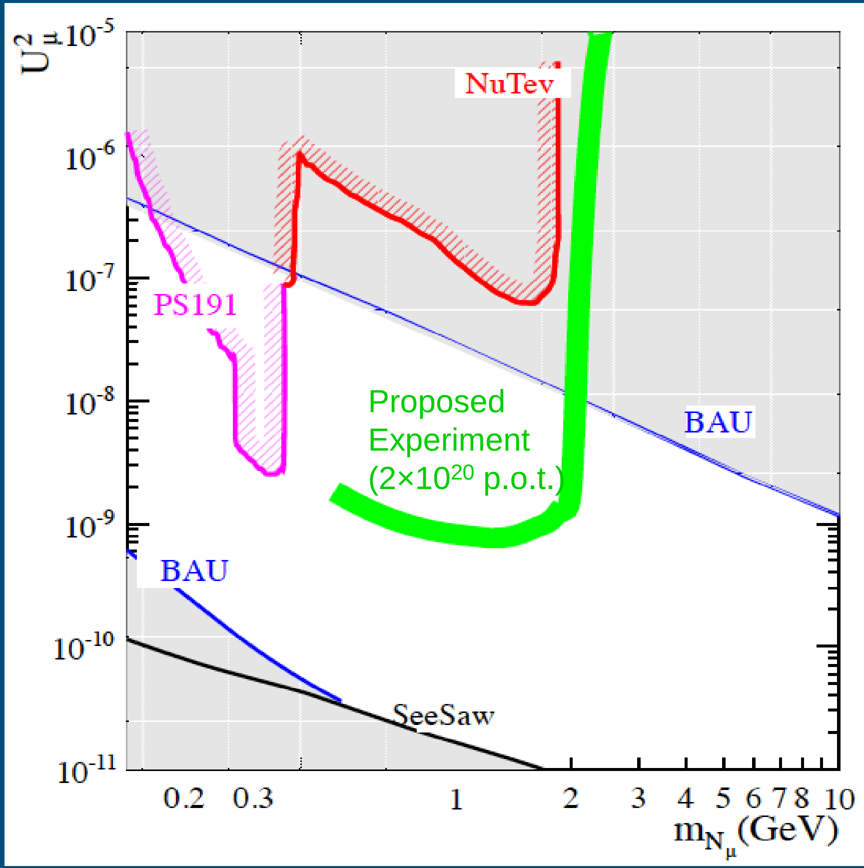
  ➔ Detection efficiency entirely dominated by the geometrical acceptance (8×10^{-5} for $\tau_N = 1.8 \times 10^{-5} s$)

Expected Event Yield $N_{2,3} \rightarrow \mu\pi$

Non-official

Based on current SPS with 2x10[20] p.o.t in ~5 years of operation (CNGS-like)

- For comparison, assume
  - $\mathcal{U}_\mu^2 = 10^{-7}$ (corresponding to the strongest current experimental limit for $M_{N_{2,3}} = 1\ GeV$)
  - $\tau_N = 1.8 \times 10^{-5} s$
  - ➔ ~12k fully reconstructed $N_{2,3} \rightarrow \mu\pi$ events are expected for $M_{N_{2,3}} = 1\ GeV$



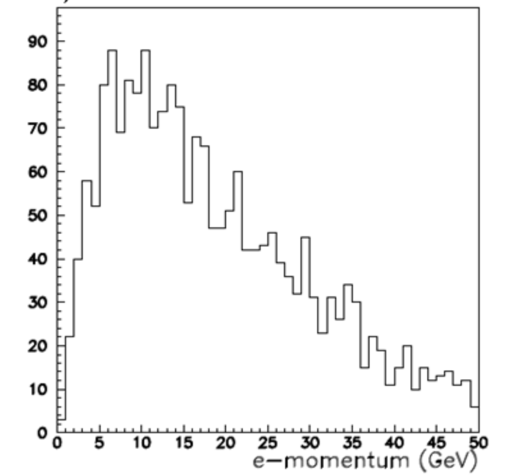
- 120 events for cosmologically favoured region: $\mathcal{U}_\mu^2 = 10^{-8}$ and $\tau_N = 1.8 \times 10^{-4} s$

