Current and future aspects of heavy fermion searches

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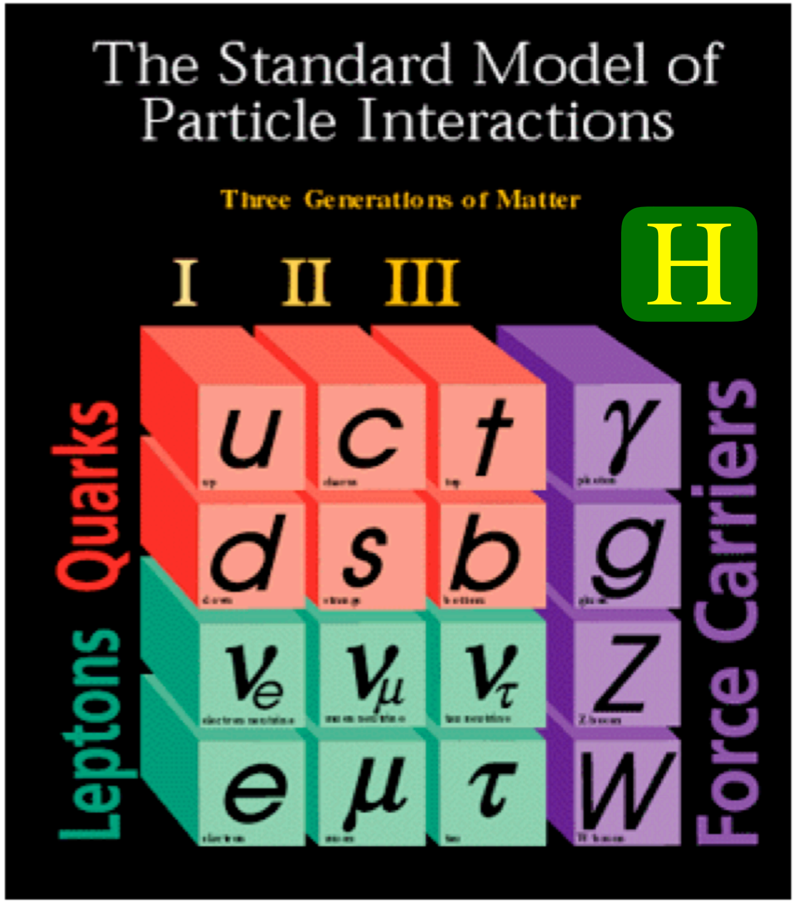
Anomalies 2020 September 13, 2020 @IIT – Hyderabad



Over the decades experiments
have found each
and every missing pieces

Verified the facts that
they belong to this family

Finally at the Large Hadron collider
Higgs has been observed
→ Its properties must be verified

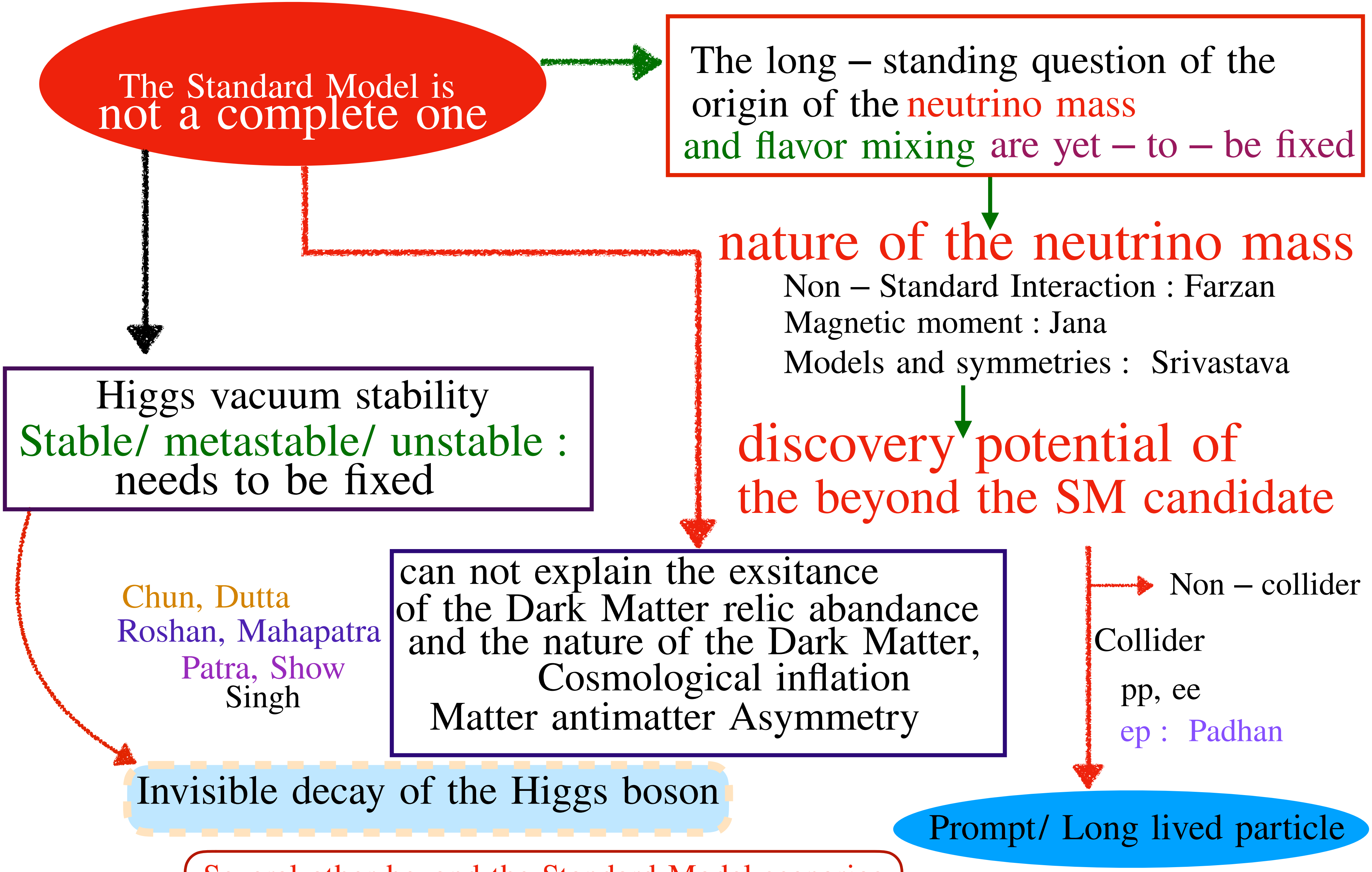
Strongly established with interesting shortcomings

Few of the very interesting anomalies :

Tiny neutrino mass and flavor mixings
Relic abundance of dark matter . . .

SM can not explain them

In a nutshell motivation of BSM physics is very strong



The Standard Model is not a complete one

The long – standing question of the origin of the neutrino mass and flavor mixing are yet – to – be fixed

nature of the neutrino mass

Non – Standard Interaction : Farzan
Magnetic moment : Jana
Models and symmetries : Srivastava

discovery potential of the beyond the SM candidate

Non – collider

Collider

pp, ee

ep : Padhan

Prompt/ Long lived particle

Higgs vacuum stability
Stable/ metastable/ unstable : needs to be fixed

can not explain the exsitance of the Dark Matter relic abandance and the nature of the Dark Matter,
Cosmological inflation
Matter antimatter Asymmetry

Chun, Dutta
Roshan, Mahapatra
Patra, Show
Singh

Invisible decay of the Higgs boson

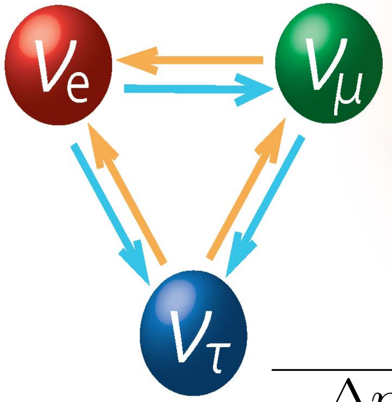
Several other beyond the Standard Model scenarios
e.g. Flavor physics

Results in the neutrino Sector

Goswami

Super- Kamiokande, Sudbury Neutrino Observatory 1999 ,
Neutrino oscillation between mass and flavor eigenstates

Neutrinos are very special



Physics Nobel Prize 2015

ν

Neutrino oscillation data

Δm^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$	SNO
$\lvert\Delta m_{31}\rvert^2$	$2.4 \times 10^{-3}\mathrm{eV}^2$	Super – K
$\sin^2 2\theta_{12}$	0.87	KamLAND, SNO
$\sin^2 2\theta_{23}$	0.999	T2K
	0.90	MINOS
$\sin^2 2\theta_{13}$	0.084	DayaBay2015
	0.1	RENO
	0.09	DoubleChooz

- Nature of the neutrino mass : Majorana/ Dirac
- Ordering : Normal/Inverted
- Nature of the mixing between :
  Flavor and mass eigenstate

Models of Neutrino mass

Mitra

There is a wide variety of neutrino mass models

The predicted models extend the SM minimally

At the tree level SM can be extended by Singlet fermions

- Right handed neutrinos seesaw mechanism
  inverse seesaw mechanism

Minkowski, Ramond, Slansky, Yanagida, Gell – Mann, Glashow, Mohapatra, Senjanovic

Linear, Hybrid

Alternative ideas extending the Standard Model

- SU(2) triplet scalar : type – II seesaw

Schecter, Valle, Lazarides, Shafi, Wetterich, Mohapatra, Senjanovic

SU(2) triplet fermion : type – III seesaw

Foot, Lew, He, Joshi, Ma

One – loop and even at 2/3 – loop models also exist

- For example : Ma – model, Zee – Model, Zee – Babu model, BNT, KNT, etc .

Babu, Leung, Hirsch, King, Nasri, Volkas Dev, Pilaftsis AD, Nomura, Okada, Roy AD, Enomoto, Kanemura, Yagyu

- Gauge extended : U(1), Left – Right

Pati, Salam; Mohapatra, Pati; Senjanovic, Mohapatra Buchmuller, Greub; FileviezPerez, Han, Li; Deppisch . Desai, Valle; Kang, Ko, Li; Heeck, Teresi; Gluza, Chakrabortty Keung, Senjanovic; Ferrari et . al . ; Nemevsek, Nesti, Senjanovic, Zhang; Chen, Dev, Mohapatra; Dev, Mohapatra, Zhang; Dev, Goswami, Mitra AD, Dev, Mohapatra; AD, Okada, Papapietro AD, Goswami, Nomura, Vishnudath; Bandyopadhyay, Bhattacharyya, Das, Raychaudhuri; Bandyopadhyay, Raychaudhuri

Particle content

Dobrescu, Fox; Cox, Han, Yanagida; AD, Okada, Raut; AD, Dev, Okada;
Chiang, Cottin, AD, Mandal; AD, Takahashi, Oda, Okada

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$			$U(1)_X$
q_L^i	**3**	**2**	$+1/6$	x_q	$=$	$\frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	**3**	**1**	$+2/3$	x_u	$=$	$\frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	**3**	**1**	$-1/3$	x_d	$=$	$-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	**1**	**2**	$-1/2$	x_ℓ	$=$	$-\frac{1}{2}x_H - x_\Phi$
e_R^i	**1**	**1**	-1	x_e	$=$	$-x_H - x_\Phi$
H	**1**	**2**	$+1/2$	x'_H	$=$	$\frac{1}{2}x_H$
N_R^i	**1**	**1**	0	x_ν	$=$	$-x_\Phi$
Φ	**1**	**1**	0	x'_Φ	$=$	$2x_\Phi$

$$m_{Z'} = 2\, g_X v_\Phi$$

x_H, x_Φ will appear the coupling with Z'

3 generations of SM singlet right handed neutrinos (anomaly free)

Charges before the anomaly cancellations

Charges after Imposing the anomaly cancellations

$U(1)_X$ breaking

$$\mathcal{L}_Y \supset -\sum_{i,j=1}^{3} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{i=k}^{3} Y_N^k \Phi \overline{N_R^{k\,c}} N_R^k + \text{h.c.},$$

$$\boxed{m_D^{ij} = \frac{Y_D^{ij}}{\sqrt{2}} v_h} \qquad \boxed{m_{N^i} = \frac{Y_N^i}{\sqrt{2}} v_\Phi}$$

$$m_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \qquad m_\nu \simeq -M_D M_N^{-1} M_D^T$$

Seesaw mechnism

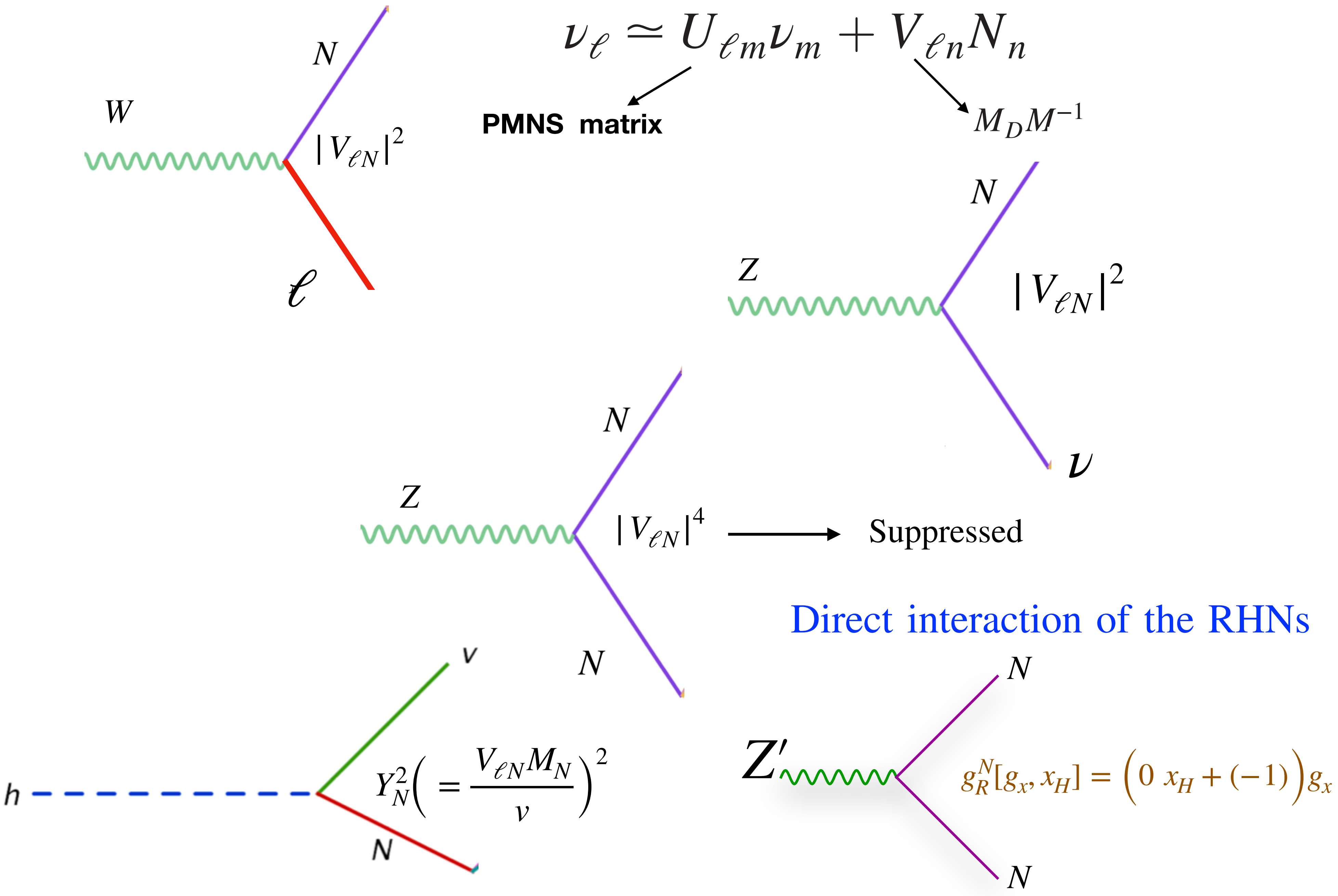
Direct interaction of the Right Handed Neutrinos through light – heavy mixing

