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Prospects for Heavy Neutrino Searches at Accelerators

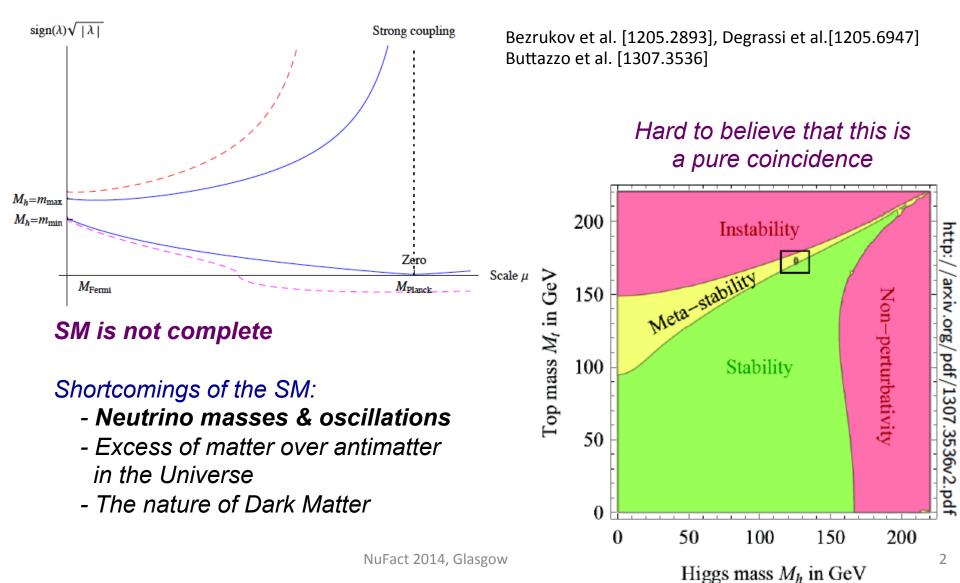
Outline:

- Brief summary on the current status of the Standard Model

- Heavy Neutral Leptons in vMSM model
- Recent experimental results and future prospects

Current status of the Standard Model

✓ Discovery of the 126 GeV Higgs boson → Triumph of the Standard Model The SM may work successfully up to the Planck scale !



Search for New Physics

✓ No signs of NP seen at √s = 8 TeV.

