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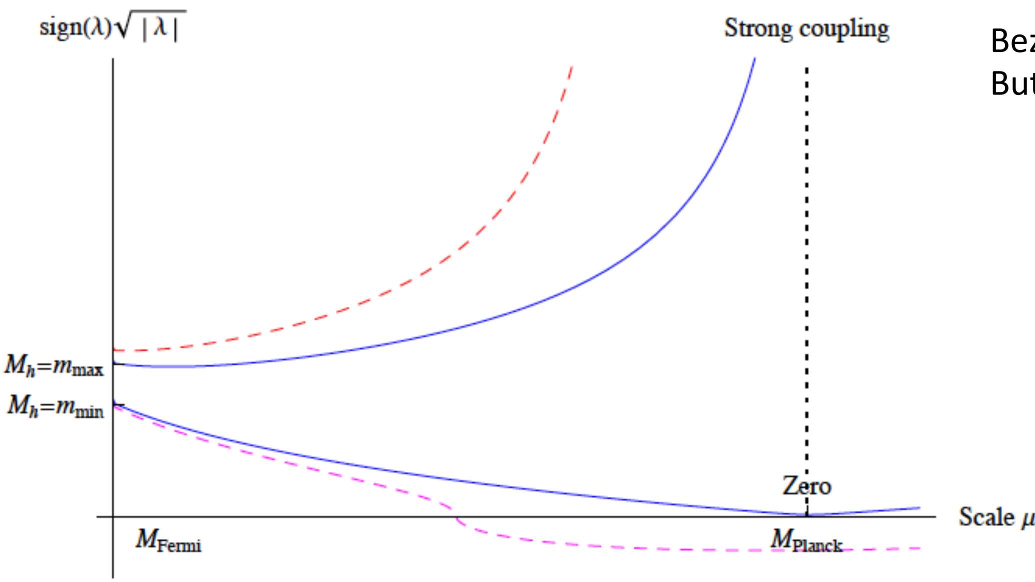
Prospects for Heavy Neutrino Searches at Accelerators

Outline:

- *Brief summary on the current status of the Standard Model*
- *Heavy Neutral Leptons in νMSM model*
- *Recent experimental results and future prospects*

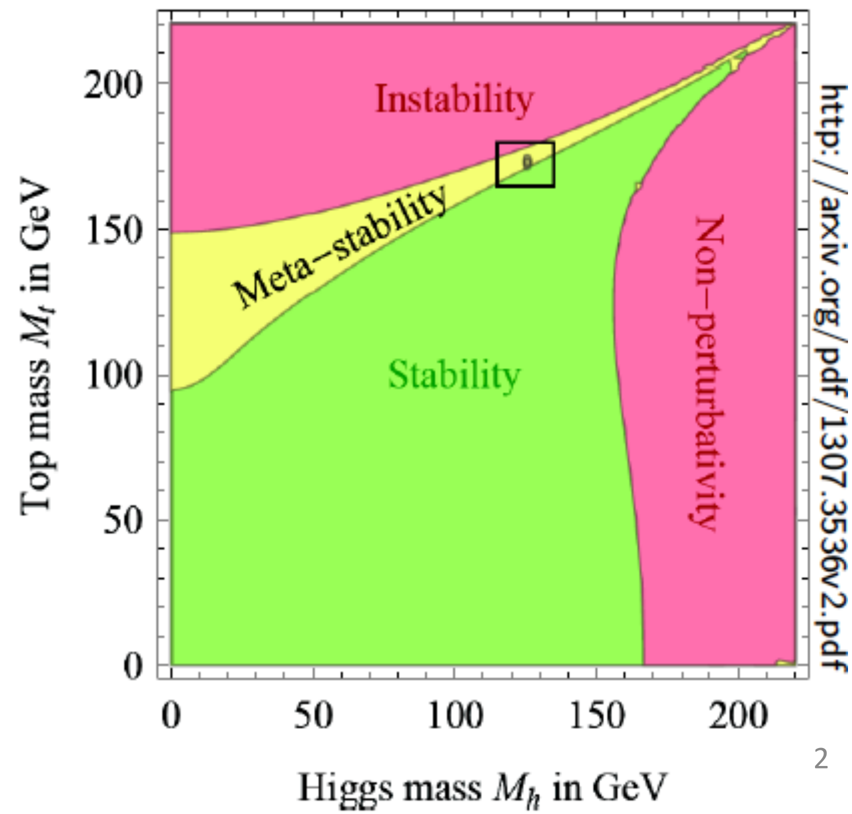
Current status of the Standard Model

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



Bezrukov et al. [1205.2893], Degrassi et al.[1205.6947]
Buttazzo et al. [1307.3536]

Hard to believe that this is a pure coincidence



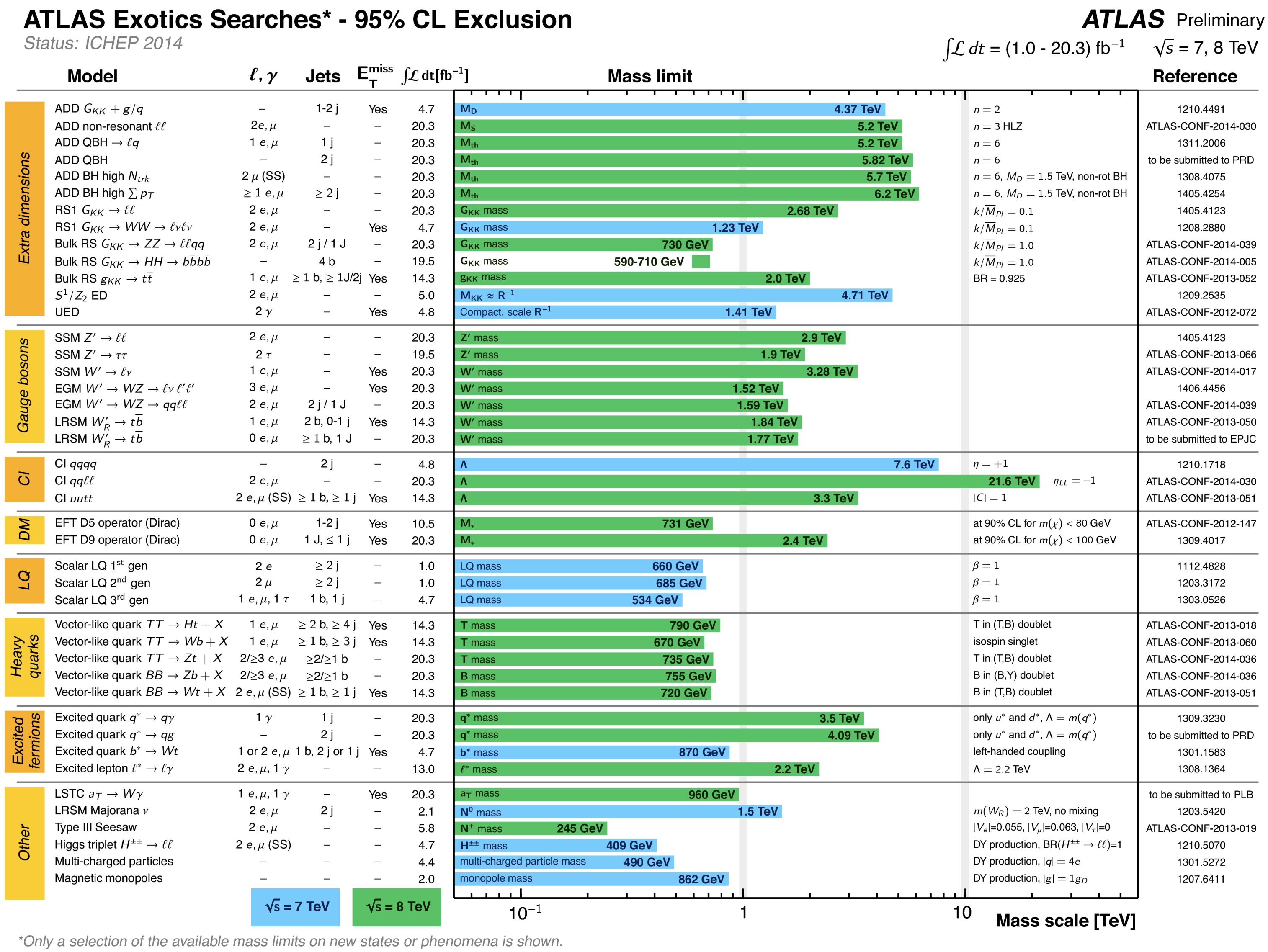
SM is not complete

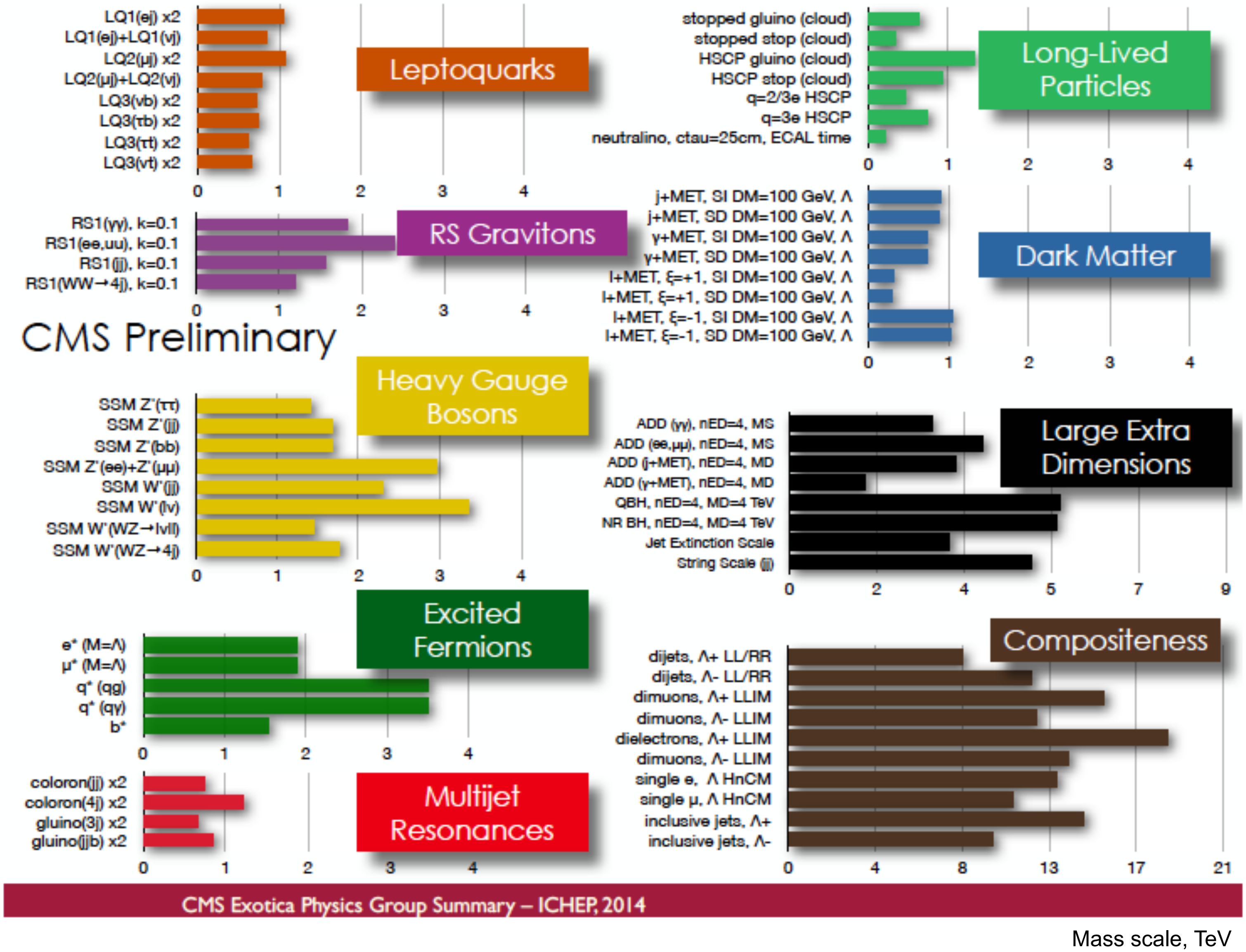
Shortcomings of the SM:

- ***Neutrino masses & oscillations***
- *Excess of matter over antimatter in the Universe*
- *The nature of Dark Matter*

