arXiv:1310.1762v1

Search for Heavy Neutral Leptons @ the SPS

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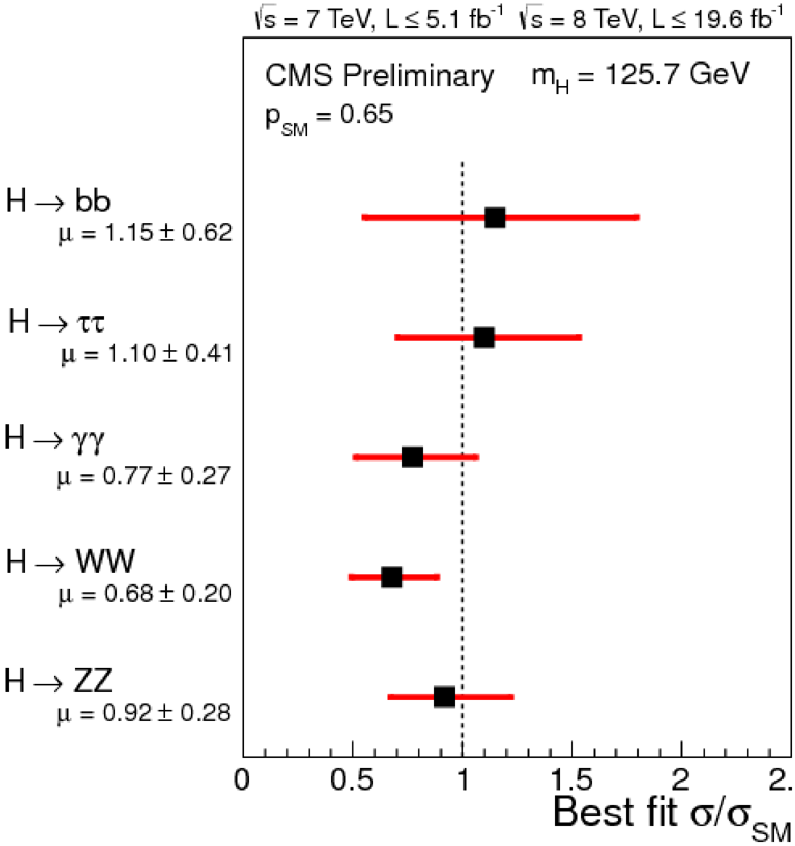
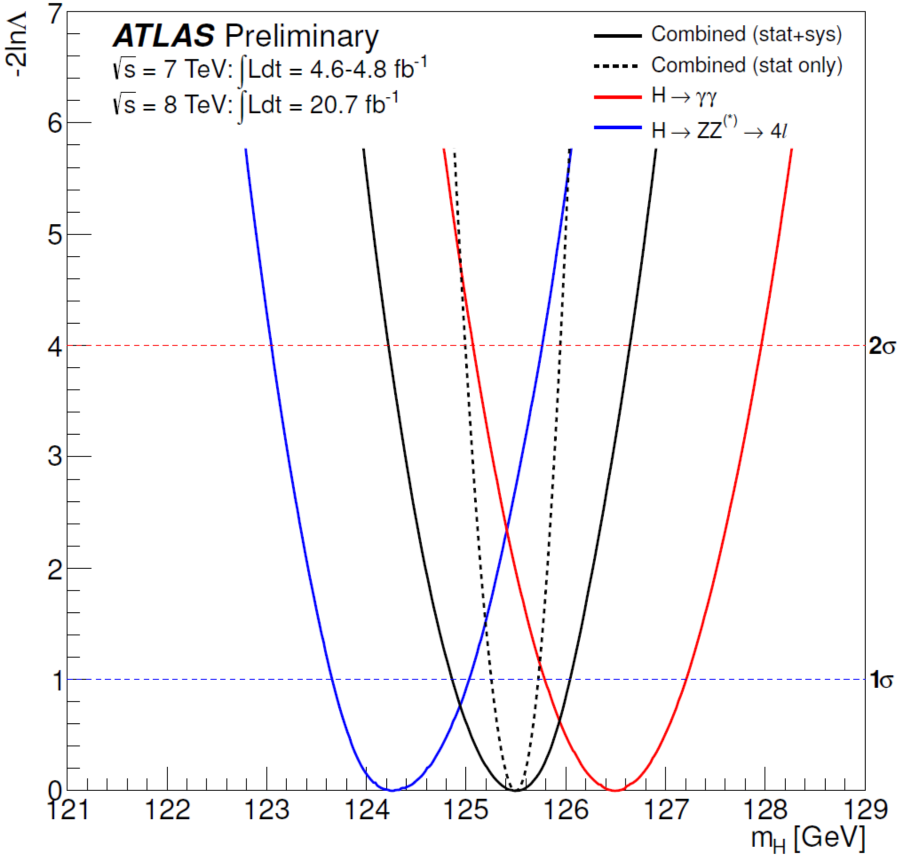
- How does this proposal fit in the physics landscape?
- Why HNLs?
- How to produce/detect HNLs.
- Backgrounds.
- The experimental set-up.
- Symbiosis with “active” ν physics.
- Conclusions.

Triumph of SM: Higgs found!

- Boson found consistent with SM-Higgs.
- Atlas: $M_H = 125.5 \pm 0.2_{stat} {}^{+0.5}_{-0.6 syst}$ GeV
  CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ GeV





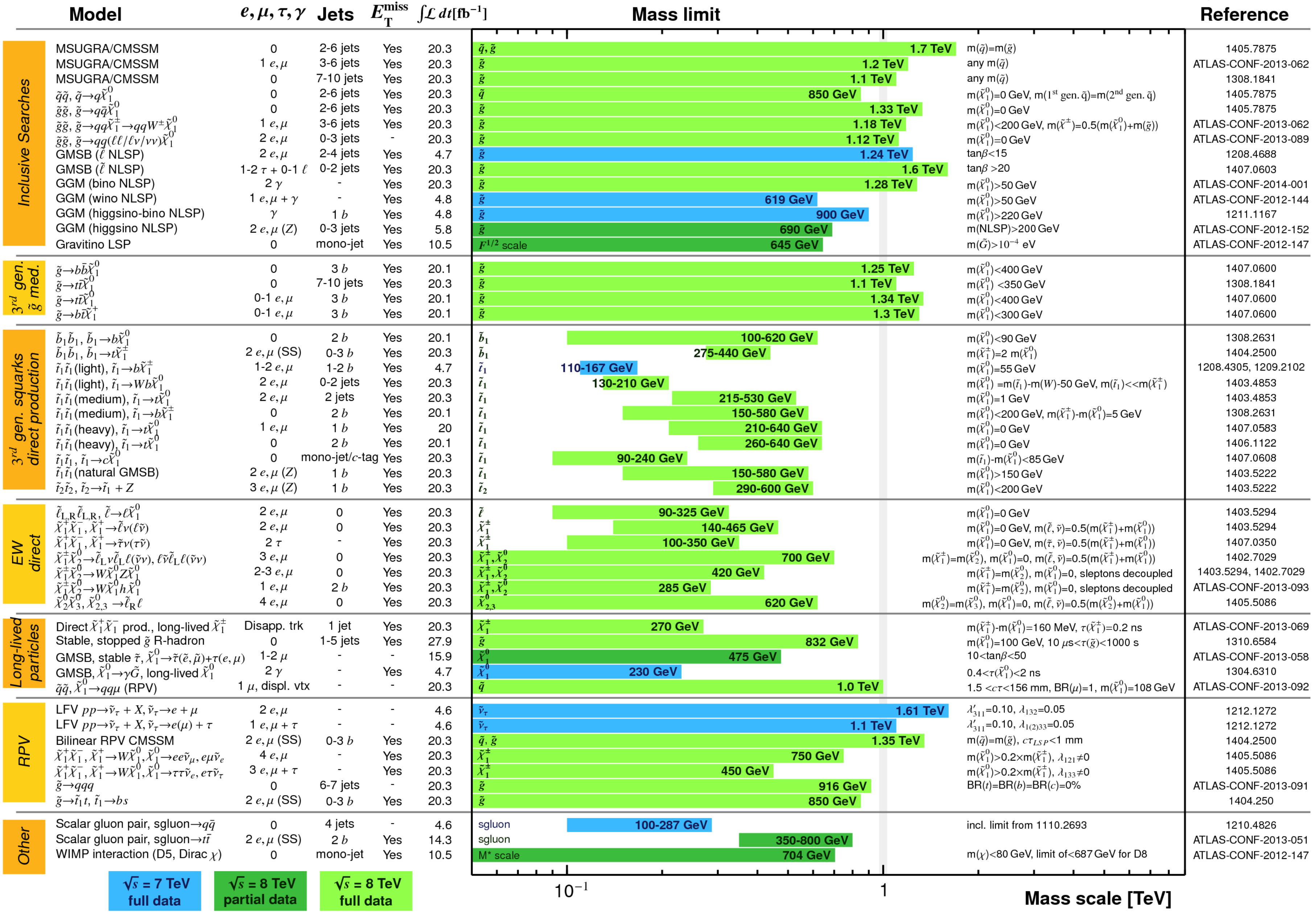
What is not found..

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

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

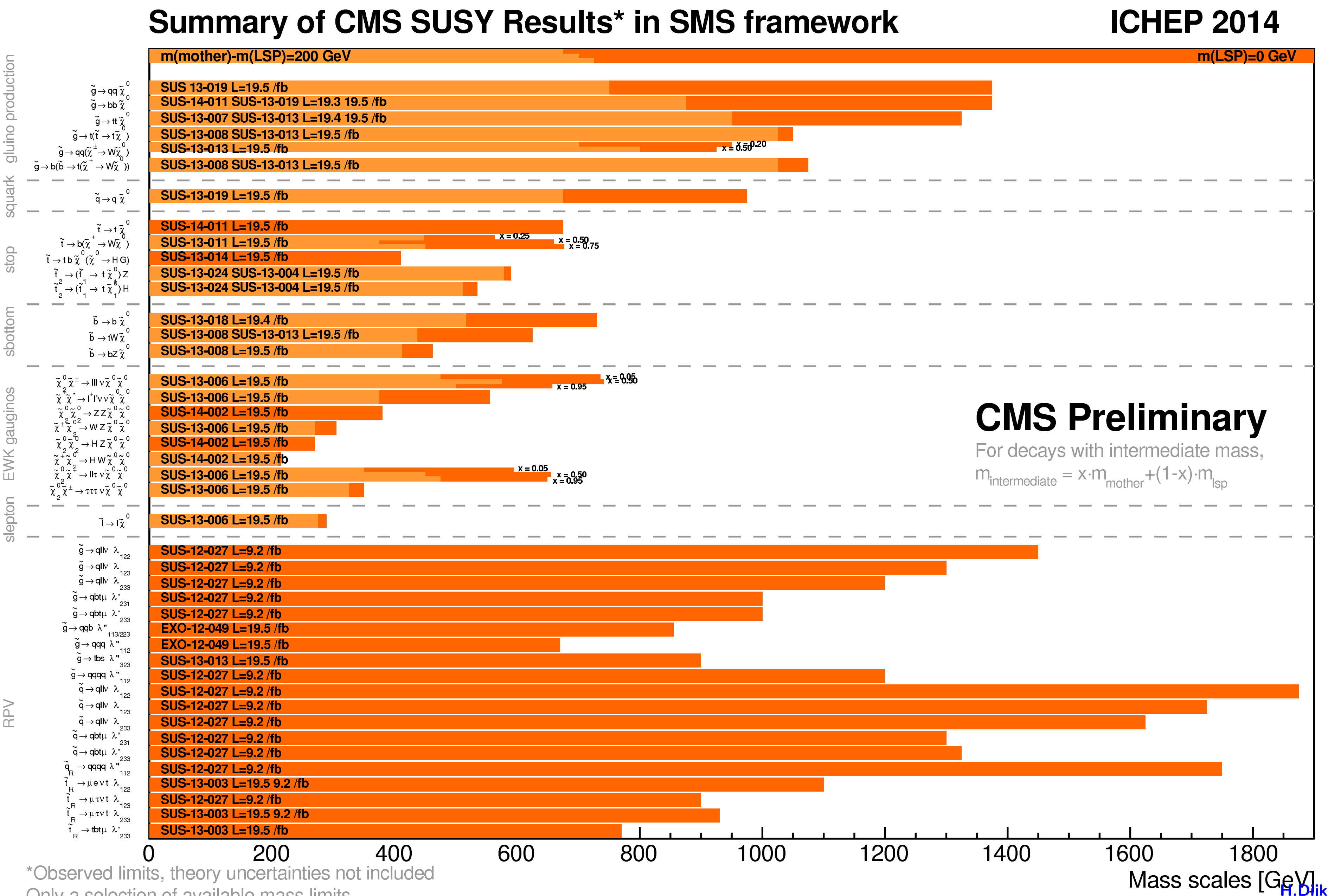


	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow qq\tilde{\chi}_1^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	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 + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	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(NLSP)>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.	$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g} \rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	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 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$	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), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	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 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(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 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$	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), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(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 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(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
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	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	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \rightarrow \tilde{\ell}\nu(\ell\tilde{\nu})$	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	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
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	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 $\tilde{\chi}_1^+\tilde{\chi}_1^-$ 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	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, 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
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0 \rightarrow qq\mu$ (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 $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	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	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121} \neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133} \neq 0$	1405.5086
	$\tilde{g} \rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g} \rightarrow \tilde{t}_1 t$, $\tilde{t}_1 \rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\rightarrow q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\rightarrow t\bar{t}$	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

🟦	$\sqrt{s}$ = 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.

What is not found..



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

H.Dijkstra

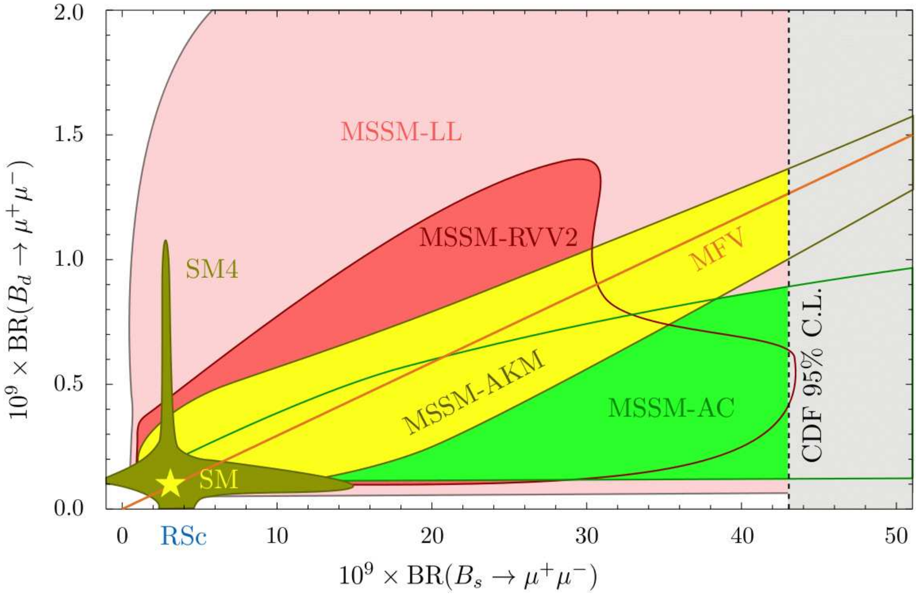
$B_s \to \mu\mu$ found and $\equiv$ SM

SM:

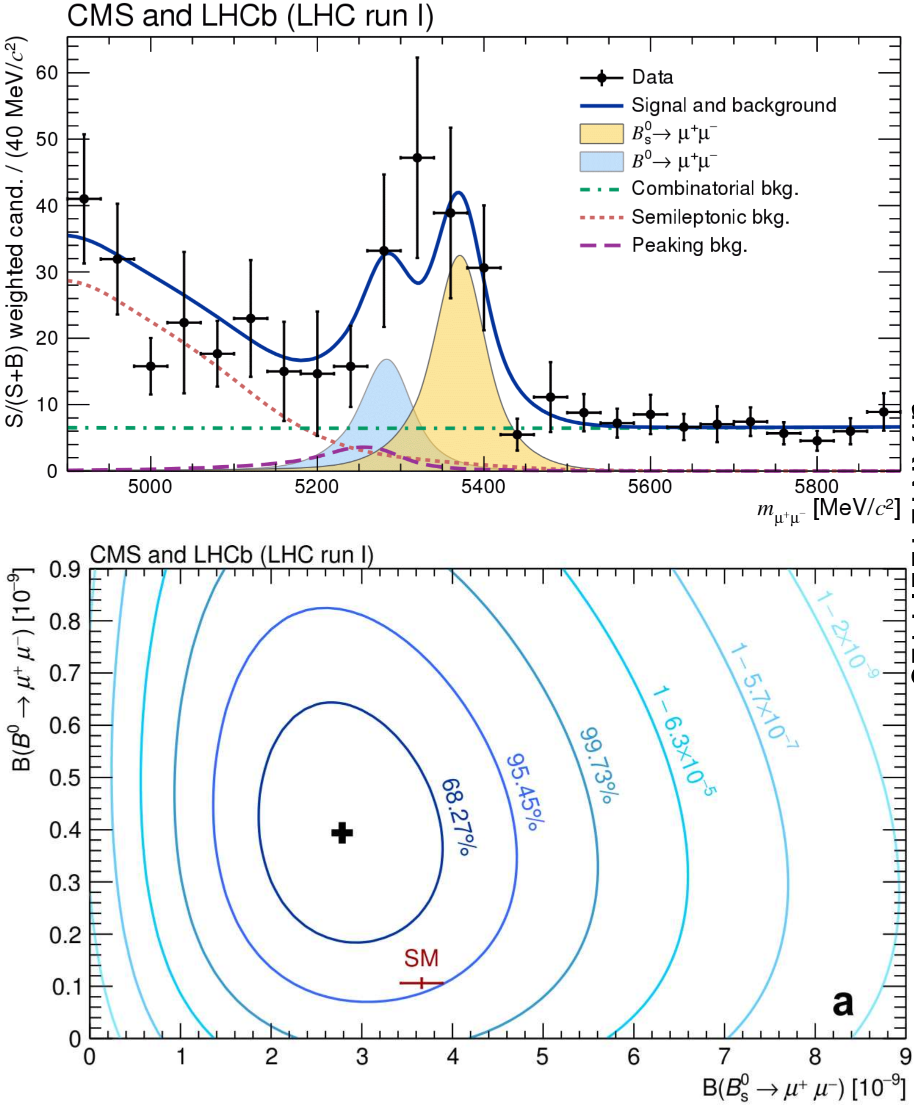
- No tree level decay
- Helicity suppressed
- Expected: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$ (Phys. Rev. Lett. 109 (2012) 041801)

NP:

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



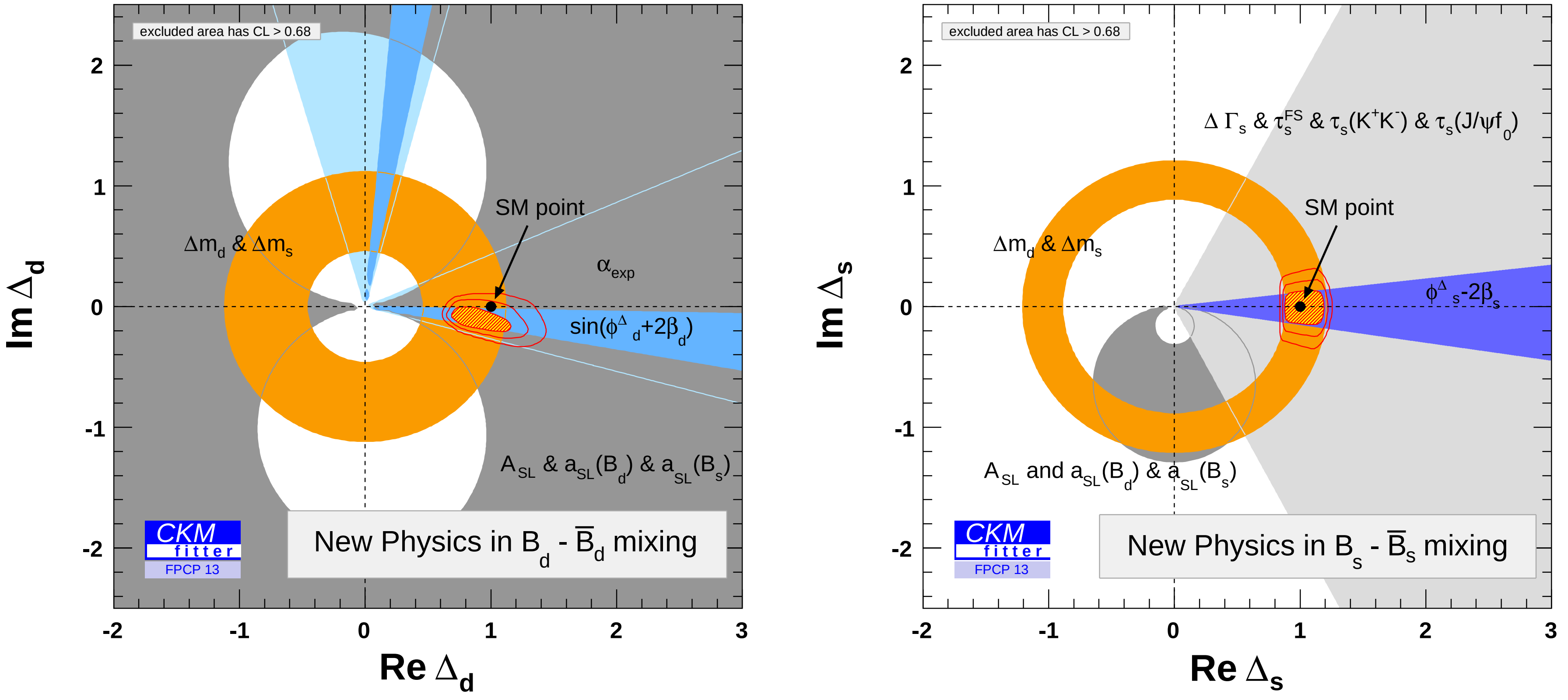
D.Straub: arXiv:1012.3893



arXiv:1411.4413

NP from quark flavour observables

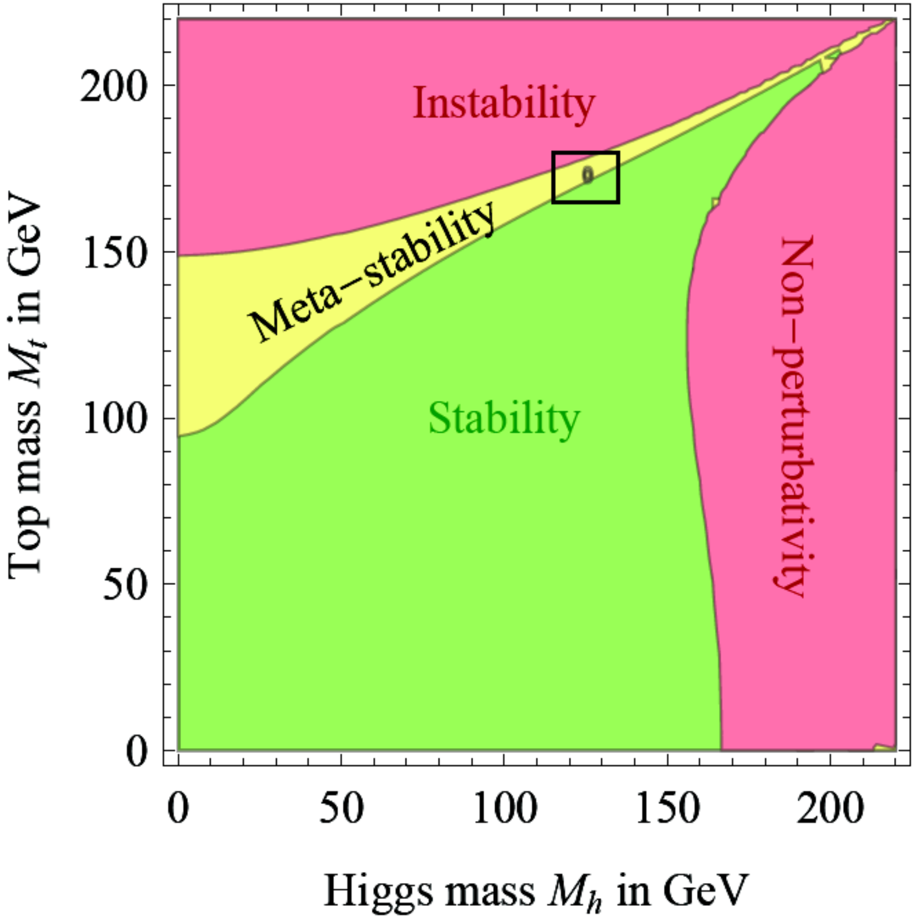
CKM-fitter



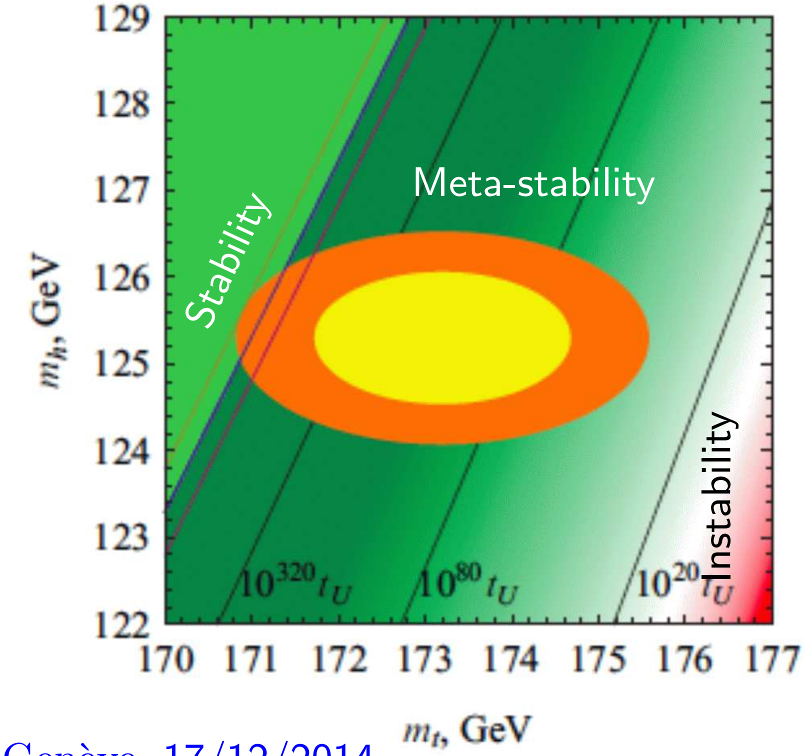
Scale of NP in $B\bar{B}$-mixing: $> 0.5 - 10^4$ TeV depending on assumptions of couplings.

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(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



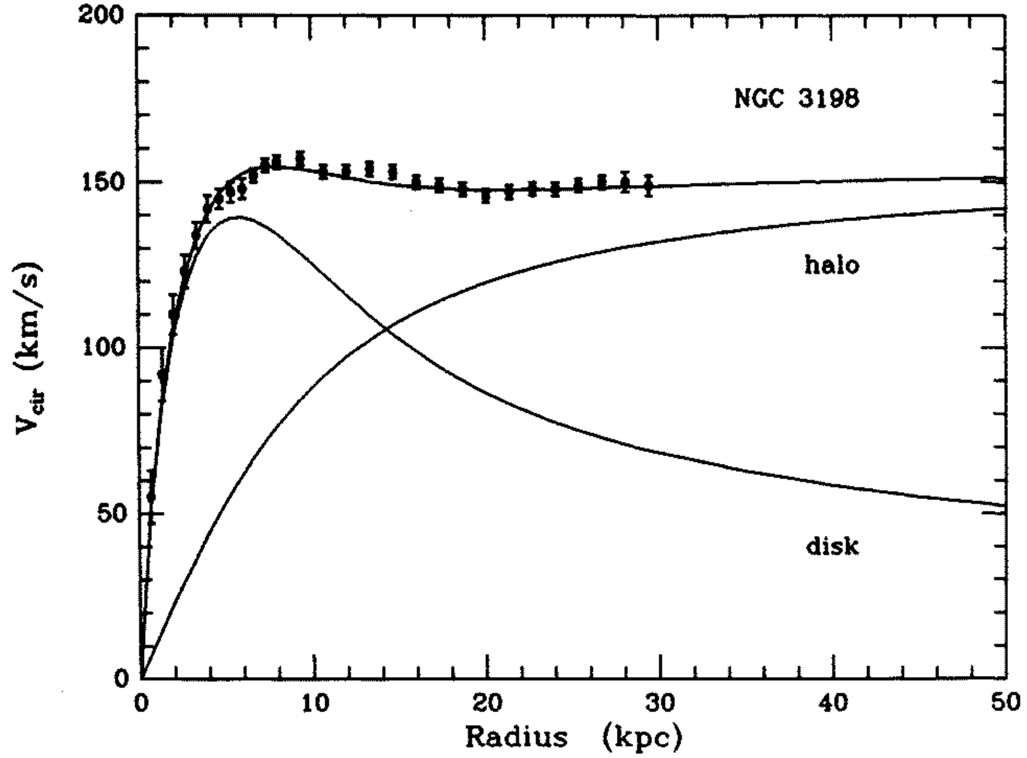
http://arxiv.org/pdf/1307.3536v2.pdf



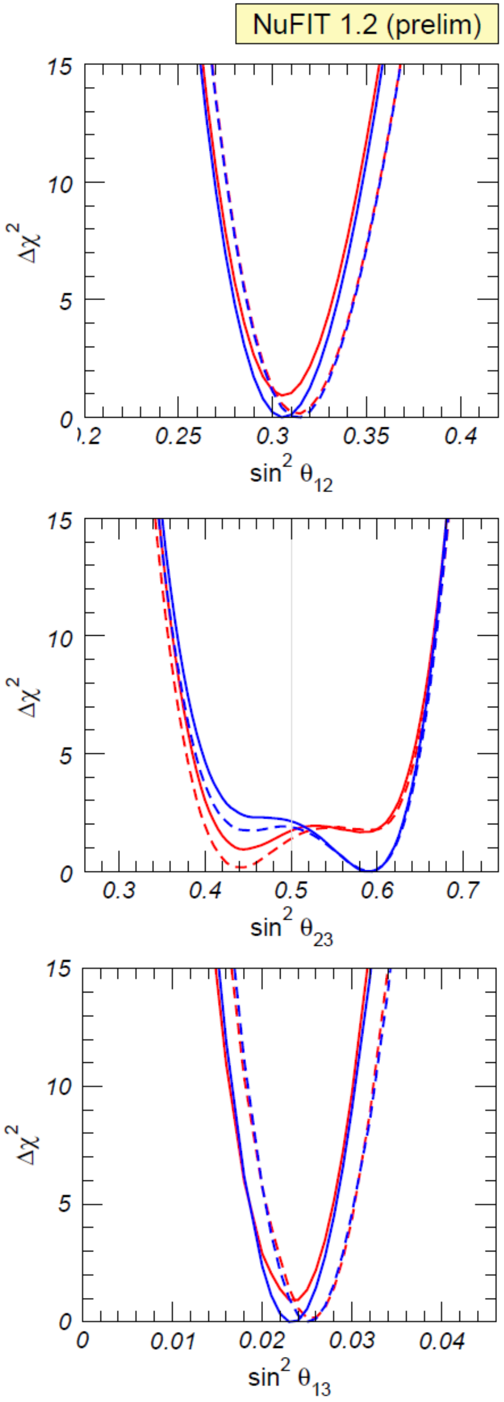
SM case closed?

NO, SM unable to explain:

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



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

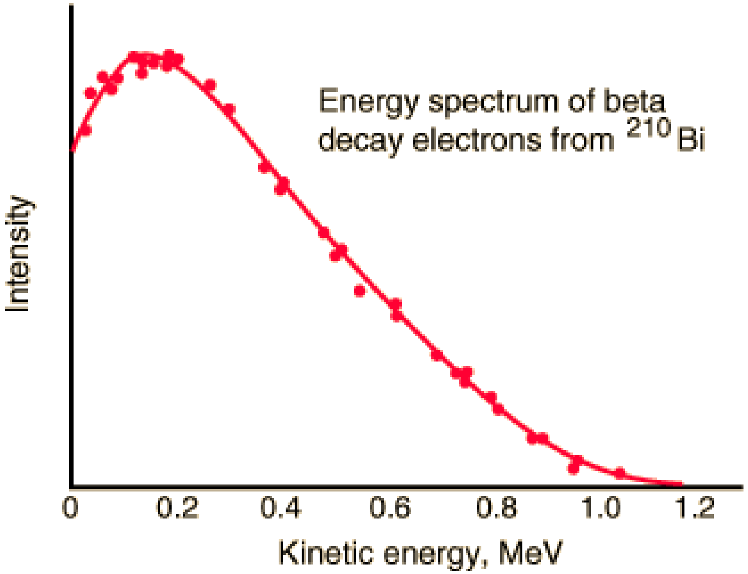


History Lesson(s)

(after B. Batell)

First decades of last century:

- β-decay: Meitner, Hahn, Ellis, Neary
- Continous 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".