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

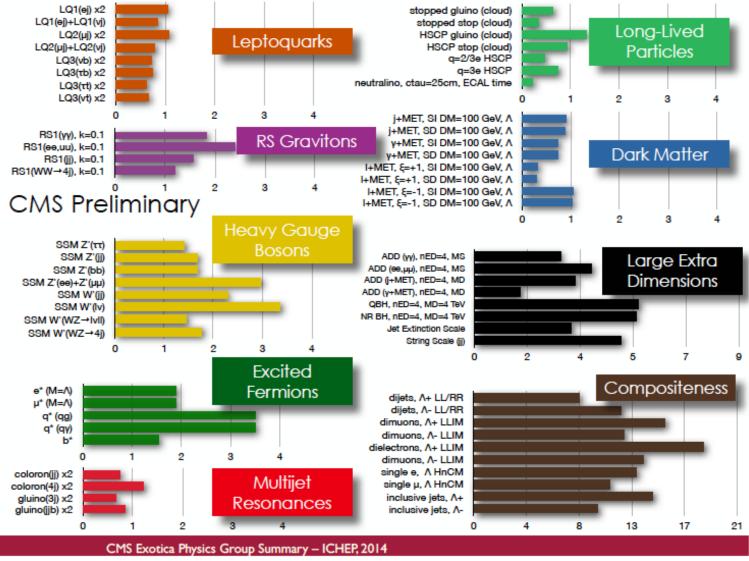
	Model	<i>ℓ</i> ,γ	Jets	$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[fl			Reference
Extra dimensions	$\begin{array}{l} \text{ADD } G_{KK} + g/q \\ \text{ADD non-resonant } \ell\ell \\ \text{ADD QBH} \to \ell q \\ \text{ADD QBH} \\ \text{ADD QBH high } N_{trk} \\ \text{ADD BH high } \sum p_T \\ \text{RS1 } G_{KK} \to \ell\ell \\ \text{RS1 } G_{KK} \to WW \to \ell \nu \ell \nu \\ \text{Bulk RS } G_{KK} \to WW \to \ell \nu \ell \nu \\ \text{Bulk RS } G_{KK} \to HH \to b \bar{b} b \bar{b} \\ \text{Bulk RS } g_{KK} \to t \bar{t} \\ S^1/Z_2 \text{ ED} \\ \text{UED} \end{array}$	$\begin{array}{c} - \\ 2e, \mu \\ 1 e, \mu \\ - \\ 2\mu (SS) \\ \ge 1 e, \mu \\ 2 e, \mu \\ 2 e, \mu \\ 2 e, \mu \\ 2 e, \mu \\ - \\ 1 e, \mu \\ 2 \\ 2 e, \mu \\ 2 \gamma \end{array}$	1-2 j - 1 j 2 j - 2 j / 1 J 4 b ≥ 1 J, - - - - - - - - - - - - -	Yes - - - Yes - Yes 2j Yes - Yes	4.7 20.3 20.3 20.3 20.3 20.3 20.3 20.3 4.7 20.3 19.5 14.3 5.0 4.8	M _D 4.37 TeV Ms 5.2 TeV M _{th} 5.7 TeV M _{th} 6.2 TeV G _{KK} mass 1.23 TeV G _{KK} mass 590-710 GeV G _{KK} mass 590-710 GeV G _{KK} mass 2.0 TeV M _{KK} ≈ R ⁻¹ 4.71 TeV Compact. scale R ⁻¹ 1.41 TeV	$\begin{split} n &= 2 \\ n &= 3 \text{ HLZ} \\ n &= 6 \\ n &= 6 \\ n &= 6, \ M_D &= 1.5 \text{ TeV, non-rot BH} \\ n &= 6, \ M_D &= 1.5 \text{ TeV, non-rot BH} \\ k / \overline{M}_{Pl} &= 0.1 \\ k / \overline{M}_{Pl} &= 0.1 \\ k / \overline{M}_{Pl} &= 1.0 \\ B = 0.925 \end{split}$	1210.4491 ATLAS-CONF-2014-030 1311.2006 to be submitted to PRD 1308.4075 1405.4254 1405.4123 1208.2880 ATLAS-CONF-2014-039 ATLAS-CONF-2014-052 1209.2535 ATLAS-CONF-2012-072
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell \ell \\ \operatorname{SSM} Z' \to \tau \tau \\ \operatorname{SSM} W' \to \ell \nu \\ \operatorname{EGM} W' \to WZ \to \ell \nu \ell' \ell' \ell' \\ \operatorname{EGM} W' \to WZ \to q q \ell \ell \\ \operatorname{LRSM} W'_R \to t \overline{b} \\ \operatorname{LRSM} W'_R \to t \overline{b} \\ \end{array}$	$2 e, \mu 2 \tau 1 e, \mu 3 e, \mu 2 e, \mu 1 e, \mu 0 e, \mu -$	_ _ _ 2 j / 1 J 2 b, 0-1 j ≥ 1 b, 1 J 2 j	- Yes Yes - Yes -	20.3 19.5 20.3 20.3 20.3 14.3 20.3 4.8	Z' mass 2.9 TeV Z' mass 1.9 TeV W' mass 3.28 TeV W' mass 1.52 TeV W' mass 1.59 TeV W' mass 1.64 TeV W' mass 1.77 TeV	$\eta = +1$	1405.4123 ATLAS-CONF-2013-066 ATLAS-CONF-2014-017 1406.4456 ATLAS-CONF-2014-039 ATLAS-CONF-2013-050 to be submitted to EPJC 1210.1718
CI	CI qqll CI uutt	2 e, μ 2 e, μ (SS)	-	-	20.3 14.3	Λ	$\eta = +1$ 21.6 TeV $\eta_{LL} = -1$ C = 1	ATLAS-CONF-2014-030 ATLAS-CONF-2013-051
MD	EFT D5 operator (Dirac) EFT D9 operator (Dirac)	0 e,μ 0 e,μ	1-2 j 1 J, ≤ 1 j	Yes Yes	10.5 20.3	M. 731 GeV M. 2.4 TeV	at 90% CL for $m(\chi) < 80$ GeV at 90% CL for $m(\chi) < 100$ GeV	ATLAS-CONF-2012-147 1309.4017
ГО	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e, μ, 1 τ	≥ 2 j ≥ 2 j 1 b, 1 j	- - -	1.0 1.0 4.7	LQ mass 660 GeV LQ mass 685 GeV LQ mass 534 GeV	$egin{array}{lll} eta = 1 \ eta = 1 \ eta = 1 \ eta = 1 \ eta = 1 \end{array}$	1112.4828 1203.3172 1303.0526
Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$ Vector-like quark $TT \rightarrow Wb + X$ Vector-like quark $TT \rightarrow Zt + X$ Vector-like quark $BB \rightarrow Zb + X$ Vector-like quark $BB \rightarrow Wt + X$	 1 e, μ 2/≥3 e, μ 2/≥3 e, μ 		j Yes – –	14.3 14.3 20.3 20.3 14.3	T mass 790 GeV T mass 670 GeV T mass 735 GeV B mass 755 GeV B mass 720 GeV	T in (T,B) doublet isospin singlet T in (T,B) doublet B in (B,Y) doublet B in (T,B) doublet	ATLAS-CONF-2013-018 ATLAS-CONF-2013-060 ATLAS-CONF-2014-036 ATLAS-CONF-2014-036 ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \rightarrow q\gamma$ Excited quark $q^* \rightarrow qg$ Excited quark $b^* \rightarrow Wt$ Excited lepton $\ell^* \rightarrow \ell\gamma$	1 γ - 1 or 2 e, μ 2 e, μ, 1 γ	1 j 2 j 1 b, 2 j or 1 –	– – jYes –	20.3 20.3 4.7 13.0	q* mass 3.5 TeV q* mass 4.09 TeV b* mass 870 GeV (* mass 2.2 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ left-handed coupling $\Lambda = 2.2 \text{ TeV}$	1309.3230 to be submitted to PRD 1301.1583 1308.1364
Other	LSTC $a_T \rightarrow W\gamma$ LRSM Majorana γ Type III Seesaw Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$ Multi-charged particles Magnetic monopoles	$1 e, \mu, 1 \gamma 2 e, \mu 2 e, \mu 2 e, \mu (SS) - - \sqrt{s} = 7$	- 2 j - - - 7 TeV	Yes 	20.3 2.1 5.8 4.7 4.4 2.0 8 TeV	ar mass 960 GeV N° mass 1.5 TeV N* mass 245 GeV H±± mass 409 GeV multi-charged particle mass 490 GeV monopole mass 862 GeV 10 ⁻¹ 1	$\begin{split} m(W_{\mathcal{R}}) &= 2 \text{ TeV}, \text{ no mixing} \\ V_e &= 0.055, V_{\mu} &= 0.063, V_{\tau} &= 0 \\ \text{DY production}, & R(H^{\pm\pm} \to \ell) &= 1 \\ \text{DY production}, & q &= 4e \\ \text{DY production}, & g &= 1 \\ g_D \end{split}$	to be submitted to PLB 1203.5420 ATLAS-CONF-2013-019 1210.5070 1301.5272 1207.6411

*Only a selection of the available mass limits on new states or phenomena is shown.

NuFact 2014, Glasgow

ATLAS Preliminary

 $\int \mathcal{L} dt = (1.0 - 20.3) \text{ fb}^{-1}$ $\sqrt{s} = 7, 8 \text{ TeV}$



Mass scale, TeV

✓ M_{NP} > 10⁴ TeV from observables in neutral meson mixing (for generic Yukawa coupling

✓ Strong motivation to search for Heavy Neutrinos

See-saw generation of neutrino masses

✓ Heavy Neutral Lepton (HNL) is simplest and most elegant way to accommodate non-zero neutrino mass in the SM

