The Hunt for right-Handed Neutrinos at the FCC

Alain Blondel University of Geneva
with many thanks to
S. Ganjour, M. Mitra, S. Pascoli, E. Graverini, P. Mermod, N. Serra, M. Shaposhnikov, O. Fischer, P. Hernandez, and many others

courtesy J. Wenninger

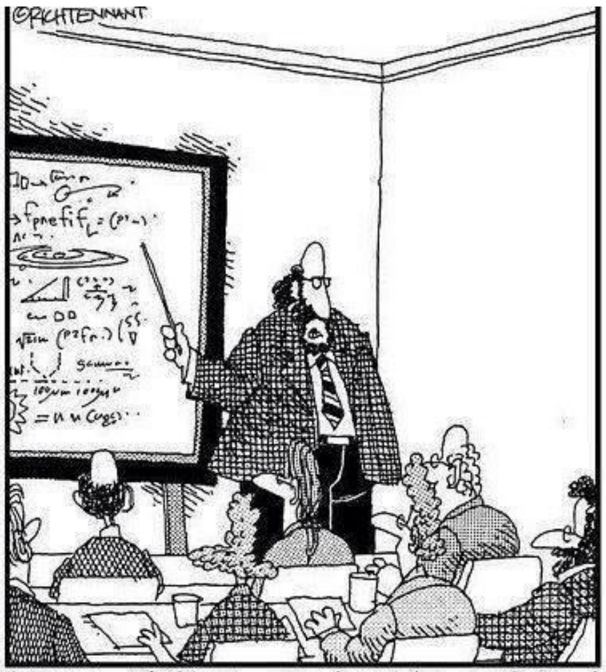
Electroweak eigenstates

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

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? –

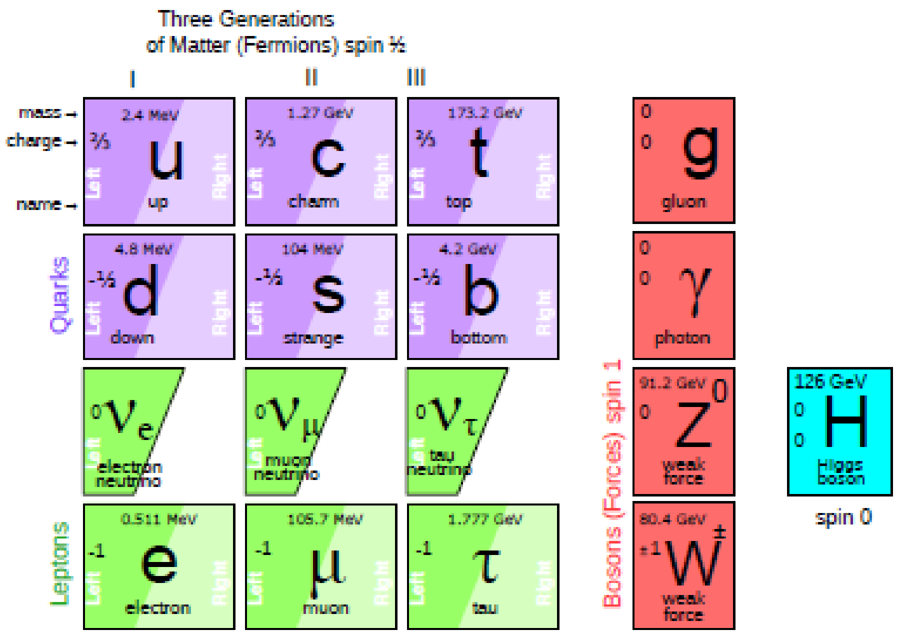
Also called 'sterile'

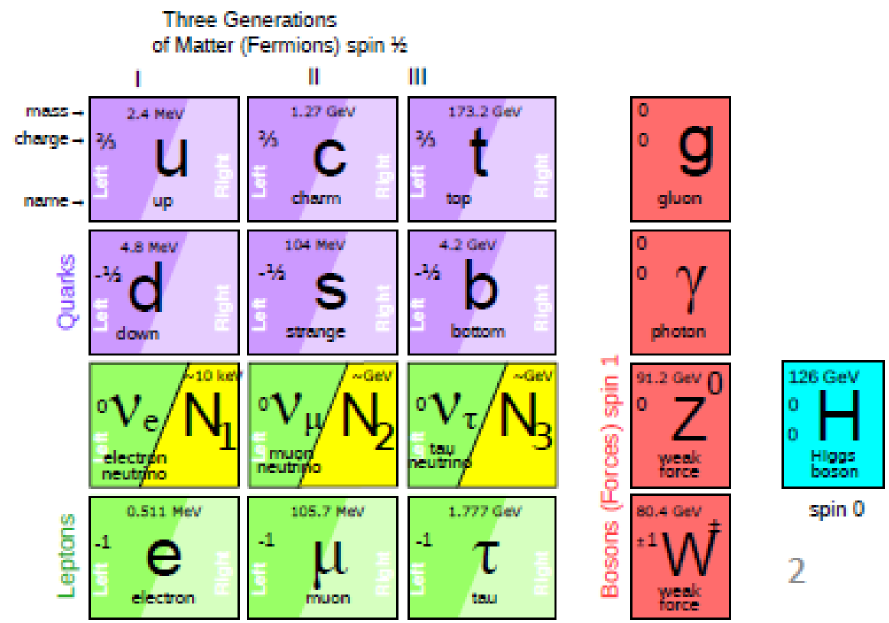


"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

THE STANDARD MODEL IS COMPLETE .....

But at least 2 or 3 pieces are still missing





neutrinos have mass...

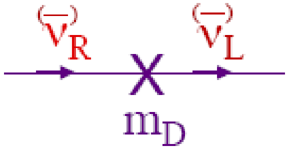
and this very <u>probably</u> implies new degrees of freedom

➔ Right-Handed, Almost «Sterile» (*very* small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossile to find.

.... but could perhaps explain: DM, BAU, small ν-masses

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

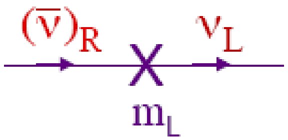
$$m_D \nu_L \overline{\nu_R}, \qquad m_D \overline{\nu_L} \nu_R$$



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 :

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

$M_R \neq 0$
$m_D \neq 0$
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

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

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

4 states , 2 mass levels

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

A few REFERENCES

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

PHYSICAL REVIEW D VOLUME 29, NUMBER 11 1 JUNE 1984

Extending limits on neutral heavy leptons

Michael Gronau*

Department of Physics, Syracuse University, Syracuse, New York 132

FLAVOUR(267104)-ERC-23 TUM-HEP 850/12 SISSA 25/2012/EP CFTP/12-013

arxiv:1208.3654

Higgs Decays in the Low Scale Type I See-Saw Model

C. Garcia Cely[a], A. Iba

JHEP — Published for SISSA by Springer

Received: September 23, 2013
Accepted: December 25, 2013
Published: January 29, 2014

First look at the physics case of TLEP

arxiv:1308.6176

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s]

Search for Heavy Right Handed Neutrinos at the FCC-ee

A. Blondel (presenter)[a], E. Graverini[b], N. Serra[b], M. Shaposhnikov[c]

arXiv:1411.5230v2

CERN–PPE/96–195

18 December 1996

Neutral Heavy Leptons ...uced in Z Decays

DELPHI Collaboration

The Role of Sterile Neutrinos in Cosmology and Astrophysics

Alexey Boyarsky, Oleg Ruchayskiy and Mikhail Shaposhnikov

The νMSM, Dark Matter and Neutrino Masses

Takehiko Asaka, Steve Blanchet, and Mikhail Shaposhnikov

Phys.Lett.B631:151-156,2005

arXiv:hep-ph/0503065

FCC design study and FCC-ee http://cern.ch/fcc-ee and presentations at *FCC-ee physics workshops* http://indico.cern.ch/category/5684/

Preprint typeset in JHEP style - HYPER VERSION

FERMILAB-PUB-08-086-T, NSF-KITP-08-54, MADPH–06–1466, DCPT/07/198, IPPP/07/99

The Search for Heavy Majorana Neutrinos

Anupama Atre[1,2], Tao Han[2,3,4], Silvia Pascoli[5], Bin Zhang[4*]

Testable Baryogenesis in Seesaw Models

21 June

arXiv:1606.06719v1

P. Hernández,[a] M. Kekic,[a] J. López-Pavón,[b] J. Racker,[a] J. Salvado.[a]

Some Recent papers:

The seesaw path to leptonic CP violation
A. Caputo, P. Hernandez, M. Kekic, J. Lopez-Pavon, J. Salvado **arXiv:1611.05000**

Sterile neutrino searches at future e−e+, pp, and e−p colliders
Stefan Antusch, Eros Cazzato, Oliver Fischer **arXiv:1612.02728v2**

things are moving fast!

Manifestations of right handed neutrinos

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

$$\nu = \nu_L \cos\theta - N^c_R \sin\theta$$

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

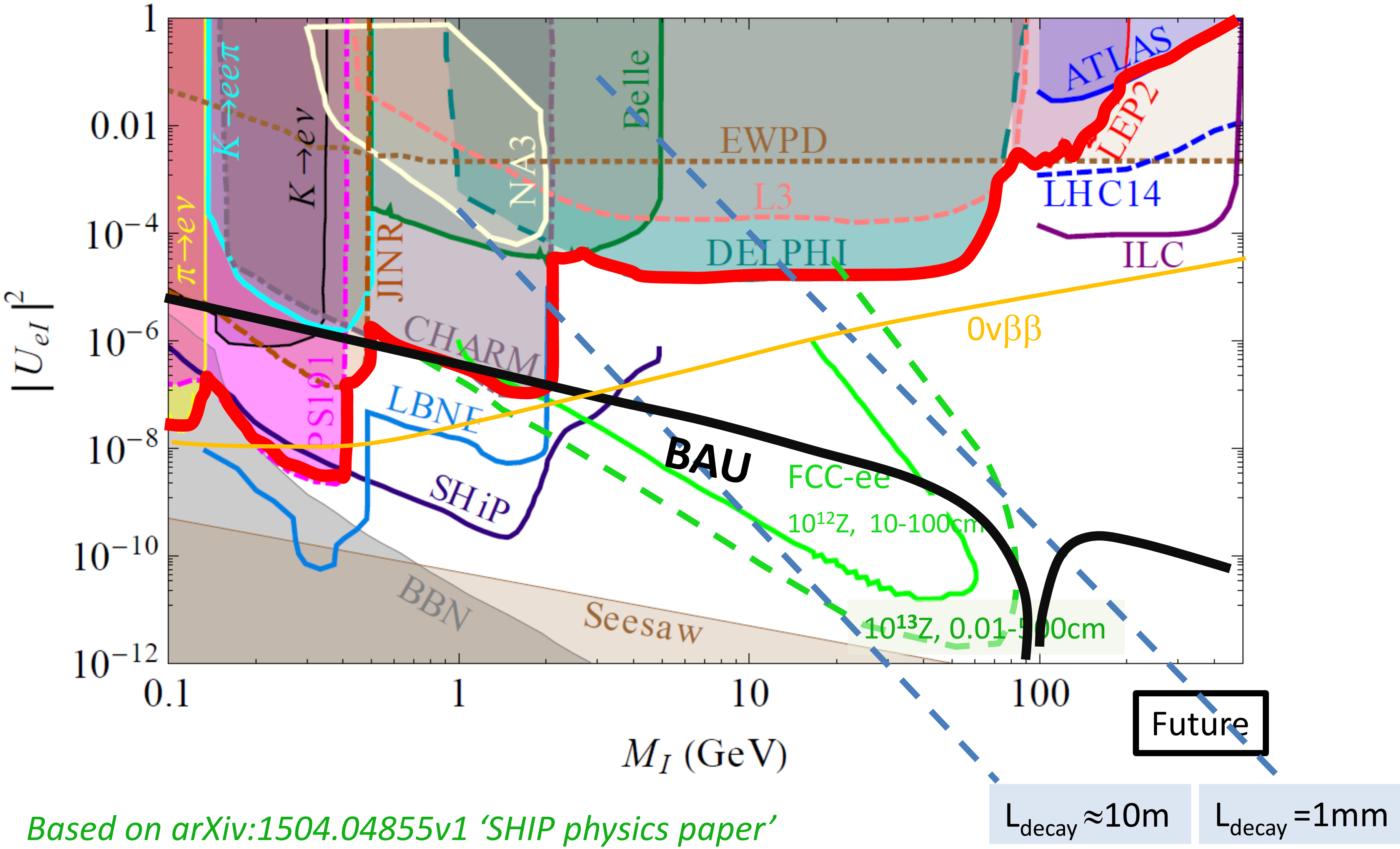
what is produced in W, Z decays is:

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

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
  -- 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

(indirect) Effect of right handed neutrinos on EW precision observables

The relationship $|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$ is valid for one family see-saw.
For two or three families the mixing can be larger (*Shaposhnikov*)
Antush and Fisher have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos. ***Worth exploring.***

«$\boldsymbol{\nu_L} = \boldsymbol{\nu}\cos\theta + \boldsymbol{N} \sin\theta$» → $(\cos\theta)^2$ becomes parametrized as 1+ $\varepsilon_{\alpha\beta}$ ($\varepsilon_{\alpha\alpha}$ is negative)
the coupling to light neutrinos is typically suppressed.
In the G_F, M_Z α_{QED} scheme, G_F (extracted from $\mu \to e \nu_e \nu_\mu$) and *g* should be increased
This leads to *correlated* variations of all predictions upon e or mu neutrino mixing.
Only the 'number of neutrinos' (R_{inv} and σ_{had}^{peak}) is sensitive to the tau-neutrino mixing.

Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\mathrm{SM}}\,(1 - 0.15(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\mathrm{SM}}\,(1 + 0.03(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\mathrm{SM}}\,(1 - 0.06(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma^0_{had}]_{\mathrm{SM}}\,(1 - 0.25(\varepsilon_{ee} + \varepsilon_{\mu\mu}) - 0.27\varepsilon_\tau)$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\mathrm{SM}}\,(1 + 0.75(\varepsilon_{ee} + \varepsilon_{\mu\mu}) + 0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\mathrm{SM}}(1 - 0.11(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\mathrm{lept}}]_{\mathrm{SM}}(1 - 0.59(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s^{\ell,\mathrm{lep}}_{W,\mathrm{eff}})^2]_{\mathrm{SM}}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,\mathrm{had}}_{W,\mathrm{eff}})^2]_{\mathrm{SM}}(1 + 0.71(\varepsilon_{ee} + \varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters $\varepsilon_{\alpha\beta}$. The theoretical predictions and experimental values are taken from Ref. [16]. The values of $(s^{\ell,\mathrm{lep}}_{W,\mathrm{eff}})^2$ and $(s^{\ell,\mathrm{had}}_{W,\mathrm{eff}})^2$ are taken from Ref. [17].

