# Neutrinophillic scalar detection prospects at a future muon collider

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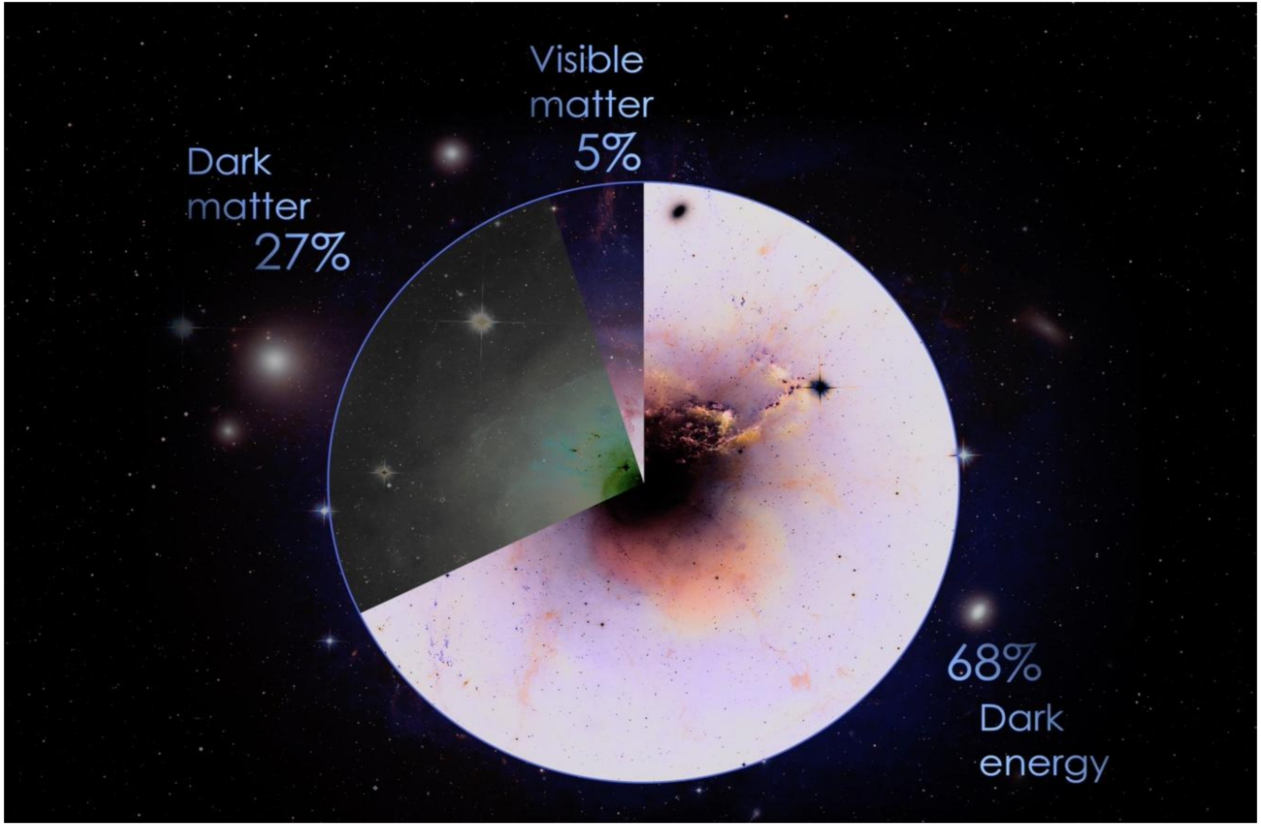
# The universe in a pie chart



# Dark matter evidences

## The Redshift of Extragalactic Nebulae

by F. Zwicky.

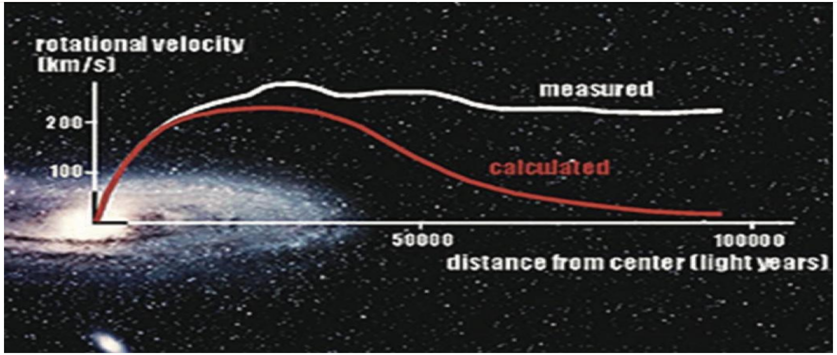
(16.II.33.)

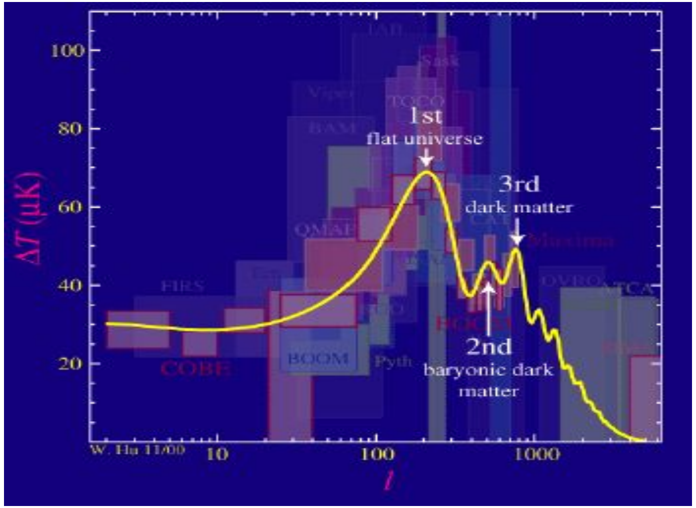
*Contents.* This paper gives a representation of the main characteristics of extragalactic nebulae and of the methods which served their exploration. In particular, the so called redshift of extragalactic nebulae is discussed in detail. Different theories which have been worked out in order to explain this important phenomenon will be discussed briefly. Finally it will be indicated to what degree the redshift promises to be important for the study of penetrating radiation.

## ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

*Received 1969 July 7; revised 1969 August 21*

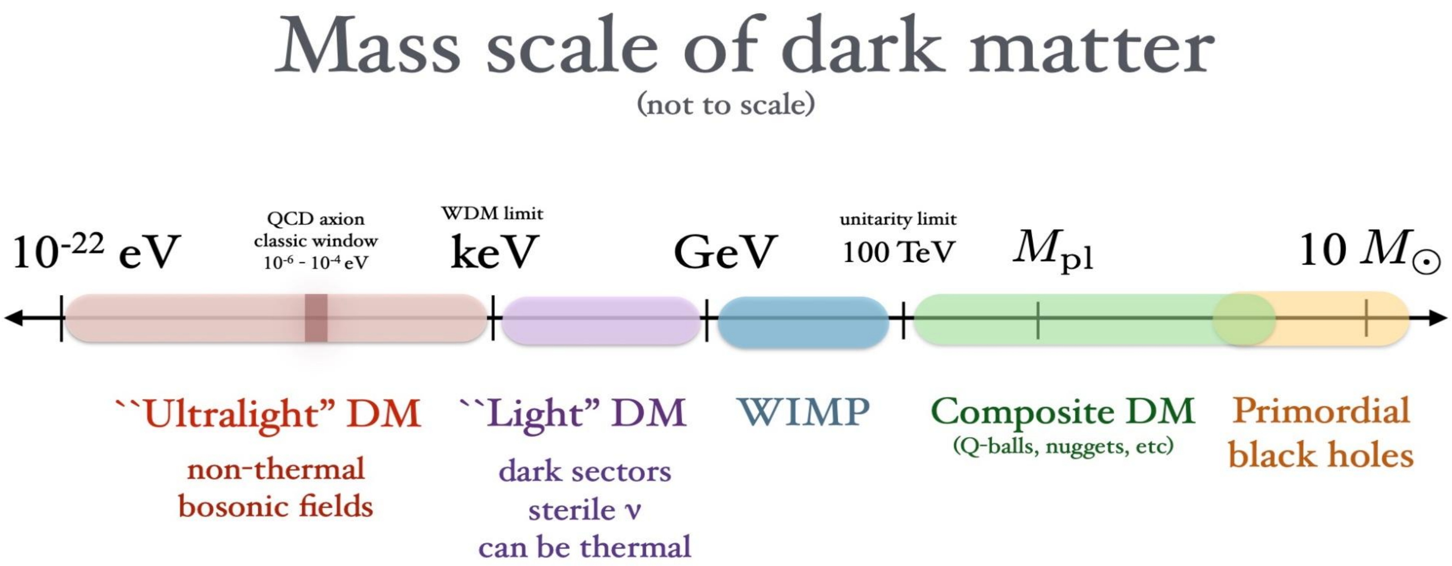


## What can dark matter be and not be

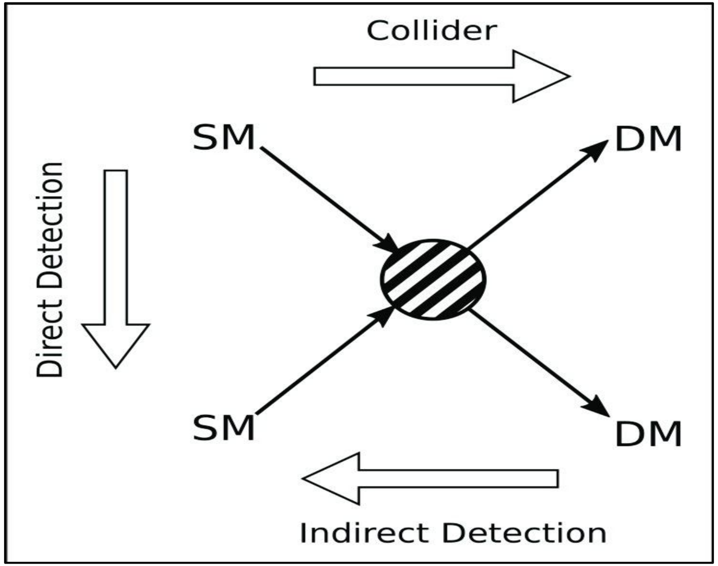
- Must be non baryonic
- Stable
- Electrically neutral
- Non relativistic
- Must be produced in sufficient quantity in the early universe

