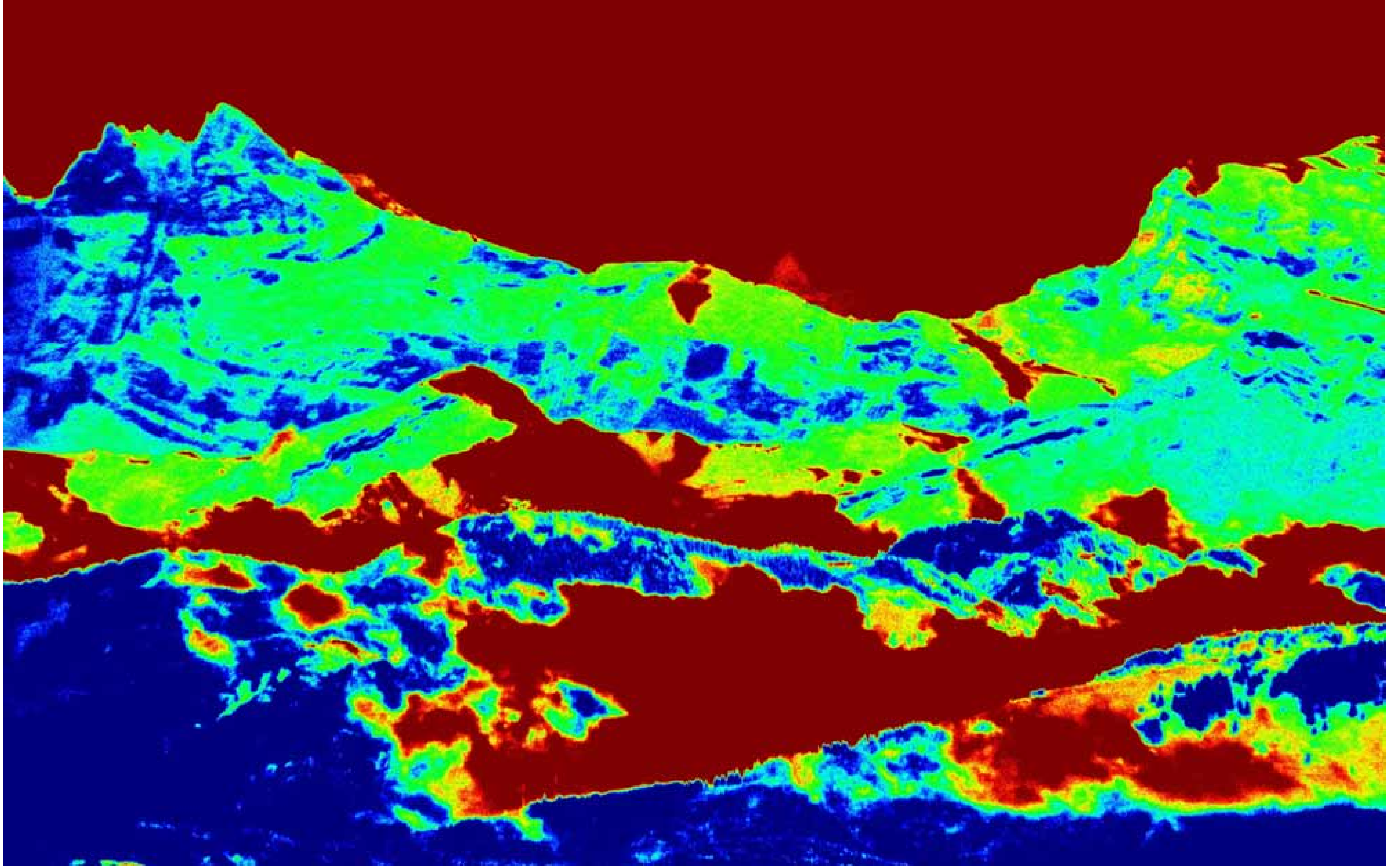
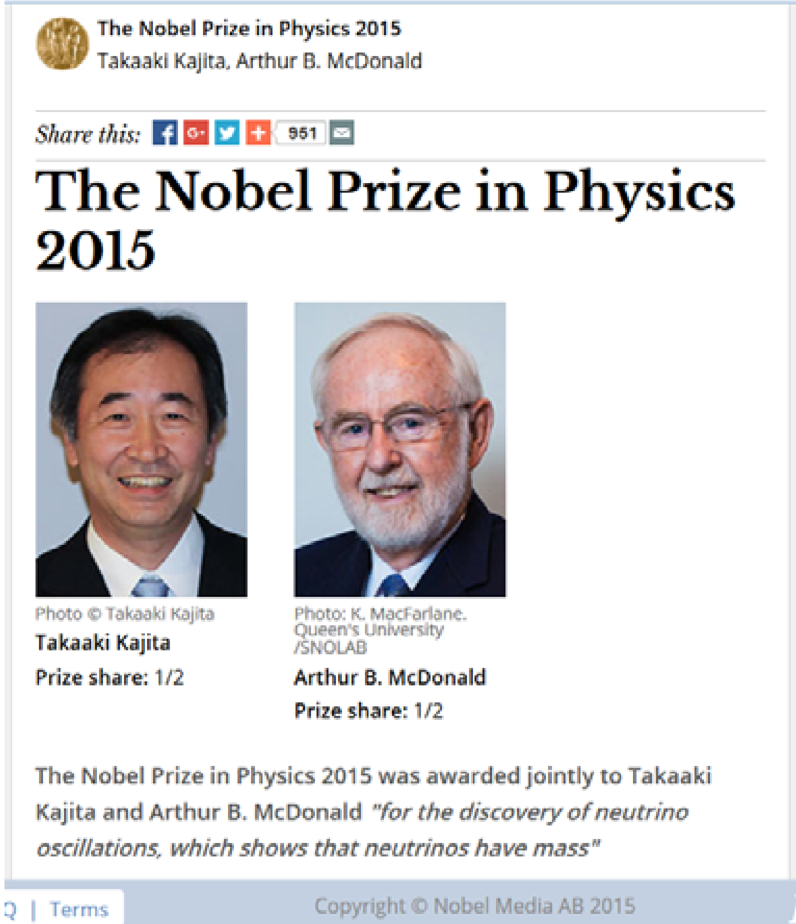
The Search for the Right-Handed Neutrinos




The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Terms

The discovery that neutrino flavours transform (Neutrino Oscillations) was a long process initiated in 1968 and completed in 1998-2001.
➔ **Neutrinos have mass !**

There is no unique way to incorporate this in the Standard Model
It almost certainly implies the existence of
-- new mass-generation mechanism
-- new phenomena such as right-handed neutrinos

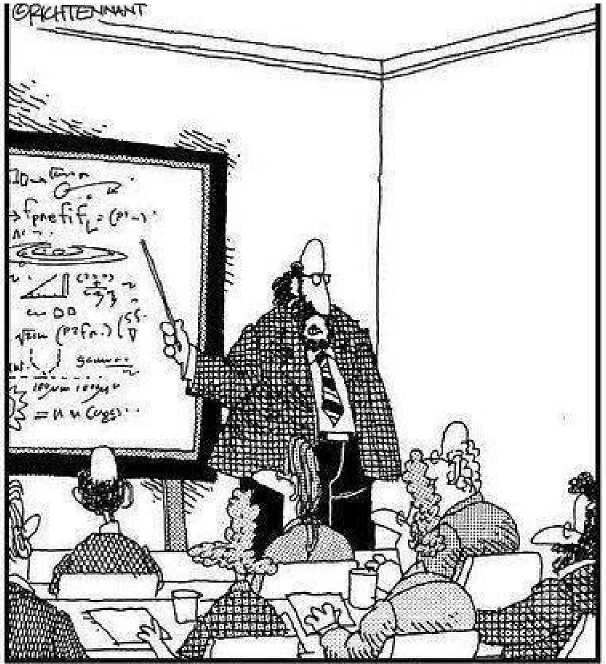
➔ possible explanations for the baryon asymmetry of the universe and for dark matter

Neutrino masses? Mixings? Ordering?
Majorana mass term? CP violation
eV, keV, GeV, TeV, …, ZeV RH neutrinos?

This opens a deep field of research for many many years.

Electroweak eigenstates

I = 1/2	I = 0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

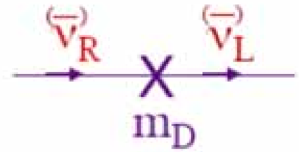
Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

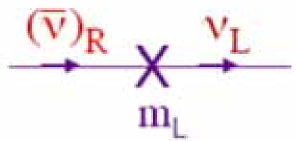
$$m_D \nu_L \overline{\nu_R} \qquad m_D \overline{\nu_L} \nu_R$$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry</u> prevents adding then a term like

$$m_M \overline{\nu_R{}^c}\, \nu_R$$



and this simply means that a neutrino turns into a antineutrino

It is perfectly conceivable ('natural'?) that both terms are present.