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

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

Majorana term which carries no gauge charge

Wide range of possibilities for the see-saw scale

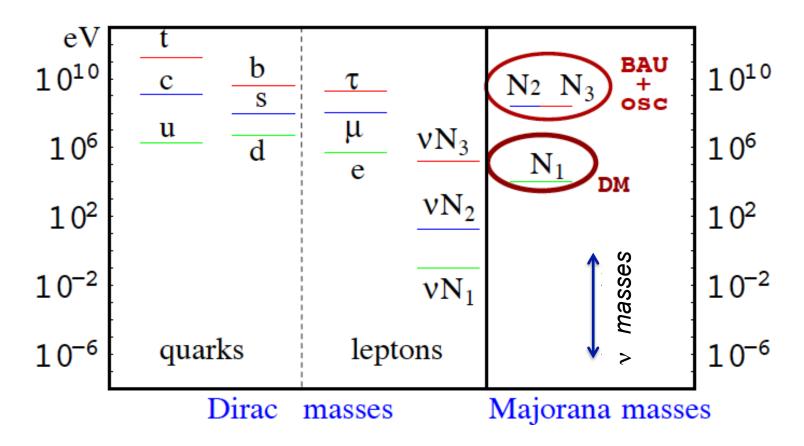
The scale of the active neutrino mass is given by the see-saw formula: $m_v \sim m_D^2 / M$, where $m_D \sim Y_{i\alpha} \times v.e.v$

Example:

For $M \sim 1$ GeV and $m_v \sim 0.05$ eV it results in $m_D \sim 10$ keV and Yukawa coupling $\sim 10^{-7}$

strong coupling Yukawa coupling 1000 are too large neutrino masses are too small 10^{-17} 10-13 10⁻⁷ 10^{11} 0.1 10^{5} 10^{17} LSND v MSM LHC see-saw Majorana mass, GeV

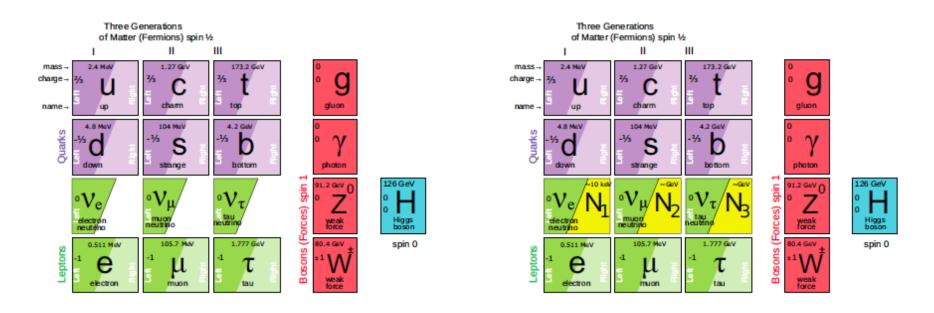
HNL masses



- ✓ Strong hierarchy between neutrino and charged fermion masses
- ✓ For HNL masses similar to the masses of other leptons their Yukawa couplings are as those of electron or smaller

v Minimal Standard Model (vMSM)

vMSM (T.Asaka, M.Shaposhnikov PL B620 (2005) 17) can also explain all three SM shortcoming by adding 3 HNL: N₁, N₂ and N₃



- ✓ N_1 plays a role of DM candidate $M(N_1) \sim a$ few keV
- ✓ N_{2,3} explain BAU and non-zero neutrino mass (using see-saw mechanism) M(N_{2,3}) ~ a few GeV

Heavy Neutral Leptons: N₁

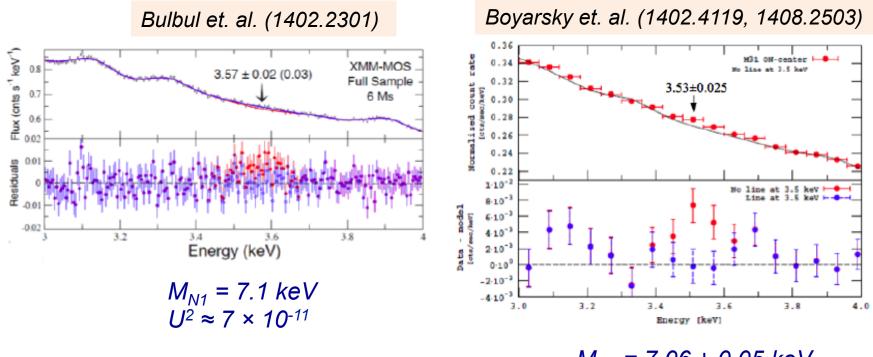
 \checkmark N₁ should be sufficiently stable

→ super-weak N_1 -to-v mixing such that $\tau(N_1) > \tau(Universe)$

Observable decay mode: $N_1 \rightarrow v\gamma$

 \rightarrow search for mono-line in galactic photon spectrum, $E_{\gamma} = M_N / 2$

Hints for a signal have been recently reported in:



 $M_{N1} = 7.06 \pm 0.05 \text{ keV}$ $U^2 = (2.2 - 20) \times 10^{-11}$

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Heavy Neutral Leptons: N₁

✓ There are also recent papers on non-detection of dark matter 10⁻⁶ $\Omega_{N_1} > \Sigma_{DI}$ sterile neutrino candidates: 10⁻⁷ 10⁻⁸ M.E.Anderson et. al. (1408.4115) X-ray constraints (1408.3531) D.Malyshev et.al. 10⁻⁹ density 10⁻¹⁰ $\sin^2(2\theta_1)$ constraints ✓ Ongoing discussions e-space 10⁻¹¹ on reliability of the signal ... 10⁻¹² 10⁻¹³ ✓ Accuracy of the measurements *limited by systematics* 10⁻¹⁴ $\Omega_{N_1} < \Omega_{DM}$ 10⁻¹⁵ 50 5 10 M₁ [keV]

Will soon be checked by the Astro-H mission (to be launched in 2015) with better energy resolution, $\Delta E/E \sim 0.1\%$

Heavy Neutral Leptons: N_{2,3}

HNL oscillations as a source of BAU:

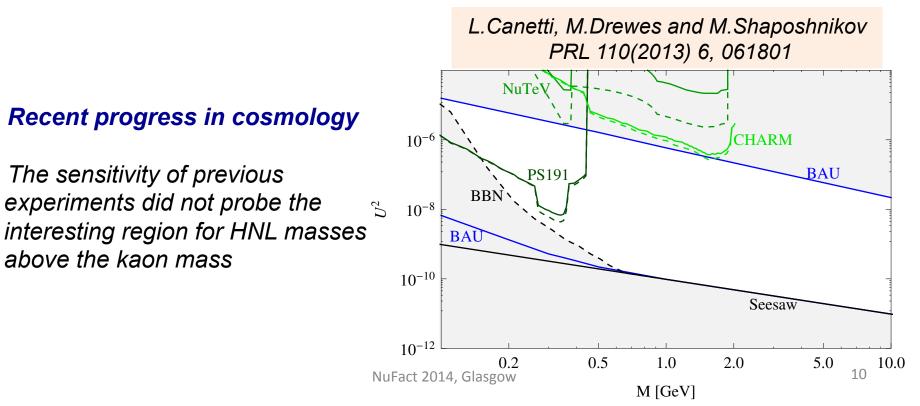
Akhmedov, Rubakov, Smirnov '98 Asaka, Shaposhnikov '05