Search for New Physics

- ✓ *No signs of NP seen at $\sqrt{s}$ = 8 TeV.*





- ✓ ***$M_{NP} > 10^4$ 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*

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

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

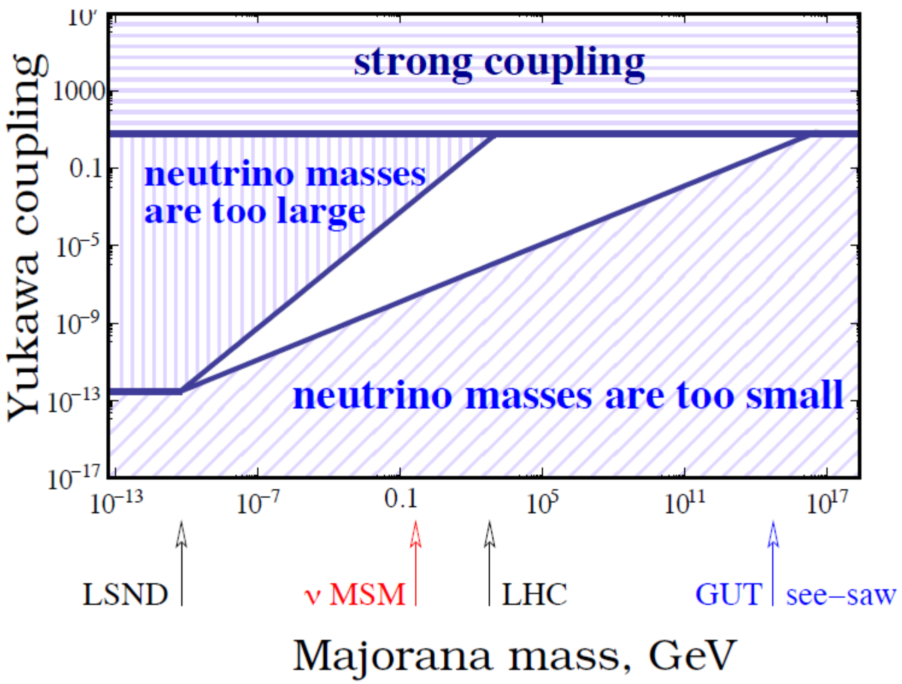
Majorana term which carries no gauge charge

Wide range of possibilities for the see-saw scale

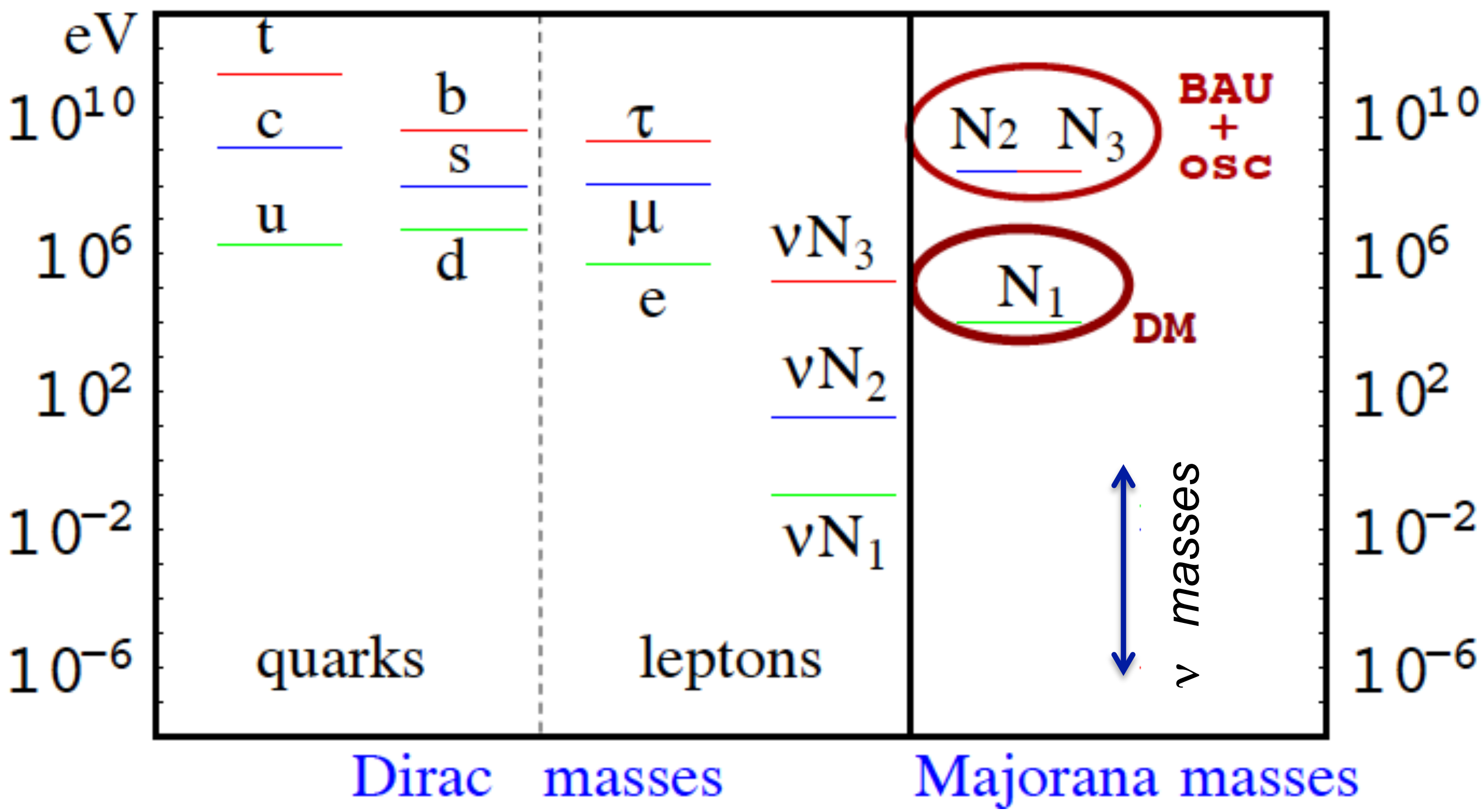
The scale of the active neutrino mass is given by the see-saw formula: $m_\nu \sim m_D^2 / M$, where $m_D \sim Y_{i\alpha} \times$ v.e.v

Example:

For M ~ 1 GeV and m_ν ~ 0.05 eV it results in m_D ~ 10 keV and Yukawa coupling ~ 10^{-7}



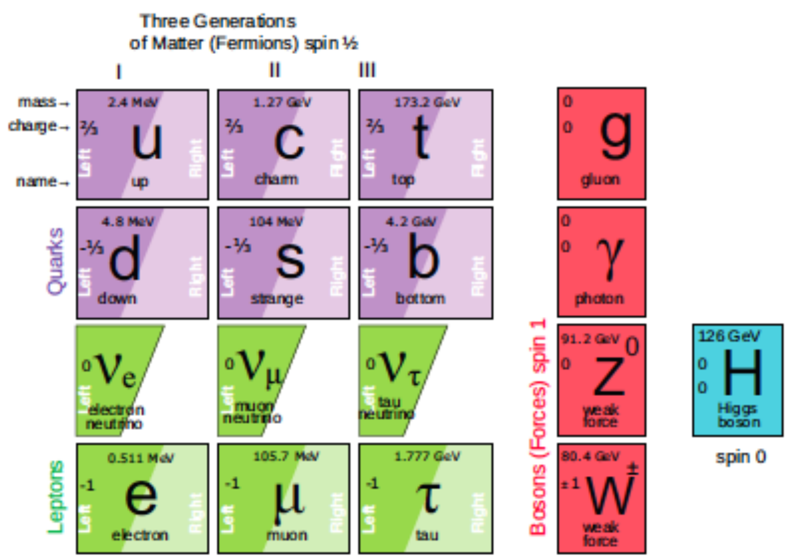
HNL masses

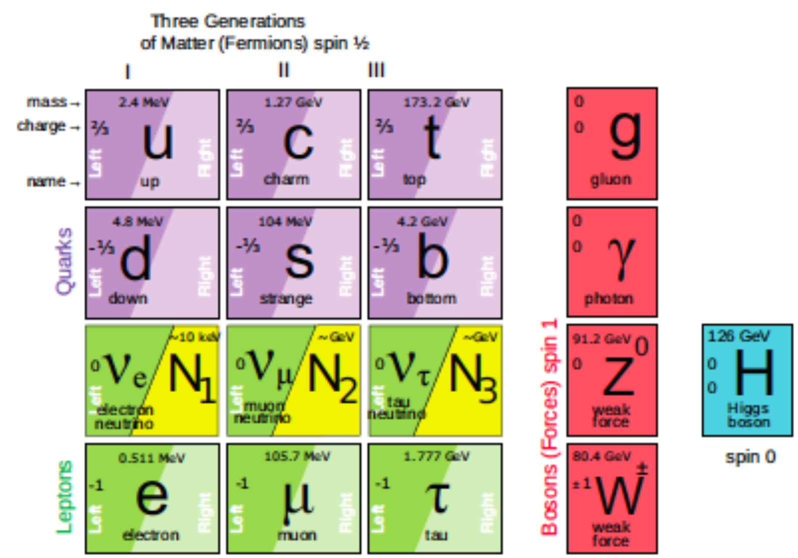


- ✓ *Strong hierarchy between neutrino and charged fermion masses*
- ✓ ***For HNL masses similar to the masses of other leptons their Yukawa couplings are as those of electron or smaller***

ν Minimal Standard Model (νMSM)

νMSM *(T.Asaka, M.Shaposhnikov PL **B620** (2005) 17) can also explain all three SM shortcoming by adding 3 HNL: **N_1, N_2 and N_3***





- ✓ *N_1 plays a role of DM candidate*
  $M(N_1)$ ~ 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: N_1

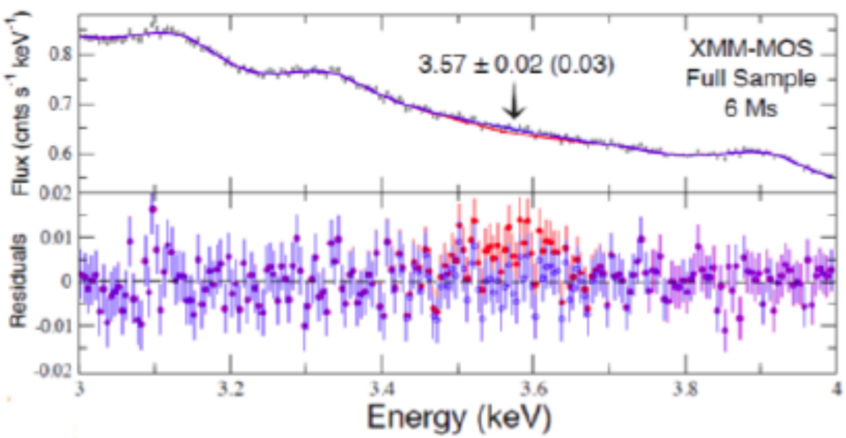
- ✓ *N_1 should be sufficiently stable*
  - → *super-weak N_1-to-ν mixing such that $\tau(N_1) > \tau(\text{Universe})$*

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

- → *search for mono-line in galactic photon spectrum, $E_\gamma = M_N / 2$*

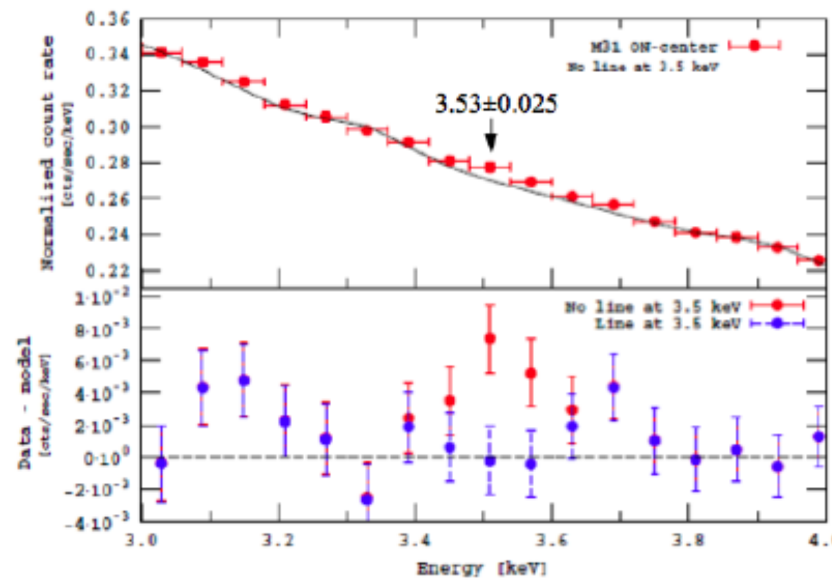
Hints for a signal have been recently reported in:

Bulbul et. al. (1402.2301)



$M_{N1} = 7.1$ keV
$U^2 \approx 7 \times 10^{-11}$

Boyarsky et. al. (1402.4119, 1408.2503)



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

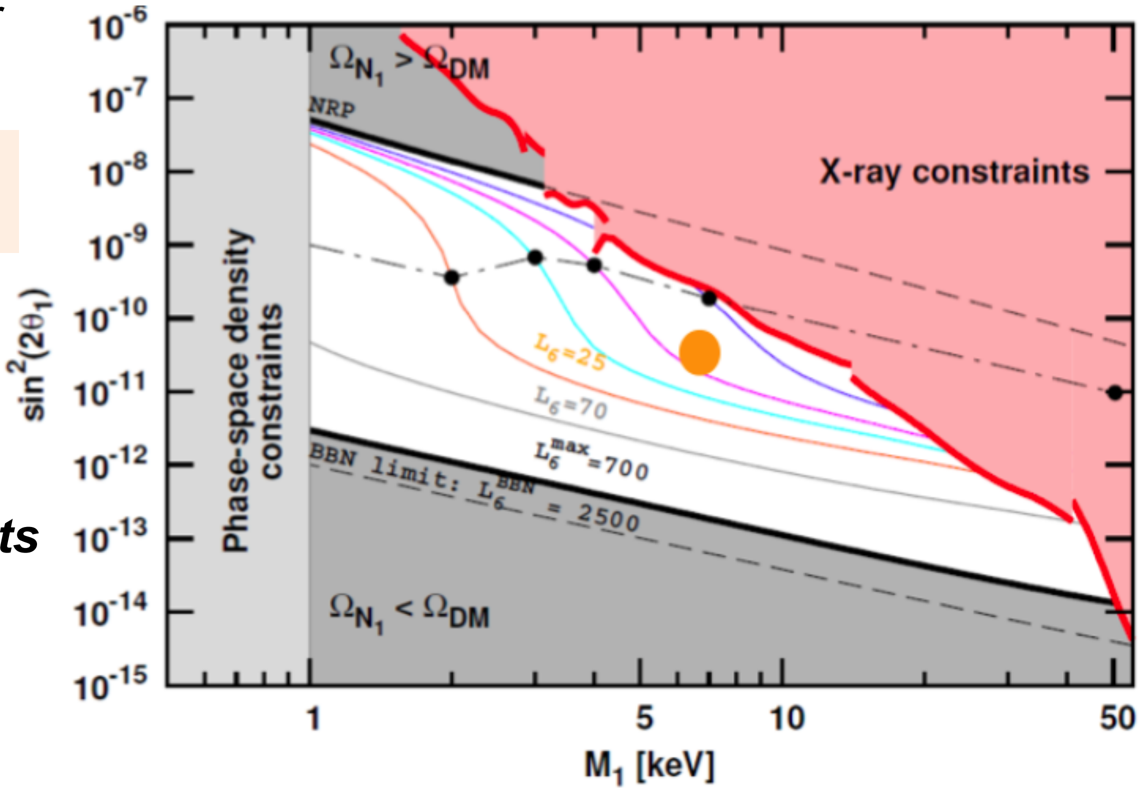
Heavy Neutral Leptons: N_1

- ✓ *There are also recent papers on non-detection of dark matter sterile neutrino candidates:*

M.E.Anderson et. al. (1408.4115)
D.Malyshev et.al. (1408.3531)

- ✓ *Ongoing discussions on reliability of the signal …*

- ✓ ***Accuracy of the measurements limited by systematics***



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:

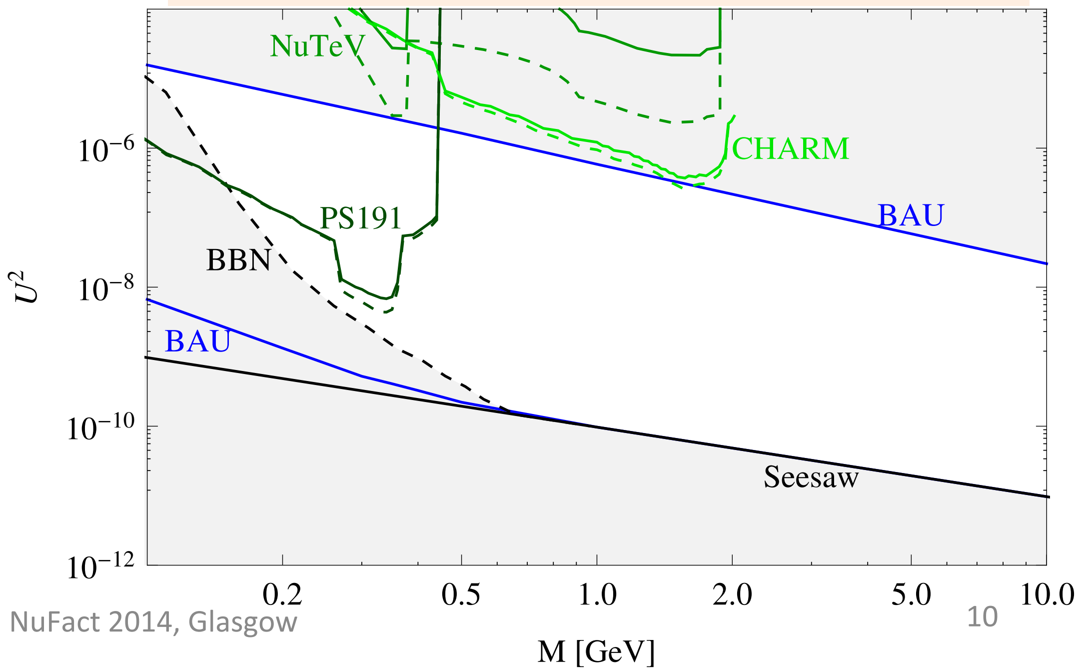
Akhmedov, Rubakov, Smirnov '98
Asaka, Shaposhnikov '05

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

L.Canetti, M.Drewes and M.Shaposhnikov
PRL 110(2013) 6, 061801

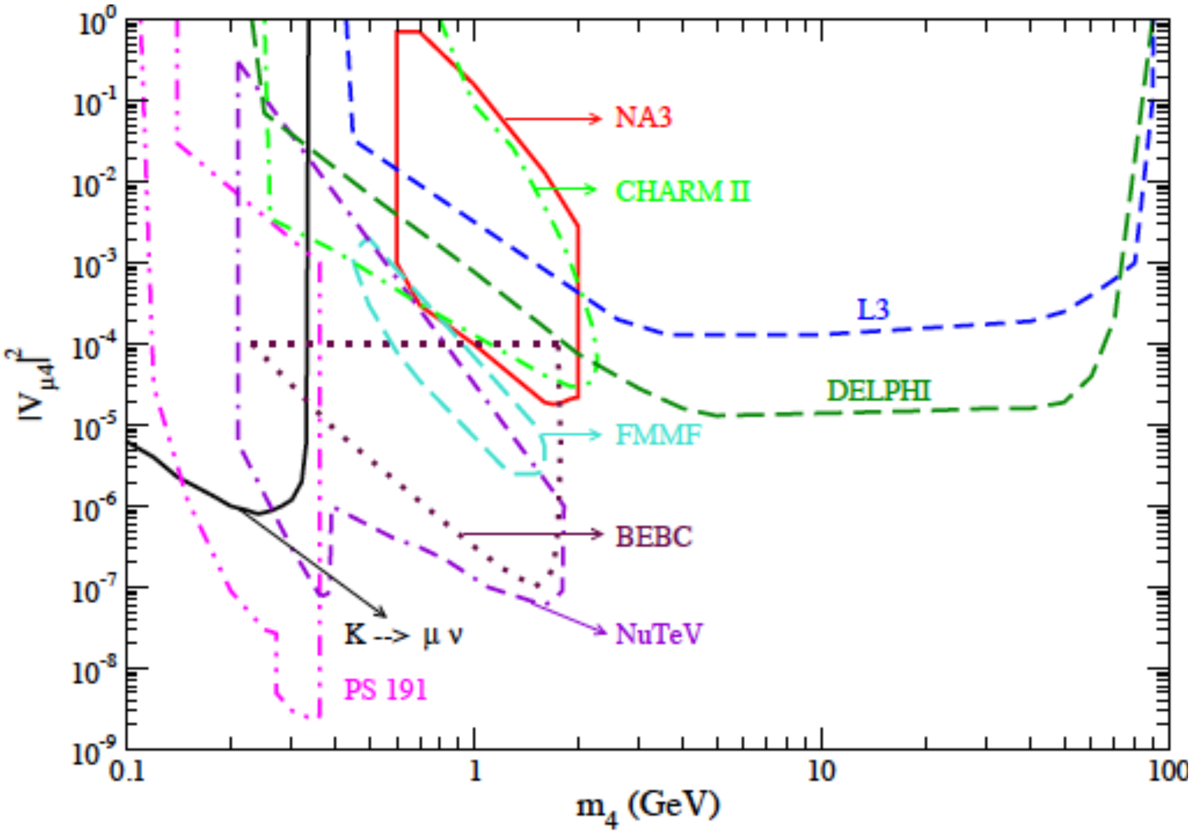
- ✓ ***Recent progress in cosmology***
- ✓ *The sensitivity of previous experiments did not probe the interesting region for HNL masses above the kaon mass*



Search for HNL at accelerators

(Recent results and future perspectives }

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



from Atre et. al. (0901.3589)

- ✓ *Coupling strength to active neutrinos is U^2, where $U^2=U_e^2+U_\mu^2+U_\tau^2$ ($V_{\mu 4}^2=U_\mu^2$, etc…)*
- ✓ *Stringent constraints on the light M_N below kaon mass*
- ✓ *The mass range above charm is relatively poor explored*

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 $M_N \geq \approx 300$ GeV
(Sakharov condition → 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

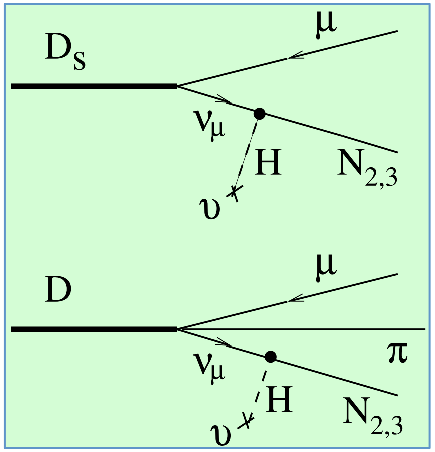
✓ $M_N < M_Z$
Can be best explored at Future Circular Collider in e+e- mode

✓ $M_N > M_Z$
Prerogative of the ATLAS / CMS in the high luminosity phase of LHC

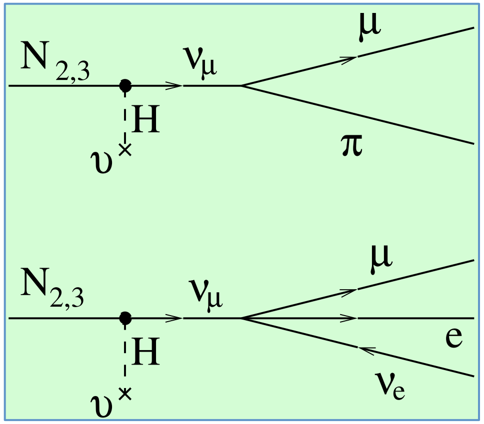
HNL production and decay

In Heavy Flavour decays:

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



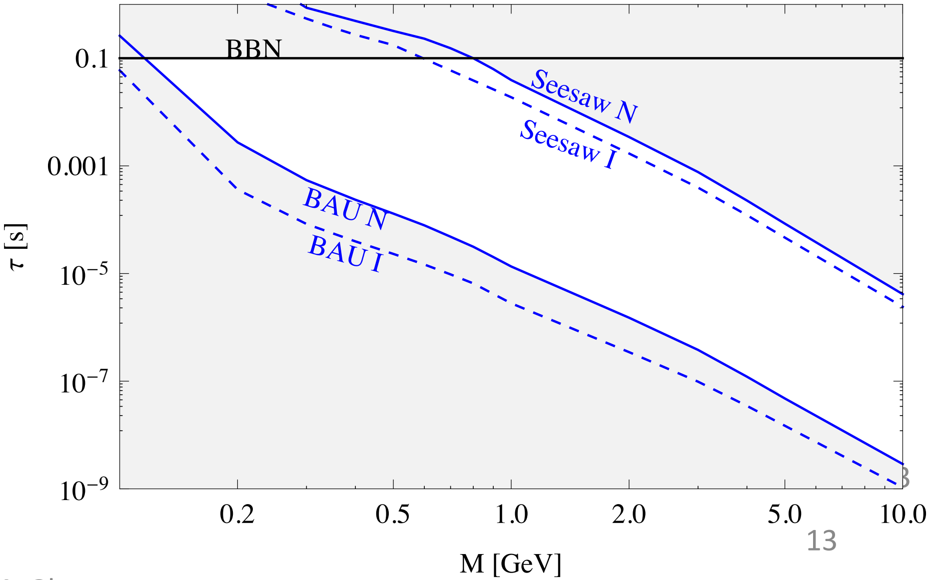
and subsequent decays



- ✓ *Typical lifetimes > 10 μs for*
  $M(N_{2,3})$ ~ 1 GeV
  Decay distance O(km)

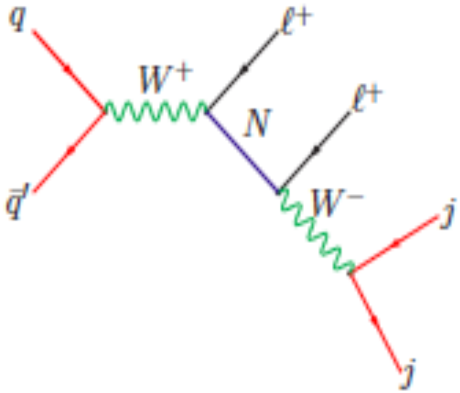
- ✓ *Typical BRs (depending on the flavour mixing):*
  Br(N → μ/e π) ~ 0.1 – 50%
  Br(N → μ^-/e^- ρ^+) ~ 0.5 – 20%
  Br(N → $\nu\mu$e) ~ 1 – 10%

Advances in theoretical understanding give bounds on HNL lifetime



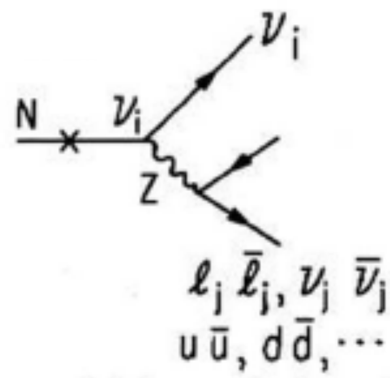
HNL production and decay

In W



Requires significant mixing with active neutrinos to have observable effects

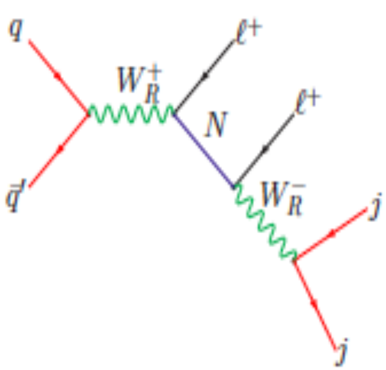
and Z decays: $Z^0 \to \nu\nu \to \nu N$ **with** $BR(Z^0 \to \nu N) = 2\times BR(Z^0 \to \nu\nu)\times|U^2|\times(1-M_N^2/M_Z^2)^2\times(1+M_\nu^2/2M_Z^2)$

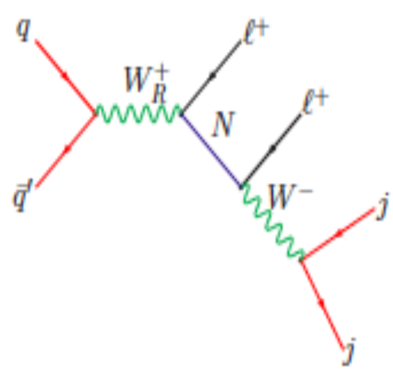


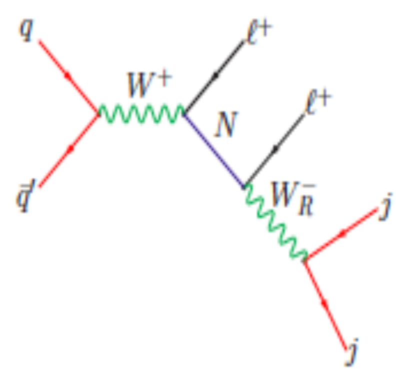
- ✓ *Experimental signal is a pair of the same-sign leptons and two jets with no missing E_T*
- ✓ *With current data one can effectively probe M_N < 300 GeV*

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





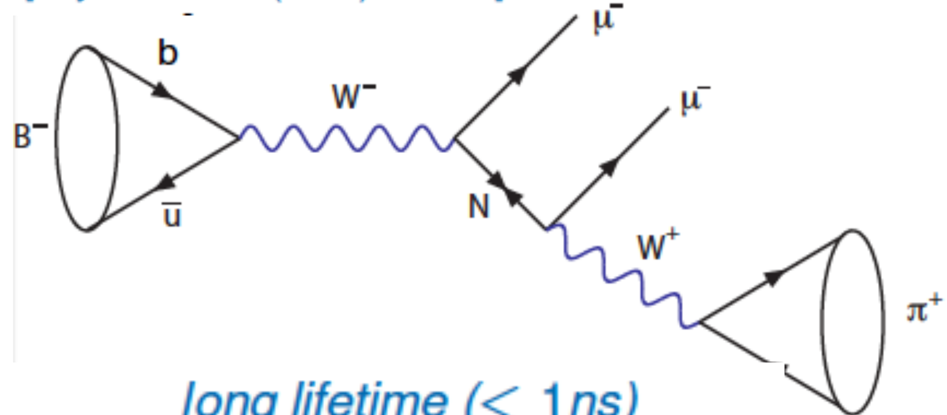


LHCb search for HNL in $B^- \to \pi^+\mu^-\mu^-$

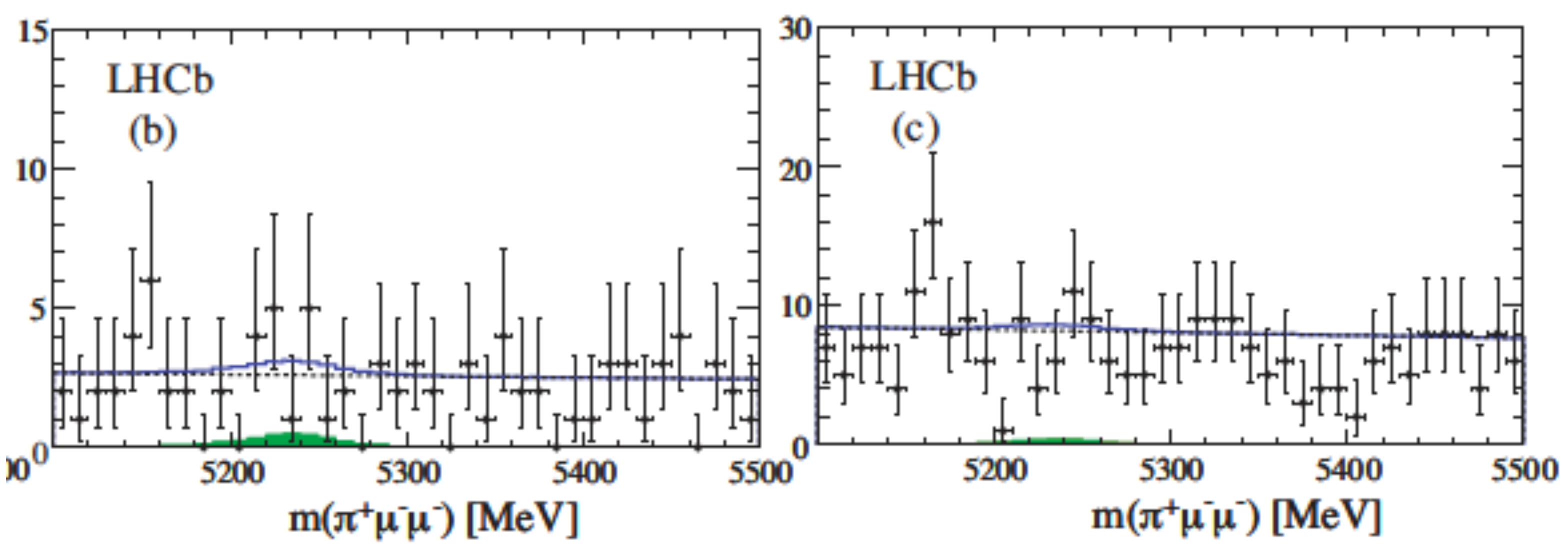
- CLEO: $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 1400 \times 10^{-9}$ [Phys.Rev. D65 (2002) 111102]
- Babar: $\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 107 \times 10^{-9}$ [Phys.Rev. D85 (2012) 071103]

Advantages of LHCb:

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



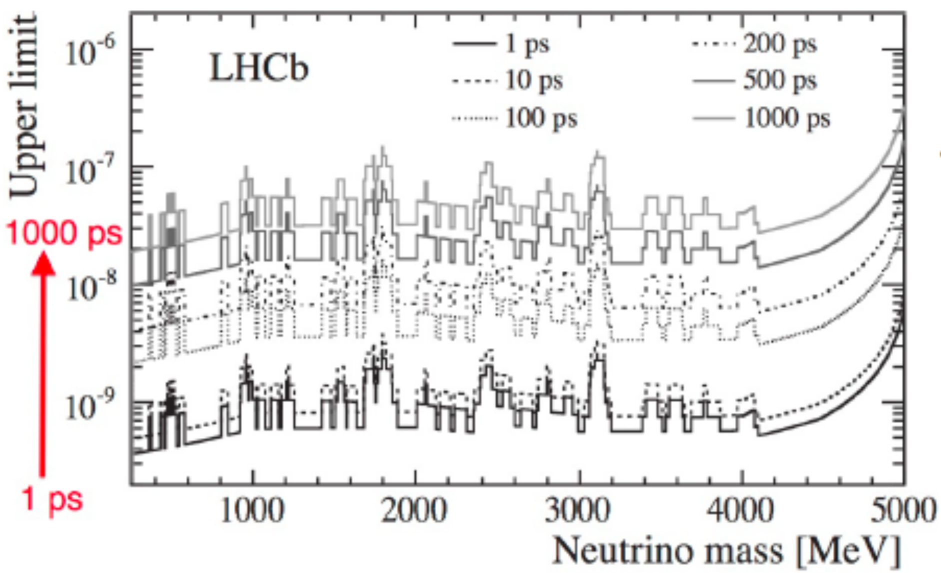
short lifetime ($< 1ps$) | long lifetime ($< 1ns$)

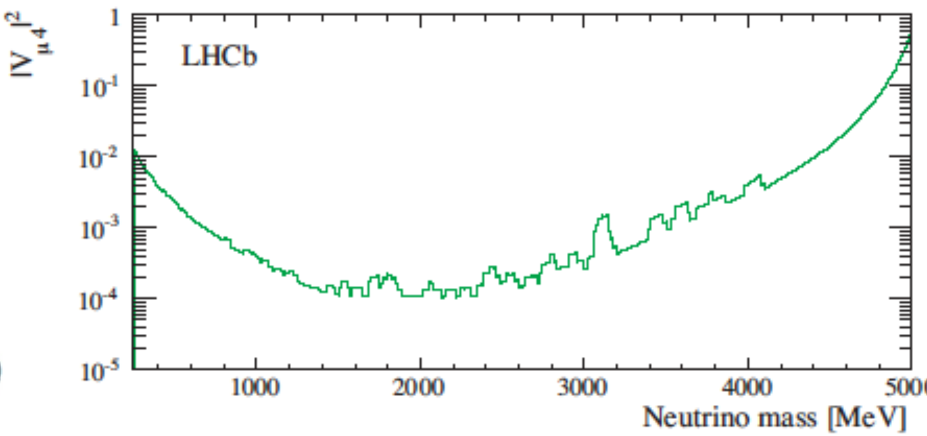


No signal observed in the B mass window

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

- ✓ *BR ($B^- \to \pi^+\mu^-\mu^-$) < 4×10^{-9} at 95% CL (current best limit for τ_N < 1 ps)*
- ✓ *Translated into the upper limit on U_μ^2*