Other quantities that could be sensitive to the light-heavy mixing

1. the tau life time would be sensitive to $\varepsilon_{\tau\tau}$

→ how well can we measure the tau life time with 10^{11} $\tau\tau$?

τ_τ = (290.3 ± 0.5) × 10−15 s $c\tau_\tau$ = 87.03 µm

Mass m = 1776.86 ± 0.12 MeV limits the sensitivity to 0.3 10^{-4}

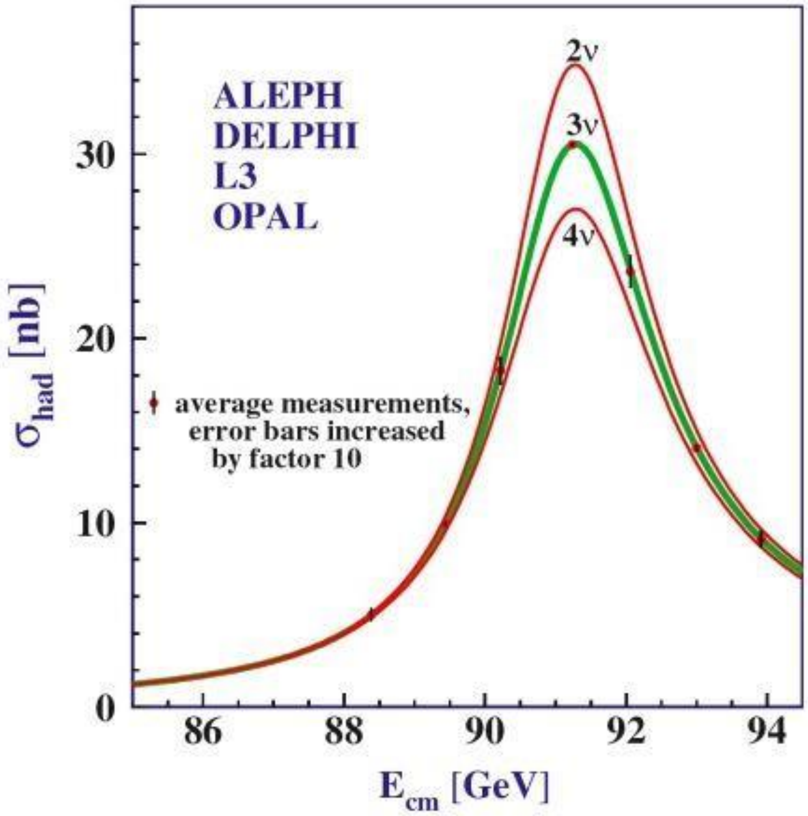
2. the measurement of the 'number of neutrinos'

At the end of LEP:

Phys.Rept.427:257-454,2006

N_ν = 2.984 ±0.008

- 2 σ :^) !!



This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔ little parametric dependence

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) and QED effects which represents an error of ±0.0046 on N_ν

Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation

Error may decrease to 0.002….

Volume 241, number 4 PHYSICS LETTERS B 24 May 1990

NEUTRINO COUNTING AT THE Z-PEAK AND RIGHT-HANDED NEUTRINOS

C. JARLSKOG
CERN, CH-1211 Geneva 23, Switzerland
and Department of Physics, University of Stockholm, S-113 46 Stockholm, Sweden

Received 20 February 1990

We consider the implications of extending the minimal standard model, with n families of quarks and leptons, by introducing an arbitrary number of right-handed neutrinos, for neutrino-counting via the "invisible width" of the Z. It is shown that the effective number of neutrinos, $\langle n \rangle$, satisfies, the inequality $\langle n \rangle \leqslant n$, where $\langle n \rangle$ is defined by $\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0$ and Γ_0 is the standard width for one massless neutrino. Thus, in the case of three families, the neutrino-counting can give a result which is less than three, if there are right-handed neutrinos.

Theorem.

In the standard model, with n left-handed lepton doublets and $N-n$ right-handed neutrinos, the effective number of neutrinos, $\langle n \rangle$, defined by

$$\Gamma(\mathrm{Z} \to \text{neutrinos}) \equiv \langle n \rangle \Gamma_0 ,$$

where Γ_0 is the standard width for one massless neutrino, satisfies the inequality

$$\langle n \rangle \leqslant n . \tag{15}$$

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \to ee, \mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma e, \mu}\,(SM)}$$

The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of $O(10^{12})$ Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma e}(SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for $|\cos\theta_\gamma|$ <0.95

161 GeV (10^7 s) running at $1.6\times10^{35}/cm^2/s$ x 4 exp ➔ 3×10^7 γ Z(inv) evts, ΔN_ν=0.0011
adding 5 yrs data at 240 and 350 GeV .... ΔN_ν=0.0008

A better point may be 1 125GeV (20pb and higher luminosity) may allow ΔN_ν=0.0004?

needs to be harmonized with running plan

The interest of these ‘indirect’ tests

They constrain the coupling to the RH neutrinos independently of their mass

-- very high mass sensitivity if one assumes large coupling **(10^{-4})**

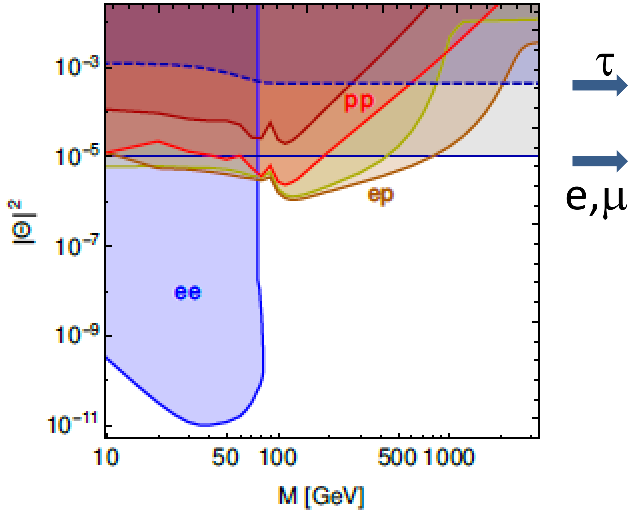


Figure 16: Summary of selected estimated sensitivities of the FCC-ee, -hh, and -eh colliders, including the HL-LHC and the LHeC. The best sensitivity for heavy neutrino masses $M < m_W$ is obtained from the displaced vertex searches at the Z pole run of the FCC-ee shown by the blue line, which are sensitive to $|\theta|^2 = |\theta_e|^2 + |\theta_\mu|^2 + |\theta_\tau|^2$. For heavy neutrino masses above m_Z the pp colliders (red: FCC-hh, dark-red: HL-LHC) and e^-p colliders (brown: FCC-eh, yellow: LHeC) have the best prospects for discovering sterile neutrinos via the LFV signatures. The lepton-dijet signature at the pp colliders with final states $\ell^\pm_\alpha \ell^\mp_\beta jj$, $\alpha \neq \beta$ yields sensitivities to the active-sterile mixing parameter combinations $|\theta_\alpha \theta_\beta|^2/|\theta|^2$, and it is shown by the red lines. The lepton-trijet signature at the e^-p colliders with final states $\ell_\alpha jjj$, $\alpha \neq e$ is sensitive to $|\theta_e \theta_\alpha|^2/|\theta|^2$, and it is shown by the brown lines. Finally, for very large heavy neutrino masses the best sensitivity is given by the EWPO measurements at the FCC-ee. The solid and dashed horizontal blue line denotes the sensitivity to $|\theta_e|^2 + |\theta_\mu|^2$ and $|\theta_\tau|^2$, respectively.

Experimentally some new requirements

-- tau life time measurement?

-- Single gamma N_ν counting needs to be included

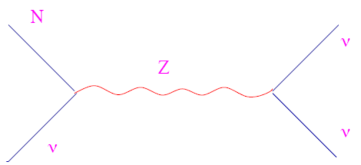
arXiv:1612.02728v2

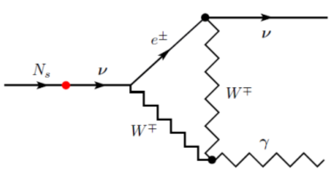
Direct searches

Search Processes (I)

m_N Below m_π:

N→ 3ν; N→ νγ w $E_\gamma = m_N/2$





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

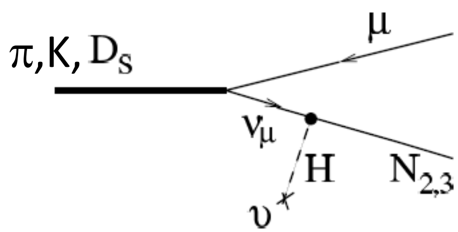
Long life, **dark matter candidate**

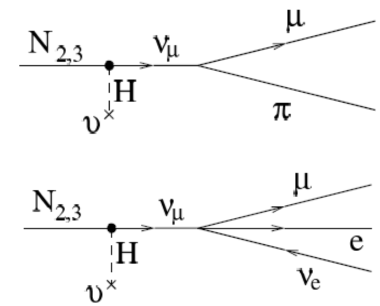
Equilibrium with neutrinos produced in the stars

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

Drewes et al; arXiv:1602.04816v1

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





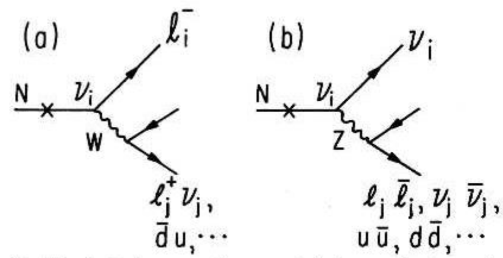


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

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

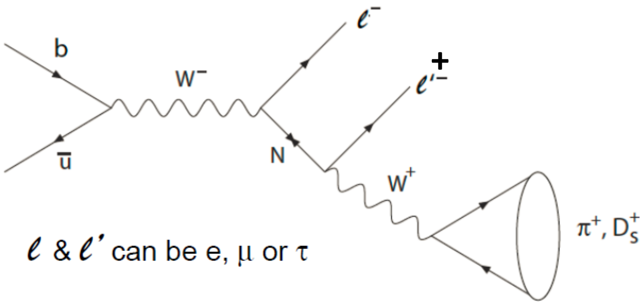
Decay via W gives at least two charged particles, and amounts to ~60% of decays.

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

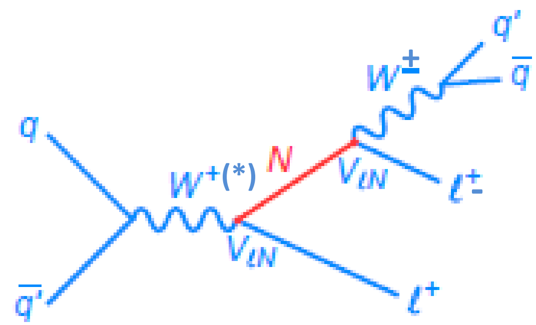
Processes (II)

Search for heavy right-handed neutrinos in collider experiments.

B factories



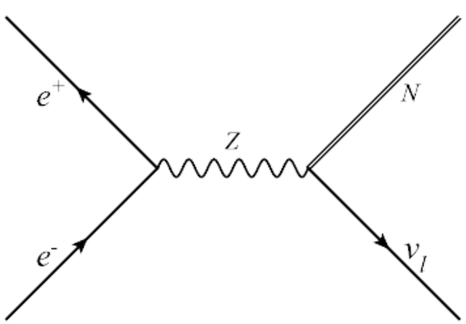
Hadron colliders



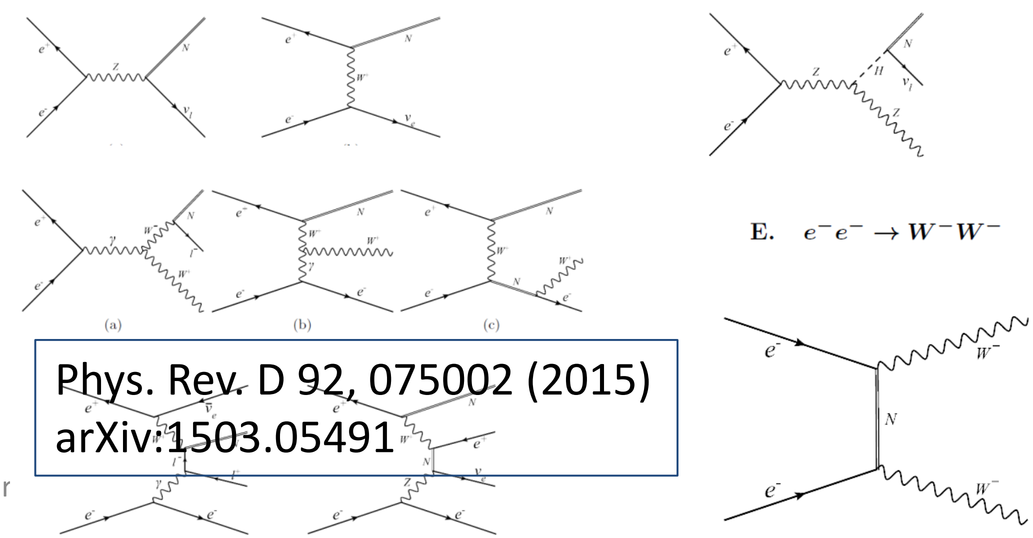
or $l^{\pm}\nu$

Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



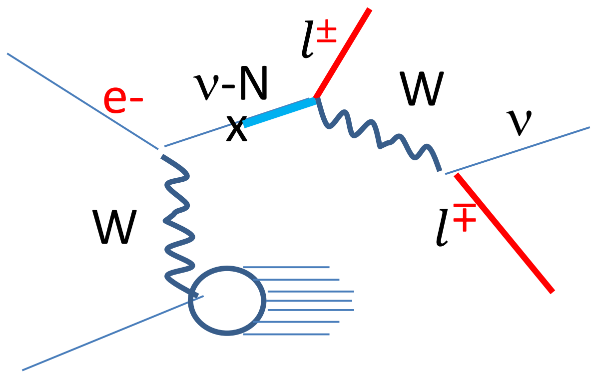
HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)

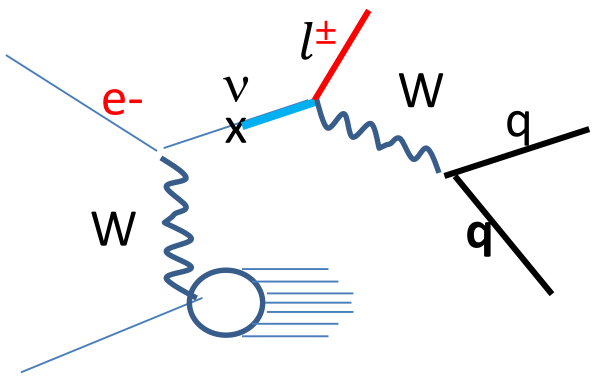


Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

FCC-ep

Clearly the ep collisions produce abundant numbers of neutrinos, which will be mixed with RH neutrinos.





hard lepton can have 'wrong sign'!

