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SHiP: Search for Hidden Particles

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Interplay between Particle and Astrophysics 2014

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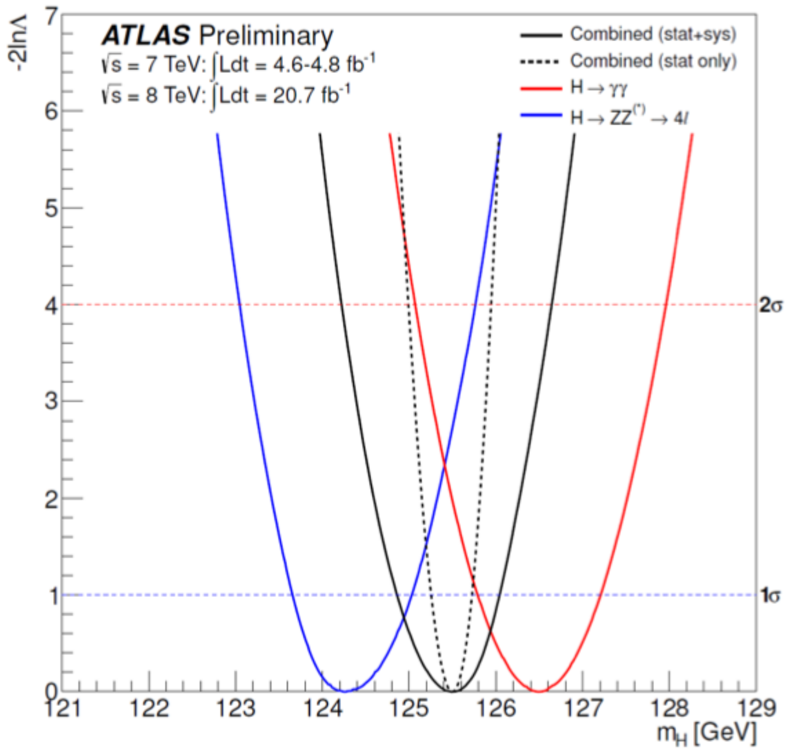
Outline

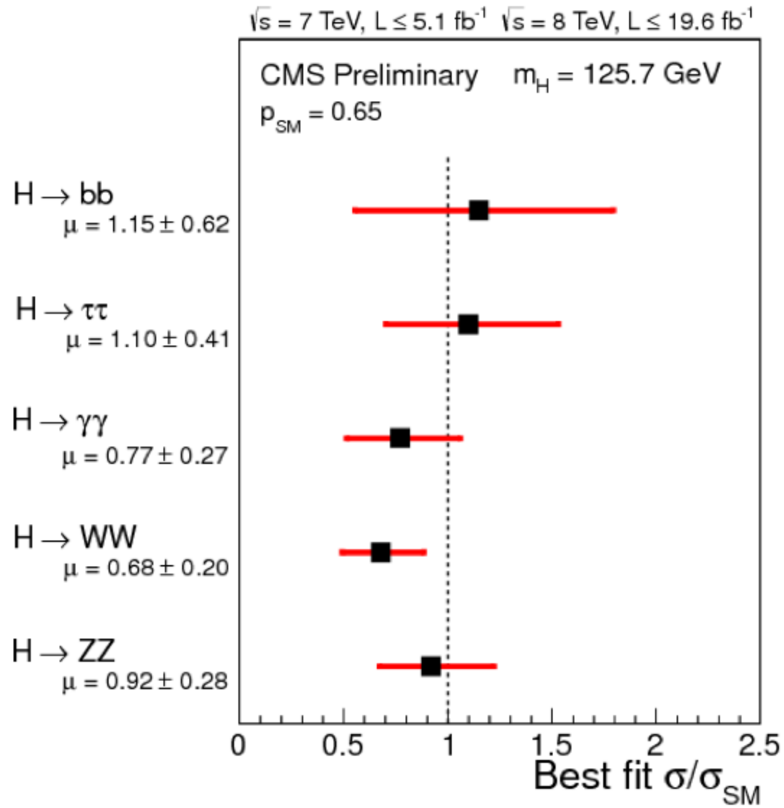
- The physics landscape
- Hidden sector theories – the neutrino minimal Standard Model
- Design of a new beam-dump experiment
- Sensitivity and future plans

The triumph of the Standard Model

- Boson consistent with the SM-Higgs has been found!

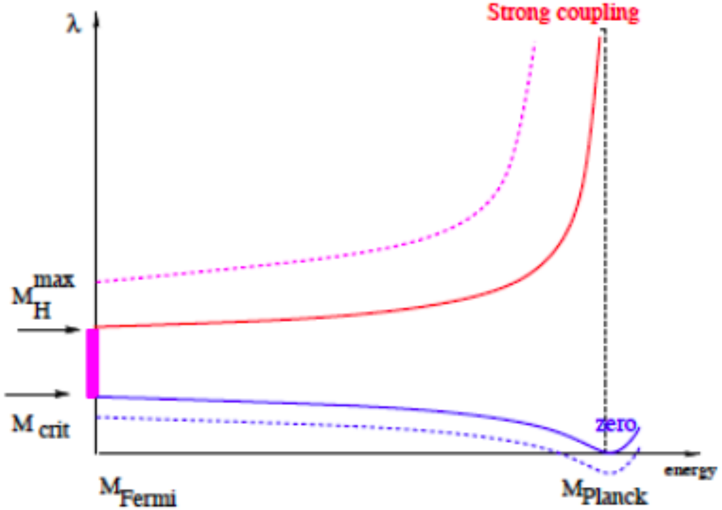
- ATLAS : M_H=125.5 ± 0.2 (stat) $^{+0.5}_{-0.6}$ (syst) GeV
- CMS: M_H=125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

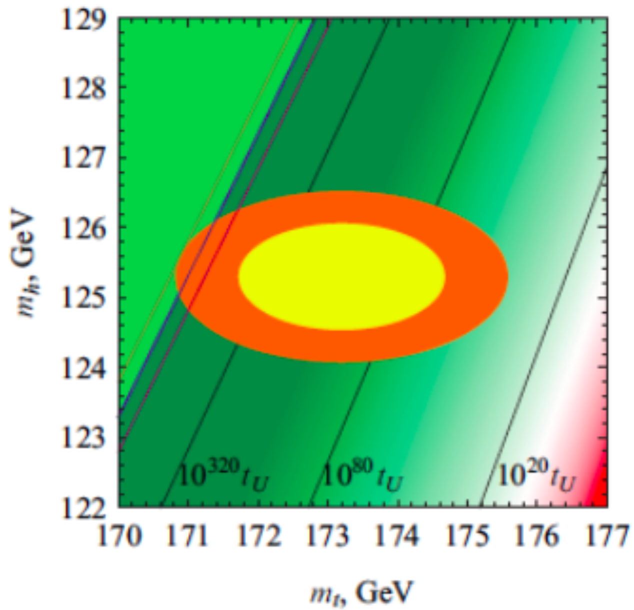




The triumph of the Standard Model

- Mass value important for the stability of the vacuum:
  - M_H < 175 GeV → SM weakly coupled 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.*)





- But we still have a number of significant problems
  - Theory : radiative corrections to Higgs mass → fine-tuning
  - Experiment: Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter

Unfortunately…

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int \mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

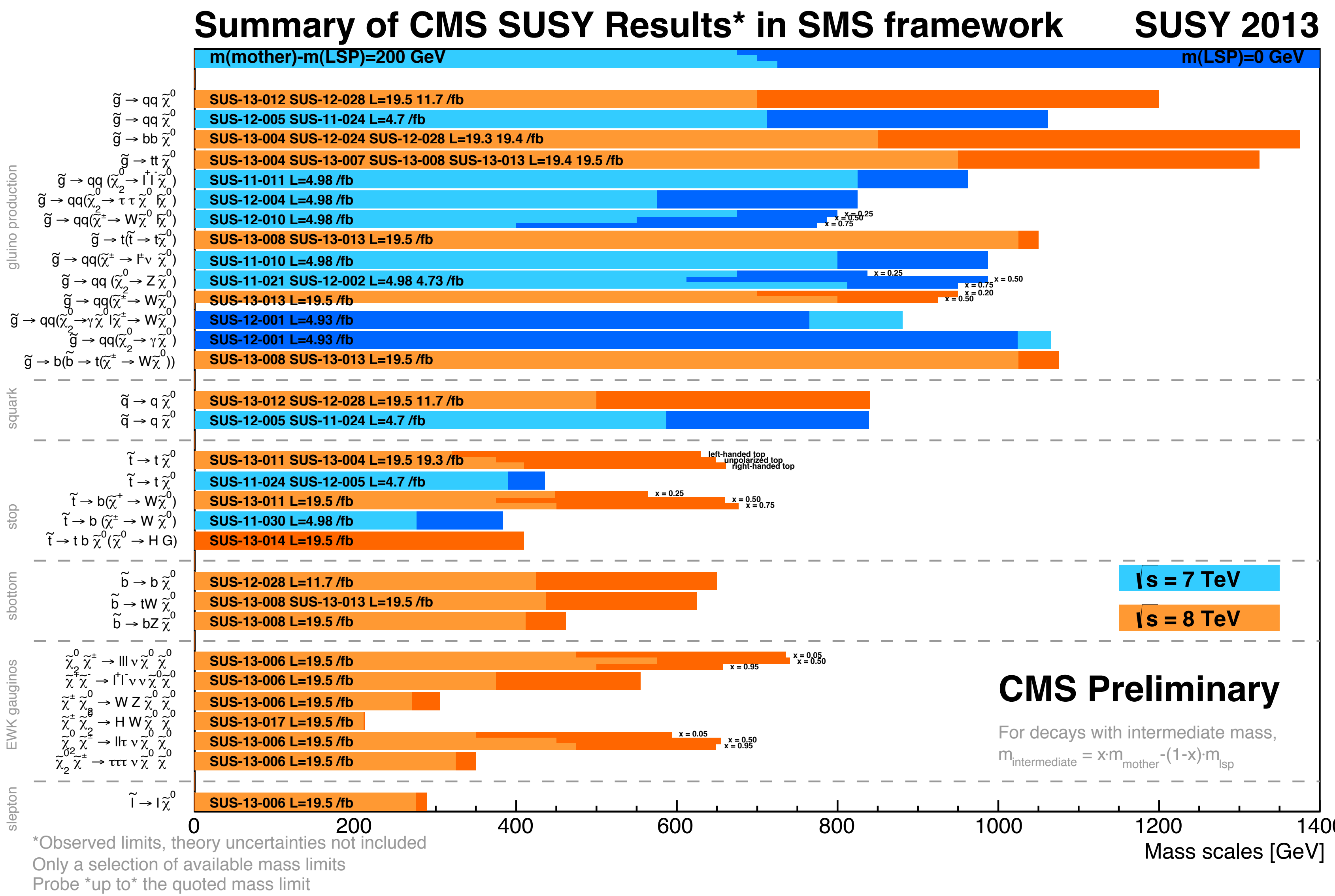
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt$ [fb^{-1}]		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$	1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Unfortunately…



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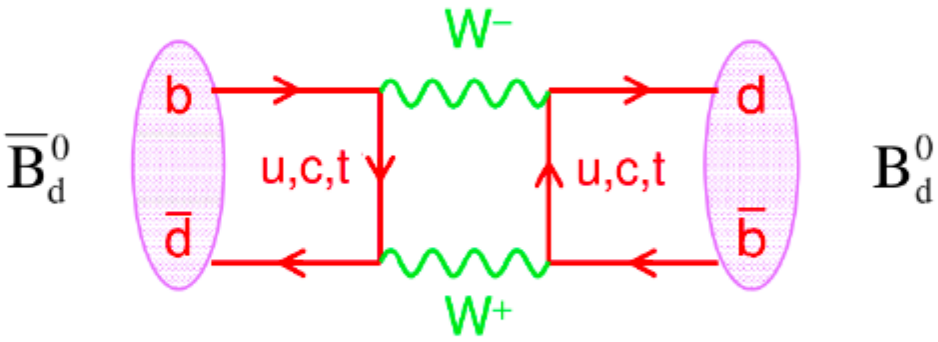
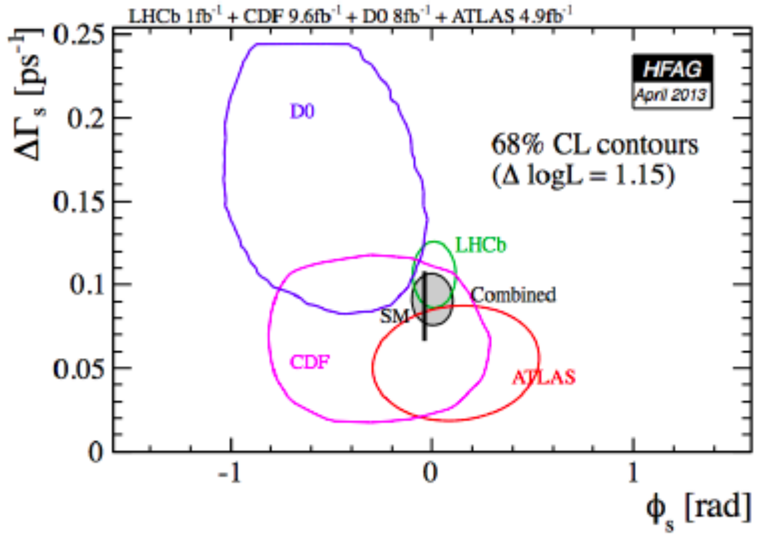


$$M(B_d\text{–}\bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP}\frac{1}{\Lambda^2}$$



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]

Outline

- The physics landscape
- Hidden sector theories – the neutrino minimal Standard Model
- Design of a new beam-dump experiment
- Sensitivity and future plans

A hidden sector?

