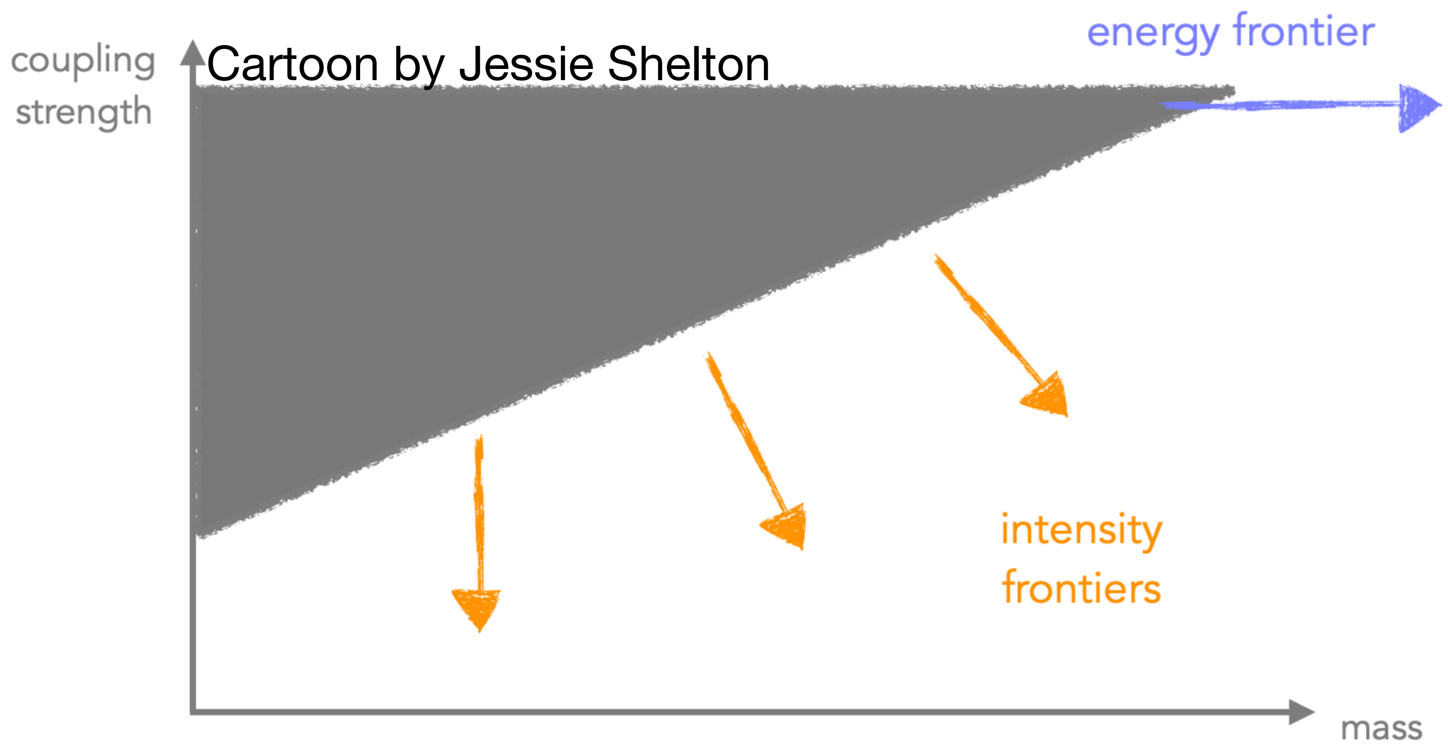
Exploring new physics at lifetime frontier

Suchita Kulkarni
Elise - Richter Fellow
HEPHY, Vienna
@suchi_kulkarni

Based on: arXiv:1905.11889 with F. Deppisch, W. Liu

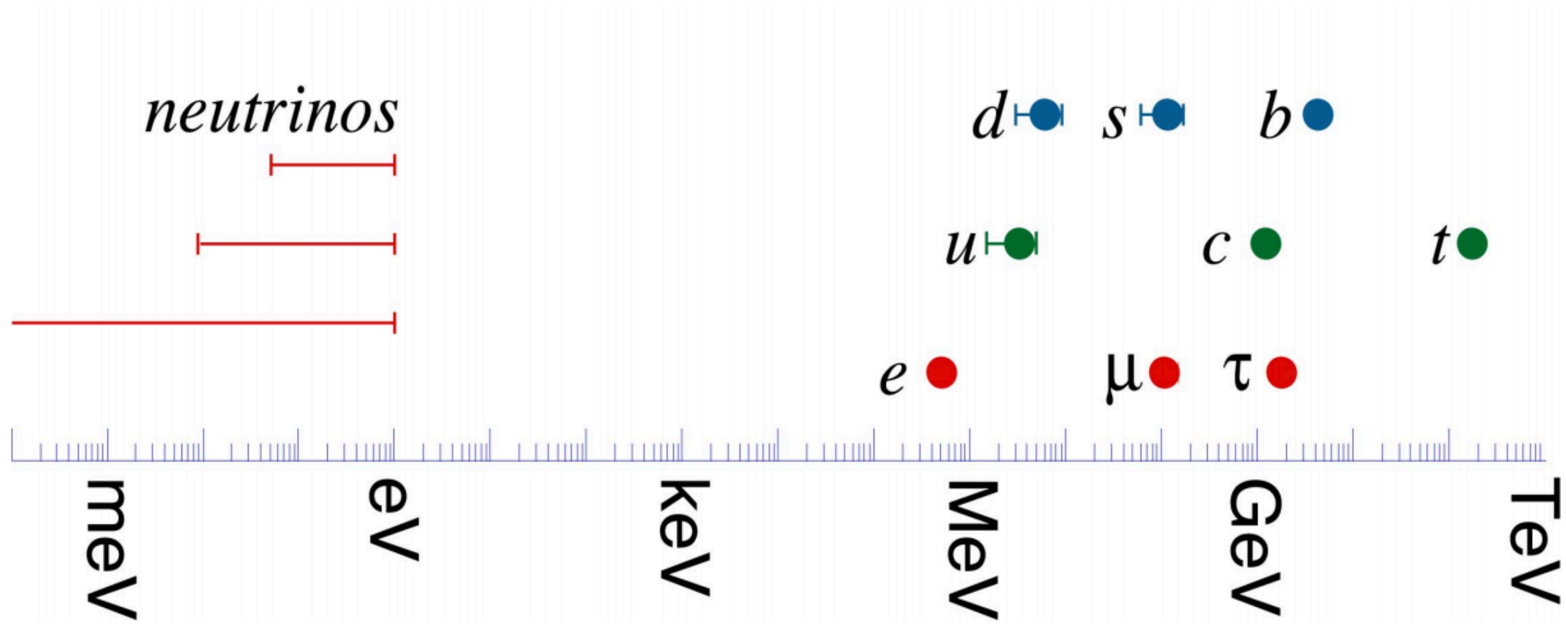
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK
FWF
Der Wissenschaftsfonds.
ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Beyond the standard model physics



- Third dimension: lifetime!
- Not well explored, LHC (ATLAS/CMS) not necessarily designed for lifetime dimension exploration
- Long lived particle searches: very little to no background

- Evidence of BSM physics
- Intimately related to new physics at lifetime frontier



Neutrino mass generation mechanisms

- SM + right handed fields —Tiny Yukawa→ • Small Dirac neutrino masses

- RH fields mass term —Lepton number violation→ • Baryogenesis through leptogenesis

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^\mathsf{T} & M_N \end{pmatrix}$$

Dirac mass, usually small Y_ν

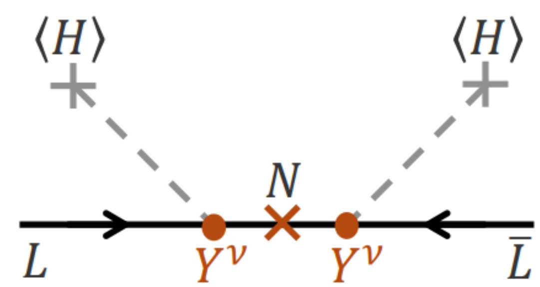
Majorana mass, can be heavy, can have $Y_N \sim 1$, introduces Lepton number violation

$$\mathcal{L} \supset Y_{ij}^{\nu} \overline{N}_i \ L_j \cdot H - \frac{1}{2} M_{ij} \overline{N}_i \ N_j^c$$

See e.g. Deppisch, New J. Phys. 17 (2015) 075019

Many faces of lifetime

- Let us go to one extreme $M_N \approx 10^{14}$ GeV (GUT scale)



$$\mathcal{L} \supset Y^\nu_{ij} \bar{N}_i \; L_j \cdot H - \frac{1}{2} M_{ij} \bar{N}_i \; N^c_j \xrightarrow[\langle H \rangle \ll M_N]{} \frac{1}{2} (Y^\nu_{ki} M^{-1}_{kl} Y^\nu_{lj}) (\bar{L}^c_i \cdot H)(H^T \cdot L_j)$$

