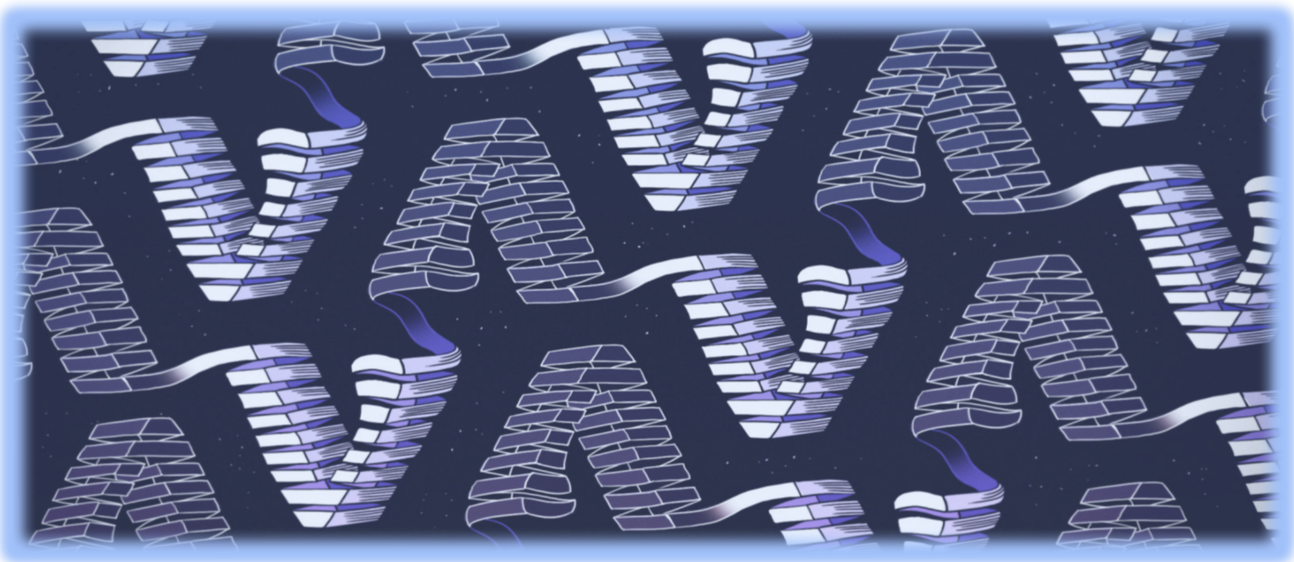
Long-lived Heavy Neutrinos From Higgs Decays

YTF Talk



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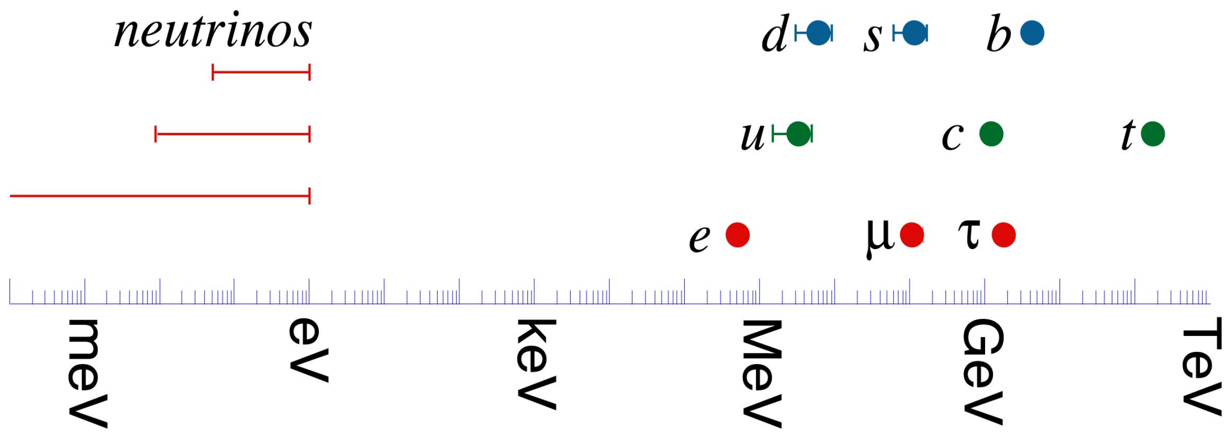
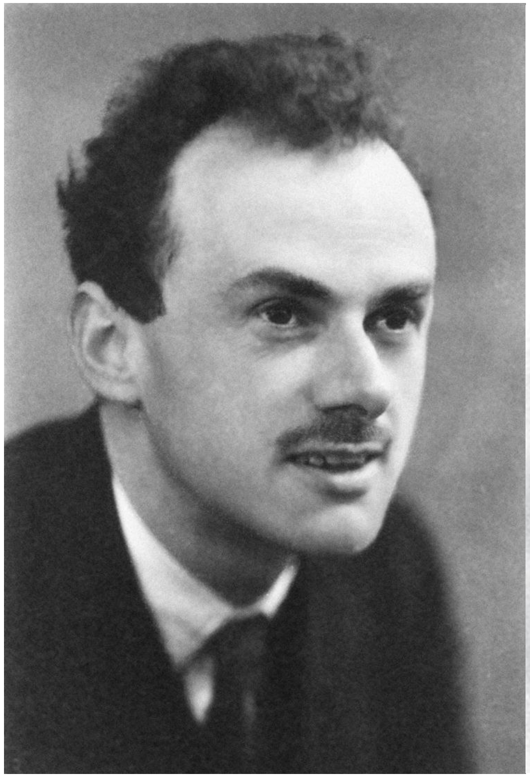
Neutrino Mass

Introduction and Motivation



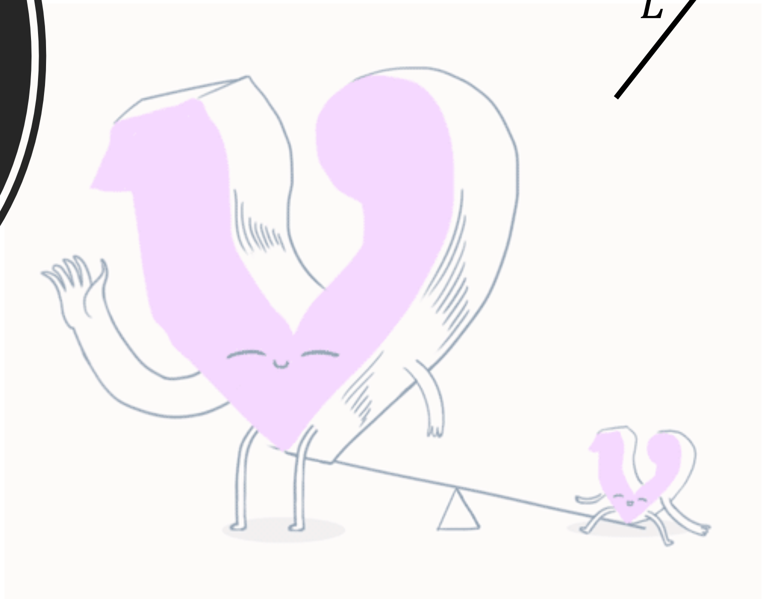
Dirac or Majorana?

