Prospects of Sterile Neutrino Search with the FCC-ee

Sissel Bay Nielsen

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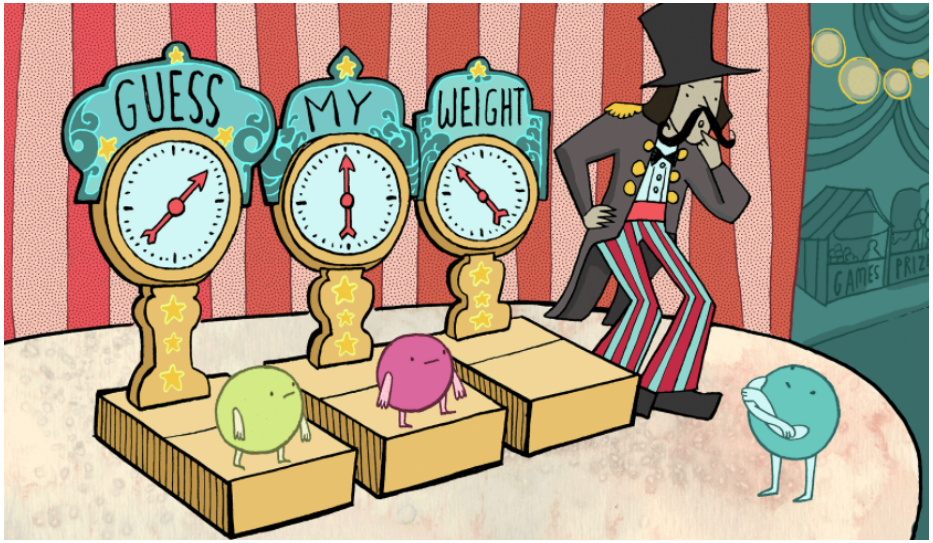
Outline

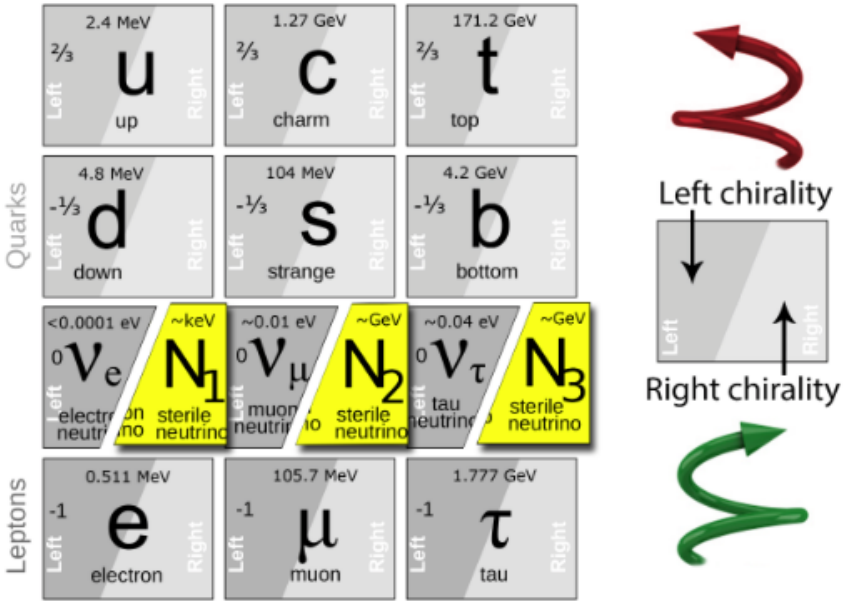
- Neutrino Minimal Standard Model: νMSM
- Future Circular Collider: FCC-ee
- Previous bounds on sterile neutrinos
- Two different searches :
  1. Sterile neutrinos with long lifetime
  2. Sterile neutrinos with short lifetime



Theoretical Motivation for Sterile Neutrinos and the νMSM

- SM very successful theory measured with high precision.
- Physics beyond the Standard Model.
- νMSM [4] accommodates explanations for

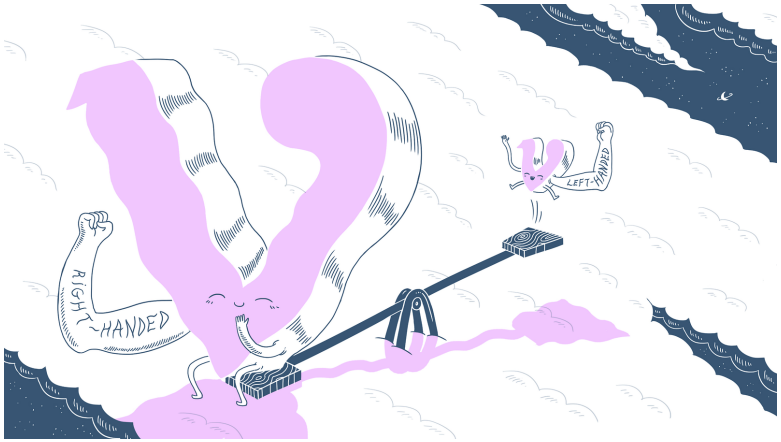
  - Mass of the neutrinos
  - Dark Matter
  - Baryon asymmetry in the Universe



Seesaw Mechanism

$$m_\nu \simeq \frac{(m_{\text{Dirac}})^2}{M_{\text{Majorana}}} \ , \qquad m_N \simeq M_{\text{Majorana}} \ ,$$

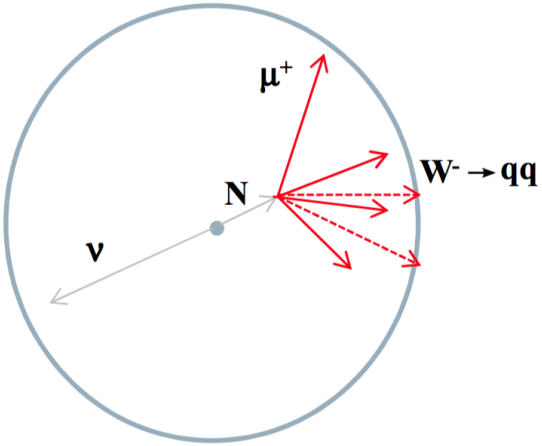
$$\nu_L \simeq \nu \cos(\theta) + N \sin(\theta) \quad [5]$$

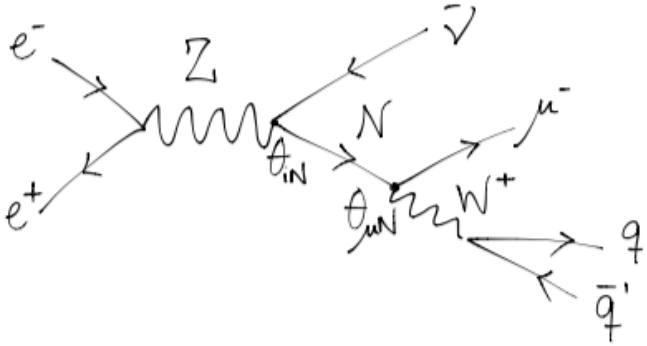


Phenomenology of the Sterile Neutrino

Sterile Neutrinos produced from Z decays:

$$e^+e^- \to Z \to N\bar{\nu}$$





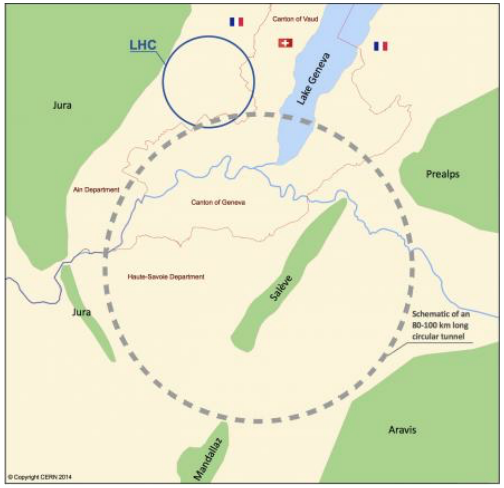
[6]