 ✓ HNL are created in the early Universe Dramatic increase of CPV possible

 \checkmark

- ✓ Lepton number goes from HNL to active neutrinos
- The lepton number of the active left-handed neutrinos is transferred to baryons in equilibrium sphaleron processes

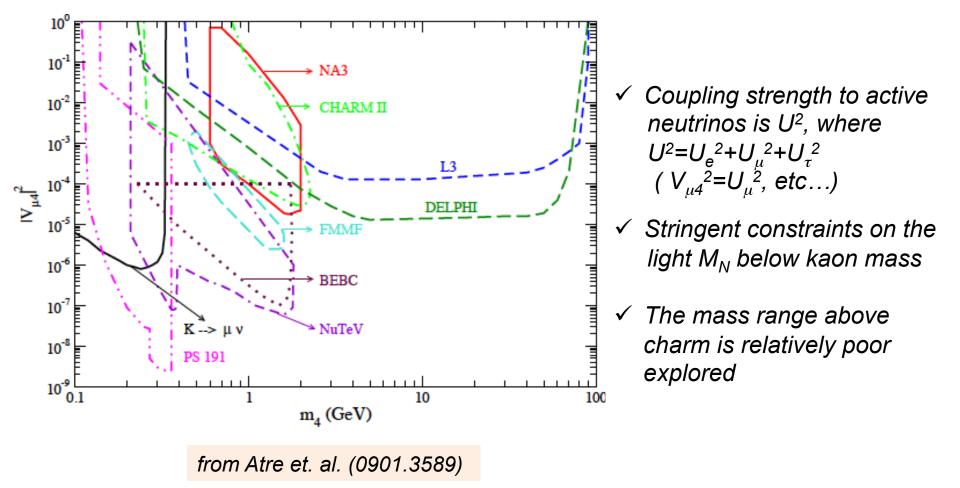
Experimental and cosmological constraints



Search for HNL at accelerators

(Recent results and future perspectives }

To set the scene (summary of the past results) :



Search for HNL at accelerators

(Recent results and future perspectives }

M.Shaposhnikov NP B763 (2007) 45-59 A.Pilaftsis et.al. PR D72 (2005) 113001

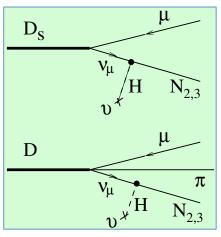
From cosmology: $M_N < M_W$ or $M_N \ge \approx 300 \text{ GeV}$ (Sakharov condition \rightarrow CP has to be violated out of thermo-equilibrium)

- ✓ M_N < M_K
 Impressive limits exist from PS-191
 Will soon be validated by NA62
- ✓ M_N < M_{heavy flavour} LHCb, BELLE
 New beam-dump experiment at the SPS (SHIP) has the best sensitivity reach
- ✓ M_N < M_Z
 Can be best explored at Future Circular Collider in e+e- mode
- ✓ $M_N > M_Z$ Prerogative of the ATLAS / CMS in the high luminosity phase of LHC

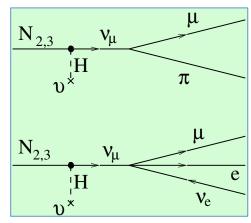
HNL production and decay

In Heavy Flavour decays:

Example: $N_{2,3}$ production in charm (similar diagrams exist in beauty sector)

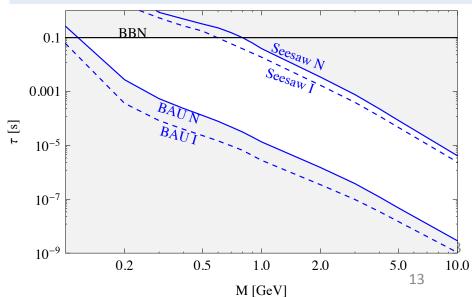


and subsequent decays

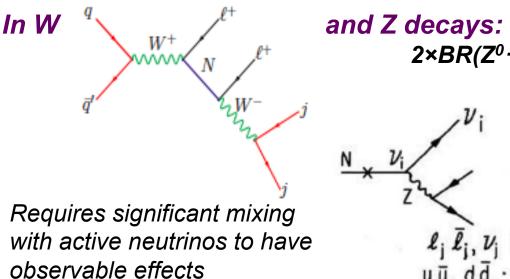


- ✓ Typical lifetimes > 10 µs for M(N_{2,3}) ~ 1 GeV Decay distance O(km)
- Typical BRs (depending on the flavour mixing):

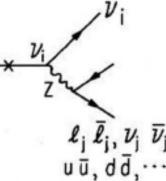
Br(N → μ/e π) ~ 0.1 - 50% Br(N → μ⁻/e⁻ ρ⁺) ~ 0.5 - 20% Br(N → νμe) ~ 1 - 10% Advances in theoretical understanding give bounds on HNL lifetime



HNL production and decay



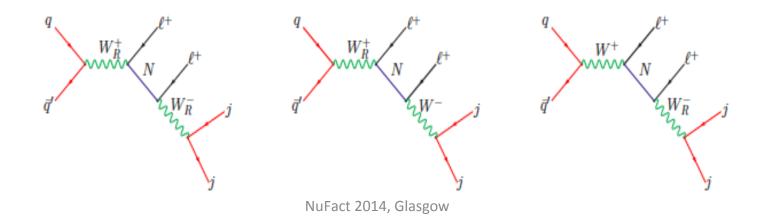
 $Z^0 \rightarrow vv \rightarrow vN$ with $BR(Z^0 \rightarrow vN) =$ $2 \times BR(Z^0 \rightarrow vv) \times |U^2| \times (1 - M_N^2 / M_7^2)^2 \times (1 + M_v^2 / 2M_7^2)$



✓ Experimental signal is a pair of the same-sign leptons and two jets with no missing E_{τ}

