A Facility for Hidden Sector exploration at SPS CERN

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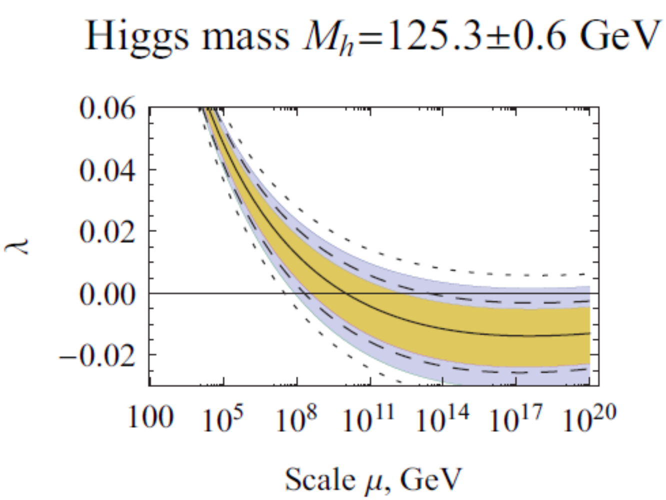
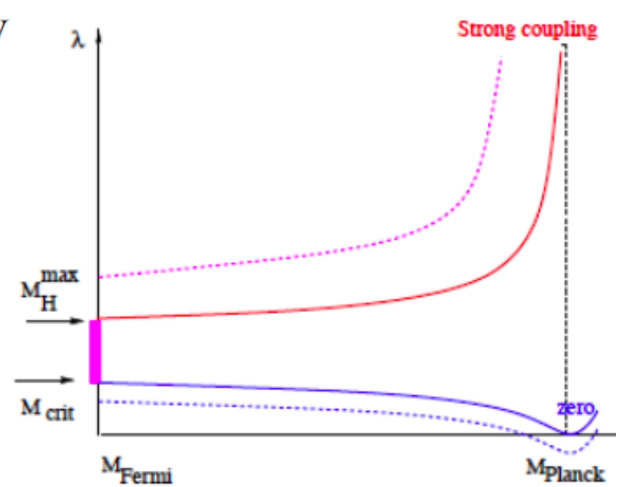
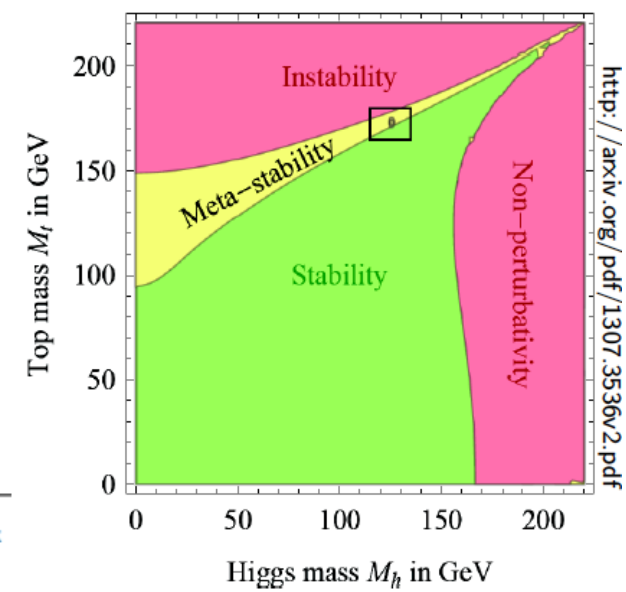
Triumph of the Standard Model

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

- ✓ *All constituents of the SM found*
- ✓ *M_H < 175 GeV → SM is a weakly coupled theory up to the Plank energies !*
- ✓ *M_H > 111 GeV → EW vacuum is stable or metastable with a lifetime greatly exceeding the age of our Universe (Espinosa et al)*







SM is not a complete theory

Experimental facts of BSM physics

- *Neutrino masses & oscillations*
- *The nature of non-baryonic Dark Matter*
- *Excess of matter over antimatter in the Universe*
- *Cosmic inflation of the Universe*

Theoretical shortcomings

Gap between Fermi and Planck scales, Dark Energy, connection to gravity, resolution of the strong CP problem, the naturalness of the Higgs mass, the pattern of masses and mixings in the quark and lepton sectors, …

No clear guidance on the scale of NP and on its coupling strength to the SM particles !

An example: See-saw generation of neutrino masses

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

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

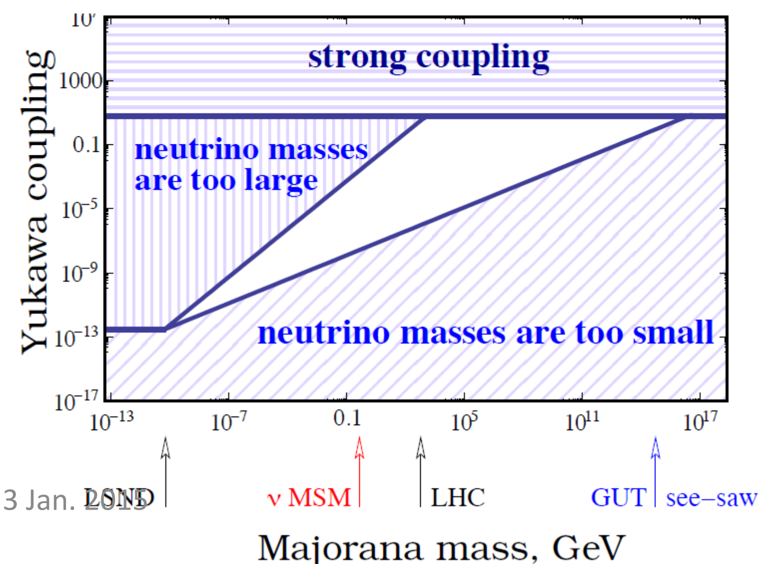
Yukawa term: mixing of N_I with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

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

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

Smallness of the neutrino mass hints either on very large M or very small $Y_{I\alpha}$



BSM theories with a new energy scale
(which may also have light particles)

SUSY is an example

- ✓ *From naturalness expect SUSY masses comparable to the Higgs mass to avoid significant fine tuning*

- ✓ *Could still have light NP. SUSY breaking may be accompanied by s-goldstinos (P,S) with couplings ~ 1 / (SUSY breaking scale) → may have evaded detection*

[Gorbunov, 2001, LHCb: Aaij et al., 2013]

e.g. $D \to \pi X$, then $X \to l^+ l^-$

$B_s^0 \to P S$, then $P, S \to \mu^+ \mu^-$

- ✓ *R-parity violating neutralinos in some SUSY models*

e.g., [Dedes et al., 2001]

e.g. $D \to l \tilde{\chi}$, then $\tilde{\chi} \to l^+ l^- \nu$

Models with Dark sector: impressive list of ideas in the past

(pioneered by Bjorken and Okun)

Holdom, Galison, Manohar, Arkani-Hamed, Weiner, Schuster, Essig, Pospelov, Toro, Batell, Ritz, Andreas, Goodsell, Abel, Khoze, Ringwald, Fayet, Cheung, Ruderman, Wang, Yavin, Morrissey, Poland, Zurek, Reece, Wang, ...

- ✓ *Hidden particles are singlets with respect to the SM gauge group*
- ✓ *Very weak interactions with the SM particles through portals described by various operators with vector, Higgs, neutrino and axion forms*
- ✓ *Isolated Dark sector naturally provides DM candidates*
- ✓ *Dark Sector may have a rich structure of light hidden messengers between Dark sector and SM particles*
- ✓ *No theoretical input on the Dark Sector mass scale → may well happen to be accessible at future experiments*

Vector portal

Mirror matter: to restore P, C and CP

Okun, Voloshin, Ellis, Schwarz, Tyupkin, Kolb, Seckel, Turner, Georgi, Ginsparg, Glashow, Foot, Volkas, Blinnikov, Khlopov, Gninenko, Ignatiev, Berezhiani,...

Dim 2: Hypercharge U(1) field, $B_{\mu\nu}$

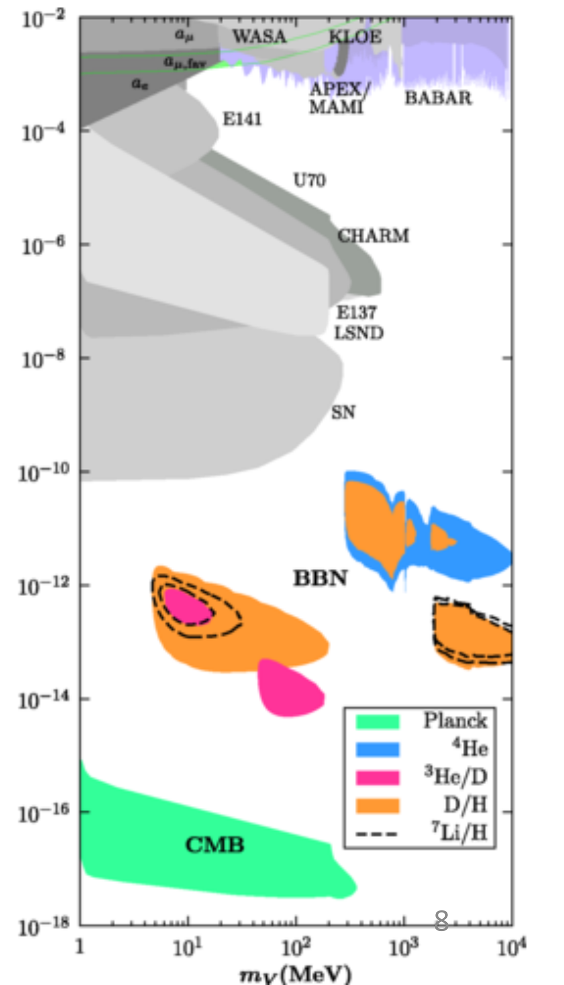
New particle – massive vector photon (paraphoton, secluded photon, …)

renormalisable coupling – kinetic mixing → $\varepsilon B_{\mu\nu} F'^{\mu\nu}$

Production: through a virtual photon: electron or proton fixed-target experiments, e^+e^- and hadron colliders, $\sigma \propto \epsilon^2$. Decay due to the mixing with photon to the pair of charged particles: $e^+e^-,\ \mu^+\mu^-, \pi^+\pi^-,\ etc,\ etc$ or to invisible particles from the dark sector.

Constraints are coming from:

- SLAC and Fermilab beam dump experiments E137, E141, E774
- electron and muon anomalous magnetic moments
- KLOE, BaBar
- PS191, NOMAD, CHARM (CERN)



Higgs portal

Patt, Wilczek, Schabinger, Wells, No, Ramsey-Musolf, Walker, Khoze, Ro, Choi, Englert, Zerwas, Lebedev, Mambrini, Lee, Jaeckel, Everett, Djouadi, Falkowski, Schwetz, Zupan, Tytgat, Pospelov, Batell, Ritz, Bezrukov, Gorbunov, Gunion, Haber, Kane, Dawson,...

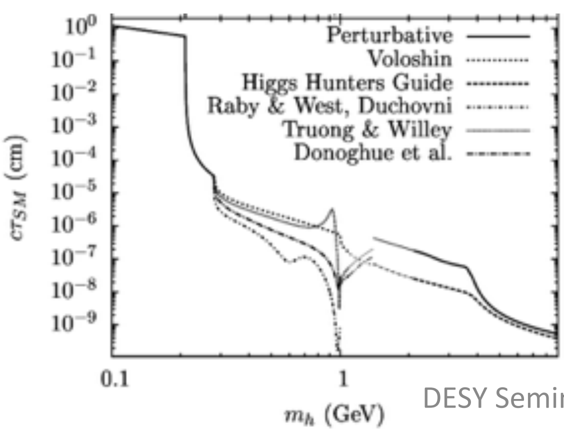
Dim 2: Higgs field $H^\dagger H$

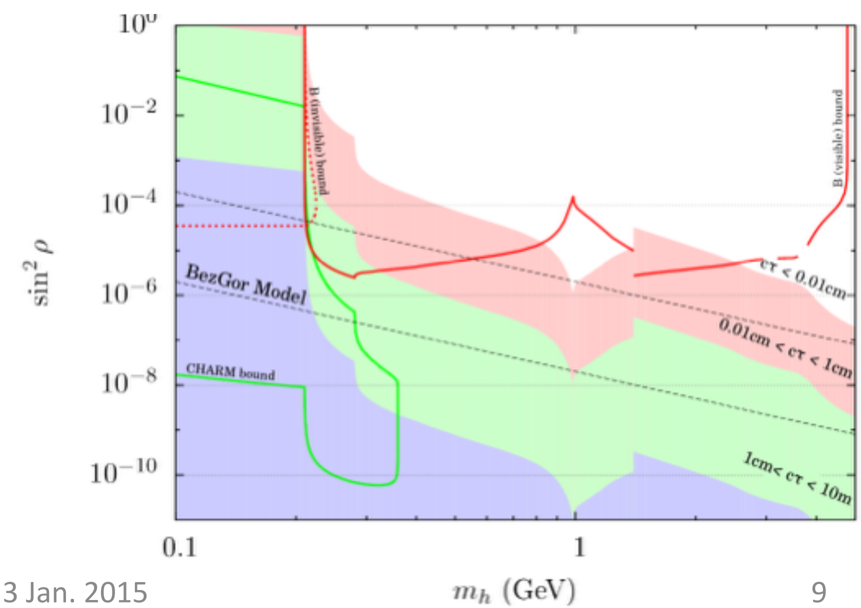
New particle – hidden (dark) scalar with renormalisable coupling

$$(\mu\chi + \lambda\chi^2)H^\dagger H$$

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

- ✓ *Convenient parameterization of an extended Higgs sector: two Higgs doublets, SUSY (e.g. light s-goldstino, scalar singlets, Higgs triplets, …*
- ✓ *Extra scalars may help in solving hierarchy problem, flavour problem, baryogenesis, Dark Matter, neutrino masses, inflaton, etc*
- ✓ *Production*
  - *direct:* *p+target* → χX
  - *in flavour decays:* $B \to \chi K^*$
  - $\tau \approx \sin^2\rho$



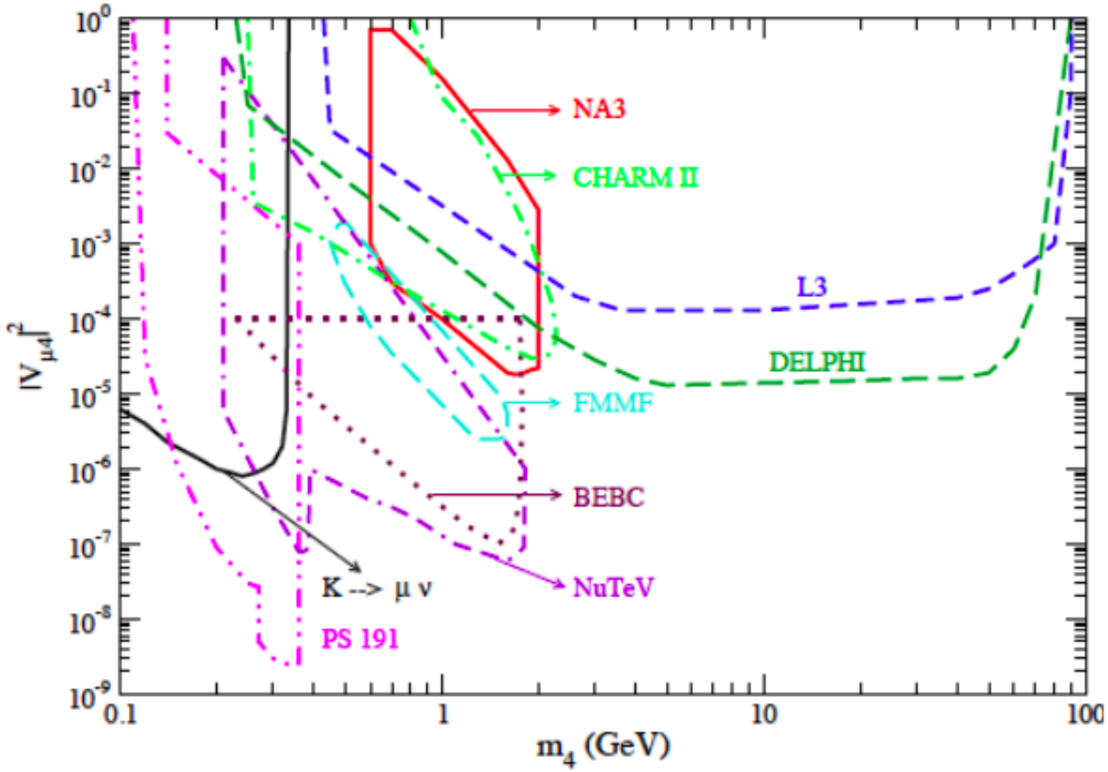


Neutrino portal

Minkowski, Yanagida, Gell-Mann, Ramond, Slansky, Glashow, Mohapatra, G. Senjanovic + too many names to write, the whole domain of neutrino physics

Dim 5/2 Higgs-lepton $H^T L$
renormalisable coupling → $Y H^T \bar{N} L$

To set the scene (summary of the past results) :



- ✓ *Coupling strength to active neutrinos is U^2, where $U^2=U_e^2+U_\mu^2+U_\tau^2$ ($V_{\mu 4}^2=U_\mu^2$, etc…)*
- ✓ *Stringent constraints on the light M_N below kaon mass*
- ✓ *The mass range above charm is relatively poor explored*

from Atre et. al. (0901.3589)

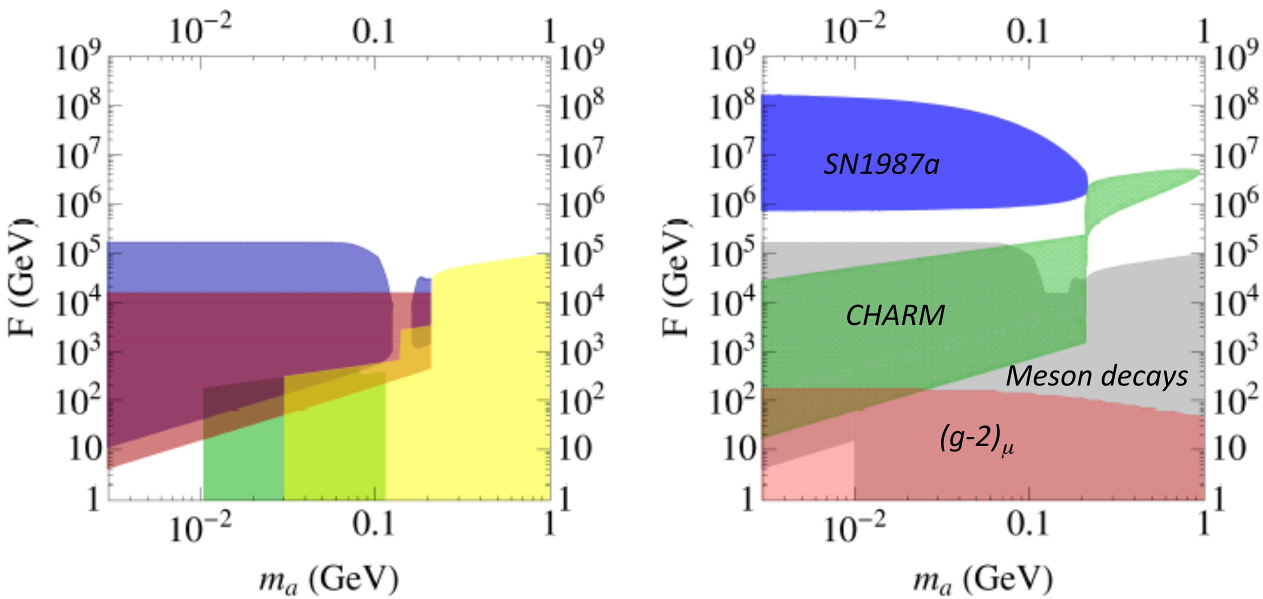
Axion portal

Weinberg, Wilczek, Witten, Conlon, Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, Cicoli, Goodsell, Ringwald, Lazarides, Shafi, Choi, Essig, Harnik, Kaplan, Toro, Gorbunov,...