A question more than a statement: does this cause any problem of trigger? acceptance? background?

Searches for heavy neutrinos ν_h in B decays

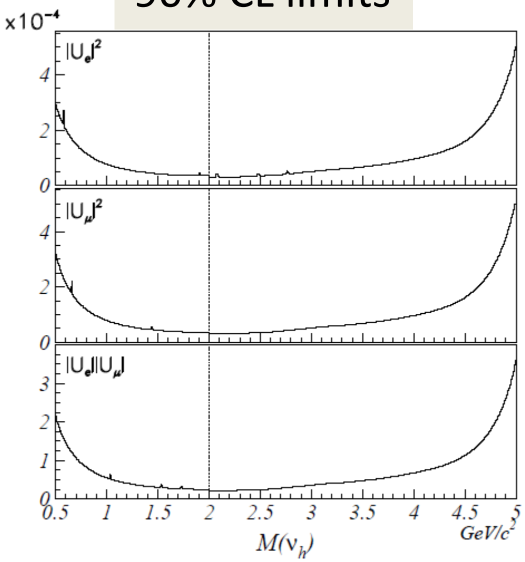
-- **BELLE** *Phys. Rev. D. 87, 071102 (2013), arXiv:1301.1105*

7.8 10^8 B mesons at Υ_{4s}!

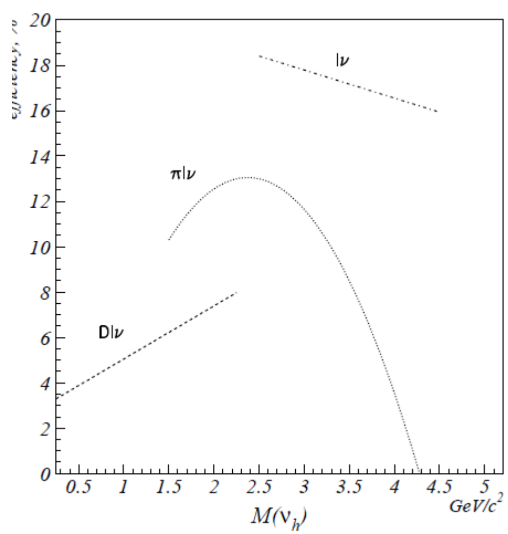
Search for ℓ_2 +($\ell_1\pi$), where ℓ_1 and π have **opposite charge and displaced vertex** for $M(\nu_h)$ =1GeV/c2 and $|U_e|^2 = |U_\mu|^2 = 10^{-4}$ the flight length is $c\tau \simeq$ 20m.

➔ 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

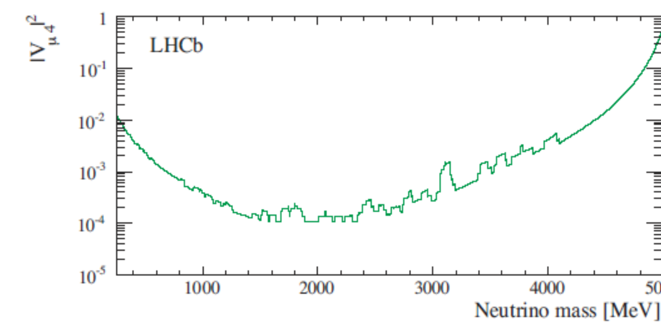


Efficiency for the search



LHCb collaboration,
PRL 112, 131802 (2014)

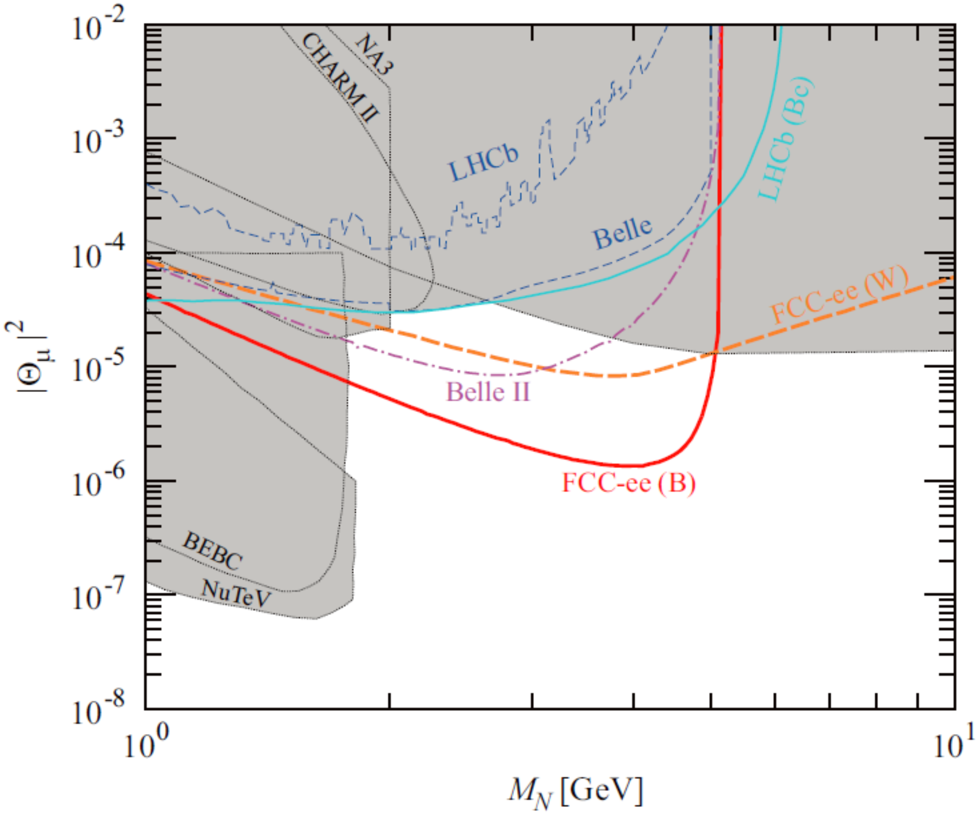
$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$ at 95%



Scope for 10-100x improvement at SuperKEKb

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

SuperKEKb (soon) and FCC-ee (Z-> $b\bar{b}$)

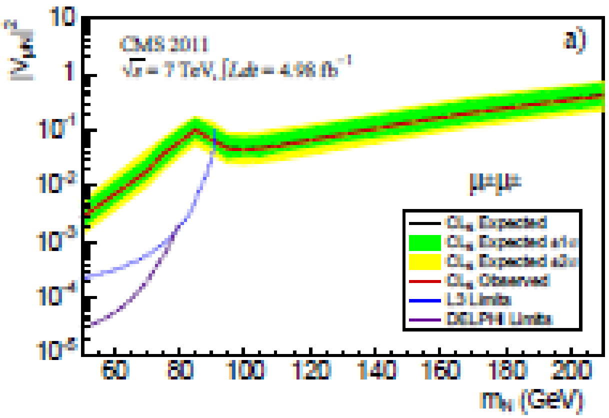


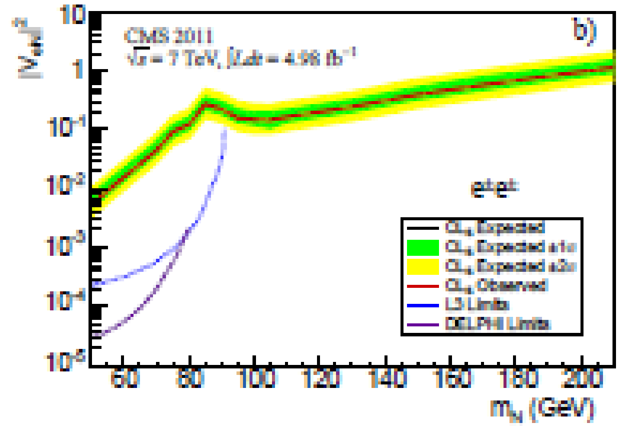
1609.06113v2

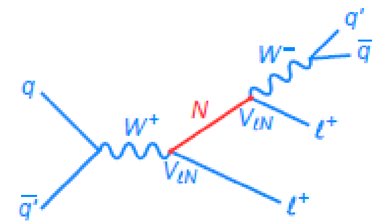
Figure 2: The sensitivity limits on $|\Theta_\mu|^2$ from the LNV decay $B^+ \to \mu^+\mu^+\pi^-$ due to heavy neutrino at Belle II with $N_B = 5 \times 10^{10}$ (magenta dot-dashed line) and at FCC-ee with $N_Z = 10^{13}$ (red solid line). The orange long-dashed line is the limit from $W^+ \to \mu^+\mu^+\pi^-$ at FCC-ee with $N_W = 2 \times 10^8$. For comparision we also show the limit from the LNV decays $B_c^+ \to \mu^+\mu^+\pi^+$ at LHCb for LHC run 3 [24] (cyan solid line). The blue dashed lines are the upper bounds from the LNV B decays by LHCb [30] and Belle [29]. The gray region is excluded by search experiments: DELPHI [32], NA3 [33], CHARM II [34], BEBC [35], and NuTeV [36].

NB it will be better since HNL decays mix both charges and flavour this should be investigated.

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

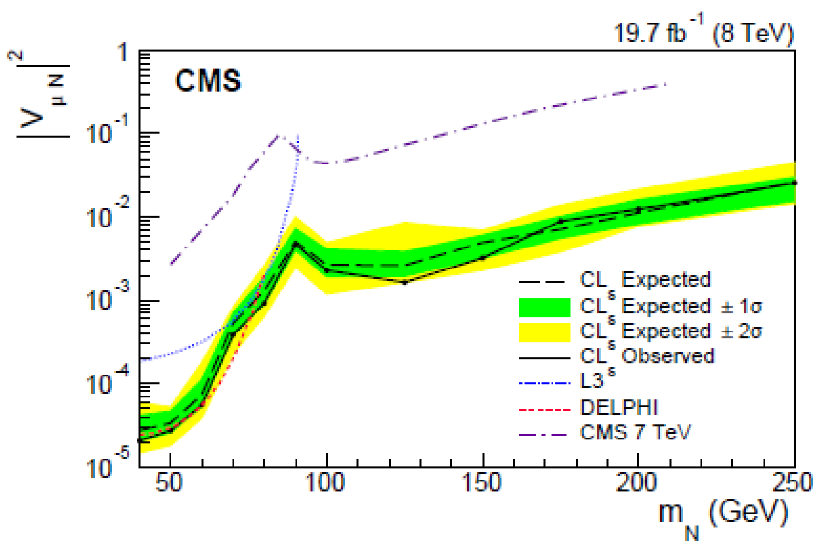






CMS arXiv:1207.6079.

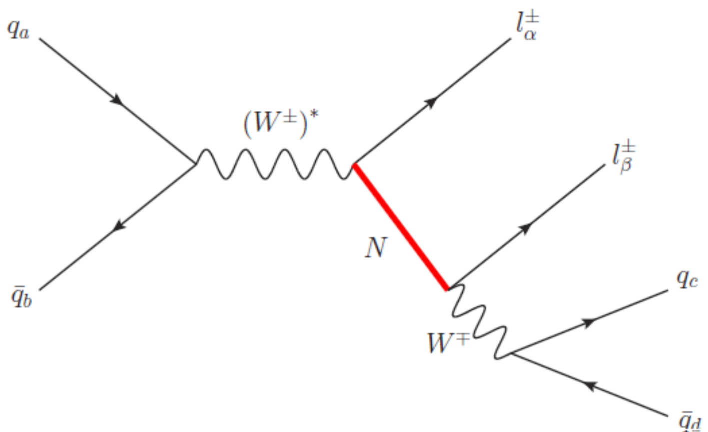
arXiv:1501.05566



Begin to match/superseed the DELPHI limit.

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

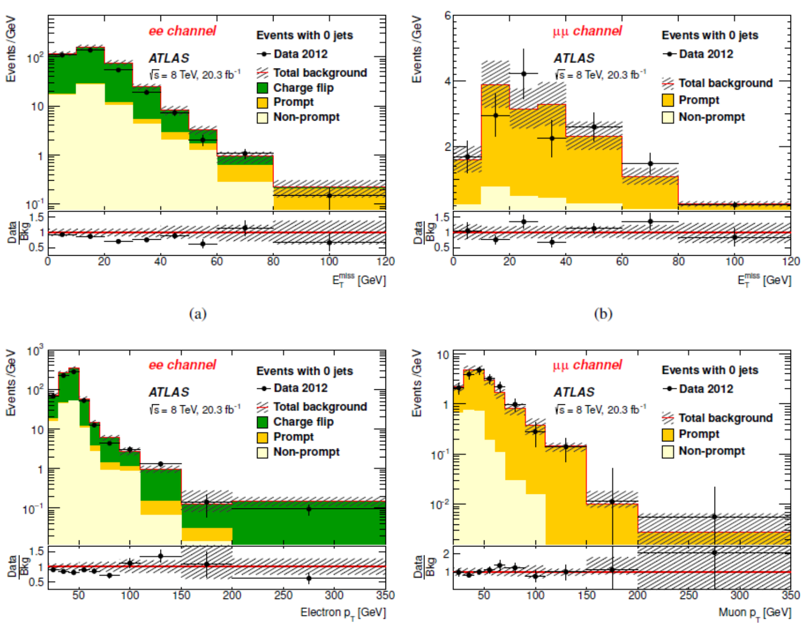
ATLAS search for Heavy Neutrinos at LHC *JHEP07(2015)162 arXiv:1506.06020*



or lv

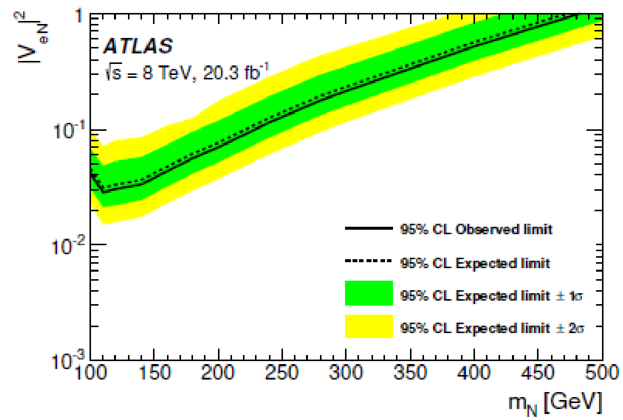
e^-e^-, e^+e^+, $\mu^-\mu^-$, $\mu^+\mu^+$ final states
(like sign, like flavour leptons)
Concentrates on m_N>100 GeV
'because <100 GeV excluded by LEP'