✓ With current data one can effectively probe $M_N < 300 \text{ GeV}$

Sensitivity is much increased in left-right symmetric models with W_R and Z_R - Both HNL production and decay receives new contribution via W_R/Z_R exchange



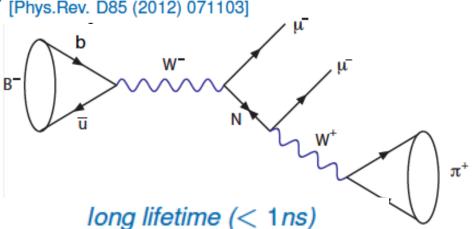
LHCb search for HNL in $B^- \rightarrow \pi^+ \mu^- \mu^-$

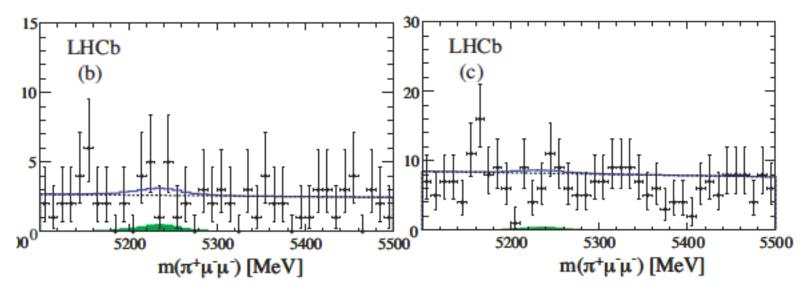
■ CLEO: $\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) < 1400 \times 10^{-9}$ [Phys.Rev. D65 (2002) 111102] ■ Babar: $\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) < 107 \times 10^{-9}$ [Phys.Rev. D85 (2012) 071103]

Advantages of LHCb:

- Large data sample
- Flexible trigger with low threshold
- Good PID

short lifetime (< 1ps)



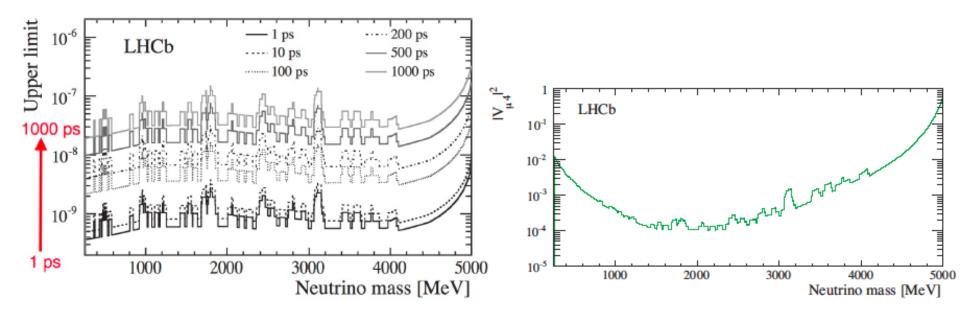


No signal observed in the B mass window

LHCb search for HNL in $B^- \rightarrow \pi^+ \mu^- \mu^-$

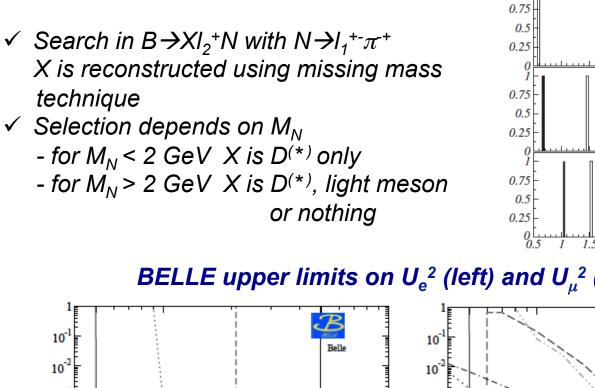
✓ BR (B^- → $\pi^+\mu^-\mu^-$) < 4×10⁻⁹ at 95% CL (current best limit for τ_N < 1 ps)

✓ Translated into the upper limit on U_{μ}^{2}



Sensitivity will be improved with more data and analyzing more decay channels

BELLE search for HNL



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M_v(GeV/c²)

10-3

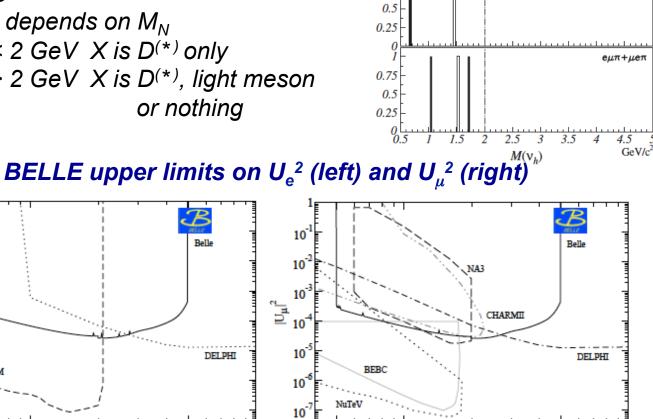
10-2

10-0

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05

M_v(GeV/c²)

Expect much improved sensitivity with BELLE-2 data

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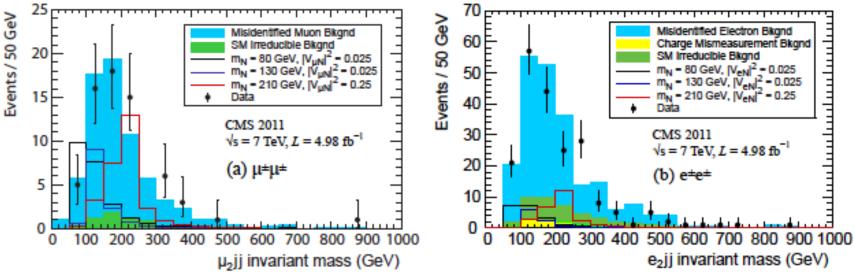
μμπ

