Imperial College
London

SHiP
Search for Hidden Particles

Search for HIdden Particles

Ulrik Egede, on behalf of SHIP collaboration

Lund, 28 May 2014

A contradiction?

The Standard Model seems perfect and can exist without corrections to the Planck scale

But the same Standard Model can't explain dark matter, neutrino masses and baryogenesis.

I will propose a set of possible ways out of this

Outline

The physics landscape

Hidden sector theories

The neutrino minimal Standard Model

Design of a new beam-dump experiment

Sensitivity and future plans

Who are we?

www.cern/ch/ship

CERN-SPSC-2013-024 / SPSC-EOI-010
October 8, 2013

Proposal to Search for Heavy Neutral Leptons at the SPS

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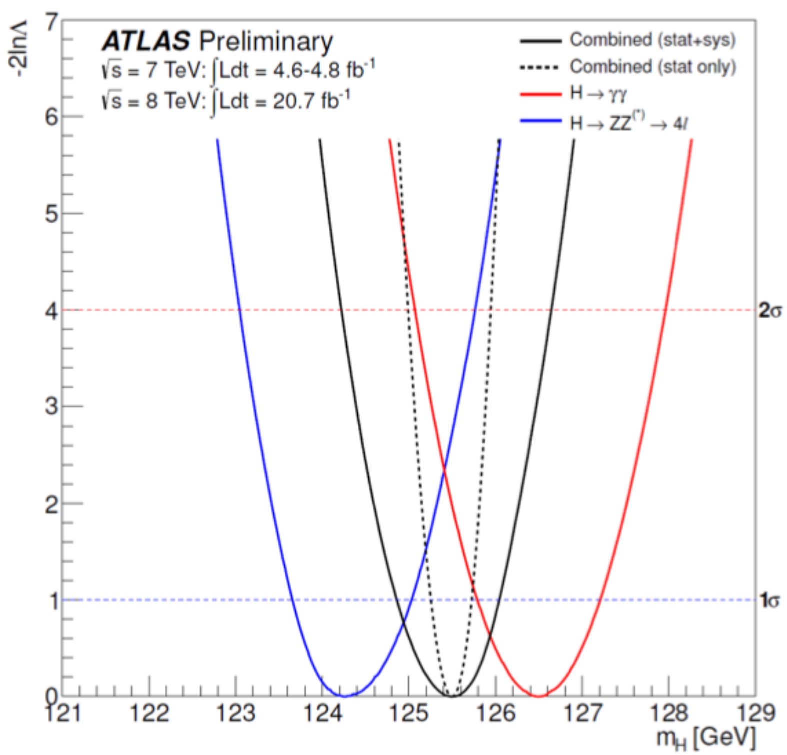
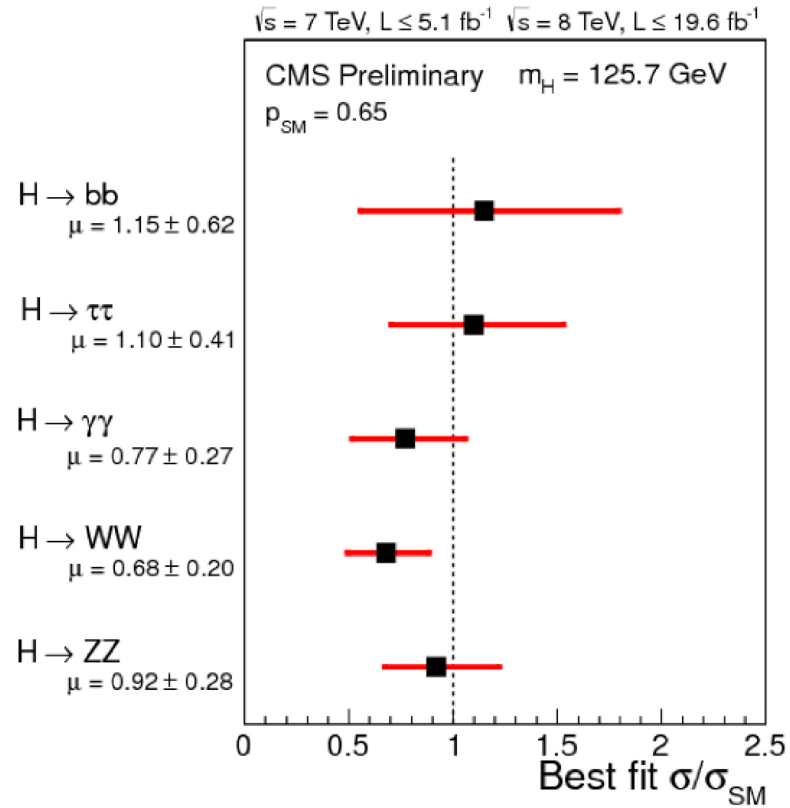
The triumph of the Standard Model

Boson consistent with the SM-Higgs has been found!

ATLAS : M_H=125.5 ± 0.2 (stat) +0.5-0.6 (syst) GeV/c^2

CMS : M_H=125.7 ± 0.3 (stat) ± 0.3 (syst) GeV/c^2

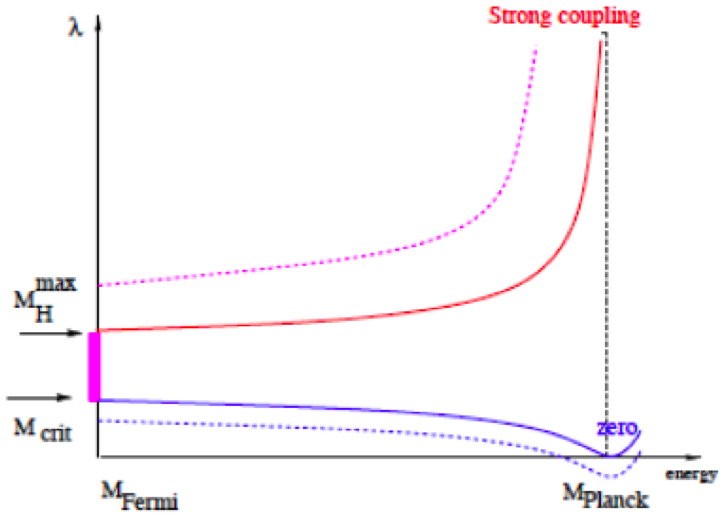


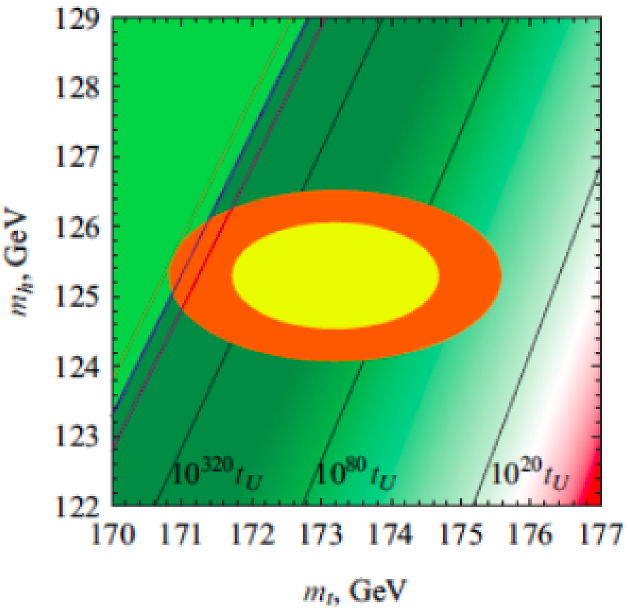


The triumph of the Standard Model

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 (JHEP 1208 (2012) 098)





The limitations of the Standard Model

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
- Dark Energy

Direct searches ...

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

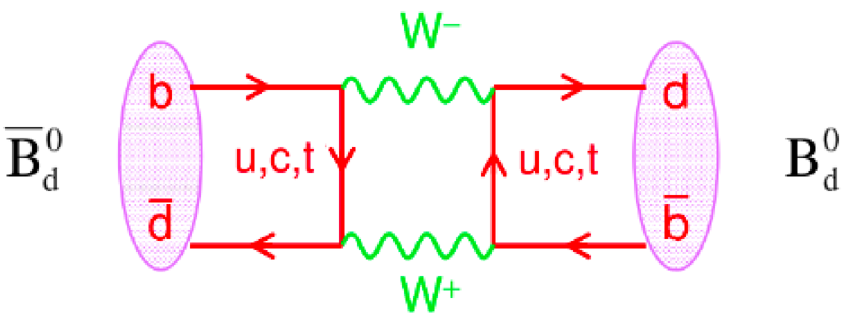
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [fb^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	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

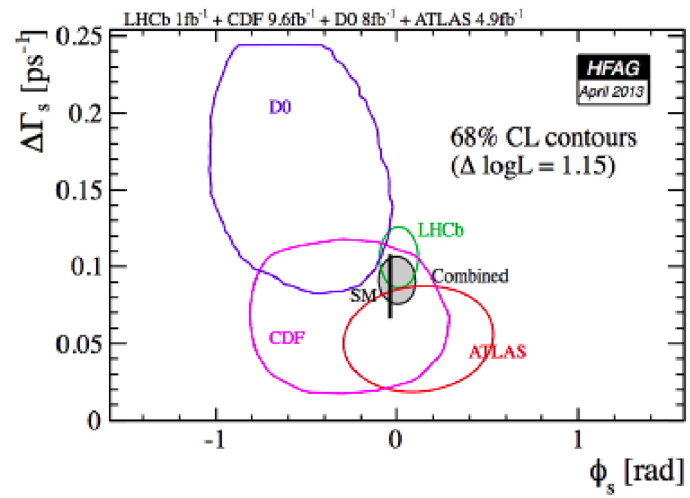
10^{-1} 1   **Mass scale [TeV]**

$\sqrt{s}$ = 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.

... and indirect searches





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

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]

A hidden sector?

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

- A new, light “hidden sector” of particles
- Singlets with respect to gauge group of the SM

How could we have missed it?

- Key is that it only interacts with SM particles through some kind of mixing through a “portal” particle

A hidden sector?

