SEARCH FOR STERILE NEUTRINO WITH LIGHT GAUGE INTERACTIONS

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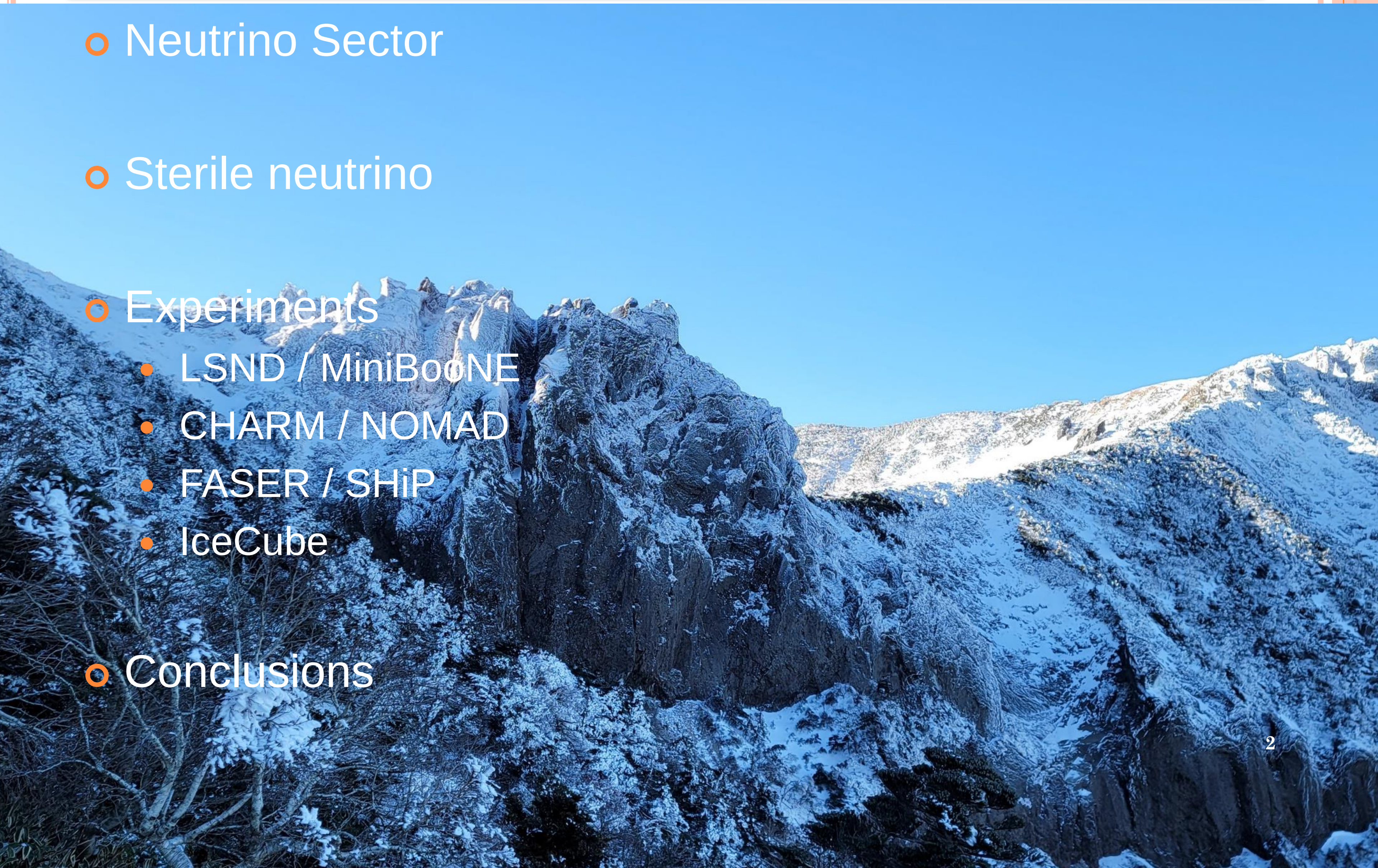
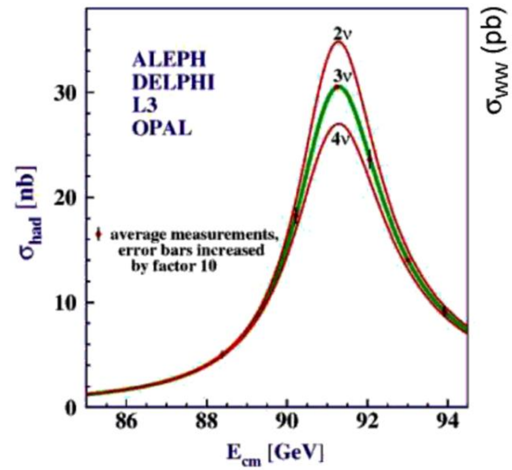


Neutrino sector in the SM

- Neutrino properties
  - Weak force: $-\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} \sum_l \bar{\nu}_{Ll} \gamma^\mu l_{\bar{L}} W^+_\mu + {\rm h.c.}$, $-\mathcal{L}_{\rm NC} = \frac{g}{2\cos\theta_W} \sum_l \bar{\nu}_{Ll} \gamma^\mu \nu_{Ll} Z^0_\mu.$
  - Electrically neutral
  - Lepton number → $L_e = \pm 1,\ L_\mu = \pm 1,\ L_\tau = \pm 1$

- The number of neutrino species
  - Z decay width @ LEP → $N_\nu = 2.984 \pm 0.008$ PDG 2020
  - Effective number of neutrino species: $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ Planck 2018

- Neutrinos are massless
  - No right-handed neutrino
  - No mass terms: $m_\nu \left(\bar{\nu}_L \nu_R + {\rm h.c.}\right)$