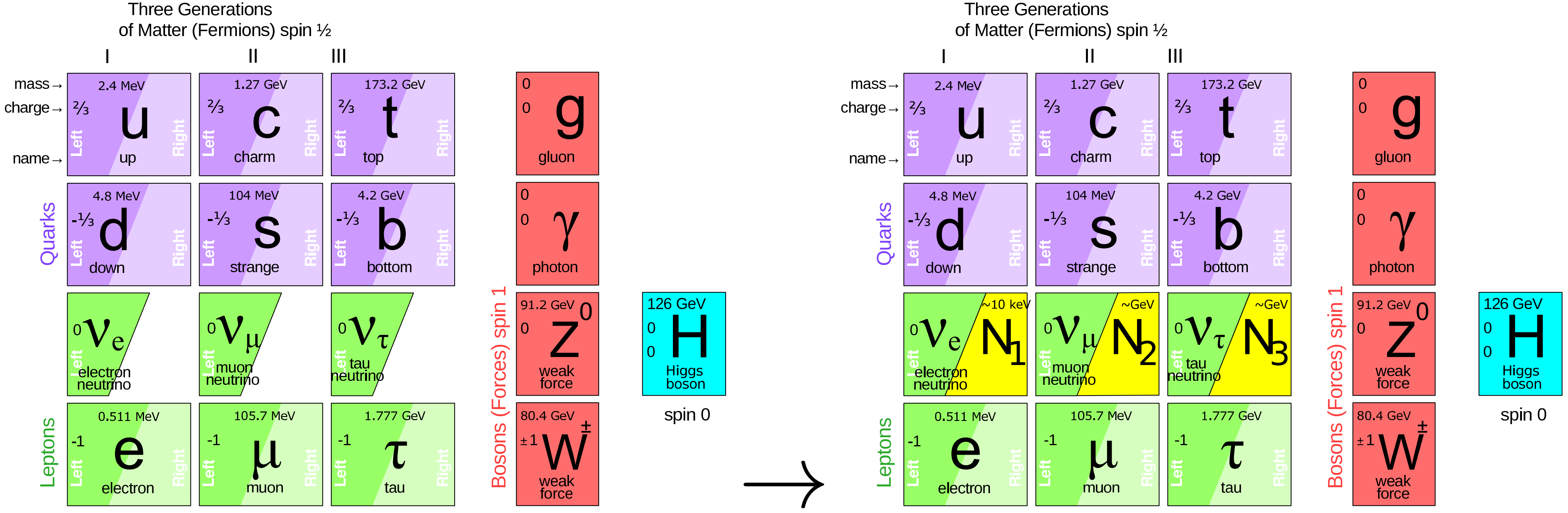
Ptolomy (∼90-168 AD):
It is a good principle to explain phenomena by the simplest hypothesis possible!

νMSM: T.Asaka, M.Shaposhnikov

PL B620 (2005) 17

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

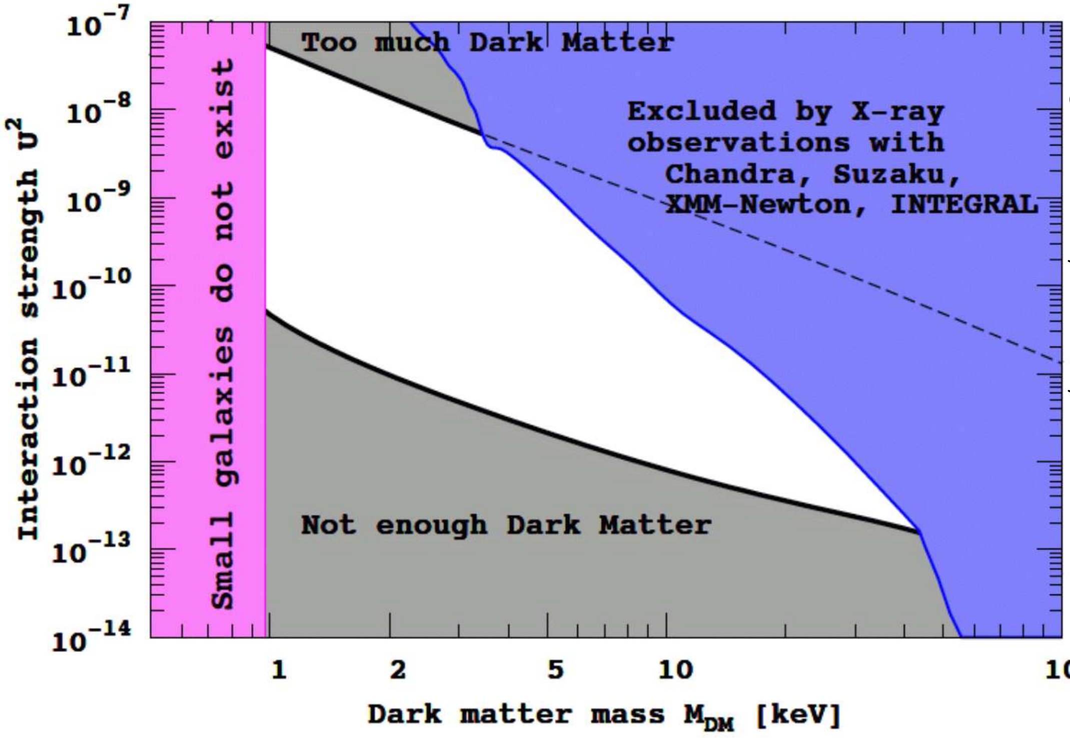
- N_1 can provide dark matter candidate
- $N_{1,2,3}$ can provide neutrino masses via Seesaw mechanism
- $N_{2,3}$ can induce leptogenesis→baryogenesis.



νMSM: closer look at N_1

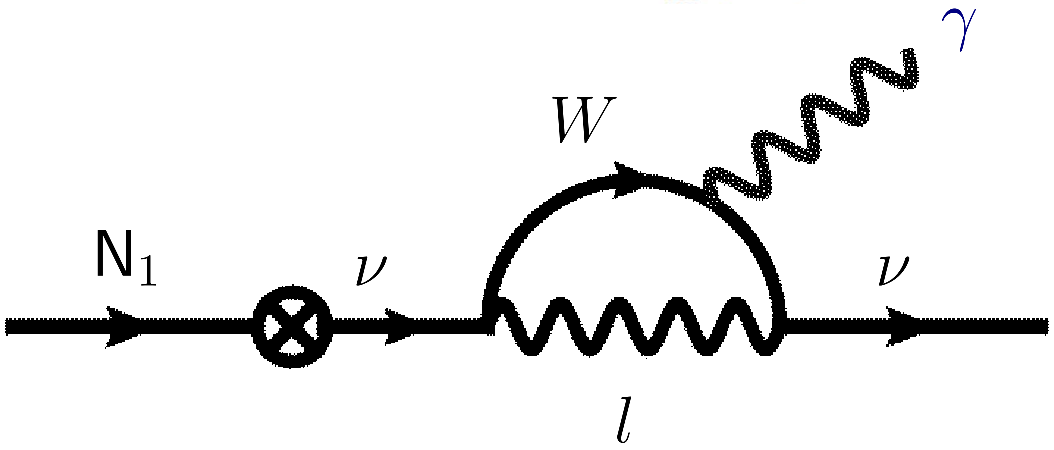
N_1 can provide dark matter candidate:

- very weak mixing with other leptons
- hence, stable enough for dark matter
- Seesaw: one $M_{\nu-\text{active}} \sim 10^{-5}$ eV



inspirehep.net/record/1215490?ln=en

- Radiative decay: $\tau > \tau_{\text{universe}}$
- $E_\gamma = \frac{M_{N_1}}{2}$
- X-ray detection:
  - View dwarf spheroidal galaxies
  - $\frac{\Delta E}{E} \sim 10^{-3} - 10^{-4}$
  - Proposed missions: Astro-H, LOFT, Athena+, Origin/Xenia

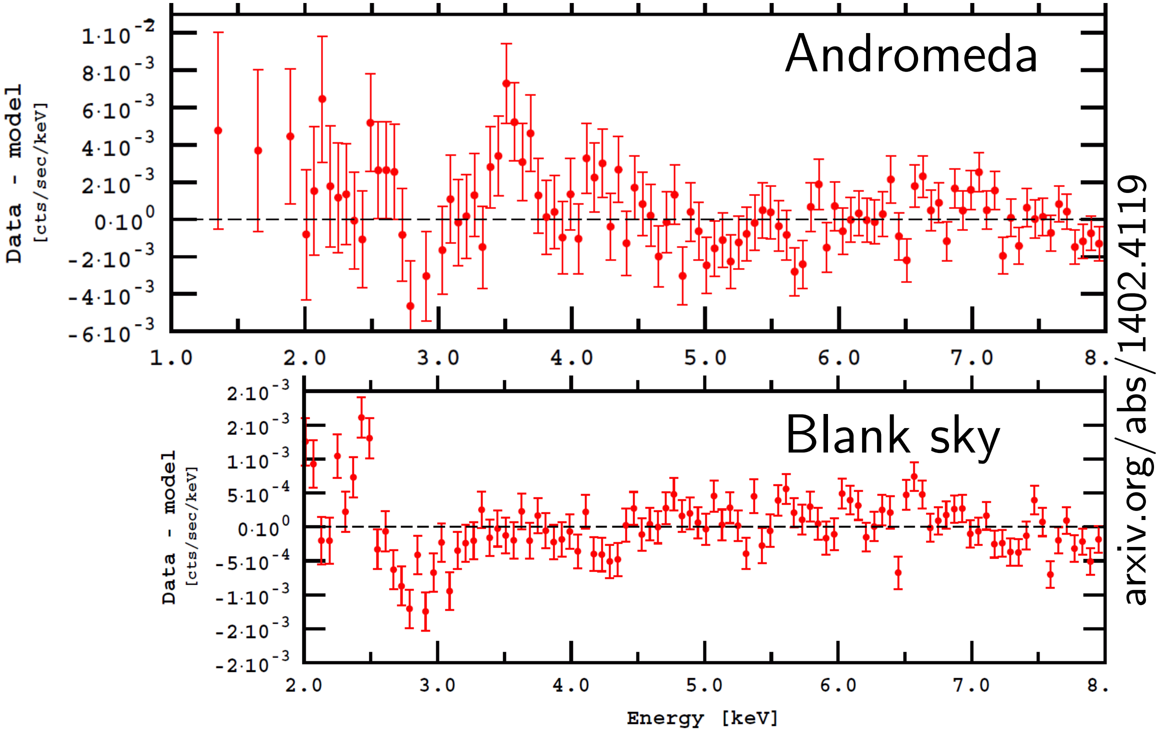


N_1: stop the press...

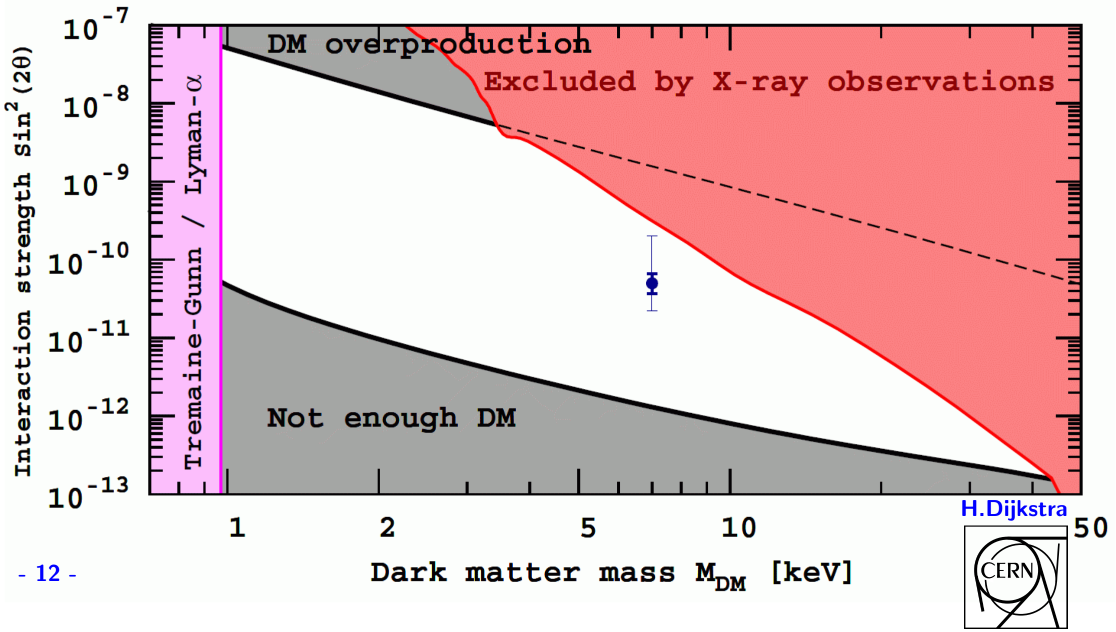
2/2014: two papers on ArXiv:

- 10/2/14: arxiv.org/abs/1402.2301: Detection of an Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters $E_\gamma \sim 3.56$ keV
- 17/2/14: arxiv.org/abs/1402.4119: An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster $E_\gamma \sim 3.5$ keV

Both papers refer to Astro-H (with Soft X-Ray Spectrometer, 2015 launch) to confirm/rule-out the DM origin of this signal.



arxiv.org/abs/1402.4119



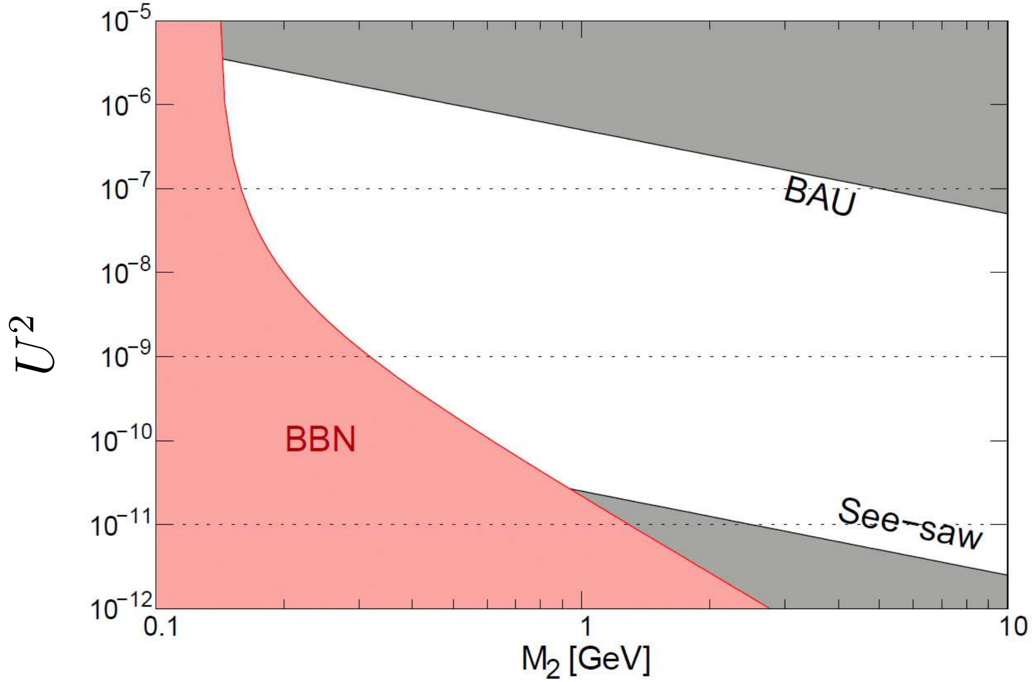
H.Dijkstra

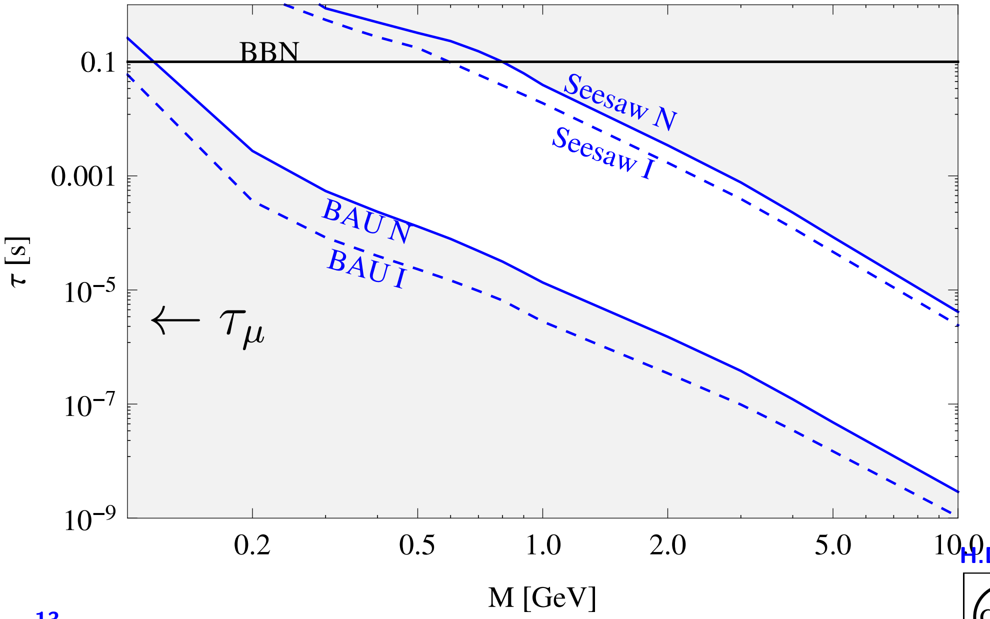
$\mathrm{N}_{2,3}$

Use $\mathrm{N}_{2,3}$ to explain:

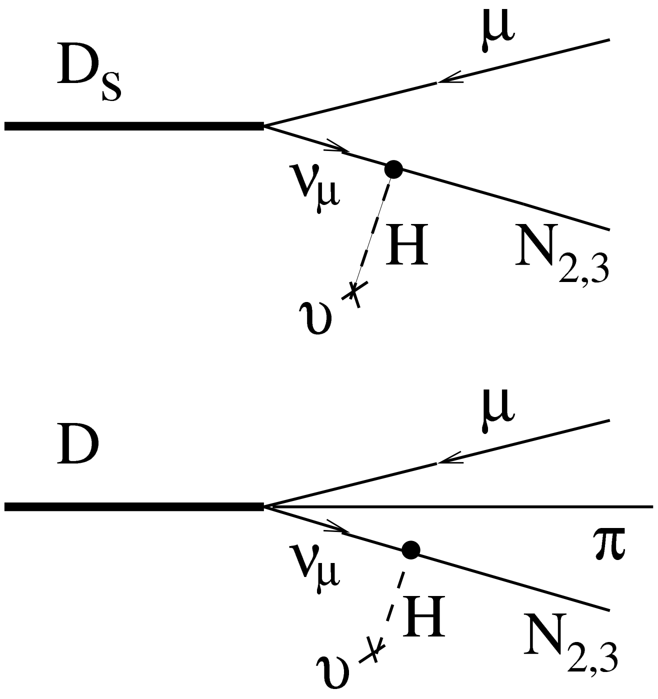
- ν masses:
  Seesaw constrains Yukawa coupling and $M_{\mathrm{N}_{2,3}}$, i.e. $M_\nu \propto U^2/M_{\mathrm{N}_{2,3}}$
- Baryo(Lepto)genesis: make N_2 nearly degenerate with N_3, and tune CPV-phases to explain baryon asymmetry of universe (BAU).
- $1/\tau_{N_{2,3}} \propto M^3_{\mathrm{N}_{2,3}}$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

These are the particles SHiP is after!