- Light neutrino mass

$$m_\nu \approx 0.1 \text{ eV} \left(\frac{Y_\nu \langle H \rangle}{100 \text{ GeV}} \right)^2 \left(\frac{10^{14} \text{ GeV}}{M} \right)$$

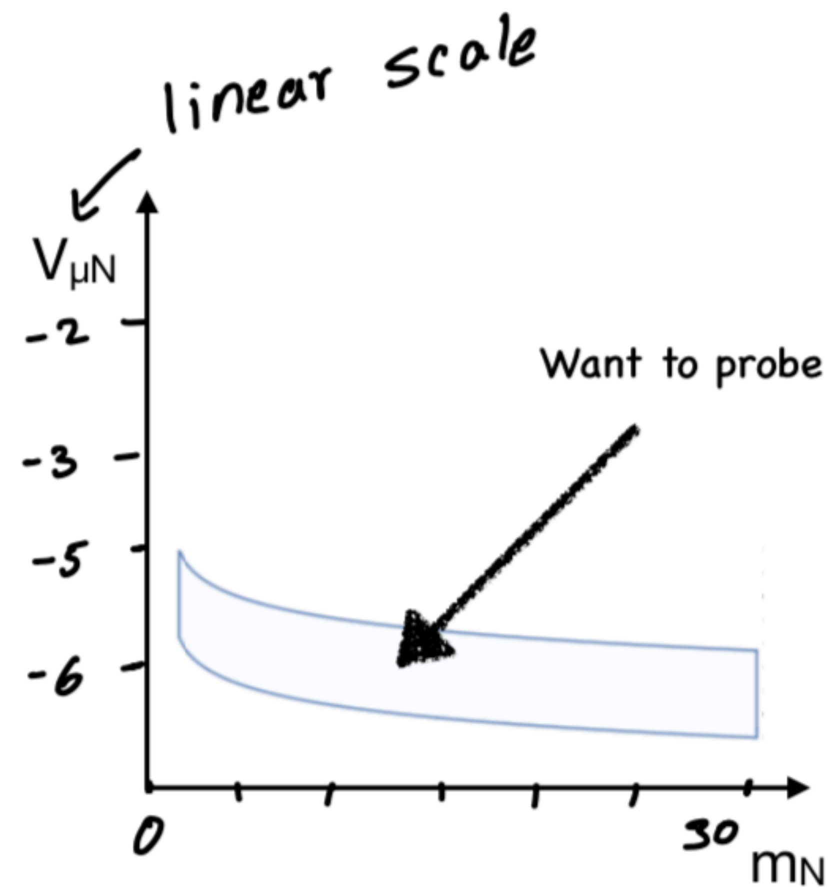
- Sterile neutrino mass scale M_N unknown
  - $\approx 10^{14}$ GeV — Naive seesaw, GUTs
  - $\gtrsim 10^{9}$ GeV — Thermal leptogenesis
  - $\approx 10^{3}$ GeV — Production at the LHC
  - ≈ 1 keV — Dark matter candidate
  - ≈ 1 eV — Oscillations, cosmology, 0νββ

Region of interest for this talk

Neutrino masses - a simple model

- Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- Characteristics
  - **Particle content**: B-L gauge boson (Z'), Higgs boson (χ_{B-L}), 3 heavy neutrinos (N)
  - **Couplings**: g'_{B-L} (B-L coupling), $\sin\alpha$ (χ_{B-L}, Higgs mixing), V_{lN} (neutrino mixing)
  - **Free parameters**: 5 masses, 5 couplings (diagonal V_{lN})
    - Assume only light muon neutrino → 3 masses, 3 couplings
  - **Charges**: χ: +2; N: -1; q: 1/3; l:-1

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad m_\nu \approx -\frac{M_D^2}{M_R} = -V_{lN}^2 M_R$$



- Heavy neutrino lifetime

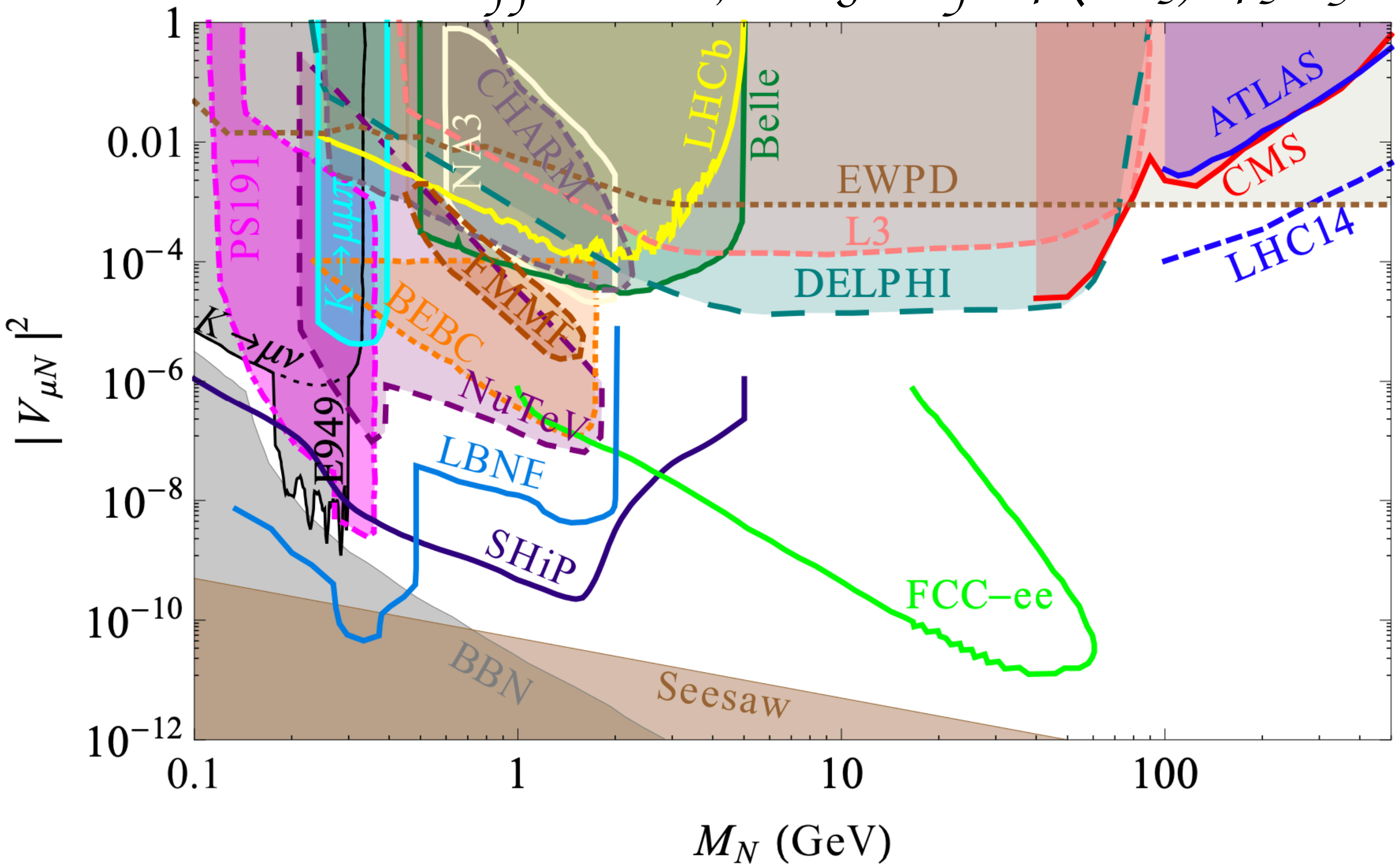
$$L_N \approx 0.025\ \text{m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100\ \text{GeV}}{m_N}\right)^5$$

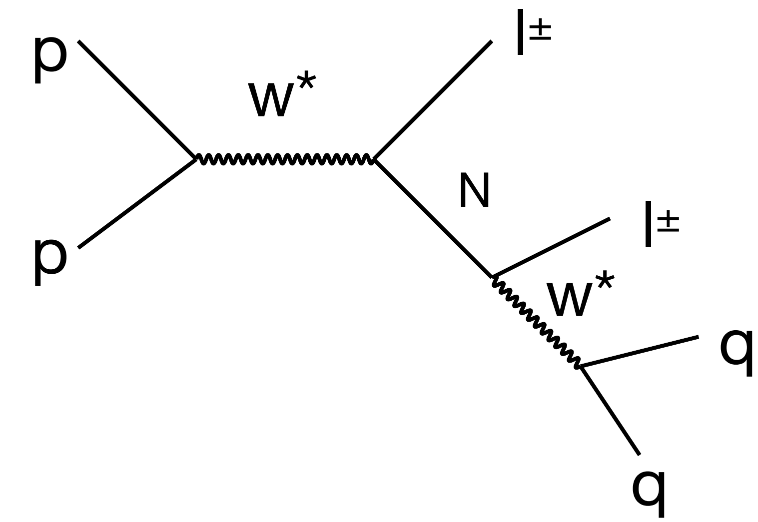
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