Several possibilities for renormalisable singlet operators

- Vector portal, U(1) $B_{\mu\nu}$
  - Massive vector photon (paraphoton, secluded photon…) mixing with regular photon → $\varepsilon B_{\mu\nu}F^{\mu\nu}$
- Higgs portal
  - Scalar field χ, $(\mu\chi+\lambda\chi^2)H^\dagger H$
- Axial portal
  - Pseudo Nambu-Goldstone bosons
  - Axion like vector field , $(a/F)G_{\mu\nu}G^{\mu\nu}$, $(\partial_\mu a/F)\psi^\dagger\gamma_\mu\gamma_5\psi$
- Neutrino portal
  - Heavy neutral leptons (HNL), $YH^TN'L$

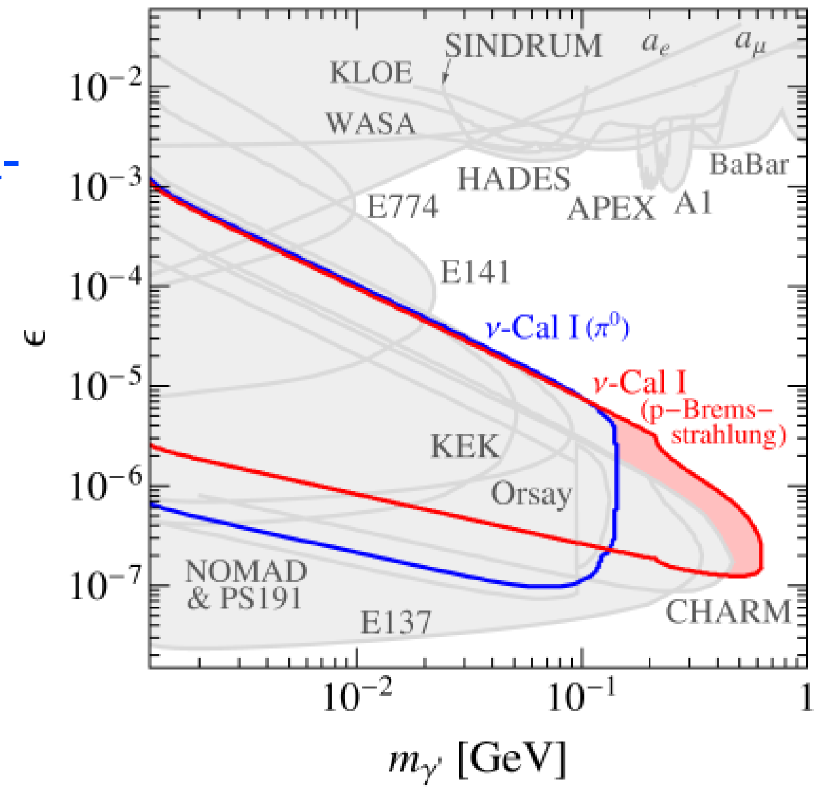
Vector Portal

Produce a virtual photon in fixed-target, mix into a dark photon (~ε), dark photon, mix back into a SM photon (~ε), decay into e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ etc

- No other interactions with SM particles - "light-shining-through-a-wall" experiments

Constraints from a wide range of experiments – note results from CERN CHARM experiment

[arXiv:1311.3870]

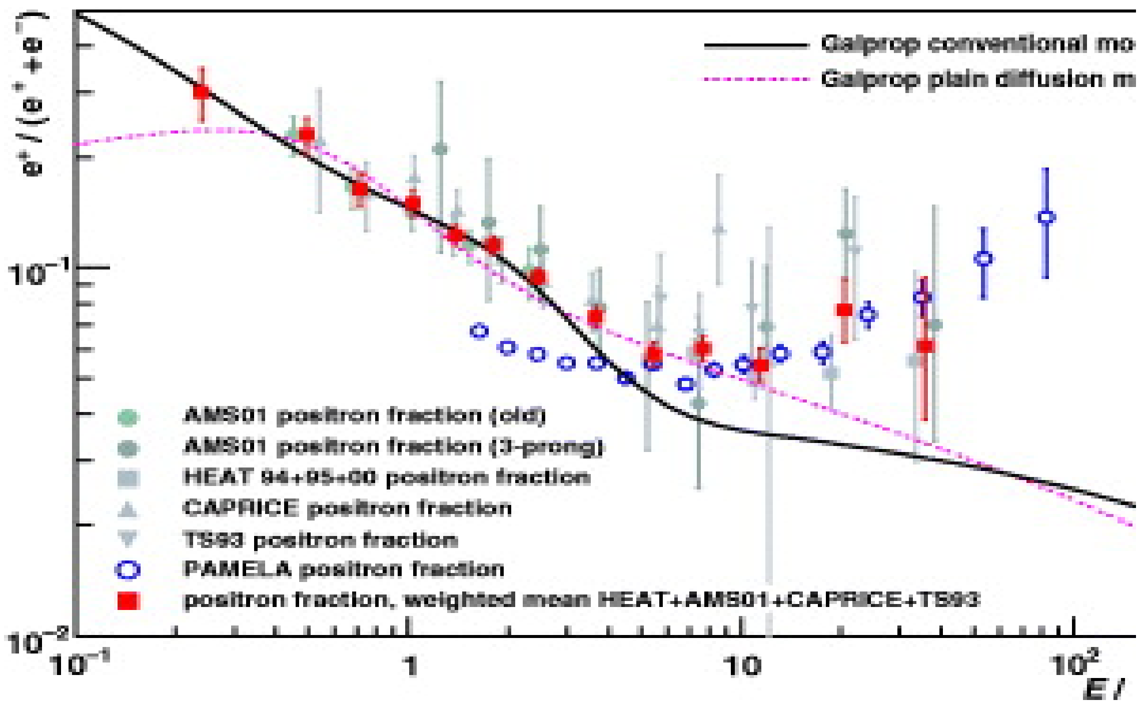


Vector Portal

Arkani-Hamed, Weiner [arXiv:0810.0713]

PAMELA cosmic ray experiment observes a sharp upturn in the positron fraction

- DM annihilation?
- Requires large cross section, but not in hadron signature



Vector Portal

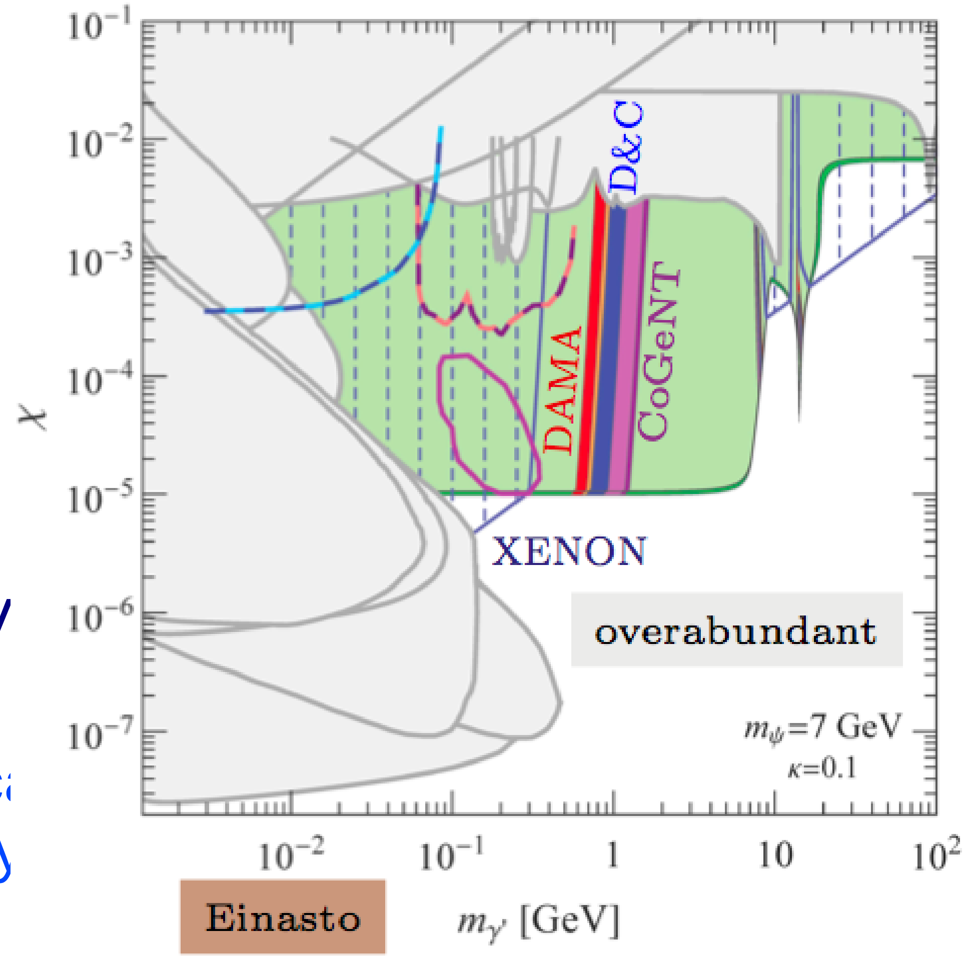
Arkani-Hamed, Weiner [arXiv:0810.0713]

ATIC, WMAP, EGRET all suggest excess electronic production

INTEGRAL 511 keV suggests far more annihilation in the galactic centre than can be explained by supernovae

Annihilation can be into a new force carrier m~1 GeV

- Low mass can make hadronic modes kinematica inaccessible, forcing decay dominantly into leptons



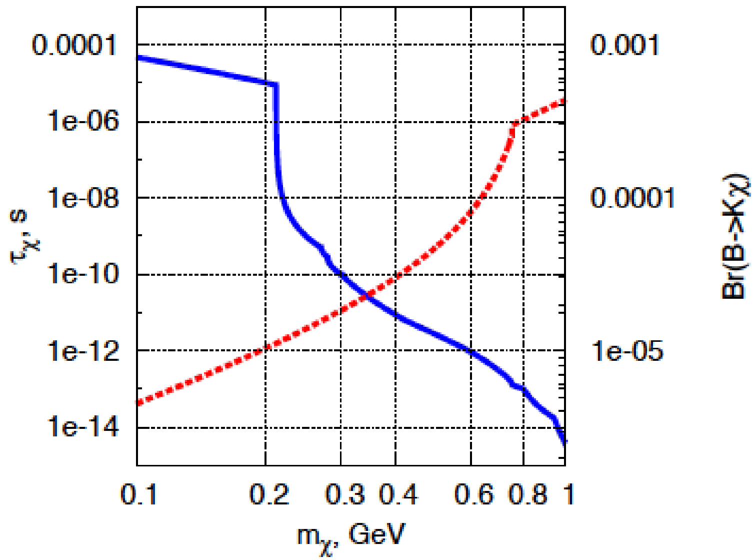
Higgs Portal

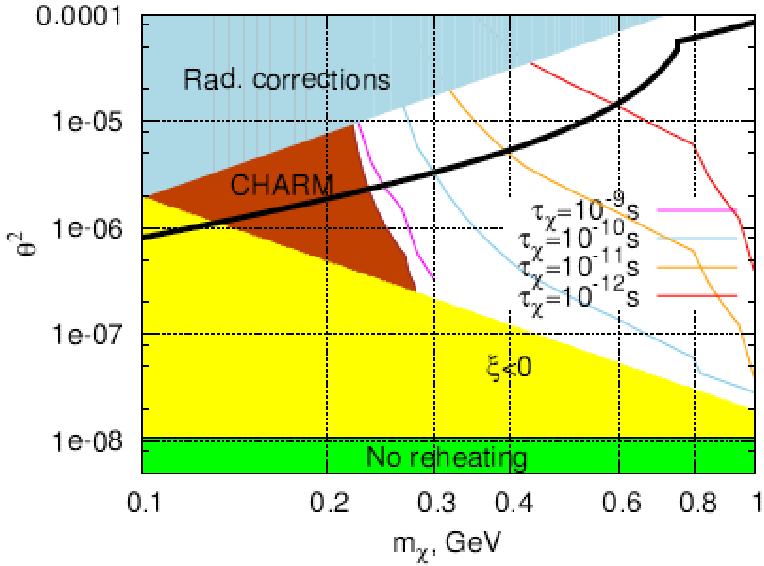
arXiv:1403.4638

Example of inflaton

- Together with Higgs, generates inflation of the early Universe
- Model has a 7 keV (warm) DM candidate and respects constraints from BICEP2 and Planck
- Interesting mass region 0.3 GeV < m_χ < 1 GeV