Dim 4: Axion-like Particles, pseudoscalars
Non-renormalisable couplings → $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad \frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$

- ✓ *Axions → to solve strong CP-problem, string theory, extra dimensions*
- ✓ *Axion-Like Particles (or pseudo-Nambu-Goldstone bosons) → dark matter, SUSY …*

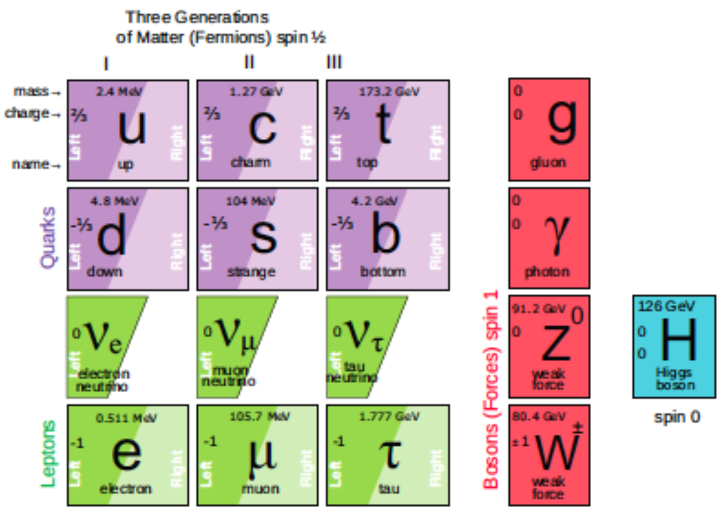
Similar to the Higgs portal, from arXiv:1008.0636, Essig et al

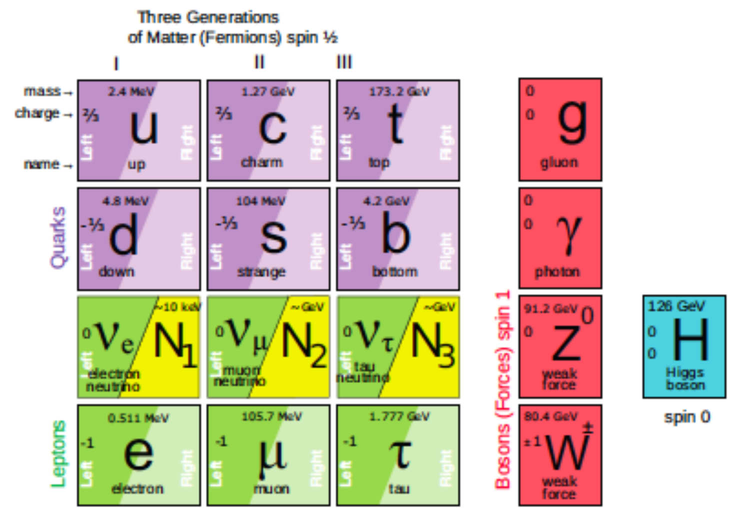


Left: $K^+ \to \text{anything} + e^+e^-$ (green); $K^+ \to \pi^+ +$ invisible (blue); $B^+ \to K^+ l^+ l^-$ (yellow) ($l = e, \mu$); $B^+ \to K^+ +$ invisible (red).
Right: Gray: the combined exclusion region from meson decays; green: CHARM; blue: supernova SN 1987a; red: muon anomalous magnetic moment.

BSM theories with no NP between Fermi and Planck scales
(minimalistic approach)

νMSM *(T.Asaka, M.Shaposhnikov PL **B620** (2005) 17)* ***explains all experimental short comings of the SM at once by adding 3 HNL: N_1, N_2 and N_3***





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: "give" masses to neutrinos and produce baryon asymmetry of the Universe

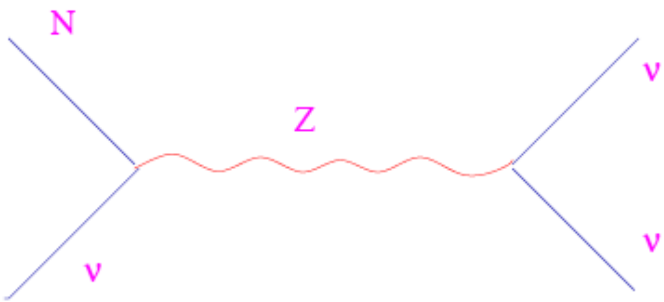
Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Constraints on DM HNL N_1

- ✓ ***Stability*** → *N_1 must have a lifetime larger than that of the Universe*
- ✓ ***Production*** → *N_1 are created in the early Universe in reactions $l\bar{l} \rightarrow \nu N_1$, $q\bar{q} \rightarrow \nu N_1$ etc. Need to provide correct DM abundance*
- ✓ ***Structure formation*** → *N_1 should be heavy enough ! Otherwise its free streaming length would erase structure non-uniformities at small scales (Lyman-α forest spectra of distant quasars and structure of dwarf galaxies)*

Dark Matter candidate HNL N_1

Yukawa couplings are small $\rightarrow$ N can be very stable.



Main decay mode: $N \rightarrow 3\nu$.

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

For one flavour:

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

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

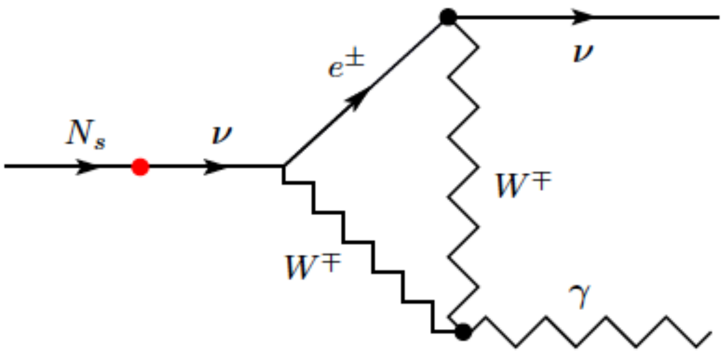
Dark Matter candidate HNL N_1

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

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

Photon energy:

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

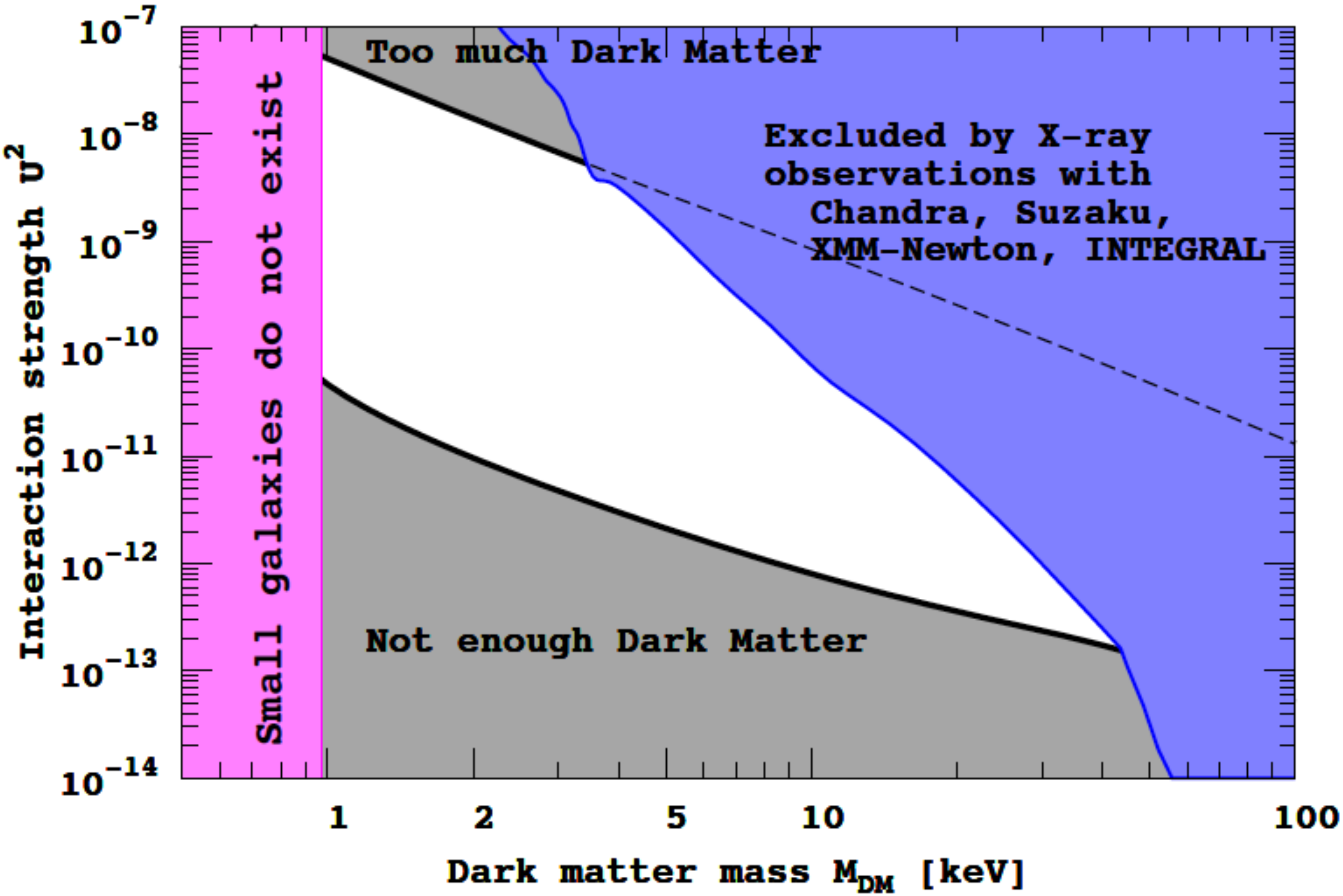


Radiative decay width:

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

$N_1 \to \gamma\nu$ produce a mono-line in photon galaxies spectrum.

Allowed parameter space for DM HNL N_1



Searches for DM HNL N_1 in space

- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*

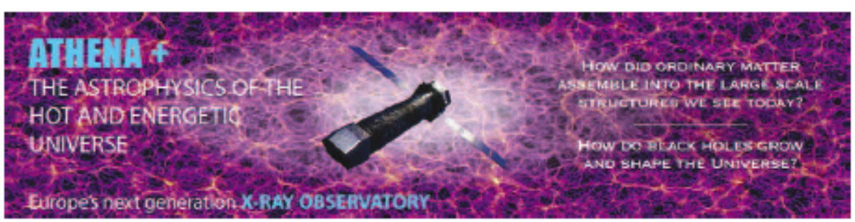
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)

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

Astro-H

LOFT

Athena+



Origin/Xenia

Heavy Neutral Leptons: N_1

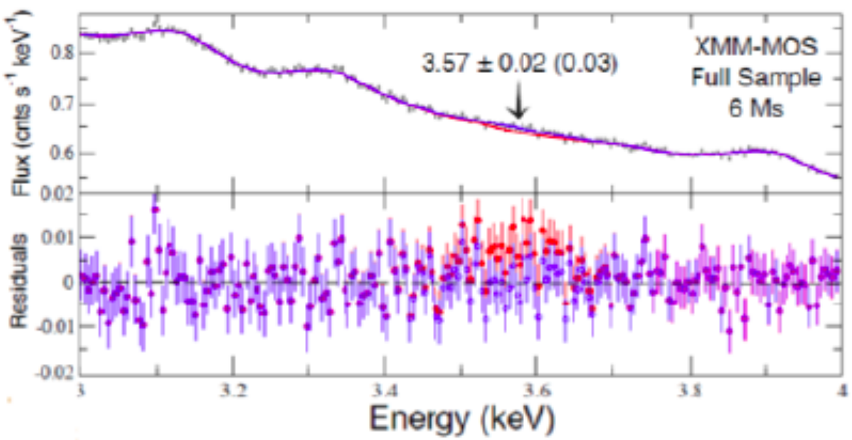
- ✓ *N_1 should be sufficiently stable*
  - *→ super-weak N_1-to-ν mixing such that $\tau(N_1) > \tau(\text{Universe})$*

Observable decay mode: $N_1 \rightarrow \nu\gamma$

- *→ search for mono-line in galactic photon spectrum, $E_\gamma = M_N / 2$*

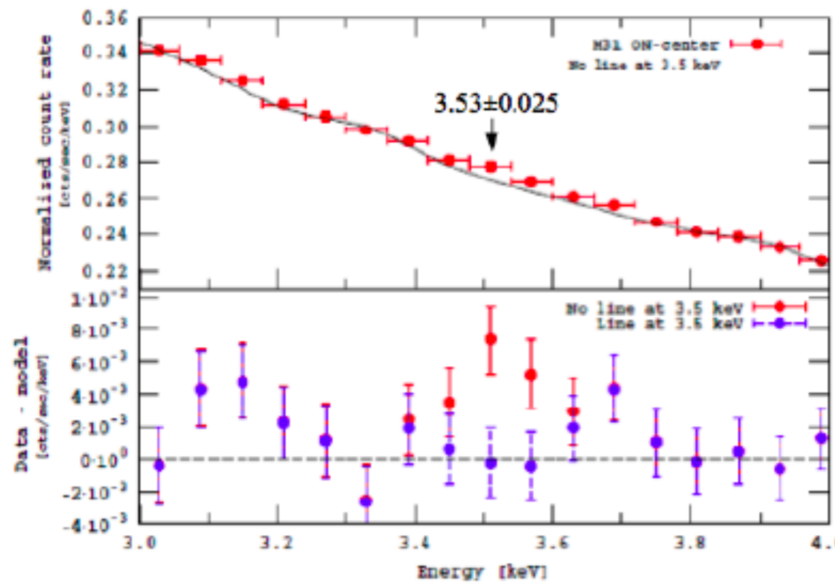
Hints for a signal have been recently reported in:

Bulbul et. al. (1402.2301)



$M_{N1} = 7.1$ keV
$U^2 \approx 7 \times 10^{-11}$

Boyarsky et. al. (1402.4119, 1408.2503)