ATLAS / CMS search for HNL

Unique possibility to explore HNL mass range above 100 GeV

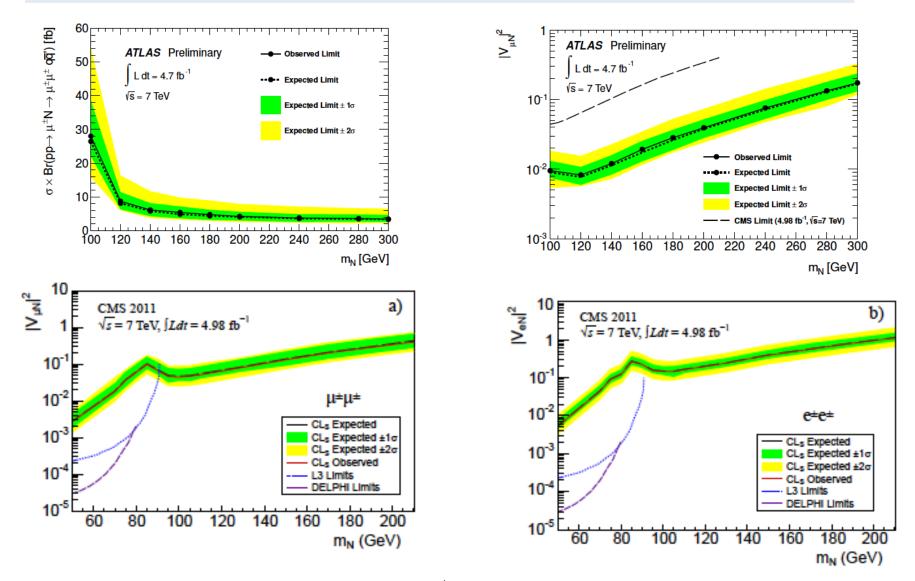
- Experimental signature: two same-sign leptons and no missing energy Majorana-type N would contribute to the signal with both opposite-sign and same-sign leptons. Same-sign lepton events have much lower SM background
- ✓ With currently available data samples experiments are only sensitive to large U² (or short lifetimes) of N
 For U² > 10⁻⁴ (and M_N ≥ 50 GeV) a typical N flight distance is ≤ 100 microns

- No use of detached vertex possible
 - → large backgrounds from multi-jet events with faked leptons or leptons from b-decays



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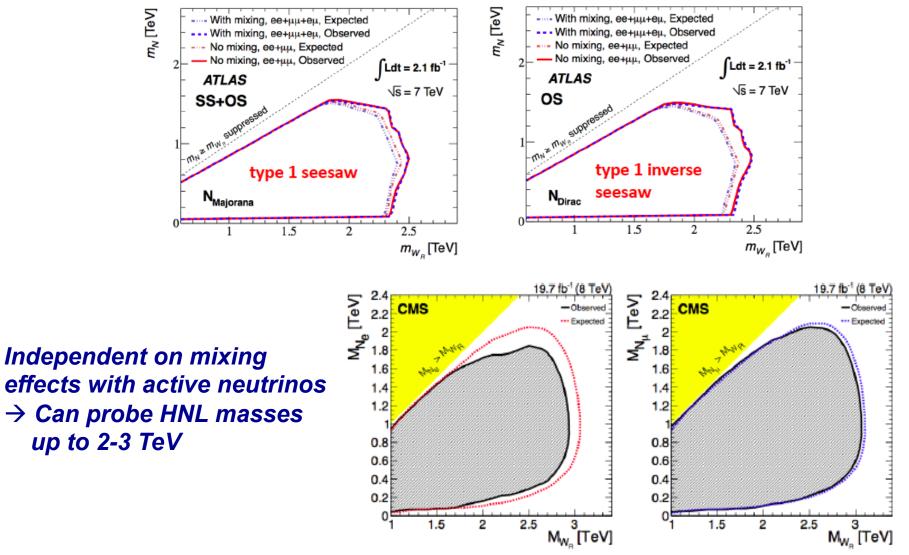
First direct limits on $U_e^2(CMS)$ and $U_{\mu}^2(ATLAS\&CMS)$ for $M_N > M_Z$ (assuming that only one heavy neutrino contributes to the production cross-section)



Expect more stringent limits with \sqrt{s} = 8 TeV, and 14 TeV LHC data

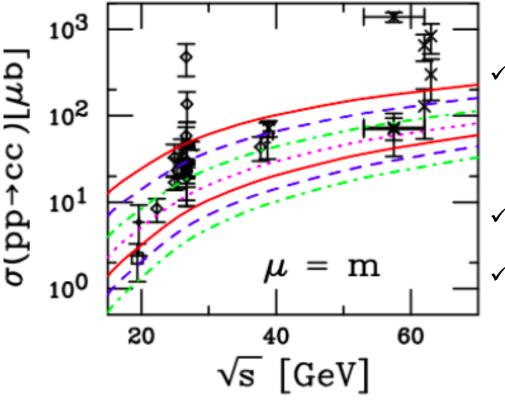
Increased sensitivity to HNL in left-right symmetric models

Model-dependent ATLAS and CMS limits on M_N (and W_R)



New beam-dump experiment at the SPS

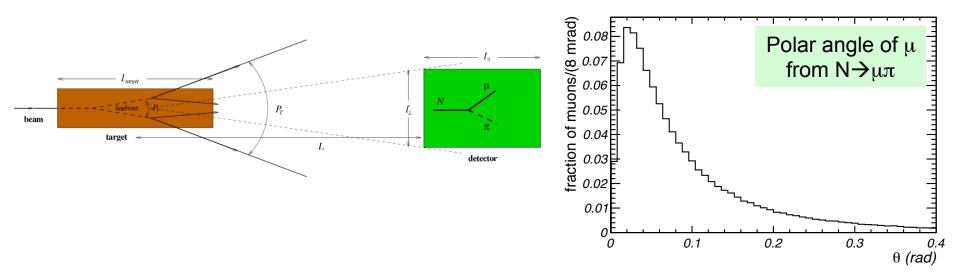
New possibilities in intensity frontier (SHIP facility) at the SPS/CERN "Beam-dump" is an ideal instrument to search for weakly interacting heavy neutrinos (below charm mass)



- ✓ SPS can provide ~2×10²⁰ protons-ontarget in 4-5 years assuming the same operation as has been demonstrated during CNGS run
 - C Large charm production cross-section
 - data sample with >10¹⁷ D, >10¹⁵ τ !

