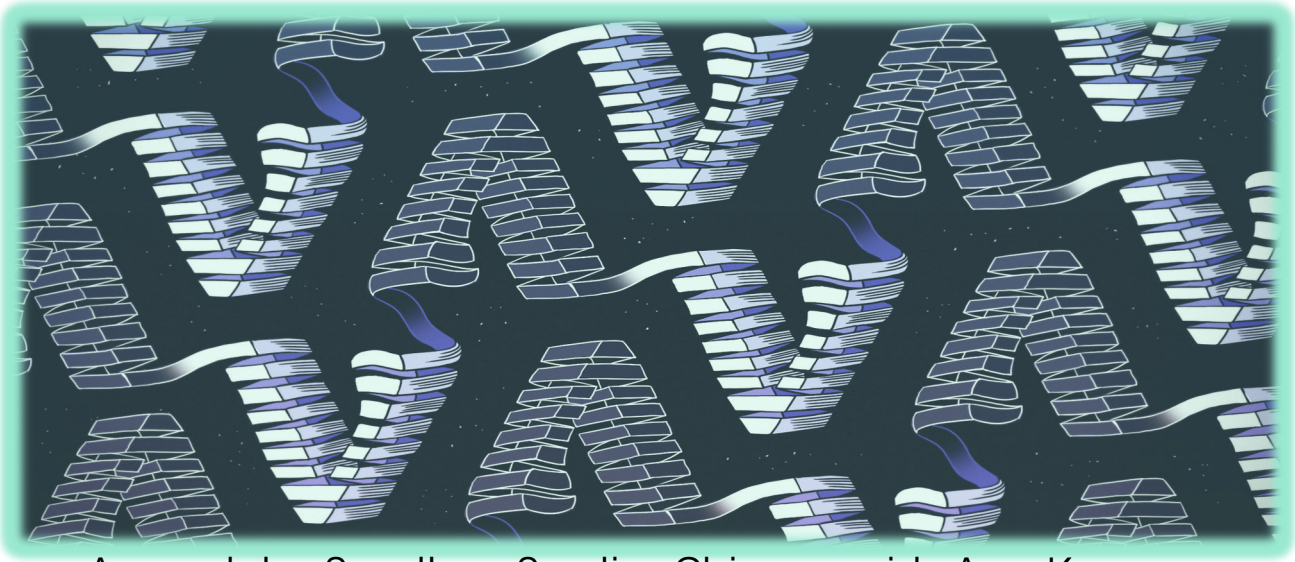
南京理工大学
NANJING UNIVERSITY OF SCIENCE & TECHNOLOGY

Probing B-L Models and the Seesaw From Displaced Vertex Signal



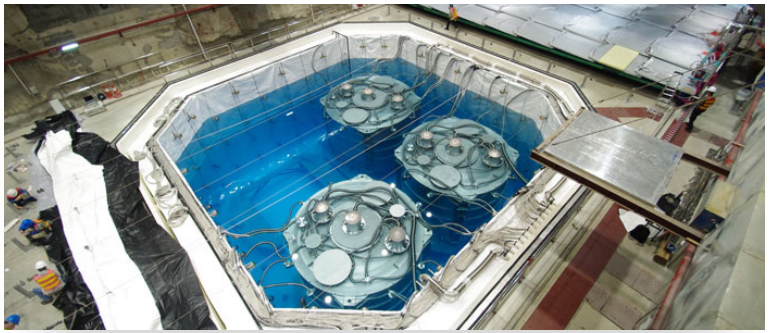
Artwork by Sandbox Studio, Chicago with Ana Kova

Wei Liu（刘威）

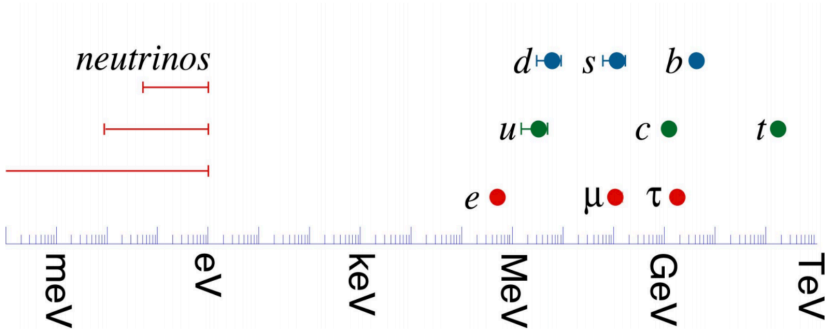
Nanjing University of Science and Technology

JHEP 08 (2018) 181, PRD100 (2019)3, 035005

Work in collaboration with F.F. Deppisch, Suchita Kulkarni, Manimala Mitra….

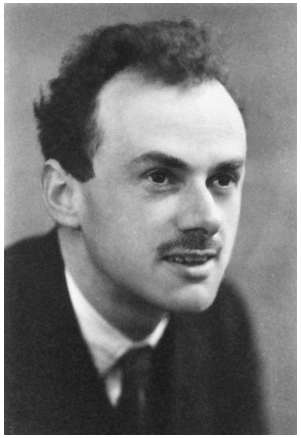


https://physicsworld.com/a/daya-bay-nails-neutrino-oscillation/



From Hitoshi Murayama

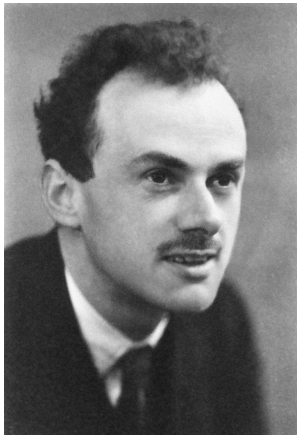
Neutrino Mass

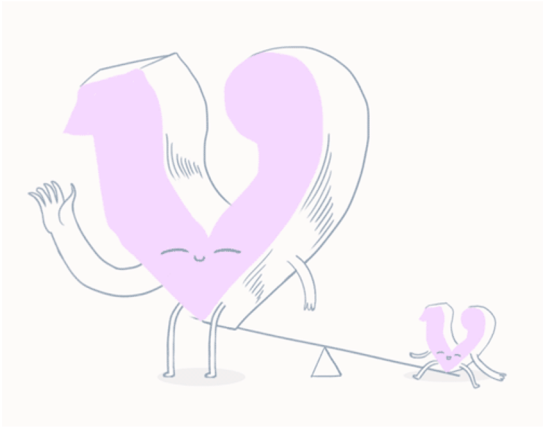


- $L_{\text{Dirac}} = -y\overline{l_L}\widetilde{H}\nu_R$ $L_{Majorana} = -M\overline{\nu_R{}^c}\nu_R$
- Tiny Yukawa coupling $\sim 10^{-12}$ for pure Dirac mass!

