Search for Heavy Neutral Leptons (HNL) at the SPS

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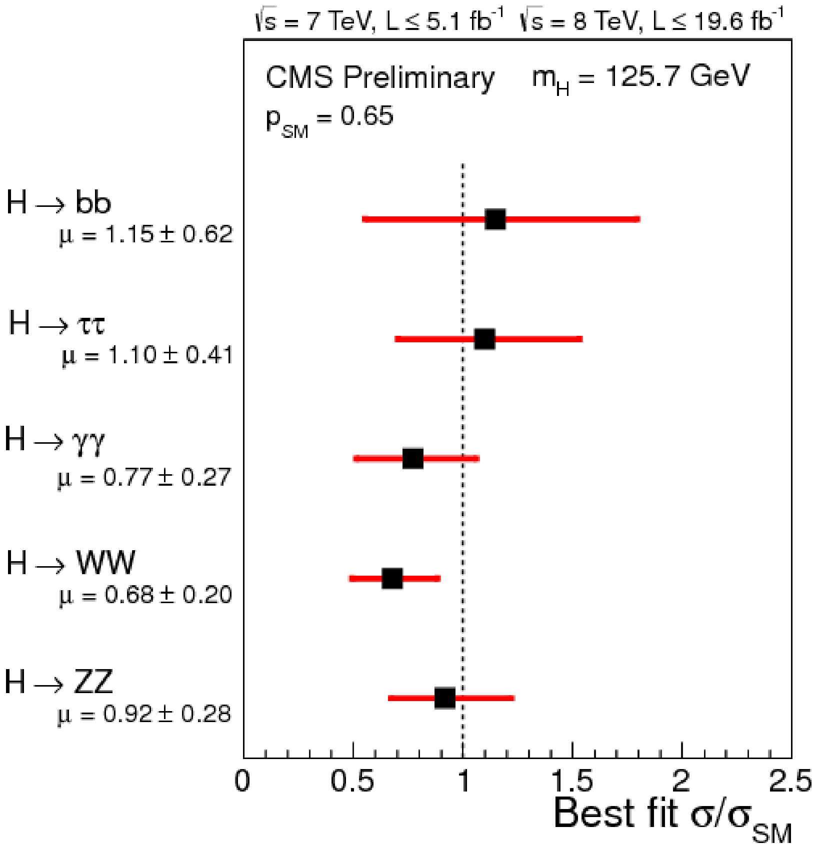
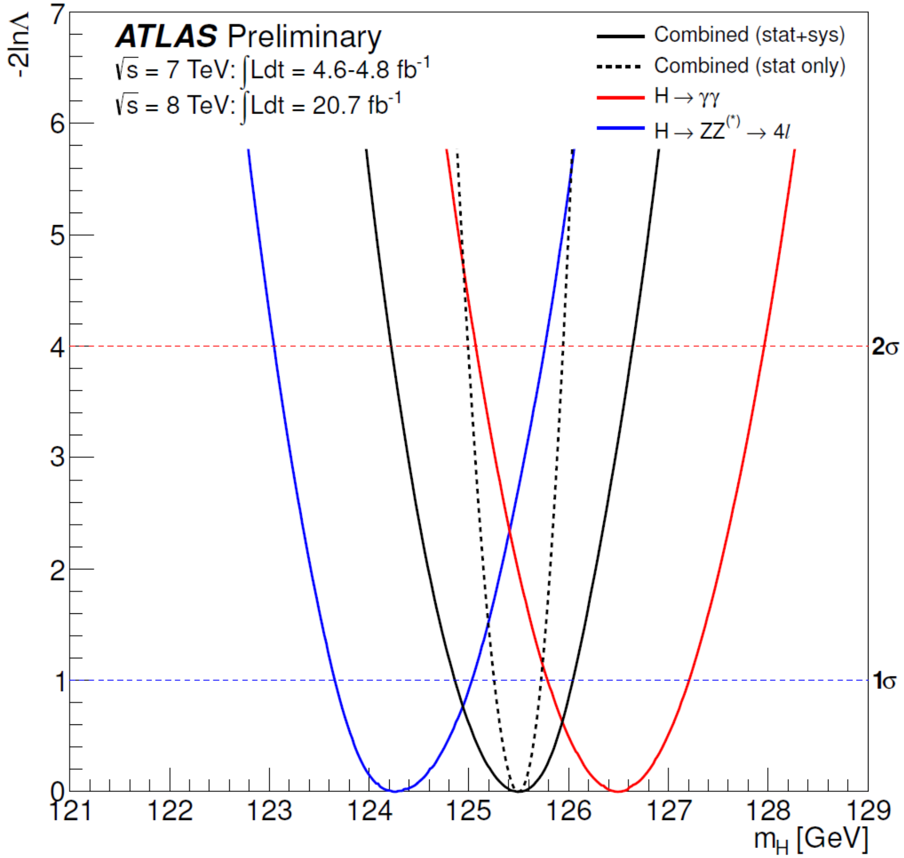
- How does this proposal fit in the physics landscape?
- Why HNLs?
- How to produce/detect HNLs.
- Backgrounds.
- The experimental set-up.
- Symbiosis with "active" ν physics.
- Conclusions.

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: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \text{fb}^{-1}$ $\sqrt{s}$ = 7, 8 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	$m(\tilde{q})=m(\tilde{g})$	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	$\tan\beta<15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta>18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	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
3rd 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
3rd 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	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(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	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
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	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	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	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	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, $\tau(\tilde{\chi}_1^\pm)$=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<$\tau(\tilde{g})$<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<$\tan\beta$<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<$\tau(\tilde{\chi}_1^0)$<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)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

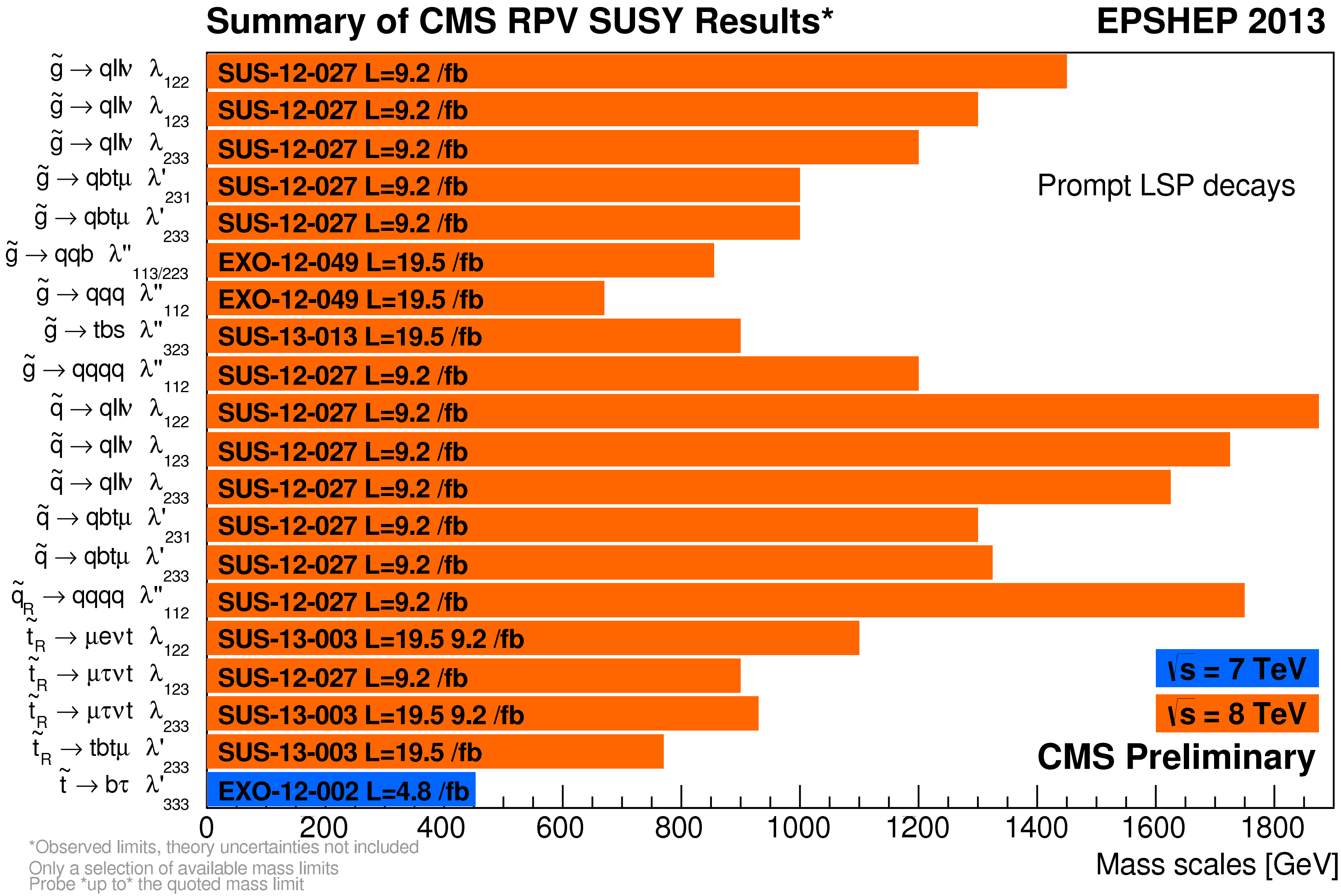
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

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 1σ theoretical signal cross section uncertainty.

H.Dijkstra

What is not found..



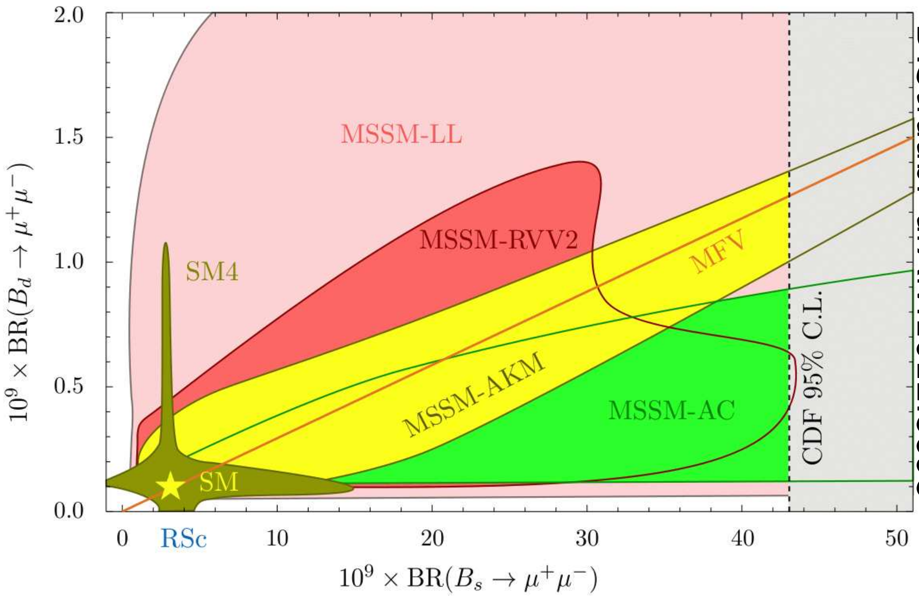
$B_s \to \mu\mu$ found and $\equiv$ SM

SM:

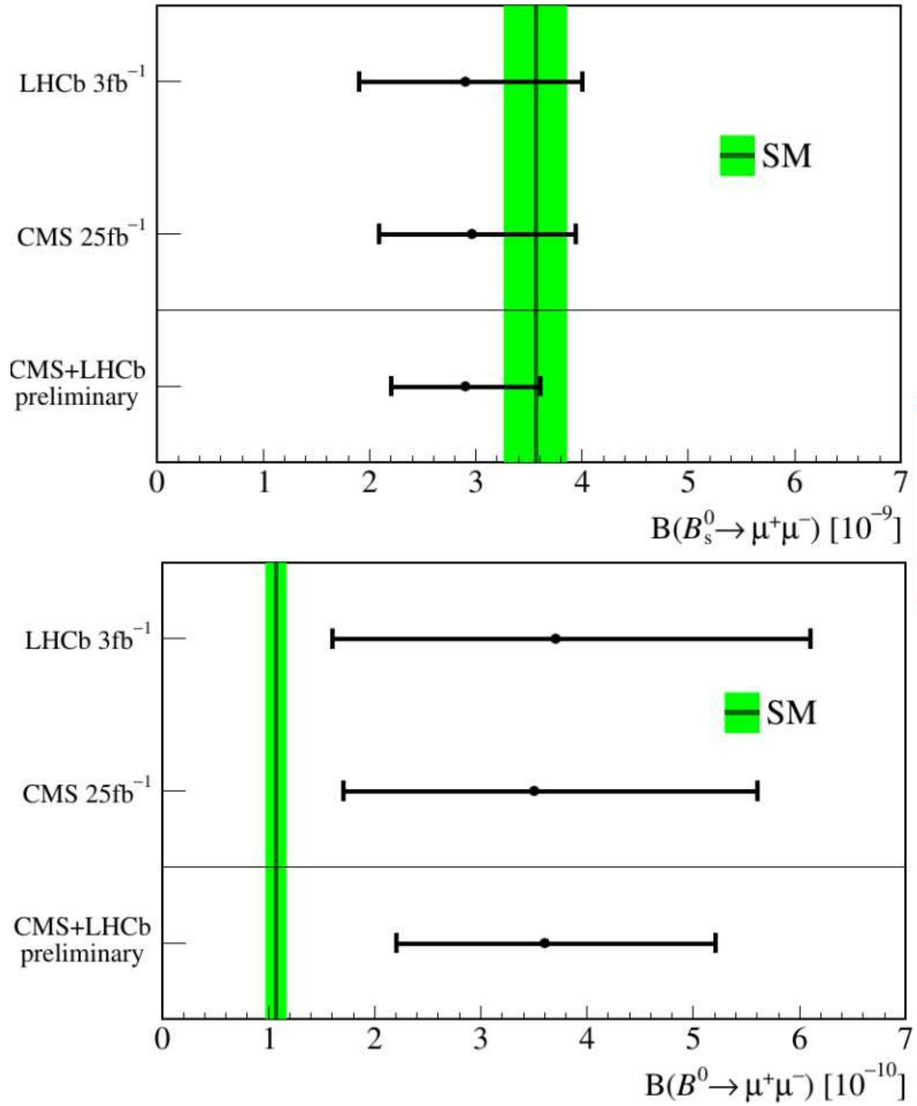
- No tree level decay
- Helicity suppressed
- Expected: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.54 \pm 0.30) \times 10^{-9}$ (Phys. Rev. Lett. 109 (2012) 041801)

NP:

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

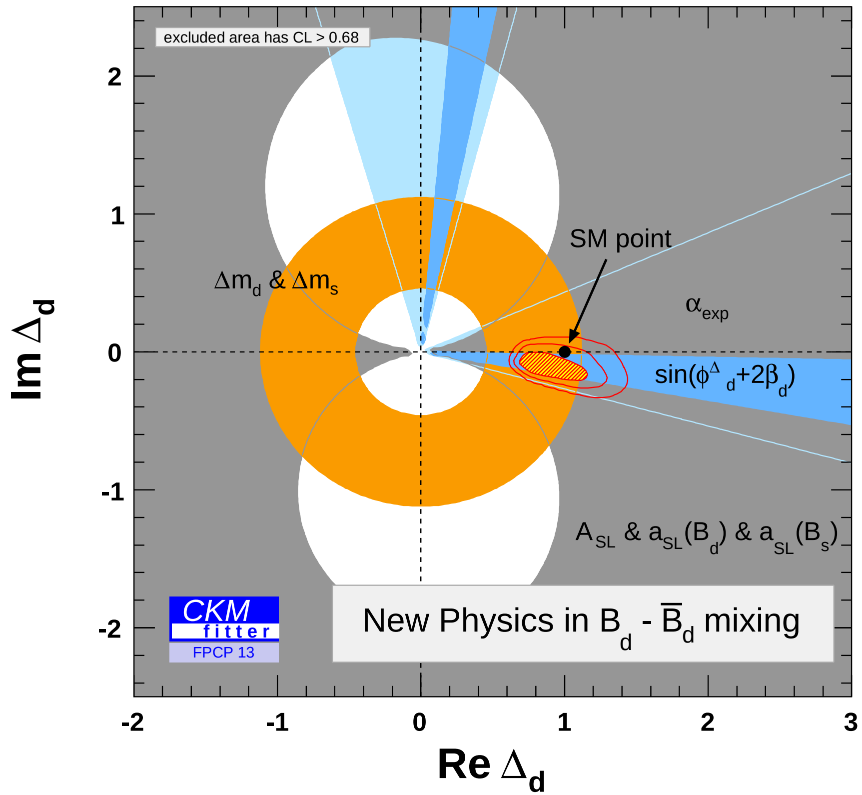


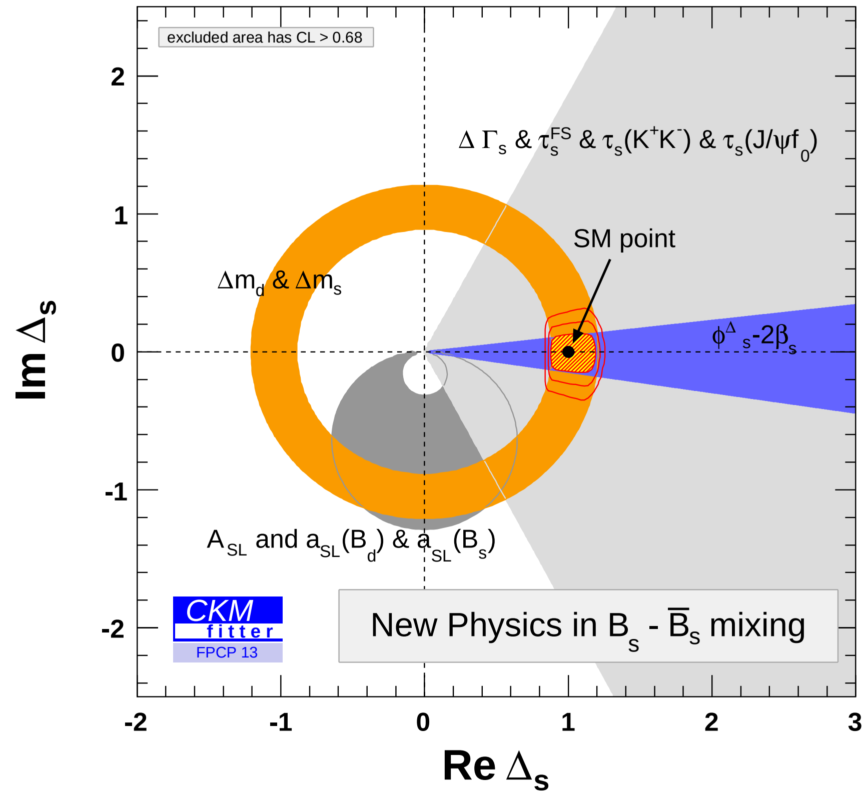
D.Straub: arXiv:1012.3893



NP from quark flavour observables

CKM-fitter

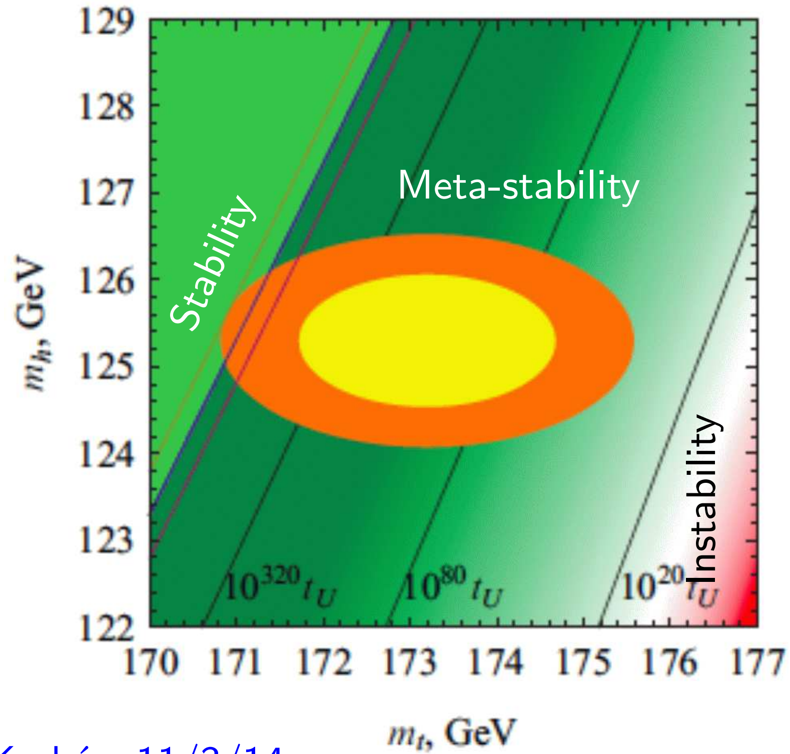


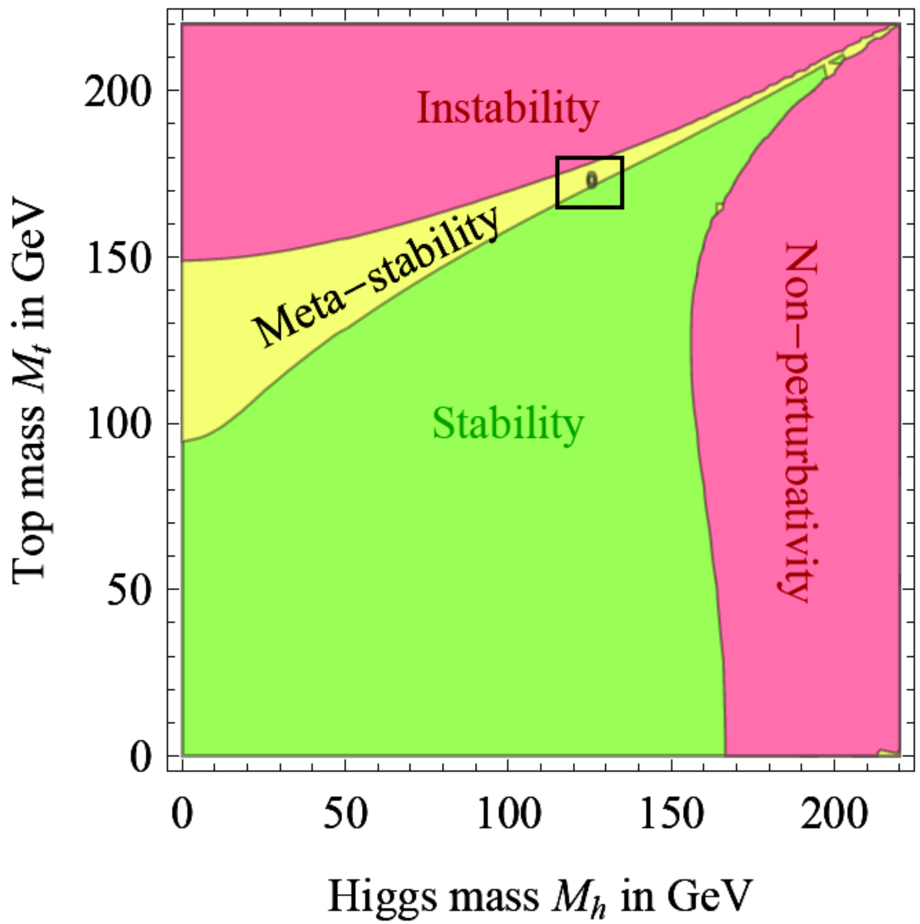


Scale of NP in $B\bar{B}$-mixing: $> 0.5 - 10^4$ TeV depending on assumptions of couplings.

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 $\tau \gg \tau_{\rm universe}$
- SM may work successfully up to Planck scale, i.e. no need for a new mass scale



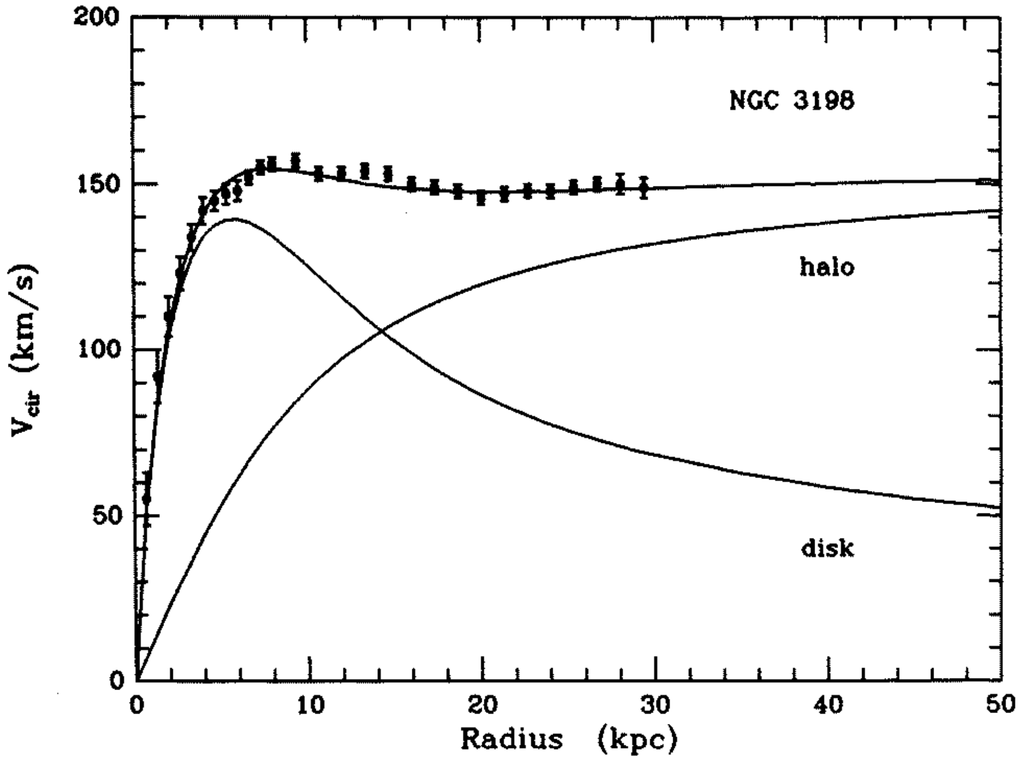


http://arxiv.org/pdf/1307.3536v2.pdf

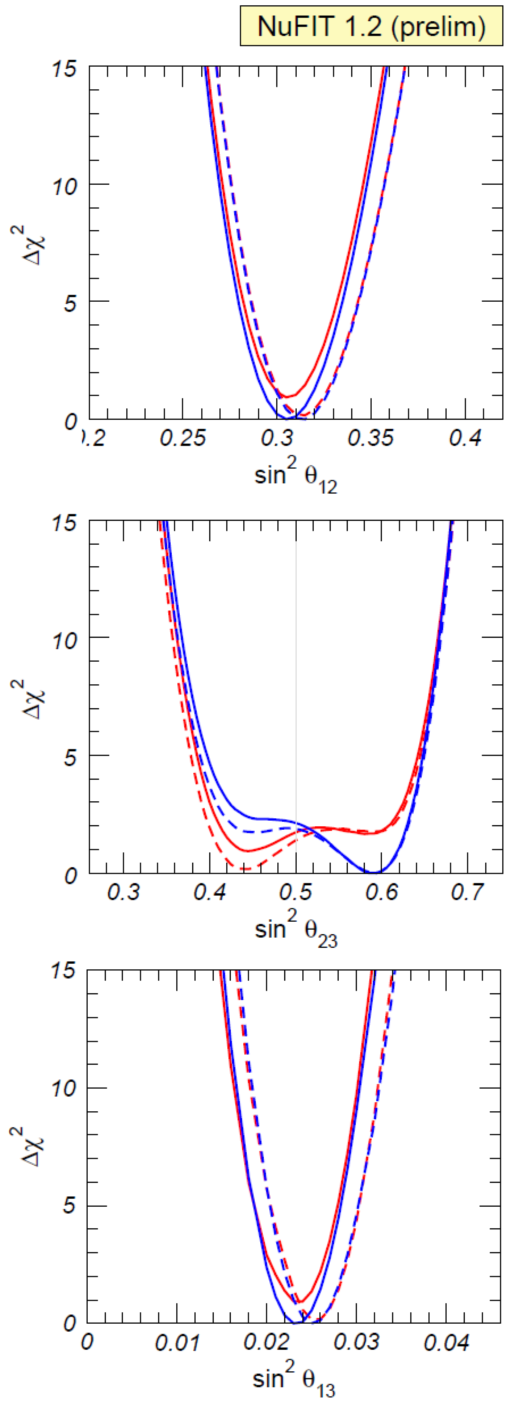
SM case closed?

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



Ptolomy (∼90-168 AD):

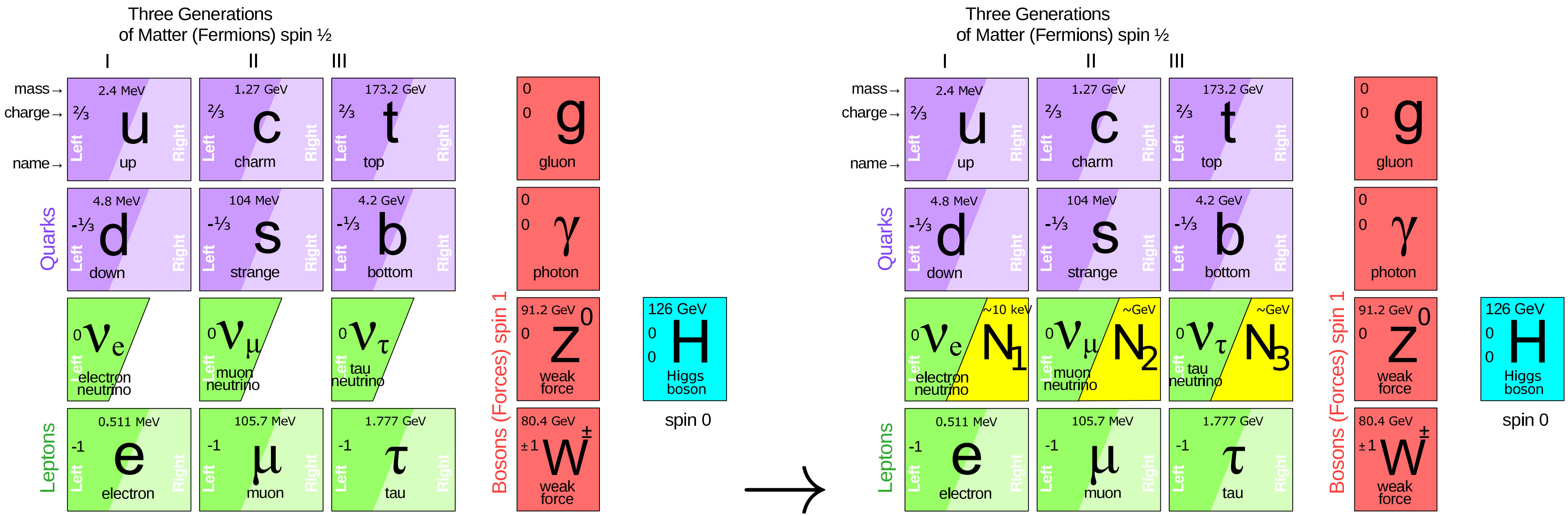
It is a good principle to explain phenomena by the simplest hypothesis possible!

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:

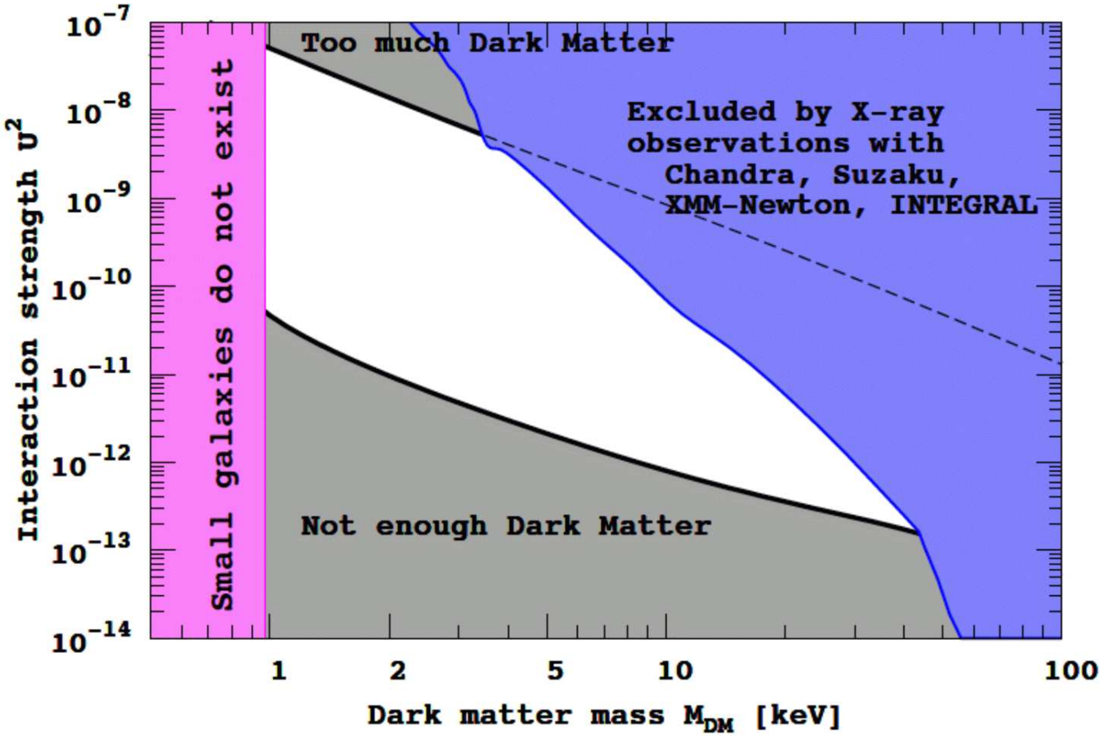
- N_1 can provide dark matter candidate
- $N_{2,3}$ can provide neutrino masses via Seesaw mechanism
- $N_{2,3}$ can induce leptogenesis→baryogenesis.