Flavor eigenstate can be expressed in terms of the mass eigenstate

$$\nu_\ell \simeq U_{\ell m}\nu_m + V_{\ell n}N_n$$

PMNS matrix

$M_D M^{-1}$



$|V_{\ell N}|^4 \longrightarrow$ Suppressed

Direct interaction of the RHNs

Properties of the model and phenomenology

New particles

Z' boson

Heavy Majorana Neutrino

$U(1)_X$ Higgs boson

Phenomenology

Z' boson production and decay

Z' boson mediated processes

Heavy neutrino production

$U(1)_X$Higgs phenoemenology : Vacuum Stability

collider

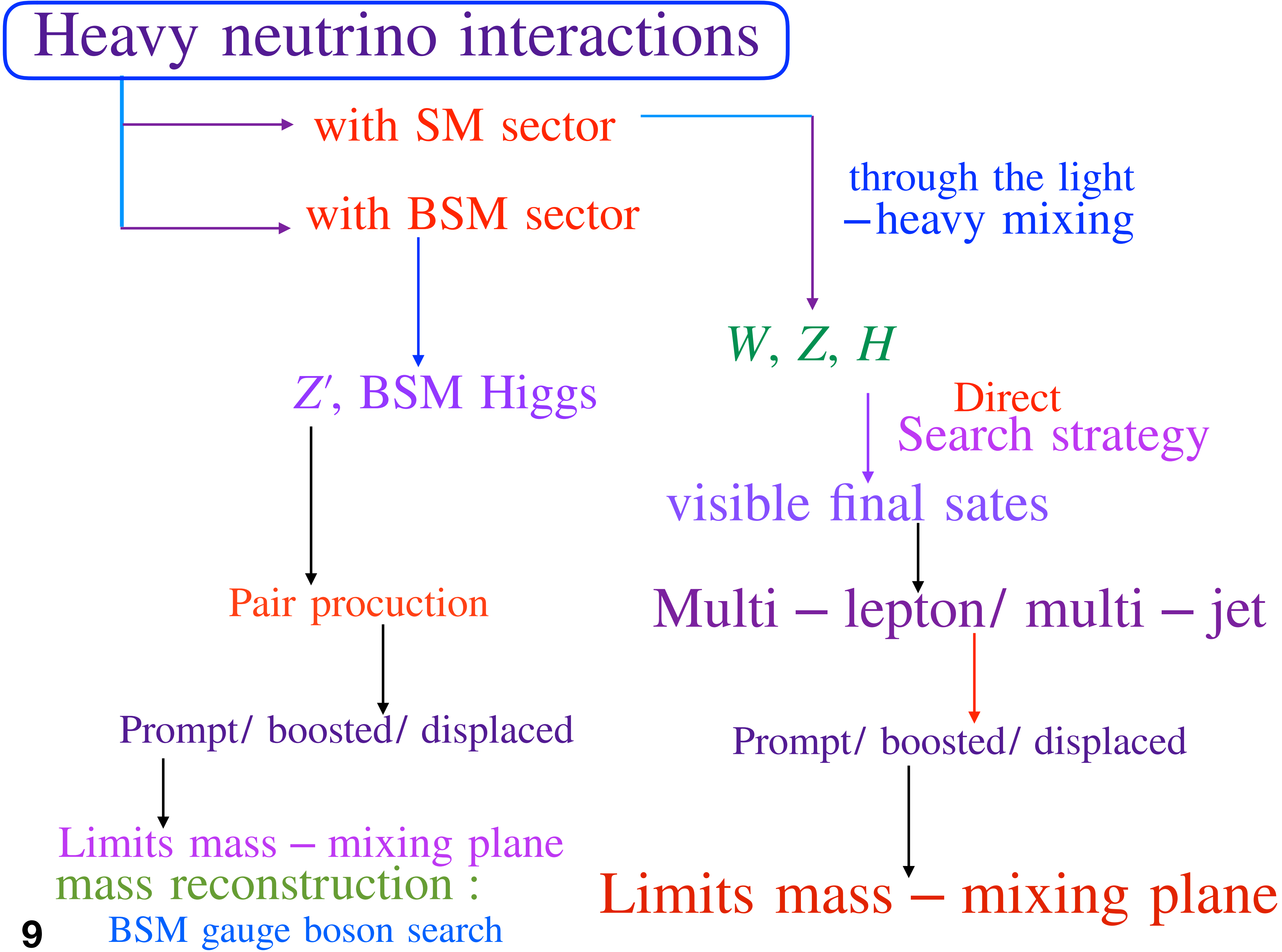
Dark Matter

Leptogenesis and many more

Dev, Pilaftsis; Iso, Okada, Orikasa

Orikasa, Okada, Yamada; Dev, Mohapatra, Zhang

Z′ boson and heavy neutrino phenomenology



Heavy neutrino interactions

with SM sector

with BSM sector

Z', BSM Higgs

Pair procuction

Prompt/ boosted/ displaced

Limits mass – mixing plane

mass reconstruction :

BSM gauge boson search

through the light –heavy mixing

W, Z, H

Direct Search strategy

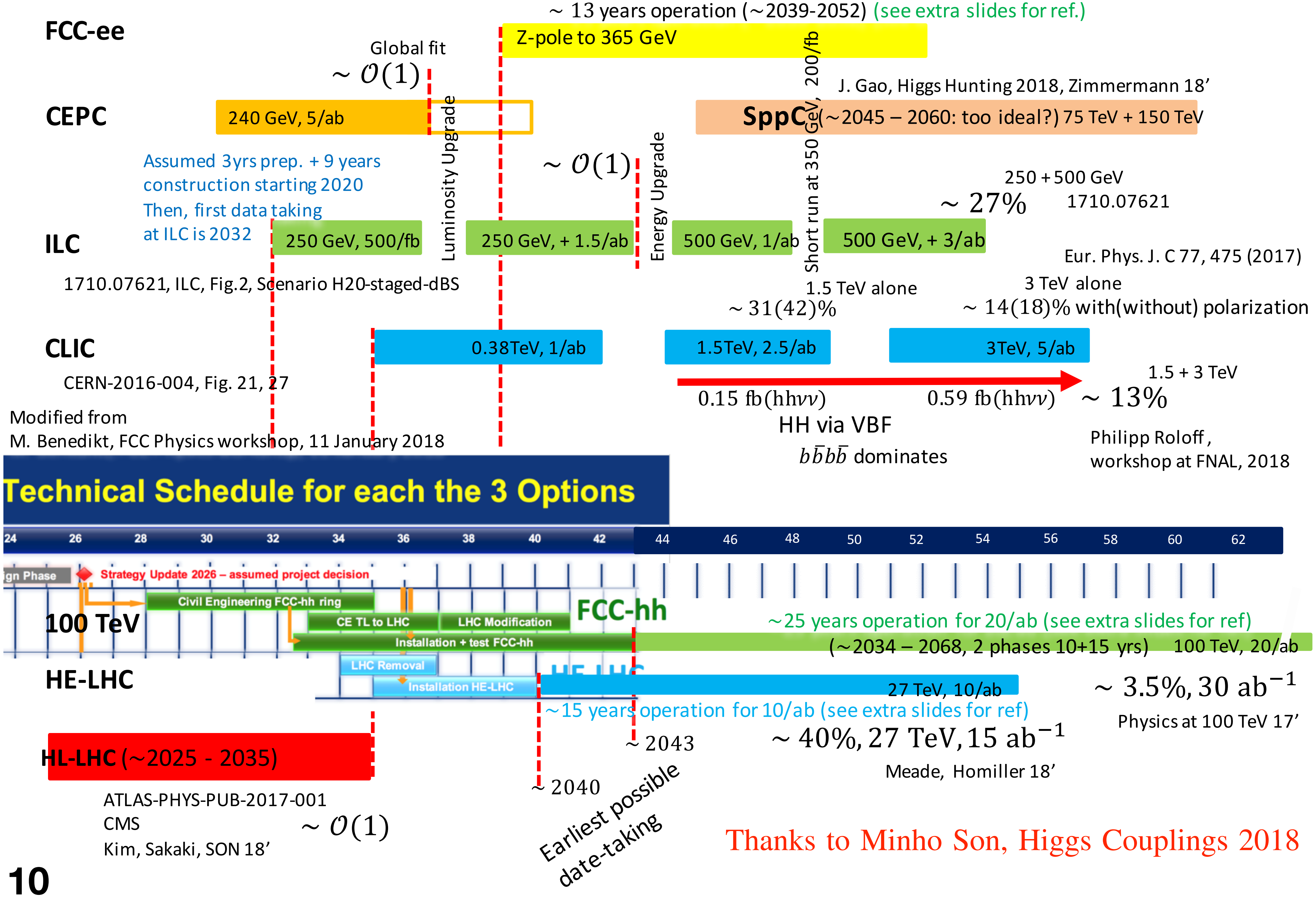
visible final sates

Multi – lepton/ multi – jet

Prompt/ boosted/ displaced

Limits mass – mixing plane

Future landscape @ Energy Frontier



$\sim$ 13 years operation ($\sim$2039-2052) (see extra slides for ref.)

FCC-ee

Z-pole to 365 GeV

Short run at 350 GeV, 200/fb

Global fit

$\sim \mathcal{O}(1)$

J. Gao, Higgs Hunting 2018, Zimmermann 18’

CEPC

240 GeV, 5/ab

Luminosity Upgrade

SppC ($\sim$2045 – 2060: too ideal?) 75 TeV + 150 TeV

Assumed 3yrs prep. + 9 years construction starting 2020
Then, first data taking at ILC is 2032

$\sim \mathcal{O}(1)$

Energy Upgrade

250 + 500 GeV

$\sim 27\%$

1710.07621

ILC

250 GeV, 500/fb

250 GeV, + 1.5/ab

500 GeV, 1/ab

500 GeV, + 3/ab

Eur. Phys. J. C 77, 475 (2017)

1710.07621, ILC, Fig.2, Scenario H20-staged-dBS

1.5 TeV alone

$\sim 31(42)\%$

3 TeV alone

$\sim 14(18)\%$ with(without) polarization

CLIC

0.38TeV, 1/ab

1.5TeV, 2.5/ab

3TeV, 5/ab

CERN-2016-004, Fig. 21, 27

1.5 + 3 TeV

$0.15\ \text{fb}\,(hh\nu\nu)$

$0.59\ \text{fb}\,(hh\nu\nu)$

$\sim 13\%$

HH via VBF

$b\bar{b}b\bar{b}$ dominates

Philipp Roloff, workshop at FNAL, 2018

Modified from
M. Benedikt, FCC Physics workshop, 11 January 2018

Technical Schedule for each the 3 Options

100 TeV

FCC-hh

$\sim$25 years operation for 20/ab (see extra slides for ref)

($\sim$2034 – 2068, 2 phases 10+15 yrs) 100 TeV, 20/ab

HE-LHC

27 TeV, 10/ab

$\sim 3.5\%, 30\ \text{ab}^{-1}$

Physics at 100 TeV 17’

$\sim$15 years operation for 10/ab (see extra slides for ref)

$\sim$ 2043

$\sim 40\%, 27\ \text{TeV}, 15\ \text{ab}^{-1}$

Meade, Homiller 18’

HL-LHC ($\sim$2025 - 2035)

$\sim$ 2040

Earliest possible date-taking

ATLAS-PHYS-PUB-2017-001
CMS
Kim, Sakaki, SON 18’

$\sim \mathcal{O}(1)$

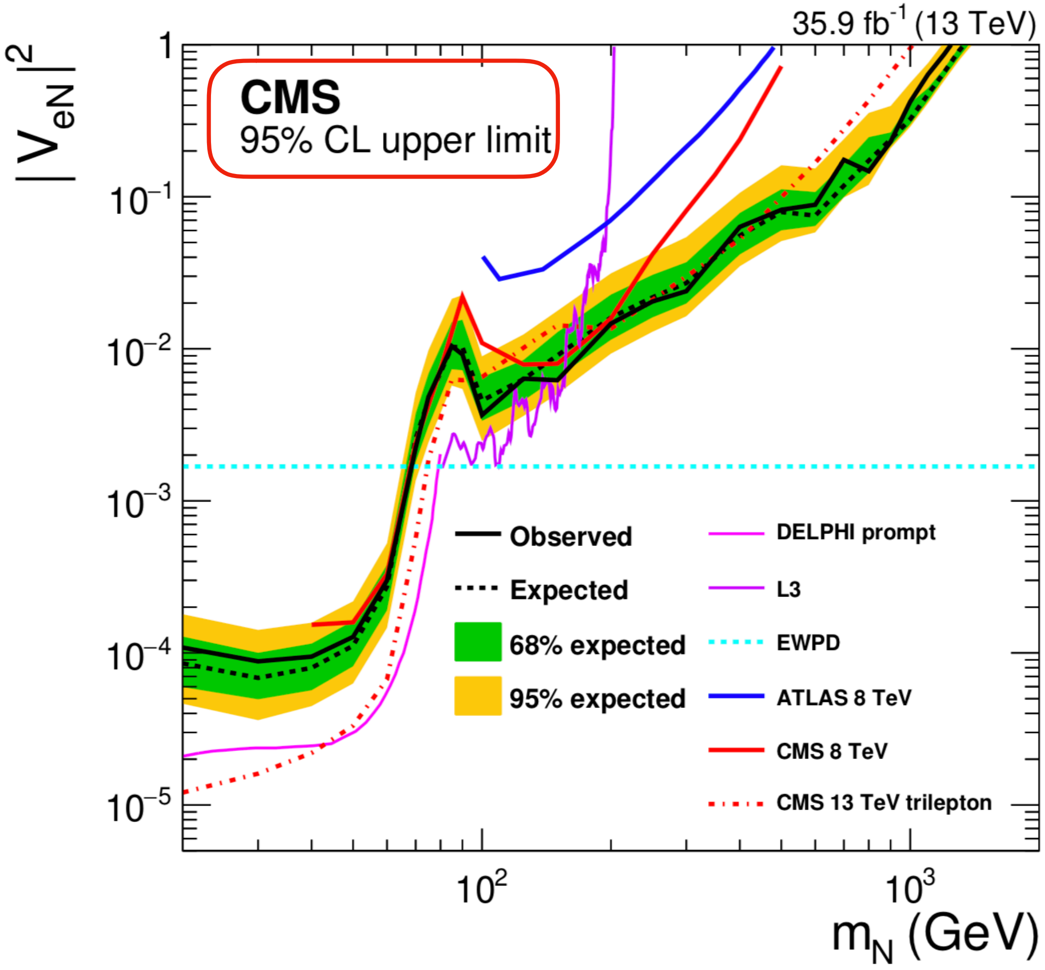
Thanks to Minho Son, Higgs Couplings 2018