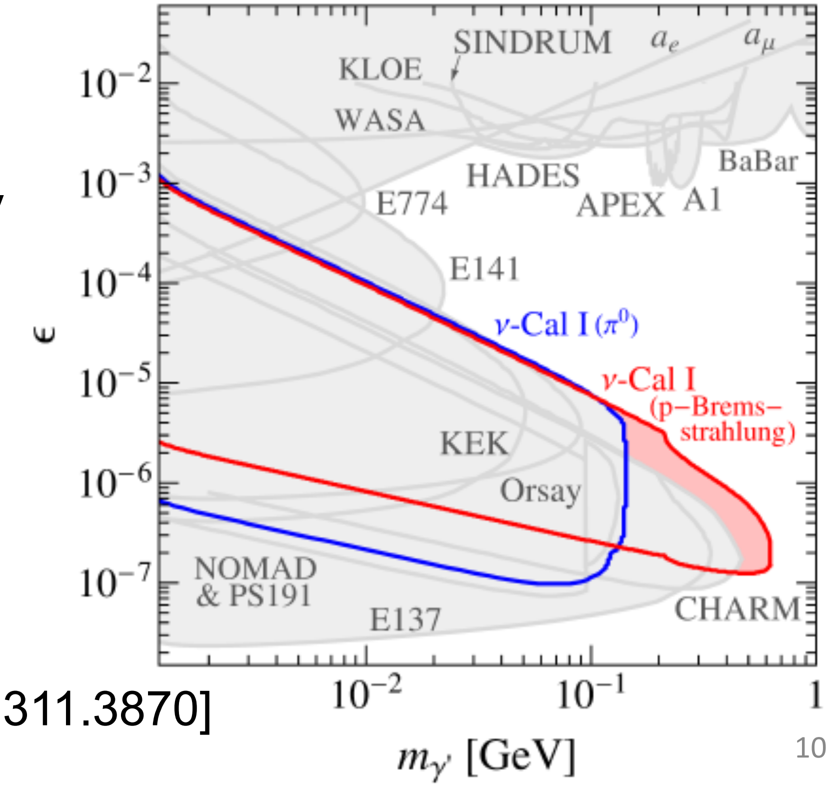
- Rather than being heavy, could new particles be light but *very* weakly interacting?

- e.g. new, light "hidden sector" of particles which are singlets wrt gauge group of the SM

- Several possibilities for renormalisable singlet operators which each involve some hidden sector particle **mixing** with some SM "portal particle" :
  - **Vector portal** – new U(1) $B_{\mu\nu}$ – massive vector photon (paraphoton, secluded photon…) mixing with regular photon → $\varepsilon B_{\mu\nu}F^{\mu\nu}$
  - **Higgs portal** – new scalar field χ → $(\mu\chi+\lambda\chi^2)H'H$
  - **Axial portal** – new axial-vector field a – Axion Like Particles (to distinguish from Peccei–Quinn axion) → $(a/F)G_{\mu\nu}G^{\mu\nu}$, $(\delta_\mu a/F)\psi'\gamma_\mu\gamma_5\psi$
  - **Neutrino portal** – new heavy neutral leptons (HNL) → $YH^TN'L$

Vector Portal

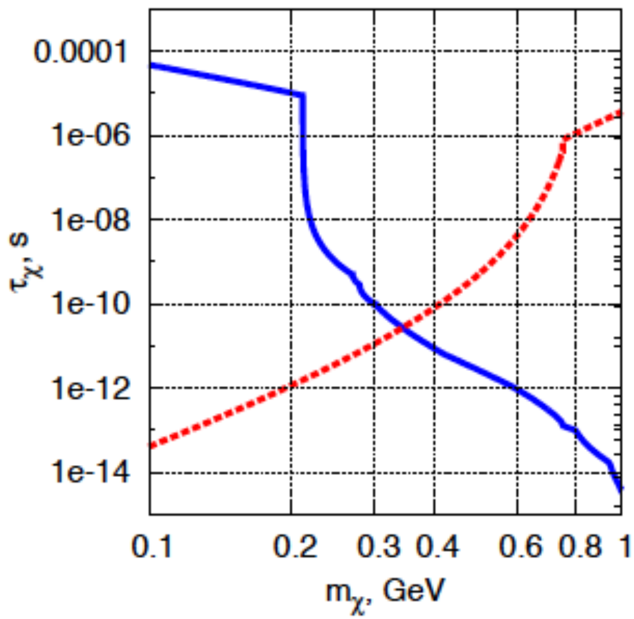
- Motivated by range of astrophysical observations e.g. positron excess, excess annihilation in the galactic centre (see e.g. arXiv:0810.0713)
- Experiments can produce a virtual photon in fixed-target, mixes into a dark photon (~ε), dark photon mixes back into a SM photon (~ε) then decays into e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ etc.
- As dark photon has no other interactions with SM particles - can fly through material : "light-shining-through-a-wall" experiments
- Constraints from a wide range of experiments – note results from CERN CHARM experiment

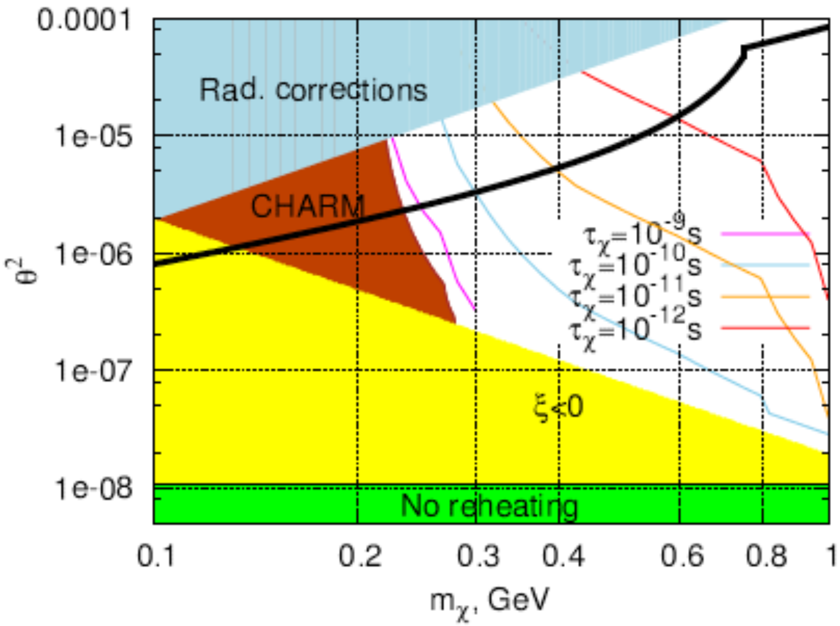


[arXiv:1311.3870]

Higgs Portal

- [arXiv:1403.4638] gives example of the inflaton – new scalar which, together with the Higgs, generates inflation of the early Universe
- Model has a 7 keV (warm) DM candidate and paper claims that model respects constraints from BICEP2 and Planck
- Interesting mass region 0.3 GeV < m_χ < 1 GeV
- Little experimental exploration of interesting region…

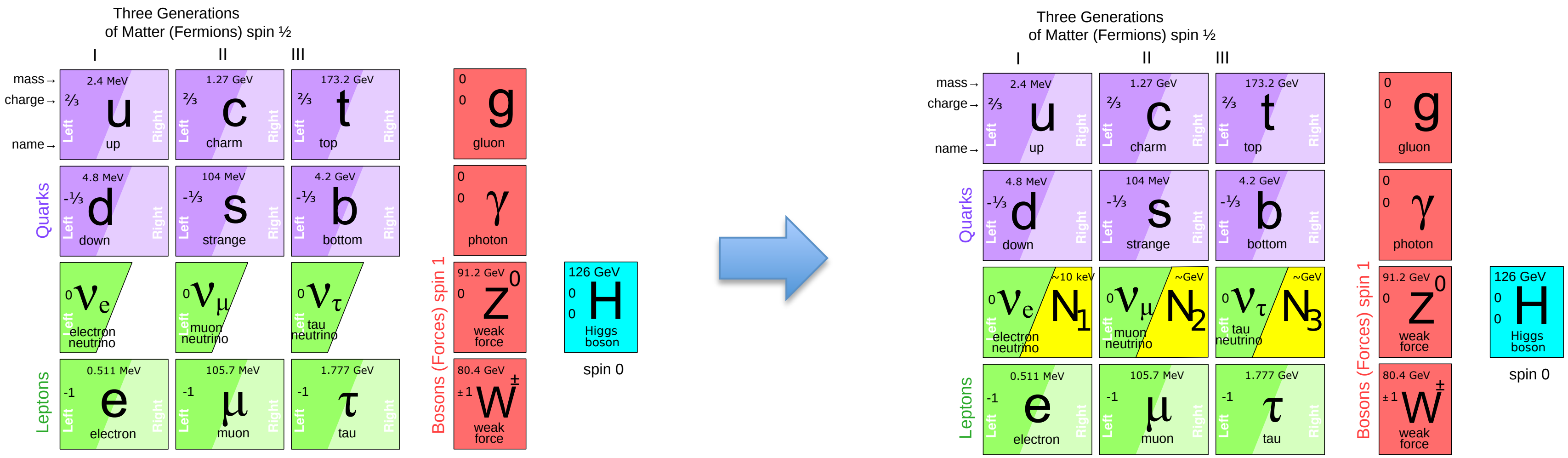




Neutrino Portal

- The **neutrino Minimal Standard Model** (**νMSM**) [T.Asaka, M.Shaposhnikov, Phys. Lett B620 (2005) 17] aims to explain
  - Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter

by adding three right-handed, Majorana, Heavy Neutral Leptons (HNL), **N_1, N_2 and N_3**



- **N_1** – mass in keV region, (warm) dark matter candidate
- **$N_{2,3}$** – mass in 100MeV – GeV region – generate neutrino masses via see-saw mech. and produce baryon asymmetry of the Universe

Constraints on N_1 as DM

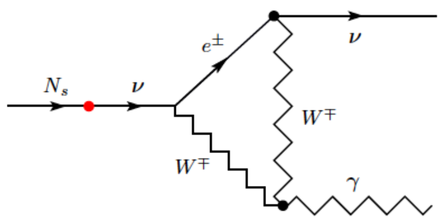
- **Stability** → **N_1** must have a lifetime larger than that of the Universe
  - Small yukawa couplings mean that N_1 can be very stable

- **Production** → **N_1** are created in the early Universe in reactions ll→ νN_1 , qq→νN_1 etc. Need to provide correct DM abundance