HNL at colliders - current status

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Deppisch et al, New J. Phys. 17 (2015) 075019



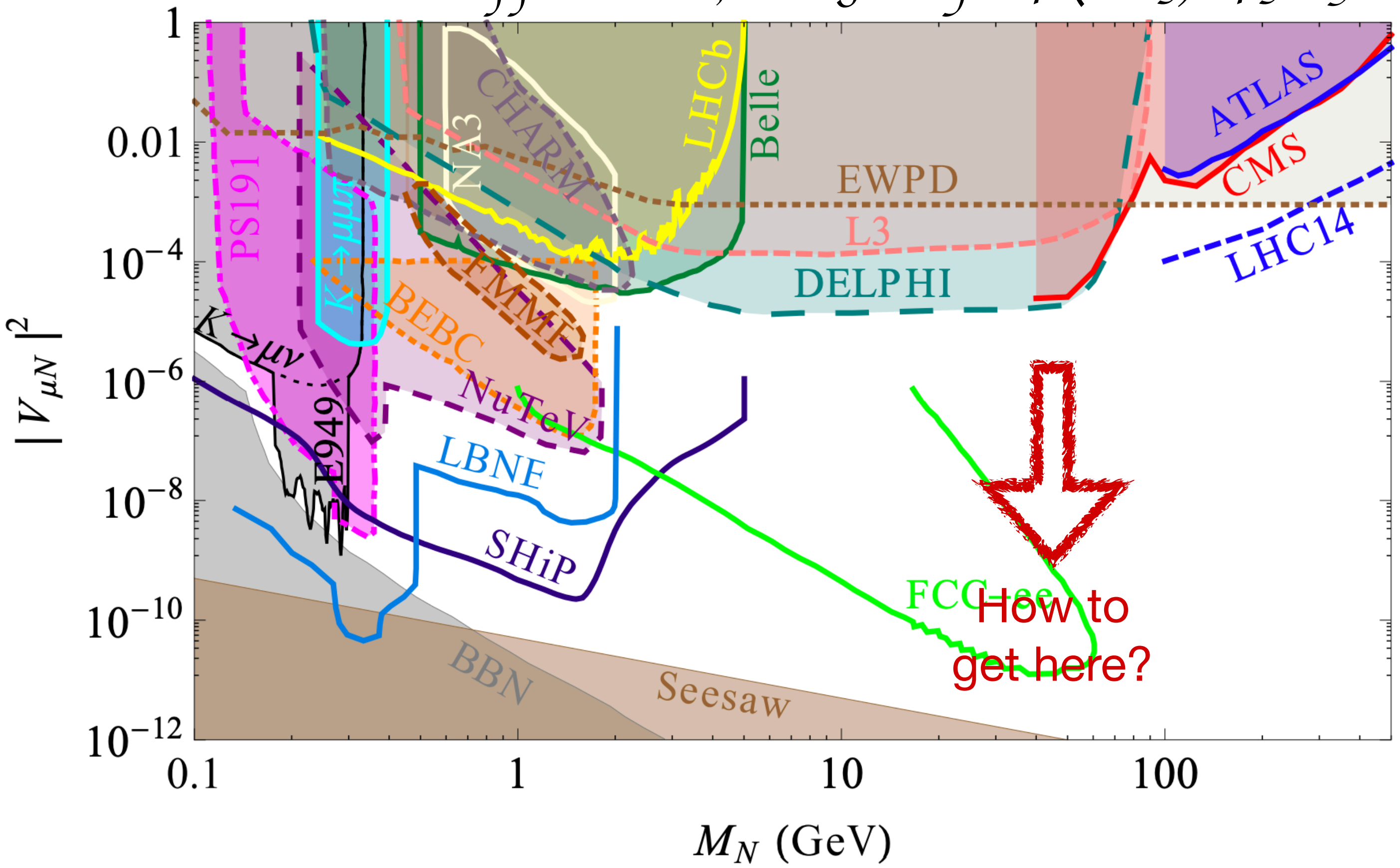


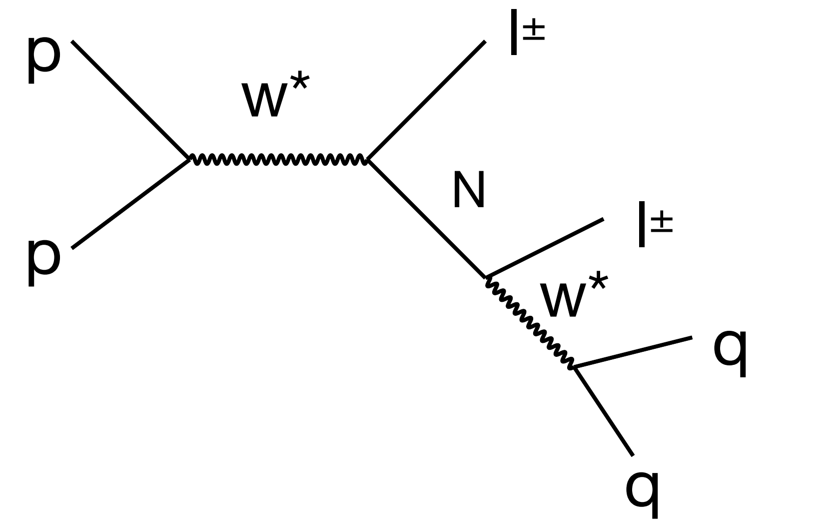
- Typical LHC search, minimal process

- Several probes for heavy neutrinos (aka heavy neutral leptons; HNL)
- Intensity frontier typically covers low masses; small mixing angles
- Limit plot corresponds to HNL production via SM mediators, B-L charges not taken into account
- At the LHC, same sign leptons from production (decays) of heavy neutrinos via SM W boson
- Current LHC limits very weak, rapidly changing situation