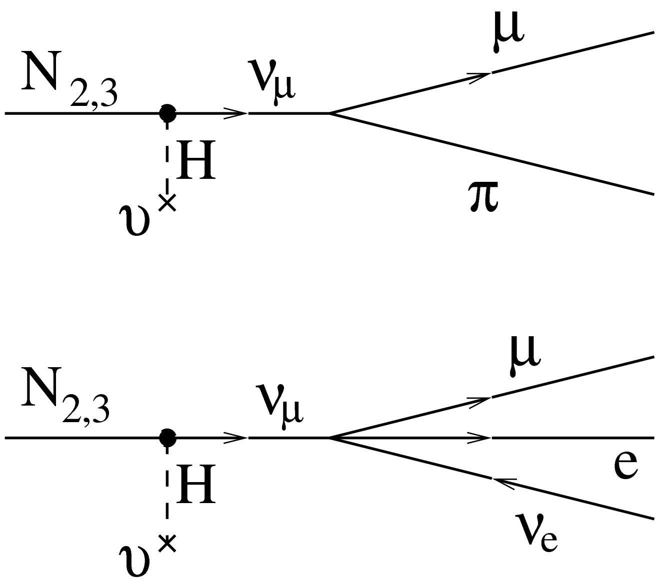




$\mathrm{N}_{2,3}$ production and decay



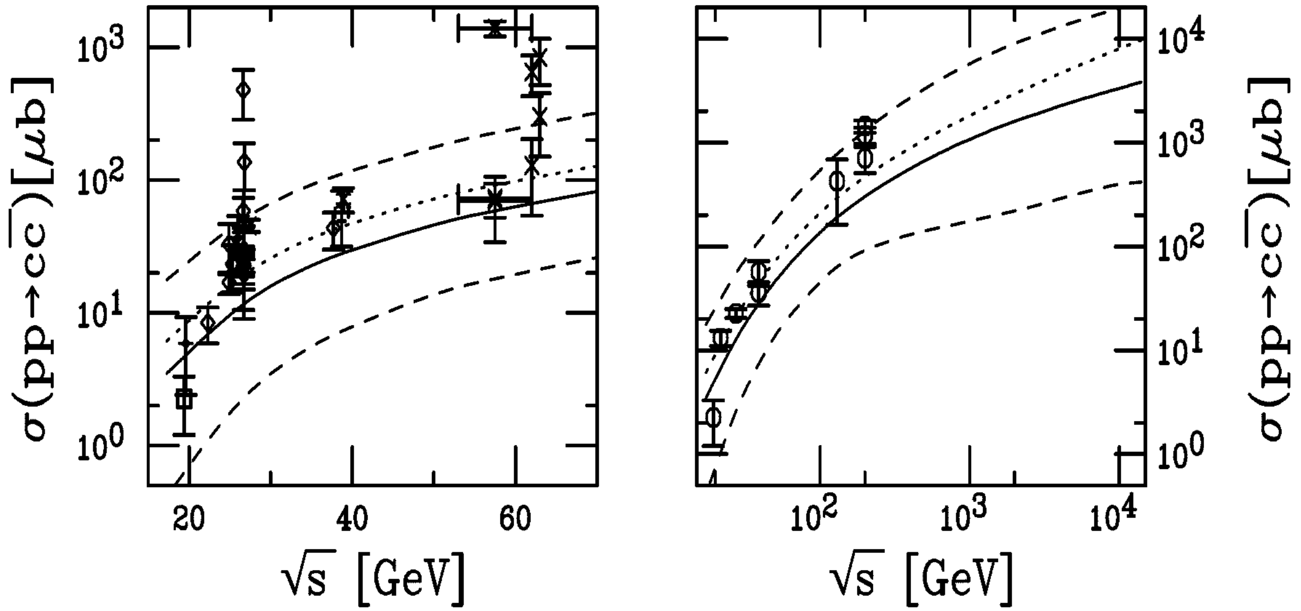
- $\mathrm{N}_{2,3}$ mix with ν
- Produced in (semi-)leptonic decays, f.i. $\mathrm{K} \rightarrow \mu\nu,\ \mathrm{D} \rightarrow \mu\nu\mathrm{X},\ \mathrm{B} \rightarrow \mu\nu\mathrm{X},\ \mathrm{Z} \rightarrow \nu\bar{\nu}$
- $\propto \sigma_D \times U^2$
- $U_2^2 = U_{2,\nu_e}^2 + U_{2,\nu_\mu}^2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



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

Sensitivity for $\mathrm{N}_{2,3} \propto \mathrm{U}^4$!

- SHiP looks for (light) HNL from D-decays, i.e. $M < 2$ GeV
- B-decays: 20-100 smaller σ, and $\rightarrow D\mu\nu$, i.e. still limited to ~ 3 GeV.



arxiv.org/pdf/0709.2531v1

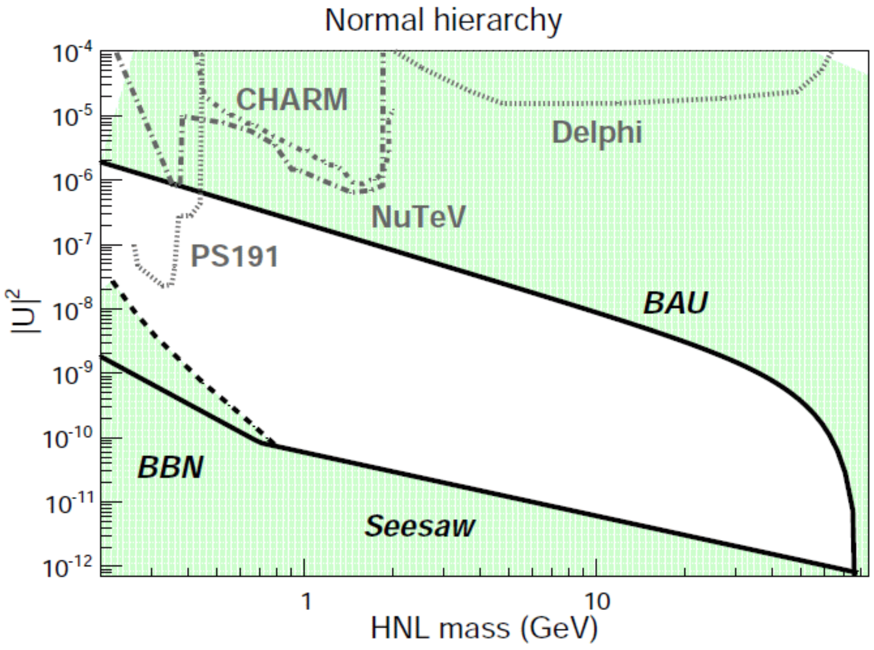
- Where to produce charm?
  - LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} (i.e. 3-4 years): $\sim 2.10^{16}$ in 4π.
  - SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV): with 2.10^{20} pot (i.e. 3-4 years): $\sim 2.10^{17}$
  - Fermilab: 120 GeV pot, $10\times$ smaller $\sigma_{c\bar{c}}$, 10×pot by 2025 for LBNE..

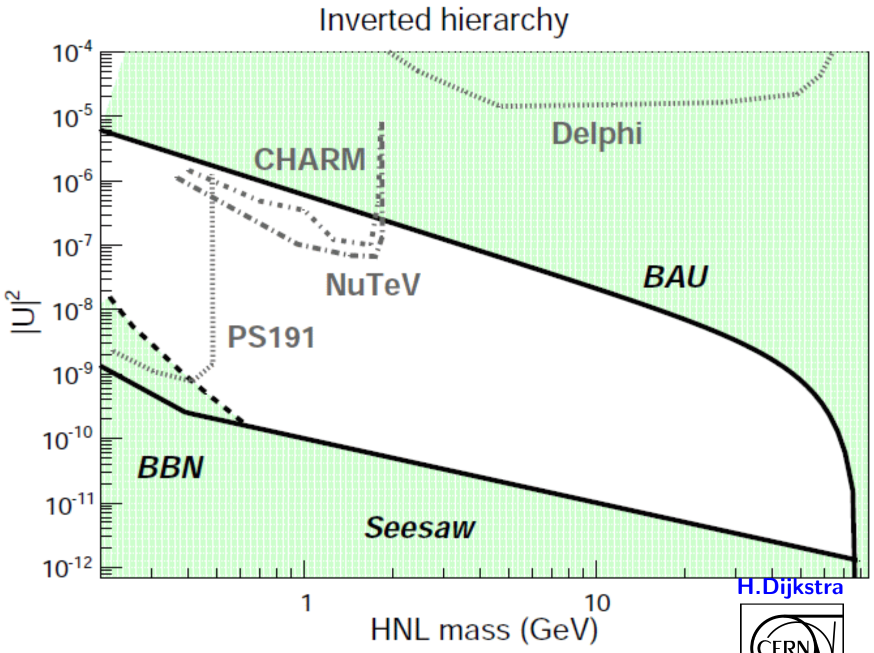
Experimental status on searches

Already searches in $K/D/Z$-decay performed:

- 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.
- DELPHI('97)@LEP 91 GeV,
  $\sim 10^6\ Z^0 \to \nu\bar{\nu}$.

- BBN, BAU and Seesaw constrain more than experimental searches for $M_{\mathrm{N}} > 400$ MeV.





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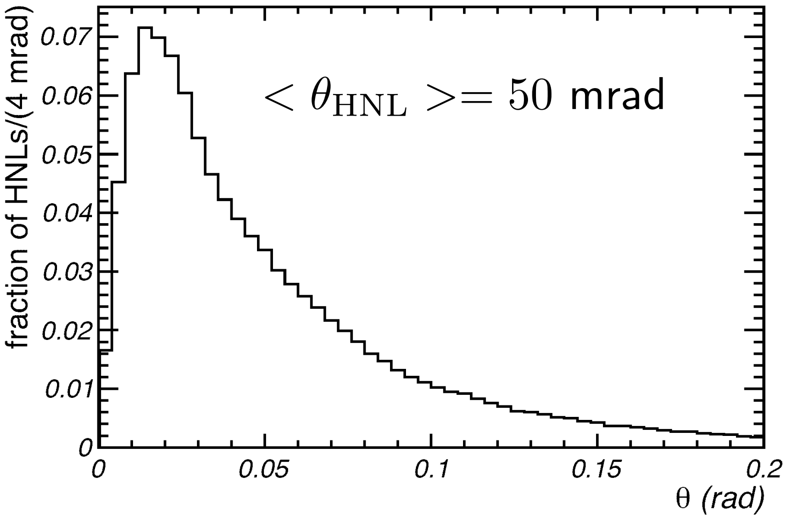
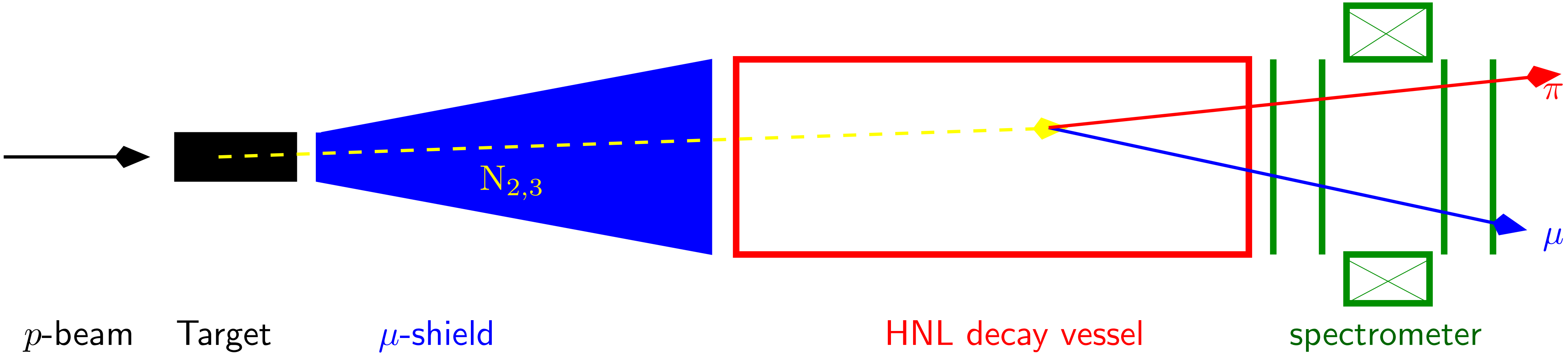
Spectrometer for 2×10^{20} 400 GeV pot

HNL search is different from $\nu_\mu,\ \nu_e$ physics (but ν_τ similar):

- $\nu_\mu,\ \nu_e$ cause background:
  heavy (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

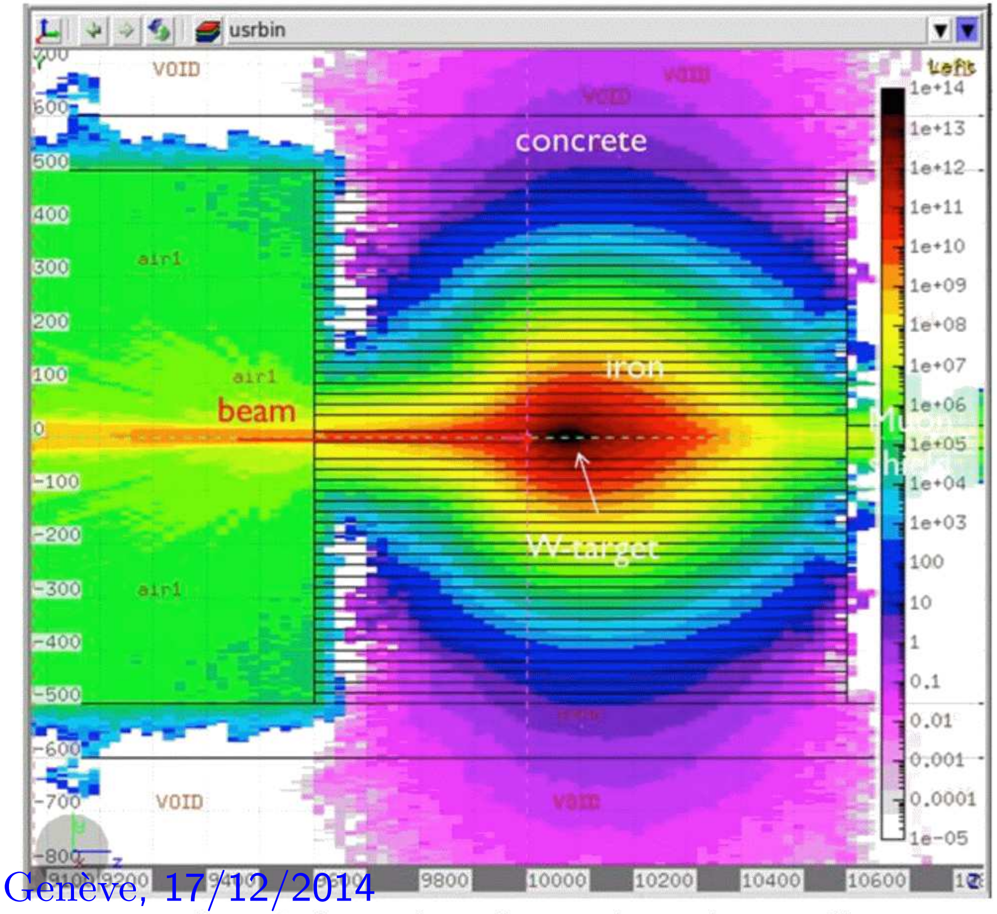
- Where to put this spectrometer?
- Some words about the target bunker
- The muon shield
- Decay vessel, and ν-interaction background
- The spectrometer:
  - Straw chambers
  - Magnet
  - Calorimeter
- Expected sensitivity