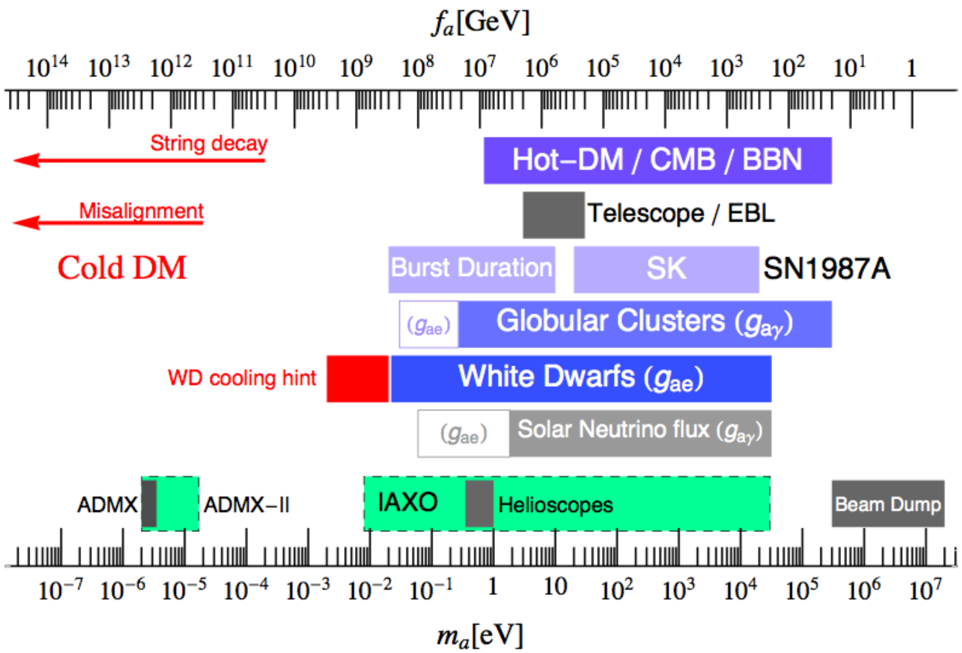
Little experimental exploration of interesting region…

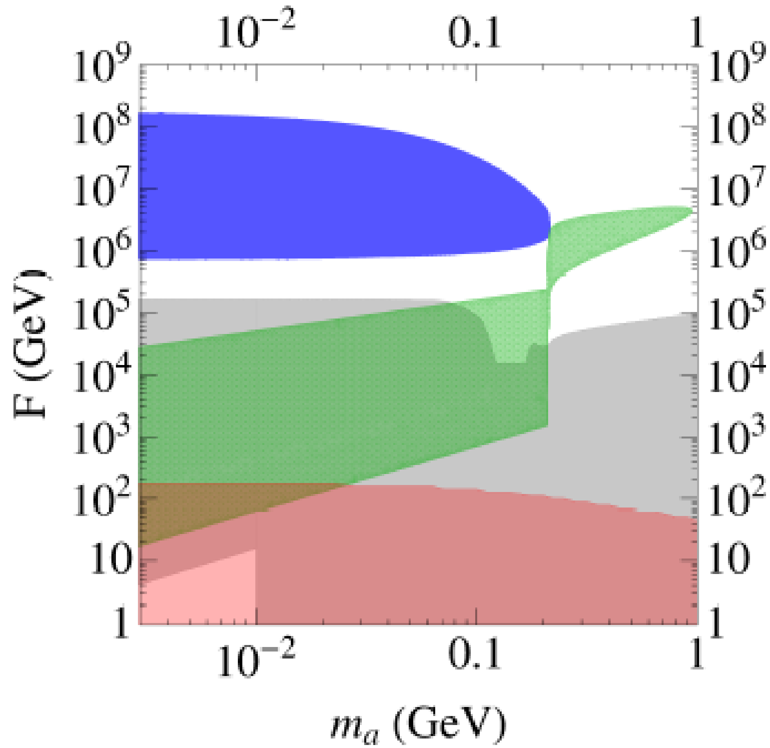




Axion Portal

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





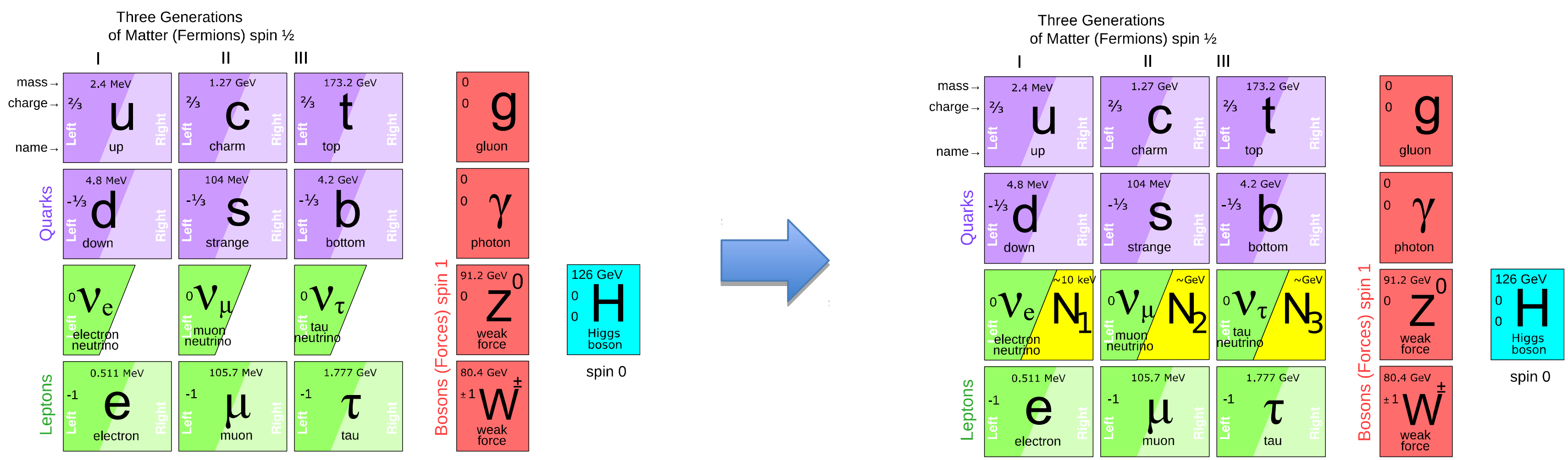
Right: Gray: the combined exclusion region from meson decays; green: CHARM; blue: supernova SN 1987a; red: muon anomalous magnetic moment.

Neutrino Portal

[T.Asaka, M.Shaposhnikov, Phys. Lett B620 (2005) 17

The neutrino Minimal Standard Model (υMSM) aims to explain

- Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter
- Adds three right-handed, Majorana, Heavy Neutral Leptons (HNL), N_1, N_2 and N_3



Neutrino Portal

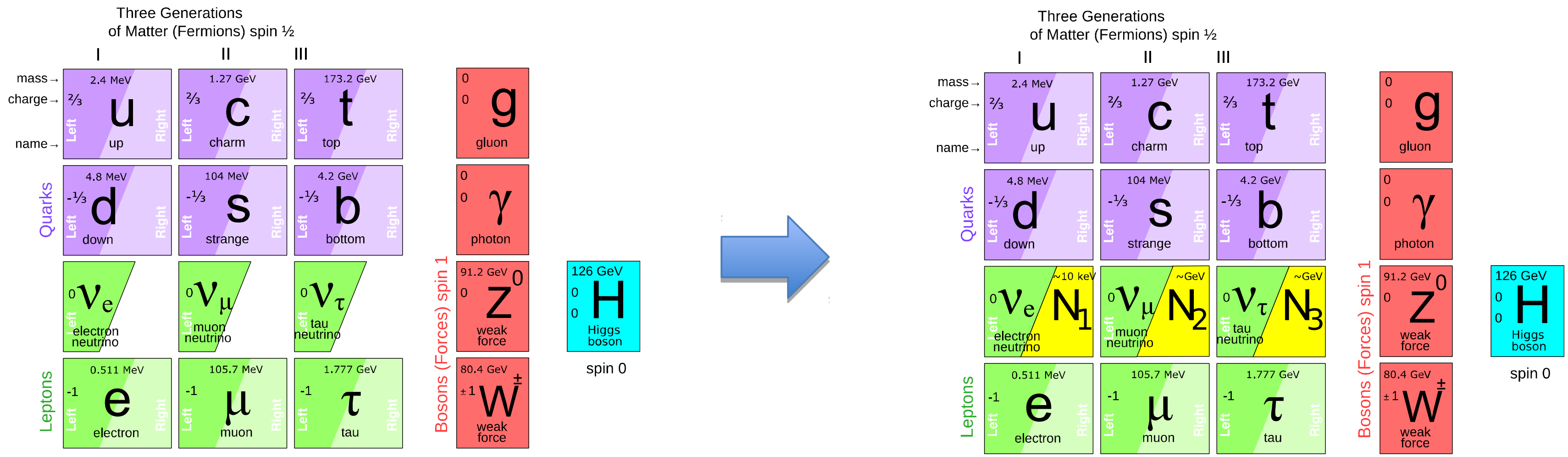
[T.Asaka, M.Shaposhnikov, Phys. Lett B620 (2005) 17

N_1

- Mass in keV region, (warm) dark matter candidate

$N_{2,3}$

- Mass in 100 MeV – GeV region
- Generate neutrino masses via see-saw and produce baryon asymmetry of the Universe



See-saw for ν mass

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

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

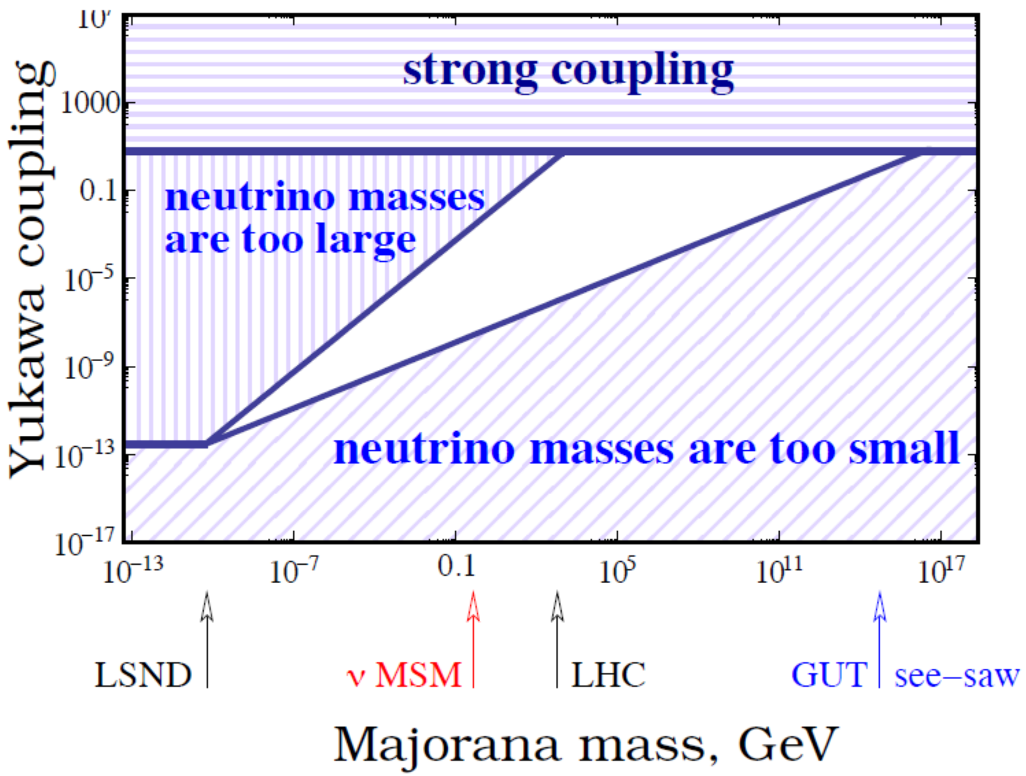
Yukawa term: mixing of N_I with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

See-saw for ν mass

The scale of the active neutrino mass is given by the see-saw formula, $m_\nu = m_D^2/M$

Typical value of the Dirac mass term is linked to the Yukawa coupling of the I-th neutrino by $m_D \sim Y_{Ia} v$



Constraints on N_1 as DM

Stability

- Must have a lifetime larger than that of the Universe

Production

- Created in the early Universe in reactions $l^+l^- \rightarrow \nu N_1$, $qq \rightarrow \nu N_1$ etc.
- Need to provide correct DM abundance

Structure formation

- Should be heavy enough to not erase non-uniformities at small scales

Decay

- Should not produce decays we have already excluded!