HNL at colliders - the final frontier

Deppisch et al, New J. Phys. 17 (2015) 075019





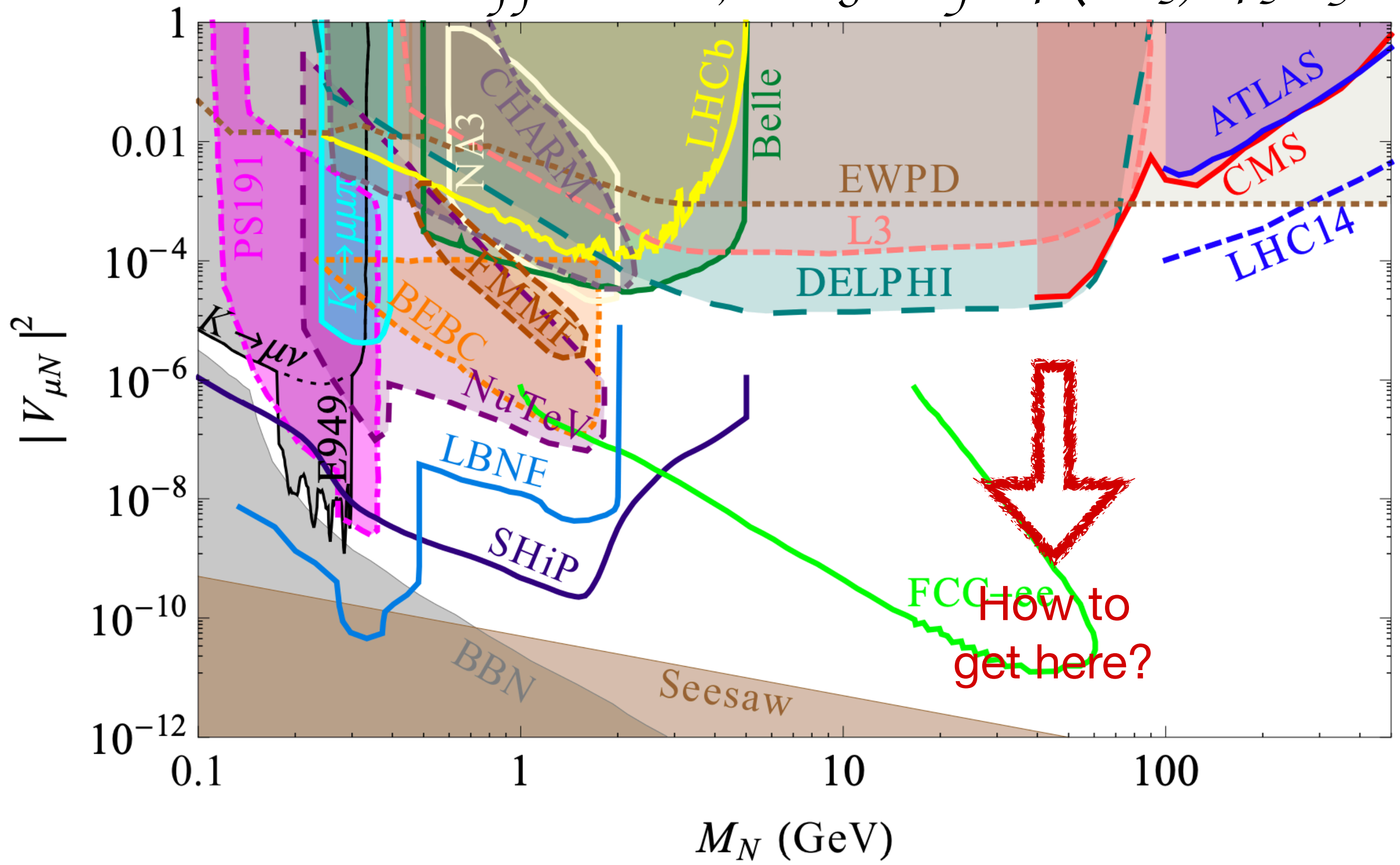
- Heavy neutrino decay length

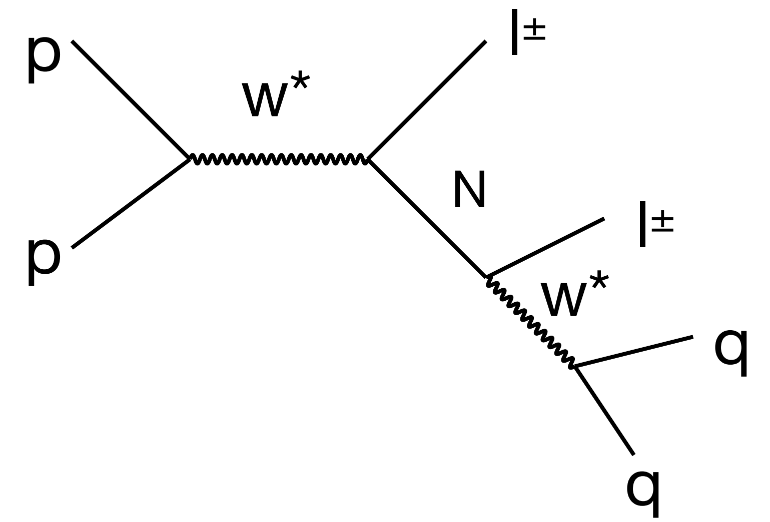
$$L_N \approx 0.025 \text{ m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100 \text{ GeV}}{m_N}\right)^5$$

- Build FCC!
- Heavy neutrino phenomenology at LHC necessitates exploration at lifetime frontier
- For neutrino masses ≈ 100’s of GeV, $V_{\mu N} \approx 10^{-6} \rightarrow L_N \approx$ 25mm
- Problem: $V_{\mu N}$ suppression → have higher luminosity
- Neutrino mass of order 10 GeV, $V_{\mu N} \approx 10^{-6}$, $L_N \approx$ 100m, decays outside of the LHC → build bigger detectors; several proposals exist

HNL at colliders - new processes

Deppisch et al, New J. Phys. 17 (2015) 075019

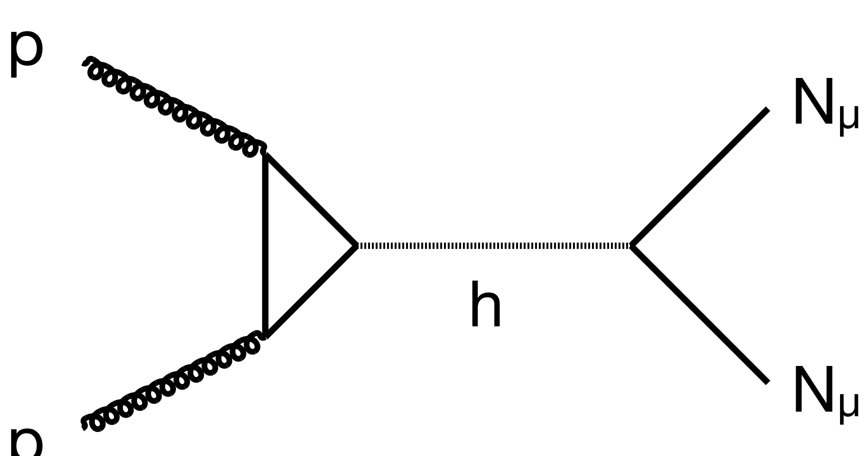




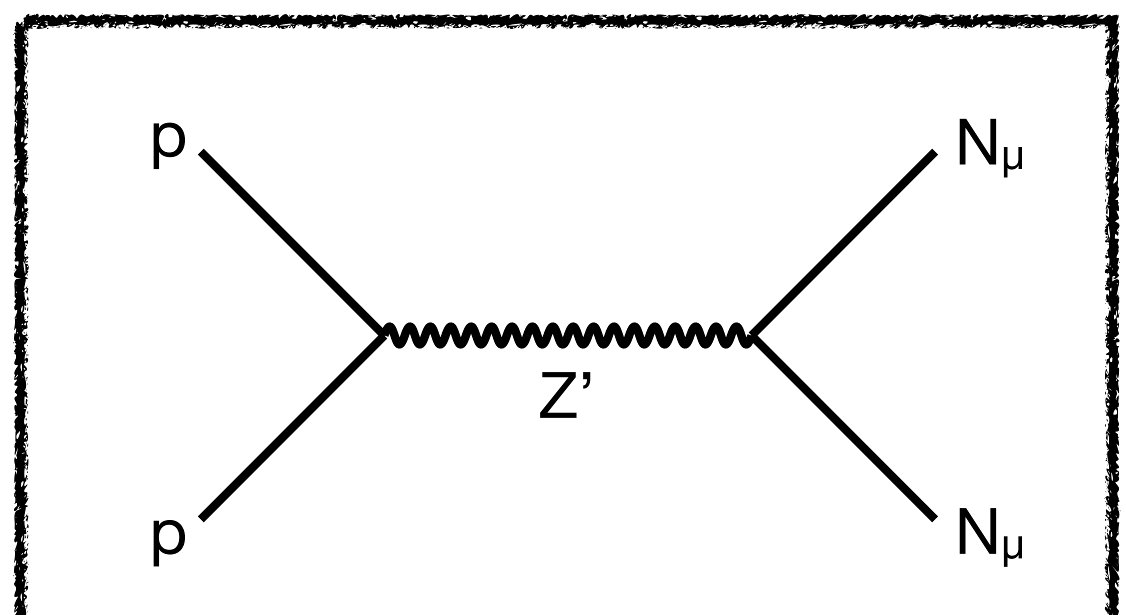
- Heavy neutrino decay length

$$L_N \approx 0.025\ \mathrm{m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100\ \mathrm{GeV}}{m_N}\right)^5$$