$N_{2,3} \to \mu\rho, e\pi$

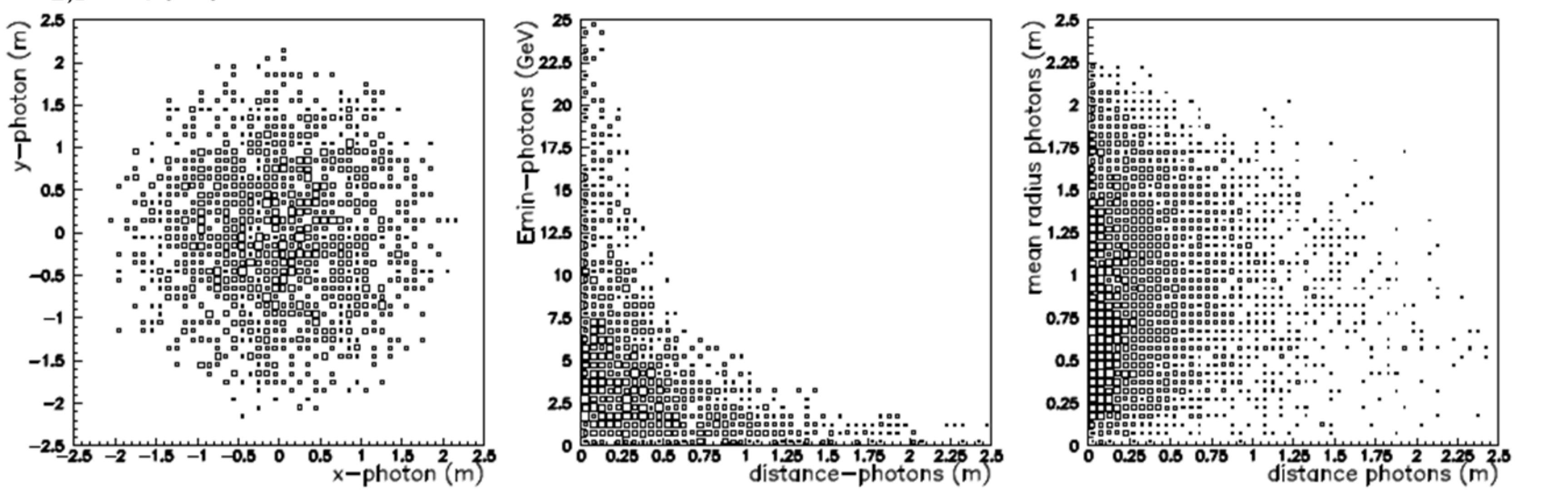
Non-official

- Calorimeter will allow reconstruction of additional decay modes
  - $N_{2,3} \to \mu^{\mp}\rho^{\pm}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
  - $N_{2,3} \to e\pi$ allow probing $\mathcal{U}_e^2$
- E_e > 1. GeV: 99.9% for electron in acceptance
- Assume 10cm calorimeter cells:
  - To have resolved π^0 need at least 20 cm between photons
  - Need to require E > 0.5 GeV to distinguish from MIP

