SHiP
Search for Hidden Particles

An Experiment to Search for Hidden Particles at the SPS

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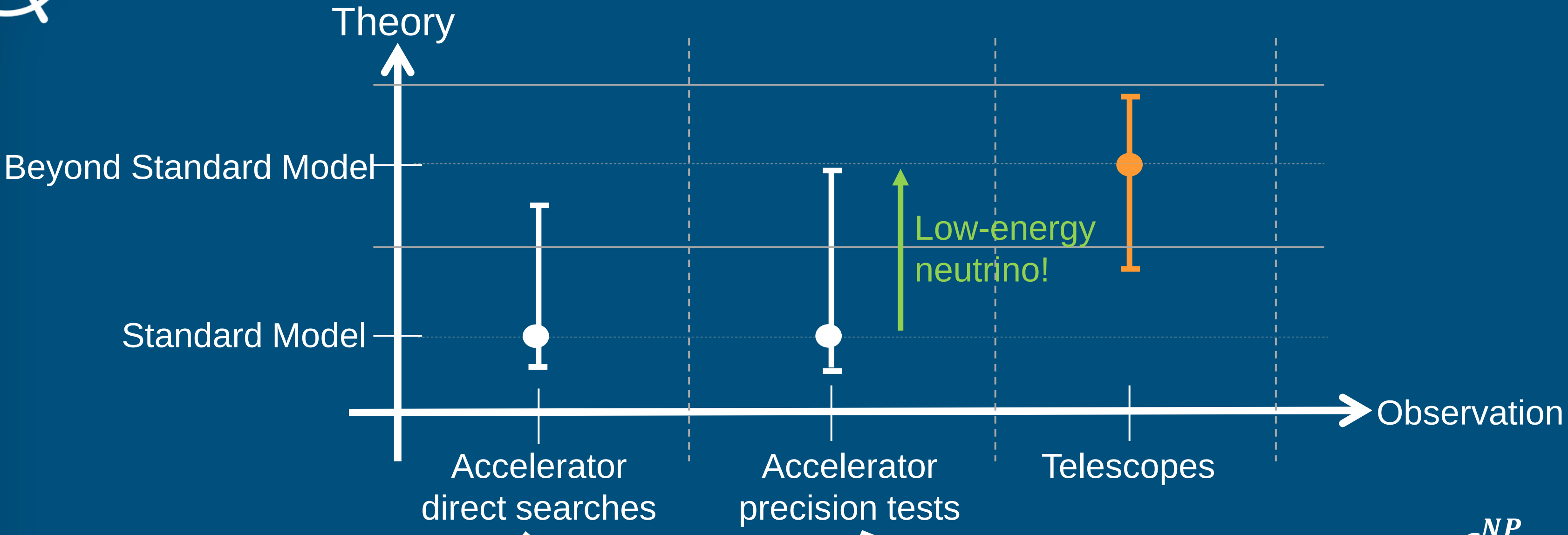
on behalf of the SHiP Collaboration

Discovery Physics at the LHC Era, Kruger, South Africa, December 1 - 6, 2014

Physics Scenario after LHC Run 1



Theory

Beyond Standard Model

Standard Model

Low-energy neutrino!

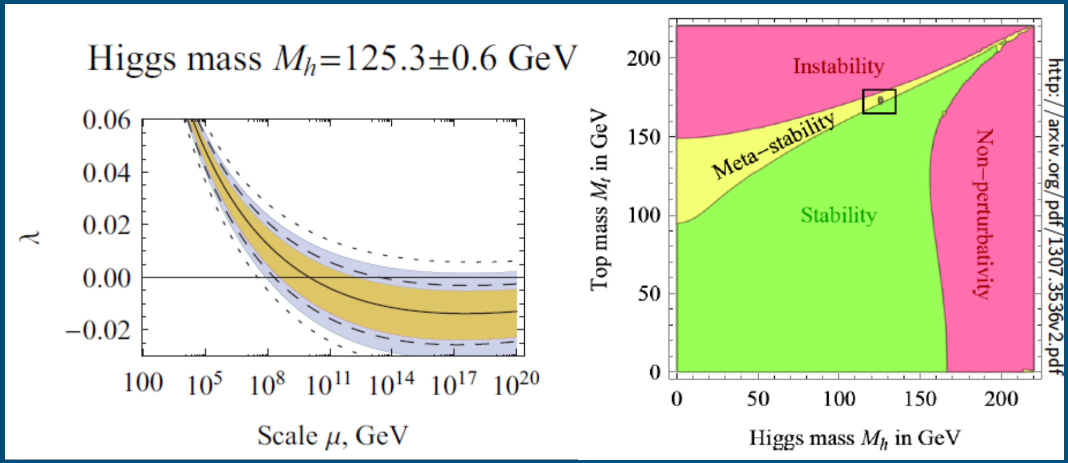
Observation

Accelerator direct searches

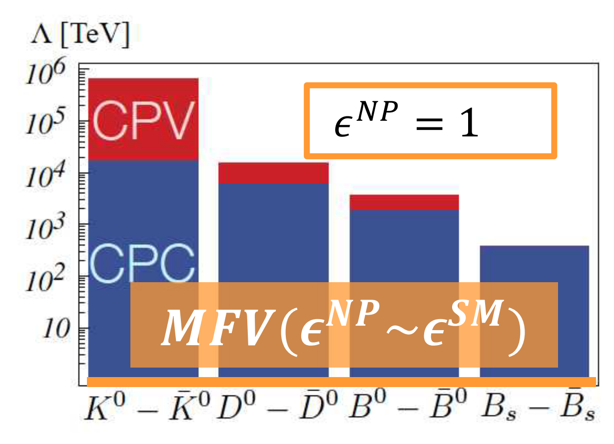
Accelerator precision tests

Telescopes

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta C\left[\frac{\epsilon^{NP}}{\Lambda^2_{NP}}\right]$$



arXiv:0906.0954



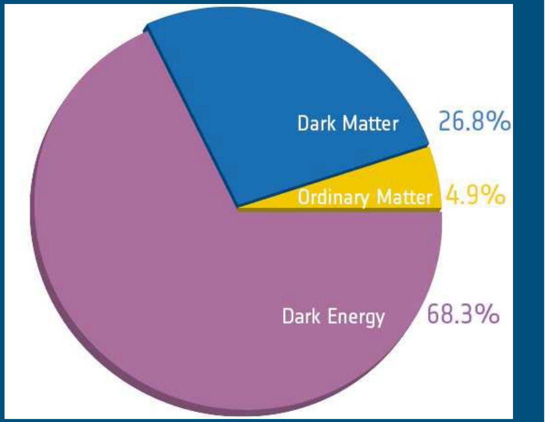
- No tangible evidence for the scale of the new physics!

Physics Situation after LHC Run 1

- *With a mass of the Higgs boson of 125 − 126 GeV, the Standard Model may be 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!?

Experimental evidence for New Physics

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 and Inflation



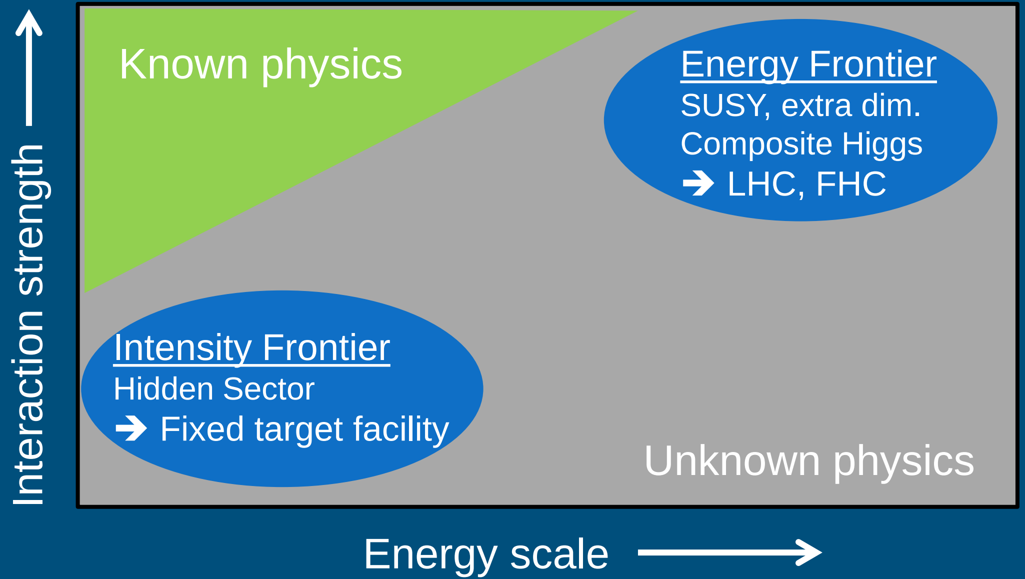
Theoretical “evidence” for New Physics

1. Hierarchy problem and stability of Higgs mass
2. SM flavour structure
3. Strong CP problem
4. Unification of coupling constants
5. Gravity
6. ….

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

What if...?

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



Known physics

Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC

Intensity Frontier
Hidden Sector
➔ Fixed target facility

Unknown physics

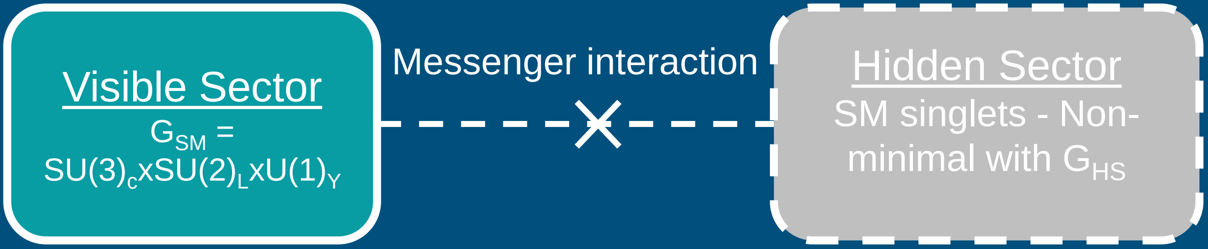
Interaction strength ⟶

Energy scale ⟶

➔Must have very weak couplings ➔ Hidden Sector (Not the first time! Cmp. neutrino)

Hidden Sector Exploration

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



Visible Sector

$G_{SM} = SU(3)_c x SU(2)_L x U(1)_Y$

Messenger interaction

Hidden Sector

SM singlets - Non-minimal with G_{HS}

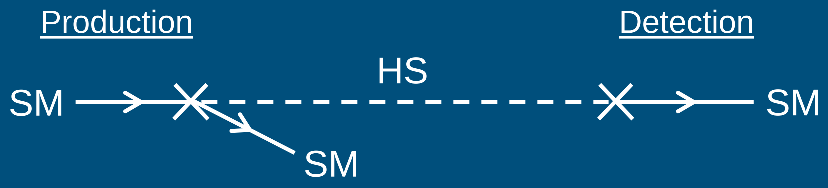
- New light hidden particles are singlet under the SM gauge group
- Composite operators (hoping there is not just gravity…)

$$\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)} \mathcal{O}_{SM}^{(l)}}{\Lambda^n}$$

- Lowest dimension SM operator makes up “portals” to the Hidden Sector

➔ *Dynamics of Hidden Sector may drive dynamics of Visible Sector!*

1. “Indirect detection” through portals in (missing mass)
2. “Direct detection” through both portals in and out



New Physics prospects in Hidden Sector

- Standard Model portals:
  - **D = 2: Vector portal**
    - Kinetic mixing with massive dark/secluded/paraphoton V : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$

    ➔ Interaction with 'mirror world' constituting dark matter

  - **D = 2: Higgs portal**
    - Mass mixing with dark singlet scalar χ : $(\mu\chi + \lambda\chi^2)H^\dagger H$

    $$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

    ➔ Mass to Higgs boson and right-handed neutrino, and function as inflaton in accordance with Planck and BICEP measurements

  - **D = 5/2: Neutrino portal**
    - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $YH^\dagger \bar{N}L$

    ➔ Neutrino oscillation, baryon asymmetry, dark matter

  - **D = 4: Axion portal**
    - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