Charge flip significant bkgd for ee channel

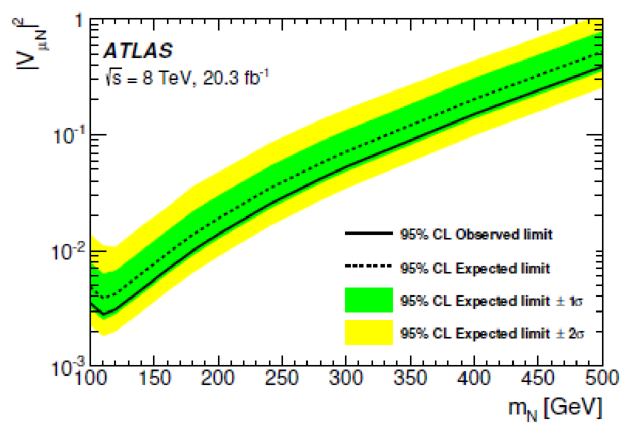


(a) (b)

(c) (d)



(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 $\leq m_W$ could be visible if mixing angle O($10^{-7,8}$)

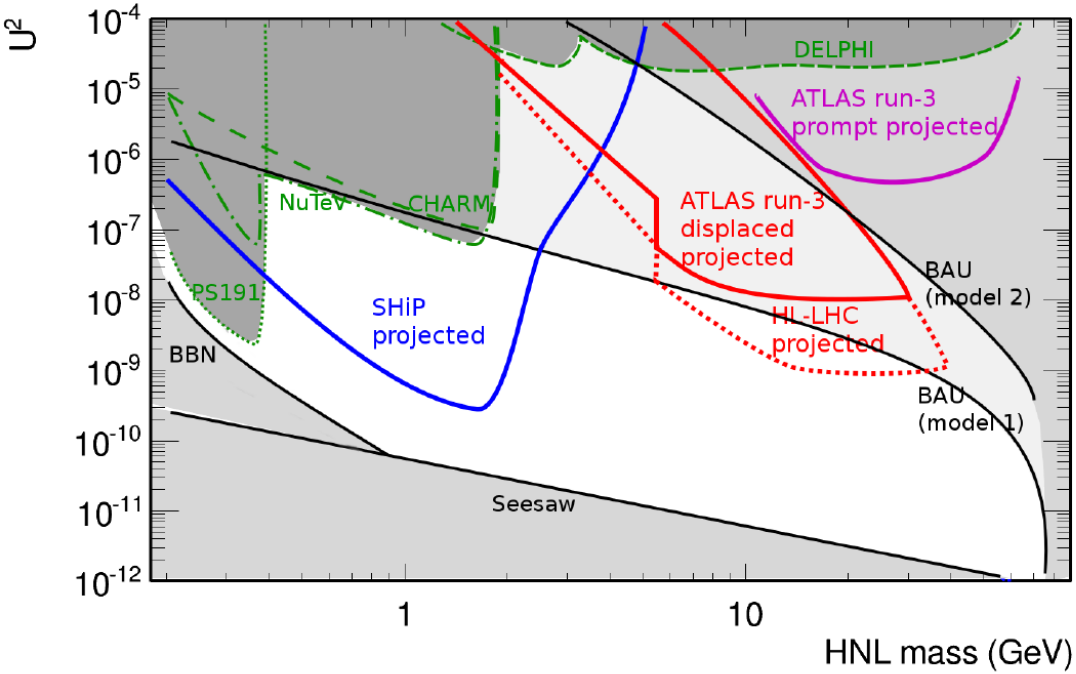
The keys for that region of phase space

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

If lifetime is short
require triple lepton signature

Hope for considerable improvement in W decays at LHC!

Ph. Mermod



RHASnu's production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\bar{\nu}\right)|U|^2 \left(1 - \frac{m_{\nu_m}^2}{m_{Z^0}{}^2}\right)^2 \left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{m_{Z^0}{}^2}\right)$$

multiply by 2 for antineutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

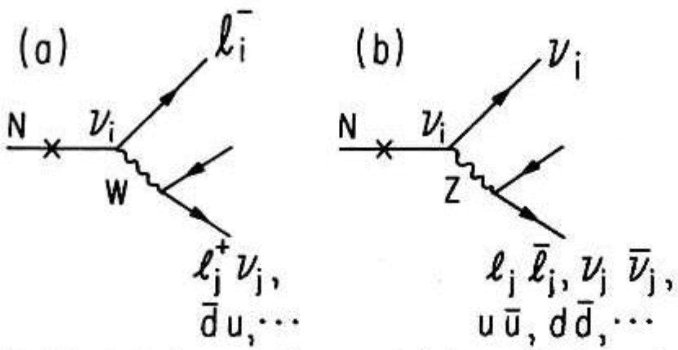


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

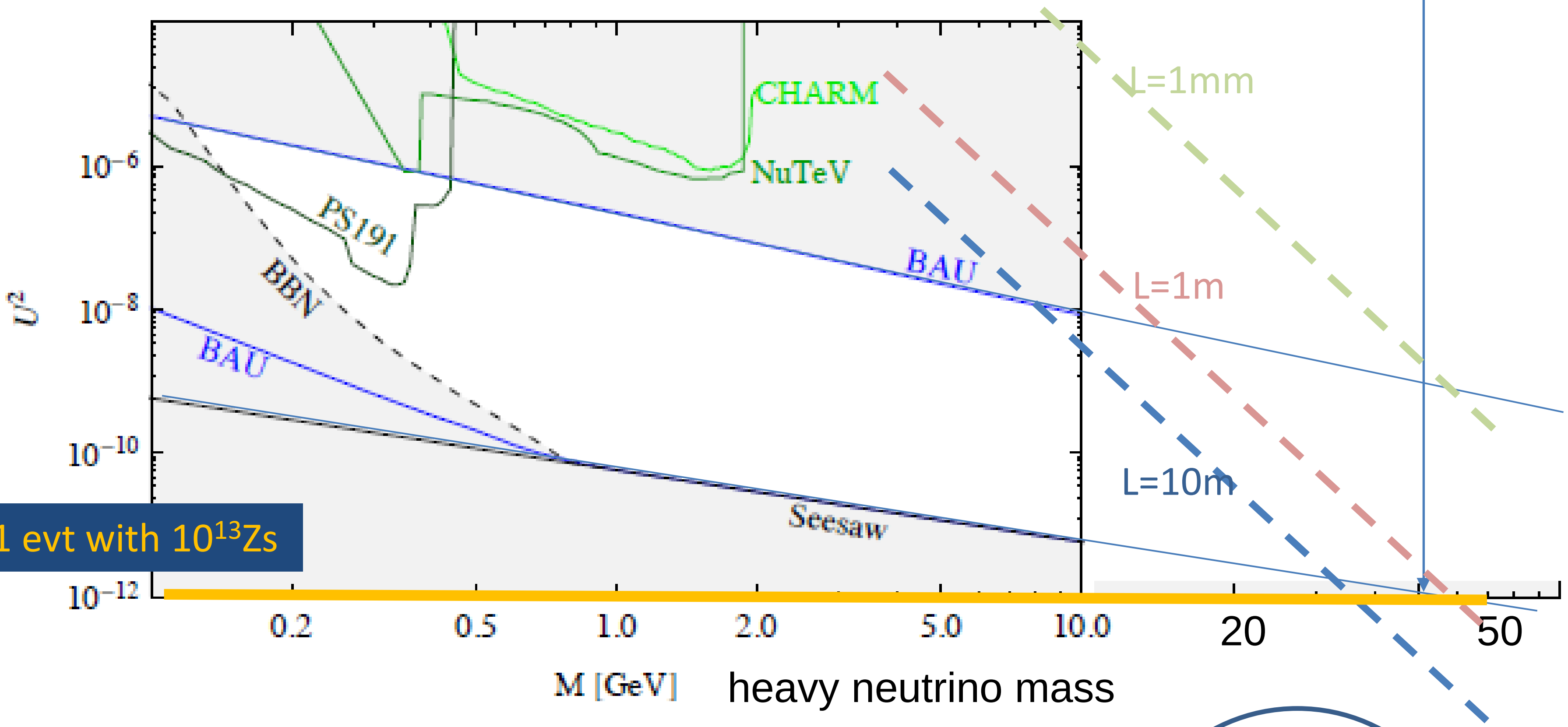
$$L \approx \frac{3 \text{ cm}}{|U|^2 \left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to $\geq$ 2 charged tracks

Backgrounds : four fermion: e+e- → $W^{*+} W^{*-}$ e+e- → $Z^*(\nu\nu)$ + $(Z/\gamma)^*$

Decay length

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



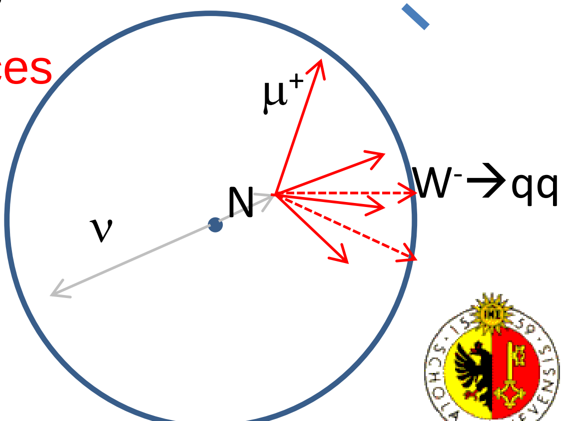
~1 evt with 10^{13}Zs

heavy neutrino mass

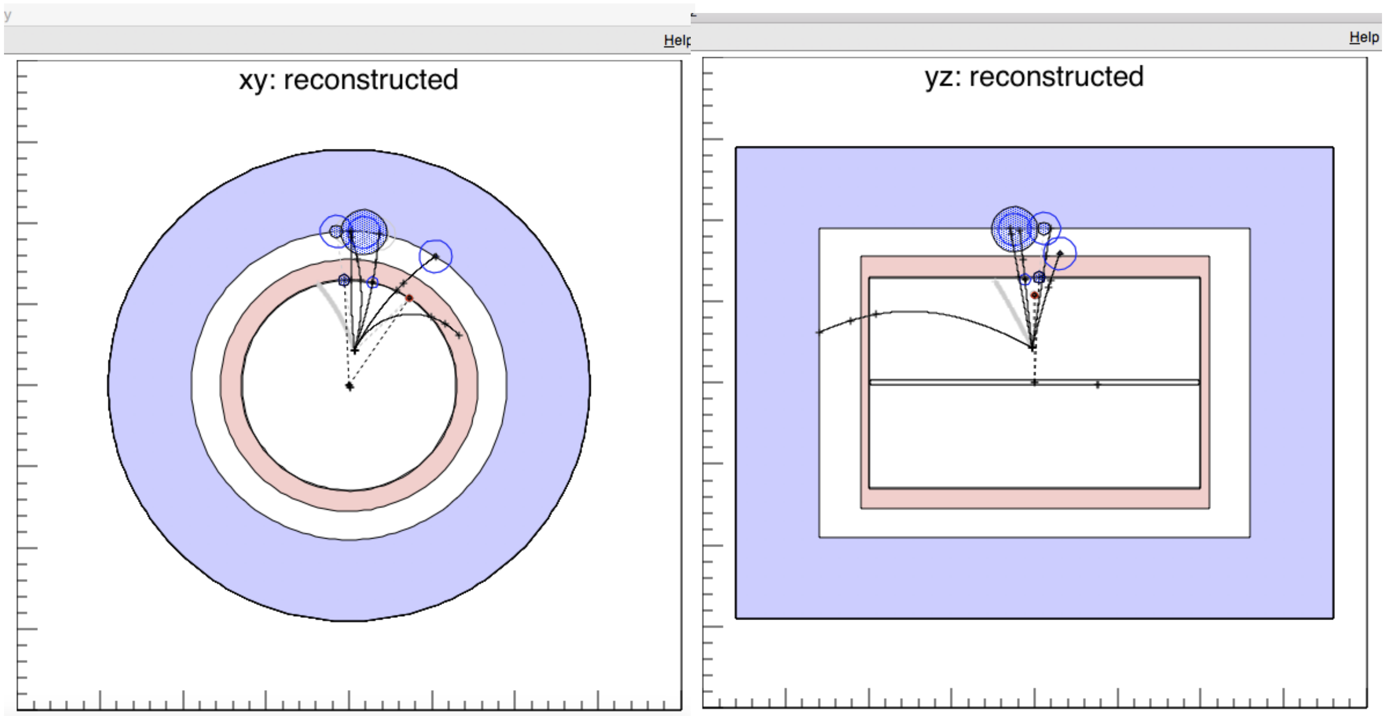
a large part of the interesting region will lead to detached vertices

... ➔very strong reduction of background!

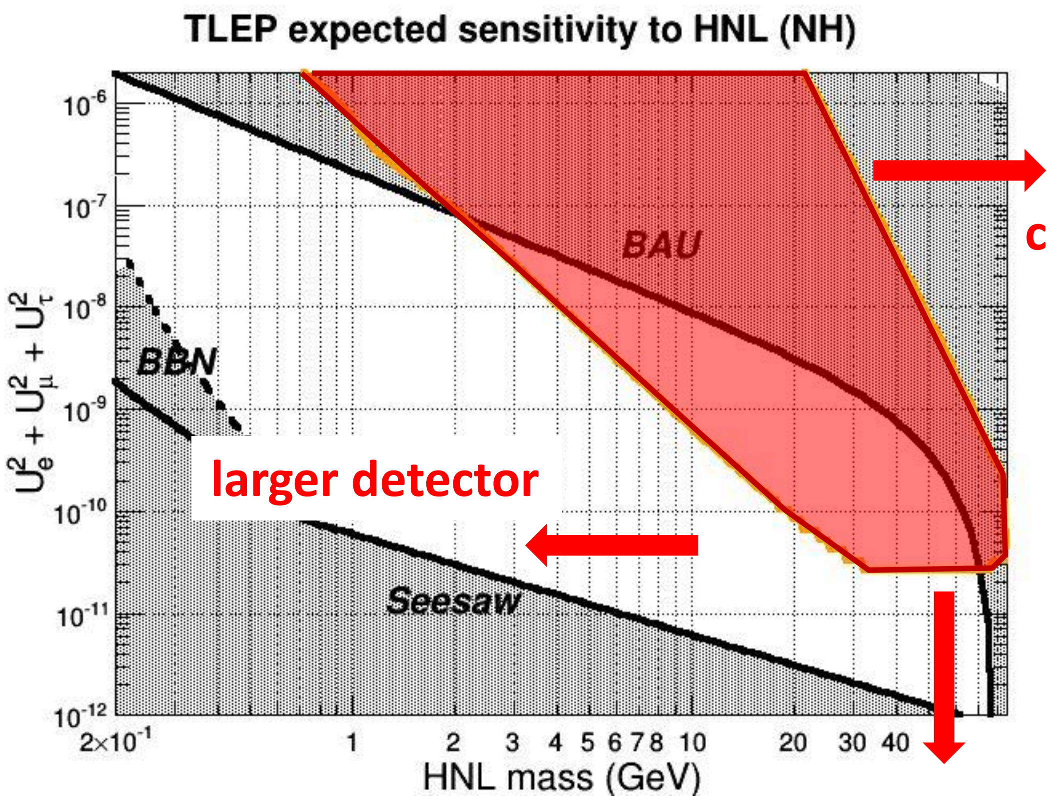
Exact reach domain will depend on detector size
and details of displaced vertex efficiency & background