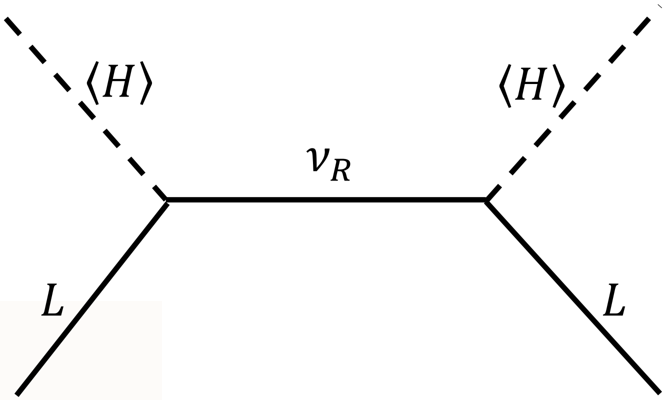
Introduction
and
Motivation




Seesaw Mechanism – Heavy Neutrinos

Introduction and Motivation





$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

$$m_1 \approx -\frac{{M_D}^2}{M_R}$$

$$m_2 \approx M_R$$

A conserved *B-L* quantum number?

Introduction and Motivation

- **Baryon and lepton numbers**
  Accidental symmetries in the SM,
  can be broken by anomalies

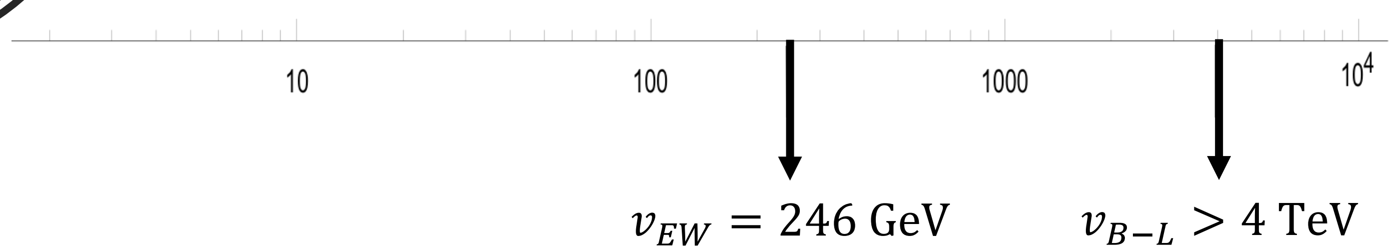
- ***B-L* number**
  Anomaly free

- **What is the origin of this symmetry?**

Gauged *B-L* Model

Model

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
  Phys. Rev. Lett. 44 (1980) 1316
- Additional Z' and Higgs singlet χ
- *B-L* symmetry breaking close to EW scale



Symmetry Breaking and Higgs Mixing

Model

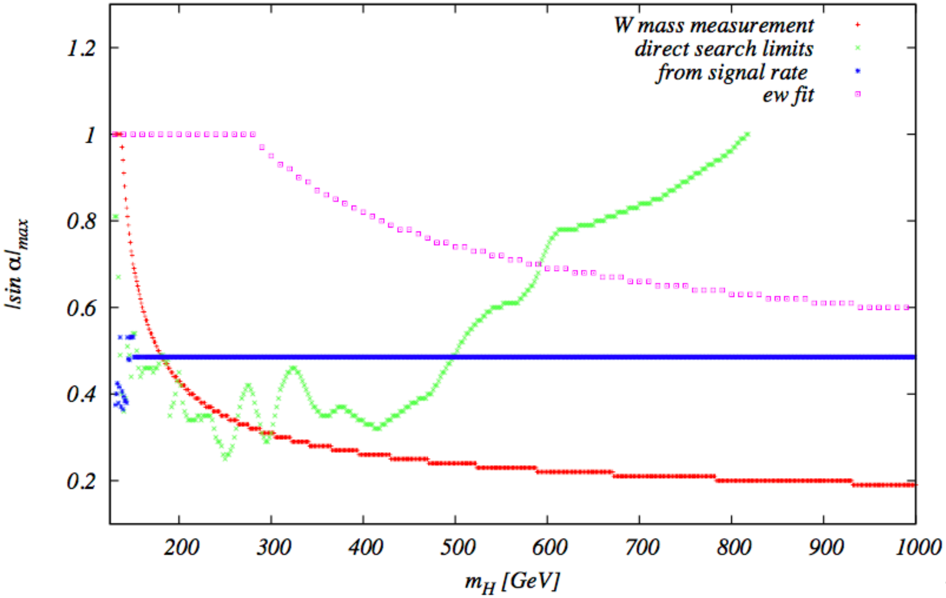
- **Scalar potential**

$$V(H,\chi) = m^2 H^+ H + \mu^2|\chi|^2 + \lambda_1 (H^+ H)^2 + \lambda_2 |\chi|^4 + \lambda_3 H^+ H |\chi|^2$$

- **Higgs mixing**

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ \chi \end{bmatrix}$$

We take the largest experimentally allowed value $sin\ \alpha$ = 0.3 ($m_{h_2} \approx 450$ GeV)



Heavy Neutrinos and Mixing

Model

- **Additional heavy neutrinos $\boldsymbol{\nu_{R_i}}$**
  Only charged under $U(1)_{B-L}$

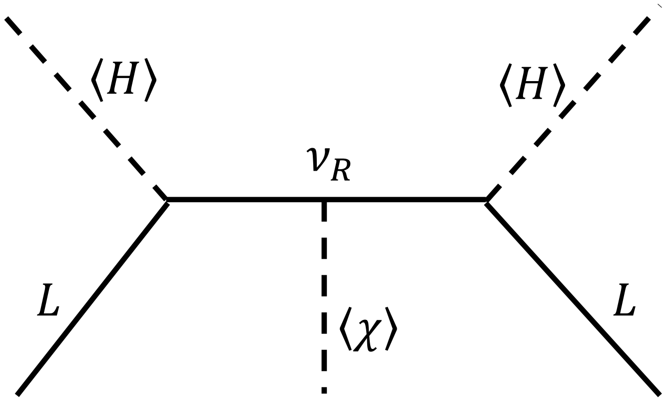
- **Yukawa couplings → Majorana mass**
  $L_{Majorana} = -y^M_{jk}\overline{(\nu_R)^c_j}(\nu_R)_k\chi$