$N_{2,3} \to e\pi$: Energy of electrons



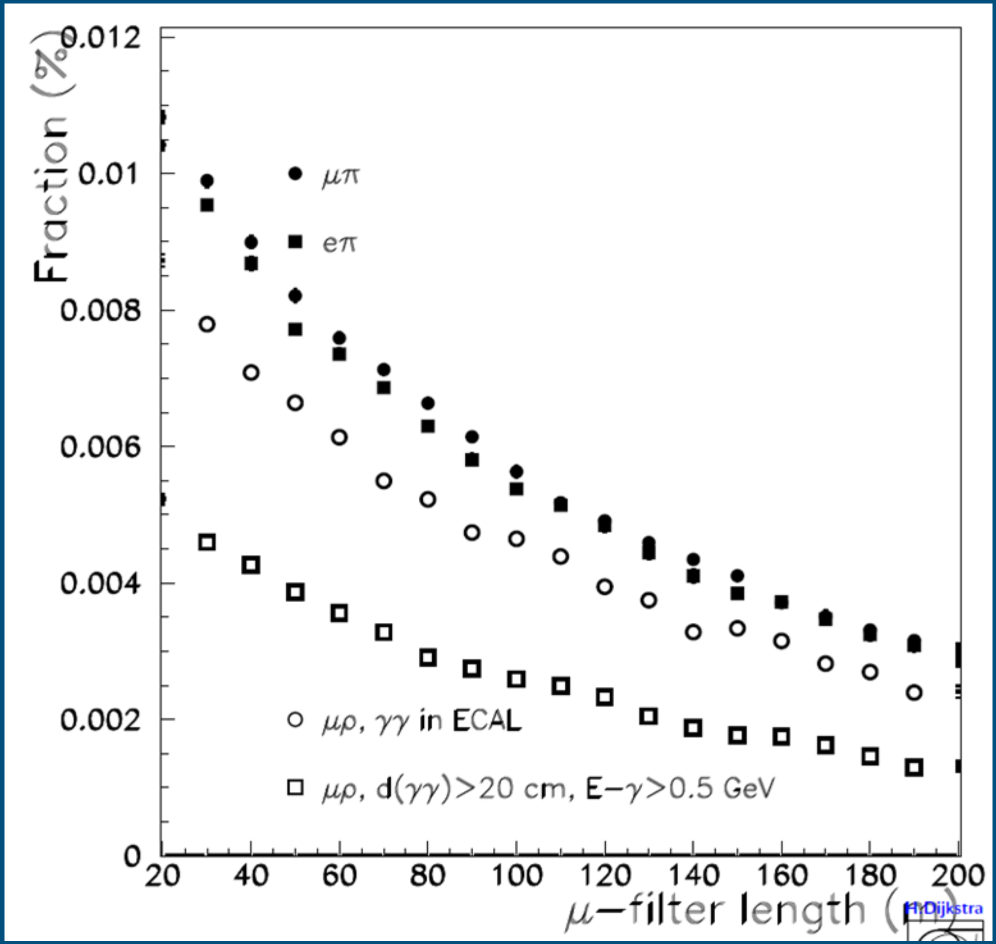
$N_{2,3} \to \mu\rho,\ \rho \to \pi\pi^0$: Position and energy of photons



Efficiency for $N_{2,3} \to e\pi, \mu\rho$

Non-official

- Assume $\mathcal{U}_\mu^2 = 10^{-7}$ and $\tau_N = 1.8 \times 10^{-5} s$ for mass $M_{N_{2,3}} = 1\ GeV$



- Reconstruction efficiency for $N_{2,3} \to \mu\rho$ is 45% of efficiency for $N_{2,3} \to \mu\pi$

Evaluation of Full Physics Program

Non-official

- General Purpose (Beam) Dump: Explore sensitivities to
  - *all less constraining "variants" of νMSM*
  - all BSM models with HNLs
  - all models with light, very weakly interacting, long-lived "exotic" particles out of reach at LHC
    - Sensitive to the same physics as CHARM and LHCb ➔ Longer lifetimes and smaller couplings
  - ν_τ physics with additional upstream emulsion detector: 1500 - 2000 events expected

Examples with mass~$\mathcal{O}(GeV)$ and production branching ratio ~ $\mathcal{O}(10^{-10})$

➔ Light super-goldstinos [Gorbunov, 2001] "Axion- and dilaton-like"

➔ $D \to \pi X,\ X \to \pi^+\pi^-,\ \pi^0\pi^0,\ l^+l^-$

- $N_{\pi^+\pi^-}(N_{pot} = 2\times10^{20}) \cong 2\times\left(\frac{1000\ TeV}{\sqrt{F}}\right)^8\left(\frac{M_{\lambda g}}{3\ TeV}\right)^4\left(\frac{m_X}{1\ GeV}\right)^2$

➔ R-parity violating neutralinos in SUSY [Dedes et al., 2001] "Heavy-neutrino like"