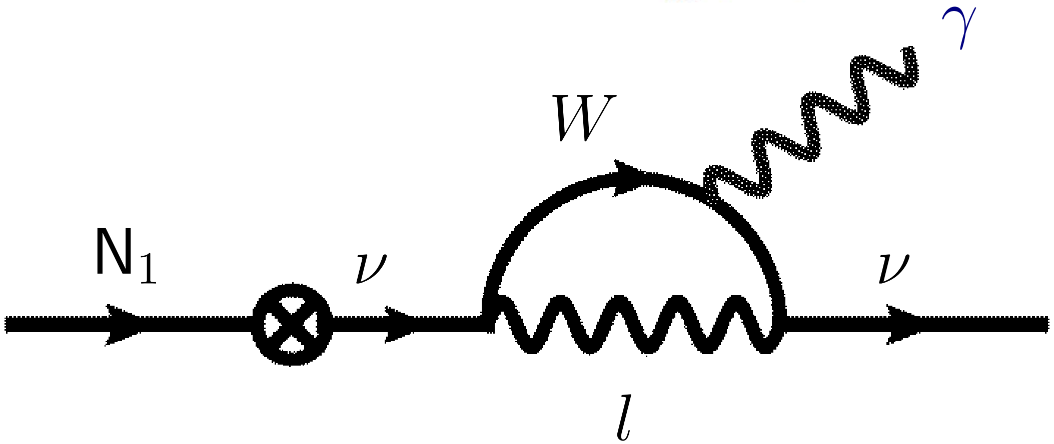
νMSM: closer look at N_1

N_1 can provide dark matter candidate:

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



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

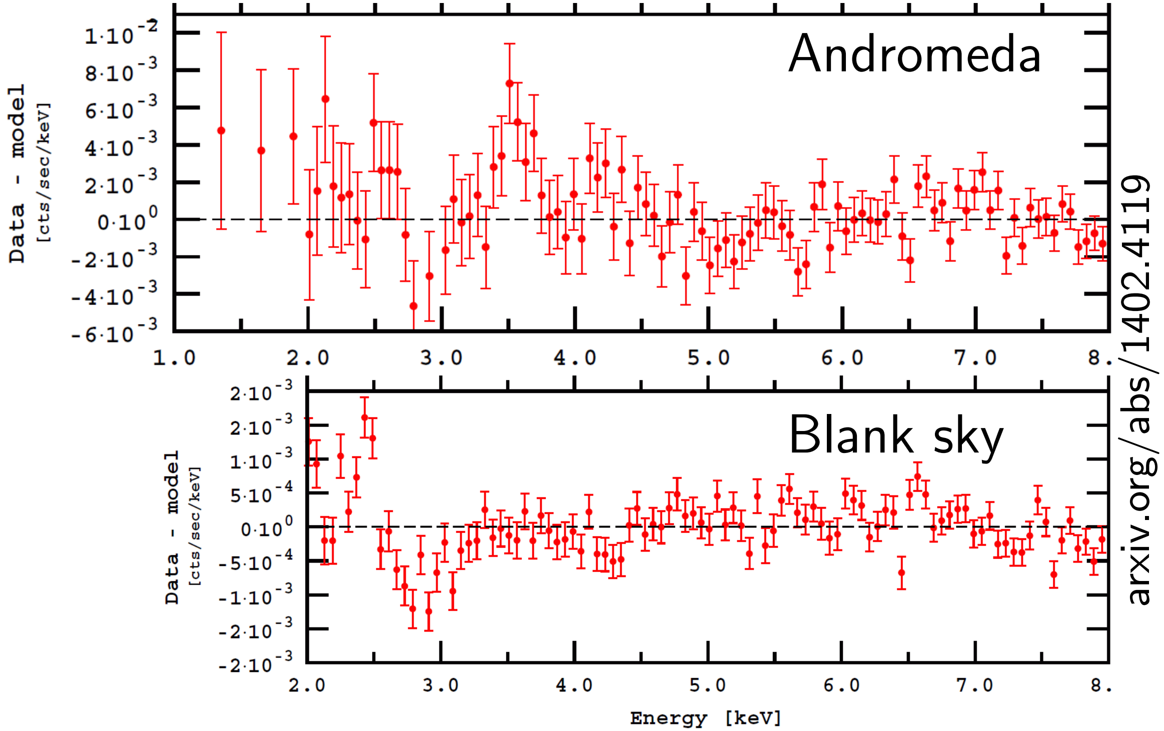


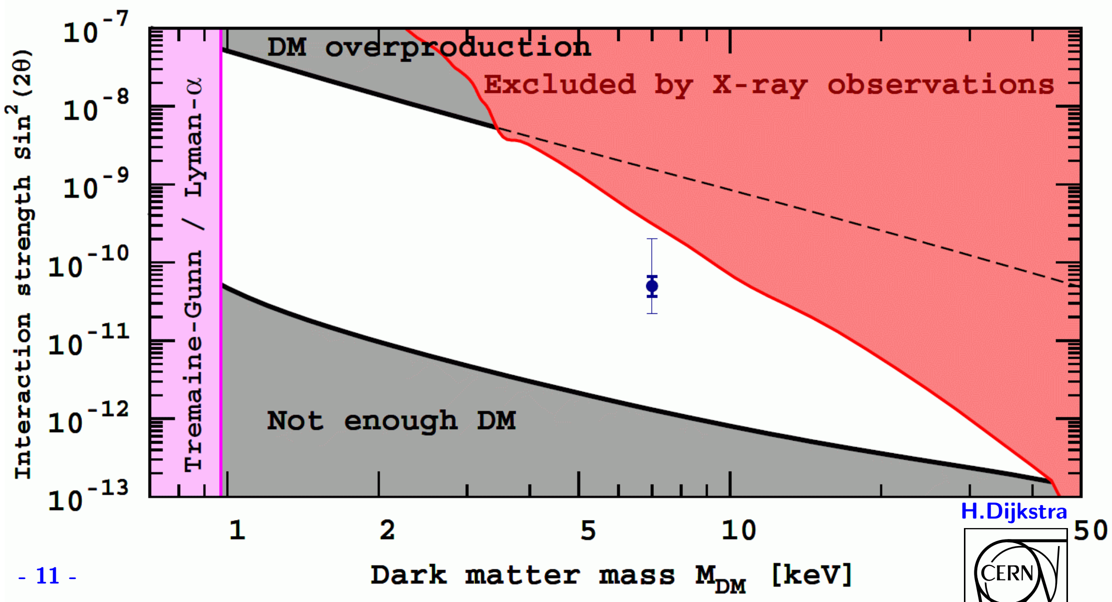
N_1: stop the press...

Recently 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.



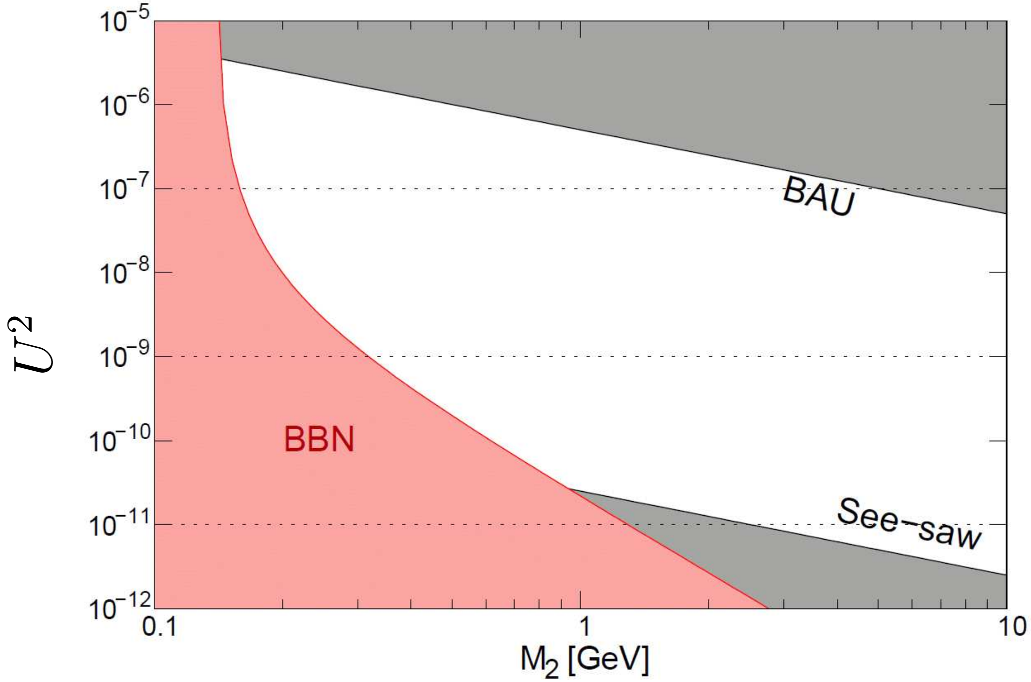


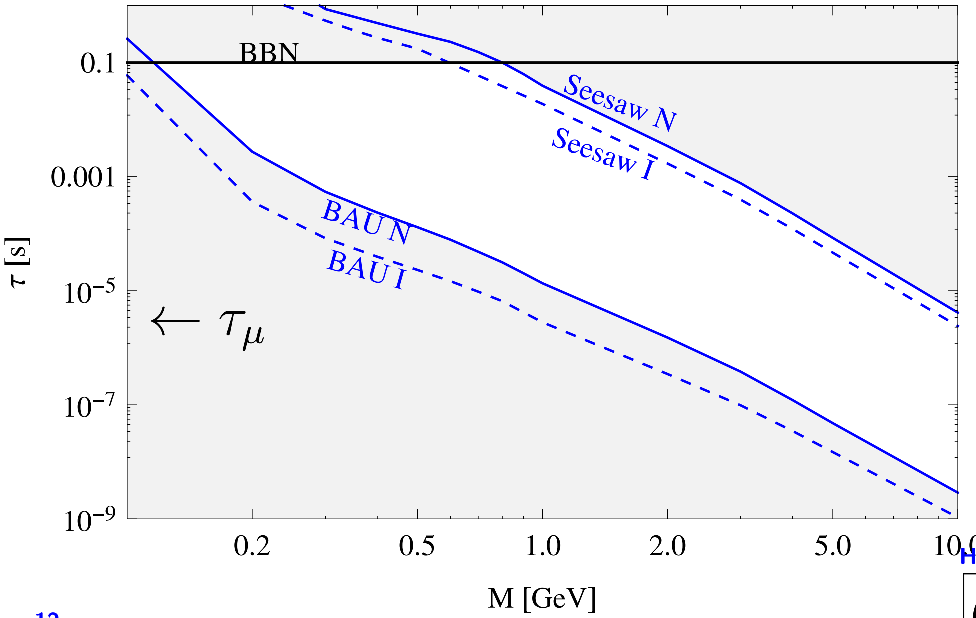
$\mathbf{N}_{2,3}$

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

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

These are the particles we are after!



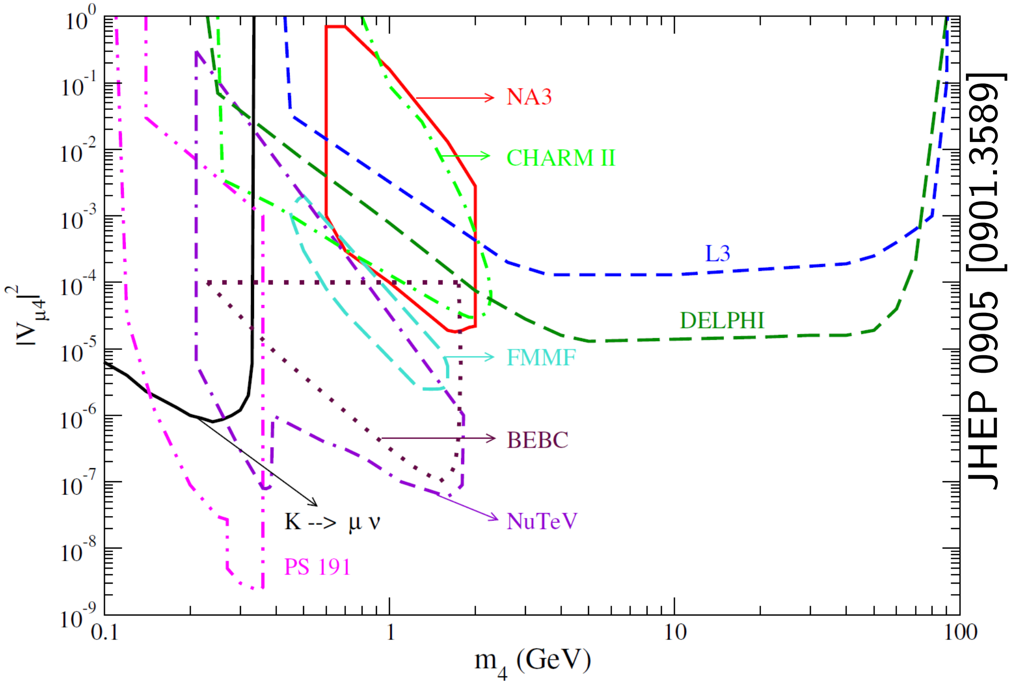


If Ptolomy was wrong?