- **Naturally small Yukawa couplings**
  Only parameters (spurions) breaking $B-L$

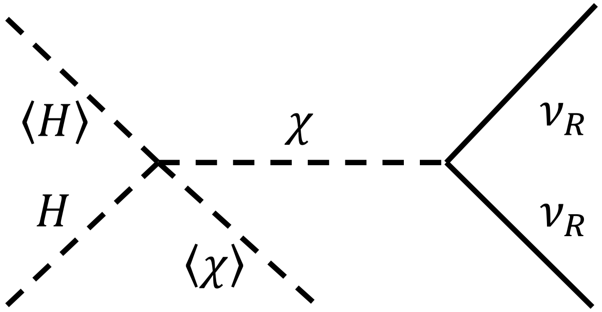
- **Neutrino mixing**
  $\begin{bmatrix}\nu_L\\ \nu_R\end{bmatrix} = \begin{bmatrix}V_{LL} & V_{RL}\\ V_{LR} & V_{RR}\end{bmatrix}\begin{bmatrix}\nu\\ N\end{bmatrix}$
  We only consider one heavy neutrino mixing with one light lepton, specifically $V_{\mu N}$

Effective Operators

- **Weinberg operator**
  Mass for light neutrinos



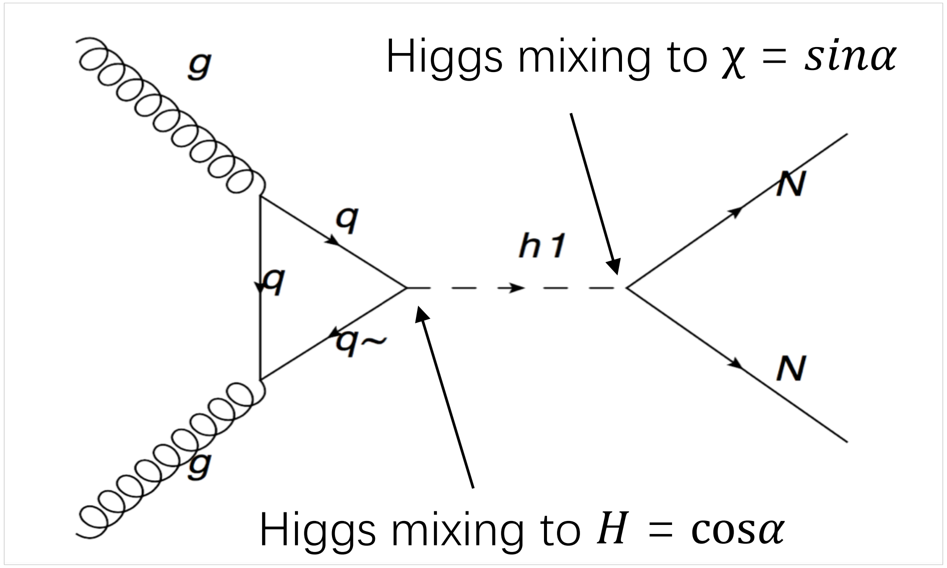
- **Higgs Decay**



Pair-Production of N at the LHC

Heavy Neutrinos from Higgs Decays

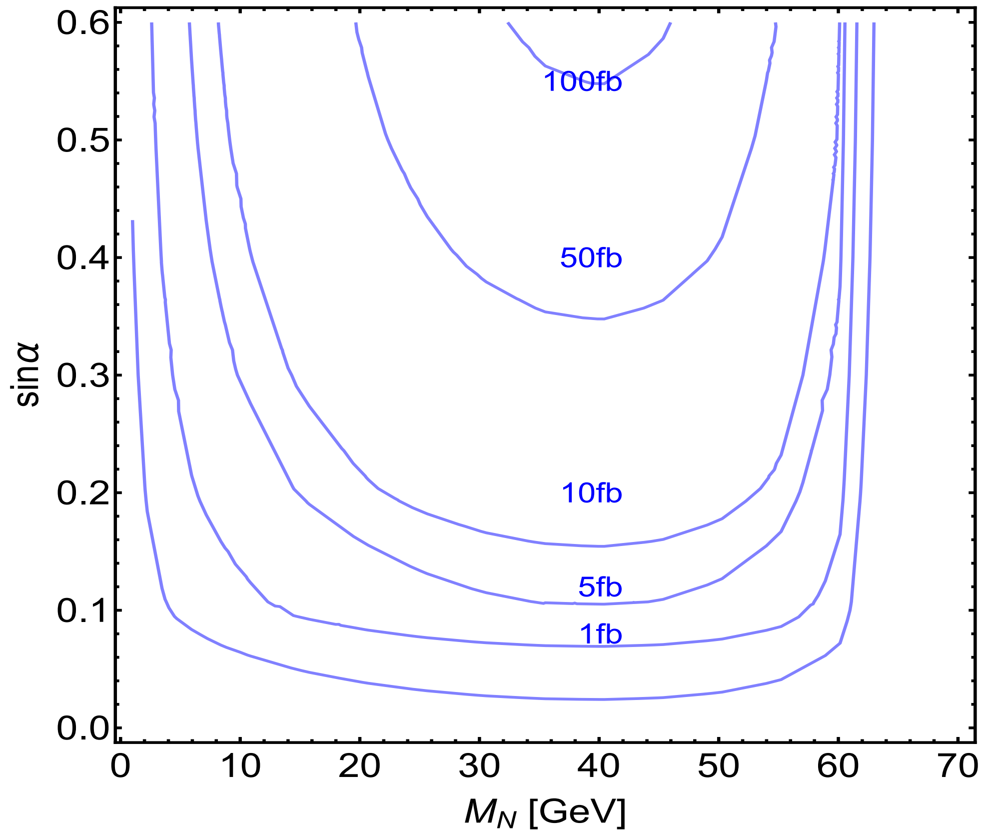
- **Depends on Higgs mixing $\propto sin^2(2\alpha)$**
  Unsuppressed by neutrino mixing