# Possible dark matter candidates

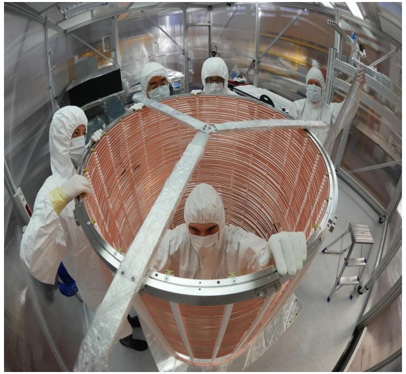



Credit:Tongyan Lin,
TASI lectures on DM models and direct detection

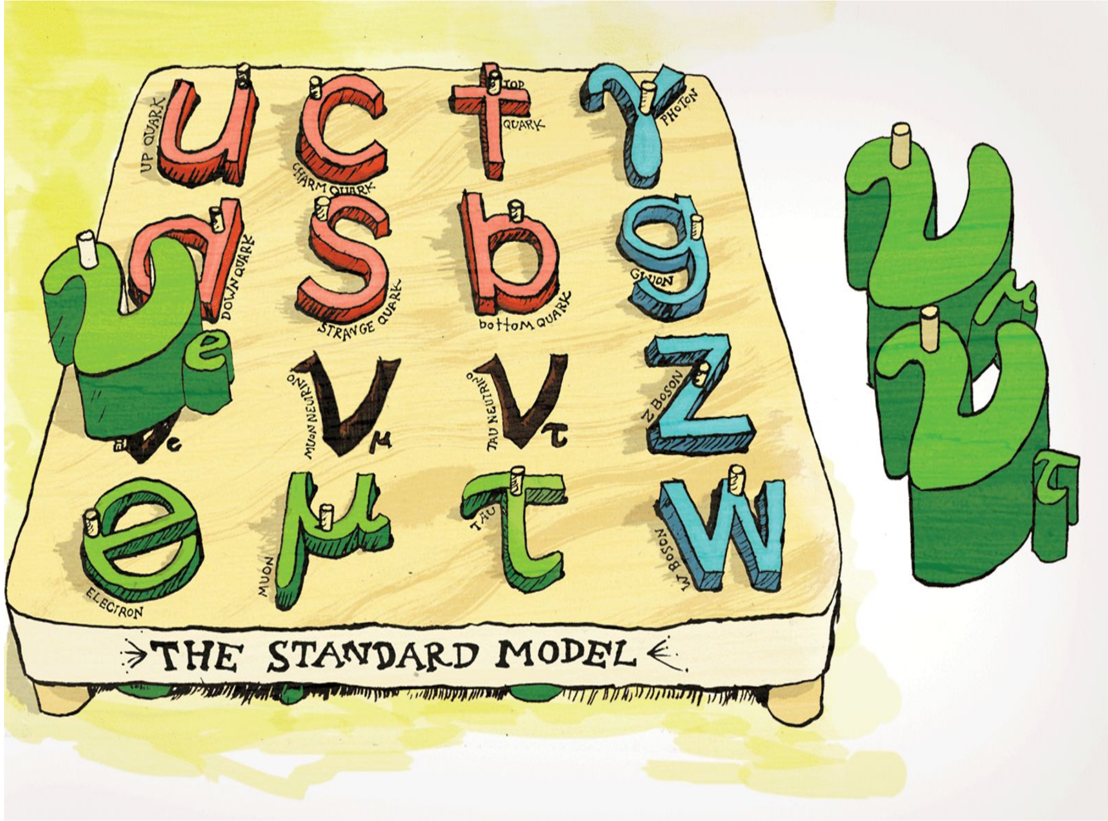
# The hunt for dark matter




Credit: Stefano Giagu



# Neutrinos


UP QUARK
CHARM QUARK
TOP QUARK
PHOTON
DOWN QUARK
STRANGE QUARK
bottom QUARK
GLUON
MUON NEUTRINO
TAU NEUTRINO
Z BOSON
ELECTRON
MUON
TAU
W BOSON
THE STANDARD MODEL

# The model

Introduction of $\phi$

$$\phi$$

Complex scalar carrying lepton number -2

Effective coupling to neutrinos:

Violates $SU(2)_L$

$$\frac{1}{2} \sum_{\alpha,\beta=e,\mu,\tau} \lambda_{\alpha\beta} \nu_\alpha \nu_\beta \phi + \text{h.c.}$$

Credit: G.B. GELMINI, M. RONCADELLI

# Model origin

Neutrino mass generation:

Simplest operator for neutrino mass generation:

Weinberg operator

$$\mathcal{L}_5 = \frac{c}{\Lambda}(\bar{\tilde{L}}H)(\tilde{H}^\dagger L)$$

Lorentz and SU(2) invariant

Higgs gets vev

$$m_\nu \simeq \frac{c}{\Lambda}v^2$$

# Model origin

Neutrino self interactions can be generated in theories that explain the origin of neutrino mass . Introduction to Majoron

$$\mathcal{L}_{\rm portal} = \frac{(L_\alpha H)(L_\beta H)}{\Lambda^2_{\alpha\beta}}\phi$$

Introduction of complex scalar field

# Model origin

Neutrino self interactions can be generated in theories that explain the origin of neutrino mass . Introduction to Majoron

$$\mathcal{L}_{\text{portal}} = \frac{(L_\alpha H)(L_\beta H)}{\Lambda^2_{\alpha\beta}}\phi$$

$\phi$ gets a vev at scale $f/\sqrt{2}$,

$$\phi = (f + \sigma + iJ)/\sqrt{2}.$$

Majoron

$$M_\nu = -\frac{v^2 f}{2\sqrt{2}\Lambda^2}$$

Majorana neutrino mass

- After Higgs field getting vev, in unitary gauge,

$$H = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

So

$$\mathcal{L}_{portal} = \frac{1}{\Lambda^2_{\alpha\beta}} \begin{pmatrix} l_\alpha & \nu_\alpha \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \begin{pmatrix} l_\beta & \nu_\beta \end{pmatrix} \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \phi$$

$$= \frac{1}{\Lambda^2_{\alpha\beta}} \nu_\alpha \frac{v}{\sqrt{2}} \nu_\beta \frac{v}{\sqrt{2}} \phi + h.c$$

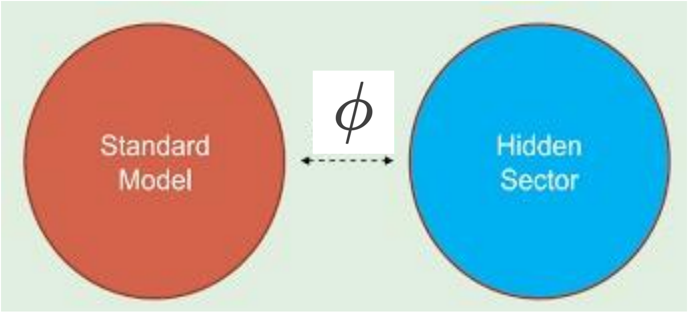
$$= \frac{1}{\Lambda^2_{\alpha\beta}} \frac{v^2}{2} \nu_\alpha \nu_\beta \phi + h.c$$

$$\mathcal{L}_{portal} = \frac{v^2}{2\Lambda^2_{\alpha\beta}} \nu_\alpha \nu_\beta \phi + h.c$$

$$\boxed{\mathcal{L}_{portal} = \frac{1}{2} \lambda_{\alpha\beta} \nu_\alpha \nu_\beta \phi + h.c}$$

$\phi$ Becomes neutrinophillic

$$\mathcal{L}_{\rm int} = \frac{M_\nu}{f} \nu\nu(\sigma + iJ)$$




Dirac Fermion Dark Matter

Lagrangian: $$\mathcal{L} = \frac{1}{2} y_{IB} \bar{\chi}^c \chi \phi + \text{h.c.}$$

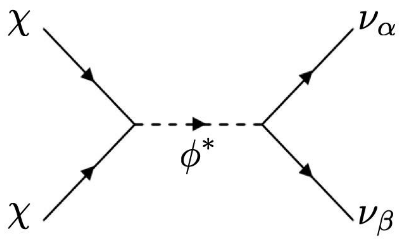
An ad-hoc Z2 symmetry is introduced under which $\chi$ is odd so that it is stabilized.

