جامعة نيويورك أبوظبي

NYU | ABU DHABI

Heavy Neutral Leptons without Prejudice

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Neutrinos and Flavor: a stairway to new physics, Pisa, April 2025

Work done in collaboration with Nicolas Bernal and Kuldeep Deka

Outline

1. Motivation

2. Neutrino mass models

3. Long Lived Particles

4. Current experimental results

5. Projections for future collider experiments

Motivation

LHC results of Higgs discovery and measurement of physical properties.

First evidence of existence of a scalar particle with SM Higgs boson properties

Into the era of precision Higgs physics

No new elementary particles discovered with m ~ 1TeV

New physics via higher dimension operators or very weak interactions.

What is the NP scale?

eV keV MeV GeV TeV

Energy ranges that have been covered by accelerator experiments seem to imply the NP is weakly coupled (or phase space suppressed).

Accelerator Produced Detection

Search for very weakly coupled NP, and including for new long lived particles.

1. Colliders
2. Fixed target/Beam dump
3. High intensity Beams

The basics and some history.....

Studying weak interaction with neutrinos…... Two neutrino types...

Pontecorvo 1959
Schwartz 1960
Danby et al 1962

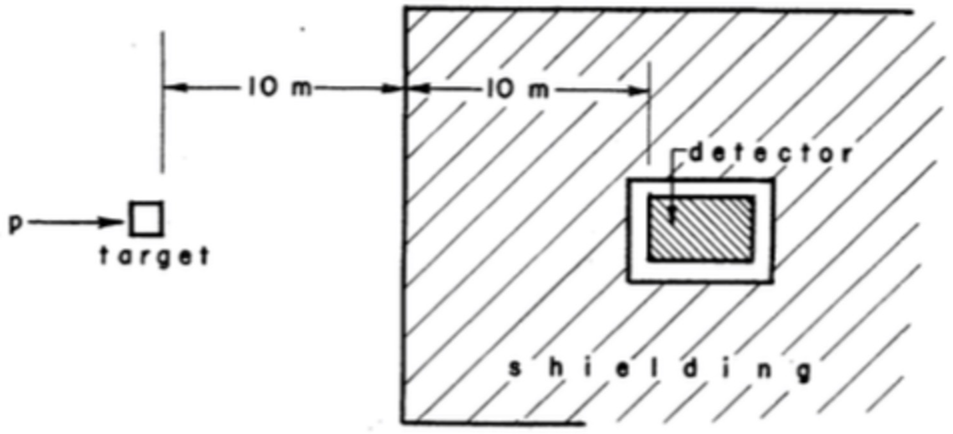


FIG. 1. Proposed experimental arrangement.

I = 5 x 10^{12} protons/sec

I/10 pions produced at target, E > 2 GeV, 2 steradians

$c\,\tau = 7.8\text{m} \Rightarrow d = 111\text{m}$

10% of pions decay

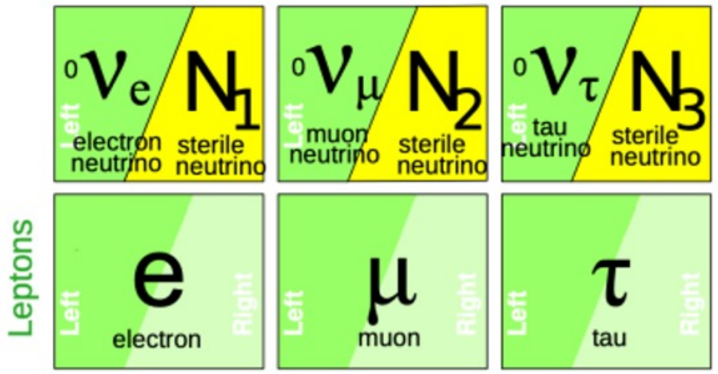
$N_{flux} = 10^{-9}\, I$

events ~ 1 per hour

Led to first neutrino beam and discovery of $\nu_e \neq \nu_\mu$

Why Heavy Neutral Leptons ?

- Neutrino masses
- Leptogenesis
- Dark matter candidate
- Neutrino anomalies



arXiv:1301.5516

Naturally introduces Yukawa-type couplings,
Connect HNLs with Higgs physics

However, it is completely unknown:

If the neutrino mass mechanism involves HNL what is the correct model?

Are there additional interactions of the HNL?

What is the nature of the HNL: Dirac or Majorana?

What is the HNL mass scale?

mN ~ eV. for oscillation anomalies

mN ~ keV for warm dark matter

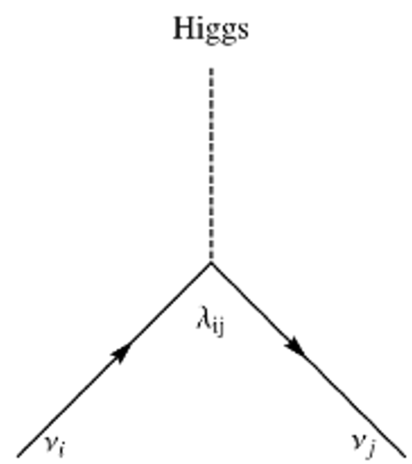
mN ~ MeV- GeV in deviations of SM

mN ~ GeV-TeV for BAU

Minimal neutrino mass models

$$-\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c. \leftrightarrow \bar{L}\tilde{\Phi}\lambda\nu_R + h.c.$$

Dirac particles

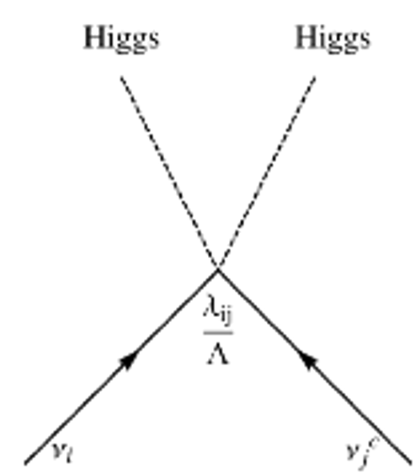


$$m_\nu \sim \lambda v$$

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \leftrightarrow \bar{L}\tilde{\Phi}\ \alpha\ \tilde{\Phi}L^c + h.c.$$

Majorana particles

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

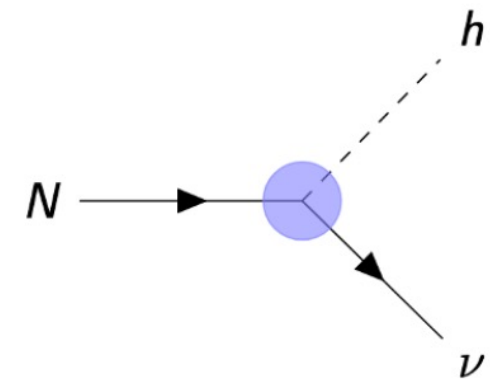


Minimal neutrino mass models

$$\mathcal{L} \supset y_{N\alpha}\, \overline{N}\, \widetilde{H}^{\dagger}\, L_{\alpha} + h.c + ...$$

where $\widetilde{H} = i\sigma^2 H^*$ and L_α are SM lepton doublets.

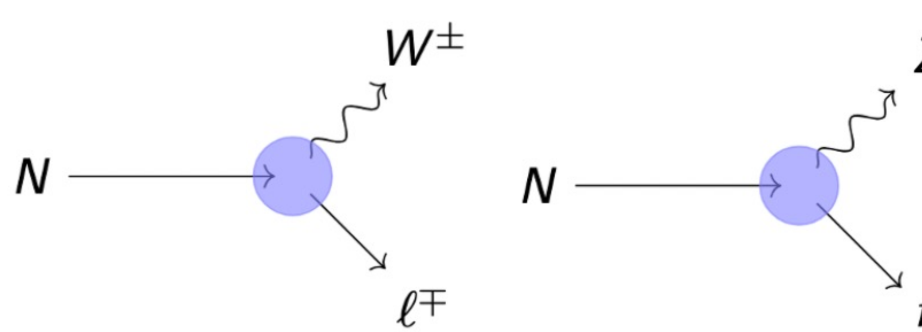
$$(M_D)_{N\alpha} = \frac{y_{N\alpha} v_h}{\sqrt{2}}$$



$\equiv \boldsymbol{y}$

Diagonalisation of the mass matrix may result in mixing:

$$\nu_{L,\ell} = \sum_{\text{mass},i} U_{i,\ell}\nu_i + \sum_{\text{mass},j} V_{\ell,j} N_j$$



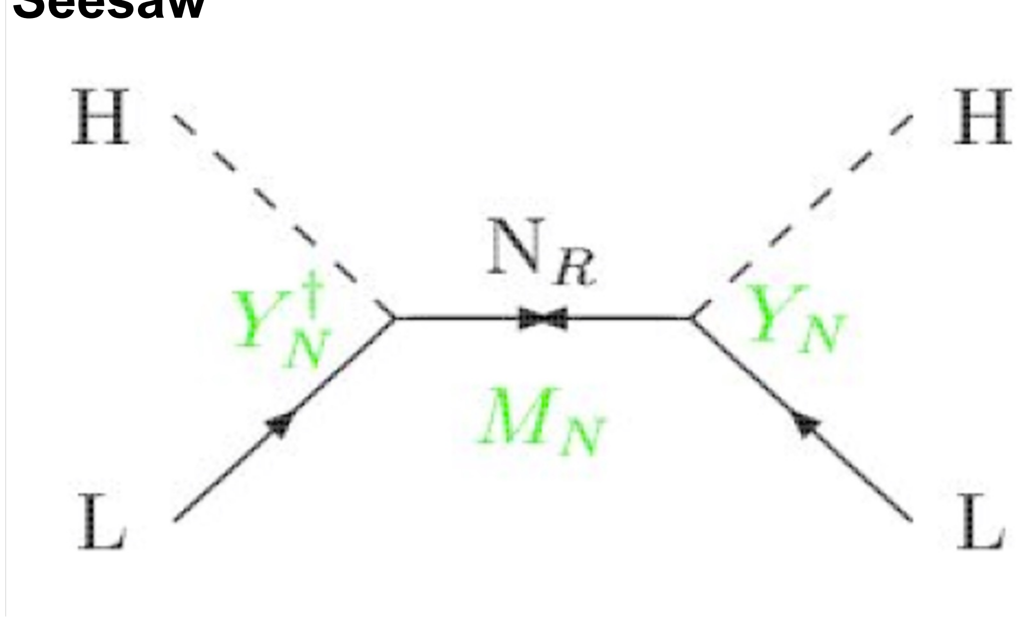
$\equiv \boldsymbol{V}$

Type I Seesaw/Inverse Seesaw Mechanism

$$\mathcal{L} \supset y_{N\alpha} \overline{N}\, \widetilde{H}^{\dagger} L_{\alpha} + h.c + ...$$

where $\widetilde{H} = i\sigma^2 H^*$ and L_α are SM lepton doublets.

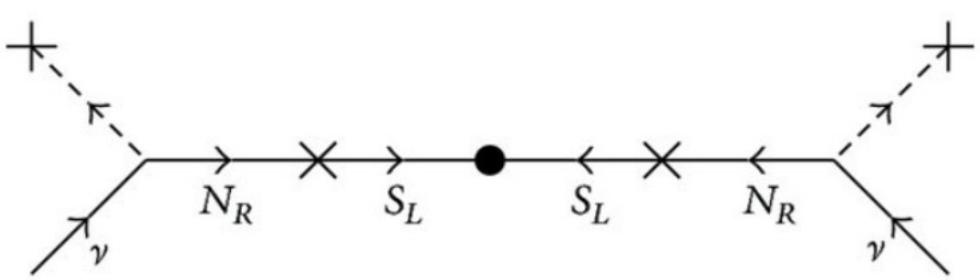
Type I Seesaw



$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$

$$|V_{N\alpha}|^2 \simeq \left(|y_{N\alpha}| \frac{v}{m_N} \right)^2$$

Inverse Seesaw



$$|V_{N\alpha}|^2 \simeq \left(|y_{N\alpha}| \frac{v}{m_N} \frac{\mu}{m_N} \right)^2$$

Neutrino mass models - continued

Alternatively, consider a simple model with Dirac neutrinos and extra symmetries to decouple ν_L and N_R and still have non-zero masses.

Introduce the following fields: HNL given by (N_L, N_R) a right handed neutrino ν_R, and a complex scalar singlet.

arXiv:1411.5042
arXiv:1606.04543

$$\mathcal{L} \supset y\bar{L}_L\tilde{H}N_R + g\bar{N}_L\chi\nu_R + M\bar{N}_LN_R$$

Neutrino mass matrix

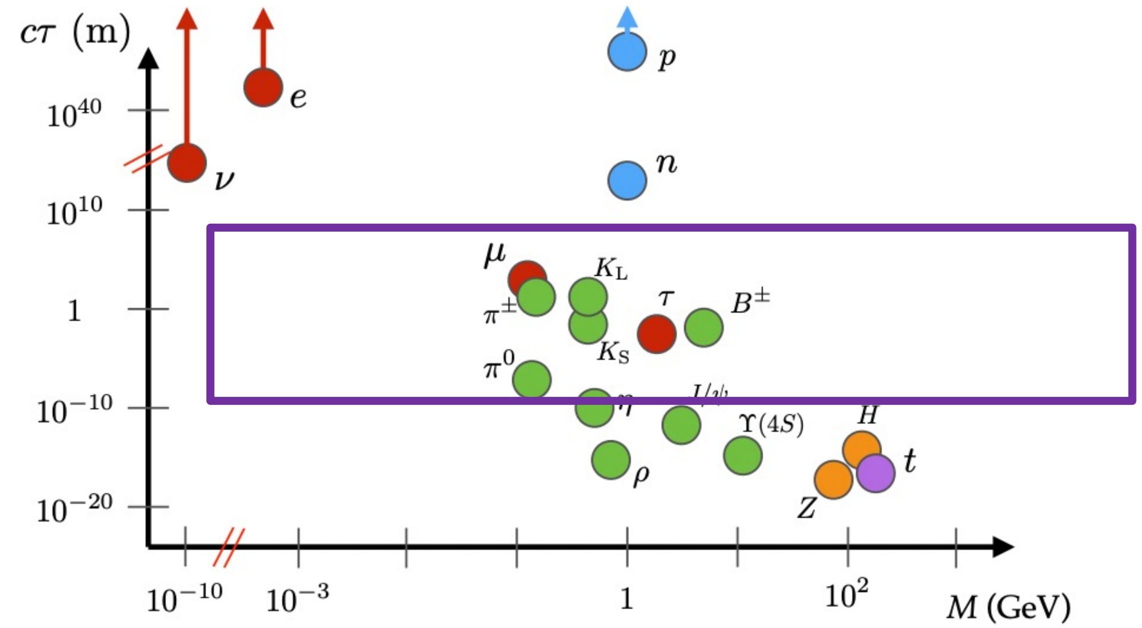
$$\mathcal{M} = \begin{pmatrix} 0 & m_1 \\ m_2 & M \end{pmatrix}$$

Can make mixing V to be zero taking m_2 = 0.

Phenomenologically we will just take a model independent approach such that the **mixing matrix, Yukawa coupling and the mass** as independent parameters

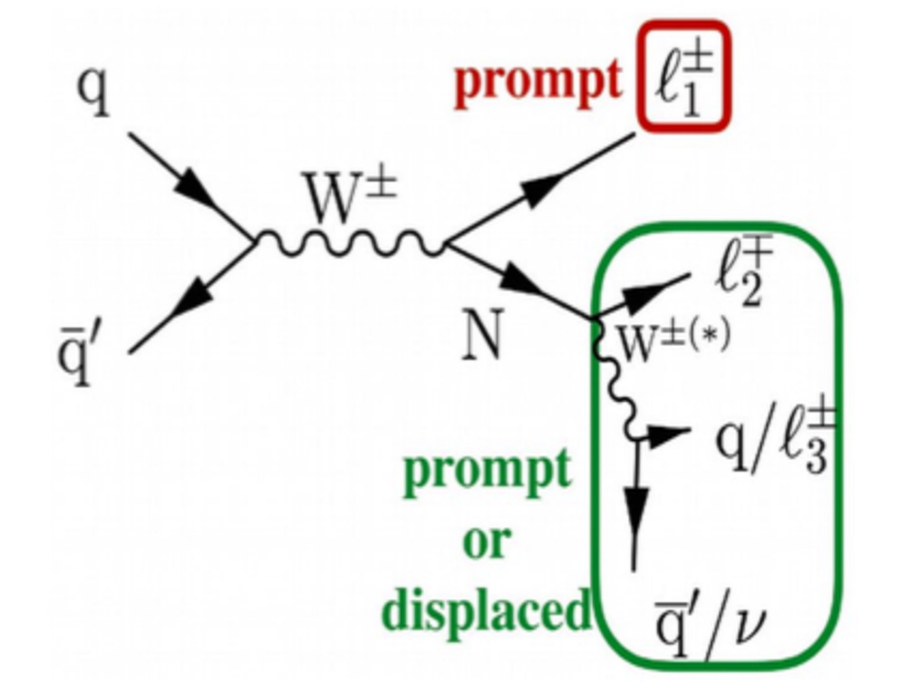
Long lived Particles

arxiv.org/pdf/1903.04497



Displaced vertices in collider detectors

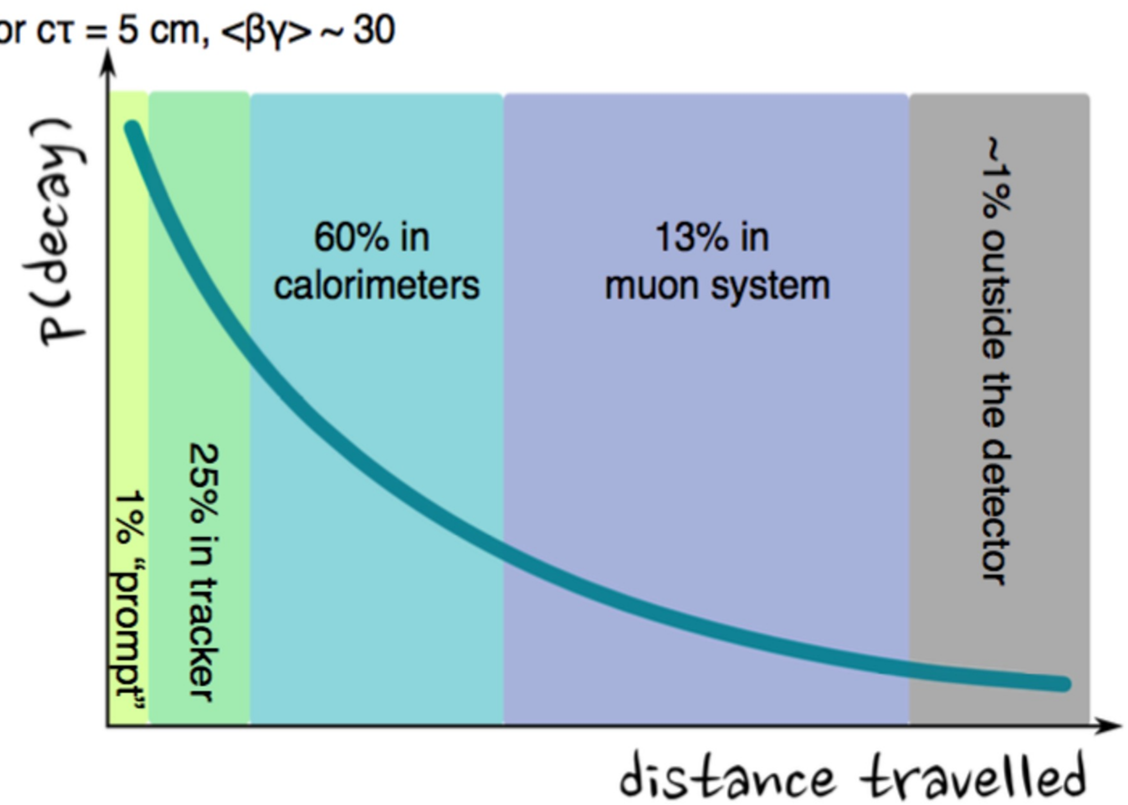
Longer lived LLPs use dedicated detectors



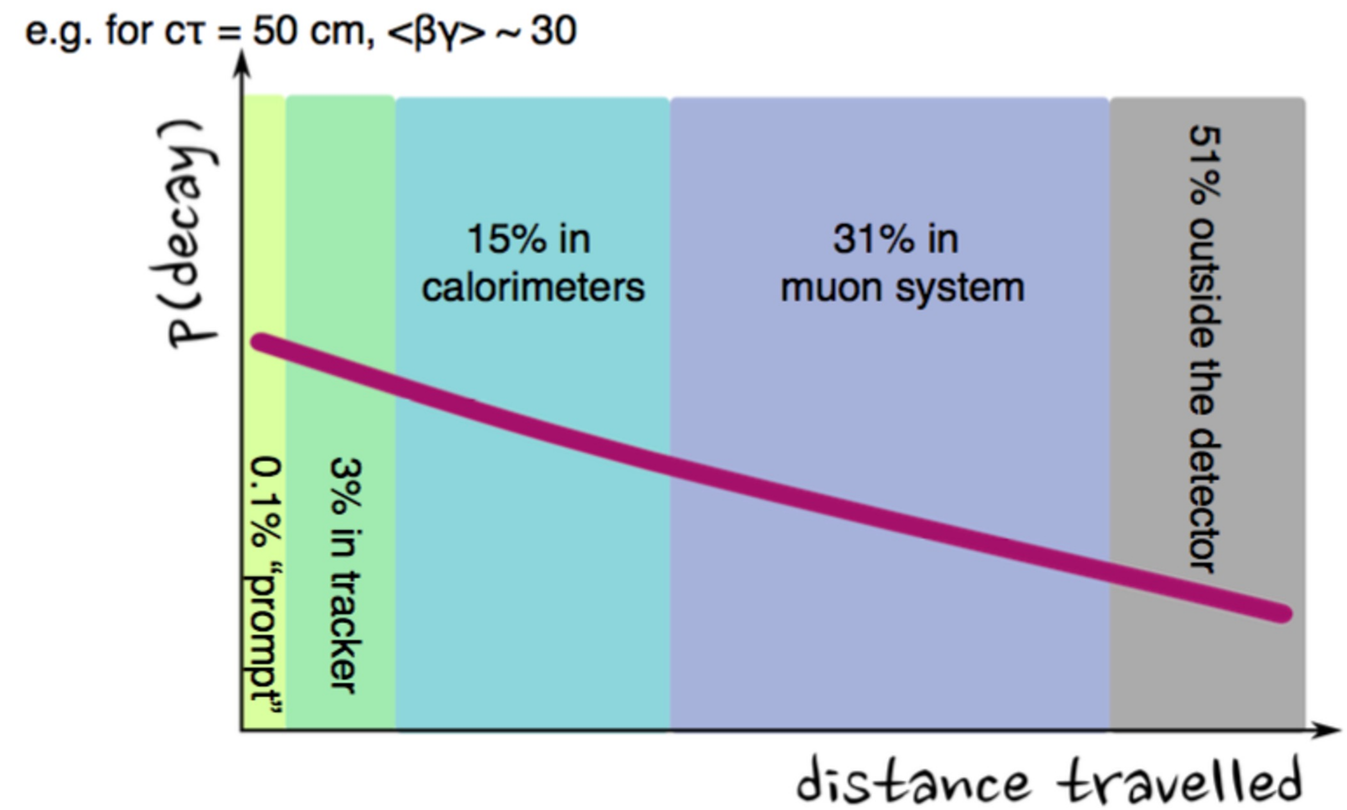
- Calculate the decay rate of the LLPs, Γ
- Corresponding lifetimes as a function of coupling and mass.
- Decay length: $d = p/M\, c\tau$

Sensitivity

Many factors affect signatures, exploit all detector components…...