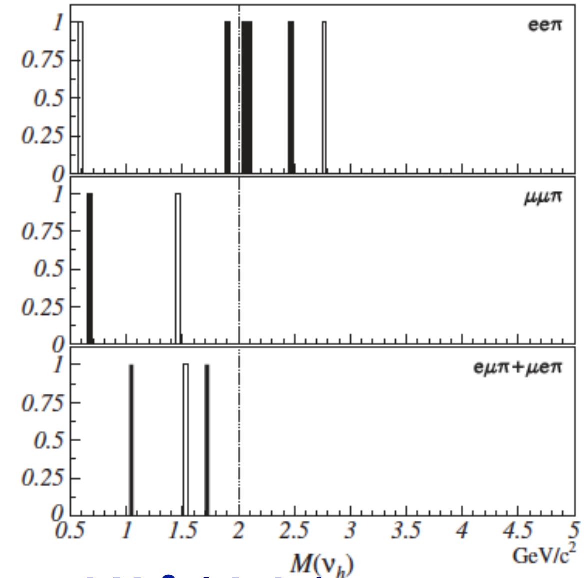




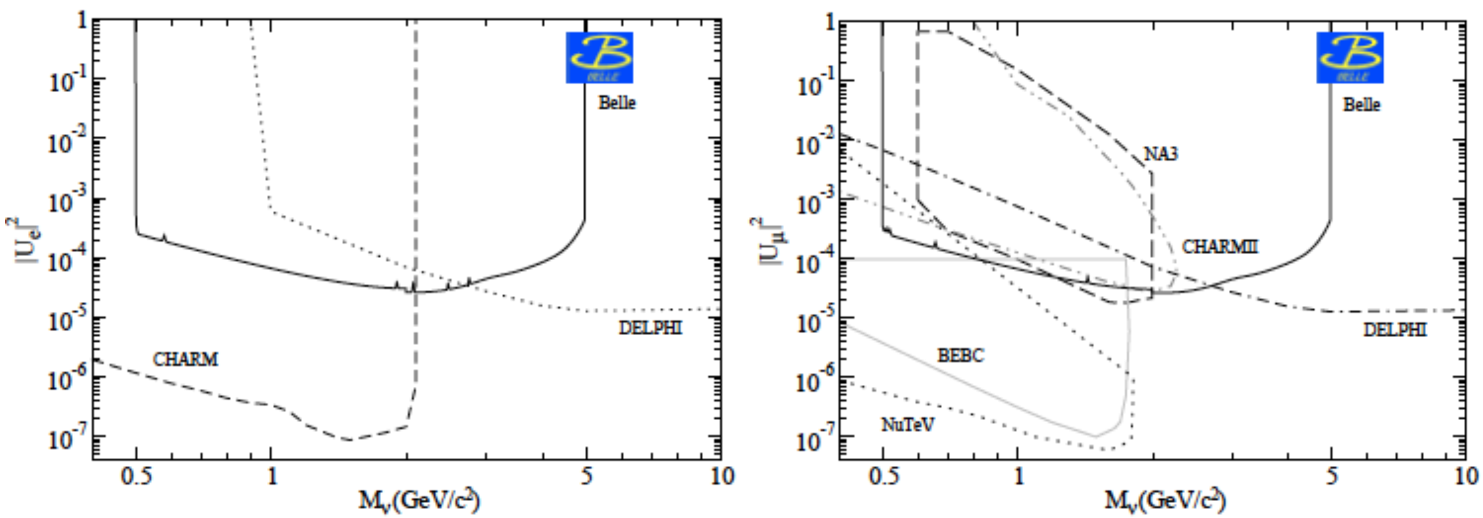
Sensitivity will be improved with more data and analyzing more decay channels

BELLE search for HNL

- ✓ Search in $B \rightarrow X l_2^{+} N$ with $N \rightarrow l_1^{+-} \pi^{-+}$
  X is reconstructed using missing mass technique
- ✓ Selection depends on M_N
  - for $M_N < 2$ GeV X is $D^{(*)}$ only
  - for $M_N > 2$ GeV X is $D^{(*)}$, light meson or nothing



BELLE upper limits on U_e^2 (left) and U_μ^2 (right)



Expect much improved sensitivity with BELLE-2 data

ATLAS / CMS search for HNL

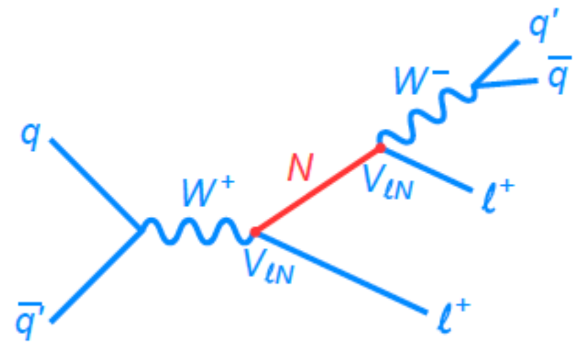
Unique possibility to explore HNL mass range above 100 GeV

✓ ***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

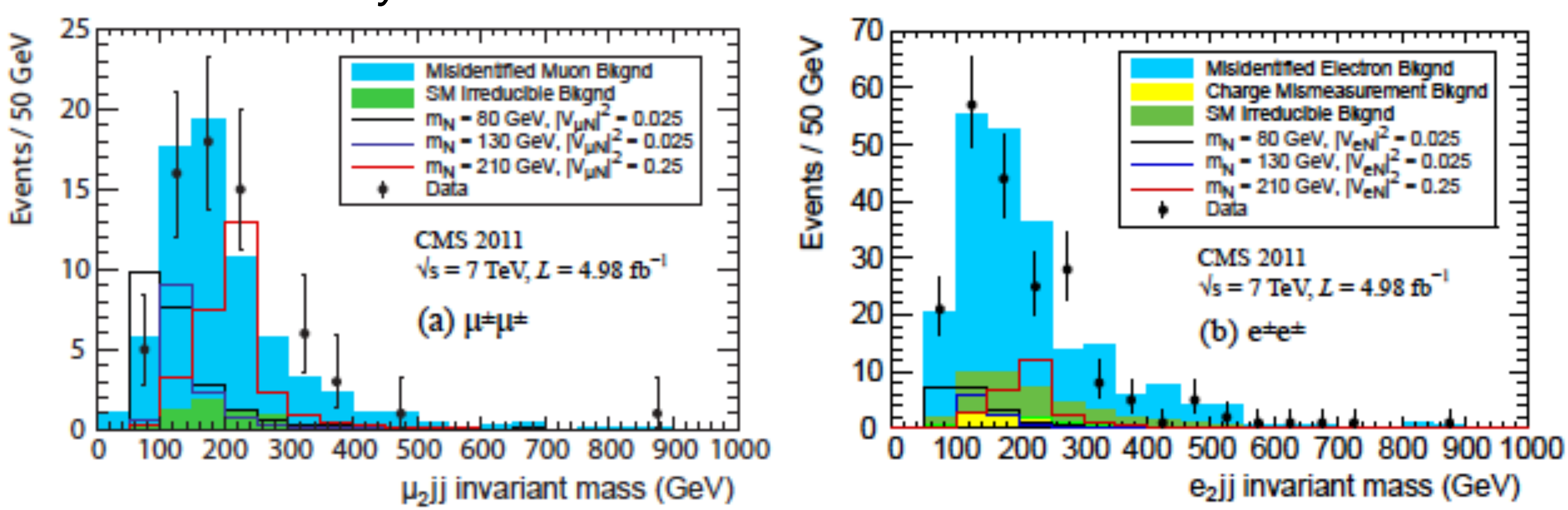
✓ *With currently available data samples experiments are only sensitive to large U^2 (or short lifetimes) of N*

For $U^2 > 10^{-4}$ (and $M_N \geq 50$ GeV) a typical N flight distance is ≤ 100 microns



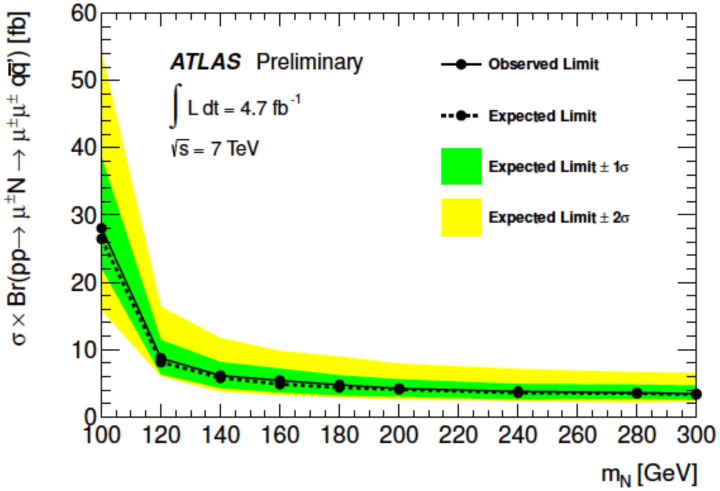
✓ *No use of detached vertex possible*

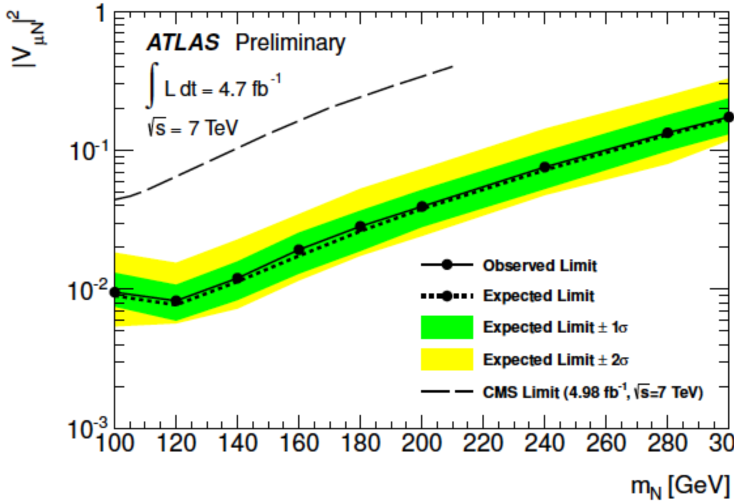
→ *large backgrounds from multi-jet events with faked leptons or leptons from b-decays*

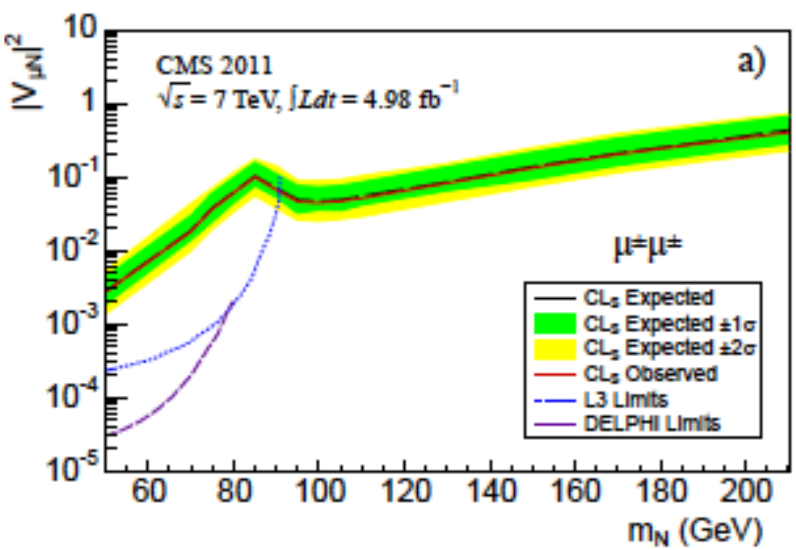


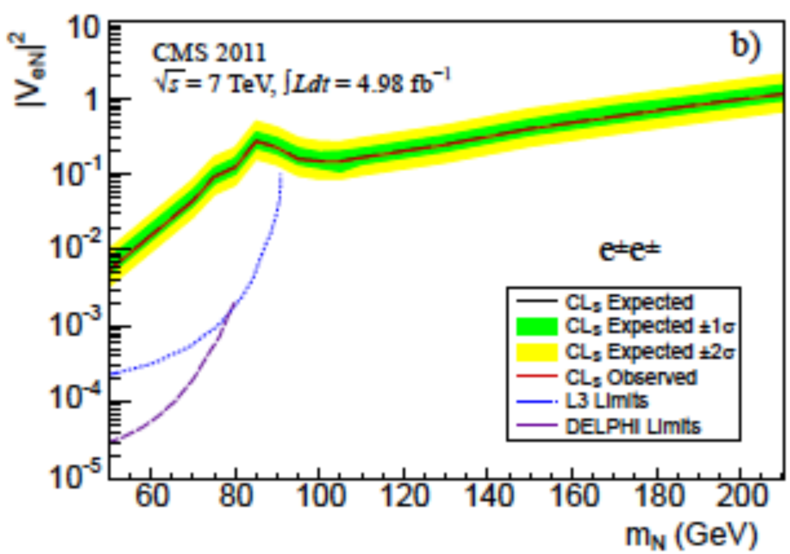
First direct limits on U_e^2(CMS) and U_μ^2(ATLAS&CMS) for $M_N > M_Z$