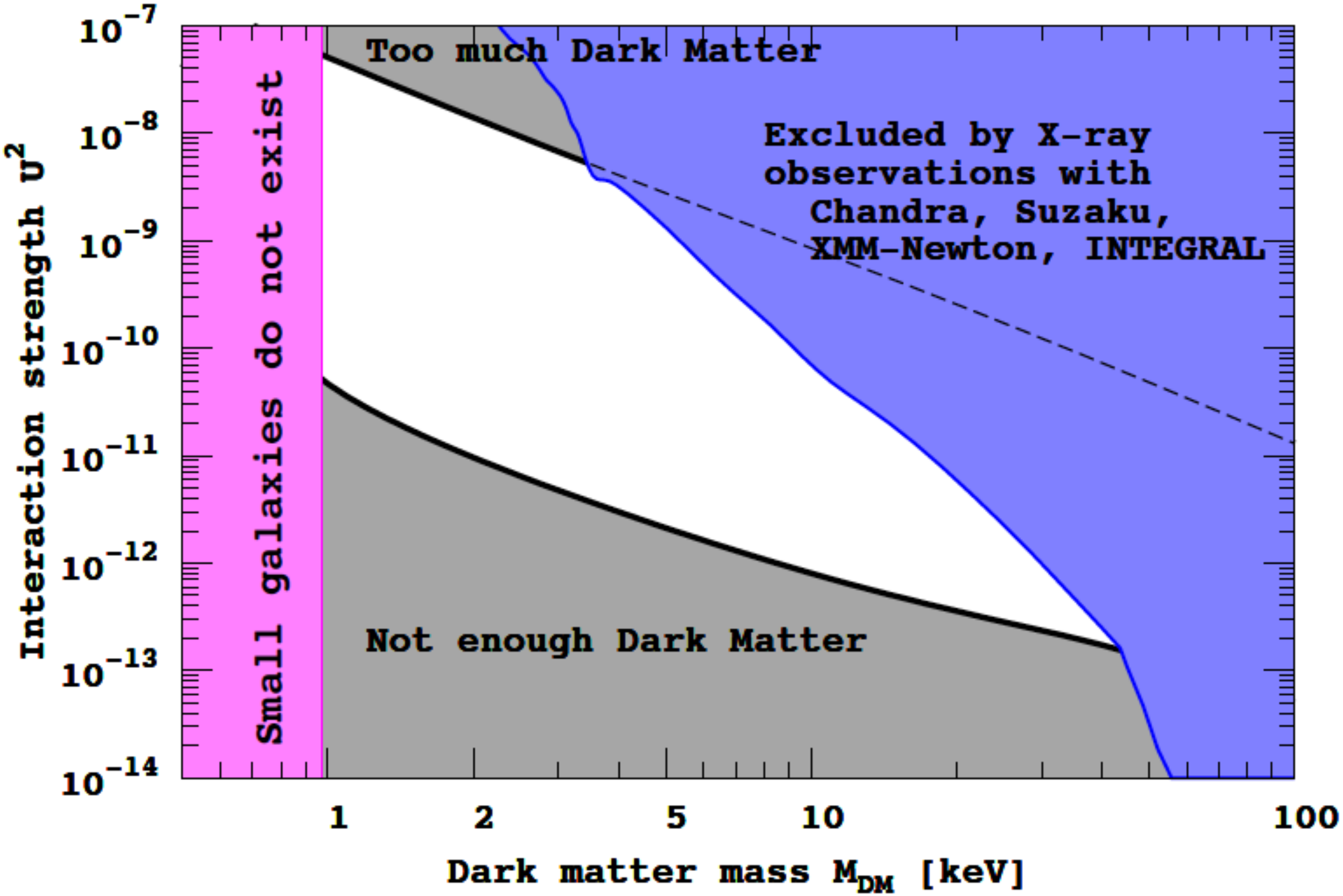
- **Structure formation** → **N_1** should be heavy enough so it does not erase non-uniformities at small scales

- **Decay** → **N_1** should not produce decays we have already excluded!
  - Main decay mode **$N \to 3\nu$,** clearly unobservable
  - Subdominant radiative decay **$N \to \nu\gamma$** would give a monoenergetic photon with **$E_\gamma = M_N/2$**

    [some claims such a photon has been seen see e.g. arXiv:1402.4119, arXiv:1402.2301]



N_1 allowed parameter space

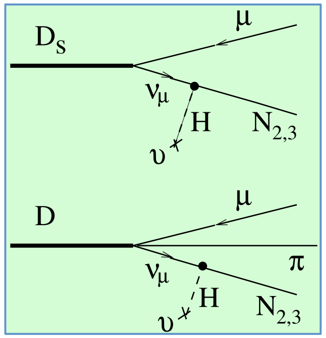


$N_{2,3}$ production and decay

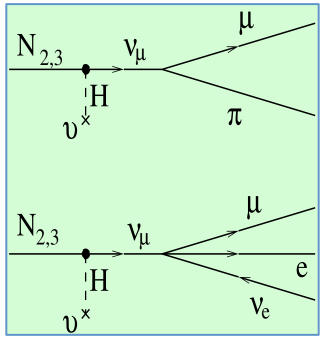
- **$M(N_2) \approx M(N_3)$ ~ a few GeV** → can dramatically increase amount of CPV to explain Baryon Asymmetry of the Universe (**BAU**)

- **Very weak $N_{2,3}$-to-ν mixing (~ U^2)** → **$N_{2,3}$** are much longer-lived than the SM particles
  - Typical lifetimes **>10 μs** for **($N_{2,3}$) ~ 1 GeV** → decay distance O(km)
  - too large U erases any BAU

- **$N_{2,3}$** can be produced in charm decays…

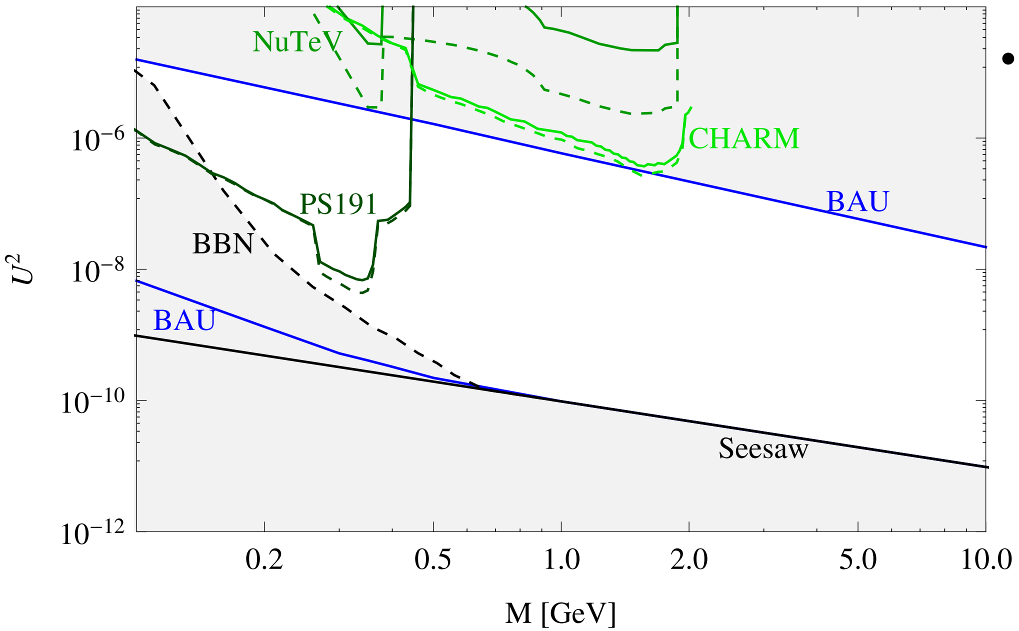


… and subsequently decay



Experimental and cosmological constraints

- Baryon Asymmetry of the Universe **(BAU), Seesaw** and Big Bang Nucleosynthesis (**BBN)** constraints indicate that previous expts probed the interesting region only below the kaon mass :

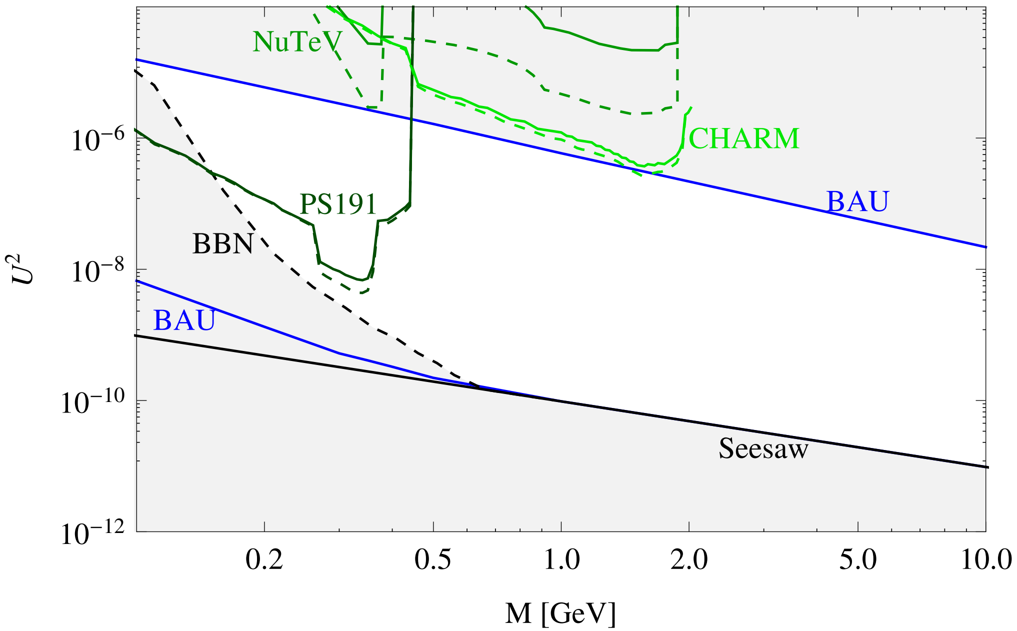


- Previous searches :
  - PS191('88)@PS 19.2 GeV 1.4×10^{19} pot, 128 m from target
  - CHARM('86)@SPS 400 GeV, 2.4×10^{18} pot, 480 m from target
  - NuTeV('99)@Fermilab 800 GeV, 2.5×10^{18} pot, 1.4 km from target

- **BBN, BAU** and **Seesaw** give stronger constraints than experimental searches for M_N > 400 MeV

Experimental and cosmological constraints

- Baryon Asymmetry of the Universe **(BAU), Seesaw** and Big Bang Nucleosynthesis (**BBN)** constraints indicate that previous expts probed the interesting region only below the kaon mass :



- Mixing at both production and decay
- For D mesons, typical BF expected in allowed νMSM parameter space then,

  $\mathbf{B_{D \to N} \sim 10^{-8} - 10^{-12}}$

- τ can give further factor $\mathbf{10^{-4}}$ **→ need >10^{16} D mesons!**

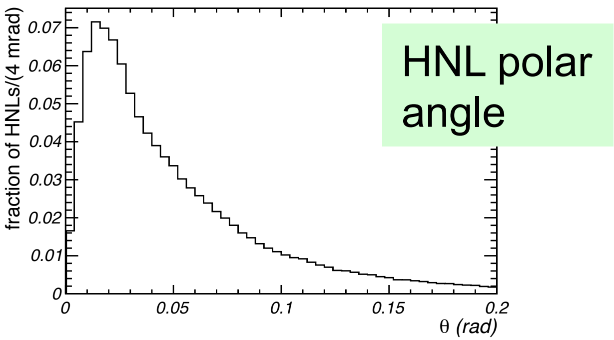
- Strong motivation to explore allowed space in region accessible with charm decays (m<2 GeV) but need >10^{16} D mesons!