Dirac or Majorana?

Artwork by Sandbox Studio, Chicago with Ana Kova





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

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

$$m_2 \approx M_R$$

Seesaw Mechanism by hand? υMSM

Natural Seesaw by symmetry breaking

- **Baryon and lepton numbers**
  Accidental symmetries in the SM,
  can be broken by anomalies
- ***B-L* number**
  Anomaly free

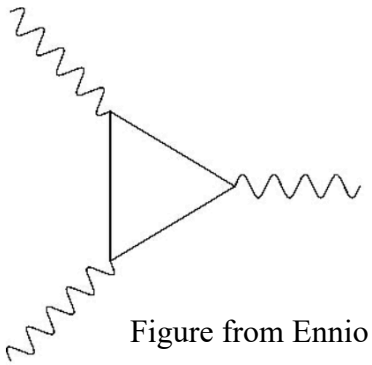


Figure from Ennio SALVIONI

A conserved B-L?

Gauged B-L Model

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
  R. N. Mohapatra and R. E. Marshak
  Phys. Rev. Lett. 44 (1980) 1316
- **Additional Z' and Higgs singlet χ**
- ***B-L* symmetry breaking close to EW scale to have LHC Observables**
- **(Resonant Leptogenesis，Leptogenesis via Oscillations)**

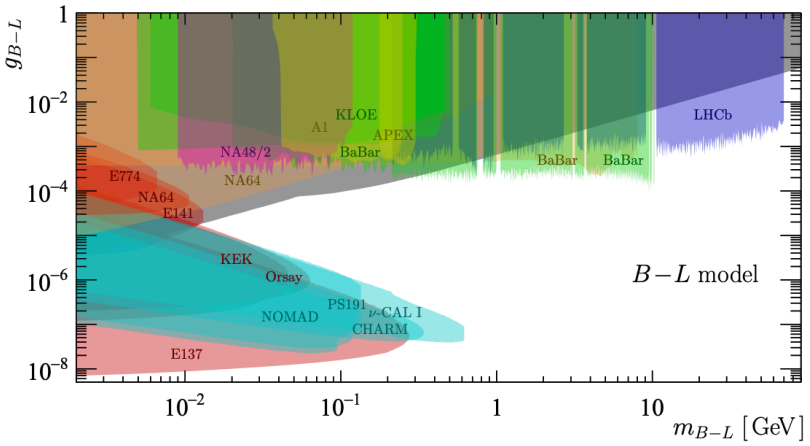
Symmetry Breaking and Higgs Mixing

- **Scalar potential**
  $V(H,\chi) = m^2 H^+ H \; + \; \mu^2|\chi|^2 + \lambda_1 (H^+ H)^2 + \; \lambda_2 |\chi|^4$
- **Higgs mixing**

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

Current limits via Dark Photon Searches

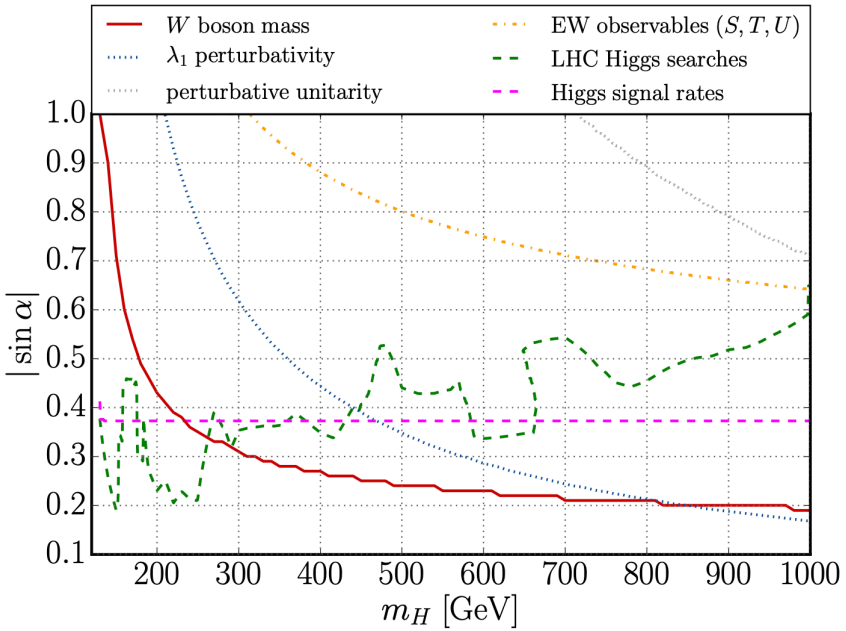
- P. Ilten, Y. Soreq, M. Williams and W. Xue
- **JHEP 1806 (2018) 004**
  arXiv:1801.04847



Current limits via Higgs Searches and EW Measurements

- Agnieszka Ilnicka, Tania Robens, and Tim Stefaniak
- *Mod. Phys. Lett.*, A33(10n11):1830007, 2018.

arXiv:1803.3594

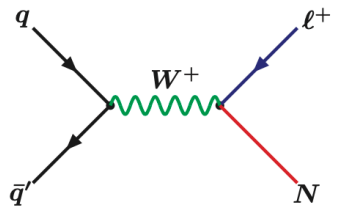


Heavy Neutrinos and Mixing

- **Additional heavy neutrinos $\boldsymbol{\nu_{Ri}}$**
  Only charged under $U(1)_{B-L}$
- **Yukawa couplings → Neutrino mass**
  $L_{\text{Dirac}} = -y\overline{l_L}\widetilde{H}\nu_R$, $L_{Majorana} = -y^M_{jk}\overline{(\nu_R)^c_j}(\nu_R)_k\chi$
- **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 $V_{\mu N}$
- $\boldsymbol{V^2_{lN} \approx \frac{m_\nu}{mN} < \frac{eV}{GeV} < 10^{-10}}$

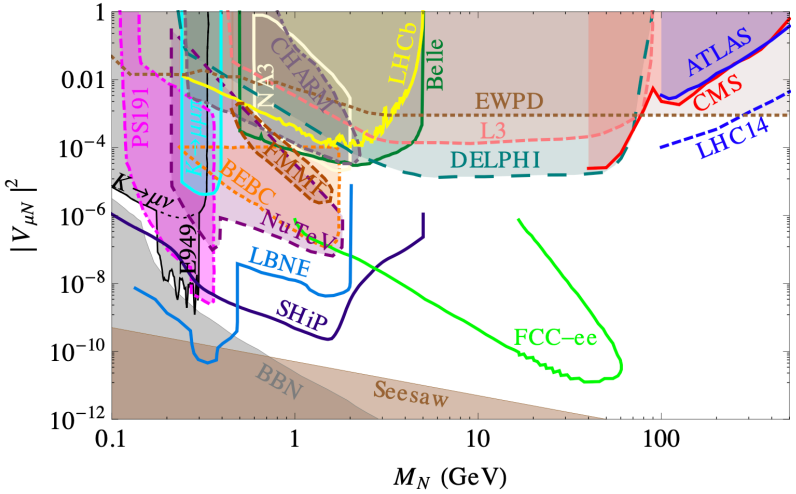
Current limits via Heavy Neutrino Searches