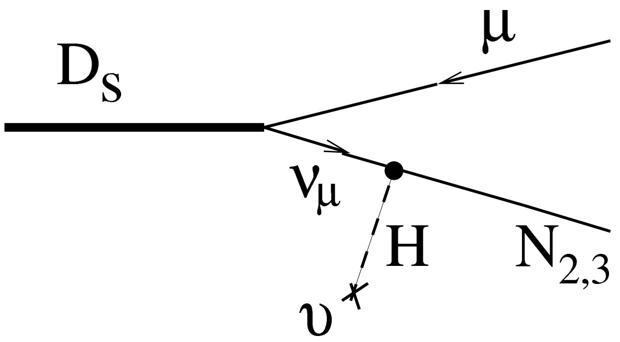
Model	1	2	3	4	5
ν-masses	✓	✓	✓		
BAU	✓	✓			
Dark Matter	✓			✓	

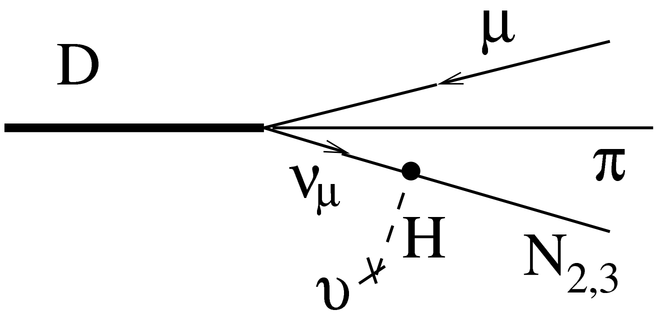
1. νMSM: strongest parameter constraints
2. All active ν could be "heavy", and
   - No $M_2 \leftrightarrow M_3$ degeneracy necessary.
   - U^2 constraint relaxed, up to $U_\mu^2 \sim 10^{-3}$
3. Still $U^2 \gtrsim 10^{-10}$
4. HNL as dark matter only
   - with keV mass: $\tau \gg \tau_{\text{universe}}$
   - Can only be found with X-ray telescopes.
5. Many (cosmology) papers still use HNLs

HNL (U_μ) searches:

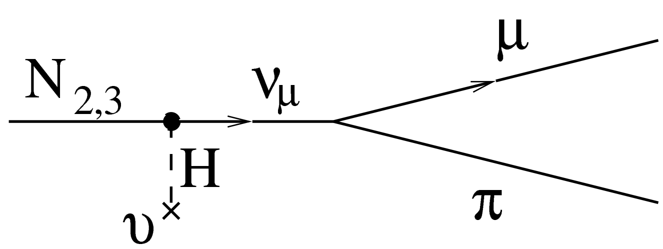


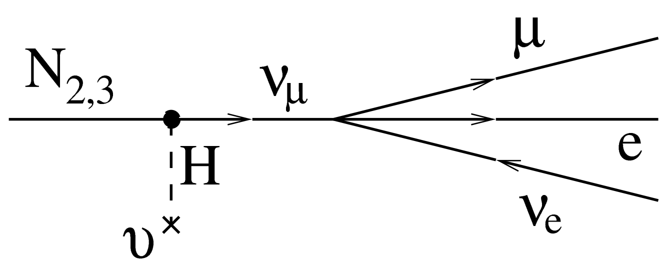
$\mathrm{N}_{2,3}$ production and decay





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



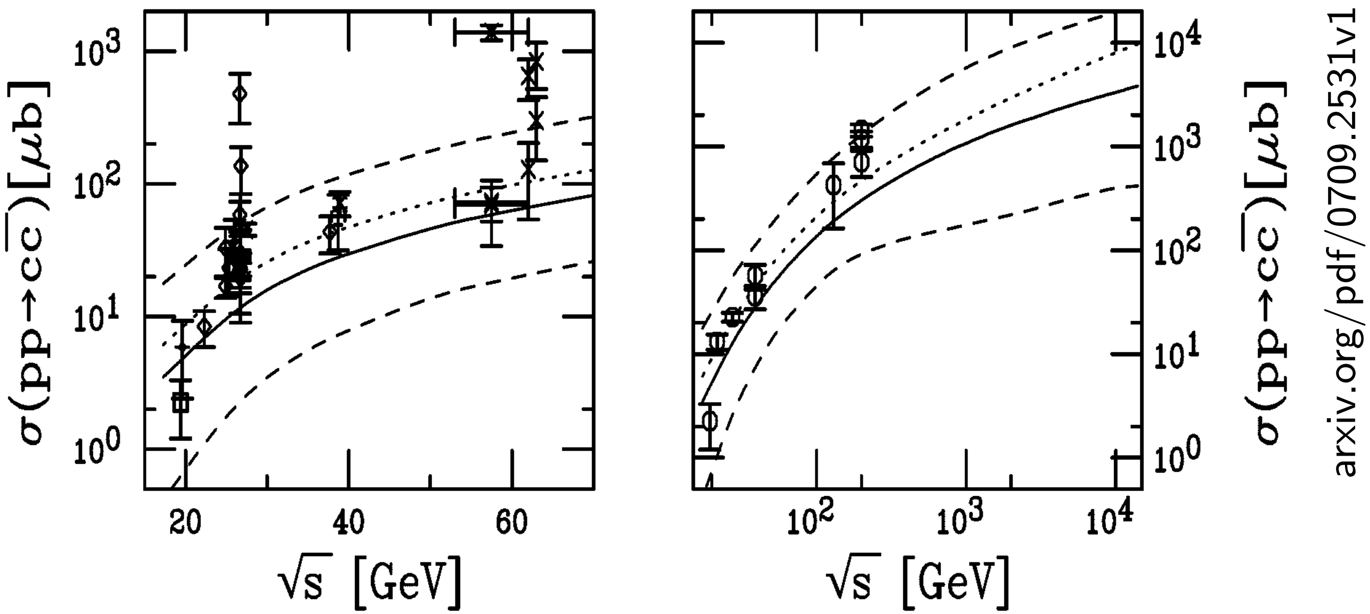


- $\mathcal{B}(\mathrm{N} \to \mu/e\ \pi)$: $\sim 0.1 - 50\ \%$
- $\mathcal{B}(\mathrm{N} \to \mu/e\ \rho)$: $\sim 0.5 - 20\ \%$
- $\mathcal{B}(\mathrm{N} \to \nu\mu e)$: $\sim 1 - 10\ \%$
- $\tau_{\mathrm{N}_{2,3}} \propto U^{-2}$, i.e. $c\tau$ O(km)

H.Dijkstra

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

- Look for 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.

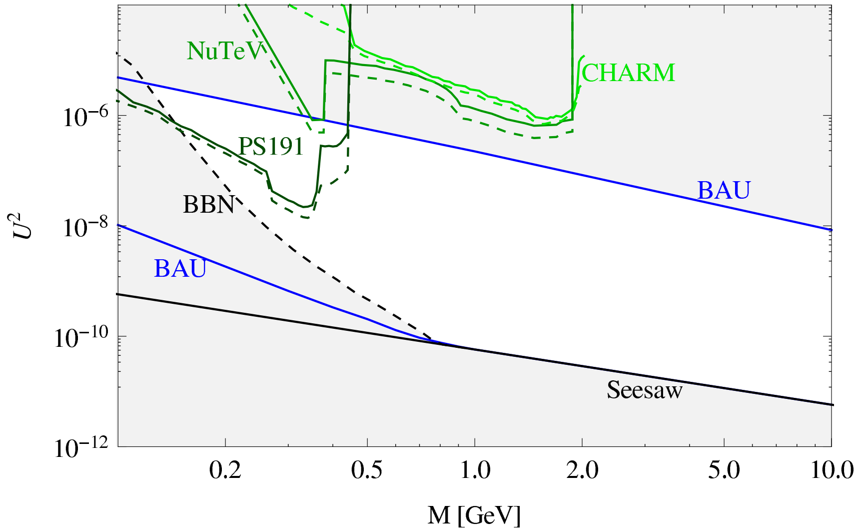


- Where to produce charm?
  - LHC ($\sqrt{s} = 14$ TeV): with 1 ab^{-1} (i.e. 3-4 years): $\sim 2.10^{16}$ in 4π.
  - SPS (400 GeV p-on-target (pot) $\sqrt{s} = 27$ GeV): with 2.10^{20} pot (i.e. 3-4 years): $\sim 2.10^{17}$
  - Fermilab: 120 GeV pot, $10\times$ smaller $\sigma_{c\bar{c}}$, 10×pot by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

Experimental status on searches

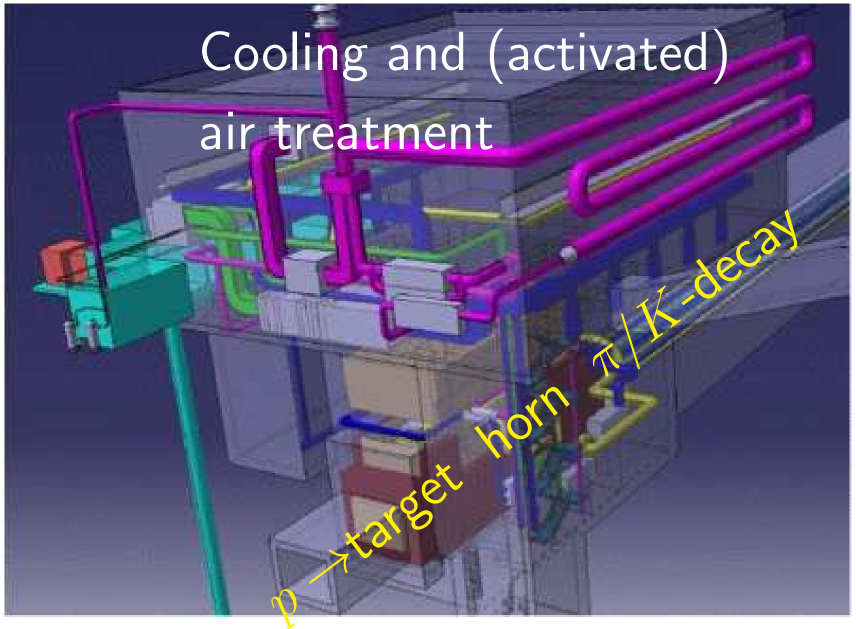
Already searches in K/D-decay performed:

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



What has been achieved, is being prepared:

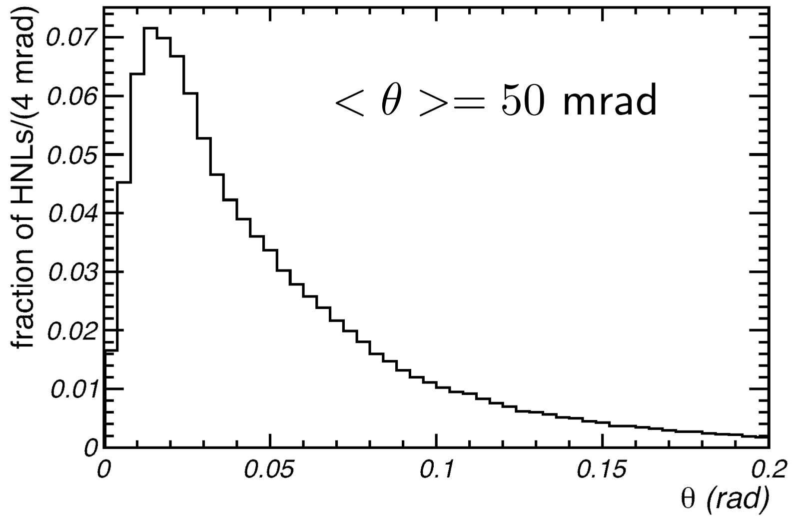
- CNGS: 1.8×10^{20} pot, 2011: 4.8×10^{19}
- CERN neutrino R&D platform. Design of target area in progress.

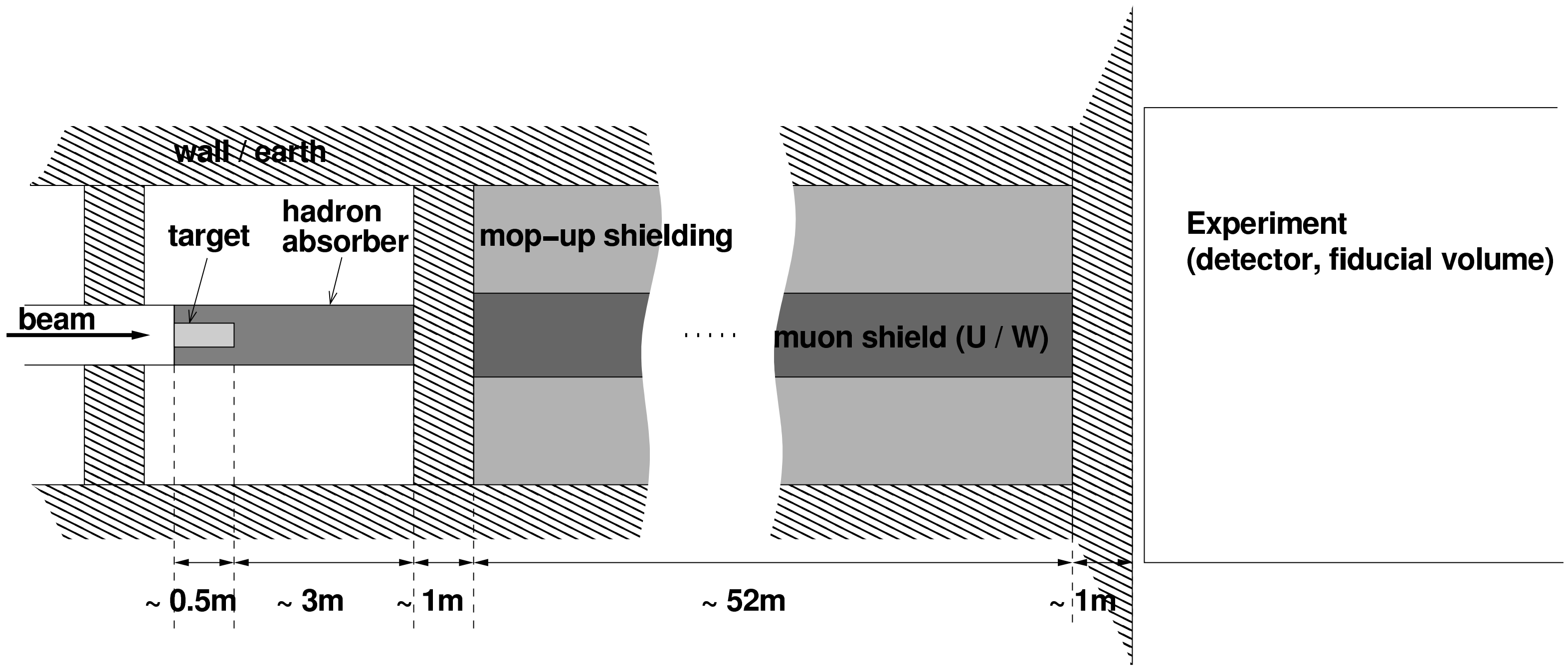


2×10^{20} 400 GeV pot

HNL search is different from ν_μ, ν_e physics (but ν_τ similar):

- ν_μ, ν_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?



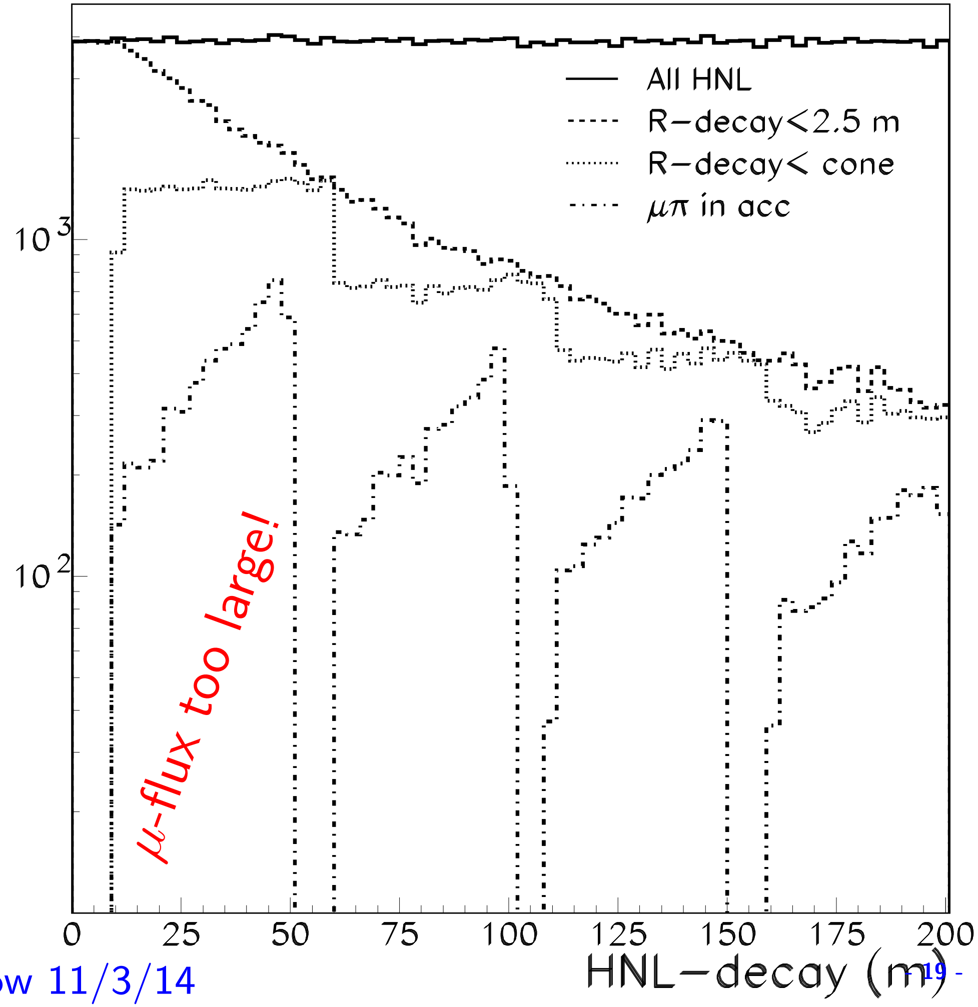


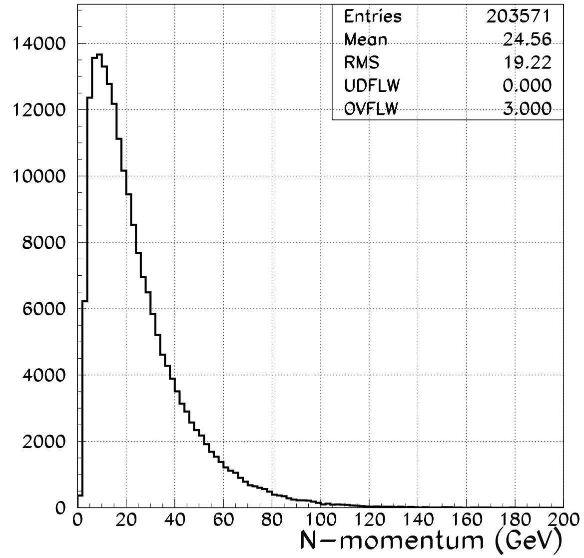

DETECTOR
Filler trench/tunnel
TARGET
Splitters and TCC2
CLASSIFIED
CERN Prévessin site
Le Lion
Route Gentner