    ➔ Solve strong CP problem, Inflaton

  - And possiby higher dimensional operator portals and **SUper-SYmmetric portals** (light neutralino, light sgoldstino,…)

    ➔ SUSY parameter space explored by LHC

    ➔ Some of SUSY low-energy parameter space open to complementary searches

HS Common experimental features

- Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
  - ➔ Production through meson decays (π, K, D, B), proton bremsstrahlung,…
  - ➔ Decay to l^+l^-, $\pi^+\pi^-, l\pi$, $l\rho$, $\gamma\gamma$, etc (and modes including neutrino)
  - ➔ Full reconstruction and particle ID aim at maximizing the model independence

- Production and decay rates are very suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects
  - Travel unperturbed through *ordinary* matter
  - ➔ Challenge is background suppression

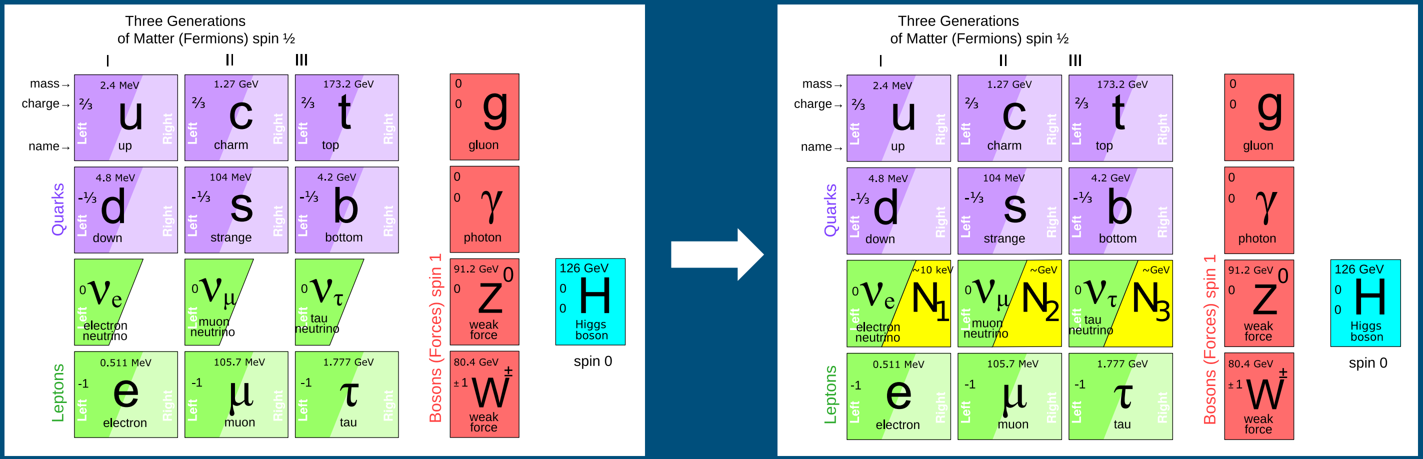
➔ Fixed-target (“beam-dump”) experiment

- ➔ Large number of protons on target and large decay volume!

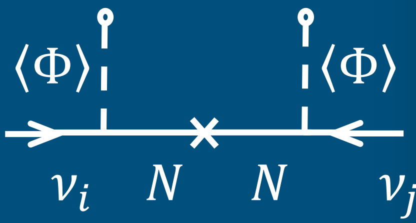
➔ Complementary physics program to searches for new physics by LHC!

➔ *For development of experimental facility, initial detector concept, and sensitivity studies: neutrino portal and the vector portal used*

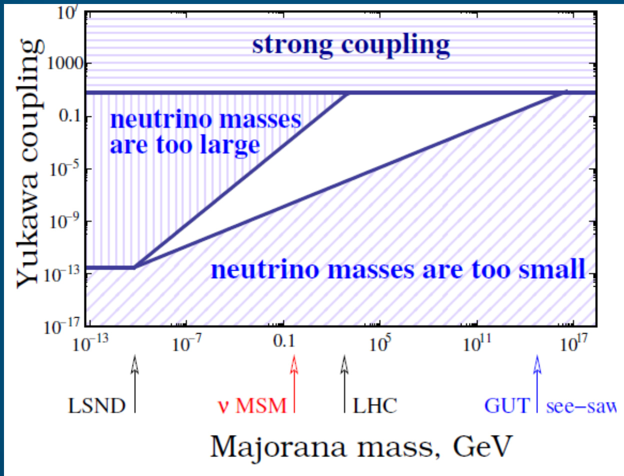
Ex. “Neutral Fermion” Portal - Ockham’s Razor

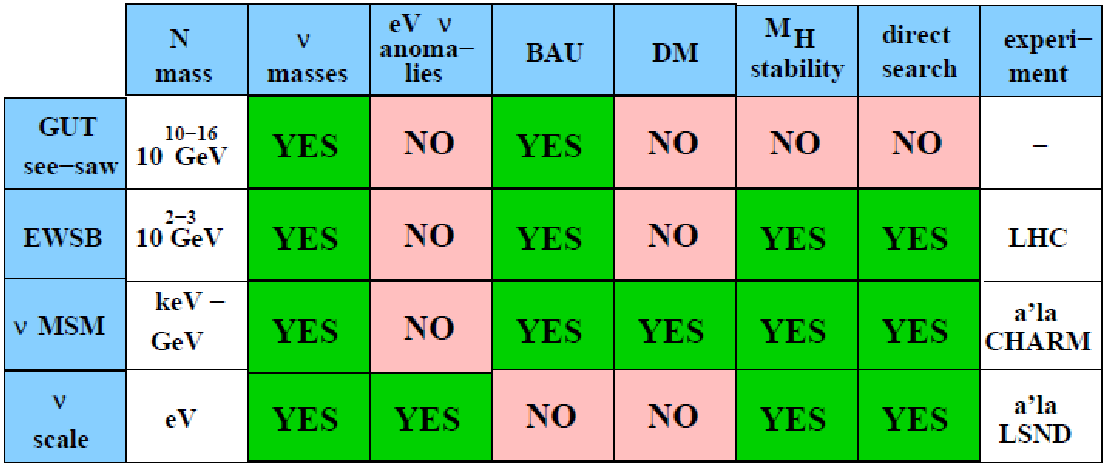


- $Y_{I\ell}H^{\dagger}\bar{N}_I L_\ell$ lepton flavour violating term results in mixing between N_I and SM active neutrinos when the Higgs SSB develops the $< VEV > = v \sim 246\ GeV$
  - ➔ Oscillations in the mass-basis and CP violation
  - ➔ Type I See-Saw with $m^R >> m_D (= Y_{I\ell}v)$



- Four “popular” N mass ranges:





	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a’la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a’la LSND

arXiv:1204.5379

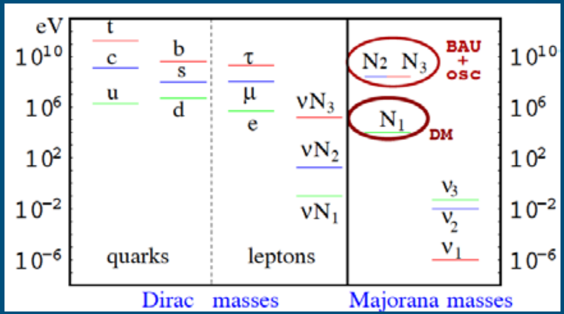
Just one example: HNLs in νMSM (Asaka, Shaposhnikov)

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

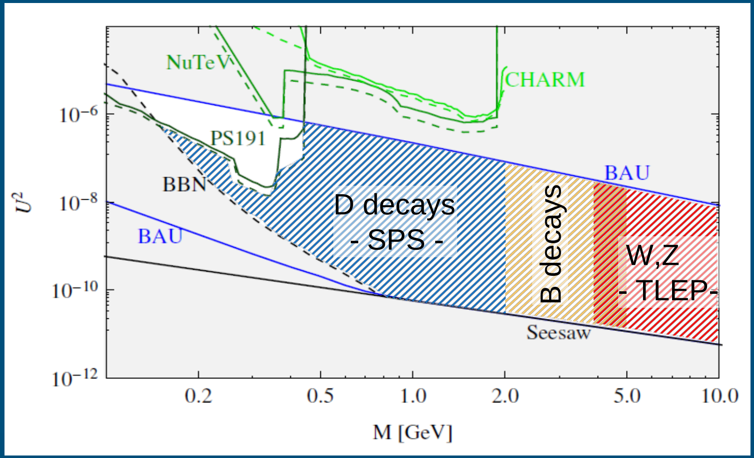
Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU

➔ Assumption that N_I are $\mathcal{O}(m_q/m_l)$: No new energy scale!

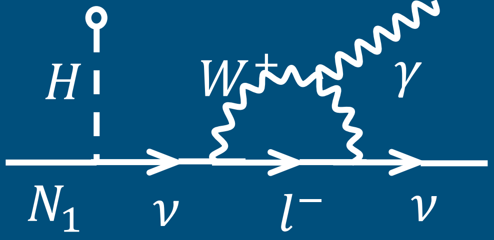
- $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\ GeV, m_\nu = 0.05\ eV)$
- $\mathcal{U}^2 \sim 10^{-11}$ ➔ Intensity Frontier!



Current limits on N_2 and N_3



N_1 Subdominant radiative decay

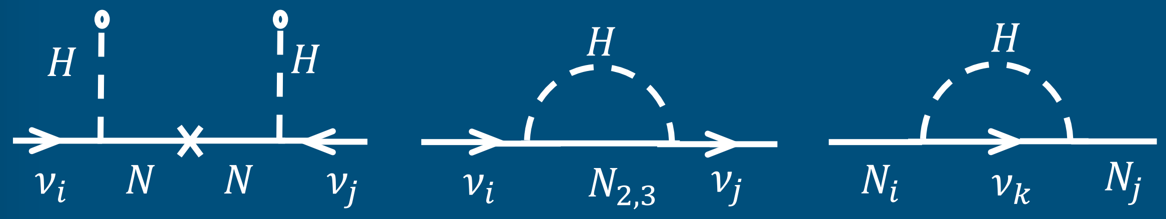


$$E_\gamma = \frac{M_{N_1} c^2}{2}$$

N_2 and N_3 in νMSM

- 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 with 3 CP violating phases
      - ➔ Two mixing angles related to active neutrinos and mass difference measured in low-energy neutrino experiment

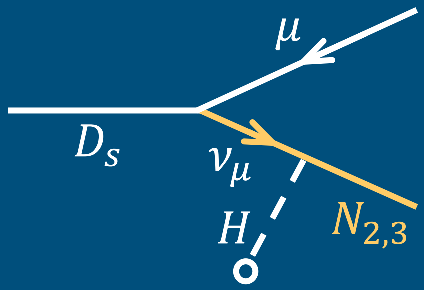
- Generation of BAU with degenerate N_2 and N_3 (Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov)
  1. Leptogenesis from coherent resonant oscillations with interference between CP violating amplitudes
     - ➔ Two fermion singlets should be quasi-degenerate
  2. Out of equilibrium ($\Gamma_{N_{2,3}}$ < Hubble rate of expansion) at the E.W. scale above 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

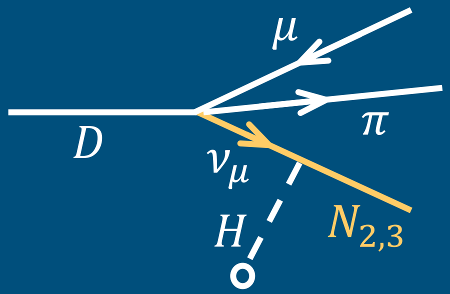


Production and decay in νMSM

- **Production:** Mixing with active neutrino from leptonic/semi-leptonic weak decays of mesons

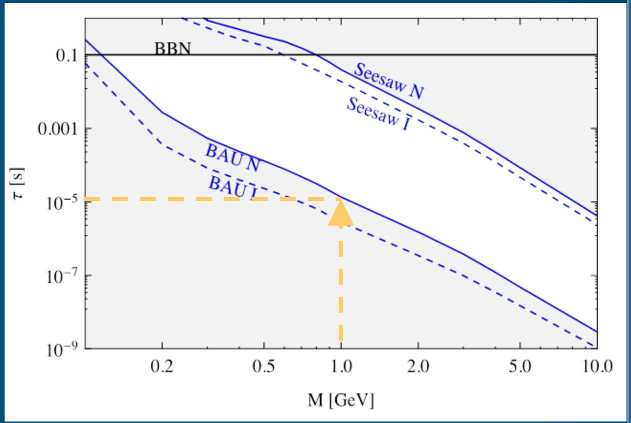
E.g.