Pair-Production of N at the LHC

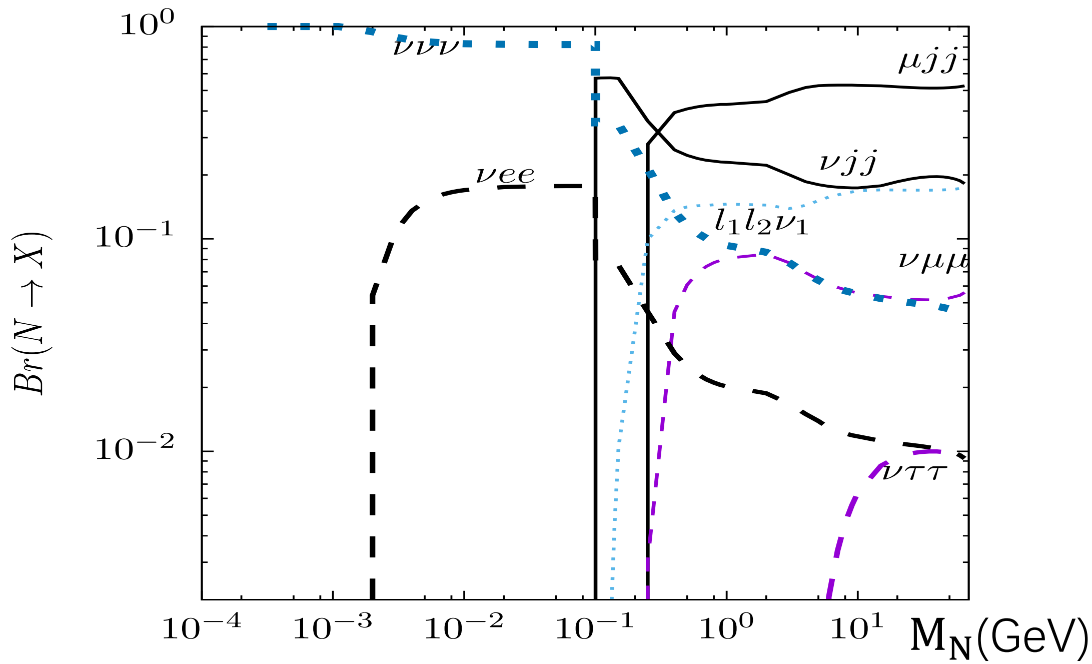
Heavy Neutrinos from Higgs Decays

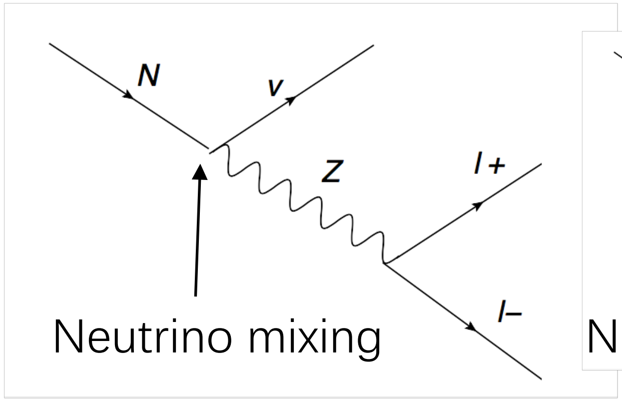
- **Depends on Higgs mixing $\propto sin^2(2\alpha)$**
  Unsuppressed by neutrino mixing
- $\sigma(pp \to h_1 \to NN)$ **(13 TeV)**

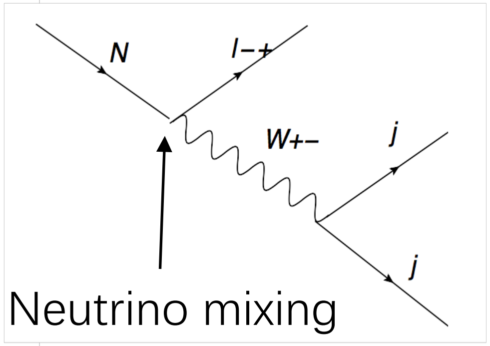


Neutrino Decay Channels

Heavy Neutrino Decays







Heavy Neutrino Decays

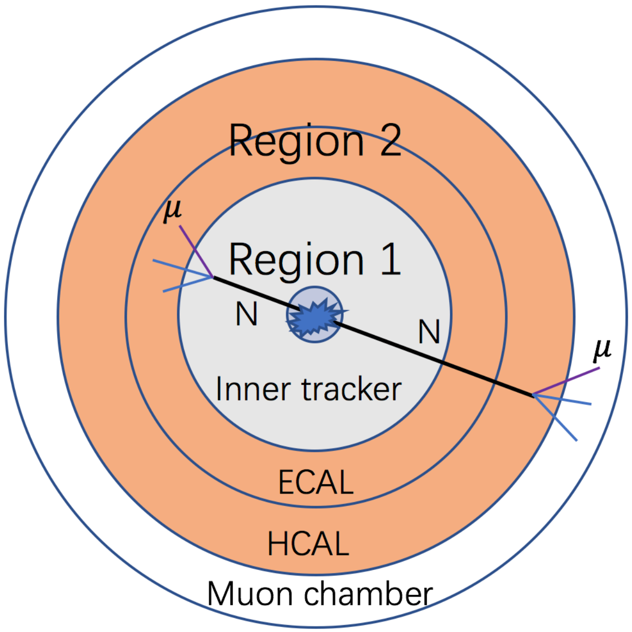
Neutrino Decay Length

- **Long-lived heavy neutrinos**

$$L \approx 5\ \mathrm{cm} \times \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \times \left(\frac{100\ \mathrm{GeV}}{M_N}\right)^5$$

- **Displaced vertices**

  Inner tracker and inside muon chamber



Theoretical Estimation

Heavy Neutrino Decays

- **Effective Event Rate**

$$\sigma_{Eff} = \sigma(pp \to h_1 \to NN) \times Br(N \to X) \times P(x_1 < x_N < x_2)$$

- **Probability of N decay within certain distance**

$$P(x_1 < x_N < x_2) = \int_0^{\pi} d\phi_N \int_0^{1} d\beta_H \, p(x_1 < x_N < x_2) f(\beta_H) g(\phi_N)$$