H. Russell



$$N_{\mathrm{events}} = \mathscr{L} \int d\sigma(\mathrm{SM} \rightarrow \mathrm{LPP}) \times BR(\mathrm{LPP} \rightarrow \mathrm{SM}) \times P_N(L) \times \varepsilon_{\mathrm{geo}}$$

Sensitivity will depend on:

location, size, luminosity,...particle ID,

Also will depend essentially on

Mass of LLP

Interaction strength

LLP Production and Decay

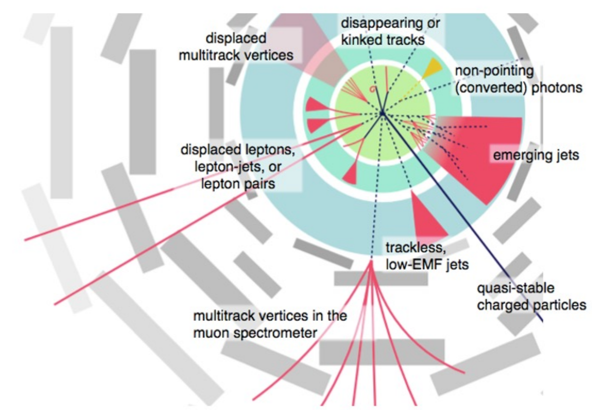
Colliders: LLP Production

- Heavy resonance
- Pair Production
- Parent decay
- Higgs decay
- Charged current

LLP LHC White paper.

Colliders: LLP decay modes and signatures

- Diphoton OR single photon
- Hadronic
- Semi-leptonic
- Leptonic
- Flavored leptonic
- Invisible decay



From H. Russell

Intermediate lifetimes

LLP LHC White paper.

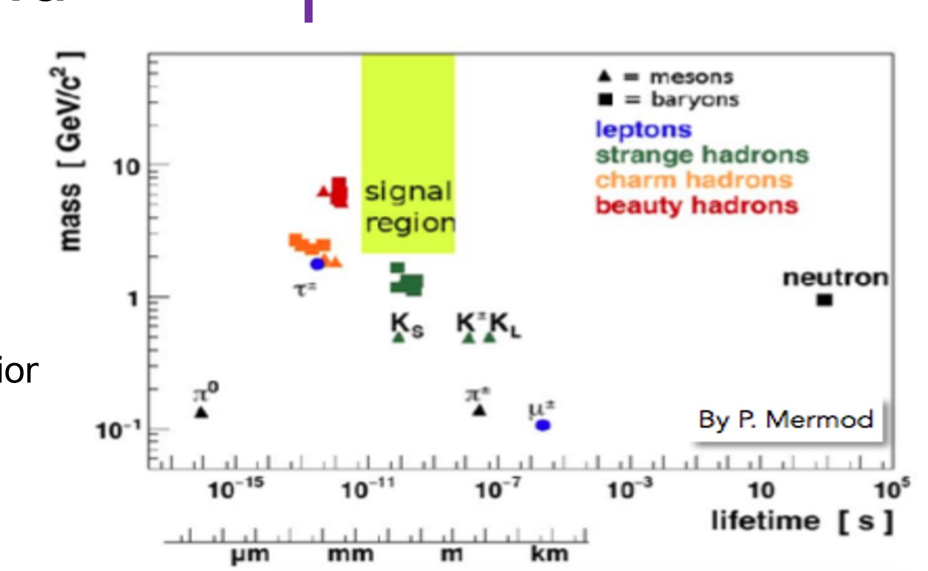
New objects not suitable to standard defs and algorithms

----triggering!!!

Examples:

Unconventional backgrounds

long lived particles in SM
hadronic detector interactions
particles from outside of collisior
algothmically induced fakes



Requiring more data-driven/AI techniques

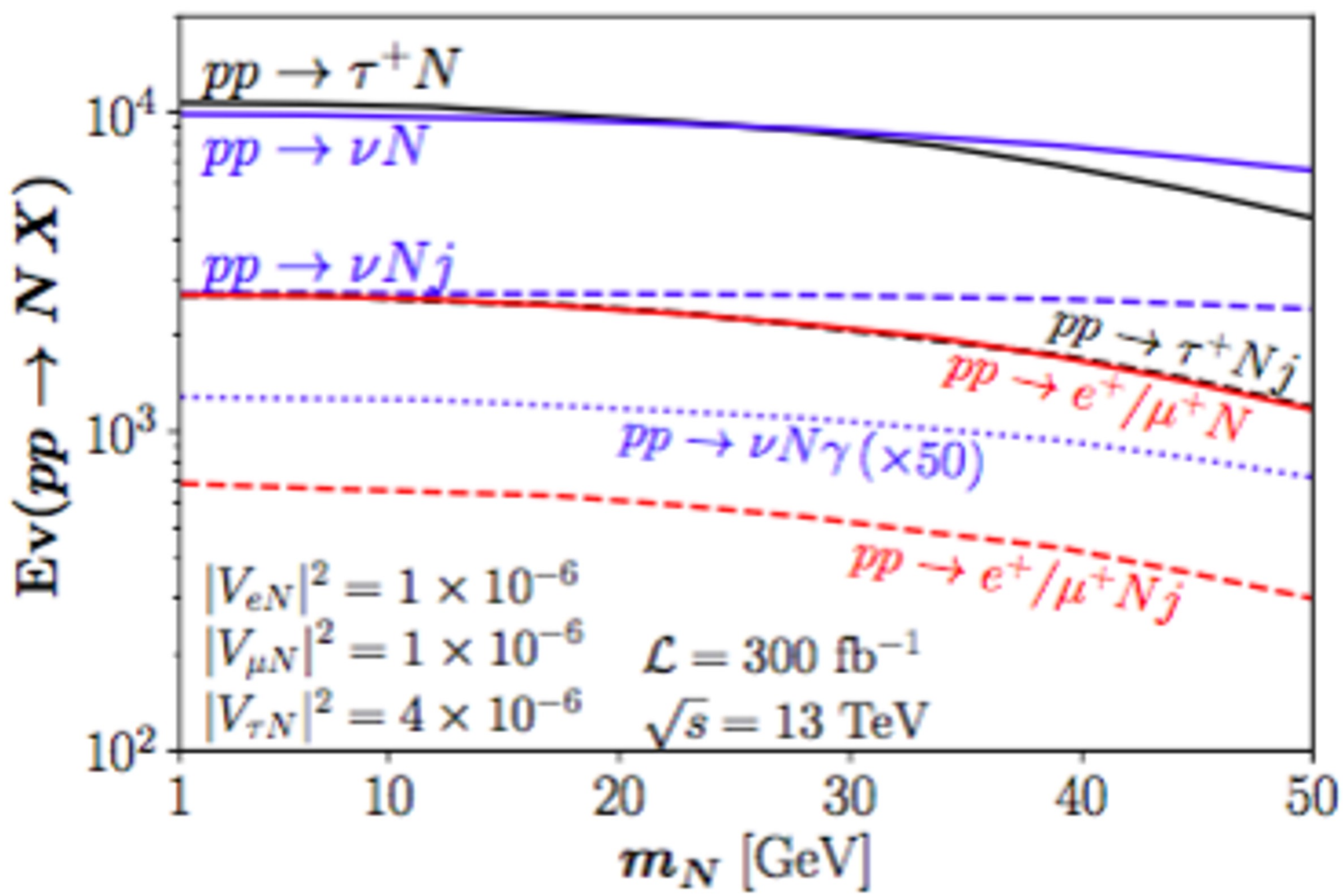
The basics for HNL in type I SM + N

Width

$$\text{BR}_{W^\pm \to \ell^\pm N} \propto |V_{\ell N}|^2$$

$$\text{BR}_{Z \to \nu N} \propto \sum_\ell |V_{\ell N}|^2, \quad \text{BR}_{H \to \nu N} \propto \left(\frac{m_N}{m_W}\right)^2 \sum_\ell |V_{\ell N}|^2$$

Production



Decay

Length

The basics for HNL in type I SM + N

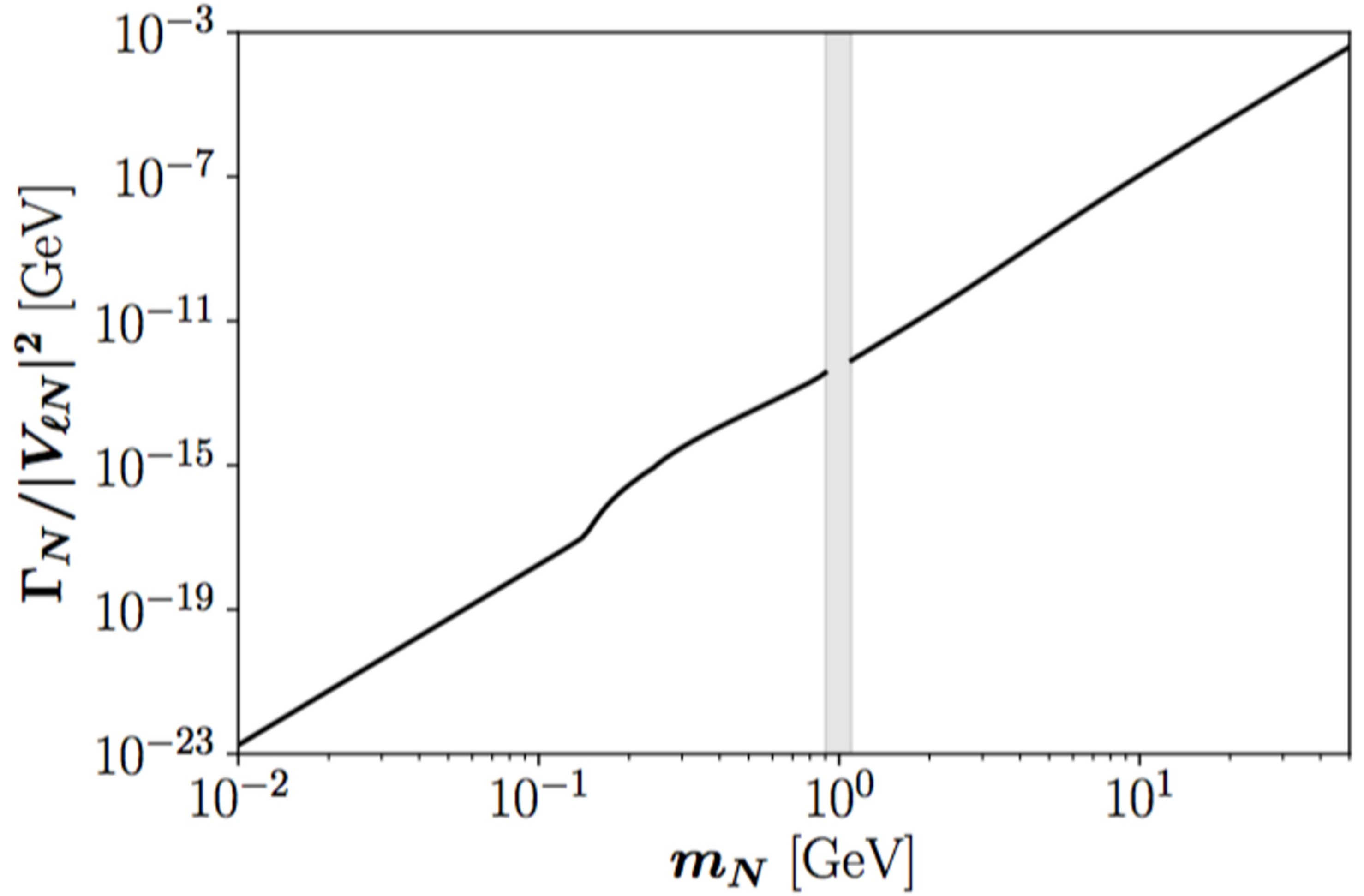
Width

$$\Gamma_N \propto G_F^2 m_N^5 \sum_{\ell=e,\mu,\tau} |V_{\ell N}|^2$$

Production

Decay

Length



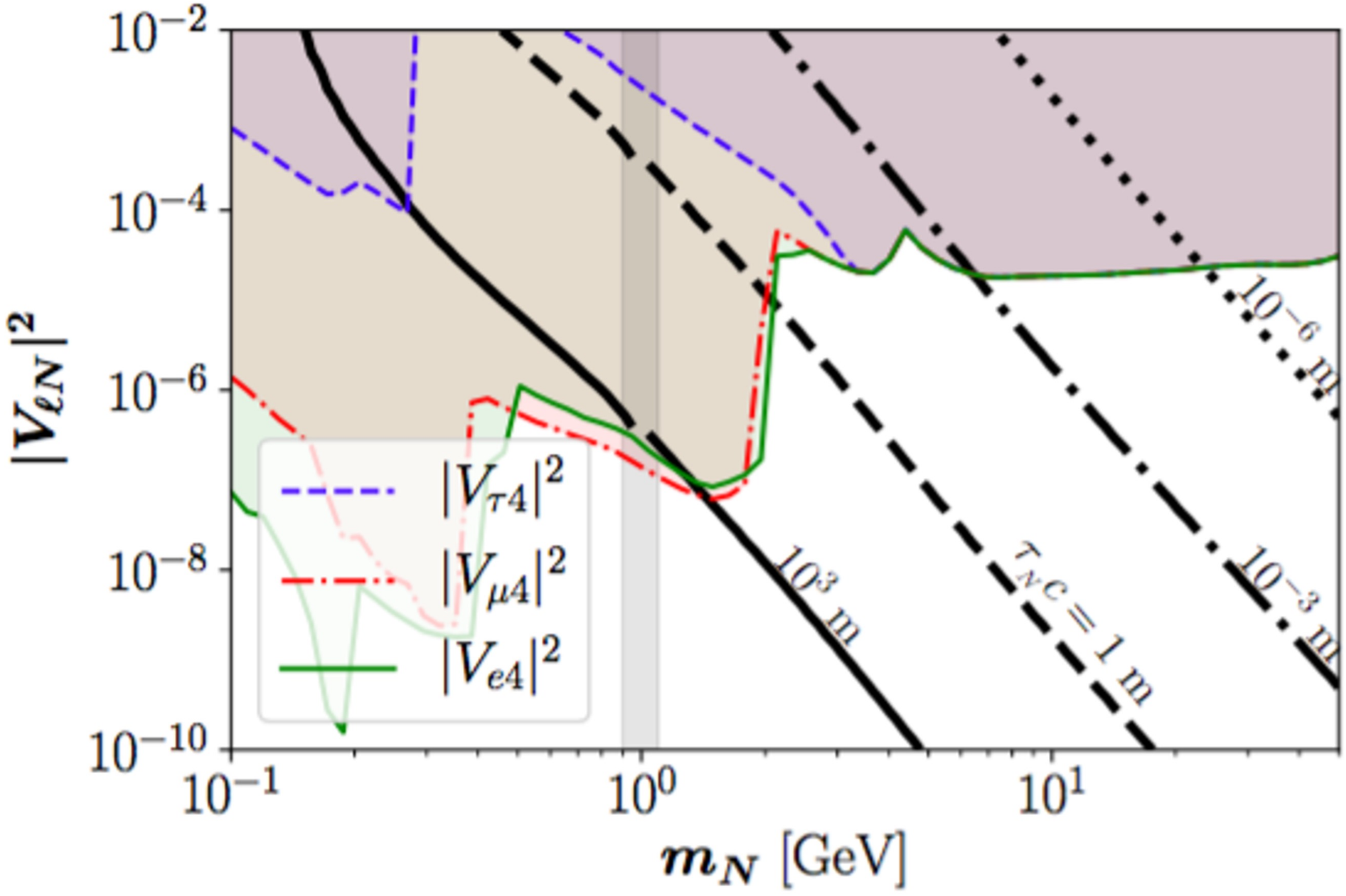
The basics for HNL in type I SM + N

Width

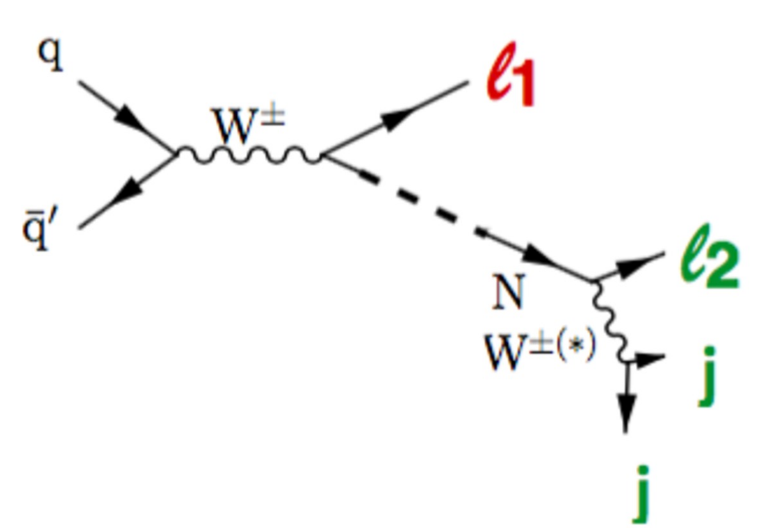
Production

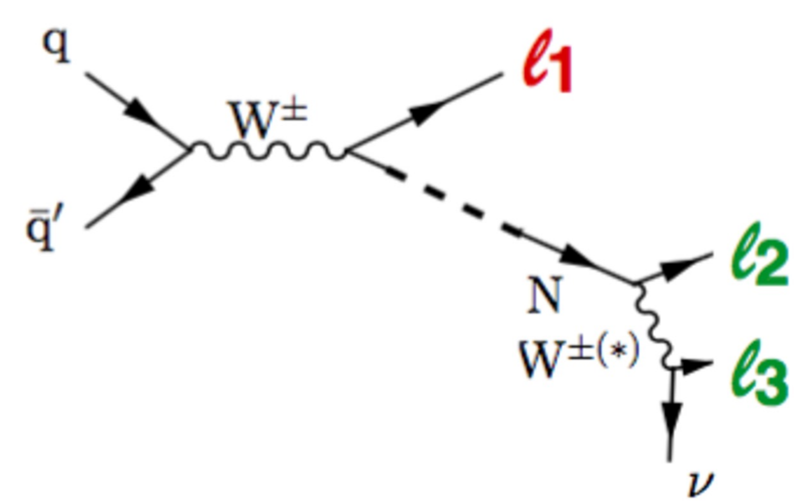
Decay

Length



Signatures





Dilepton + 2 jets
Invariant mass of N
Mostly sensitive to large m_N

No invariant N mass
Sensitive to low N

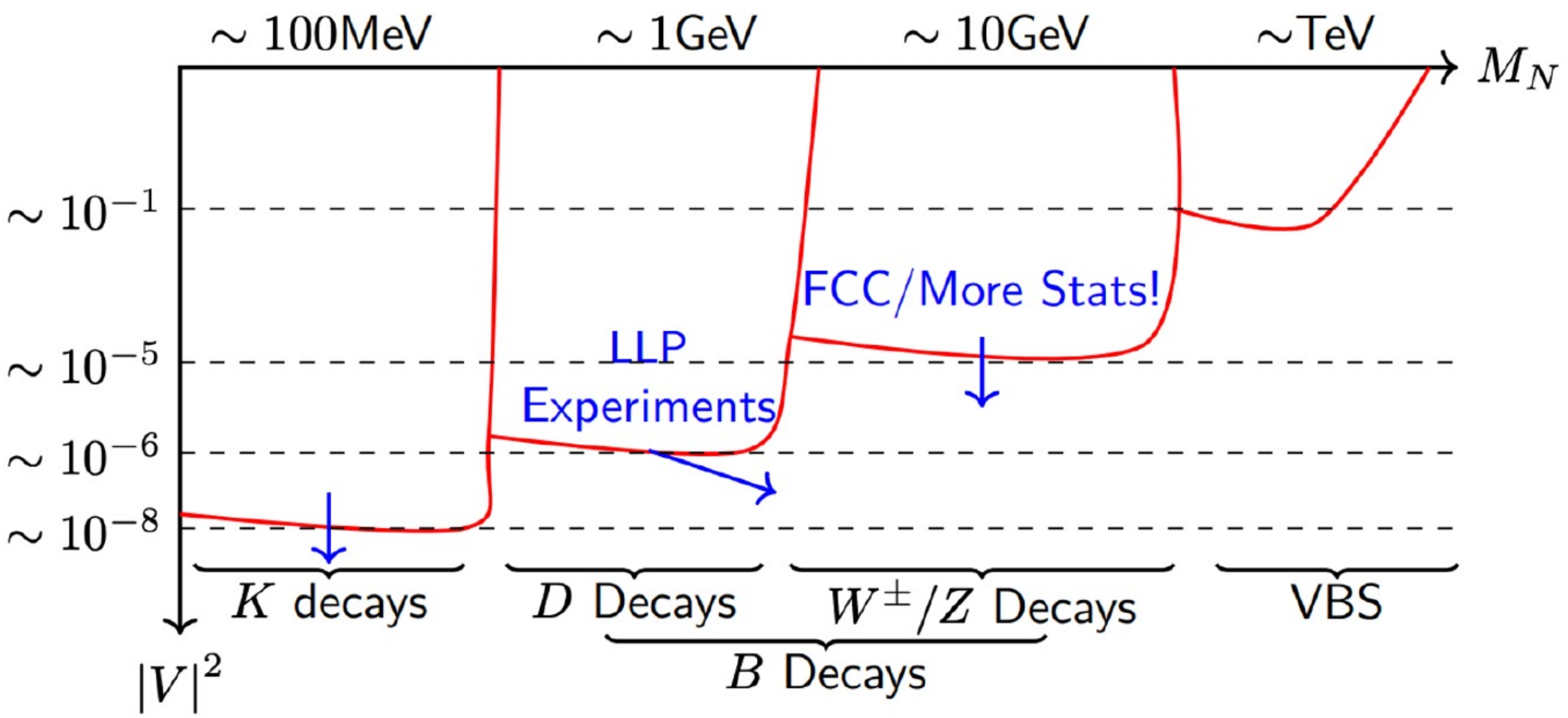
LNV and LNC, depending on OS and SS of the two higher p_t leptons

Experimental Results

Pushing the experimental frontiers

Collider constraints are usually shown in $V^2 - m_N$ plane

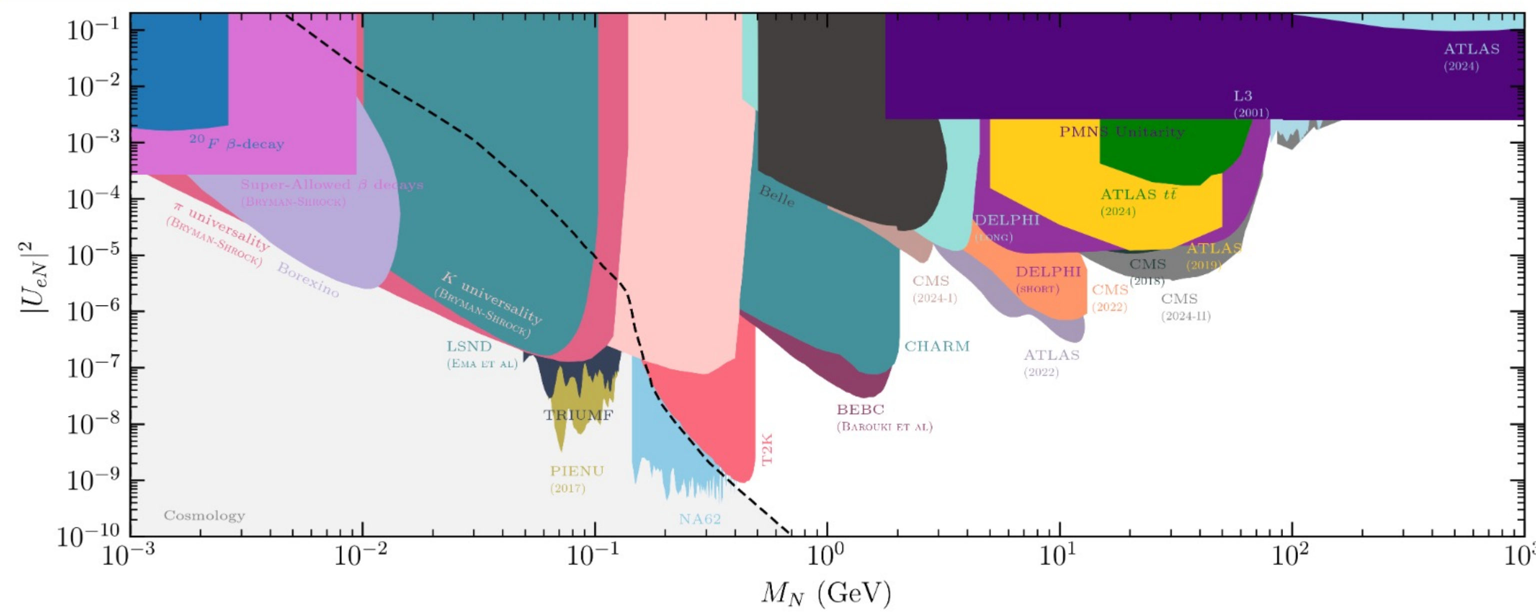
- **Below Kaon mass**
  - Kaon decays
    - e.g. NA62
- **Below B or D masses**
  - Heavy flavour decays
    - e.g. Belle, LHCb
- **Below W, Z masses**
  - Displaced and prompt searches
    - e.g. LEP, **LHC**
- **Above W,Z masses**
  - Decays to on shell bosons
    - e.g. **LHC**