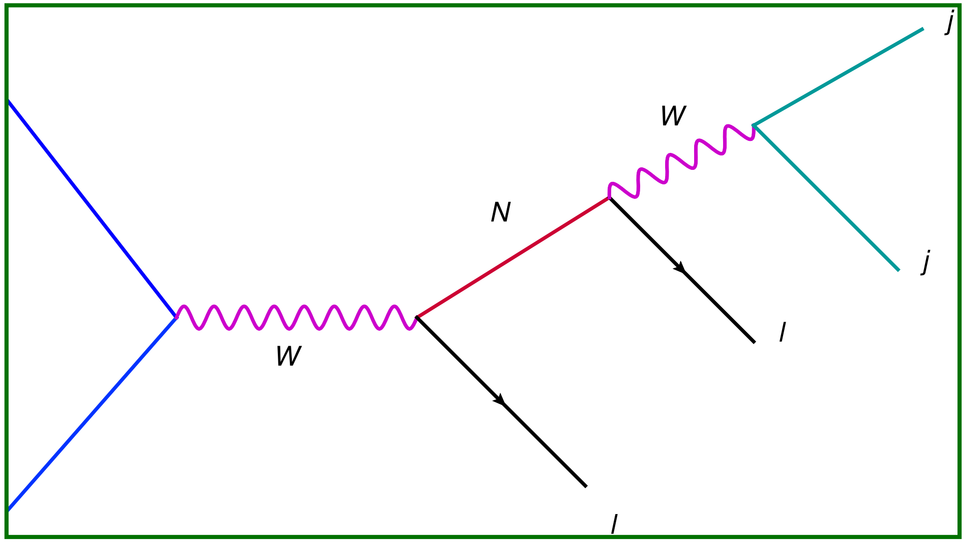
Experimental limits

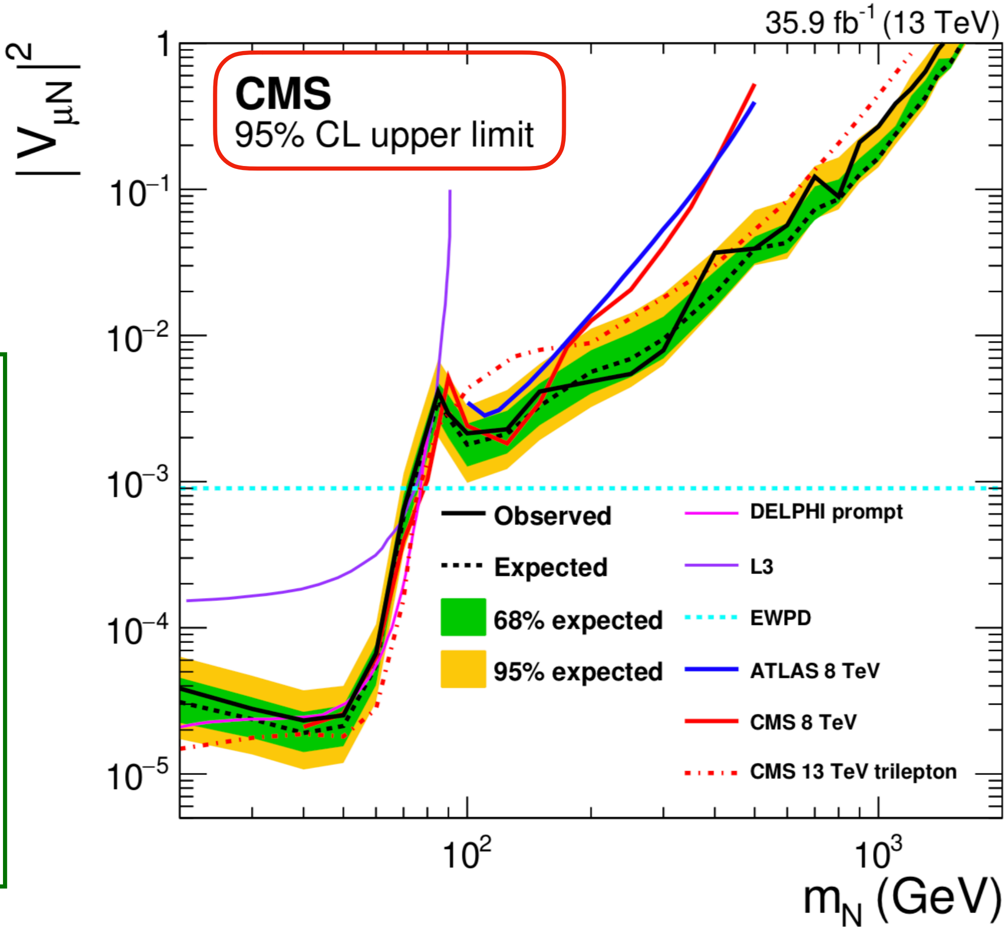
$\ell^{\pm}\ell^{\pm} + \text{jets}$

CMS

1806.10905 13 TeV, 35.9 fb^{-1}

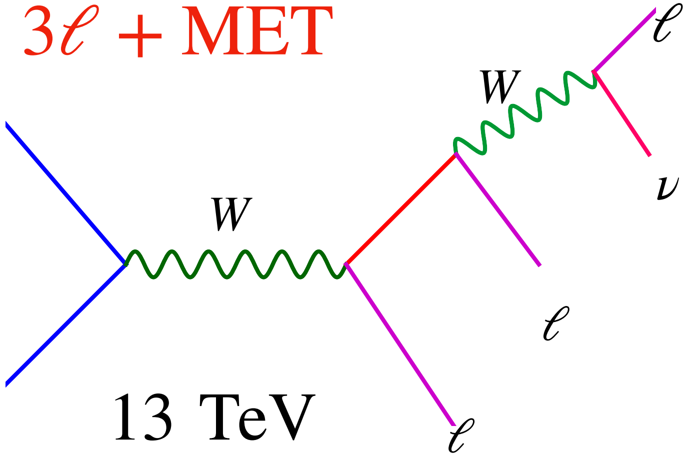




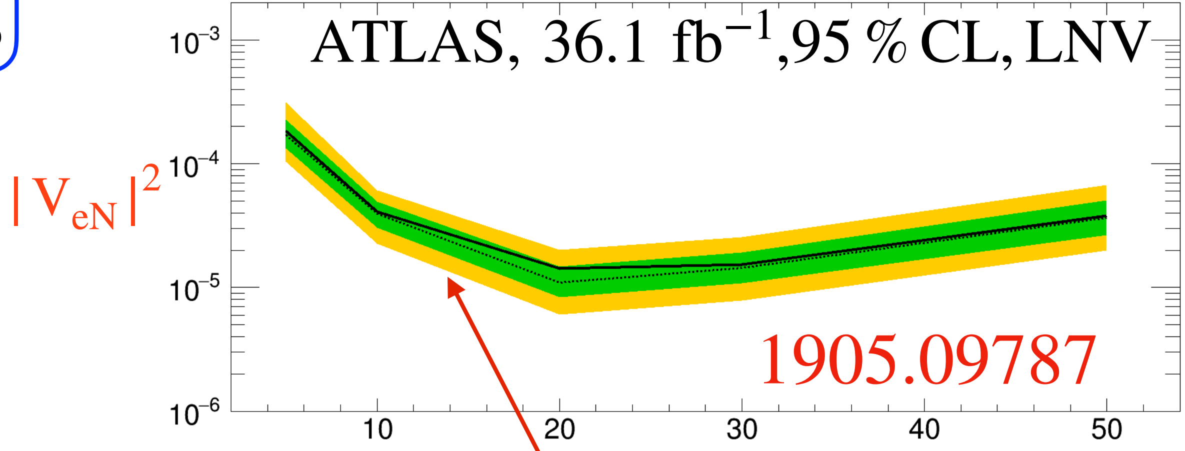


Experimental limits

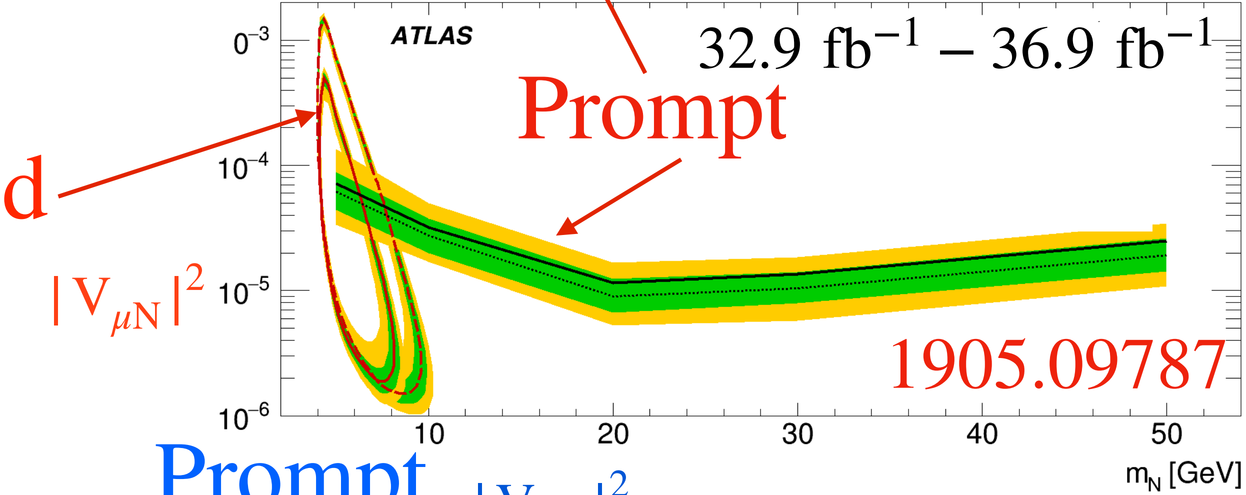
3ℓ + MET



13 TeV



1905.09787



32.9 fb^{-1} – 36.9 fb^{-1}

Prompt

Displaced

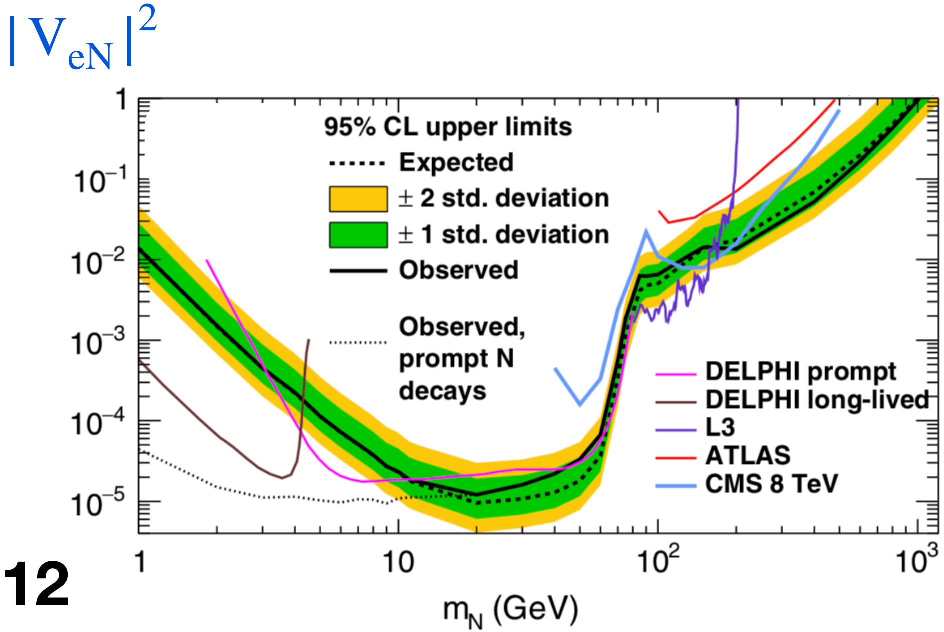
LNV

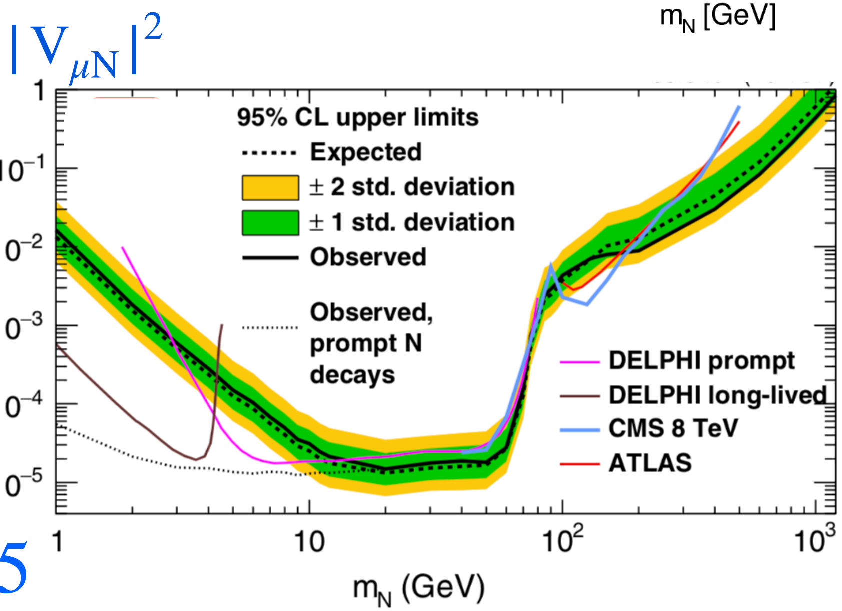
LNC

1905.09787

Prompt

CMS





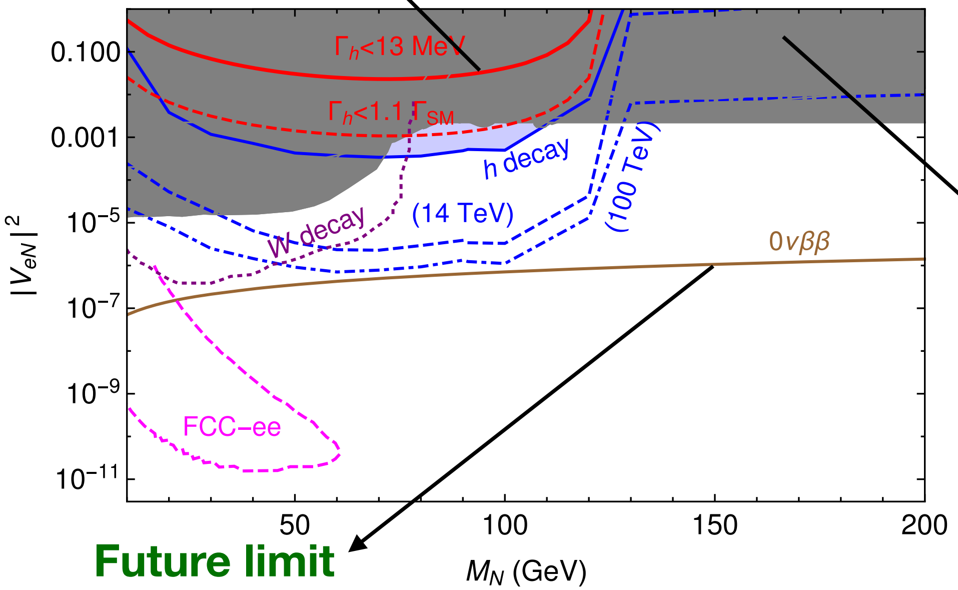
35.9 fb^{-1}

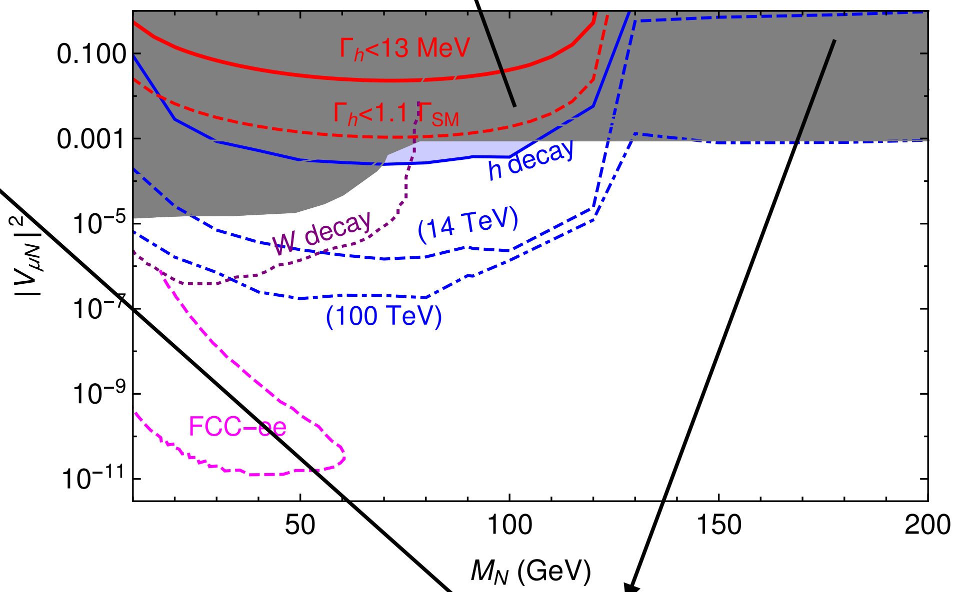
1802.02965

$2\ell + p_T^{\text{miss}}$: bounds from the Higgs decay $(h \to N\nu, N \to 2\ell\nu)$

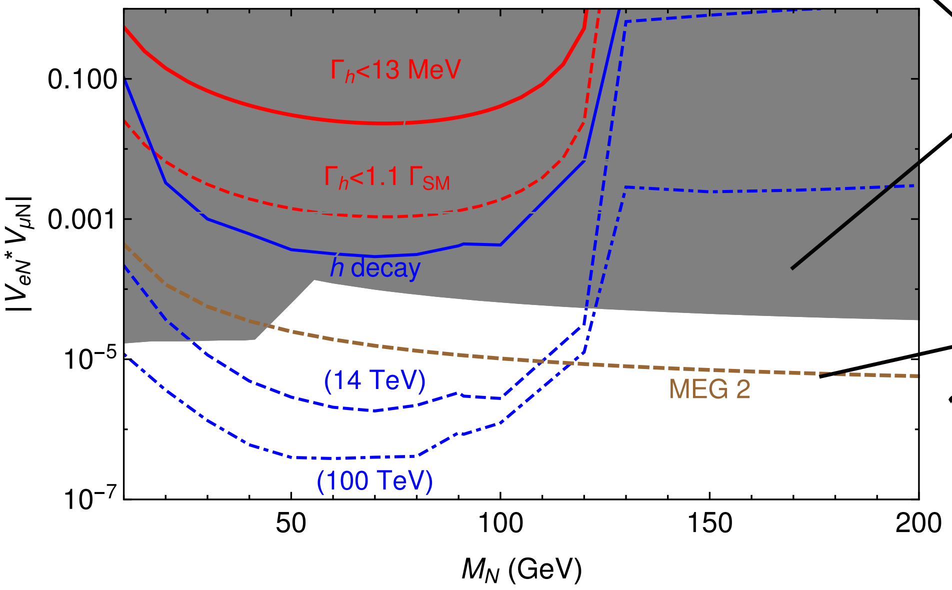
CMS, JHEP 09 (2016) 051: 7&8 TeV combined H ⟶ W W*, upper limit on Yukawa as well as mixing

Future sensitivity can go down to 10%precise result at pp collider: arXiv:1606.09408