Simulation of heavy neutrino decay in a FCC-ee detector



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



closer vertexing

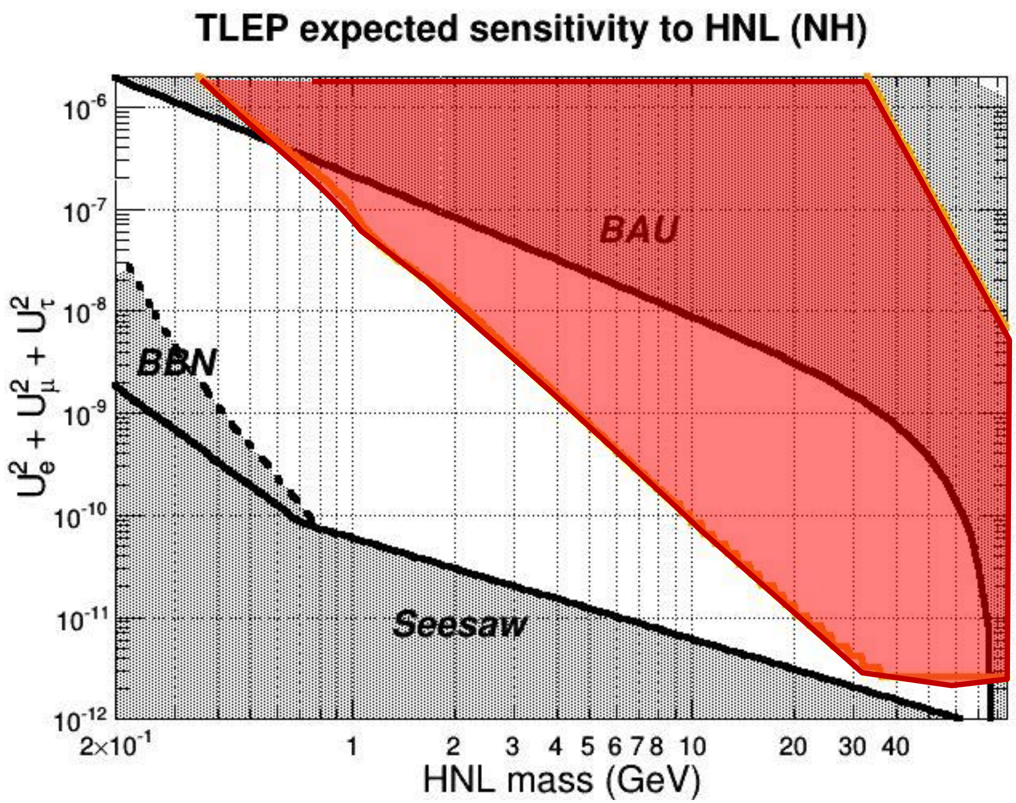
region of interest

FCC-ee sensitivity

more luminosity

A.B, Elena Graverini, Nicola Serra, Misha Shaposhnikov [**arXiv:1411.5230**]

contrary to bb or pp, like sign lepton does not occur.



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

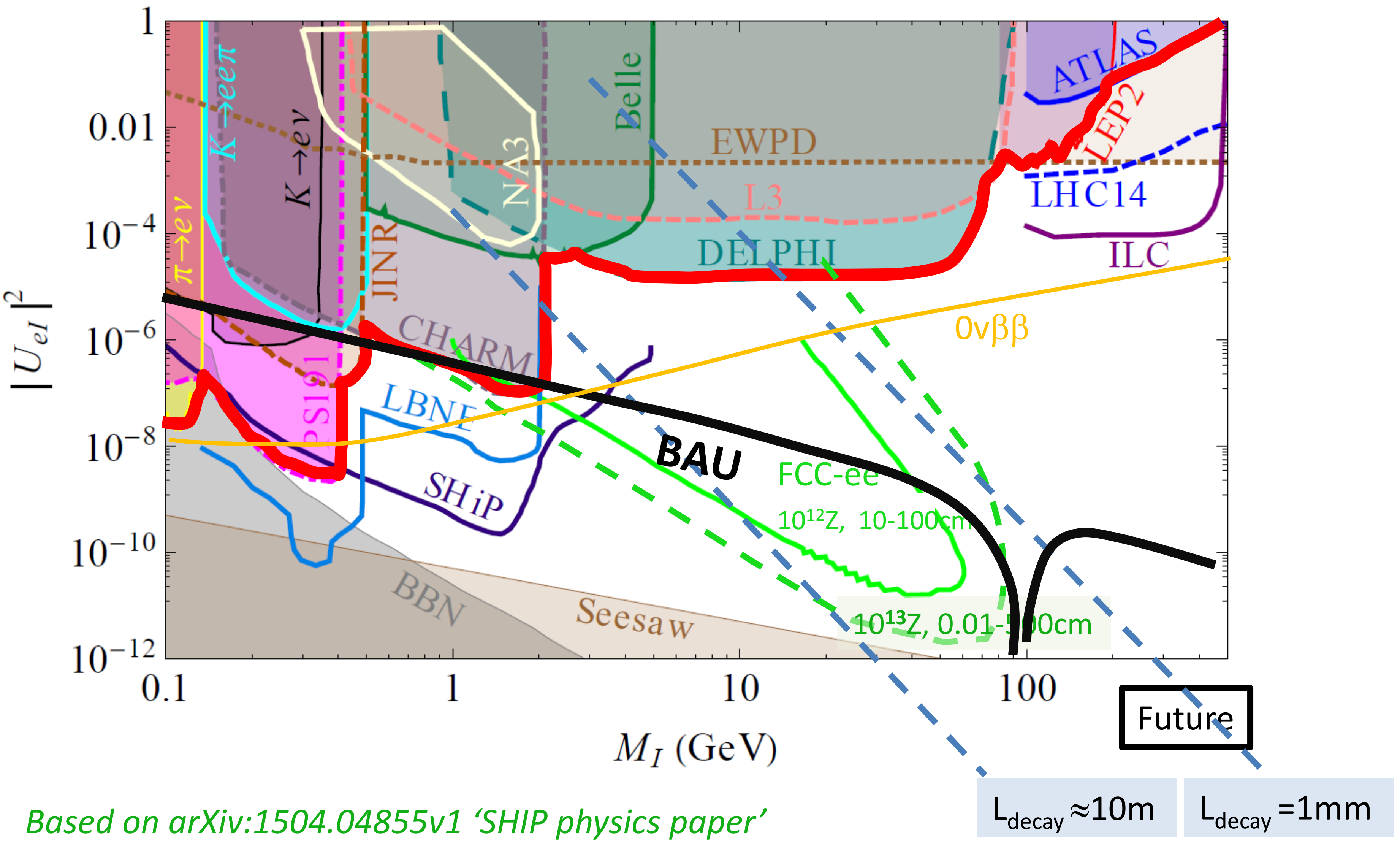
region of interest

FCC-ee sensitivity

the **blind region** between 5 and ~20 GeV is reduced directly as function of the size of the detector.

8m radius? Under evaluation in the FCC-ee detector group

Present limits



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

Testable Baryogenesis in Seesaw Models

P. Hernández,[a] M. Kekic,[a] J. López-Pavón,[b] J. Racker,[a] J. Salvado.[a]

[a] *Instituto de Física Corpuscular, Universidad de Valencia and CSIC, Edificio Institutos Investigación, Catedrático José Beltrán 2, 46980 Spain*

[b] *INFN, Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy*

Abstract: We revisit the production of baryon asymmetries in the minimal type I seesaw model with heavy Majorana singlets in the GeV range. In particular we include for the first time "washout" effects from scattering processes with gauge bosons and higgs decays and inverse decays, besides the dominant top scatterings. We show that in the minimal model with two singlets, and for an inverted light neutrino ordering, future measurements from SHiP and neutrinoless double beta decay could in principle provide sufficient information to predict the matter-antimatter asymmetry in the universe up to a sign. We also show that SHiP measurements could provide very valuable information on the PMNS CP phases.

Keywords: Beyond Standard Model, Cosmology of Theories beyond the SM, Neutrino physics, CP violation

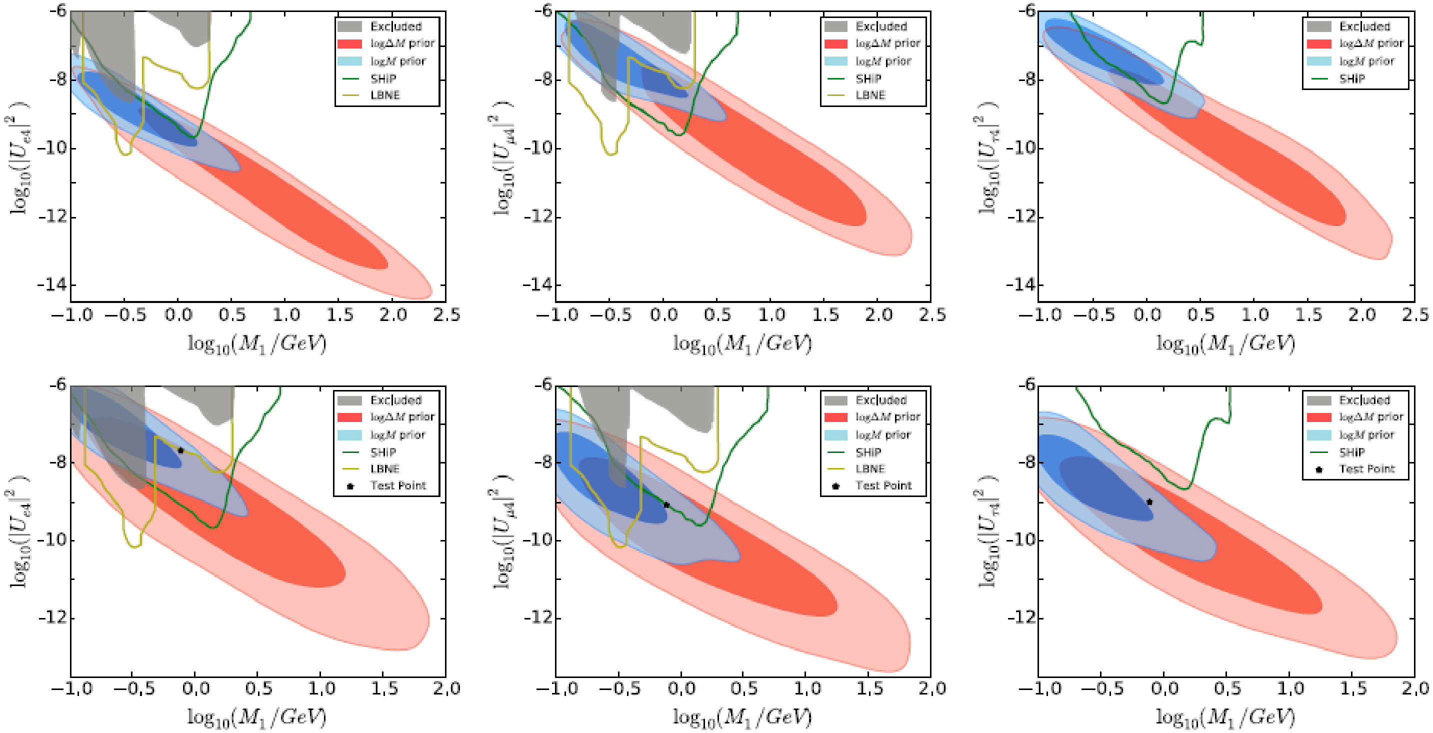
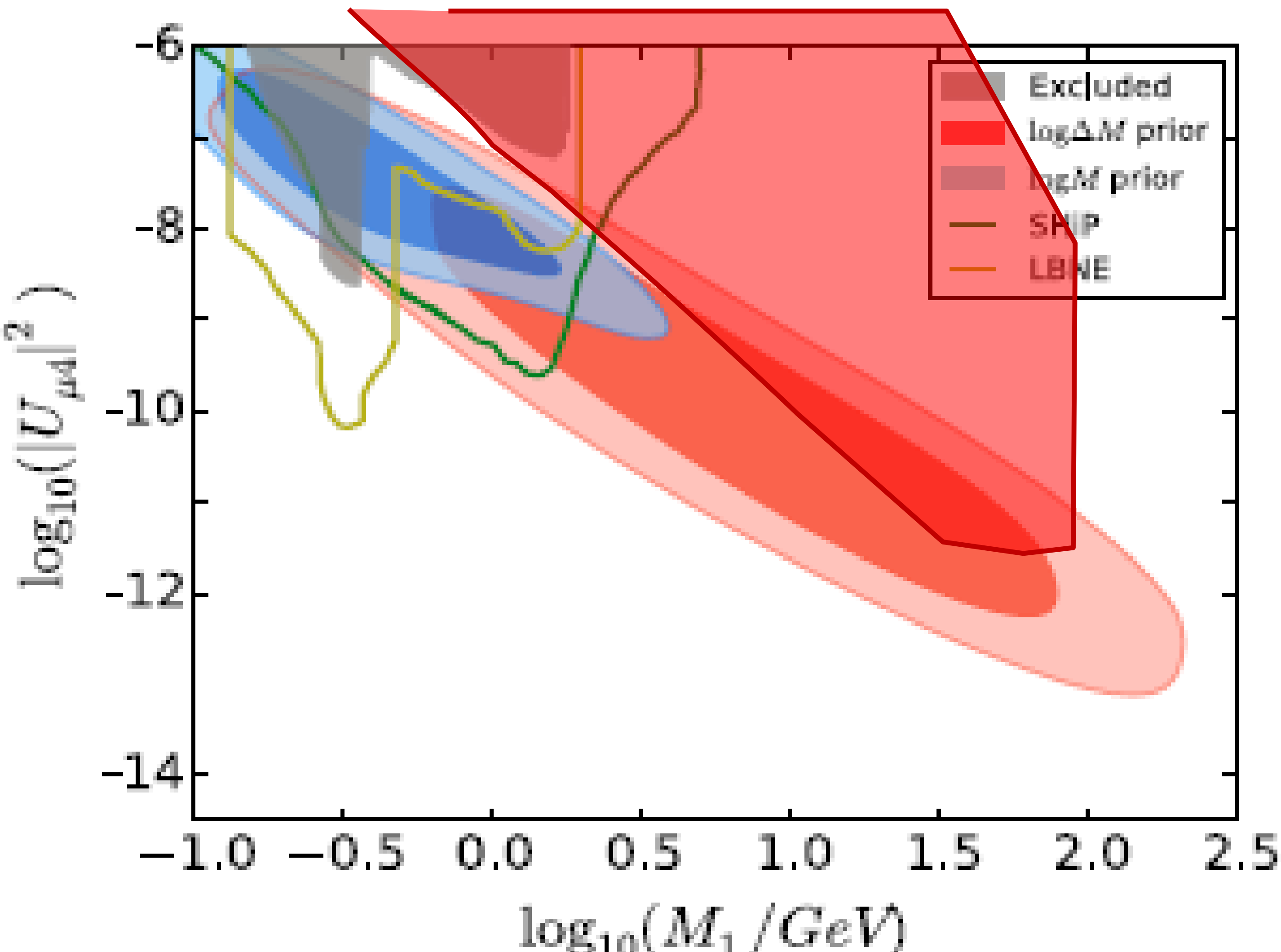


Figure 6. Comparison of the posterior probability contours at 68% and 90% on the planes mixings with e, μ, τ versus masses, with the present (shaded region) and future constraints from LBNE and SHiP for NH (up) y IH (down).

region of interest

FCC-ee sensitivity

$N_Z = 10^{13}$ 100μm <L<5m



CP violation!