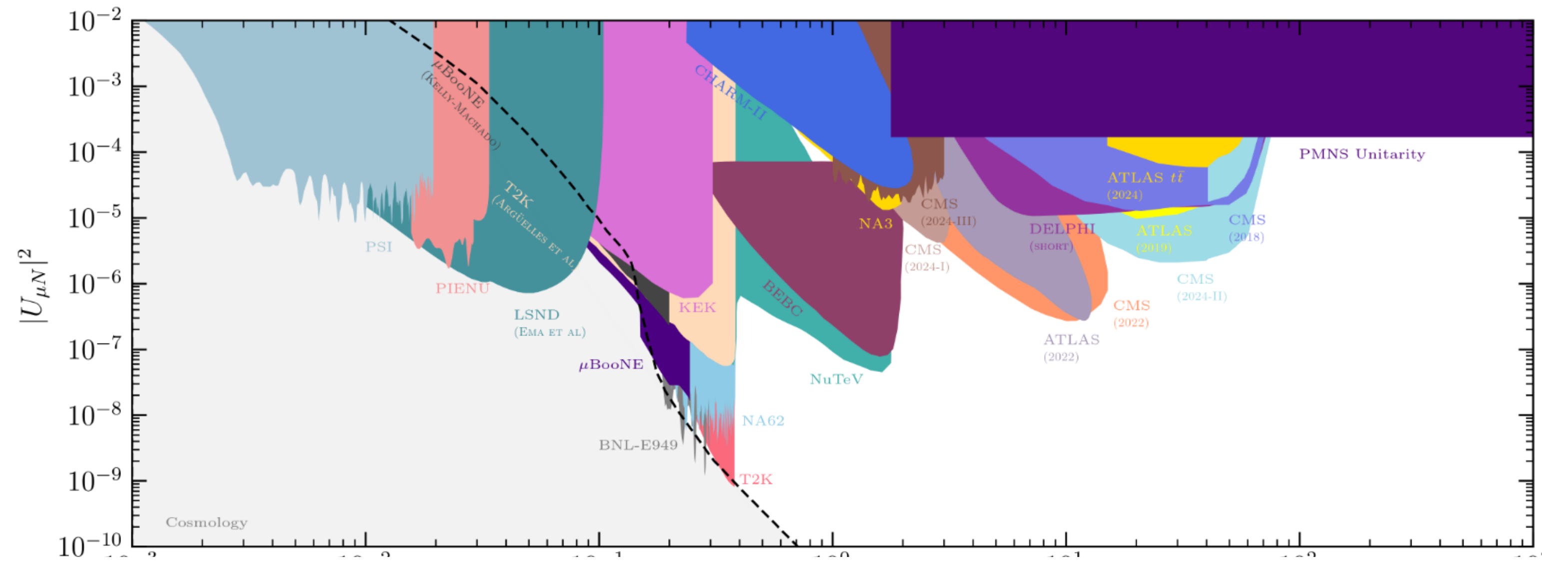
https://warwick.ac.uk/fac/sci/physics/research/epp/events/seminars/hnl_seminar_warwick_g_bird.pdf

Current Bounds

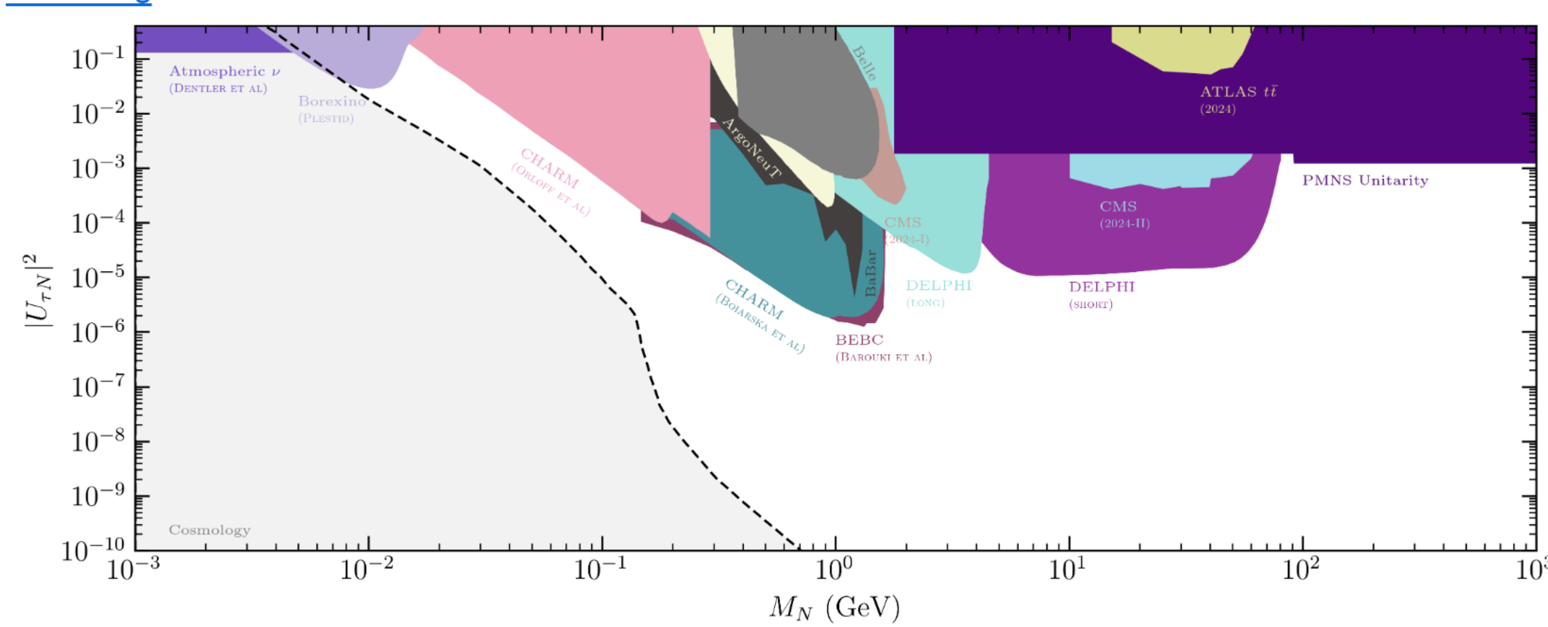
Electron mixing



Muon mixing



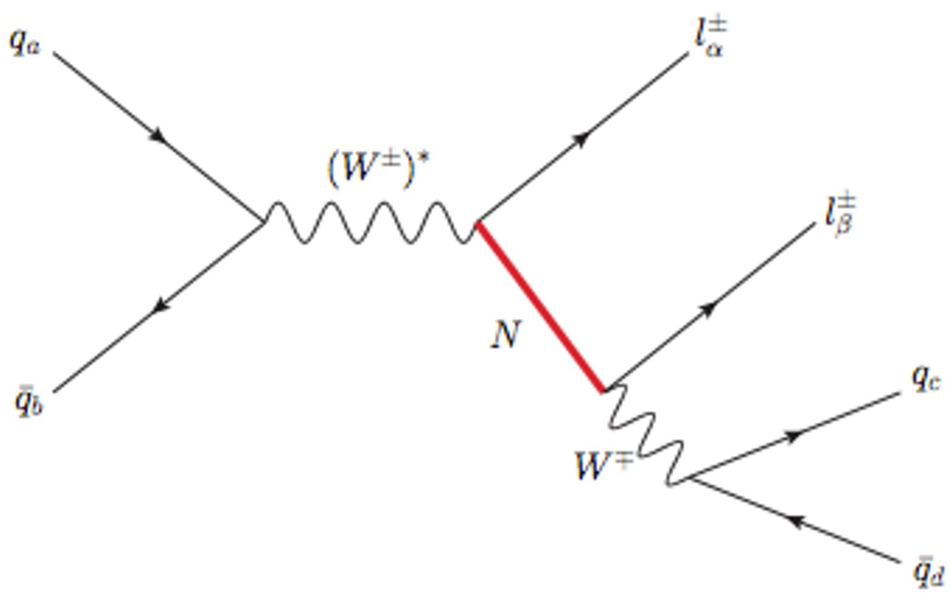
Tau mixing



E. FERNANDEZ ET AL
2304.06772

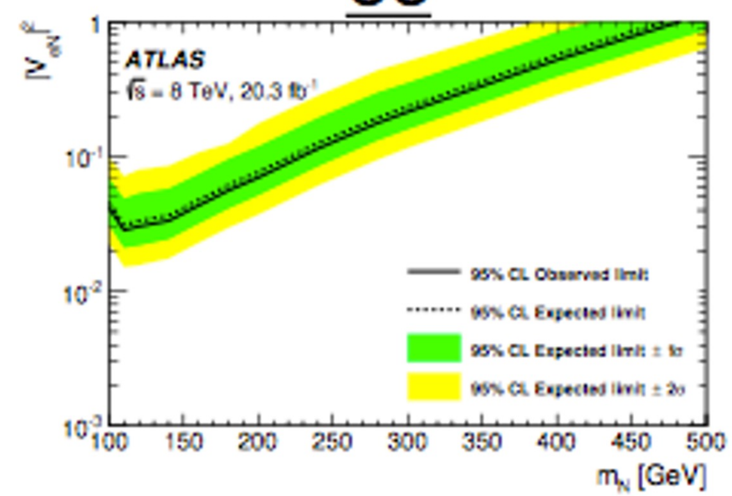
LHC Results: Prompt HNL ATLAS, CMS searches

$M_N > M_Z$

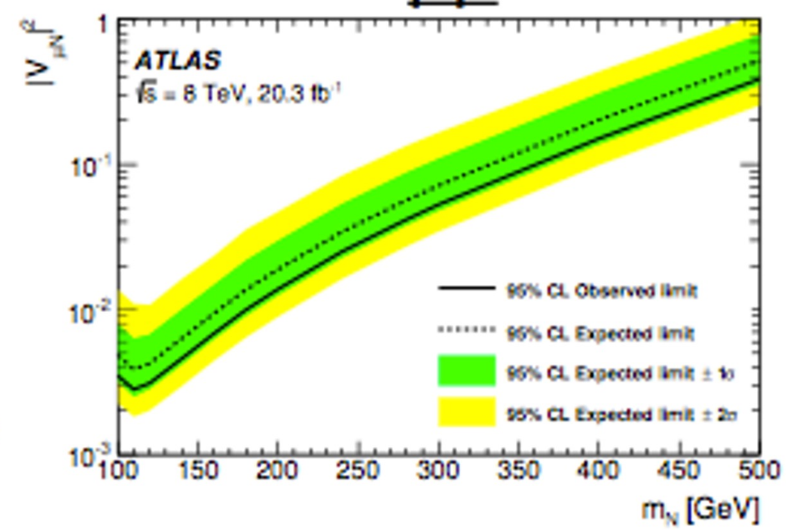


$|V_{\ell N}|^2$

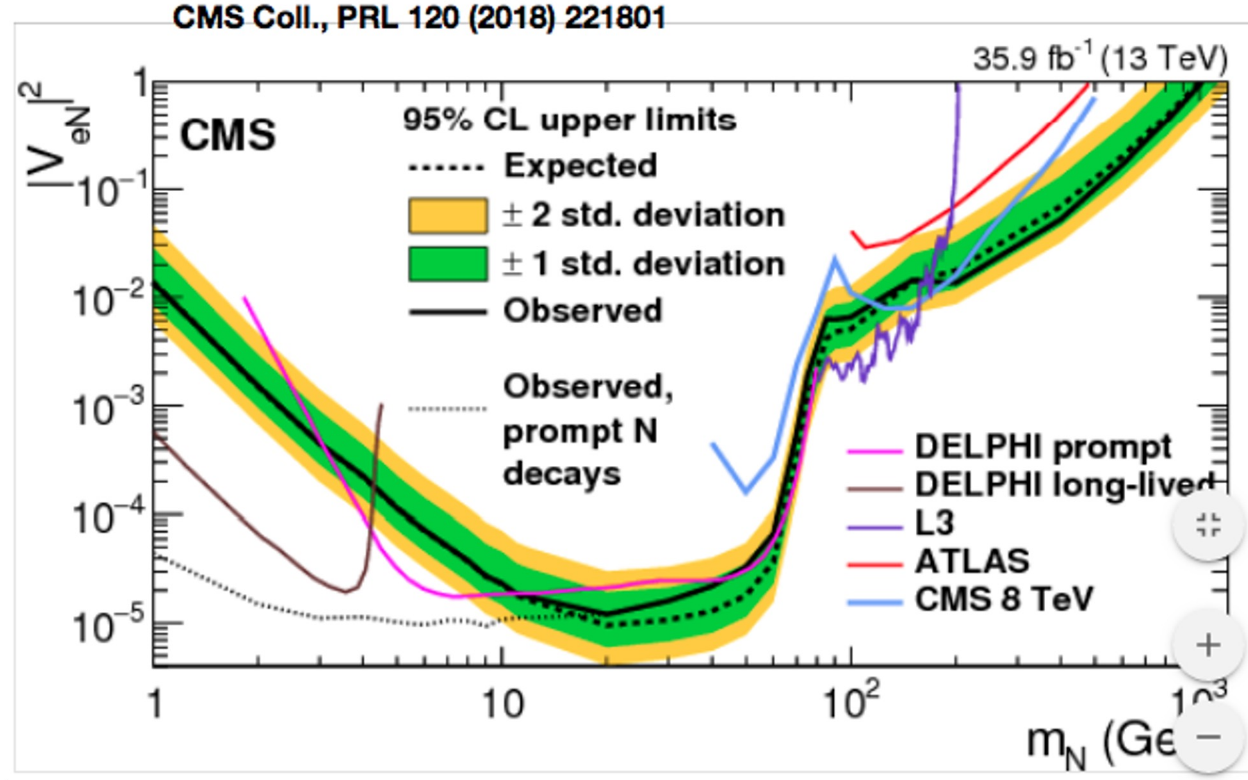
ee



μμ



CMS Coll., PRL 120 (2018) 221801

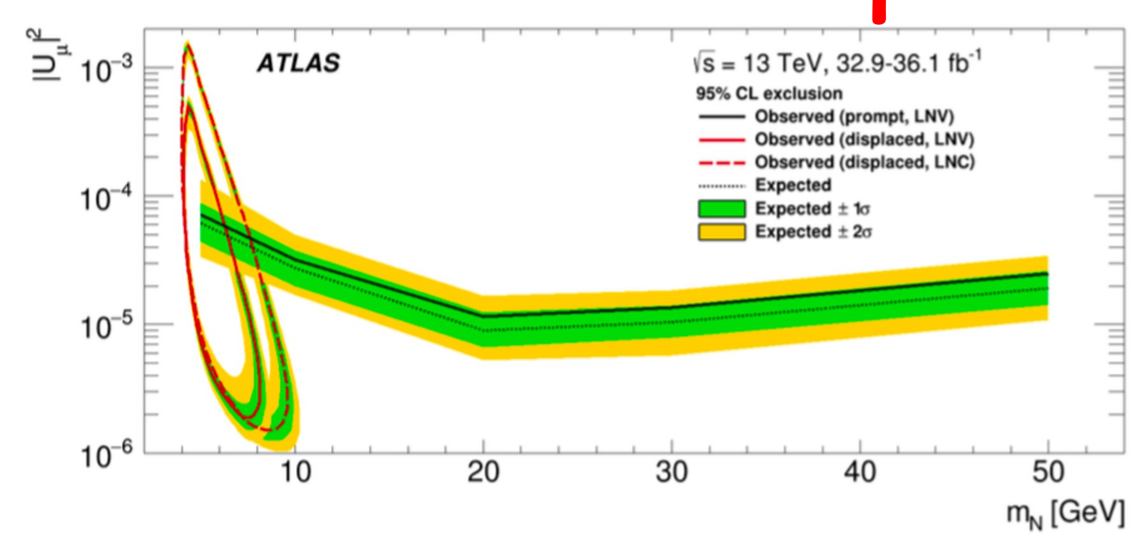


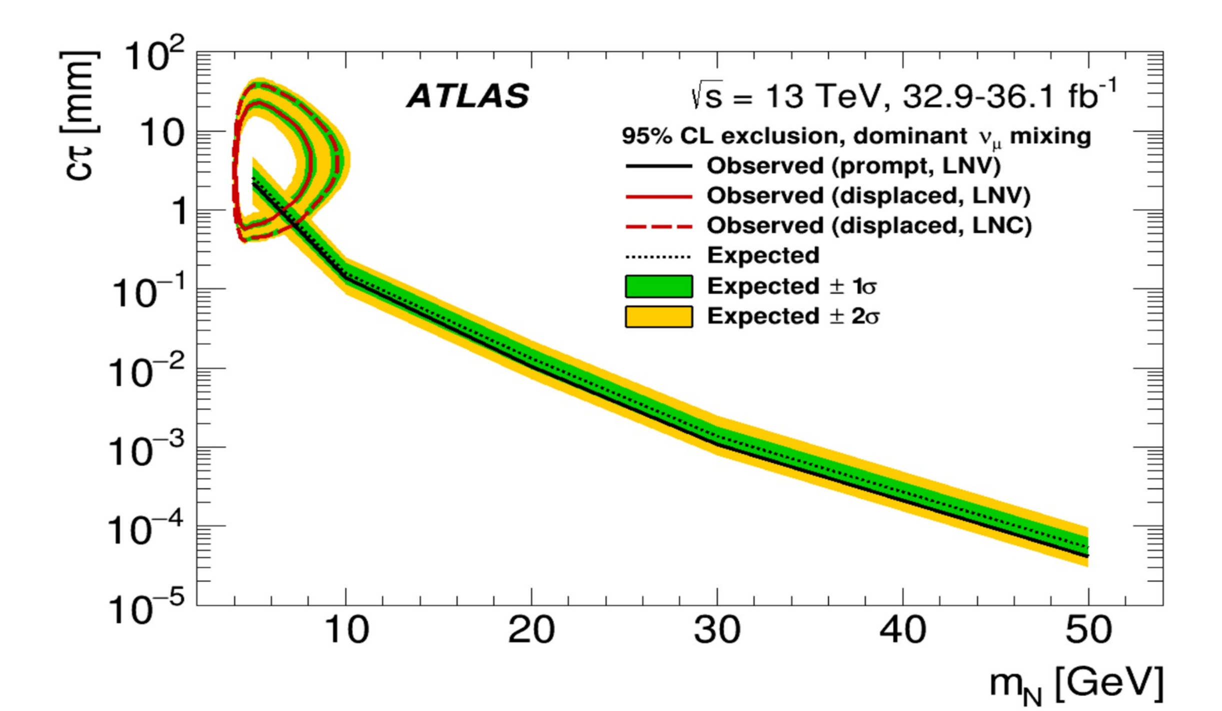
ATLAS/CMS DV

$M_N < M_W$

1905.09787

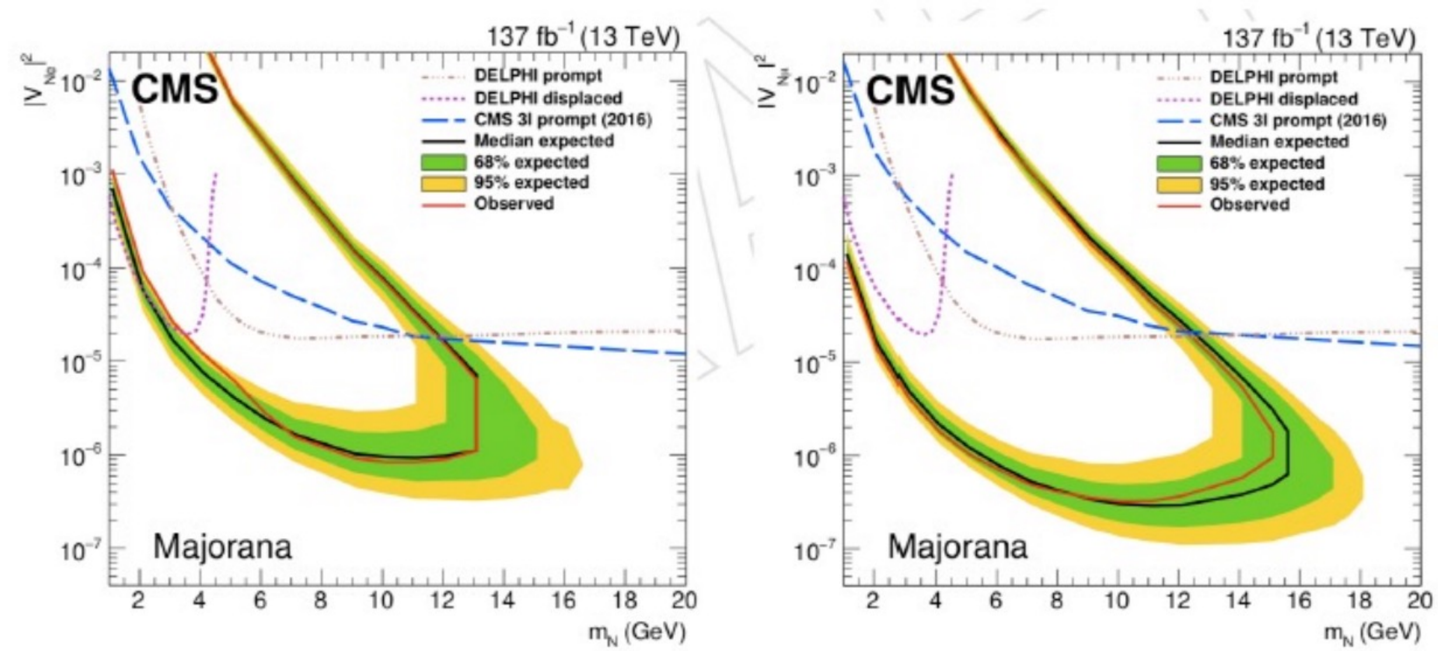
$W \to N\mu$





Electrons and Muons

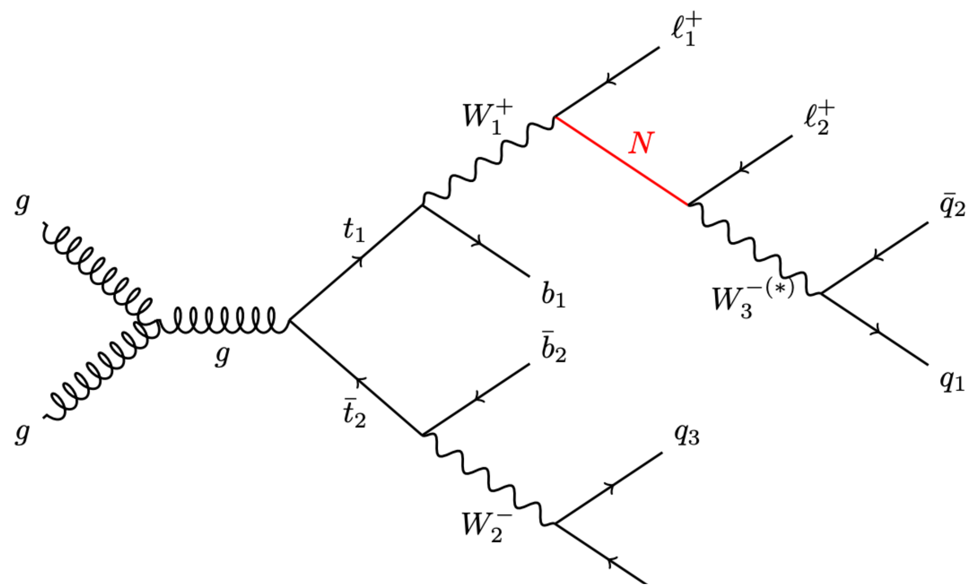
2201.05578.