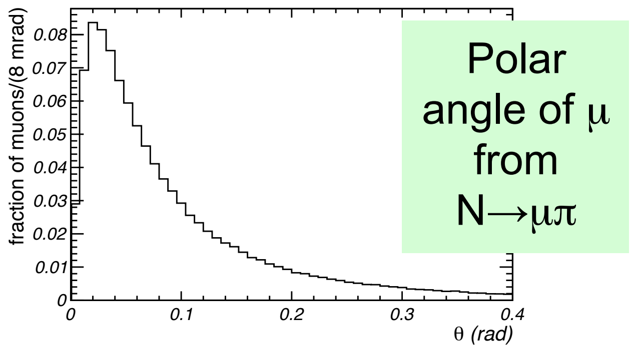
Outline

- The physics landscape
- Hidden sector theories – the neutrino minimal Standard Model
- Design of a new beam-dump experiment
- Sensitivity and future plans

Experimental design

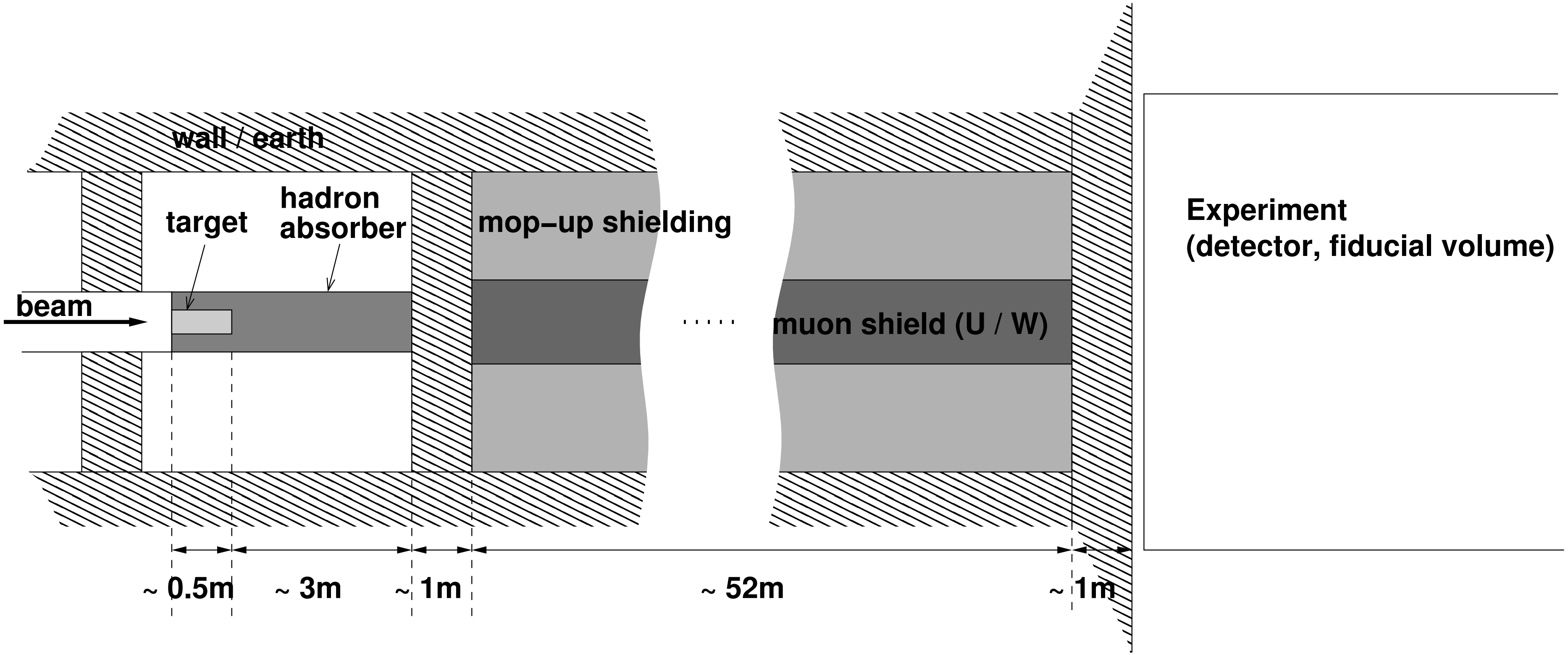
- Propose a beam dump experiment at the CERN SPS with a total of **$\sim 2\times10^{20}$ protons on target** (pot)
- Crucial design parameters: **residual neutrino and muon fluxes** - can produce e.g **K^0** that decay in detector and mimic signal events
  - Short-lived resonances generate **10^9** muons/spill → **muon shield**
  - Neutrinos from light meson decays → **dense target/hadron absorber/ evacuate decay volume**
- HNLs produced in charm decays have significant **p_T** :





  - Detector must be close to target to maximise geometrical acceptance
  - Shielding for muons must be as short as possible

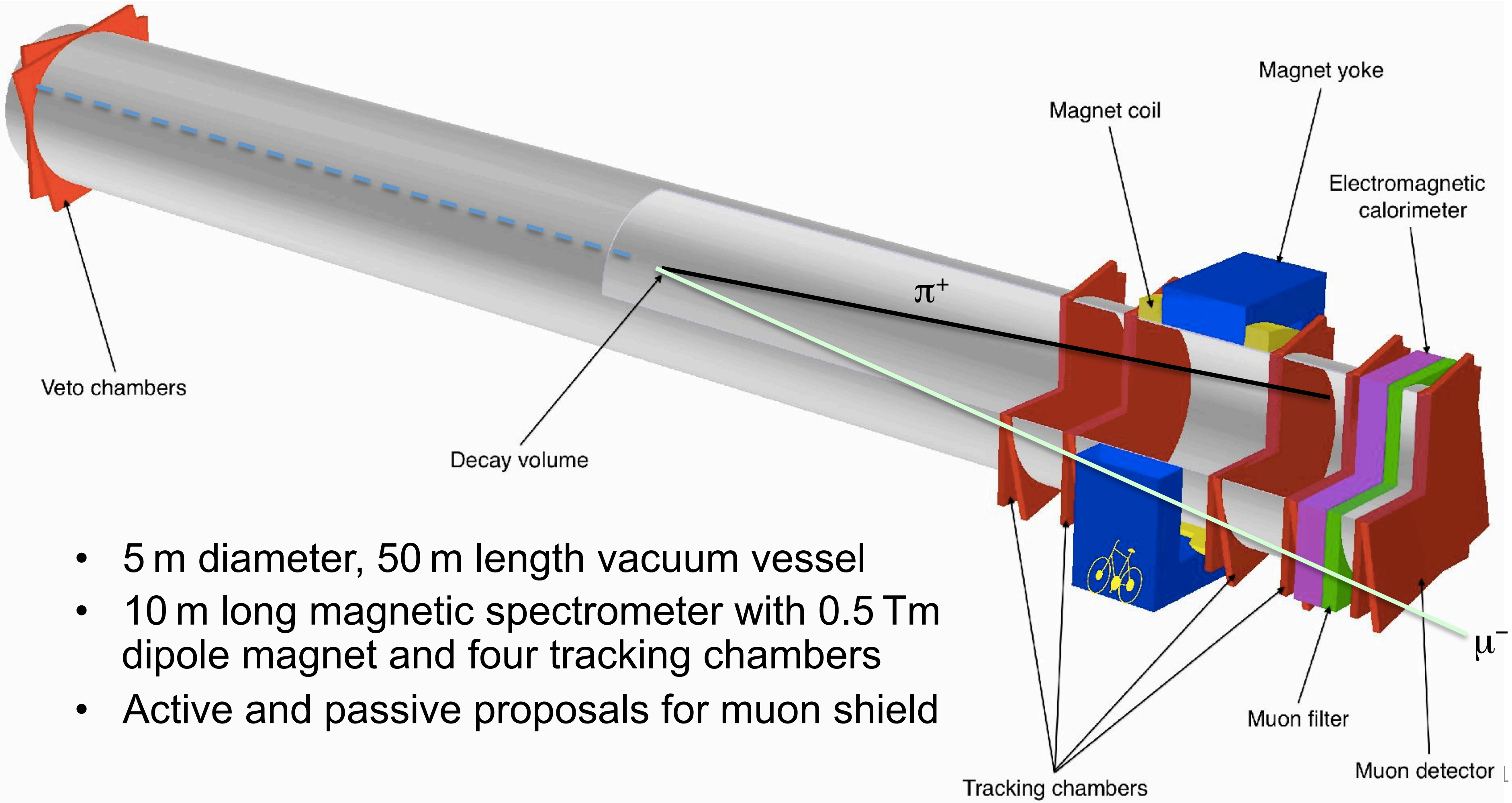
Secondary beam-line



- Proton target
  - Preference for relatively slow beam extraction O(s) to reduce detector occupancy
  - No requirement to have a small beam spot

Detector Concept

- Aim to reconstruct HNL decays into the final states: **$\mu^-\pi^+$, $\mu^-\rho^+$, $e^-\rho^+$**
- Require long decay volume, magnetic spectrometer, muon detector and EM calorimeter – **can all be made with existing technologies**



- 5 m diameter, 50 m length vacuum vessel
- 10 m long magnetic spectrometer with 0.5 Tm dipole magnet and four tracking chambers
- Active and passive proposals for muon shield

Status of the proposal

- Submitted our EOI in Oct 2013 [CERN-SPSC-2013-024 / SPSC-EOI-010 / arXiv:1310.1762]

- SPSC discussed our proposal Jan 2014, 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."

- From 17 authors of EOI → 43 groups from 15 countries expressed an interest to join

- Following SPSC review, CERN DG formed a dedicated Task Force to evaluate required infrastructure …

CERN task force

- Relevant CERN divisions have made detailed assessments of :
  - Target design
  - Radiological aspects
  - Civil engineering
  - Site selection
  - Costs and manpower requirements

- Task Force report published and discussed at the extended CERN directorate meeting in July ’14 → encouraged to prepare a technical proposal

- New CERN management in 2015!

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CERN
CH1211 Geneva 23
Switzerland