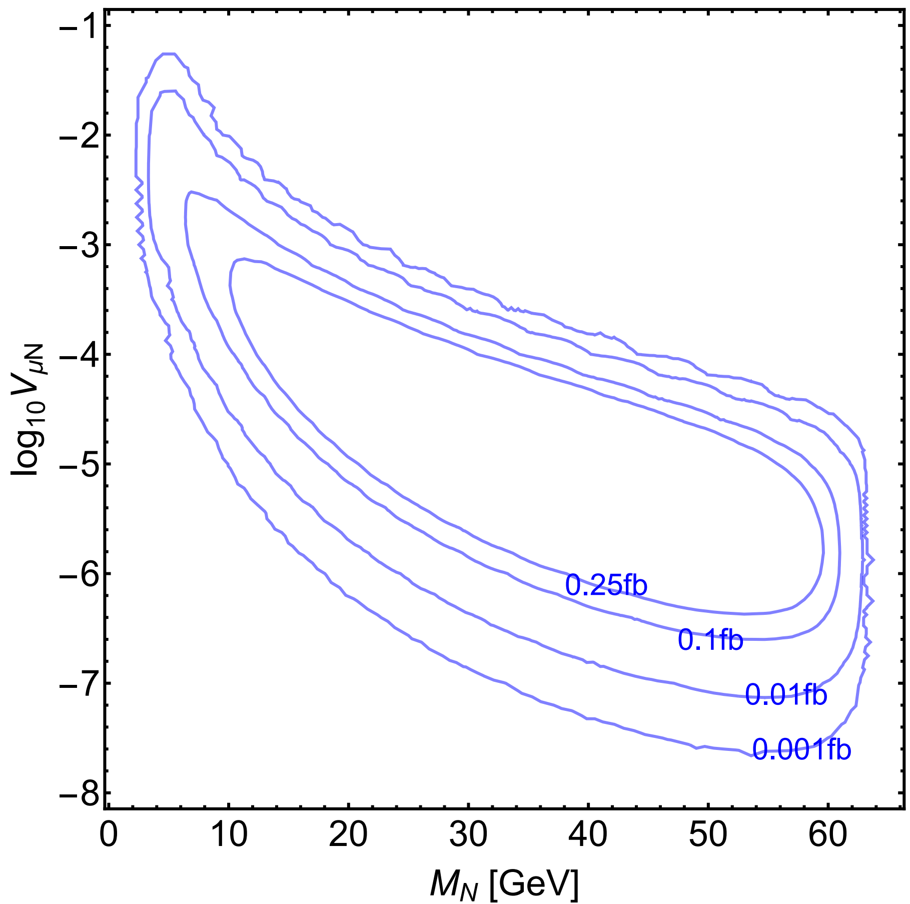
- **Probability of a single N**

$$p(x_1 < x_N < x_2) = e^{-\frac{x_1}{l'_N}} - e^{-\frac{x_2}{l'_N}}$$

Theoretical Estimation

Heavy Neutrino Decays

- **Effective Event Rate for N decay to two muons decaying within 1 cm and 5 m**



Event Generation Tools

Monte Carlo Simulation

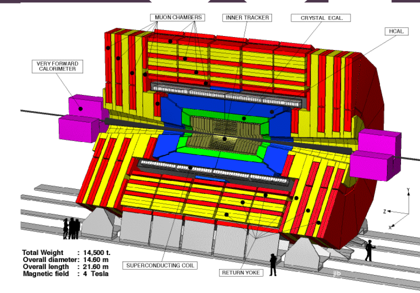
FeynRules

MG5@aMC (Patron Level)

LHE (Les Houches event file)

Upgraded FeynRules model from arXiv:0812.4313

Displaced Vertex Geometry



Monte Carlo Simulation

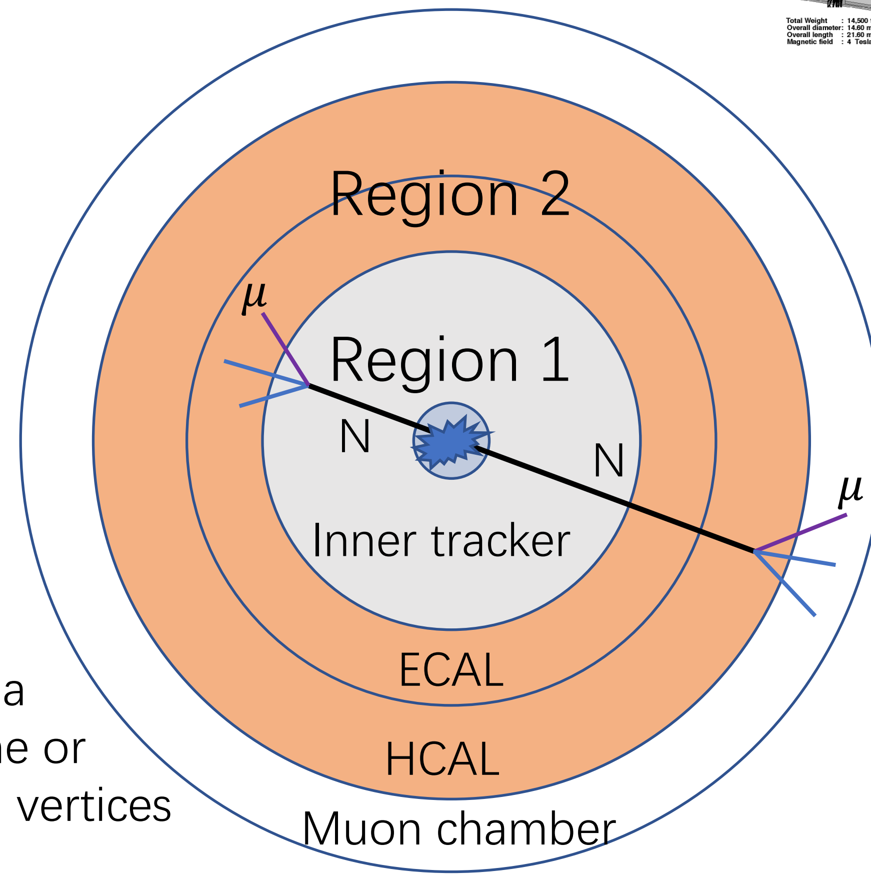


Illustration of a signal with one or two displaced vertices

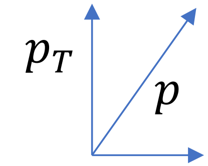
perpendicular to the beam line

Kinematical Cuts

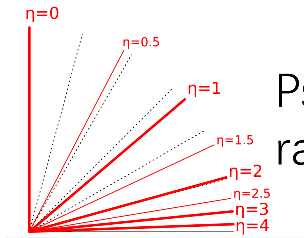
CMS, Phys. Rev. D 91 052012

Monte Carlo Simulation

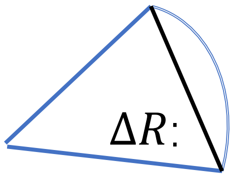
- $\mathbf{p_T(\mu) >}$ $\mathbf{26\ GeV}$ **, two muons**