➔ $D \to l\tilde{\chi},\ \ \tilde{\chi} \to l^+l^-\nu$

- $N_{\mu^+\mu^-\nu}(N_{pot} = 2\times10^{20}) \cong 20\times\left(\frac{m_{\tilde{\chi}}}{1\ GeV}\right)^6\left(\frac{\lambda}{10^{-8}}\right)^2\left(\frac{BR(D\to l\tilde{\chi})}{10^{-10}}\right)$, λ is R-violating coupling

➔ Massive vectors in secluded dark matter models [Pospelov et al., 2008] "Paraphoton-like"

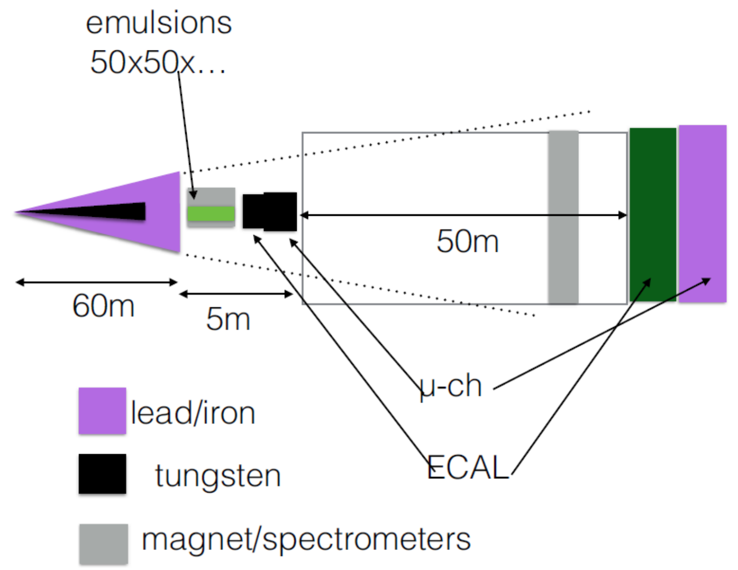
- Production of γ' through bremsstrahlung, J/ψ decay, $\gamma' \to l^+l^-$

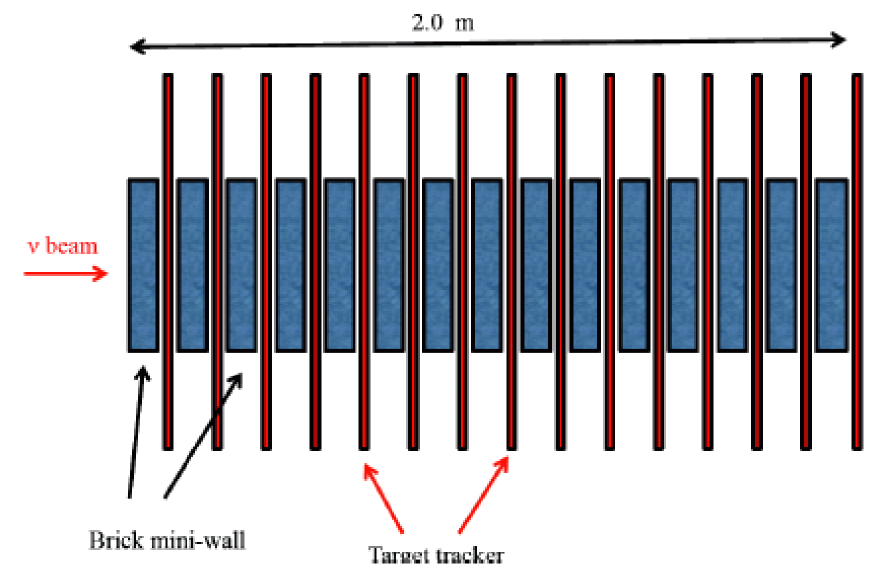
➔ Specifying the full physics program is one of the main goals of the next few months

Prospects for ν_τ Physics

Non-official

- Scaling from the DONUT experiment
  - 20 times more ν_τ CC interactions assuming the same neutrino fiducial mass
  - Realistic to increase fiducial mass from 260 kg (DONUT) to 3000 kg with OPERA style lead/emulsion bricks (3% of OPERA emulsion surface)
  - → 1500 – 2000 events expected





- → Negligible loss of acceptance for HNL detector
- → HNL detector function as forward spectrometer for ν_τ physics program
- → Use of calorimeter/muon detector allow tagging neutrino NC/CC interactions → normalization