The seesaw path to leptonic CP violation

A. Caputo[a,1,2], P. Hernandez [b,1,2], M. Kekic [c,1], J. López-Pavón [d,2], J. Salvado[e,1]

[1]Instituto de Física Corpuscular, Universidad de Valencia and CSIC, Edificio Institutos Investigación, Catedrático José Beltrán 2, 46980 Spain.
[2]CERN, Theoretical Physics Department, Geneva, Switzerland.

arXiv:1611.05000v1 (SHIP, B factory, Z factory)

$$|U_{ei}|^2 M_i \simeq A\left[r s_{12}^2 - 2\sqrt{r}\theta_{13}\sin(\delta+\phi_1)s_{12} + \theta_{13}^2 + \mathscr{O}(\varepsilon^{5/2})\right],$$
$$|U_{\mu i}|^2 M_i \simeq A\left[s_{23}^2 - \sqrt{r}\, c_{12}\sin\phi_1 \sin 2\theta_{23} + r c_{12}^2 c_{23}^2 \right.$$
$$\left. + 2\sqrt{r}\,\theta_{13}\sin(\phi_1+\delta)s_{12}s_{23}^2 - \theta_{13}^2 s_{23}^2 + \mathscr{O}(\varepsilon^{5/2})\right]. \quad (6)$$

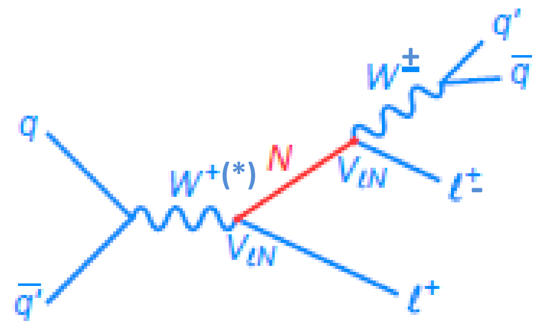
The ratio of decays in muons to electrons is directlly related to the ratio of phases (and the known PMNS angles)

➔ *the discovery of a massive neutrino and the measurement of its mass and its mixings to electrons and muons can result in a 5σ CL discovery of leptonic CP violation in very significant fraction of the CP-phase parameter space (> 80%/>60%) for IH/NH for mixings above O(10^{-8}) in SHiP and above O(10^{-10}) in FCC-ee.*

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.



or $l^{\pm}\nu$

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... **to be further investigated.**
Requirements: displaced vertex trigger or triple lepton signature

Conclusion

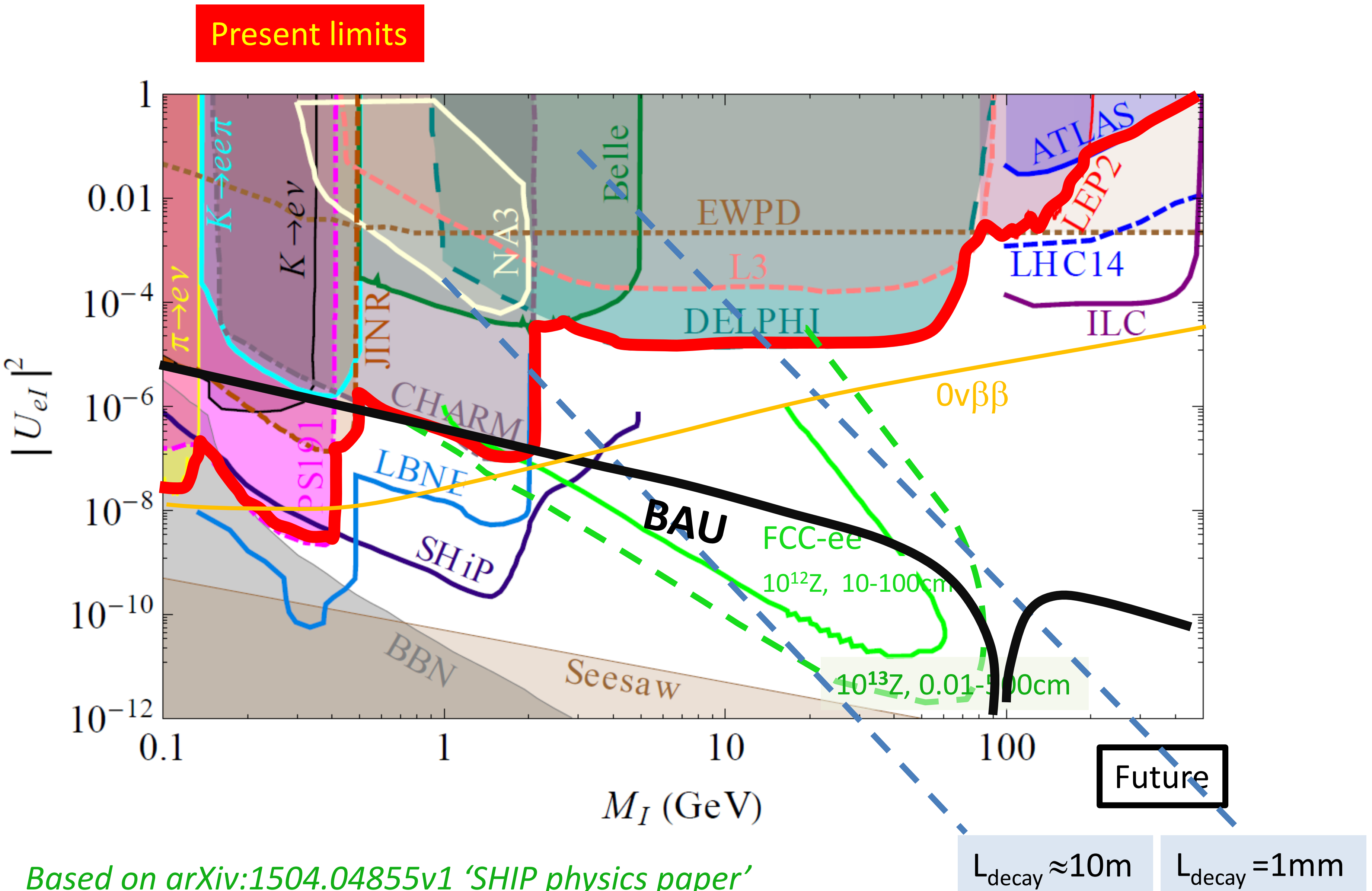
The quest for the right-handed neutrinos is very well motivated
…. we have already seen the tail of the dinosaur!

The three FCCs can have their say:

-- precision EW observables, and number of neutrinos at FCC-ee give limits up to very high masses but limited to reletively high couplings

-- direct searches for RH neutrinos :
mass below Z mass down to very low couplings (relevant to BAU) at FCC-ee in clean environment
similarly in FCC-hh iff detached vertices can be triggered on or in triple lepton final state
in FCC-eh access to ν_e-mixed RH neutrino allows direct reach to higher masses (larger mixing)

→ different regions of phase space, different capabilities.



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

e+ e- Search for heavy neutral leptons

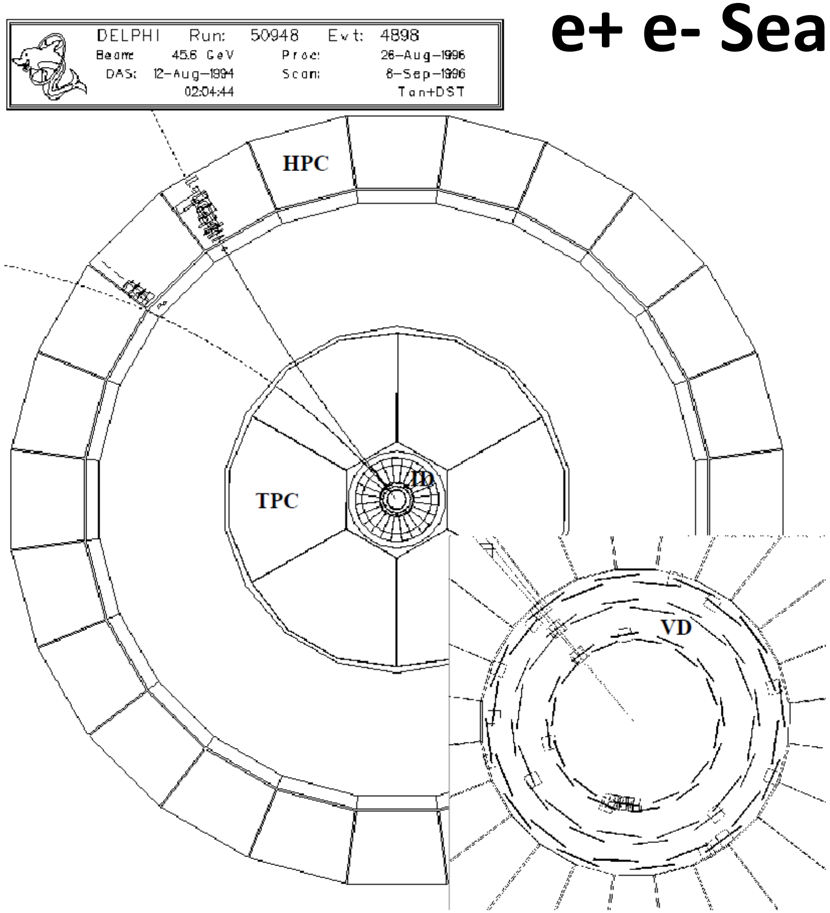
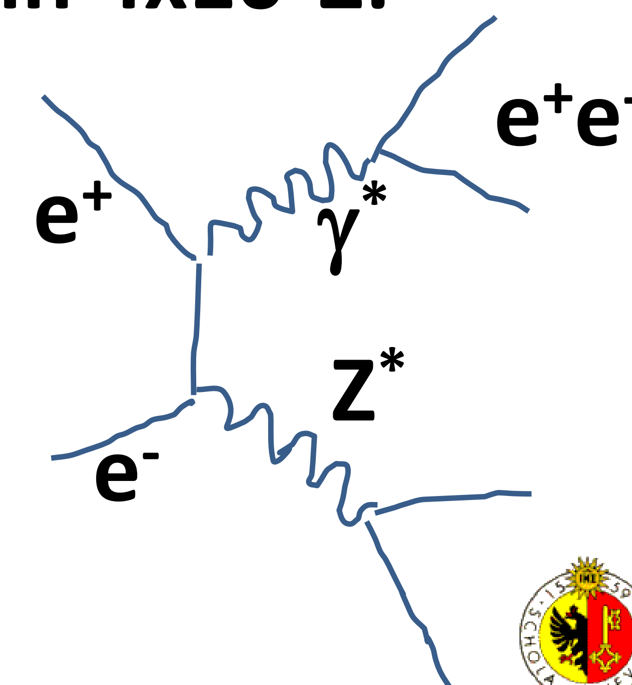


Fig. 3. Surviving event in the monojet search. It has an invariant mass of 300 MeV/c^2 and a missing p_t of 6 GeV/c and is probably an $e^+e^- \rightarrow e^+e^-\nu\bar{\nu}$ interaction

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

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

Find: one event in $4\text{x}10^6$Z:



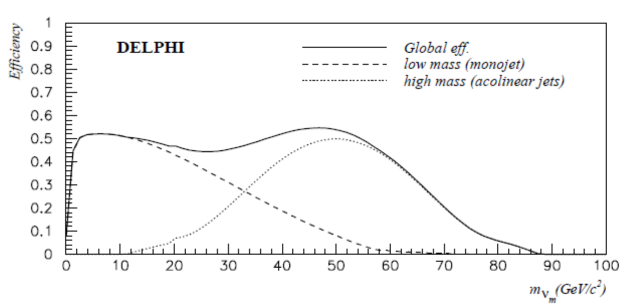
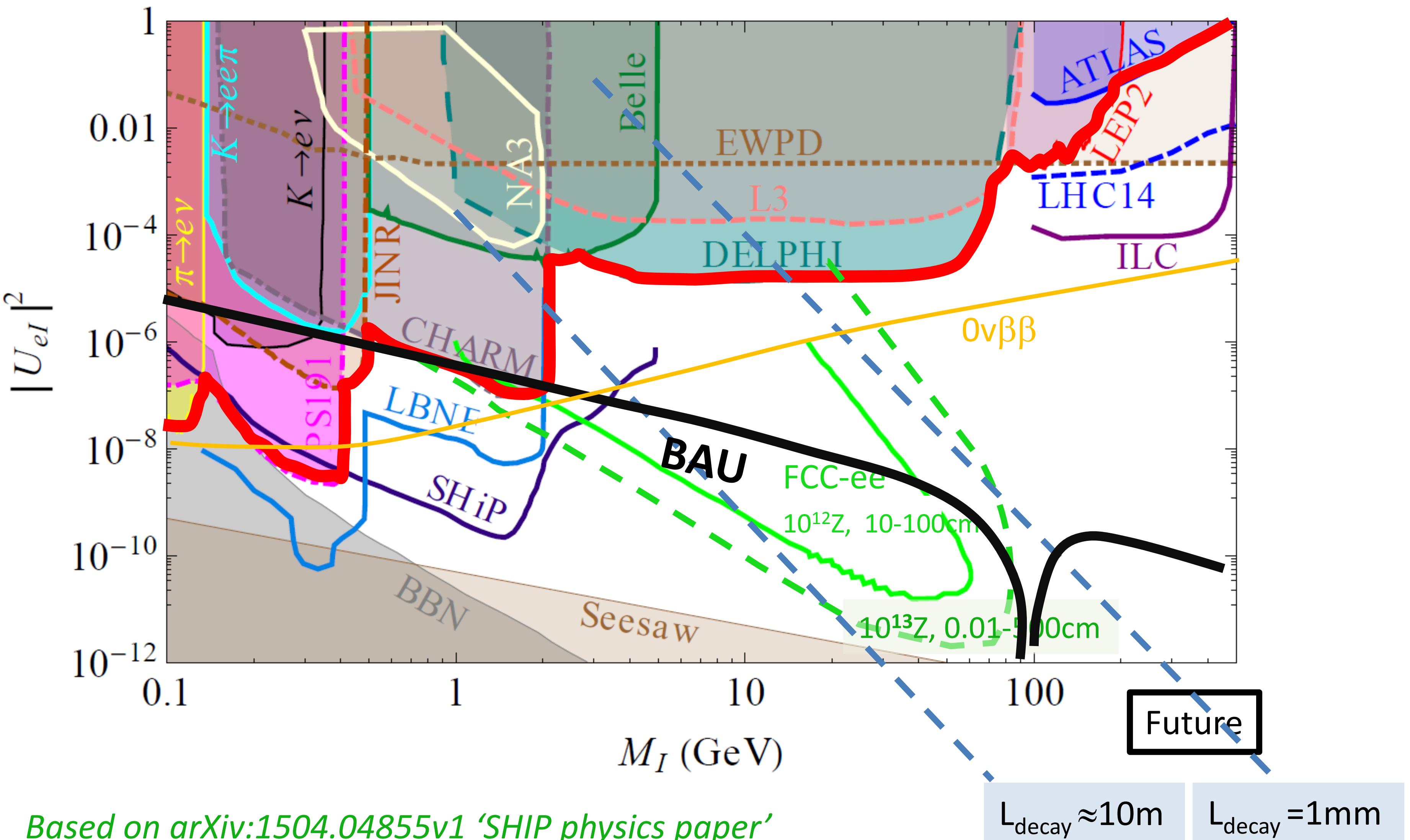