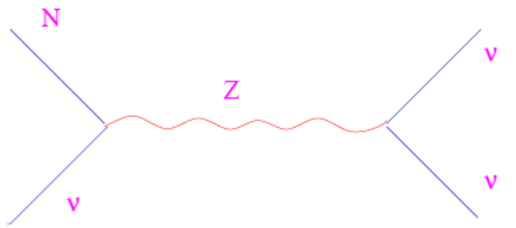
N_1 – dark matter candidate

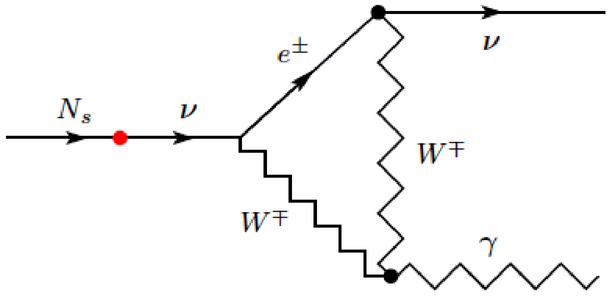
Small Yukawa couplings mean that N_1 can be very stable

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

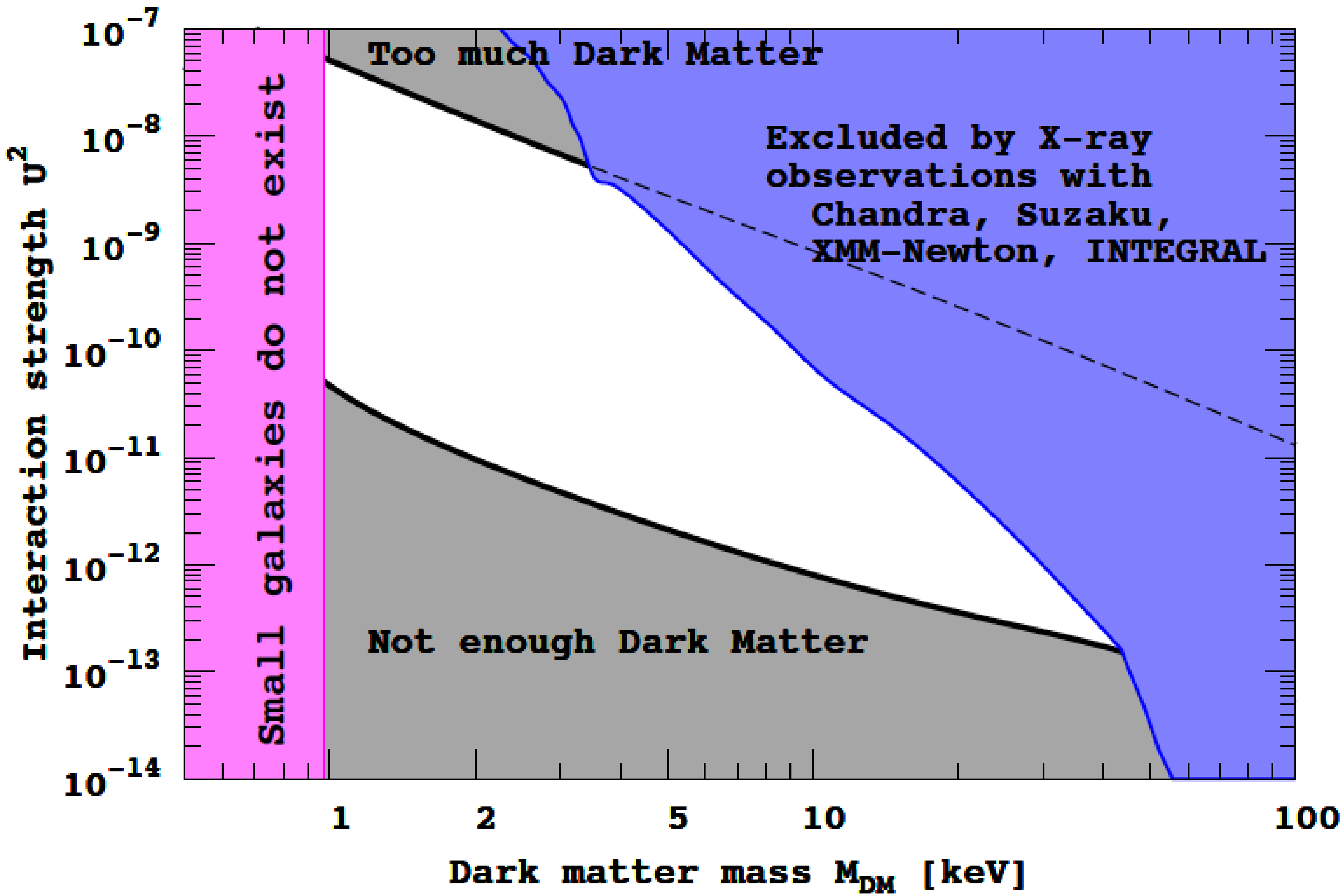
Main decay mode $N \rightarrow 3\nu$, clearly unobservable

Subdominant radiative decay $N \rightarrow \nu\gamma$ would give a monoenergetic photon with $E_\gamma = M_N/2$





N_1 allowed parameter space



Space-based searches for N_1

Existing searches by XMM-Newton, Chandra, Suzaku, INTEGRAL

- Relatively poor spectral resolution – need $\Delta E/E \sim 10^{-3}$ to separate from lots of line from iron

Four future satellite missions planned :

- Astro-H – approved for 2015 launch but has rather limited field of view
- Athena+
- LOFT
- Origin/Xenia … timescale ~2020

New line in galaxy spectrum?

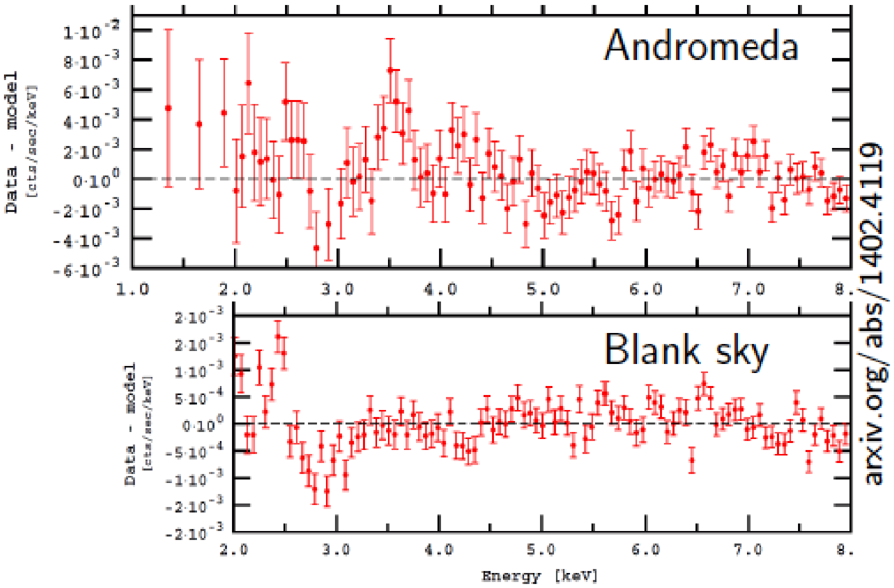
ArXiv:1402.4119

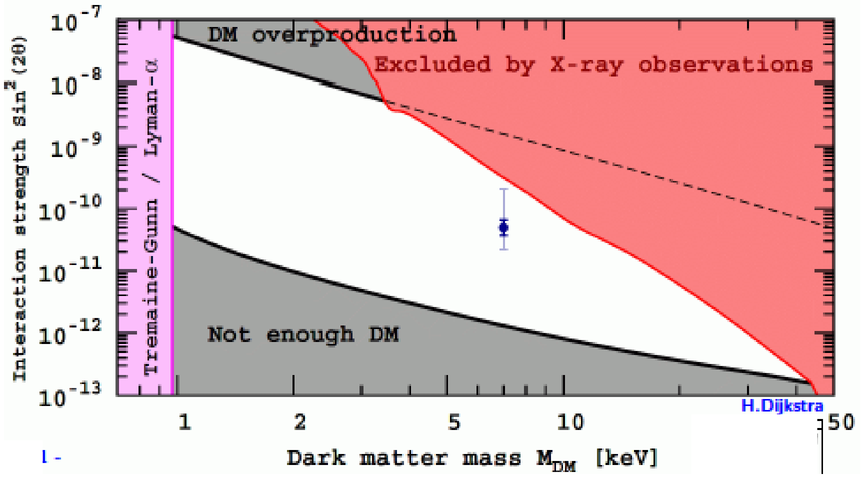
An unidentified line in the x-ray spectrum of the Andromeda galaxy and Perseus galaxy cluster E_γ= ~3.5 keV

ArXiv:1402.2301

Detection of an unidentified emission line in the stacked x-ray spectrum of galaxy clusters E_γ=~3.56 keV

Astro-H will be able to check these claims with better energy resolution





Generating the baryon asymmetry

CP is not conserved in the νMSM :

- 6 new CP-violating phases in lepton sector

Process for Baryon asymmetry

- HNL are created in the early Universe
- CPV in the interference of HNL production and decay
- Lepton number asymmetry goes from HNL to active neutrinos
- Asymmetry transferred to baryons via “sphaleron processes”

$N_{2,3}$ 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)

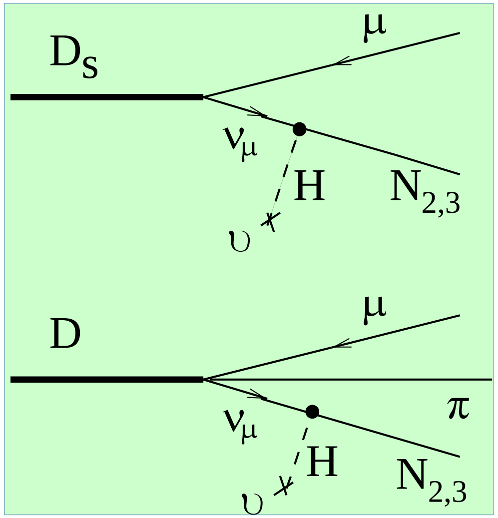
- Explanation of DM with N_1 reduces number of free parameters, need degeneracy to ensure sufficient CPV

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

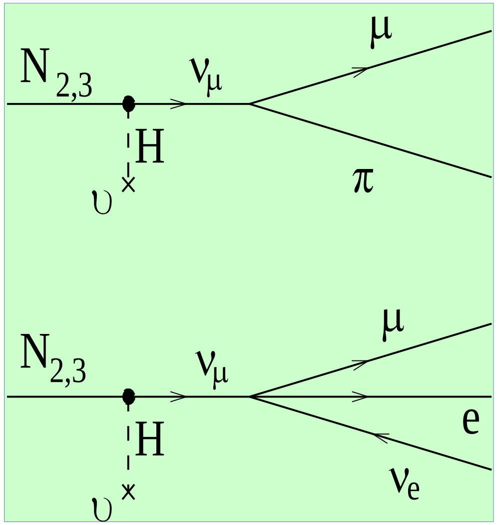
- Typical lifetimes >10 ms for $(N_{2,3})$ ~ 1 GeV → decay distance O(km)
- too large U erases any BAU