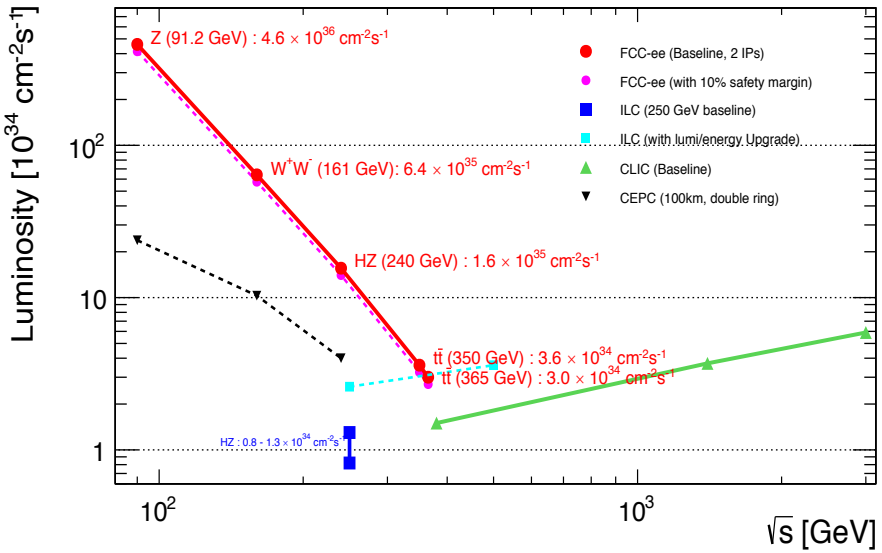
FCC-ee

Precision machine: Z, h, WW, tt factory

Improve measurements of $m_Z, \Gamma_Z, m_W, m_t, m_H$ by a factor 25

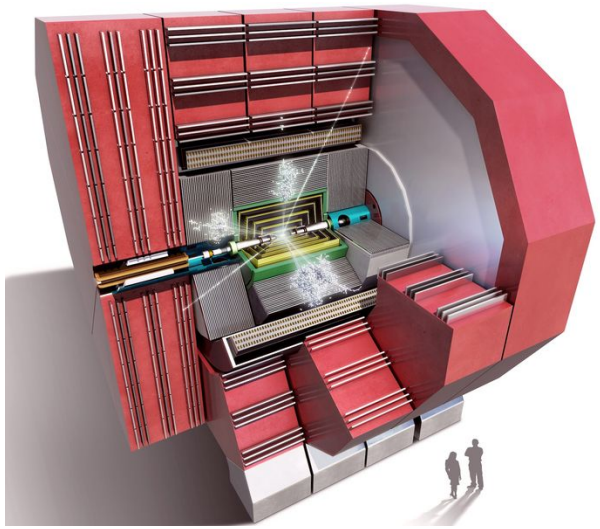
- Z : 10^{12} events
- WW : 10^8 events
- h : $2 \cdot 10^6$ events
- $t\bar{t}$: 10^6 events

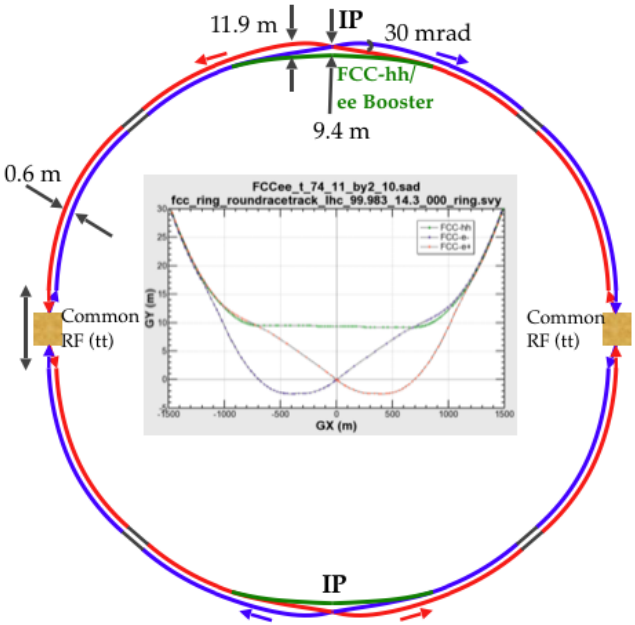




FCC-ee

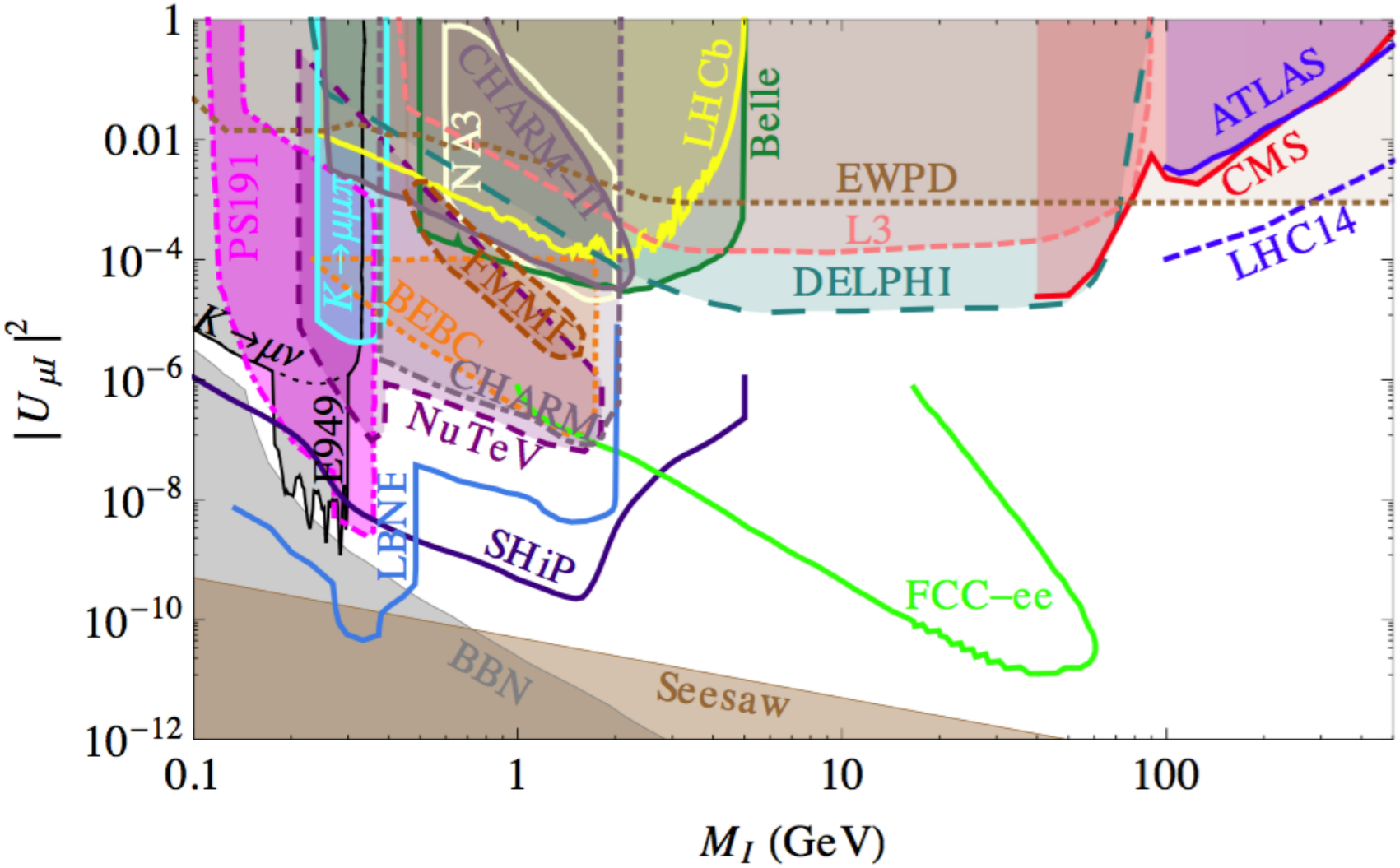
- Adapting CLIC [10] detector to the FCC-ee
- Accelerator technology inspired by state-of-the-art accelerators





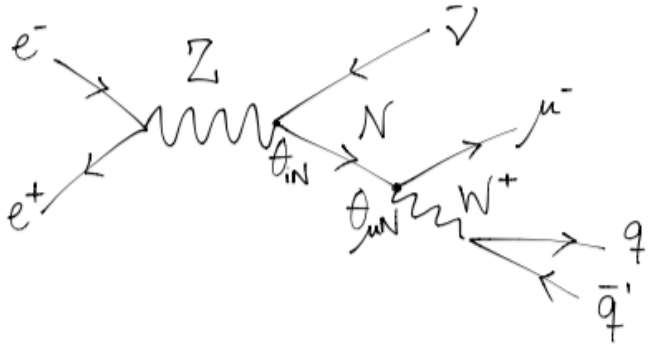
[9]