- Frank F. Deppisch, P.S. Bhupal Dev, Apostolos Pilaftsis
- **New J. Pjys 17 (2015) 7, 075019** **arXiv:1502.06541**



$$\propto V_{lN}^2$$

$$10^7 pb \times V_{lN}^2 < \text{fb}$$



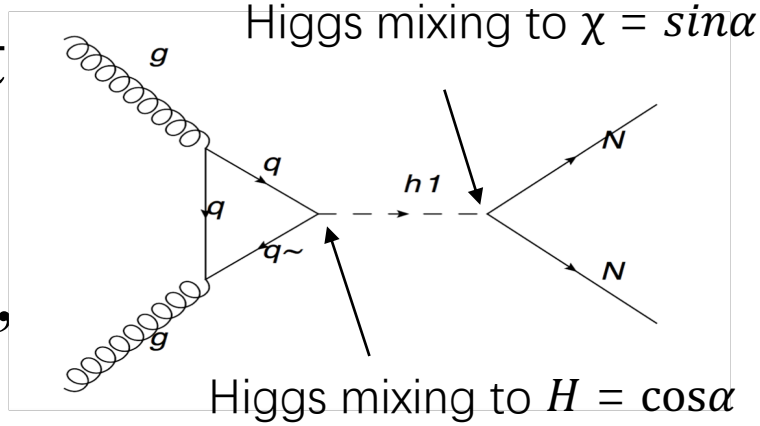
Pair-Production of N at the LHC

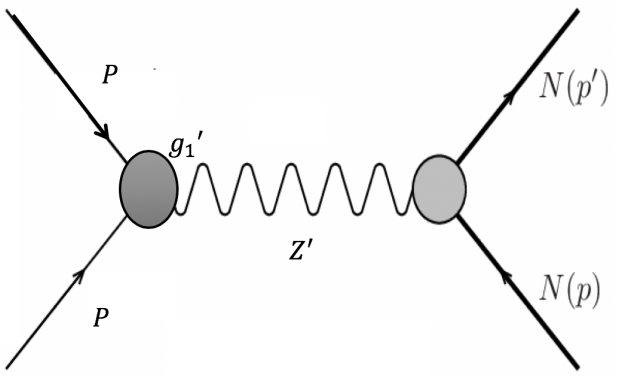
- **N pair production from 'SM' Higgs**

Depends on $\propto sin^2(2\alpha)$, Unsuppressed by neutrino mixing

- **N pair production from Z'**

dependent by $M_{Z'}$, $g_1{}'$ and M_N, at forward direction if Z' is light





Pair-Production of N at the LHC

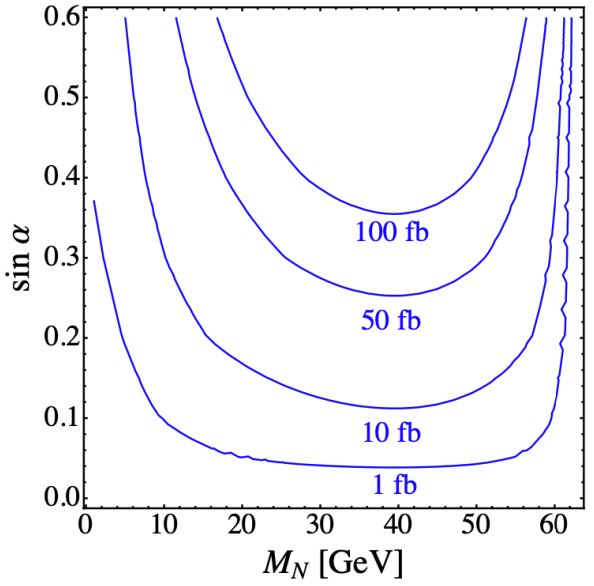
- **Direct mixing to EW processes**

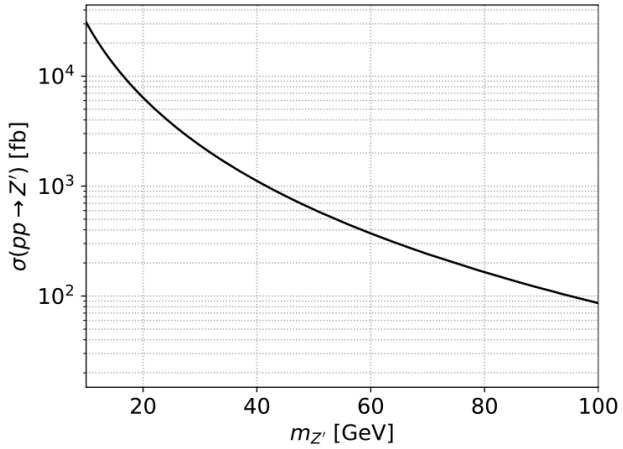
$10^7 pb \times V_{lN}^2 <$ fb

- **Potential sizeable cross section**

Current limits ~50 fb (Br~10% for bottom panel)

- **Independent of the V_{lN}**





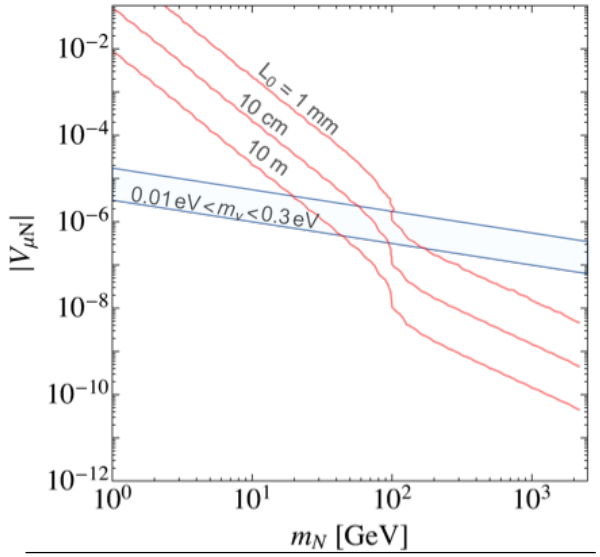
Neutrino Decay Channels

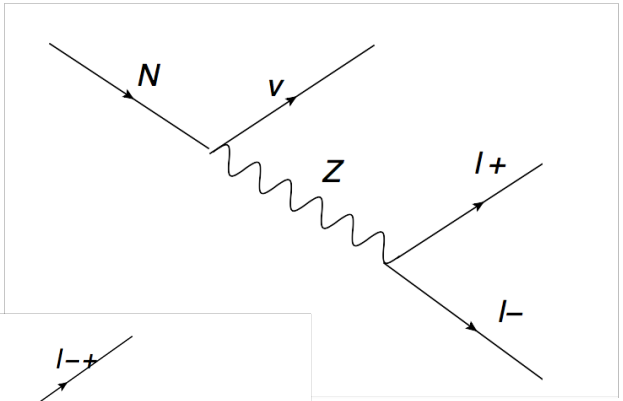
- **Decay only via mixing to the SM neutrino**