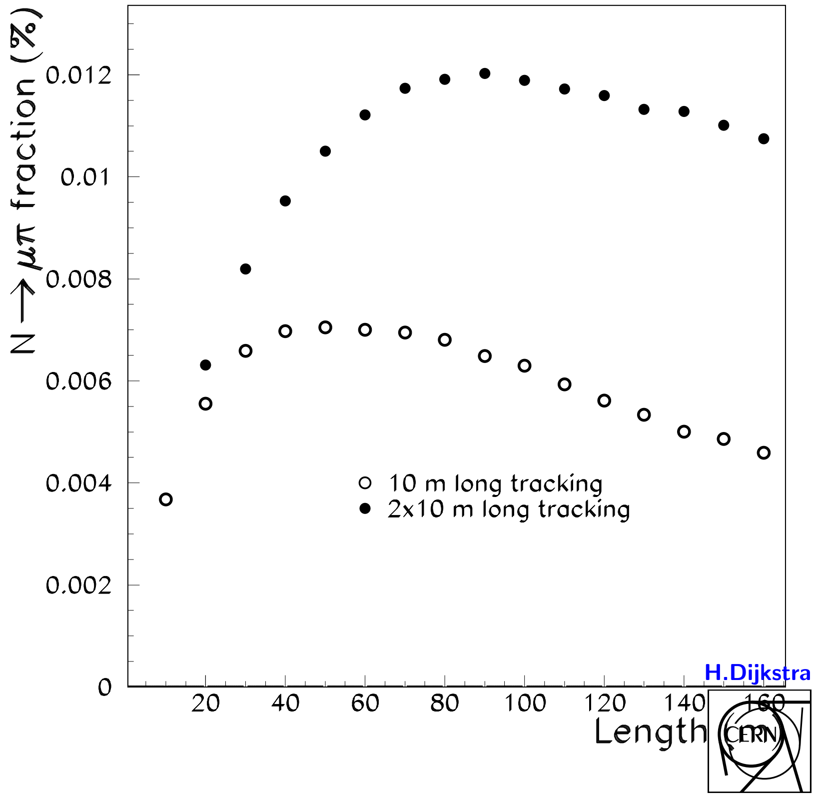
H.Dijkstra

Designing the Spectrometer

- Take $N_{2,3} \to \mu\pi$, mass=1 GeV as proxy.
- $c\tau_N$ is kms, $< p >= 25$ GeV!
- Assume spectrometer $\varnothing = 5$ m.
- Decay volume length saturates at ~ 40 m.
- 2nd spectrometer of 50 m adds 70 % in acceptance.

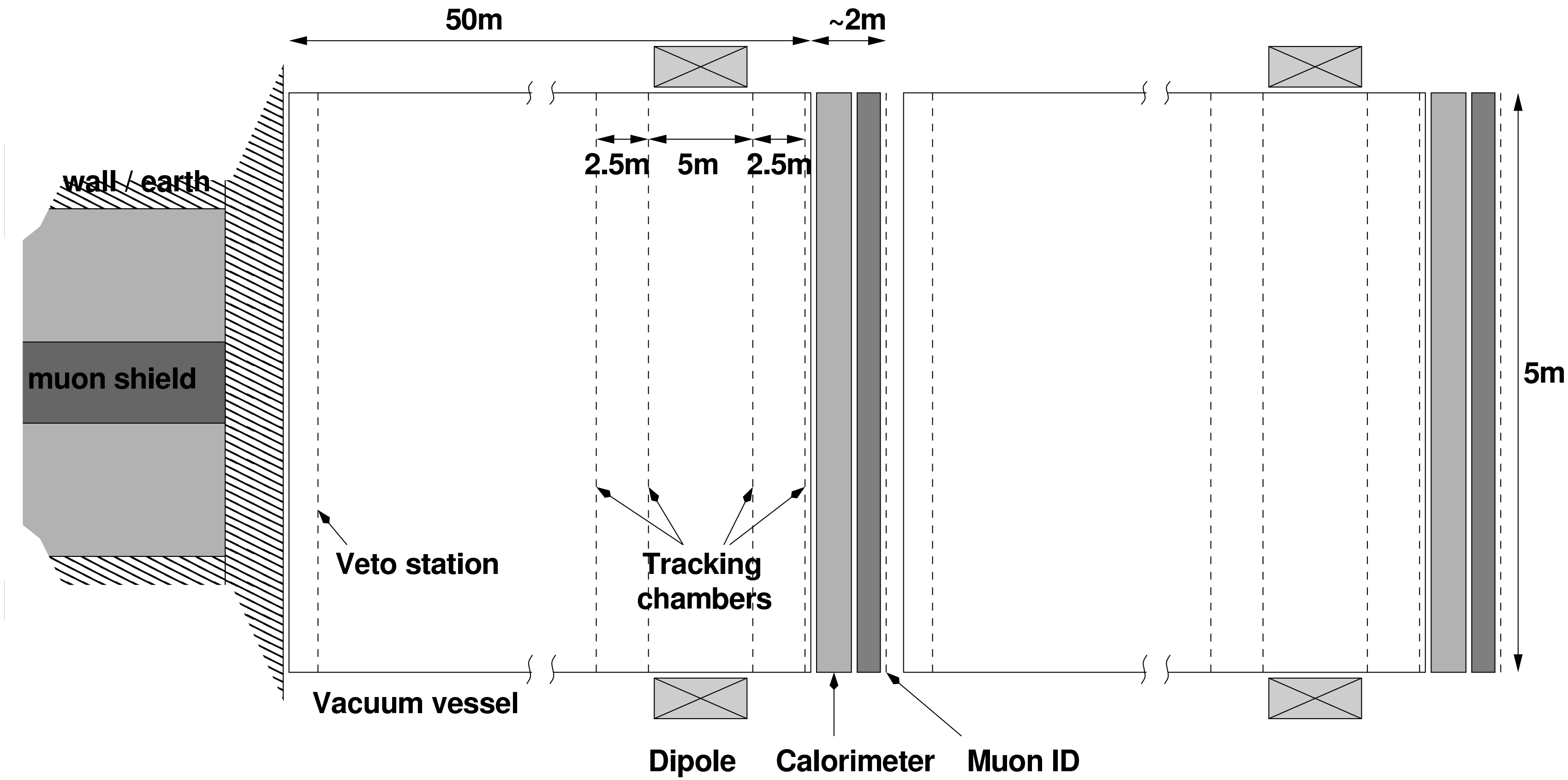






Spectrometer(s)

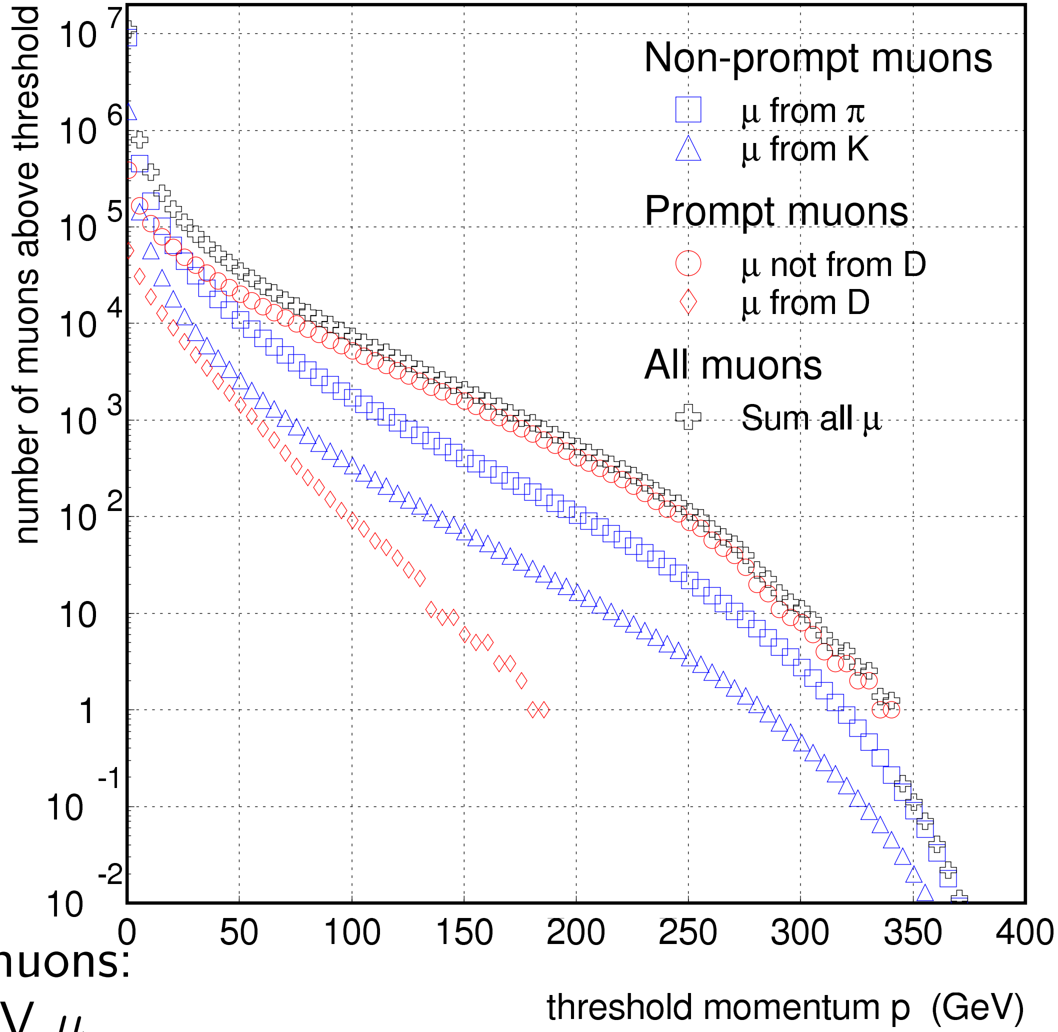
- ~ 40 m long decay volume, $\varnothing = 5$ m, 10 m long spectrometer
- Go for exclusive decays: $\mathrm{N} \to \mu\ \pi, \quad \to e\ \pi, \quad \to \mu\rho(\pi\pi^0)$
- measure momenta of decay particles $\rightarrow$mass-peak and impact parameter,
- identify μ, e, measure γ momentum.
- Put two behind each other to increase acceptance.



Background: μ Flux

Without μ-filter:
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.

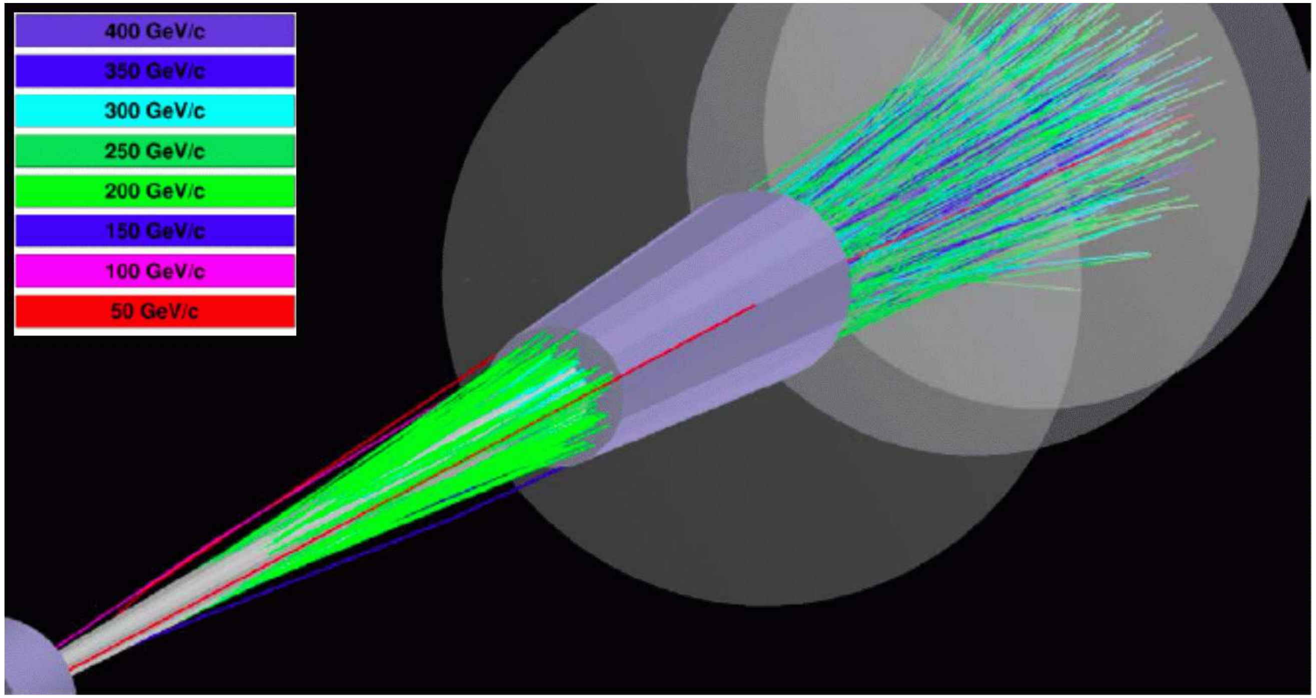


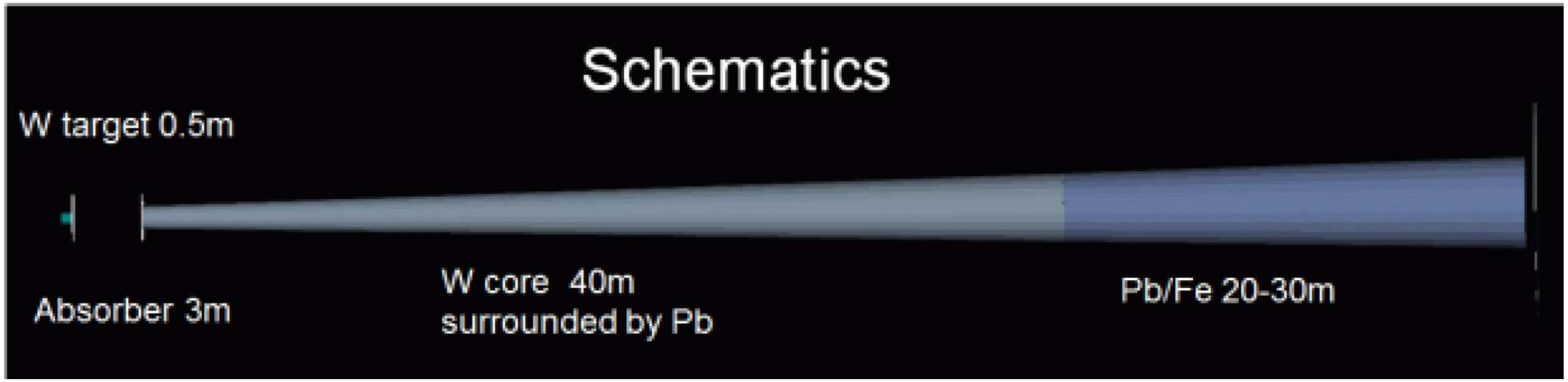
Two alternatives for filter:

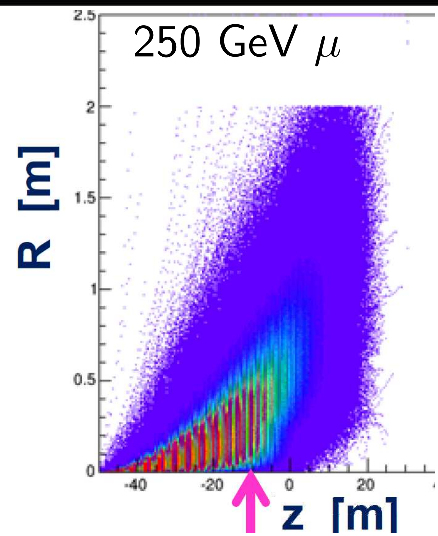
- Passive: i.e. use high Z material to stop muons:
  Example: need 54 m of W to stop 400 GeV μ.
- Active (+passive): use magnets to deflect muons:
  Example: need 40 Tm to deflect 400 GeV μ outside acceptance.