Dirac mass term + Majorana mass term ➔ 'see-saw'

B. Kayser, the physics of massive neutrinos (1989)

Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

I_{weak}=	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

I_{weak}=	ν_L	$\bar{\nu}_R$
	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ — see-saw

Dirac + Majorana

m ↑

dominantly:

I_{weak}=	ν	N	$\bar{\nu}$	$\bar{N}$
	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

There even exists a scenario that explains everything: the νMSM

Shaposhnikov et al

TeV

GeV

MeV

keV

eV

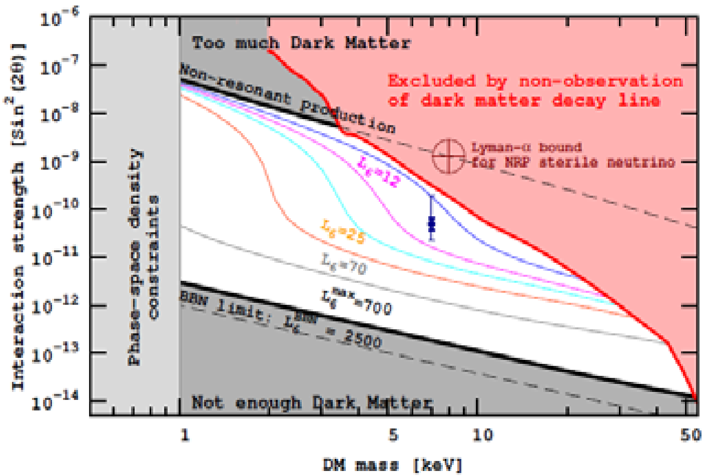
meV

N_2, N_3

can generate Baryon Asymmetry of Universe
if $m_{N2,N3}$ > 140 MeV

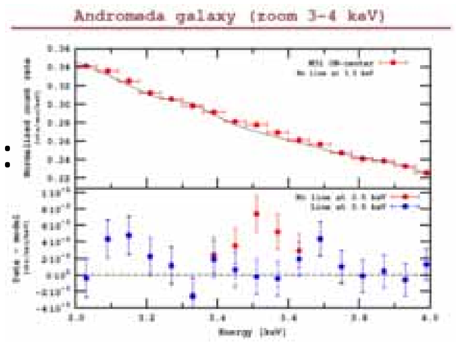
N_1

constrained:
mass: 1-50 keV
mixing :
10^{-7} to 10^{-13}
decay time:
$\tau_{N1} > \tau_{Universe}$



ν_3
ν_2
ν_1

$N_1 \rightarrow \nu\,\gamma$
may have been seen:
arxiv:1402:2301
arxiv:1402.4119



Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu_L \cos\theta - N^c{}_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

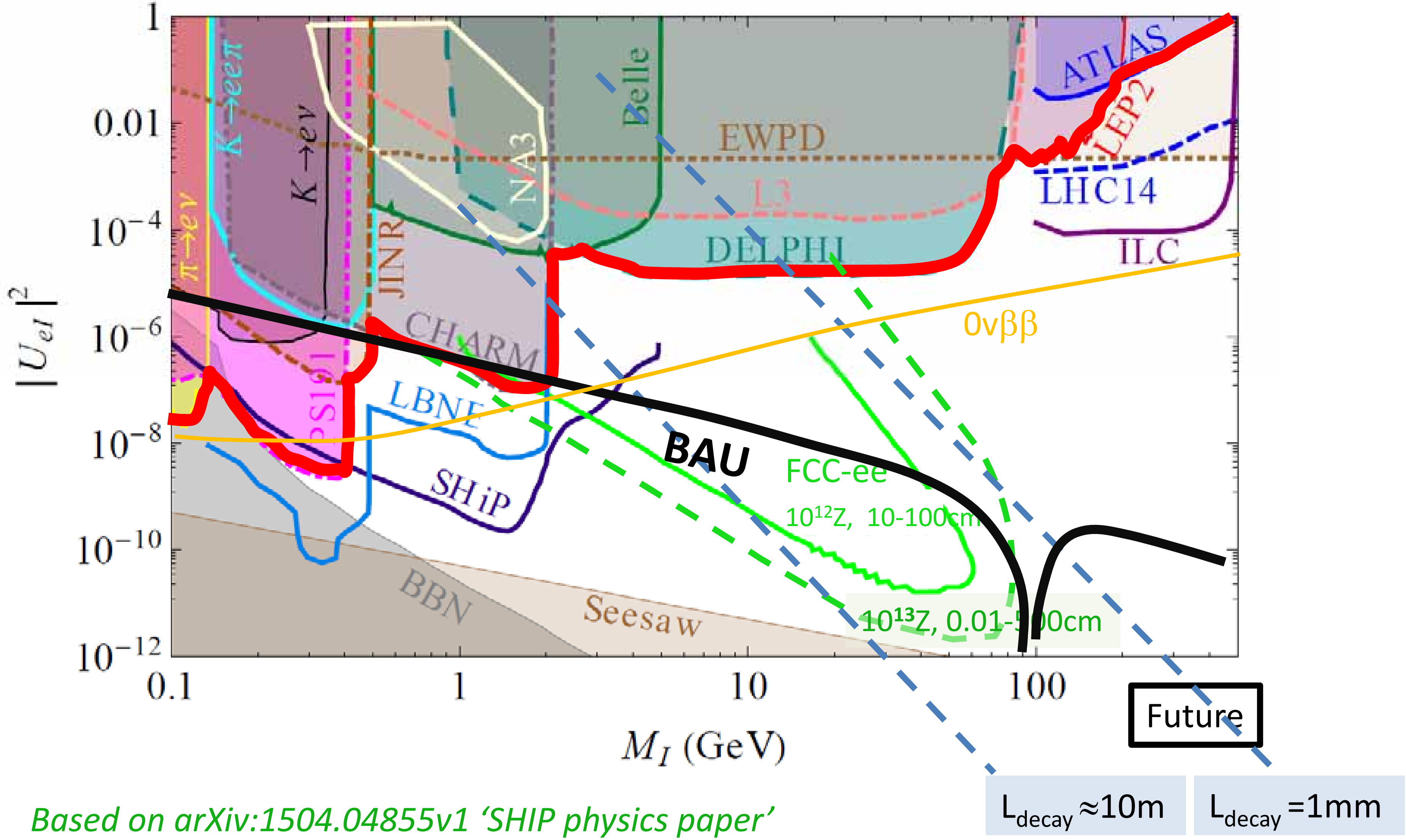
what is produced in W, Z decays is:

$$\nu_L = \nu \cos\theta + N \sin\theta$$

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
-- if very light (eV) , possible effect on neutrino oscillations (see talks later today)
-- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$
-- possibly measurable effects at High Energy
If N is heavy it will decay in the detector (not invisible)
➔ PMNS matrix unitarity violation and deficit in Z «invisible» width
➔ Higgs, Z, W visible exotic decays $H \rightarrow \nu_i \bar{N}_i$ and $Z \rightarrow \nu_i \bar{N}_i$, $W \rightarrow l_i \bar{N}_i$
➔ also in K, charm and b decays via $W^* \rightarrow l_i^{\pm} \bar{N}$, $N \rightarrow l_j^{\pm}$
with any of six sign and lepton flavour combination
➔ violation of unitarity and lepton universality in Z, W or τ decays
-- etc... etc...
-- Couplings are very small (m_ν / m_N) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

Present limits

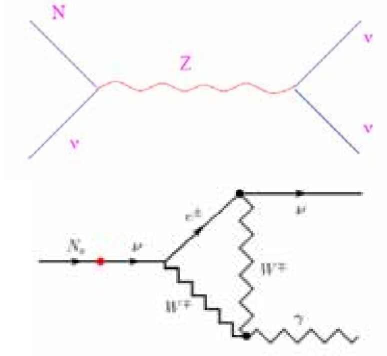


Based on arXiv:1504.04855v1 'SHIP physics paper'
And Pilar Hernandez, HEP-EPS Vienna

Search Processes (I)

m_N Below m_π:

N→ 3ν; N→ νγ w $E_\gamma = m_N/2$



$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

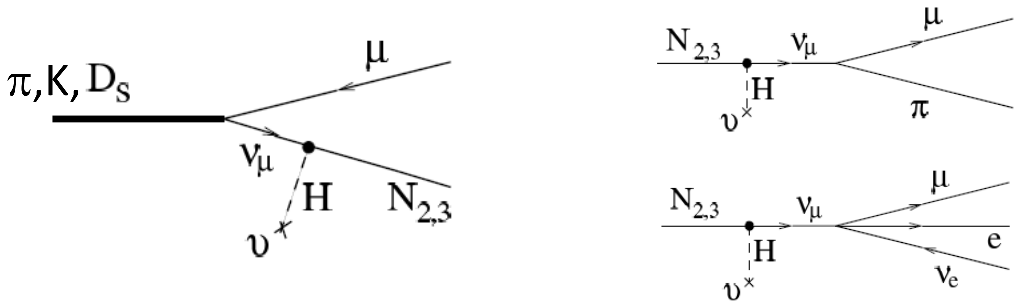
Long life, **dark matter candidate**

Equilibrium with neutrinos produced in the stars

➔ Search for gamma emission line (such as 3.5 keV line)

Drewes et al; arXiv:1602.04816v1

Meson decay (π,K: neutrino beams) examples:



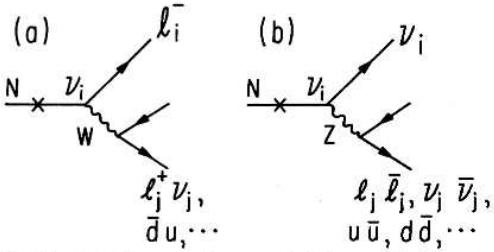


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

$$L \approx \frac{3}{|U|^2\,(m_{\nu_m}(\mathrm{GeV}/c^2))^6} \times \frac{P_\nu}{45GeV/c}$$

Decay via W gives at least two charged particles, and amounts to ~60% of decays.