Experimental requirements

HNLs produced in charm decays have significant P_{T}



Detector must be placed close to the target to maximize geometrical acceptance

Effective (and "short") muon shield is essential to reduce muon-induced backgrounds (mainly from short-lived resonances accompanying charm production)

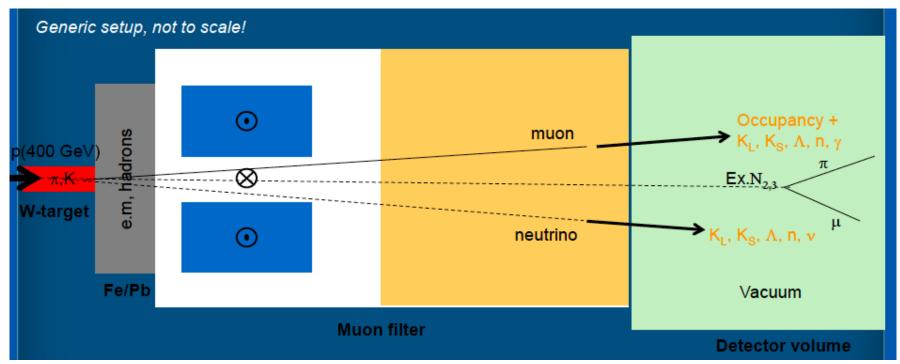
SHIP experimental area

Initial reduction of beam induced backgrounds

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

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

For 1s spill duration \rightarrow < 50×10⁶ muons

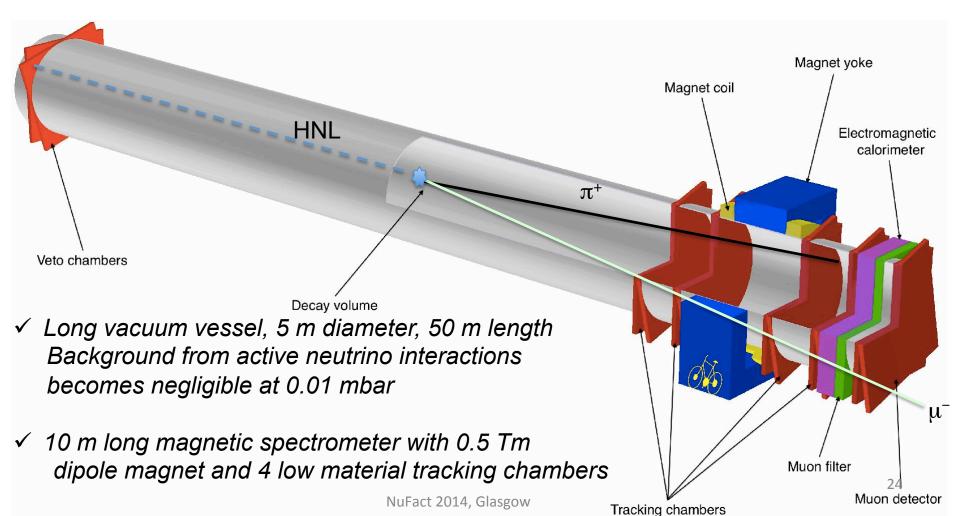


Proper optimization of the muon shield is one of the key issues!

Initial detector concept

Detector uses existing technologies and would require a modest R&D phase

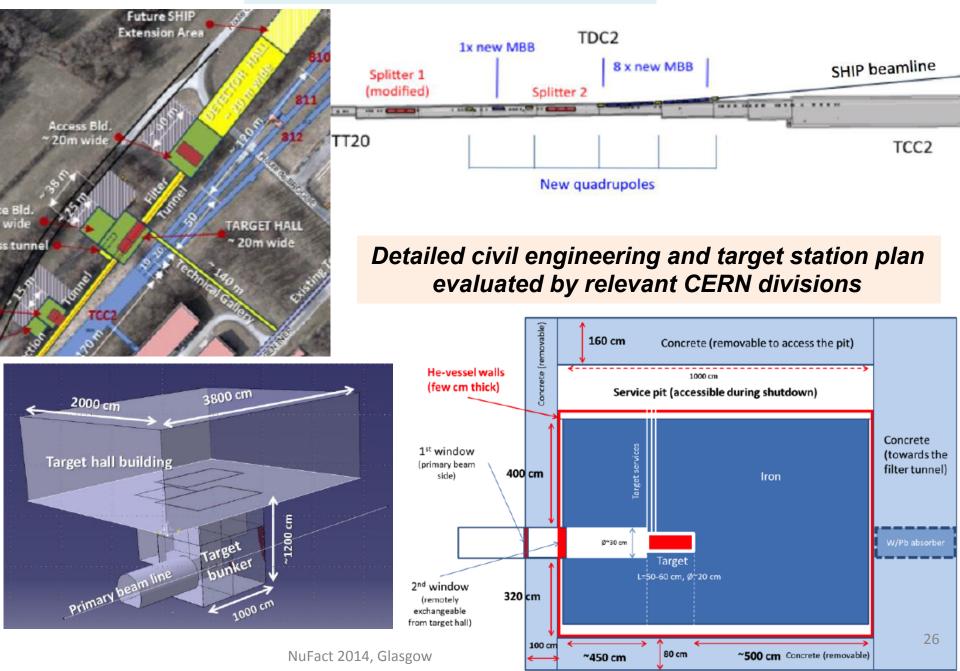
Main elements: long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building



CERN Task Force to evaluate required infrastructure

- EDMS NO. REV. VALIDITY 1.0 1369559 RELEASED CERN REFERENCE EN-DH-2014-007 CH1211 Geneva 23 EN Engineering Department Switzerland Date : 2014-07-02 Report A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area Preliminary Project and Cost Estimate The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN. DOCUMENT PREPARED BY: DOCUMENT CHECKED BY: DOCUMENT APPROVED BY: G.Arduini, M.Calviani, S.Baird, O.Brüning, J-P.Burnet, F.Bordry, P.Collier, E.Cennini, P.Chiggiato, F.Duval, M.J.Jimenez, L.Miralles, K.Cornelis, L.Gatignon, B.Goddard, A.Golutvin, R.Saban, R.Trant D.Forkel-Wirth, R.Jacobsson, J. Osborne, R.Jones, M.Lamont, R.Losito, S.Roesler, T.Ruf, H.Vincke, D.Missiaen, H.Vincke M.Nonis, L.Scibile, D.Tommasini,
- ✓ Following SPSC review, CERN DG has formed a dedicated Task Force to evaluate required infrastructure
- The Task Force report published and discussed at the extended CERN directorate meeting in July