$M_{N1} = 7.06 \pm 0.05$ keV
$U^2 = (2.2 - 20) \times 10^{-11}$

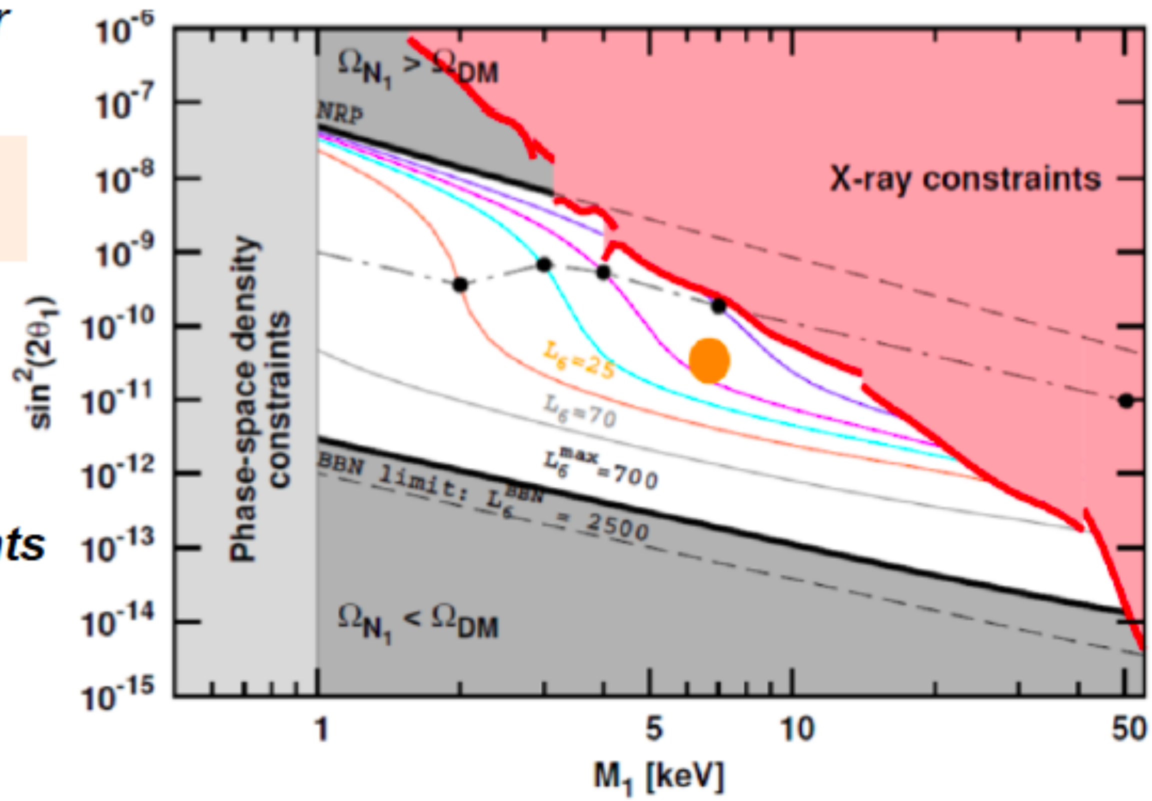
Heavy Neutral Leptons: N_1

- ✓ *There are also recent papers on non-detection of dark matter sterile neutrino candidates:*

  M.E.Anderson et. al. (1408.4115)
  D.Malyshev et.al. (1408.3531)

- ✓ *Ongoing discussions on reliability of the signal …*

- ✓ ***Accuracy of the measurements limited by systematics***



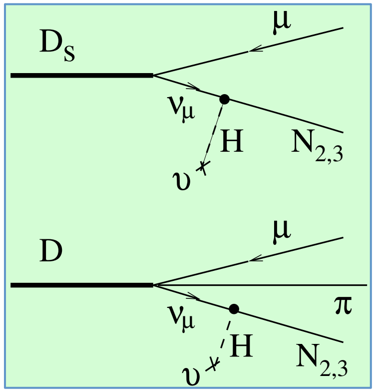
Will soon be checked by the Astro-H mission (to be launched in 2015) with better energy resolution, $\Delta E/E \sim 0.1\%$

Masses and couplings of HNLs: N_2, N_3

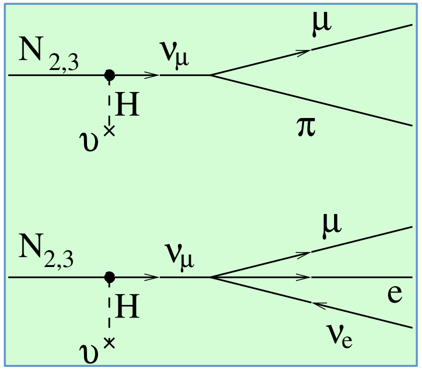
- ***$M(N_2) \approx M(N_3)$ ~ a few GeV→ CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)***

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



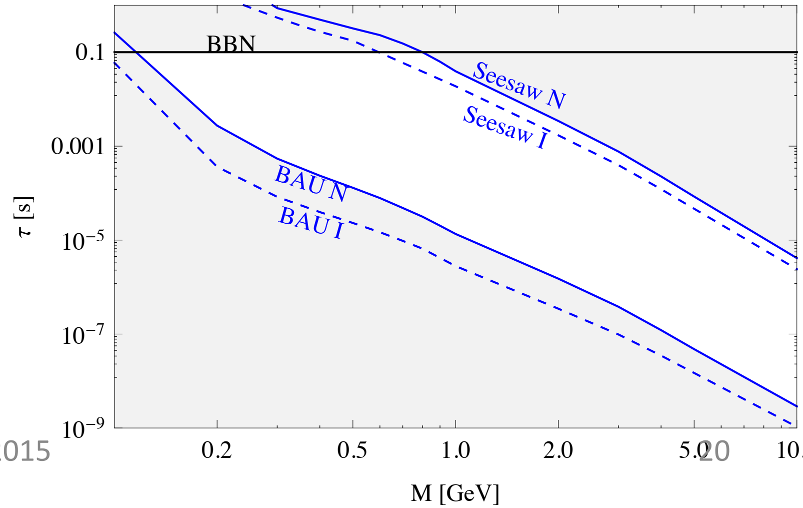
and subsequent decays



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

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

  Br(N → μ/e π) ~ 0.1 – 50%
  Br(N → μ^-/e^- ρ^+) ~ 0.5 – 20%
  Br(N → $\nu\mu e$) ~ 1 – 10%



Baryon asymmetry

Sakharov conditions:

- *CP is not conserved in νMSM*

  6 CPV phases in the lepton sector and 1 CKM phase in the quark sector (to be compared with only one CKM phase in the SM)

- *Out of thermal equilibrium*

↓

✓ ***HNL are created in the early Universe***

✓ ***CPV in the interference of HNL production and decay***

✓ ***Lepton number goes from HNL to active neutrinos***

✓ ***Then lepton number transfers to baryons in the equilibrium sphaleron processes***

PS *Explanation of DM with N_1 reduces a number of free parameters*
→ Degeneracy of $N_{2,3}$ masses is required to ensure sufficient CPV

Masses and couplings of HNLs

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

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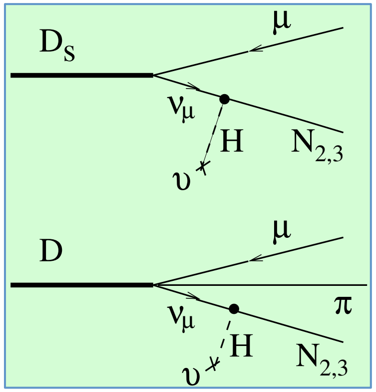

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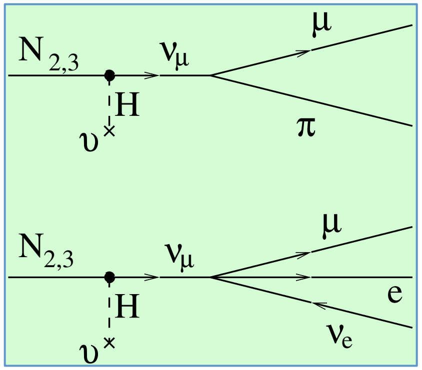

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  Decay distance O(km)
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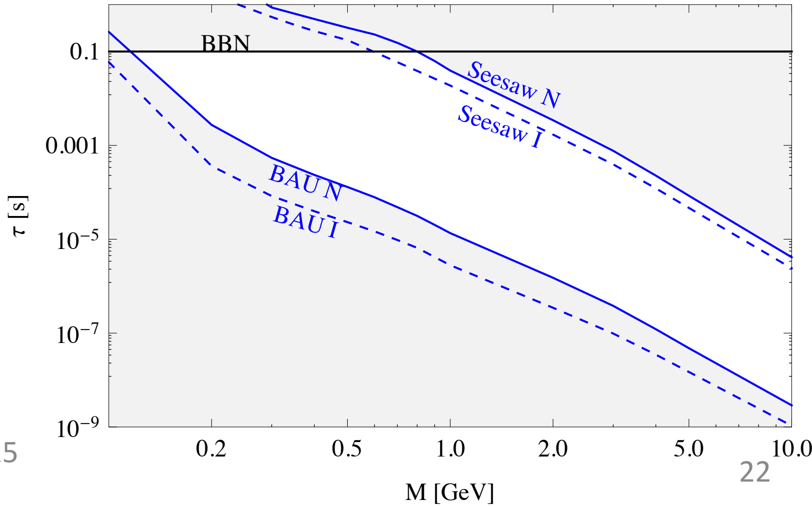
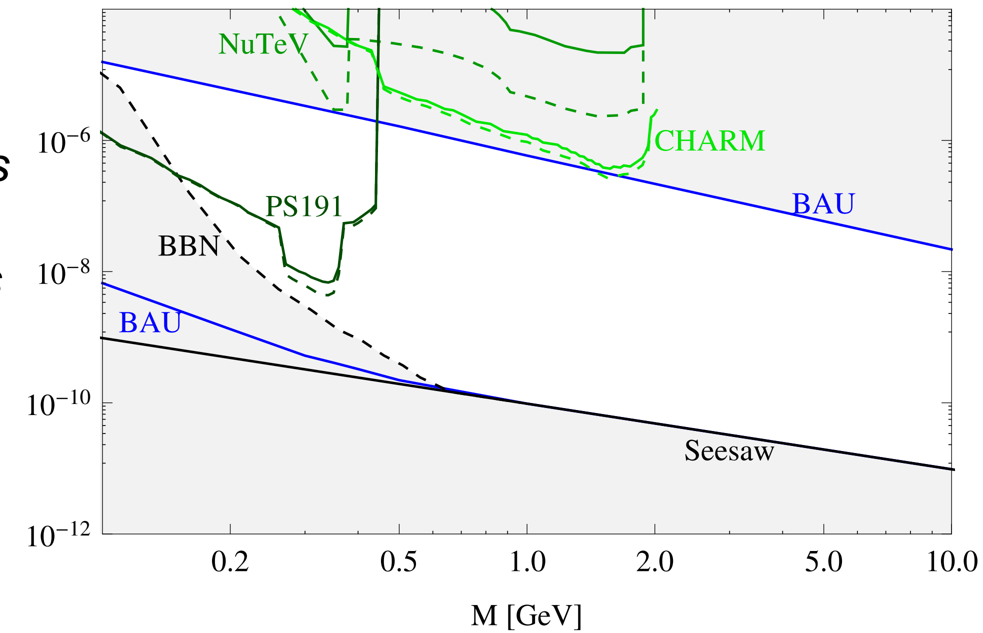
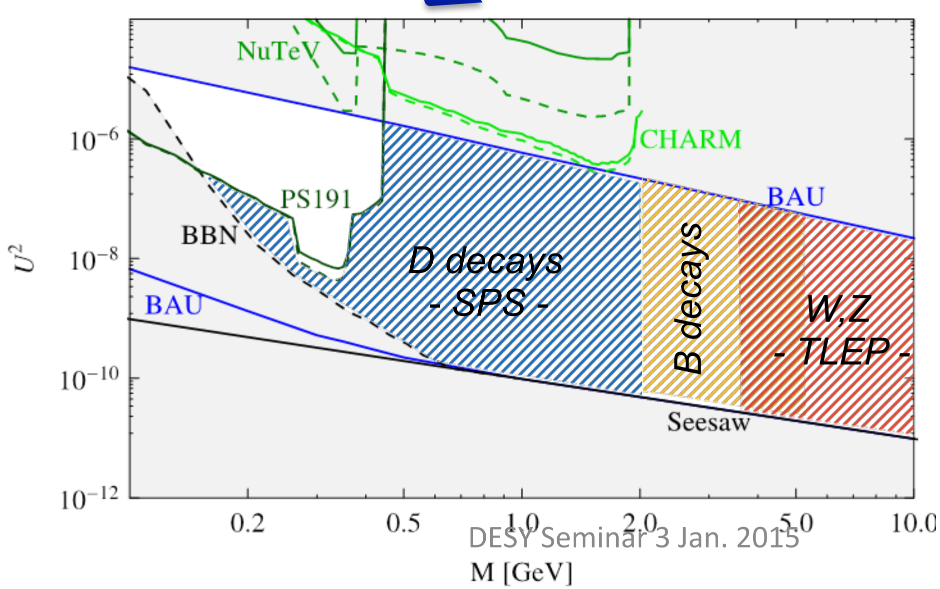


Experimental and cosmological constraints

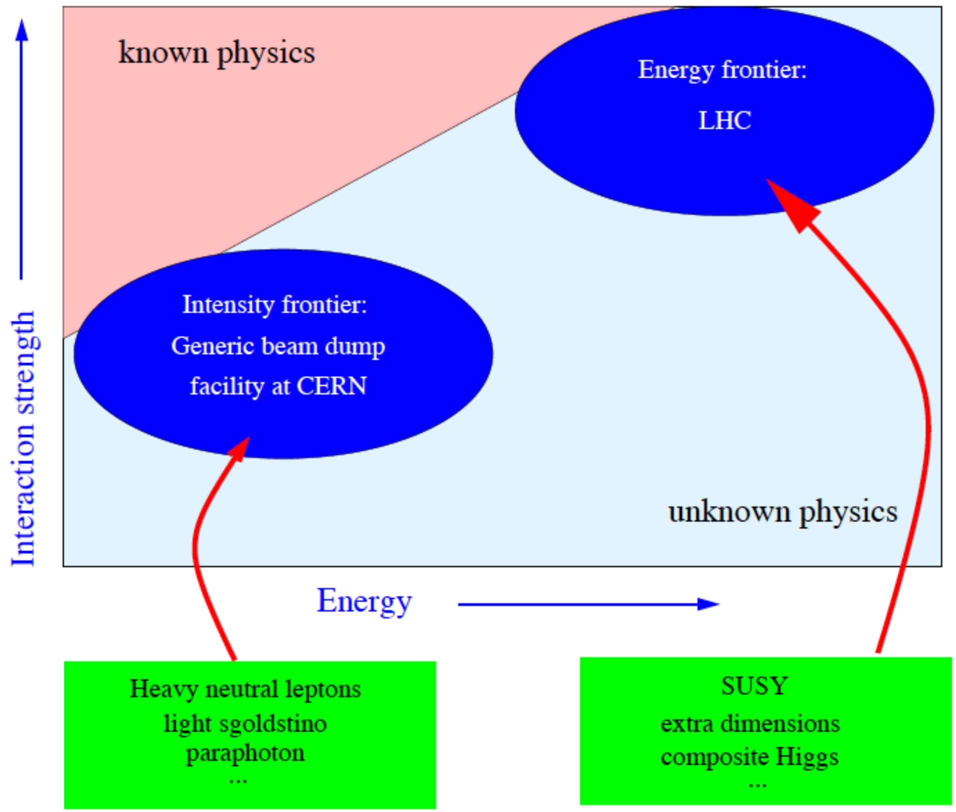
- ✓ ***Recent progress in cosmology***
- ✓ *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*
- ✓ ***Use heavy flavour and W,Z decays to extend mass sensitivity reach***





Main goal of current and near future experiments: exploration of the Fermi scale

(and a bit beyond)



Experiments at the both energy and intensity frontiers are essential !

hidden sector:

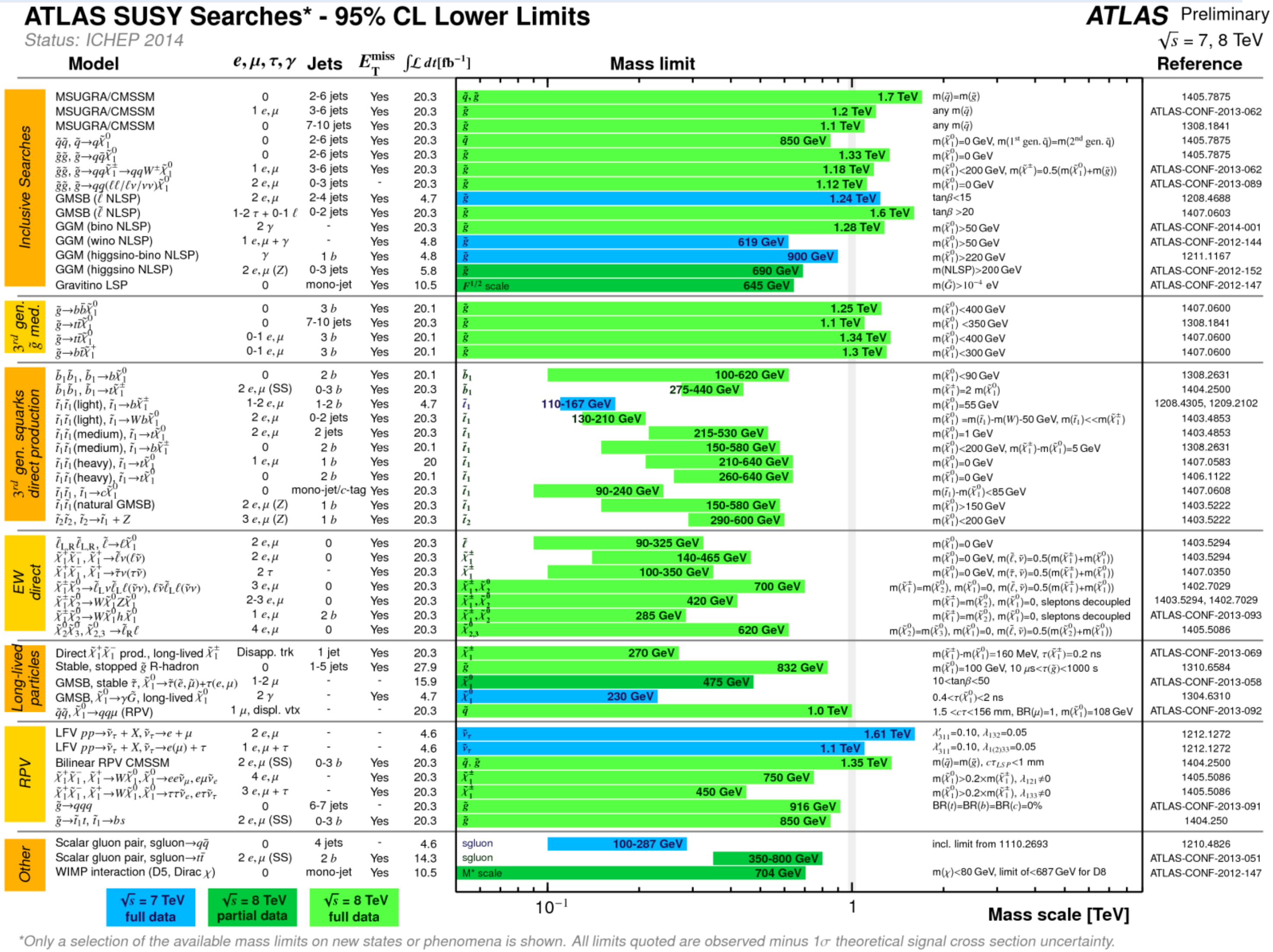
HNL: baryon asymmetry of the Universe, dark matter, neutrino masses

sgoldstino, light neutralino: SUSY

paraphoton: mirror matter, dark matter

Energy Frontier: No sign of New Physics yet !