EN Engineering Department

Date : 2014-07-02

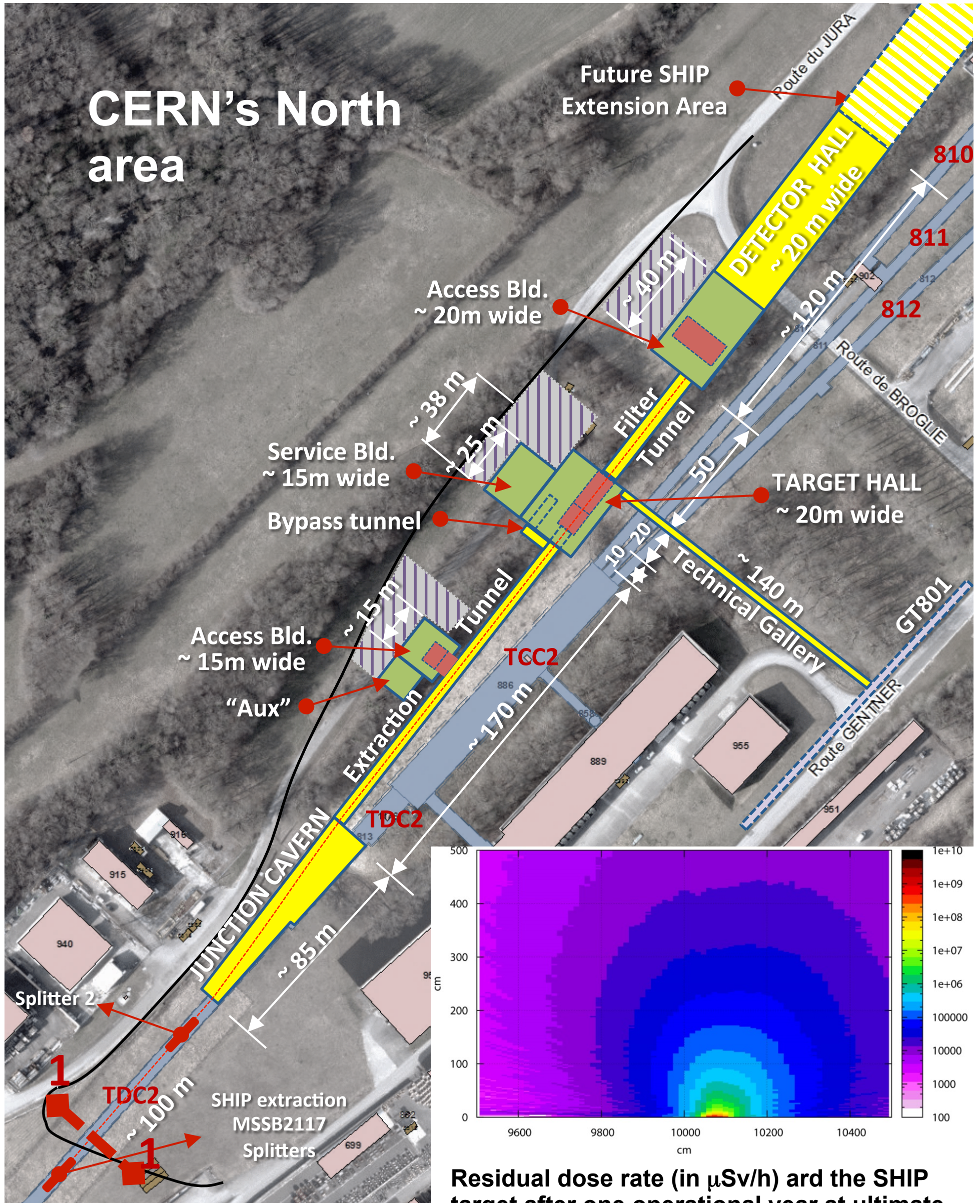
Report

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

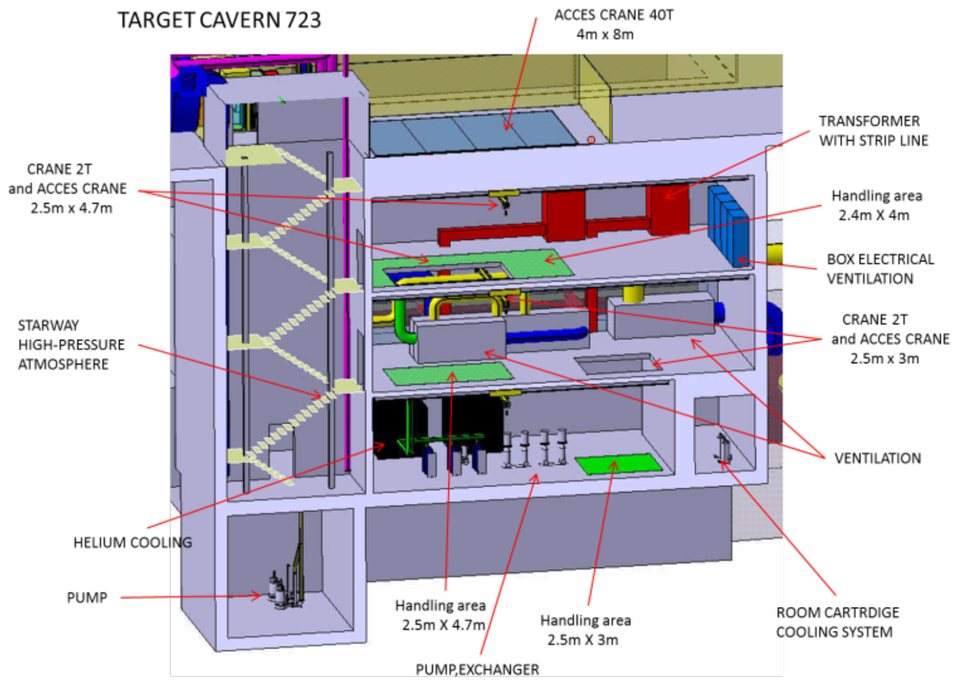
Preliminary Project and Cost Estimate

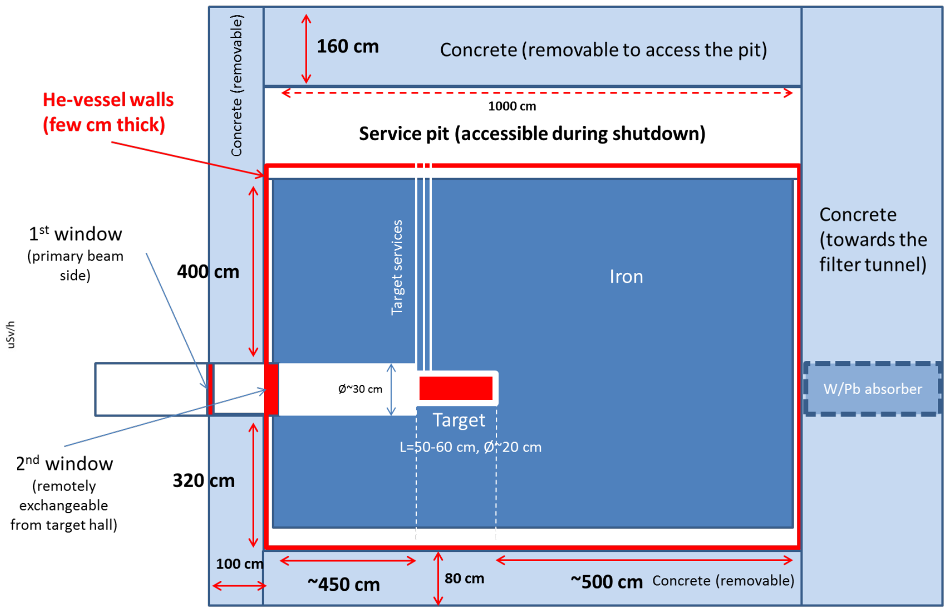
The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for Hidden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

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



Residual dose rate (in μSv/h) ard the SHIP target after one operational year at ultimate intensity and 1 month of cooling time

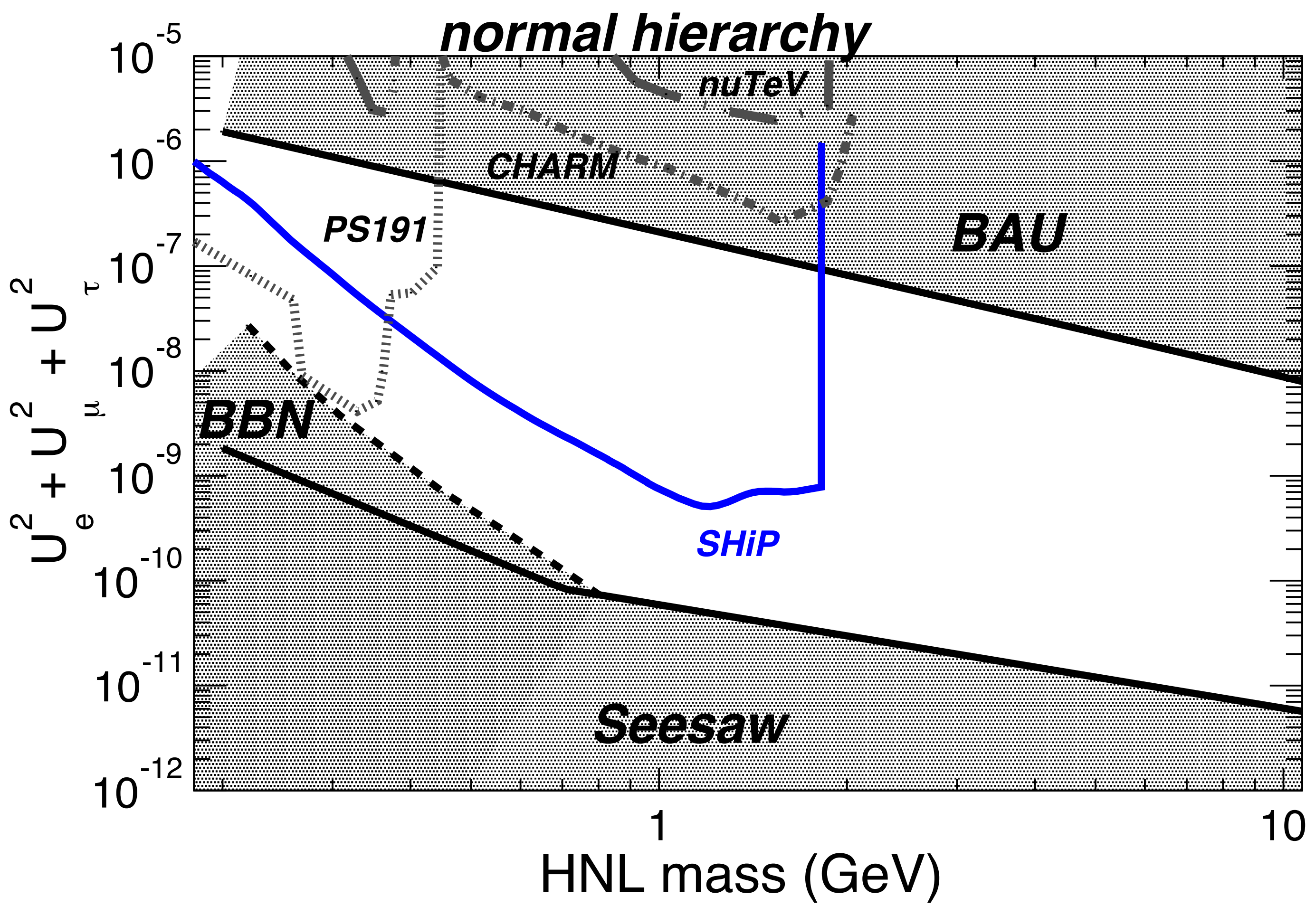




Outline

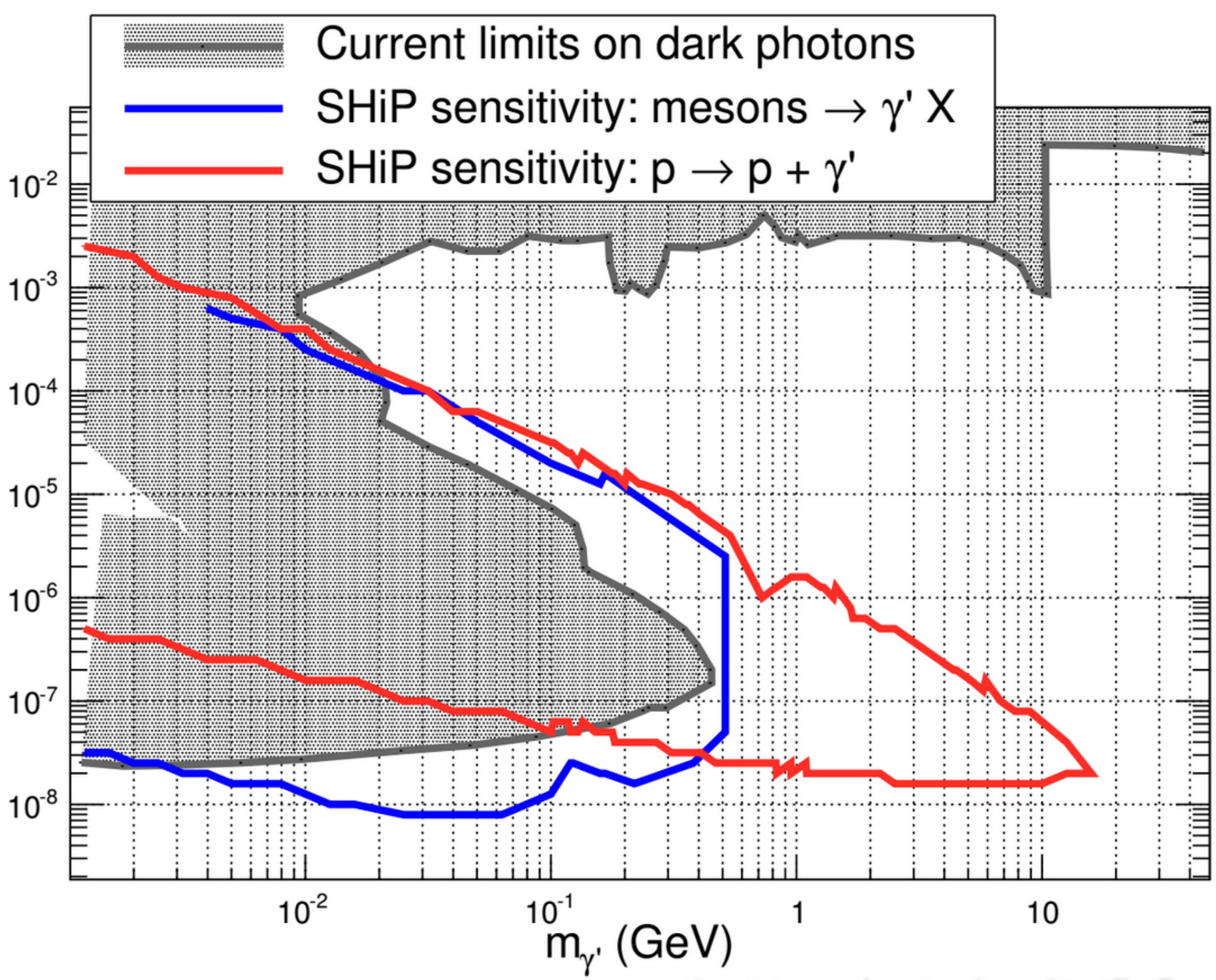
- The physics landscape
- Hidden sector theories – the neutrino minimal Standard Model
- Design of a new beam-dump experiment
- Sensitivity and future plans