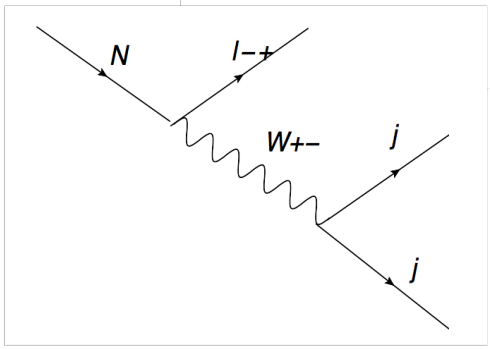
Three body decays

- **Large decay length for probing the Seesaw!**
- **Seesaw points out**

$$V_{lN}^2 \approx \frac{m_\nu}{mN} < \frac{eV}{GeV} < 10^{-10}$$







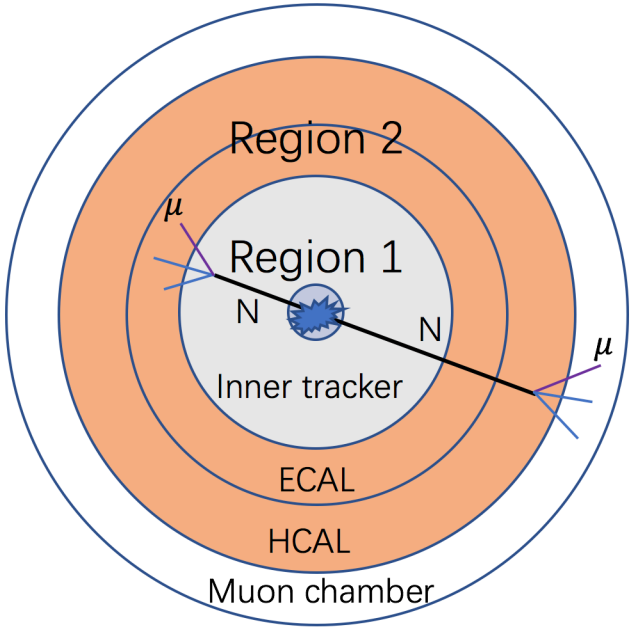
Neutrino Decay Length

- **Long-lived heavy neutrinos**

$$L \approx 3\ \text{cm} \times \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \times \left(\frac{100\ \text{GeV}}{M_N}\right)^5$$

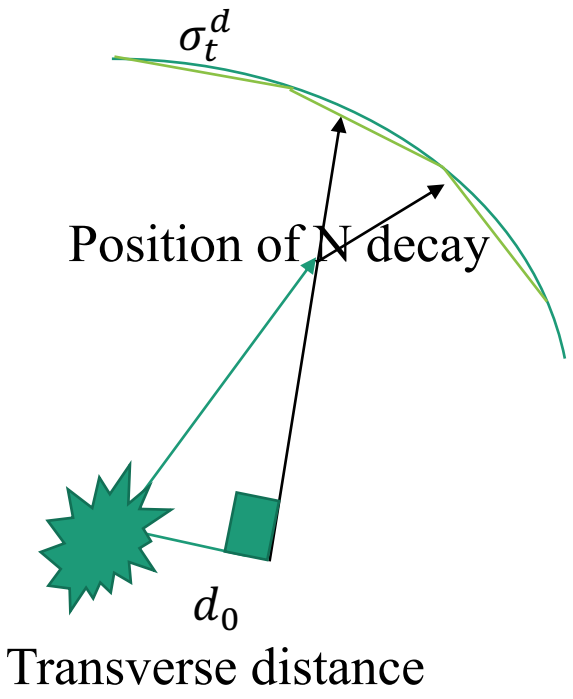
- **Displaced vertices**

  Inner tracker and inside muon chamber



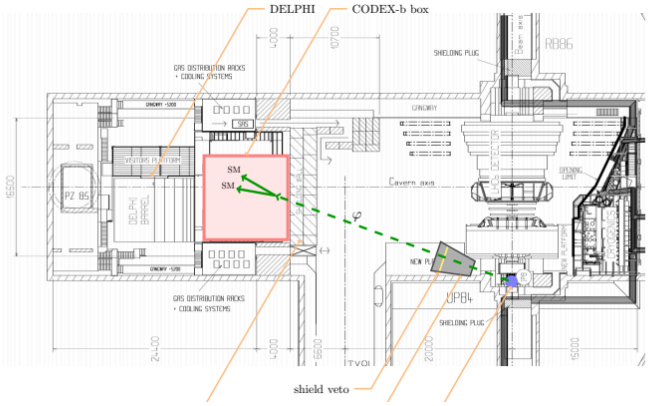
Geometric Selection

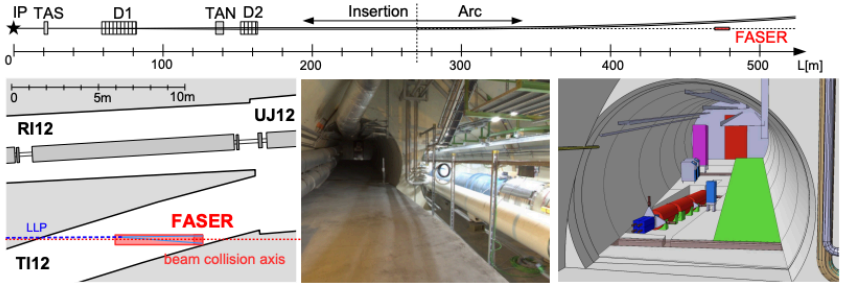
- **Heavy neutrinos decay in Region 1 or 2**
- **Cut on transverse distance from interaction point**
- $|d_0| = |x\ p_y\ - y\ p_x|/p_T$