(assuming that only one heavy neutrino contributes to the production cross-section)





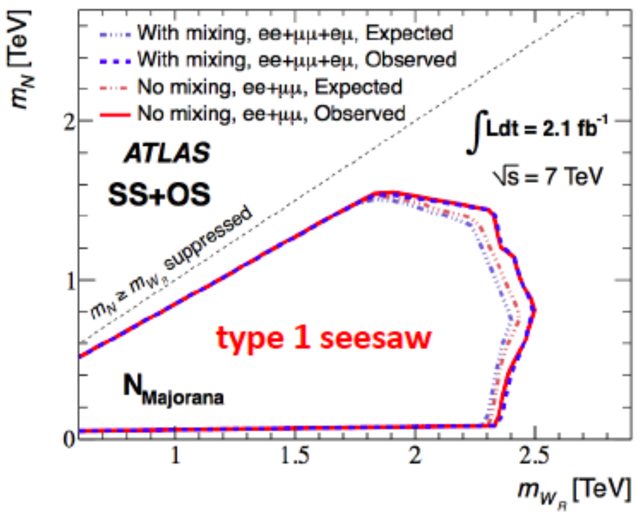


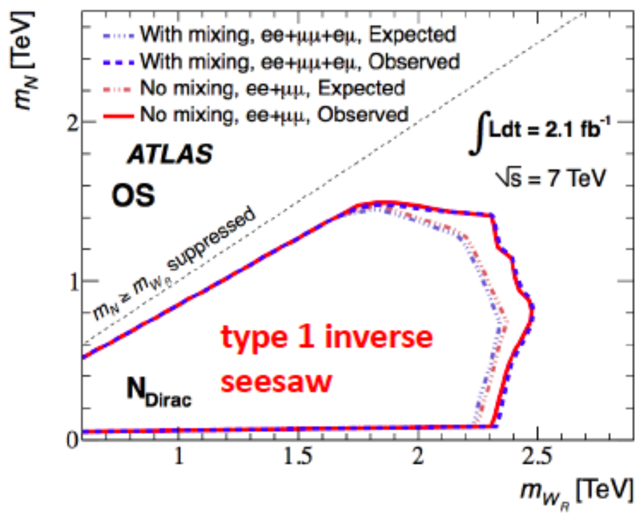


Expect more stringent limits with $\sqrt{s}$ = 8 TeV, and 14 TeV LHC data

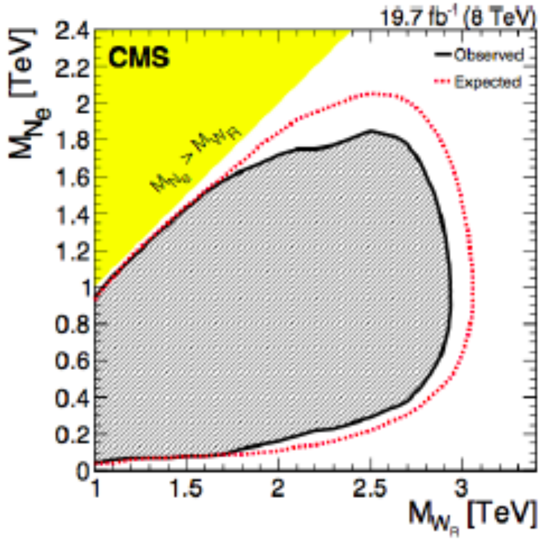
Increased sensitivity to HNL in left-right symmetric models

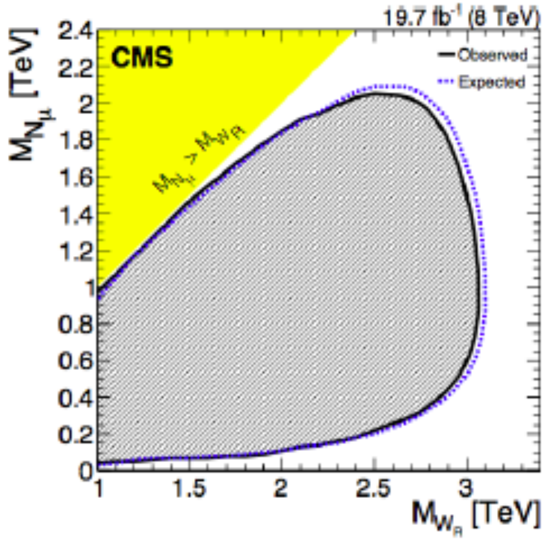
Model-dependent ATLAS and CMS limits on M_N (and W_R)





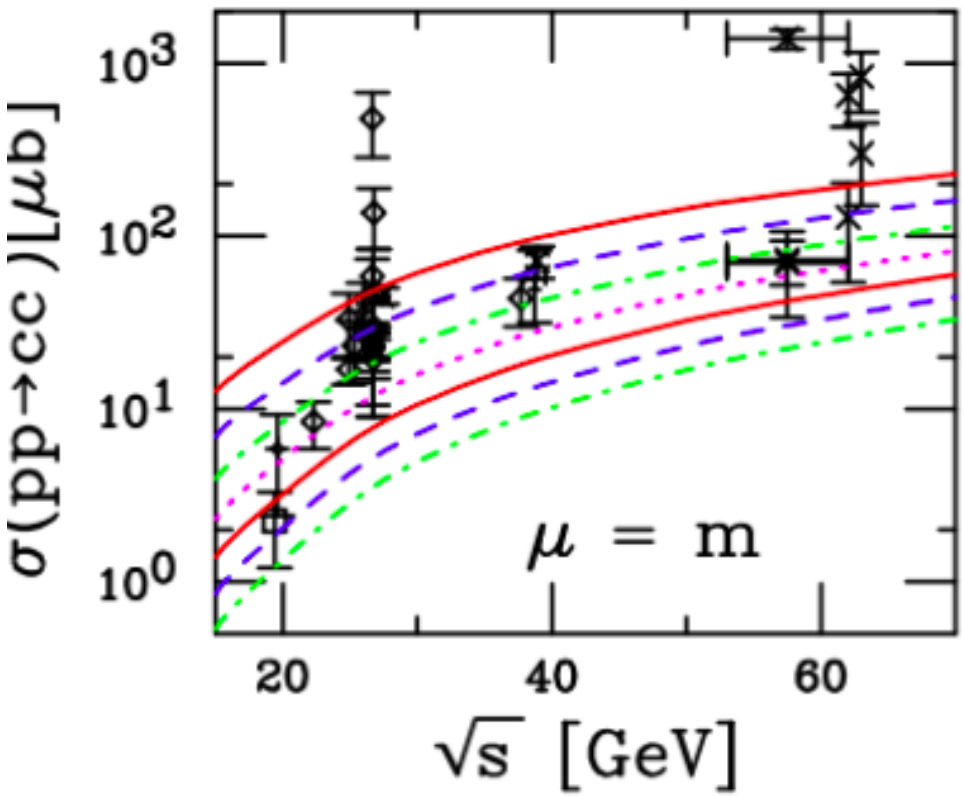
Independent on mixing effects with active neutrinos
→ Can probe HNL masses up to 2-3 TeV





New beam-dump experiment at the SPS

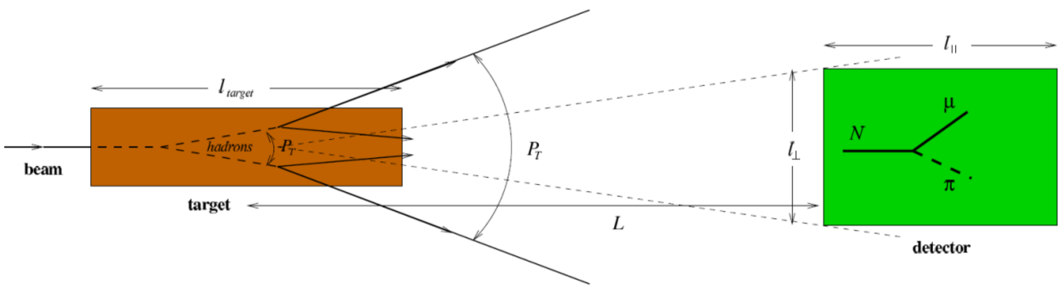
New possibilities in intensity frontier (SHIP facility) at the SPS/CERN
" Beam-dump " is an ideal instrument to search for weakly interacting heavy neutrinos (below charm mass)

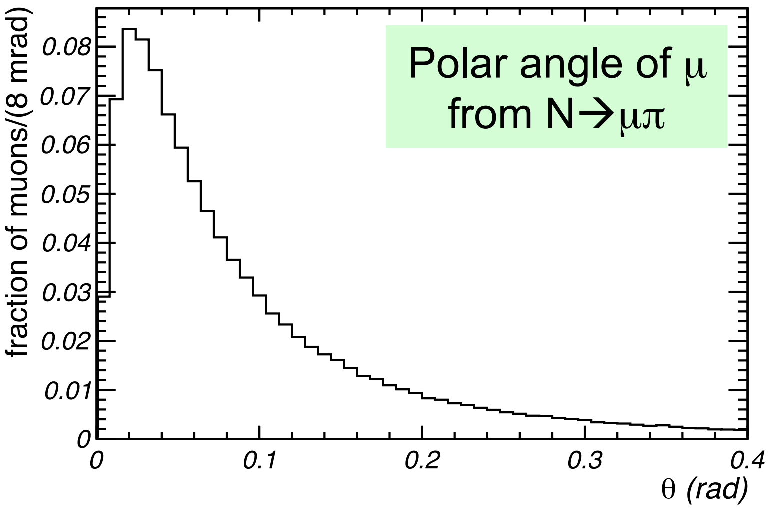


- ✓ *SPS can provide ~2×10^{20} protons-on-target in 4-5 years assuming the same operation as has been demonstrated during CNGS run*
- ✓ *Large charm production cross-section*
- ✓ ***data sample with >10^{17} D, >10^{15} τ !***

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)