SHIP experimental area



Planning schedule of the SHIP facility

		2014	2015	2016	2017		118	2019	2020	2021	2022	2023	2024	2025	2026	_
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I .	LHC operation															
	SPS operation													_		
erat)	Facility HW commissioning/dry runs on availability	I														
	SHIP facility commissioning with beam	I										_ ,	Ļ	4		
	SHIP facility operation															
Detector	SHIP Technical Proposal															
	SHIP Project approval	I														
	Technical Design Reports and R&D	I														
	TDR approval	I		i							İ	i	i	İ		
	Detector production	I														
	Detector installation		4							·						
GMI	Pre-construction activities(Design, tendering, permits)						L									
	CE works for extraction tunnel, target complex															
	CE works for TDC2 junction cavern	I		1	ĺ	İ I					ĺ	l I	1			
	CE works for filter tunnel and detector hall							+					L			_
a tr	Installation in TT20 (150m)															
25	Installation for new beam line to target	I														
infrastructure Systems	installation in target complex, filter tunnel	I														
2	Installation in detector hall				L											
Beam Line	Design studies, specs and tender docs	I]		ſ	1	
	Integration studies	I														
	Technical Design Report	I														
	Manufacturing new components	I														
	Refurbishment existing components	I														
	TT20 dismantling (150m)	I						- *								
I .	TT20 re-installation and tests	I			l l	İ.					l l	l l	1			
I	New beam line to target installation and tests	I														
	Muon filter installation		+													_
Targot mplex/Targ	Target complex design studies, specs and tender docs															
	Target complex integration studies															
	Target complex services - design and manufacturing Target studies and prototyping		*													
	Target studies and procovping Target production and installation															
6	railler biographic and ustraismont															_

A few milestones:

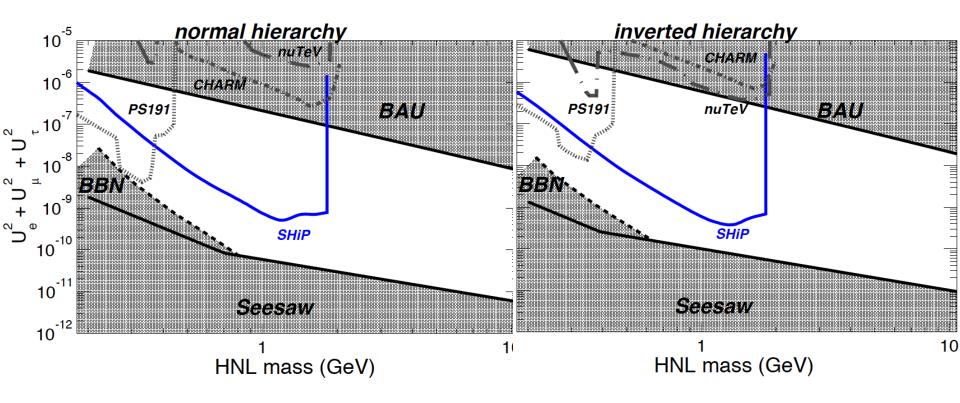
- ✓ Form SHIP collaboration
- ✓ Technical proposal
- ✓ Technical Design Report
- ✓ Construction and installation
- ✓ Commissioning
- ✓ Data taking and analysis of 2×10^{20} pot →

- → June-September 2014
- \rightarrow 2015
- → 2018
- → 2018 2022
- → 2022 2023

2023 - 2027

SHIP sensitivity to HNL

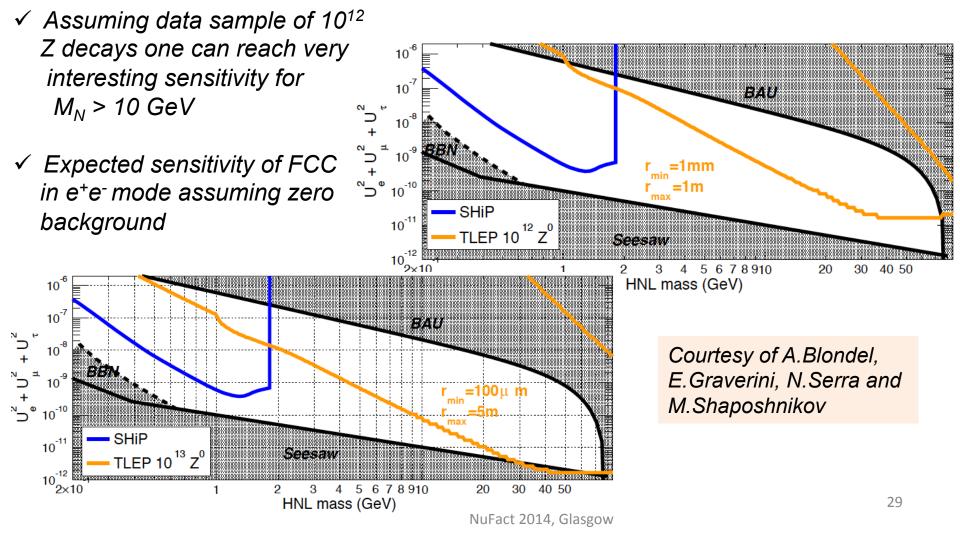
- ✓ SHIP will scan most of the cosmologically allowed region below the charm mass
- ✓ Reaching the see-saw limit would require increase of the SPS intensity by an order of magnitude (does not currently seem realistic)



How to extend sensitivity to higher masses

 \checkmark Use processes $Z \rightarrow N_V$ with $N \rightarrow$ lepton + 2 jets

 $BR(Z \rightarrow vN) \cong BR(Z \rightarrow vv) \times U^2$, $\Gamma_N \cong G_F^2 \times M_N^5 \times U^2 \times N_{decay \ channels} / 192\pi^3$



Summary

✓ New experimental campaign to search for heavy neutrinos is very timely

- ✓ The impact of the discovery of a heavy neutrino is hard to overestimate
- ✓ Impressive prospects:
 - NA-62 ($< M_K$) starts data taking this year
 - LHCb upgrade and BELLE 2 (< M_{beauty}) after 2018
 - SHIP ($< M_{charm}$) is planned to be ready in 2022 Will also explore other hidden portals of the SM
 - LHC in high luminosity phase ($> M_Z$) after 2025
 - FCC in e^+e^- or TLEP (< M_Z) after 2030