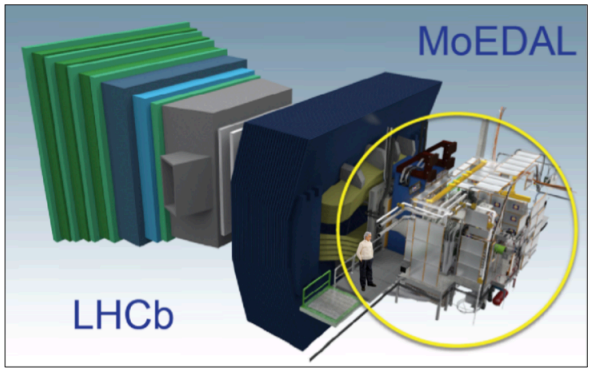


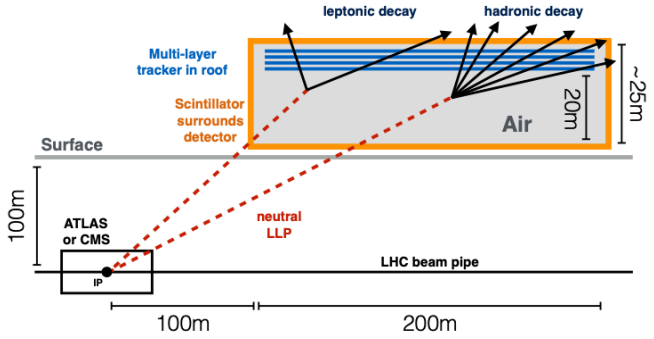
Geometric Selection

- Several far detectors are proposed
- CODEX-b, FASER, MAPP(MoEDAL), MATHUSLA…
- FASER already in construction!
- Figure from 1903.04497









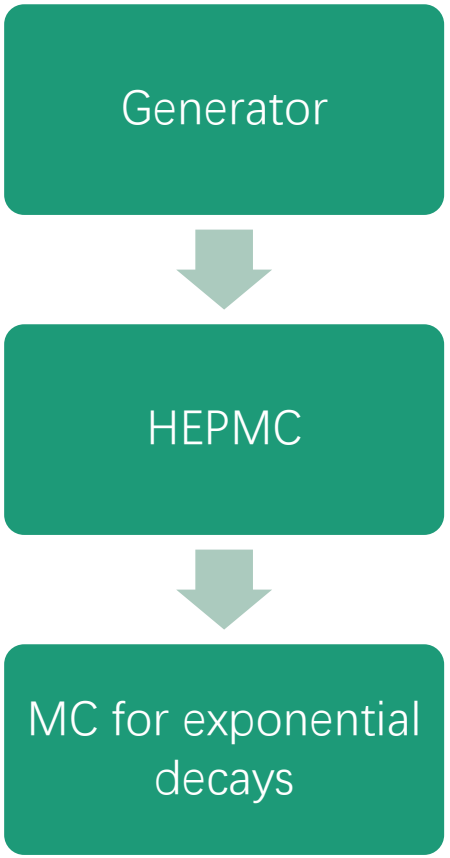
Geometric Selection

- **Detector level simulation:**

Taking enormous time to get distribution of exponential decays!
No information for new detectors

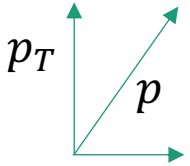
- **Simple MC:**

Using MC to get the distribution of exponential decays
Easy to rescale for different proper decay length

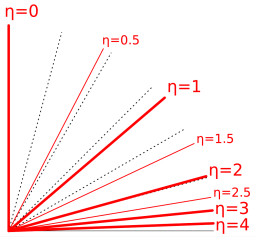


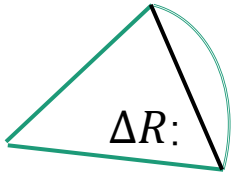
Kinematical Cuts

- $\mathbf{p_T(\mu) >}$ **26 GeV , two muons**
- $\mathbf{|\eta| < 2.0}$
- $\mathbf{\Delta R > 0.2}$
- $\mathbf{cos\theta_{\mu\mu} > -0.75}$
- CMS, Phys. Rev. D 91 052012

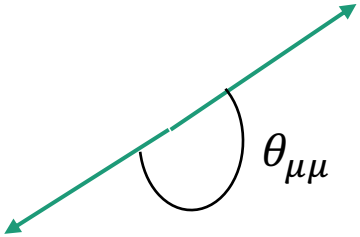


Beam line





separation



Cosmic ray muons

Background

- **Long-lived mesons**
- **Drell-Yan dilepton production**
  Faking displaced vertex
- **Cosmic ray muons**
  Removable by $cos\theta_{\mu\mu}$ cuts and beam collision time
- **We consider above backgrounds negligible after cuts**