Previous Searches



Sterile Neutrinos with Short Lifetime

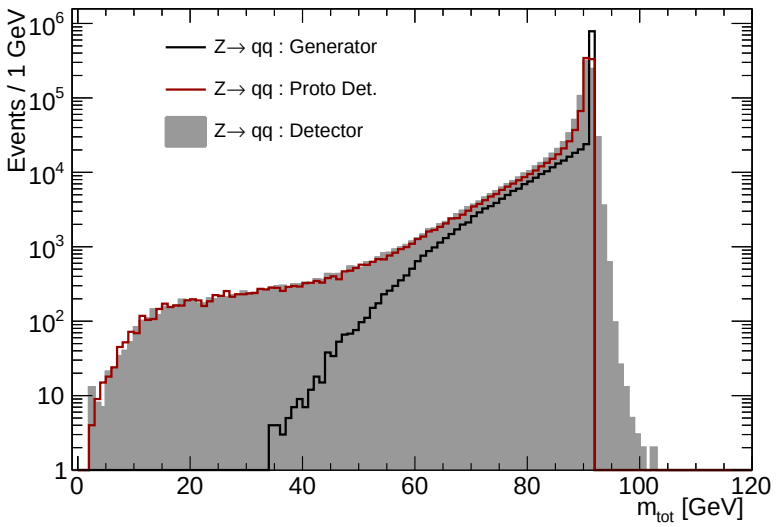
- Sterile Neutrinos produced from Z decays
- Free parameters: $|\theta|^2$ and M $(10 - 80$ GeV$)$
- Too short lifetime to detect a displaced vertex
- Monte Carlo study (PYTHIA and WHIZARD)
- Generated 10^8 $Z \to q\bar{q} \Rightarrow L = 3.33\ \mathrm{fb}^{-1}$



Detector Parametrisation

- **Tracker**
  Target: All charged particles:
  $e, p, \pi^{\pm}, \mu, \ldots$
  Efficiency: 99.5%
- **EM-Calorimeter**
  Target: All EM-interacting particles (not charged part.): γ
- **Hadronic Calorimeter**
  Target: all neutral hadrons: $n, K^0_{S,L}, \ldots$

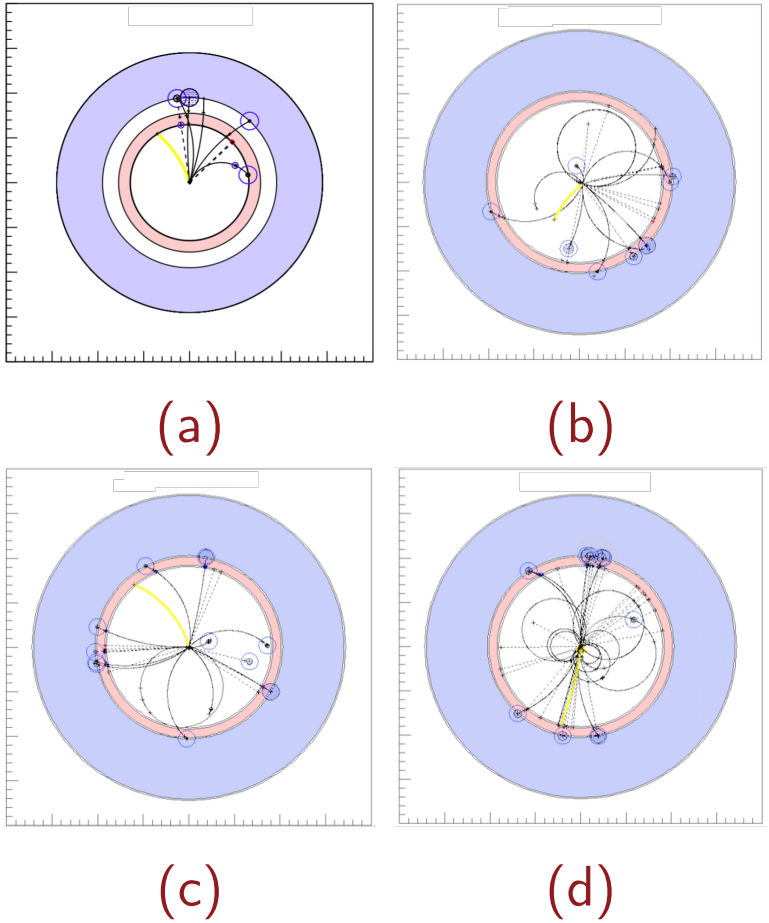
- Based on the ILC detector design [13]
- Particle flow
- Misidentification of pions as muon with 0.25%



Signal Signature

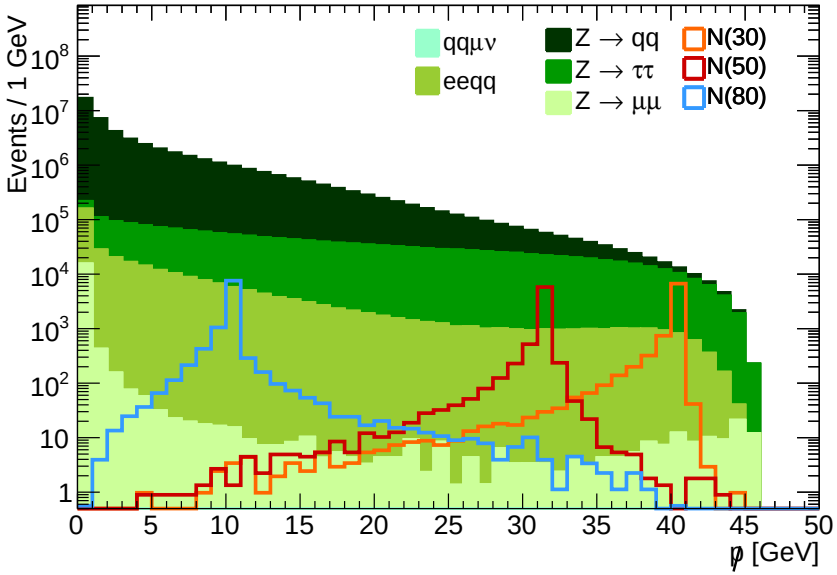
- $Z \to N\nu$ with $N \to \mu q\bar{q}$
- Final state: $\nu\mu$ jet(s)
- Active neutrino recoiling a jet system
- Muon separated from the jet

- Low mass ana.: mono-jet
- High mass ana.: di-jet



Considered Background

- $Z \to q\bar{q}$ with 10^8 events
- $Z \to \tau^+\tau^-$ with $5 \cdot 10^6$ events
- $Z \to \mu^+\mu^-$ with $5 \cdot 10^6$ events
- Four-fermion processes:
  - $e^+e^- \to e^+e^- q\bar{q}$ with $4.2 \cdot 10^6$ events
  - $e^+e^- \to q\bar{q}\mu\nu$ with 14 events