Sensitivity – neutrino portal



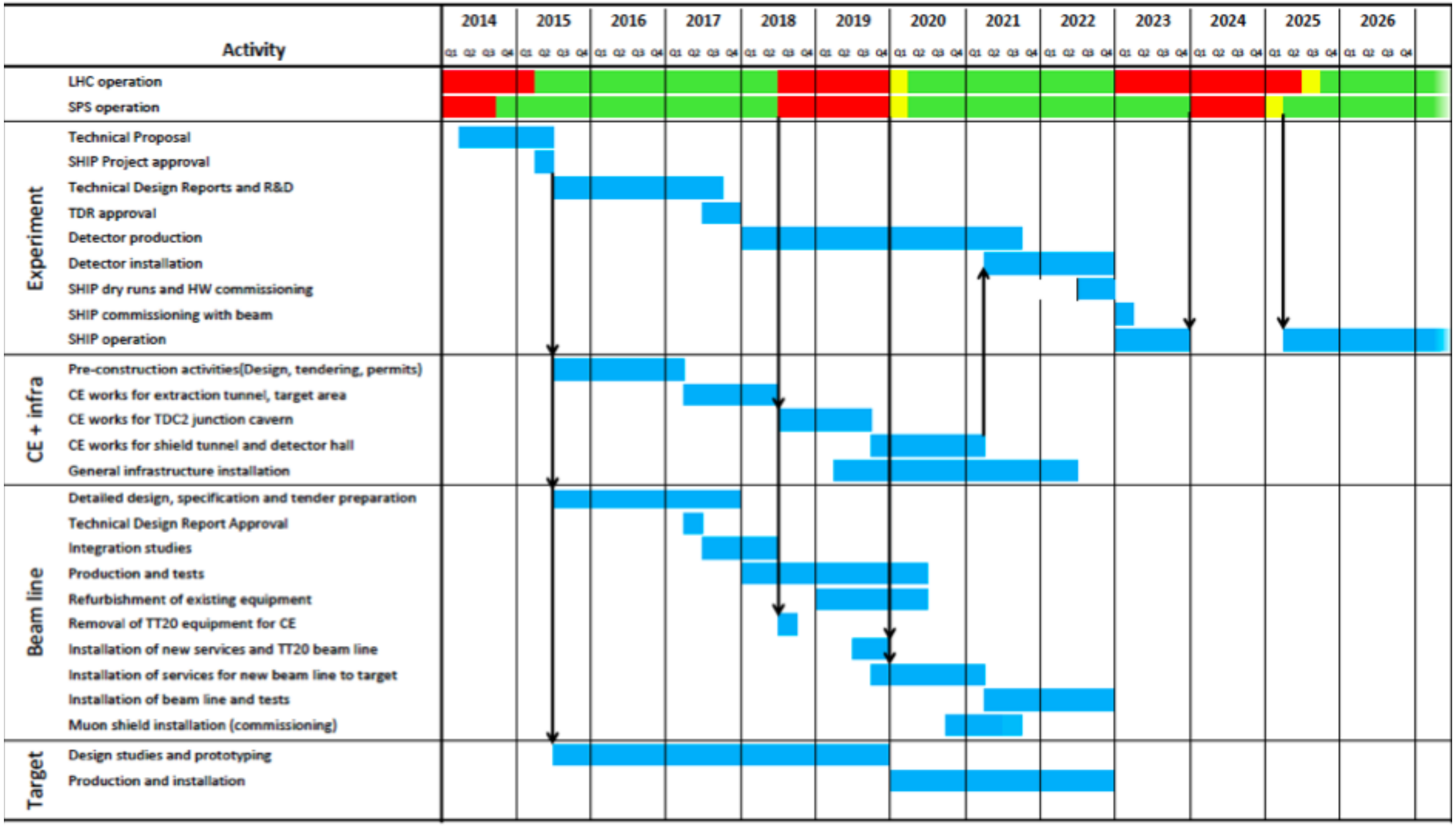
- **For M_N < 2 GeV the proposed experiment has discovery potential for the cosmologically favoured region with $10^{-6} < U^2 <$ a few × 10^{-9}**

Sensitivity – vector portal



- Comparable studies for axion, higgs portals, R-parity violating neutralinos, light-goldstinos… in progress

Schedule



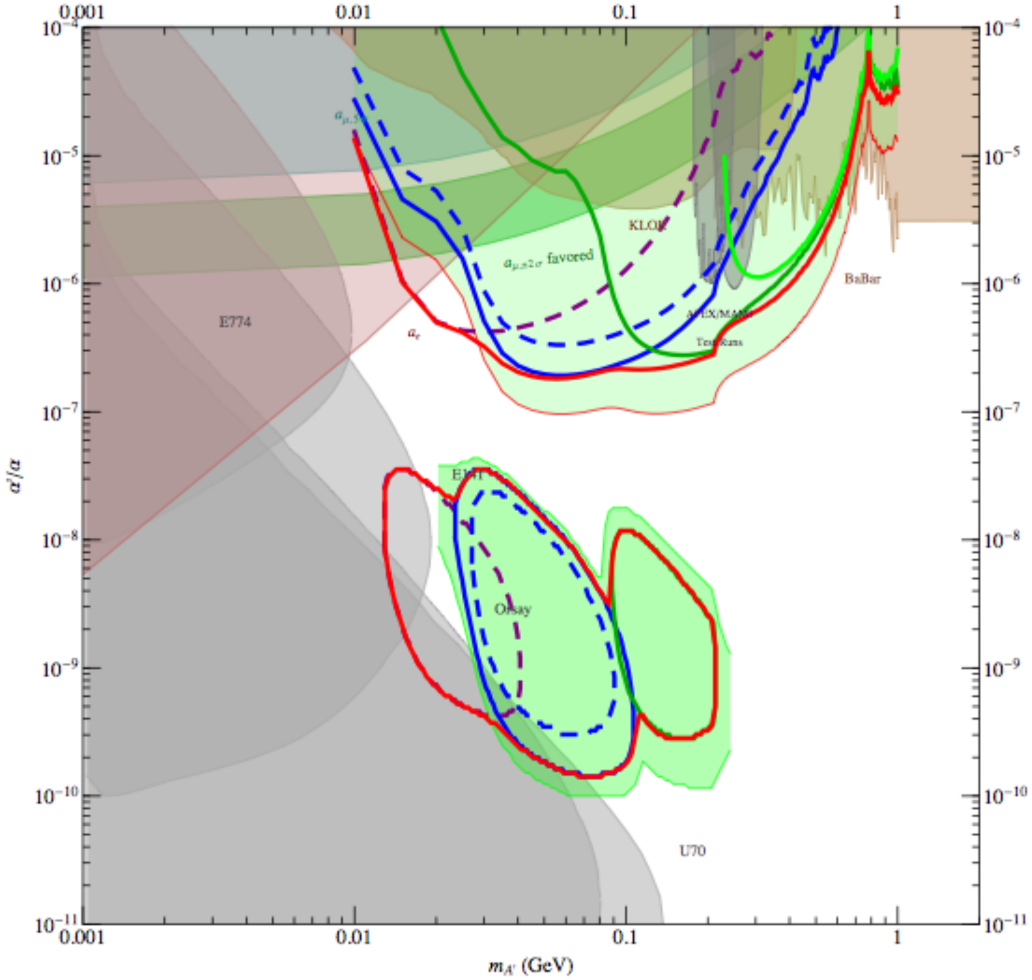
- Technical proposal (2015)
- Technical Design Report (2018)
- Construction and installation (2018-2022)
- Commissioning (2022-2023)
- Data taking and analysis of 2×10^{20} pot (2023-2027)

Conclusions

- The proposed experiment SHIP will search for NP in the largely unexplored domain of new, very weakly interacting particles with masses below the Fermi scale
- Detector is based on existing technologies
- Ongoing discussion of the infrastructure with CERN experts
- **The discovery of a HNL would have enormous impact – could solve several of the significant problems of the SM**
  - The origin of the baryon asymmetry of the Universe
  - The origin of neutrino mass
  - The results of this experiment, together with cosmological and astrophysical data, could be crucial to determine the nature of Dark Matter
- Wide range of other hidden sector physics under investigation

Backup

HPS



0.001
0.01
0.1
1
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
α'/α
$m_{A'}$ (GeV)
E774
a_e
$a_{\mu,\pm 2\sigma}$ favored
KLOE
BaBar
Test Runs
E141
Orsay
U70

Expected event yield

- Integral mixing angle U^2 is given by $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$
- Make a conservative estimate of the sensitivity by only considering the decay $N_{2,3} \rightarrow \mu^- \pi^+$ – probes U_μ^2
- Expected number of signal events then,

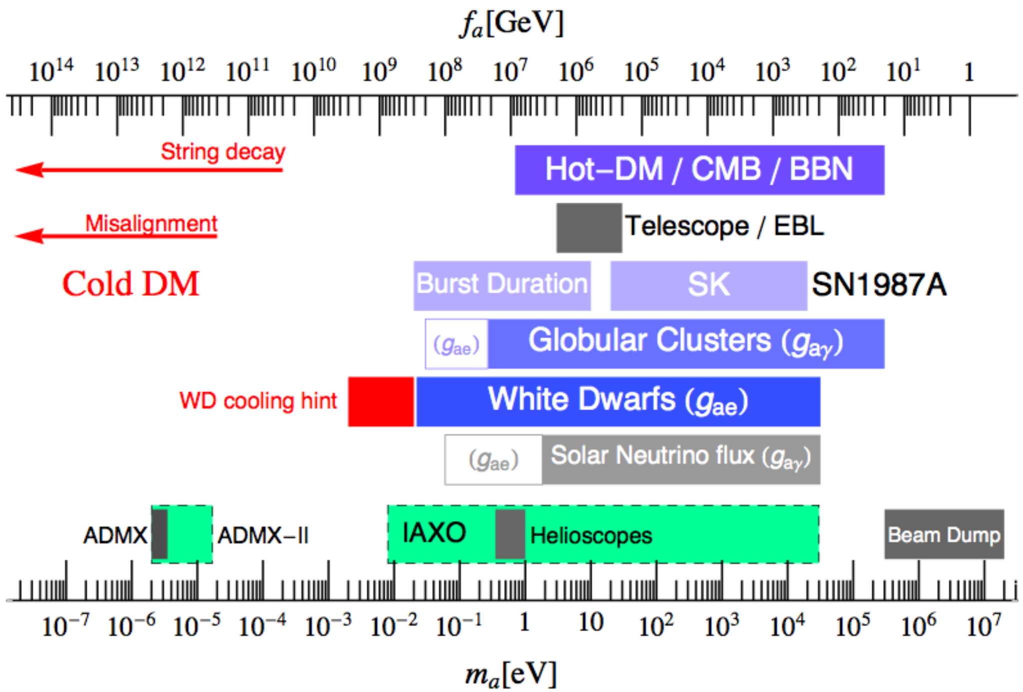
$$N_{signal} = n_{pot} \times 2\chi_{cc} \times BR(U_\mu^2) \times \varepsilon_{det}(U_\mu^2)$$

