



SHiP: a new multipurpose beam-dump experiment at SPS

- Physics landscape after Run-1.
- Why Heavy Neutral Leptons?
- How to produce/detect HNLs.
- The experimental set-up.
- Backgrounds & Sensitivity
- Symbiosis with “active” ν physics.
- Conclusions.



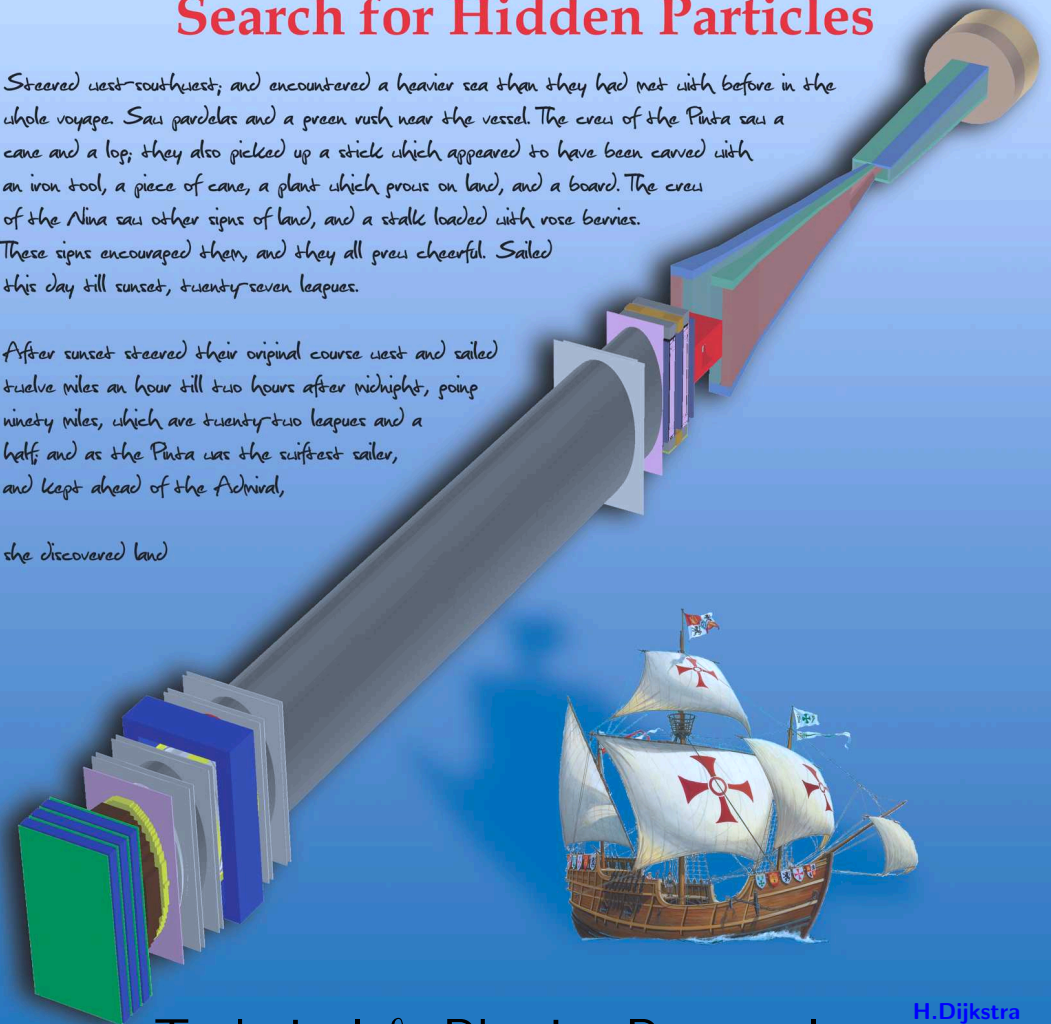
CERN/SPSC 2015-xxx
SHiP TP
10 April 2015

Search for Hidden Particles

Steered west-southwest; and encountered a heavier sea than they had met with before in the whole voyage. Saw pardeles and a green rush near the vessel. The crew of the Pinta saw a cane and a log; they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a plant which grows on land, and a board. The crew of the Nina saw other signs of land, and a stalk loaded with rose berries. These signs encouraged them, and they all grew cheerful. Sailed this day till sunset, twenty-seven leagues.

After sunset steered their original course west and sailed twelve miles an hour till two hours after midnight, going ninety miles, which are twenty-two leagues and a half; and as the Pinta was the swiftest sailer, and kept ahead of the Archival,

she discovered land



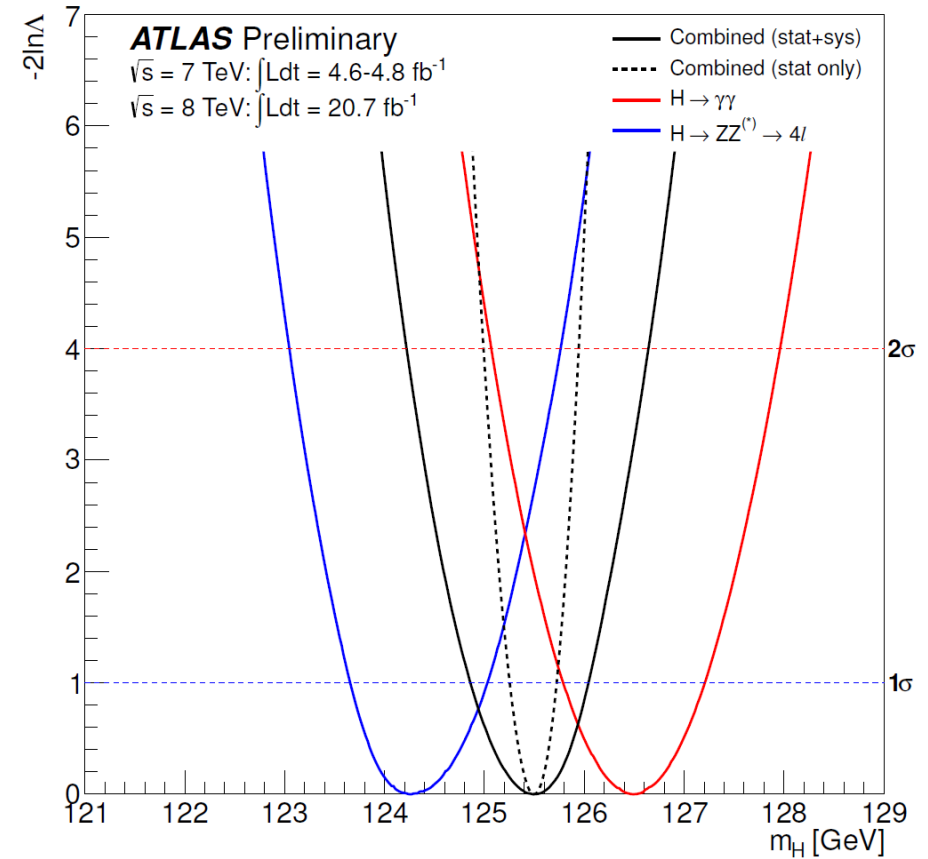
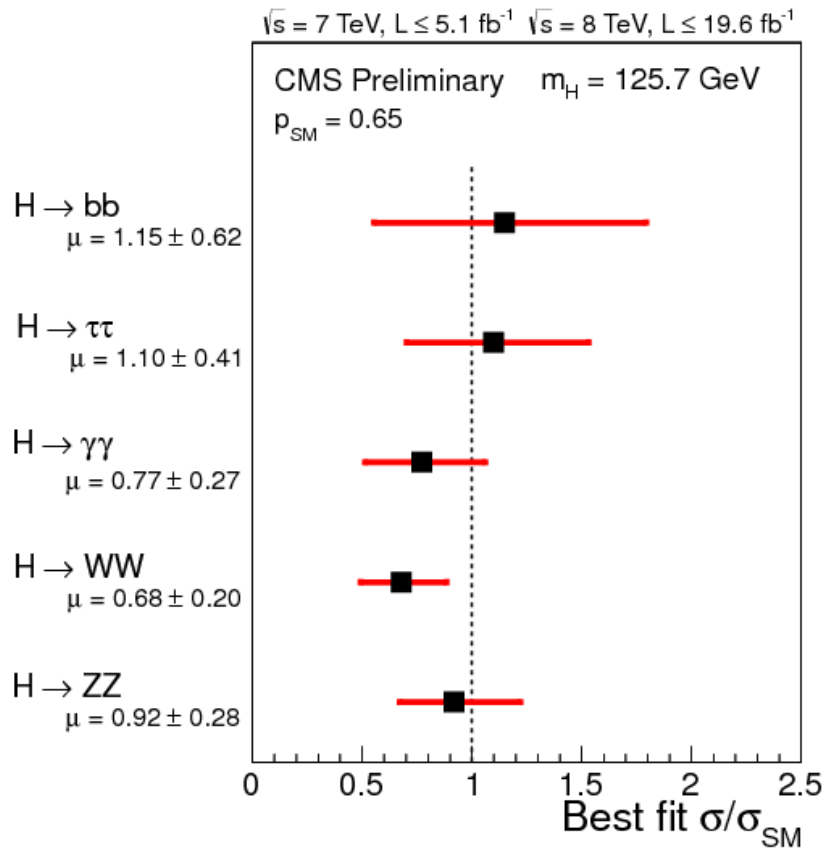
Technical & Physics Proposals





Triumph of SM: Higgs found!

- Boson found consistent with SM-Higgs.
- Atlas: $M_H = 125.5 \pm 0.2_{stat} \pm 0.5_{syst}$ GeV
- CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ GeV





What is not found..