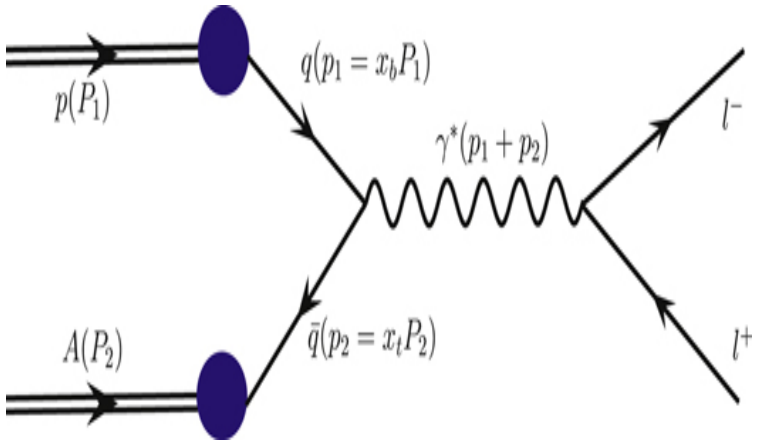


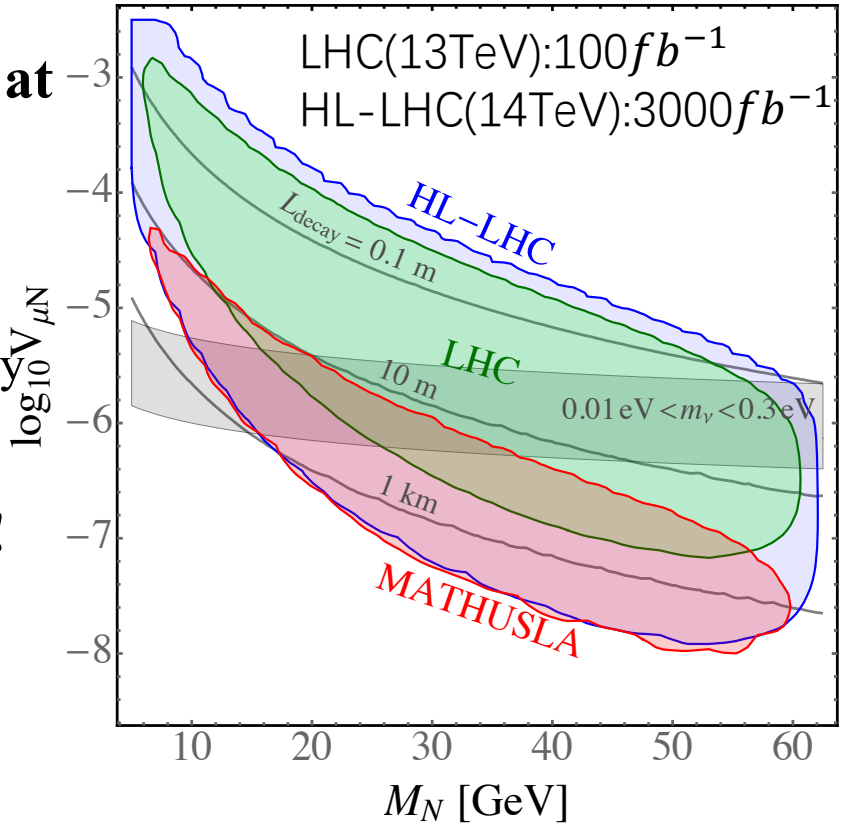
Figure from 1606.04645

Sensitivities of Different Colliders in Higgs channel

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

Assuming **no** events with **single displaced vertex** in any region are observed

- We take the largest experimentally allowed value $sin\ \alpha = 0.3$
- **Probing the Seesaw region!**
- **JHEP 08 (2018) 181**



Sensitivities of Different Colliders in Higgs channel

- **Excluded parameter space at 95% C.L.**
  Assuming **no** events with **single displaced vertex**
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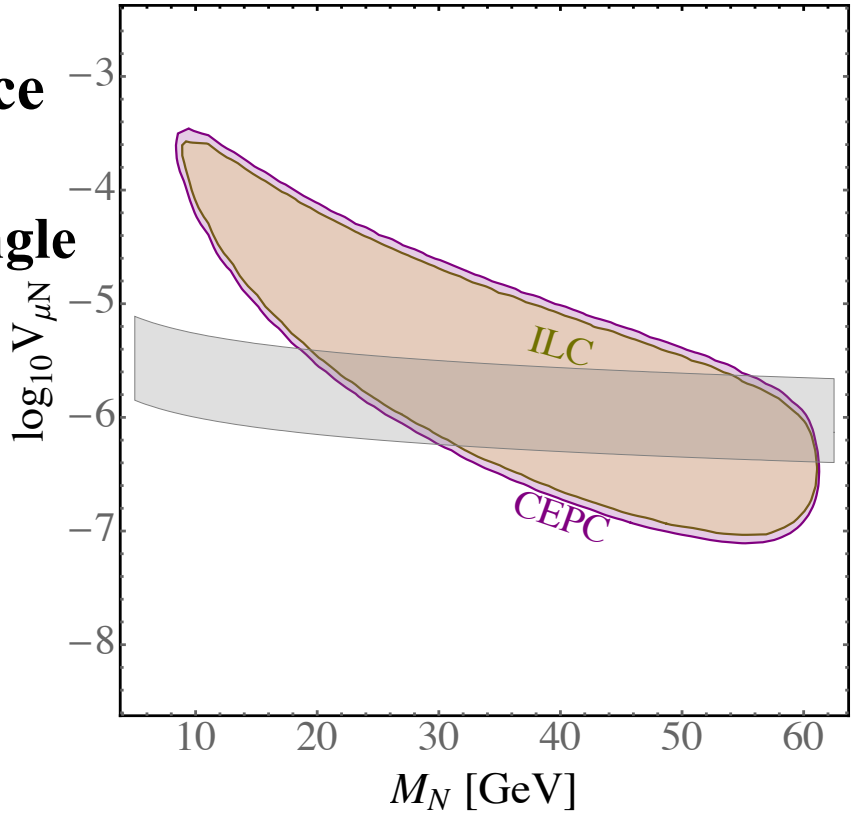
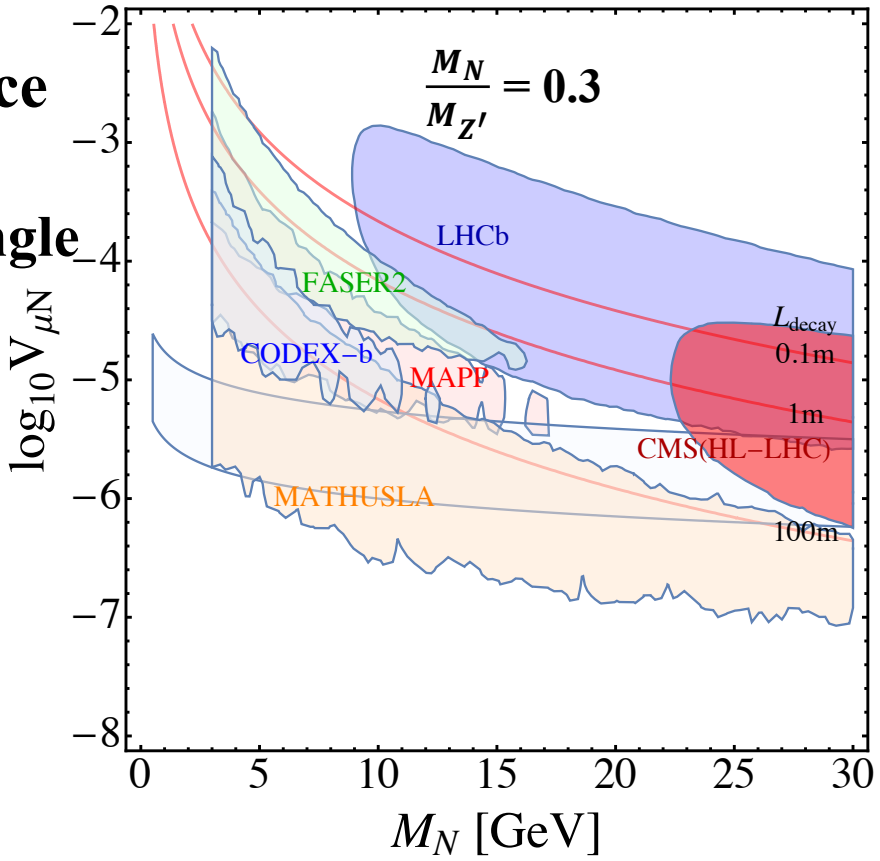


Sensitivities of Different Colliders in Z' channel

- **Excluded parameter space at 95% C.L.**
  Assuming **no** events with **single displaced vertex** in any region are observed
- **PRD100 (2019)3, 035005**