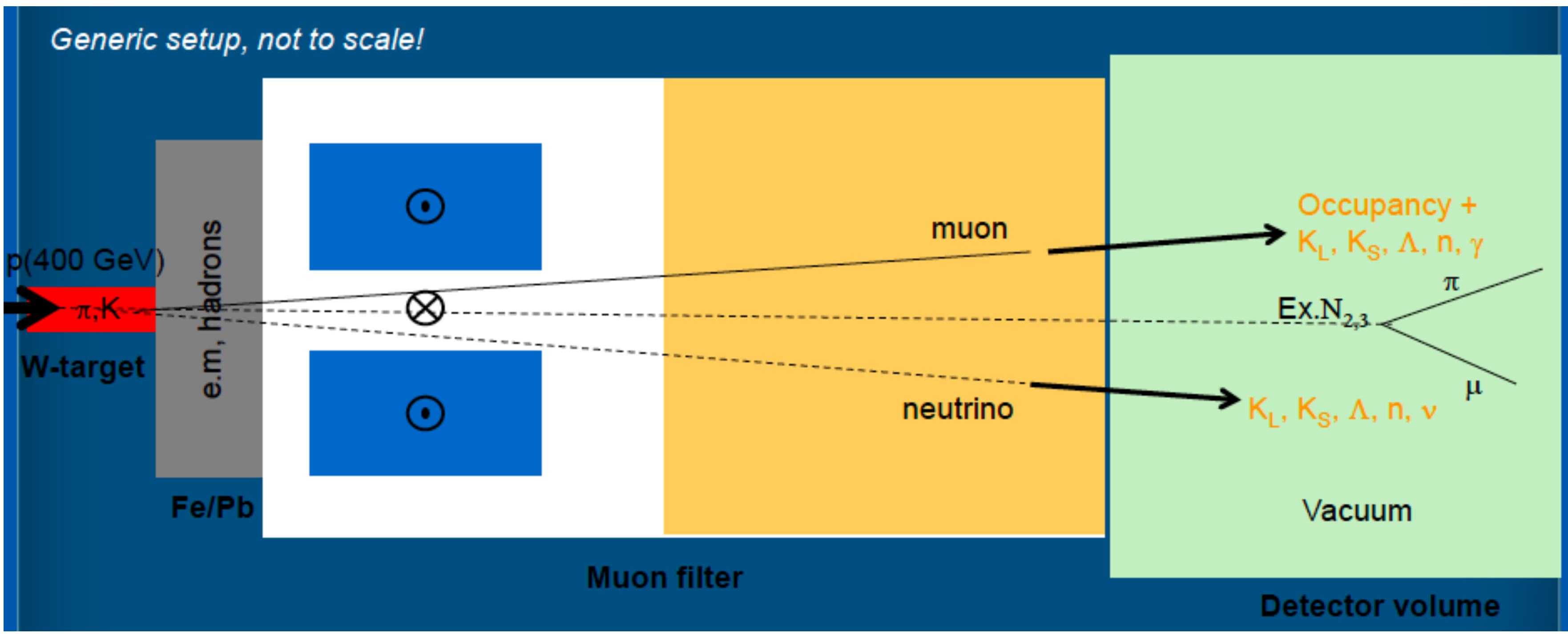
SHIP experimental area

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 → < 50×10^{6} muons

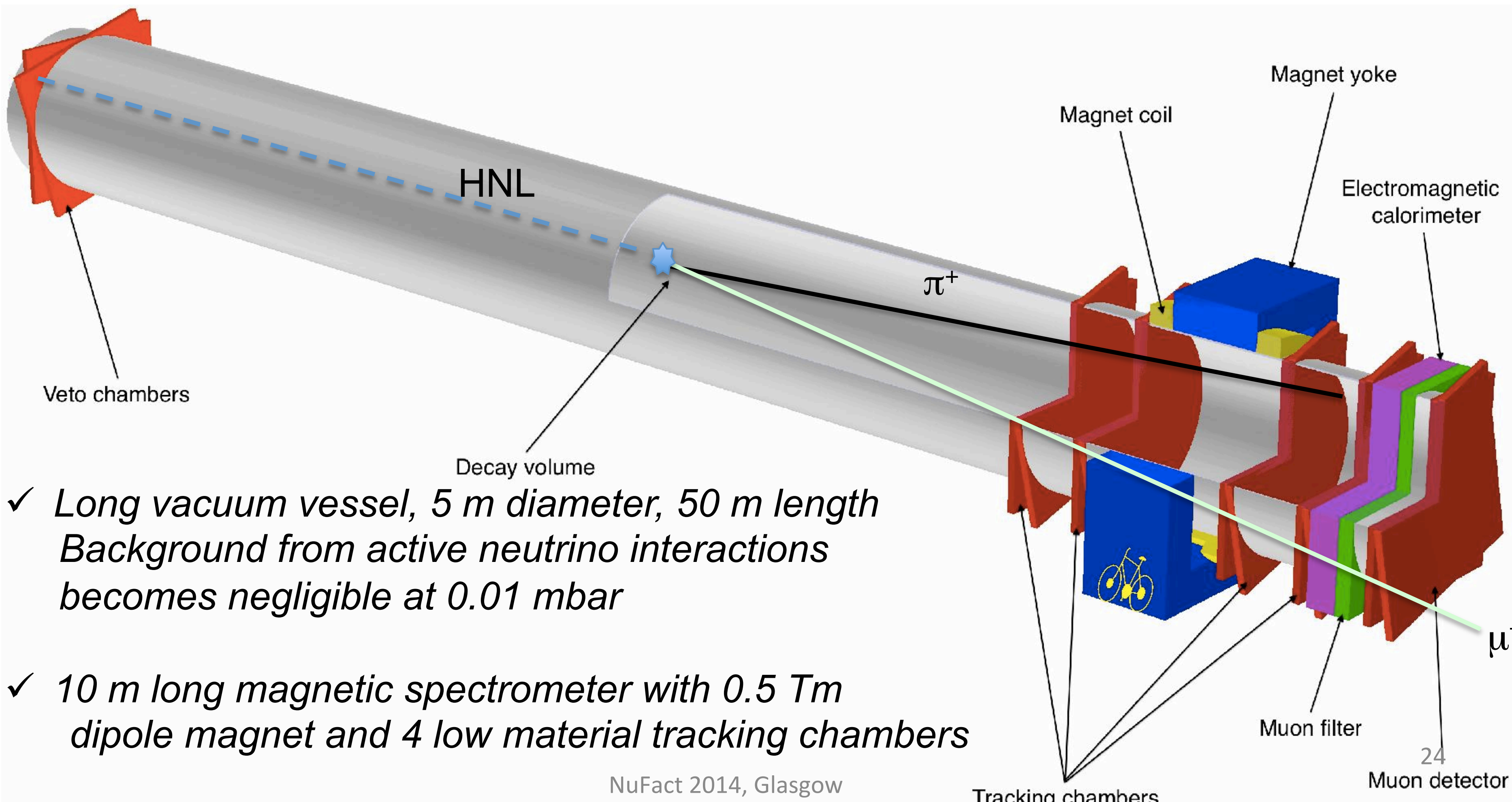


Proper optimization of the muon shield is one of the key issues!

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*



- ✓ *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- ✓ *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

CERN Task Force to evaluate required infrastructure

- ✓ *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*

CERN
CH1211 Geneva 23
Switzerland

EN Engineering Department

EDMS NO.	REV.	VALIDITY
1369559	1.0	RELEASED

REFERENCE
EN-DH-2014-007

Date : 2014-07-02

Report

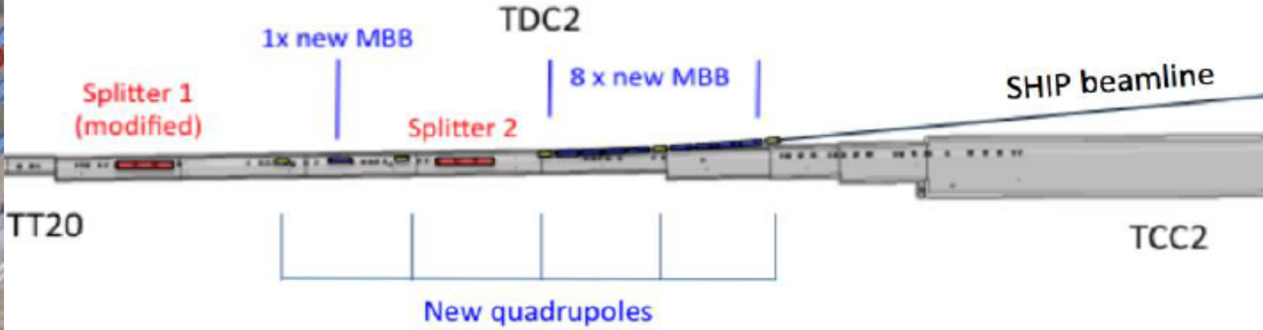
A new Experiment to Search for Hidden Particles (SHIP) at the SPS North Area

Preliminary Project and Cost Estimate

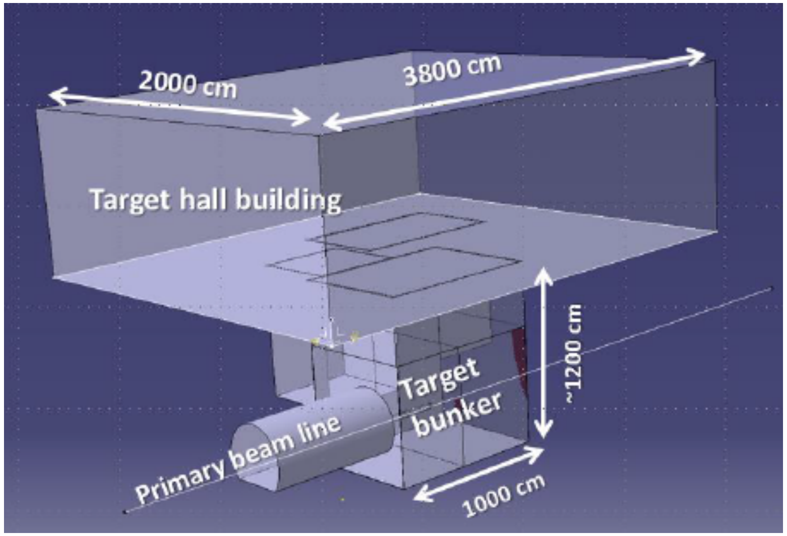
The scope of the recently proposed experiment Search for Heavy Neutral Leptons, EOI-010, includes a general Search for HIdden Particles (SHIP) as well as some aspects of neutrino physics. This report describes the implications of such an experiment for CERN.

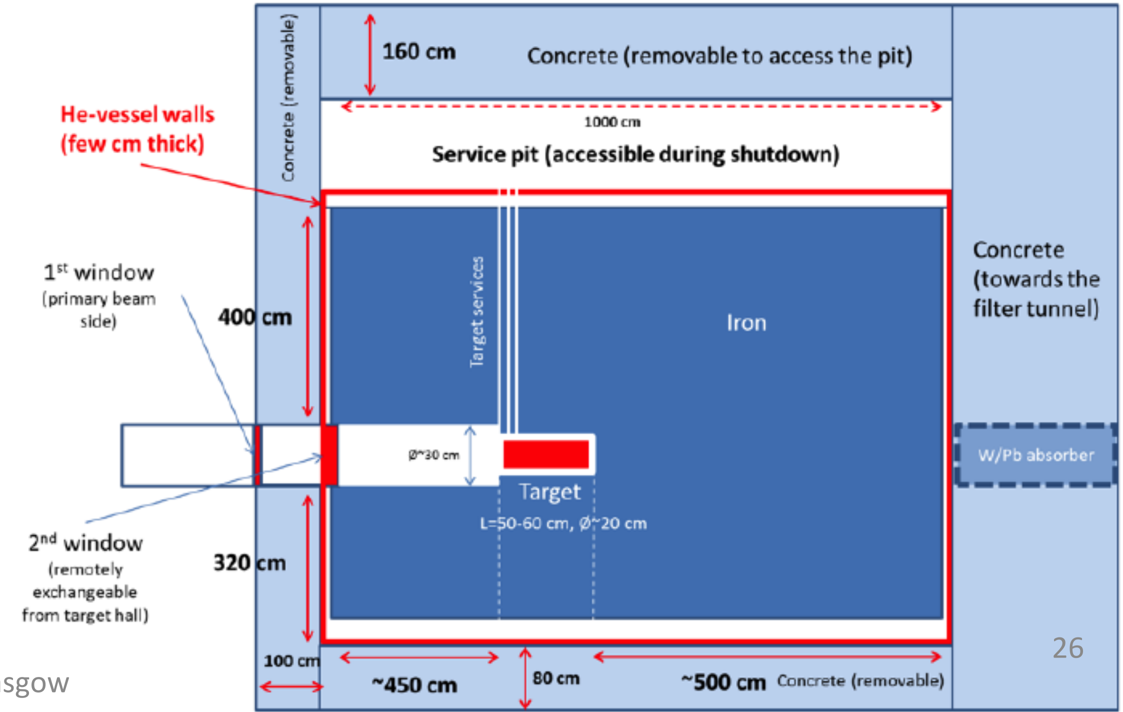
DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:	DOCUMENT APPROVED BY:
G.Arduini, M.Calviani, K.Cornelis, L.Gatignon, B.Goddard, A.Golutvin, R.Jacobsson, J. Osborne, S.Roesler, T.Ruf, H.Vincke, H.Vincke	S.Baird, O.Brüning,J-P.Burnet, E.Cennini,P.Chiggiato, F.Duval, D.Forkel-Wirth, R.Jones, M.Lamont, R.Losito, D.Missiaen, M.Nonis, L.Scibile, D.Tommasini,	F.Bordry, P.Collier, M.J.Jimenez, L.Miralles, R.Saban, R.Trant