Fig. 4. Efficiency of the monojet search (Sect. 3) and the acollinear jets search (Sect. 4). The *full curve* shows the efficiency of the two searches combined

ers

Present limits



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

HERE COMES THE FCC

Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

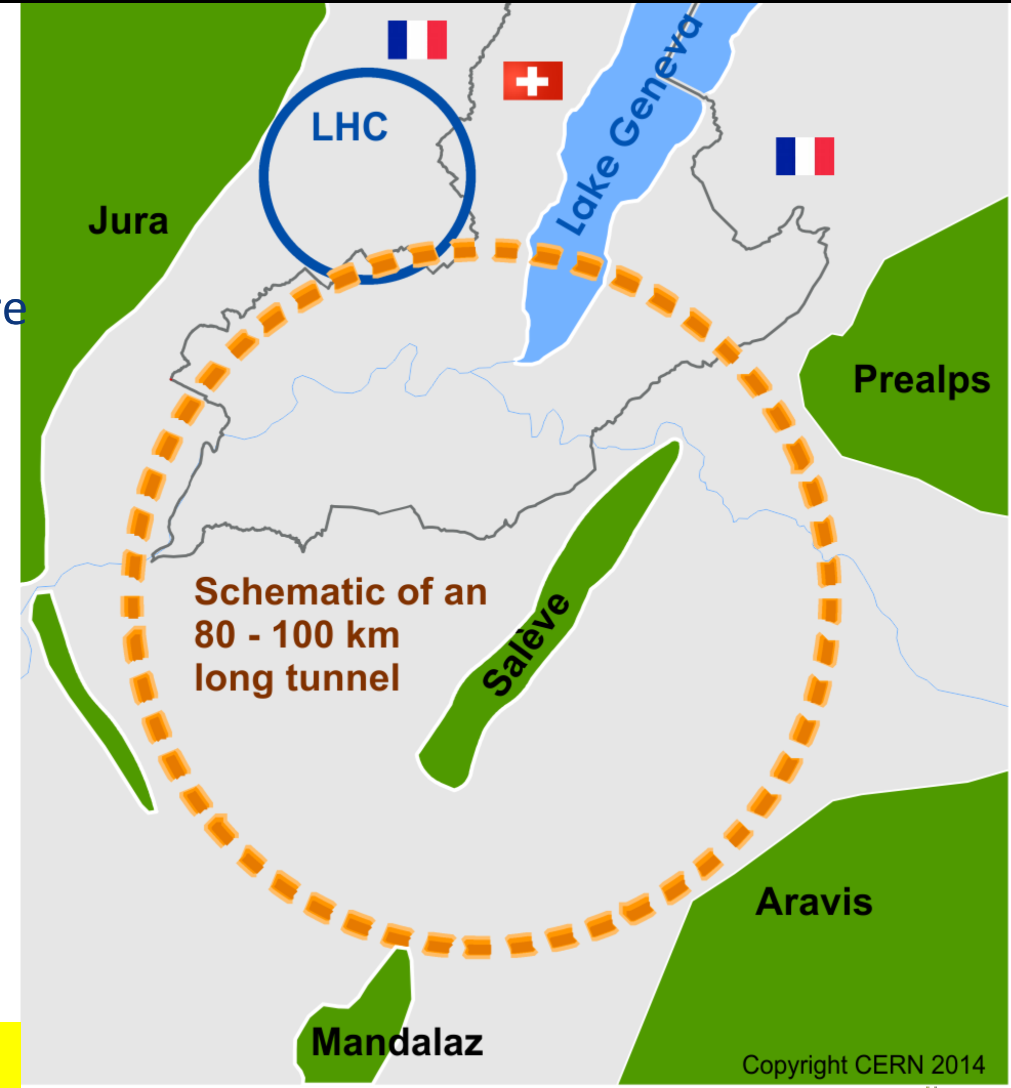
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*) *O(100) TeV***
  main emphasis, defining infrastructure requirements

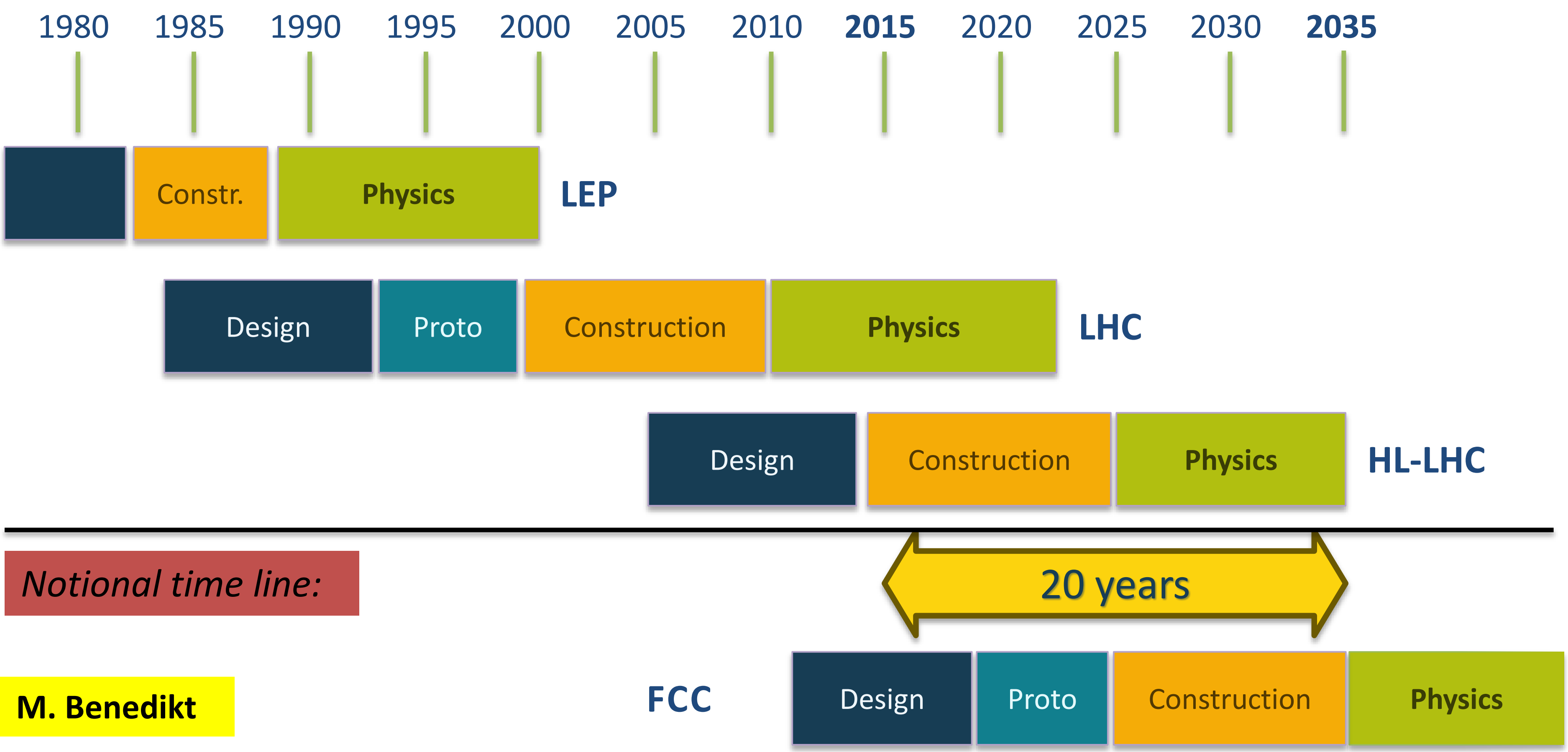
~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area
- ***e^+e^-* collider (*FCC-ee*) 90-400GeV**
  as possible first step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology

M. Benedikt



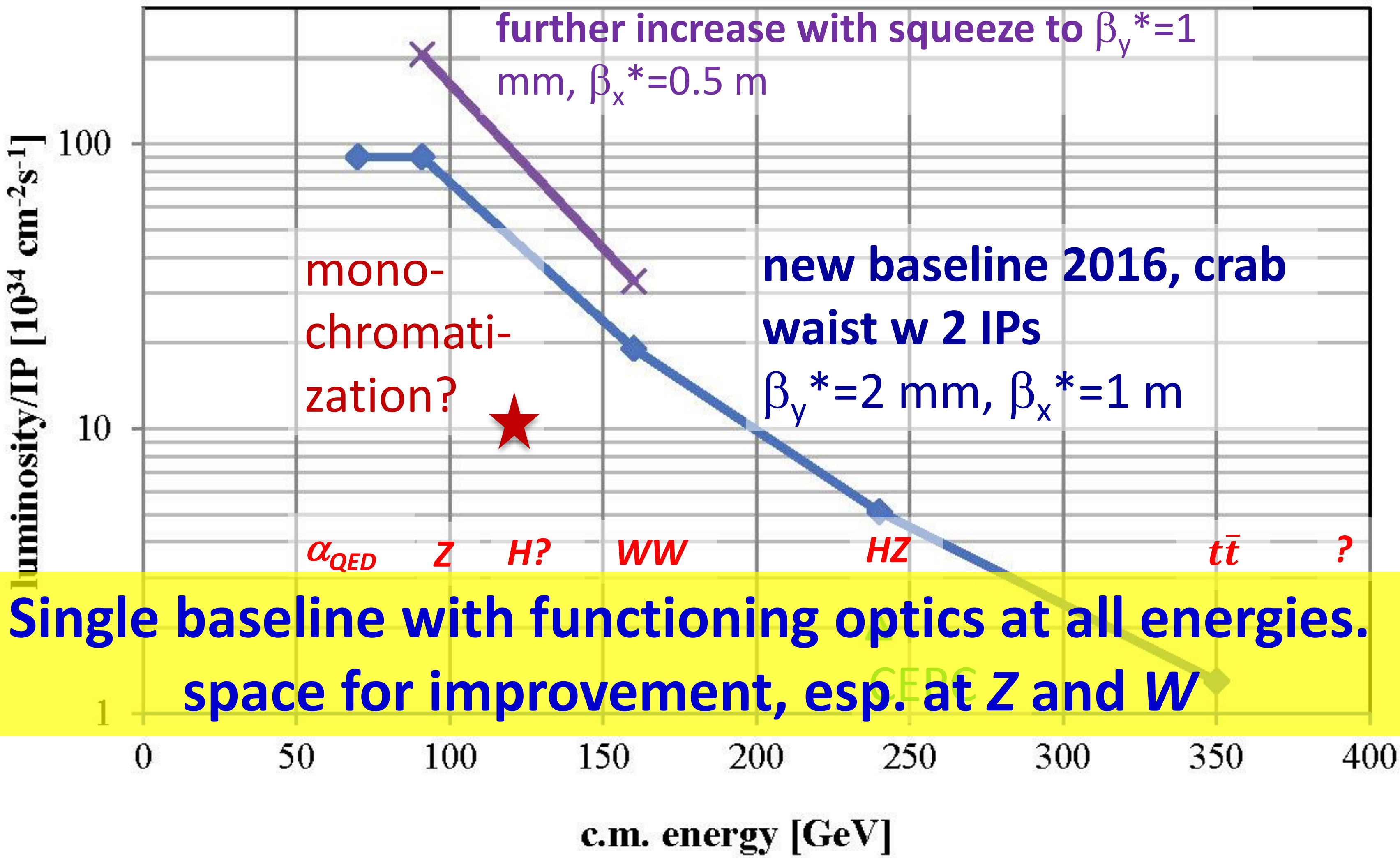
CERN Circular Colliders and FCC



(FCC-ee)

Now is the right time to plan for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

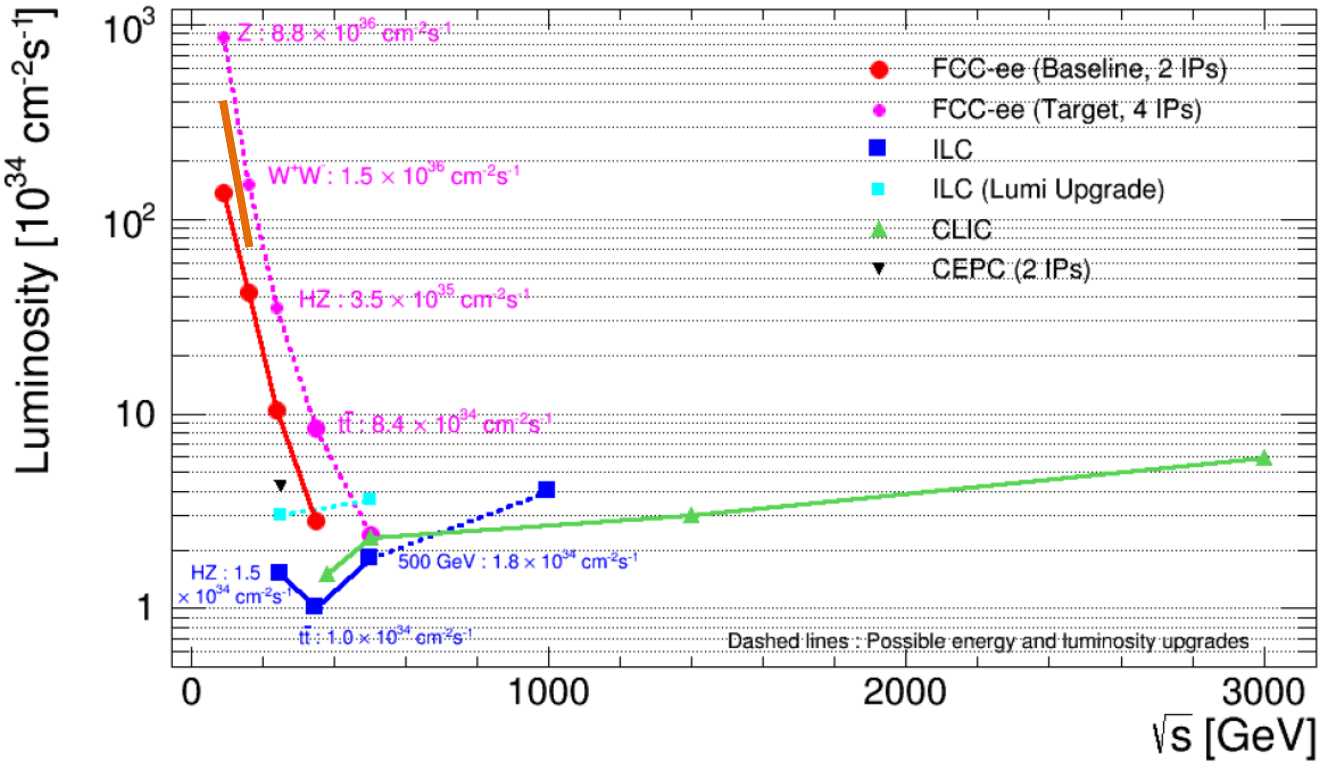
FCC-ee luminosity per IP



Single baseline with functioning optics at all energies.
space for improvement, esp. at *Z* and *W*