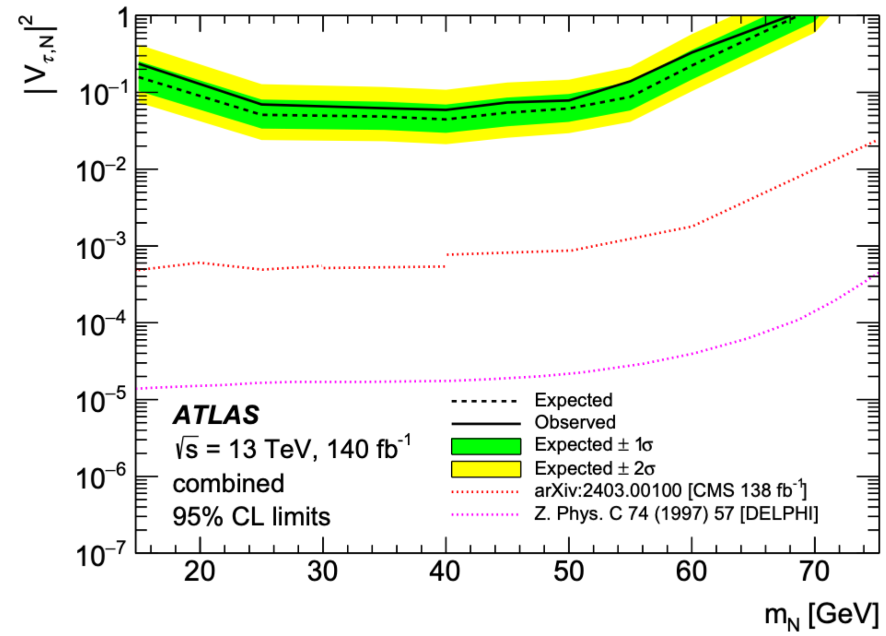


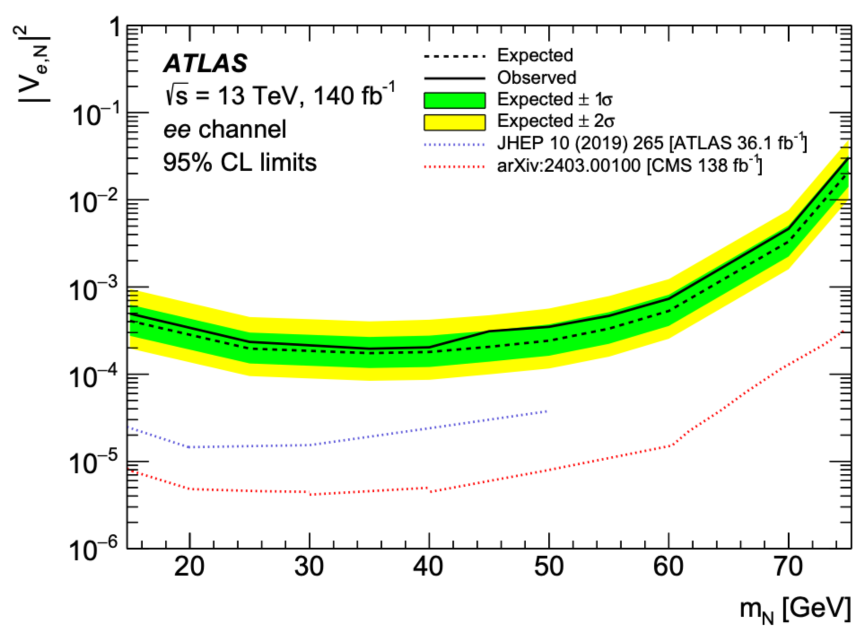
RECENT ANALYSIS

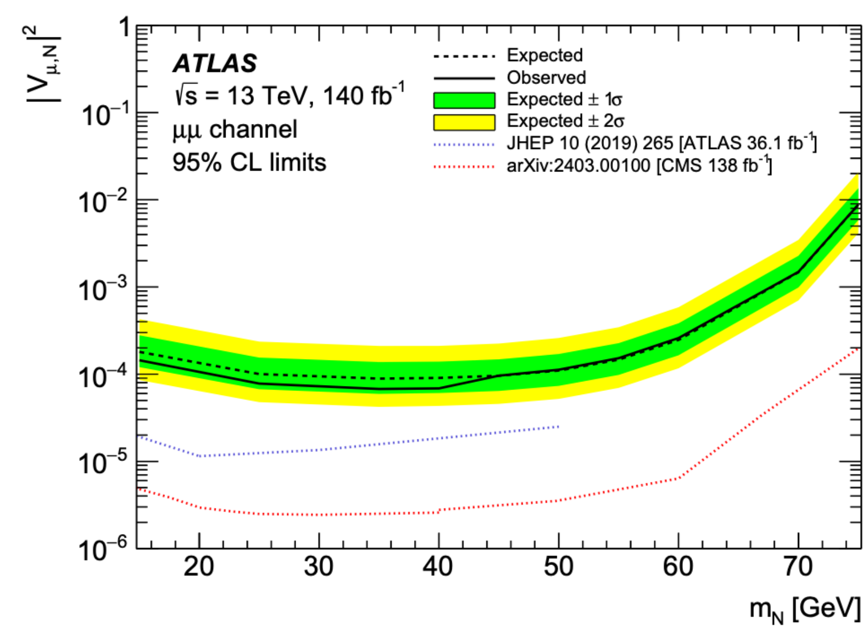
ATLAS ttbar analysis

2408.05000

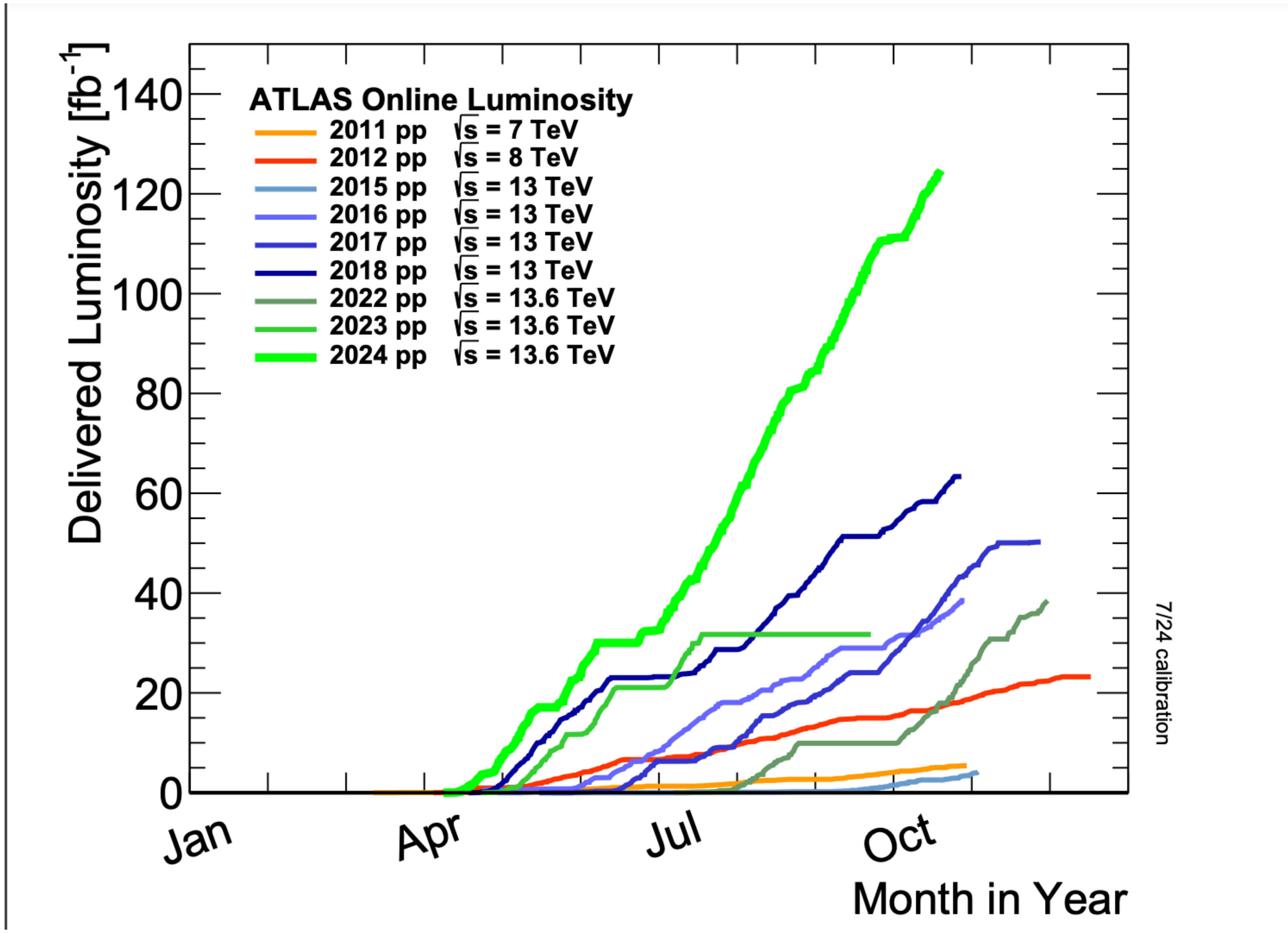








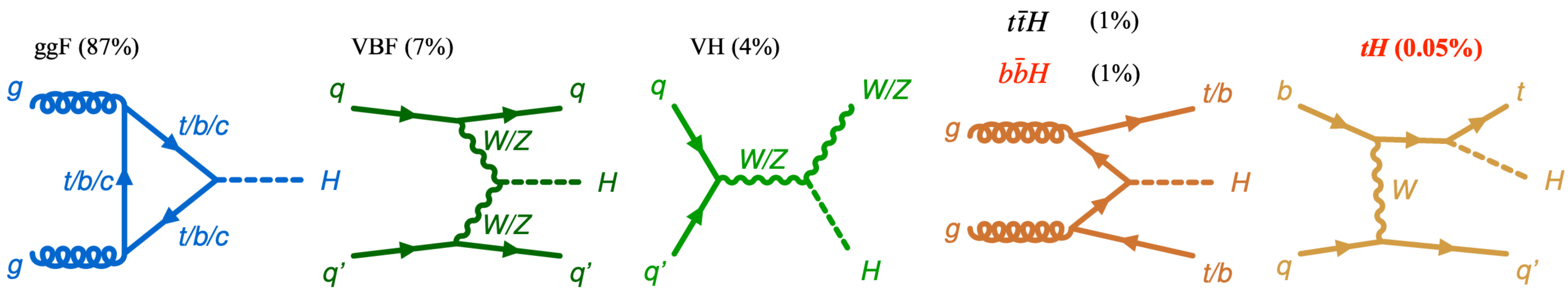
LHC delivery for 13.6 TeV an integrated luminosity of 195 fb^{-1}

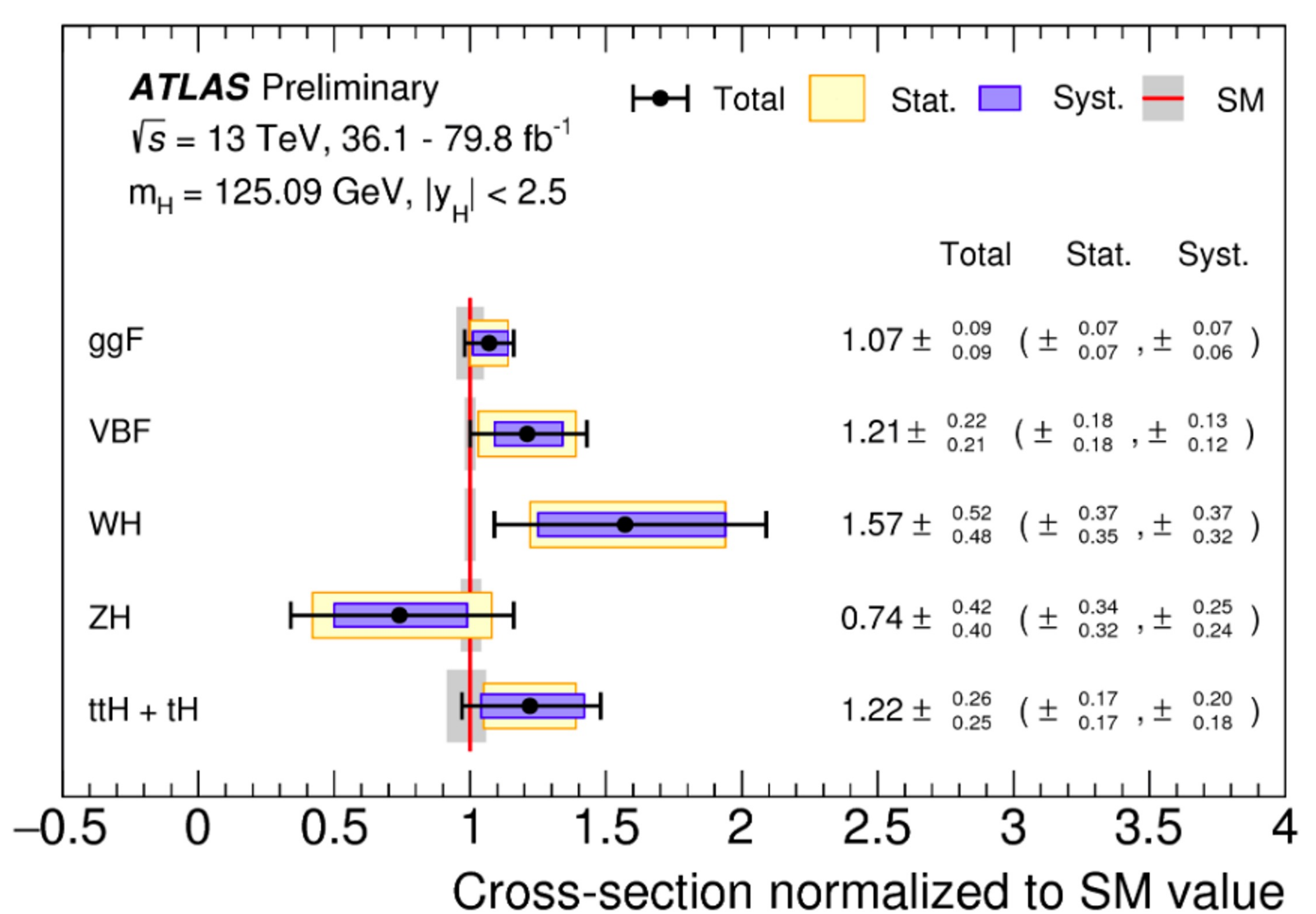


Still only about 10% of data that will be produced.

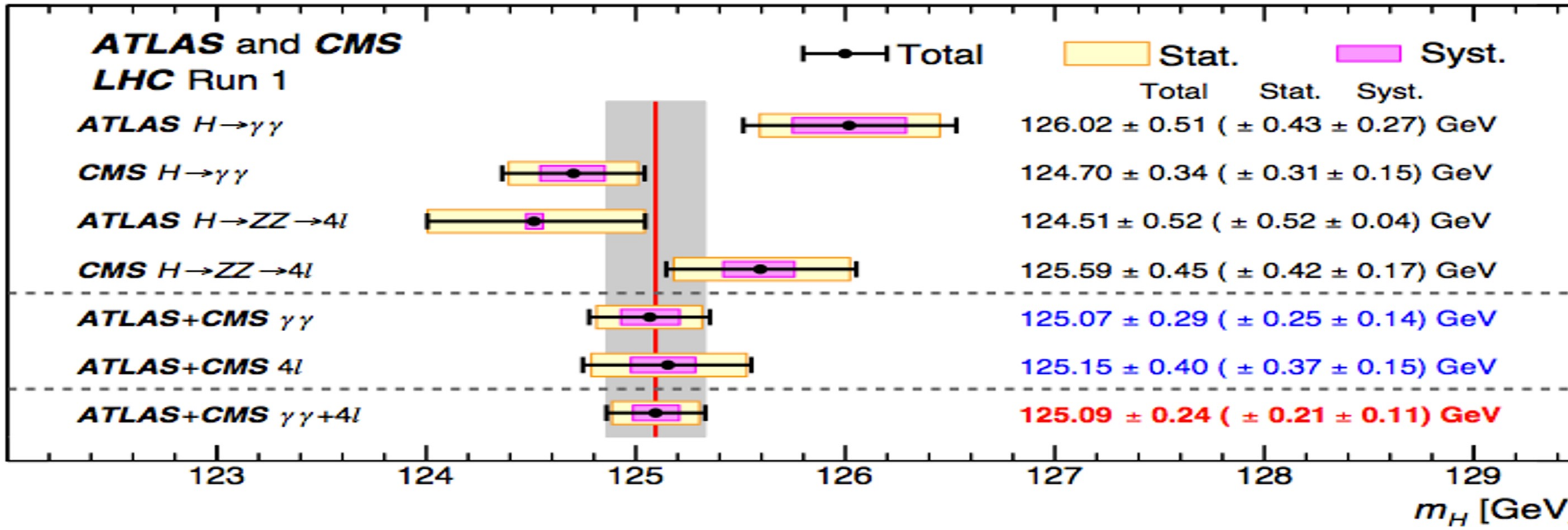
Key parameter is the integrated luminosity $N_{events} = \sigma \int L \, dt$

Higgs production





Mass measurement Run I



$$\hat{m}_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)\ \text{GeV}$$

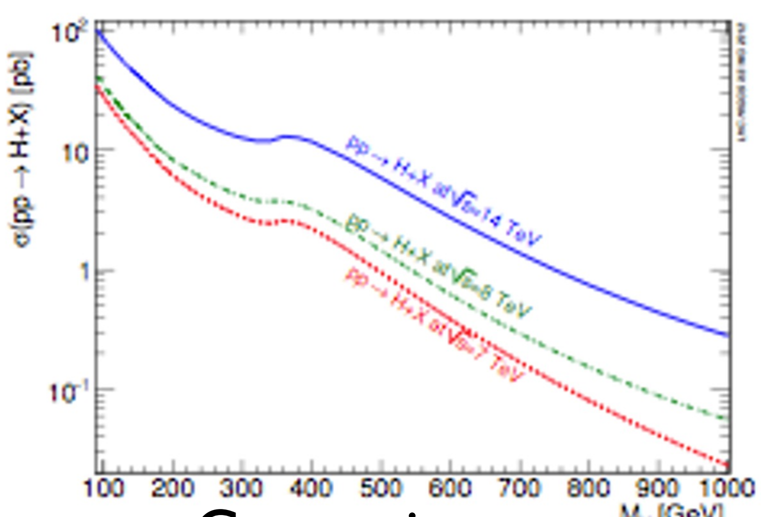
@ m_H = 125 Gev

$H \to WW$	22%
$H \to ZZ$	2.9%
$H \to bb$	58%
$H \to cc$	2.8%
$H \to \gamma\gamma$	0.23%
$H \to \gamma Z$	0.16%

Currently (PDG):
$m_H = (125.20 \pm 0.11)$ GeV
$m_t = (172.57 \pm 0.29)$ GeV

With known mass then everything is fixed

cross-section

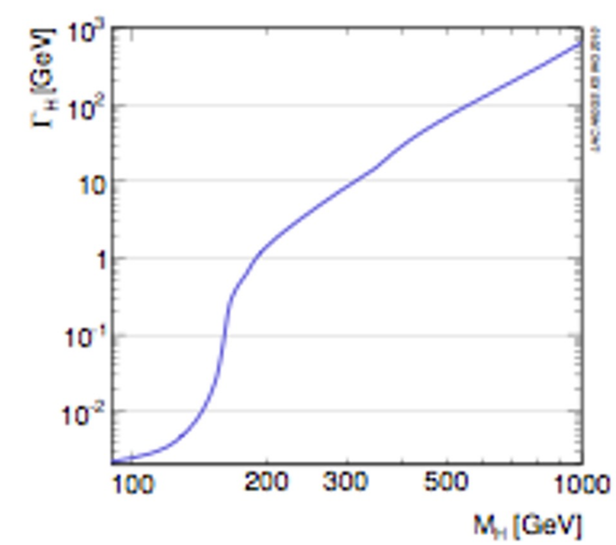


Constrain

B_{BSM}

ATLAS
$Br(h \to inv) < 10.7\%$

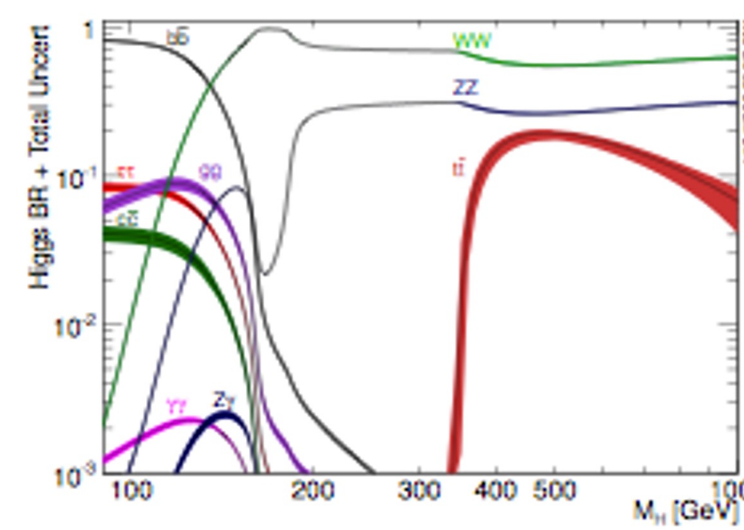
decay width



$\Gamma \approx 4.1$ MeV

ATLAS: 4.5 $^{+3.3}/_{-2.5}$ MeV,
CMS: 2.9 $^{+2.3}/_{-1.7}$ MeV

branching ratios

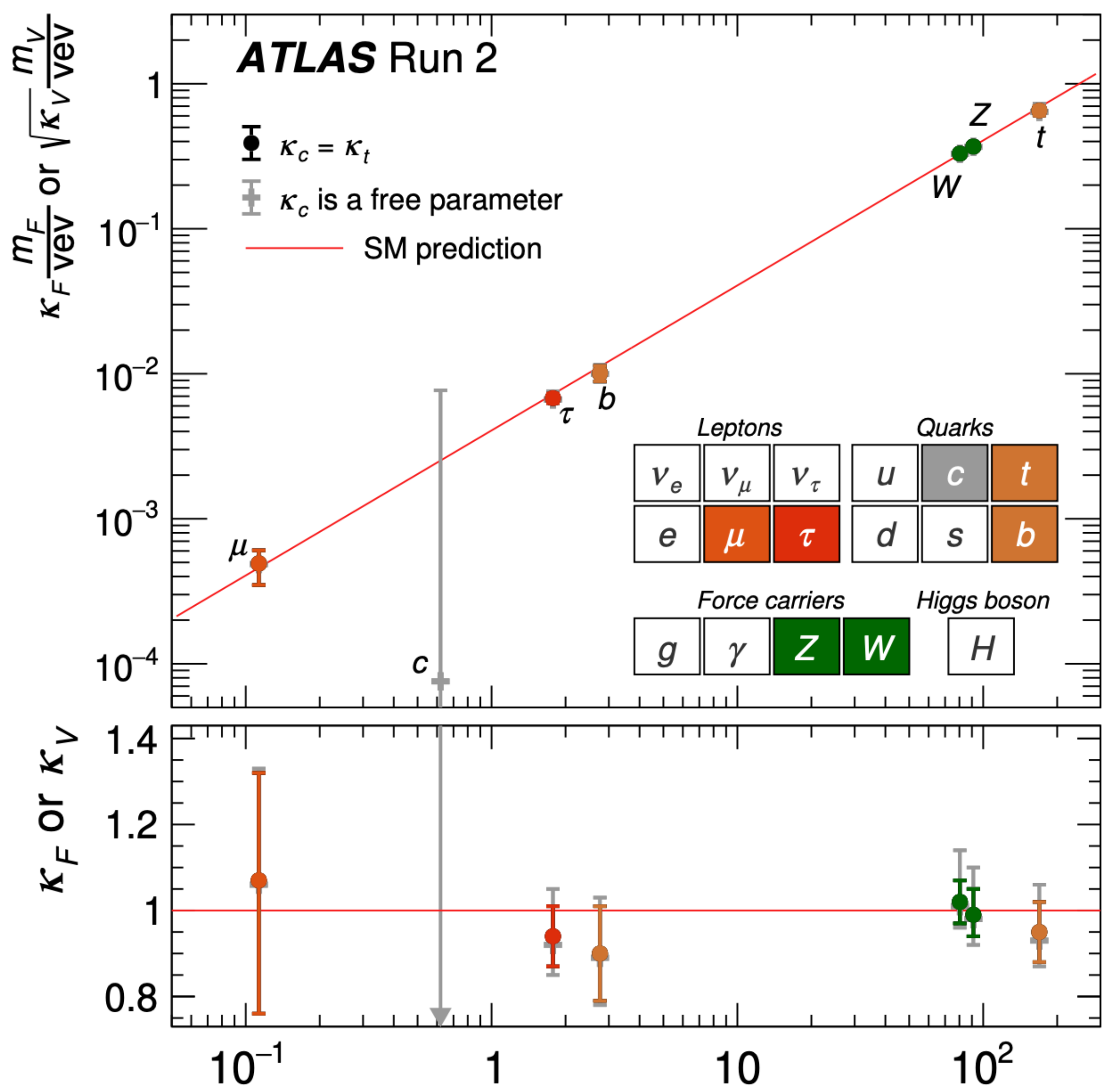


$\lambda = (m_H/v)^2 = 0.131$

$$\Gamma_h = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

Run II Probe Yukawa couplings

Cross section 4 X higher @ 13 TeV wrt 8 TeV



CERN-EP-2022-057

2018 : direct observation of top quark Yukawa

2020: evidence for muon Yukawa

2022:: hints of Higgs responsible for c-quark mass

Increasing precision way above expectation

Until now all consistent with the SM !!