$N_{2,3}$ production and decay

Production in charm decays…



... and decays to lighter SM particles

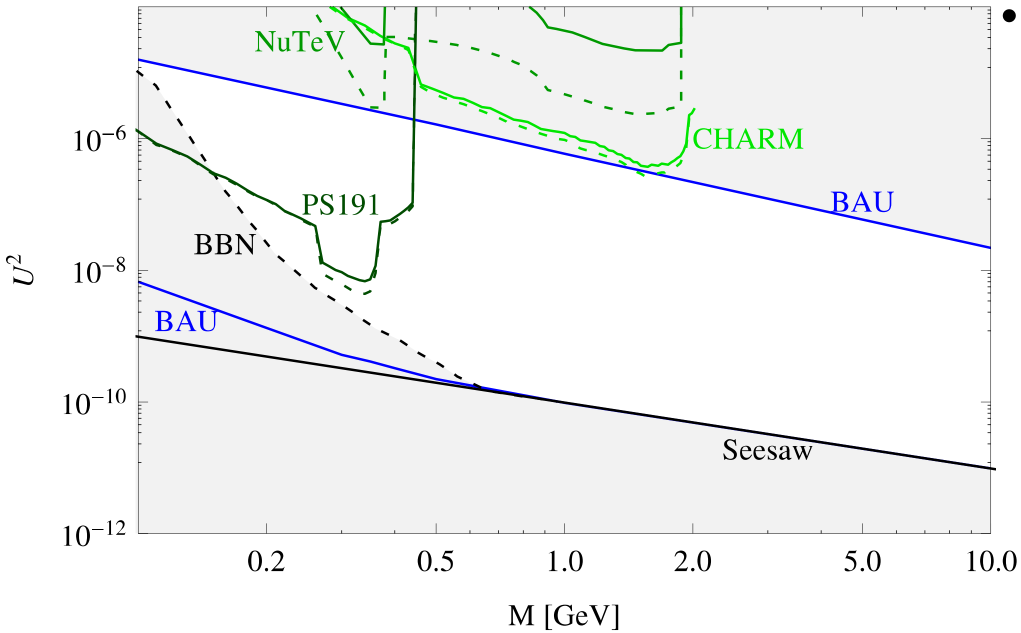


For what follows will focus on $N\rightarrow\mu-\pi+$ decay, BF~0.1-50%

- Similar BF for $N\rightarrow\mu^-\rho^+$,
- BF($N\rightarrow\nu\mu e$) ~ 1-10%

Experimental and cosmological constraints

BAU, See-saw and Big Bang Nucleosynthesis (BBN) constraints indicate that previous experiments 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

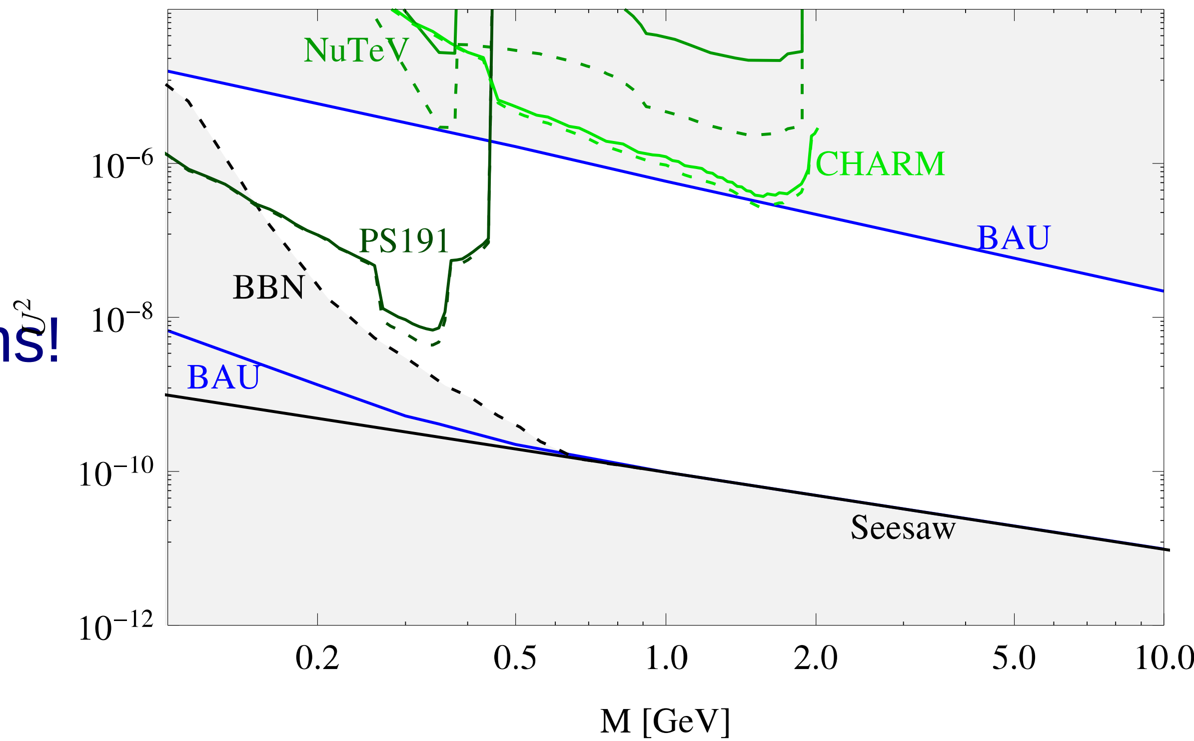
Experimental and cosmological constraints

BAU, Seesaw and Big Bang Nucleosynthesis (BBN) constraints indicate that previous experiments probed the interesting region only below the kaon mass:

Mixing at both production and decay

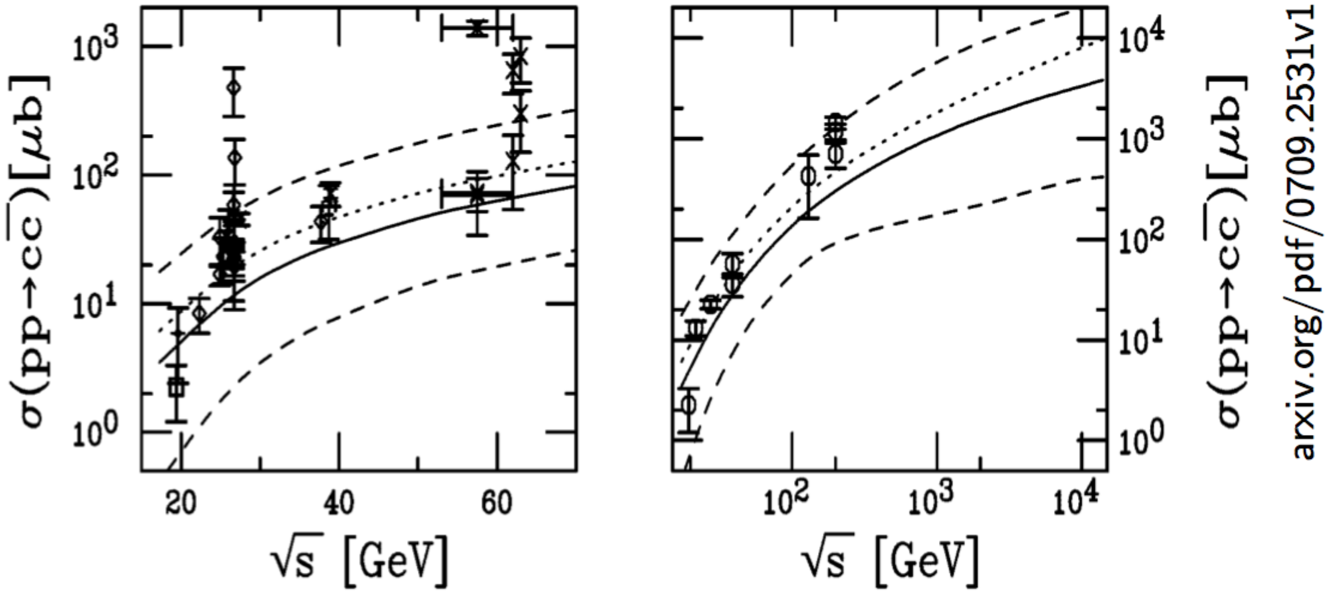
- BF(D → NX) around $10^{-8} - 10^{-12}$
- Lifetime can give further factor 10^{-4}

Need $>10^{16}$ D mesons!



Where to produce charm?

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



- LHC ($\sqrt{s}$ = 14 TeV)
  - 1 ab^{-1} (i.e. 3-4 years), ~ 2×10^{16} in 4π
- SPS (400 GeV p-on-target (pot) $\sqrt{s}$ = 27 GeV)
  - 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

Could mass range be extended?

Would neutrinos from B-decays extend the mass range for $N_{2,3}$ upwards?

- Produced with factor 20-100 smaller cross-section
- Dominant semi-leptonic decay $B \to D\mu\nu$
  - Similar limit for neutrino mass
- Charmless $B \to \pi\mu\nu$ heavily Cabibbo suppressed

B decays are not at all competitive

Experimental design

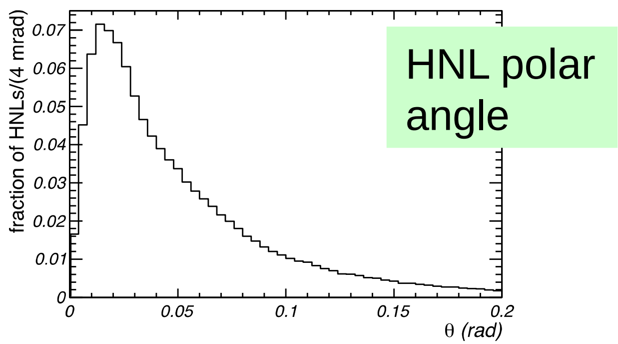
Propose a beam dump experiment at the CERN SPS with a total of $\sim 2\times10^{20}$ protons on target

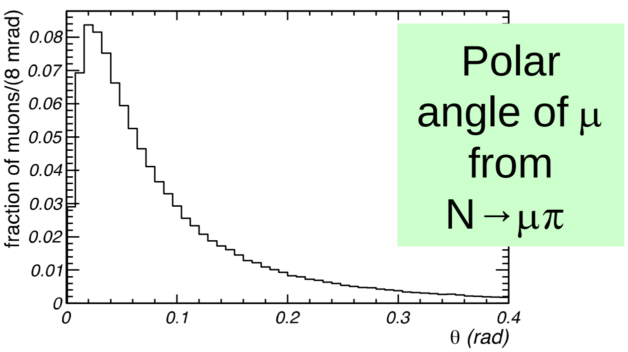
Crucial design parameters:

- Minimise residual neutrino and muon fluxes
  - Can produce 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
- Prevent neutrino interactions from mimicking HNL decay
  - Evacuate decay volume