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**
- **100 keV energy Calibration.**



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

typical running scenario

Z pole: 1-2 10^{36}/cm^2/s/IP → 2.5 10^{12} Z events (per experiment) 3-5 years
+ Z scan 1 year
WW threshold: 3.5 10^{35}/cm^2/s/IP 1 year

m_Z, Γ_Z (100 KeV), m_W (500 keV), $\sin^2\theta_W^{eff}$ (<10^{-5} from asymmetries & tau polar.), R_b, $\alpha_{QED}(m_z)$ (3 10^{-5}), $\alpha_s(m_z)$ (O(10^{-4}) from B_{zh} & B_{wh}), N_ν from Zγ (0.0004) etc…

ZH threshold : 5 10^{34}/cm^2/s/IP : >500’000 Higgs / exp 4 years

tt (E_{CM} 350-365 GeV) 1.3 10^{34}/cm^2/s/IP 4 years

Higgs width (<1%), invisible width (<0.2%), HZZ (<0.1%) etc. etc.
Top quark mass (O(10 MeV)) and top couplings from top cross-section and polarization

above luminosities according to March 2016 baseline (with room for improvement);
optimization will continue as luminosity figures evolve; there is no pile-up at FCC-ee!
in addition possible run at e+e- → H (125.2 GeV)

FCC-ee discovery potential

of course discovery depends on the goodwill of nature;
a few things that FCC-ee could do and discover (if they exist):

EXPLORE 10 TeV energy scale (and beyond) with Precision Measurements
~20-50 fold improved precision on many EW quantities (eq. factor 5-7 in mass)
$m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z), α_s (m_z), Higgs and top couplings

DISCOVER that SM does not fit → *<u>for sure</u>* exist extra ~weakly coupled particle(s)

DISCOVER a violation of flavour conservation

- **ex FCNC (Z → $\mu\tau$, $e\tau$) in 5 10^{12} Z decays.**
  + flavour physics (10^{12} bb events!)

M. Bicer et al.,
"First Look at the Physics Case of TLEP,"
JHEP01 (2014) 164

DISCOVER dark matter as «invisible decay» of H or Z

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: right-handed neutrinos, dark photons etc…

…..

A Sample of Essential Quantities:

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(161 GeV)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	**±0.000015**	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<0.5 MeV**	E_cal & Statistics	Backgrounds, QED/EW
m_{top} MeV/c2	**Input**	173340 ± 760	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 50 MeV?

Theoretical limitations

FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm 0.0002_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\Delta\alpha_{had}} \pm 0.0001_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0040_{theo}$$

0.0005

$$\sin^2\theta^{\ell}_{\rm eff} = 0.231496 \pm 0.0000015_{m_t} \pm 0.000001_{M_Z} \pm 0.00001_{\Delta\alpha_{had}} \pm 0.0000014_{\alpha_S} \pm 0.000000_{M_H} \pm 0.000047_{theo}$$

0.00001

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
<u>Will require significant theoretical effort and additional measurements!</u>

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!
<u>Suggest including manpower for theoretical calculations in the project cost.</u>

Higgs Coupling Summary

M. Klute LCWS2015

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee	FCC-hh
m_H [MeV]	40	0.06	40	30	5.5	8	
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04	
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15	
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2	
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4	
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5	
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5	
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7	
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8	
g_{Htt} [%]	4.0	-	4.5	18	-	-	1
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2	1
g_{HHH} [%]	30	-	24	-	-	-	5
g_{Hee}/SM						<2	

* Estimate for two HL-LHC experiments

** ILC lumi upgrade improves precision by factor 2

For ~10y operation. Lots of "!,*,?"

Every number comes with her own story.

To be added to such a table: rare decays and CP violation

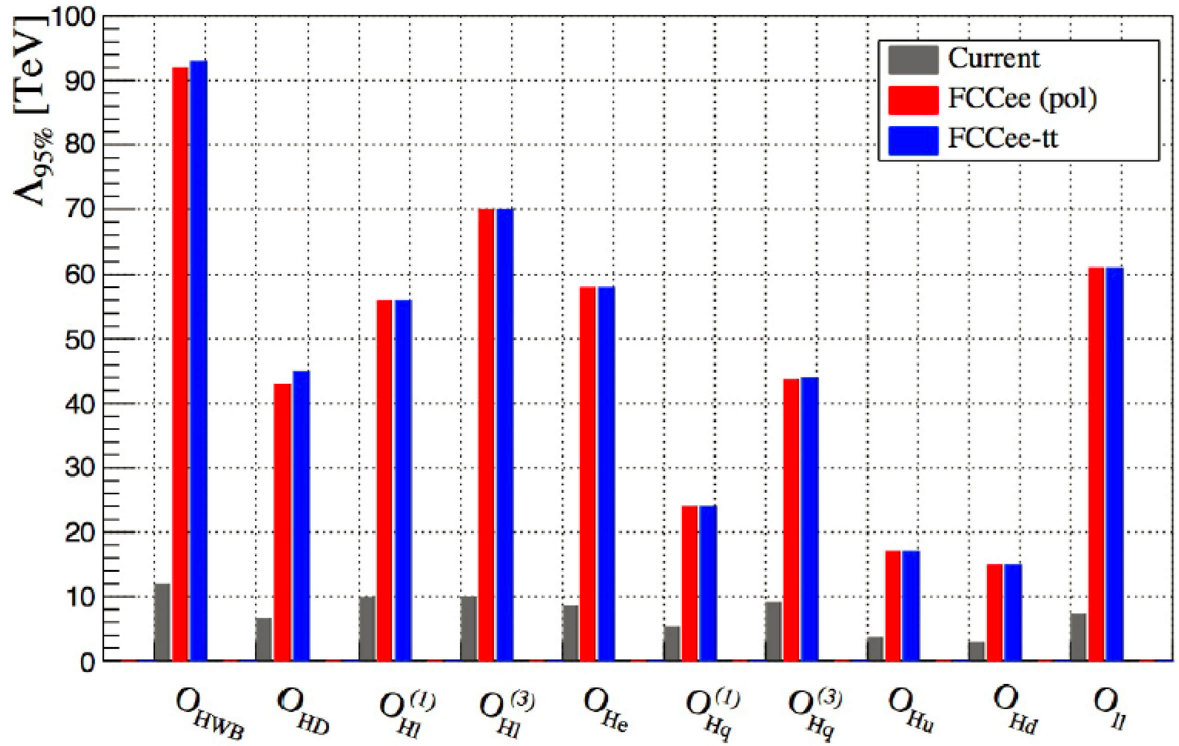
precision H & EW physics at FCC-ee: exploratory each

$\mathcal{O}_{Hl}^{(3)}$ $(H^\dagger i \overleftrightarrow{D}_\mu^a H)(\overline{l_L}\gamma^\mu \sigma_a l_L)$
$\mathcal{O}_{He}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e_R}\gamma^\mu e_R)$
$\mathcal{O}_{Hq}^{(1)}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{q_L}\gamma^\mu q_L)$
$\mathcal{O}_{Hq}^{(3)}$ $(H^\dagger i \overleftrightarrow{D}_\mu^a H)(\overline{q_L}\gamma^\mu \sigma_a q_L)$
$\mathcal{O}_{Hu}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{u_R}\gamma^\mu u_R)$
$\mathcal{O}_{Hd}$ $(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d_R}\gamma^\mu d_R)$
$\mathcal{O}_{ll}$ $(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$

EW limits on NP: dimension 6 SMEFT

- Dimension six SMEFT: **Present vs. Future**

1 operator at a time. Flavor universal.



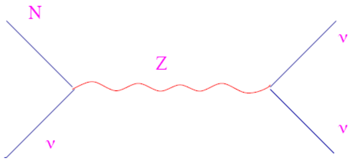
FCCee: NP scale >15-90 TeV

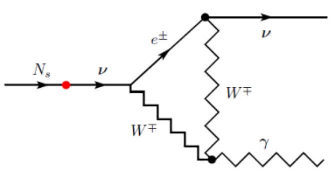
J. de Blas

NOW BACK TO THE SEARCH FOR RIGHT-HANDED NEUTRINOS

Search Processes (I)

m_N Below m_π:
N→ 3ν; N→ νγ w $E_\gamma = m_N/2$

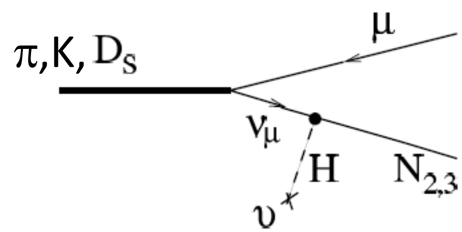


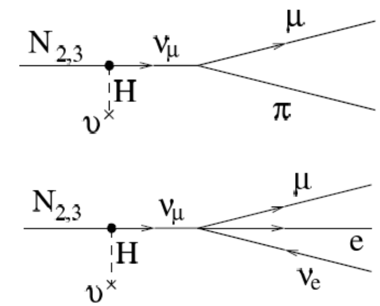


$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\text{ keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

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:





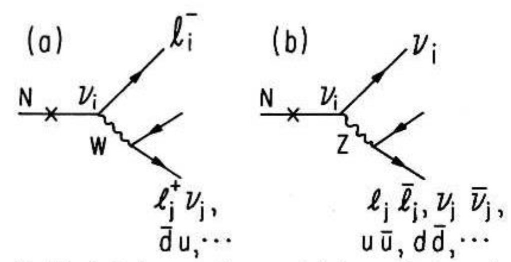


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

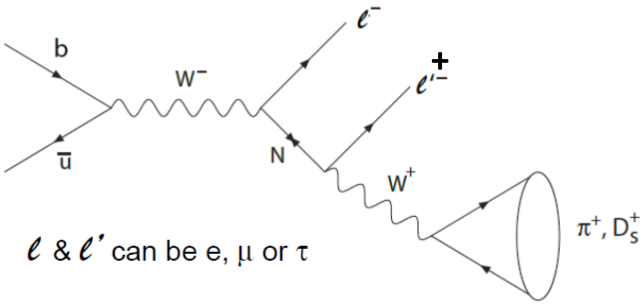
$$L \approx \frac{3}{|U|^2\ (m_{\nu_m}(\mathrm{GeV}/c^2))^6} \times \frac{P_\nu}{45GeV/c}$$

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

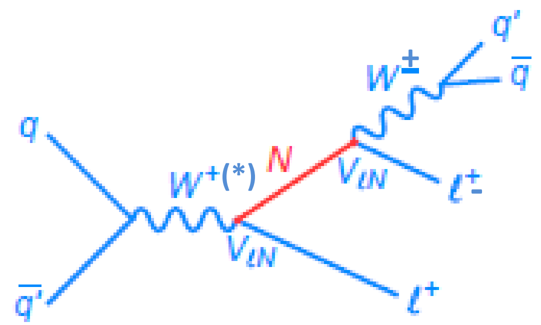
Processes (II)

Search for heavy right-handed neutrinos in collider experiments.

B factories

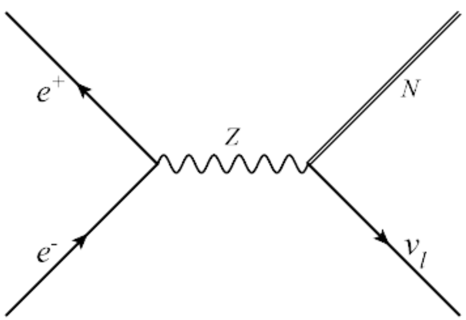


Hadron colliders

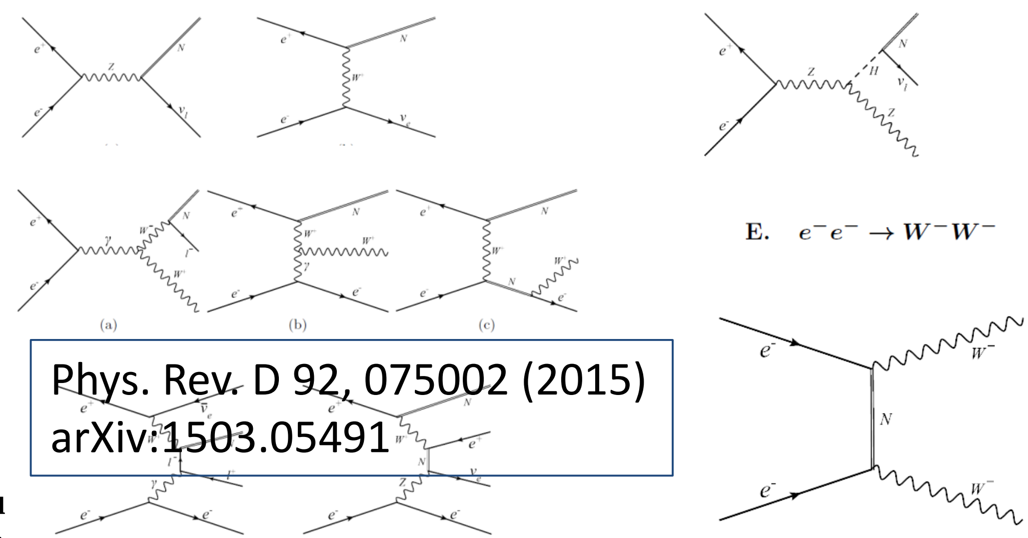


Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



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



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arXiv:1503.05491