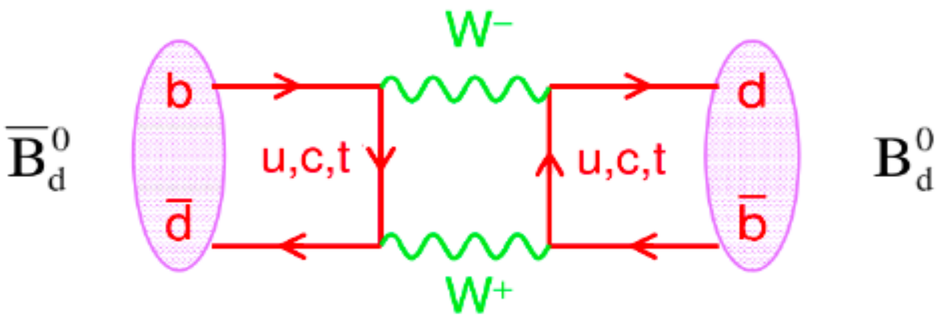
(or what has yet not been found)

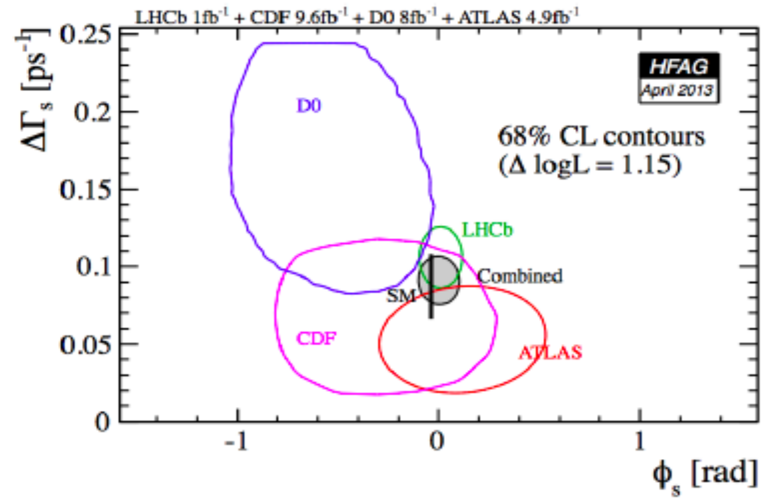


Wait for new LHC data at √s = 13 TeV

Indirect bounds on the scale of New Physics

Most stringent limits come from observables in K^0 & B^0 mixing





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

c_{NP}:

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

Wait for new data from LHCb, NA-62 and later from BELLE-2 and LHCb Upgrade

Search for Heavy Majorana Neutral Leptons at accelerators
(recent results and future perspectives)

M.Shaposhnikov NP B763 (2007) 45-59
A.Pilaftsis et.al. PR D72 (2005) 113001

From cosmology: $M_N < M_W$ or $M_N \geq \approx 300$ GeV
(Sakharov condition → CP has to be violated out of thermo-equilibrium)

✓ $M_N < M_K$
Impressive limits exist from PS-191
Will soon be validated by NA62

✓ $M_N < M_{heavy\ flavour}$
LHCb, BELLE
New beam-dump experiment at the SPS (SHIP) has the best sensitivity reach

✓ $M_N < M_Z$
Can be best explored at Future Circular Collider in e+e- mode

✓ $M_N > M_Z$
Prerogative of the ATLAS / CMS in the high luminosity phase of LHC

Intensity frontier: New fixed target facility is very timely to explore Hidden Sector and to search for HNL

Common experimental features:

✓ *Production through meson decays (π, K, D, B, proton bremstrahlung, …)*

✓ *Decays*

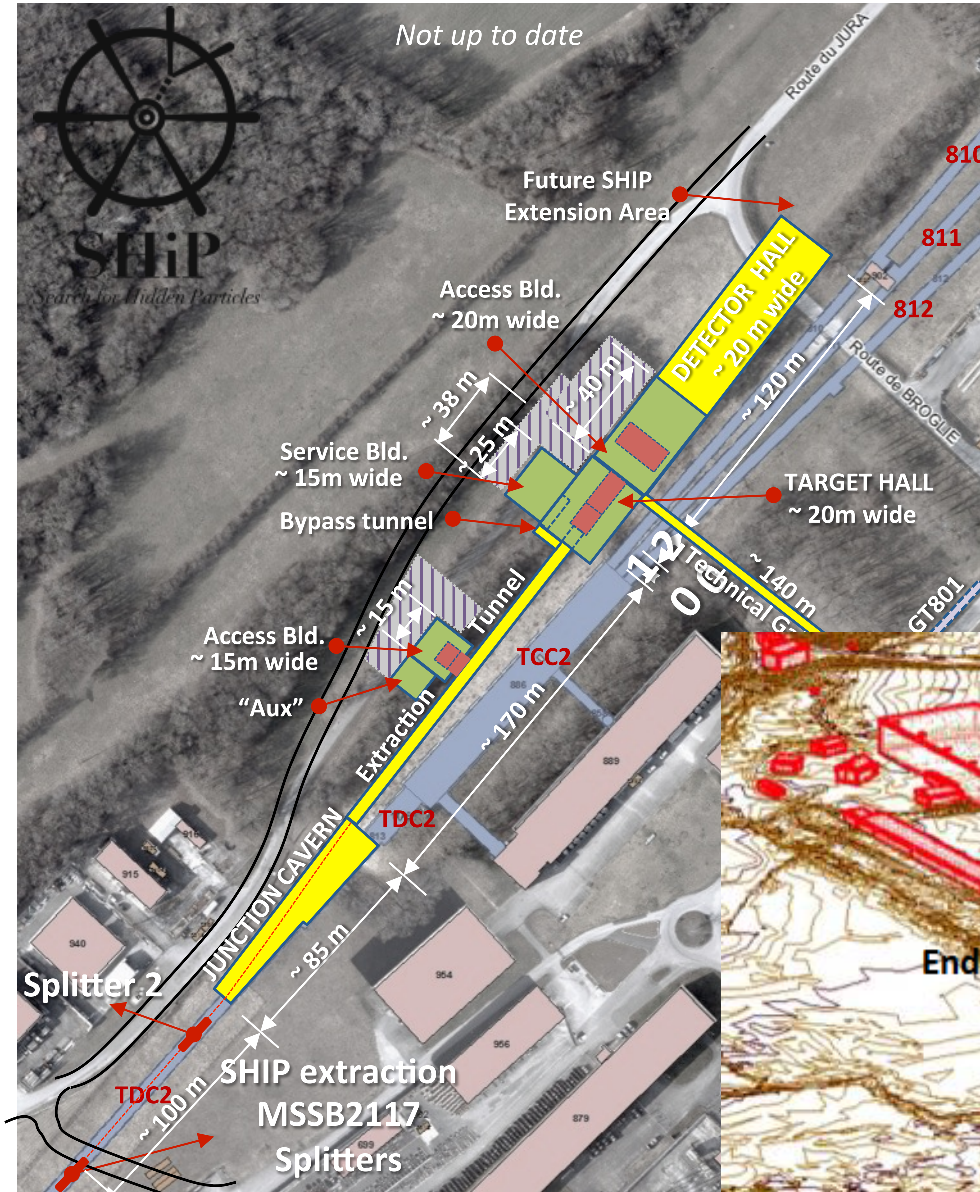
Final states	Models tested
$\pi l, Kl, \rho l, l = (e, \mu, \nu)$	ν portal, HNL, SUSY neutralino
$e^+e^-, \mu^+\mu^-$	V, S and A portals, SUSY s-goldstino
$\pi^+\pi^-, K^+K^-$	V, S and A portals, SUSY s-goldstino
$l^+l^-\nu$	HNL, SUSY neutralino

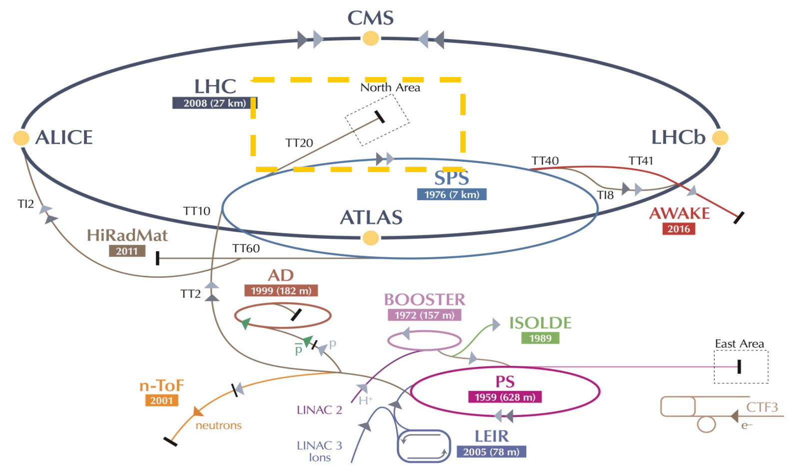
✓ *Full reconstruction and PID are essential to minimize model dependence*

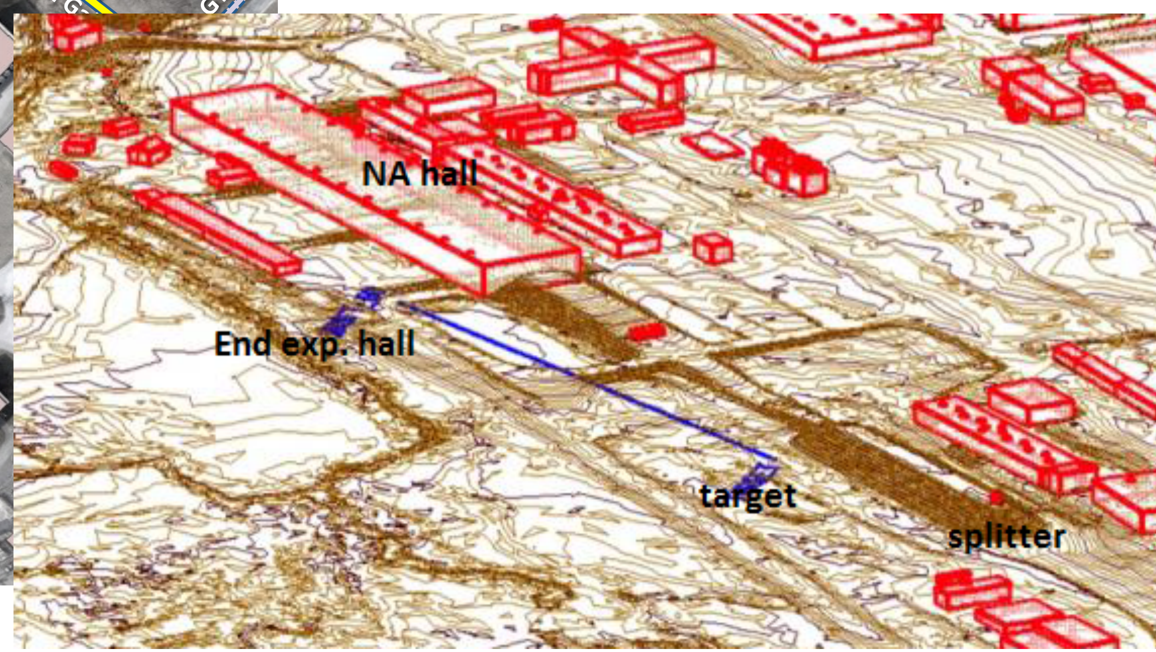
✓ *Production and decay rates are strongly suppressed relative to SM*
- *Production branching ratios O(10^{-10})*
- *Long-lived objects*
- *Travel unperturbed through ordinary matter*

✓ ***Challenge is background suppression → requires O(0.01) carefully estimated***

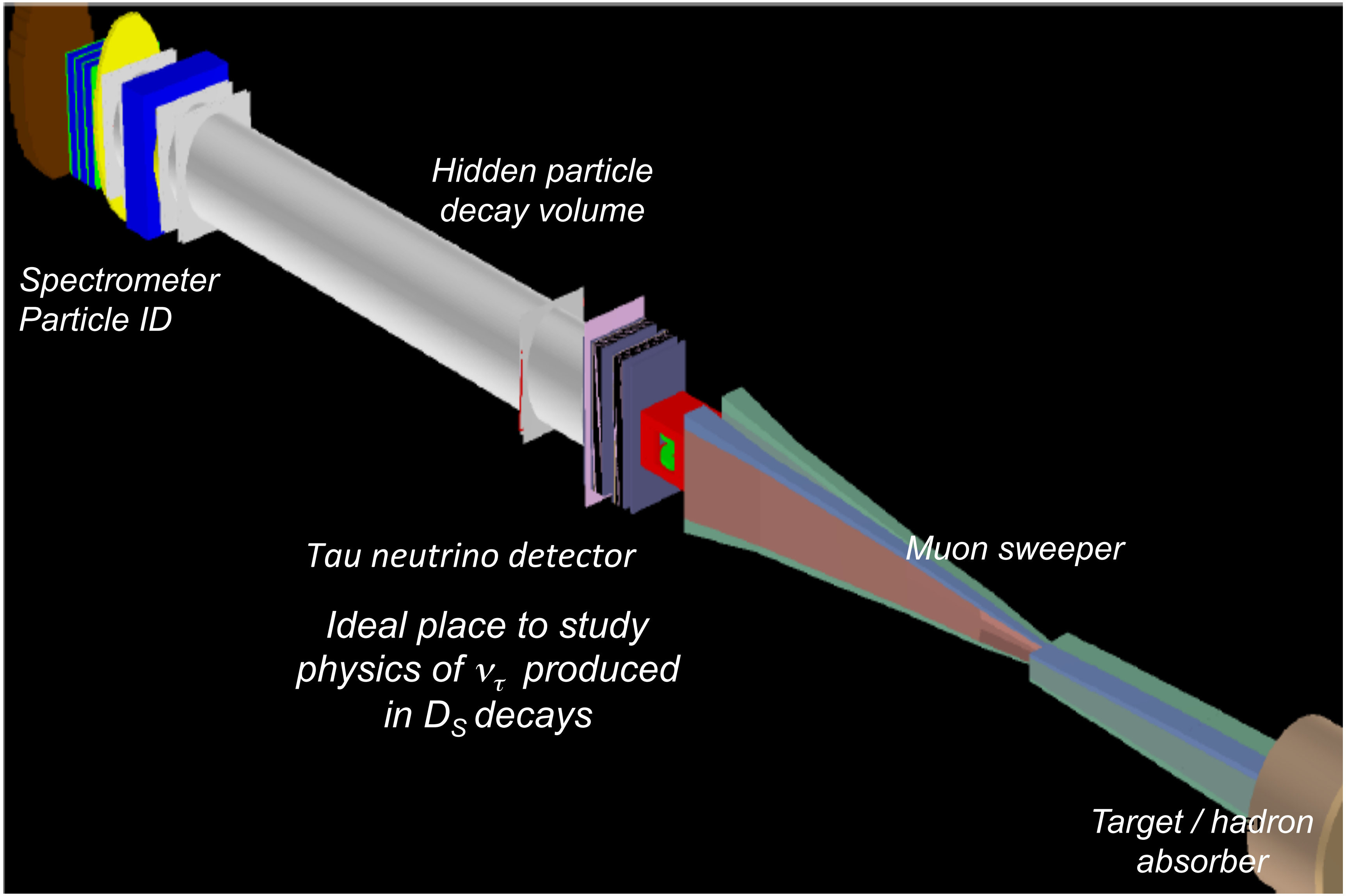
The Fixed-target facility at the SPS (Prevessin North Area site)