Searches for long lived decays in neutrino beams PS191, NuTeV, CHARM; SHIP and DUNE proposals

New proposal

Experiment	PS191	NuTeV	CHARM	SHiP
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\cdot 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0

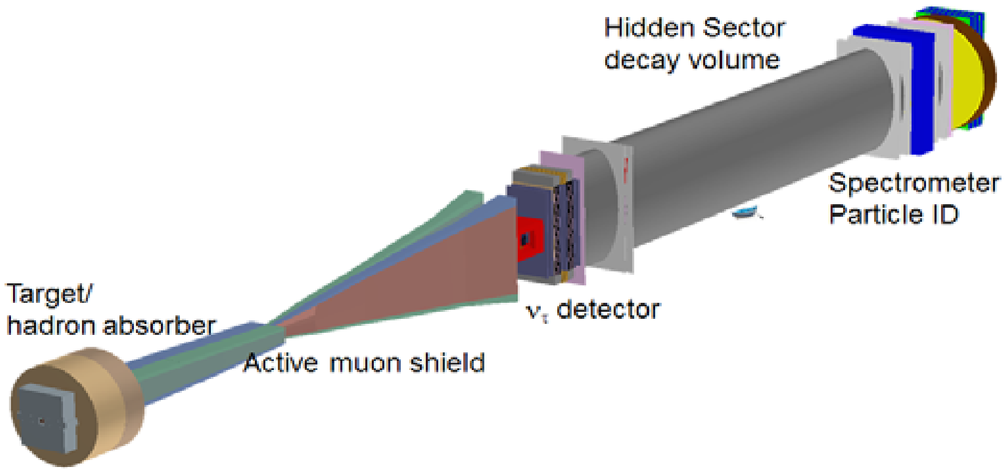
Next generation heavy neutrino search experiment SHIP

-- focuses on neutrinos from charm to cover 0.5 – 2 GeV region

-- uses beam dump to reduce background from neutrino interactions from pions and Kaons and bring the detector as close as possible to source.

-- increase of beam intensity and decay volume

status: proposal, physics report and technical report exist. R&D phase approved at CERN



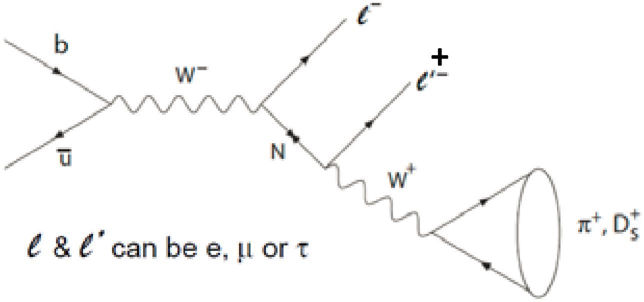
arXiv:1504.04855

arXiv:1504.04956

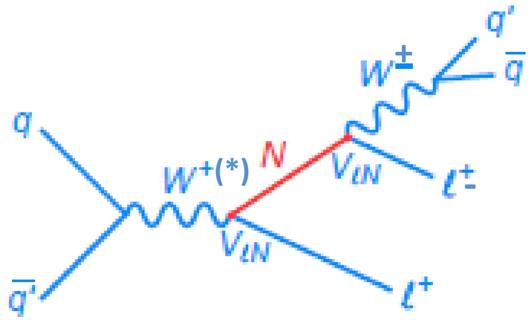
Processes (II)

Search for heavy right-handed neutrinos in collider experiments.

B factories

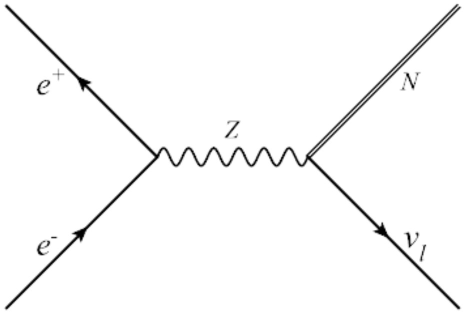


Hadron colliders

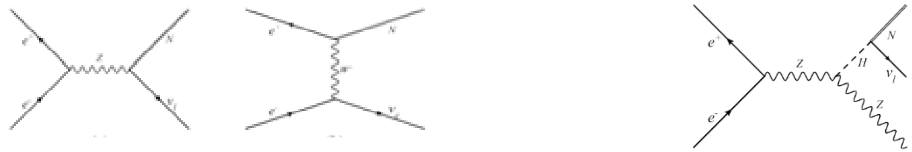


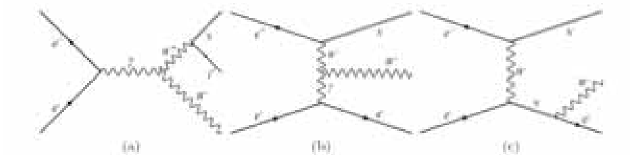
Z factory (FCC-ee, Tera-Z)

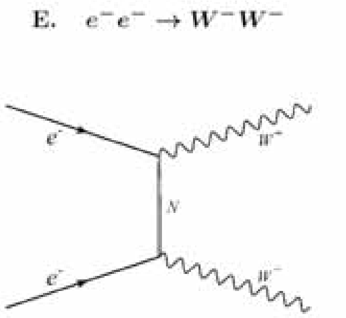
arXiv:1411.5230

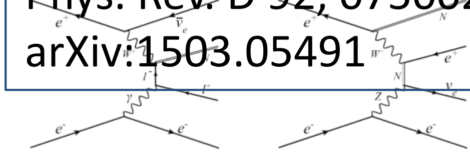


HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)









Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

Searches for heavy neutrinos ν_h in B decays

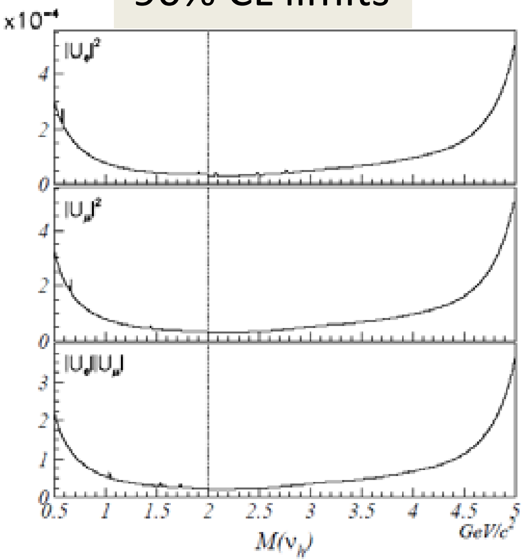
-- **BELLE** *Phys. Rev. D. 87, 071102 (2013), arXiv:1301.1105*

7.8 10^8 B mesons at Υ_{4s}!

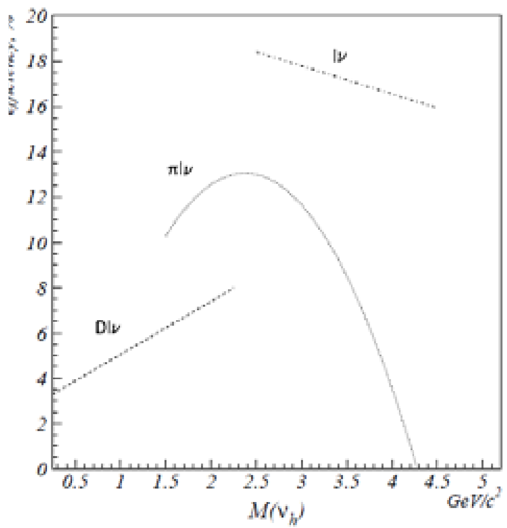
Search for ℓ_2 +($\ell_1\pi$), where ℓ_1 and π have **opposite charge and displaced vertex** for $M(\nu_h)$ =1GeV/c2 and $|U_e|^2 = |U_\mu|^2 = 10^{-4}$ the flight length is $c\tau \simeq$ 20m.

➔ charge and flavour of $\boldsymbol{\ell_2\ell_1}$ can be **any combination of e, μ, + or -** because the heavy neutrino is assumed to be Majorana. (If Dirac fermion, -> opposite charges only).
A few signal events, no 'peak'.