Future limit considering Majorana heavy neutrinos only



Excluded by LEP LHC,EWPD,

LFV limits from CMS is also included in the lower panel

$\mu \to e\gamma$

~ future branching ratio $O(10^{-15})$

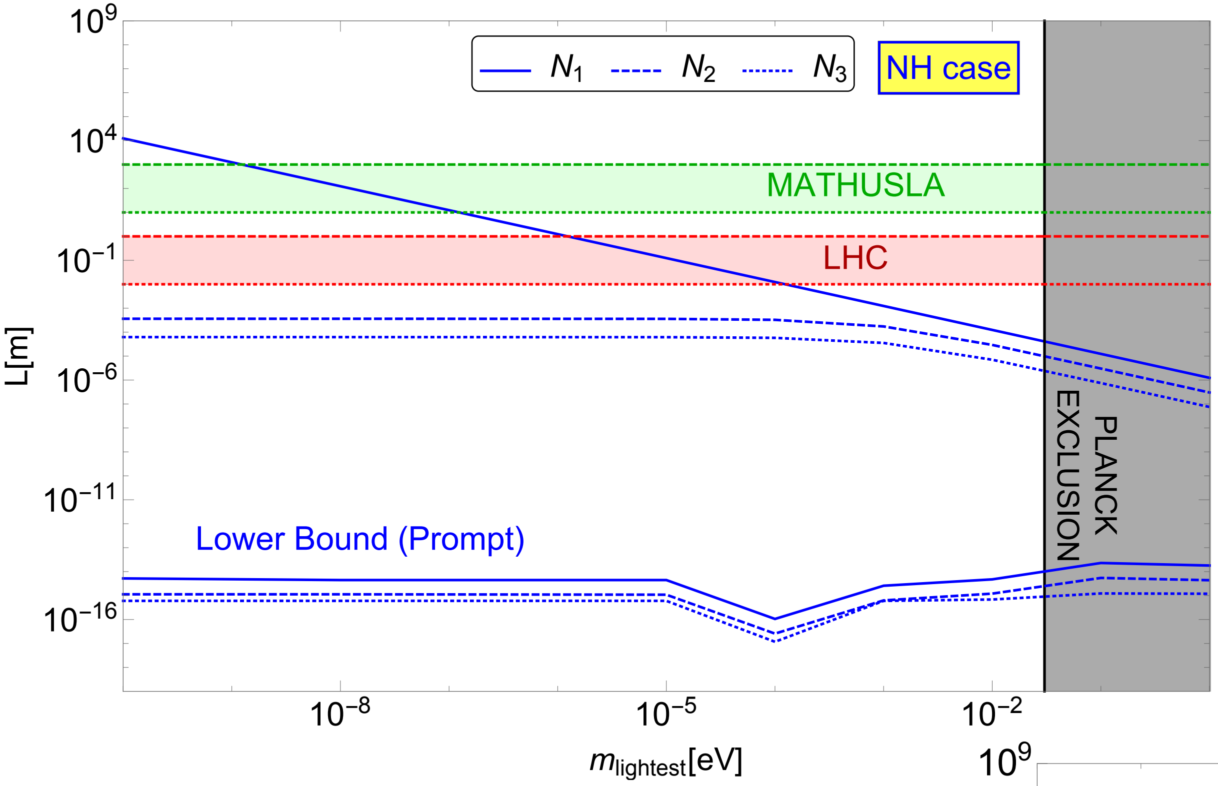
FCC-ee : Limits from Z decay

W-decay @LHC

Future limits

Dev, Franceschini, Mohapatra; Cely, Ibarra, Molinaro, Petcov; AD, Dev, Kim; AD, Gao, Kamon; Antusch, Fischer

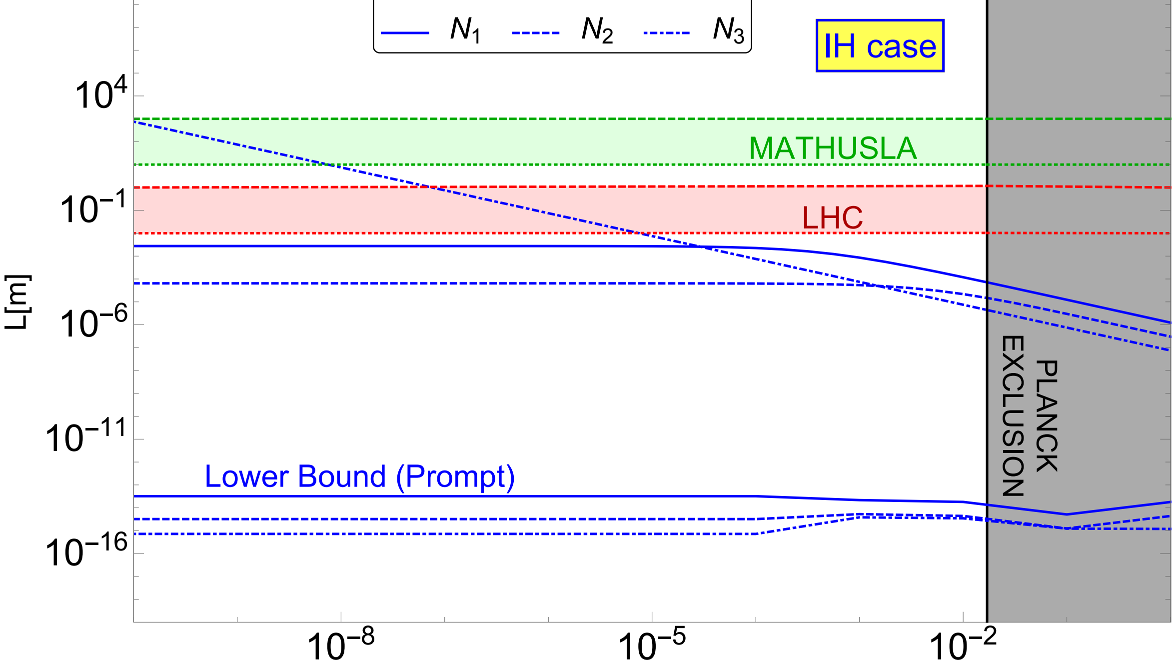
Decay length of RHNs neutrinos as a function of lightest active neutrino mass



$$M_{N_1} = 500\ \mathrm{GeV}\ \ M_{N_2} = 1\ \mathrm{TeV}$$

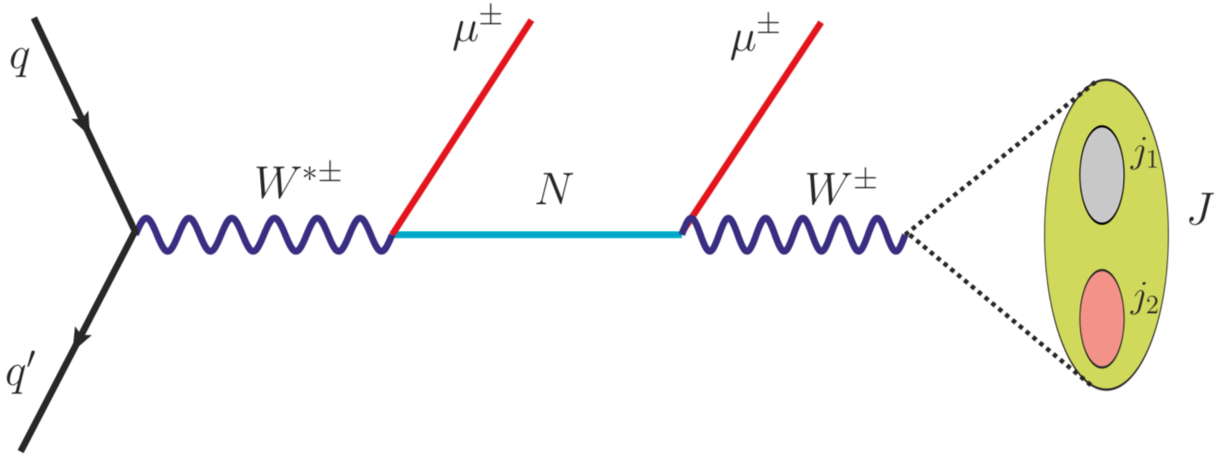
$$M_{N_3} = 2\ \mathrm{TeV}$$

AD, Dev, Okada

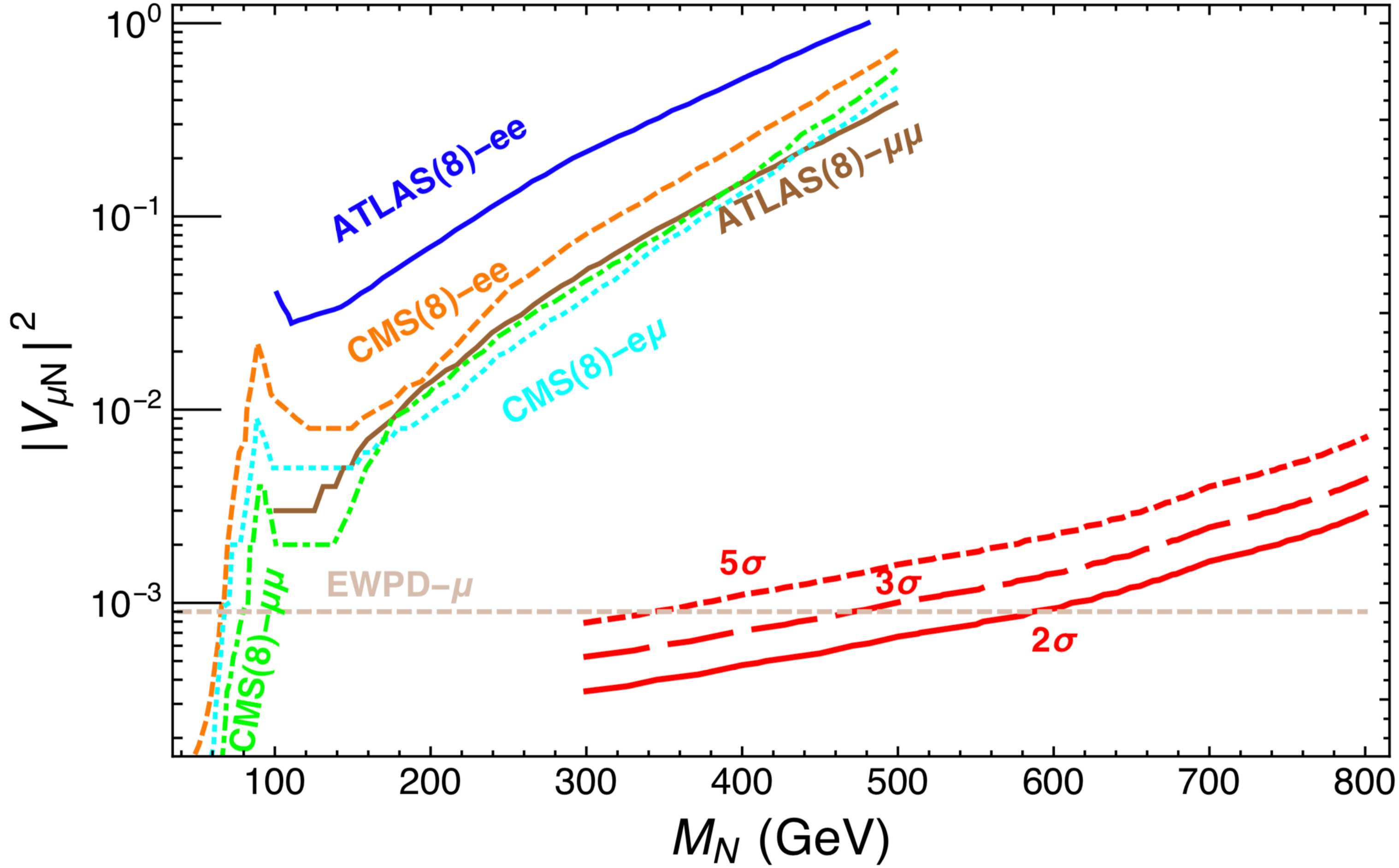


2ℓ + Fat jet

Das, Konar, Thalapillil



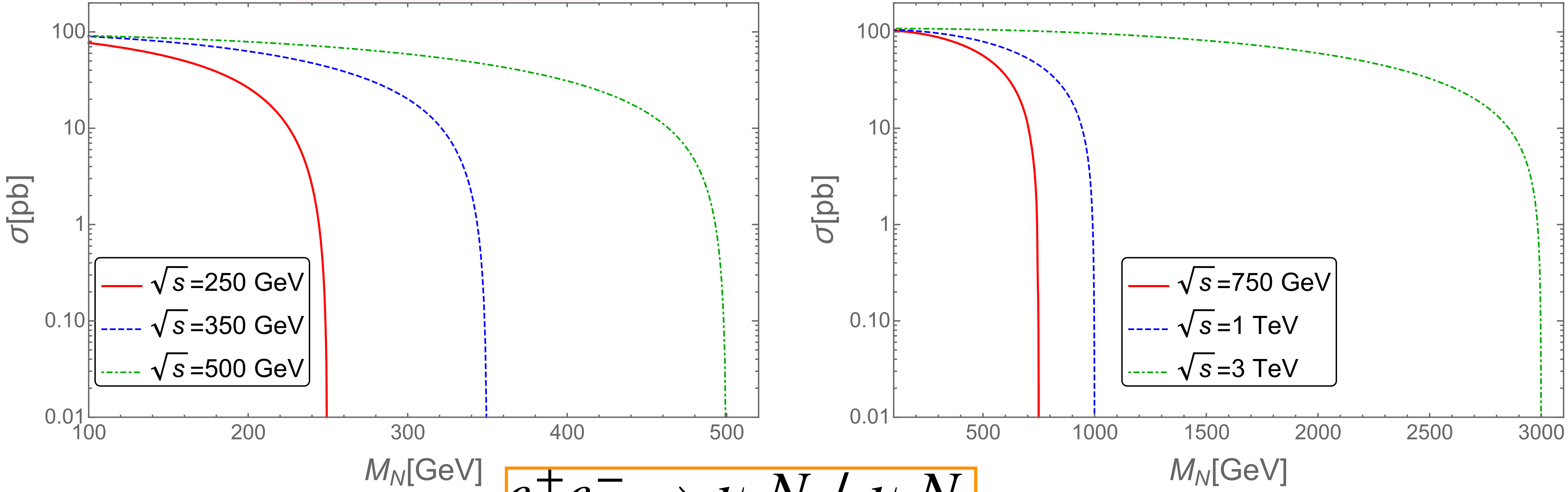
$$R = 0.8,\ p_T^J > 150\ \text{GeV},\ \tau_{21}^{\mathrm{J}} < 0.5,\ \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} < 35\ \text{GeV},\ \mathrm{M}^{\mathrm{J}} > 50\ \text{GeV}$$



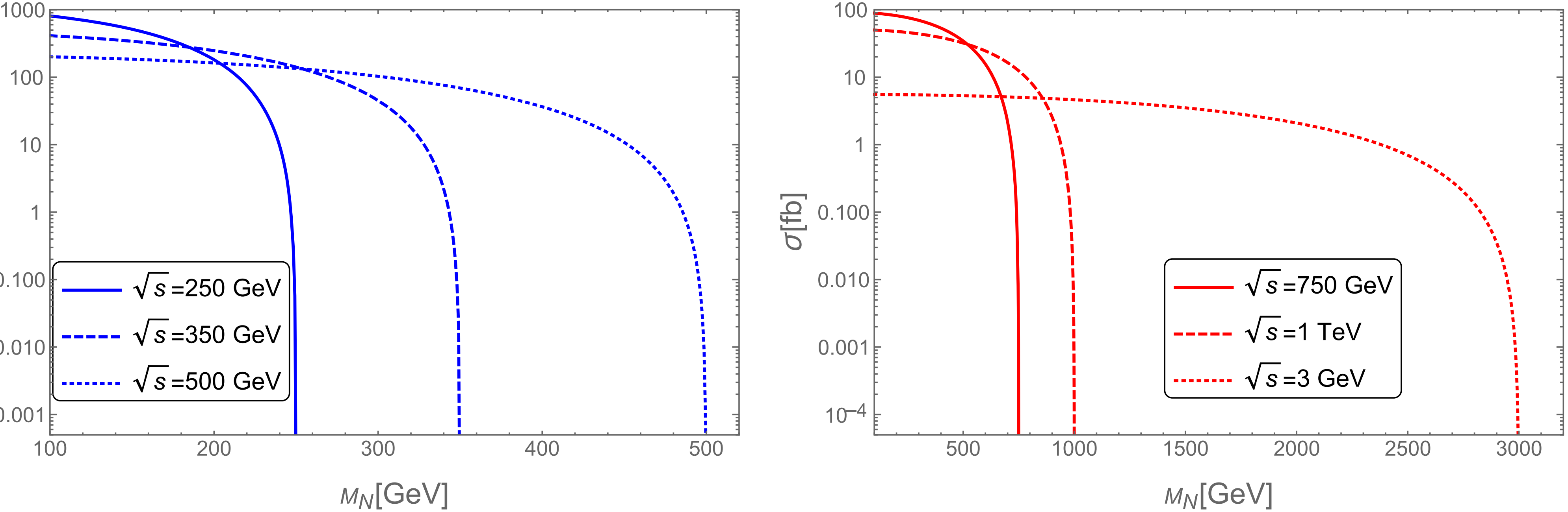
Production of the heavy neutrinos at the Linear Collider using fat jet

$$e^+e^- \to \nu_1 N_1$$

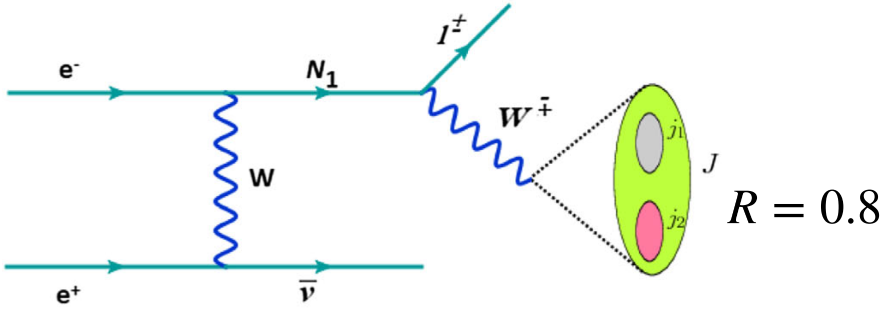
AD, Jana, Nandi, Mandal
Chakraborty, Mitra, Shil
Banerjee, Dev, Ibarra, Mandal, Mitra
Antusch, Fischer

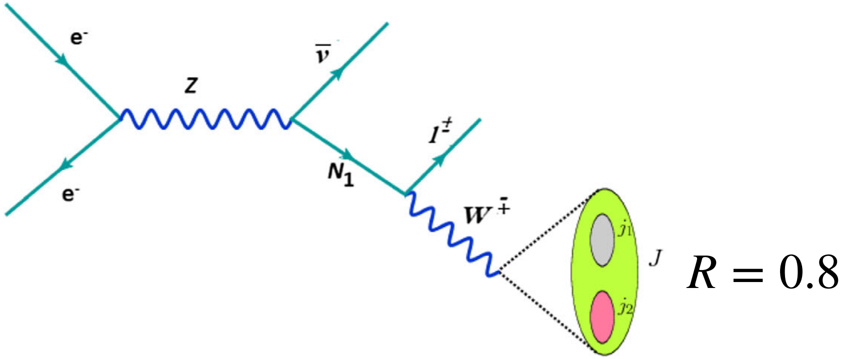


$$e^+e^- \to \nu_2 N_2 /\ \nu_3 N_3$$



$e + J + p_T^{\text{miss}}$ final states at the linear colliders.