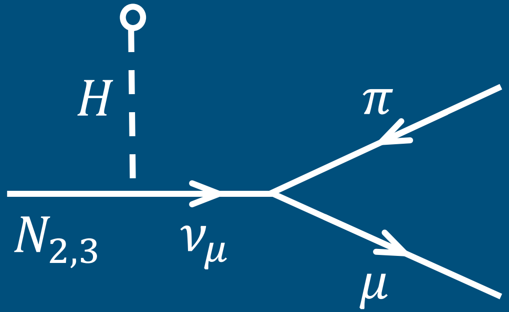
$$\mathcal{U}_\mu{}^2 = \sum_{I=2,3} \frac{v^2 |Y_{\mu I}|^2}{m_I^{R\,2}}$$

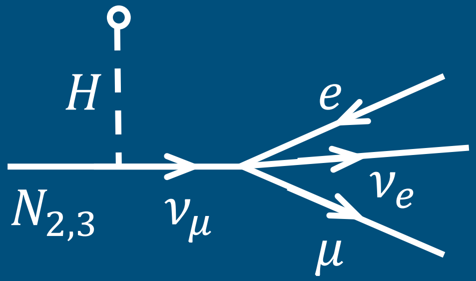
$$\mathrm{Br}(D \to NX) \sim 10^{-8} - 10^{-12}$$



- **Decay:** Very weak HNL-active neutrino mixing
  - → $N_{2,3}$ much longer lived than SM particles
  - ➔ $N \to \mu e\nu, \pi^0\nu, \pi e, \mu\mu\nu, \pi\mu, Ke, K\mu, \eta\nu, \eta'\nu, \rho\nu, \rho e, \rho\mu, \ldots$
  - ➔ Typical lifetimes > 10 μs for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$

E.g.



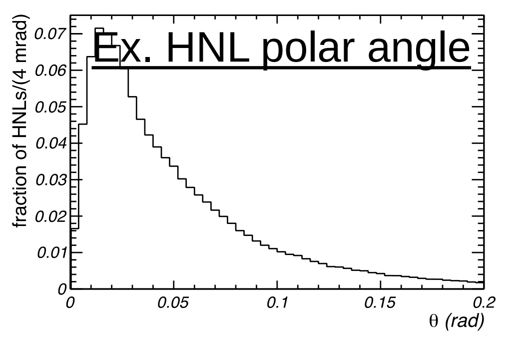


Decay mode	Branching ratio
$N_{2,3} \to \mu/e + \pi$	*0.1 - 50 %*
$N_{2,3} \to \mu^-/e^- + \rho^+$	*0.5 - 20 %*
$N_{2,3} \to \nu + \mu + e$	*1 - 10 %*

Experimental Requirements/Challenges

Proposal: ***fixed-target (beam dump like) experiment at the SPS***

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


Ex. HNL polar angle

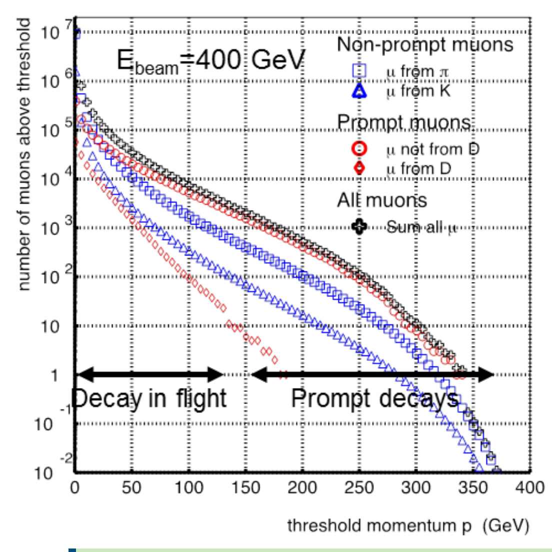
➔ Defines the list of critical parameters and layout for the sensitivity of the experiment

➔ Incompatible with conventional neutrino facility

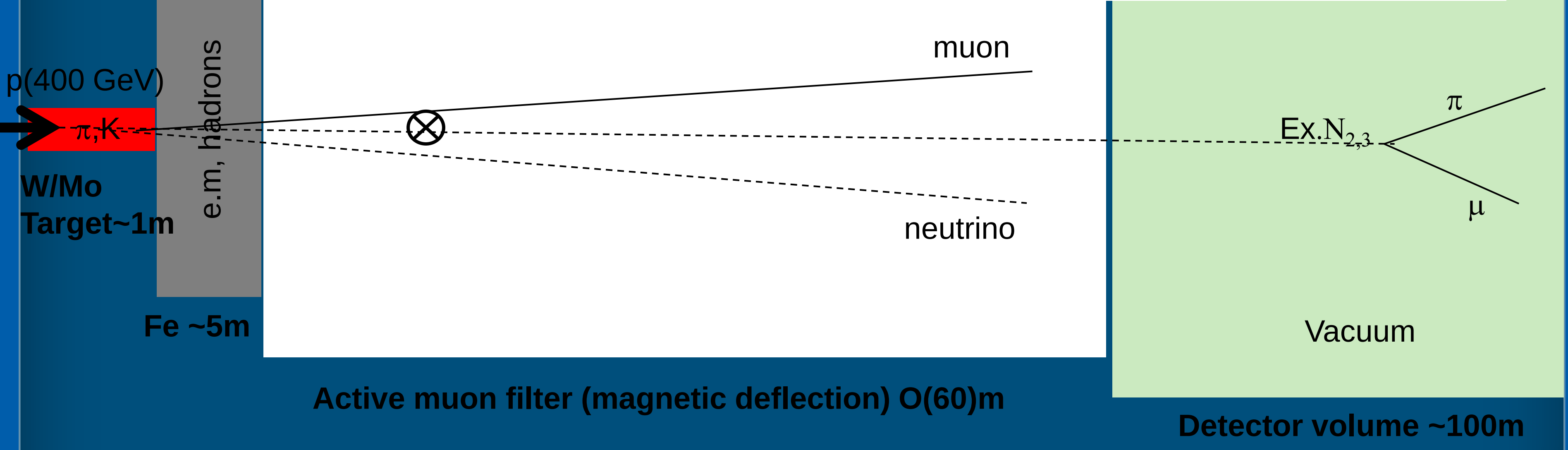
➔ But a very powerful general-purpose facility for now and later!

Schematic Principle of Experimental Setup

- Initial reduction of beam induced background:
  - Heavy target
  - Hadron absorber
  - Muon filter (Without: Rate at detector 5×10^9 muons / 5×10^{13} p.o.t.)



Generic setup, not to scale!



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

Schematic Principle of Experimental Setup

- Residual backgrounds:
  1. Neutrinos scattering (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$) ➔ Detector under vacuum, accompanying charged particles (timing), topological
  2. Muon inelastic scattering ➔ Accompanying charged particles (timing), topological
  3. Muon combinatorial (e.g. $\mu\mu$ with μ mis-ID)➔ Tagging, timing and topological

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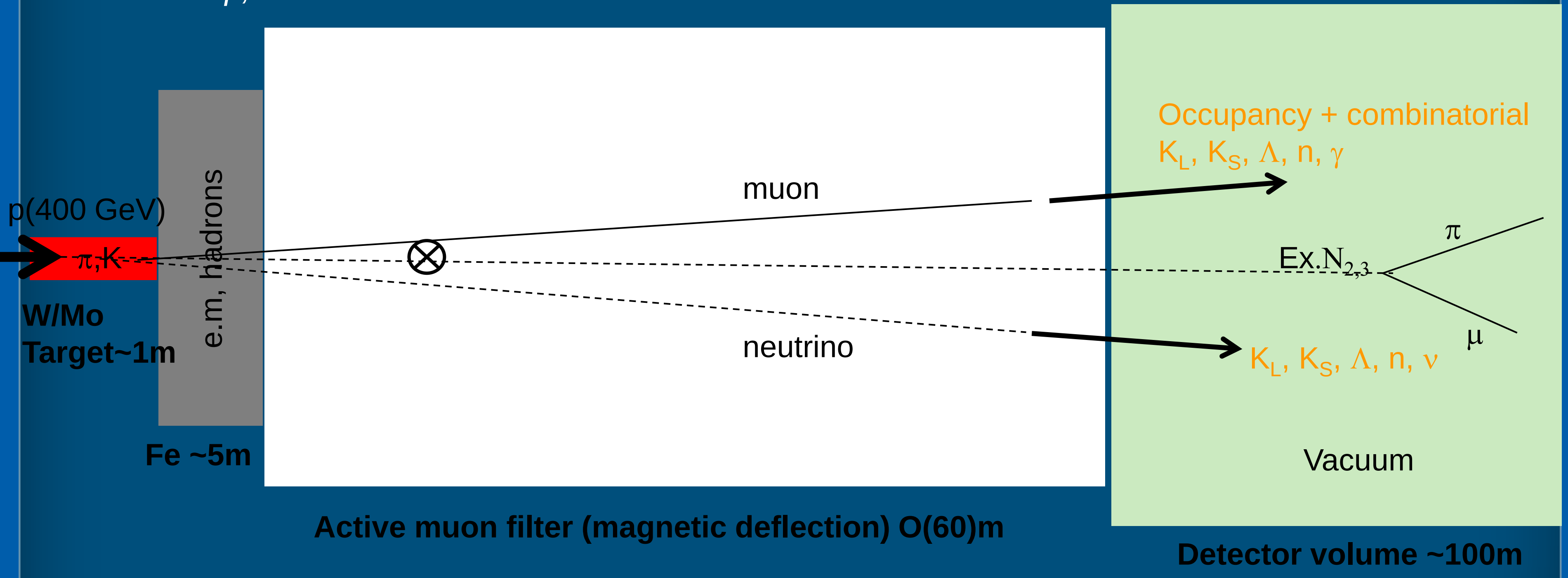

Crucial to study background in detailed simulation with full detector description

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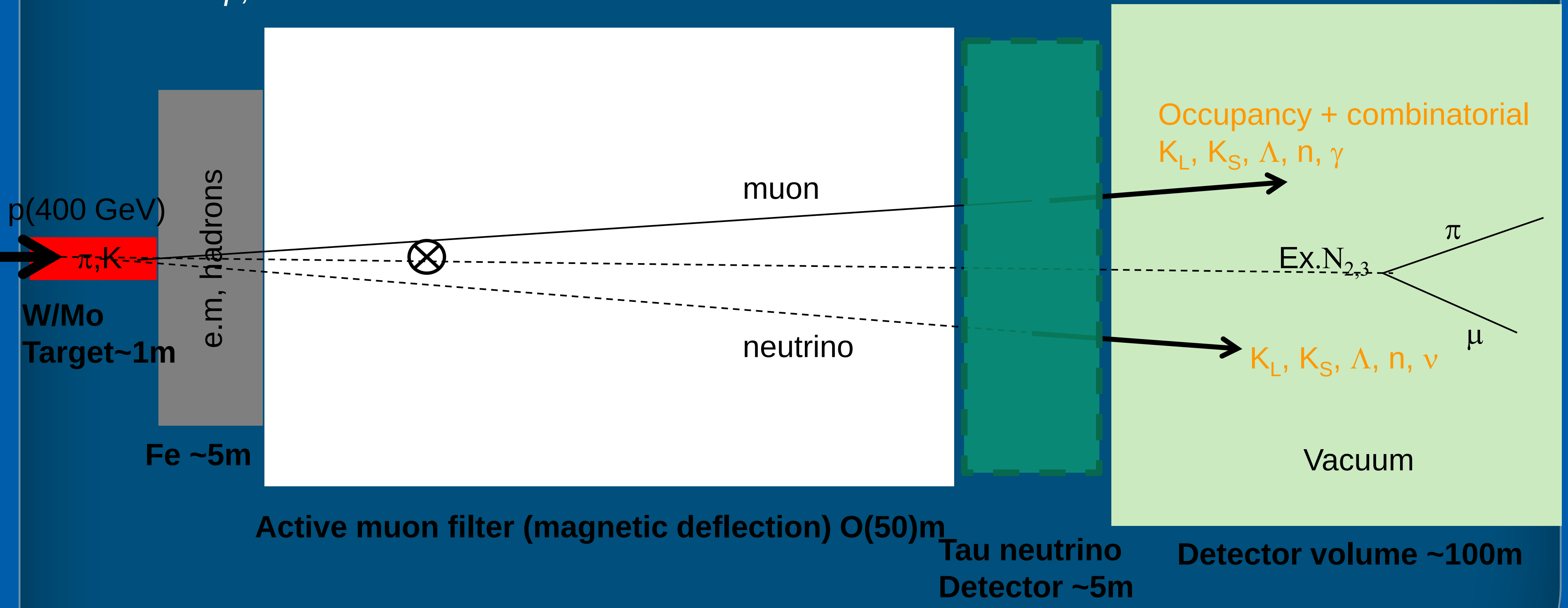


p(400 GeV)