Future Experiments and Colliders

HL-LHC
FCC-ee
FCC-hh
CEPC
CLIC

FASER/FASER-2

Codex-b

Mathusla

milliQan

NA62

SeaQuest

SHIP

DUNE-ND

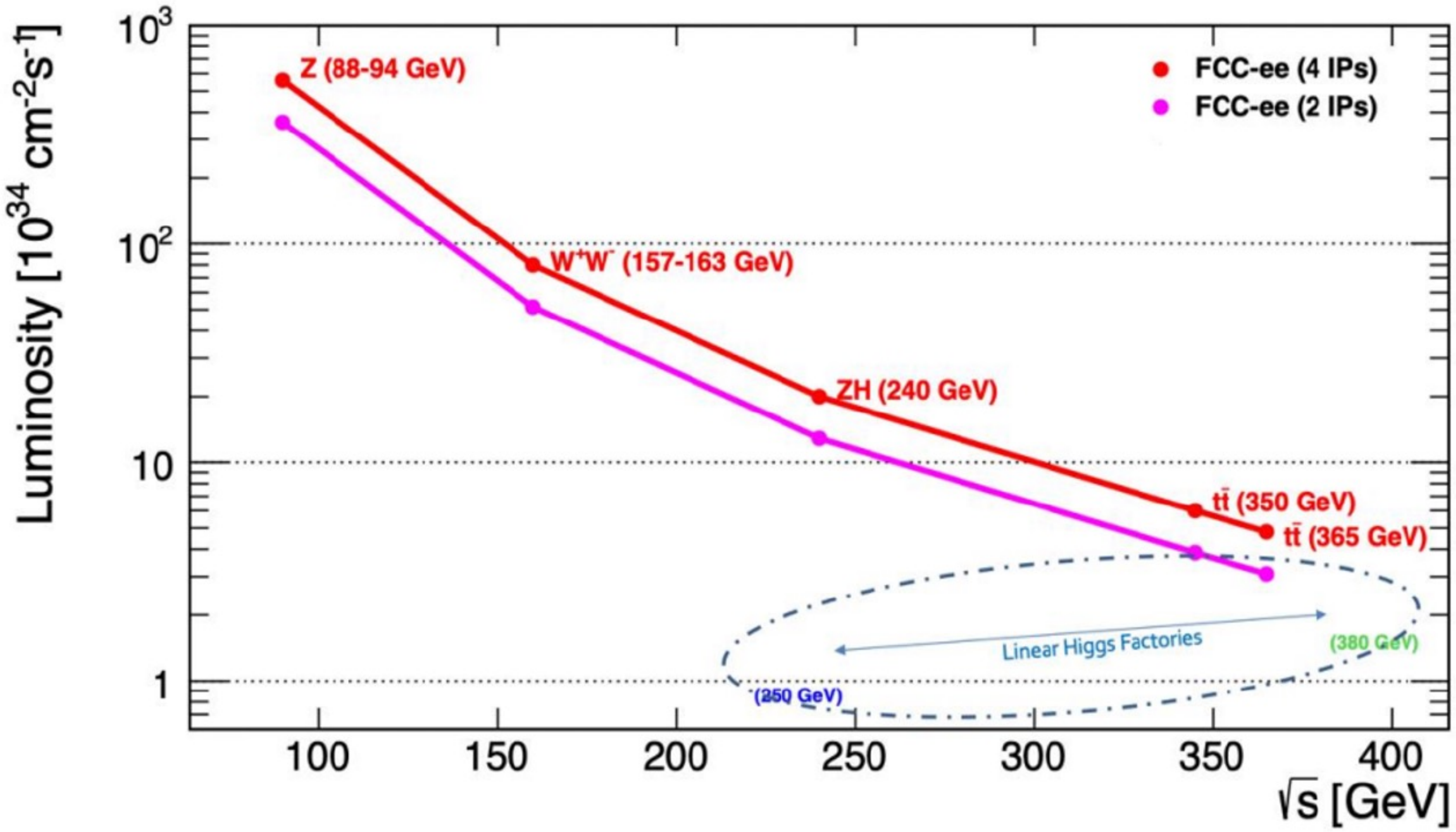
....

Mixing with **electrons**: NA62-dump, NA62 K+ decays, FASER, PIONEER, SHADOWS, DarkQuest, SHiP, DUNE, T2K, Hyper-K

Mixing with **muons**: NA62-dump, NA62 K+ decays, FASER, DarkQuest, SHADOWS, PIONEER, SHiP, DUNE, Hyper-K

Mixing with **taus**: NA62-dump, FASER, SHADOWS, DUNE, DarkQuest, and SHiP

FCC



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW $\rightarrow$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\rightarrow$ H	

https://indico.cern.ch/event/1307378/contributions/5720989/attachments/2789031/4879011/Grojean.pdf

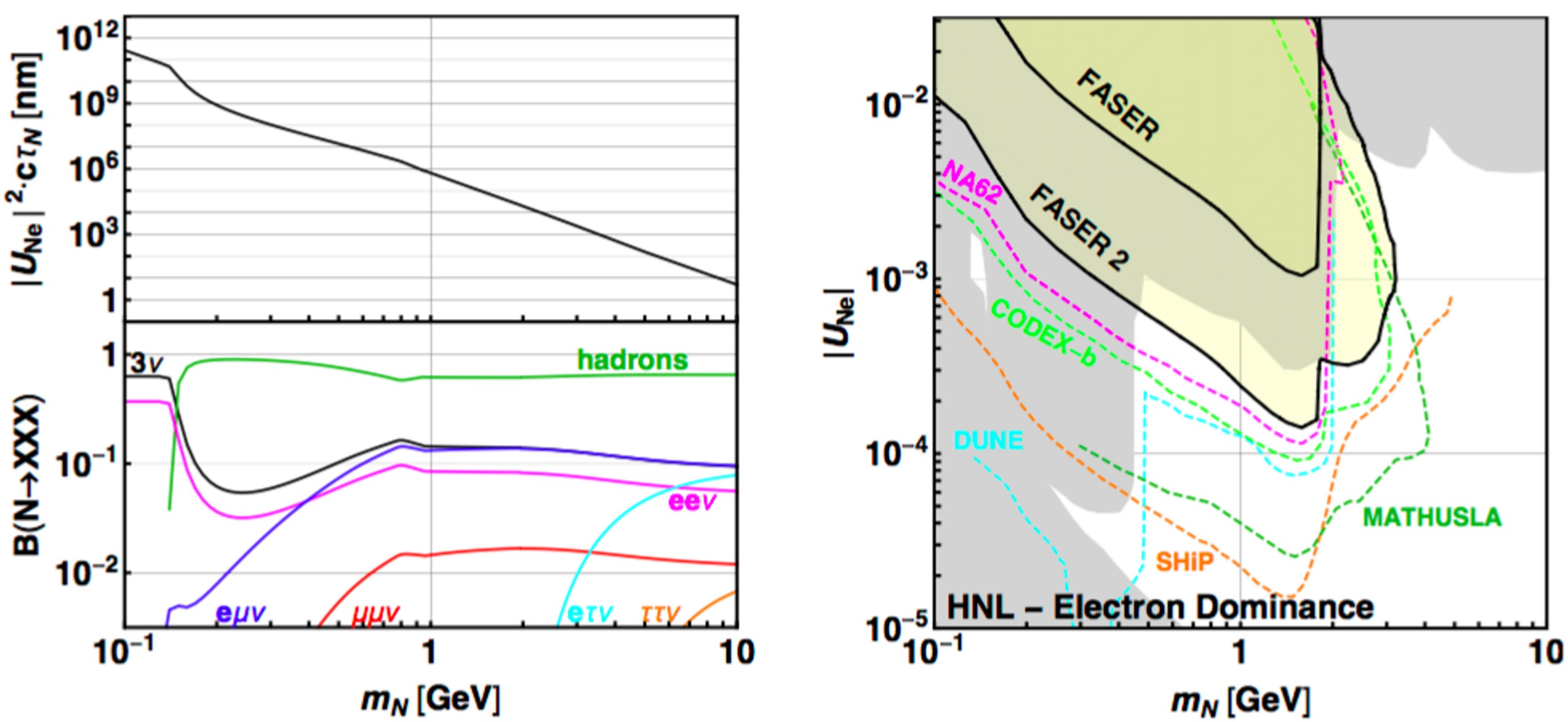
FASER/FASER2

Inelastic cross section producing for 150 fb^{-1}

$$N_{\pi^0} \approx 2.3 \times 10^{17}, \quad N_\eta \approx 2.5 \times 10^{16}, \quad N_D \approx 1.1 \times 10^{15}, \quad \text{and} \quad N_B \approx 7.1 \times 10^{13}$$

FASER-2

Larger detector for total integrated luminosity of 3 ab^{-1}



Higgs decays in Type I

For L = 3000 fb^{-1}
~ 10^{11} W will be produced
~ 10^{8} H will be produced

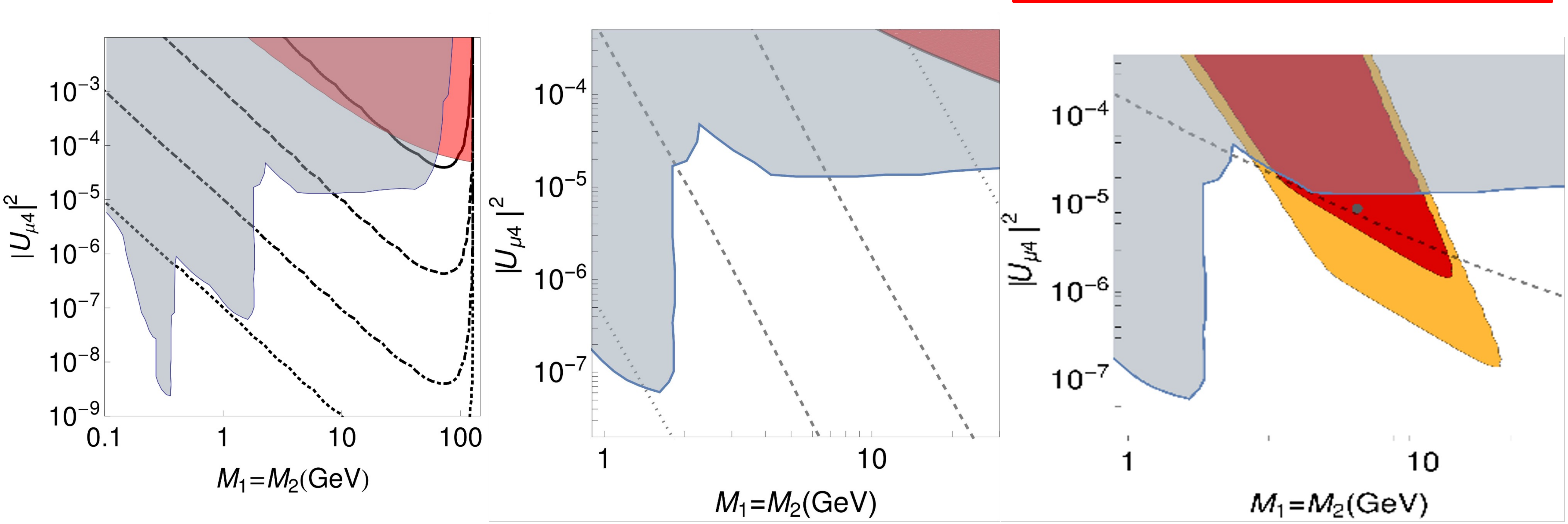
Consider ggF production mode, only 2 HNL

Directly test seesaw :
From Higgs production and decay explore heavy neutrinos with large lifetimes, which lead to a displaced vertex with leptonic and semi-leptonic decays

250 events with 300 fb^{-1}

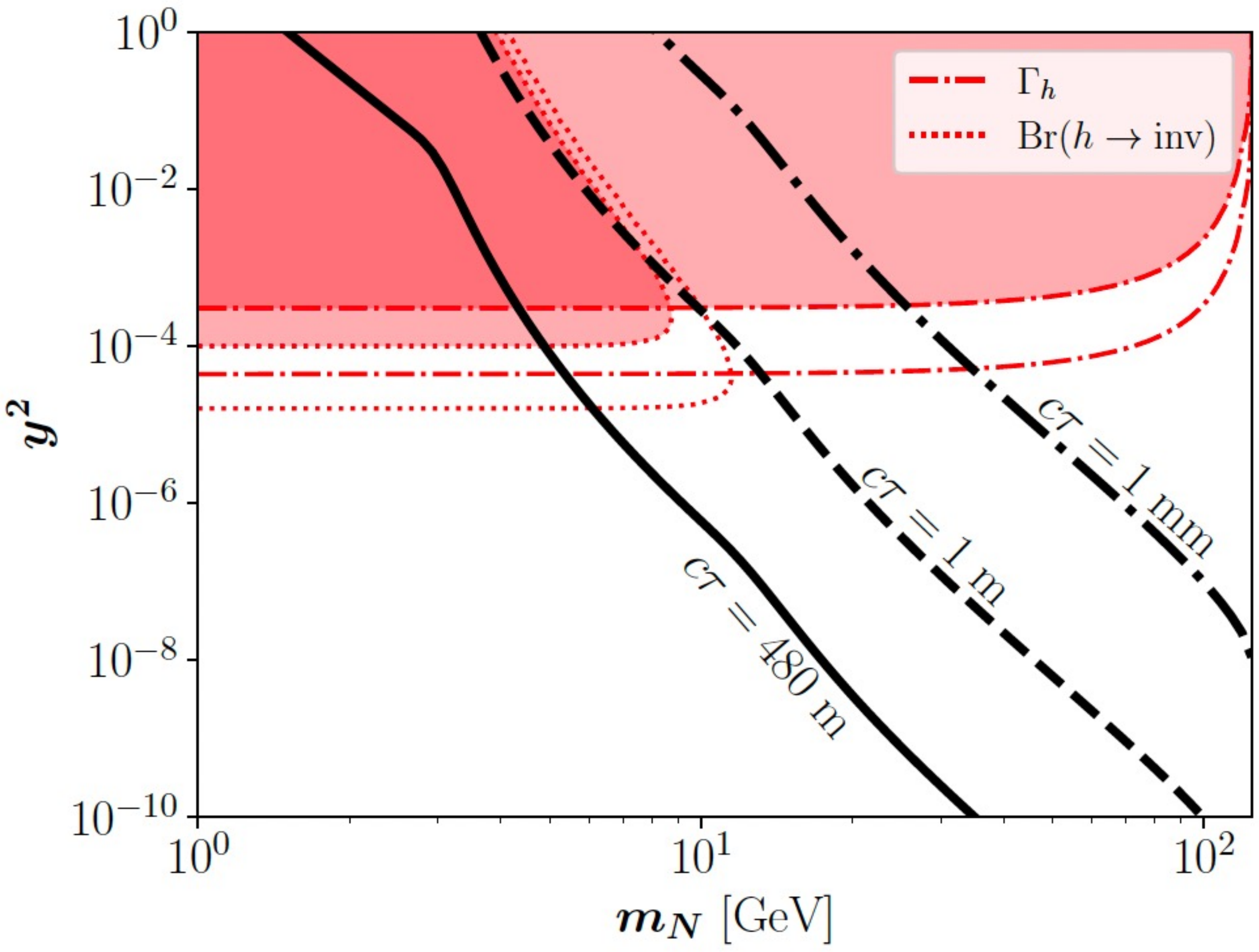
w/o cuts

Gago, Jones, Hernández, Losada, Moreno



Higgs Decays: Only Yukawa coupling: Lifetime + BR

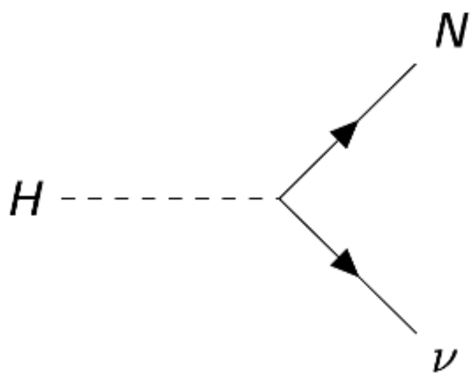
Take mixing to zero. Only have the Yukawa coupling, what are the experimental constraints and sensitivity?

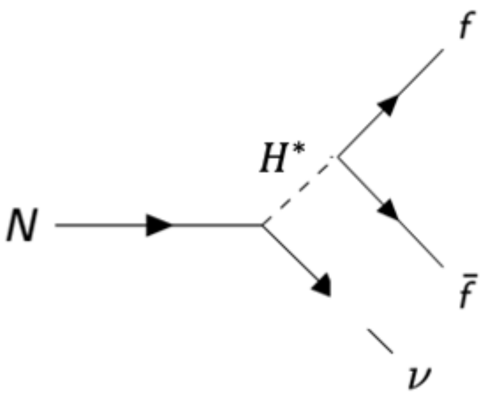


Bernal, Deka, Losada 2023

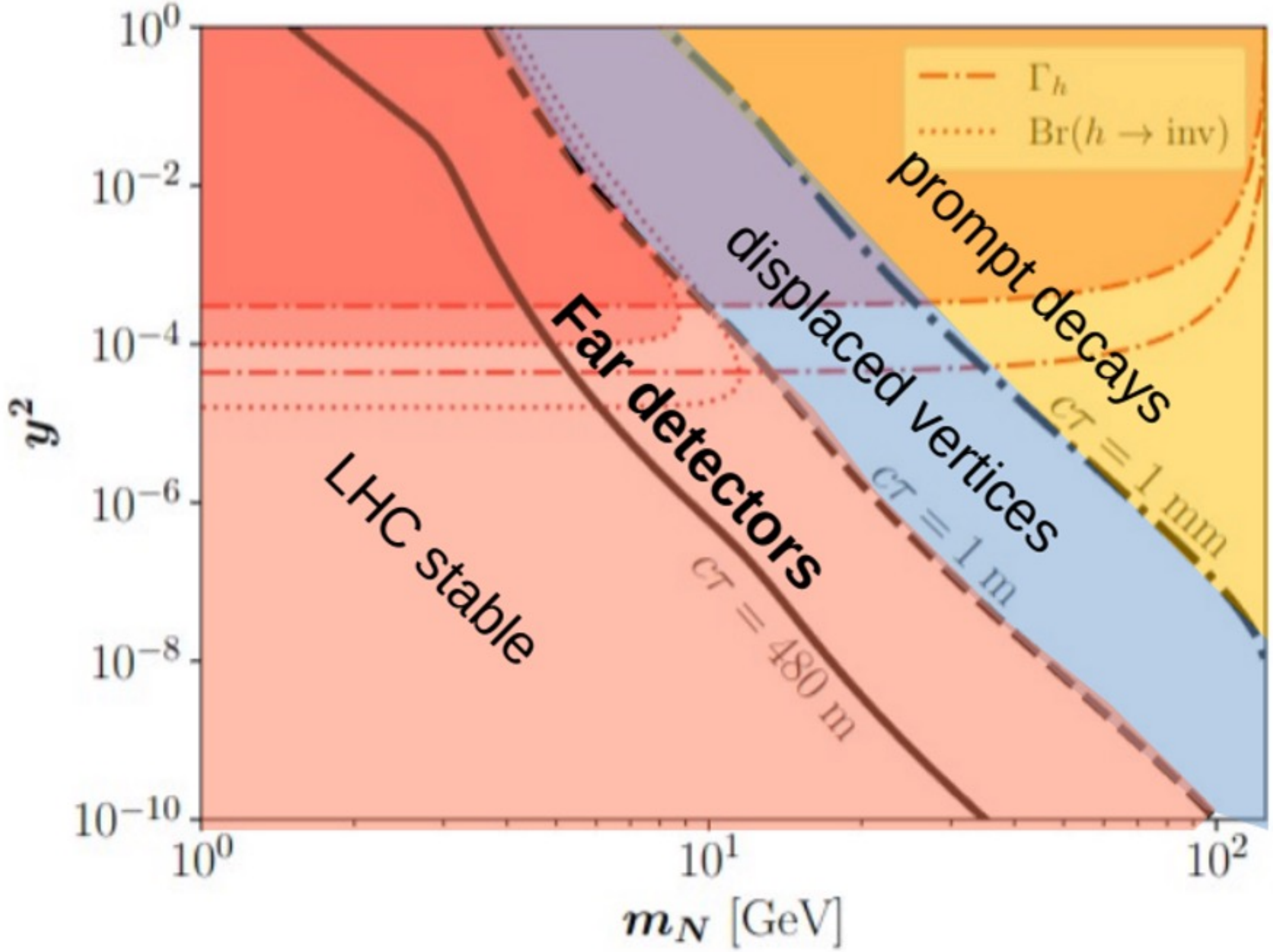
HNL Production through Higgs decays

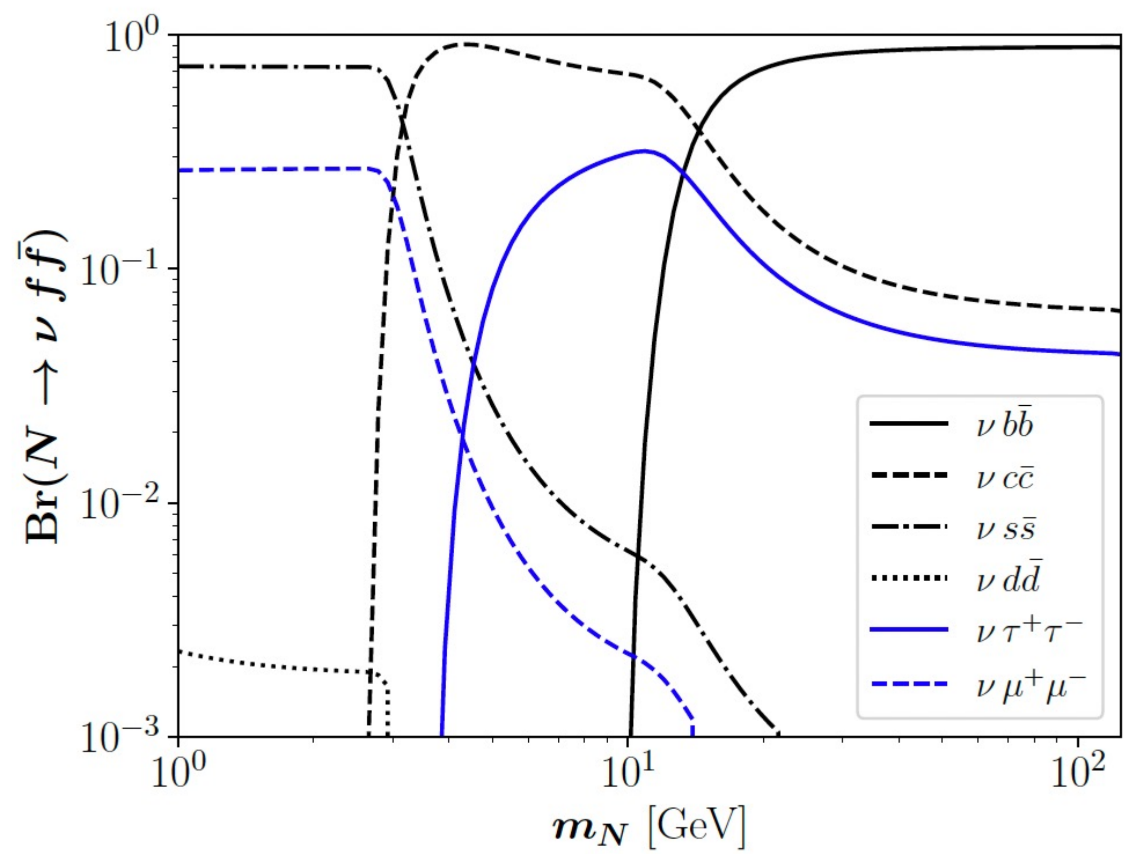
$$\Gamma(h \to N\nu) = \frac{y^2}{8\pi} m_h \left[1 - \left(\frac{m_N}{m_h}\right)^2\right]^2$$