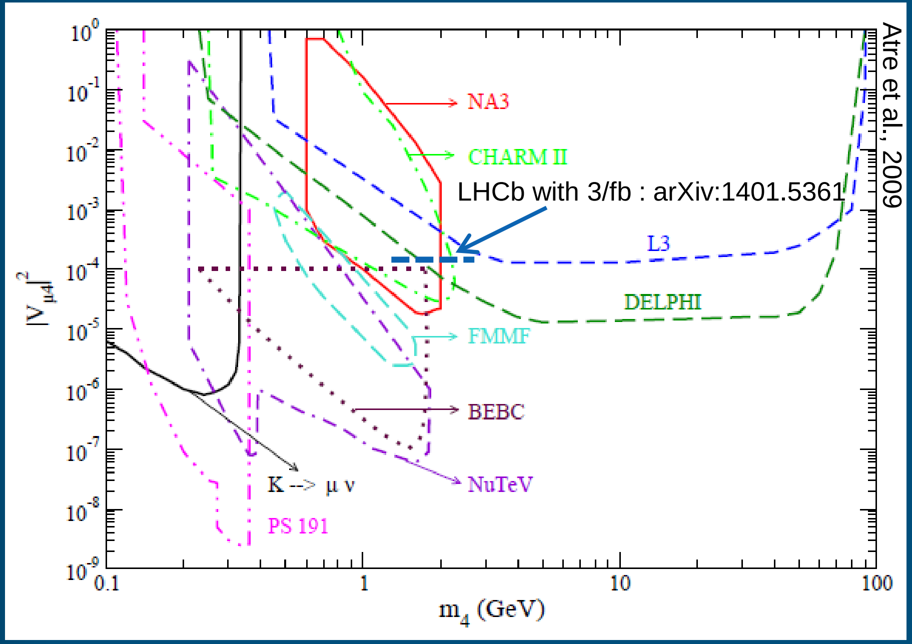
Prospects for Future

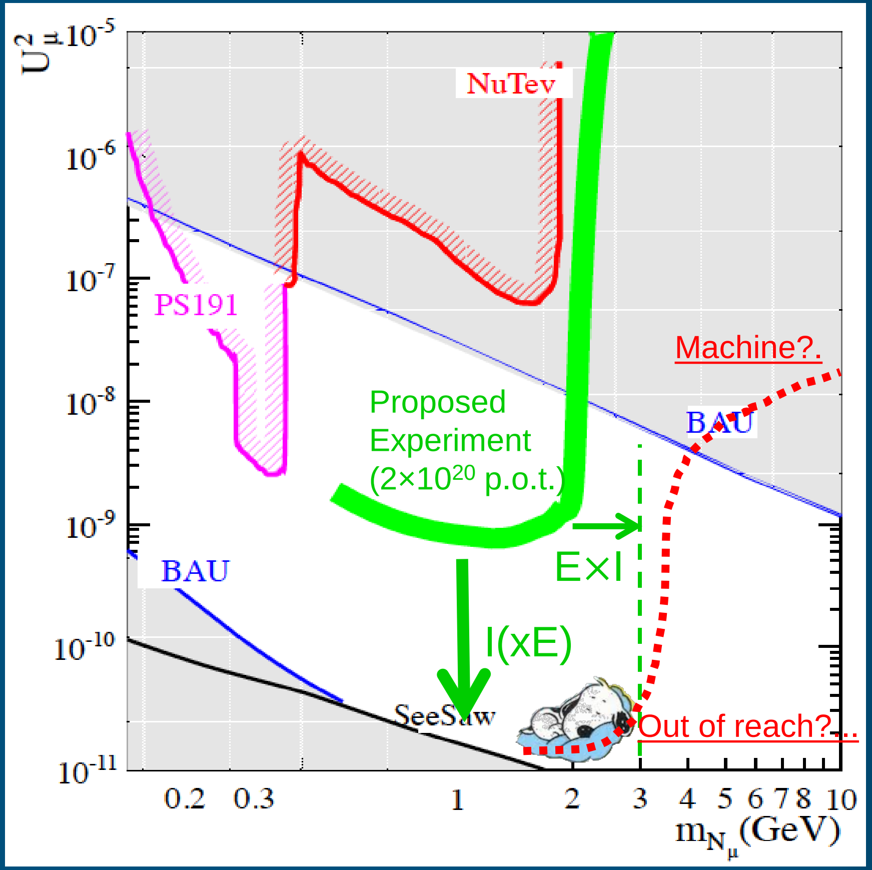
Non-official

Current sensitivity based on current SPS with 2x10^20 p.o.t in ~5 years of operation