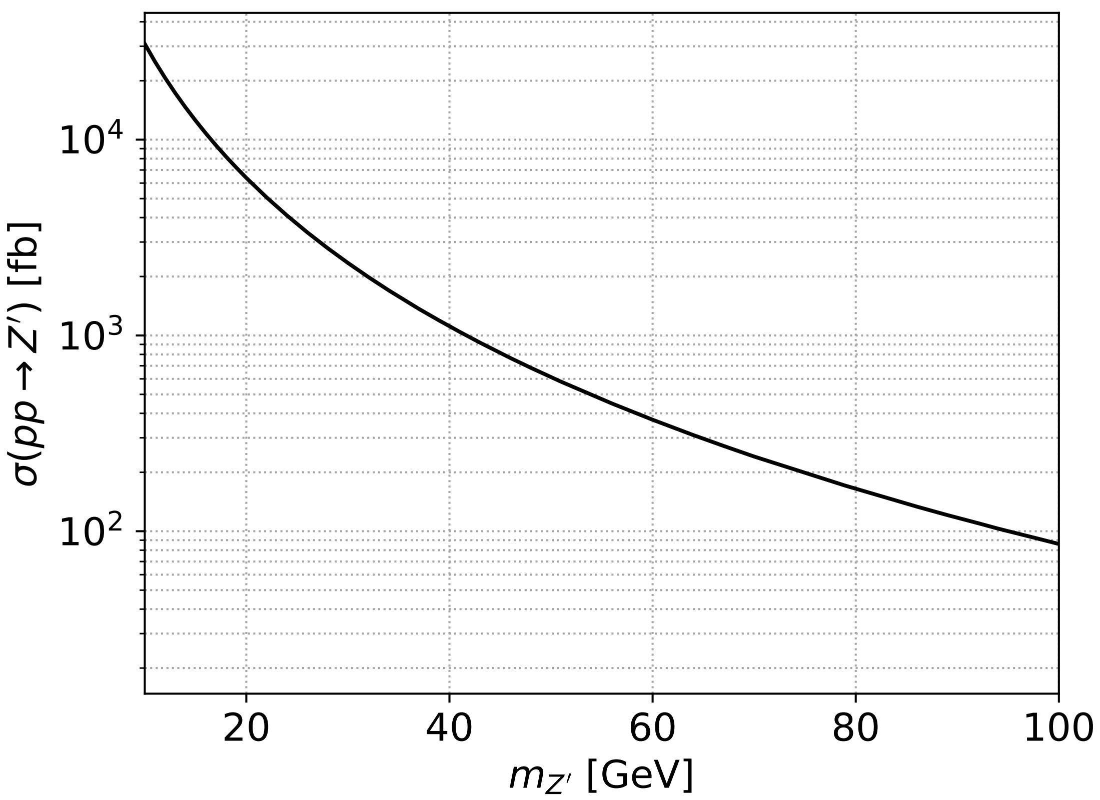
- B-L specific processes

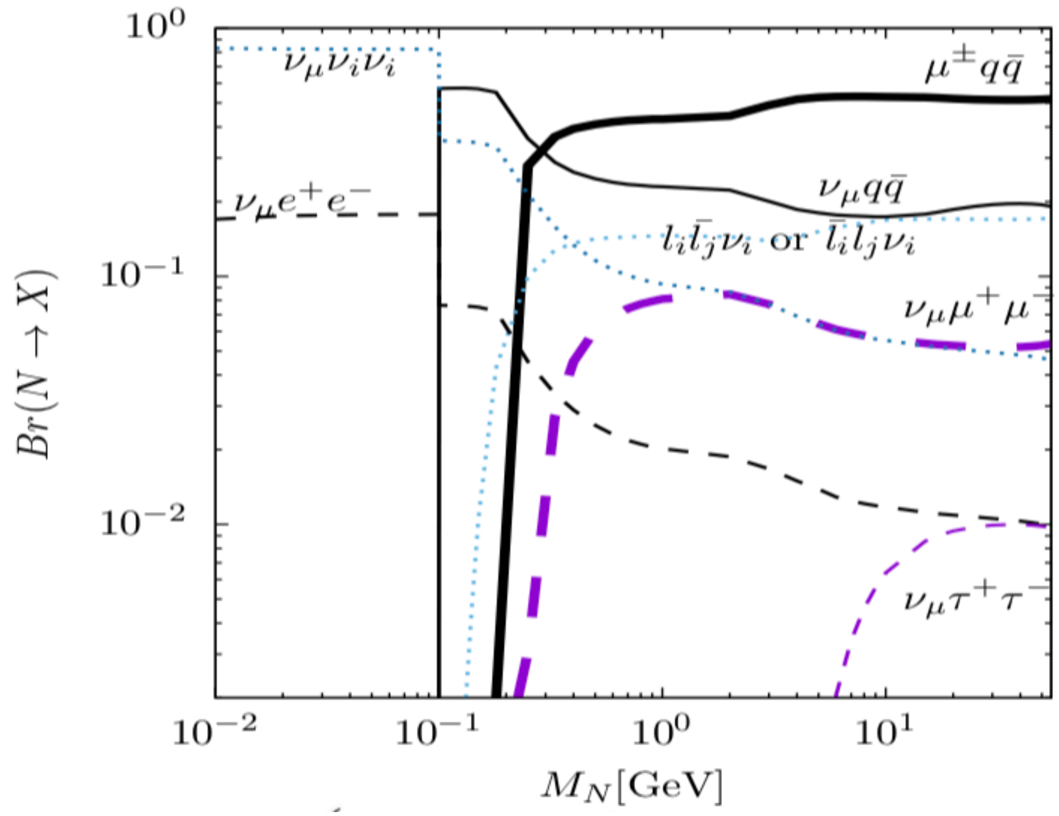


Deppisch et al, JHEP 1808 (2018) 181



Back of the envelope

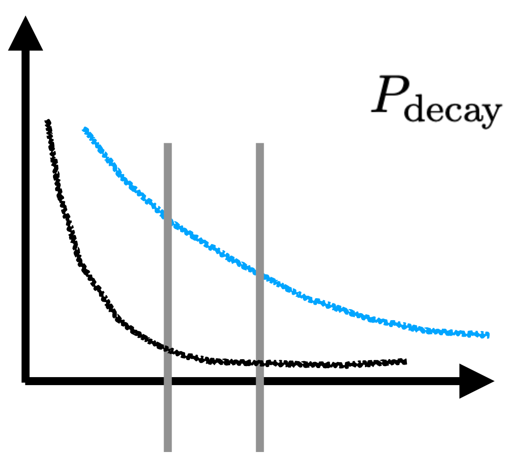




- Significant Z' production cross section
- BR(Z'→ N N) ~ 8% (per specie)
- Branching ratio N to at least one muon final state between 10 to 30%
- Typical HNL decay lengths ($V_{\mu N} \approx 10^{-6}$): O(100) m
- Potential for good reach in neutrino mixing angle at future facilities

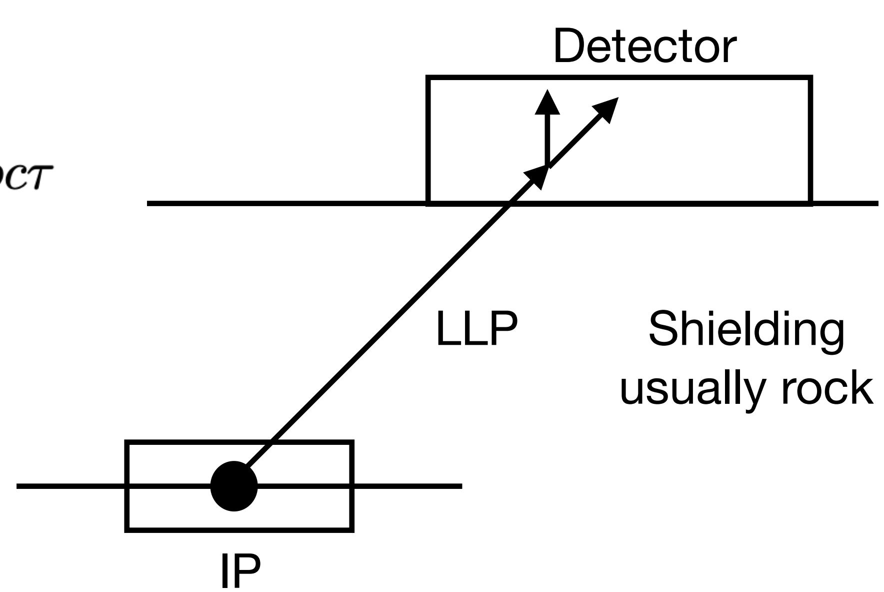
Proposed lifetime frontier detectors

Detector	Location	Distance from IP (m)	Dimensions (m)	Luminosity (fb^{-1})
FASER-2	ATLAS	480	Cylinder 5 X1	3000
CODEX-b	LHC cavity	3	10 X 10 X 10	300
MAPP	LHCb/ MoEDAL	50	7 - 10 tunnel 5 - 25 degrees angle	300
MATHUSLA	CMS	100	200 X 200 X 20	3000



$$P_{\rm decay}(bc\tau, L_1, L_2) = e^{-\frac{L_1}{bc\tau}} - e^{-\frac{L_2}{bc\tau}}$$