SHIP_Taskforce_Report_v1.0.pdf

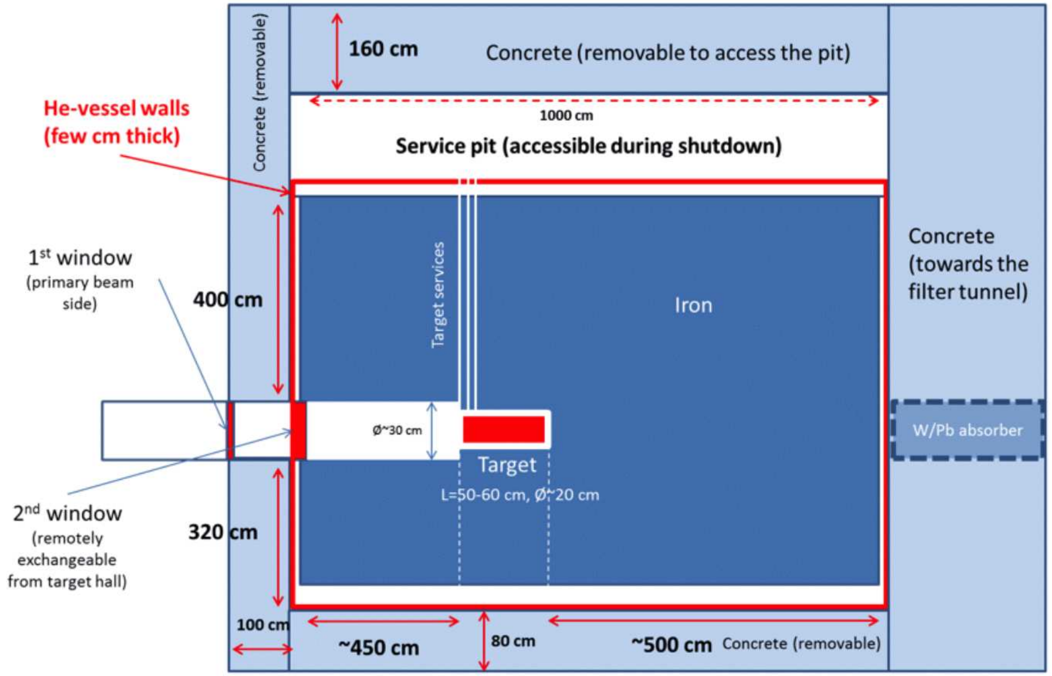
Target Bunker

Accelerator department studies:

- Beam-line from SPS
- Civil engineering
- Target design
- Radiation environment



Units of the colour legend are in µSv/h.

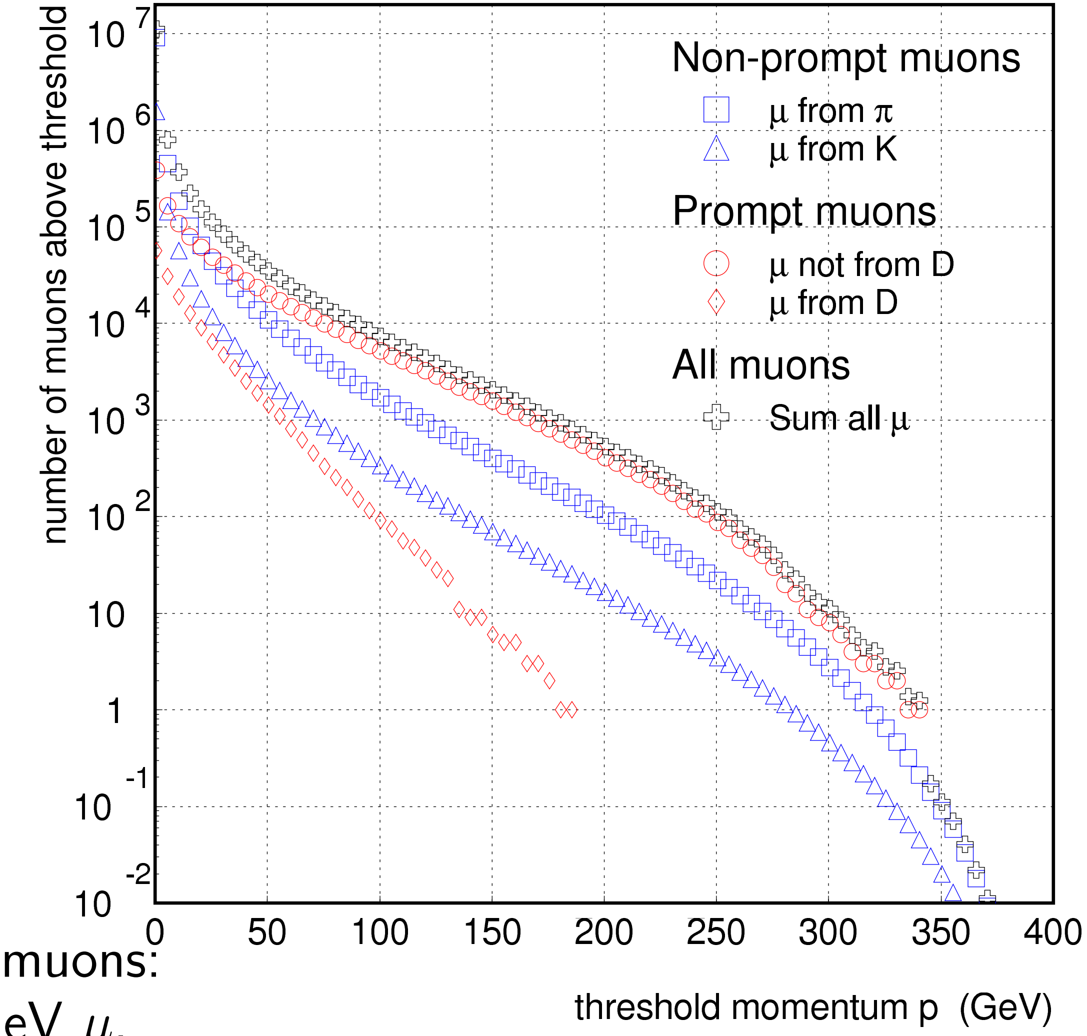


ship.web.cern.ch/ship/Document/SHIP_Taskforce_Report_v1.0.pdf

μ Flux and Shield

Without μ-shield:
5×10^9/SPS-spill(5×10^{13} pot)

- Low-p: still from π/K-decay
- High-p: ω/ρ-decays to $\mu\mu$
- Reduce background from μ-interactions to below ν-background (see later)
- Acceptable μ rate $\sim 10^5$/spill.

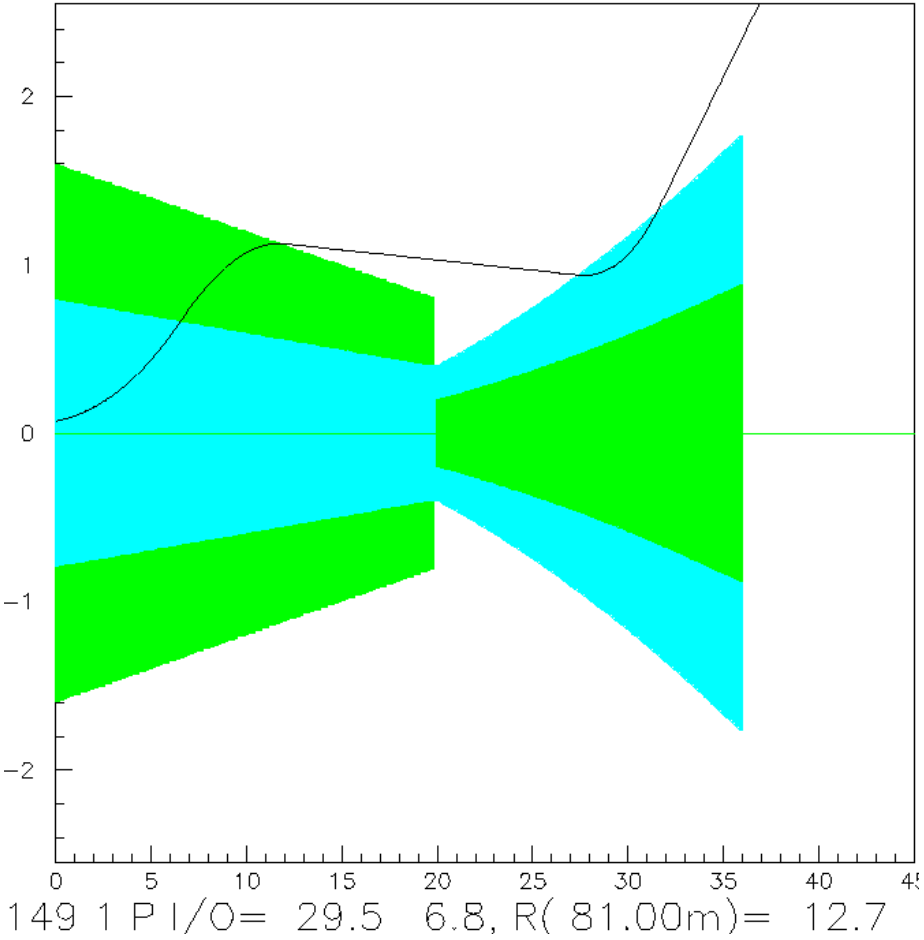


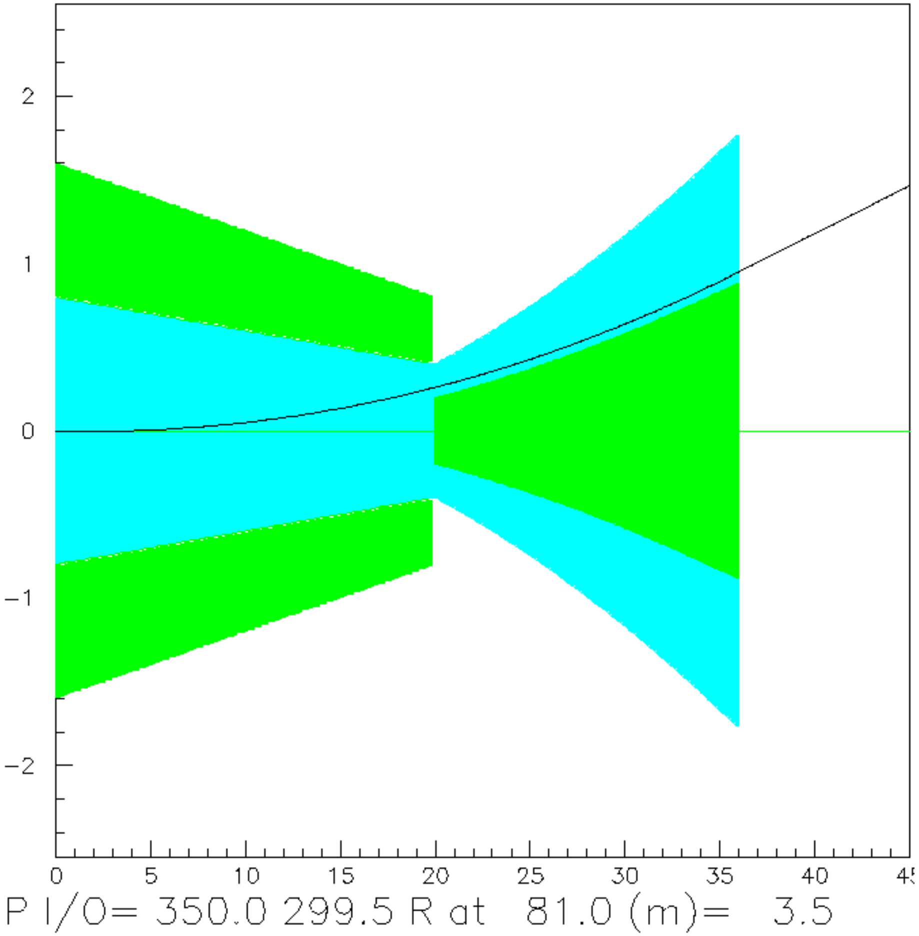
Two alternatives for shield:

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

Active μ-Shield

- 350 GeV: $\mu^{\pm}$ separated by ± 20 cm in x @ z=20 m, close to x=0: no more muons!
- Put the return field of 2nd magnet in centre, to avoid back-scatter from return field.





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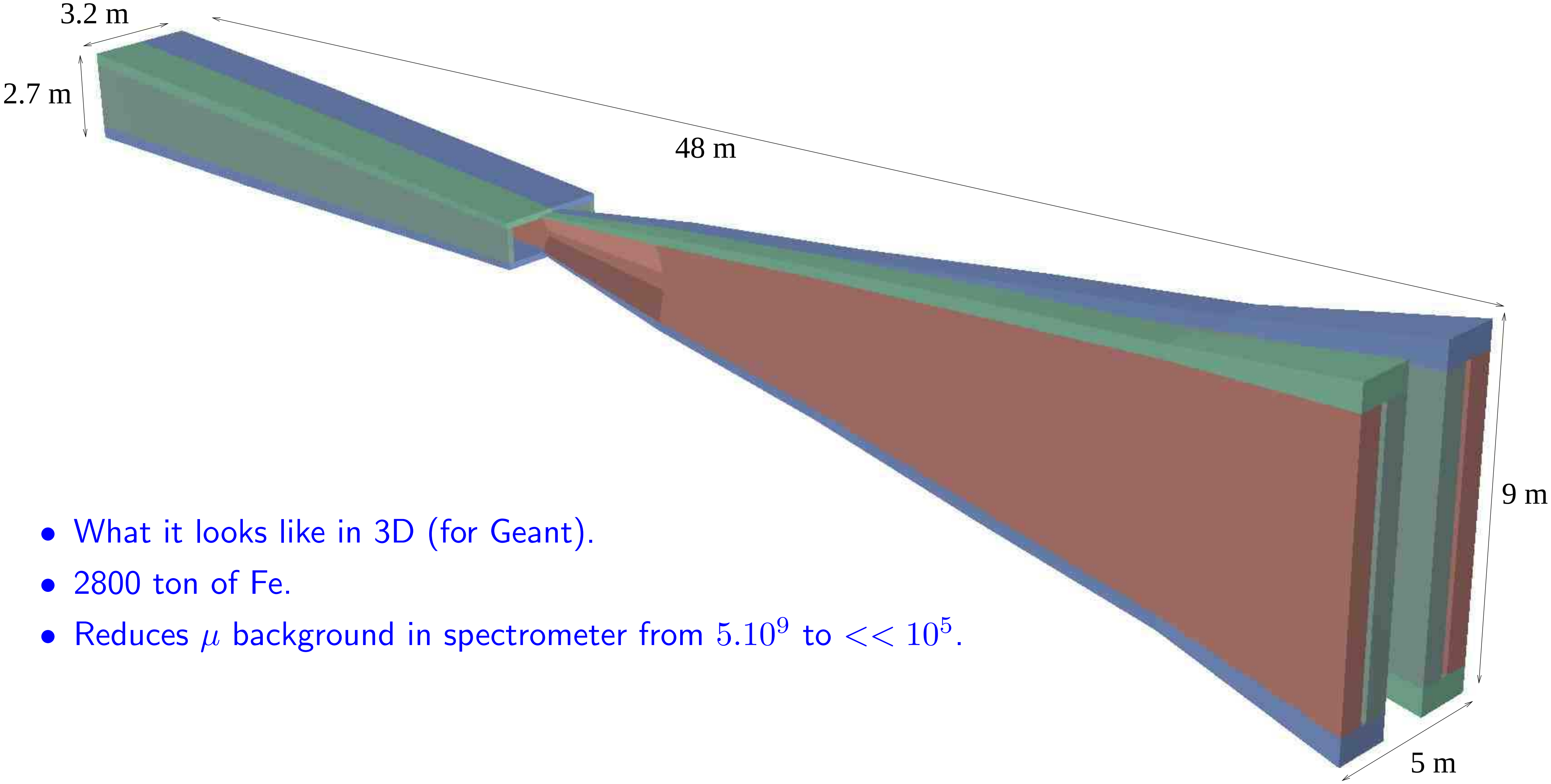
Active μ-Shield



- What it looks like in 3D (for Geant).
- 2800 ton of Fe.
- Reduces μ background in spectrometer from 5.10^9 to $<< 10^5$.