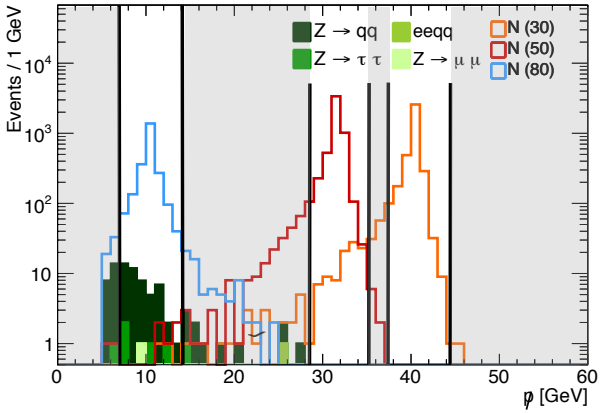


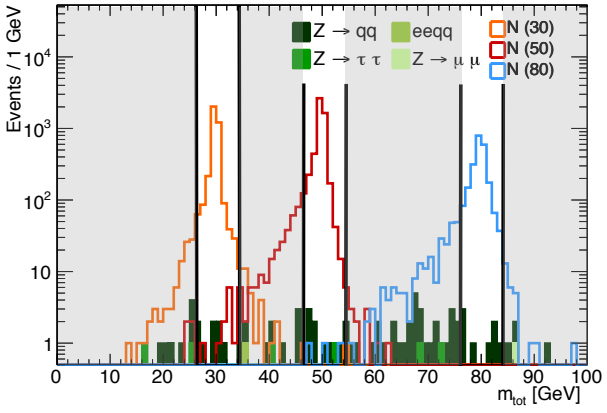
Cut-flow

Selecting events with	Number background events	$\epsilon_{\text{signal}}(N_{50})$ [%]
Initial	$1.14 \cdot 10^8$	100
> 3 ch. part.	$1.02 \cdot 10^8$	99.69
$\not{p}$	$1.50 \cdot 10^7$	99.67
$\geq 1\ \mu$	$4.24 \cdot 10^6$	97.74
Exactly $1\ \mu$	$3.54 \cdot 10^6$	95.14
No $\not{p}$ in beam pipe	$3.20 \cdot 10^6$	88.23
$\not{p}$ and muon in opposite direction	$4.88 \cdot 10^5$	85.40
1 (2) jet(s)	$4.83 \cdot 10^5$	82.66
No di-jets back to back	$3.61 \cdot 10^3$	74.07
Muon not inside jet	490	65.5
a-coplanar jets (3 jets)	218	62.09
jet mass $> m_\tau$	83	56.14

Sliding Cuts

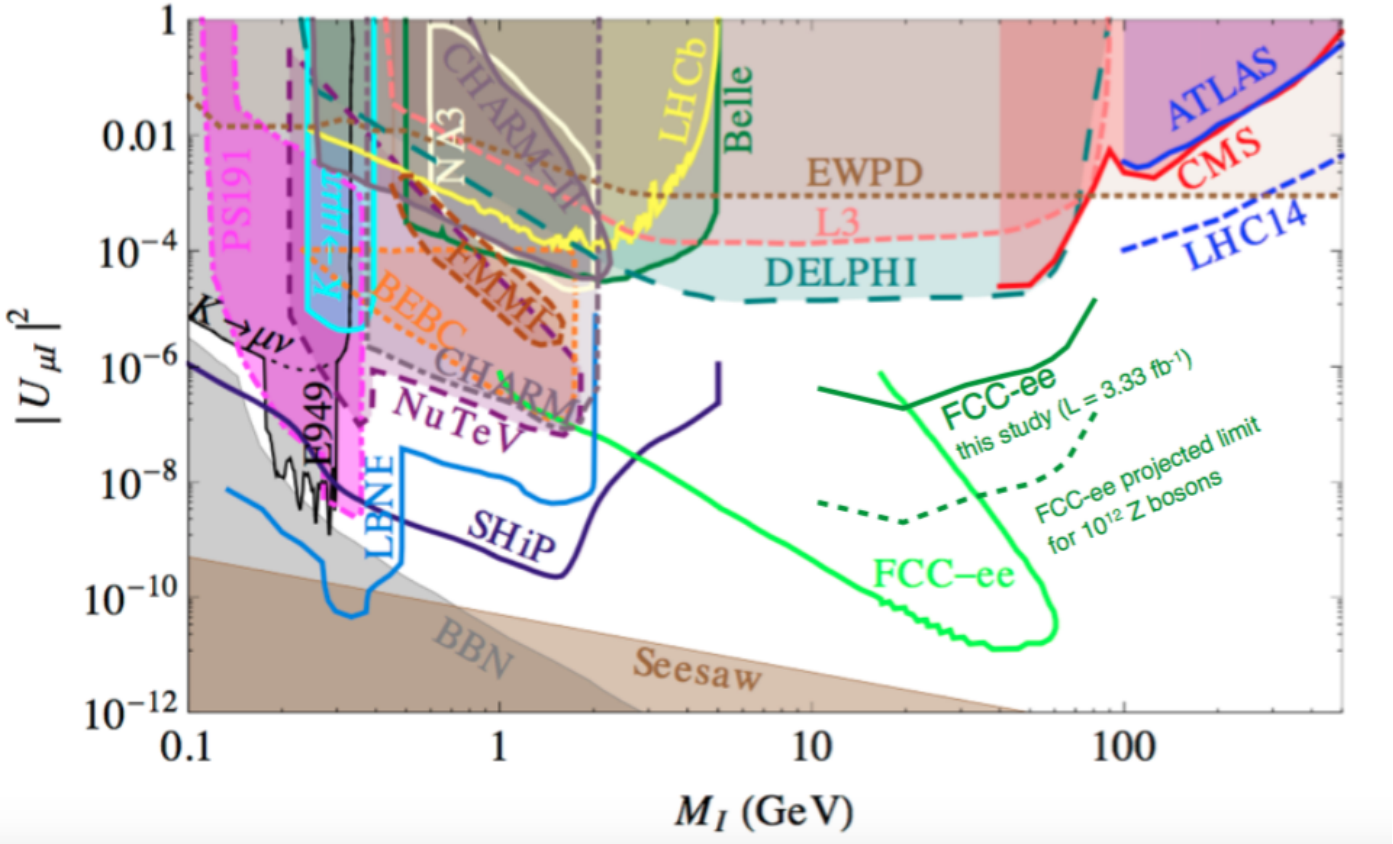
Isolating window around	Number background events	$\epsilon_{\text{signal}}(N_{50})$ [%]
$p_\nu \pm 3.5$ GeV	0	53.52
$M_N \pm 4$ GeV	0	52.07





- Background-free samples (except two samples with 1 and 3 bkg event)

Projected Sensitivity for Sterile Neutrinos at the FCC-ee



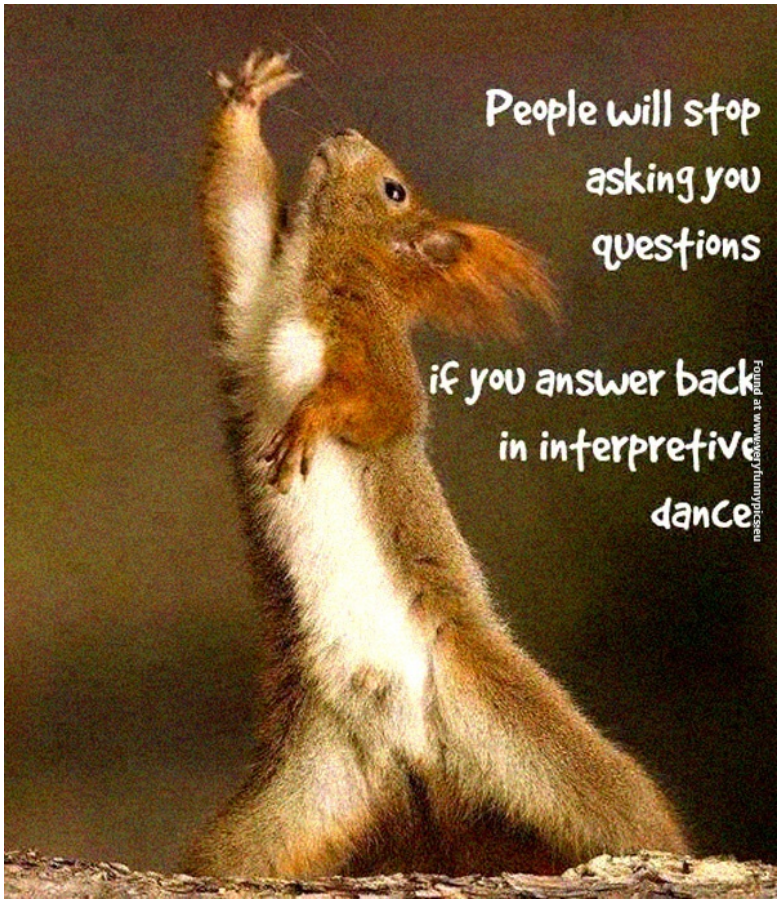
$$Z = \frac{s}{\sqrt{b+s}} \geq 2$$

Summary

- Sterile neutrinos and the νMSM
- FCC-ee
- Search for sterile neutrinos with masses from $10 - 80$ GeV
- Sensitivity reach of $|\theta|^2$ down to 10^{-8} for short lived N.
- Sensitivity reach of $|\theta|^2$ down to 10^{-11} for long lived N!
- This is very promising for the future search of sterile neutrinos.