- Transverse momentum for fat-jet $p_T^J > 150$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^J > 250$ GeV for M_N mass range 700 GeV-900 GeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 100$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^{e^\pm} > 200$ GeV for M_N mass range 700 GeV-900 GeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

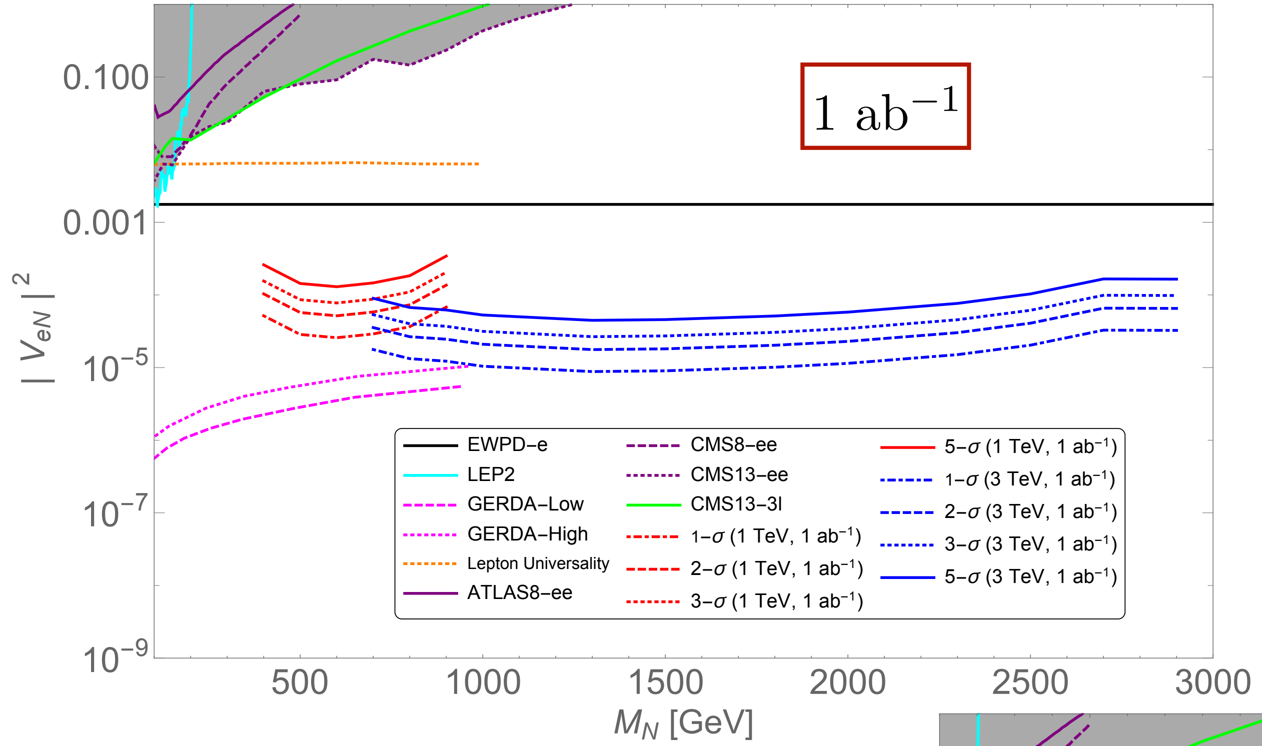
1 TeV e^-e^+ collider

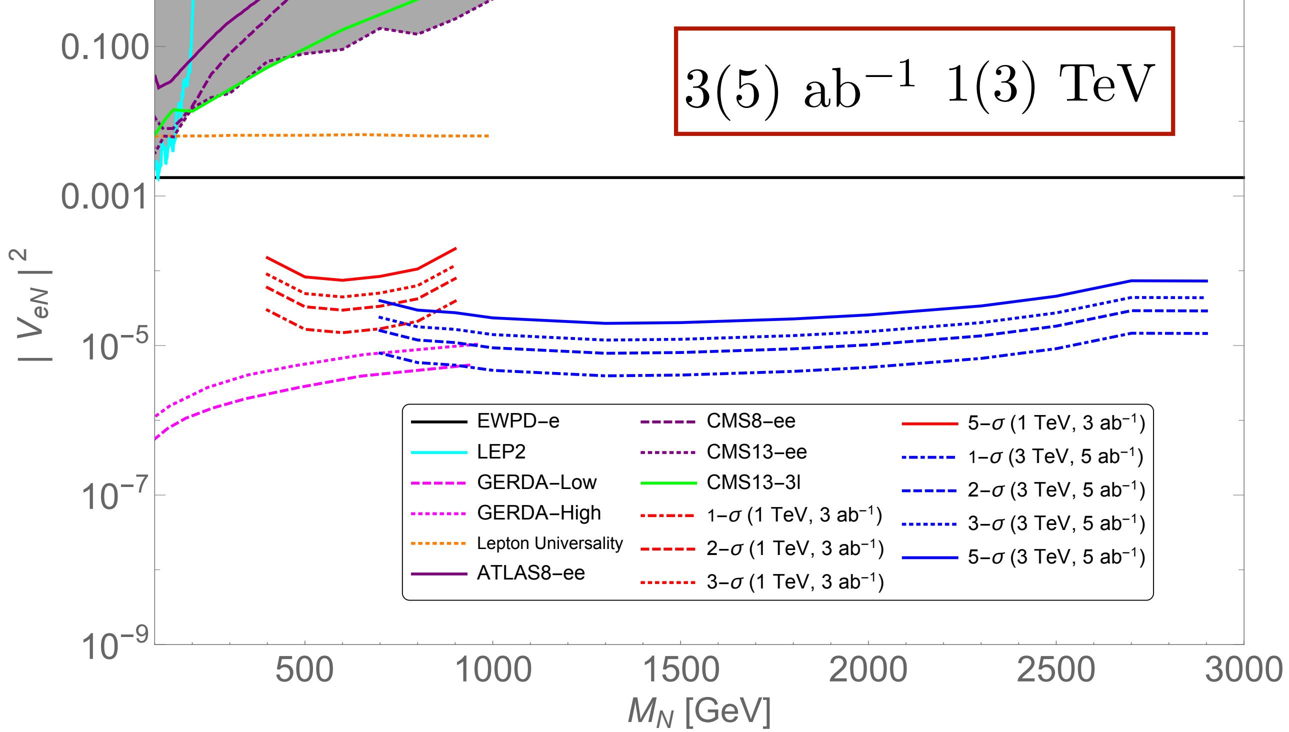
- Transverse momentum for fat-jet $p_T^J > 250$ GeV for the M_N mass range 700 GeV-900 GeV and $p_T^J > 400$ GeV for M_N mass range $1 - 2.9$ TeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 200$ GeV for M_N mass range $700 - 900$ GeV and $p_T^{e^\pm} > 250$ GeV for M_N mass range $1 - 2.9$ TeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

3 TeV e^-e^+ collider

Mass-mixing limit plots

$\sqrt{s} =$ 1 TeV (red band) and 3 TeV (blue band)





Alternative scenario under $\mathrm{U}(1)_{\mathrm{X}}$

AD, Okada, Raut
AD, Okada, Okada, Raut

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_{L_i}	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)$
u_{R_i}	**3**	**1**	$2/3$	$(2/3)x_H + (1/3)$
d_{R_i}	**3**	**1**	$-1/3$	$-(1/3)x_H + (1/3)$
ℓ_{L_i}	**1**	**2**	$-1/2$	$(-1/2)x_H - 1$
e_{R_i}	**1**	**1**	-1	$-x_H - 1$
H	**1**	**2**	$-1/2$	$(-1/2)x_H$
$N_{R_{1,2}}$	**1**	**1**	0	-4
N_{R_3}	**1**	**1**	0	$+5$
H_E	**1**	**2**	$-1/2$	$(-1/2)x_H + 3$
Φ_A	**1**	**1**	0	$+8$
Φ_B	**1**	**1**	0	-10
Φ_C	**1**	**1**	0	-3

Possible alternative B – L, with $\mathrm{x_H} = 0$

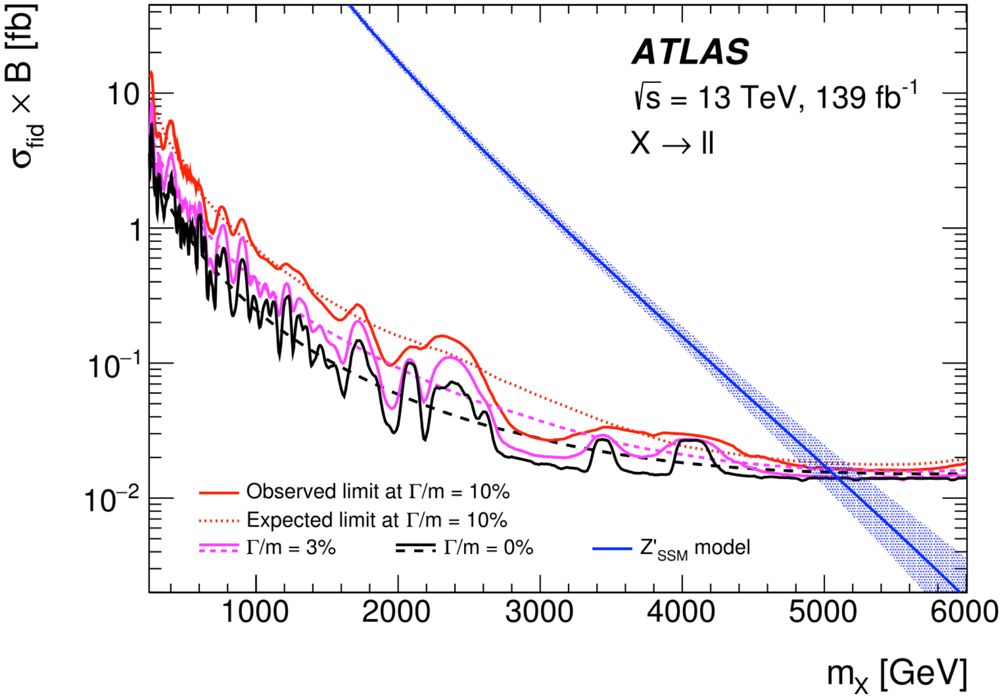
Detailed scalar sector study

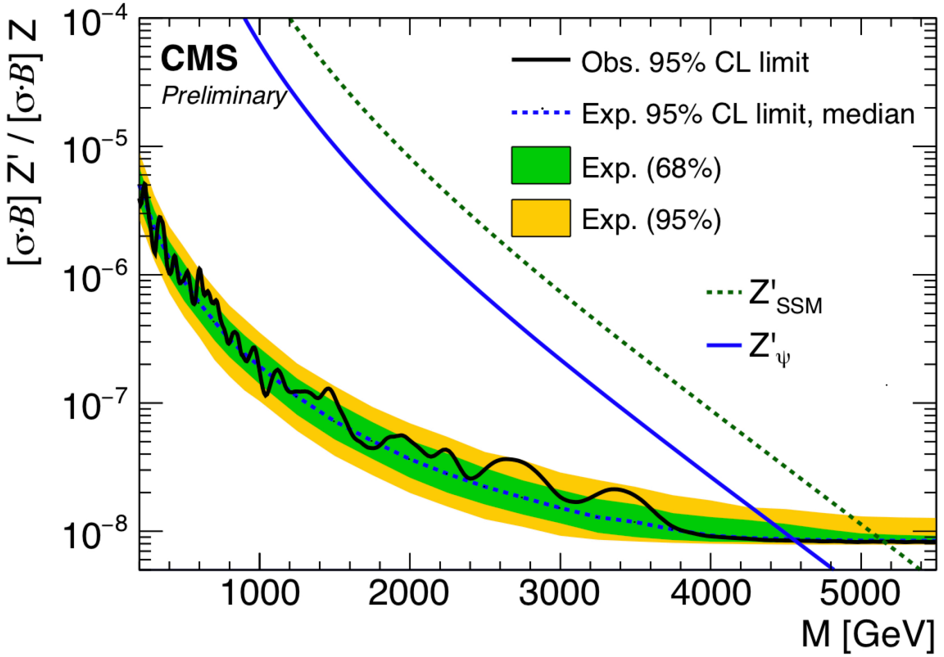
In Progress

$$\mathcal{L}_Y \supset -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\overline{\ell_L^i} H_E N_R^j - \frac{1}{2}\sum_{k=1}^{2} Y_N^k \Phi_A \overline{N_R^{kc}} N_R^k - \frac{1}{2} Y_N^3 \Phi_B \overline{N_R^{3c}} N_R^3 + \mathrm{h.c.}$$

Bounds on the $U(1)_X$ gauge coupling

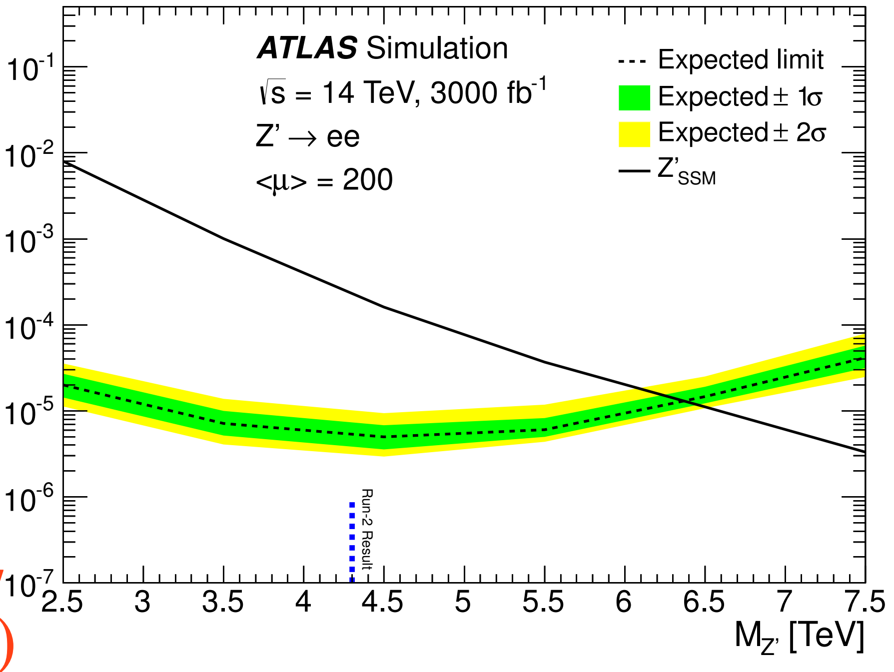
CMS PAS EXO – 19 – 019
$ee(139\ \mathrm{fb}^{-1}) + \mu\mu(140\ \mathrm{fb}^{-1})$



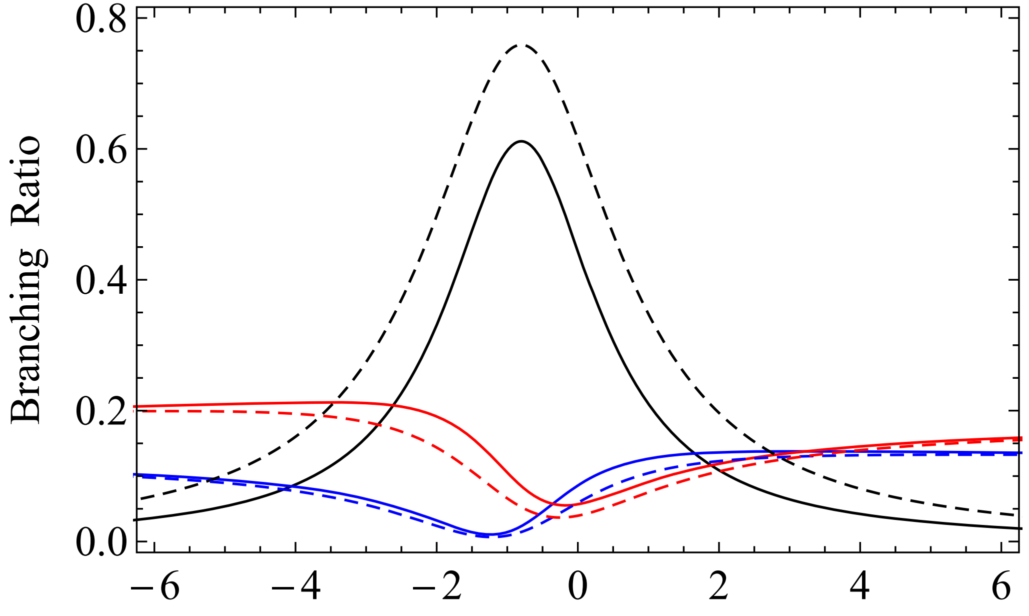


2ℓ, ATLAS : 1903.06248 $(139\ \mathrm{fb}^{-1})$

$$g' = \sqrt{\frac{\sigma^{\text{Observer}}_{\text{ATLAS/CMS}}}{\frac{\sigma_{\text{Model}}}{g^2_{\text{Model}}}}}$$



ATLAS – TDR – 027
ee (Prospective)



$m_{Z'} = 3$ TeV.