↓

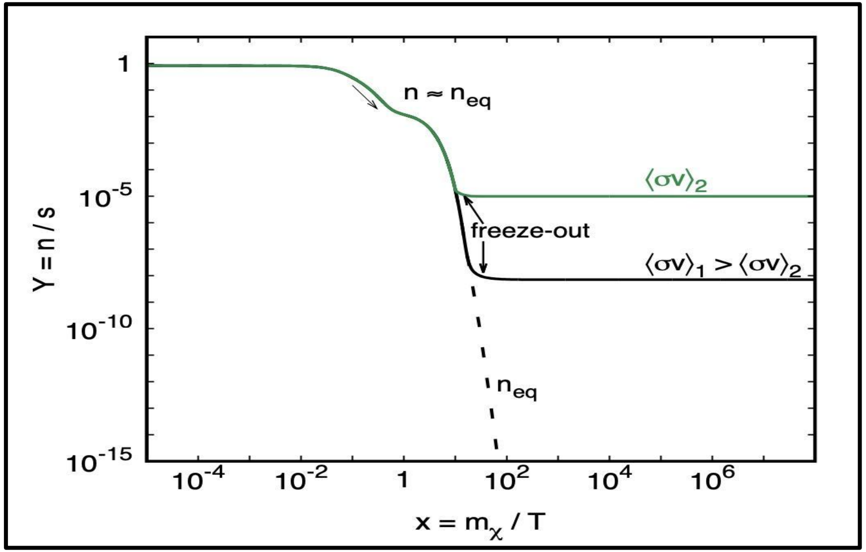
Can be promoted to U(1) lepton number global symmetry with $\chi$ having charge +1.

K. Kelly, Y. Zhang
arXiv: 1901.01259

# Relic Density via thermal freeze out




Relic density is set by P-wave annihilation.




Credit: Roszkowski et. al.

$$\sigma v_{\rm rel}(\chi\chi \to \nu_\alpha \nu_\beta) = \frac{|\lambda_{\alpha\beta} y_{IB}|^2 m_\chi^2 v_{\rm rel}^2}{16\pi(4m_\chi^2 - m_\phi^2)^2(1+\delta_{\alpha\beta})} \,.$$

Suppressed indirect detection rate

# Sterile neutrino dark matter

$$\nu_4 = \nu_s \cos\theta + \nu_a \sin\theta$$

Gauge singlet fermion

Active neutrino states from SM

Dodelson-Widrow (DW) mechanism :

- In the early universe, active neutrinos are in thermal equilibrium with other Standard Model (SM) particles. Sterile neutrinos , on the other hand, are not in equilibrium and have negligible initial abundance.
- The active neutrinos are constantly produced in the plasma and can propagate freely for a certain time interval t.
- During this time interval t, if it is long enough, neutrino oscillations can occur. This means that the neutrino state ν(t) can evolve and develop a component of sterile neutrino.

# Sterile neutrino dark matter

Dodelson-Widrow (DW) mechanism :

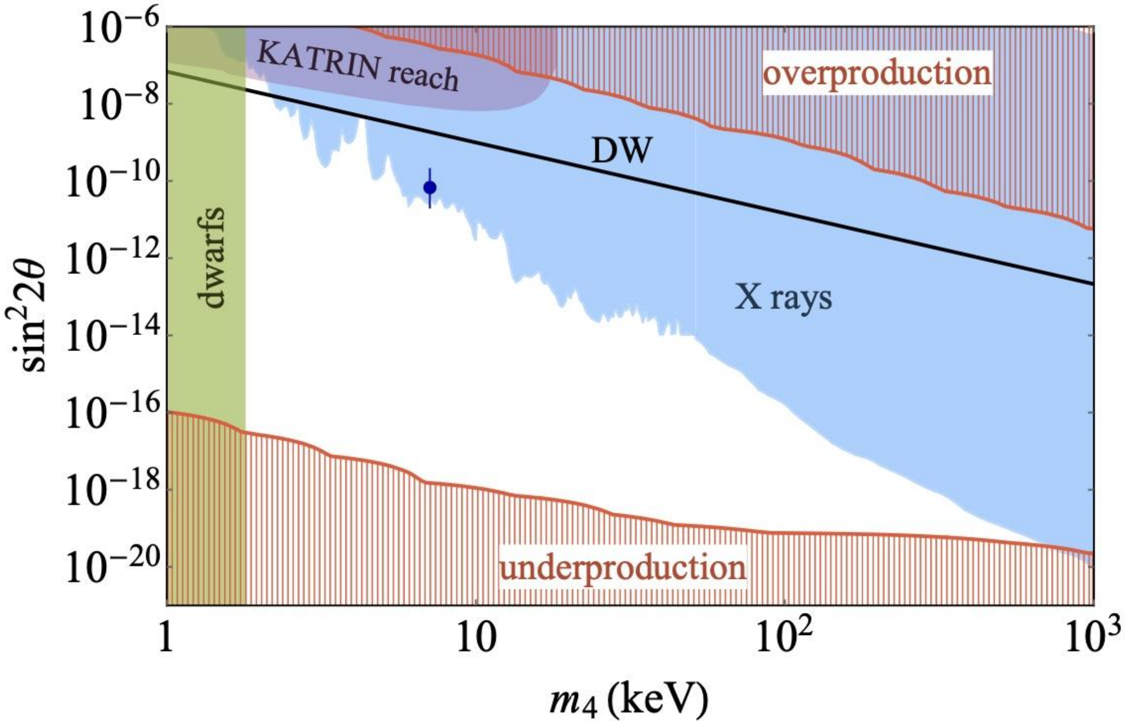
- When a "measurement" occurs through a weak-interaction reaction, there is a small probability that the neutrino will collapse into the sterile state.
- Once the neutrino collapses into a sterile state, it mostly remains in that state and does not interact further through the weak force.
- This process continues until weak decoupling occurs.

## No introduction of mediator yet! What goes wrong?

- For $\theta \neq 0$ – allows the ν4 to decay, very slowly, into a neutrino plus a photon. (P. B. Pal and L. Wolfenstein, "Radiative Decays of Mas- sive Neutrinos," Phys. Rev. D 25, 766 (1982))
- Predicts the existence of an X-ray line from regions of the universe where DM accumulates.

Already excluded by indirect detection experiments

# Sterile neutrino dark matter




Gouvêa et. al. arXiv: 1910.04901

# Sterile neutrino dark matter

What changes after introducing $\phi$

The new force enables more frequent active neutrino scattering than normal weak interactions, thereby, sterile neutrino dark matter can be produced with a smaller mixing angle than required by Dodelson- Widrow mechanism.

$$f_{\nu_4}(E,T) = \int_0^\infty \frac{\Gamma f_{\nu_a} dz}{4Hz} \sin^2\theta_{\text{eff}}$$