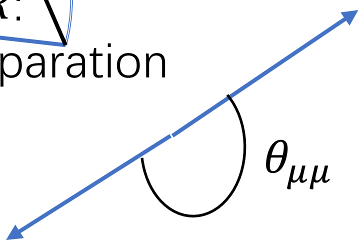
- $\mathbf{|\eta| < 2.0}$



- $\mathbf{\Delta R > 2.0}$



- $\mathbf{\cos\theta_{\mu\mu} > -0.75}$

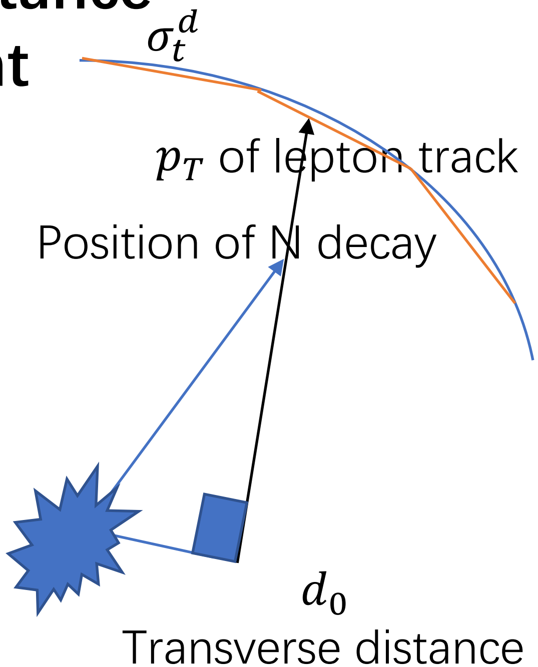


Geometric Selection

Monte Carlo Simulation

- **Heavy neutrinos decay in Region 1 or 2**
- **Cut on transverse distance from interaction point**

$$|d_0| = |x\, p_y - y\, p_x| / p_T$$



Monte Carlo Simulation

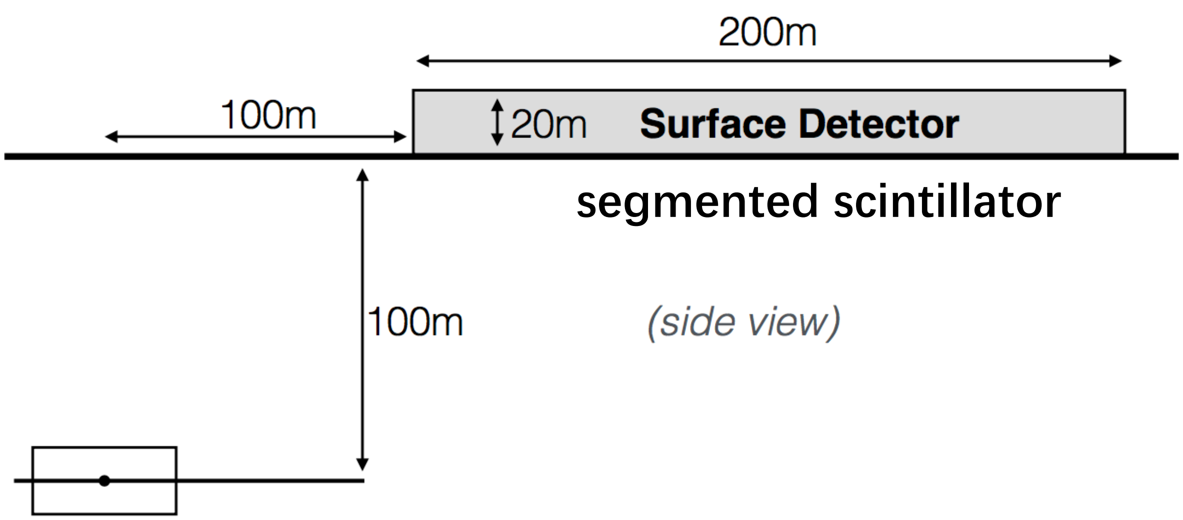
Dimensions of Generic Detectors

Region	Inner Radius (cm)	Outer Radius (cm)	Z Extent (cm)	d_0/σ_d^t
LHC Region 1	10	50	140	12
LHC Region 2	50	500	800	4
ILC Region 1	21.7	120	152	12
ILC Region 2	120	330	300	4
CEPC Region 1	15.3	180	240	12
CEPC Region 2	180	440	400	4

MATHUSLA

Monte Carlo Simulation

- **MAssive Timing Hodoscope for Ultra Stable neutraL pArticles**
  Proposed surface detector