Solid

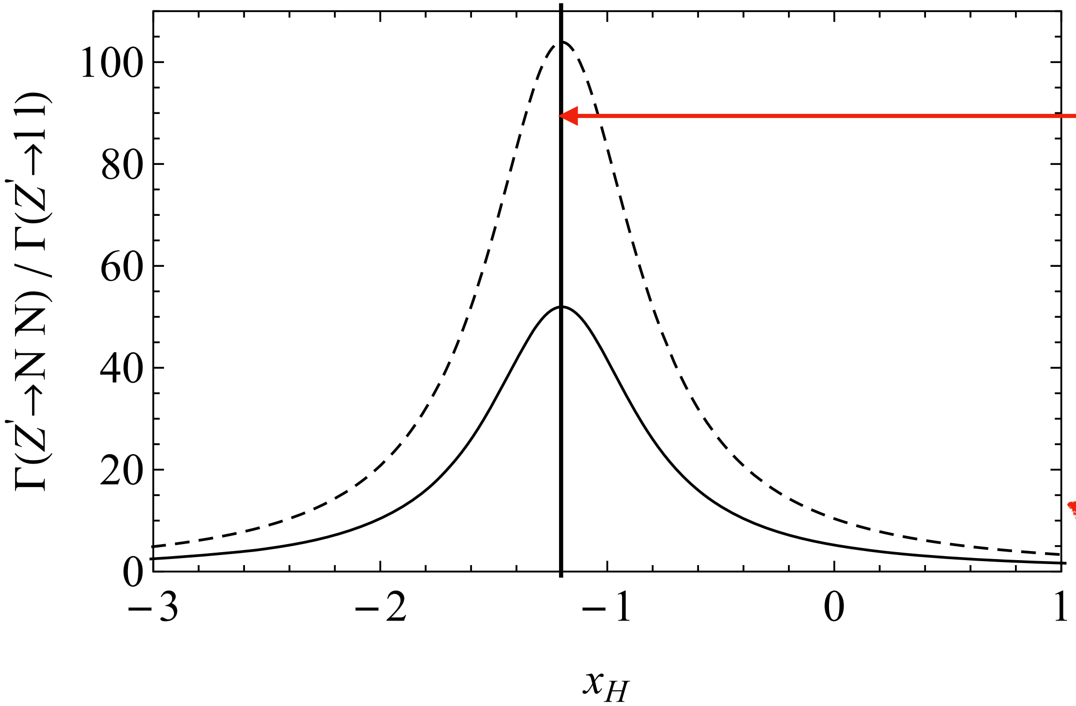
$m_{N^1} = m_{Z'}/4$
$m_{N^2} > m_{Z'}/2,$

Dashed

$m_{N^{1,2}} = m_{Z'}/4.$

Top → bottom : Solid (Red, Black, Blue) x_H

Up and down quarks   Heavy neutrinos   Charged leptons



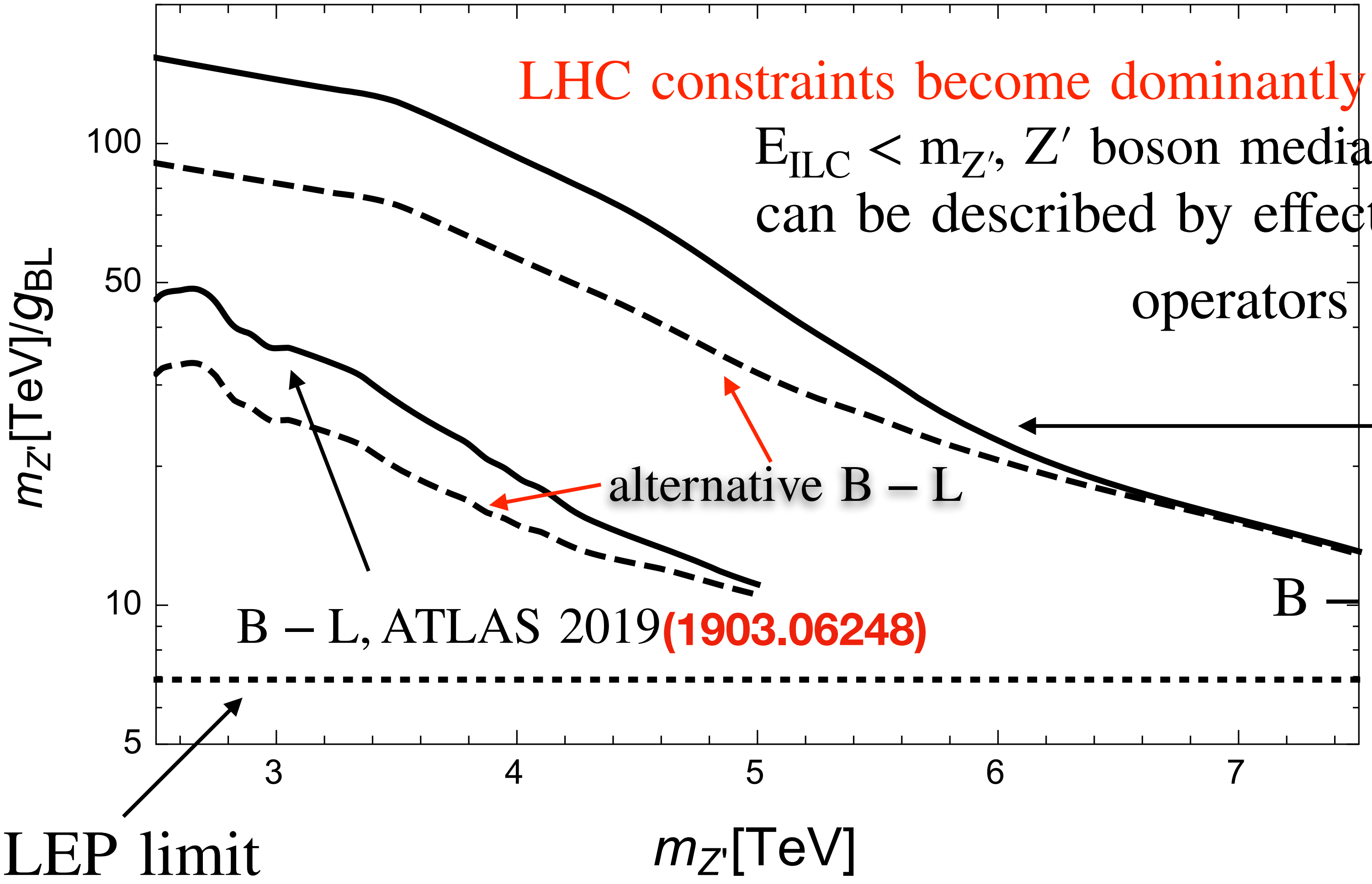
$x_H = -1.2$

Solid $m_{N^1} = m_{Z'}/4$
$m_{N^2} > m_{Z'}/2,$

Dashed $m_{N^{1,2}} = m_{Z'}/4.$

$$\frac{\Gamma(Z' \to NN)}{\Gamma(Z' \to \bar{\ell}\ell)} = \frac{64}{8 + 12x_H + 5x_H^2}\left(1 - \frac{4m_N^2}{m_{Z'}^2}\right)^{3/2}$$

Production of the heavy neutrino at the ILC



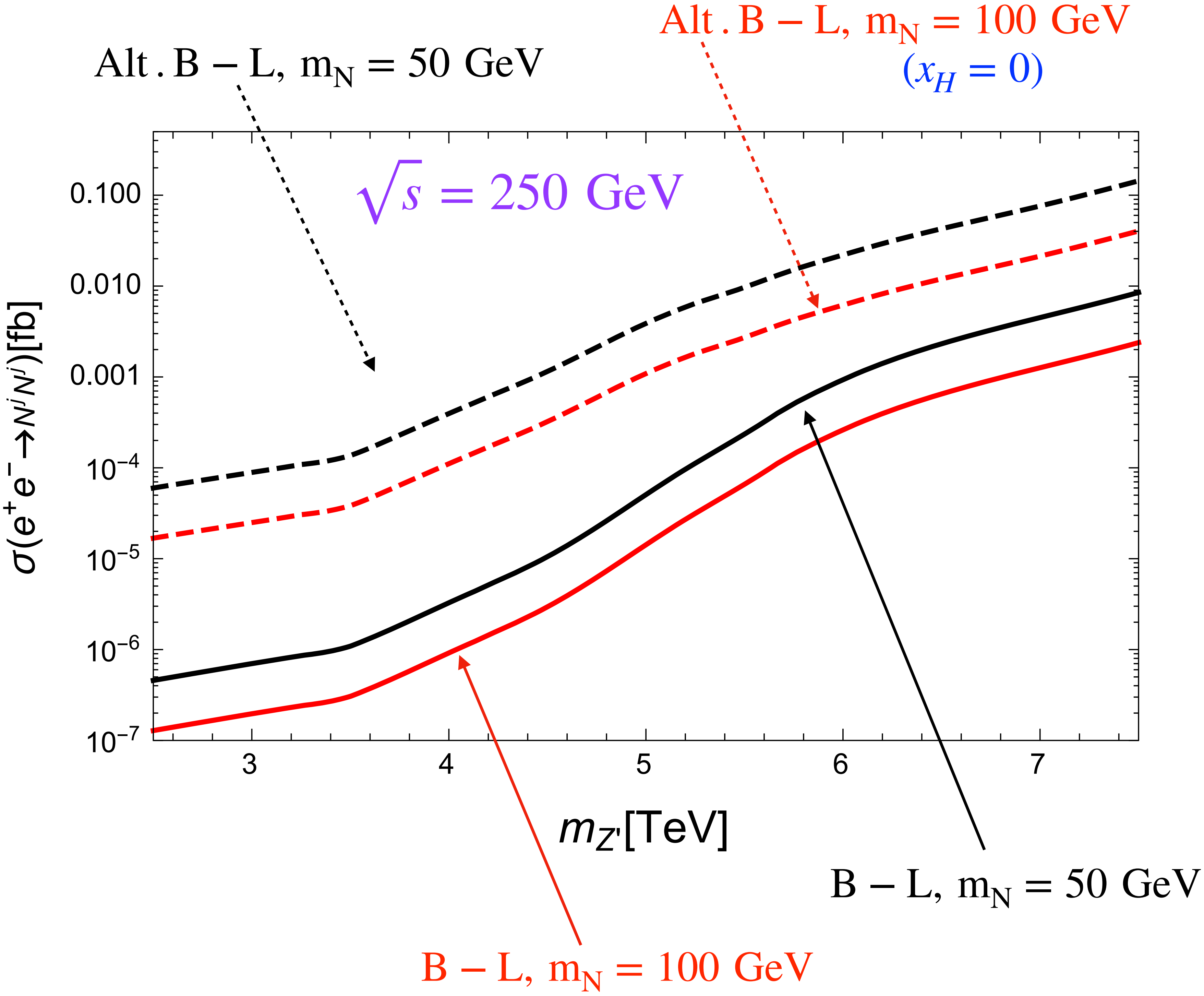
LHC constraints become dominantly weaker with heavier Z′

$E_{ILC} < m_{Z'}$, Z′ boson mediated processes at the ILC can be described by effective higher dimensional operators $\propto \left(\frac{m_{Z'}}{g_{BL}}\right)^2$

Dashed lines represent the Atl. B − L case

As a result ILC is a powerful machine to probe Z′ beyond HL − LHC

$$\sigma(e^+e^- \to Z'^* \to N^i N^i) \simeq \frac{(Q_{N^i})^2}{24\pi} s \boxed{\left(\frac{g_{BL}}{m_{Z'}}\right)^4} \left(1-\frac{4m_{N^i}^2}{m_{Z'}^2}\right)^{\frac{3}{2}}.$$



Alt . B − L, $m_N = 50$ GeV

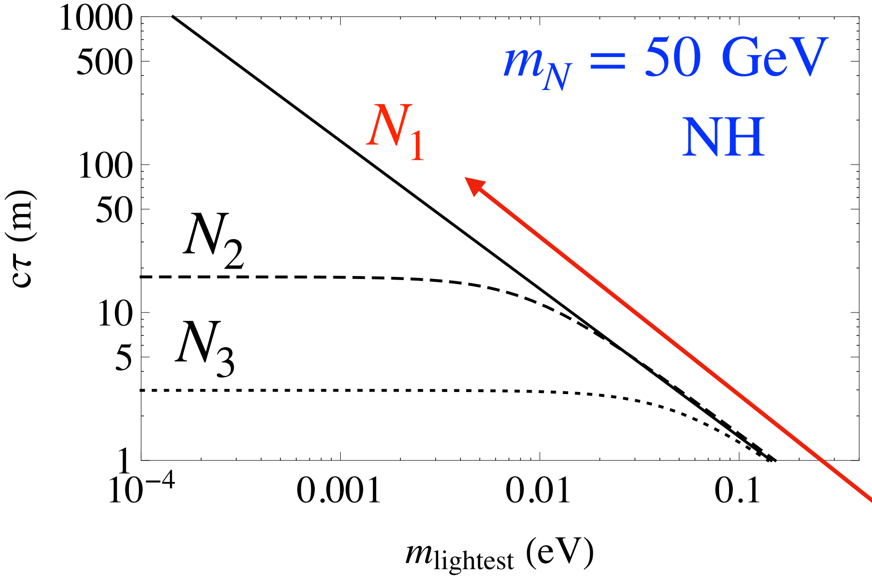
Alt . B − L, $m_N = 100$ GeV
($x_H = 0$)