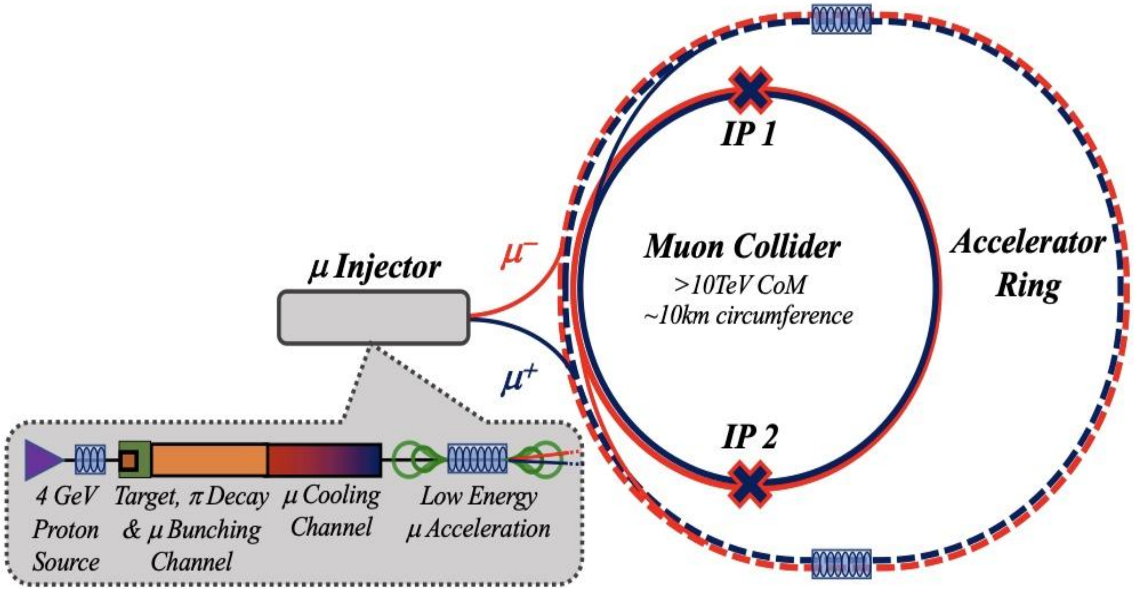
Phase space number density

Sum of neutrino self interaction and weak interaction rates

In-medium active-sterile neutrino mixing angle

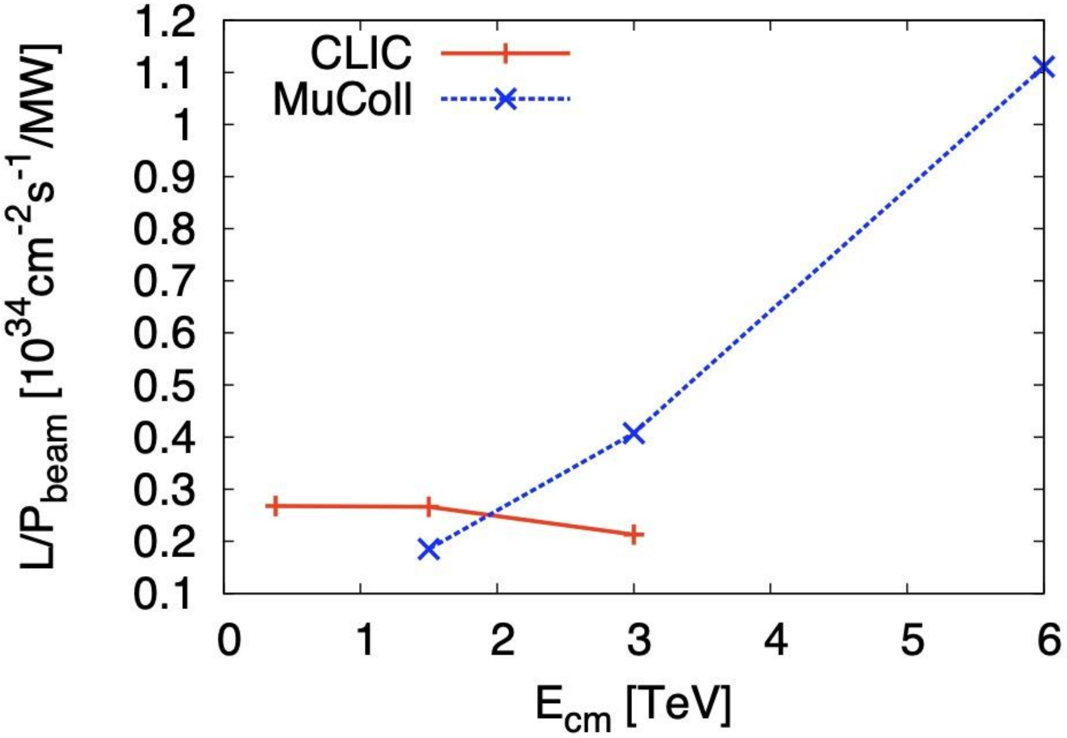
Gouvêa et. al. arXiv: 1910.04901

# The muon collider




MuCol interim report arXiv: 2407.12450

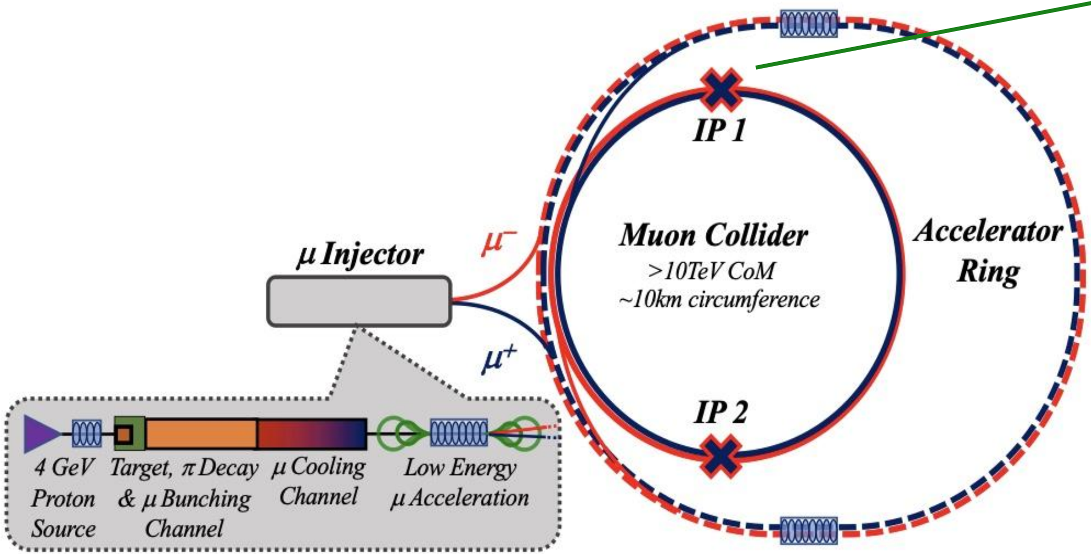
# The muon collider

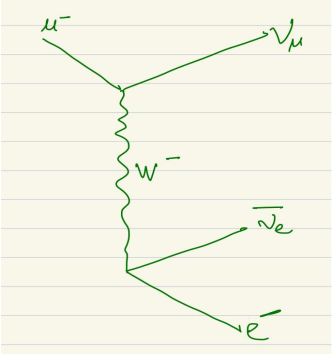



Luminosity normalised to the beam power and as a function of the centre-of-mass energy comparison of the Compact Linear Collider (CLIC) and a muon collider

MuCol interim report arXiv: 2407.12450

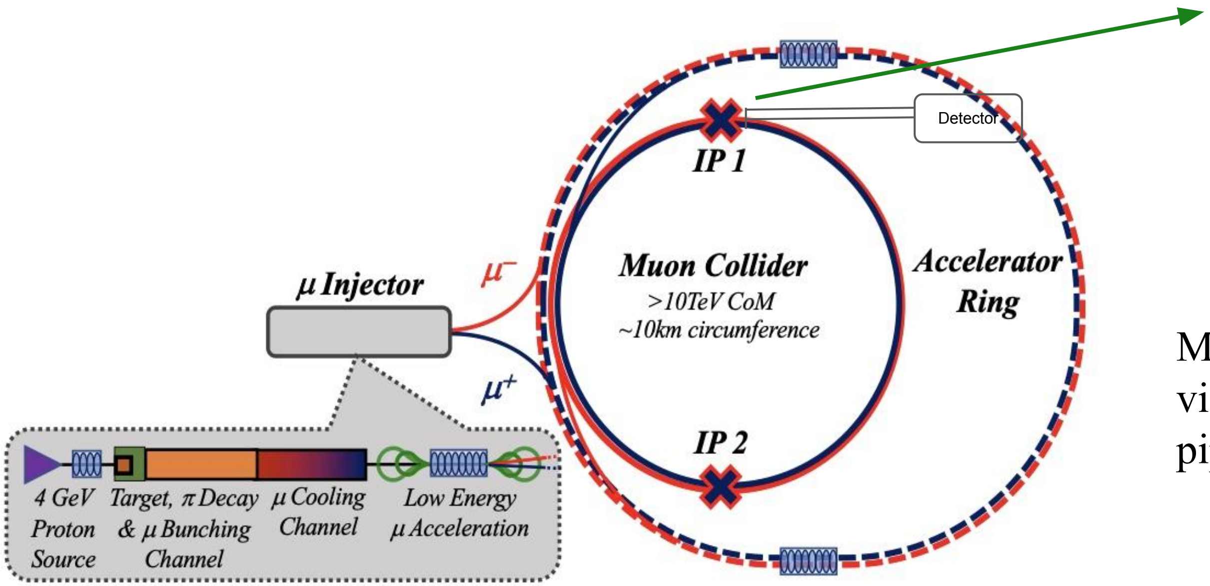
# The muon collider

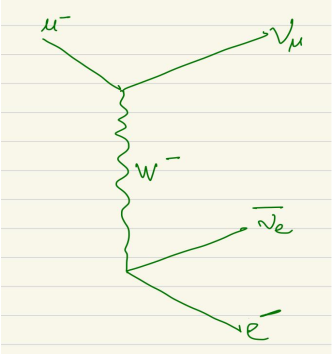



Muon neutrinos are produced via muon decay in the beam pipe

# The muon collider




Muon neutrinos are produced via muon decay in the beam pipe

Expected: At least $9 \times 10^{16}$ neutrinos of each species emitted in a narrow cone of 0.6 mrad average angle during one year of run at the 10 TeV MuC, and $2.4 \times 10^{17}$ neutrinos at the 3 TeV collider.