Experimental design

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

Initial reduction of beam induced backgrounds

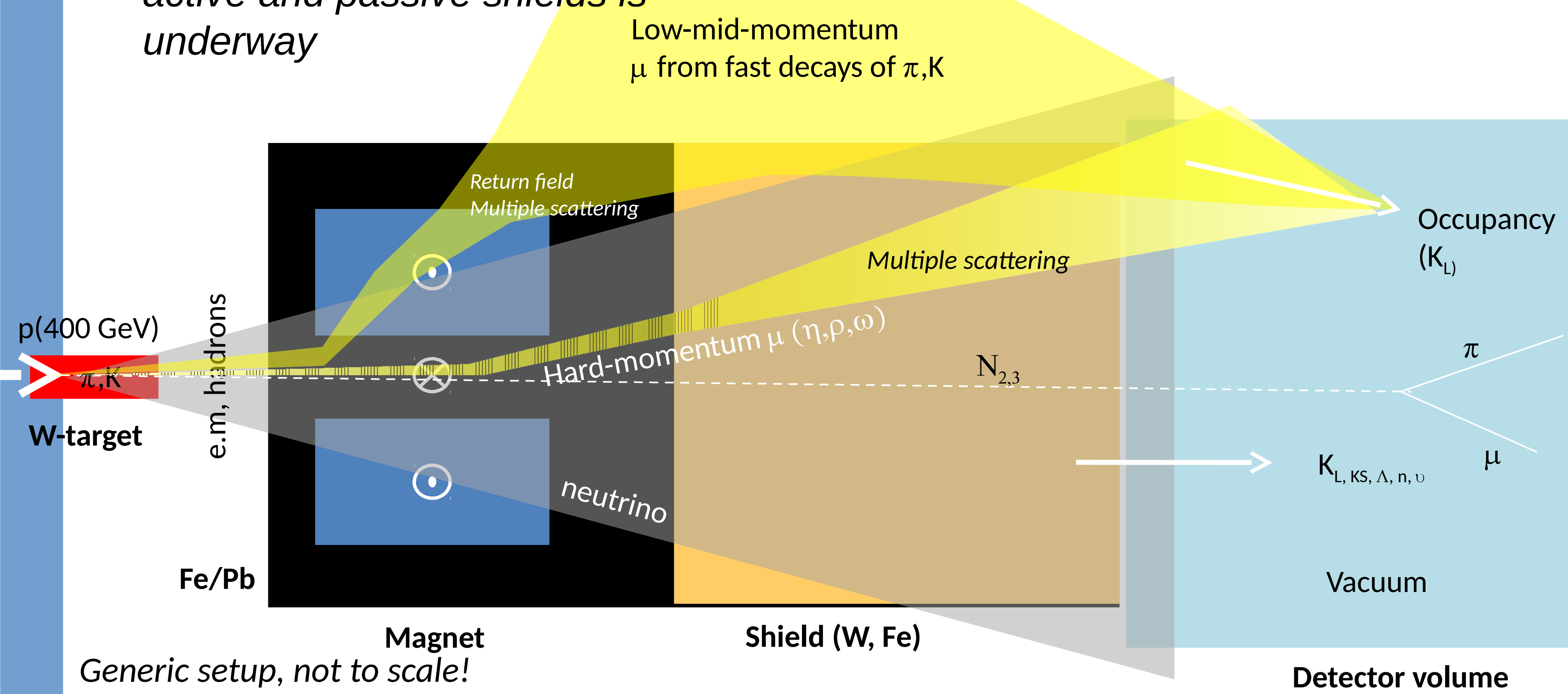
Acceptable occupancy <1% per spill of 5×10^{13} p.o.t.

spill duration 1s < 50×106 muons

spill duration 10ms < 50×103 muons

spill duration 10μs < 500 muons

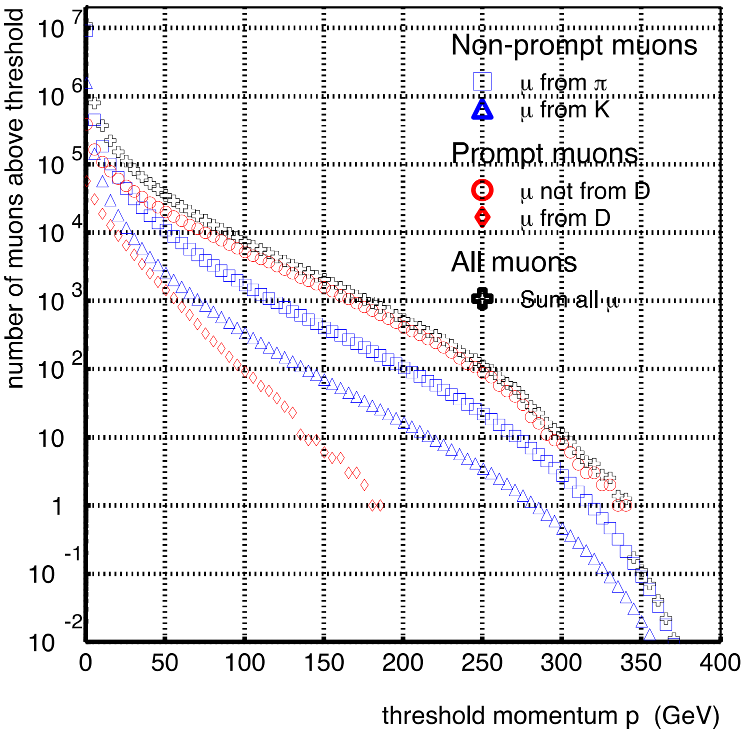
- *Heavy target (50 cm of W)*
- *Hadron absorber*
- *Muon shield: optimization of active and passive shields is underway*



Generic setup, not to scale!

Muon Shield

- Without μ-filter: 5×10^{9}/ spill (5×10^{13} pot)
- Idea to reduce background from μ-interactions to below ν-background
  - Acceptable rate ~10^{5} μ / 2×10^{20} pot
- Main sources of muons simulated using PYTHIA
- 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 :

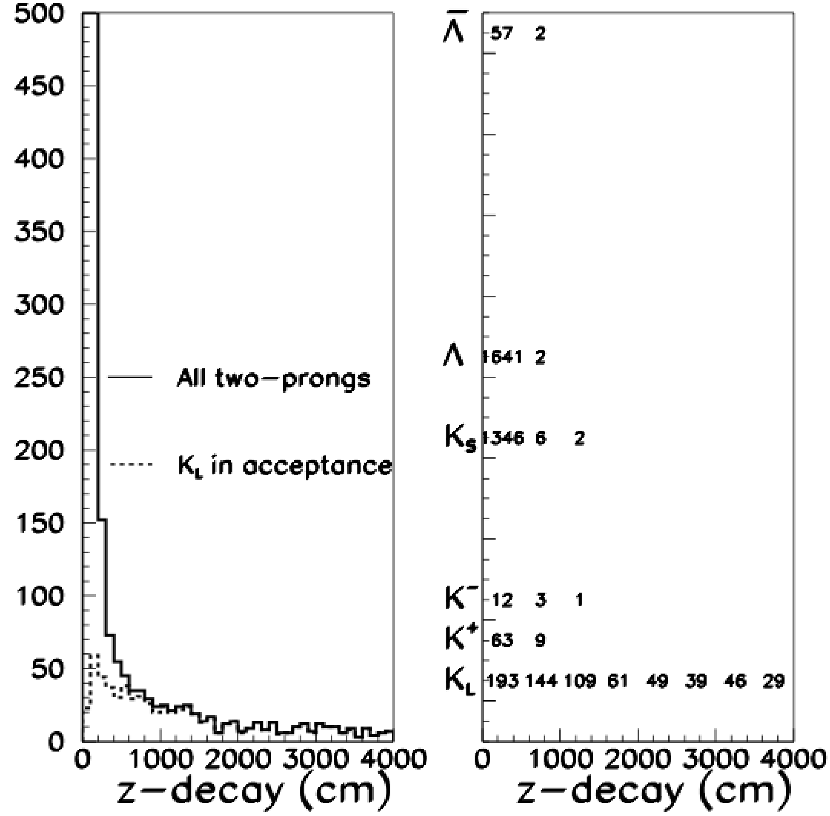
- Use GEANT and GENIE to simulate the CC and NC neutrino interactions
- CC(NC) rate of $\sim6(2)\times10^5$ per interaction length per 2×10^{20} pot
- Use veto-station to suppress short lived
- $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$ main background
- Requiring μ-id. for one of the two decay products

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

Neutrino backgrounds

Neutrino interactions in the decay volume

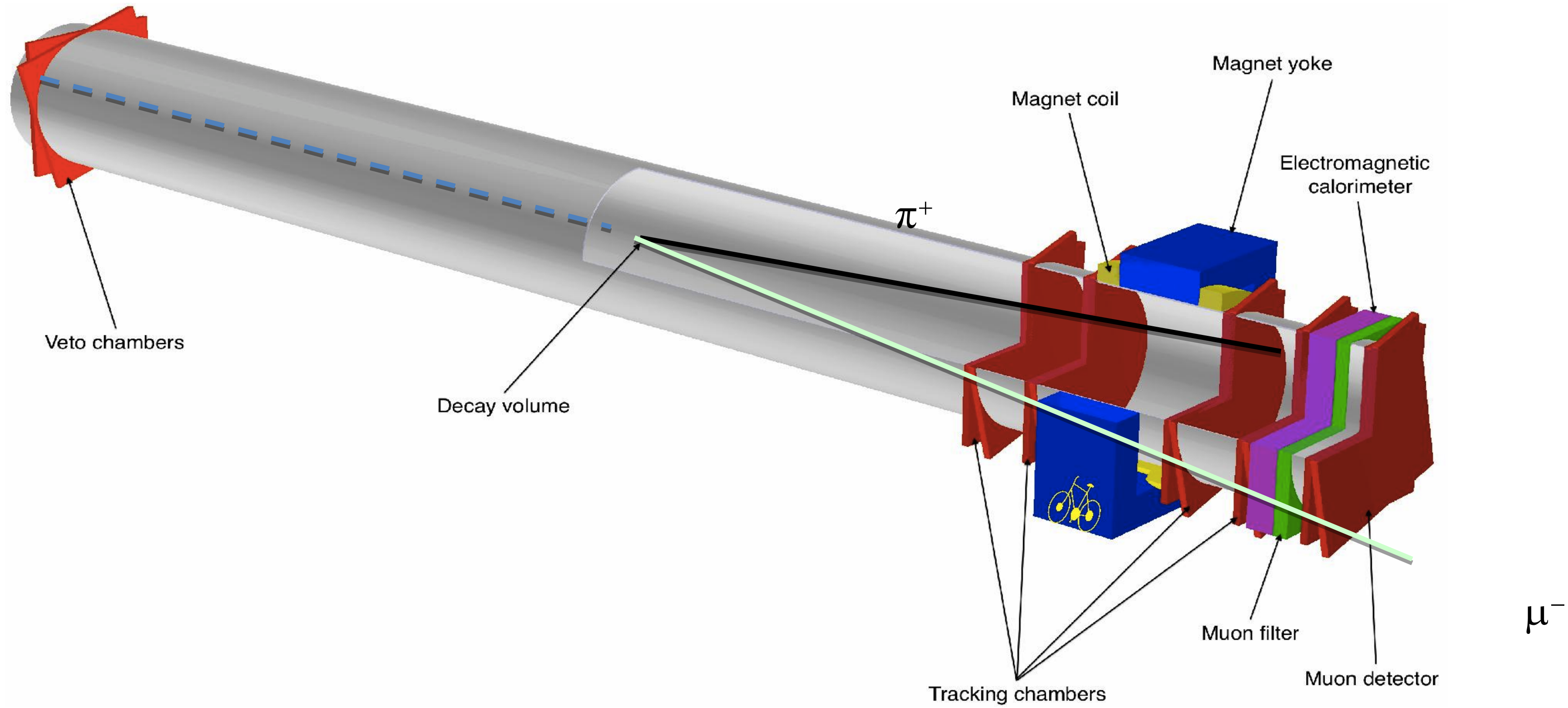
~10% of neutrino interactions in the muon shield just upstream of the decay volume produce Λ or K^0



Detector Concept

Aim to reconstruct HNL decays into the final states: $\mu^-\pi^+$, $\mu^-\rho^+$, $e^-\rho^+$