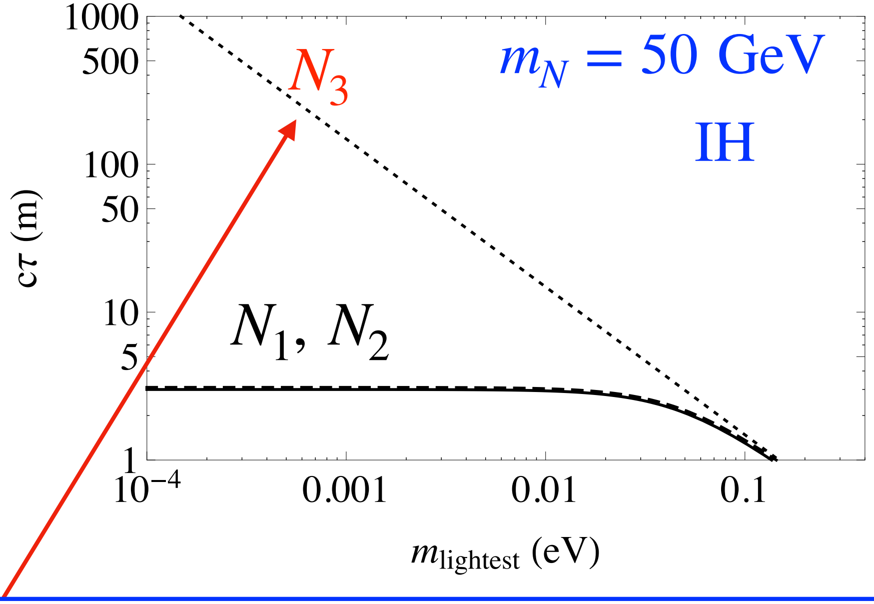
B − L, $m_N = 50$ GeV

B − L, $m_N = 100$ GeV

Long lived RHNs

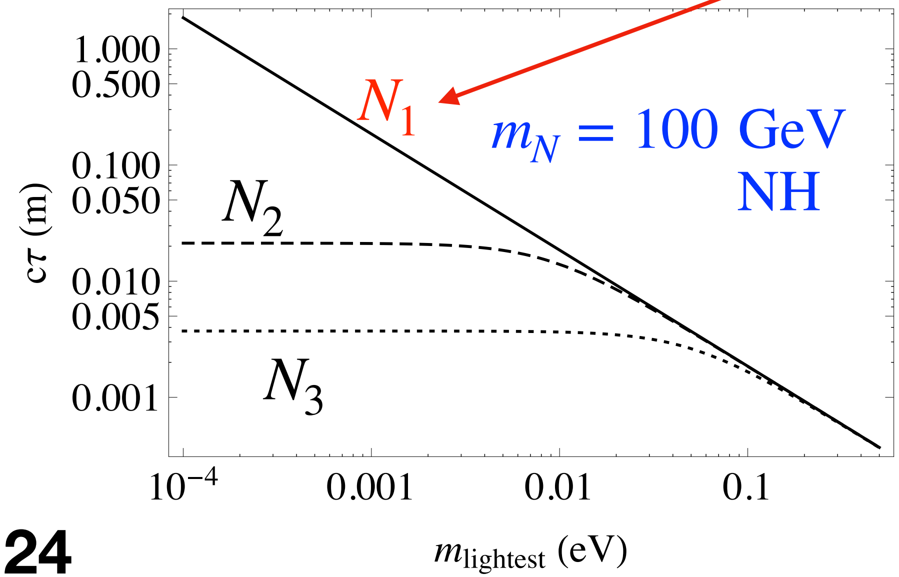
$B-L$ case, $x_H = 0$

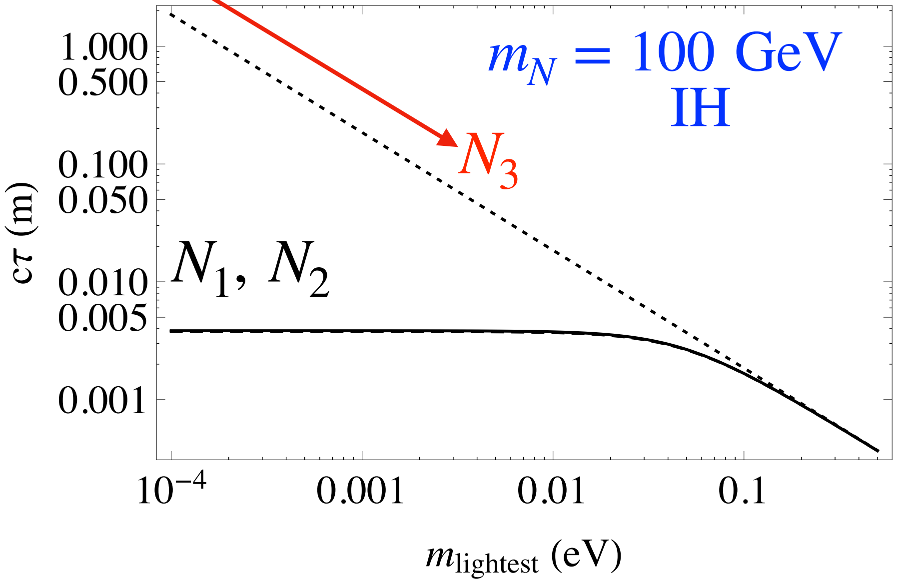




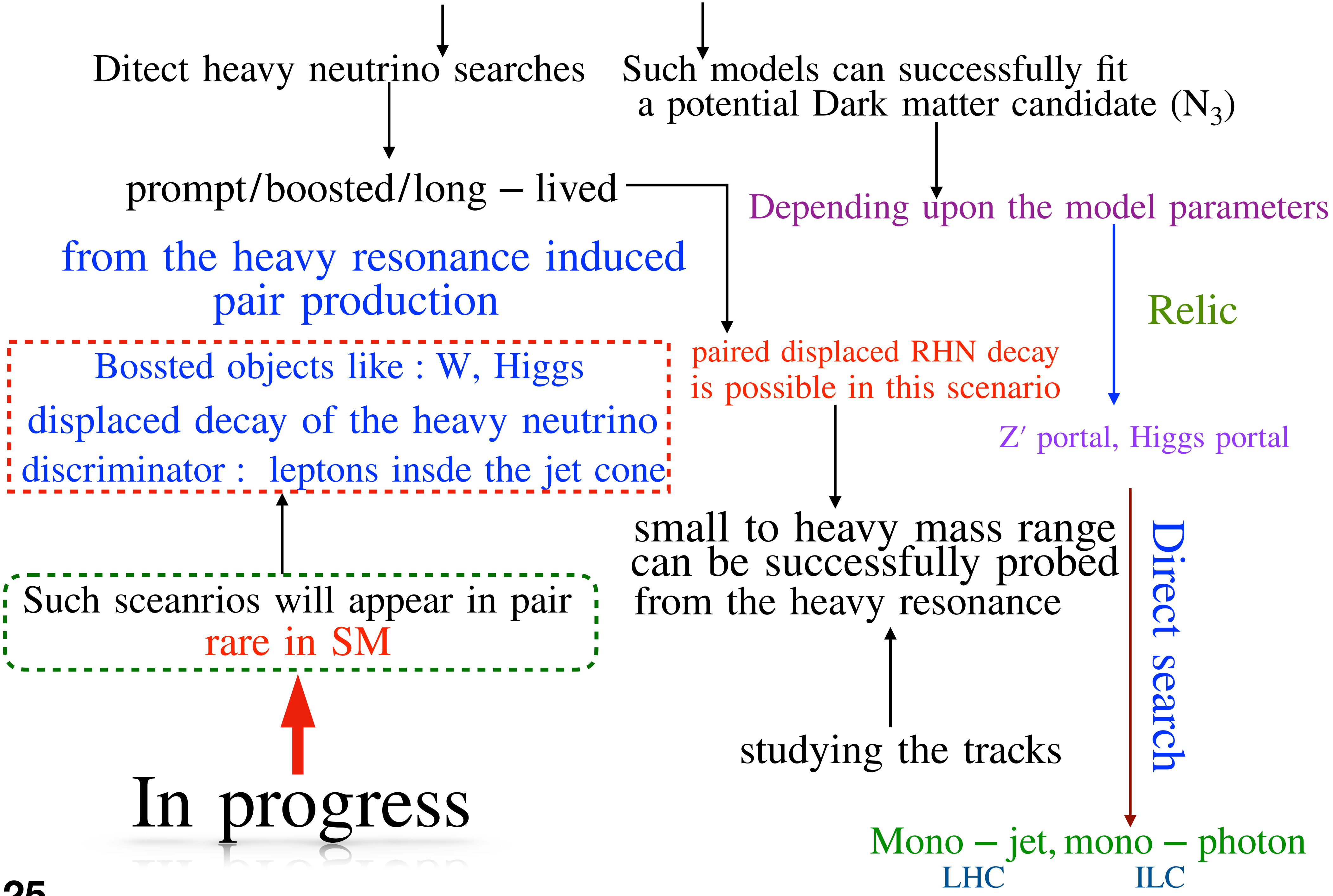
Longest lived RHN life time is inversely proportional to m_{lightest}

$m_{\text{lightest}} \to 0$ leads to the long lived species as a potential DM candiadte





Other interesting aspects in the $U(1)_X$ scenario



Ditect heavy neutrino searches

prompt/boosted/long – lived

from the heavy resonance induced
pair production

Bossted objects like : W, Higgs
displaced decay of the heavy neutrino
discriminator : leptons insde the jet cone

Such sceanrios will appear in pair
rare in SM

In progress

paired displaced RHN decay
is possible in this scenario

small to heavy mass range
can be successfully probed
from the heavy resonance

studying the tracks

Such models can successfully fit
a potential Dark matter candidate (N_3)

Depending upon the model parameters

Relic

Z' portal, Higgs portal

Direct search

Mono – jet, mono – photon
LHC ILC

Type – III seesaw

SM + SU(2)$_{\rm L}$ triplet fermion

Franceschini, Hambye, Strumia Biggio, Bonnet Goswami, Poulose
Jana, Okada, Raut; Biggio, Fernandez Martinez, Hernandez Garcia, Lopez Pavon
Goswami, Vishnudath, Khan AD, Mandal, Modak; AD, Mandal;
Bandyopadhyay, Jangid, Mitra

$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}(\overline{\Psi} i\gamma^\mu D_\mu \Psi) - \frac{1}{2} M\,{\rm Tr}(\overline{\Psi}\Psi^c + \overline{\Psi^c}\Psi) - \sqrt{2}(\overline{\ell_L} Y_D^\dagger \Psi H + H^\dagger \overline{\Psi} Y_D \ell_L)$$

$$\Psi = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix} \text{ and } \Psi^c = \begin{pmatrix} \Sigma^{0c}/\sqrt{2} & \Sigma^{-c} \\ \Sigma^{+c} & -\Sigma^{0c}/\sqrt{2} \end{pmatrix}$$

$$-\mathcal{L}_{\rm mass} = \begin{pmatrix} \overline{e}_L & \overline{\Sigma}_L \end{pmatrix} \begin{pmatrix} m_\ell & Y_D^\dagger v \\ 0 & M \end{pmatrix} \begin{pmatrix} e_R \\ \Sigma_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\Sigma_R^0} \end{pmatrix} \begin{pmatrix} 0 & Y_D^T \frac{v}{\sqrt{2}} \\ Y_D \frac{v}{\sqrt{2}} & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \Sigma_R^{0c} \end{pmatrix} + h.c.$$

$$m_\nu \simeq -\frac{v^2}{2} Y_D^T M^{-1} Y_D = M_D M^{-1} M_D^T$$

$$\Gamma(\Sigma^\pm \to \nu W) = \frac{g^2 |V_{\ell\Sigma}|^2}{32\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_W^2}{M^2}\right)^2 \left(1 + 2\frac{M_W^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi \cos^2\theta_W} \left(\frac{M^3}{M_Z^2}\right) \left(1 - \frac{M_Z^2}{M^2}\right)^2 \left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^\pm \to \ell h) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_h^2}{M^2}\right)^2,$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \pi^\pm) = \frac{2 G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi} \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e) = \frac{2 G_F^2 \Delta M^5}{15\pi}$$

$$\Gamma(\Sigma^\pm \to \Sigma^0 \mu \nu_\mu) = 0.12\,\Gamma(\Sigma^\pm \to \Sigma^0 e \nu_e)$$

$$\Gamma(\Sigma^0 \to \ell^+ W) = \Gamma(\Sigma^0 \to \ell^- W) = \frac{g^2 |V_{\ell\Sigma}|^2}{64\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_W^2}{M^2}\right)^2 \left(1 + 2\frac{M_W^2}{M^2}\right)$$

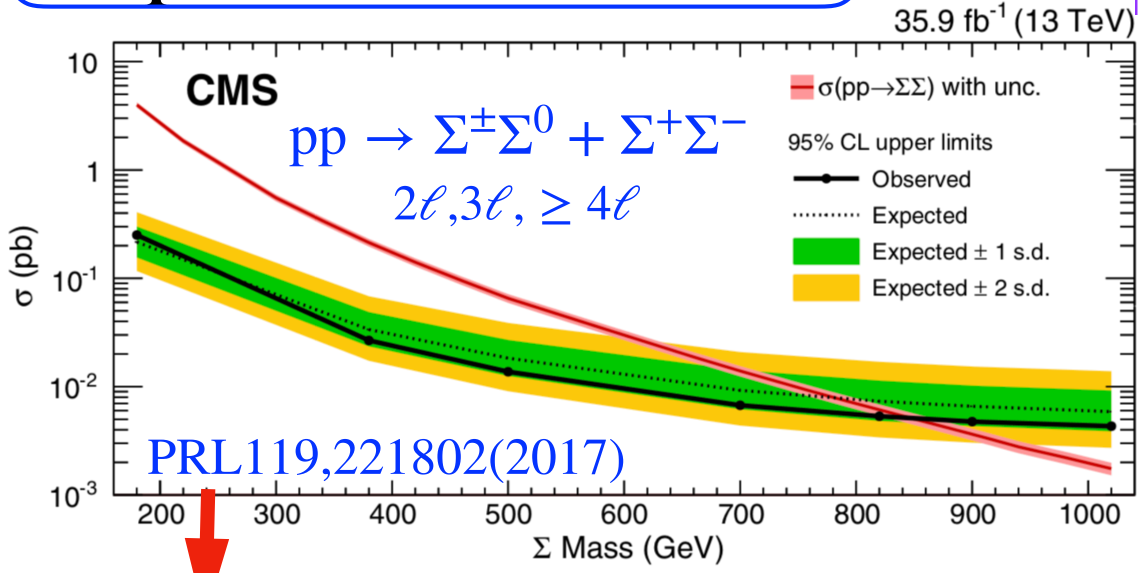
$$\Gamma(\Sigma^0 \to \nu Z) = \Gamma(\Sigma^0 \to \overline{\nu} Z) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi \cos^2\theta_W} \left(\frac{M^3}{M_Z^2}\right) \left(1 - \frac{M_Z^2}{M^2}\right)^2 \left(1 + 2\frac{M_Z^2}{M^2}\right)$$

$$\Gamma(\Sigma^0 \to \nu h) = \Gamma(\Sigma^0 \to \overline{\nu} h) = \frac{g^2 |V_{\ell\Sigma}|^2}{128\pi} \left(\frac{M^3}{M_W^2}\right) \left(1 - \frac{M_h^2}{M^2}\right)^2,$$

Experimental limits

$$\mathrm{BR} = B_\ell \propto \frac{|V_\ell|^2}{|V_e|^2 + |V_\mu|^2 + |V_\tau|^2} \qquad B_e = B_\mu = B_\tau$$

Flavor – democratic scenario



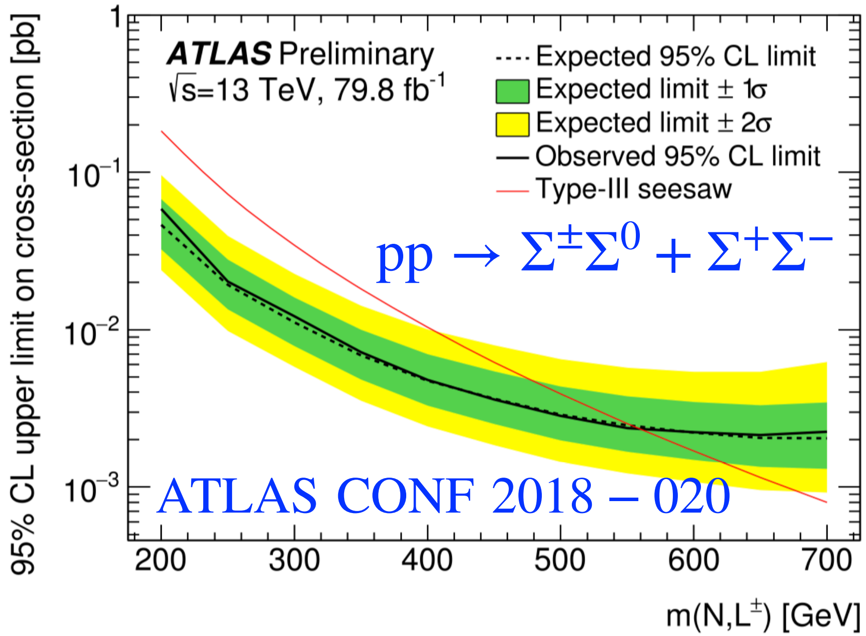
$pp \to \Sigma^\pm\Sigma^0 + \Sigma^+\Sigma^-$

$2\ell, 3\ell, \geq 4\ell$

PRL119,221802(2017)

τ – phoic, $B_\tau = 0, M_\Sigma = 900$ GeV, 90 % CL

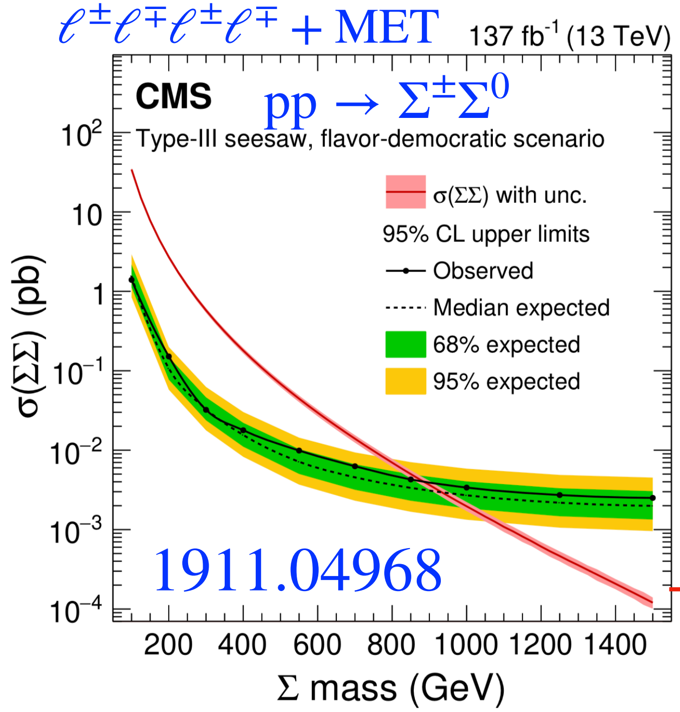
(e, μ) – phoic, $B_{e+mu} = 0, M_\Sigma = 390$ GeV, 90 % CL