π,K

W/Mo Target~1m

e.m, hadrons

Fe ~5m

muon

neutrino

Active muon filter (magnetic deflection) O(50)m

Tau neutrino Detector ~5m

Occupancy + combinatorial

K_L, K_S, Λ, n, γ

Ex.$N_{2,3}$

π

μ

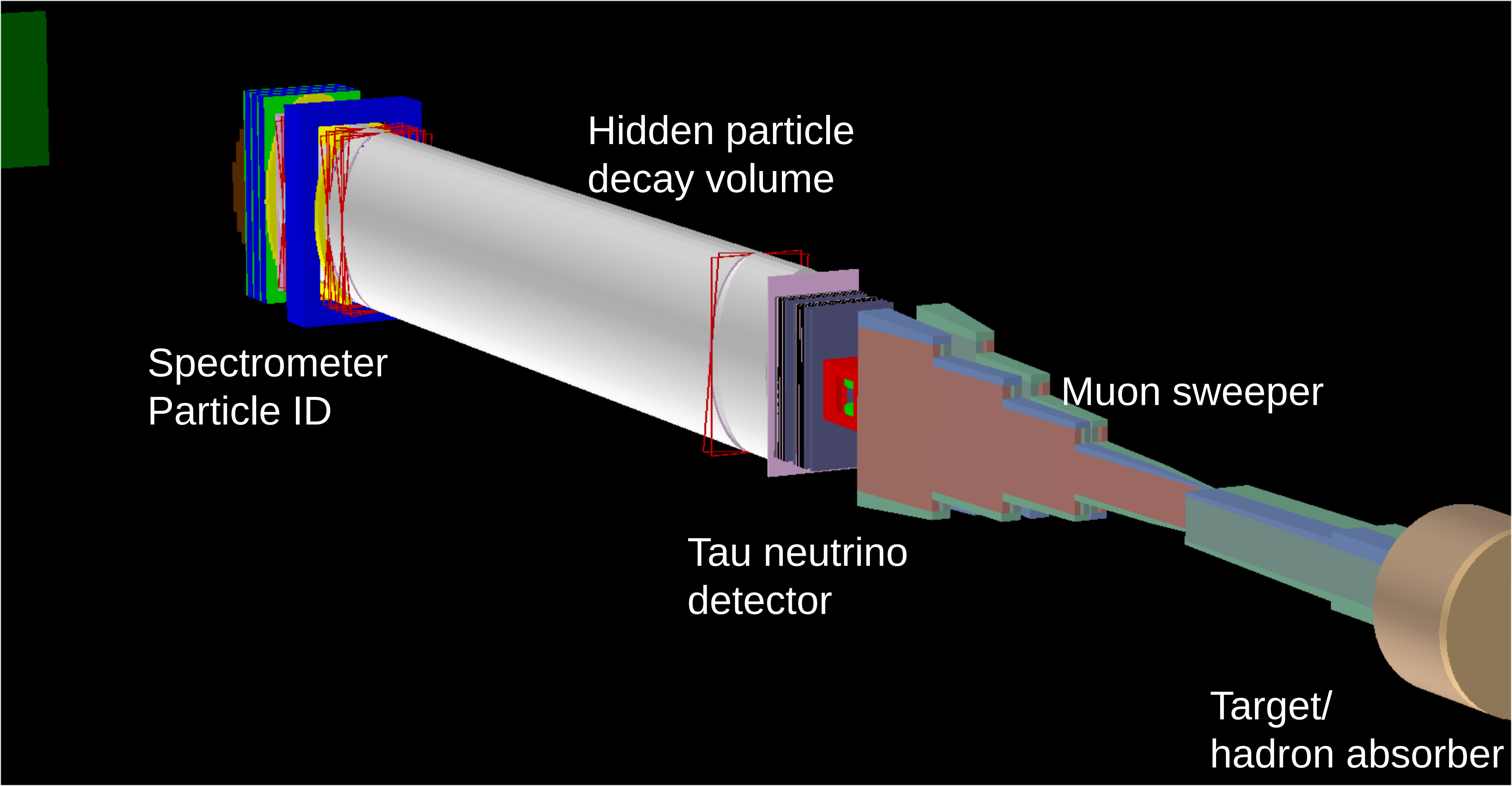
K_L, K_S, Λ, n, ν

Vacuum

Detector volume ~100m

Muon flux limit driven by emulsion based tau neutrino detector and “hidden particle” background

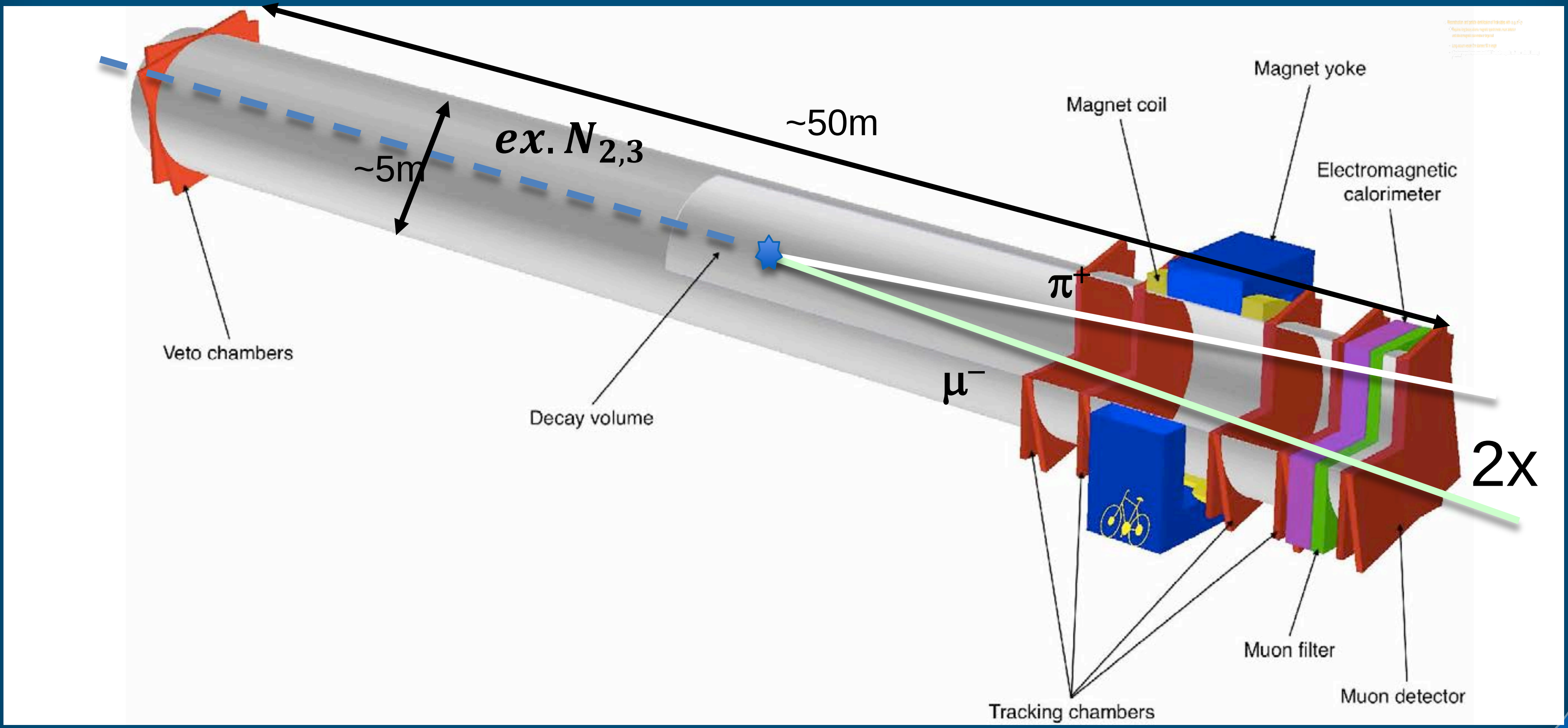
Experimental setup



Initial Detector Concept for EOI

- Reconstruction and particle identification of final states with e, $\mu, \pi^{\pm}, \gamma$
  - ➔ Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter in large hall

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



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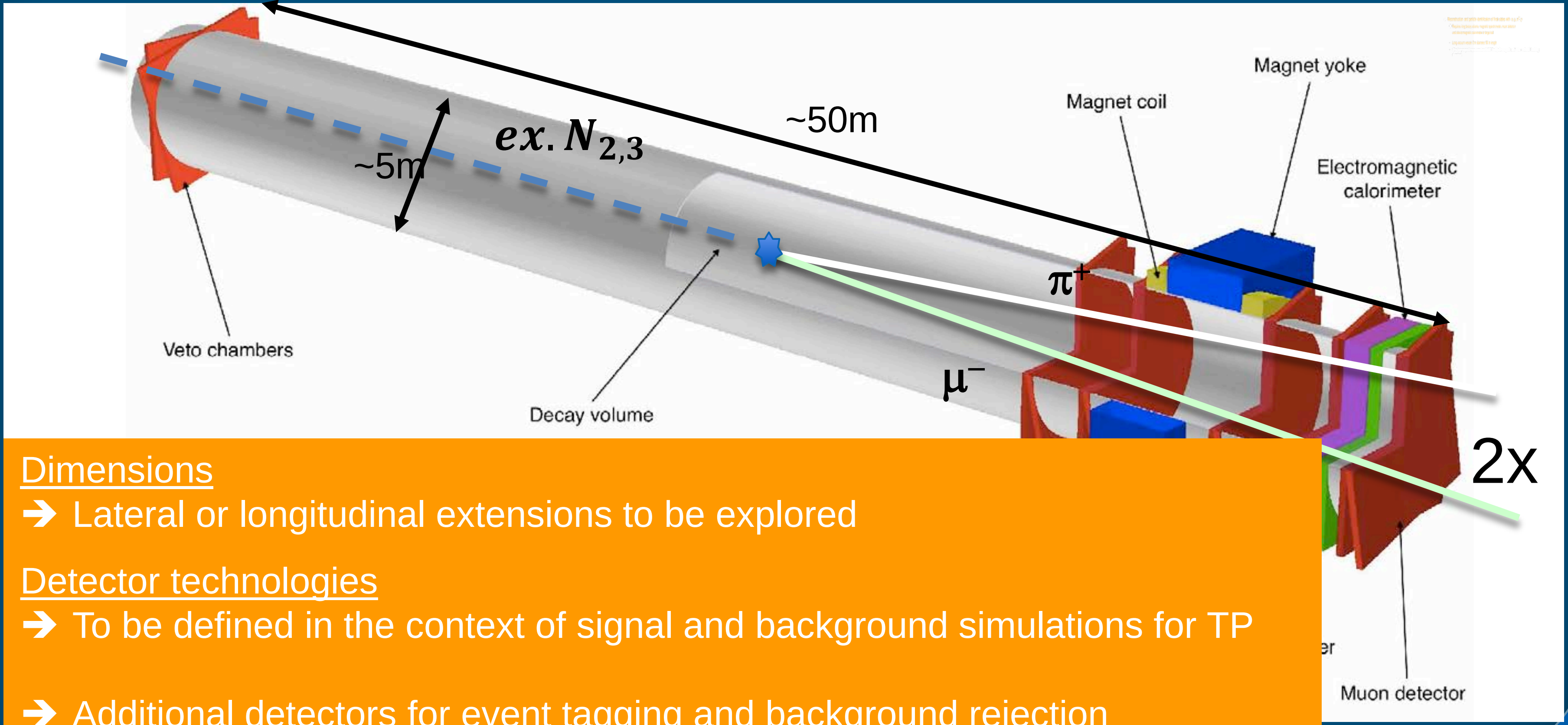
- Long vacuum vessel, 5 m diameter, 50 m length
- 10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers



Dimensions

➔ Lateral or longitudinal extensions to be explored

Detector technologies

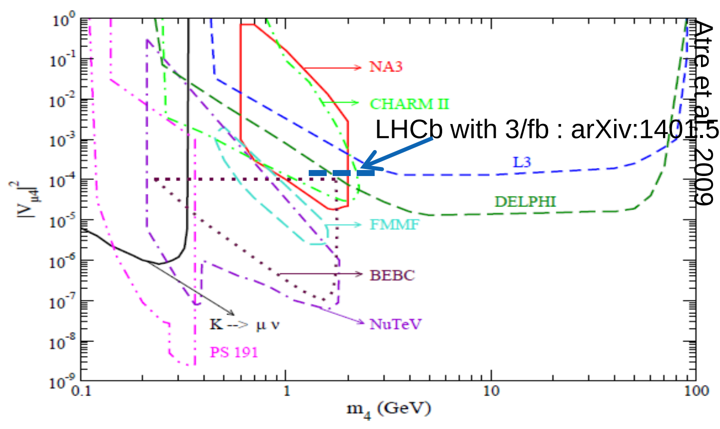
➔ To be defined in the context of signal and background simulations for TP

➔ Additional detectors for event tagging and background rejection

Example of estimates of HNL sensitivity

- Colliders out of luck with low mass / long lifetimes
  - LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1}, i.e. 3-4 years: ~ 2x10^{16} D's in 4π
  - SPS@400 ($\sqrt{s}$ = 27 GeV) with 2x10^{20} pot, i.e. ~5 years: ~ 2x10^{17} D's
  - BELLE-2 using $B \to XlN$, where $N \to l\pi$ and X reconstructed using missing mass may go well below 10^{-4} in 0.5<M_N<5 GeV

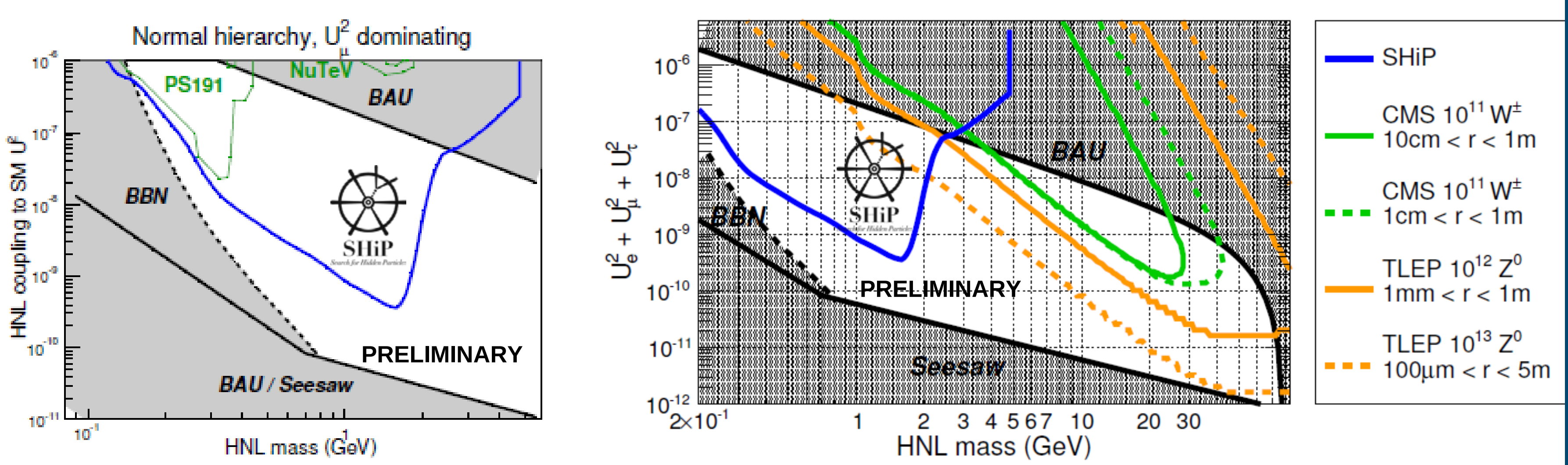
Summary of past Searches for N_I



LHCb with 3/fb : arXiv:1401.5361

Atre et al. 2009

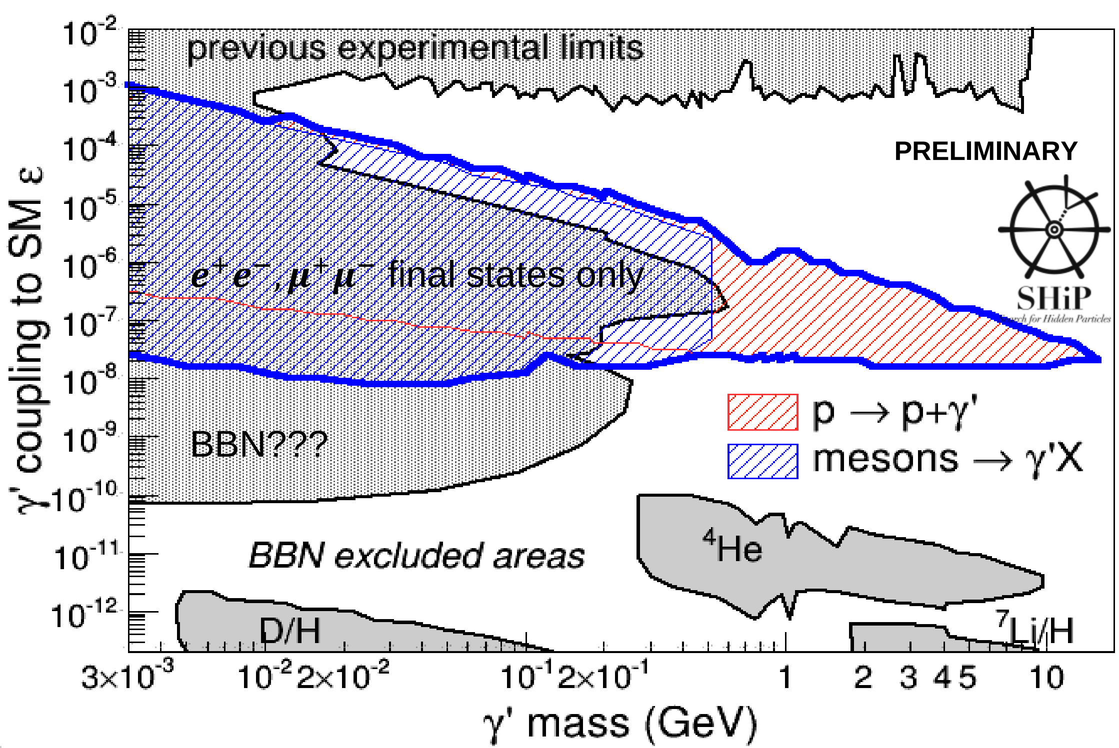
- SHiP sensitivity based on current SPS with 2x10^{20} p.o.t at 400 GeV in ~5 years of nominal CNGS-like operation

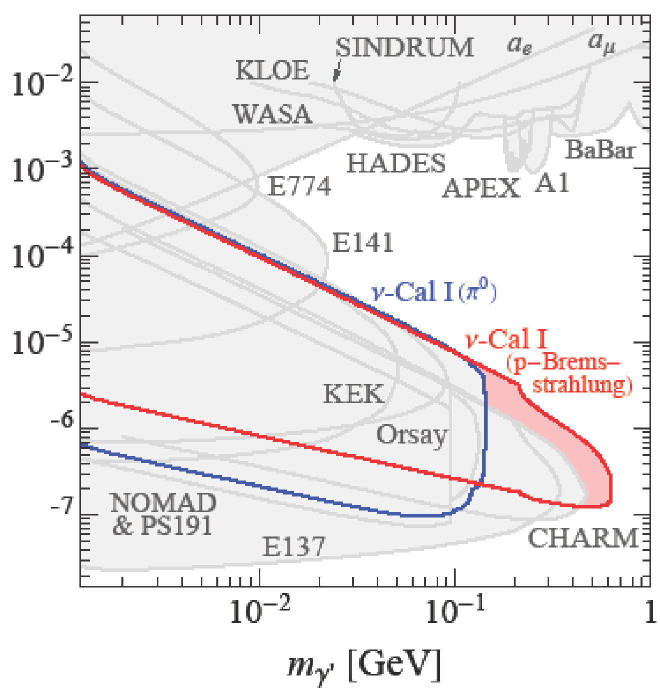


- W ➔ ℓN at LHC: extremely large BG, difficult triggering/analysis.
- Z ➔ Nν at e^+e^- collider [M. Bicer et al. 2013]: clean

Ex. Expected sensitivity to Dark Photons

- Predominant dark photon production at SPS
  - Proton bremsstrahlung
  - Pseudo-scalar meson decays ($\pi^0, \eta,\ \omega,\ \eta', \dots$)
  - Lifetime limit from BBN: $\tau_\gamma < 0.1s$
- Dark photon decays
  - $e^+e^-, \mu^+\mu^-, q\bar{q}\ (\pi^+\pi^-, \dots), \dots$