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	\tilde{q}, \tilde{g} 1.7 TeV	$m(\tilde{g})=m(\tilde{g})$ 1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	\tilde{g} 1.2 TeV	any $m(\tilde{g})$ ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	\tilde{g} 1.1 TeV	any $m(\tilde{g})$ 1308.1841
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	\tilde{q} 850 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	\tilde{g} 1.33 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	\tilde{g} 1.18 TeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell/\nu)/\nu\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	\tilde{g} 1.12 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	\tilde{g} 1.24 TeV	$\tan\beta<15$ 1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	\tilde{g} 1.6 TeV	$\tan\beta>20$ 1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g} 1.28 TeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$ ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	\tilde{g} 619 GeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$ ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	\tilde{g} 900 GeV	$m(\tilde{\chi}_1^0)>220 \text{ GeV}$ 1211.1167
GGM (higgsino NLSP)	2 $e, \mu (Z)$	0-3 jets	Yes	5.8	\tilde{g} 690 GeV	$m(\text{NLSP})>200 \text{ GeV}$ ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	10.5	\tilde{g} 645 GeV	$m(\tilde{G})>10^{-4} \text{ eV}$ ATLAS-CONF-2012-147	
3^{rd} gen. \tilde{g} med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	\tilde{g} 1.25 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	\tilde{g} 1.1 TeV	$m(\tilde{\chi}_1^0)<350 \text{ GeV}$ 1308.1841
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.34 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g} 1.3 TeV	$m(\tilde{\chi}_1^0)<300 \text{ GeV}$ 1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	\tilde{b}_1 100-620 GeV	$m(\tilde{\chi}_1^0)<90 \text{ GeV}$ 1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 $e, \mu (SS)$	0-3 b	Yes	20.3	\tilde{b}_1 275-440 GeV	$m(\tilde{\chi}_1^0)=2 m(\tilde{\chi}_1^0)$ 1404.2500
	$\tilde{t}_1\tilde{t}_1 (\text{light}), \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	1-2 e, μ	1-2 b	Yes	4.7	\tilde{t}_1 110-167 GeV	$m(\tilde{\chi}_1^0)=55 \text{ GeV}$ 1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1 (\text{light}), \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1 130-210 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)-50 \text{ GeV}, m(\tilde{t}_1)<m(\tilde{\chi}_1^0)$ 1403.4853
	$\tilde{t}_1\tilde{t}_1 (\text{medium}), \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	\tilde{t}_1 215-530 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 1403.4853
	$\tilde{t}_1\tilde{t}_1 (\text{medium}), \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	\tilde{t}_1 150-580 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}, m(\tilde{\chi}_1^0)-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 1308.2631
	$\tilde{t}_1\tilde{t}_1 (\text{heavy}), \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	\tilde{t}_1 210-640 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1407.0583
	$\tilde{t}_1\tilde{t}_1 (\text{heavy}), \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	\tilde{t}_1 260-640 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1406.1122
	$\tilde{t}_1\tilde{t}_1 (\text{heavy}), \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0	mono-jet/ c -tag	Yes	20.3	\tilde{t}_1 90-240 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1407.0608
	$\tilde{t}_1\tilde{t}_1 (\text{natural GMSB})$	2 $e, \mu (Z)$	1 b	Yes	20.3	\tilde{t}_1 150-580 GeV	$m(\tilde{\chi}_1^0)>150 \text{ GeV}$ 1403.5222
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu (Z)$	1 b	Yes	20.3	\tilde{t}_2 290-600 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}$ 1403.5222	
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1403.5294
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \ell\nu(\ell\bar{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{\chi}_1^0))$ 1403.5294
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tau\nu(\tau\bar{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{\chi}_1^0))$ 1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\tilde{\nu}\bar{\nu}), \ell\nu\tilde{\ell}_L(\tilde{\nu}\bar{\nu})$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{\chi}_1^0))$ 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^\pm Z\tilde{\chi}_1^0$	2-3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$ 1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^\pm h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$ ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_2^0, \tilde{\chi}_3^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ 1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^0)-m(\tilde{\chi}_1^0)=160 \text{ MeV}, \tau(\tilde{\chi}_1^0)=0.2 \text{ ns}$ ATLAS-CONF-2013-069
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g} 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s}<\tau(\tilde{g})<1000 \text{ s}$ 1310.6584
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(e, \mu)+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\tau}, \tilde{\chi}_1^0$ 475 GeV	$10<\tan\beta<50$ ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4<\tau(\tilde{\chi}_1^0)<2 \text{ ns}$ 1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\mu$ (RPV)	1 μ , displ. vtx	-	-	20.3	\tilde{q} 1.0 TeV	$1.5<c\tau<156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$ ATLAS-CONF-2013-092	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda_{511}^{\prime}=0.10, \lambda_{132}^{\prime}=0.05$ 1212.1272
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda_{511}^{\prime}=0.10, \lambda_{1(2)33}^{\prime}=0.05$ 1212.1272
	Bilinear RPV CMSSM	2 $e, \mu (SS)$	0-3 b	Yes	20.3	\tilde{q}, \tilde{g} 1.35 TeV	$m(\tilde{g})=m(\tilde{g}), c\tau_{LSP}<1 \text{ mm}$ 1404.2500
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow e\tilde{\nu}_\mu, e\tilde{\nu}_\tau$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^0), \lambda_{121} \neq 0$ 1405.5086
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tau\tilde{\nu}_e, e\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^0), \lambda_{133} \neq 0$ 1405.5086
	$\tilde{g} \rightarrow q\tilde{q}q$	0	6-7 jets	-	20.3	\tilde{g} 916 GeV	$\text{BR}(t)=\text{BR}(b)=\text{BR}(c)=0\%$ ATLAS-CONF-2013-091
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b s$	2 $e, \mu (SS)$	0-3 b	Yes	20.3	\tilde{g} 850 GeV	1404.250
Other	Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693 1210.4826
	Scalar gluon pair, sgluon $\rightarrow t\tilde{t}$	2 $e, \mu (SS)$	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	$m(\chi)<80 \text{ GeV}, \text{limit of } <687 \text{ GeV for D8}$ ATLAS-CONF-2012-147

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

10⁻¹ 1 Mass scale [TeV]

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

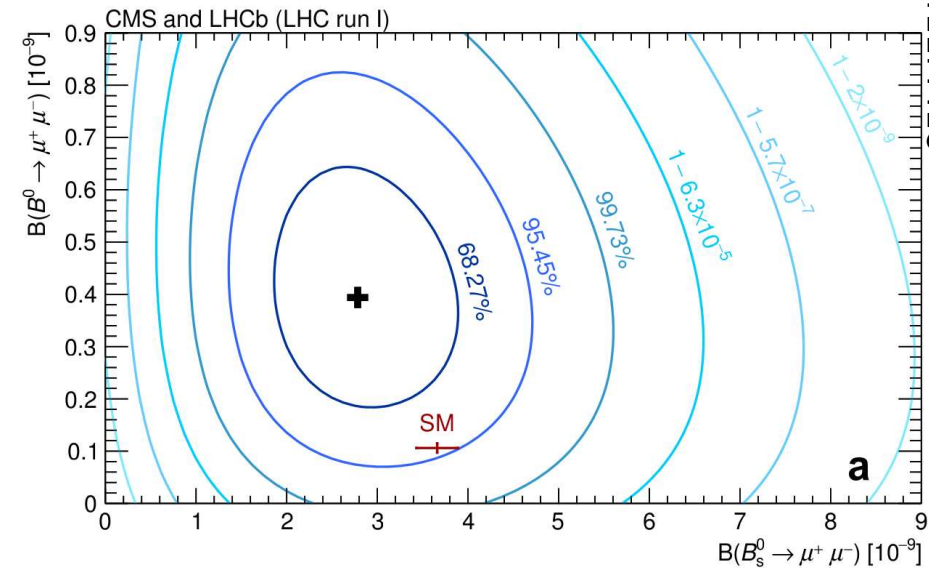
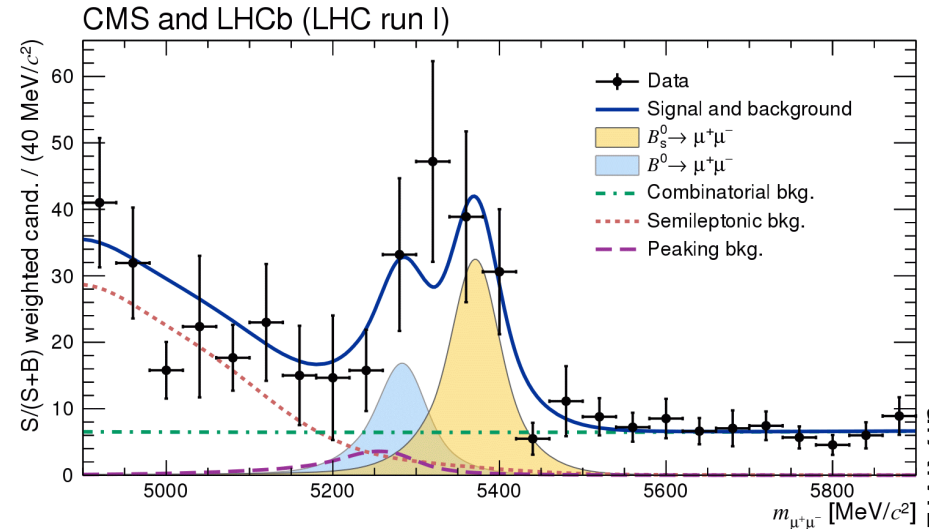
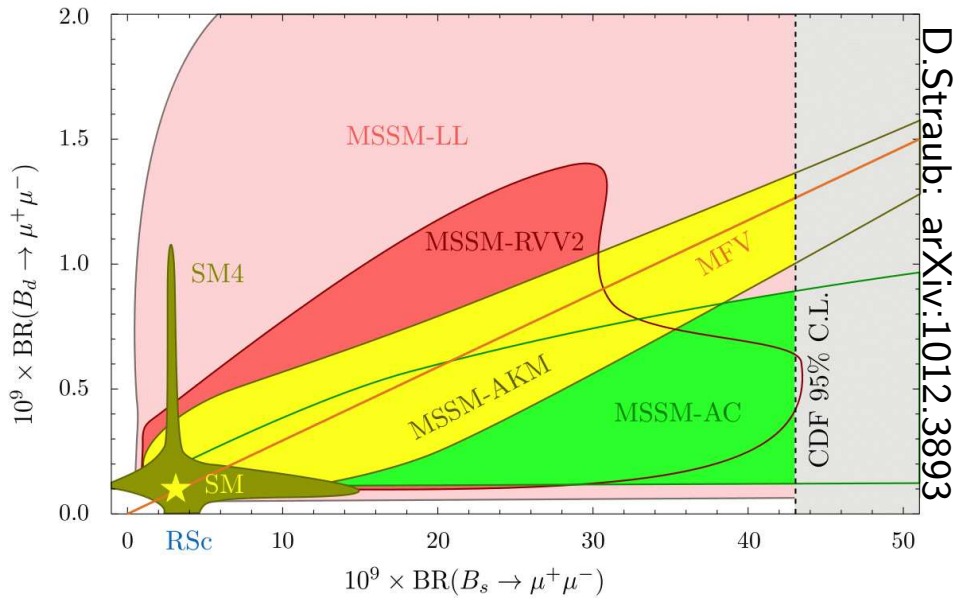


$B_s \rightarrow \mu\mu$ found and \equiv SM

- No tree level decay
- Helicity suppressed
- Expected: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$ (Phys. Rev. Lett. 109 (2012) 041801)