Passive μ-filter

- Geant studies to estimate flux.
- MS and €: limit W-length to 40 m.
- High-p at small θ: W⌀12-50 cm
- +20-30 m of Pb/Fe :
- reduction to $< 10^5$ μ/spill possible.
- Robust/easy to operate



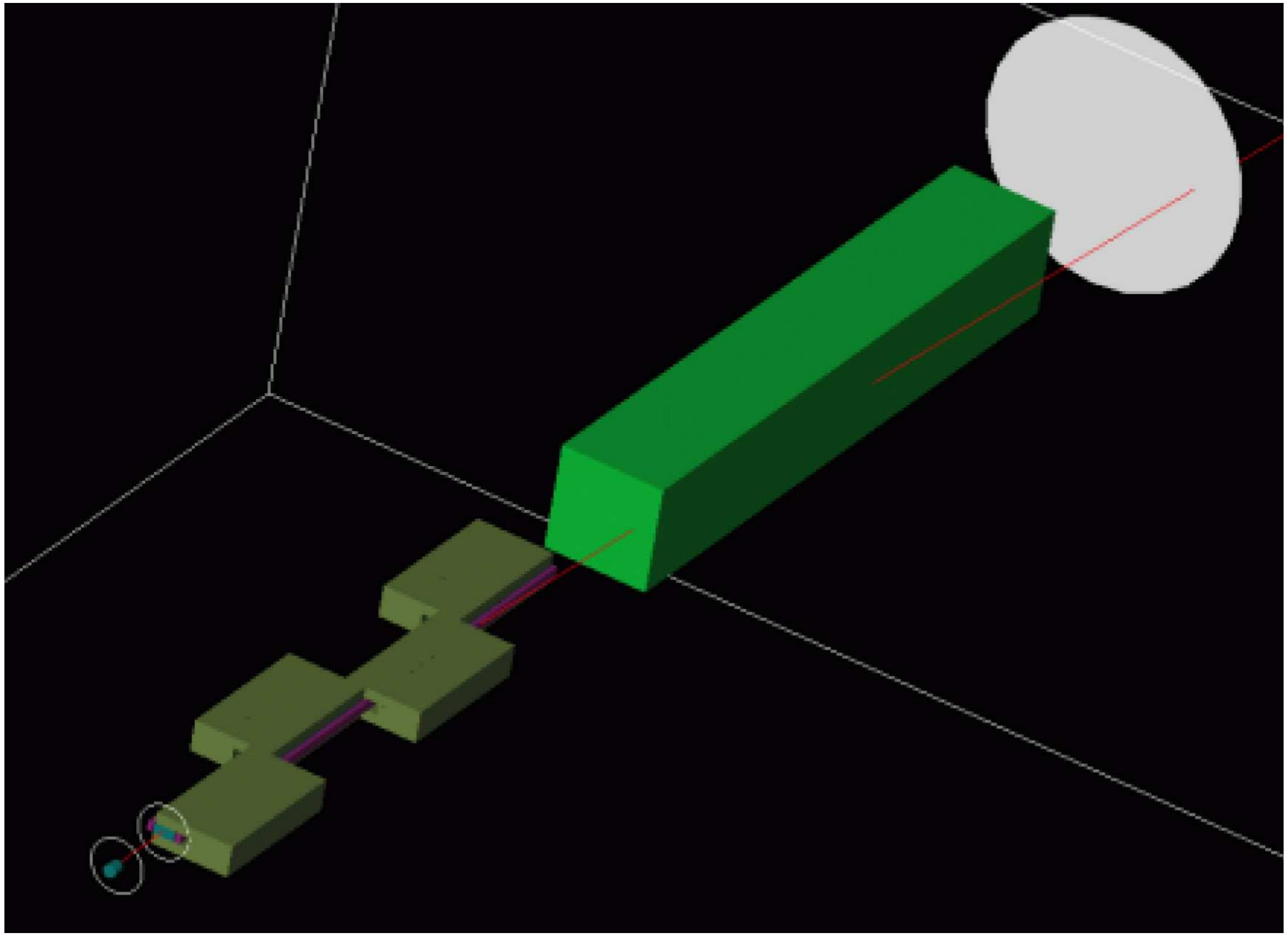




H.Dijkstra

Alternative: Active (+passive) μ-filter

- Use 6 m long C-shaped magnets.
- Produces 40 Tm total field with 4 magnets: high-p swept out.
- Problem: return-B of low-p μ:
  - alternate return-B left/right
  - Add passive Fe-shield



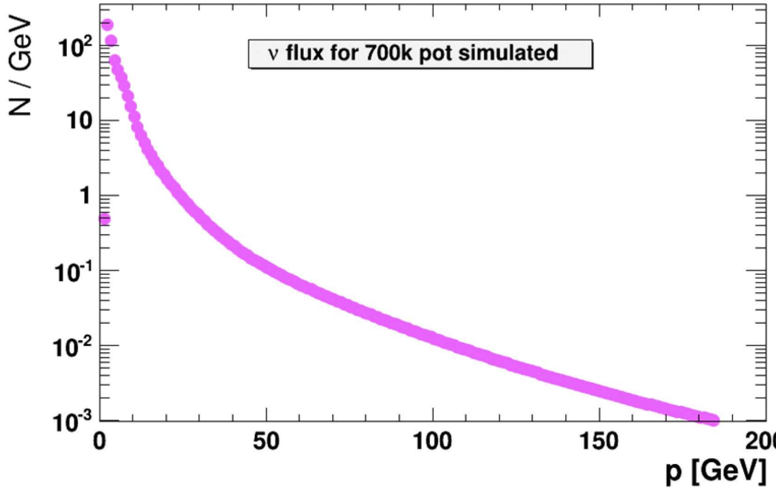
- reduction to $< 5.10^5$ μ/spill possible.

Work in progres.

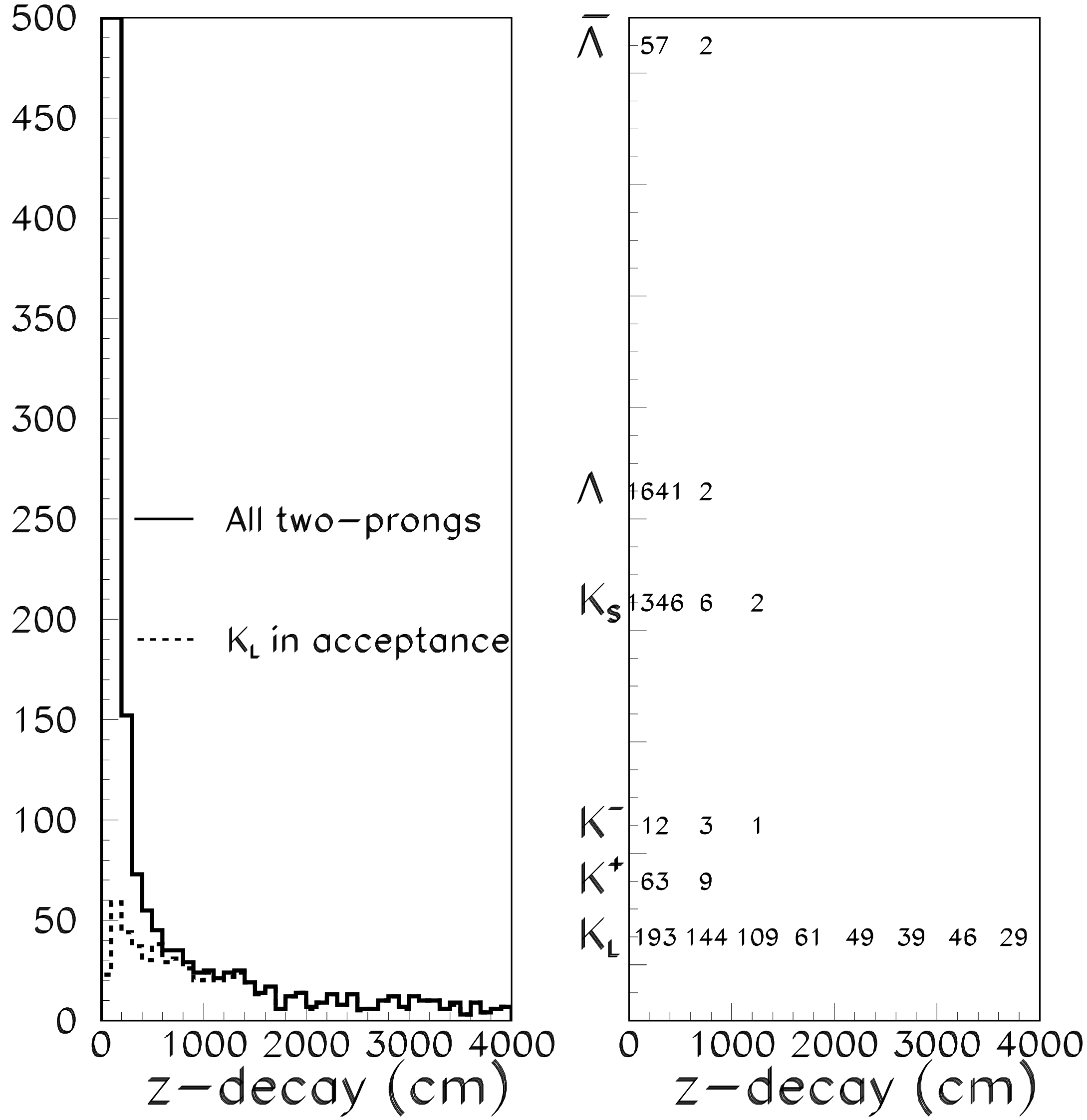
ν-Background

Pythia/Genie/Geant, compare to CHARM:

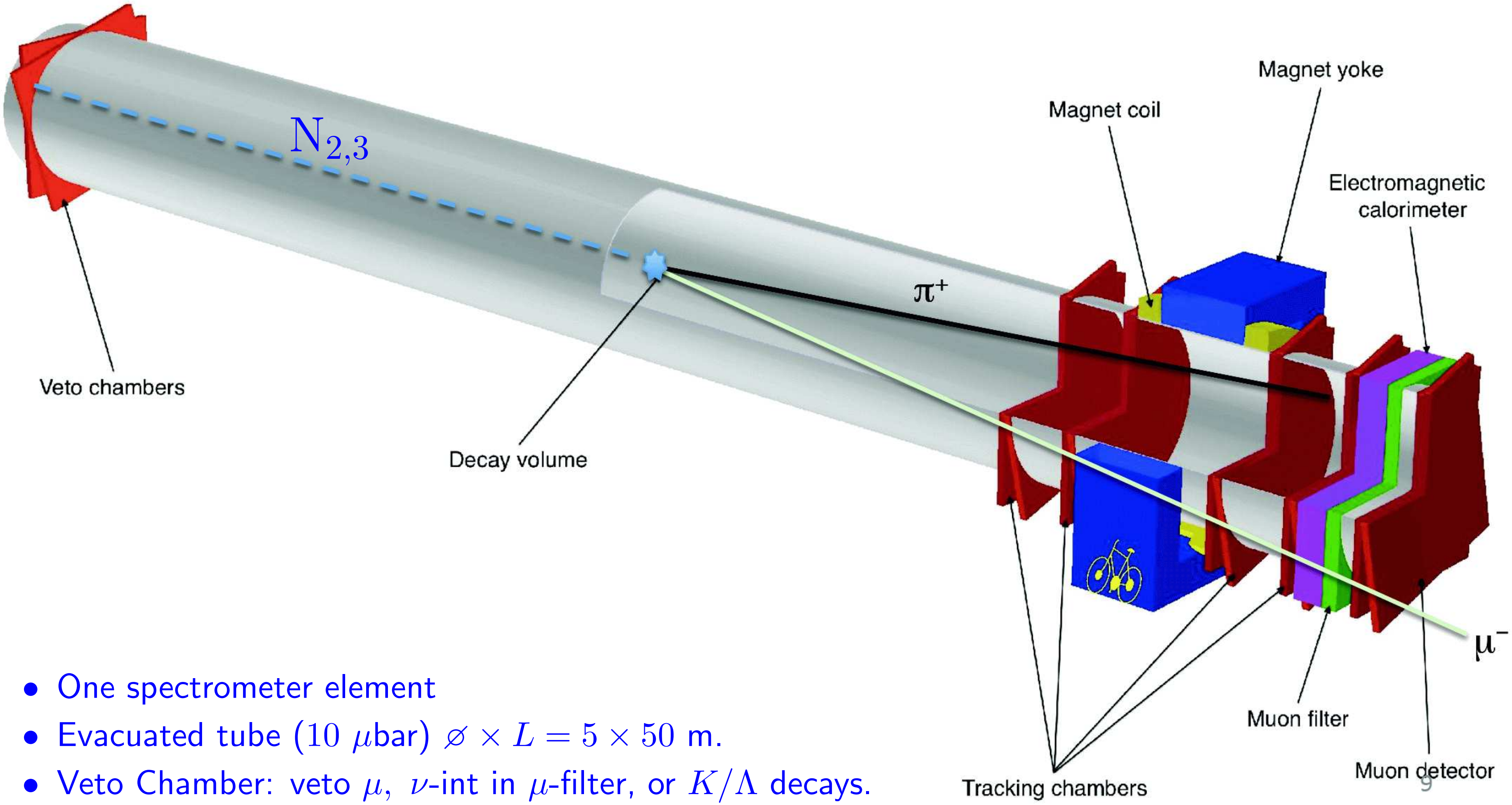
- ν-flux at end of μ-filter ($/2\times10^{20}$ pot):
  CC+NC 8×10^{5} interactions/λ



- 1 bar air in decay volume:
  2×10^{4} ν-int$/2\times10^{20}$ pot
- Reduce pressure to 10 μbar!
- ν-interactions in μ-filter:
  - Use veto-station to suppress short lived.
  - $\nu_\mu + p \to X + K_L \to \mu\pi\nu$ main background.



Spectrometer

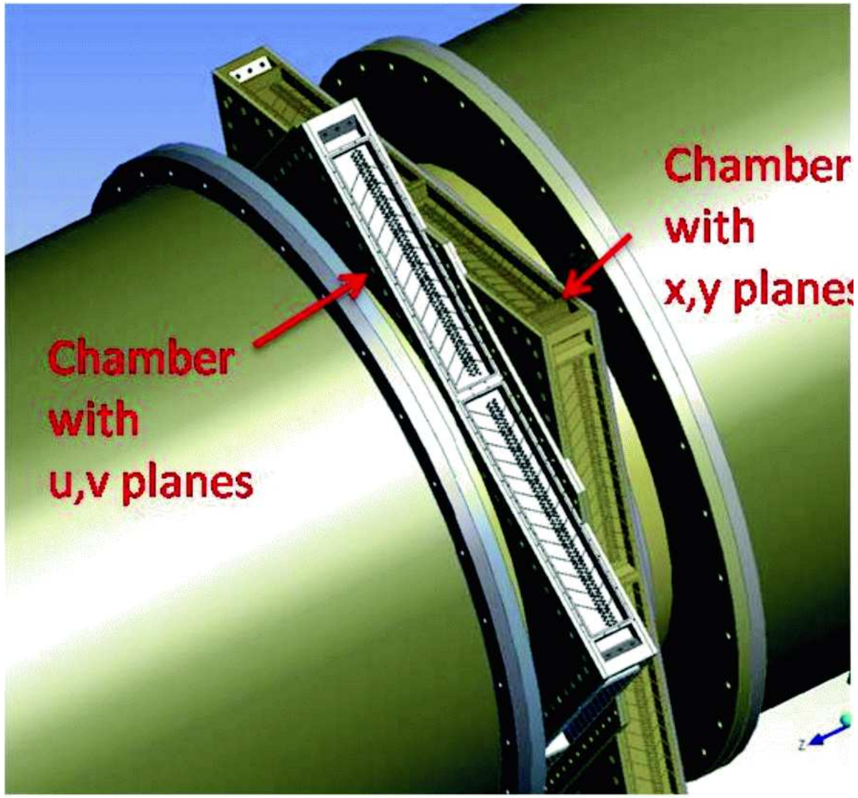


- One spectrometer element
- Evacuated tube ($10\ \mu$bar) $\varnothing \times L = 5 \times 50$ m.
- Veto Chamber: veto μ, ν-int in μ-filter, or K/Λ decays.
- Tracking chambers (thin!) and magnet for momentum measurements
- Ecal and muon filter/chambers at the end.

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.