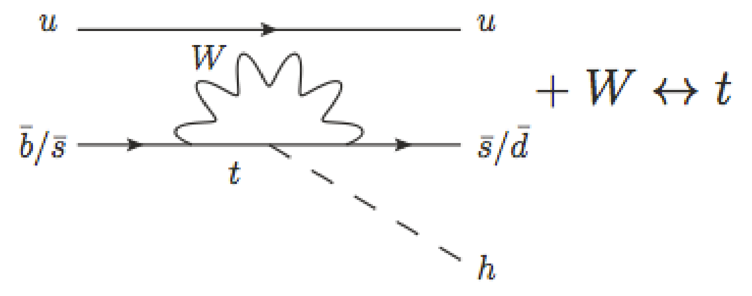


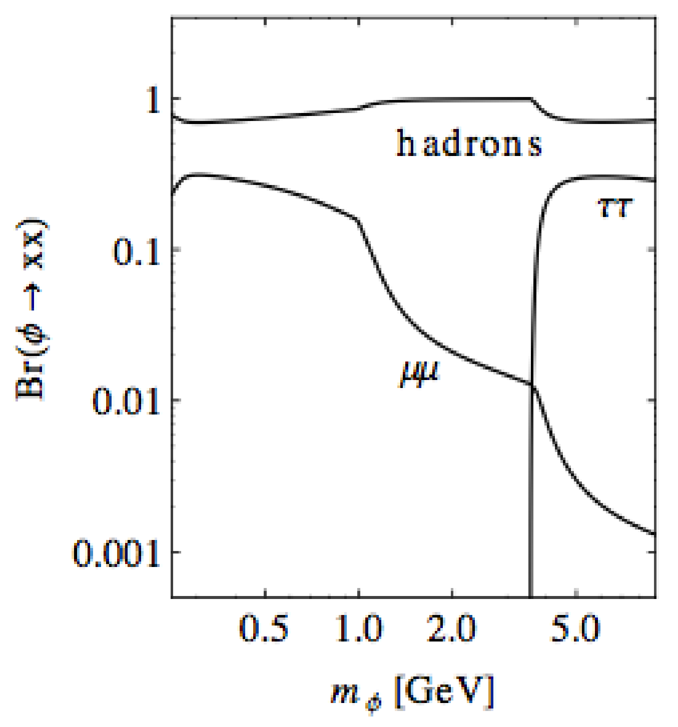


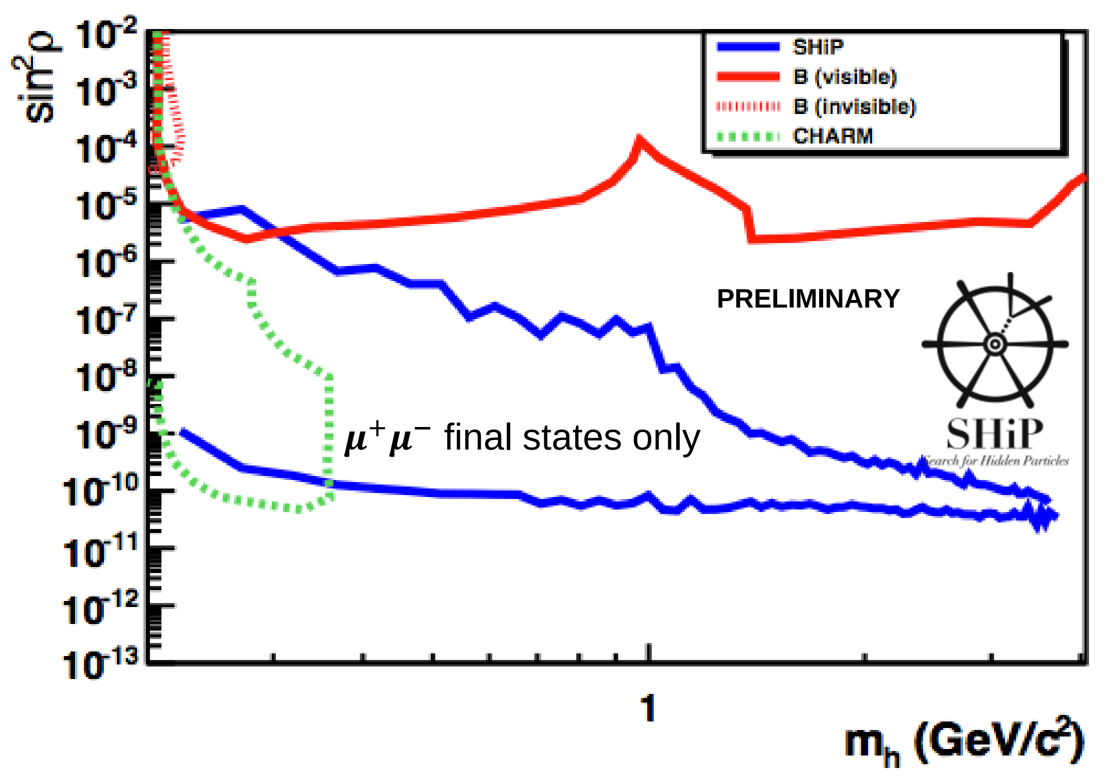
arXiv:1311.3870

Ex. Sensitivity to light scalar

- Production via meson decay

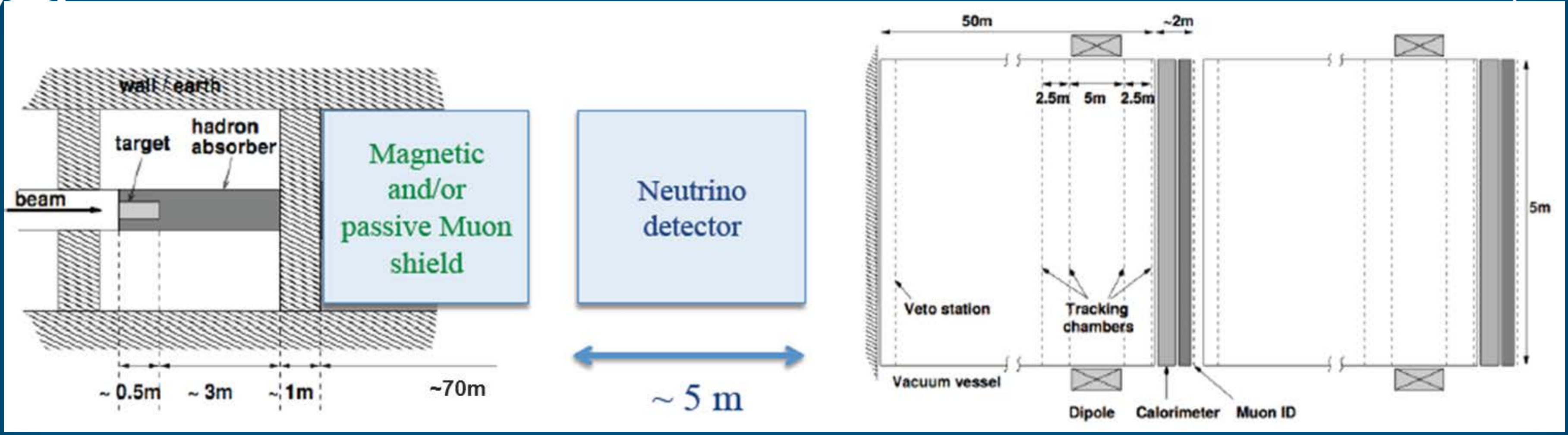






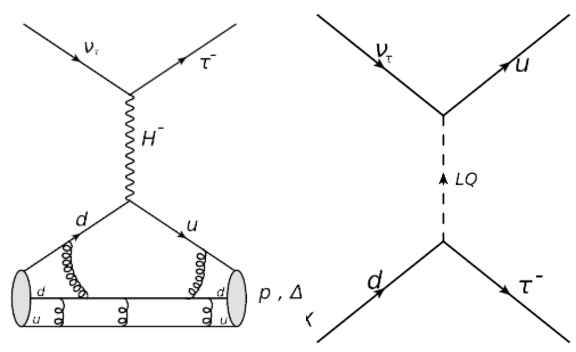
$\mu^+\mu^-$ final states only

++ SM Physics: Prospects for ν_τ



- Expecting $\mathcal{O}(3500)$ $\nu_\tau/\overline{\nu_\tau}$ interactions in 6 tons of emulsion target
  - Tau neutrino and anti-neutrino physics

- Charm physics with neutrinos and anti-neutrinos
  - ➔ ν_μ- induced charm production: 11 000 events(2000 in CHORUS)
  - ➔ $\overline{\nu_\mu}$ - induced charm production: 3500 events (32 events in CHORUS)
  - Electron neutrino studies (high energy cross-section and ν_e induced charm production ~ 2 x ν_μ induced)
    - **➔ Normalization for hidden particle search!**



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

CERN Task force

Initiated by CERN Management after SPSC encouragement in January 2014

Detailed investigation

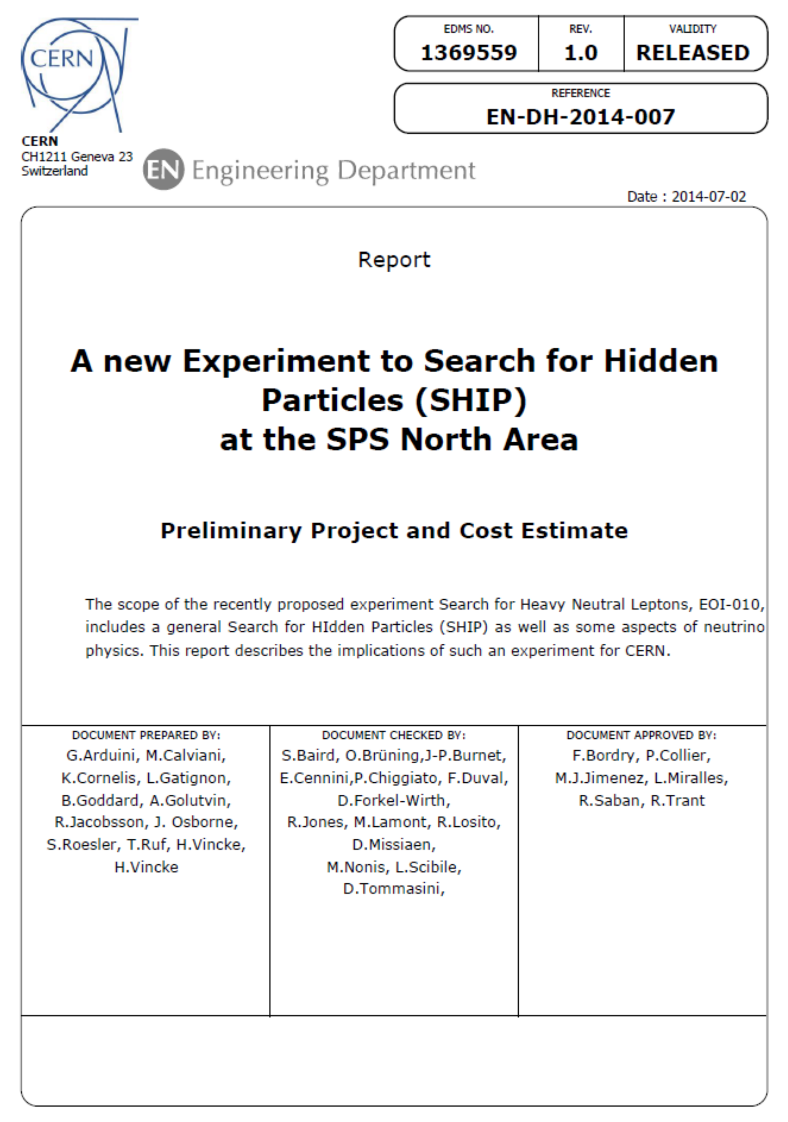
- Physics motivation and requirements
- Experimental Area
- SPS configuration and beam time
- SPS beam extraction and delivery
- Target station
- Civil engineering
- Radioprotection

➔ Aimed at overall feasibility, identifying options/issues, resource estimate

➔ Document completed with 80 pages on July 2

➔ Detailed cost, manpower and schedule

➔ Compatible with commissioning runs in 2022, data taking 2023



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CERN
CH1211 Geneva 23
Switzerland