Conclusions

- **Seesaw points out $V_{lN} \sim 10^{-5}$ at the EW scale**
  - Direct production from active-sterile mixings to EW processes $10^7 pb \times V_{lN}^2$ <fb
  - Large decay length ~meters for such mixings, needs to search for DV
- **Pair-production of N at the LHC**
  - Suppressed by potentially sizeable Higgs mixing, $g_1{}'$, $M_{Z'}$ and M_N, independent of V_{lN}, current limits~ 50 fb, enhanced!
  - Can reach neutrino mixing as small as 10^{-7} at the LHC and lepton colliders
  - 1-2 magnitude improvement at HL-LHC
- **Probing Seesaw at the LHC!**

- **Back Up**

Symmetry Breaking and Higgs Mixing

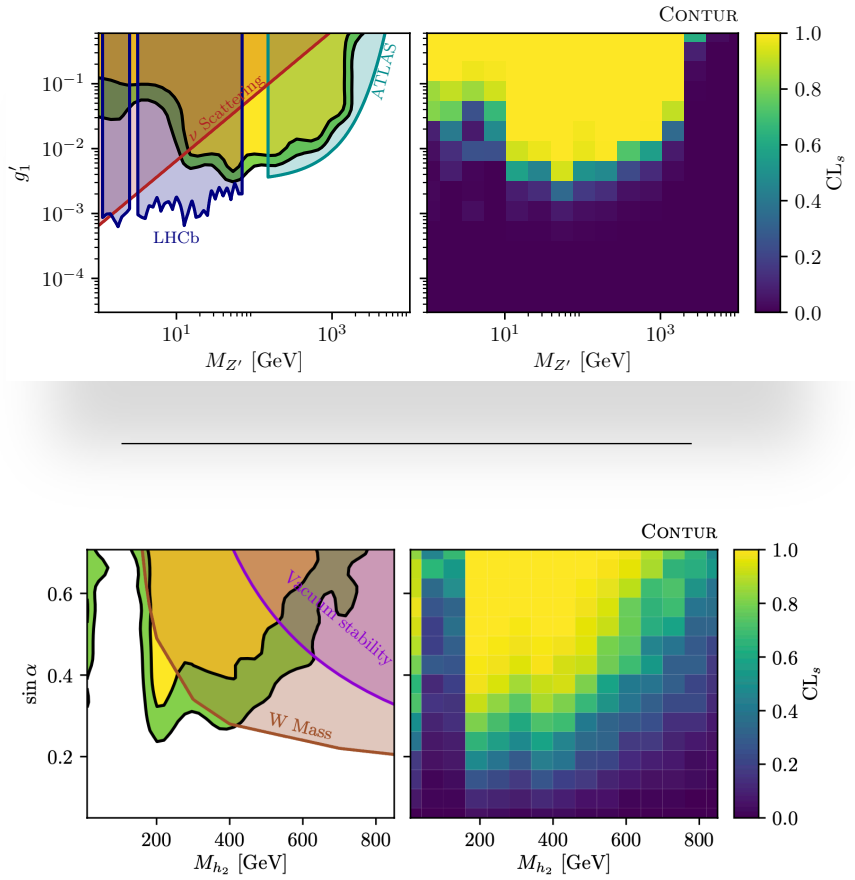
- **Mass Matrix**
  - $\boldsymbol{M} = \begin{pmatrix} \lambda_1 v^2 & \frac{\lambda_3 v_{B-L} v}{2} \\ \frac{\lambda_3 v_{B-L} v}{2} & \lambda_2 {v_{B-L}}^2 \end{pmatrix}$
  - $\boldsymbol{{M_{h_{1,2}}}^2 = \frac{1}{2}[M_{11} + M_{22} \pm \sqrt{(M_{11} - M_{22})^2 + 4{M_{12}}^2}]}$
  - $\boldsymbol{tan\, 2\alpha = \frac{2M_{12}}{M_{11} - M_{22}} = \frac{\lambda_3 v v_{B-L}}{\lambda_1 v^2 - \lambda_2 {v_{B-L}}^2}}$

Symmetry Breaking and Higgs Mixing

- **Vacuum Stability**
  - $\lambda_1 = \frac{1}{4v^2}[({M_{h_1}}^2 + {M_{h_2}}^2) - \cos 2\alpha\,({M_{h_2}}^2 - {M_{h_1}}^2)]$
  - $\lambda_2 = \frac{1}{4{v_{B-L}}^2}[({M_{h_1}}^2 + {M_{h_2}}^2) + \cos 2\alpha\,({M_{h_2}}^2 - {M_{h_1}}^2)]$
  - $\lambda_3 = \frac{1}{2vv_{B-L}}\cos 2\alpha\,({M_{h_2}}^2 - {M_{h_1}}^2)$
  - $4\,\lambda_1\,\lambda_2 - {\lambda_3}^2 > 0$ **"Mexican Hat'**
  - $\lambda_1 > 0, \lambda_2 > 0.$ **(figure from Taobao)**
- **Perturbativity Constraints**
  - $|\lambda_i| < 4\pi, i = 1,2,3$
- **Unitarity Consttraints…**