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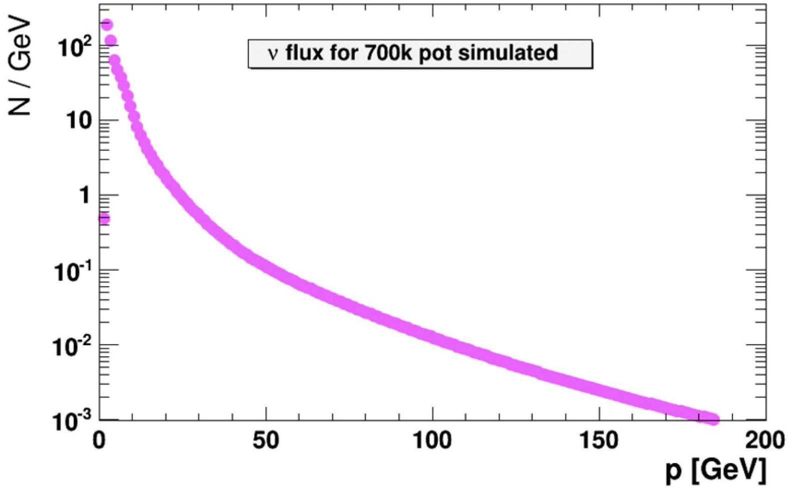
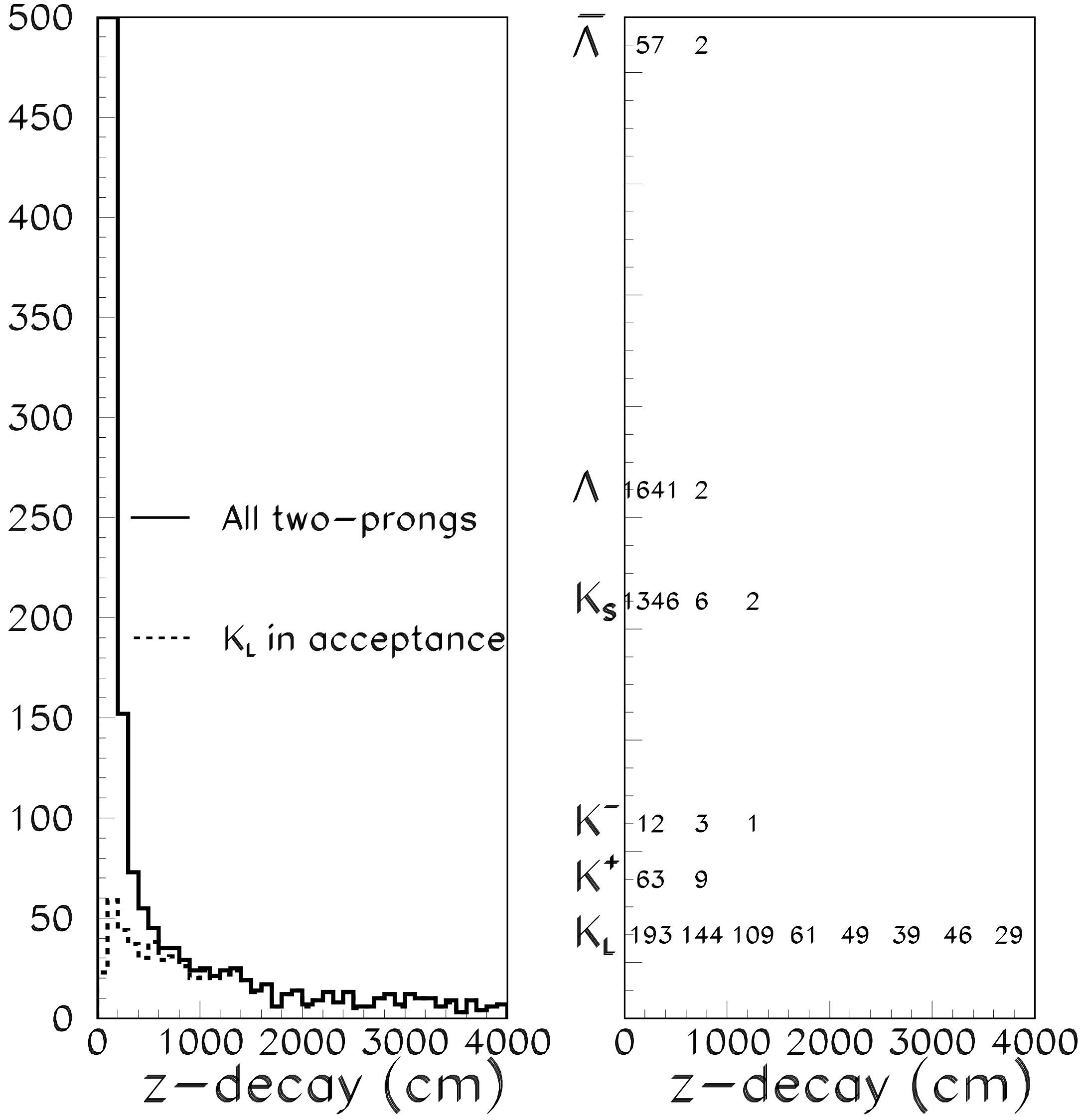
ν-Background and Decay-Vessel

Pythia/Genie/Geant, compare to CHARM:

- ν-flux at end of μ-shield ($/2 \times 10^{20}$ pot):
  CC+NC 8×10^5 interactions/λ



- 1 bar air in decay volume:
  2×10^4 ν-int$/2 \times 10^{20}$ pot
- Reduce pressure to 10 μbar!
- ν-interactions in μ-shield:
  - Use veto-station to suppress short lived.
  - $\nu_\mu + p \to X + K_L \to \mu\pi\nu$ main background.



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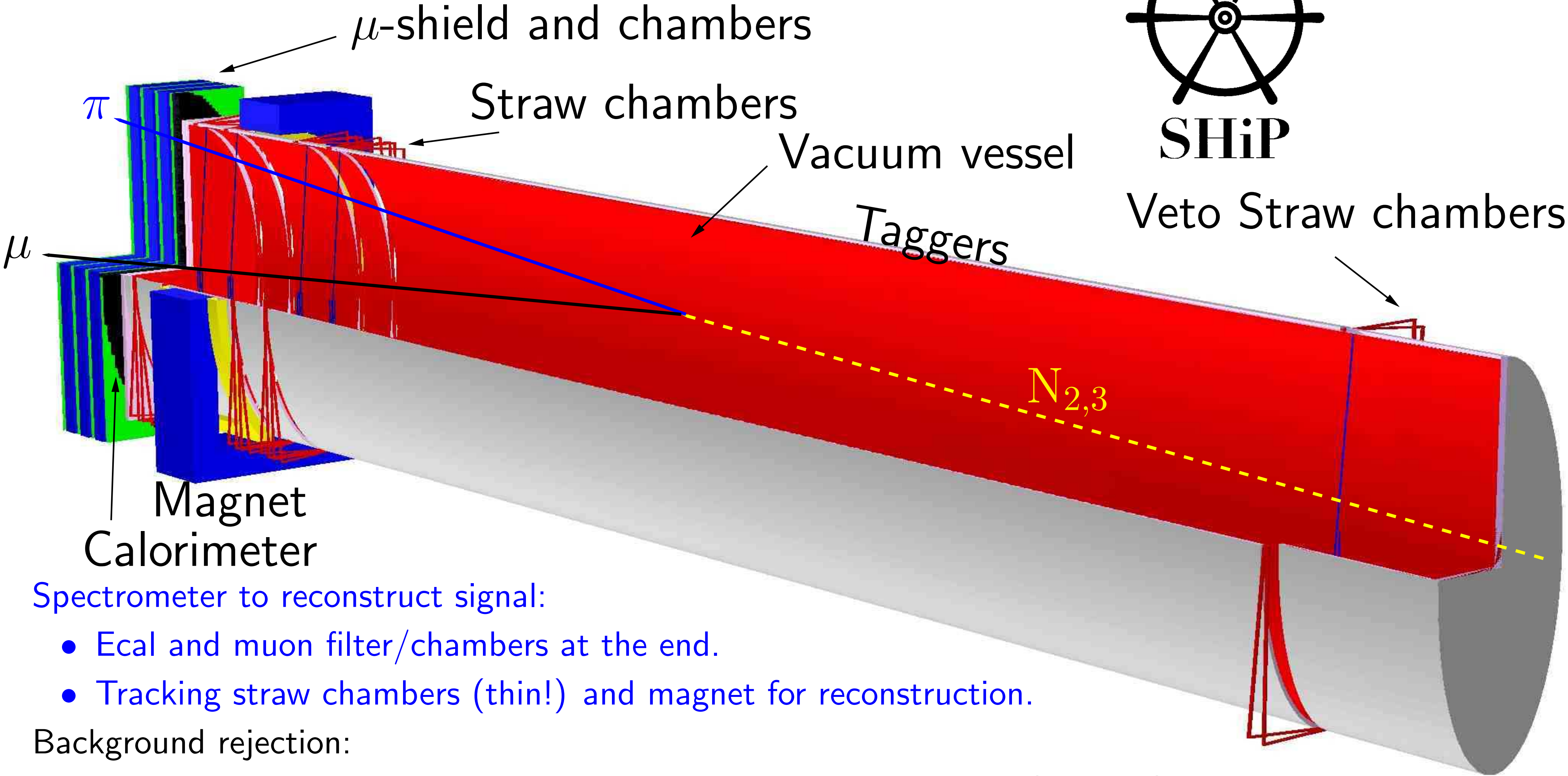


SHiP

Spectrometer to reconstruct signal:

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

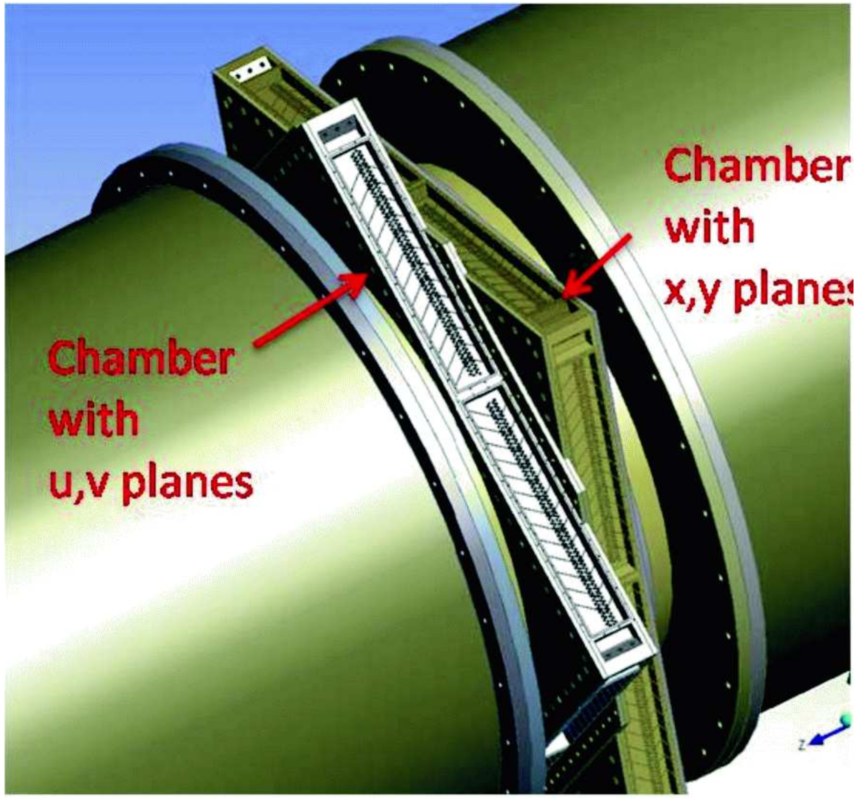
Background rejection:

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

Tracking Chambers

NA62 ($K^+ \to \pi^+\nu\bar{\nu}$):

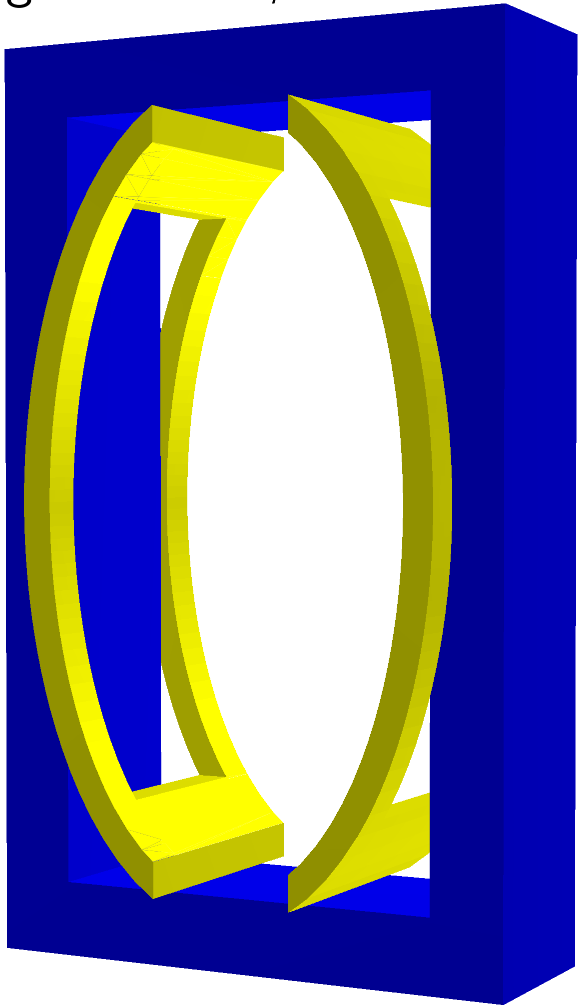
- 2 m ⌀ vessel @0.01 μbar.
- 10 mm ⌀ straws made of PET.
- Demonstrated to work in vacuum.
- X/X0=0.5 % for 4 view station!
- 120 μm resolution/straw.

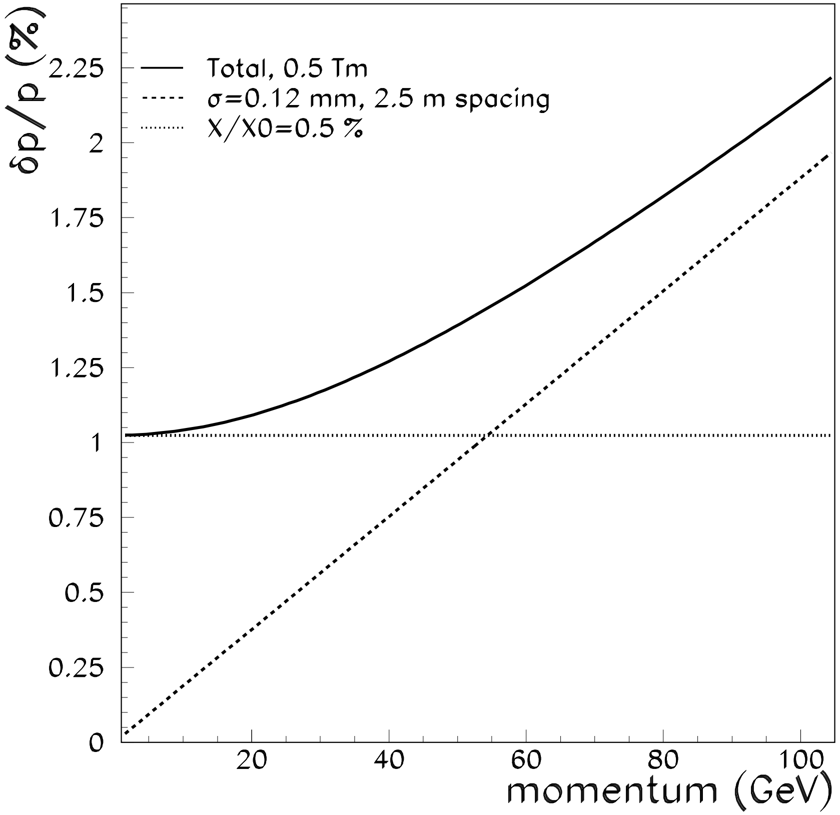


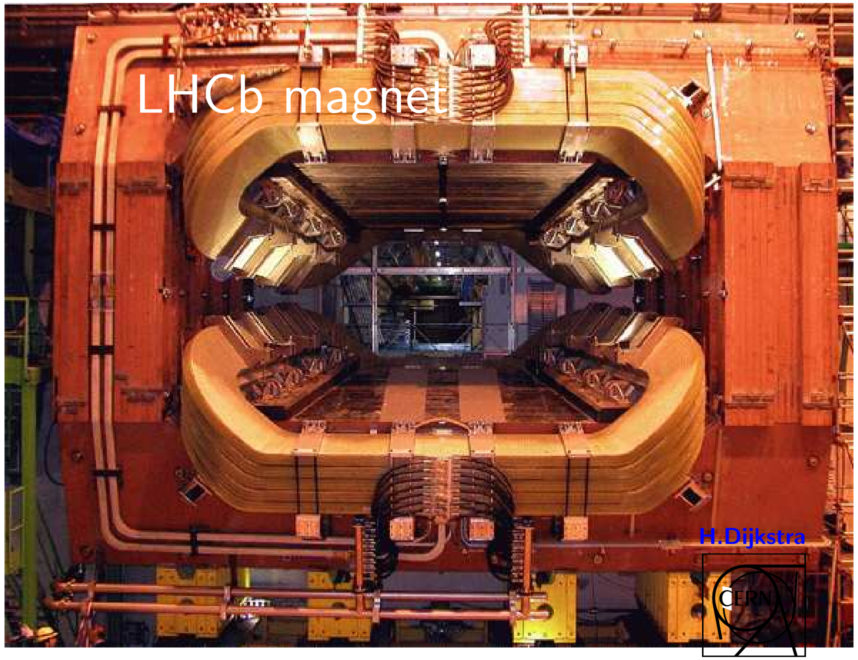
Magnet

- With X/X0=0.5 % chambers: modest 0.5 Tm
- Need $\sim 40\ \mathrm{m}^2$ aperture.