90% CL limits

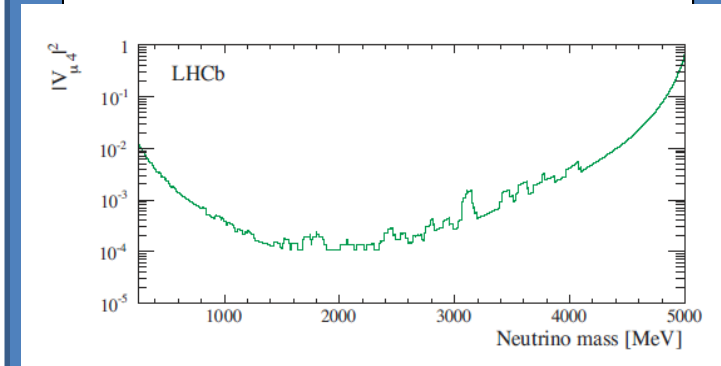


Efficiency for the search



LHCb collaboration,
PRL 112, 131802 (2014)

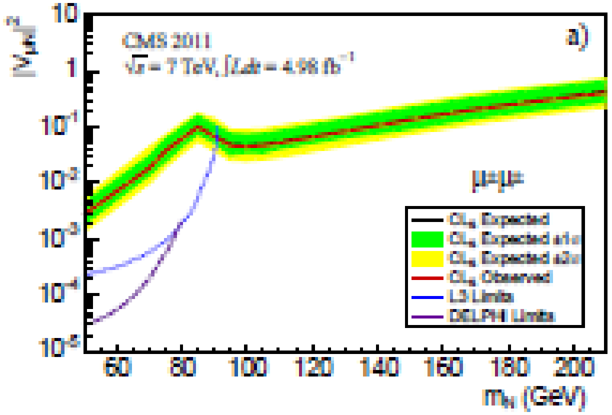
$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$ at 95%

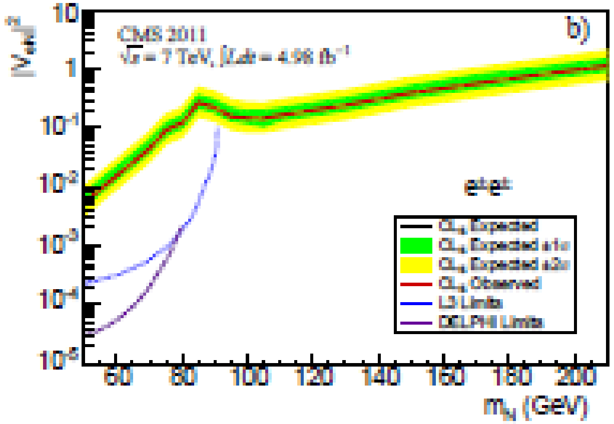


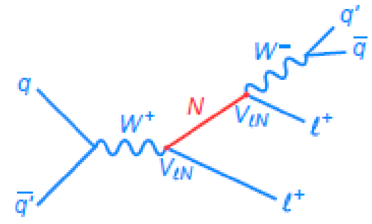
Scope for 10-100x improvement at SuperKEKb

Scope for much improvement at 13TeV&HL-LHC!

CMS search for same sign muon pairs or electron pairs at the LHC

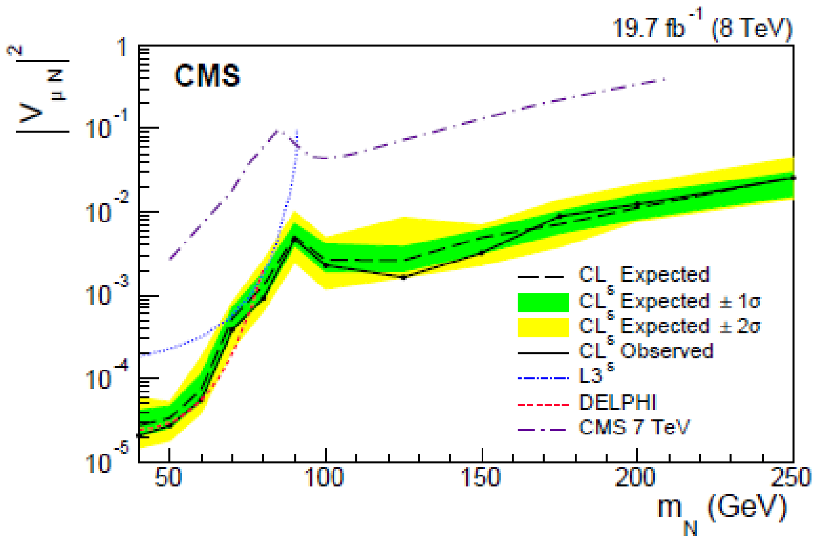






CMS arXiv:1207.6079.

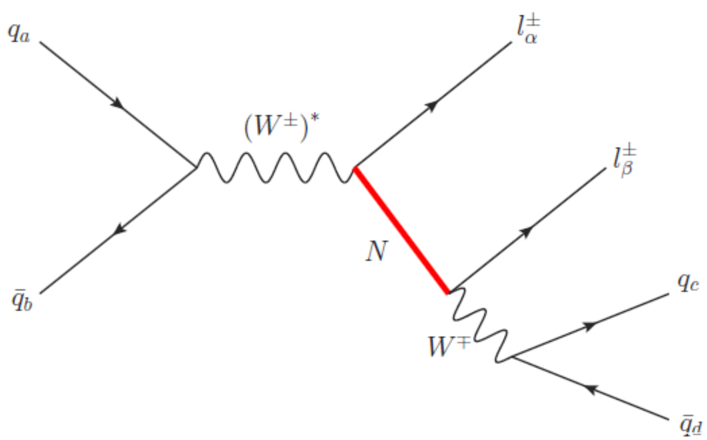
arXiv:1501.05566



Begin to match/superseed the DELPHI limit.

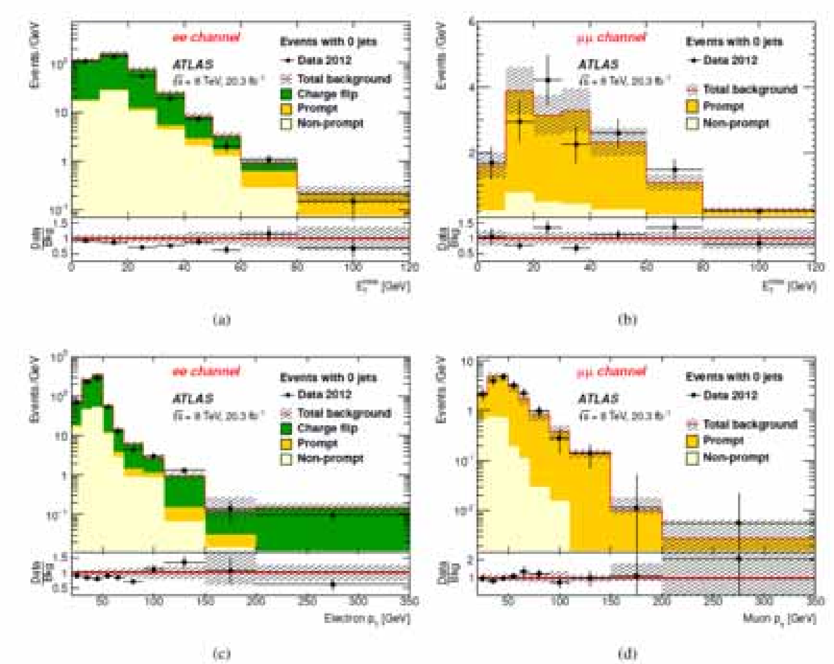
limits at $|U|^2 \sim 10^{-2-5}$ level

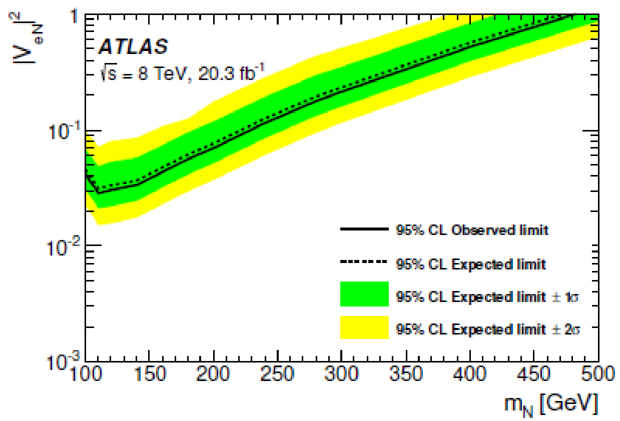
ATLAS search for Heavy Neutrinos at LHC *JHEP07(2015)162 arXiv:1506.06020*



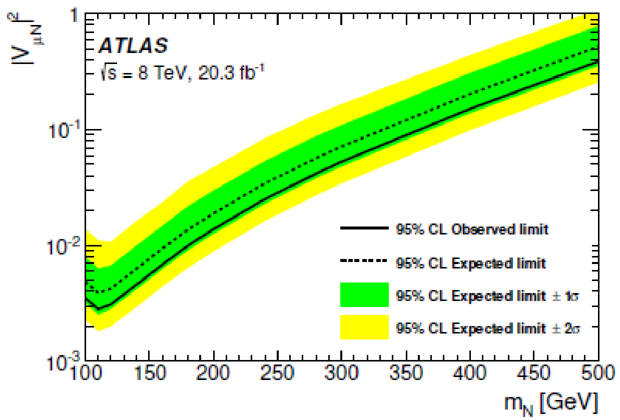
e^-e^-, e^+e^+, $\mu^-\mu^-$, $\mu^+\mu^+$ final states
(like sign, like flavour leptons)
Concentrates on m_N>100 GeV
'because <100 GeV excluded by LEP'

Charge flip significant bkgd for ee channel





(b)