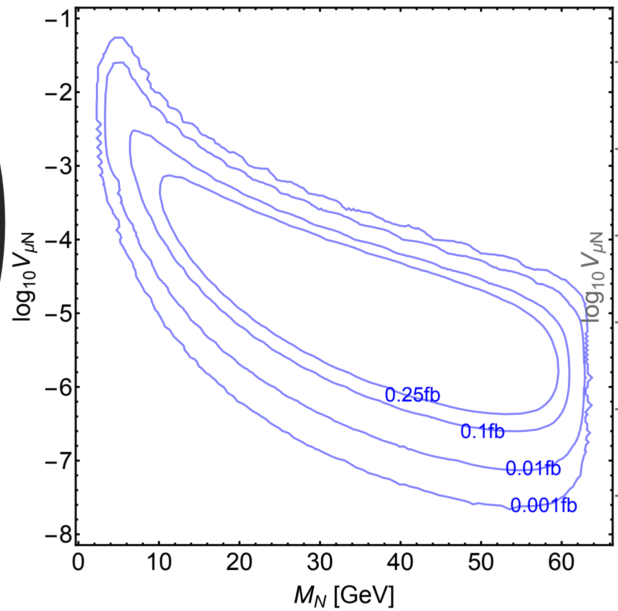


CMS or ATLAS

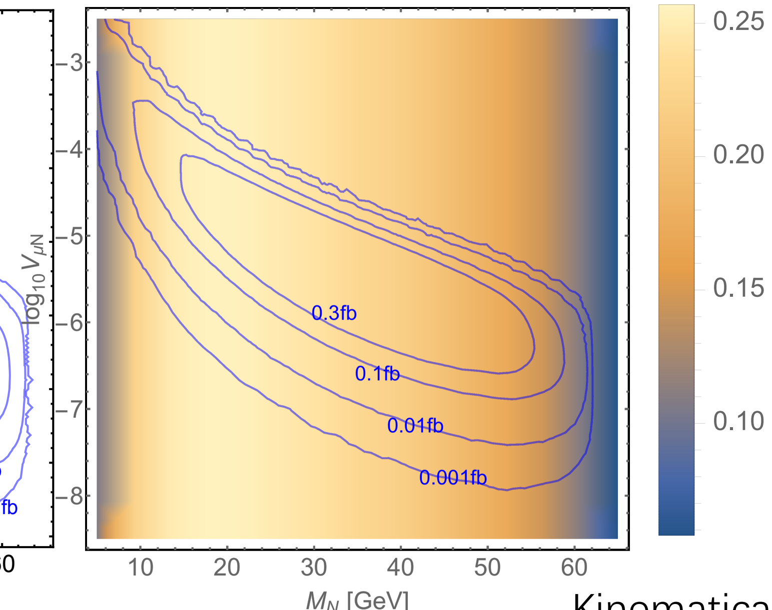
Comparison with Theoretical Estimation

Monte Carlo Simulation

Theoretical Estimation



Monte Carlo Simulation

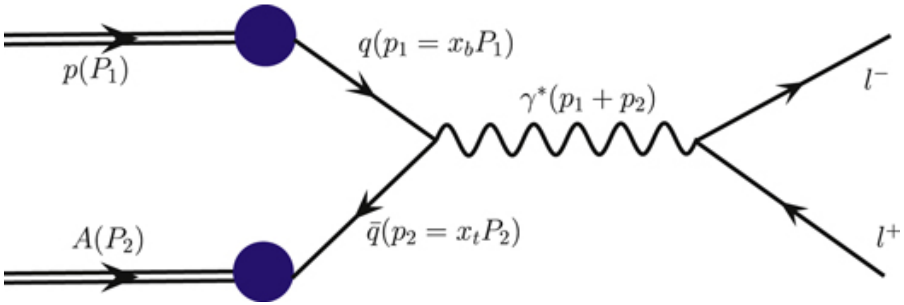


Kinematical efficiency

Future Sensitivity Estimates

Background

- **Long-lived mesons**
- **Drell-Yan dilepton production**
  Faking displaced vertex due to resolution

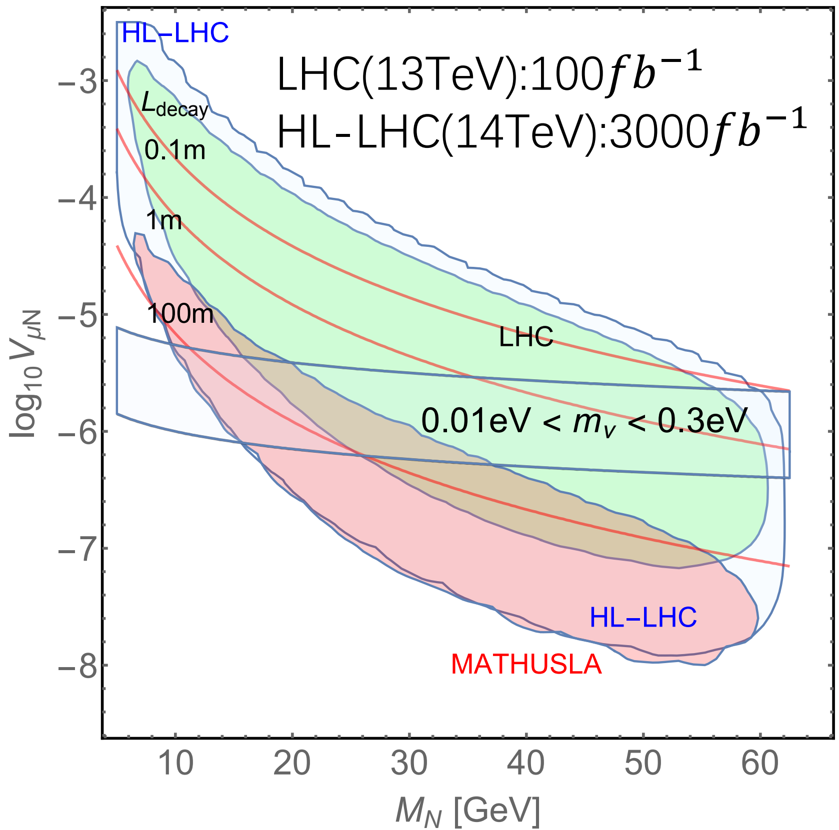


  Efficiently cut by d_0/σ_d^t
  (CMS, Phys. Rev. D91 (2015) 052012)
- **Cosmic ray muons**
  Removable by $cos\theta_{\mu\mu}$ cuts and beam collision time
- **We consider above backgrounds negligible after cuts from CMS [1][2][3]**

Sensitivities of Different Colliders

Future Sensitivity Estimates

- **Excluded parameter space at 95% C.L.**
  Assuming **no** events with **single displaced vertex** in any region are observed