- HNLs very constrained by simultaneously aiming at answering to neutrino masses, BAU and DM.
- ➔ Primary interest to reach seesaw limit

Summary of Searches for N_I





→ Colliders out of luck

➔ Search for Hidden Sector light objects ➔ Intensity Frontier

- ➔ Complementary by use of fixed target facility on FHC Injectors (fast cycling!)
- Fiducial volumes

Experiment Review Status

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010
  - ➔ Three referees appointed before the presentation, one more added since
  - ➔ EOI stimulated a lot of interest, received a list of questions for next SPSC
- Jan 3, 2014: submitted document with answers to referees
  - ➔ cern.ch/ship/EOI/SPSC-EOI-010_ResponseToReferees.pdf
- Jan 15, 2014: EOI discussed at SPSC
  - Official feedback:

    *"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."*
- Jan 31, 2014: Meeting with S. Bertolucci
  - ➔ Very supportive, proposal to present experiment at Extended Directorate
  - ➔ Proposed a task force to evaluate feasibility and required resources at CERN within ~2months
  - ➔ Supportive to the formation of a Collaboration and agreed to CERN signing
  - ➔ Task force put together
- Collaboration being formalized and preparation of Workshop/Collaboration Meeting June 10 – 12 near to CERN.

Conclusions

Non-official

- νMSM : Minimal SM extension with solutions to the main BSM questions with "*least prejudice*"
  - Origin of the baryon asymmetry of the Universe
  - Origin of neutrino oscillations and mass
  - Shed light on the nature of Dark Matter

- Evaluation of complete physics program with very weakly interacting and long-lived particles
  - General purpose beam dump facility
  - The proposed experiment perfectly complements the searches for NP at the LHC

- Sensitivity demonstrated with νMSM for $M_N < 2\ GeV$ and 2×10^{20} p.o.t.
  - ➔ Discovery potential in cosmologically favoured region with $10^{-7} < \mathcal{U}_\mu^2 < a\ few\ \times 10^{-9}$
  - Improved with the additional decay modes
  - Improved with an SPS': 7×10^{13} p.o.t. and ms / second extraction

- The impact of a discovery of HNLs on particle physics is difficult to overestimate !
  - Of course also true for any other BSM long-lived object!
  - Clearly requires a new machine ➔ Injectors for FHC and fixed target facility
  - *Challenging experimental optimization*

- SPSC recommendation Jan 2014: Encouragement to submit extended proposal (LoI)
  - ➔ "SHIP" Workshop/Collaboration meeting June 10 – 12, 2014

This is the moment to join!

Potential Collaborators

SHIP Non-official

- Proposal 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

Brazil / Chile / XXX……

Constraints in variants of νMSM

Non-official

- References:

1. [Allison, 2013] Allison, K. (2013). Dark matter, singlet extensions of the nuMSM, and symmetries. JHEP, 1305:009.
2. [Alonso et al., 2013] Alonso, R., Dhen, M., Gavela, M., and Hambye, T. (2013). Muon conversion to electron in nuclei in type-I seesaw models. JHEP, 1301:118.
3. [Appelquist et al., 2004] Appelquist, T., Piai, M., and Shrock, R. (2004). Fermion masses and mixing in extended technicolor models. Phys.Rev., D69:015002.
4. [Appelquist and Shrock, 2002] Appelquist, T. and Shrock, R. (2002). Neutrino masses in theories with dynamical electroweak symmetry breaking. Phys.Lett., B548:204-214.
5. [Appelquist and Shrock, 2003] Appelquist, T. and Shrock, R. (2003). Dynamical symmetry breaking of extended gauge symmetries. Phys.Rev.Lett., 90:201801.
6. [Araki and Li, 2012] Araki, T. and Li, Y. (2012). Q6 flavor symmetry model for the extension of the minimal standard model by three right-handed sterile neutrinos. Phys.Rev., D85:065016.
7. [Bezrukov, 2005] Bezrukov, F. (2005). νMSM-predictions for neutrinoless double beta decay. Phys.Rev., D72:071303.
8. [Bezrukov et al., 2010] Bezrukov, F., Hettmansperger, H., and Lindner, M. (2010). keV sterile neutrino Dark Matter in gauge extensions of the Standard Model. Phys.Rev., D81:085032.
9. [Blennow et al., 2010] Blennow, M., Fernandez-Martinez, E., Lopez- Pavon, J., and Menendez, J. (2010). Neutrinoless double beta decay in seesaw models. JHEP, 1007:096.
10. [Dolgov et al., 2000] Dolgov, A., Hansen, S., Raffelt, G., and Semikoz, D. (2000). Heavy sterile neutrinos: Bounds from big bang nucleosynthesis and SN1987A. Nucl.Phys., B590:562-574.
11. [Dolgov and Villante, 2004] Dolgov, A. and Villante, F. (2004). BBN bounds on active sterile neutrino mixing. Nucl.Phys., B679:261- 298.
12. [Drewes and Garbrecht, 2013] Drewes, M. and Garbrecht, B. (2013). Leptogenesis from a GeV Seesaw without Mass Degeneracy. JHEP, 1303:096.
13. [Duerr et al., 2011] Duerr, M., George, D. P., and McDonald, K. L. (2011). Neutrino Mass and μ ! eγ from a Mini-Seesaw. JHEP, 1107:103.

Constraints in variants of νMSM

Non-official

14. [Fuller et al., 2011] Fuller, G. M., Kishimoto, C. T., and Kusenko, A. (2011). Heavy sterile neutrinos, entropy and relativistic energy production, and the relic neutrino background. arXiv:1110.6479[astro-ph.CO].
15. [Fuller et al., 2009] Fuller, G. M., Kusenko, A., and Petraki, K. (2009). Heavy sterile neutrinos and supernova explosions. Phys.Lett., B670:281-284.
16. [Gelmini et al., 2008] Gelmini, G., Osoba, E., Palomares-Ruiz, S., and Pascoli, S. (2008). MeV sterile neutrinos in low reheating temperature cosmological scenarios. JCAP, 0810:029.
17. [Gorbunov and Panin, 2013] Gorbunov, D., Panin A. (2013). On the minimal active-sterile neutrino mixing in seesaw type I mechanism with sterile neutrinos at GeV scale. arXiv:1312.2887[hep-ph].
18. [Hernandez et al., 2013] Hernandez, P., Kekic, M., and Lopez-Pavon, J. (2013). Low-scale seesaw models versus Neff . arXiv:1311.2614 [hep-ph].
19. [Kang and Kim, 2007] Kang, S. K. and Kim, C. (2007). Extended double seesaw model for neutrino mass spectrum and low scale leptogenesis. Phys.Lett., B646:248-252.
20. [Khalil and Seto, 2008] Khalil, S. and Seto, O. (2008). Sterile neutrino dark matter in B - L extension of the standard model and galactic 511-keV line. JCAP, 0810:024.
21. [Khoze and Ro, 2013] Khoze, V. V. and Ro, G. (2013). Leptogenesis and Neutrino Oscillations in the Classically Conformal Standard Model with the Higgs Portal. JHEP, 1310:075.
22. [McDonald, 2011] McDonald, K. L. (2011). Light Neutrinos from a Mini-Seesaw Mechanism in Warped Space. Phys.Lett., B696:266-272.
23. [Merle and Niro, 2011] Merle, A. and Niro, V. (2011). Deriving Models for keV sterile Neutrino Dark Matter with the Froggatt-Nielsen mechanism. JCAP, 1107:023.
24. [Mitra et al., 2012] Mitra, M., Senjanovic, G., and Vissani, F. (2012). Heavy Sterile Neutrinos and Neutrinoless Double Beta Decay. Nucl. Phys. B856 (2012) 26.
25. [Pascoli et al., 2013] Pascoli, S., Mitra, M., and Wong, S. (2013). The Effect of Cancellation in Neutrinoless Double Beta Decay.
26. [Ruchayskiy and Ivashko, 2012] Ruchayskiy, O. and Ivashko, A. (2012). Restrictions on the lifetime of sterile neutrinos from primordial nucleosynthesis. JCAP, 1210:014.
27. [Terasawa et al., 1988] Terasawa, N., Kawasaki, M., and Sato, K. (1988). Radiative Decay of Neutrino and Primordial Nucleosynthesis. Nucl.Phys., B302:697-738.