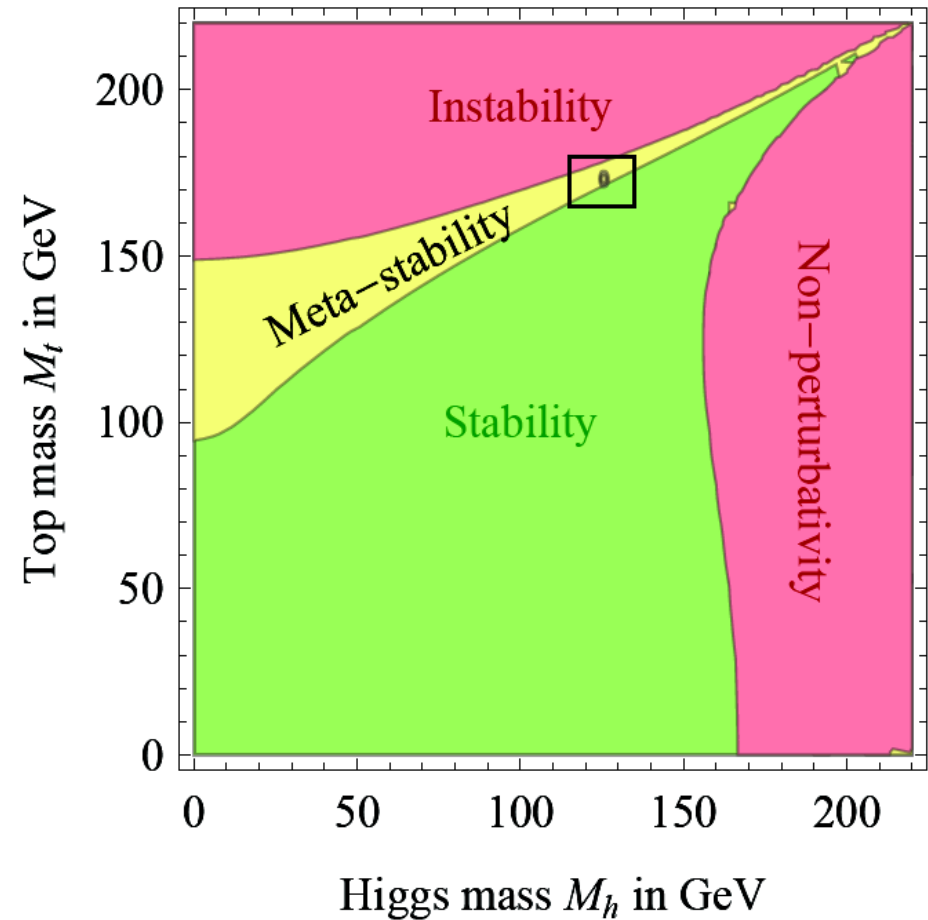
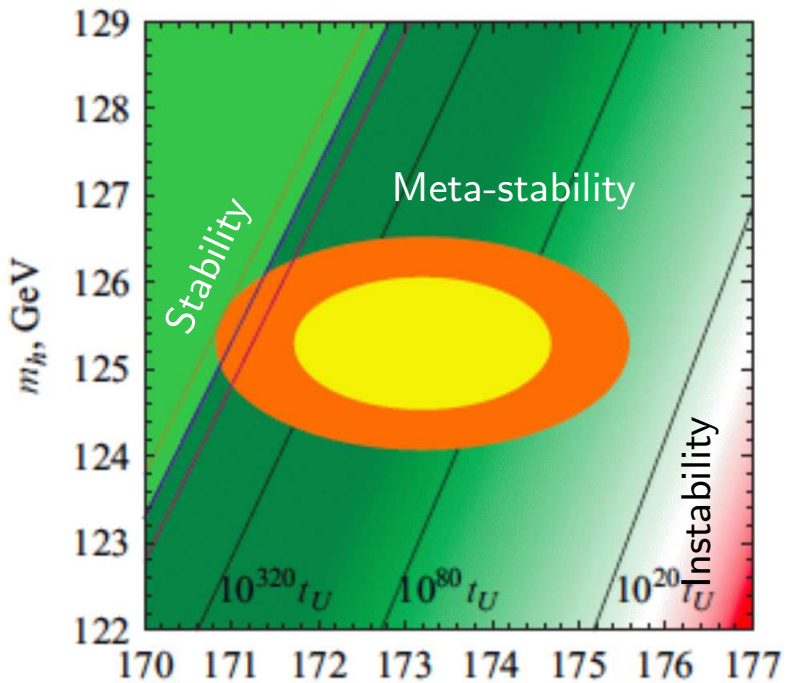
NP:

- MSSM: $\mathcal{B} \propto \tan^6\beta/M_{A^0}^4$
- Pre-LHC parameter space example:



Higgs and Vacuum Stability

- Higgs mass is “fine tuned”?
 - SM located in narrow meta-stability wedge.
 - Most likely “multiverse” near such a wedge?
 - Vast majority of sand-dunes have a slope angle roughly equal to the so-called “angle of repose”.
 - Not anthropic, but $P(\text{multiverses})$ peaks near wedge?
- Vacuum might be stable, or has a $\tau \gg \tau_{\text{universe}}$
- SM may work successfully up to Planck scale, i.e. no need for a new mass scale

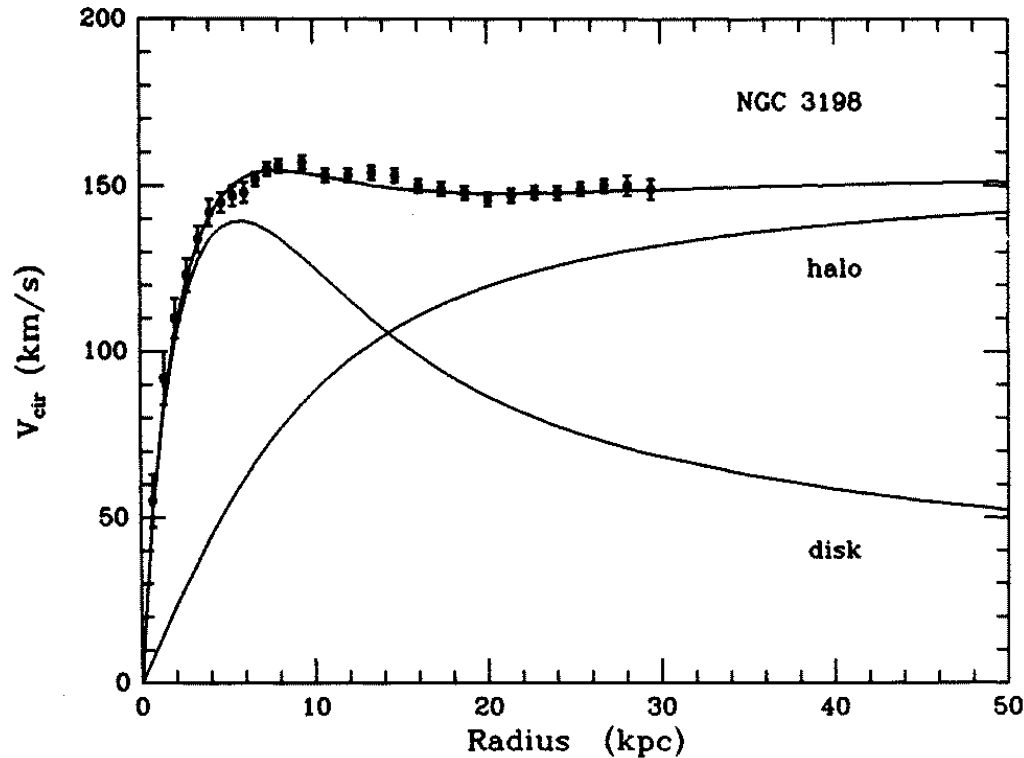




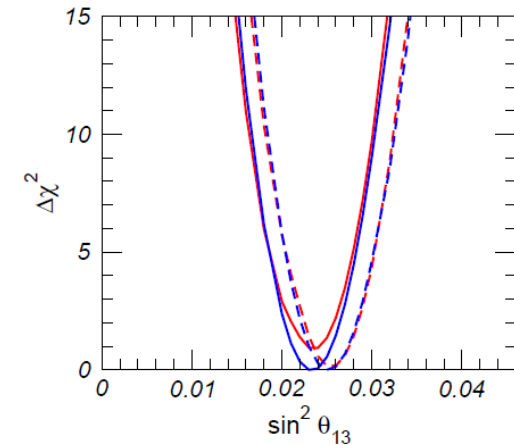
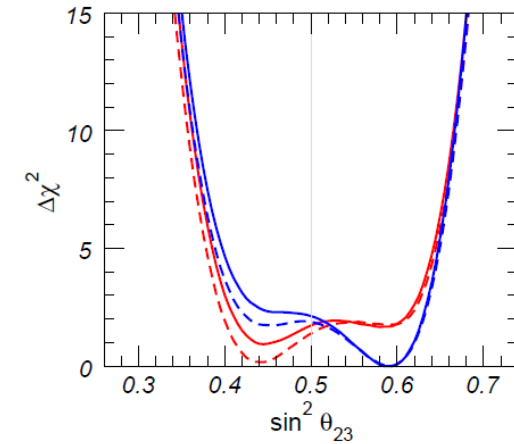
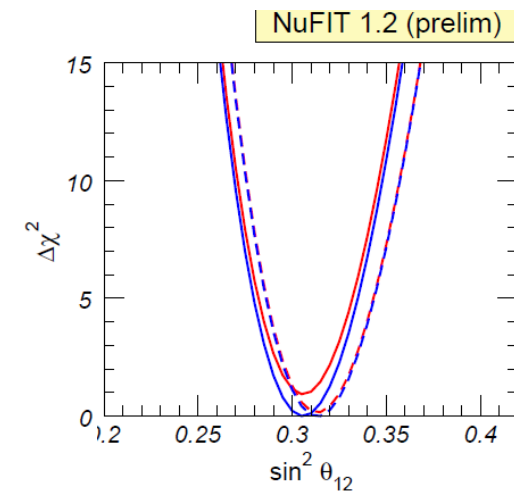
SM case closed?