Future Sensitivity Estimates

Sensitivities of Different Colliders

- **Excluded parameter space at 95% C.L.**
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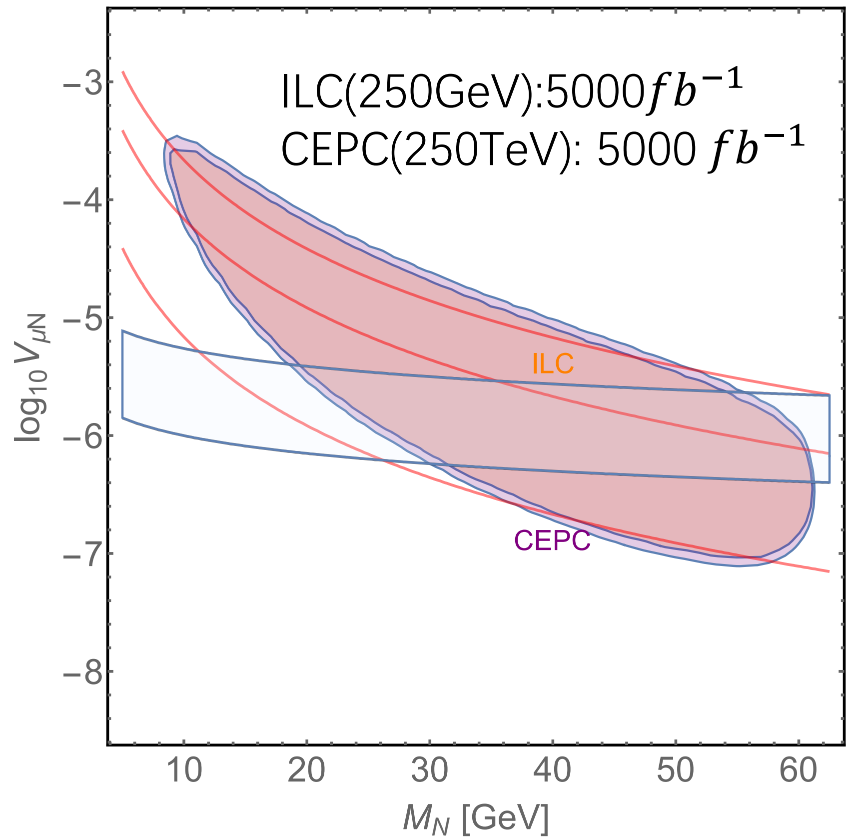
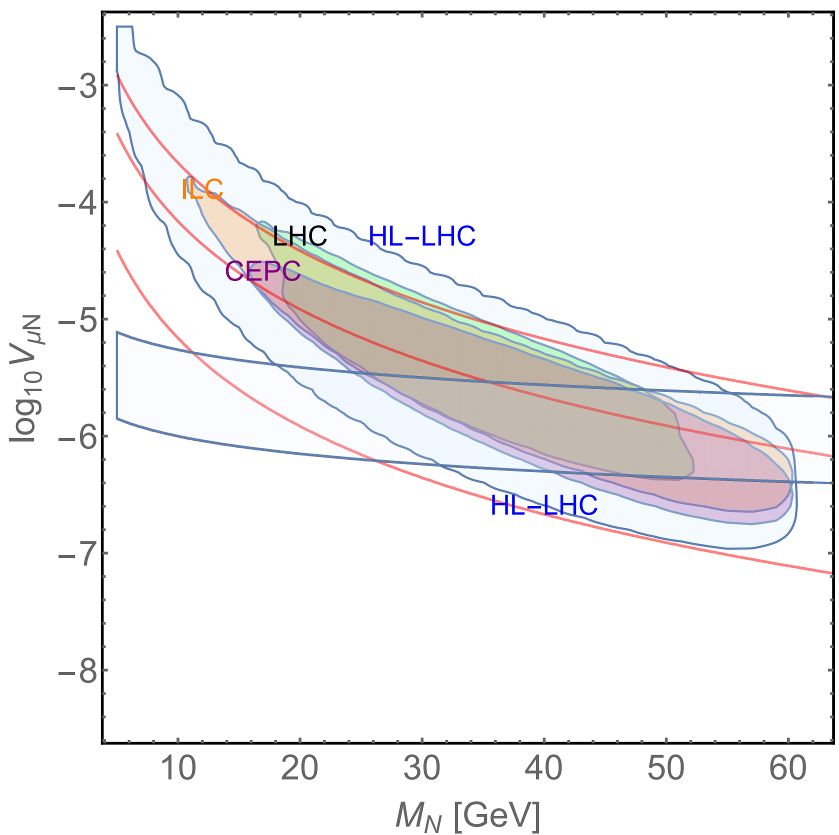


Sensitivities of Different Colliders

Future Sensitivity Estimates

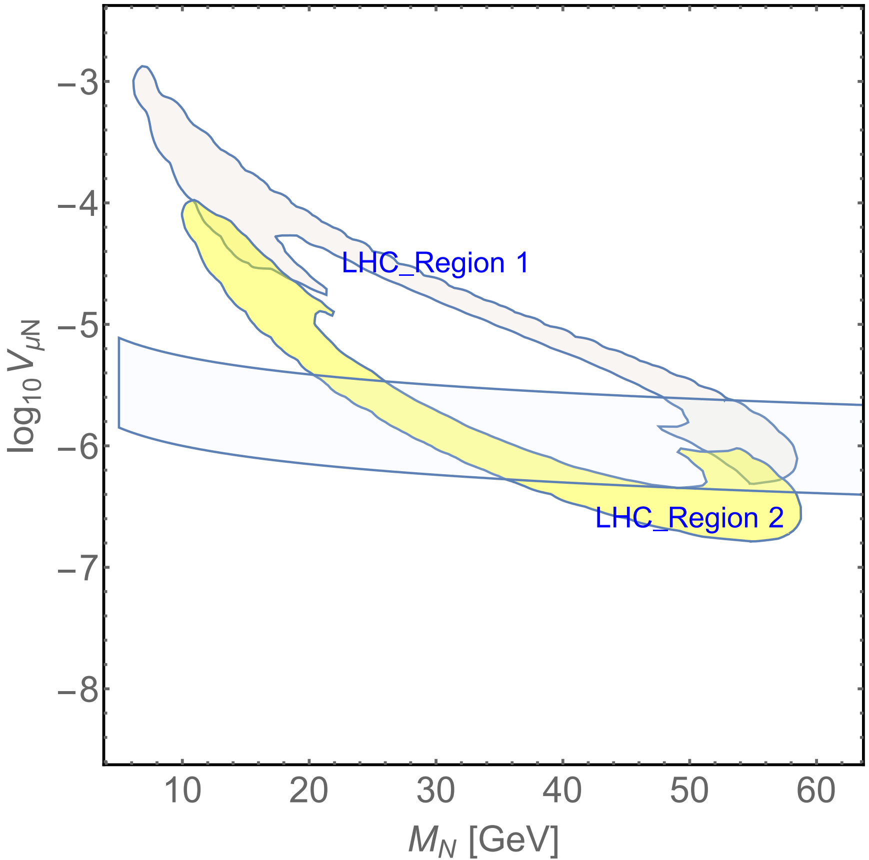
- **Excluded parameter space at 95% C.L.**
  Assuming **no** events with **two displaced vertices** in any region are observed



Example: Seeing Two Event

Future Sensitivity Estimates

- **Allowed parameter space at 95% C.L.**
  Assuming **two** events with **two displaced vertices in either region 1 or 2** are observed



Conclusions

- **Light neutrino masses**
  Not explained in the Standard Model
- **Spontaneous breaking of gauged B-L**
  Generate heavy neutrino masses
- **Type-I seesaw mechanism**
  Heavy neutrino ~50 GeV, neutrino mixing $V_{lN}\sim 10^{-6}$
  The process $pp \to W^* \to lN$ undetectable

$$m_\nu = \frac{m_D^2}{M_N} = V_{lN}^2 M_N = 0.1\text{eV} \cdot \left(\frac{V_{lN}}{10^{-6}}\right)^2 \cdot \left(\frac{M_N}{100\ \text{GeV}}\right)^2$$

- **Pair-production of N through SM Higgs**
  - Suppressed by potentially sizeable Higgs mixing
  - Can reach neutrino mixing as small as 10^{-7} at the LHC and lepton colliders
  - 1-2 magnitude improvement at HL-LHC

References

- [1] CMS Collaboration
  Phys. Rev. D91 052012(2015)
- [2] CMS-PAS-EXO-14-012
- [3] CMS-PAS-EXO-12-037