Zero mixing: Lifetime+ BR



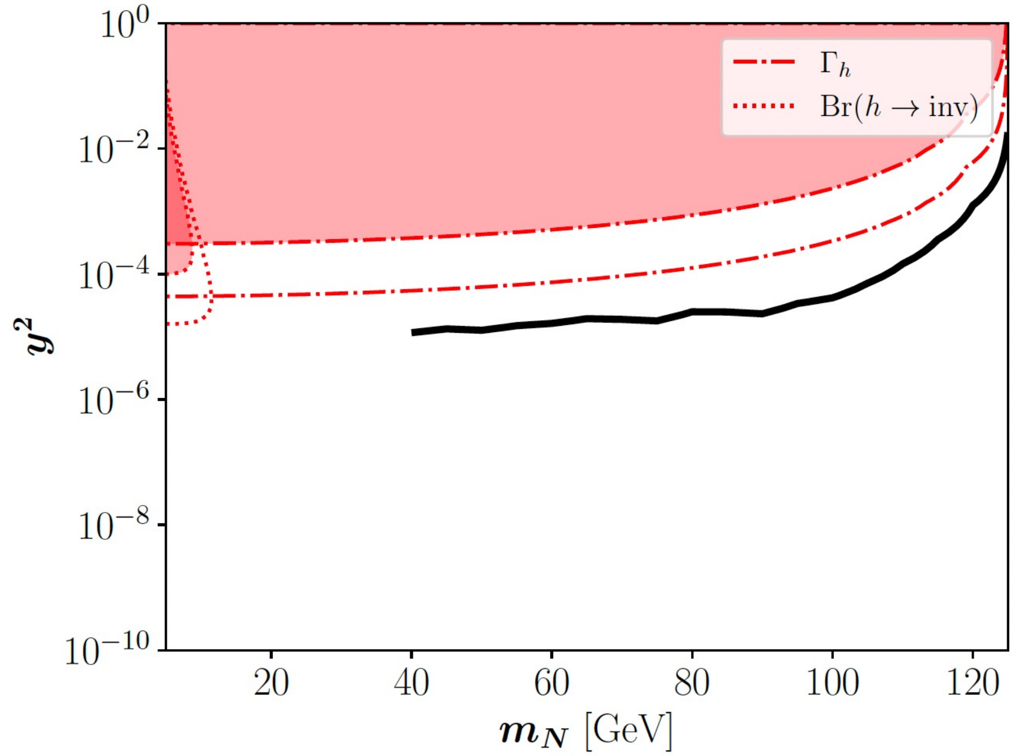


$$\Gamma(N \to \nu f \bar{f}) \propto y^2 \frac{m_f^2 m_N^5}{m_h^6}$$

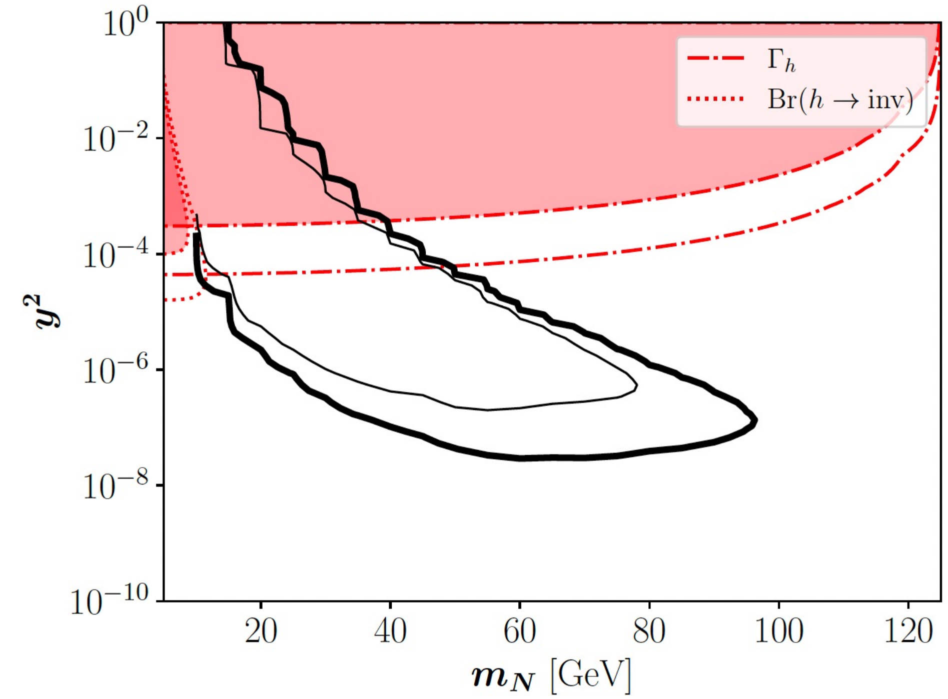
HL-LHC Results – no mixing

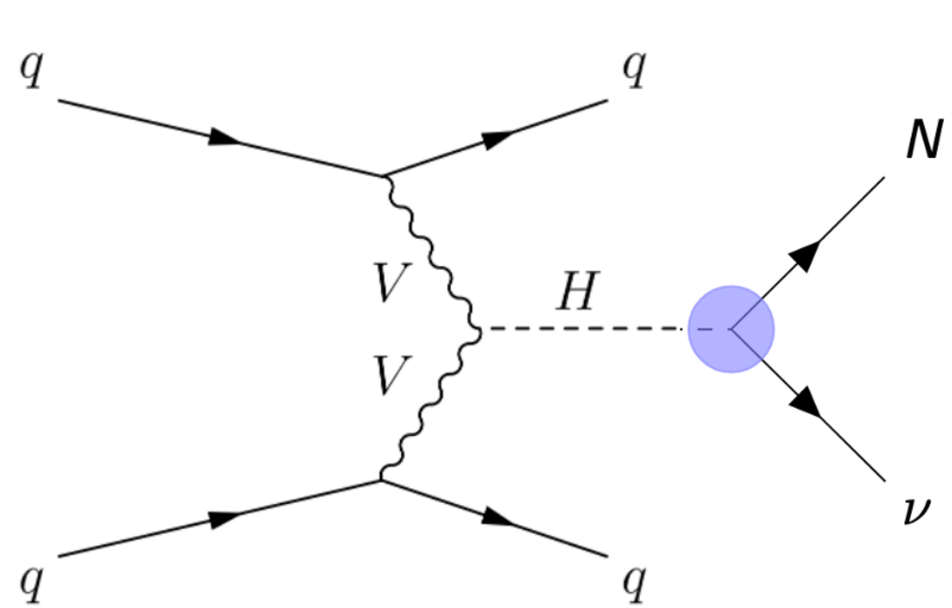
$\sqrt{s} = 14$ TeV and $\mathcal{L} = 3$ ab^{-1}

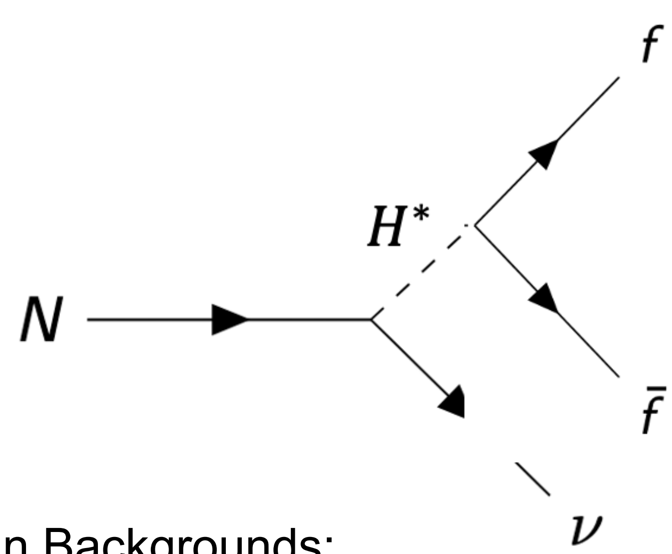
Prompt



Displaced in ATLAS/CMS detector





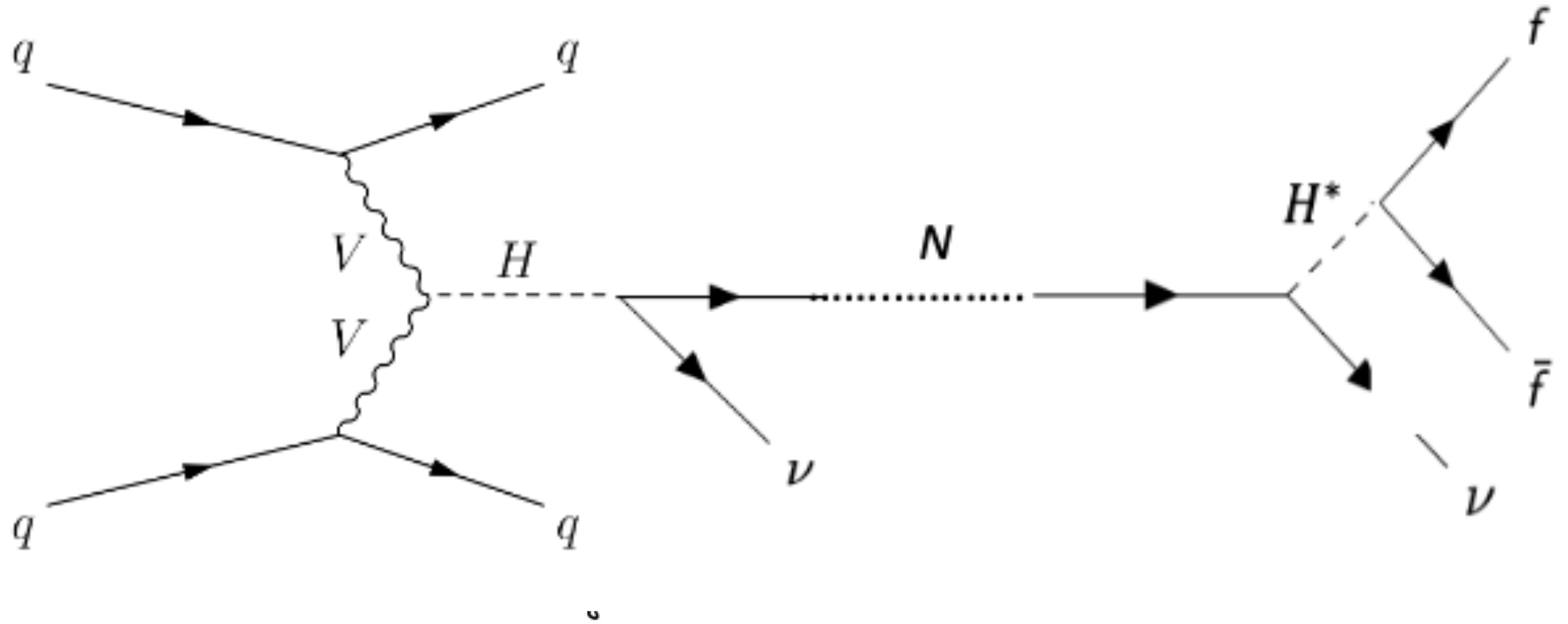


b-quark pair + MET

Main Backgrounds:

h → bb, tt + jets, and bb + jets

vLLP Results – no mixing

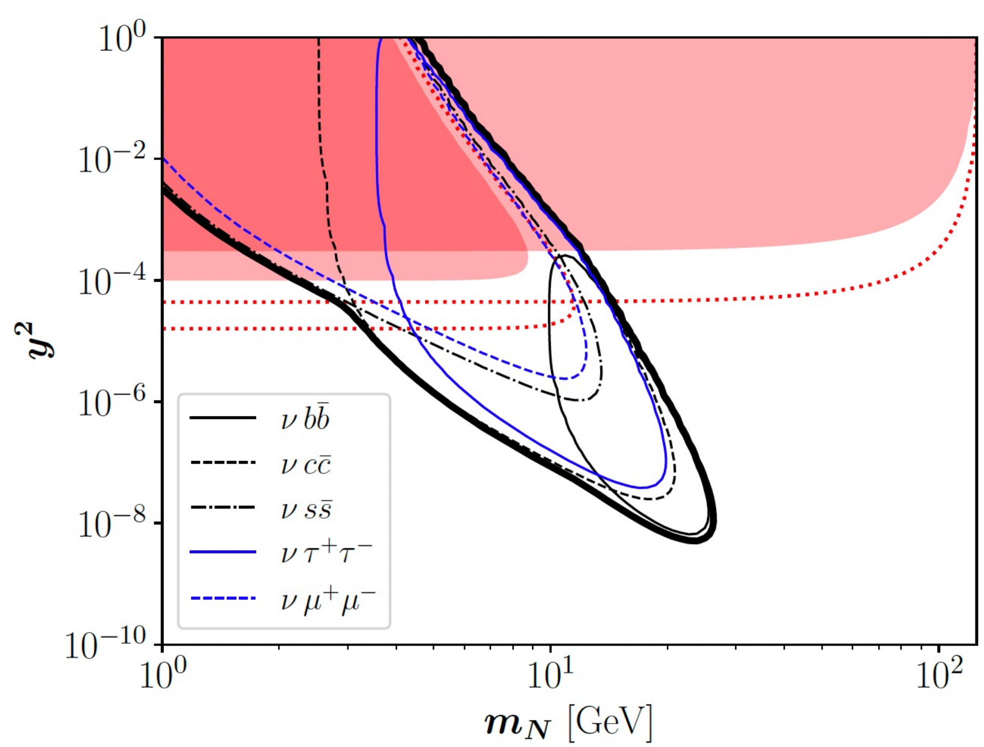


FASER-2 $\Delta = 10\text{ m},\ R = 1\text{ m}$

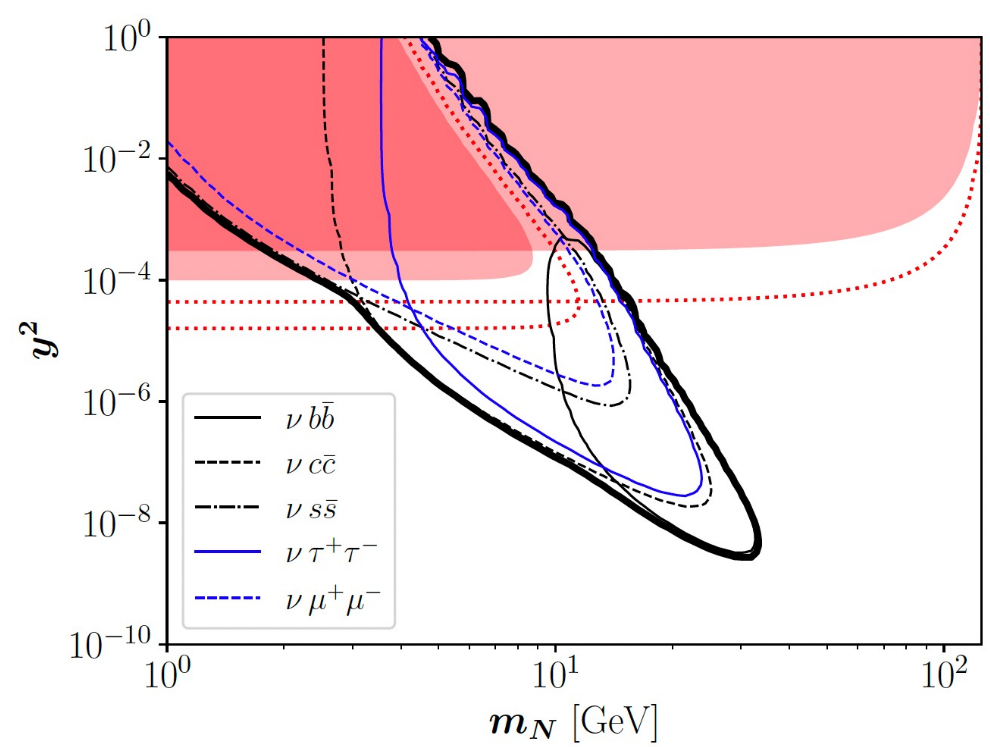
Probability of HNL decay inside the detector

$$\mathcal{P} = \left[e^{-(L-\Delta)/d} - e^{-L/d}\right]\,\Theta\left[R - L\,\tan\theta\right]$$