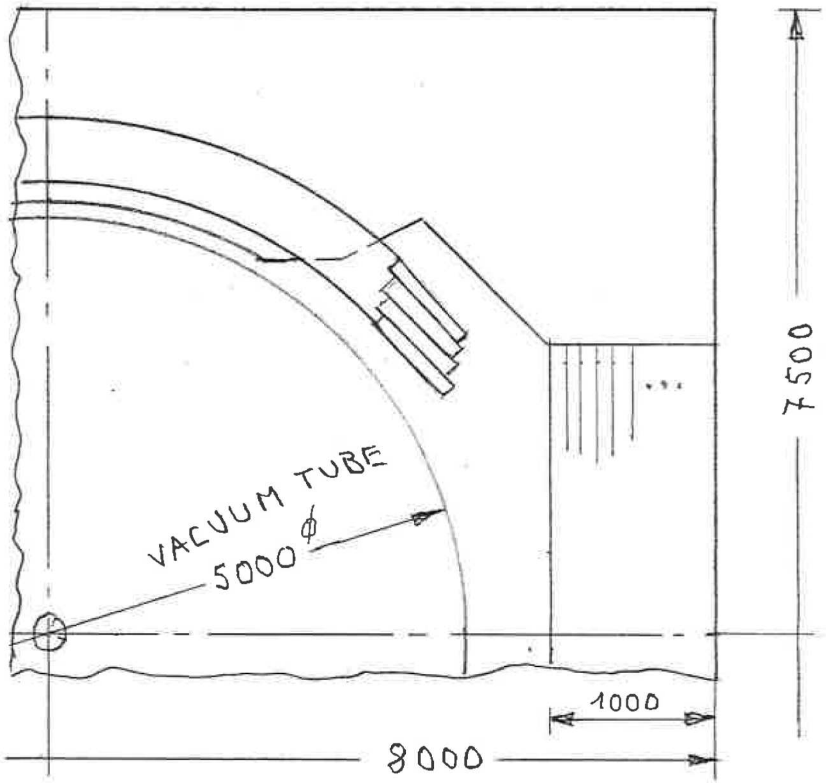


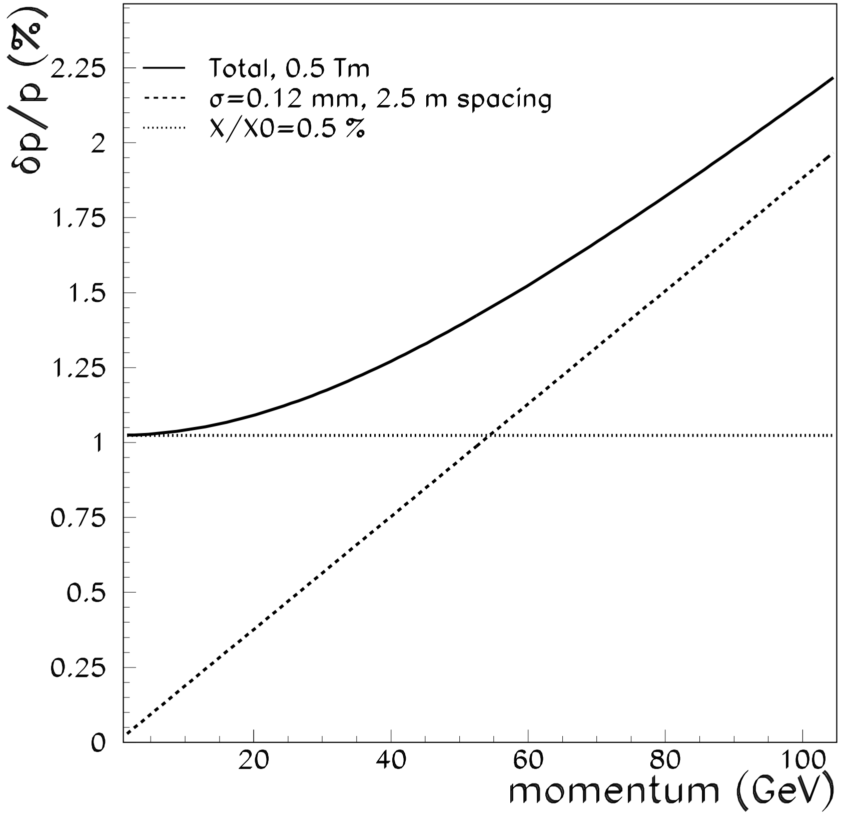
Magnet

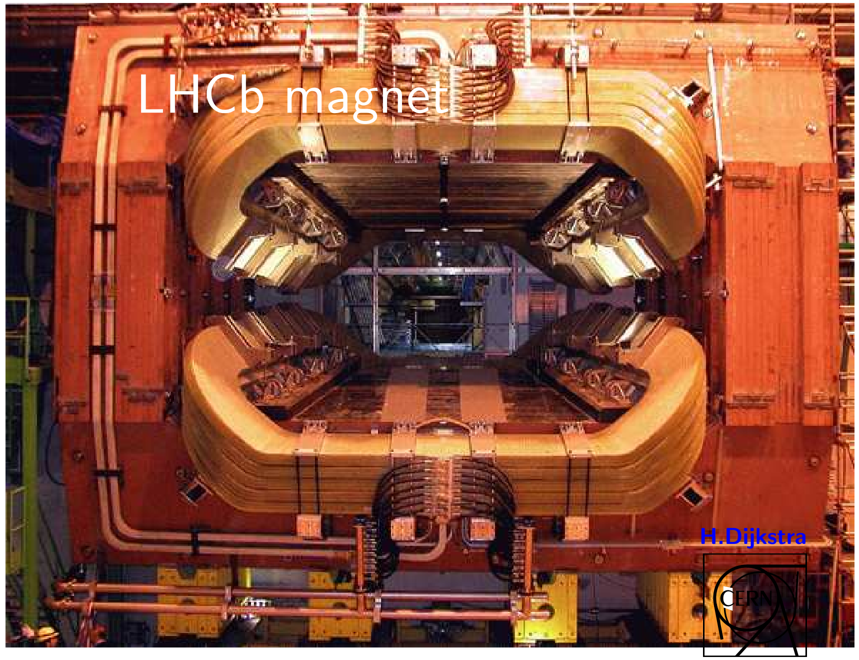
- With $X/X0=0.5$ % chambers: modest 0.5 Tm
- Need $\sim 20\ \mathrm{m}^2$ aperture.

LHCb magnet: 4 Tm, $16\ \mathrm{m}^2$ exit-aperture
Preliminary calculations (W.Flegel):

- Needs 30 % less iron/yoke than LHCb.
- Consumes 3 times less power.

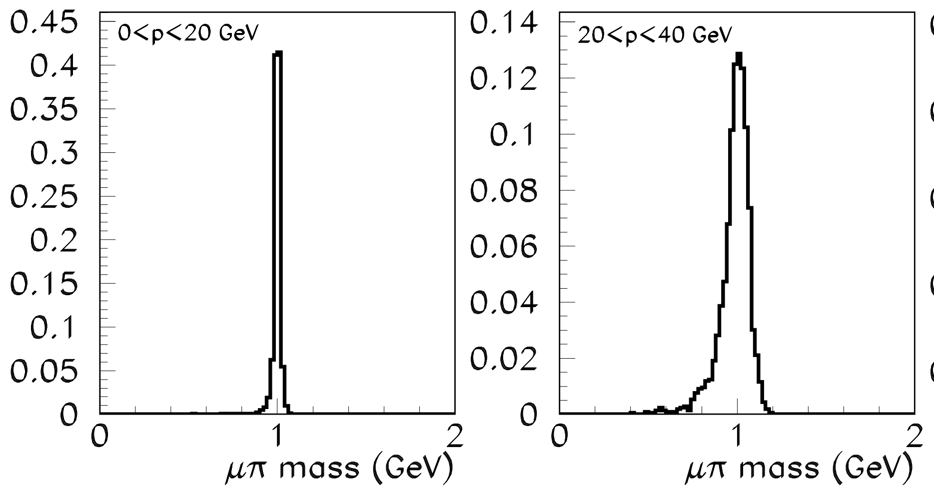






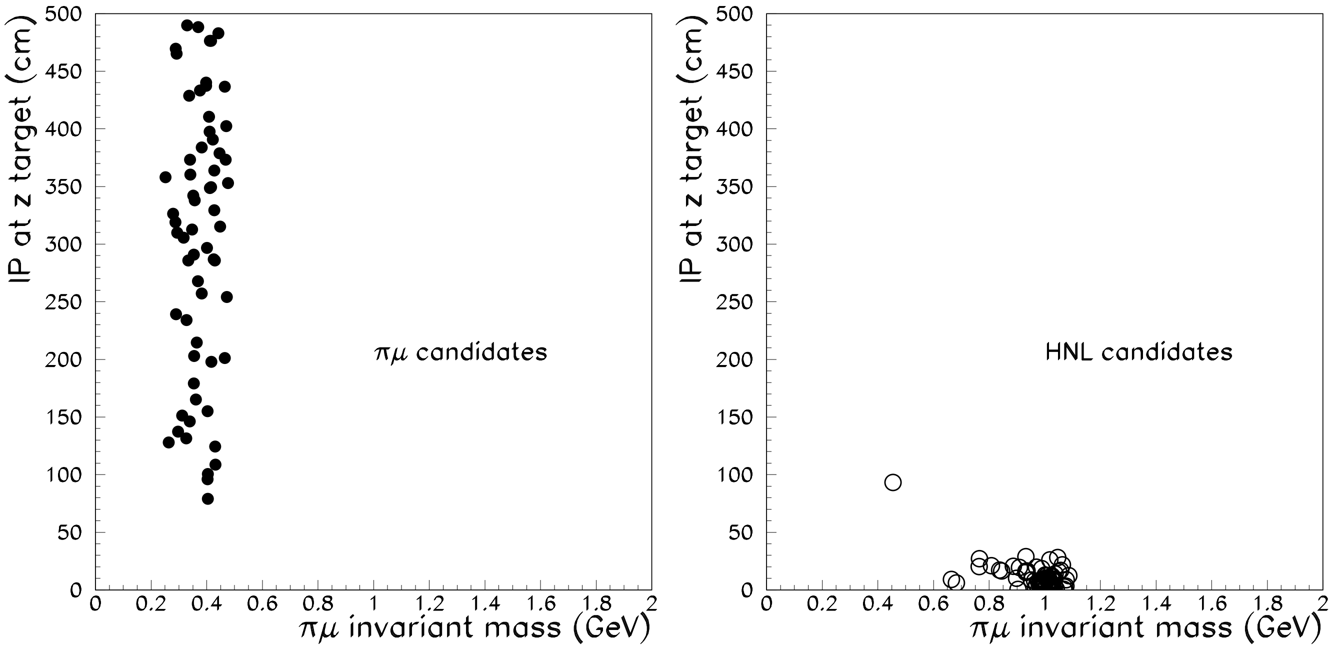
Mass resolution

- Expected resolution for 1 GeV $\mathrm{N} \to \mu\pi$



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?

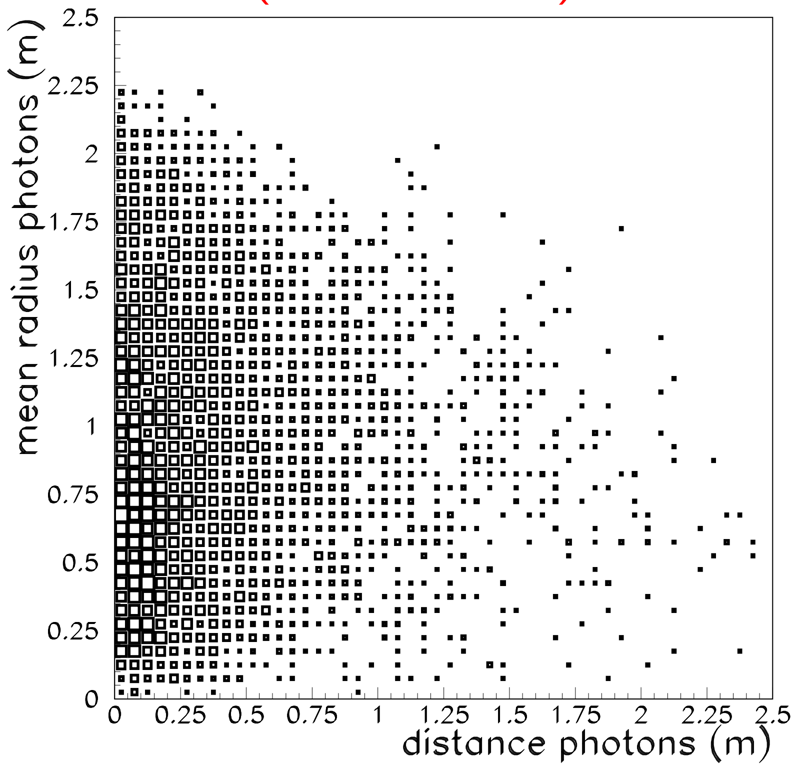


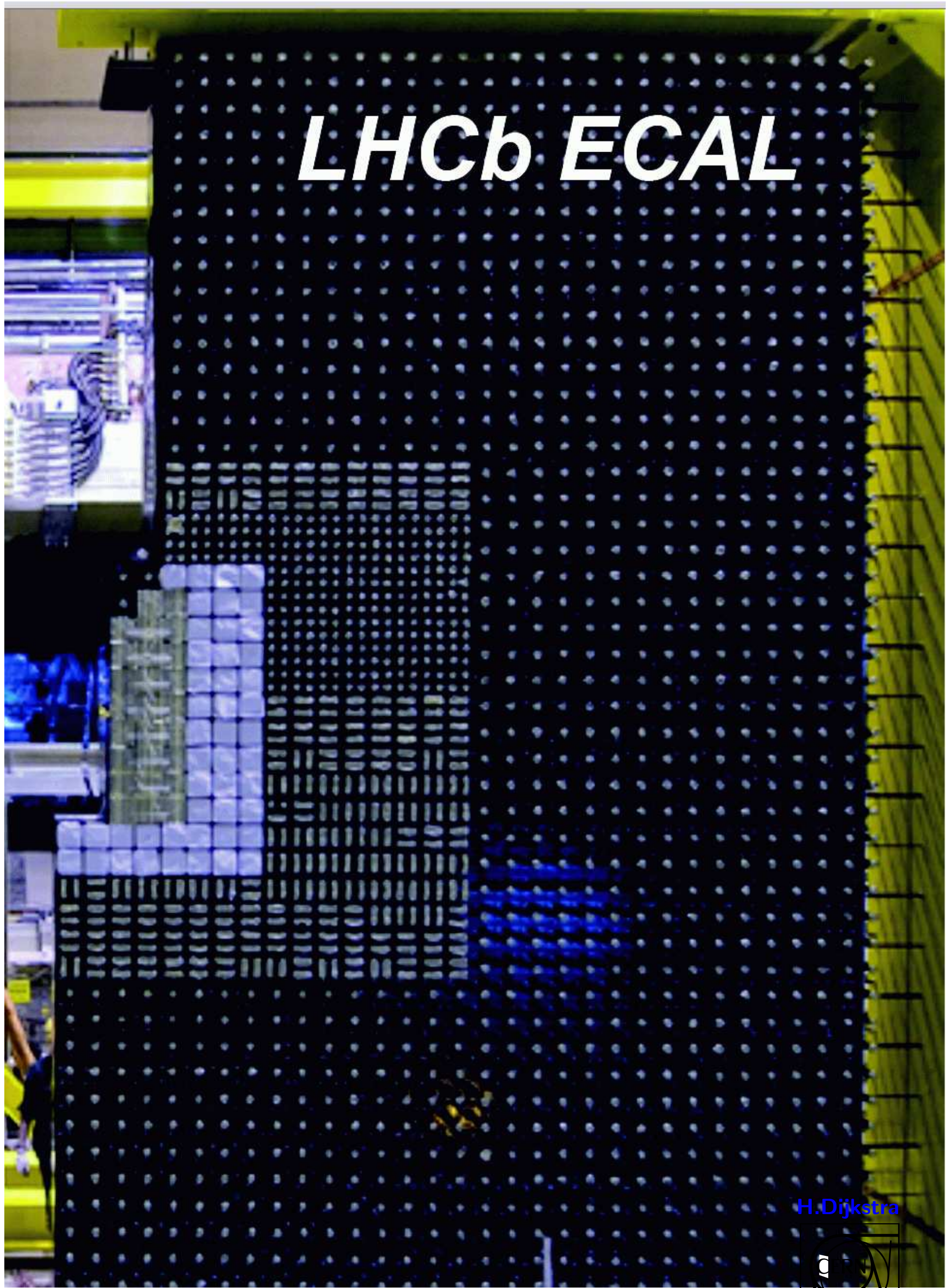
Electromagnetic Calo

LHCb Shashlik ECAL:

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

Larger/better than required.
But for $\mathrm{N} \rightarrow \mu\rho(\pi\pi^0(\gamma\gamma))$
need small $(10 \times 10\ \mathrm{cm}^2)$ cells everywhere.