NO, SM unable to explain observed:

- Matter anti-matter asymmetry in universe
- Neutrino mixing \rightarrow masses
- Non-baryonic dark matter



Astrophysical Journal, Vol. 295, Aug. 15, 1985

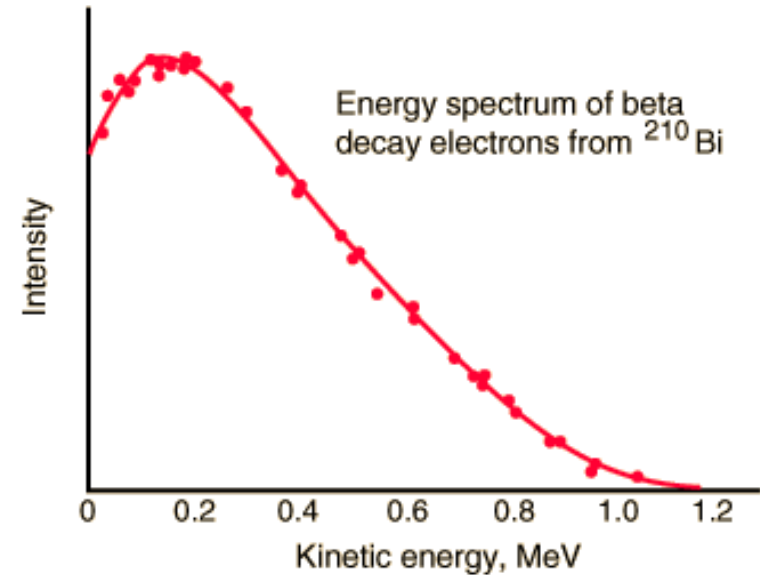


History Lesson(s)

(after B. Batell)

First decades of last century:

- β -decay: Meitner, Hahn, Ellis, Neary
- Continuous spectrum observed for $n \rightarrow p + e^-$?
- Note: SM (1930): N, e, γ
- Pauli (1930) proposed: $n \rightarrow p + e^- + \nu$
“I admit that my remedy may appear to have a small a priori probability (..).
However, only those who wager can win, (...)”



Nowadays: call this a “hidden sector”!

- New particles, neutral, very weakly interacting.
- Interacts with SM through “portal”.
- SHiP Physics Proposal: vector, Higgs, **neutrino** and axion portals.

Ptolomy (~90-168 AD):

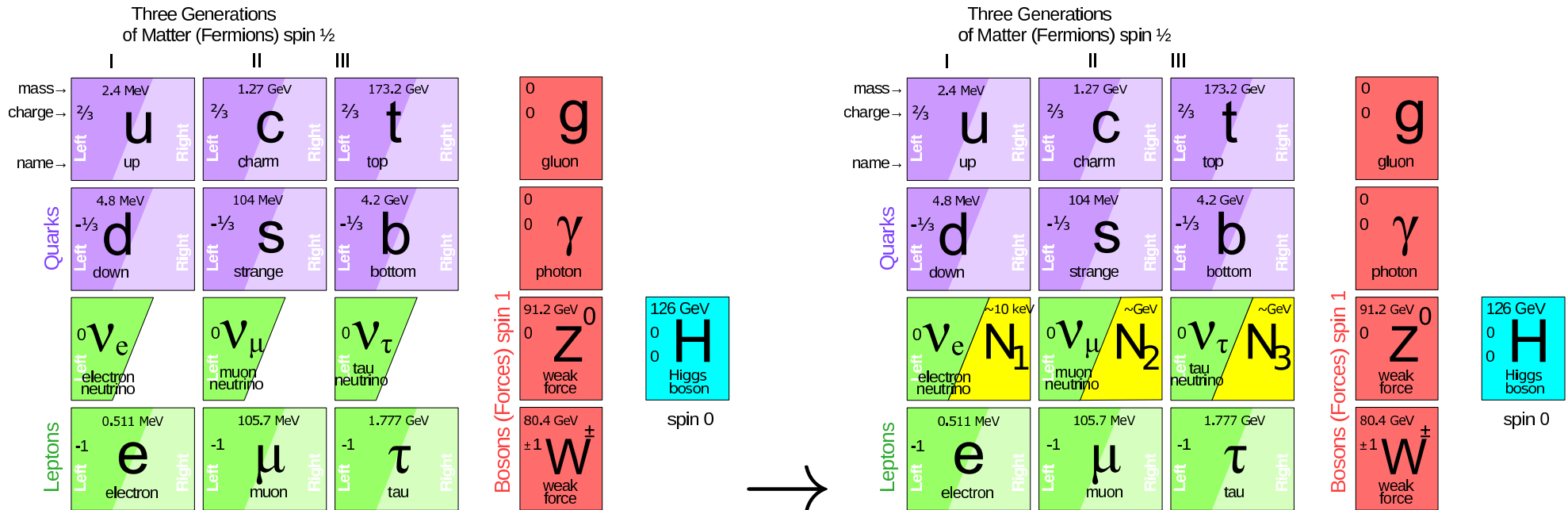
It is a good principle to explain phenomena by the simplest hypothesis possible!

MSM: T.Asaka, M.Shaposhnikov

PL B620 (2005) 17

Adding three right-handed Majorana Heavy Neutral Leptons (HNL): N_1, N_2 and N_3 :

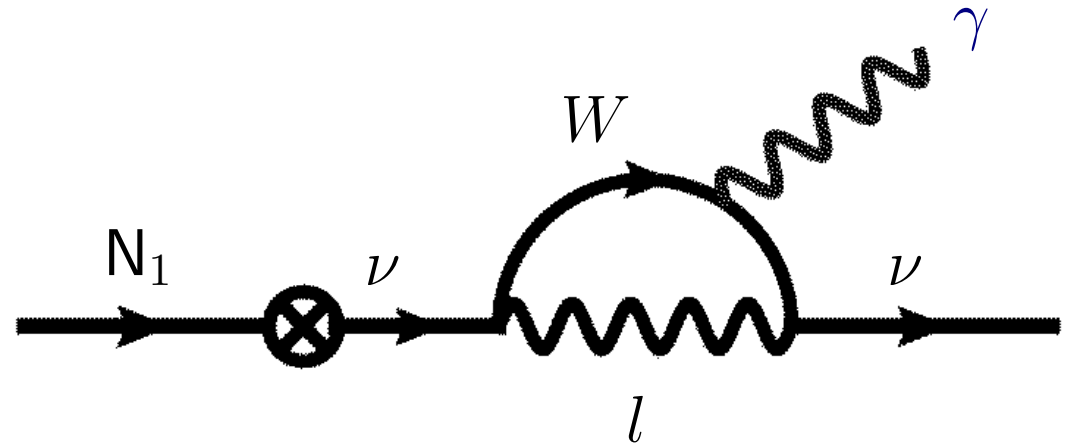
- N_1 can provide dark matter candidate
- $N_{1,2,3}$ can provide neutrino masses via Seesaw mechanism
- $N_{2,3}$ can induce leptogenesis \rightarrow baryogenesis.



ν MSM: closer look at N_1

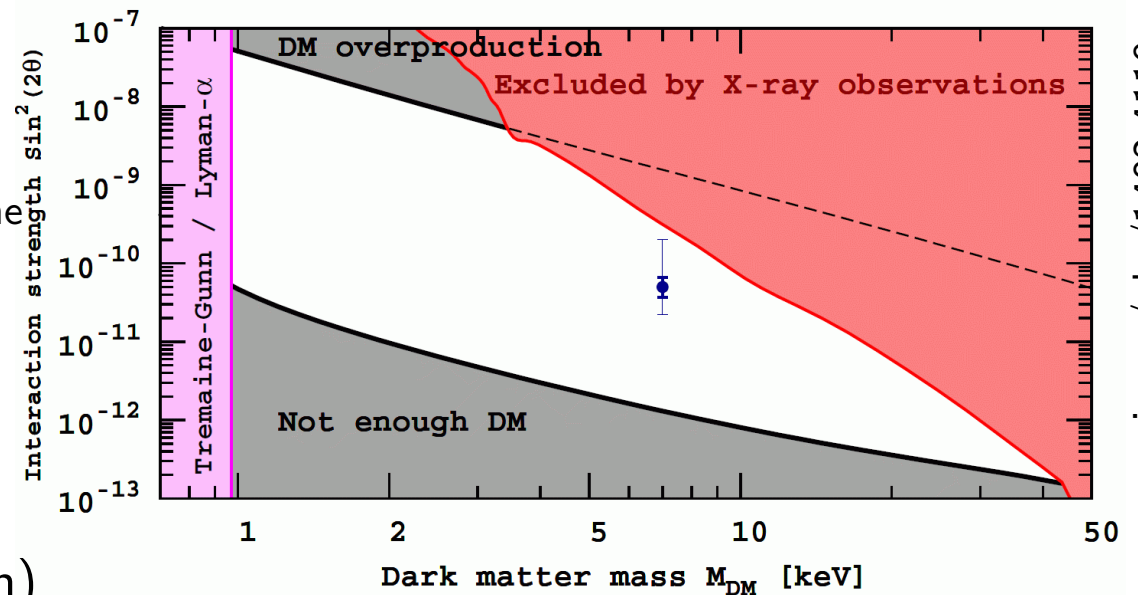
N_1 can provide dark matter candidate:

- very weak mixing with other leptons
- hence, stable enough for dark matter
- Seesaw: one $M_{\nu\text{-active}} \sim 10^{-5}$ eV
- Radiative decay: $\tau > \tau_{\text{universe}}$
- $E_\gamma = \frac{M_{N_1}}{2}$



- X-ray detection:

- 10/2/14: arxiv.org/abs/1402.2301:
Detection of an Unidentified Emission Line in the
Stacked X-ray spectrum of Galaxy Clusters
- 17/2/14: arxiv.org/abs/1402.4119:
An unidentified line in X-ray spectra of the
Andromeda galaxy and Perseus galaxy cluster
- Both papers refer to Astro-H (with
Soft X-Ray Spectrometer, 2016 launch)
to confirm/rule-out the DM origin of this signal.