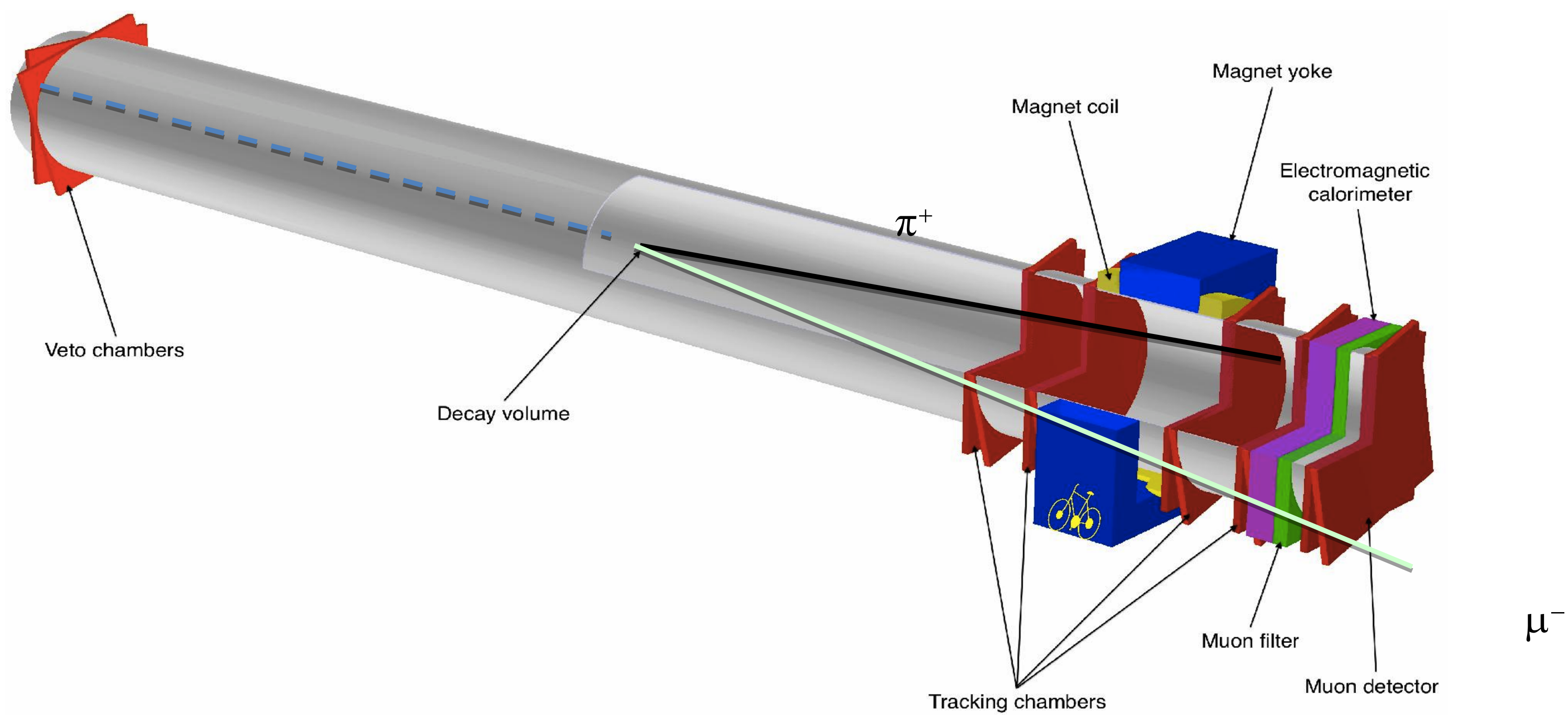
- Require long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter

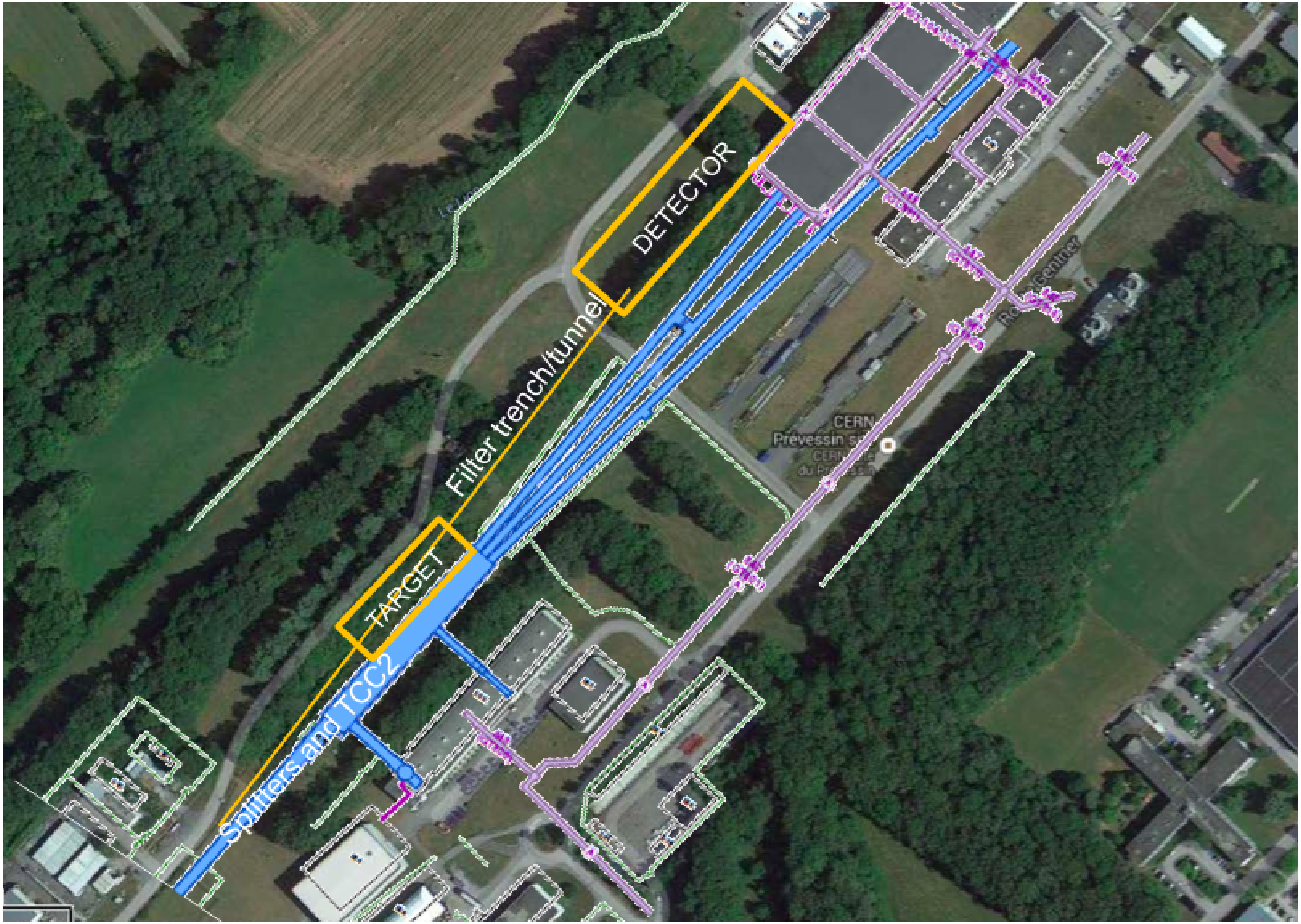


Detector Concept

5 m diameter, 50 m length vacuum vessel

10 m long magnetic spectrometer with 0.5 Tm dipole magnet and four tracking chambers




DETECTOR
Filter trench/tunnel
TARGET
Splitters and TCC2
CERN
Prévessin

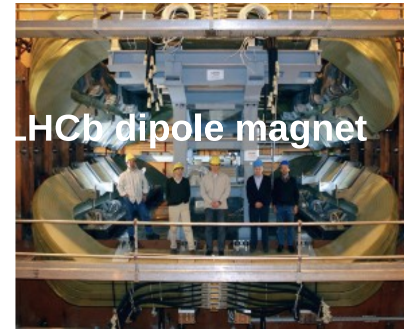
Detector Technologies

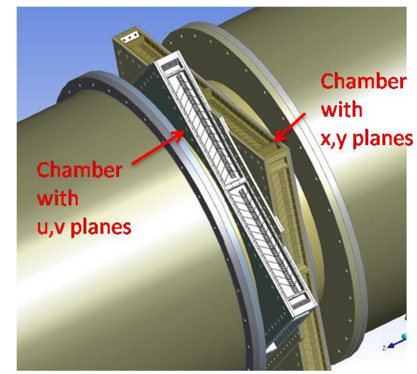
Dipole magnet

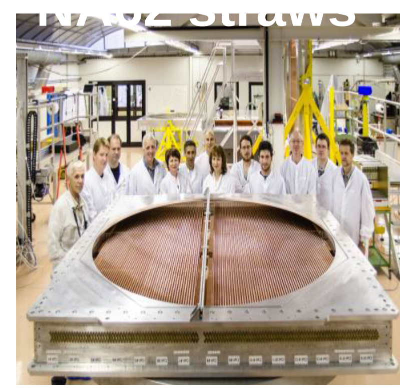
- Magnet similar to LHCb design required, but with ~40% less iron and 3× less power
- Free aperture of ~16 m^2
- Field integral ~ 0.5 Tm over 5 m length

Vacuum tank and straw tracker

- NA62 has 10^{-5} mbar pressure, only 10^{-2} mbar here
- Have demonstrated gas tightness of straw tubes with 120 μm spatial resolution and 0.5% X^0 material budget in long term tests



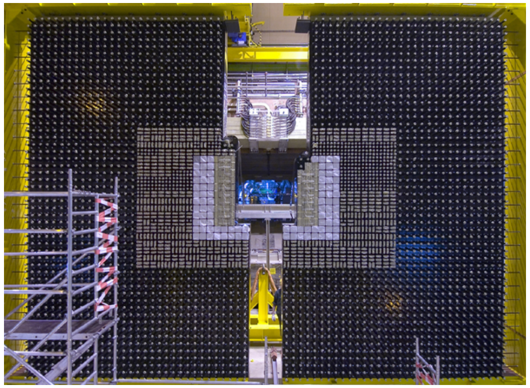




Detector Technologies

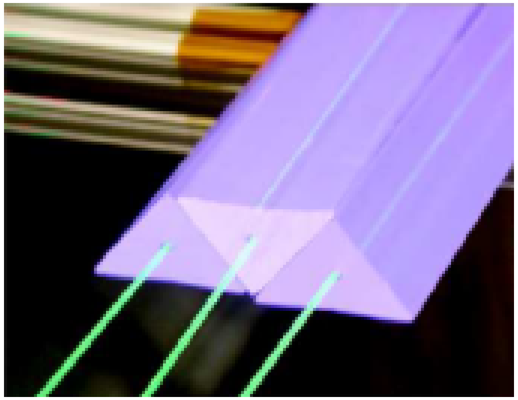
Electromagnetic calorimeter

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



Muon detector

- Scintillator strips with WLS fibres and Silicon Photomultiplier (SiPM) an attractive option