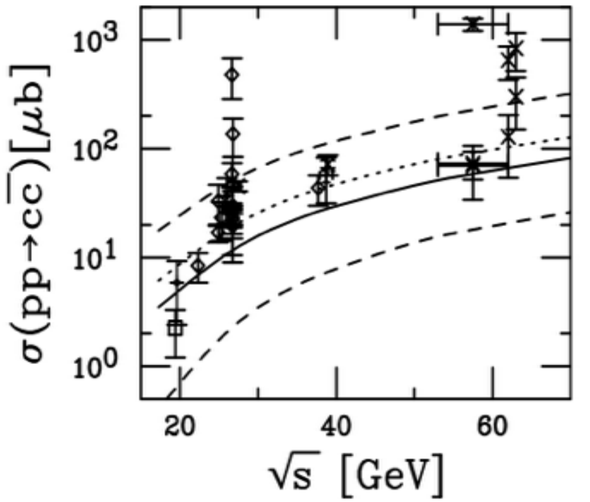
The SHiP experiment



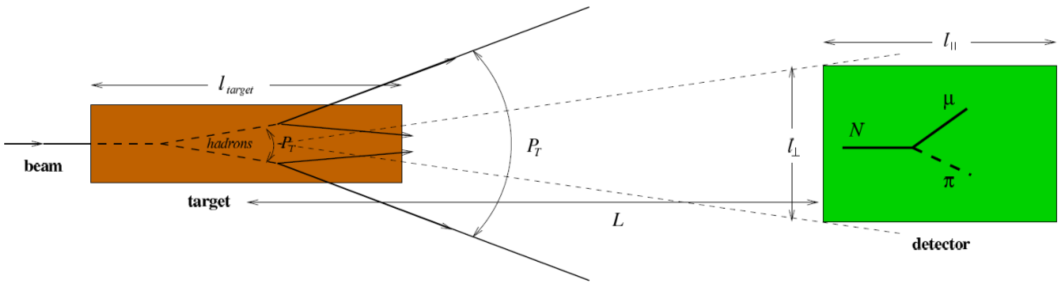
Ideal place to study physics of ν_τ produced in D_S decays

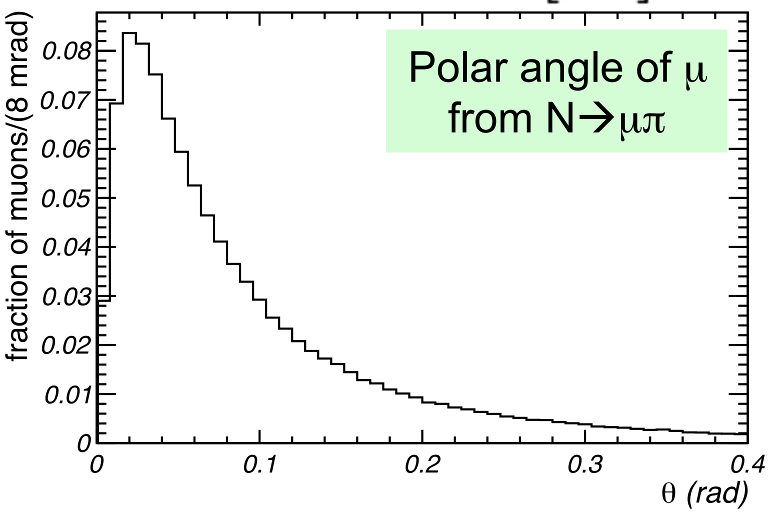
General experimental requirements

- ✓ Search for Hidden Particles (HP) 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



- ✓ HP produced in charm decays have significant P_T





Detector must be placed close to the target to maximize geometrical acceptance → compromise between HP life time and production angle

Effective (and "short") muon shield is essential to reduce muon-induced backgrounds (mainly from short-lived resonances accompanying charm production)

CERN Task Force

Initiated by CERN Management after SPSC encouragement of the SHiP project in January 2014

Detailed investigation aimed at overall feasibility, identifying options/issues & resource estimate

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

Document completed on July 2

Detailed cost, manpower and schedule

Compatible with commissioning runs in 2022, data taking 2023

Working group responsible for providing design of facility for Technical Proposal

CERN
CH1211 Geneva 23
Switzerland

EN Engineering Department

EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

Date : 2014-07-02

Report

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

Preliminary Project and Cost Estimate

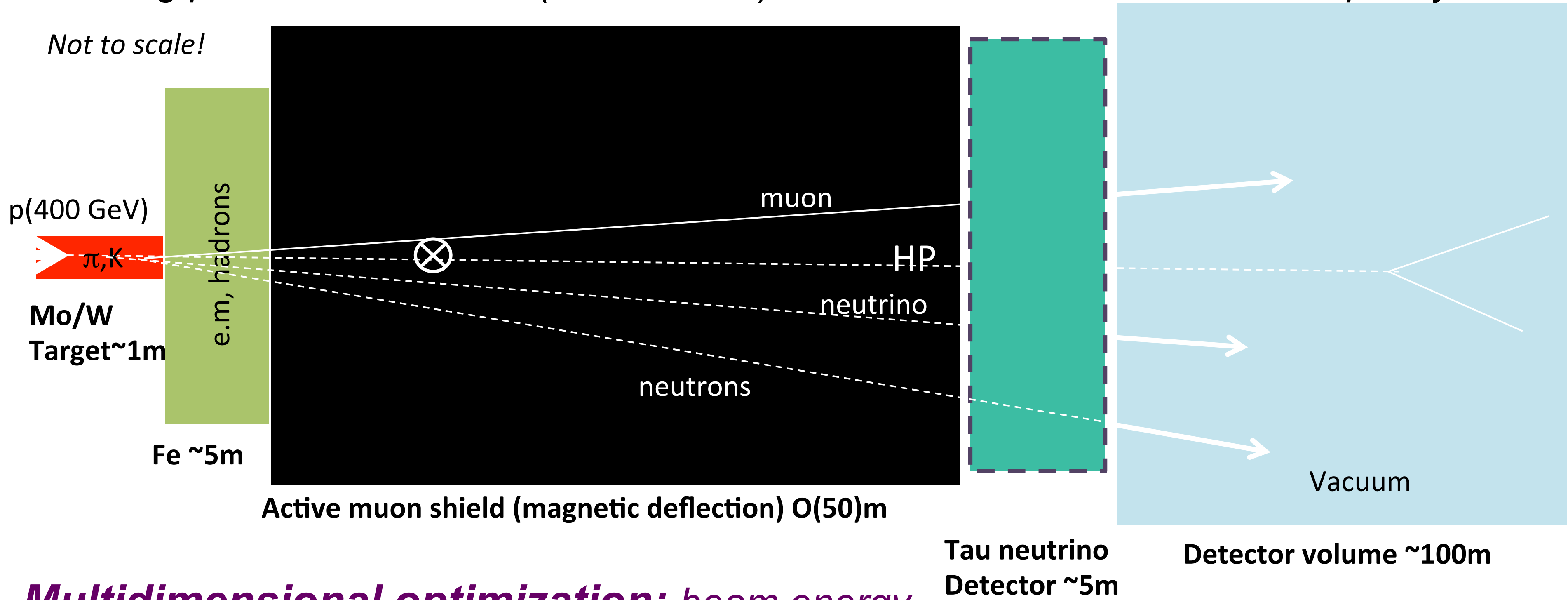
The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
G.Arduini, M.Calviani, K.Cornelis, L.Gatignon, B.Goddard, A.Golutvin, R.Jacobsson, J. Osborne, S.Roesler, T.Ruf, H.Vincke, H.Vincke	S.Baird, O.Brüning,J-P.Burnet, E.Cennini,P.Chiggiato, F.Duval, D.Forkel-Wirth, R.Jones, M.Lamont, R.Losito, D.Missiaen, M.Nonis, L.Scibile, D.Tommasini,	F.Bordry, P.Collier, M.J.Jimenez, L.Miralles, R.Saban, R.Trant

Requirements to the SHiP beam-line
(incompatible with conventional neutrino facility)

Initial reduction of beam induced backgrounds

- *Heavy target to minimize neutrinos from $\pi/K \rightarrow \mu\nu$ decays*
  → Blow up beam to dilute energy on target
- *Hadron absorber*
- *Effective muon shield (without: muon rate ~10^{10} per spill of 5×10^{13} pot)*
- *Strong preference for slow (and uniform) beam extraction to reduce occupancy*

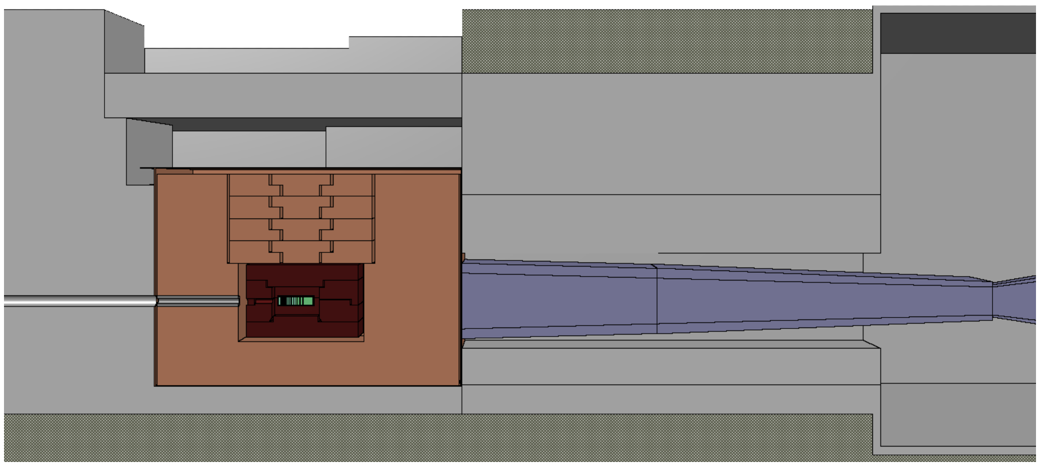


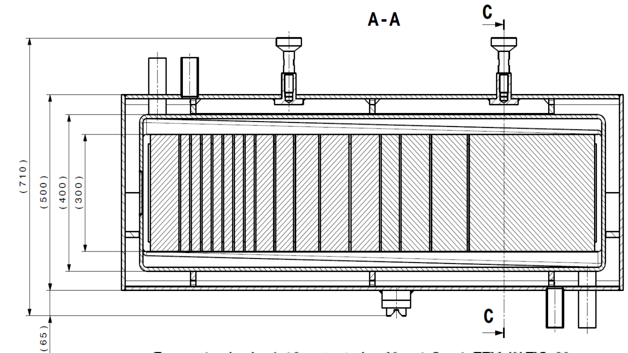
Multidimensional optimization: *beam energy, beam intensity, background conditions and detector acceptance*

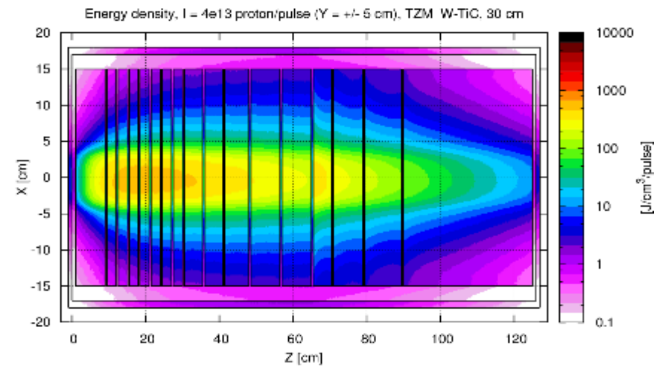
SHiP target

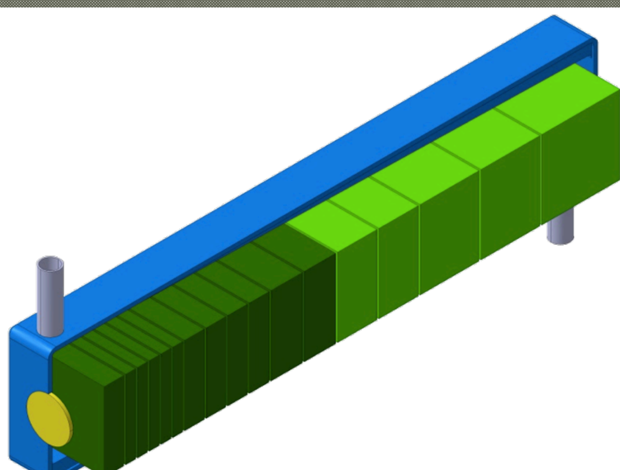
Design consideration

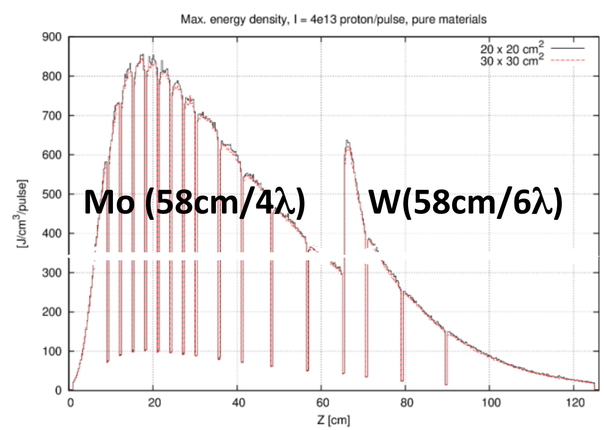
- ✓ *High temperature*
- ✓ *Compressive stresses*
- ✓ *Erosion/corrosion*
- ✓ *Material properties as a function of irradiation*
- ✓ *Remote handling (Initial dose rate of 50 Sv/h…)*





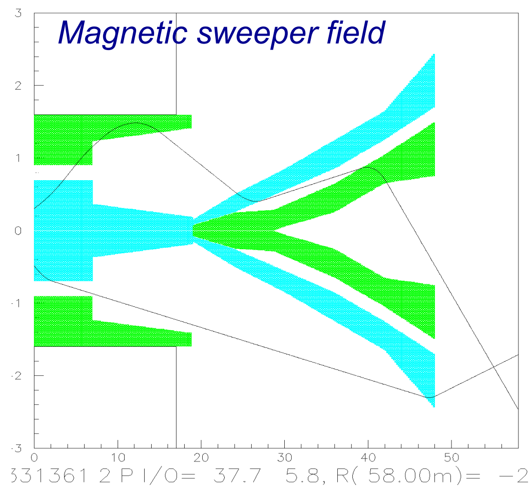


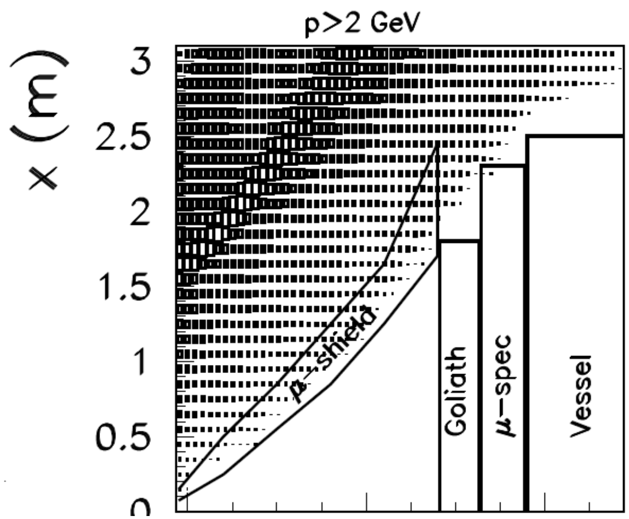


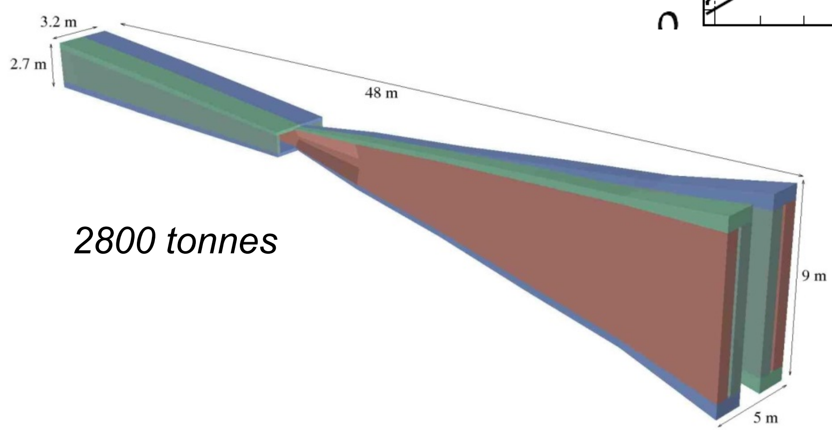


SHiP muon shield

- ✓ *Muon flux limit driven by emulsion based neutrino detector and HP background*
- ✓ *Baseline: Active muon shield based entirely on magnet sweeper / passive absorber. Realistic design of sweeper magnets in progress. Challenges: flux leakage, constant field profile, modelling magnet shape.*
- ✓ *< 100k muons / spill (E_{μ} > 3 GeV) which can potentially produce V_0 (K_L)*
- ✓ *Negligible flux in terms of detector occupancy*