arxiv.org/abs/1402.4119

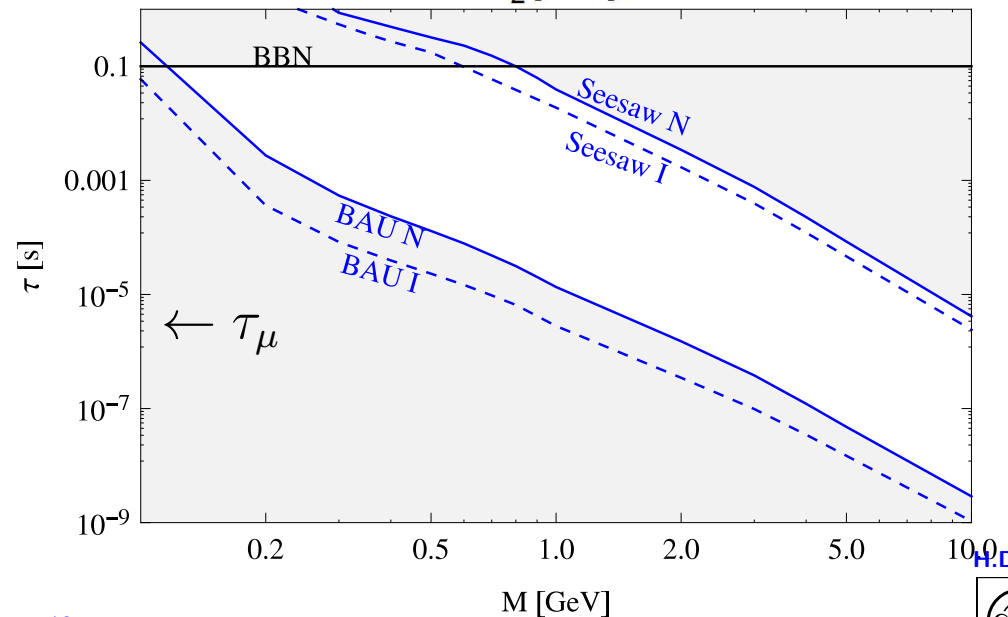
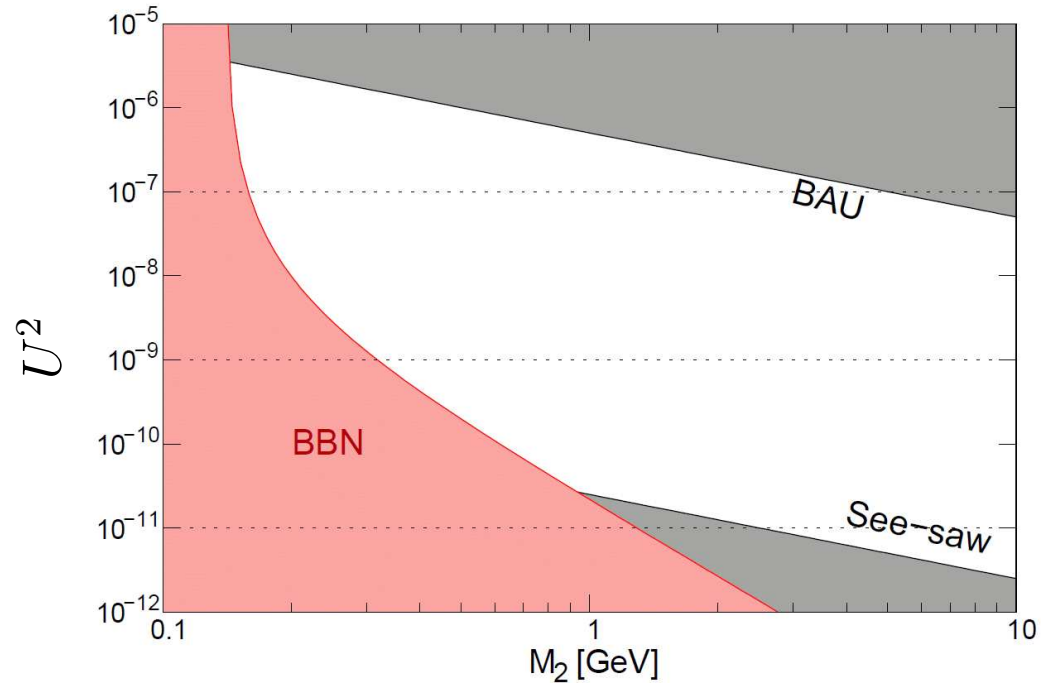


Use $N_{2,3}$ to explain:

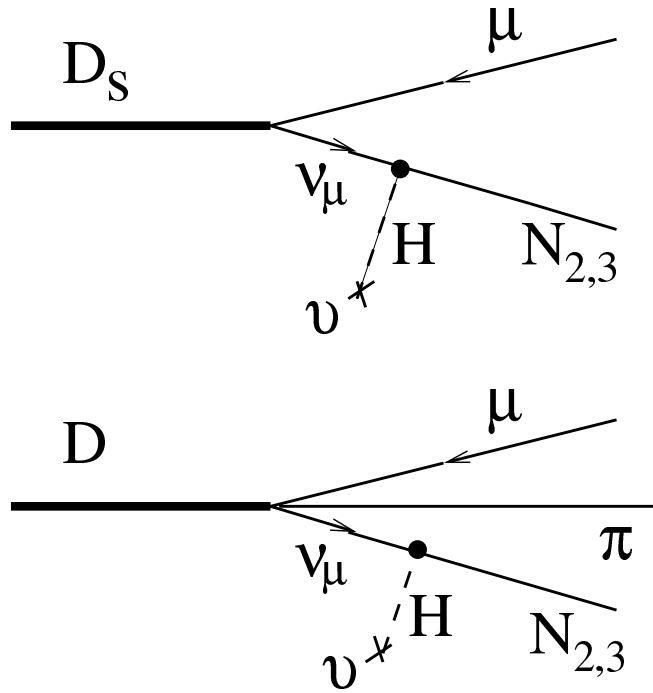
- ν masses:
Seesaw constrains Yukawa coupling and $M_{N_{2,3}}$, i.e. $M_\nu \propto U^2/M_{N_{2,3}}$
- Baryo(Lepto)genesis: make N_2 nearly degenerate with N_3 , and tune CPV-phases to explain baryon asymmetry of universe (BAU).
- $1/\tau_{N_{2,3}} \propto M_{N_{2,3}}^3$
- $\tau_{N_{2,3}} < 0.1$ s, otherwise Big Bang Nucleosynthesis (BBN, $\sim 75/25$ % H-1/He-4) would be affected by $N_{2,3}$ decays.

These are the particles SHiP is after!

$N_{2,3}$

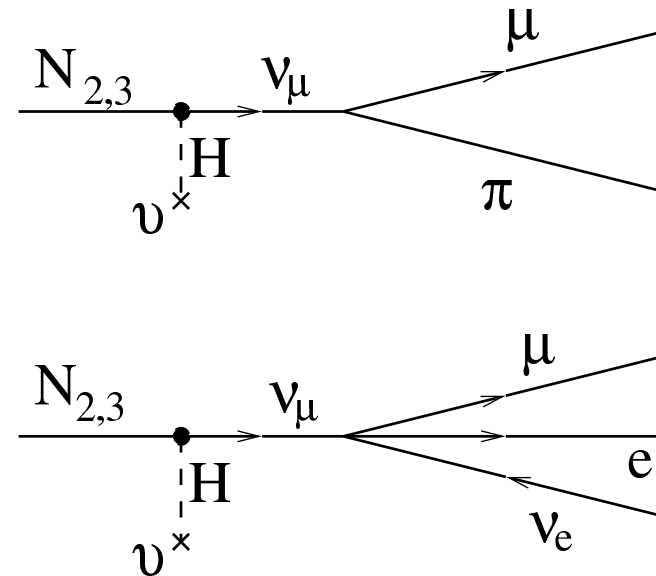


$N_{2,3}$ production and decay



- $N_{2,3}$ mix with active ν
- Produced in (semi-)leptonic decays, f.i.
 $K \rightarrow \mu\nu$, $D \rightarrow \mu\nu X$, $B \rightarrow \mu\nu X$, $Z \rightarrow \nu\bar{\nu}$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2 + U_{2,\nu_\tau}^2$

- $\mathcal{B}(N \rightarrow \mu/e \pi)$: $\sim 0.1 - 50 \%$
- $\mathcal{B}(N \rightarrow \mu/e \rho)$: $\sim 0.5 - 20 \%$
- $\mathcal{B}(N \rightarrow \nu\mu e)$: $\sim 1 - 10 \%$
- $\tau_{N_{2,3}} \propto U^{-2}$, i.e. $c\tau \sim O(\text{km})$





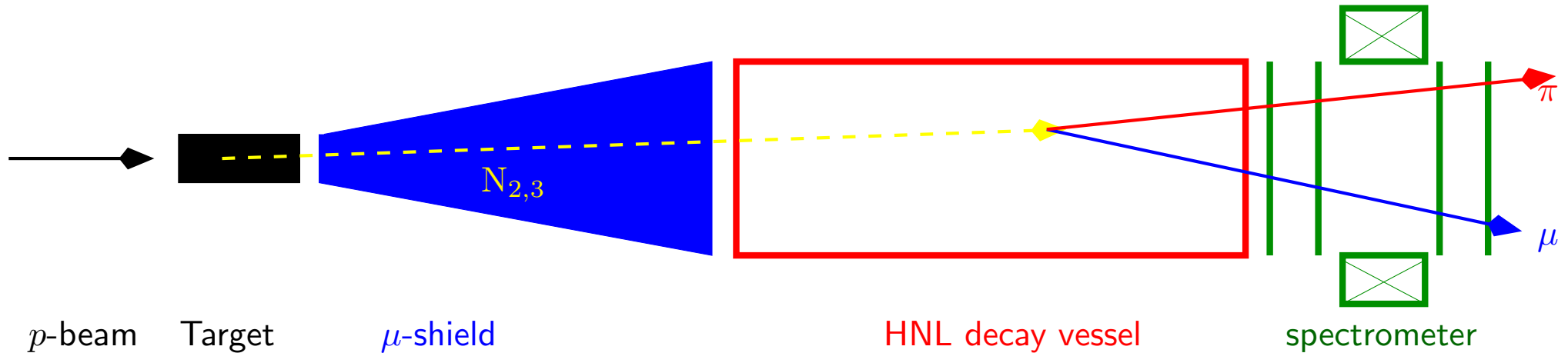
SHiP Requirements

Where to produce charm?

- LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} : $\sim 2 \cdot 10^{16}$ in 4π .
- SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV): with $2 \cdot 10^{20}$ pot: $\sim 8 \cdot 10^{17}$

Hence: go for the SPS! HNL search is different from ν_μ, ν_e physics (but ν_τ similar):

- ν_μ, ν_e cause background: heavy (Mo+W) target to avoid π/K -decay.
Example: Cu iso W-target doubles ν -background!
- Place detector as close as possible to target as background (huge μ -flux!) allows, i.e. ~ 60 m?
- Decay vessel: "vacuum" to avoid ν -interactions
- Magnetic spectrometer to reconstruct HNL mass.