Engineering Department

Date : 2014-07-02

Report

A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

Preliminary Project and Cost Estimate

The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

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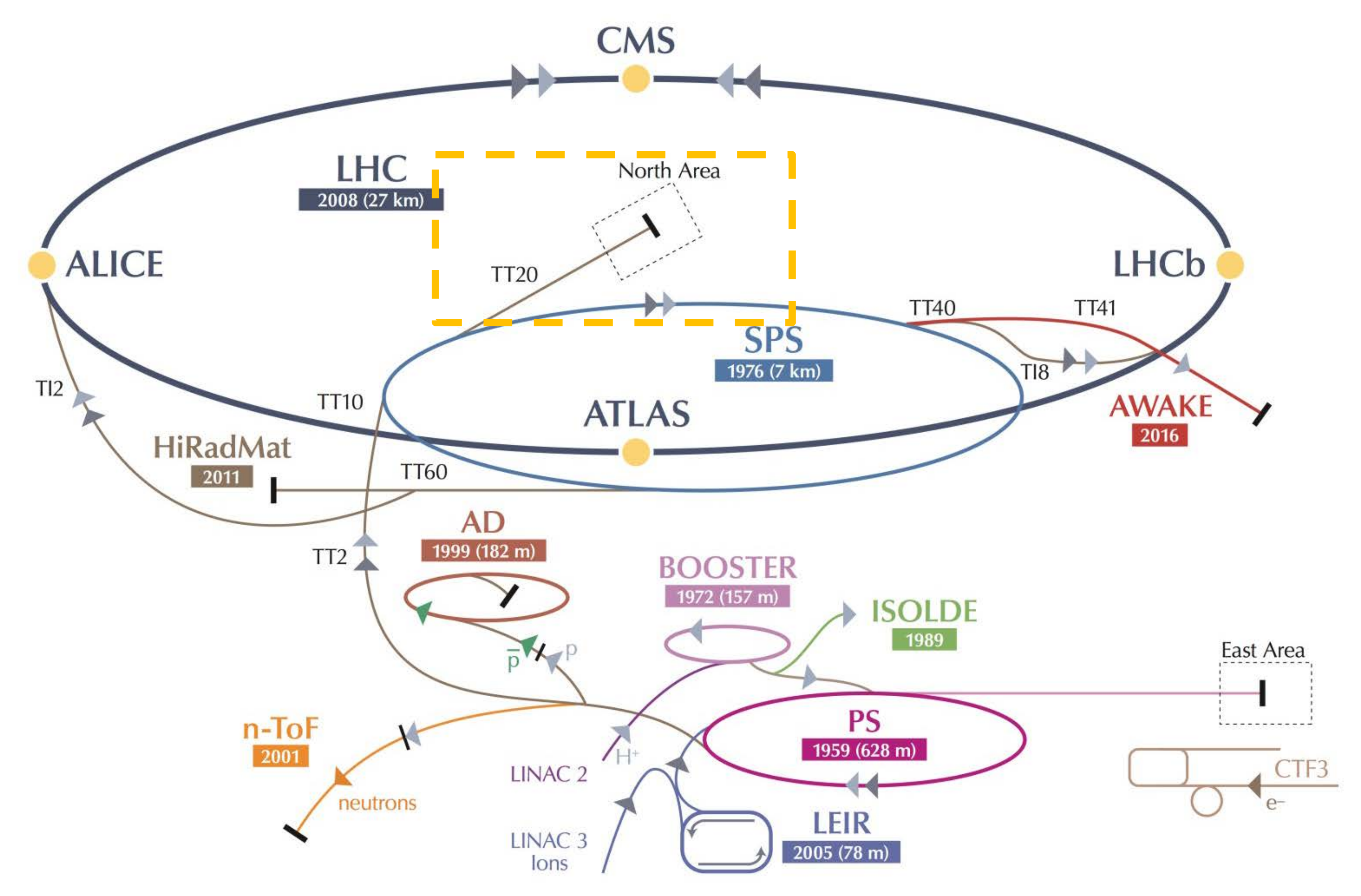
CERN Accelerator Complex

- Proposed location by CERN beams and support departments

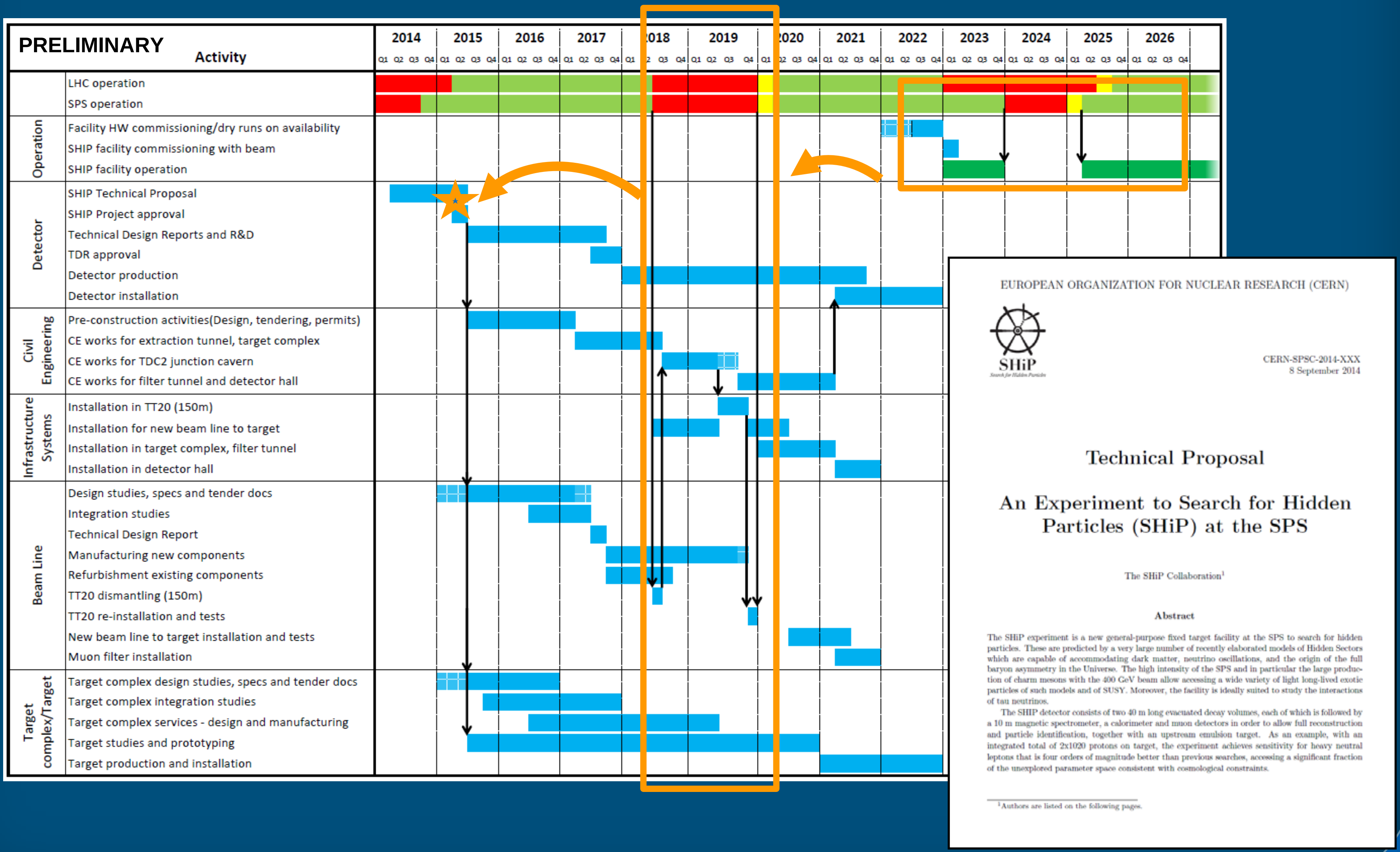


Prevessin North Area site

- From task force report:

Schedule and Technical Proposal

- Aim full force at submitting TP at beginning April 2015
  - Design of facility must start next summer (CE, beam, target, infra)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2014-XXX
8 September 2014

Technical Proposal

An Experiment to Search for Hidden Particles (SHiP) at the SPS

The SHiP Collaboration[1]

Abstract

The SHiP experiment is a new general-purpose fixed target facility at the SPS to search for hidden particles. These are predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The high intensity of the SPS and in particular the large production of charm mesons with the 400 GeV beam allow accessing a wide variety of light long-lived exotic particles of such models and of SUSY. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

The SHIP detector consists of two 40 m long evacuated decay volumes, each of which is followed by a 10 m magnetic spectrometer, a calorimeter and muon detectors in order to allow full reconstruction and particle identification, together with an upstream emulsion target. As an example, with an integrated total of 2x1020 protons on target, the experiment achieves sensitivity for heavy neutral leptons that is four orders of magnitude better than previous searches, accessing a significant fraction of the unexplored parameter space consistent with cosmological constraints.

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[1] Authors are listed on the following pages.

Conclusion

- Proposed GP experiment for HS exploration in largely unexplored domain
  - Very much increased interested for Hidden Sector after LHC Run 1
  - A very significant physics reach beyond past/current experiments in the cosmologically interesting region
  - Also unique opportunity for ν_τ physics

- Work towards Technical Proposal in full swing
  - Signal background studies and optimization, detector specification, simulation and some detector R&D

    ➔ Full detector including muon filter and surrounding structures implemented in GEANT: FairSHIP!
  - Optimization of Experimental Facility - beam line, target, and muon filter, RP, overall layout

- At SHiP Collaboration Meeting in September, ~30 institutes agreed to provide a “letter of intent” as basis for the formalization of the Collaboration at meeting on 15 December 2014.
  - Others in the pipeline to join later for TDR

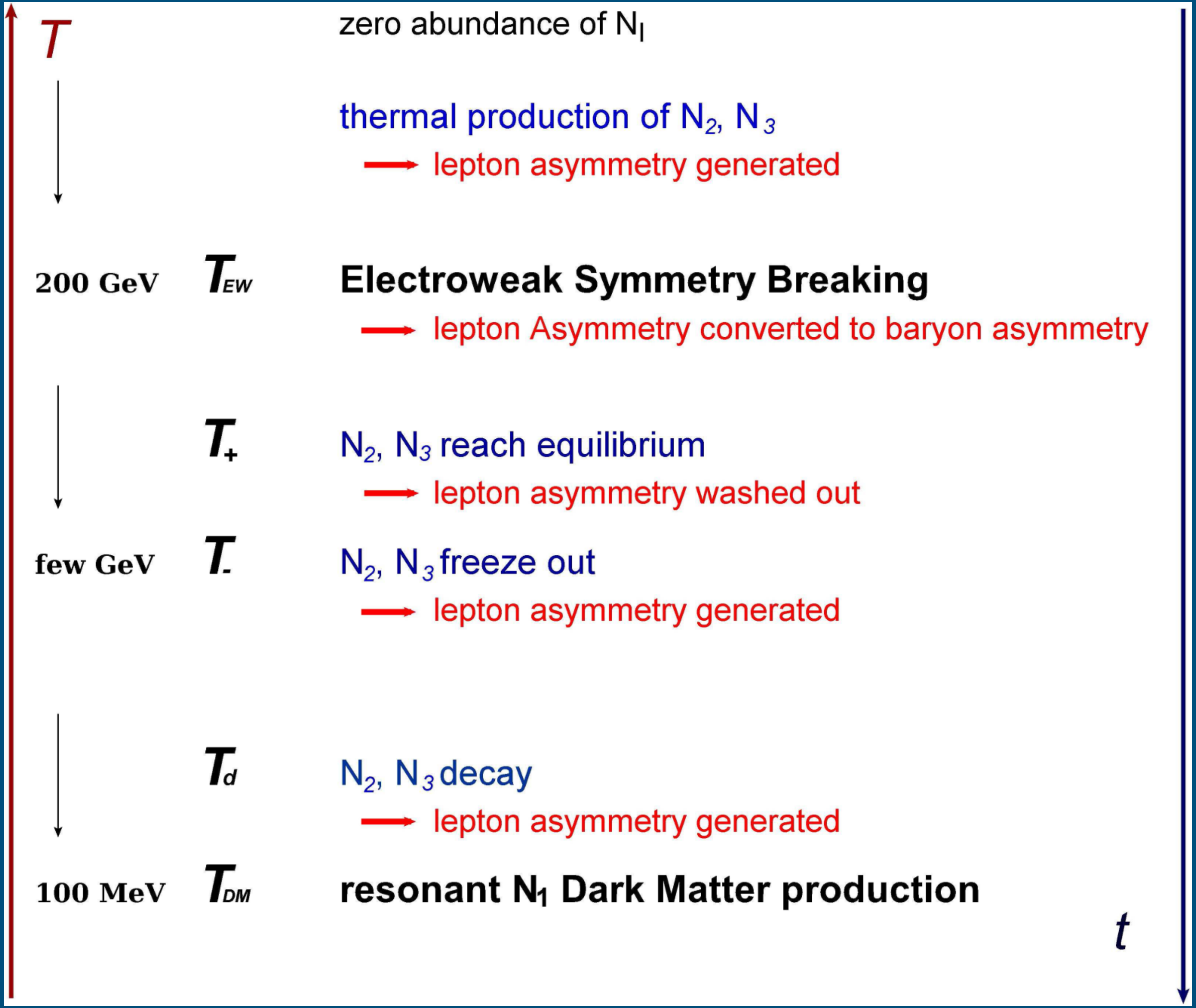
- TP will be complemented by a “Physics Proposal”
  - Prepared mainly by a large group of invited theorists
  - Contains a description of the complete physics program, and extensions beyond SHiP

- Facility and physics case based on the current injector complex and SPS
  - $2\text{x}10^{20}$ at 400 GeV in 5 nominal years by “inheriting” CNGS share of the SPS beam time <u>from 2023</u>

- *Proposed experiment perfectly complements the searches for New Physics at the LHC*