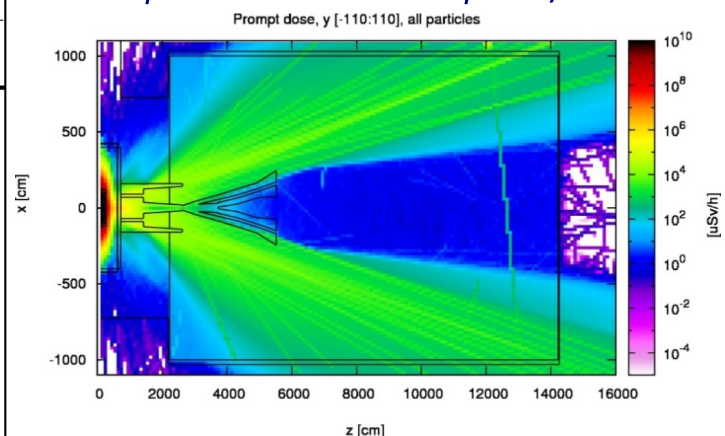


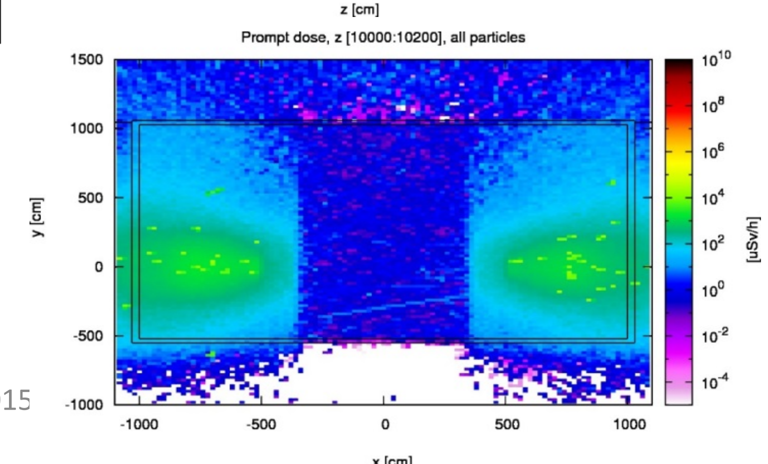




2800 tonnes

Prompt dose rates in the experimental hall 4x13 p.o.t. / 7s

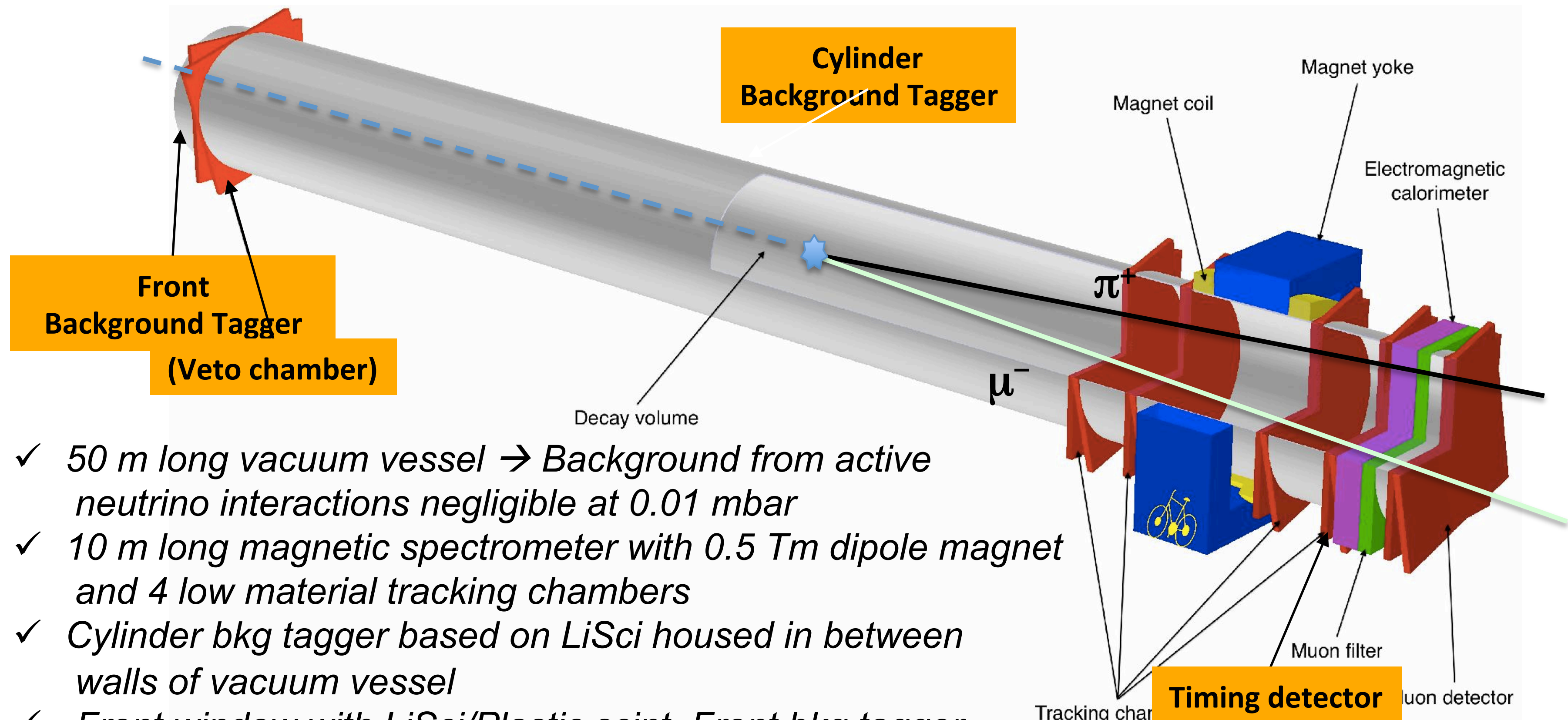




Detector concept
(based on existing technologies)

- ✓ *Reconstruction of the HP decays in various final states*

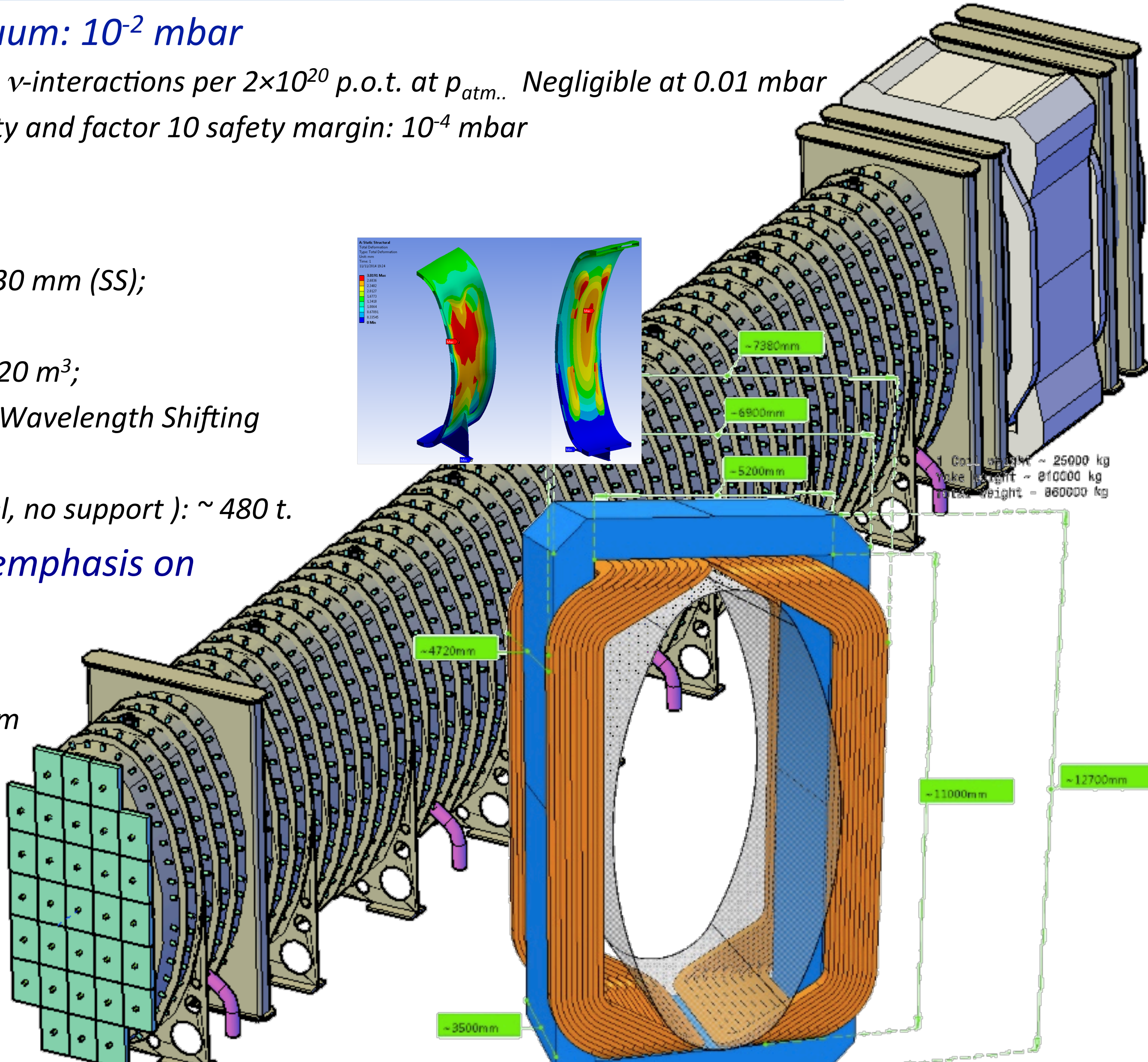
  Long decay volume, magnetic spectrometer, HCAL/Muon detector and ECAL, preferably in surface building and with walls of infrastructure away to reduce neutrino/muon interactions in proximity of detector



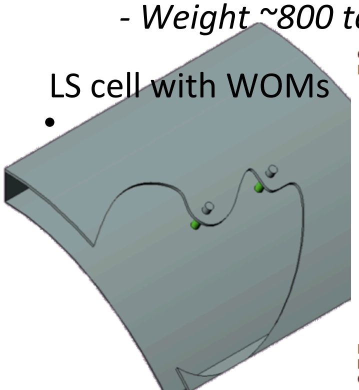
- ✓ *50 m long vacuum vessel → Background from active neutrino interactions negligible at 0.01 mbar*
- ✓ *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*
- ✓ *Cylinder bkg tagger based on LiSci housed in between walls of vacuum vessel*
- ✓ *Front window with LiSci/Plastic scint. Front bkg tagger*
- ✓ *Downstream high resolution timing detector*

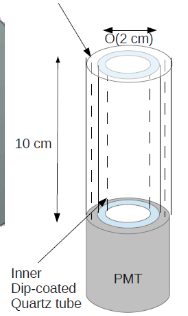
Decay volume and spectrometer magnet

- ✓ *Estimated need for vacuum: 10^{-2} mbar*
  - *- Based on neutrino flux: 2×10^4 ν-interactions per 2×10^{20} p.o.t. at $p_{atm.}$. Negligible at 0.01 mbar*
  - *- Design with factor 10 flexibility and factor 10 safety margin: 10^{-4} mbar*
- ✓ *Vacuum vessel*
  - *- 10 m x 5 m x 60 m;*
  - *- Walls thickness: 8 mm (Al) / 30 mm (SS);*
  - *- Walls separation: 100 mm;*
  - *- Liquid scintillator volume: ~120 m^3;*
  - *- 1500 WOMs (8 cm x Ø 8 cm Wavelength Shifting Modules + PMTs);*
  - *- Metal weight (stainless steel, no support): ~ 480 t.*
- ✓ *Magnet designed with emphasis on low power*
  - *- Power consumption < 1 MW*
  - *- Field integral: 0.65Tm over 5m*
  - *- Current 2500 A (1.7 A/mm2*
  - *- Weight ~800 tonnes*



LS cell with WOMs





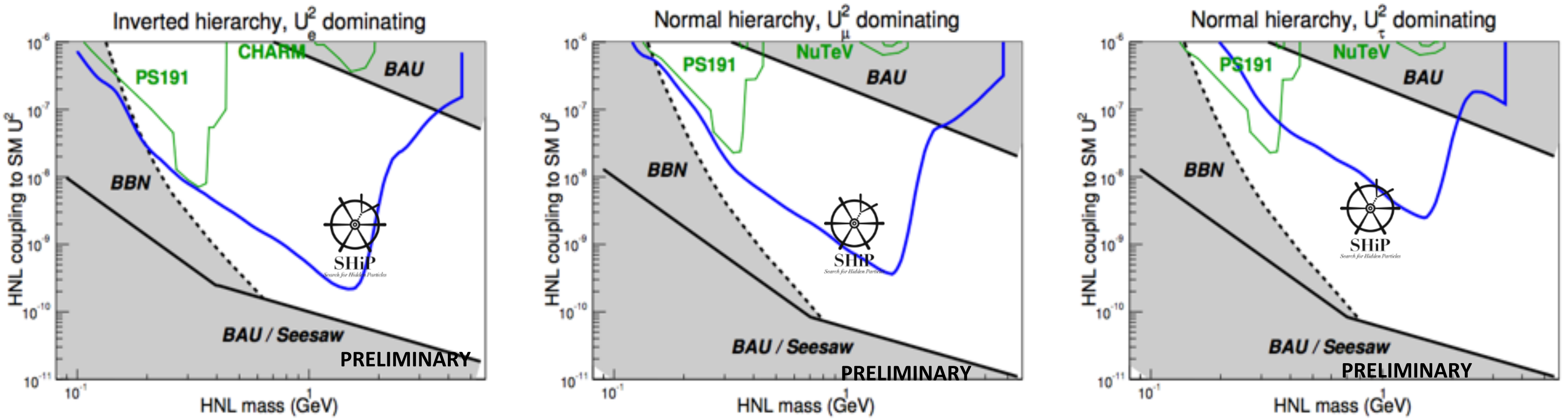
LAB (Linear alkyl benzene)	-
2.5 diphenyl oxazole (PPO)(C15H11NO)	3g/l

37

Some SHiP sensitivities: HNLs

Sensitivity based on current SPS with 2×10^20 pot in ~5 years of CNGS-like operation (visible decays = at least two tracks crossing the spectrometer)

- ✓ ***SHiP will scan most of the cosmologically allowed region below the charm mass***
- ✓ *Expect ~120 events for $M(N_{2,3})$ = 1 GeV in cosmologically favoured region with $U_\mu^2 = 10^{-8}$ and $\tau_N = 180\ \mu s$*



I $U_e^2 : U_\mu^2 : U_\tau^2 \approx 52 : 1 : 1$, inverted hierarchy

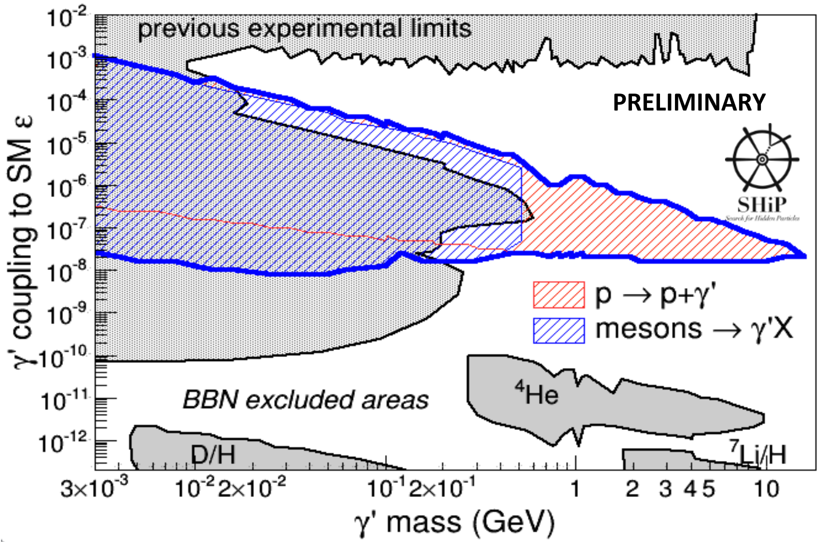
II $U_e^2 : U_\mu^2 : U_\tau^2 \approx 1 : 16 : 3.8$, normal hierarchy

III $U_e^2 : U_\mu^2 : U_\tau^2 \approx 0.061 : 1 : 4.3$, normal hierarchy

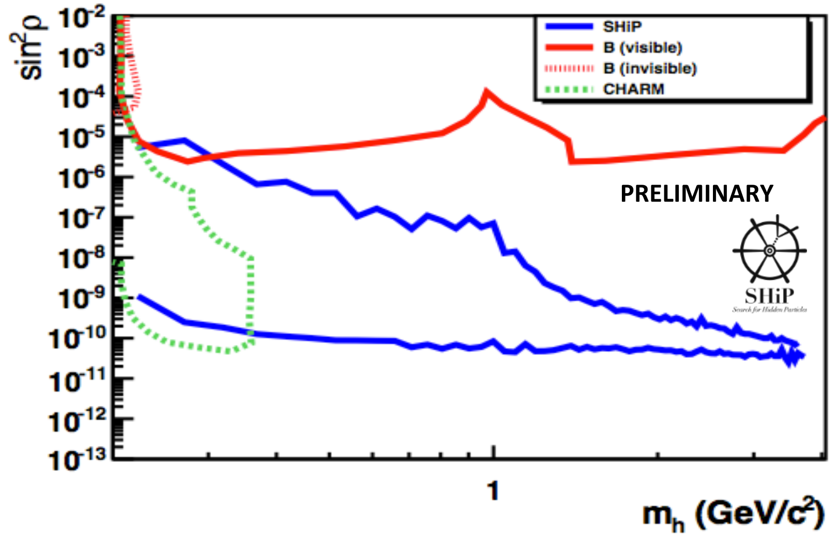
- ✓ ***Ultimate see-saw limit is almost in reach***
  Would require increase of the SPS intensity by an order of magnitude (does currently not seem realistic)