$pp \to \Sigma^\pm\Sigma^0 + \Sigma^+\Sigma^-$

ATLAS CONF 2018 – 020

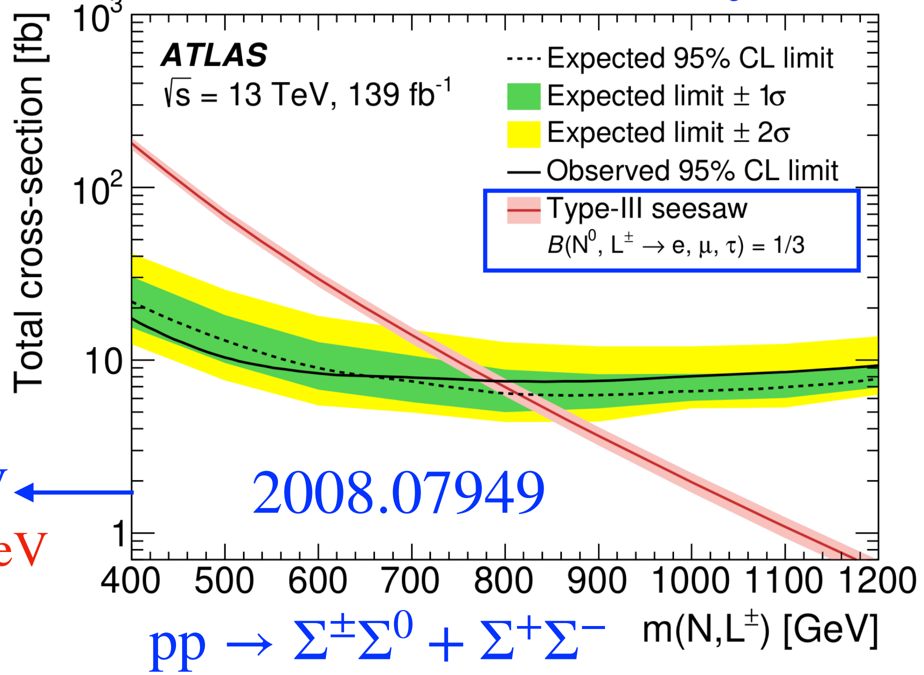
$\ell^\pm\ell^\mp\ell^\pm\ell^\mp$ + MET



$pp \to \Sigma^\pm\Sigma^0$

1911.04968

$\ell^\pm\ell^\pm + \ell^\mp\ell^\pm$ + MET + jets



2008.07949

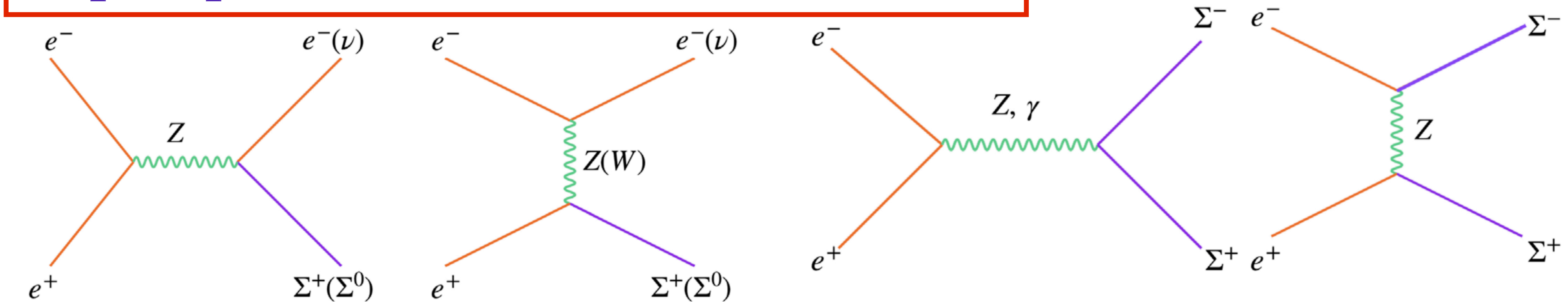
$pp \to \Sigma^\pm\Sigma^0 + \Sigma^+\Sigma^-$

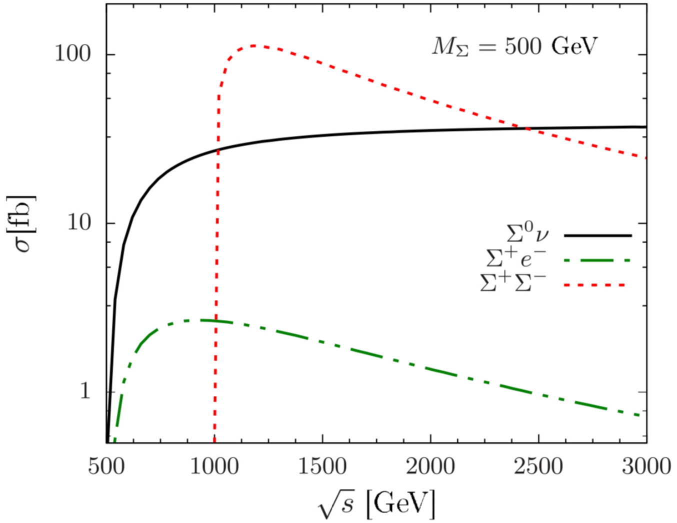
$M_\Sigma \leq 800$ GeV

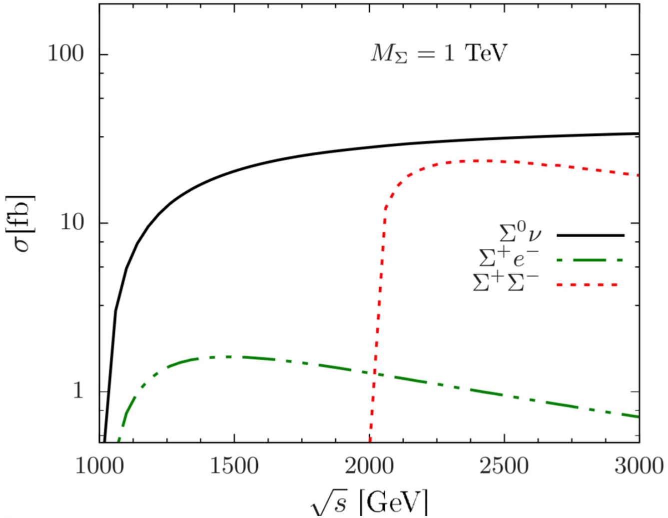
$M_\Sigma \leq 900$ GeV

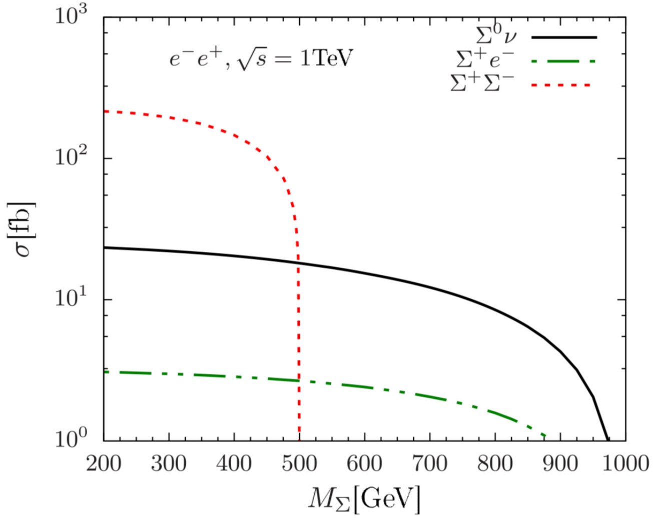
Triplet production at the e⁻e⁺ collider

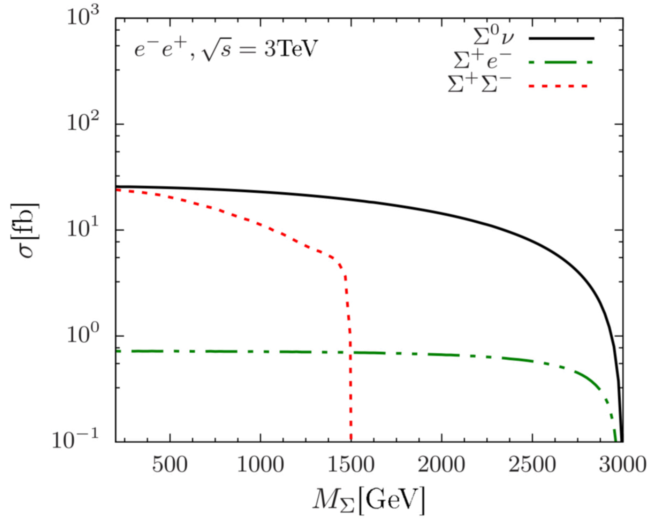
AD, Mandal, Modak;





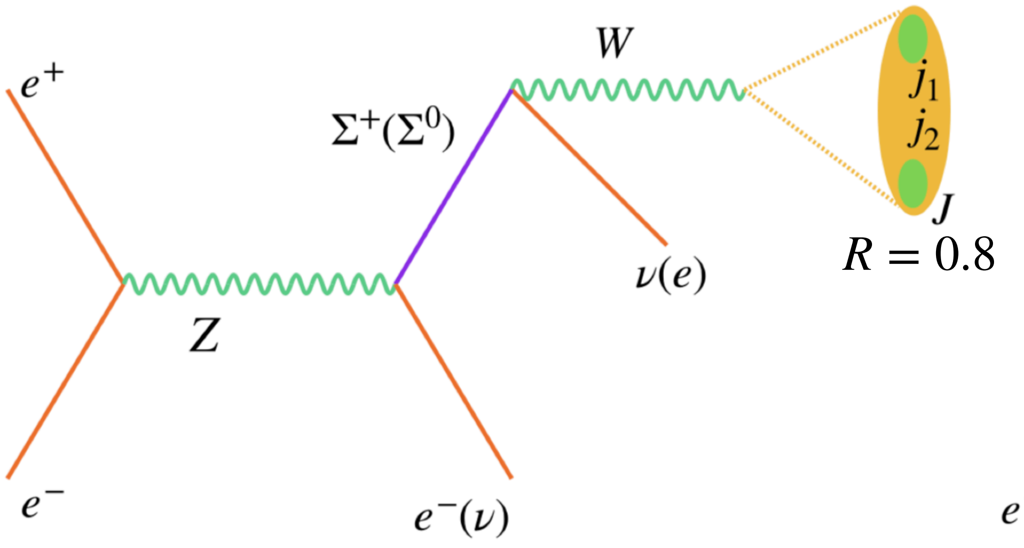


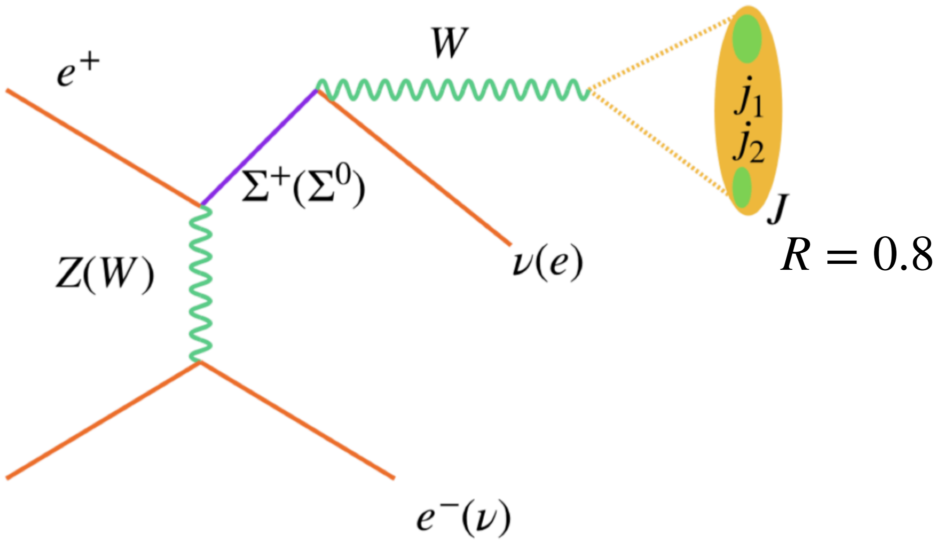


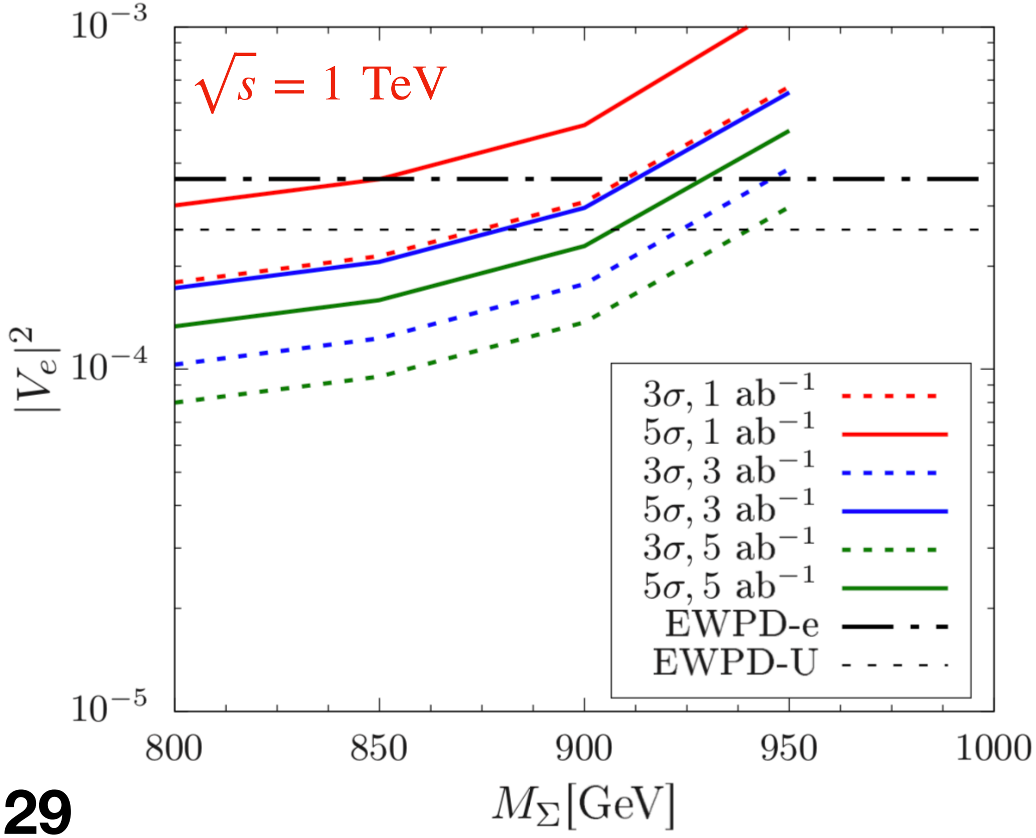


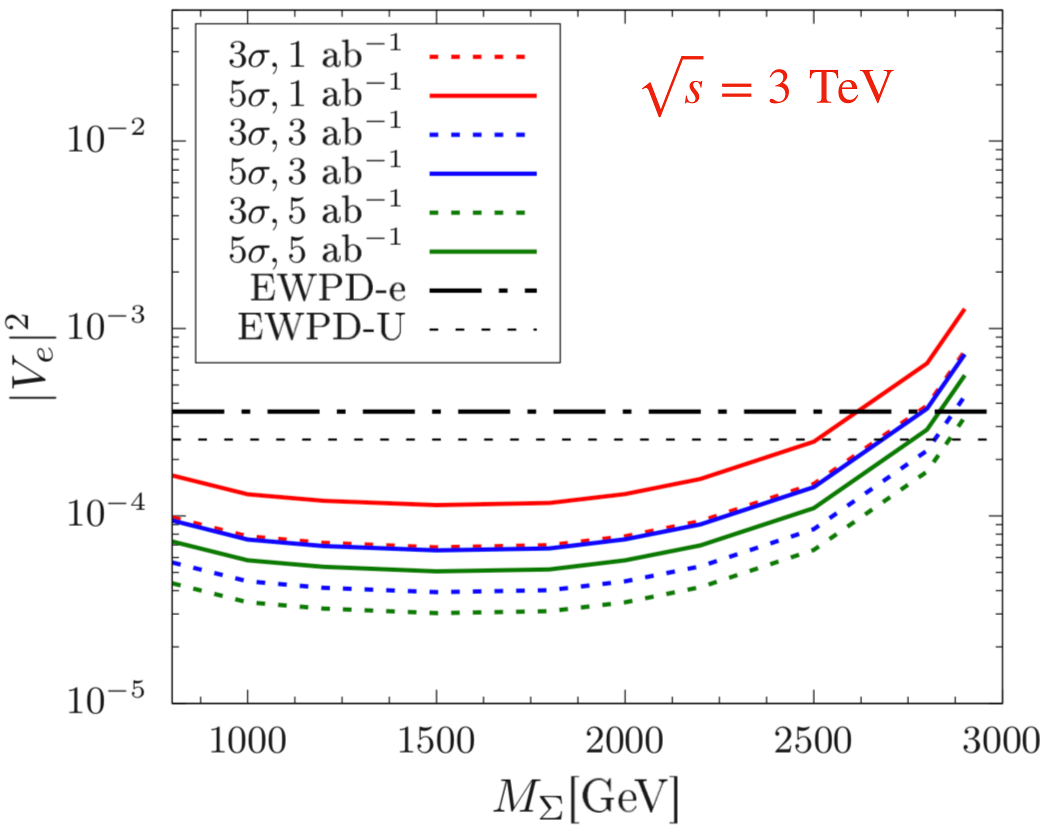
Mass-mixing limit plots

AD, Mandal, Modak;









Conclusions

We study the models with the heavy fermions under the simple extensions of the SM where the neutrino mass is generated by the seesaw mechanism at the tree level to reproduce the neutrino oscillation data.

We find that such heavy fermions can be tested at the underground experiments- at the proton-proton, electron positron and electron-proton colliders. We have calculated the bounds on the light-heavy mixings for the electron-positron collider which could be probed in the near future.

Thank You