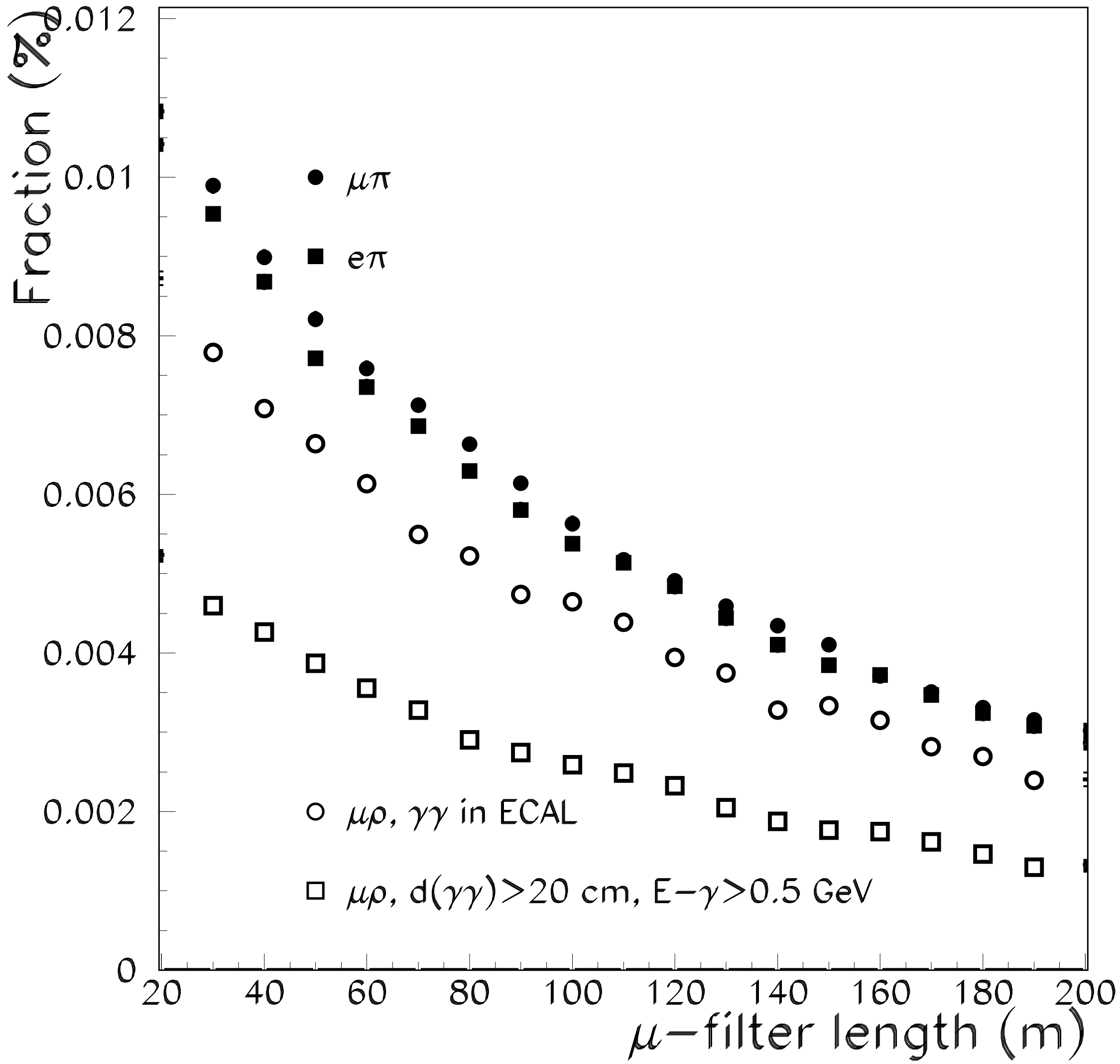
Expected acceptance/channel

$N \to \mu/e\ \pi, \quad \to \mu\ \rho(\pi\pi^0)$:

- $\tau_{\rm HNL} = 1.8 \times 10^{-5}$ s, mass=1 GeV.
- Our standard double 40+10 m vessel.

Conclusion:

- Acceptance $e\pi \sim \mu\pi$
- $\mu\rho \sim 45$ % reco-eff compared to $\mu\pi$.



Expected HNL Sensitivity

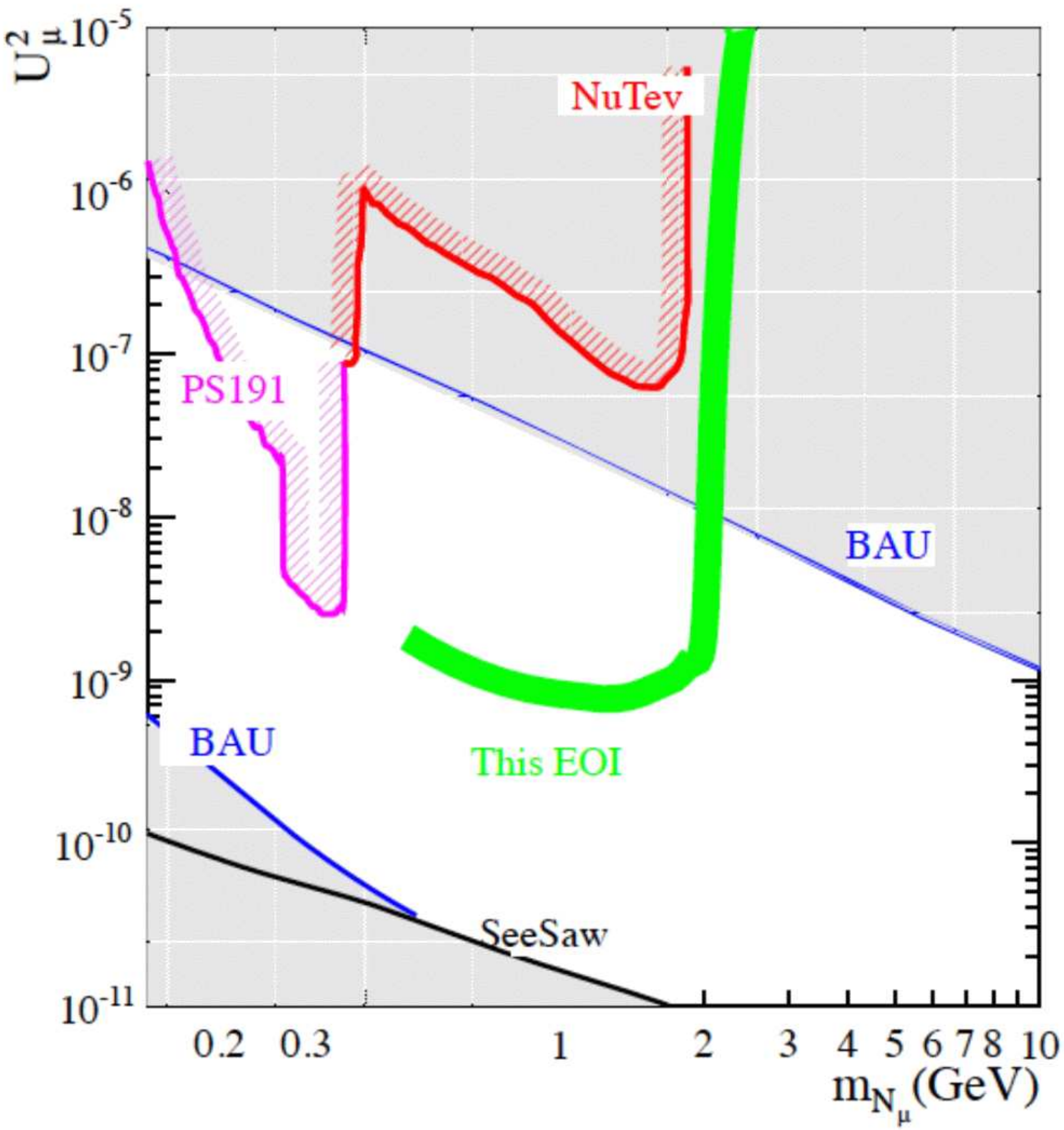
- Only consider $\mathrm{N}_{2,3} \to \mu\pi$, i.e. U_μ^2
- 400 GeV pot$=2 \times 10^{20}$
- $\mathcal{B}(\mathrm{N} \to \mu\pi) = 20~\%$

For $M_\mathrm{N} = 1$ GeV:

U_μ^2	τ_N	$\mu\pi$ events
10^{-7}	1.8×10^{-5} s	12000
10^{-8}	1.8×10^{-4} s	120
10^{-9}	1.8×10^{-3} s	1

For $U_\mu^2 = 10^{-10}$ need:

- $10\times$ more pot (and/or $\sqrt{(s)}$?), AND
- $10\times$ larger acceptance!



Extended Physics Program

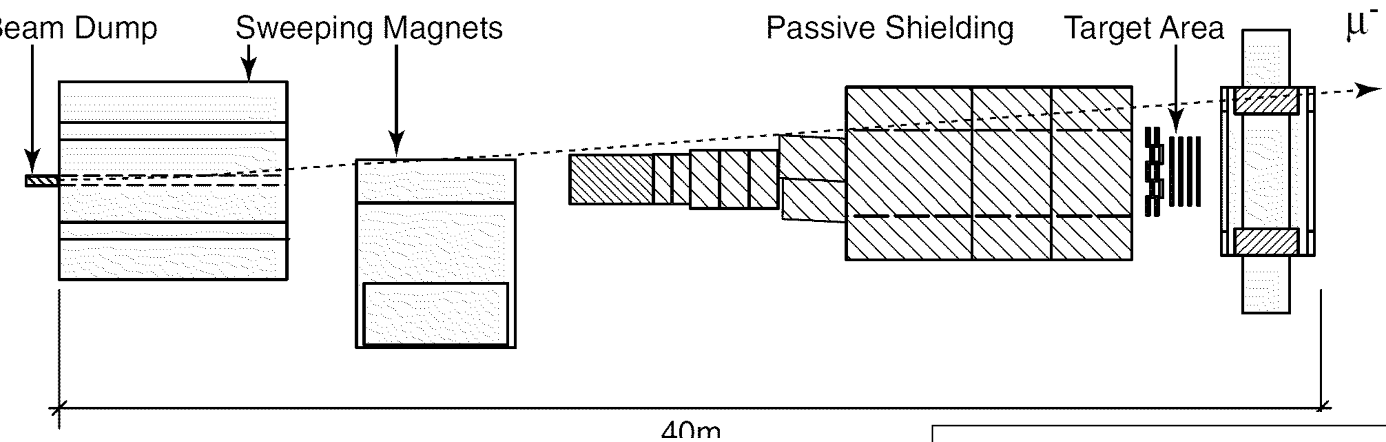
Experiment designed for HNL studies in νMSM, but..

- Ideally suited for studying interactions of ν_τ, since they are produced from D_s-decay, hence have similar kinematics as HNLs.
- Can search for any other weakly interacting, yet unstable particles with $100 < M < 2000$ MeV.
  Quite a few "hidden sector" models on the market where the experiment can enter un-explored parameter space.
  Still needs to be evaluated more quantitatively.

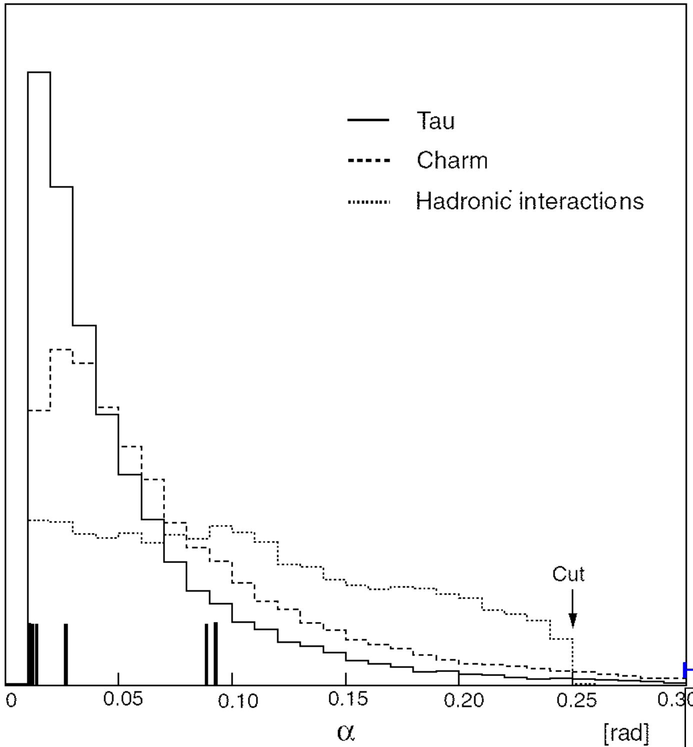
ν_τ Physics

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

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



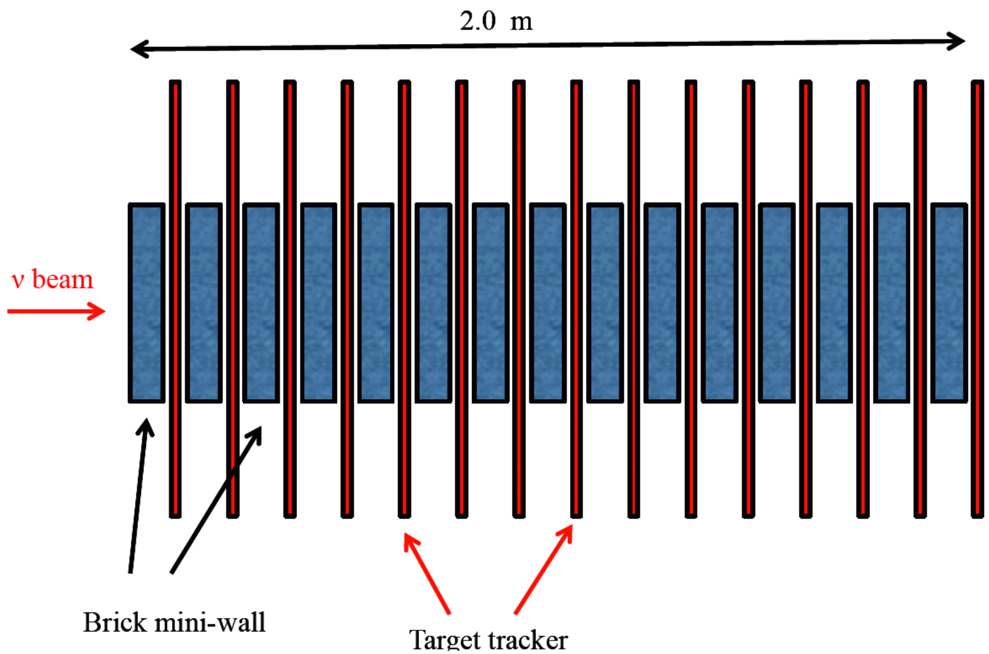
- $\alpha_{\rm kink}$ from τ-decay in CC interactions.
- Charm/hadronic-interaction background.
- 9 candidates, including 1.5 background.



H.Dijkstra

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 $3\ \%$ of OPERA emulsion surface:



- Only requires limited space along beam-line, hence "no" loss for HNL acceptance.
- HNL spectrometer is forward spectrometer of ν-physics program.
- ν-target allows to tag K_L which coincide with ν-interactions.
- Expect 1500-2000 CC ν_τ interactions.
- In addition: $5\times$ ν_μ CC charm production than CHORUS (2k).

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 deliverable that the DG is expecting for this summer is a report including the layout and the resources which are required to set-up the beam-dump and its calendar .
- Our (proto) collaboration called SHiP (Search for Hidden Particles[a], CERN, Universität Zürich, EPFL Lausanne, INFN Cagliari, Universit Federico II and INFN Napoli, Imperial College London) is organising a workshop:

  June 10-12 at Zürich

  http://ship.web.cern.ch/ship/collmtg10062014.htm

- SHiP needs reinforcements to undertake this experiment. Hence, the meeting in June aims at attracting experimental groups which are interested in participating.

[a] Logo to be decided

Conclusions

- SHiP will search for NP in the largely unexplored domain of new, very weakly interacting neutral particles.
- Detector is based on existing technologies.
  Ongoing discussions of the beam lines with experts.
  CERN directorate has set-up task force to study accelerator part.

- 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?

The SHiP collaboration is being setup, first collaboration meeting June 10-12.

Who would like to join?