Thank you for listening!

Questions?



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Patrick Janot.

Backup slides

Phenomenology

The decay width of $(Z \to \nu_i N_j)$ is [14]

$$\Gamma(Z \to \bar{\nu}_i N_j) = |\theta_{ij}|^2 \cdot \Gamma(Z \to \nu_i \bar{\nu}_i) \cdot \Pi\left(\frac{M_N}{m_Z}\right)$$
$$= |\theta_{ij}|^2 \cdot \frac{G_F m_Z^3}{3\sqrt{2}\pi} \cdot \Pi\left(\frac{M_N}{m_Z}\right),$$

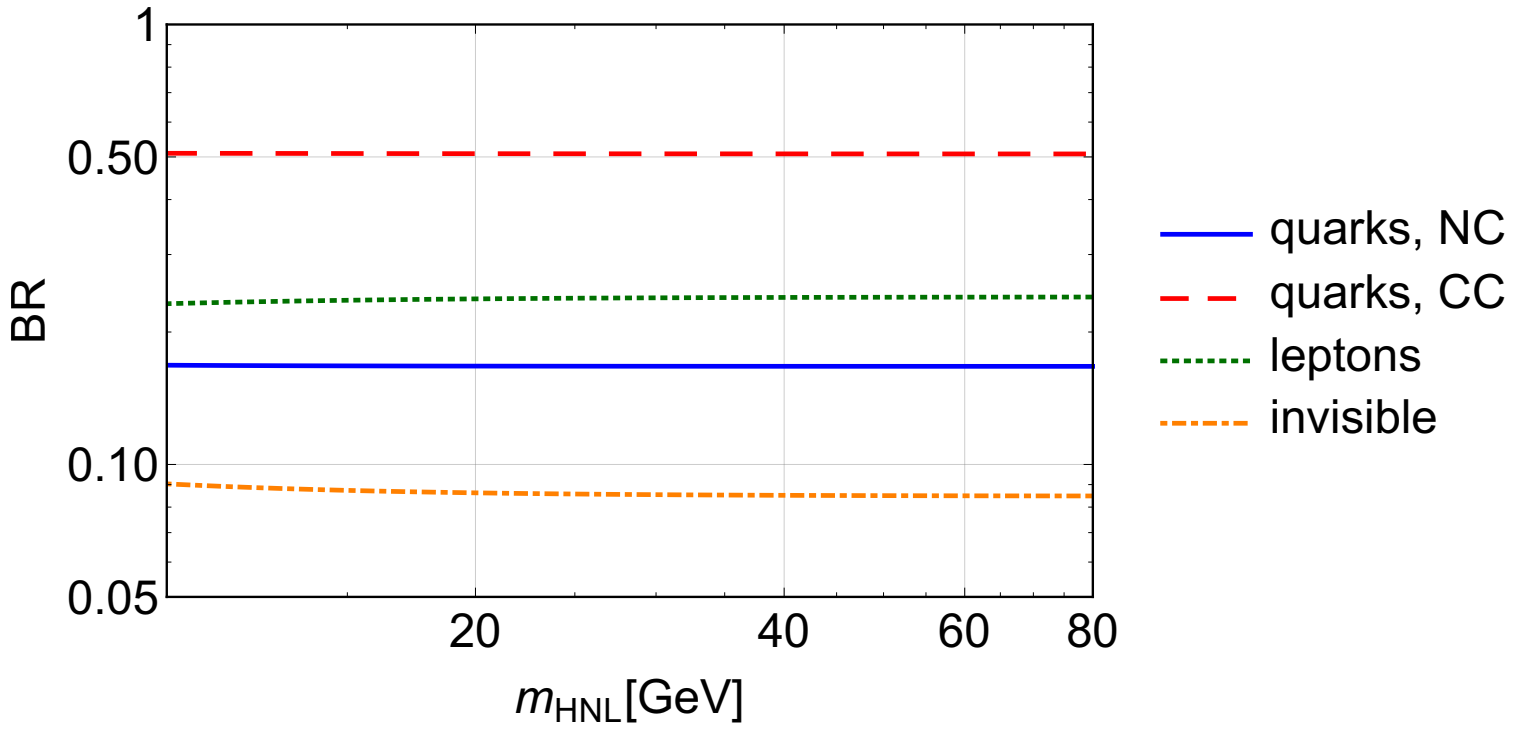
with

$$\Pi\left(\frac{M_N}{m_Z}\right) = \frac{1}{2}\left(1 - \left(\frac{M_N}{m_Z}\right)^2\right)^2 \left(2 + \left(\frac{M_N}{m_Z}\right)^2\right).$$

The lifetime:

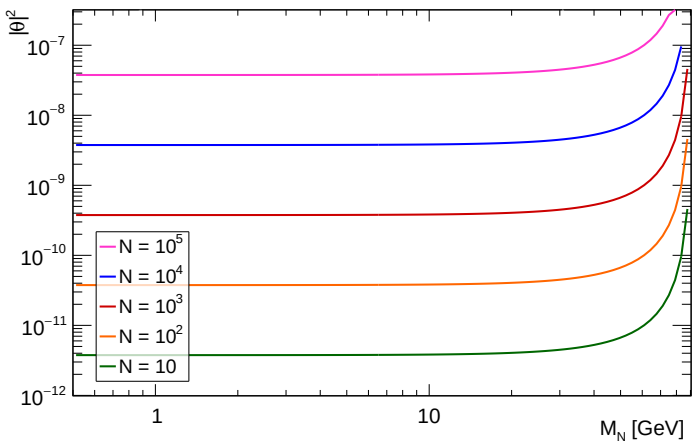
$$\tau_\mu = \frac{4.49 \cdot 10^{-12}}{|\theta|^2} \left(\frac{\mathrm{GeV}}{M_N}\right)^{5.19} \mathrm{s}$$

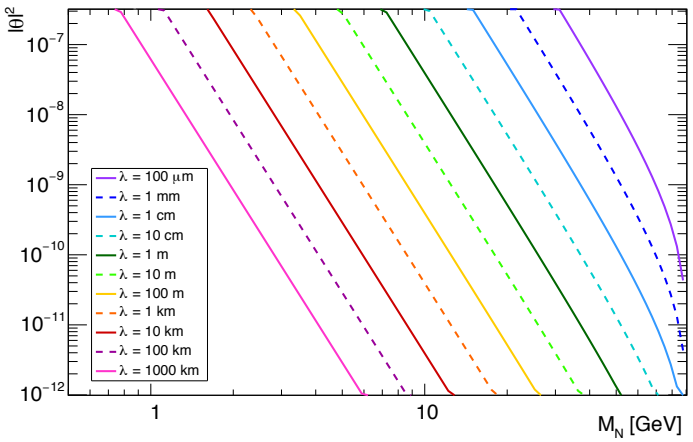
Phenomenology



Sterile Neutrinos with Long Lifetime

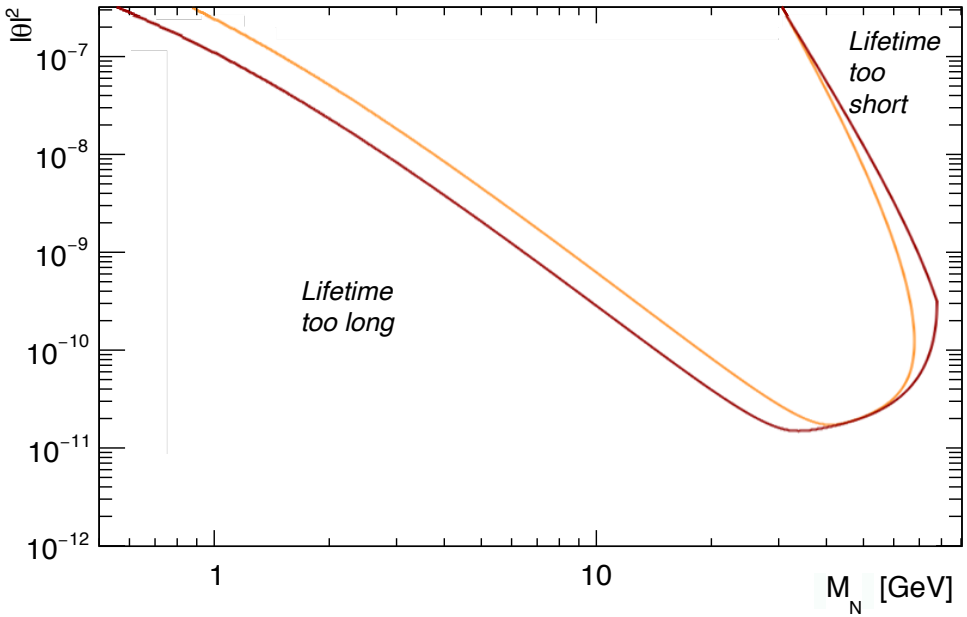
- Number N produced
- Fixed lifetime contours for N decay (lab-frame)