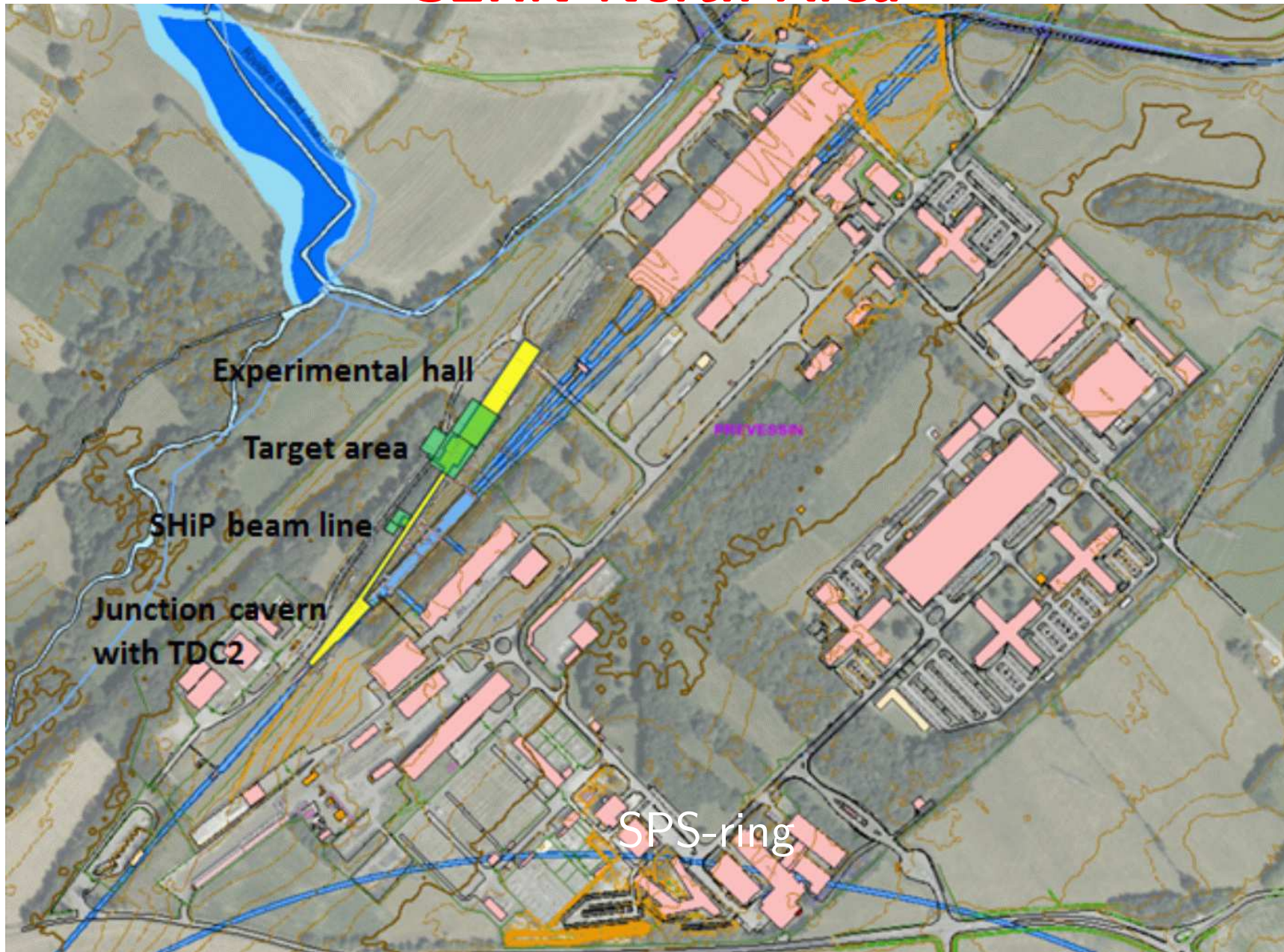


SHiP Technical Proposal

- Where to put this spectrometer?
- Some words about the target bunker
- The muon shield
- Decay vessel and Spectrometer
- Expected sensitivity



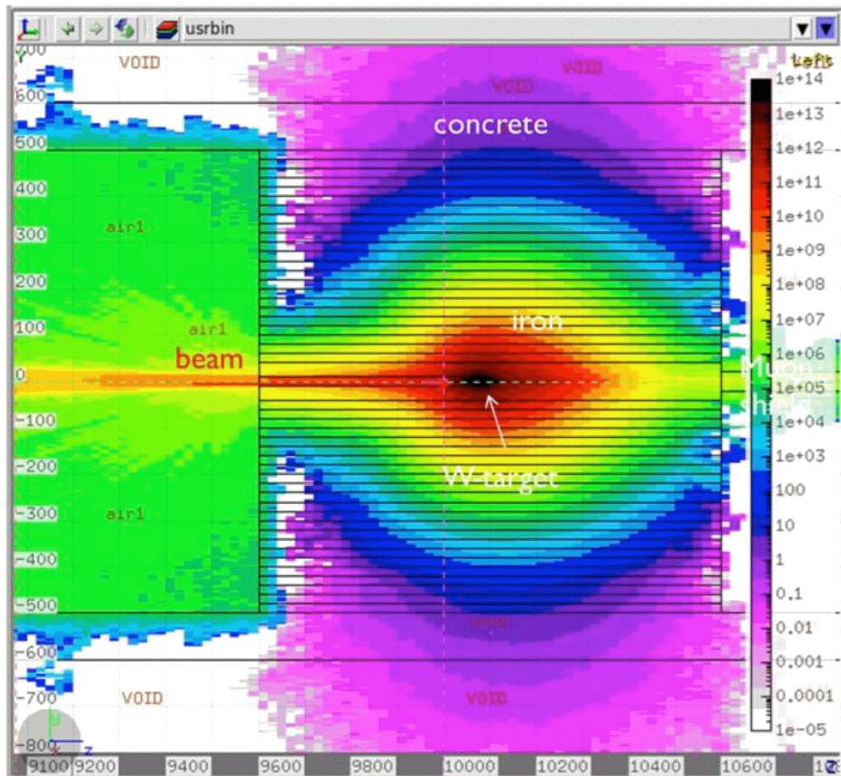
CERN North Area



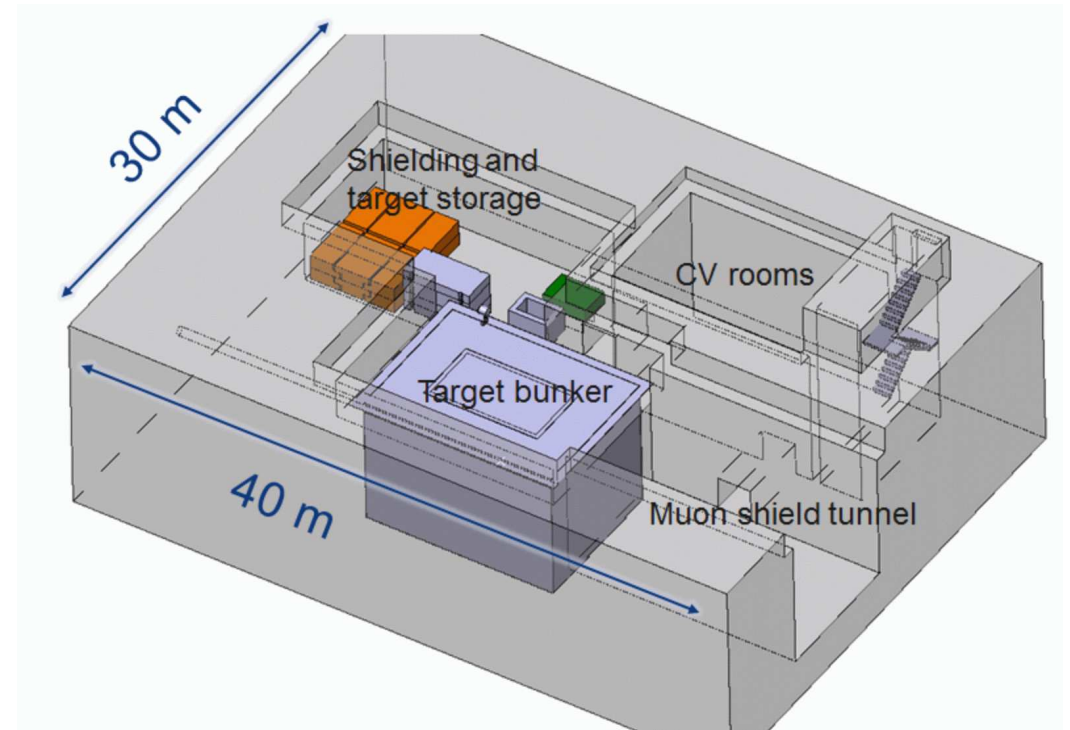
Target Bunker

Accelerator department studies:

- Beam-line from SPS
- Civil engineering
- Target design
- Radiation environment
- and cost...