LHCb magnet: 4 Tm, $16\ \mathrm{m}^2$ exit-aperture

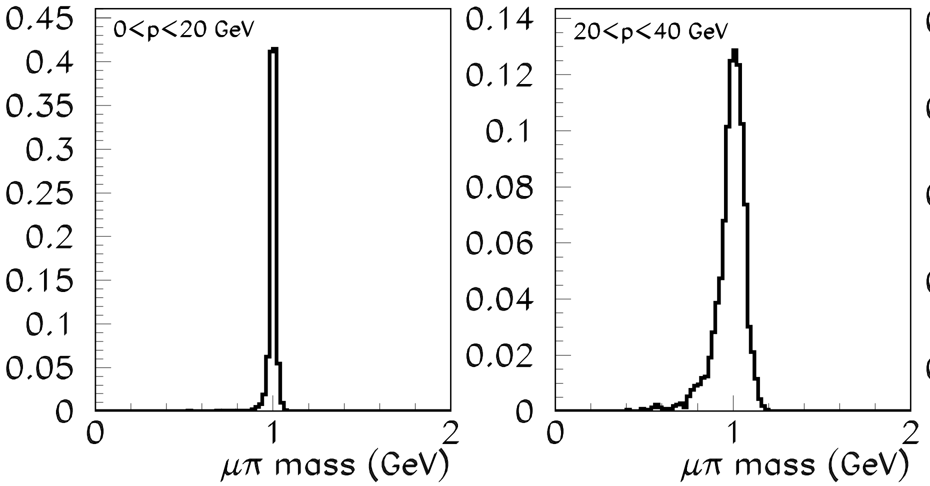






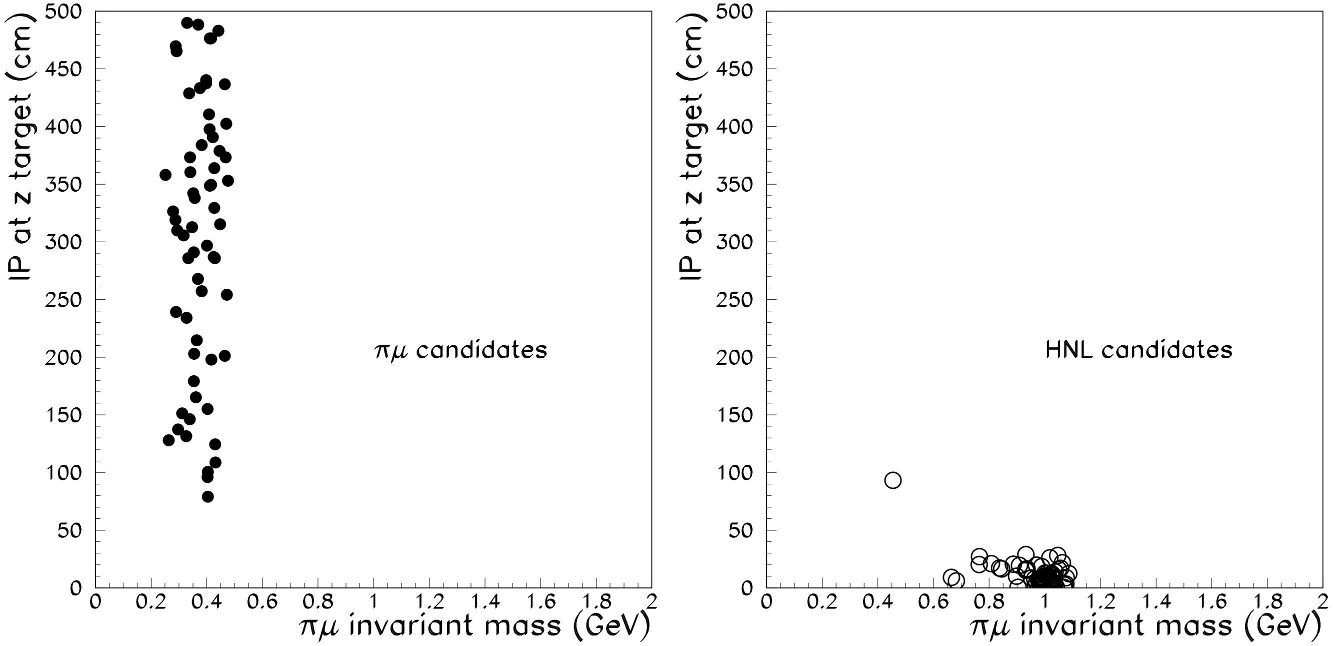
Mass resolution

- Resolution for 1 GeV N $\rightarrow \mu\pi$: $\sim$ 15 MeV.



K_L background suppression:

- Use pointing of candidates to target area
- Detect CC via extra μ in coincidence with $\mu\pi$?
- Instrument μ-filter to tag CC/NC shower?



Electromagnetic Calo

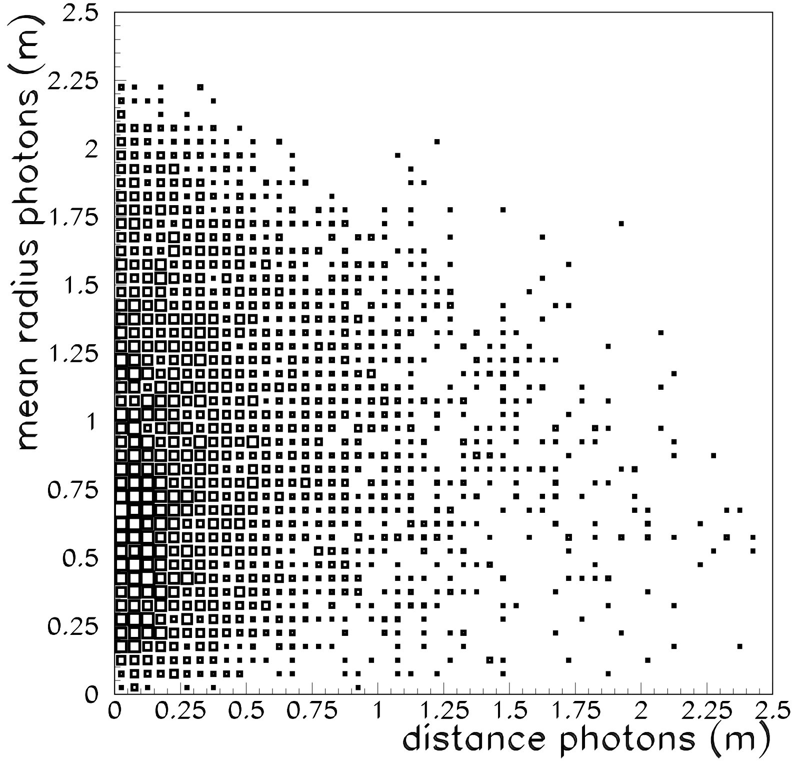
LHCb Shashlik ECAL:

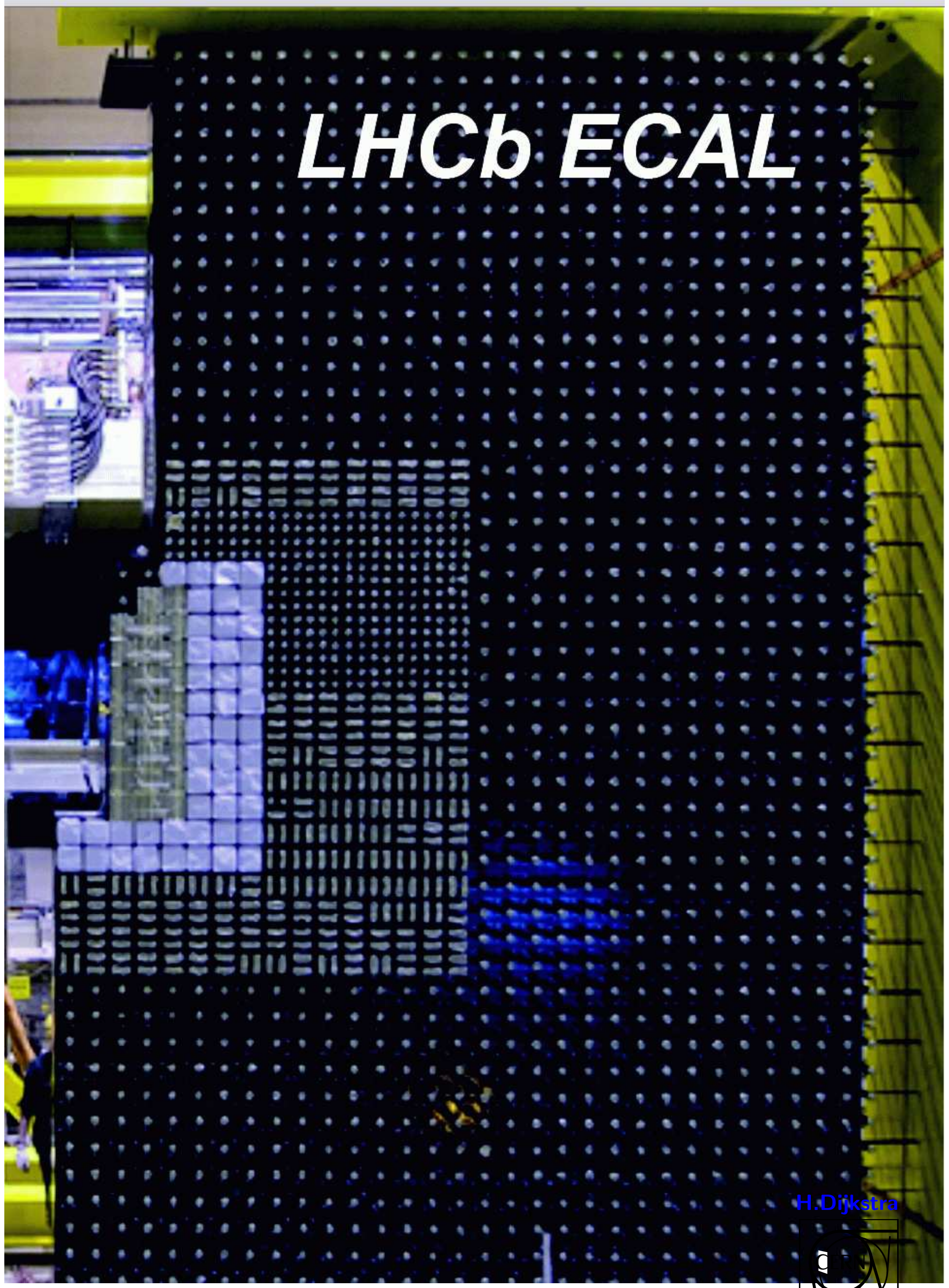
- $6.3 \times 7.8\ \mathrm{m}^2$
- $\frac{\sigma(E)}{E} < 10\%/\sqrt{E} \oplus 1.5\%$

Better than required, roughly same size

But for $\mathrm{N} \to \mu\rho(\pi\pi^0(\gamma\gamma))$

need small $(10 \times 10\ \mathrm{cm}^2)$ cells everywhere.





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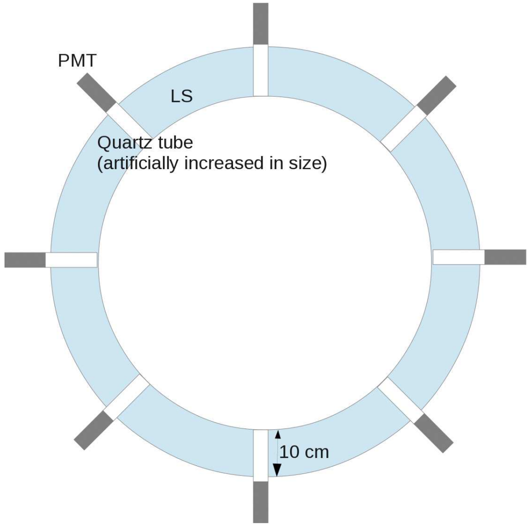
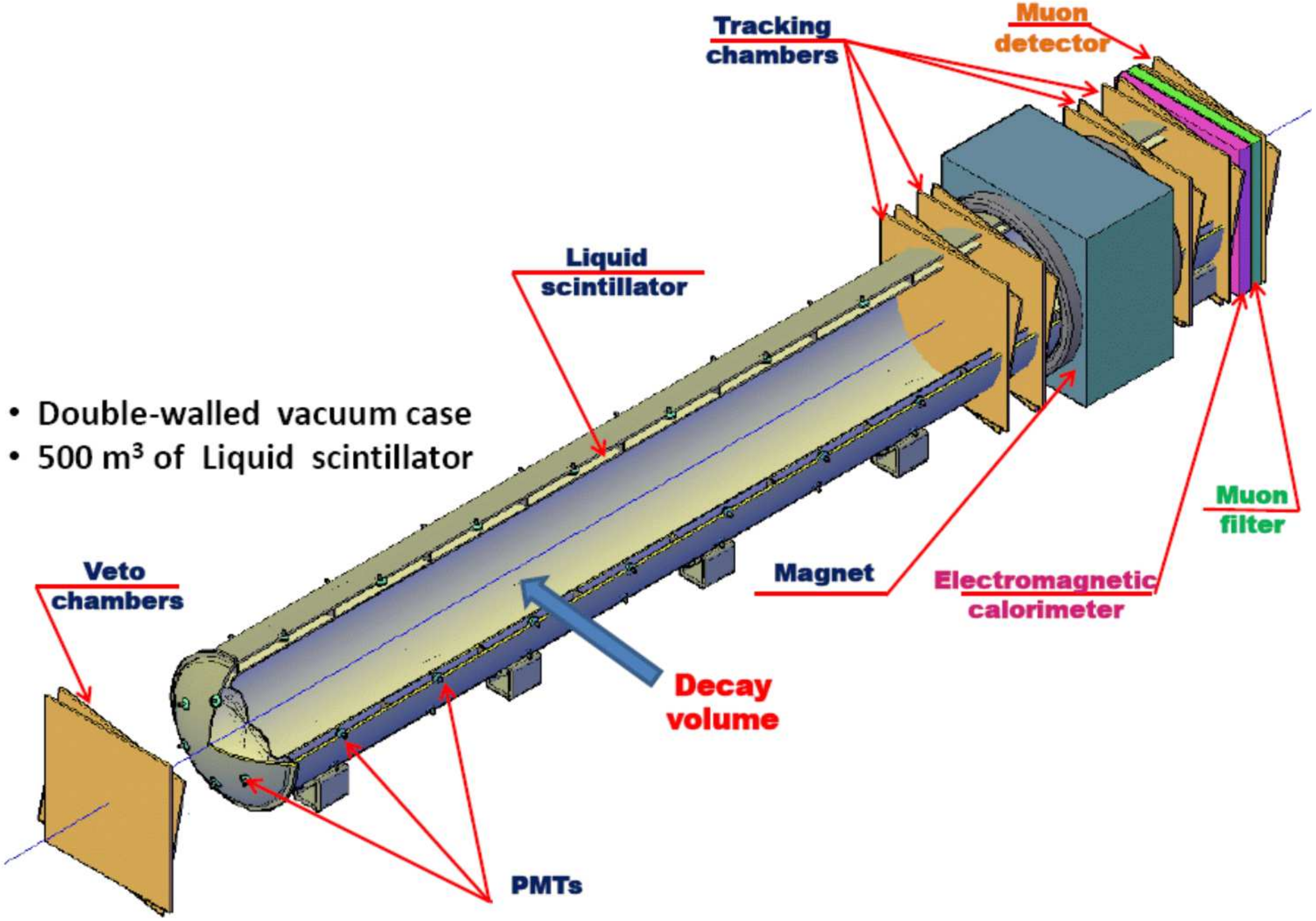
Liquid Scintillator Taggers

Taggers: liquid scintillator in double walled vessel to veto candidates with accompanying particles.