# What is the signal?

MAD/PH/15
September 1981

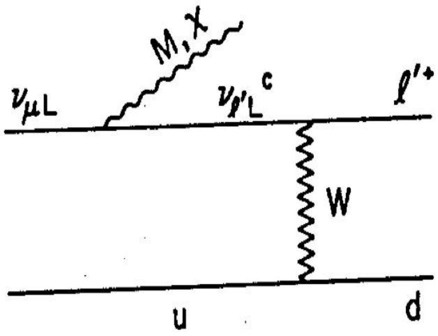
MAJORON EMISSION BY NEUTRINOS

V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

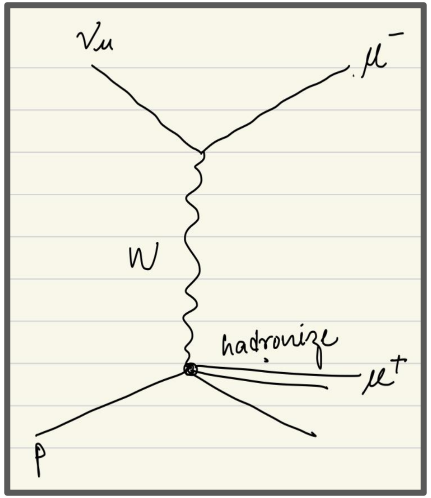
W. Y. Keung
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

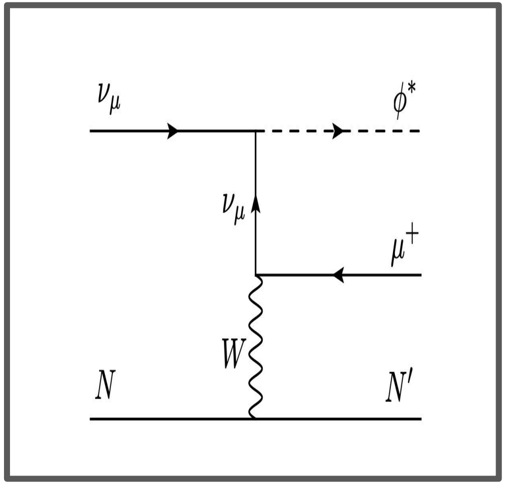
and

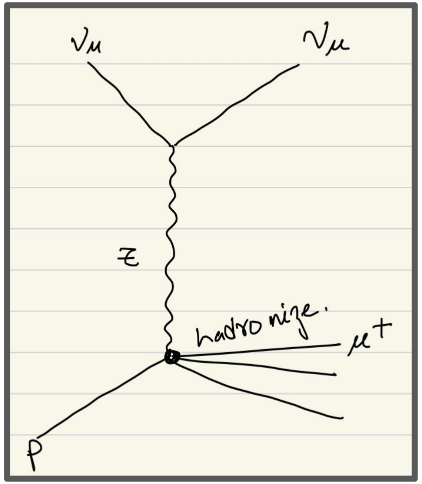
S. Pakvasa
Department of Physics and Astronomy, University of Hawaii at Manoa
Honolulu, Hawaii 96822



- The produced muon neutrinos will travel in the forward direction and will produce positive muon signature in the detector



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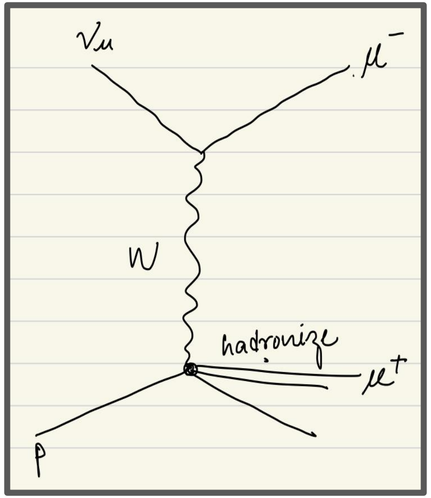
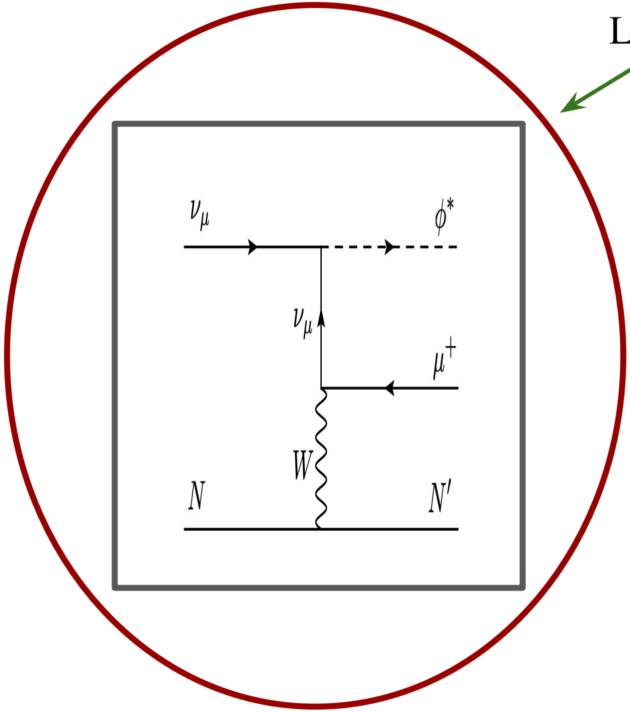
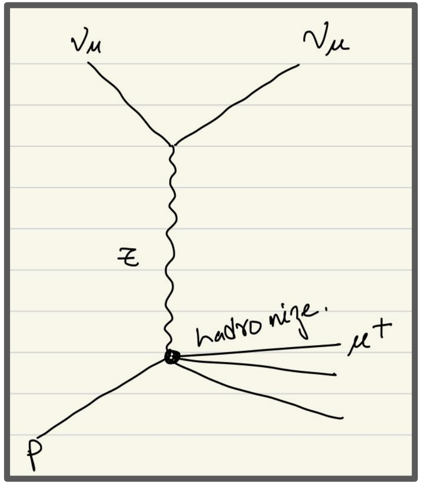
Lepton flavour violating process