Some SHiP sensitivities: hidden particles

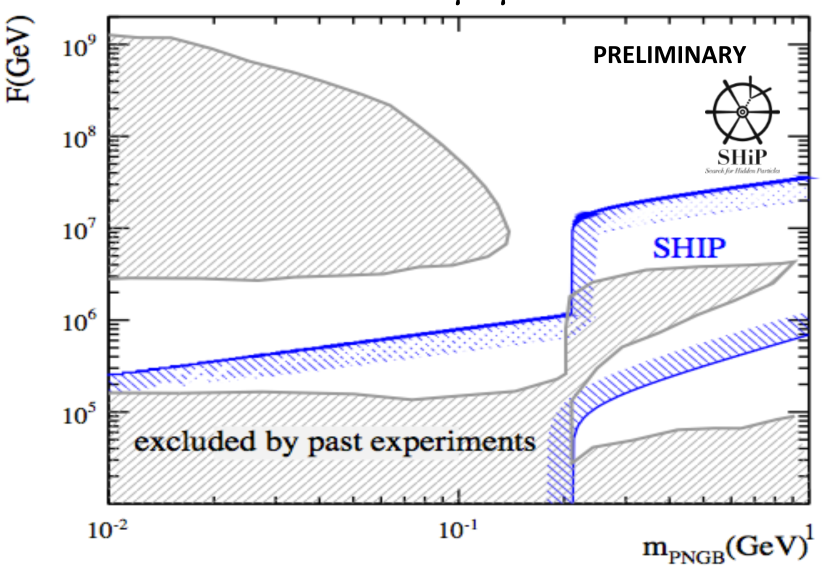
Dark photon: e^+e^- & $\mu^+\mu^-$



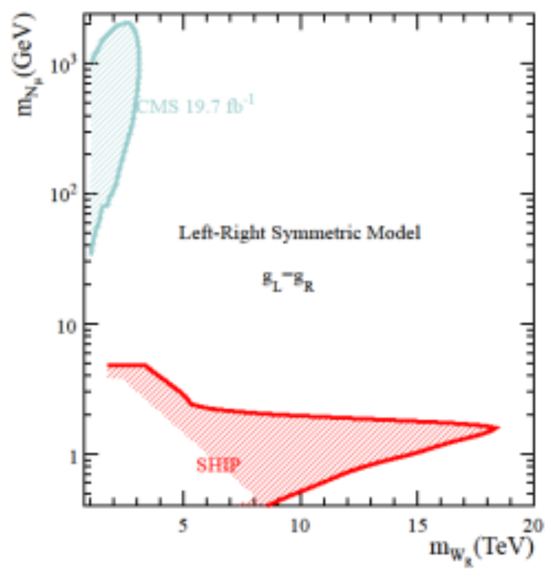
Dark scalar: $\mu^+\mu^-$



PNGB: e^+e^- & $\mu^+\mu^-$

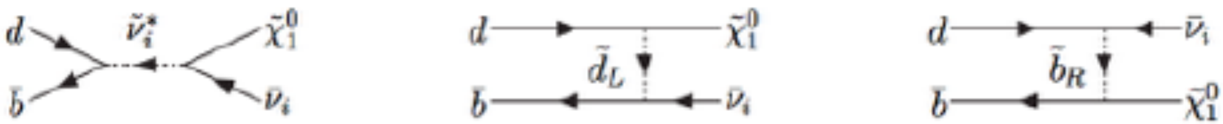


HNL in left-right symmetric models

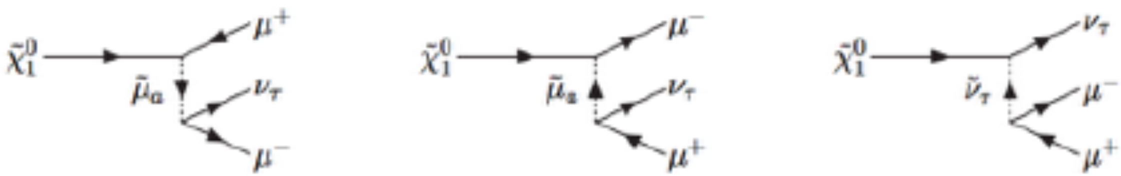


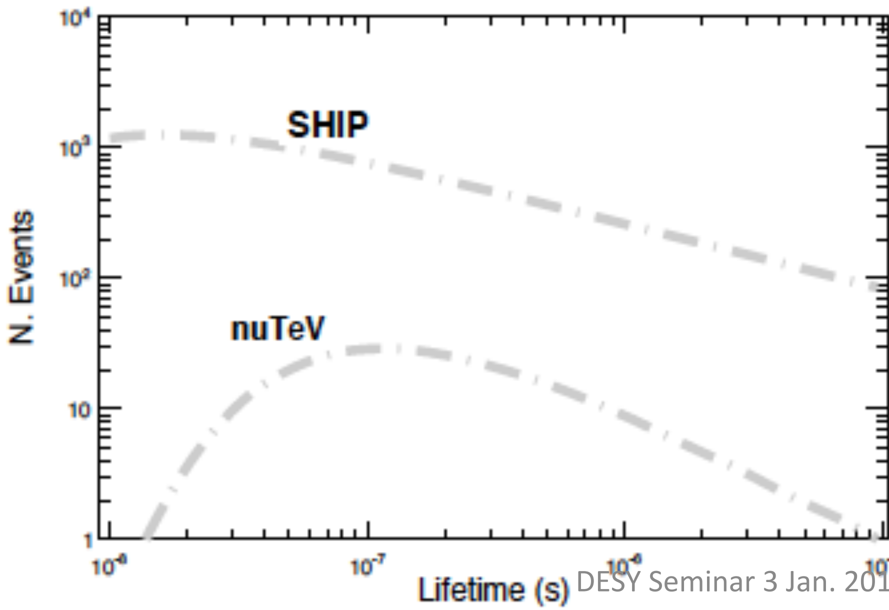
Some SHiP sensitivities: low mass SUSY

Light neutralinos produced in B and D decays, e.g. $B^0 \rightarrow \nu\chi_0$ *or* $B^+ \rightarrow \mu^+ \chi_0$



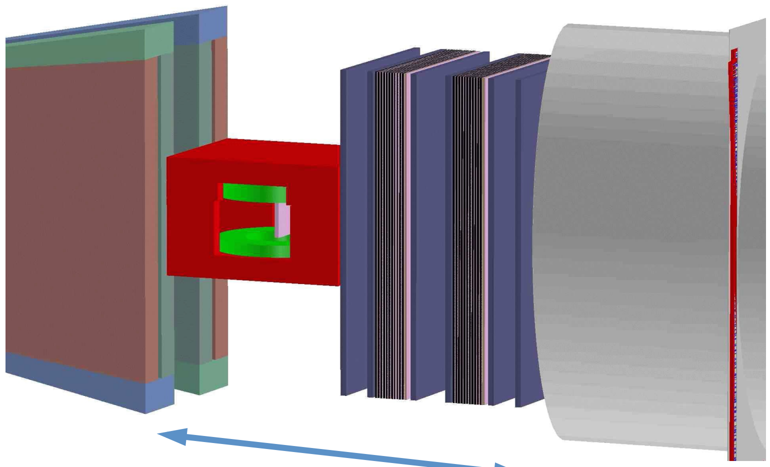
then decays:

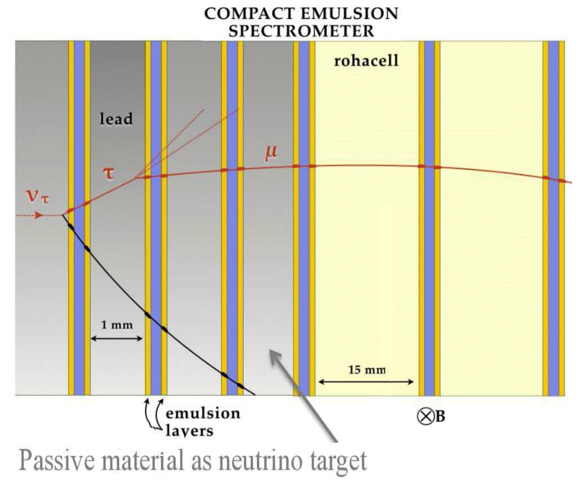




Sensitivity studies in progress

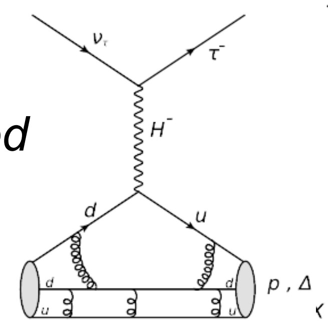
SM physics with SHiP: prospects for $\nu_\tau (\nu_e, \nu_\mu)$

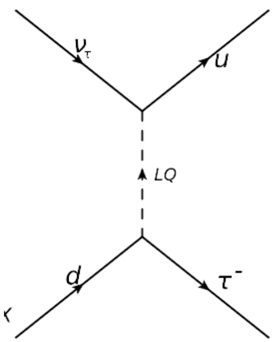




- ✓ *Expect O(4000) $\nu_\tau / \overline{\nu_\tau}$ interactions in 6 tons emulsion target with 2×10^{20} pot*

- ✓ ***Physics aims:***
  - *First observation of $\overline{\nu_\tau}$*
  - *$\nu_\tau / \overline{\nu_\tau}$ cross-section measurements*
  - *Extraction of F_4, F_5 structure functions never measured so far*
  - *Measurement of charm hadron production in $\overline{\nu_\tau}$ interactions will improve understanding of the strange quark content of nucleons*
  - *Measurement of the ν_e production in charmed hadron decays will also provide normalization for measurements of long lived HP*

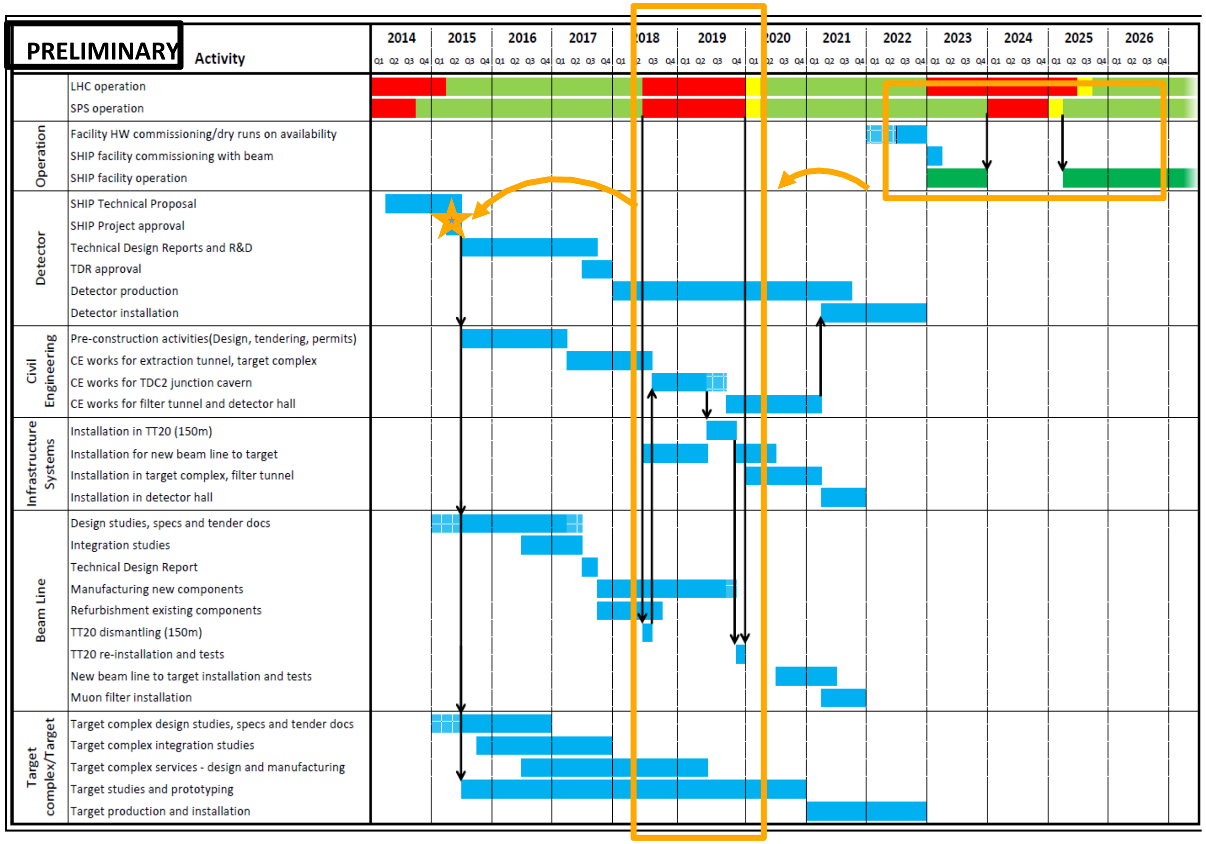


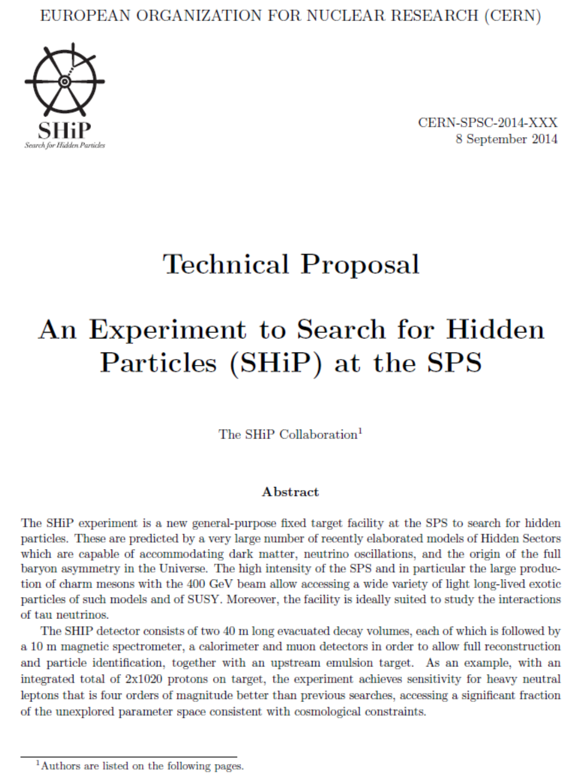


Some history and current status

- ✓ *Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010*
- ✓ *January 2014: EOI discussed at SPSC*
  - *Encouraged to produce "an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration."*
- ✓ *Work towards Technical Proposal in full swing*
  - *Extension of physics program*
  - *Signal background studies and optimization*
  - *Detector specification, simulation and even some detector R&D*
  - *Optimization of Experimental Facility - beam line, target, and muon filter, RP, overall layout*
- ✓ *1st SHiP Workshop in Zurich in June with a 100 experimentalists and theorists*
  - *41 institutes from 14 countries expressed interest to contribute to the Technical Proposal*
- ✓ *2nd SHiP Workshop/Collaboration meeting at CERN September 24-26*
  - *Revise progress in Working Groups towards Technical Proposal*
  - *Extend physics for a general purpose facility: Tau neutrino, LFV and direct Dark Matter search*
- ✓ *3rd SHiP Collaboration meeting at CERN December 15*
  - *Revise progress towards TP and Physics ProposalFormalize Collaboration as proposed by CERN management with 44 institutes (14 countries)*
- ✓ *4th SHiP Collaboration meeting in Naples, February 9-11*
  - *Finalize contents and decision for TP, first raw draft ready*

Next steps: schedule of the SHIP facility





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.

[1] Authors are listed on the following pages.