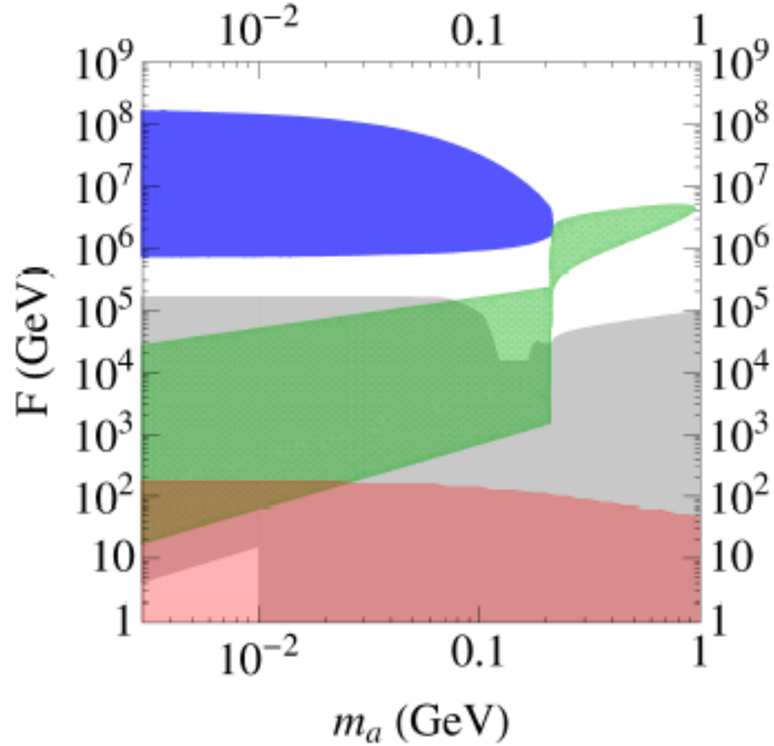
$N_{pot} = 2\times10^{20}$
$\chi_{cc} = 0.45\times10^{-3}$
$BR(U_\mu^2) = BR(D \rightarrow N_{2,3}X) \times BR(N_{2,3} \rightarrow \mu\pi)$
$\varepsilon_{det}(U_\mu^2)$ = prob. for $N_{2,3}$ to decay in detector and μ, π to be reconstructed

- Strongest experimental limit for **M_N ~1 GeV** at **$U_\mu^2 = 10^{-7}$**
  – Would then expect **$\tau_N = 1.8\times10^{-5}$s** and **~12k** fully reconstructed **$N \rightarrow \mu^- \pi^+$**
- For cosmologically favoured region **$U_\mu^2 = 10^{-8}$** (**$\tau_N = 1.8\times10^{-4}$s**)
  – Would expect **120** fully reconstructed events

Axion Portal

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

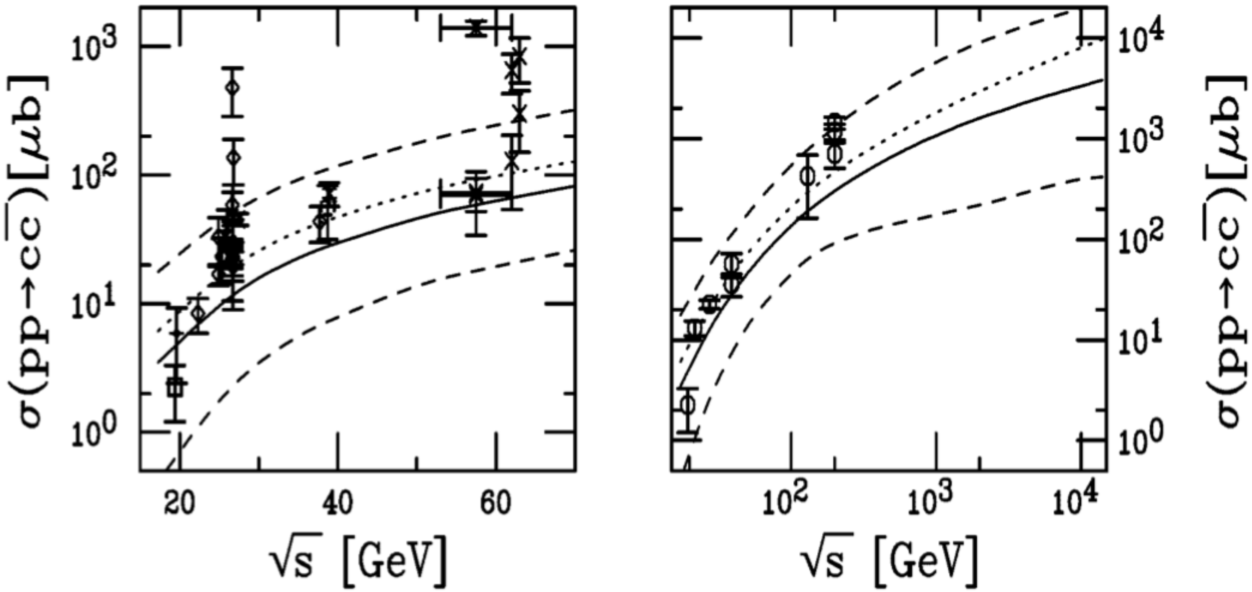




Right: Gray: the combined exclusion region from meson decays; green: CHARM; blue: supernova SN 1987a; red: muon anomalous magnetic moment.

Where to produce charm?

- $c\bar{c}$ cross-section :

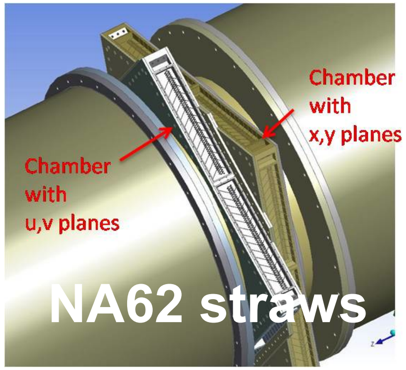


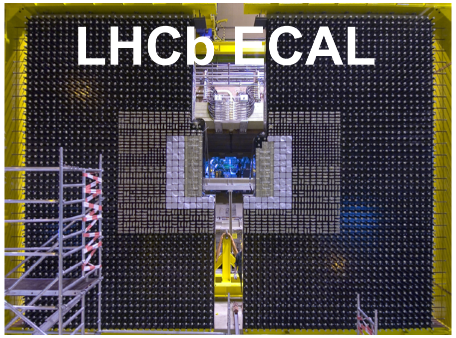
arxiv.org/pdf/0709.2531v1

  - LHC ($\sqrt{s}$ = 14 TeV): with 1 ab^{-1} (i.e. 3-4 years): ~ 2×10^{16} in 4π
  - SPS (400 GeV p-on-target (pot) $\sqrt{s}$ = 27 GeV): with 2×10^{20} pot (i.e. 3-4 years): ~ 2×10^{17}
  - Fermilab: 120 GeV, 10× smaller σ_{cc}, 10×pot by 2025 for LBNE
- Note B-decays produced with 20-100 smaller cross-section and dominant semi-leptonic decay would be $D\mu\nu$ i.e. still limited to 3 GeV

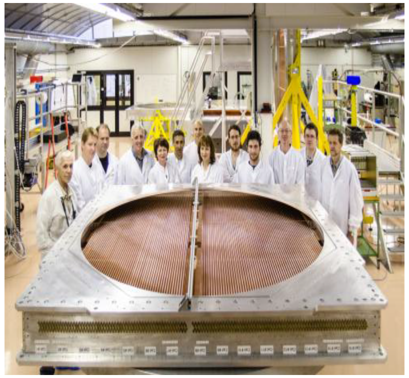
Detector Technologies

- **Dipole magnet**
  - Magnet similar to LHCb design required, but with ~40% less iron and 3× less power dissipated
  - Free aperture of ~16 m^2 and field integral ~ 0.5 Tm over 5 m length
- **Vacuum tank and straw tracker**
  - NA62 has 10^{-5} mbar pressure cf. 10^{-2} mbar required here
  - Have demonstrated gas tightness of straw tubes with **120 μm spatial resolution** and **0.5% X_0/X** material budget in long term tests



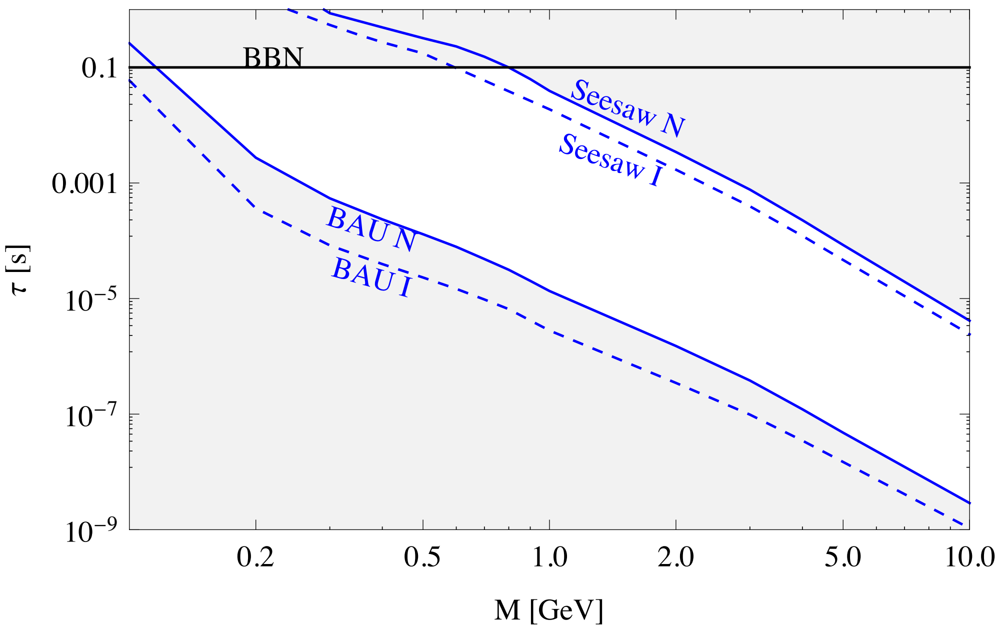


- **Electromagnetic calorimeter**
  - Shashlik technology used in LHCb would provide economical solution with good energy and time resolution



Masses and couplings of HNLs II

- Constraints from **BAU**, **Seesaw** and Big Bang Nucleosynthesis (**BBN**) :



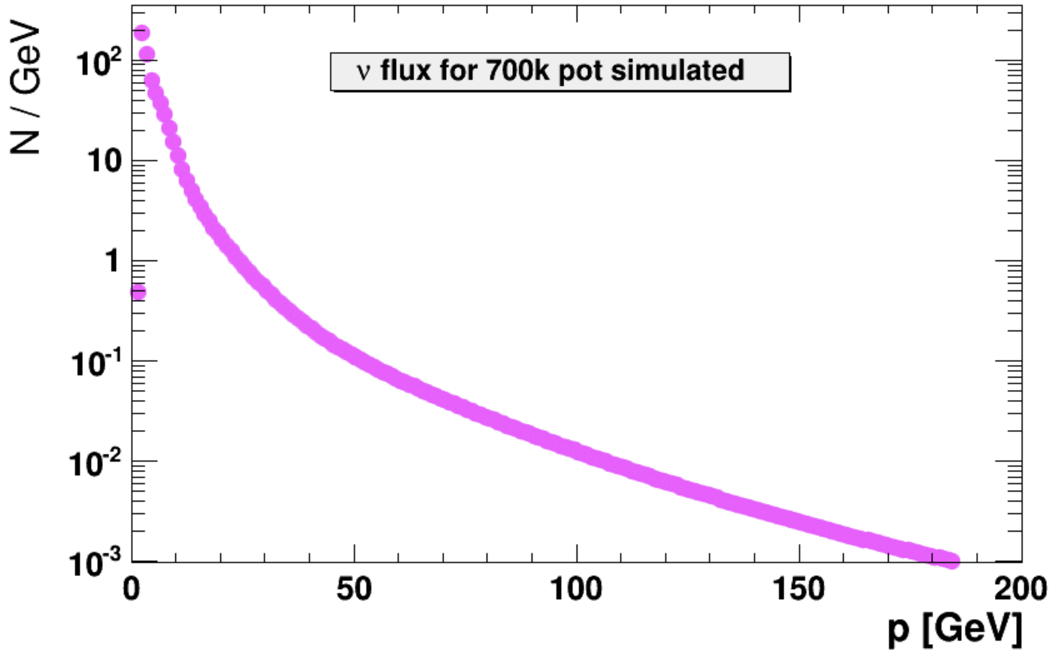
Typical lifetimes **>10 μs** for **($N_{2,3}$) ~ 1 GeV**
→ decay distance O(km)