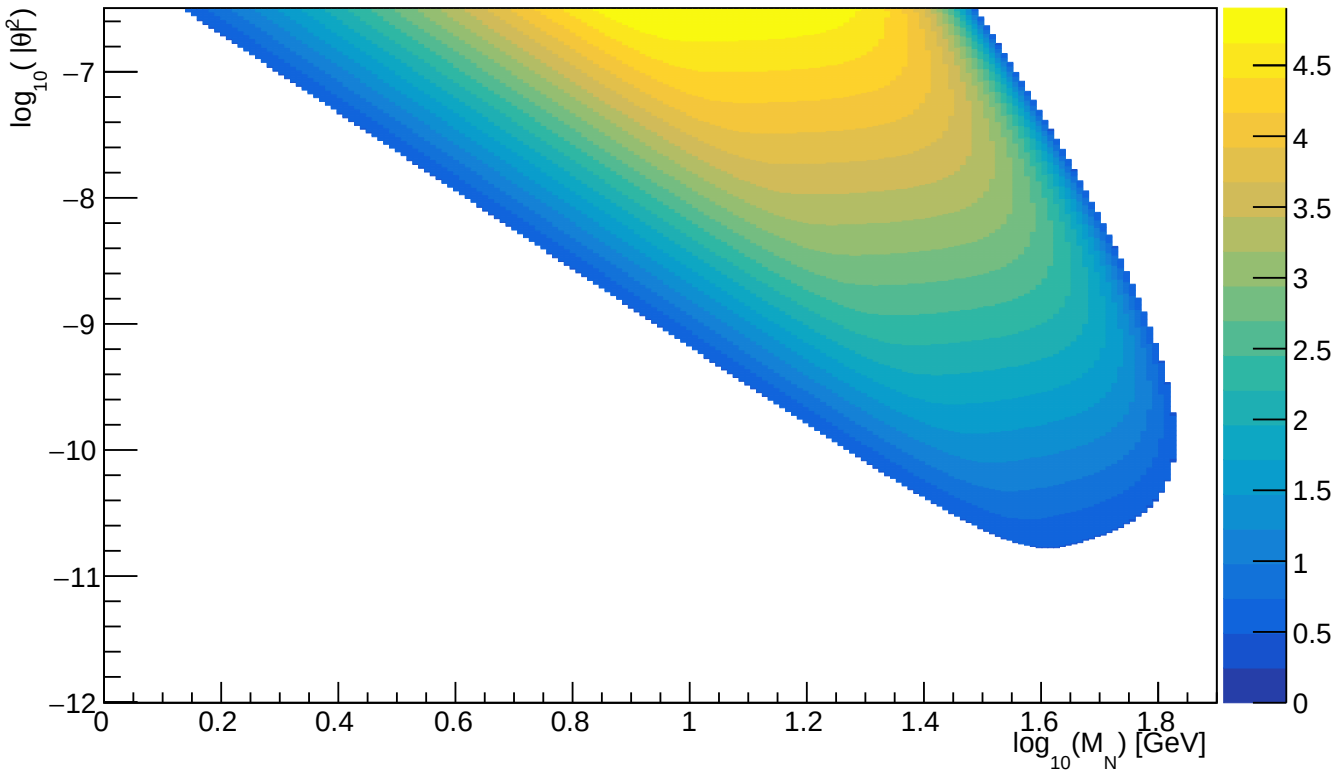


Sterile Neutrinos with Long Lifetime

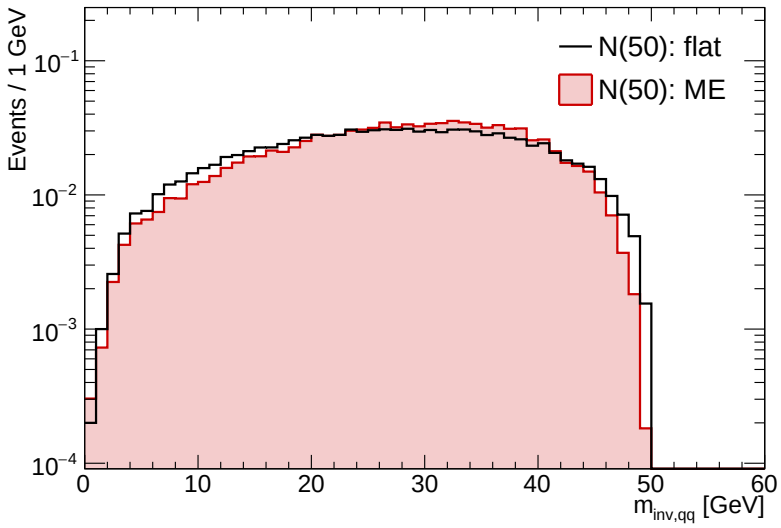
- $N_N > 4$
- Detector volumes sensitive to flight distances between:
  - 1 mm – 1 m (orange)
  - 100 μm – 5 m (red)