Other BSM Physics

Non-official

- References

1. [Adams et al., 2001] NuTeV Collaboration (Adams, T., et al.). (2001). Observation of an anomalous number of dimuon events in a high-energy neutrino beam. Phys.Rev.Lett., 87:041801.
2. [Batell et al., 2009] Batell B., Pospelov M., Ritz A. (2009). Exploring Portals to a Hidden Sector Through Fixed Targets. Phys.Rev., D80:095024.
3. [Beranek and Vanderhaeghen, 2013] Beranek, T., Vanderhaeghen, M. (2013). Study of the discovery potential for hidden photon emission at future electron scattering fixed target experiments. e-Print: arXiv:1311.5104.
4. [Brignole et al., 1997] Brignole, A., Feruglio, F., Zwirner, F. (1997). Aspects of spontaneously broken N=1 global supersymmetry in the presence of gauge interactions. Nucl.Phys., B501:332-374.
5. [Borissov et al., 2000] Borissov, L., Conrad, J.M., Shaevitz, M. (2000). Searching for the lightest neutralino at fixed target experiments. arXiv: hep-ph/0007195.
6. [Dedes et al., 2001] Dedes, A., Dreiner H. K., Richardson P., (2001). Attempts at explaining the NuTeV observation of dimuon events. Phys.Rev., D65:015001.
7. [Dicus and Nandi, 1997] Dicus, D.A., Nandi., S. (1997). New collider bound on light gravitino mass. Phys.Rev., D56:4166-4169.
8. [Dicus et al., 1991] Dicus, D.A., Nandi., S., Woodside, J. (1991). Unusual Z0 decays in supersymmetry with a superlight gravitino. Phys.Rev., D43:2951-2955.
9. [Dreiner et al., 2009] Dreiner, H.K., Grab, S., Koschade, D., Kramer, M., O'Leary, B., Langenfeld U. (2009). Rare meson decays into very light neutralinos. Phys.Rev., D80:035018.
10. [Gorbunov, 2001] Gorbunov, D.S. (2001). Light sgoldstino: Precision measurements versus collider searches. Nucl.Phys., B602:213-237.
11. [Gorbunov and Krasnikov, 2002] Gorbunov, D.S., Krasnikov, N.V. (2002). Prospects for sgoldstino search at the LHC. JHEP, 0207:043.
12. [Gorbunov and Rubakov, 2006] Gorbunov, D.S., Rubakov, V.A. (2006). On sgoldstino interpretation of HyperCP events. Phys.Rev., D73:035002.
13. [LHCb: Aaij et al., 2013] LHCb: Aaij et al., (2013) Search for rare B0(s) ! μ+μ−μ+μ− decays Phys.Rev.Lett. 110:211801. On sgoldstino interpretation of HyperCP events. Phys.Rev., D73:035002

Other BSM Physics

Non-official

14. [Perrazi et al., 2000a] Perazzi, E., Ridolfi, G., Zwirner, F. (2000). Signatures of massive sgoldstinos at e+ e- colliders. Nucl.Phys., B574:3-22.
15. [Perrazi et al., 2000b] Perazzi, E., Ridolfi, G., Zwirner, F. (2000). Signatures of massive sgoldstinos at hadron colliders. Nucl.Phys., B590:287-305.
16. [Pospelov et al., 2008] Pospelov, M., Ritz, A., Voloshin M.B. (2008). Secluded WIMP Dark Matter. Phys.Lett., B662:53-61.