Reserve slides

Thermal History in νMSM



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**

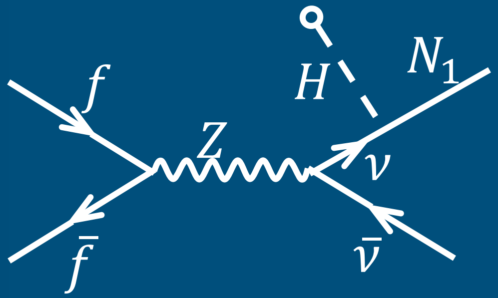
t

(arXiv:1208.4607)

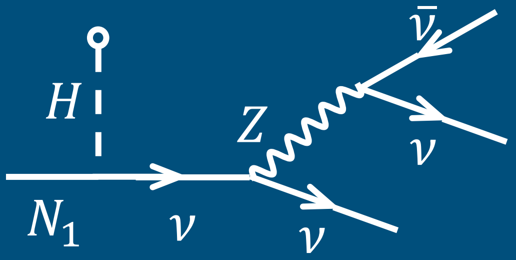
νMSM N_1 = Dark Matter

- 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)
    - ➔ Decaying Dark Matter

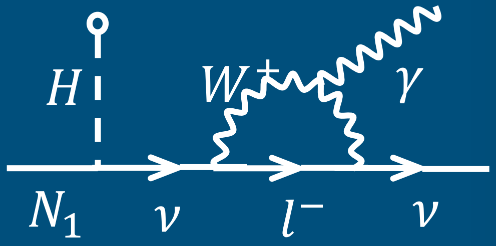
Production from υ ⟷ N oscillations



Dominant decay



Subdominant radiative decay



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

Dark Matter Constraint and Search

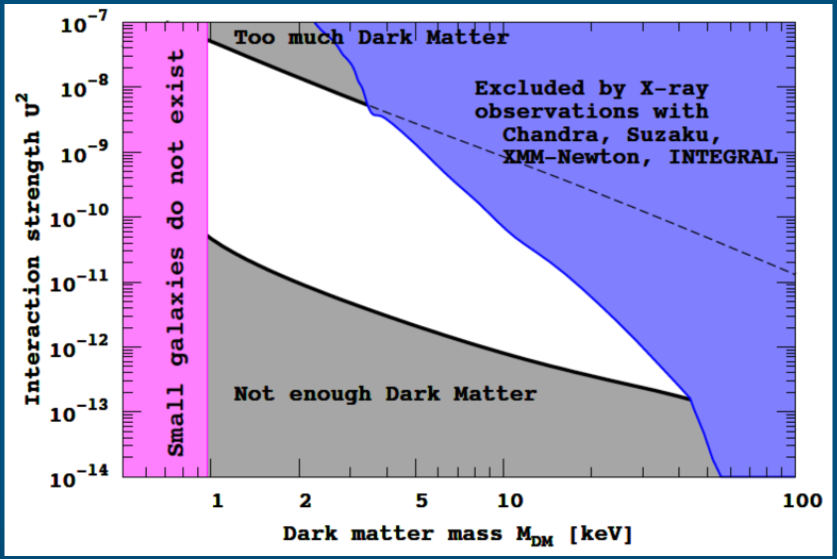
1. Tremaine-Gunn bound: average phase-space density for fermionic DM particles cannot exceed density given by Pauli exclusion principle

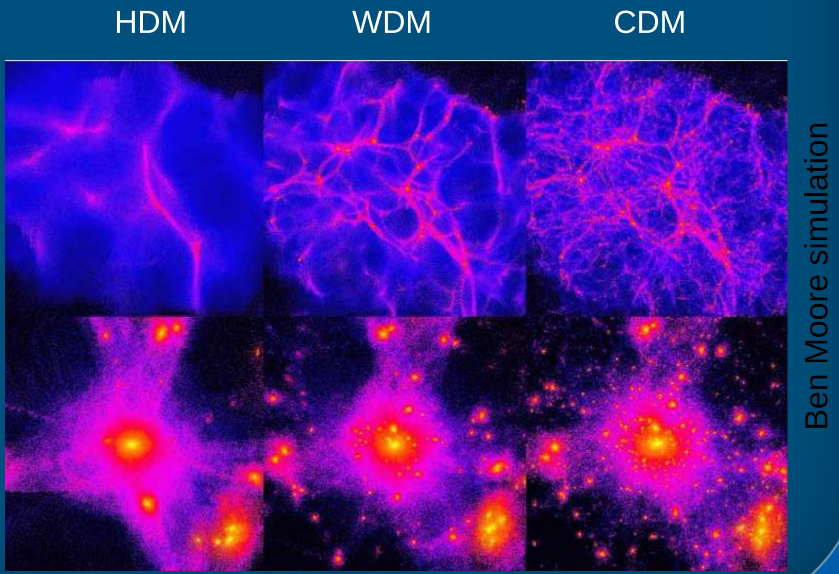
   ➔ For smallest dark matter dominated objects such as dwarf spheroidal galaxies of the Milky Way

2. X-ray spectrometers to detect mono-line from radiative decay
   - Large field-of-view ~ ~ size of dwarf spheroidal galaxies ~ 1°
   - 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

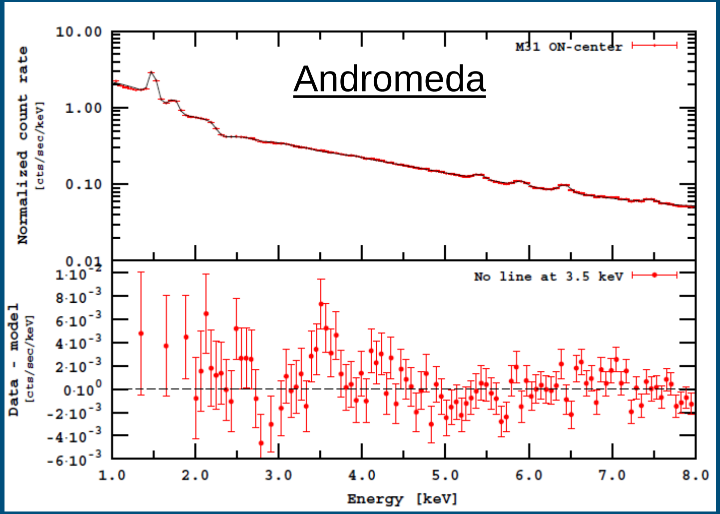
3. Lyman-α forest
   - Super-light sterile neutrino creates cut-off in the power spectrum of matter density fluctuations due to sub-horizon free-streaming $d_{FS} \sim 1\ \mathrm{Gpc}\ m_{eV}^{-1}$
   - Fitted from Fourier analysis of spectra from distant quasars propagating through fluctuations in the neutral hydrogen density at redshifts 2-5

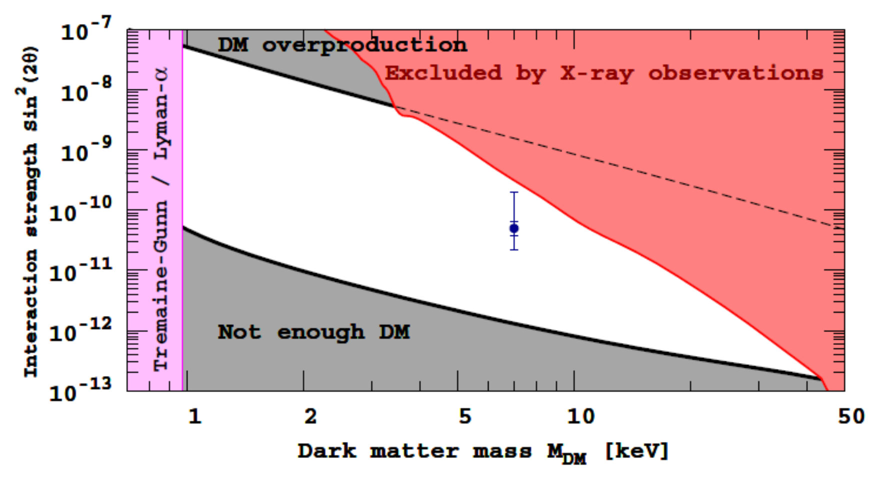


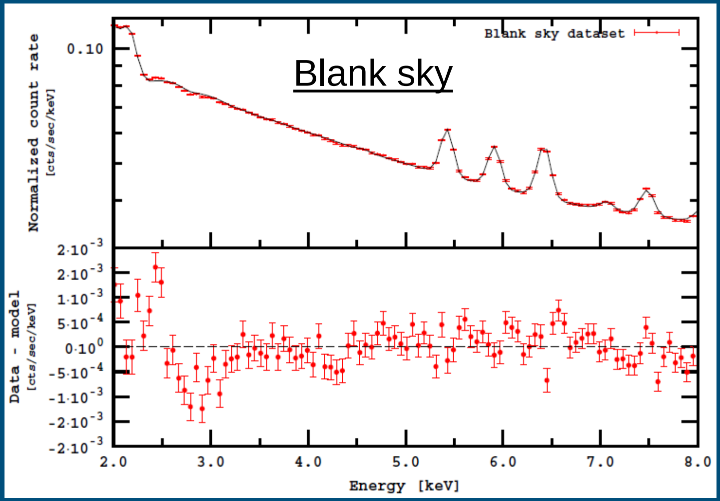


Intriguing hints from galaxy spectrum?

- Two recent publications:
  - ➔ arXiv:1402.2301 : Detection of an unidentified emission line in the stacked XMM-Newton X-ray spectra of Galaxy Clusters at $E_\gamma \sim (3.55\ - 3.57) \pm 0.03 keV$
  - ➔ arXiv:1402.4119 : An unidentified line in the X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster at $E_\gamma \sim 3.5\ keV$





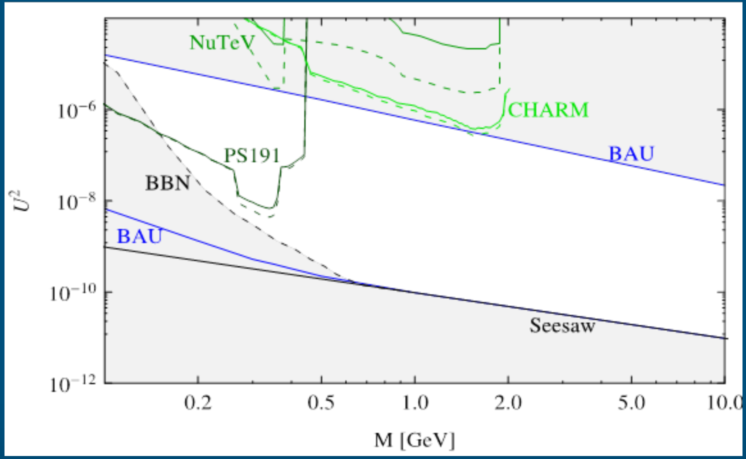


Confirmation by Astro-H with better energy resolution required

Constraints in Variants of HNLs

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



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

- 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 $N_{2,3} \rightarrow \mu\pi$ with production mechanism $D \rightarrow \mu N_{2,3} X$, which probes $\mathcal{U}_\mu^4$
  - Benchmark model II with predominant muon flavour coupling (arXiv:0605047)

- Expected number of signal events

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

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

- $Br(\mathcal{U}_\mu^2) = \mathrm{Br}(D \rightarrow \mu N_{2,3} X) \times Br(N_{2,3} \rightarrow \mu\pi)$,
  - $Br(N_{2,3} \rightarrow \mu\pi)$ is assumed to be 20%
  - Br$(D \rightarrow NX) \sim 10^{-8} - 10^{-12}$
- $\varepsilon_{det}(\mathcal{U}_\mu^2)$ 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 $(8 \times 10^{-5}$ for $\tau_N = 1.8 \times 10^{-5} s)$

Ex. Expected Sensitivity to $N_{2,3} \rightarrow \mu\pi$

Sensitivity based on current SPS with 2×10^{20} p.o.t in ~5 years of CNGS-like operation

- Ex. $\mathcal{U}_\mu^2 = 10^{-7}$ (corresponding to strongest current experimental limit for $M_{N_{2,3}} = 1\ GeV$) ($\tau_N = 18\ \mu s$)

➔ ~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 $\tau_N = 180\ \mu s$