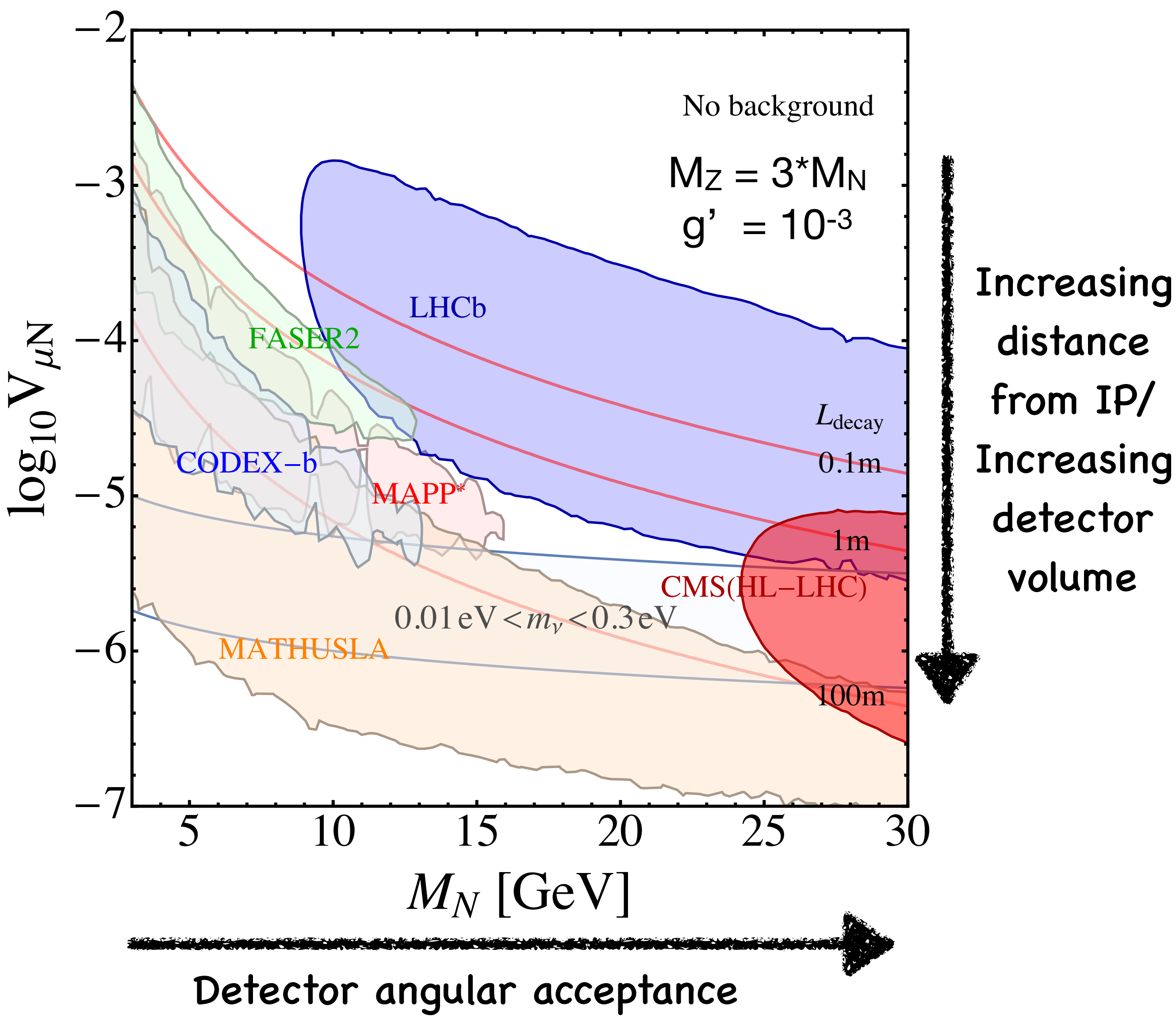
$$\approx \frac{L_2 - L_1}{bc\tau} \quad \text{for } (L_2 - L_1) \ll bc\tau$$



$$N_{obs} \approx (\sigma_{sig}^{LHC} \mathcal{L})\, \epsilon_{LLP}^{detector}\, n_{LLP}\, \epsilon_{geometric}\, P_{decay}(\bar{b}c\tau, L_1, L_2)$$

- Detectors work only for long lived neutral particles

Decays via Z'



- For LHCb, use μjj final state; CMS μμν
- For other detector any final state allowed
- Look at the decay of only one heavy neutrino
- Apply some minimal cuts on the p_T and $|\eta|$ of final state particles
- Assume all neutrino decays within the detector volume are detected
- Nice interplay of boost and lifetime
- Detector of maximal interest: MATHUSLA
- ATLAS/CMS trigger requirements too high

Conclusions

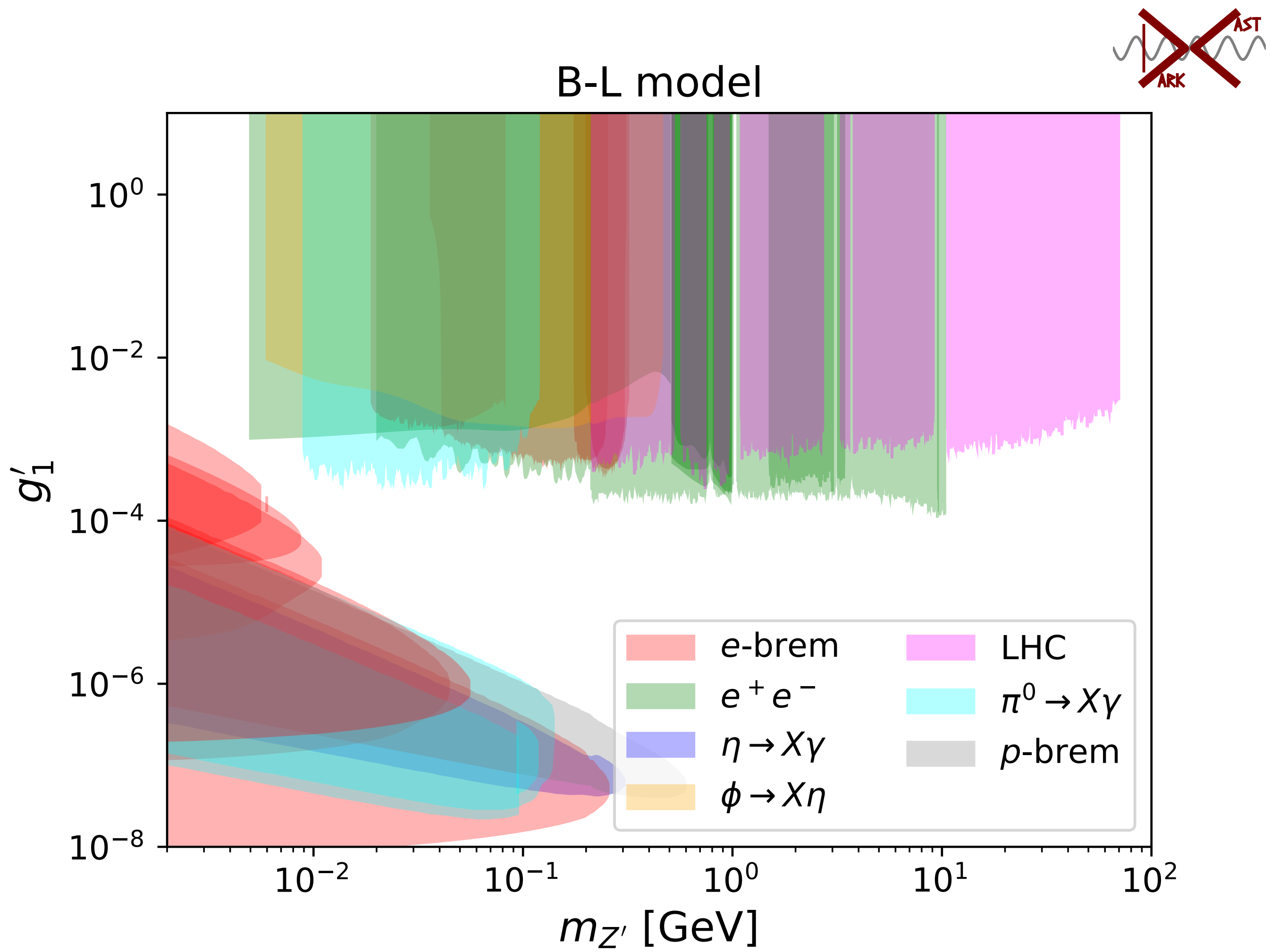
- In the hunt for new physics, exotic decays of BSM particles are less explored
- Neutrino physics provides a well motivated reason to expect new physics at the lifetime frontier
- Several new detectors to explore lifetime dimension for long lived neutral particles at the LHC are proposed
- B-L models one of the simplest extensions of SM physics providing explanations of neutrino masses
- Heavy neutrino production can take place via SM Higgs or B-L Z’ decays
- They probe different regions of B-L parameter space
- Have potential to probe neutrino mixing angles responsible for neutrino mass generations