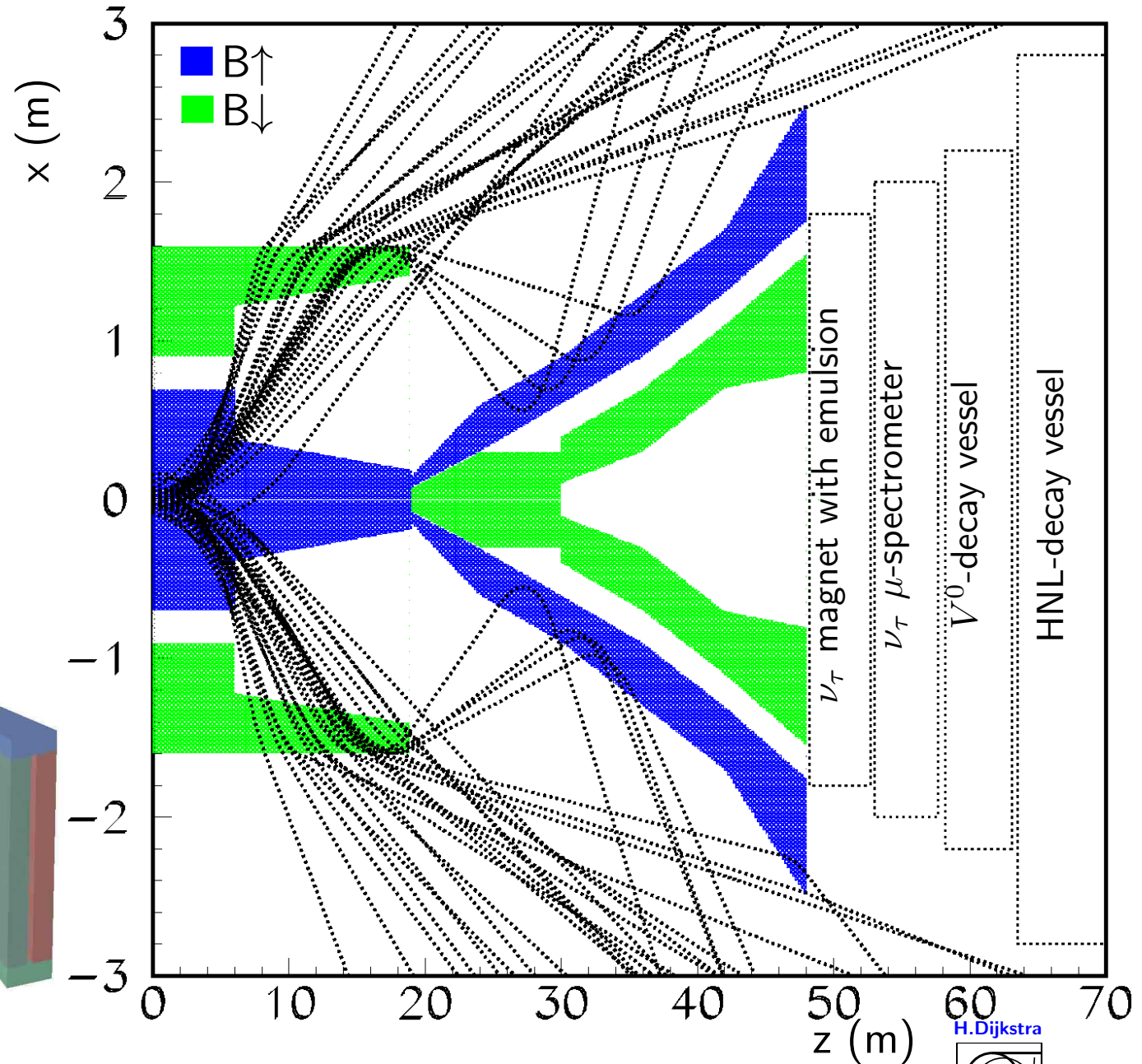
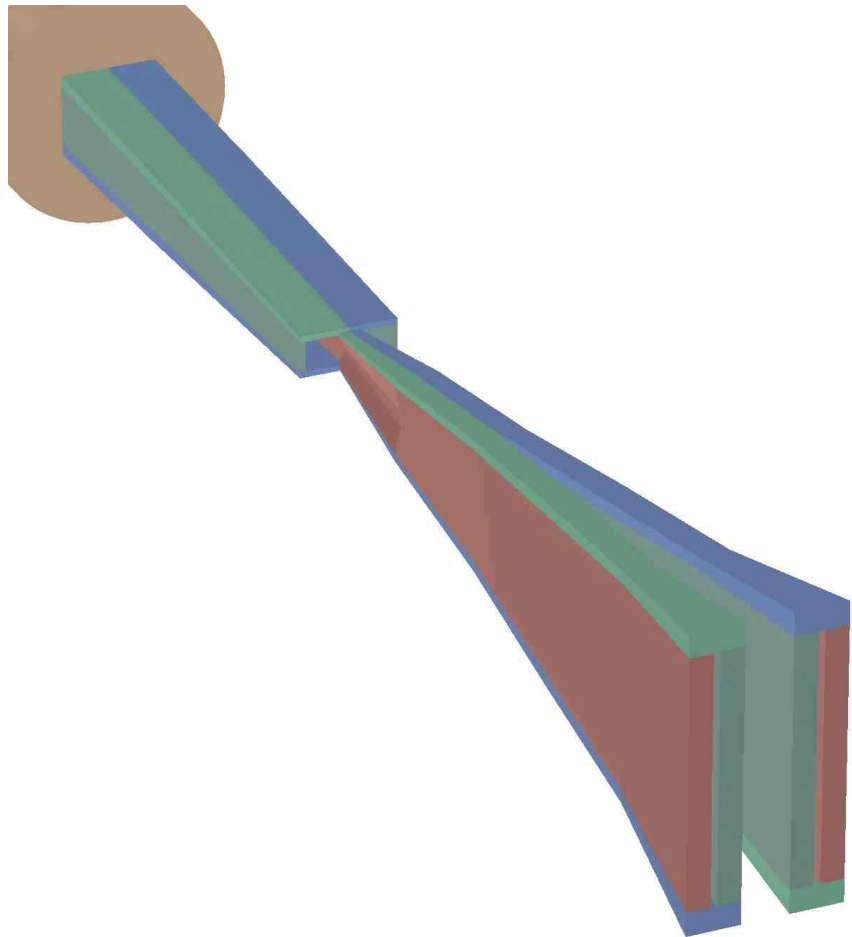


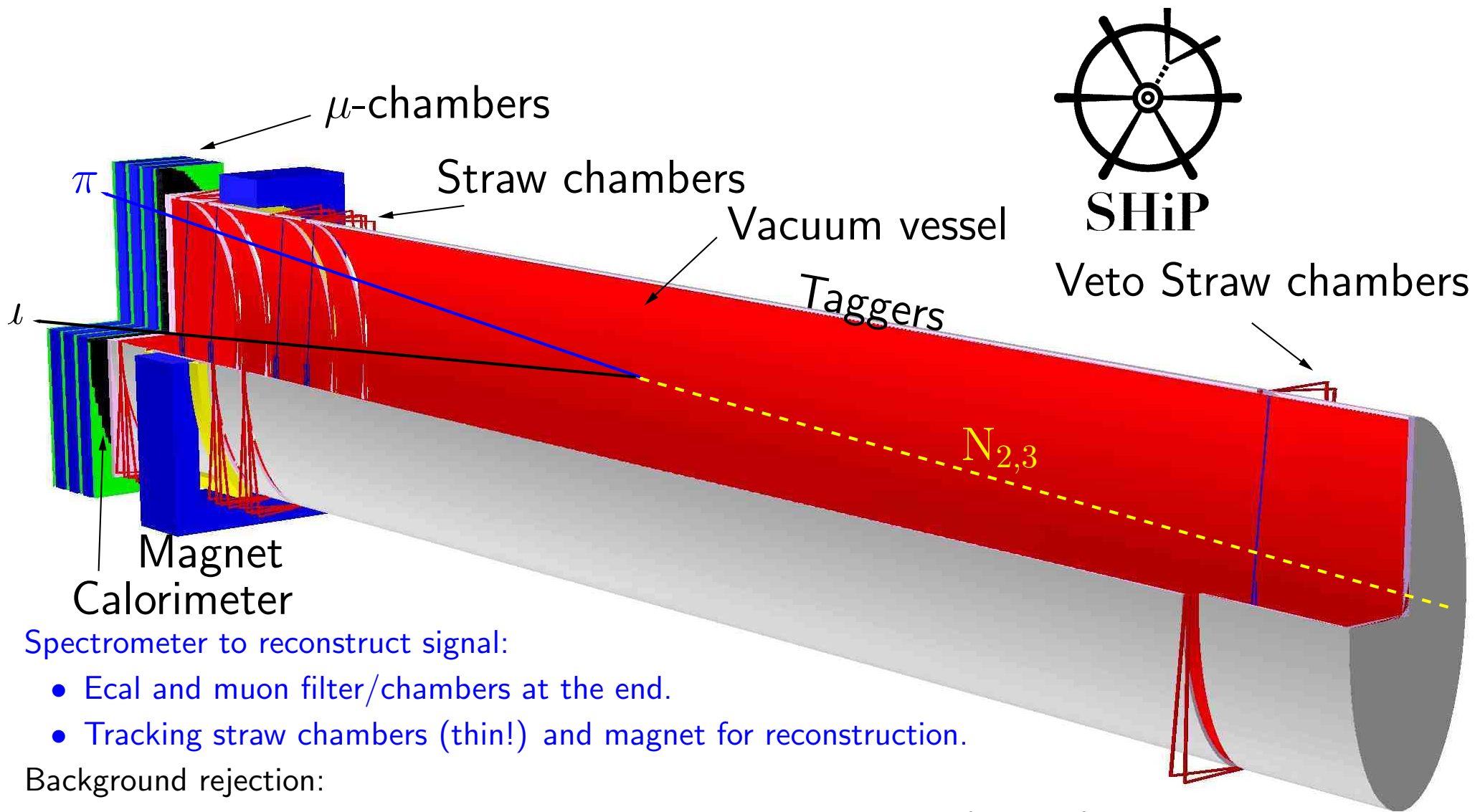
Units of the colour legend are in $\mu\text{Sv/h}$.



Active μ -Shield

- Per 1 s SPS spill:
 $\sim 10^{10} \mu^\pm$ in acceptance.
- Active μ -shield (1.8 T in Fe).





Spectrometer to reconstruct signal:

- Ecal and muon filter/chambers at the end.
- Tracking straw chambers (thin!) and magnet for reconstruction.

Background rejection:

- μ or ν interactions in decay volume: evacuated vacuum vessel: (10 μ bar)
- K/Λ -decays produced in surrounding material in μ , ν -interaction:
 - Taggers: liquid scintillator in double walled vessel to veto candidates with accompanying particles.
 - Veto: veto short lived K_S , Λ , or candidate with accompanying particles.

SHiP Physics Program Being Studied

Signature	Physics	Backgrounds
$\pi^- \mu^+, K^- \mu^+$	HNL, NEU	RDM, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$\pi^- \pi^0 \mu^+$	HNL($\rightarrow \rho^- \mu^+$)	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu (+\pi^0)$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\pi^- e^+, K^- e^+$	HNL, NEU	$K_L^0 \rightarrow \pi^- e^+ \nu_e$
$\pi^- \pi^0 e^+$	HNL($\rightarrow \rho^- e^+$)	$K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\mu^- e^+ + p^{miss}$	HNL, Higgs Portal (HP)($\rightarrow \tau\tau$)	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$
$\mu^- \mu^+ + p^{miss}$	HNL, HP($\rightarrow \tau\tau$)	RDM, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$\mu^- \mu^+$	DP, PNGB, HP	RDM, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$
$\mu^- \mu^+ \gamma$	Chern-Simons	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu (+\pi^0)$
$e^- e^+ + p^{miss}$	HNL, HP	$K_L^0 \rightarrow \pi^- e^+ \nu_e$
$e^- e^+$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- e^+ \nu_e$
$\pi^- \pi^+$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$
$\pi^- \pi^+ + p^{miss}$	DP, PNGB, HP($\rightarrow \tau\tau$), HSU, HNL($\rightarrow \rho^0 \nu$)	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$, $K_S^0 \rightarrow \pi^- \pi^+$, $\Lambda \rightarrow p\pi$
$K^+ K^-$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$, $K_L^0 \rightarrow \pi^- e^+ \nu_e$, $K_L^0 \rightarrow \pi^- \pi^+ \pi^0$, $K_L^0 \rightarrow \pi^- \pi^+$, $K_S^0 \rightarrow \pi^- \pi^+$, $\Lambda \rightarrow p\pi$
$\pi^+ \pi^- \pi^0$	DP, PNGB, HP, HNL($\eta\nu$)	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\pi^+ \pi^- \pi^0 \pi^0$	DP, PNGB, HP	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0 (+\pi^0)$
$\pi^+ \pi^- \pi^0 \pi^0 \pi^0$	PNGB($\rightarrow \pi\pi\eta$)	—
$\pi^+ \pi^- \gamma\gamma$	PNGB($\rightarrow \pi\pi\eta$)	$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$
$\pi^+ \pi^- \pi^+ \pi^-$	DP, PNGB, HP	—
$\pi^+ \pi^- \mu^+ \mu^-$	Hidden Susy (HSU)	—
$\pi^+ \pi^- e^+ e^-$	Hidden Susy	—
$\mu^+ \mu^- \mu^+ \mu^-$	Hidden Susy	—
$\mu^+ \mu^- e^+ e^-$	Hidden Susy	—