$$d = c\tau\,\beta\,\gamma = c\tau\,\frac{|\vec{p}|}{m_N}$$

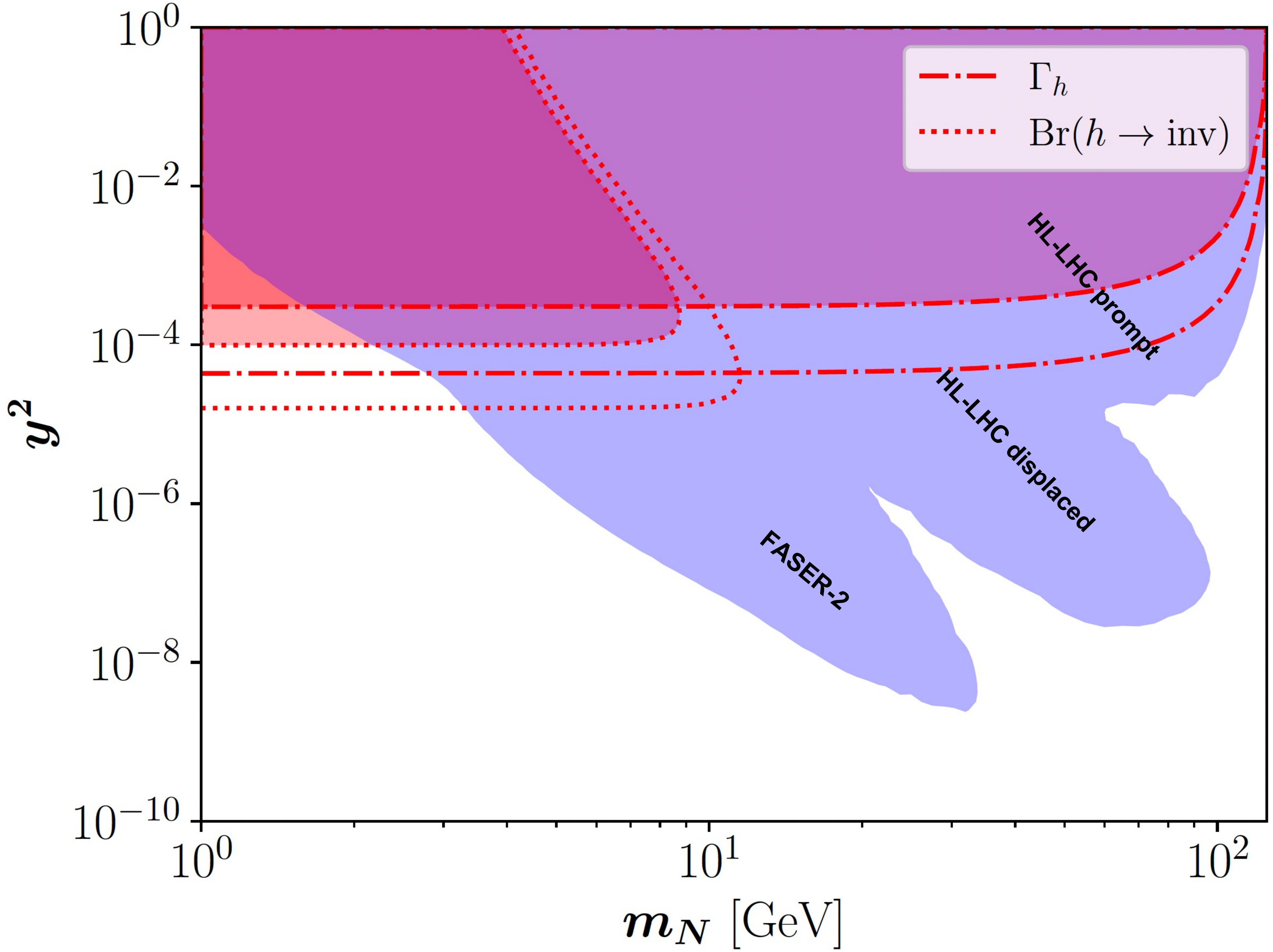


FASER-2



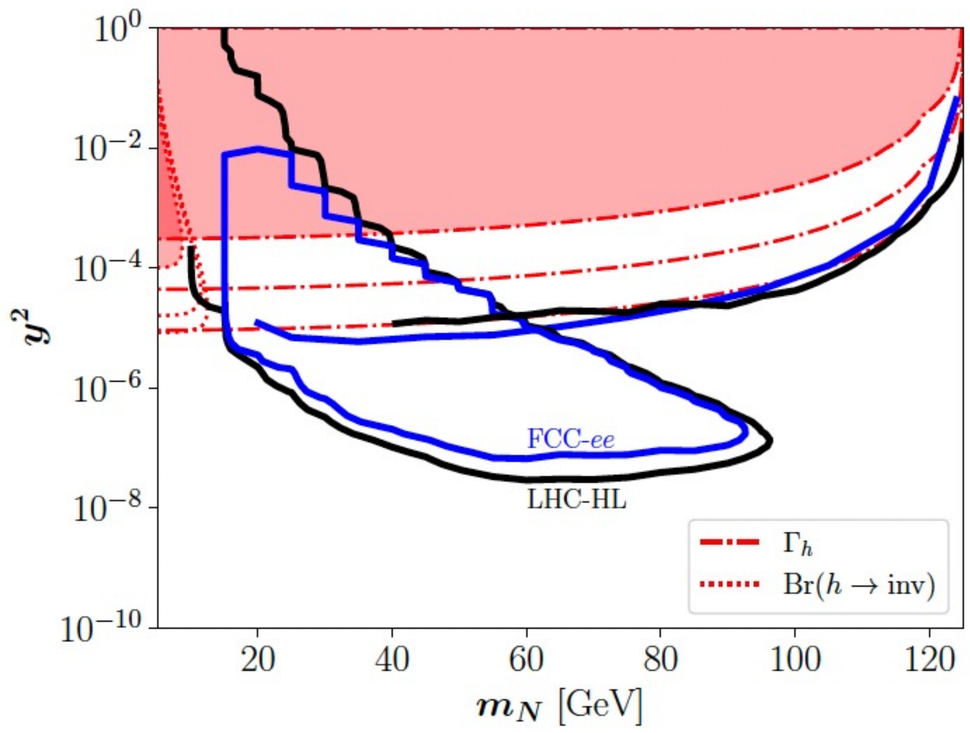
MATHUSLA

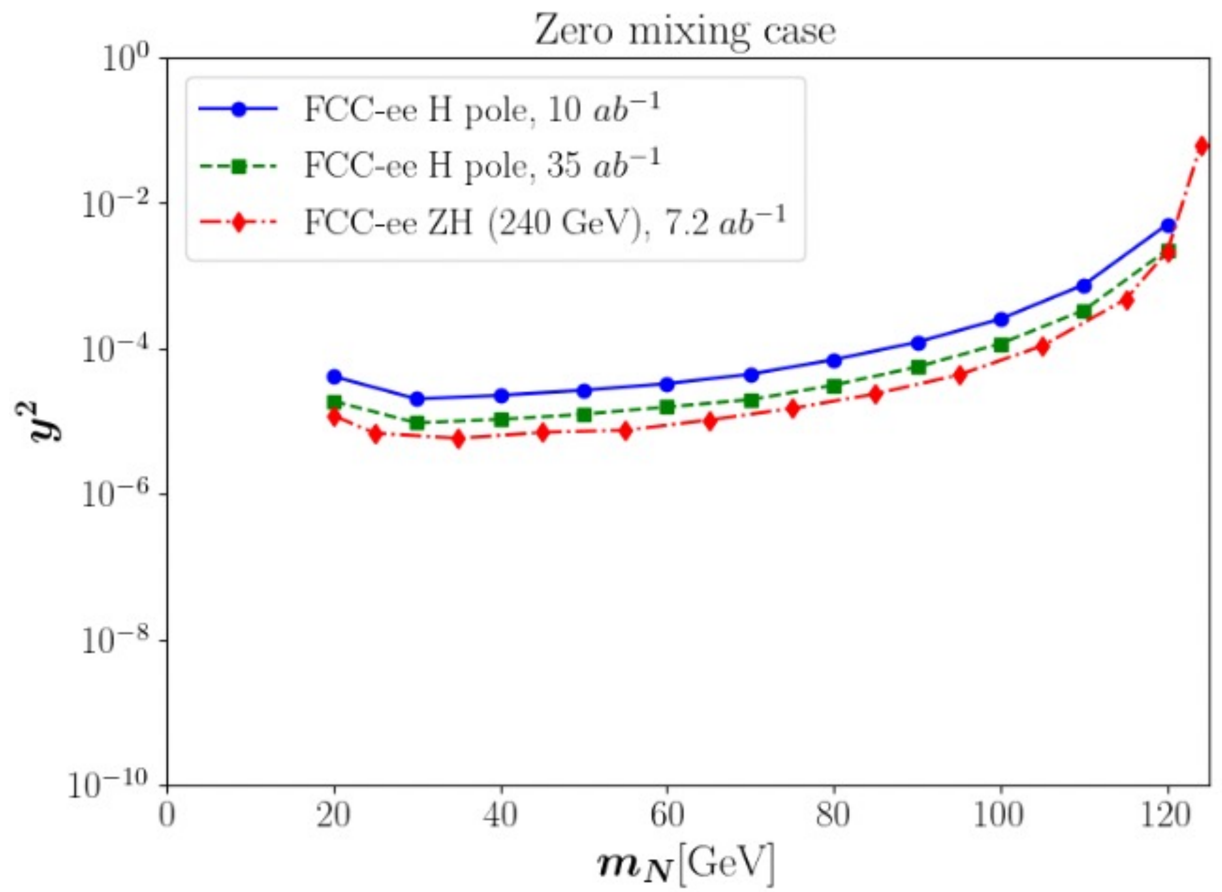
LHC Sensitivity – no mixing



HL-LHC and FCC-ee with no mixing

$$\sqrt{s} = 240 \text{ GeV}, \mathcal{L} = 7.2 \text{ ab}^{-1}.$$

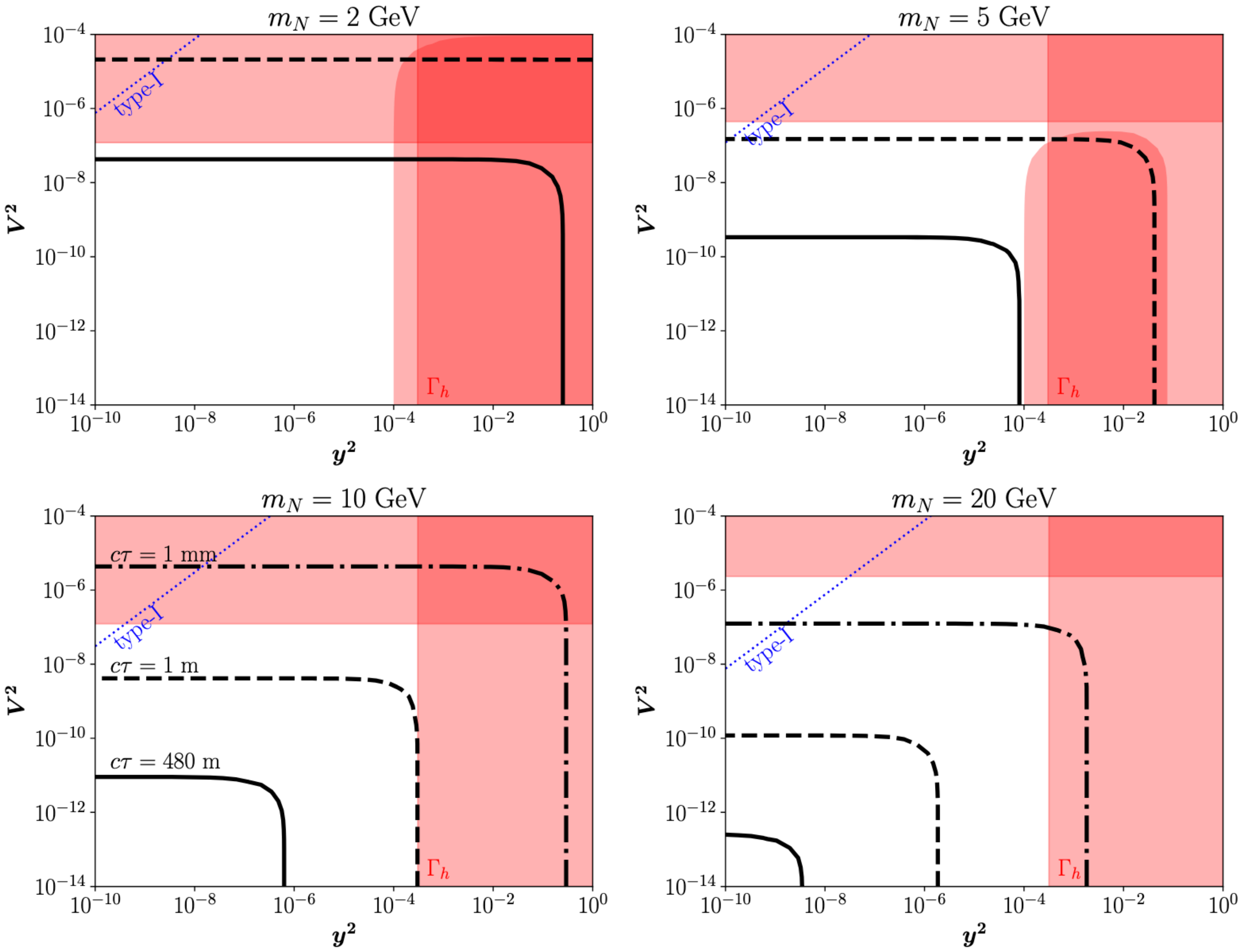




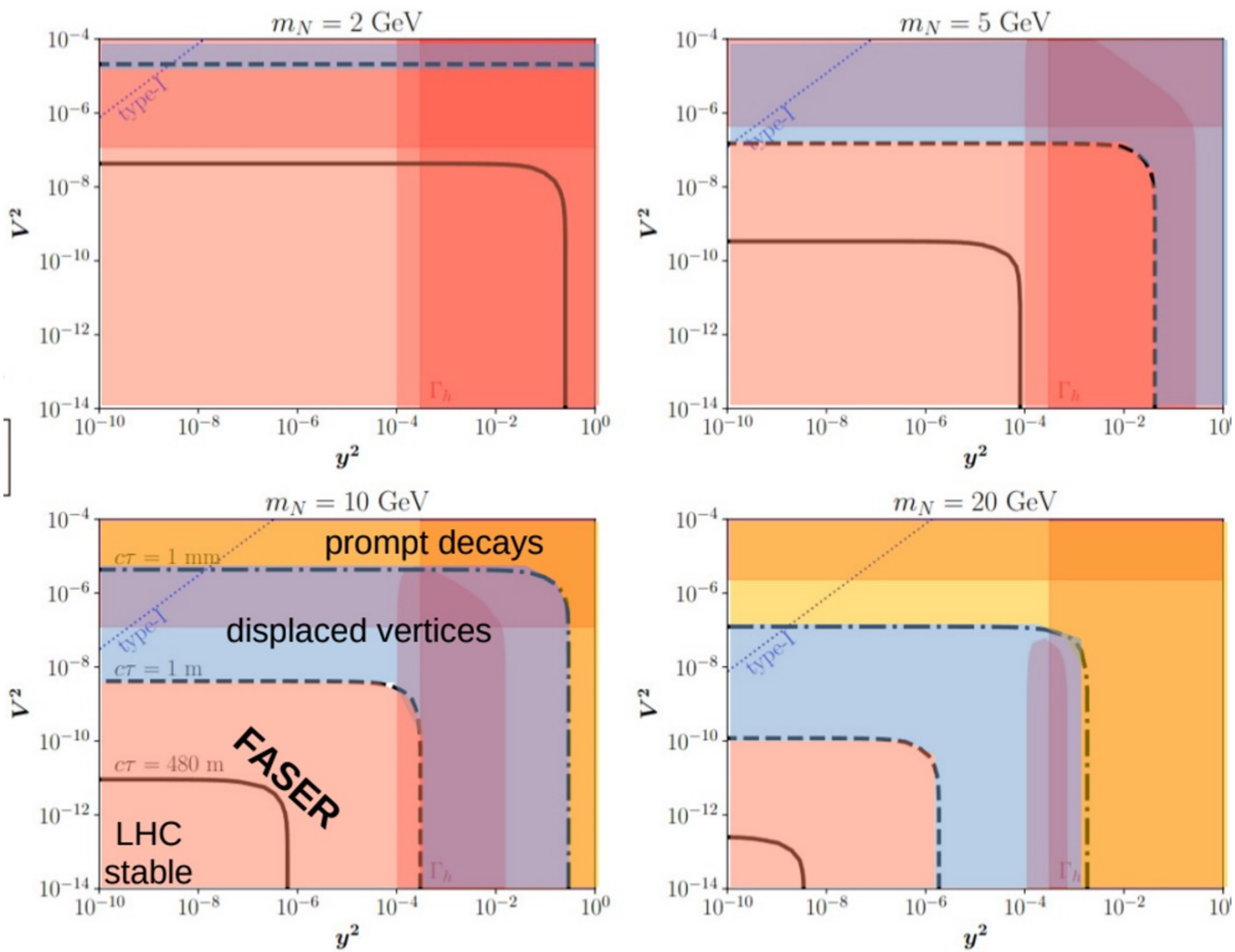
No major improvement in sensitivity with FCC-ee in this case.

No major improvement on H pole

Yukawa + Non-zero mixing: Lifetimes



Yukawas + Non-zero mixing: Lifetimes

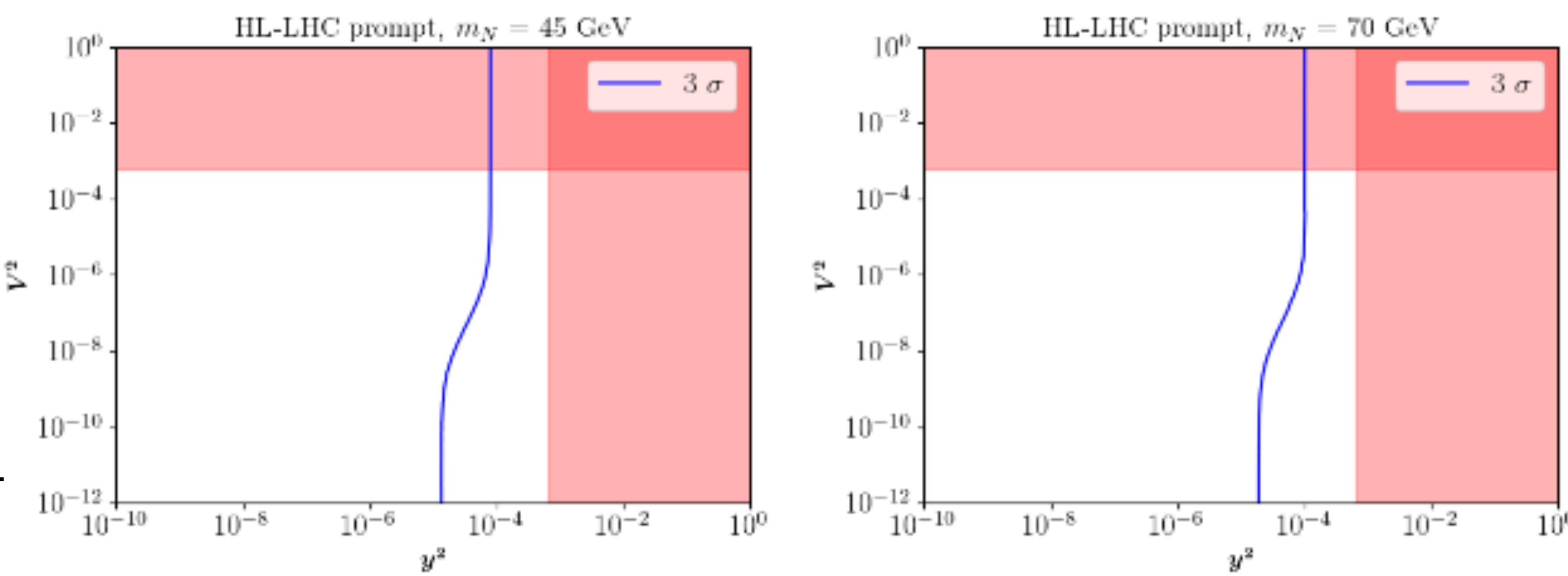


HL-LHC results with active-sterile mixing

$\sqrt{s} = 14$ TeV and $\mathcal{L} = 3$ ab^{-1}

Prompt

VBF



Again use VBF topology
for HNL via Higgs decay

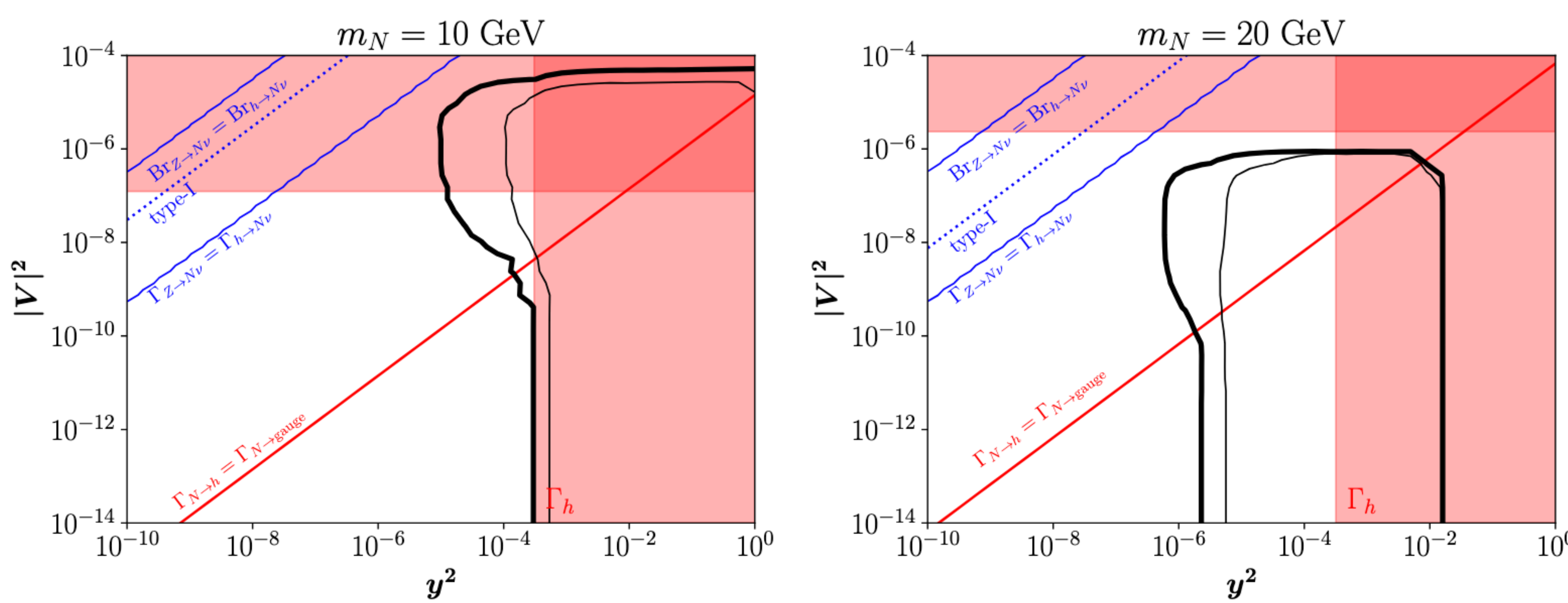
Final state: b-quark pair + MET

Main Backgrounds:

$h \to bb$, tt + jets, and bb + jets

Displaced vertex

ggF+VBF



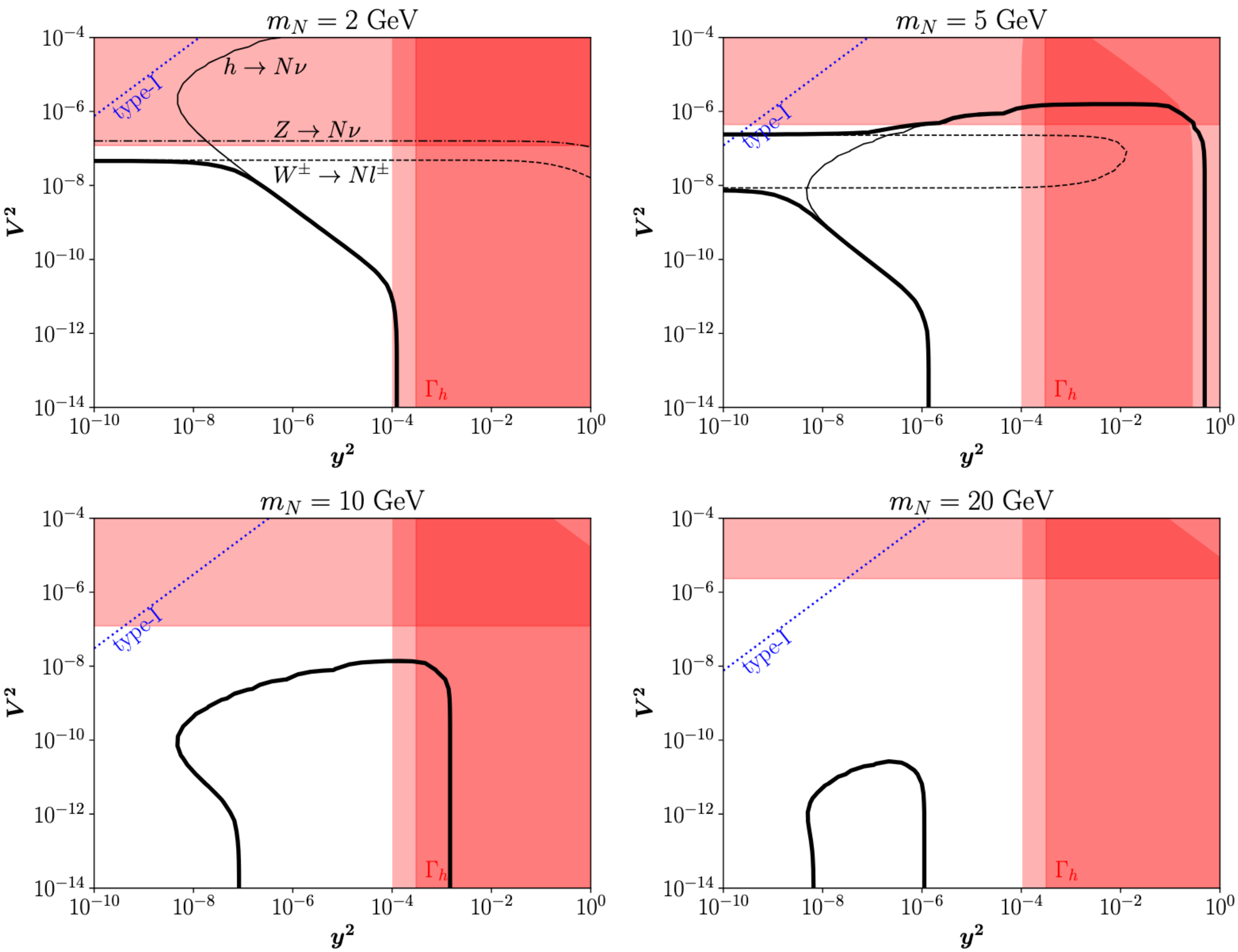
FASER

FASER-2 $\Delta = 10$ m, $R = 1$ m

Probability of HNL decay inside the detector

$$\mathcal{P} = \left[e^{-(L-\Delta)/d} - e^{-L/d}\right] \Theta\left[R - L\,\tan\theta\right]$$

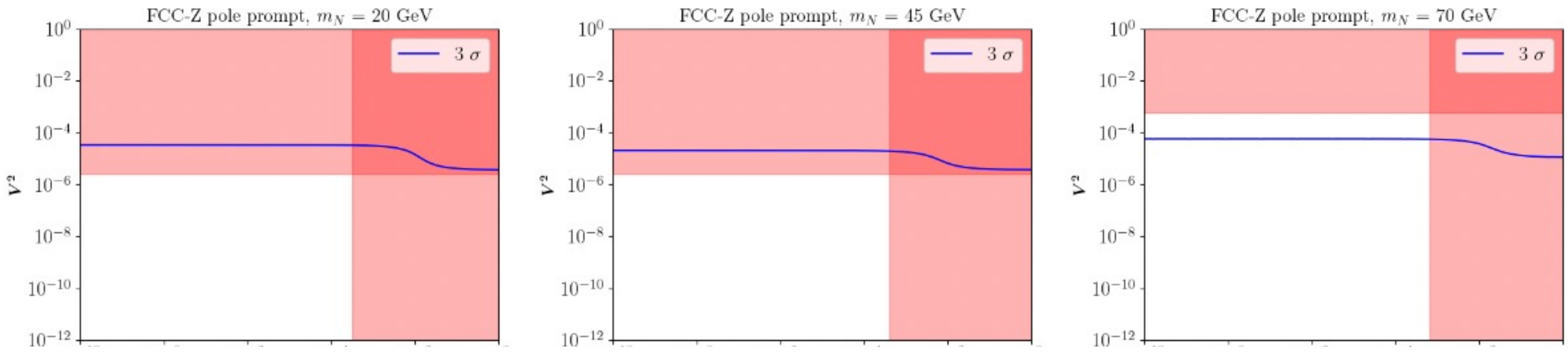
$$d = c\tau\,\beta\,\gamma = c\tau\,\frac{|\vec{p}|}{m_N}$$