LHC prospects

~10^9 νs from W decays in ATLAS and CMS with 25 fb^{-1} @8 TeV

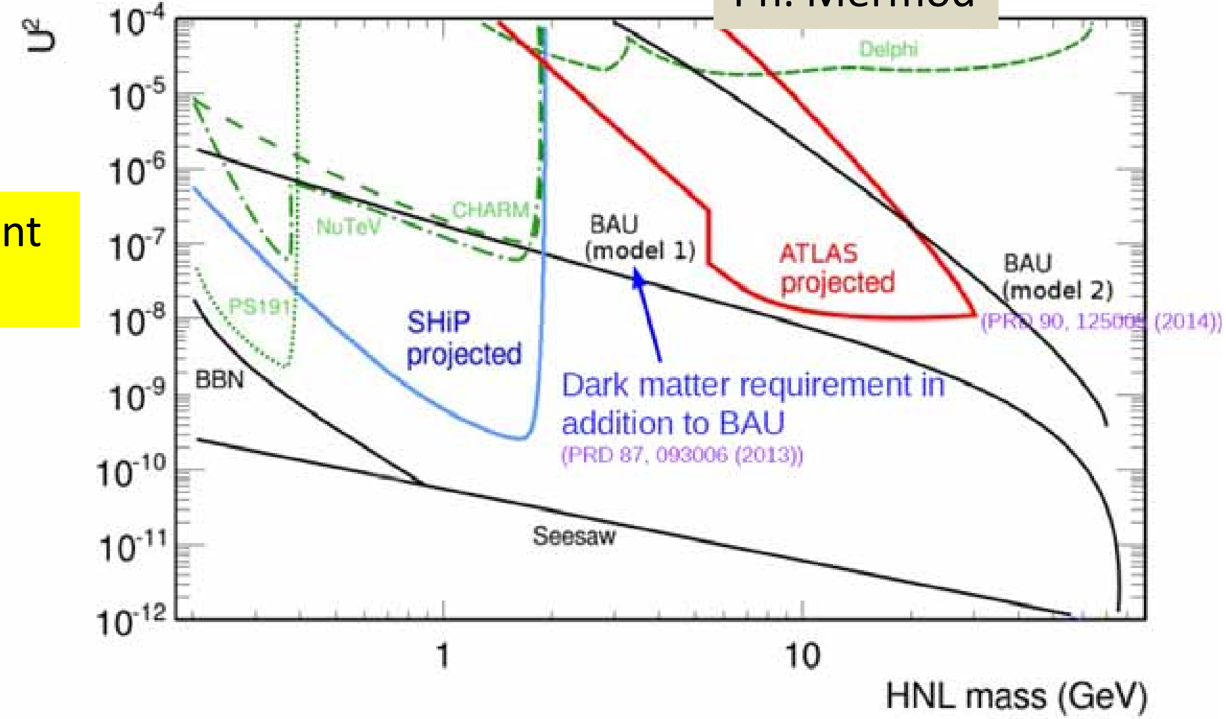
Signals of RH neutrinos with mass ≤ m_W could be visible if mixing angle $O(10^{-7,8})$

The keys for that region of phase space

-- require **displaced vertex**
-- allow leptons of different charge and flavour
-- constrain to W mass.

Ph. Mermod

Hope for considerable improvement in W decays at LHC!



e+ e- Search for heavy neutral leptons

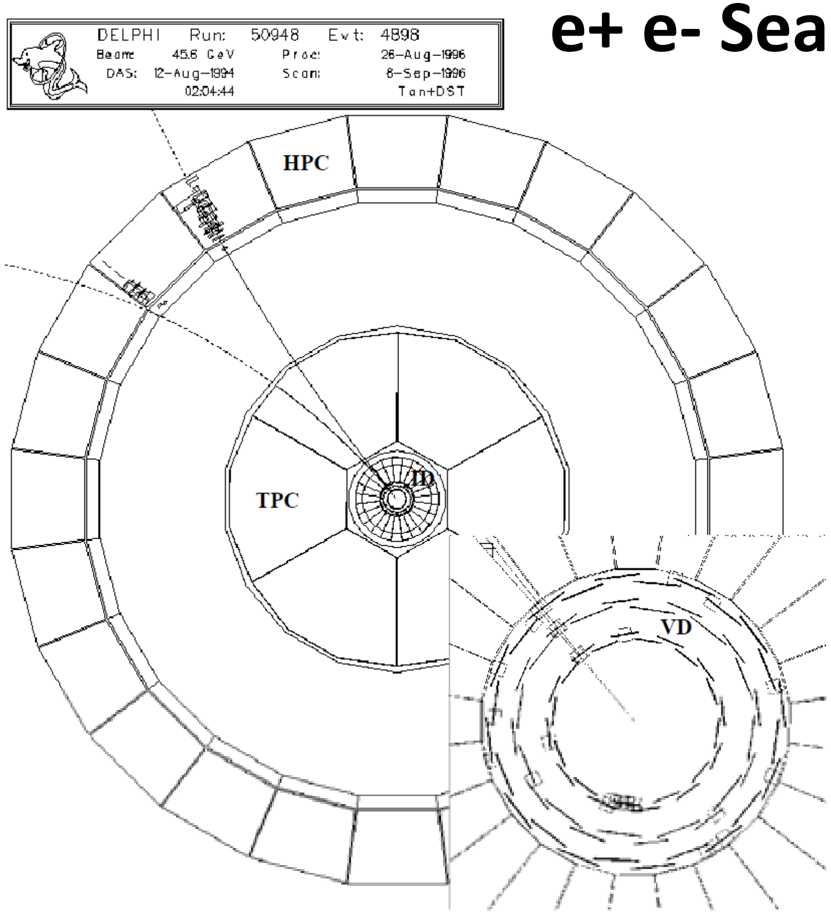


Fig. 3. Surviving event in the monojet search. It has an invariant mass of 300 MeV/c² and a missing p_t of 6 GeV/c and is probably an $e^+e^- \to e^+e^-\nu\bar{\nu}$ interaction

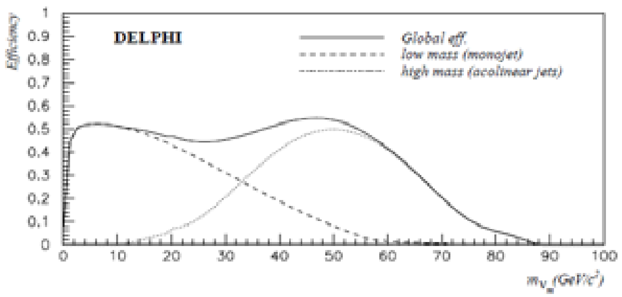
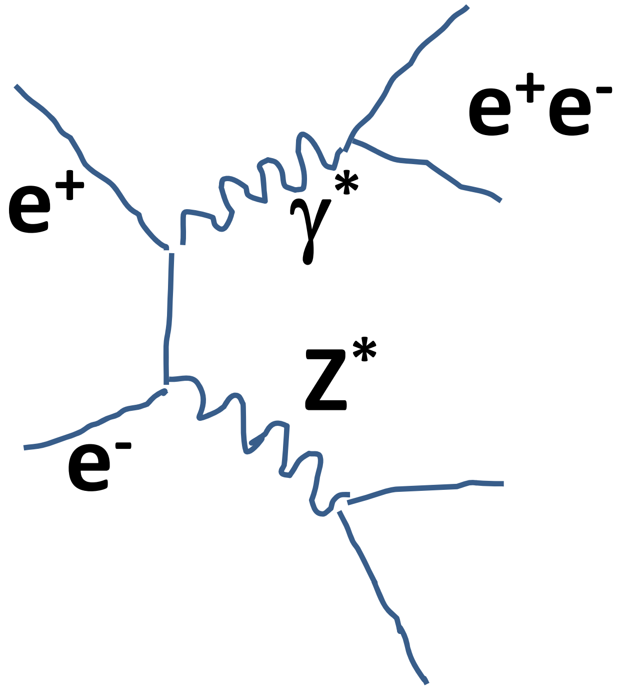


Fig. 4. Efficiency of the monojet search (Sect. 3) and the acollinear jets search (Sect. 4). The *full curve* shows the efficiency of the two searches combined

search $e^+ e^- \to \nu N$

$N \to \nu(\gamma/Z)^* \to$ monojet

Find: one event in 4×10^6Z:



Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

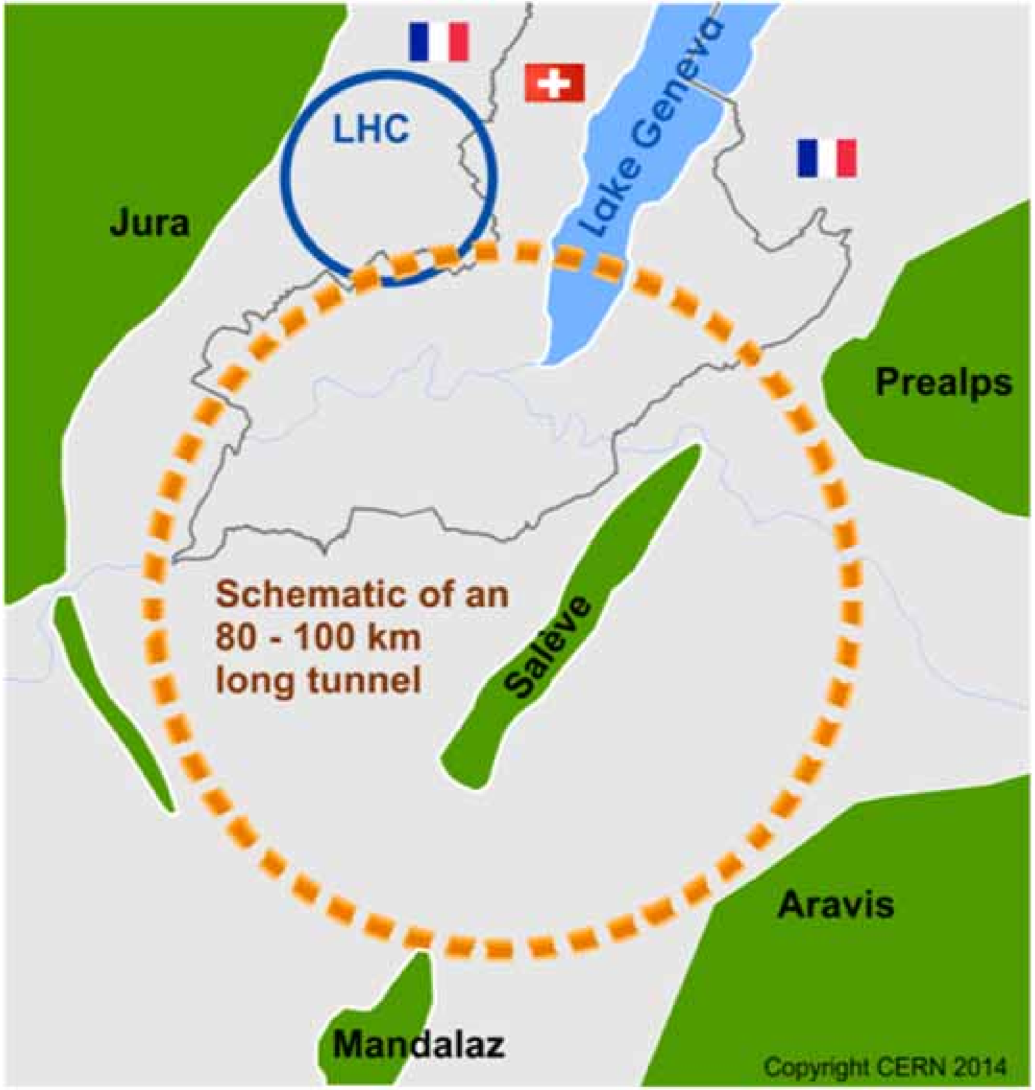
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**

~16 T ⇒ 100 TeV *pp* in 100 km

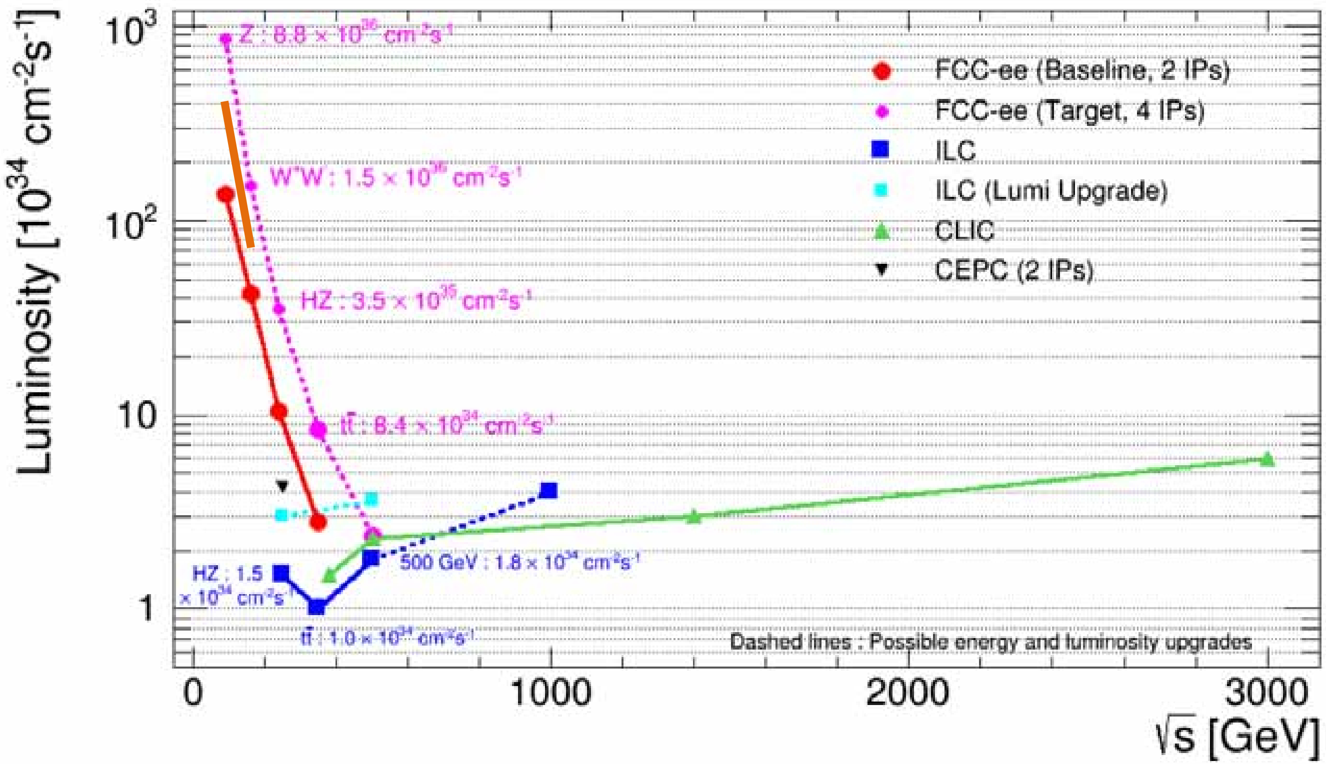
→ ultimate goal defining infrastructure requirements

- ***e⁺e⁻* collider (*FCC-ee*)** as potential first step ECM=90-400 GeV
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



FCC-ee highest possible luminosity from Z to tt by exploiting b-factory technologies:

- **separate e- and e+ storage rings**
- **very strong focussing: β*y = 1 - 2 mm (target, baseline -- work in progress!)**
- **top-up injection**
- **crab-waist crossing**

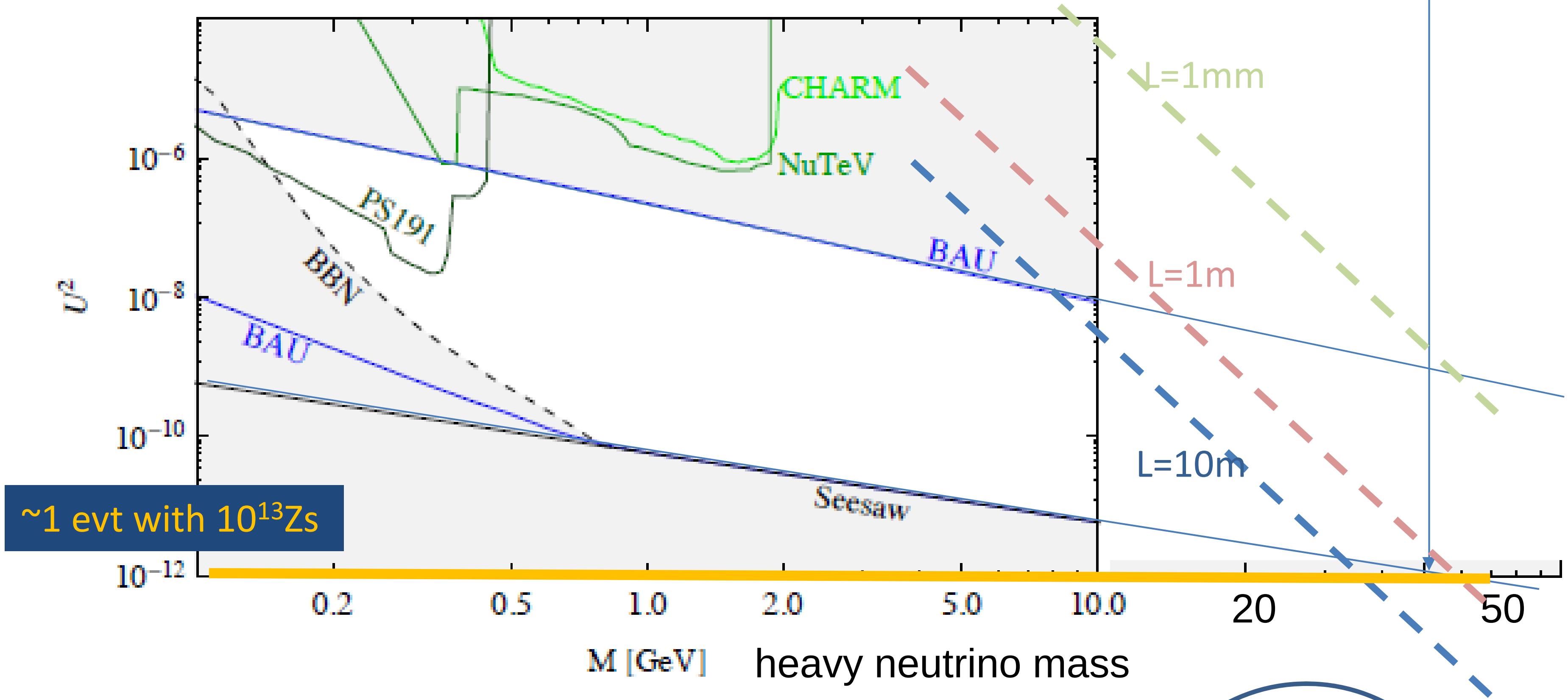


Event statistics :

Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$**	**e+e- → Z**	**LEP x 10^5**
WW threshold	**E_{cm} : 161 GeV**	**10^8**	**e+e- → WW**	**LEP x 2.10^3**
ZH threshold	**E_{cm} : 240 GeV**	**10^6**	**e+e- → ZH**	**Never done**
tt threshold	**E_{cm} : 350 GeV**	**10^6**	**e+e- → tt**	**Never done**