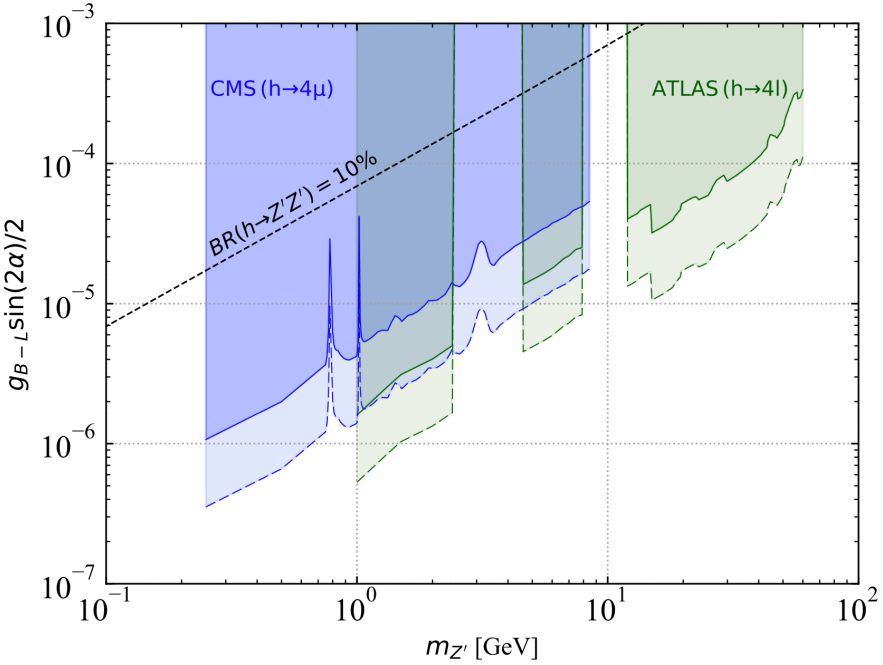
New limits using LHC Measurements

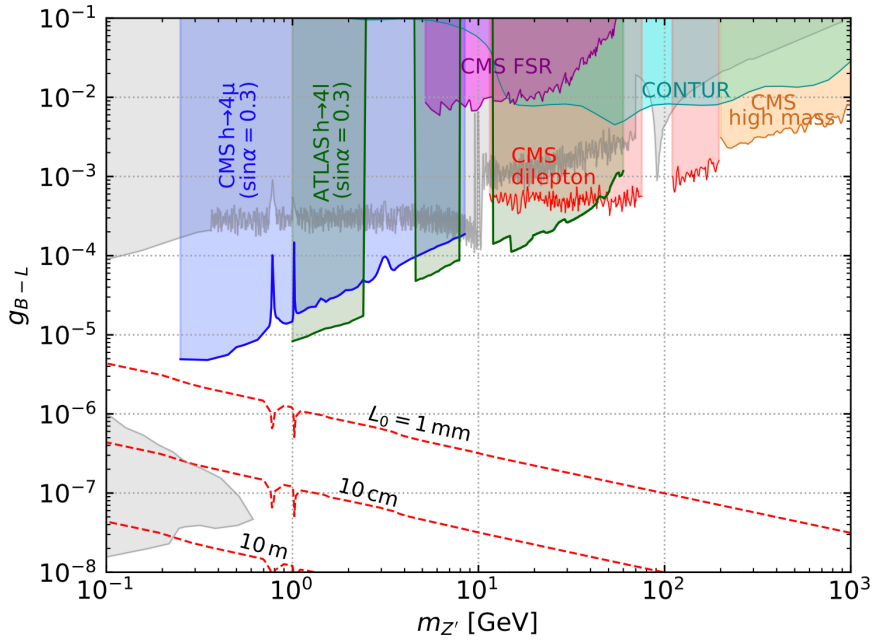
- S. Amrith, J. M. Butterworth, F. F. Deppisch, W. Liu, A. Varma and D. Yallup
- **JHEP 05 (2019) 154**
  arXiv:1811.11452



New limits using Four-lepton Searches

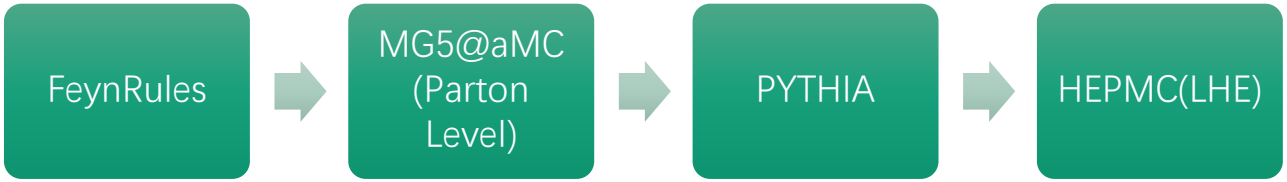
- Much better sensitivities comparing to other searches for large Higgs mixings
- Invalid after the Higgs precision measurements at future Higgs factories
- **PRD100 (2019)11, 115023**





Event Generation Tools

- Upgraded FeynRules model from arXiv:0812.4313
- **https://feynrules.irmp.ucl.ac.be/wiki/B-L-SM**



Geometric Selection

CMS:

- **Region 1**

$0.1m < R < 0.5m$, $L_Z < 1.4\text{m}$, $^{d_0}/_{\sigma_d^t} > 12$

- **Region 2**

$0.5m < R < 5m$, $L_Z < 8\text{m}$, $^{d_0}/_{\sigma_d^t} > 4$

ILC:

- **Region 1**

$0.217m < R < 1.2m$, $L_Z < 1.52\text{m}$, $^{d_0}/_{\sigma_d^t} > 12$

- **Region 2**

$1.2\text{m} < R < 3.3\text{m}$, $L_Z < 3\text{m}$

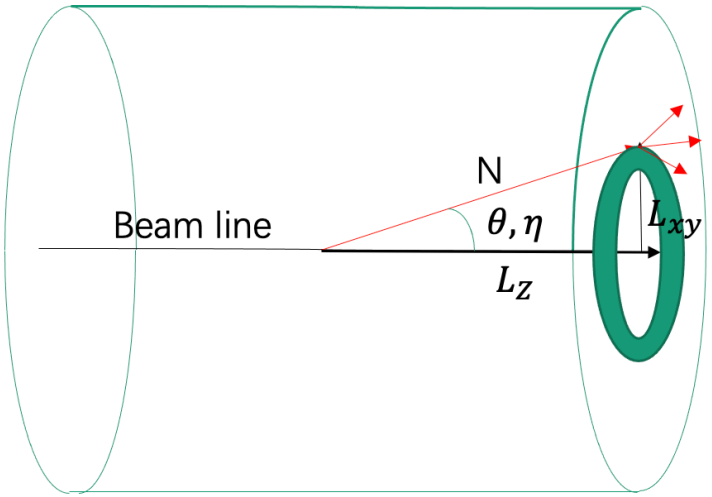
CEPC:

- **Region 1**

$1.53\text{m} < R < 1.8\text{m}$, $L_Z < 2.4\text{m}$, $^{d_0}/_{\sigma_d^t} > 12$

- **Region 2**

$1.8\text{m} < R < 4.4m$, $L_Z < 4\text{m}$, $^{d_0}/_{\sigma_d^t} > 4$



Geometric Selection

CODEX-b:
$26\text{m} < L_{\text{x}} < 36\text{m}, -3\text{m} < L_y < 7\text{m}, 5\text{m} < L_{\text{Z}} < 15\text{m}, E_{track} > 600$ MeV
FASER
$L_Z = 480\text{m}, L_d = 1.5\text{m}, 5\text{m}, \text{R} = 1\text{m}, 5\text{m}$
MAPP*
$L_Z \approx 30\sim60\text{m}, L_{\text{x}} \approx 4\sim15\text{m}, L_y \approx -10\sim10\text{m}$
LHCb
$0.02\text{m} < R < 0.5\text{m}, L_Z < 0.4\text{m}$, Vertex Locator
$0.005\text{m} < R < 0.6\text{m}, L_Z < 2\text{m}$, TT tracking station
$P_T(\mu) > 12\text{GeV}, M(\mu jj) > 4.5\text{GeV}$
MATHUSLA:
$L_x = -100\sim100\text{m}, L_y = 100\sim120\text{m}, L_z = 100\sim300\text{m}$