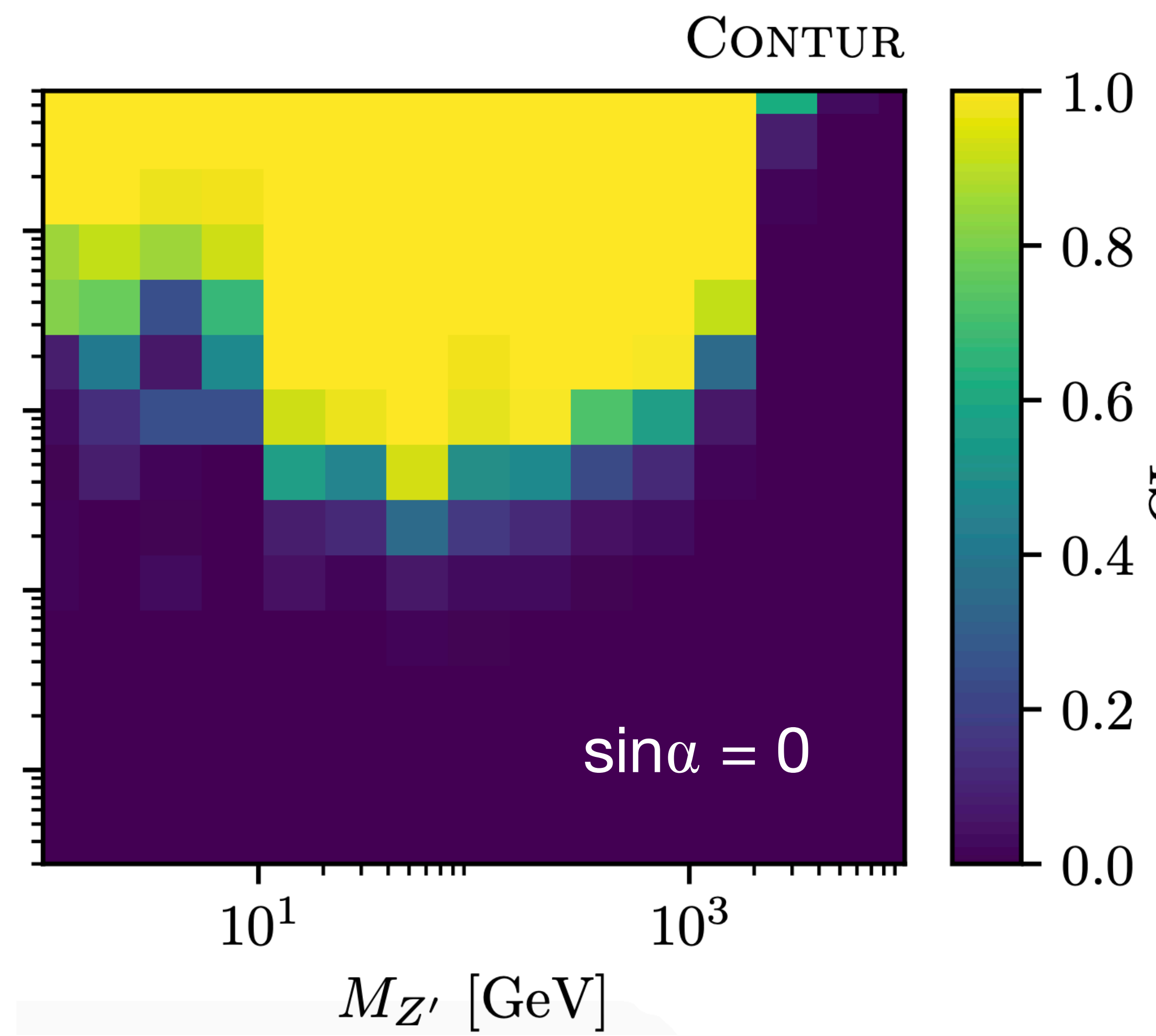
Thank you!

Backup

Current constraints

- Current constraints on the Z’ masses come from LHC as well as fixed target experiments
- Reinterpretation of LHC SM searches done via CONTUR



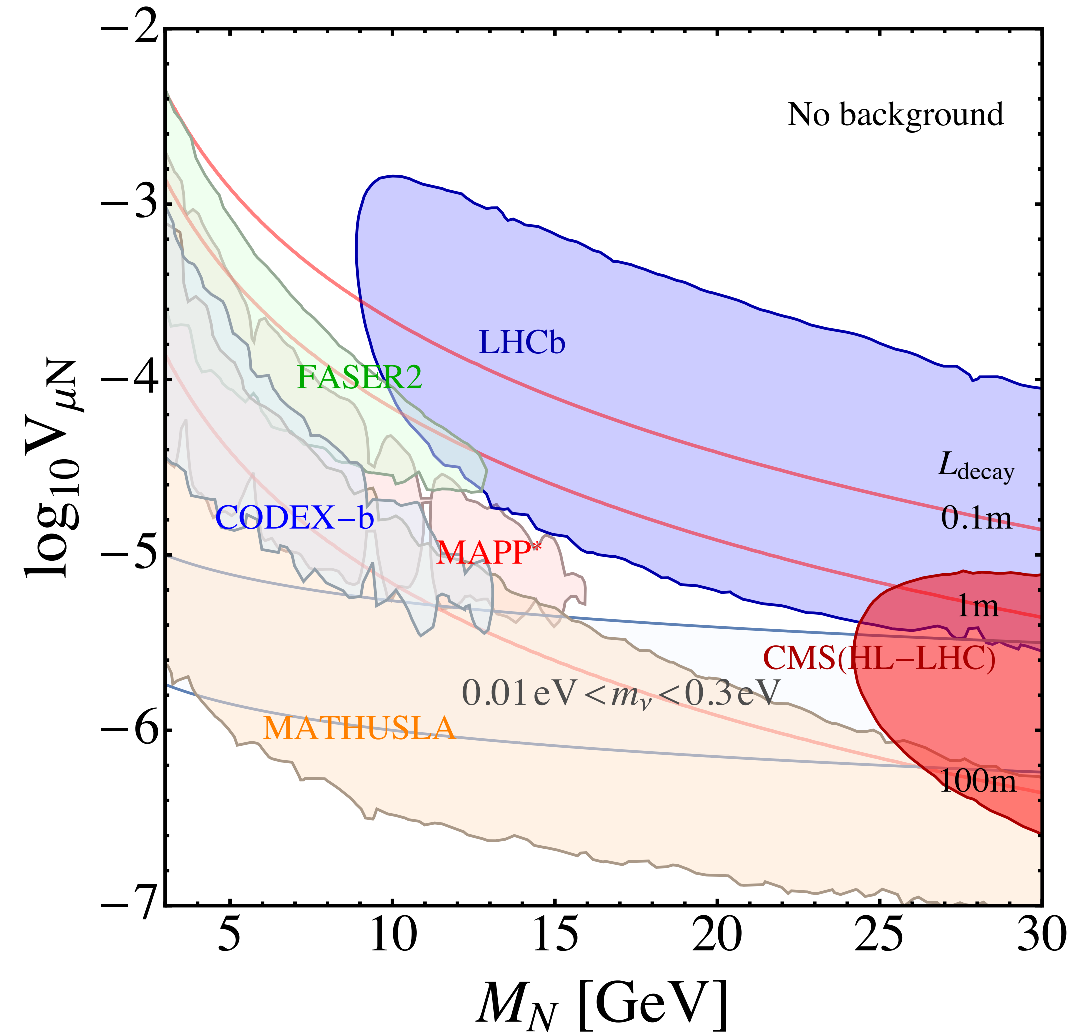


HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

Decays via Z'