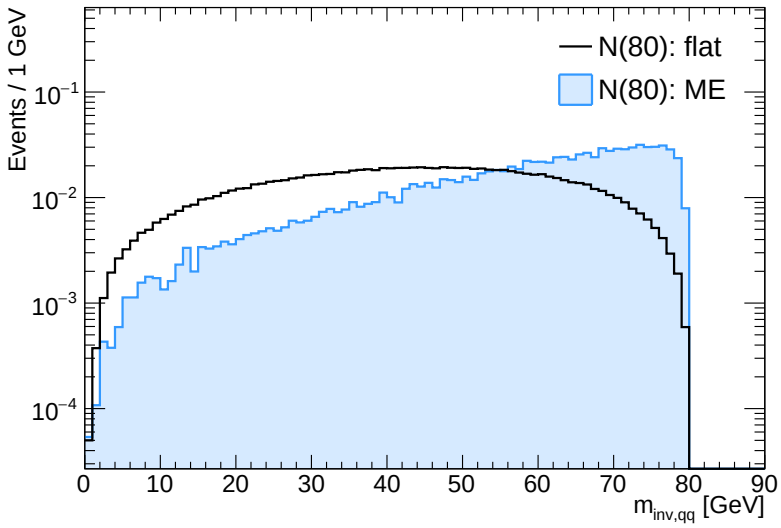


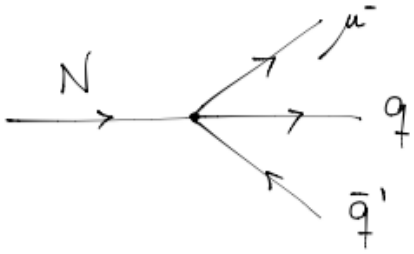
Long Lifetime

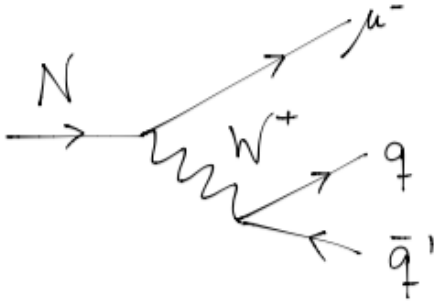


Signal Generation with Matrix Element

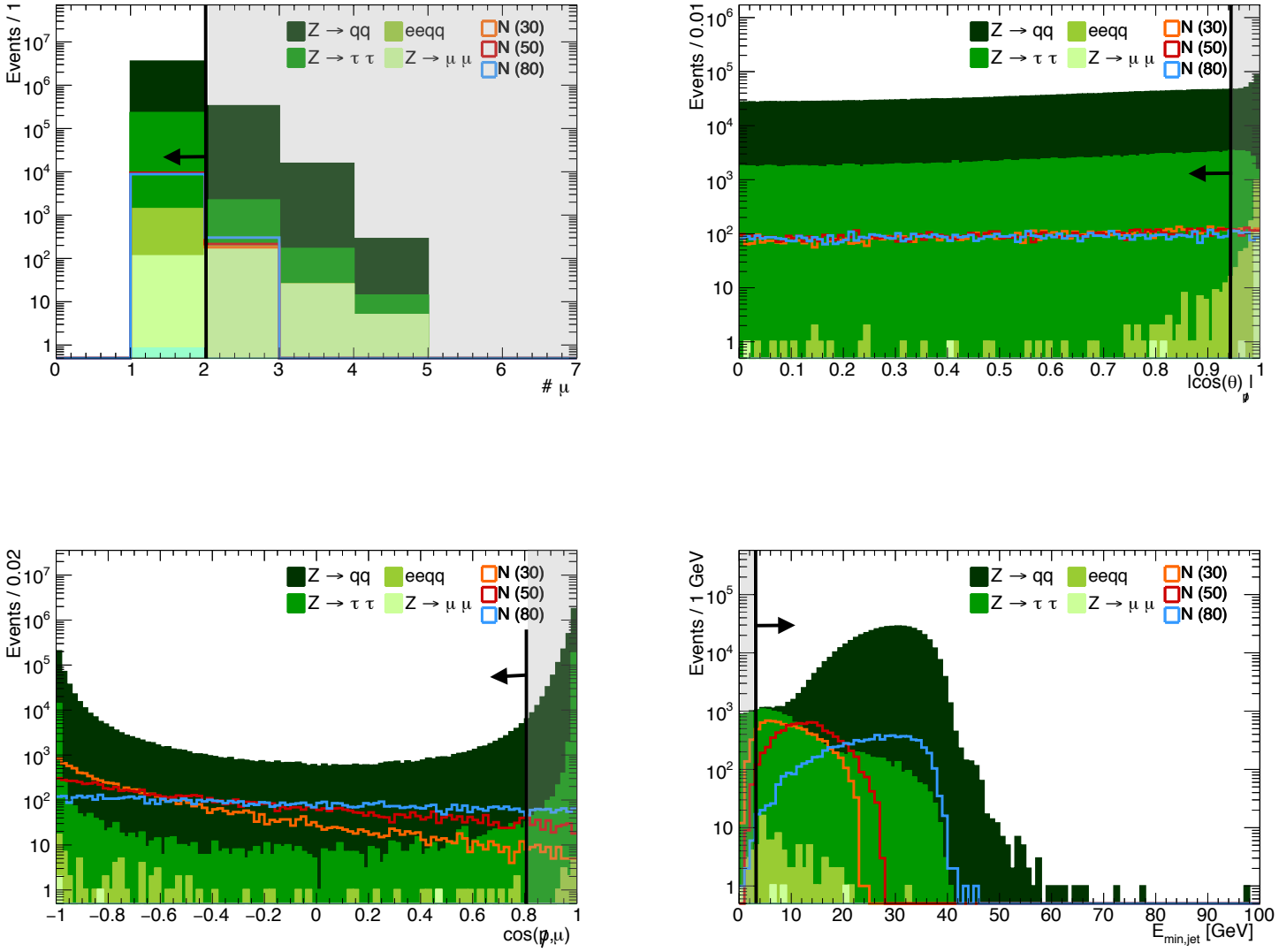




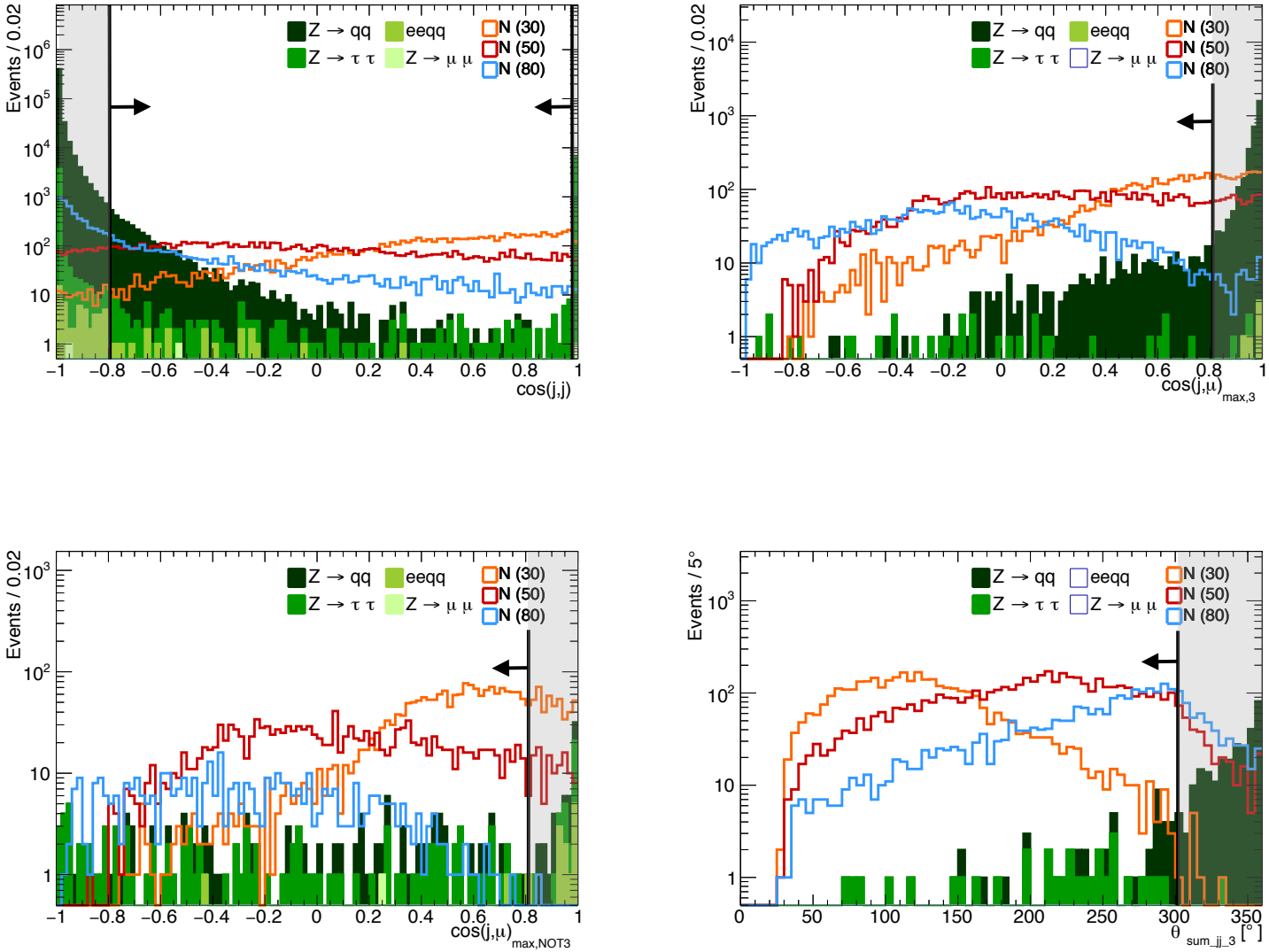




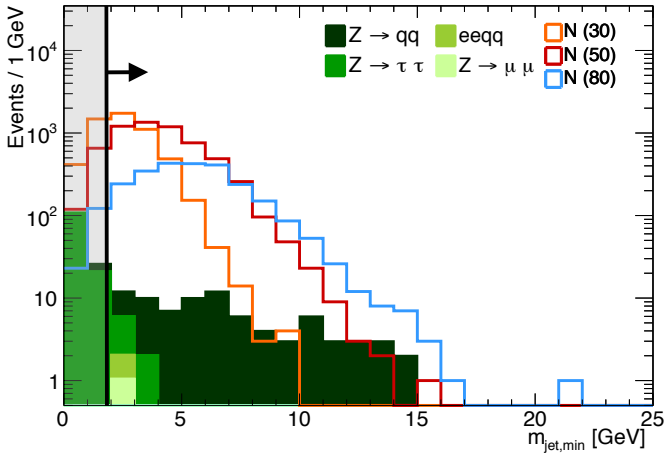
Short Lifetime



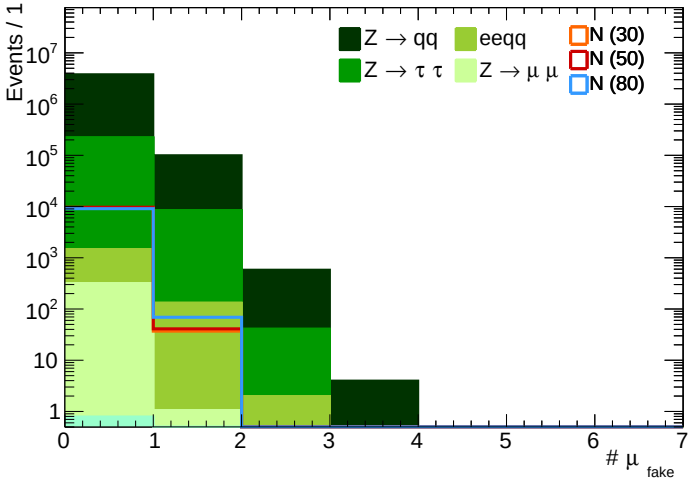
Short Lifetime

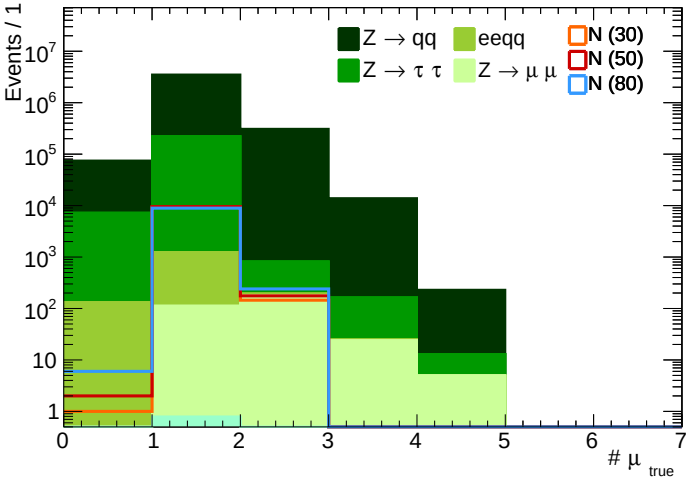


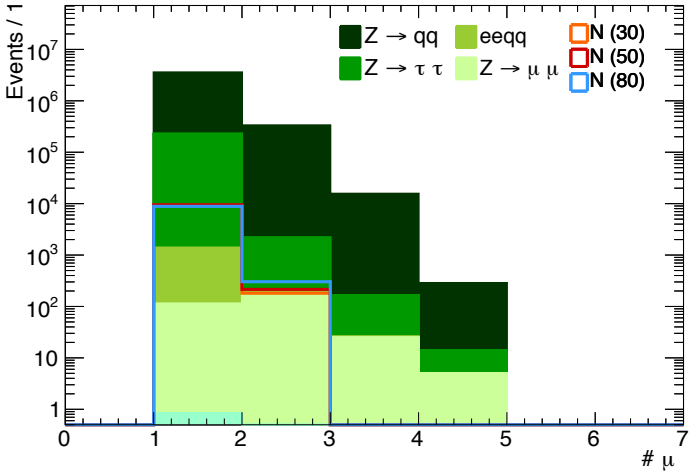
Short Lifetime



Misidentification

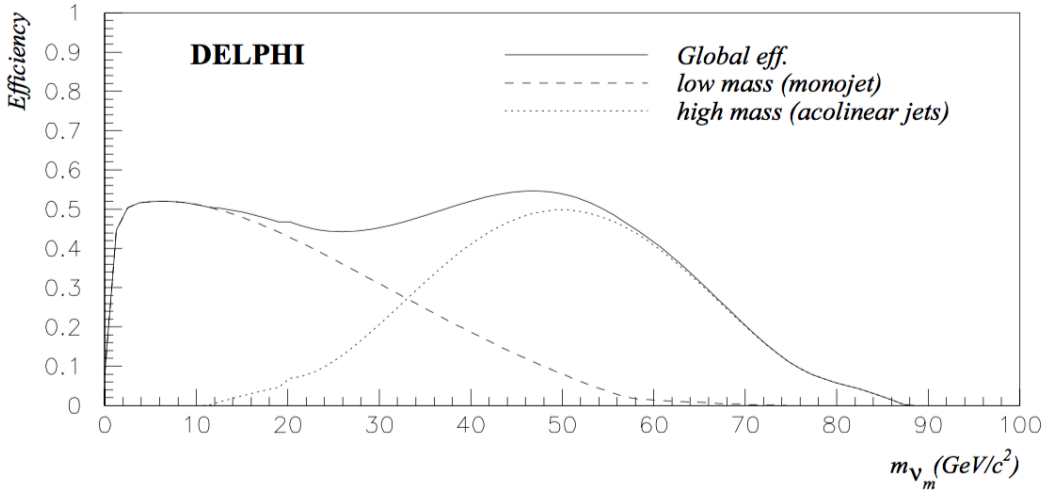
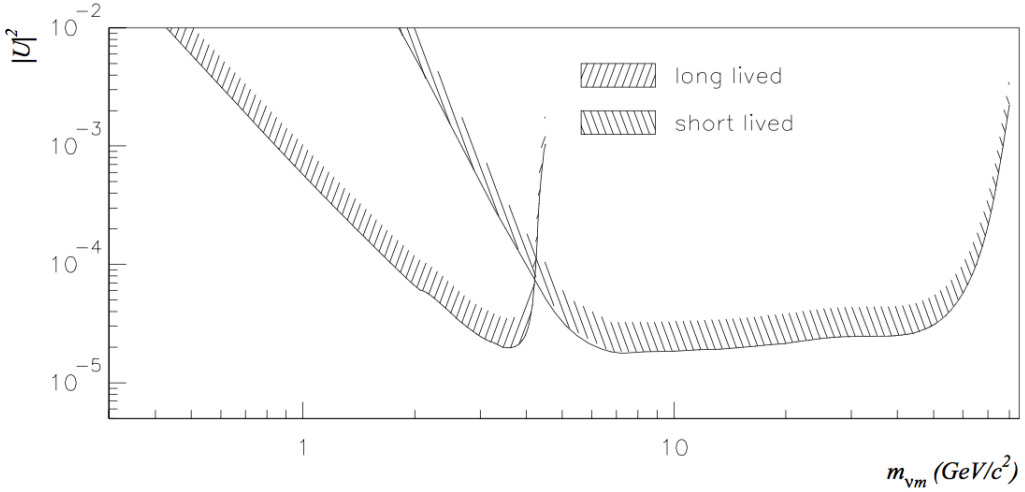






Results

$$|\theta_{\mu N}|^2 = \frac{3\sqrt{2}\pi}{G_F \cdot m_Z^3} \cdot \frac{1}{\Pi\left(\frac{M_N}{m_Z}\right)} \cdot \Gamma_Z \cdot \frac{BR(Z \to \bar{\nu}_\mu \mu q \bar{q})}{BR(N \to \mu^\pm q \bar{q}')} \quad (1)$$