SHIP experimental area

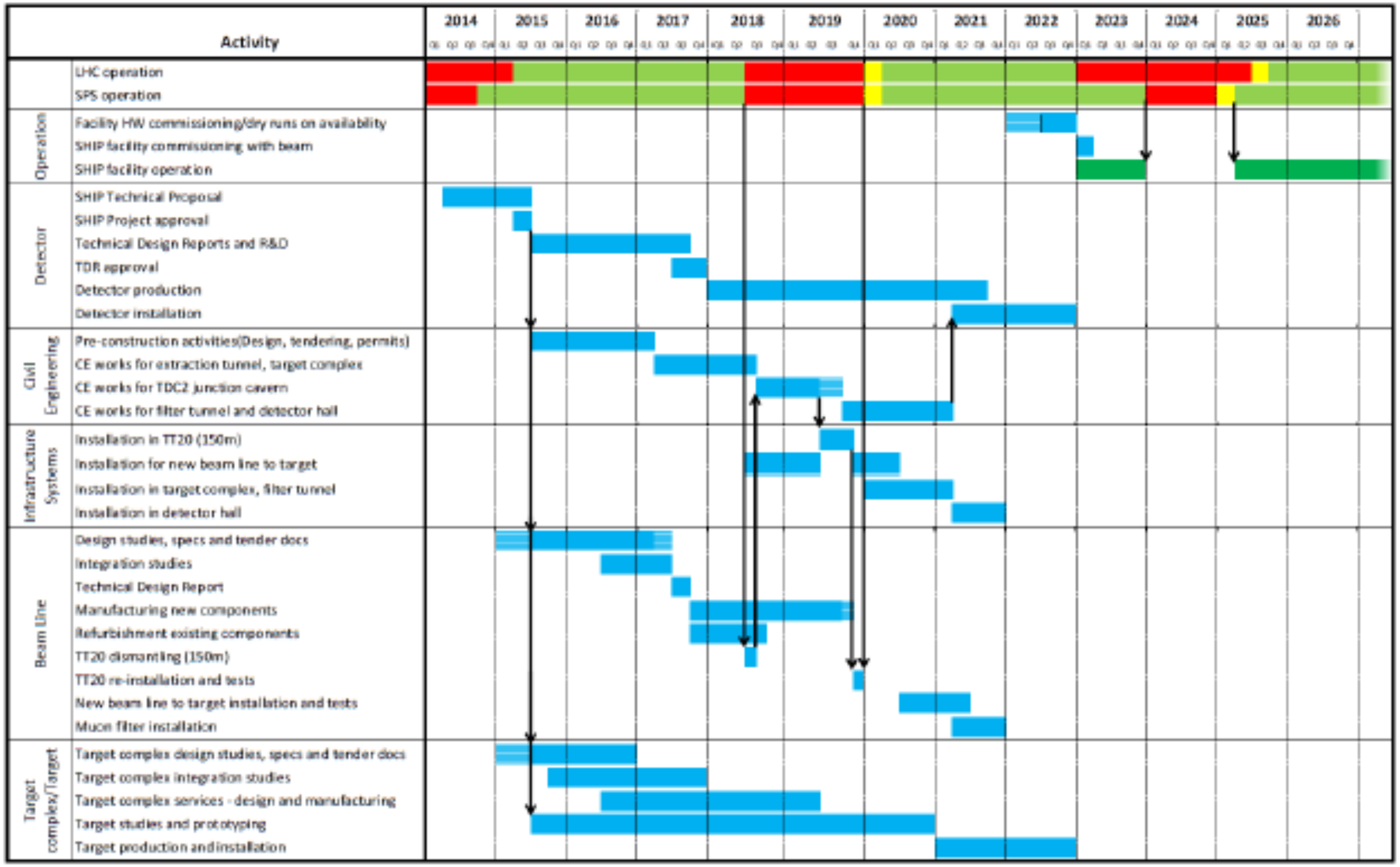


Detailed civil engineering and target station plan evaluated by relevant CERN divisions





Planning schedule of the SHIP facility

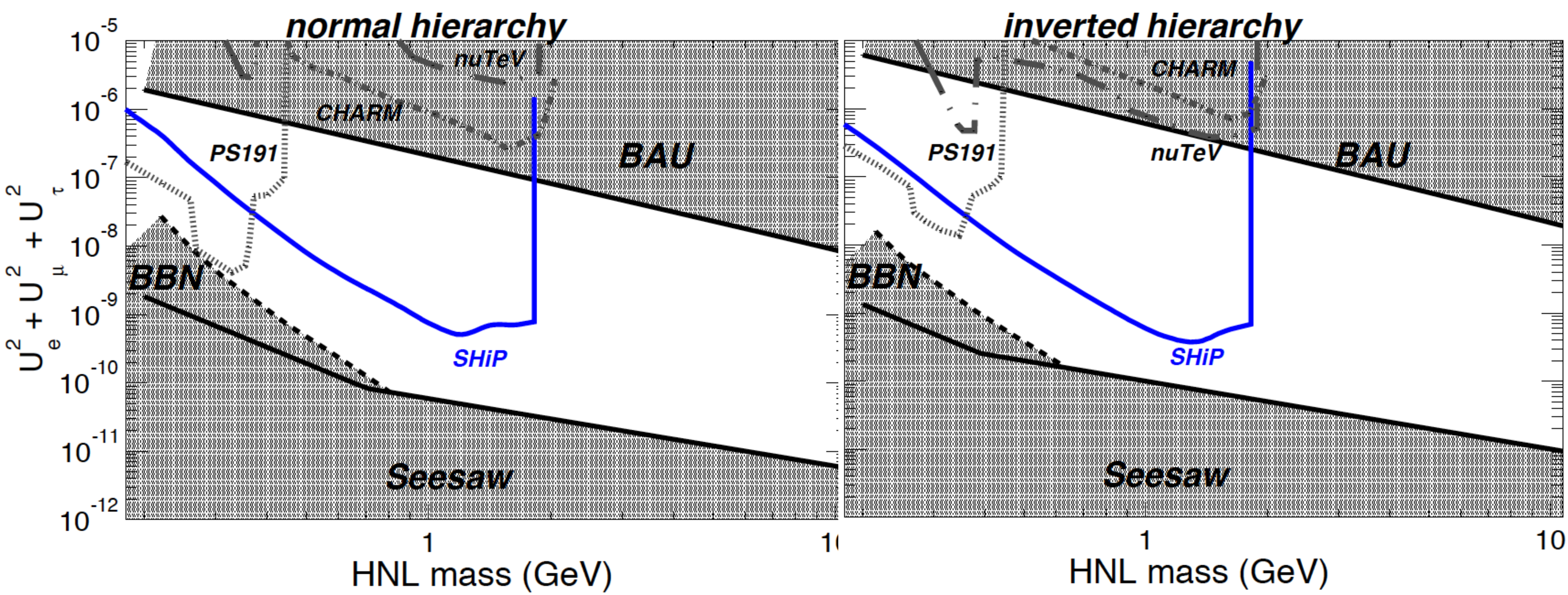


A few milestones:

- ✓ ***Form SHIP collaboration*** → ***June-September 2014***
- ✓ ***Technical proposal*** → ***2015***
- ✓ *Technical Design Report* → *2018*
- ✓ *Construction and installation* → *2018 - 2022*
- ✓ *Commissioning* → *2022 - 2023*
- ✓ *Data taking and analysis of 2×10^{20} pot* → *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)*



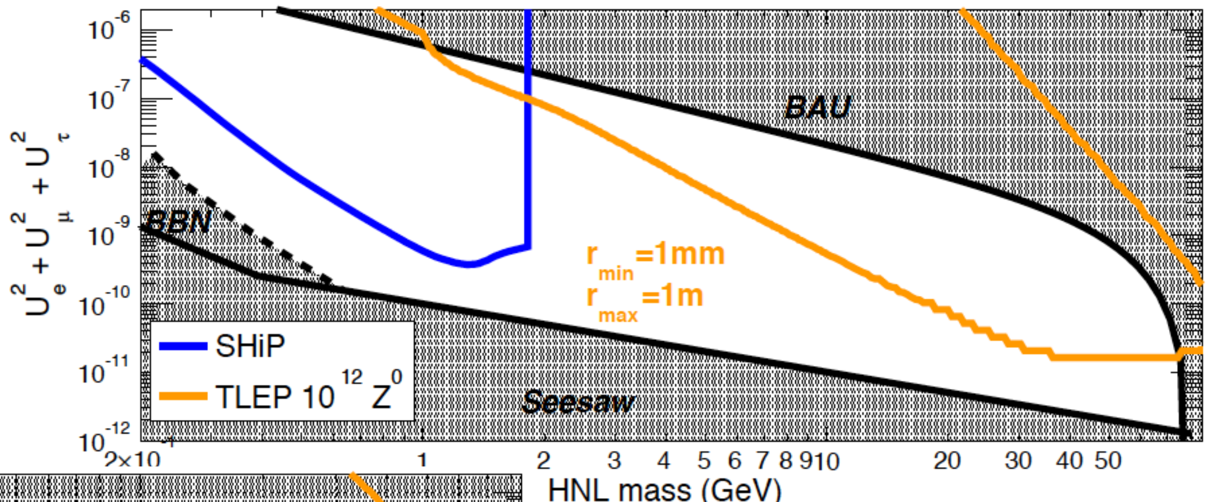
How to extend sensitivity to higher masses

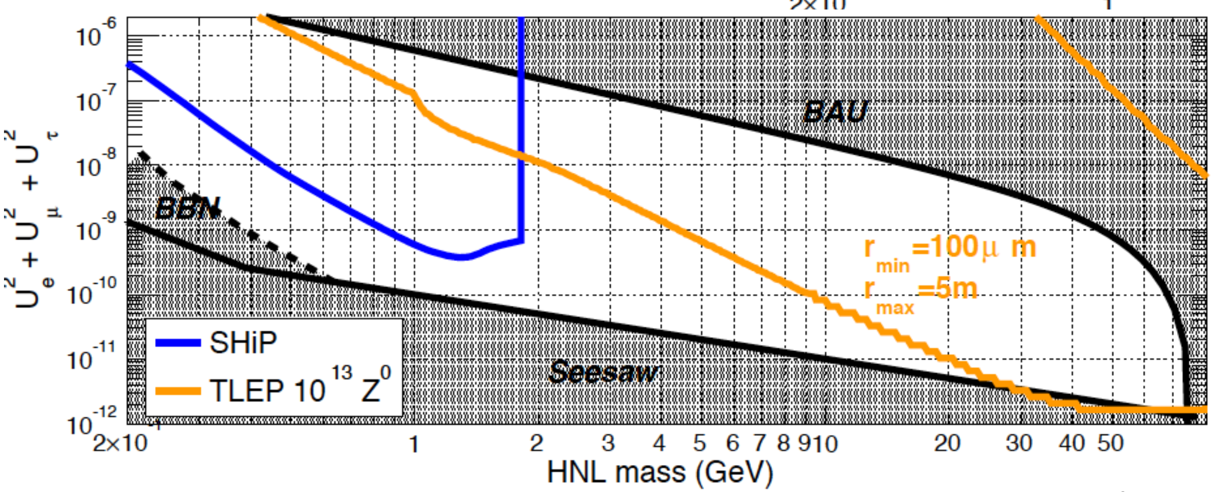
- ✓ *Use processes $Z \to N\nu$ with $N \to$ lepton + 2 jets*

$$BR(Z \to \nu N) \cong BR(Z \to \nu\nu)\times U^2, \quad \Gamma_N \cong G_F^2 \times M_N^5 \times U^2 \times N_{decay\ channels} / 192\pi^3$$

- ✓ *Assuming data sample of 10^{12} Z decays one can reach very interesting sensitivity for $M_N > 10$ GeV*

- ✓ *Expected sensitivity of FCC in e^+e^- mode assuming zero background*





Courtesy of A.Blondel, E.Graverini, N.Serra and M.Shaposhnikov

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*