A few milestones:

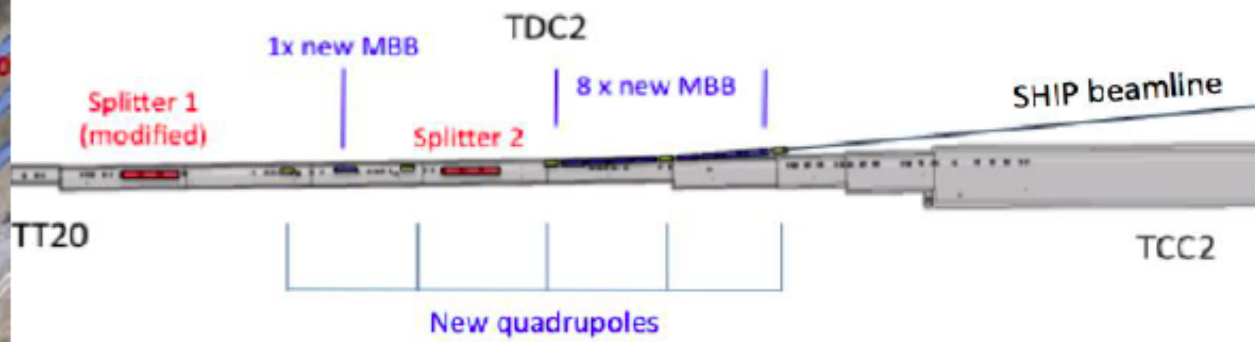
- ✓ **Technical proposal** → **March 2015**
- ✓ **CERN to decide on the strategy for the SHIP beam within a year after TP submission**
- ✓ Technical Design Report → 2018
- ✓ Construction and installation → 2018 – 2022
- ✓ Data taking and analysis of 2×10^{20} pot → 2023 – 2027++

Summary

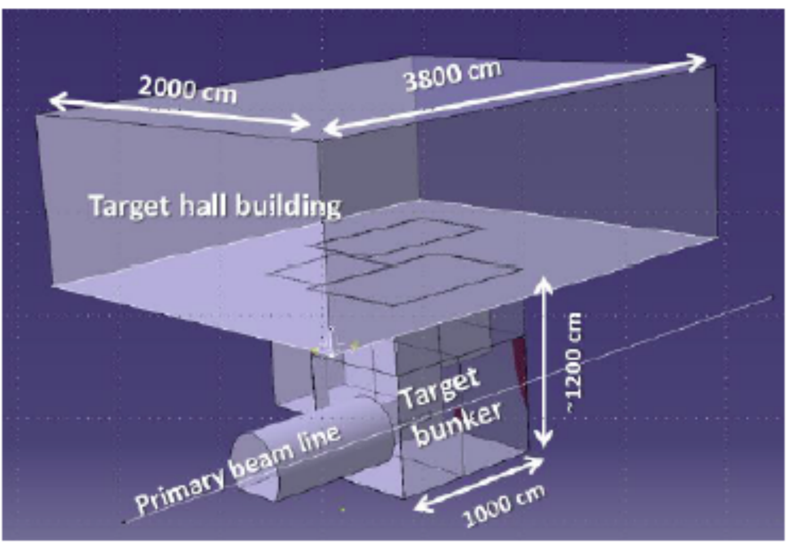
- ✓ *SHiP is proposed to search for NP in the largely unexplored domain of new, very weakly interacting particles with masses below charm*
- ✓ *Also unique opportunity for ν_τ physics*
- ✓ *Sensitivity improves previous experiments by O(10000) for hidden particles and by O(200) for ν_τ physics*
- ✓ ***The impact of the discovery of a new light hidden particle is hard to overestimate !***
- ✓ *SHiP will complement searches for NP at energy frontier and in neutrino physics*

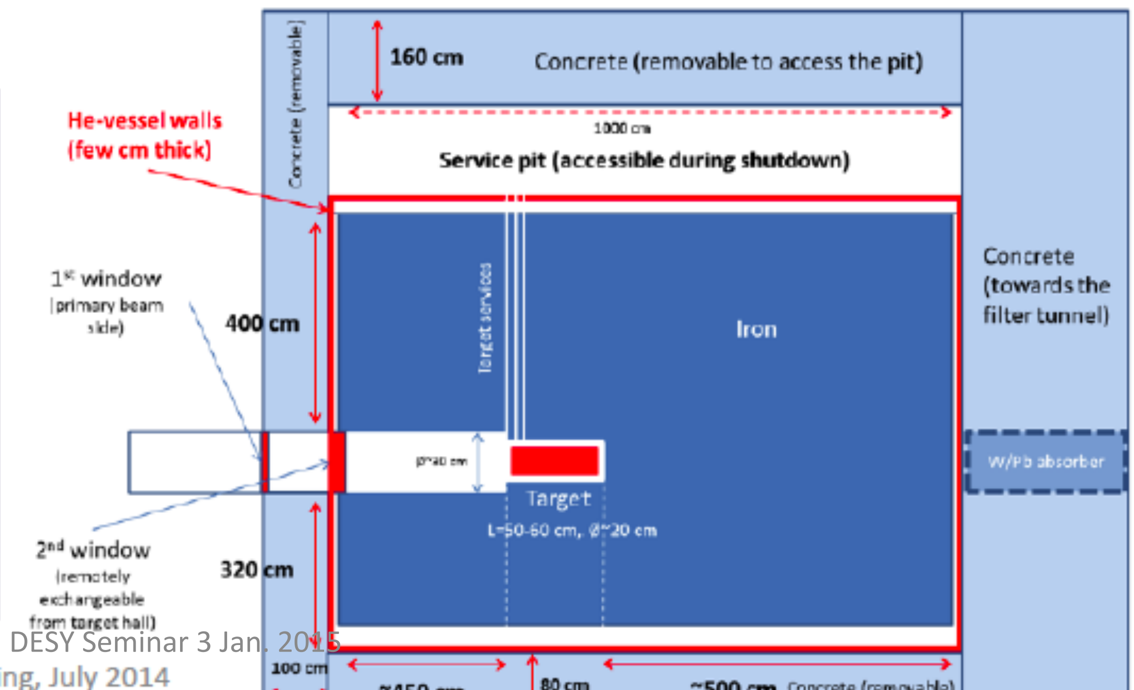
BACK UP SLIDES

SHIP experimental area



Detailed civil engineering and target station plan evaluated by relevant CERN divisions





PPAP community meeting, July 2014

Higgs portal observables *(inflaton)*

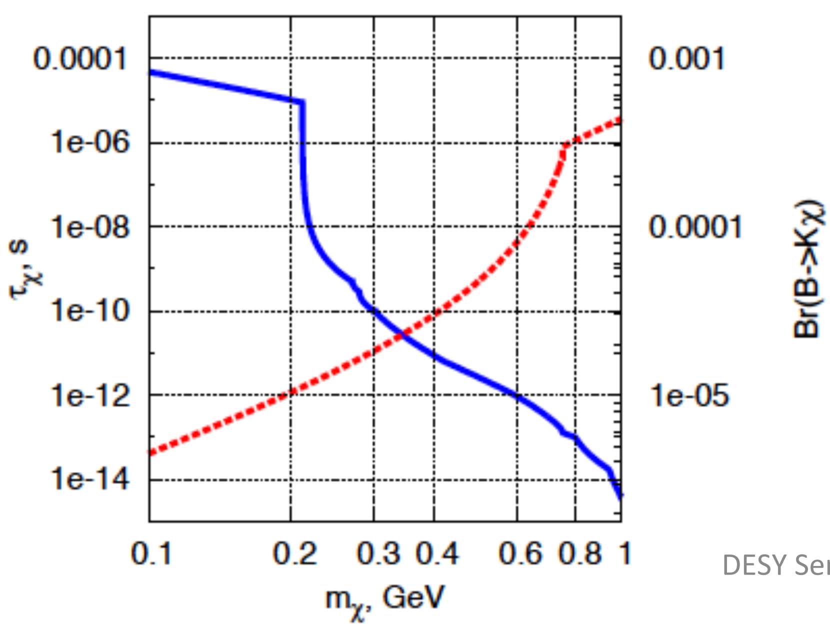
$$(\mu\chi + \lambda\chi^2)H^\dagger H + L_{SM} + L_{hidden}$$

If $\mu << v$, the new scalar χ may be long-lived

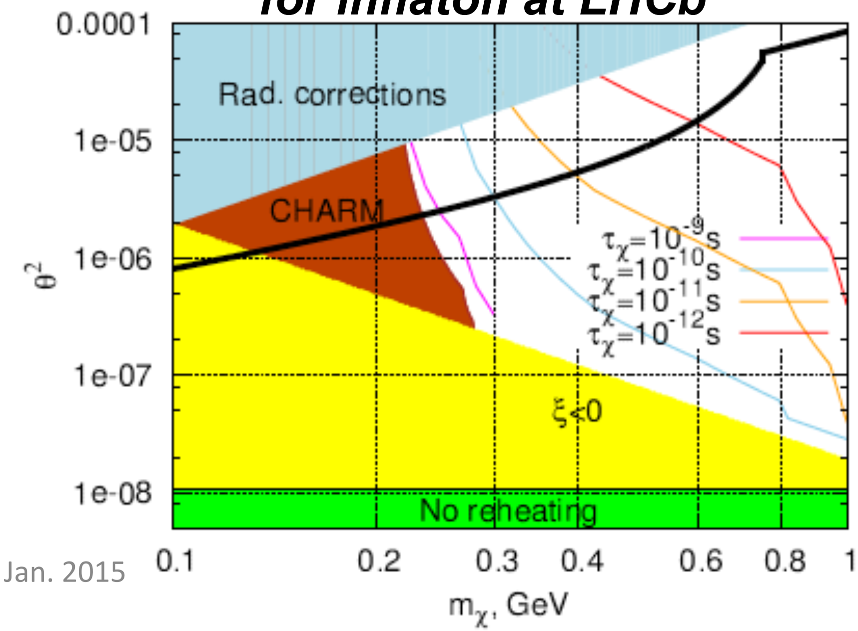
- Direct production $p + \mathbf{target} \to Y + \chi$
- Production via intermediate (hadronic) state

  $p + \mathbf{target} \to \mathbf{mesons} + ...,$ and then hadron$\to \chi + ...$
- Subsequent decay of χ to SM particles
- *Recent example – a model to produce 7 keV N_1 (DM candidate) and inflate the Universe in accordance with BICEP and Planck*

arXiv:1403.4638, Bezrukov, Gorbunov

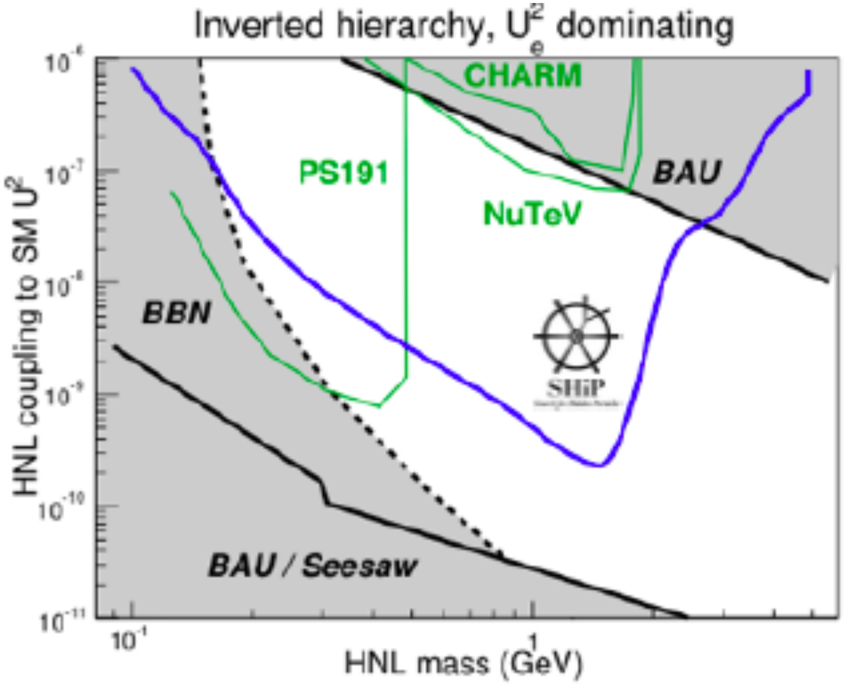


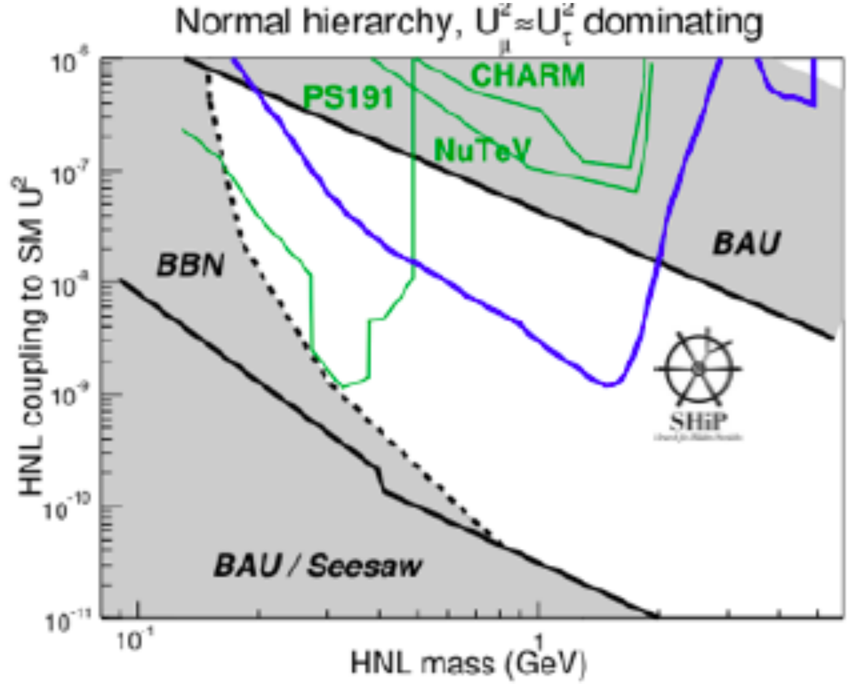
Synergy with search for inflaton at LHCb



- $D_s \to \ell N$ — $U^2_{\mu,e}$ and $N_N \leq M(D_s) - m_\ell$
- $D \to \ell K N$
- $D_s \to \tau \nu_\tau,\ \tau \to X \nu_\tau$ — U^2_τ and $N_N \leq M(\tau) - M(X)$
- $B_{(s)} \to D_{(s)} \ell N$ — $U^2_{\tau,\mu,e}$ and $N_N \leq M(B_{(s)}) - M(D_{(s)}) - m_\ell$
- $B \to \ell N$ $(B \to \pi \ell N)$ — $U^2_{\tau,\mu,e}$ and $N_N \leq M(B_{(s)}) - m_\ell$

  $\mathcal{BR} \propto V^2_{ub}/V^2_{cb}$





IV $U_e^2 : U_\mu^2 : U_\tau^2 \approx 48 : 1 : 1$, inverted hierarchy

V $U_e^2 : U_\mu^2 : U_\tau^2 \approx 1 : 11 : 11$, normal hierarchy

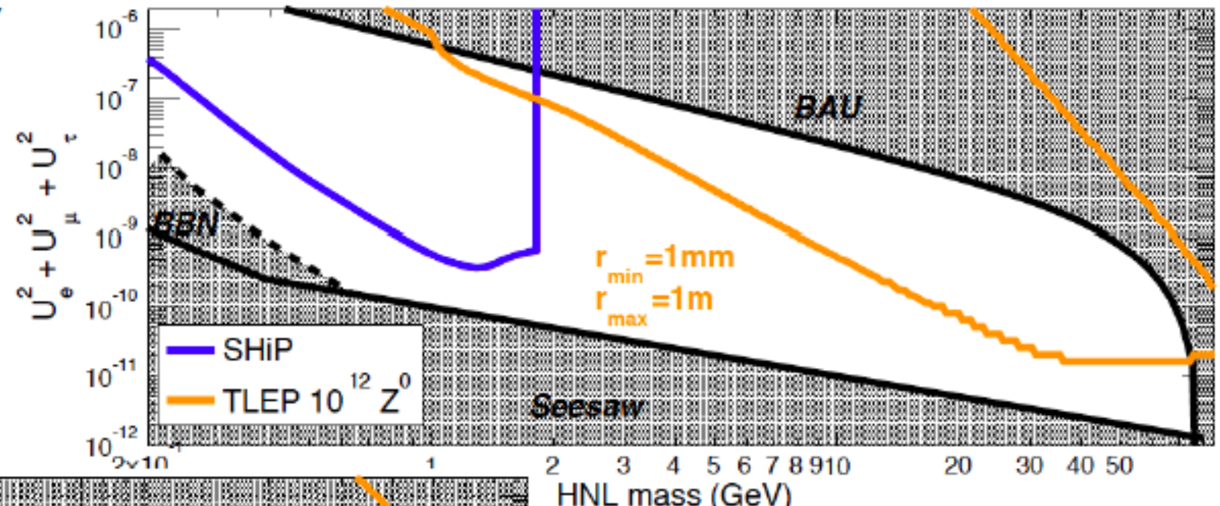
How to extend sensitivity to higher masses

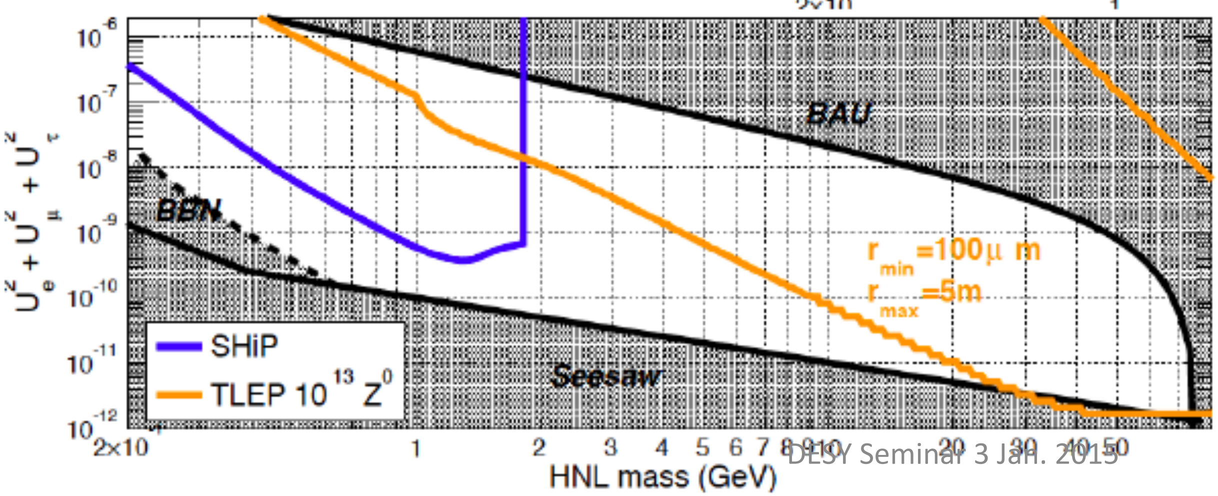
- ✓ *Use processes $Z \rightarrow N\nu$ with $N \rightarrow$ lepton + 2 jets*

$$BR(Z \rightarrow \nu N) \cong BR(Z \rightarrow \nu\nu)\times U^2, \quad \Gamma_N \cong G_F^{\,2}\times M_N^{\,5}\times U^2\times N_{decay\ channels} / 192\pi^3$$

- ✓ *Assuming data sample of 10^{12} Z decays one can reach very interesting sensitivity for $M_N > 10$ GeV*

- ✓ *Expected sensitivity of FCC in e^+e^- mode assuming zero background*





Courtesy of A.Blondel, E.Graverini, N.Serra and M.Shaposhnikov