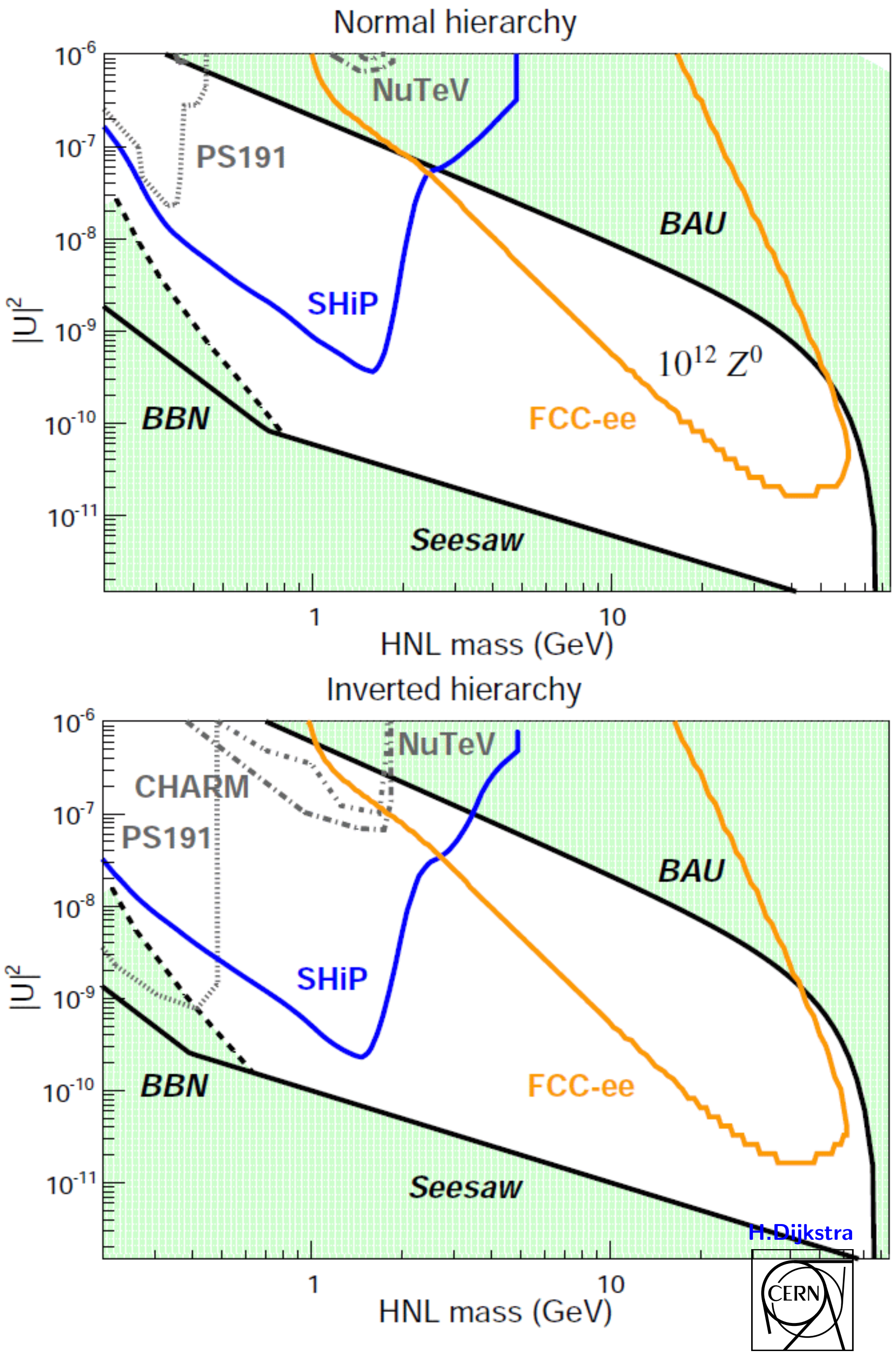
- Double-walled vacuum case
- 500 m³ of Liquid scintillator

SHiP aims for a background-less design!

Expected HNL Sensitivity

Conditions:

- $M_{\mathrm{N}} = 1$ GeV:
- $\mathrm{N} \rightarrow \geq$ 2-charged.
- $U^2_{\mu,\ e} > U^2_{\tau}$
- 2×10^{20} pot of 400 GeV.
- No (background) events observed.



arXiv:1411.5230v2

For factor 10 in U^2 need:

- $10\times$ more pot/Z^0, AND
- $10\times$ larger acceptance!

Extended Physics Program

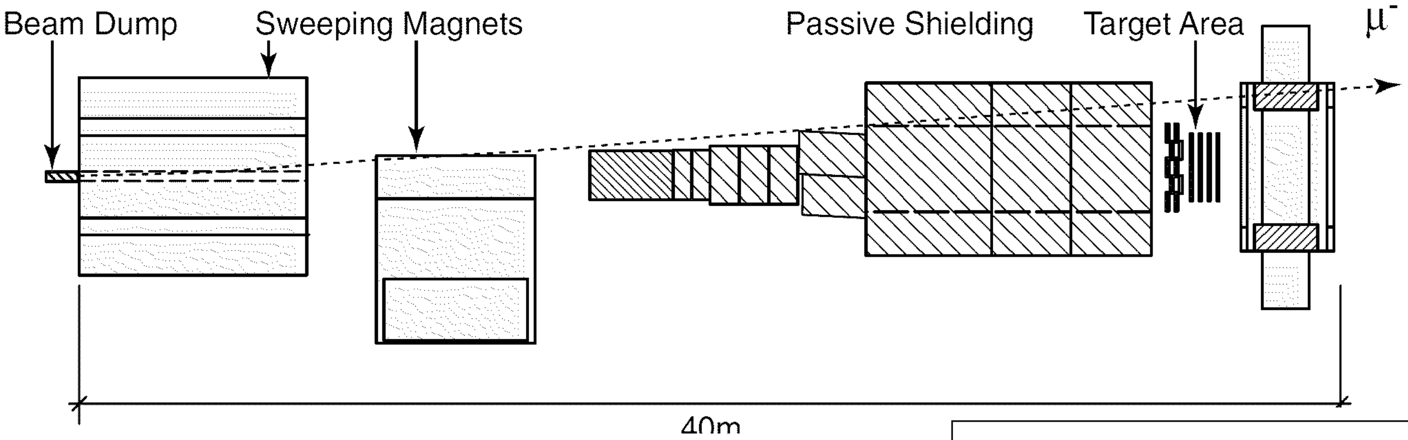
Experiment designed for HNL studies in νMSM, but..

- Ideally suited for studying interactions of ν_τ, since they are produced from D_s-decay, hence have similar kinematics as HNLs. → next slides
- Can search for any other weakly interacting, yet unstable particles with $100 < M < 2000$ MeV.
  Example of "hidden sector" models on the "market":
  - Light SUSY goldstinos (hep-ph/000735):
    - Production/decay might be like HNL, i.e. $D \to \pi X,\ X \to \pi\pi$
    - $c\tau_X$ O(km)?
  - Light R-parity violating neutralinos in SUSY (hep-ph/0106199):
    - $D \to X\chi^0,\ \chi^0 \to \mu^+\mu^-\nu$
    - LSP, with R-parity "slightly" violated: BBN: $\tau_{\chi^0} < 0.1$ s
  - Dark/massive/para photons (hep-ph/0606202):
    - Produced via p-Bremstrahlung, $\gamma^{'} \to e^+e^-,\ \mu^+\mu^-$.
    - BBN limit: $\tau_{\gamma'} < 0.1$ s.
  - Insert your "favourite" model here...
- SHiP preparing physics paper evaluating many hidden sector models!

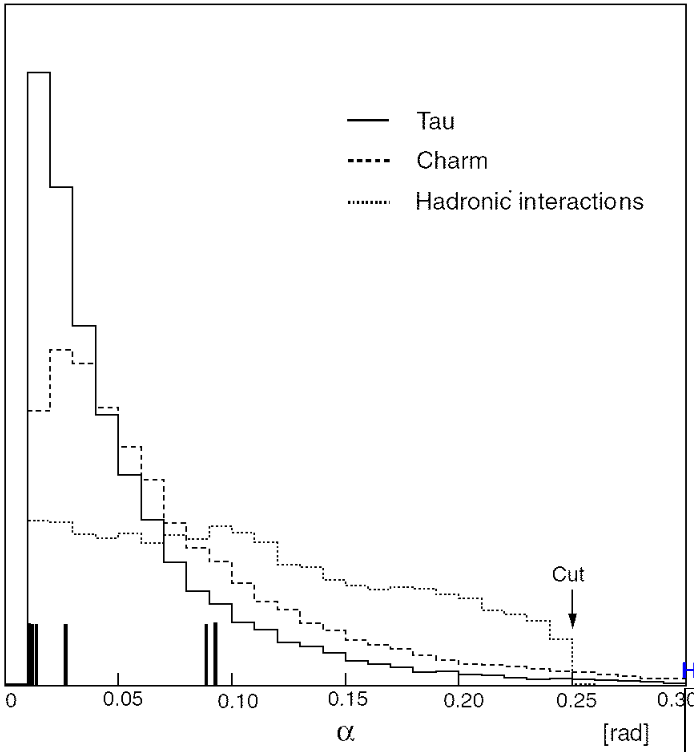
ν_τ Physics

Experimental status: DONUT results (PR D 78, 052002 (2008))

- 1997: 3.6×10^{17} pot, 800 GeV, using 260 kg emulsion ν-target.



- α_{kink} from τ-decay in CC interactions.
- Charm/hadronic-interaction background.
- 9 candidates, including 1.5 background.
- Opera: 4 candidates (from $\nu_\mu \rightarrow \nu_\tau$ oscillations)



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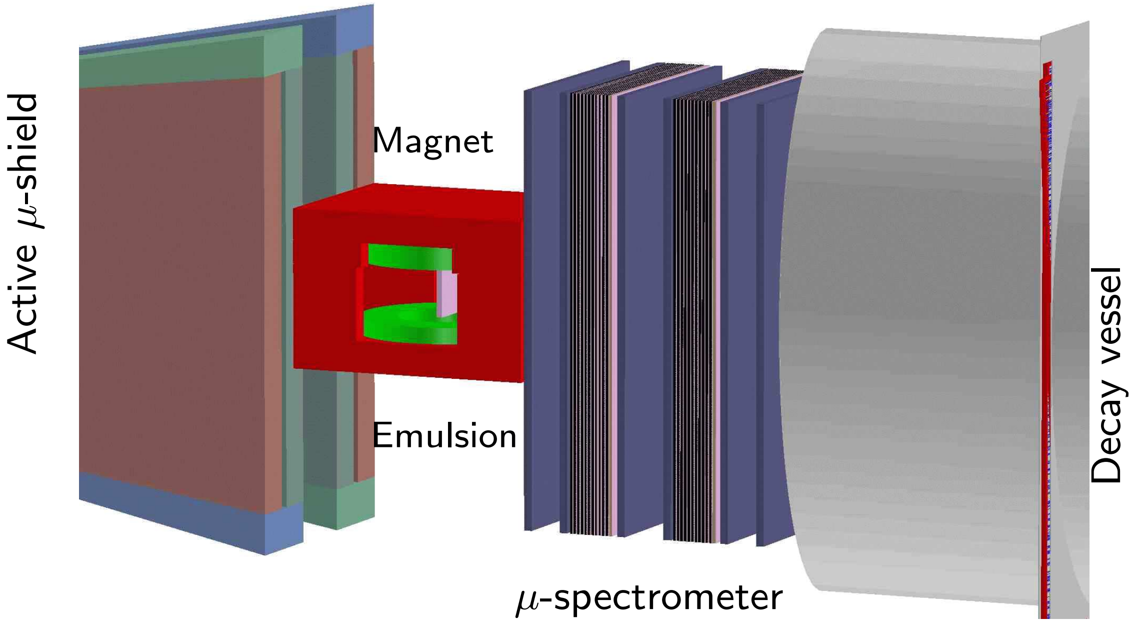
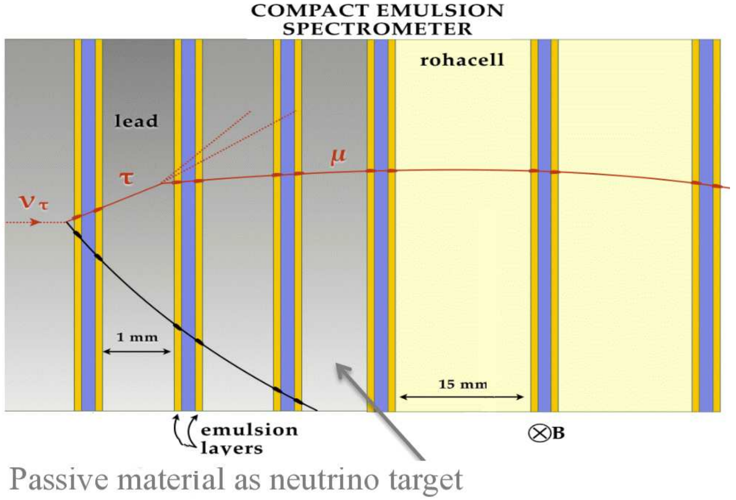
ν_τ Physics with 2×10^{20} pot

- Scaling from DONUT: 20 times more CC with same ν-target mass.
- But can increase ν-target mass “easily”, lets say to 5 % of OPERA emulsion surface:





- Expect ~ 3000 CC ν_τ interactions.
- B-field in emulsion and muon-filters in μ-spectrometer: distinguish ν_τ from $\bar{\nu_\tau}$.
- HNL-background: tag $\nu + p \rightarrow K_L + l + X$
- 10^5 ν_e interactions, produced predominantly in charm-decay: HNL normalization.

SPSC status

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010.-2013
- SPSC assigned 4 referees, who came with a list of questions.
- 3/1/2014: answers to questions: ship.web.cern.ch/ship/EOI/SPSC-EOI-010_ResponseToReferees.pdf
- 15/1/2014: SPSC discussed our proposal.

17/1/2014: The official feedback from the Committee is as follows :

"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."
Cheers,
Gavin, Lau, Matthew and Thierry
(for the SPS Committee).

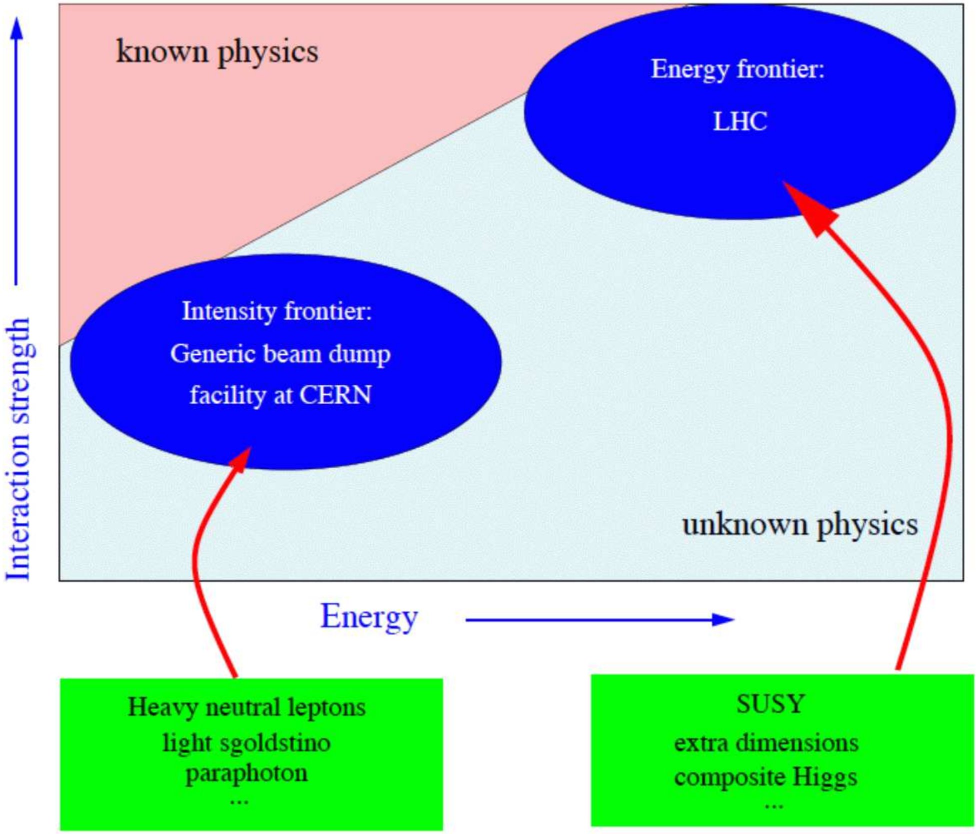
Next Steps

Following the endorsement of the SPSC:

- The CERN directorate has set-up a task force to assess the implications of the Heavy Neutral Lepton Experiment at the SPS. The CERN-DG received summer 2014 a report including the layout and the resources which are required to set-up the beam-dump and its calendar: ship.web.cern.ch/ship/Document/SHIP_Taskforce_Report_v1.0.pdf
- SHiP (Search for Hidden Particles) collaboration was officially founded 15/12/2014:
  - already ~ 170 authors from 42 institutes for producing a Technical Proposal (due spring 2015).
  - Institutes are from: Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Russia, Sweden, Switzerland, Turkey, UK.
  - Switzerland: Geneva, Lausanne, Zurich (and CERN).
- SHiP is preparing a physics paper and a Technical Proposal for spring 2015.

Conclusions

- SHiP complementary to LHC searches
- Detector is based on existing technologies.
  CERN task force to study accelerator part.
  TP expected spring 2015, if approved:
  - TDRs by 2018
  - civil engineering in LS2 (2018-2019),
  - and start experiment 2023.



- 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?