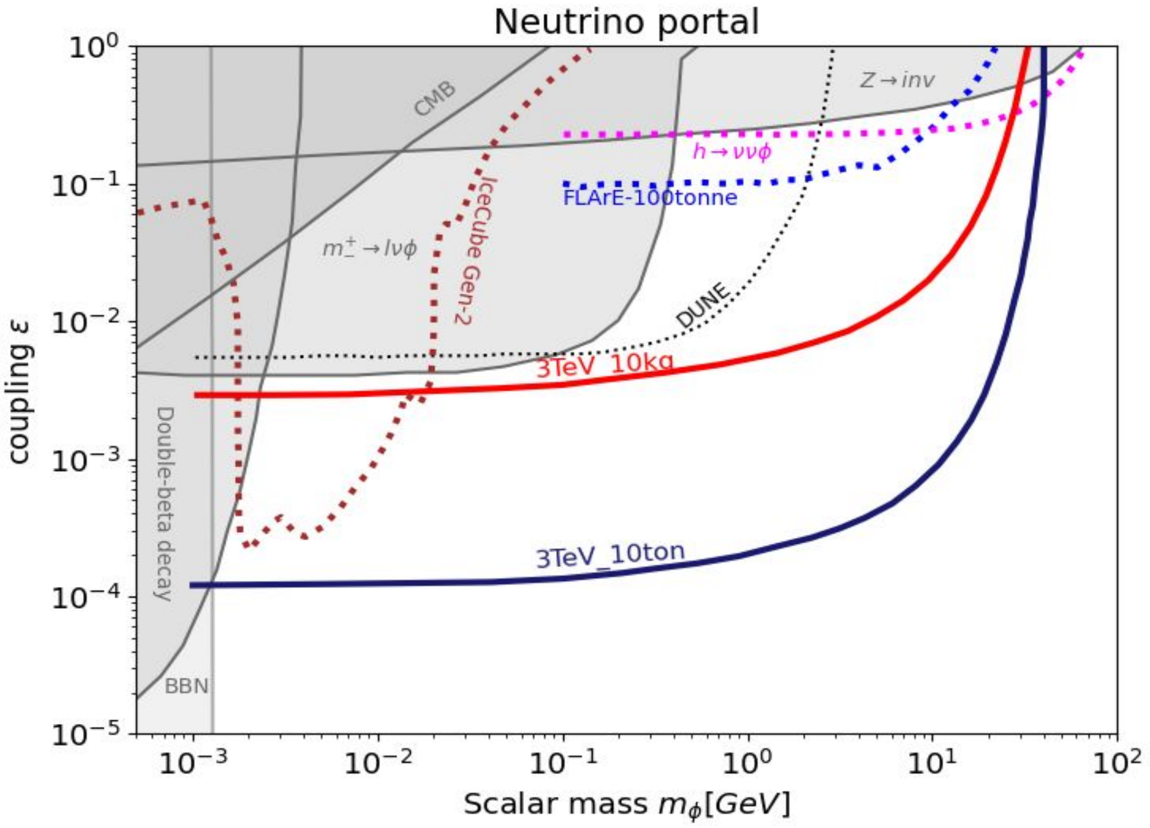



BSM signature



# Sensitivity reach




10 tonne detector 3 TeV energy

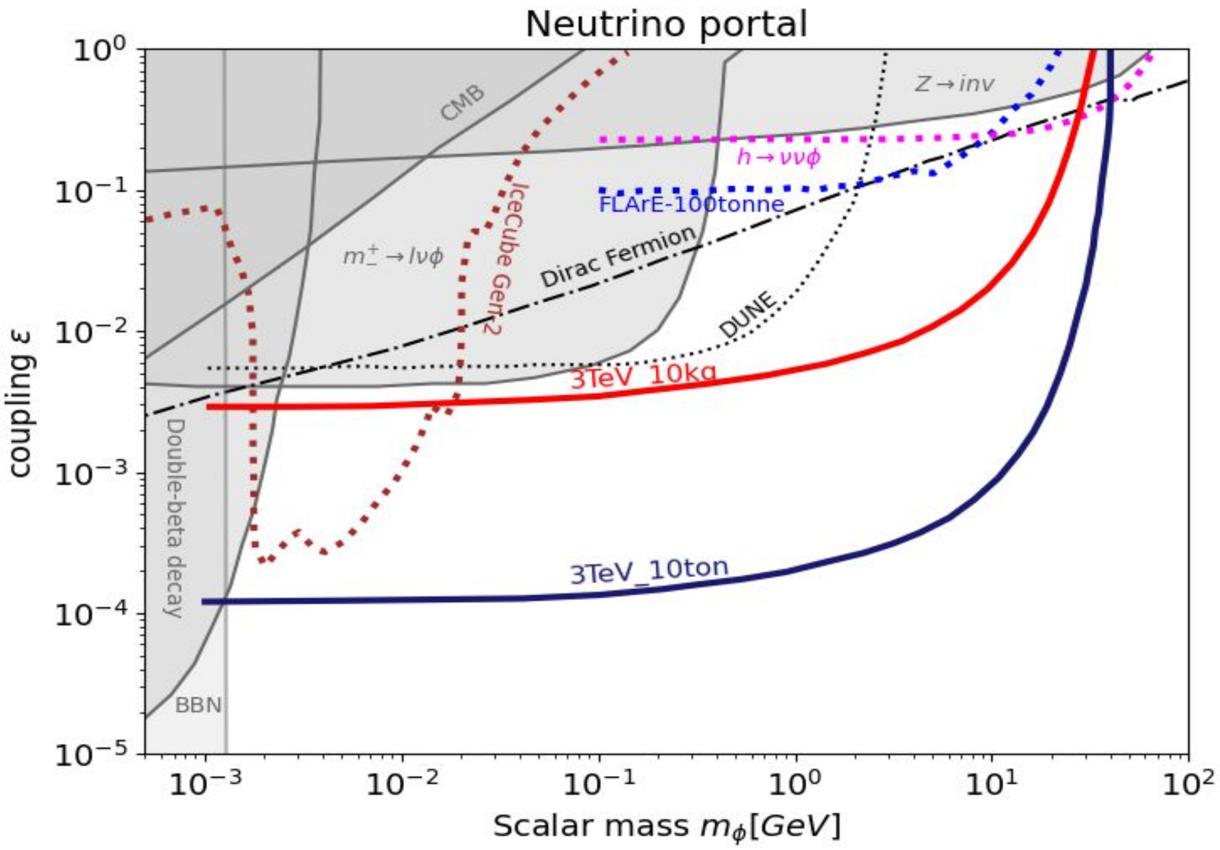
Some technical details:

- Model DIS
- Using madgraph
- Use nuclear pdf for Iron
- Find cross section for the BSM process for a number of masses
- Calculate number of events based on :

$$N_{BSM} = \frac{\sigma \times \rho \times l_{det} \times 10^{-36} \times N_{inc}}{m_p}$$

Scales as coupling$^2$

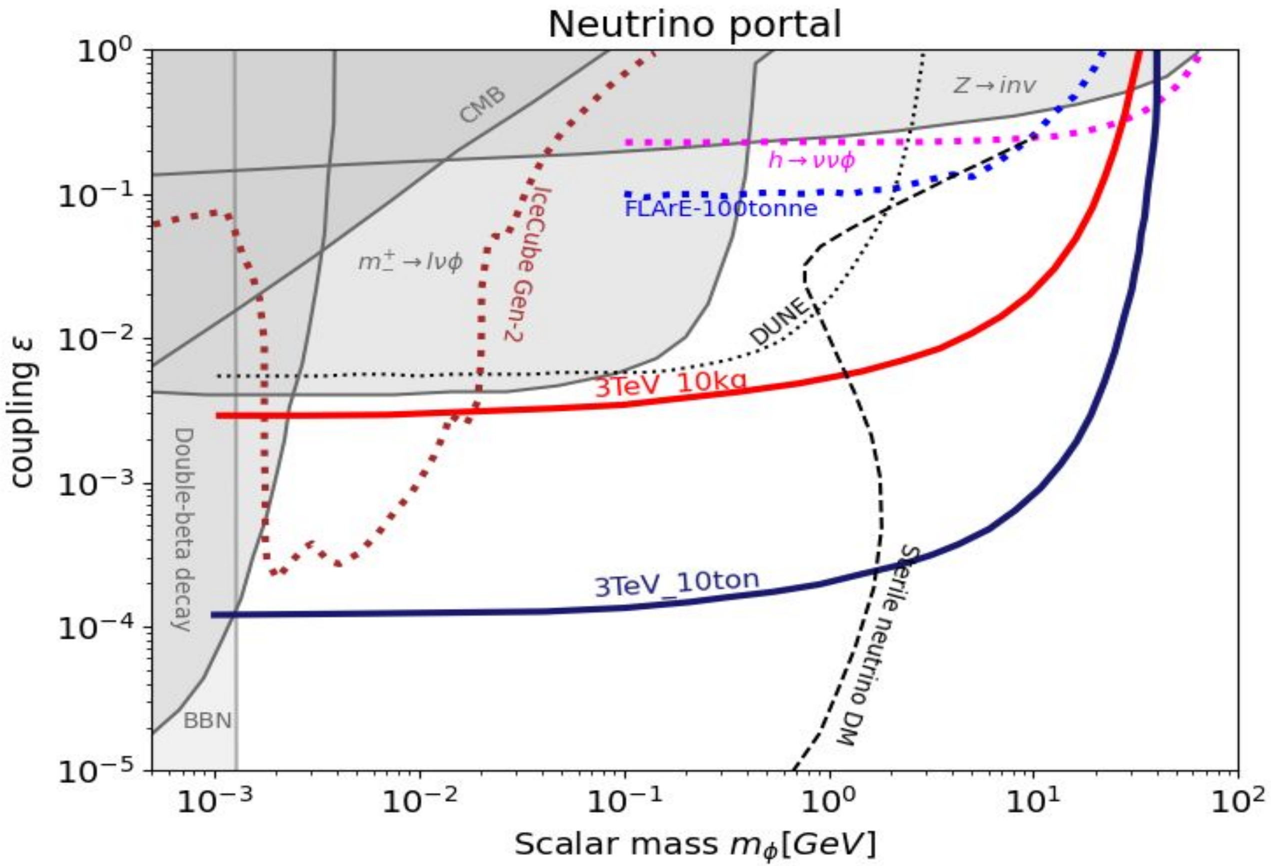
# Sensitivity reach




Dirac Fermion Dark matter

$$m_\phi = 3m_\chi, \quad y = \lambda_{\alpha\beta}$$

# Sensitivity reach



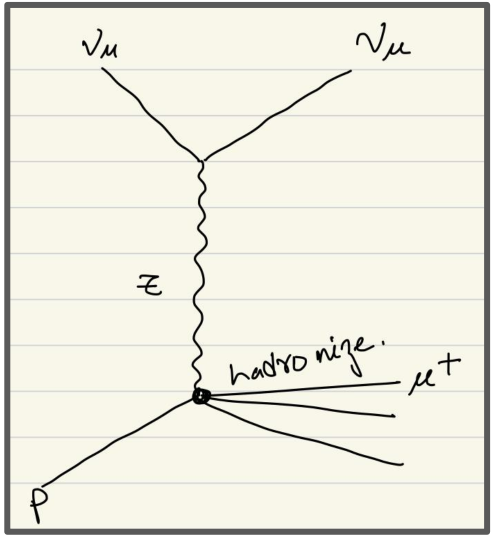

Sterile neutrino dark matter

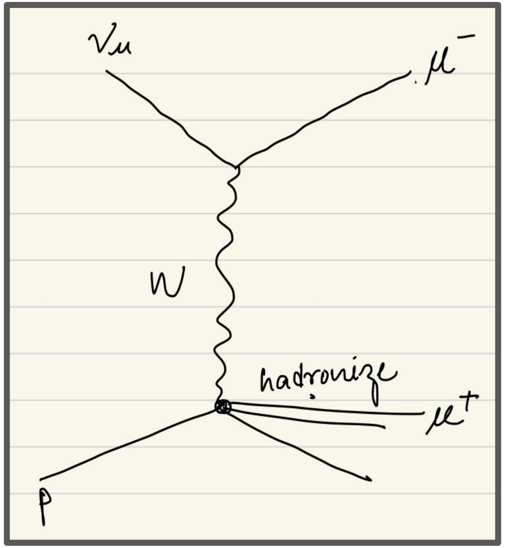
$m_4 = 4$ keV

$\sin^2(2\theta) = 10^{-9}$

## Background

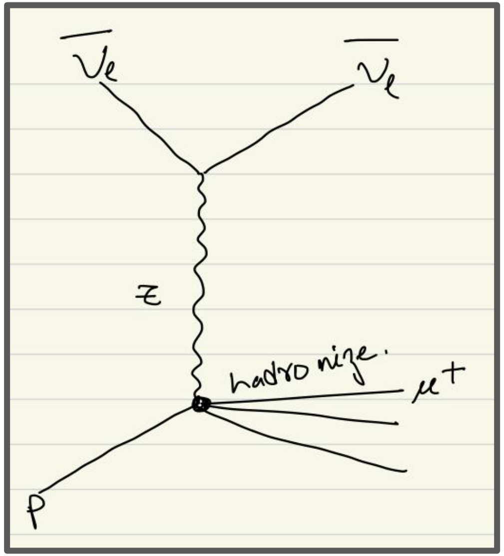
Neutral and charged current $\nu_\mu$ events