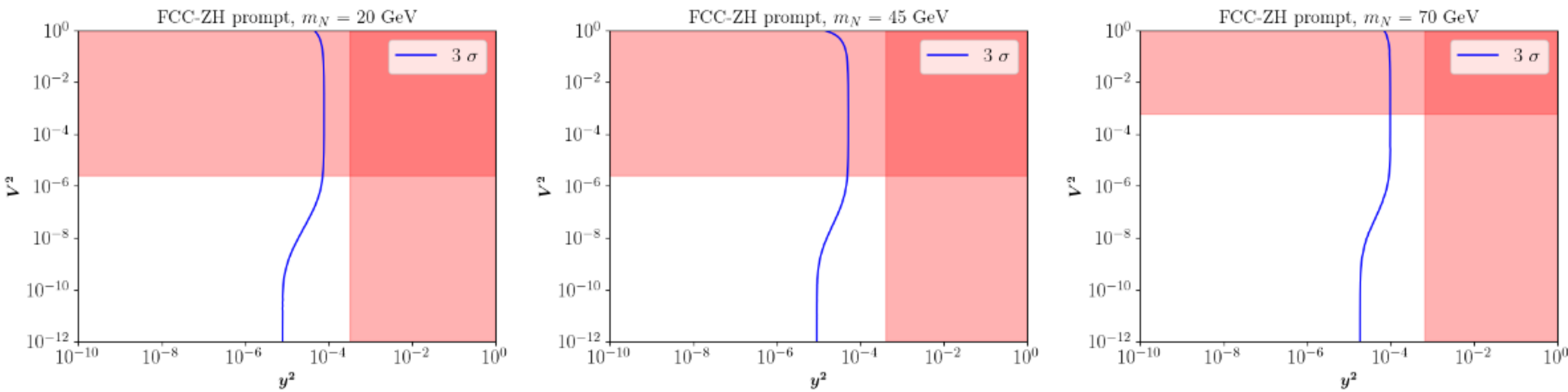
FCC with active-sterile mixing: prompt

Z pole $\mathcal{L} = 204 \text{ ab}^{-1}$

$$\Gamma(Z \to N\nu) = \frac{e^2 V^2}{96\pi c_W^2 s_W^2} m_Z \left[2 - 3\left(\frac{m_N}{m_Z}\right)^2 + \left(\frac{m_N}{m_Z}\right)^6\right]$$



ZH production

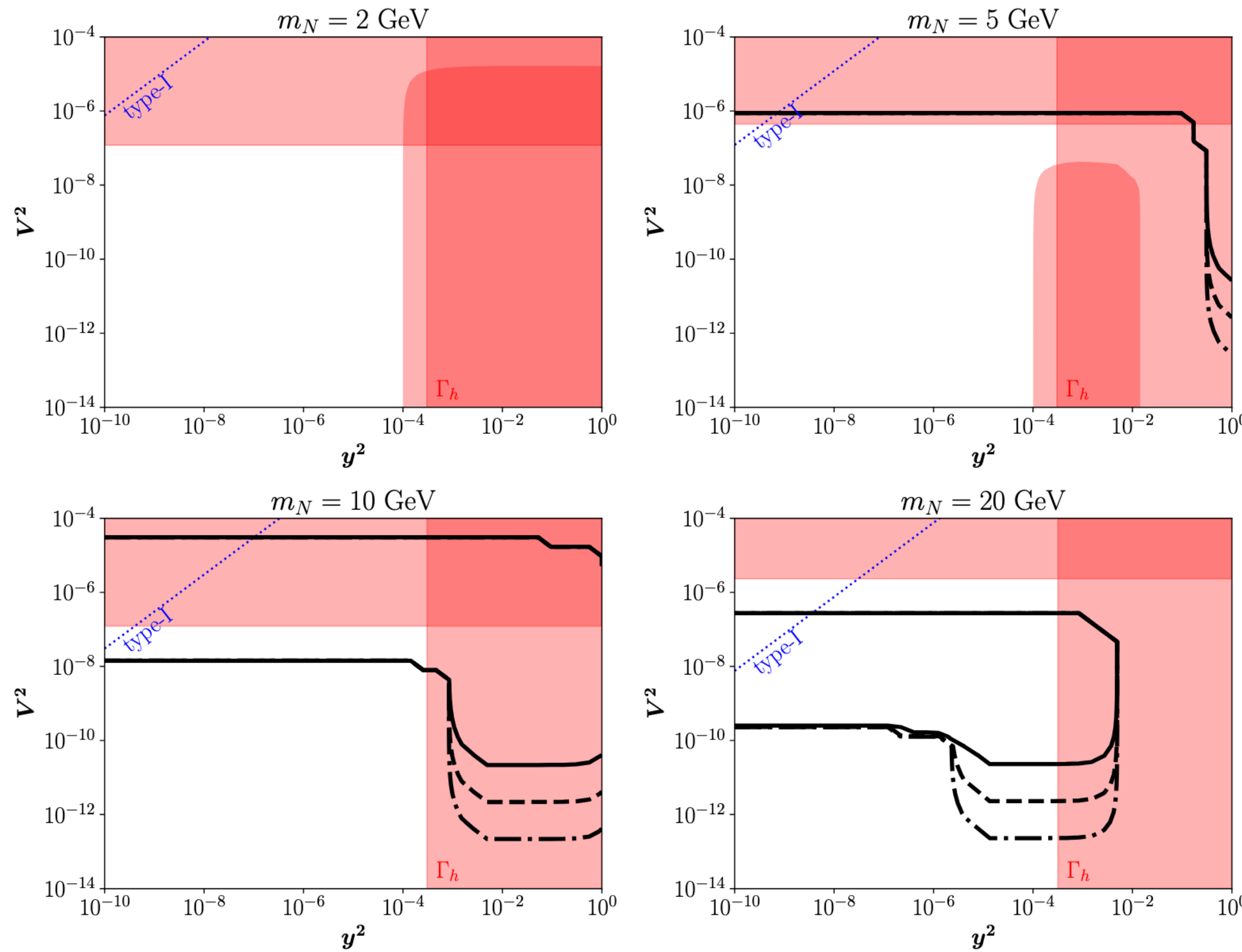


$\sqrt{s} = 240$ GeV and $\mathcal{L} = 2.4 \text{ ab}^{-1}$ per year, for 3 years: total integrated luminosity $\mathcal{L} = 7.2 \text{ ab}^{-1}$. $\sigma(e^+e^- \to Zh) = 0.2403$ pb.

FCC results with active-sterile mixing

Z pole

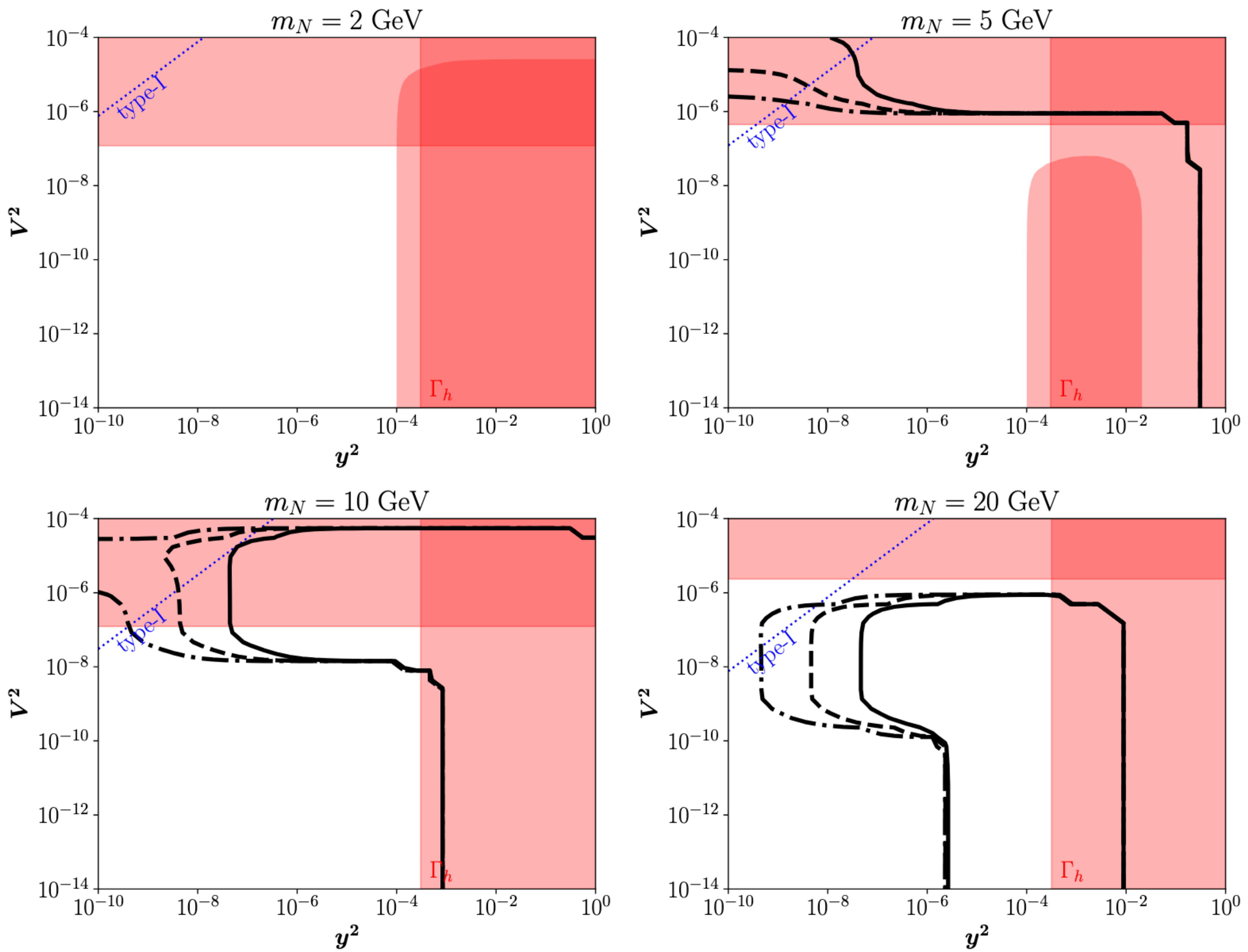
Displaced vertex



FCC results with active-sterile mixing

Combined Z+H @ 240 GeV center of mass energy

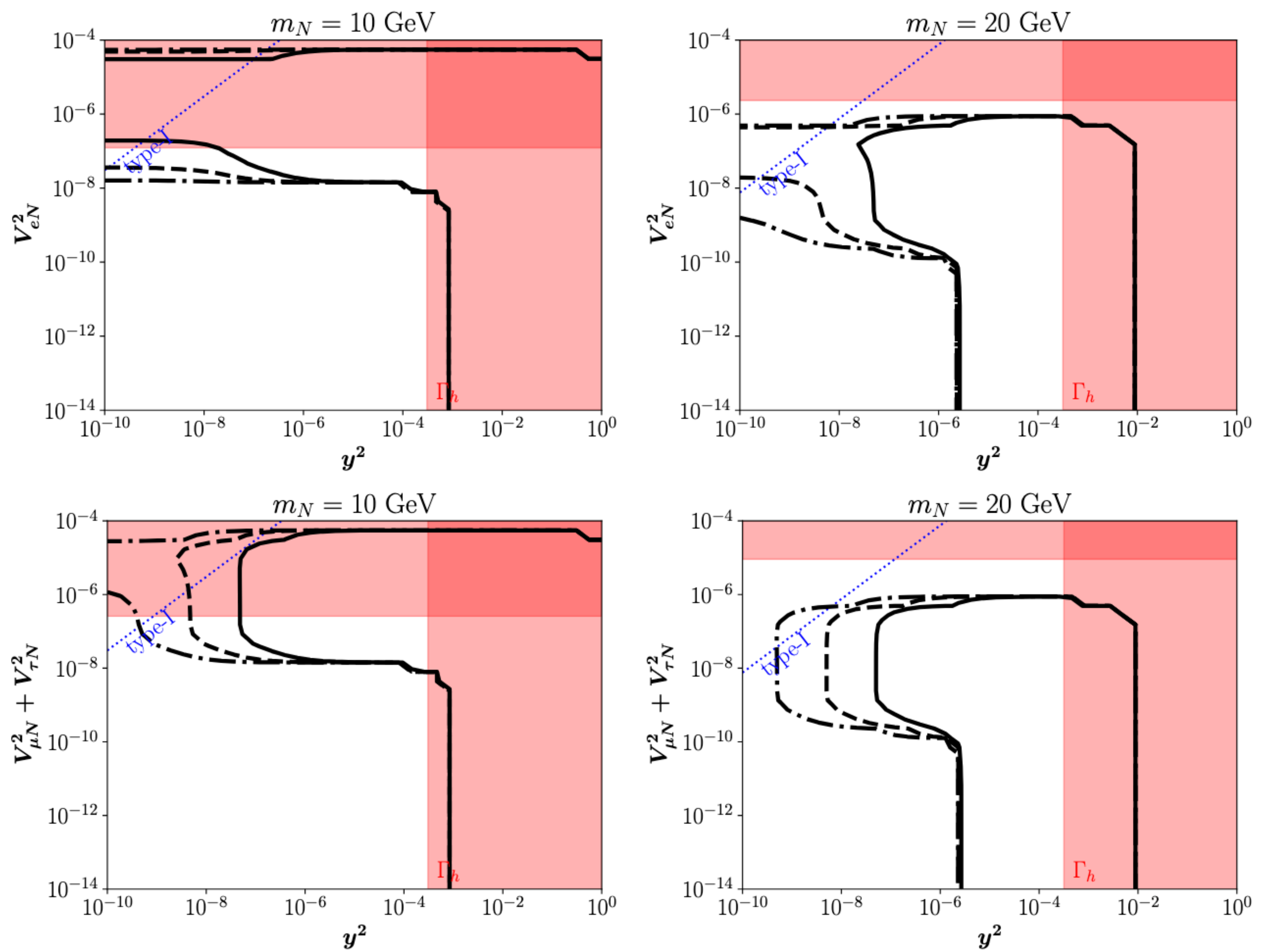
Displaced vertex



FCC-ee with active-sterile mixing

Addition of t channel W exchange,
Gives enhancement for the electron channel

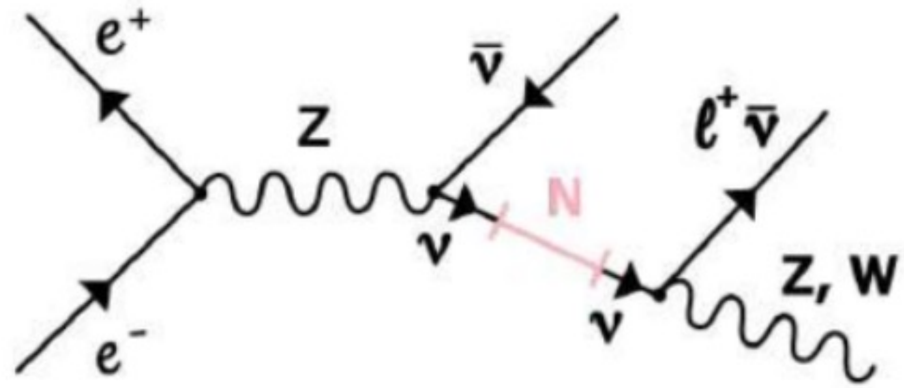
Displaced vertex

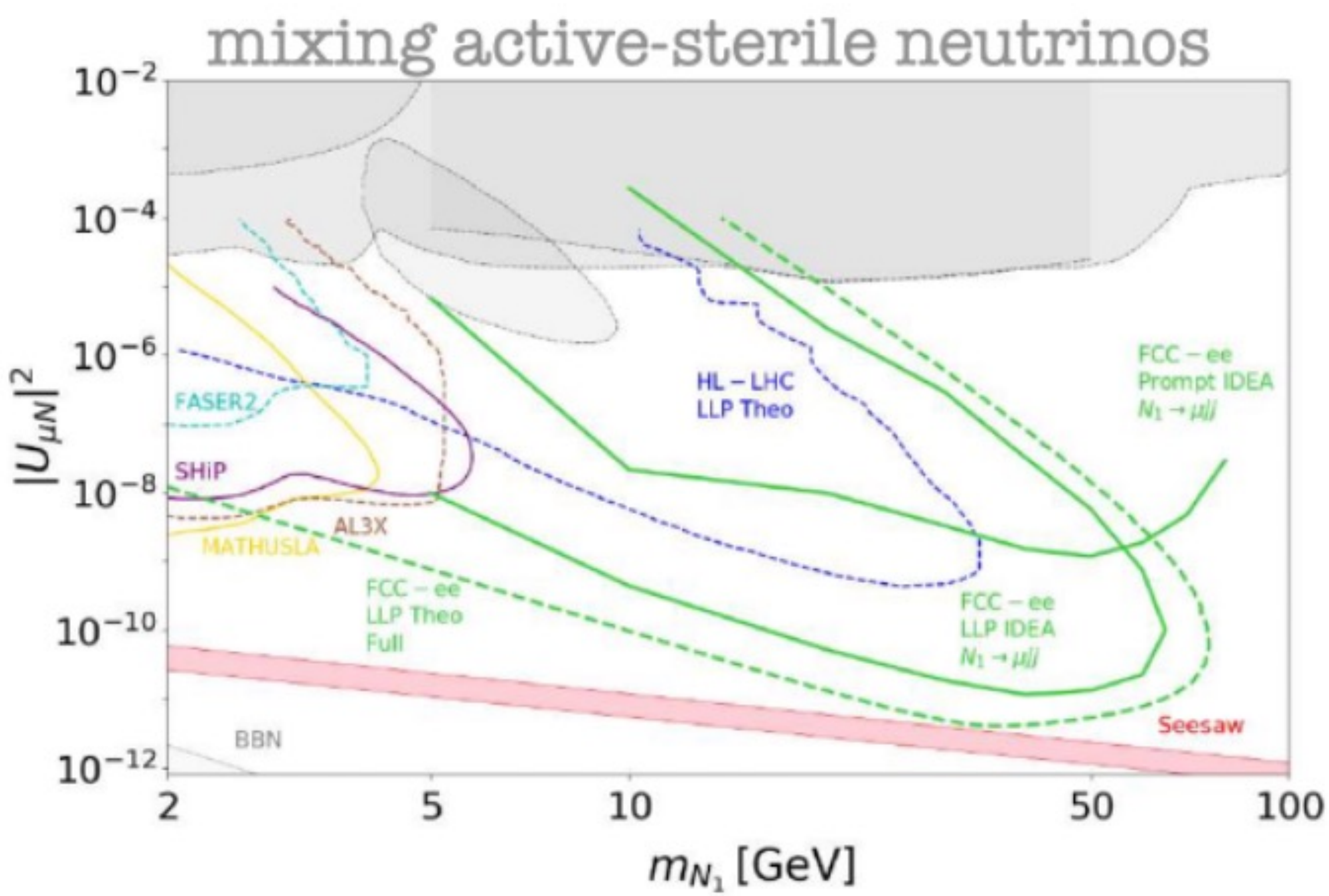


FCC-ee

https://indico.cern.ch/event/1307378/contributions/5720989/attachments/2789031/4879011/Grojean.pdf

Direct observation in Z decays from LH-RH mixing





Conclusions

1. There are compelling motivations for HNLs to solve fundamental questions related to neutrino masses, matter-antimatter asymmetry, etc.

2. In the regime of HNLs MeV-TeV a clear and more complete picture of experiments (running or proposed) can further explore in depth parameter space.

3. In the case of no active-sterile mixing there is not much of an increase in sensitivity from Higgs physics processes in the production and decay of HNLs when comparing HL-LHC and FCC.

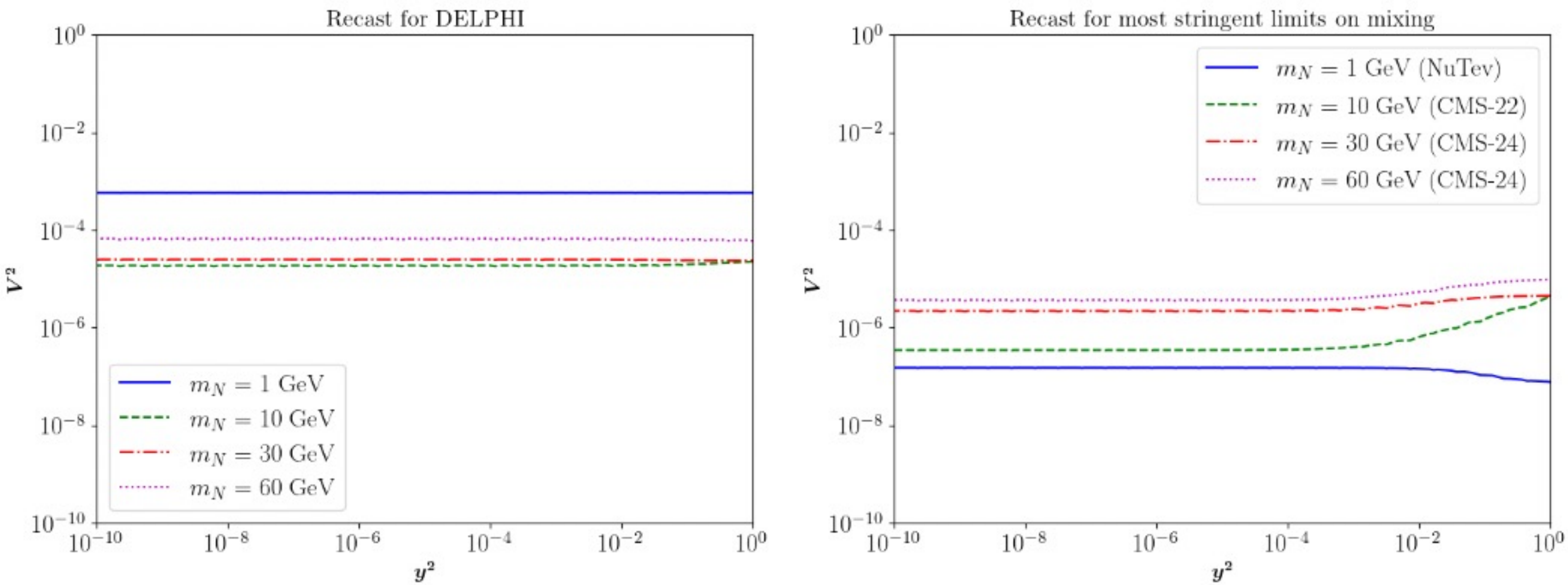
4. We've shown when you are directly sensitive to the HNL Yukawa. As soon as non-zero mixing is turned on it quickly dominates the sensitivity of the NP search.

5. With FCC a much increased sensitivity to active-sterile mixing is obtained at the Z pole.

6. Current and future constraints on the Higgs width provide the most relevant constraints on the HNL Yukawa coupling in particular for the case of zero mixing.

Thank you

Turn on mixing: Recasting previous results



$$V^2(m_N) \cdot BR^{(Z^*/W^*/h^*)}_{N\to\nu f\bar{f}}(V^2, y^2, m_N) = V^2_{\rm exp}(m_N) \cdot BR^{(Z^*/W^*)}_{N\to\nu f\bar{f}}(m_N),$$

Experiment	final states
NuTeV	Production through W (looks at electrons or muons from HNL)
DELPHI	Production through Z (looks at jets coming from HNL)
CMS22	Production through W (looks at electrons or muons from HNL) [90]
CMS24	Production through W (looks at electrons, muons or taus from HNL) [136]