M_N [GeV]	ϵ_{sig} [%]	N_{bkg}	$N_{\text{obs}}^{\text{sig}}$	$N_{\text{prod}}^{\text{sig}}$	$BR(Z \to \nu N \to \mu^\pm q\bar{q})$	$\lvert\theta_{\mu N}\rvert^2$
10	37.3	0	4	10.7	$7.51 \cdot 10^{-8}$	$5.76 \cdot 10^{-7}$
20	67.8	0	4	5.9	$4.13 \cdot 10^{-8}$	$3.35 \cdot 10^{-7}$
30	74.0	1	4.83	6.5	$4.56 \cdot 10^{-8}$	$4.10 \cdot 10^{-7}$
40	49.7	0	4	8.1	$5.63 \cdot 10^{-8}$	$5.93 \cdot 10^{-7}$
50	52.1	0	4	7.7	$5.37 \cdot 10^{-8}$	$7.19 \cdot 10^{-7}$
60	47.4	0	4	8.4	$5.90 \cdot 10^{-8}$	$1.14 \cdot 10^{-6}$
70	37.7	0	4	10.6	$7.42 \cdot 10^{-8}$	$2.56 \cdot 10^{-6}$
80	21.9	3	6	27.4	$1.92 \cdot 10^{-7}$	$1.96 \cdot 10^{-5}$

The DELPHI Limit [15]