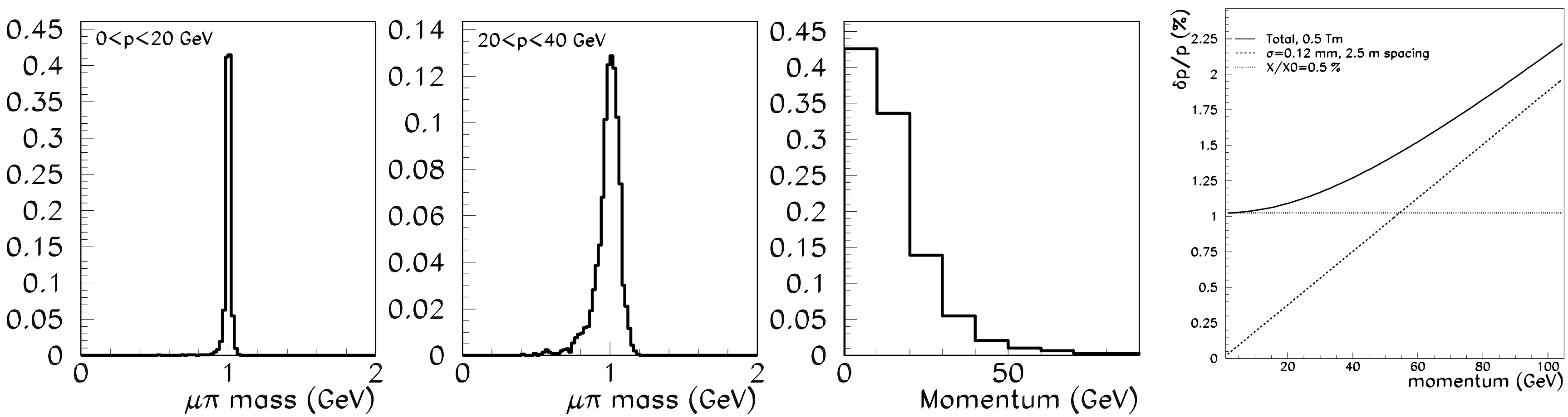
Trigger and DAQ

- Requirements on both are very modest due to low data rate

Spectrometer resolution

Arrange spectrometer such that multiple scattering and spatial resolution of straw tubes give similar contribution to the overall Δp/p

- For $m(N_{2,3})$ = 1 GeV, 75% of $\mu^-\pi^+$ decay products have p < 20 GeV



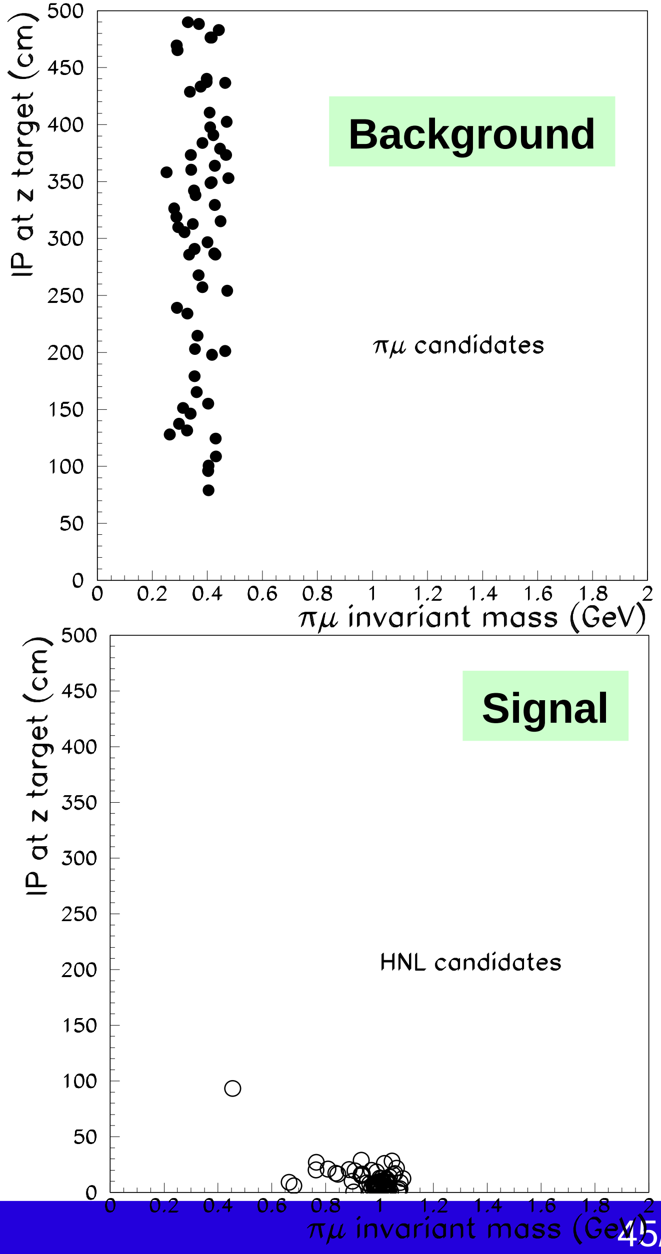
For 0.5 Tm field integral σ(mass) ~ 40 MeV for p < 20 GeV

- Good discrimination between high mass tail from small number of residual $K_L \rightarrow \mu^-\pi^+\upsilon$ and 1 GeV HNL

Residual Backgrounds

K_L produced in the final part of the muon shield have very different pointing to the target compared to signal events

- Use Impact Parameter (IP) to further suppress K_L background
- IP < 1 m is 100% efficient for signal and leaves only a handful of background events
- The IP cut will also be used to reject backgrounds induced in neutrino interactions in the material surrounding the detector



Expected event yield

Integral mixing angle U^2 is given by $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$

Make a conservative estimate of the sensitivity by only considering the decay $N_{2,3} \to \mu^- \pi^+$ – probes U_μ^2

Expected number of signal events then,

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

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 $N \to \mu^- \pi^+$

For cosmologically favoured region $U_\mu^2 = 10^{-8}$ ($\tau_N = 1.8\times10^{-4}$ s)

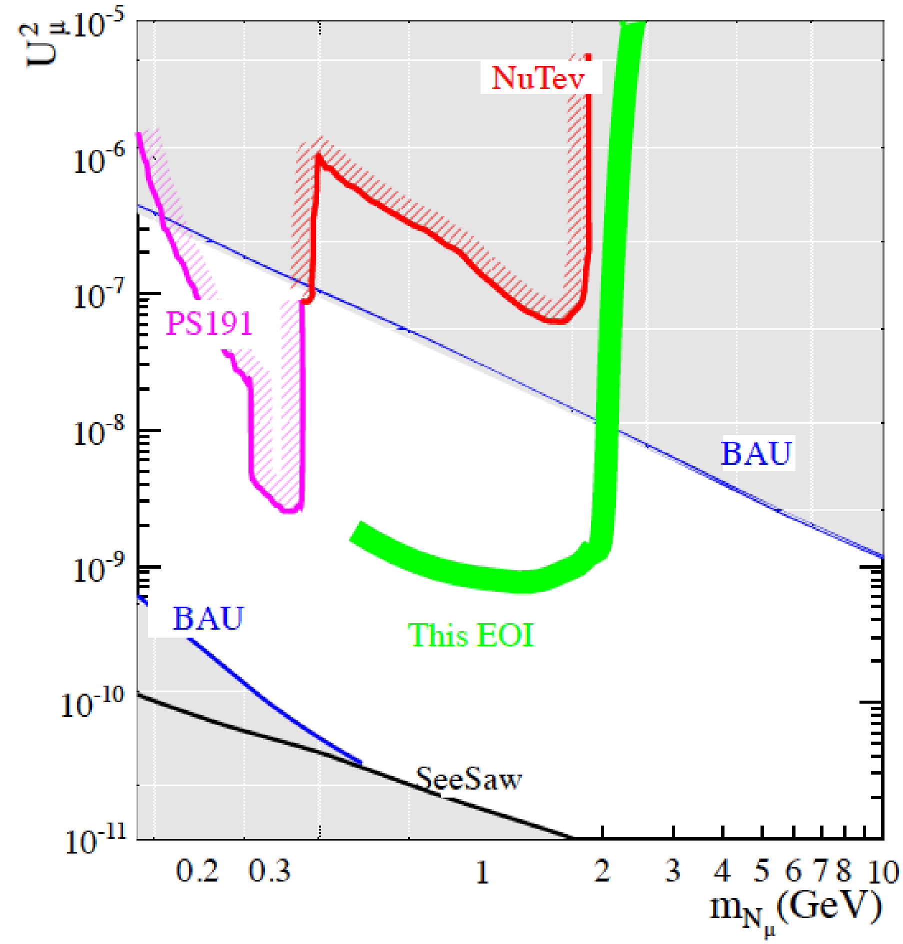
Would expect 120 fully reconstructed events

Expected sensitivity

For $M_N < 2$ GeV the proposed experiment has discovery potential for the cosmologically favoured region with $10^{-7} < U_\mu^2 <$ a few $\times 10^{-9}$

Limit from decay channels with electromagnetic not studied yet.

- Will extend search on U^2 and limit on U_e^2



Status of the SPSC review

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

SPSC assigned four referees – provided answers to their questions [http://ship.web.cern.ch/ship/EOI/SPSC-EOI-010_ResponseToReferees.pdf]

SPSC discussed our proposal Jan 2015, 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.

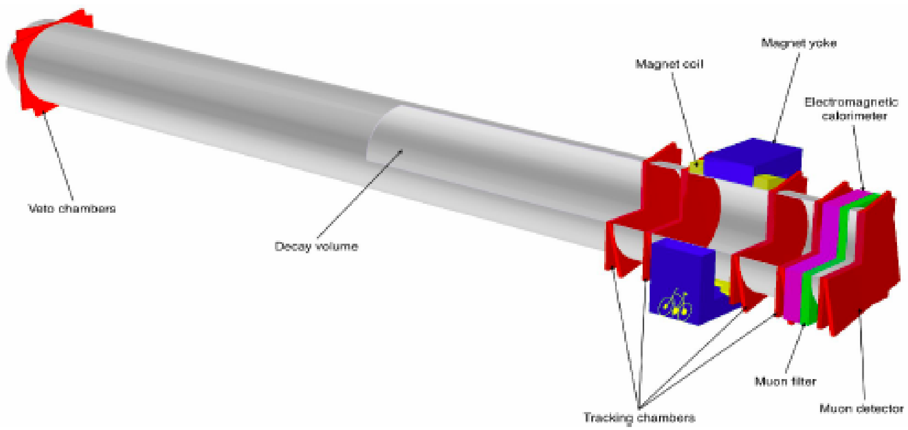
To further review the project the Committee **would need** an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration."

A strengthening collaboration

SHIP - Search for HIdden Particles

CERN, Universität Zürich, EPFL Lausanne, INFN Cagliari,
Università Federico II and INFN Napoli, Imperial College London

Experiment to search for Heavy Neutral Leptons at the SPS



We propose a new fixed-target experiment at the CERN SPS accelerator to search for *hidden particles*. In particular, to search for Heavy Neutral Leptons (HNLs) produced in charm decays. HNLs are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations, and provide a Dark Matter candidate.

SHIP is a collaboration of six institutes: CERN, Universität Zürich, École Polytechnique Fédérale de Lausanne, INFN Sezione di Cagliari, Università Federico II and INFN Napoli, Imperial College London. Groups interested in joining should contact Andrey Golutvin and Jaap Panman. The extension of the collaboration will be discussed at the ***First SHIP Workshop*** that will be take place in ***Zürich the 10-12 June 2014***.

First SHiP Workshop, 10-12th June 2014

Meeting at University of Zurich to discuss :

- Physics reach of SHiP detector
- Detector requirements and technologies

Please get in touch if you are interested …

Theoretical Overview (10th June)

Review of heavy neutral leptons, with discussions about leptogenesis and cosmological constraints

Theory review (11th June Morning)

Discussion of theoretical status and present experimental constraints

Facility and Experiment (11th June Afternoon)

Discussion on the primary beam line, target and detector design for the SHIP experiment

Tau neutrinos and SHIP detector (12th June Morning)

Discussion on the electronics and DAQ system for the SHIP experiment and on the detector for tau neutrinos

Summary and discussion (12th June Afternoon)

Conclusions

- The proposed experiment will search for NP in the largely unexplored domain of new, very weakly interacting particles with masses below the Fermi scale
- Detector is based on existing technologies
- Ongoing discussion of the beam line 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