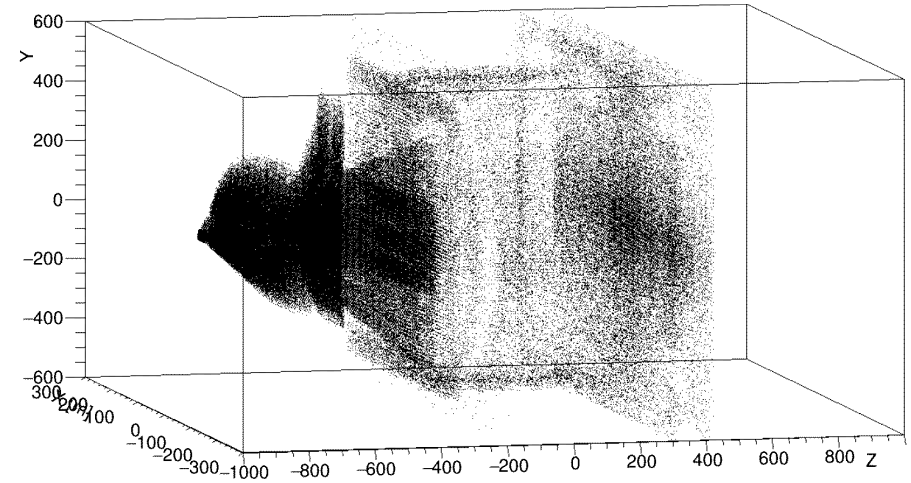
HNL=Heavy Neutral Lepton, NEU=neutralino
 DP=Dark Photon, PNGB=Pseudo-Nambu Goldstone Boson
 Background: RDM=random di-muons from the target



Expected HNL Sensitivity

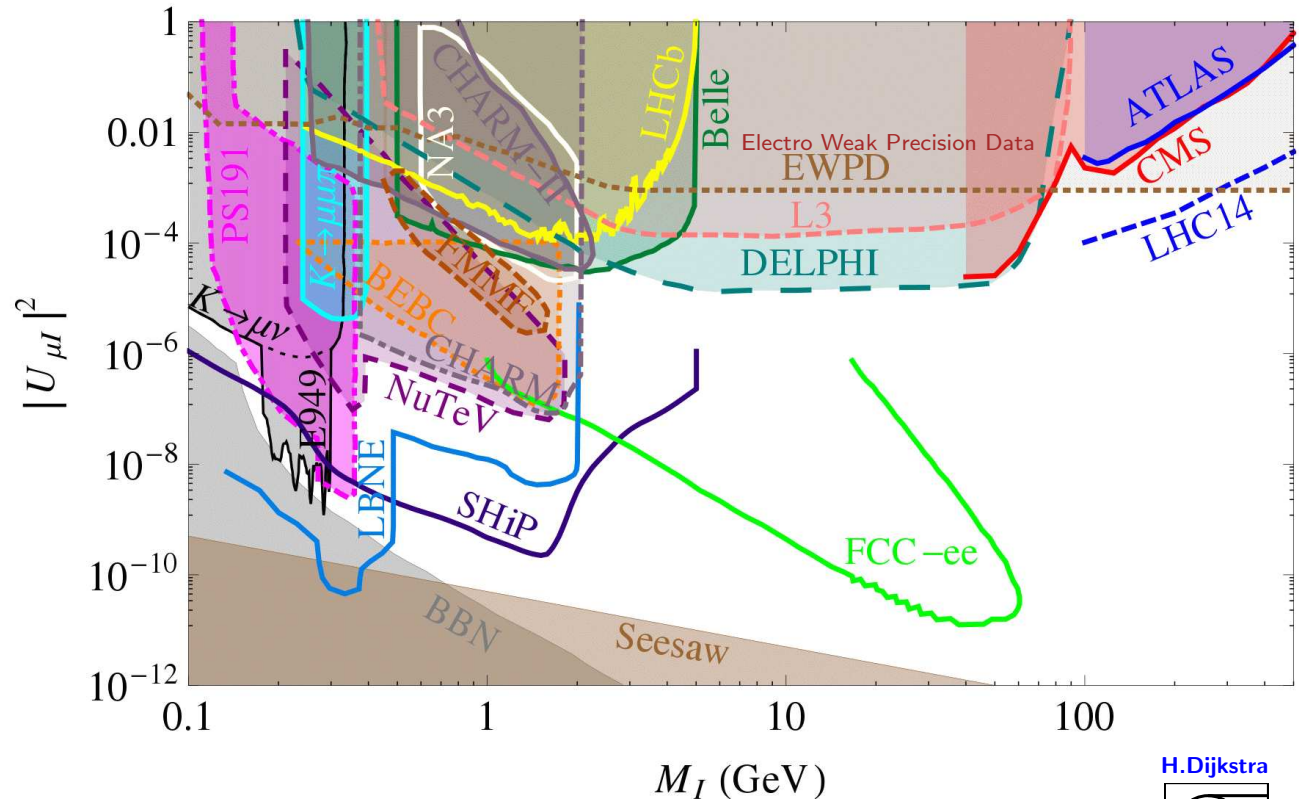
Simulated background :

- ν -tomography: Genie($\nu + N \rightarrow X$)+Geant \rightarrow
- μ -DIS: Pythia($\mu + N \rightarrow X$)+Geant
- Random $\mu\mu$: combine primary μ s from target.
- Cosmics: Pythia($\mu + N \rightarrow X$)+Geant
- No (background) events expected.



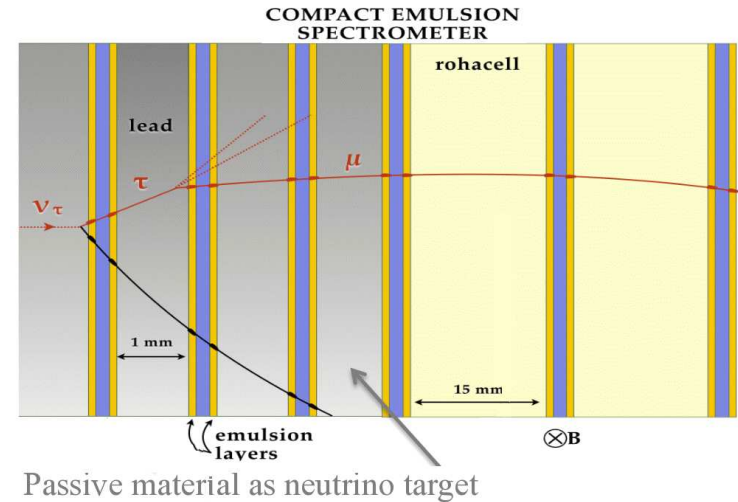
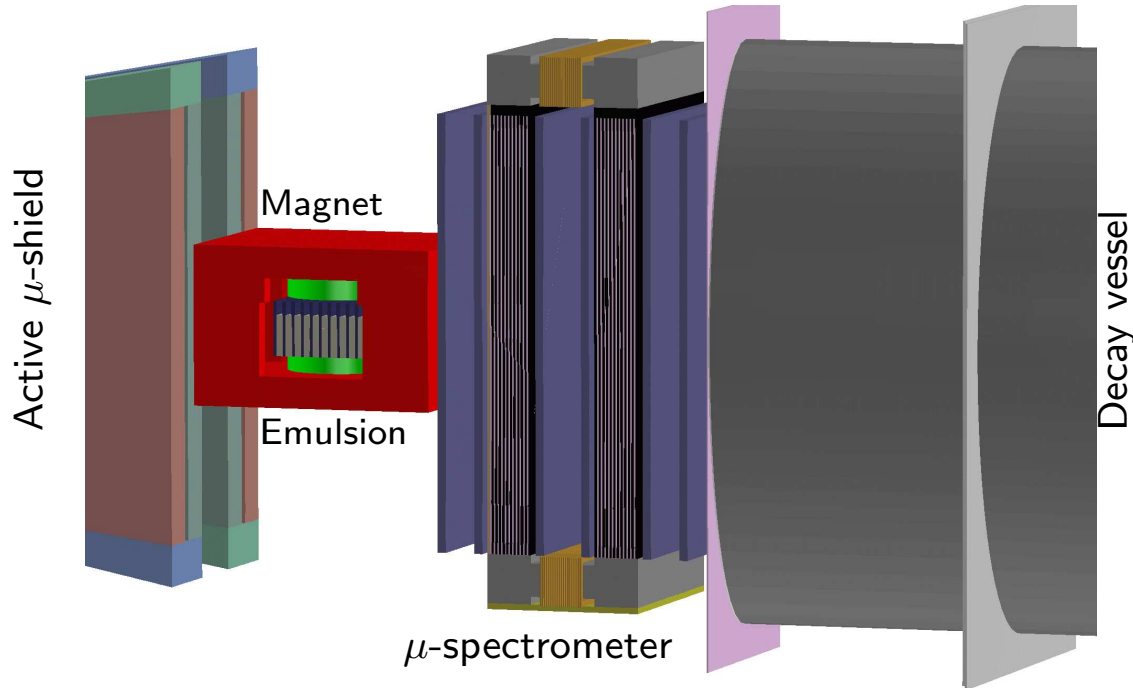
Signal sensitivity example:

- Present U_μ limits
- BAU: $U_\mu^2 < 10^{-6} - 10^{-8}$
- Future:
 - SHiP: 2×10^{20} p.o.t
 - LBNE: 5×10^{21} p.o.t
 - FCC-ee: $10^{12} Z^0$



ν_τ Physics with 2×10^{20} pot

- World $\nu_\tau N \rightarrow \tau X$ statistics: Donut ~ 7 , Opera: 5.
- Produce $5.7 \times 10^{15} \nu_\tau + \bar{\nu}_\tau$ via $pN \rightarrow XD_s(\rightarrow \tau\nu_\tau)$
- SHiP placed “mini-Opera” between μ -shield and HNL decay vessel.



- Pb/Emulsion: $\sim 10k, 340k, 2.4M$ CC ν_τ, ν_e, ν_μ interactions \rightarrow rich ν -physics program.
- B-field in emulsion and muon-filters in μ -spectrometer: distinguish ν_τ from $\bar{\nu}_\tau$.
- HNL-background: tag $\nu + p \rightarrow K_L + l + X$
- ν_e : produced predominantly in charm-decay \rightarrow HNL normalization.

- SHiP complementary to LHC searches
- SHiP under review by SPSC:
 - If approved, and (CERN) money found:
 - First civil engineering in LS2 (2019-2020),
 - and start SHiP data taking in 2026.
- The impact of HNL discovery on particle physics is difficult to overestimate! Discovery would shed light on BSM physics:
 - The origin of the baryon asymmetry of the Universe
 - The origin of neutrino mass
 - The nature of Dark Matter, did we get a hint?