- Branching fractions depend on the level of mixing, typically,
  - B(N → μ^-/e^- π^+) ~ 0.1 – 50%
  - B(N → μ^-/e^- ρ^+) ~ 0.5 – 20%
  - B(N → νμe) ~ 1 – 10%

- Focus on **$\mu^-\pi^+$** signature, below
- **$\mu^-\rho^+$** and **$e^-\pi^+$** final states could extend the sensitivity

Residual neutrino flux

- Momentum spectrum of the neutrino flux after the muon shield



- At atmospheric pressure expect **2×10^4** neutrino interactions in the decay volume per **2×10^{20} pot**

  → **becomes negligible at 0.01 mbar**

Other BSM physics

- Can make searches for other light, very weakly interacting new particles :
  - Light superpartners of goldstino in SUSY models e.g. **$D \to \pi X$, $X \to l^+l^-$** [Gorbunov (2001)]
  - R-parity violating neutralinos in SUSY models e.g. **$D \to lX$, $X \to l^+l^-\nu$** [A.Dedes, H.K Dreiner, P Richardson (2001)]
  - Massive paraphotons (in secluded dark matter models) e.g. **$\Sigma \to lX$, $X \to l^+l^-$** [M.Pospelov, A. Ritz, M.B. Voloshin (2008)]

Other facilities

- Have considered if could perform experiment elsewhere

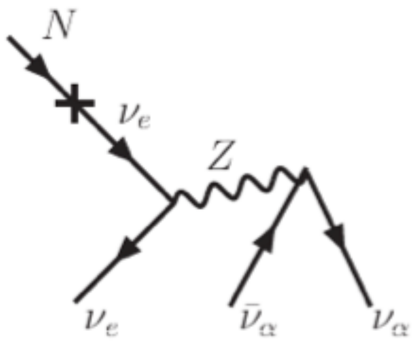
- Fermilab
  - 120 GeV proton beam, 4×10^{19} POT
    - factor ten lower event yield than in the proposed SPS experiment
  - 800 GeV proton beam, 1×10^{19} POT
    - Lower POT would be approximately compensated by higher charm cross-section
    - Would require much longer muon shield → loss of acceptance

- KEK
  - 30 GeV proton beam, 1×10^{21} POT
    - large uncertainty due to the poor knowledge of the charm cross-section at low energy
    - Estimate factor 1.5-2 lower signal yields

- Colliding beam experiment at LHC, 1000 fb^{-1}, 14 TeV
  - Assuming experiment located 60m away from the interaction region and 50 mrad off-axis to avoid LHC beams – factor 200 worse than proposal

N_1 as Dark Matter

- For small Yukawa couplings, HNL can be long-lived and therefore a dark matter candidate



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

- Characteristic signature: can have radiative decay which will give a monochromatic decay line in the spectra of galaxies

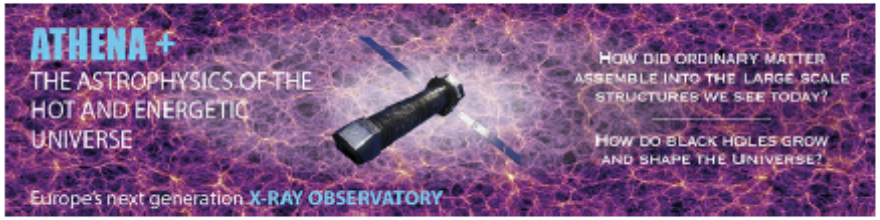
Searches for N_1

- N_1 has been searched or by the XMM-Newton, Chandra, Suzaku and Integral experiments
- Spectral resolution is insufficient (require **$\Delta E/E \sim 10^{-3}$**)
- Several proposed/planned x-ray missions which will have sufficient resolution:

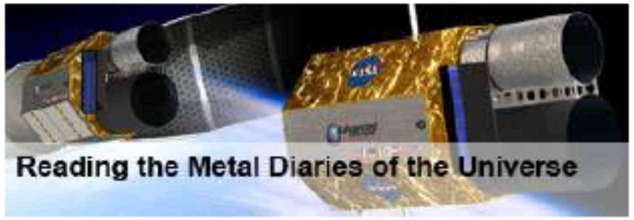
Astro-H

LOFT

Athena+

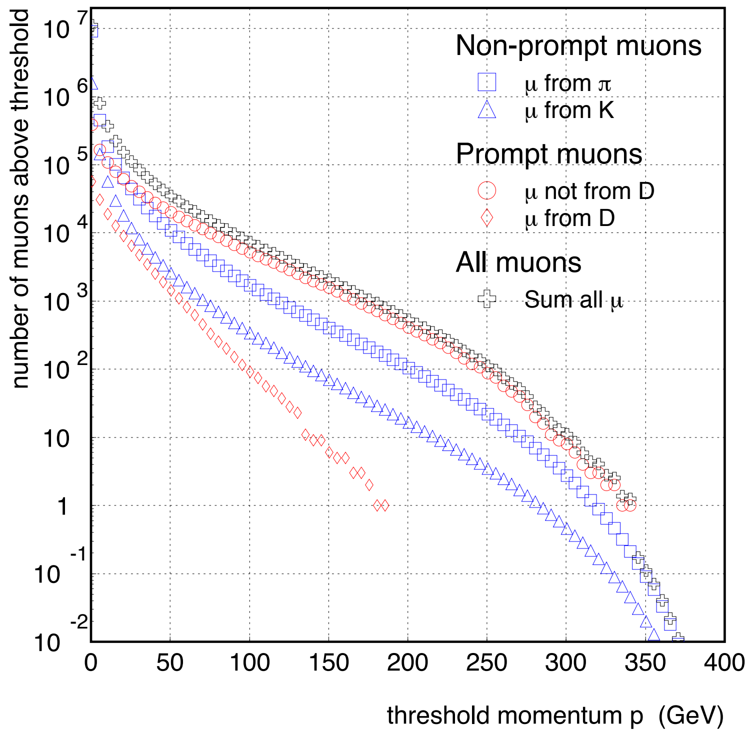


Origin/Xenia



Muon Shield

- Without μ-filter: 5×10^9/ spill (5×10^{13}pot)
  - Low-p: still from π/K-decay
  - High-p: ω/ρ-decays to μμ
- Idea to reduce background from μ-interactions to below ν-bkgrd (…)
- Acceptable rate ~10^5 μ / **2×10^{20} pot**
- Main sources of muons simulated using PYTHIA (10^9 p @ 400 GeV)



- Two alternatives for shield:
  - Passive: i.e. use high Z material: need 54 m of W to stop 400 GeV μ
  - Active (+passive): need 40 Tm to deflect 400 GeV μ outside acceptance

Neutrino backgrounds

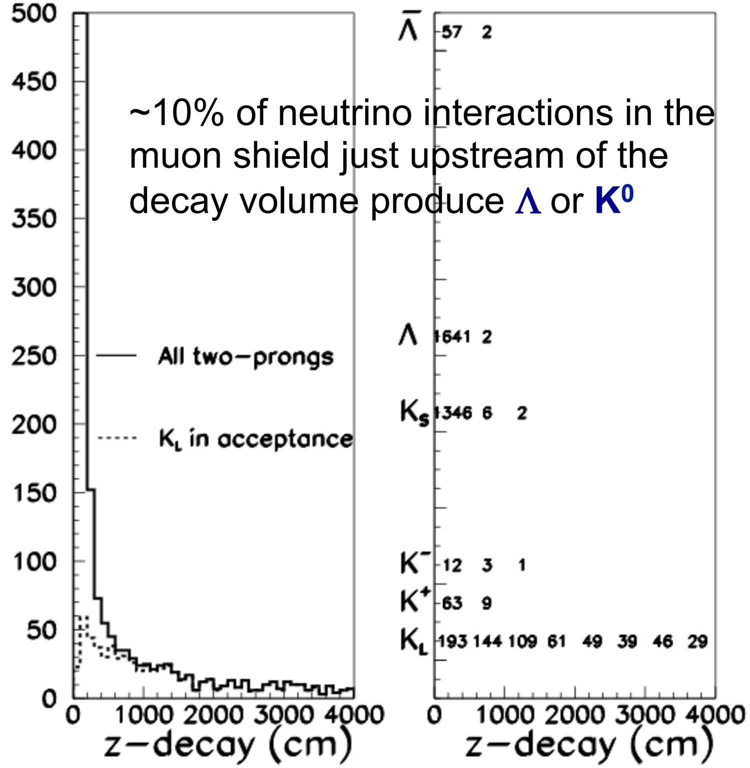
- Neutrino interactions in the decay volume :
  - After shield expect **2×10^4** per **2×10^{20} pot** at atmospheric pressure

  → **negligible at 0.01 mbar**

- Neutrino interactions in the final part of the muon shield :
  - Use GEANT and GENIE to simulate the CC and NC neutrino interactions

  → **CC(NC) rate of ~6(2)$\times10^5$ per intn. length per 2×10^{20} pot**
  - Use veto-station to suppress short lived
  - $\nu_\mu + p \rightarrow X +$ **$K_L \rightarrow \mu\pi\nu$ main bkgrd**
  - Requiring μ−id. for one of the two decay products

  → **150 two-prong vertices in 2×10^{20} pot**



~10% of neutrino interactions in the muon shield just upstream of the decay volume produce **Λ** or **K^0**

Item	Cost [MCHF]
Extraction and proton beam line	19.9
Extraction upgrades, beam interlock	0.4
New MSSB splitter/switch magnets	4.2
Other magnets	1.6
Powering, including cables	6.0
Beam vacuum	3.0
Beam instrumentation	1.9
Beam interlocks	0.4
Other beam line costs	2.4
Target Station	17.1
Target (+spare) plus exchange system	4.6
Hadron absorber	8.1
Helium enclosure of target station	2.0
Removable shielding	0.5
Controls	0.9
Prototypes and testing	1.0
Muon filter	11.0
Muon shield, passive option, reusing 800 t of lead from OPERA	11.0
Civil Engineering	45.1
Junction cavern	5.0
Extraction tunnel	8.4
Target cavern	8.9
Muon filter tunnel	1.9
Experimental cavern	15.1
New access road	0.9
Site investigation	0.2
Studies	0.7
Contingency	4.0
Infrastructure	20.8
Cooling plants	4.9
Ventilation plants	5.1
Electrical infrastructure beam line zone	0.8
Electrical infrastructure target area and muon filter	1.4
Electrical infrastructure detector cavern	1.8
Access system beam lines, target and detector cavern	1.8
Safety systems	1.0
Radiation protection	1.5
Transport: cranes target station, detector cavern, shafts	1.9
Transport and handling	0.6
Total	**113.9**

Item	Staff FTE	Fellows MCHF
Extraction and proton beam line	31.5	1.5
Extraction upgrades	1	0.1
New MSSB splitter/switch magnets	3	0.2
Other magnets	2	
Powering, including cables	12	
Beam vacuum	2	0.2
Beam instrumentation	4	0.4
Interlocks	1	
Other beam line costs	6.5	0.6
Target Station	35	1.6
Target (+spare) & exchange syst	35	0.6
Hadron absorber		0.6
Helium enclosure of target station		
Removable shielding		
Controls		0.4
Prototypes and testing		
Muon filter		
Muon shield, passive opt.,OPERA PB		
Civil Engineering	10	0.7
Junction cavern	10	0.7
Extraction tunnel		
Target cavern		
Muon filter tunnel		
Experimental cavern		
New access road		
Site investigation		
Infrastructure	14.4	1.2
Cooling plants	3.0	
Ventilation plants	2.0	
Electrical infrastructure	1.3	0.8
Access &safety beam lines+detector	1.5	
Safety systems	1.3	
Radiation protection	4.0	0.4
Transport : cranes, lifts, tooling	1.3	
Total	**90.9**	**5.0**