Decay length

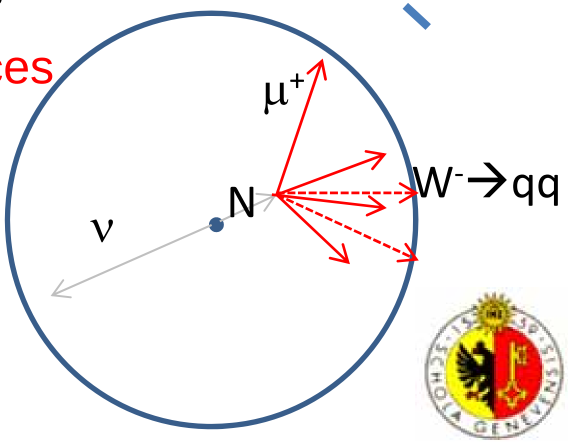
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV

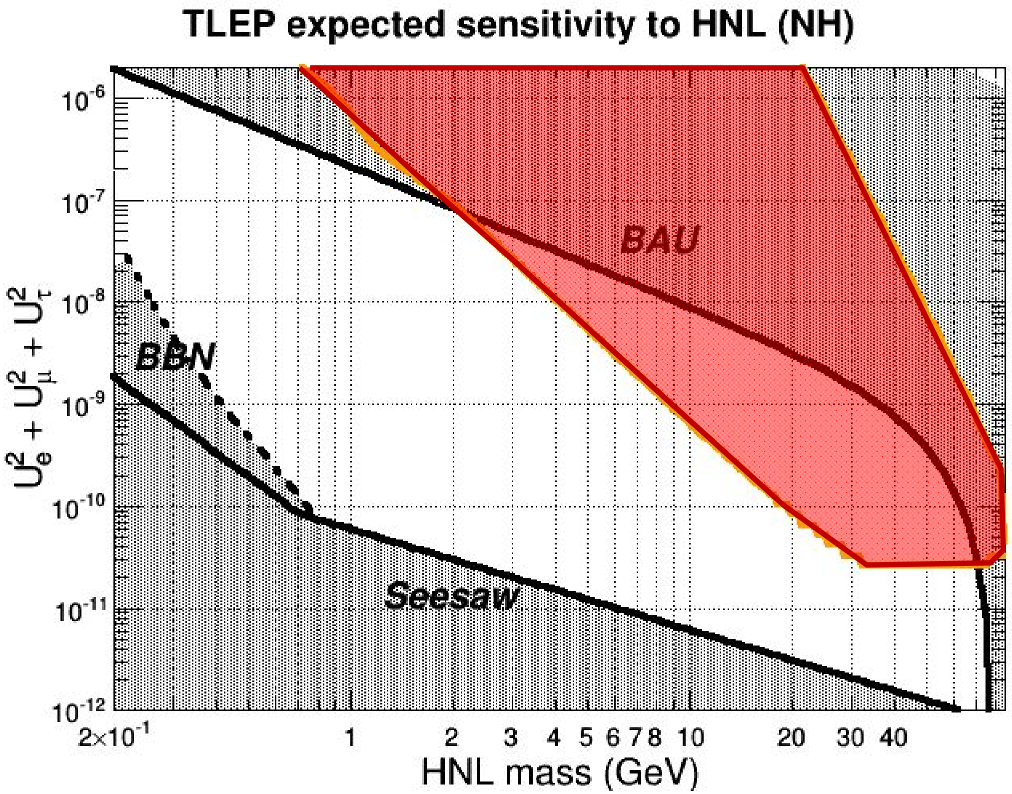


a large part of the interesting region will lead to detached vertices

... → very strong reduction of background!

Exact reach domain will depend on detector size
and details of displaced vertex efficiency & background



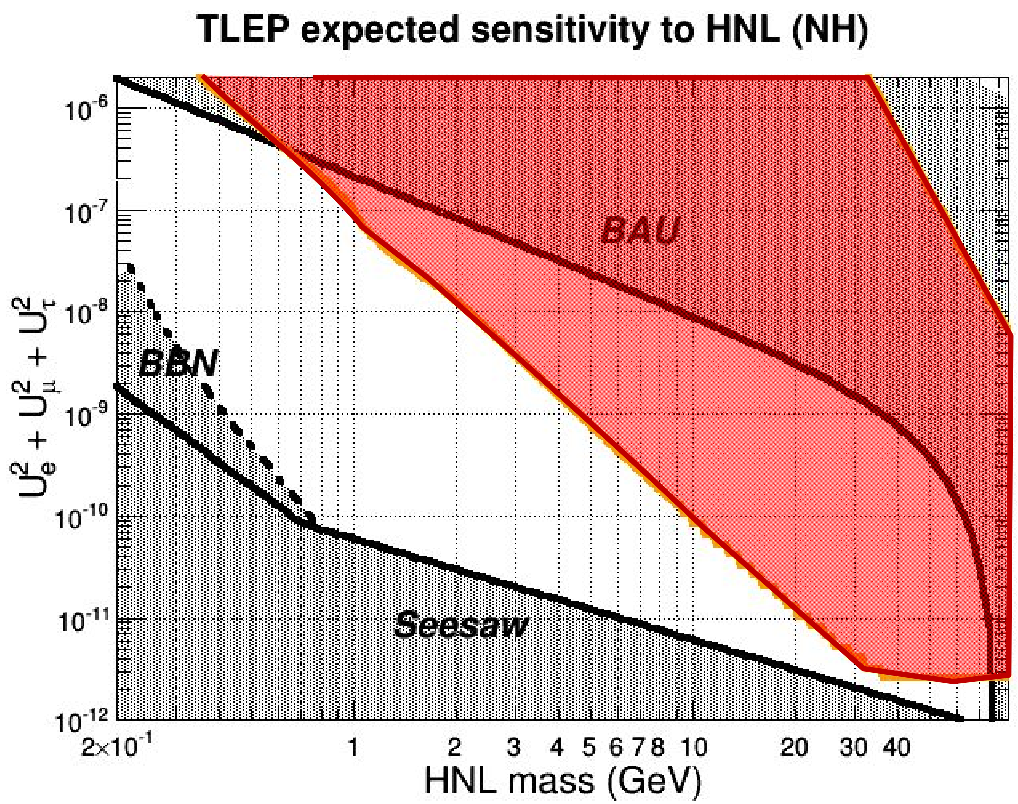


$N_Z = 10^{12}$ 1mm<L<1m

region of interest

FCC-ee sensitivity

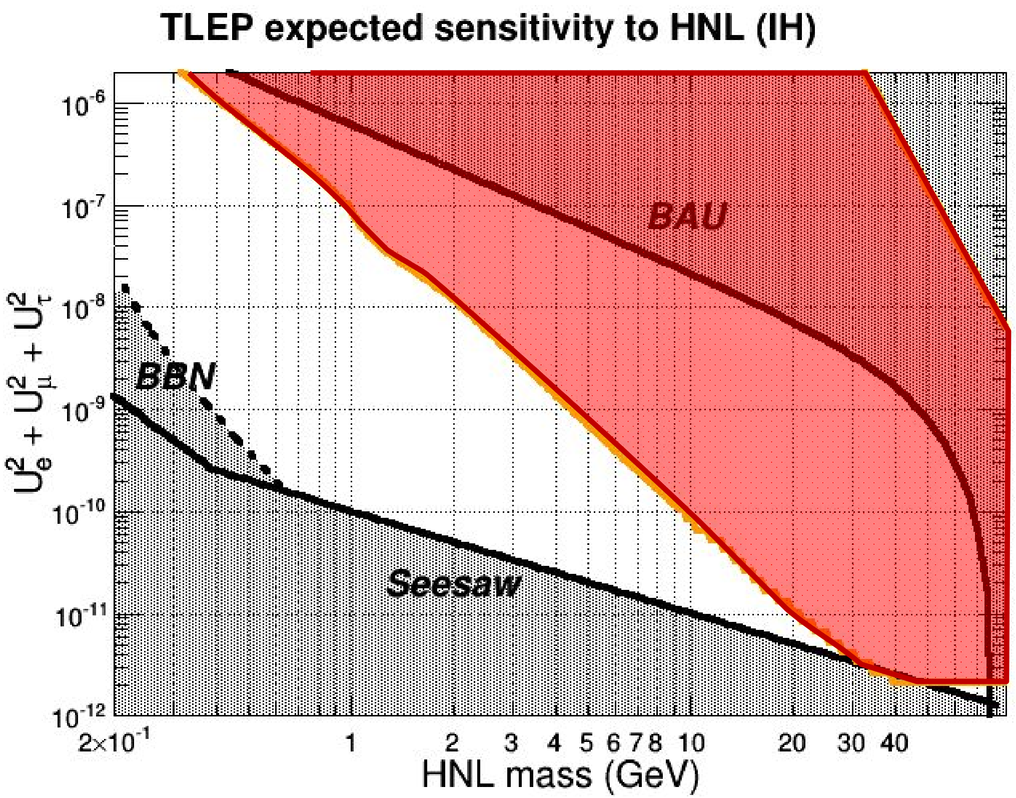
A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov



$N_Z = 10^{13}$ $100\mu m < L < 5m$

region of interest

FCC-ee sensitivity

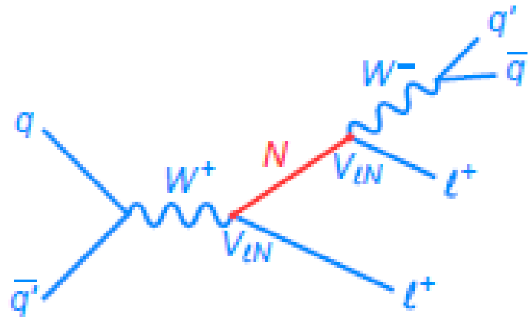


$N_Z = 10^{13}$ $100\mu m$ <L<5m

region of interest

FCC-ee sensitivity

Outlook for FCC-hh



We have seen that the Z factory offers a clean method for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders

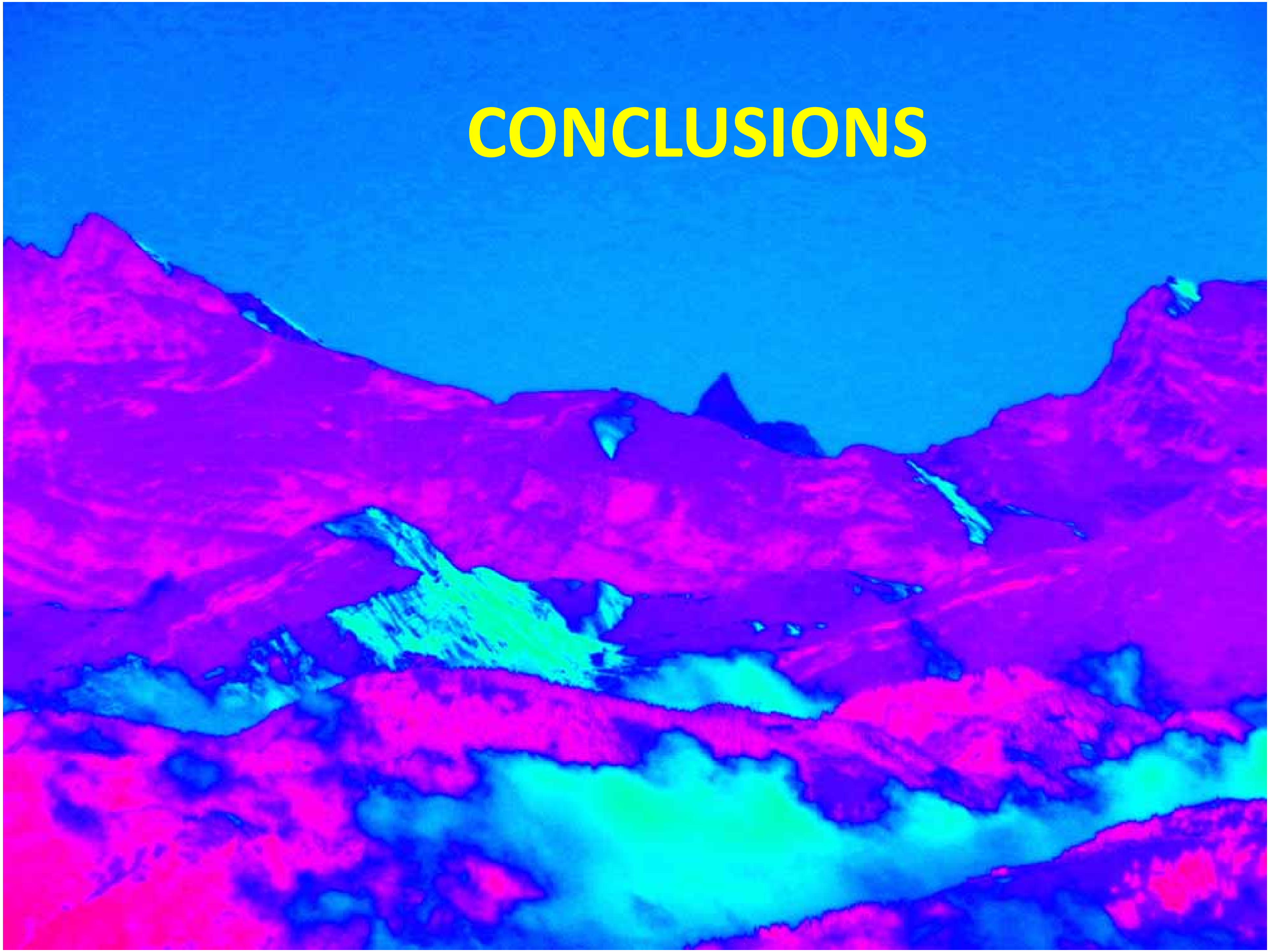
At the 100 TeV pp W is the dominant particle,
Expect 10^{13} real W's.

There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction.

But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

VERY interesting...

CONCLUSIONS



Conclusion

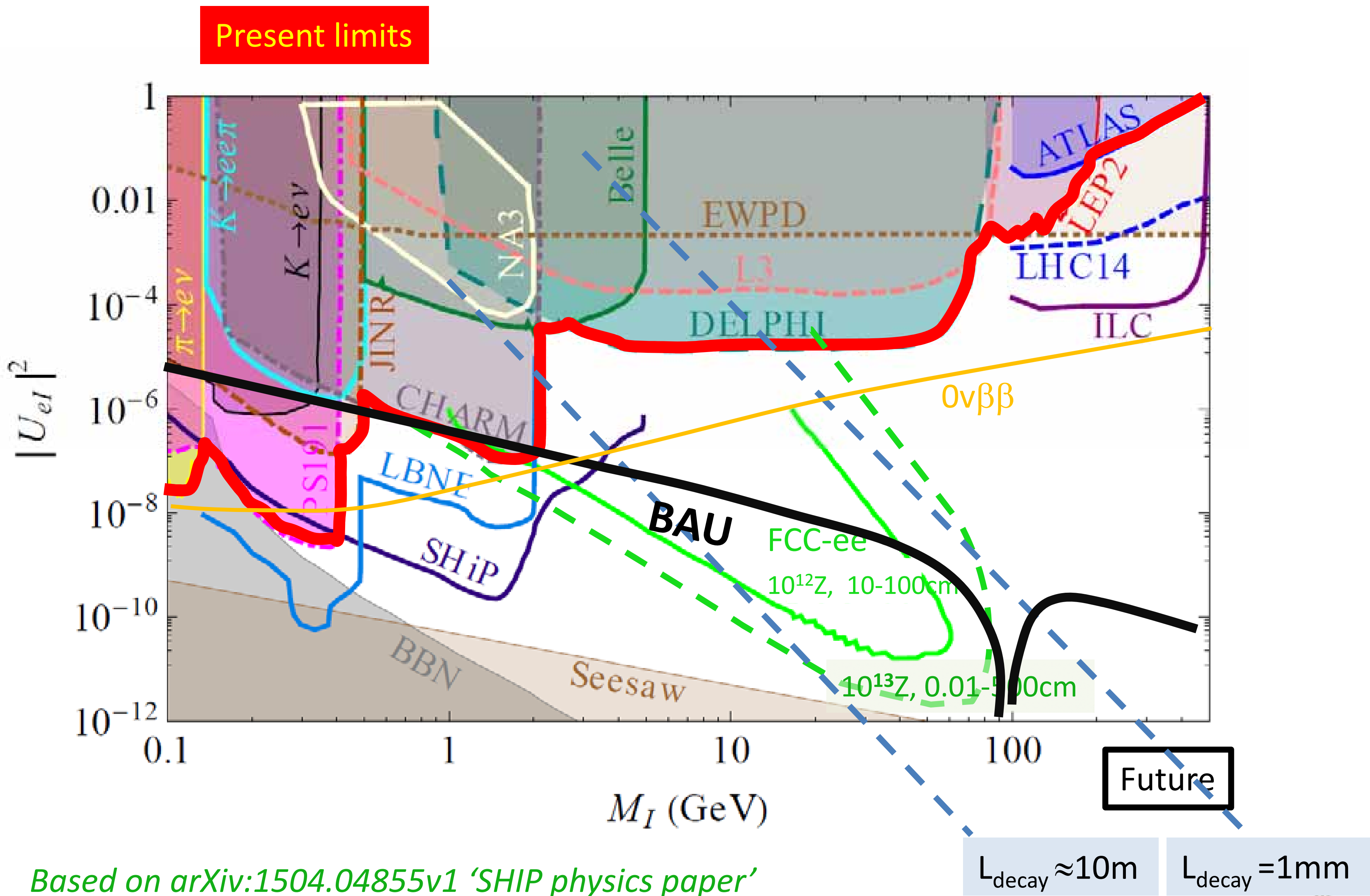
The quest for the right-handed neutrinos

(dextrinos? Right-handed neutrinos? Heavy Neutral Leptons? Heavy Majoranas? Shaposhninos? heavinos? Sterile neutrinos… etc.)

is taking place directly in astrophysics, neutrino beams and collider experiments.

It is not desperate at all

Thanks to the 'detached vertex' signatures the background can be drastically reduced.
a beam dump experiment (SHIP)
a Tera-Z factory like FCC-ee
Tera W factory like the B factories or the HL/LHC and FCC-hh
can reach definitive conclusions if the mass lies below the Z mass.



Based on arXiv:1504.04855v1 'SHIP physics paper'
And Pilar Hernandez, HEP-EPS Vienna