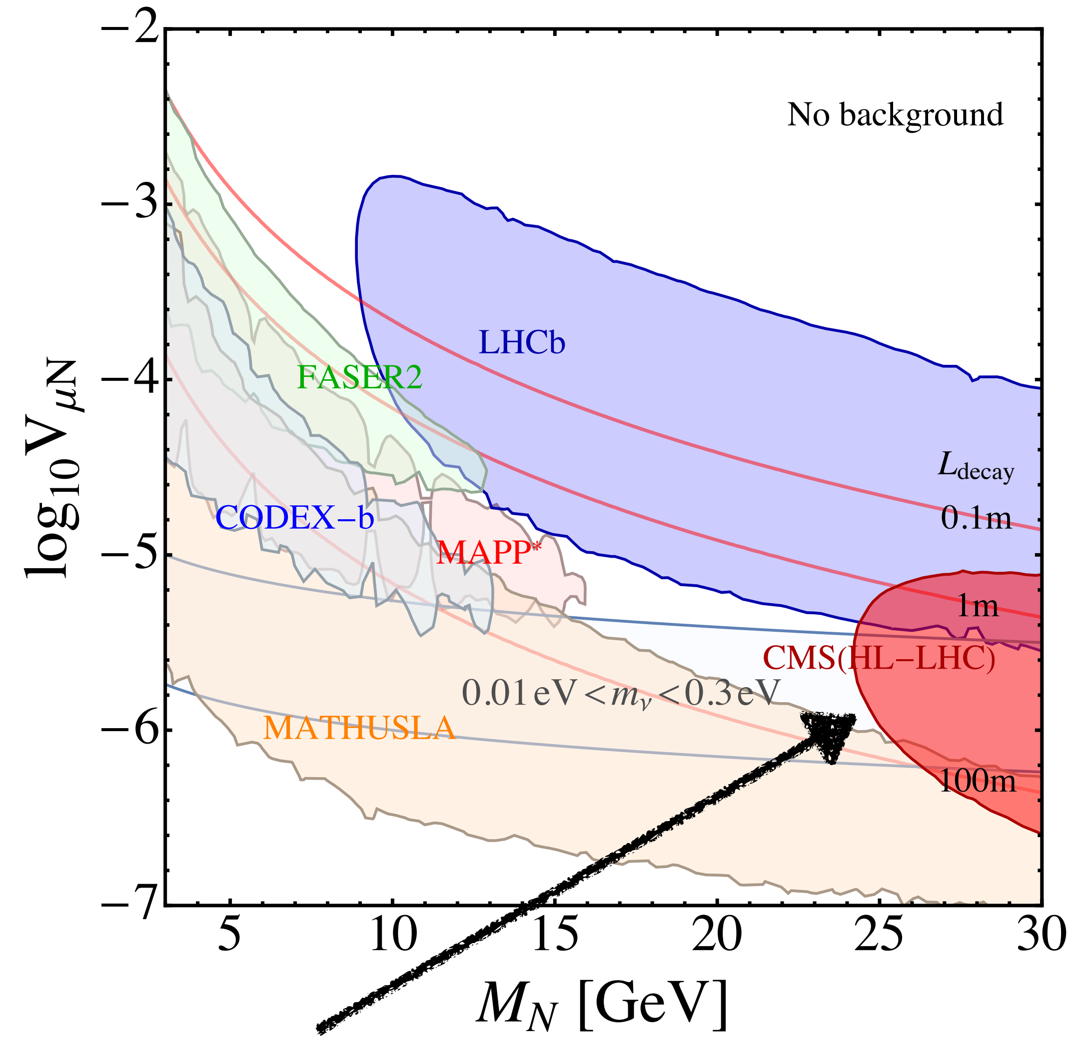
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

- Principle difference: scale of the process controlled by mass of Z', boost of neutrino controlled by mass difference between $m_{Z'}$ and m_N
- Lifetime frontier detectors considered: MATHUSLA, FASER, CODEX-b, MAPP*
- LHC detectors: general purpose LHC, LHCb
- Final states under considerations:
  - LHCb: p p → N N → N μjj
  - General purpose LHC: p p → N N → N μμν
  - MATHUSLA, FASER, CODEX-b: p p → N N
- Cuts:
  - L_z = 480m, L_d = 1.5m, 5m, R = 1m, 5m [FASER]
  - L_z~30 - 60m, L_x~4 - 15m, L_y~-10 - 10m [MAPP*]
  - L_x = –100~100m L_y= 100~120m, L_z = 100~300m [MATHUSLA]



Decays via Z’

- Principle difference: scale of the process controlled by mass of Z’, boost of neutrino controlled by mass difference between $m_{Z'}$ and m_N
- Lifetime frontier detectors considered: MATHUSLA, FASER, CODEX-b, MAPP*
- LHC detectors: general purpose LHC, LHCb
- Final states under considerations:
  - LHCb: p p → N N → N μjj
  - General purpose LHC: p p → N N → N μμν
  - MATHUSLA, FASER, CODEX-b: p p → N N
- Cuts:
  - L_z = 480m, L_d = 1.5m, 5m, R = 1m, 5m [FASER]
  - L_z~30 - 60m, L_x~4 - 15m, L_y~-10 - 10m [MAPP*]
  - L_x = –100~100m L_y= 100~120m, L_z = 100~300m [MATHUSLA]

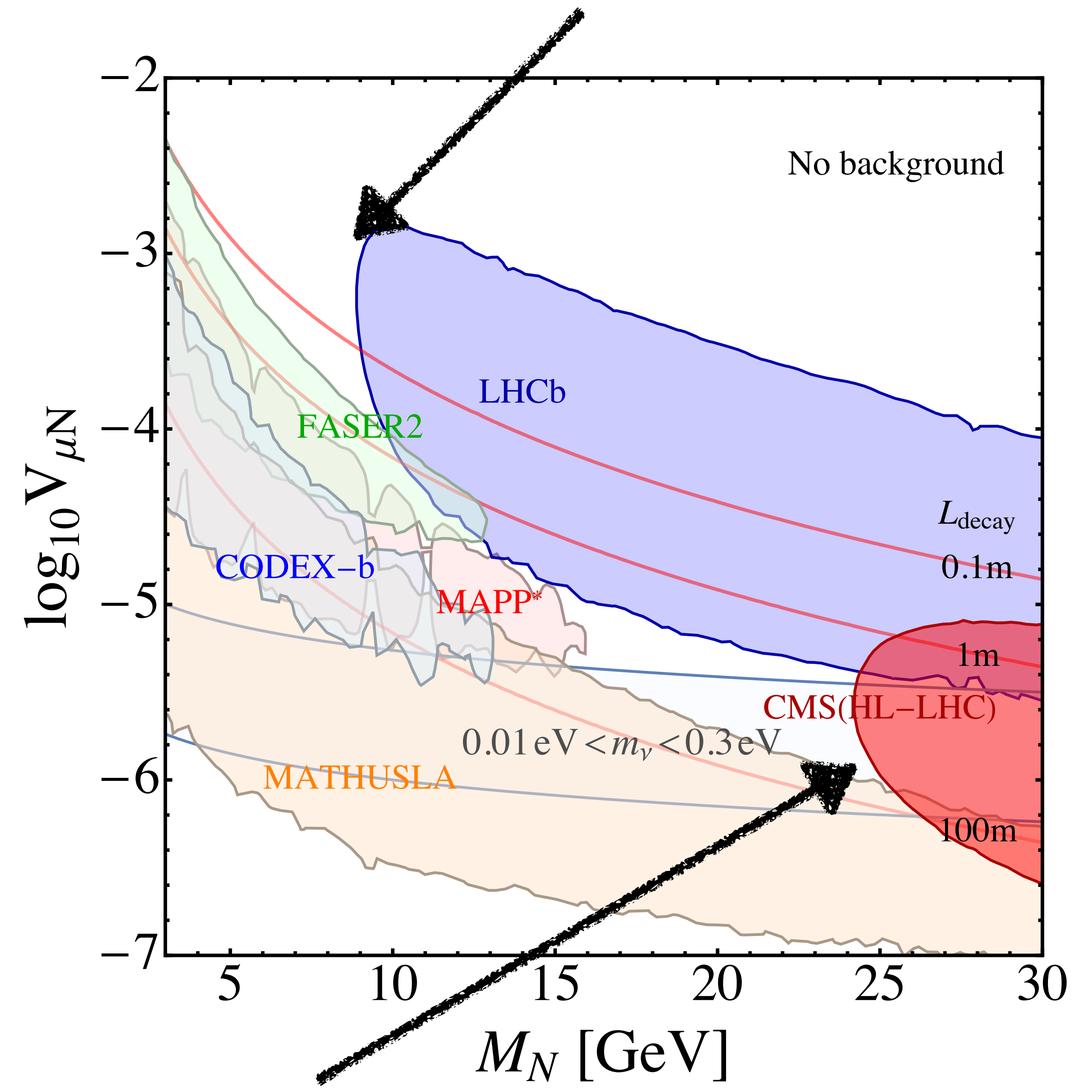


Needs better reinterpretation (ongoing)

Decays via Z’

- Principle difference: scale of the process controlled by mass of Z’, boost of neutrino controlled by mass difference between $m_{Z'}$ and m_N
- Lifetime frontier detectors considered: MATHUSLA, FASER, CODEX-b, MAPP*
- LHC detectors: general purpose LHC, LHCb
- Final states under considerations:
  - LHCb: p p → N N → N μjj
  - General purpose LHC: p p → N N → N μμν
  - MATHUSLA, FASER, CODEX-b: p p → N N
- Cuts:
  - L_z = 480m, L_d = 1.5m, 5m, R = 1m, 5m [FASER]
  - L_z~30 - 60m, L_x~4 - 15m, L_y~-10 - 10m [MAPP*]
  - L_x = –100~100m L_y= 100~120m, L_z = 100~300m [MATHUSLA]

Analysis req. μjj > 4.5 GeV



Needs better reinterpretation (ongoing)

CMS

- Two different regions

CMS:

- **Region 1**
  $0.1m < R < 0.5m,\ L_Z < 1.4\text{m}$
- **Region 2**
  $0.5m < R < 5m,\ L_Z < 8\text{m}$