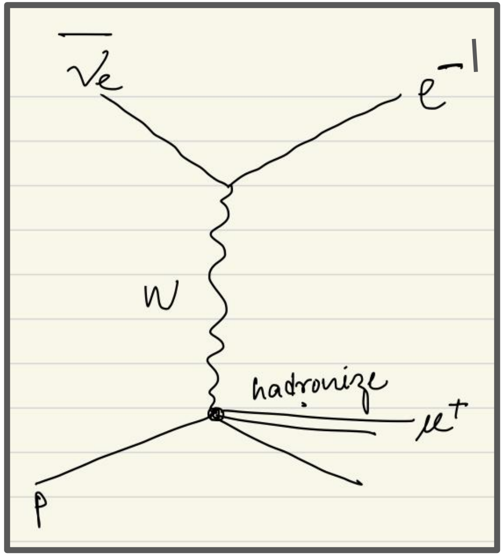


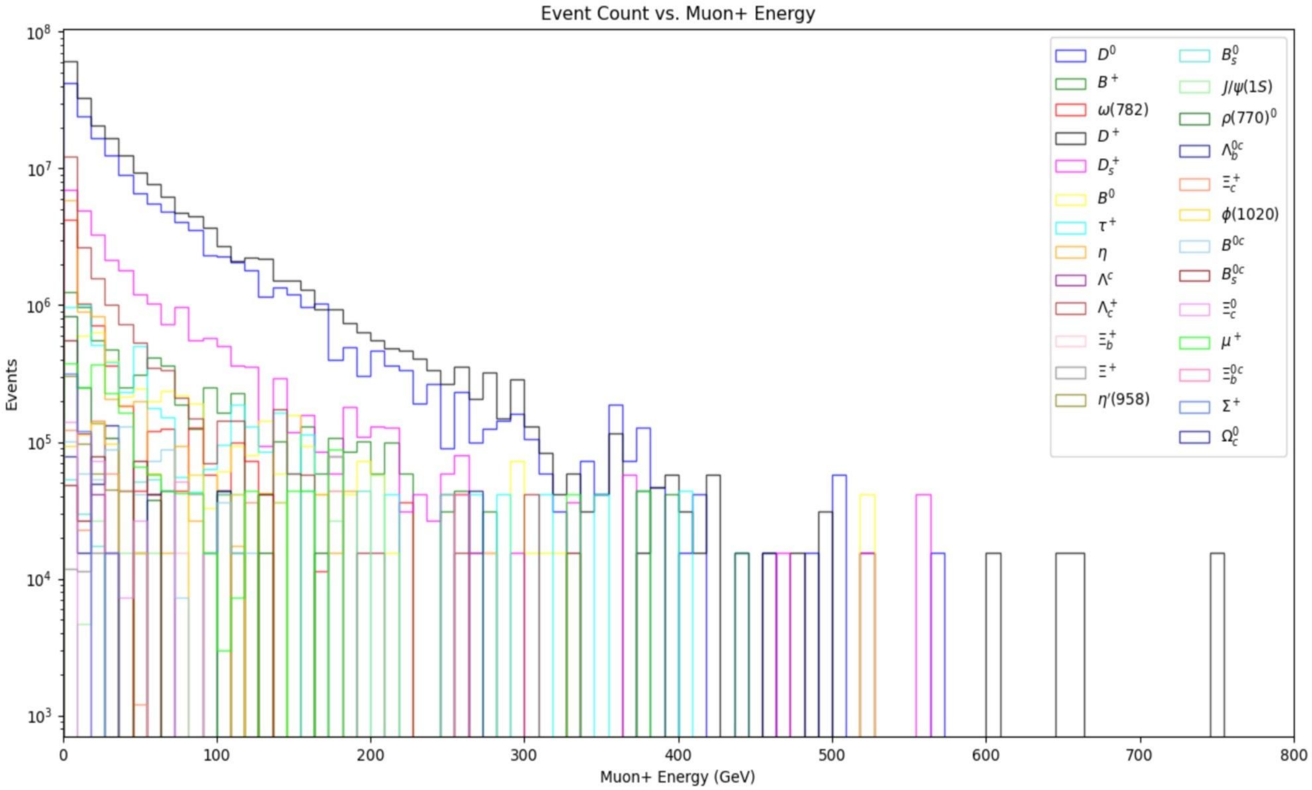
# Background

Neutral and charged current $\overline{\nu}_e$ events

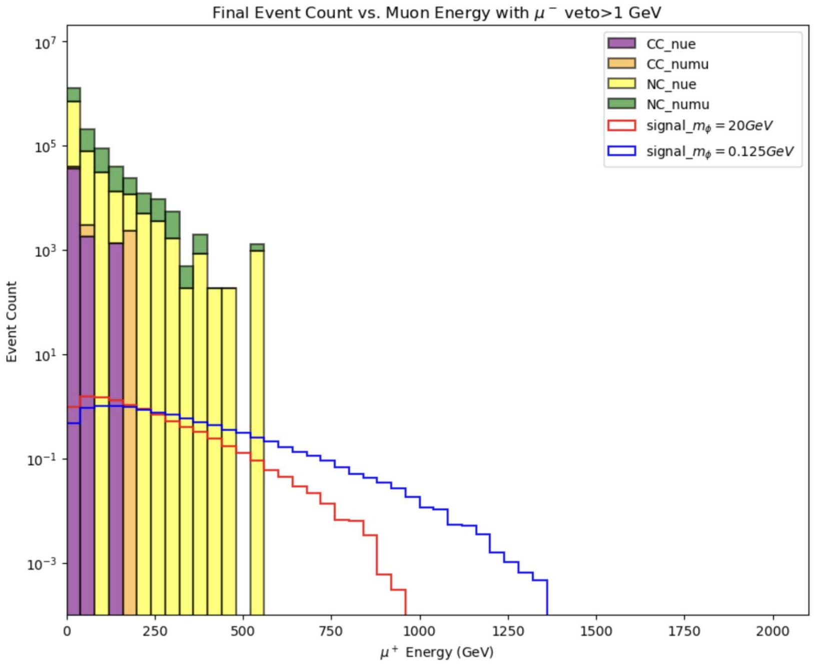


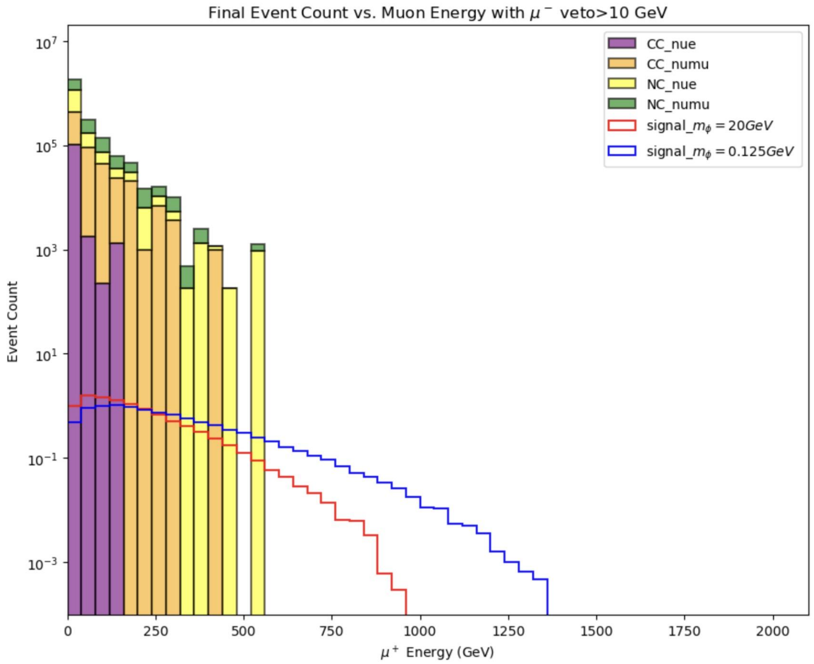



# Possible decays through which $\mu+$ can be produced



# Possible ways to reduce background



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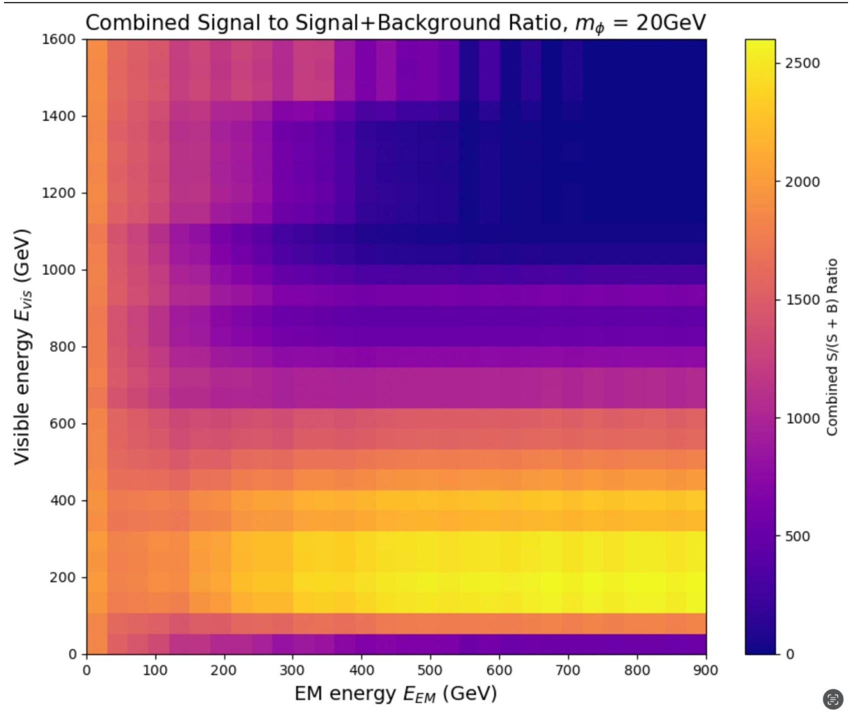
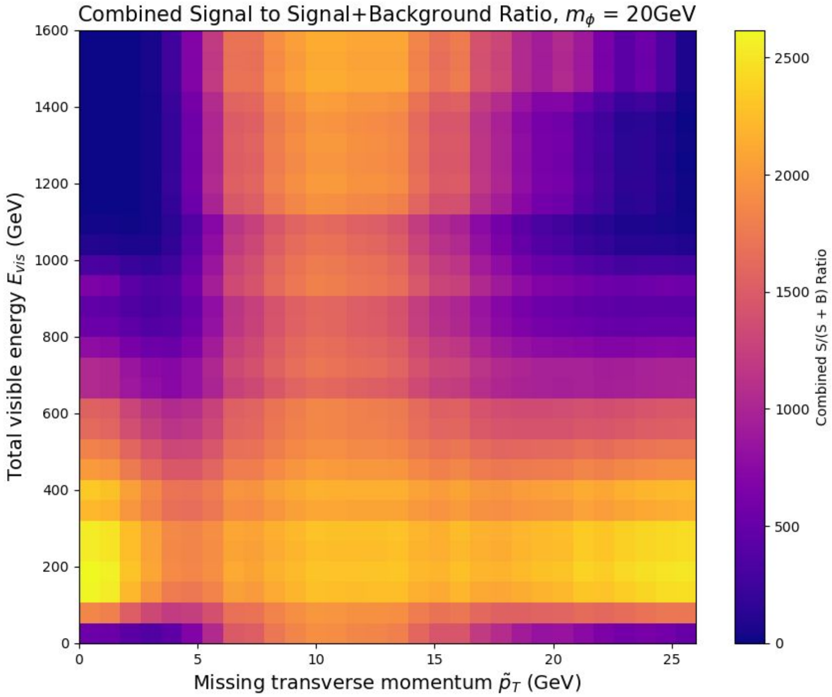
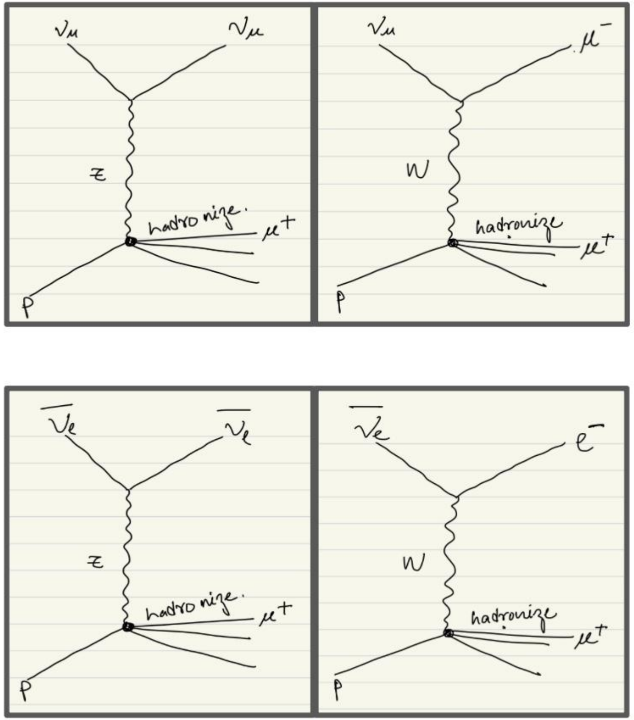


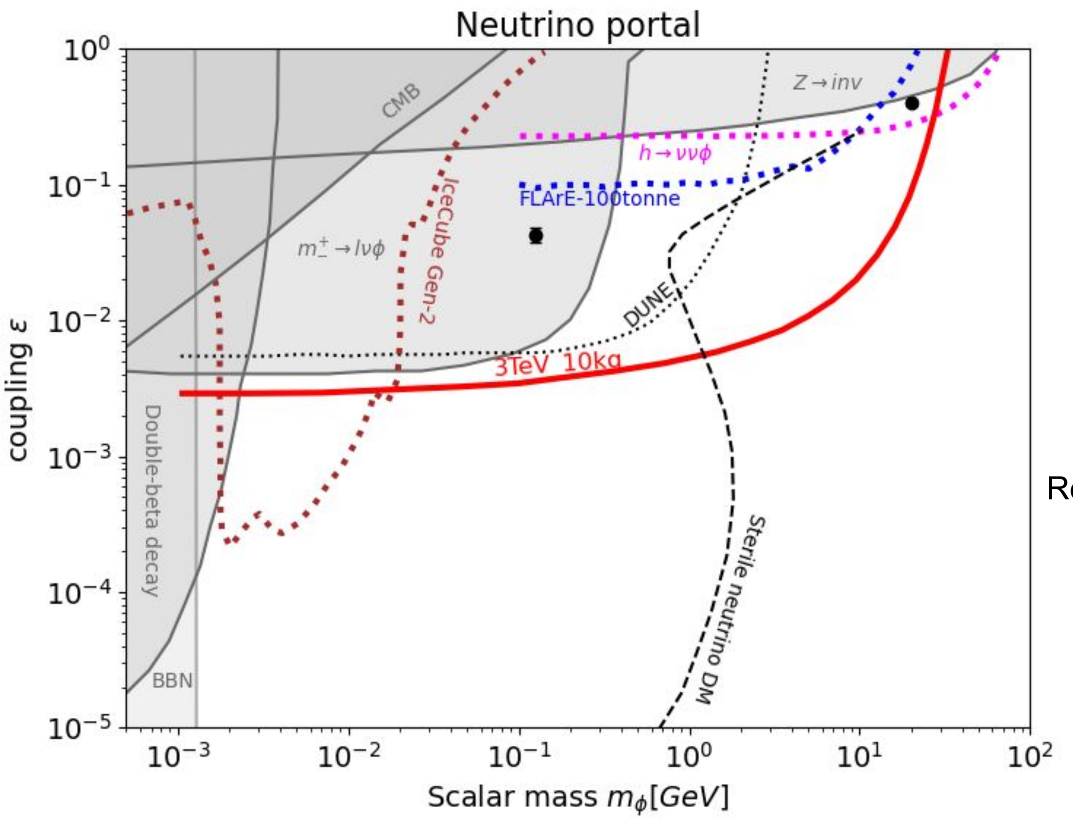



# Cut flow table




| 3TeV COM with 10 kg detector | | | | | |
|---|---|---|---|---|---|
| 10mil mc events | | | | | |
| CUTS | 20GeV signal after cut | 125MeV signal after cut | Background after cut | S/sqrt(B) 20GeV | S/sqrt(B) 125MeV |
| no cuts | 1.00E+03 | 1.00E+03 | 2.64E+07 | 0.19 | 0.19 |
| mu+ energy>100 | 8.22E+02 | 7.88E+02 | 9.18E+04 | 2.71 | 2.6 |
| mu- energy<10 | 8.21E+02 | 7.80E+02 | 3.86E+03 | 13.21 | 12.55 |
| EM energy<200 GeV | 7.81E+02 | 7.40E+02 | 3.31E+03 | 13.57 | 12.86 |
| CHARM veto 80% | 7.81E+02 | 7.40E+02 | 6.66E+02 | 30.26 | 28.67 |
| visible energy<500 GeV | 6.01E+02 | 4.77E+02 | 3.00E+02 | 34.69 | 27.53 |
| missing pT>6GeV | 2.14E+02 | 2.54E+01 | 1.29E+01 | 59.58 | 6.96 |

# Preliminary results




Reach after background reduction

# Conclusion

1. With this work we have tried to probe neutrinophillic mediator in the muon collider.

2. The search for mediator will also open windows to probe dark matter models that couple via the mediator to standard model particles.

3. Neutrinos have always been a loose string in the standard model and there are plans to study neutrino physics in muon collider along with BSM physics.

4. Interested people in neutrinos are welcome to read our current paper discussing new physics and neutrino physics in the forward kinematic region of the FCC-hh(arXiv:2409.02163)

**FPF@FCC: Neutrino, QCD, and BSM Physics Opportunities with Far-Forward Experiments at a 100 TeV Proton Collider**

Roshan Mammen Abraham[1], Jyotismita Adhikary[2], Jonathan L. Feng[1], Max Fieg[1], Felix Kling[3], Jinmian Li[4], Junle Pei[5,6], Tanjona R. Rabemananjara[7,8], Juan Rojo[7,8], and Sebastian Trojanowski[2]