Neutrino oscillation

- Neutrino oscillation
  - Implies that at least two neutrinos are massive

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}\ \mathrm{eV}^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)

PDG 2020

$$\mathcal{L}_{\text{mass}} = -Y^e_{ij}\bar{L}^i H e^j_R - Y^\nu_{ij}\bar{L}^i \widetilde{H}\nu^j_R$$

- Simplest solution
  - Introduce singlet RH neutrino & its Yukawa interaction
  - Generate **pure Dirac-type mass**: $m_\nu\left(\bar{\nu}_L\nu_R + \text{h.c.}\right)$
  - The required Yukawa couplings are extremely small

Neutrino oscillation

Minkowski 1977 & Yanagida 1979

- Seesaw mechanism
  - Introduce Heavy right-handed neutrino
    - Uncharged under both the weak & electromagnetic force

$$\mathcal{L}_{\text{mass}} = -Y^e_{ij}\bar{L}^i H e^j_R \boxed{- Y^\nu_{ij}\bar{L}^i \widetilde{H}\nu^j_R - iM_{ij}(\nu^i_R)^c \nu^j_R} + h.c.$$

  - After electroweak symmetry breaking, neutrino mass matrix

$$\mathcal{L}_{\nu,\text{mass}} = -m\bar{\psi}_L\psi_R - \frac{M}{2}\bar{\psi}_R\psi_R \longrightarrow \begin{pmatrix} 0 & M_D \\ M_D & M_N \end{pmatrix}$$

  - Diagonalizing the matrix, we get light and heavy neutrino
    - Light neutrino mass ~ eV
    - Heavy neutrino mass >> 1 TeV

Sterile Neutrino

- Full neutrino mass term

$$-\mathcal{L}_m^\nu = \frac{1}{2}\left(\sum_{a=1}^{3}\sum_{b=1}^{n}(\overline{\nu_{aL}}\; m_{ab}^\nu\; N_{bR} + \overline{N_{bL}^c}\; m_{ba}^{\nu *}\; \nu_{aR}^c) + \sum_{b,b'=1}^{n}\overline{N_{bL}^c}\; B_{bb'}\; N_{b'R}\right) + \text{h.c.}$$

$$= \frac{1}{2}\left(\sum_{m=1}^{3} m_{\nu_m}\;\overline{\nu_{mL}}\;\nu_{mR}^c + \sum_{m'=4}^{3+n} M_{N_{m'}}\;\overline{N_{m'L}^c}\; N_{m'R}\right) + \text{h.c.}$$

  - Mixing relations

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{3+n} V_{am'}N_{m'L}^c,\;\; UU^\dagger + VV^\dagger = I.$$

- Gauge interaction Lagrangian

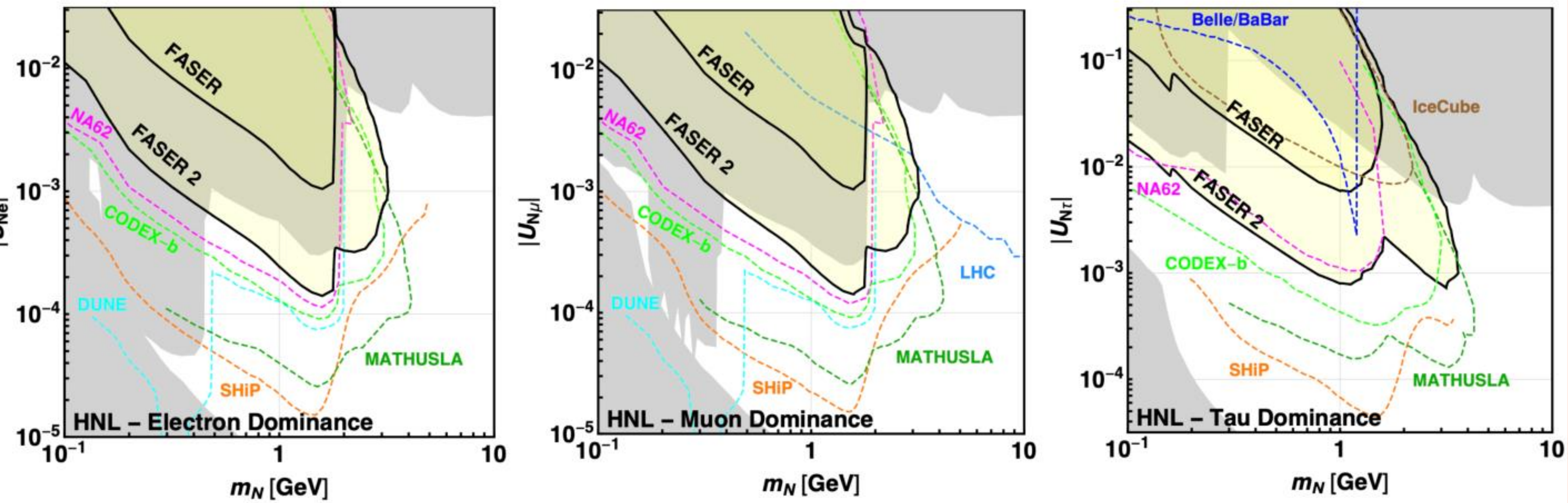
$$-\mathcal{L} = \frac{g}{\sqrt{2}}W_\mu^+\left(\sum_{\ell=e}^{\tau}\sum_{m=1}^{3}U_{\ell m}^*\;\overline{\nu_m}\gamma^\mu P_L\ell + \sum_{\ell=e}^{\tau}\sum_{m'=4}^{3+n}V_{\ell m'}^*\overline{N_{m'}^c}\gamma^\mu P_L\ell\right) + \text{h.c.}$$

$$+\frac{g}{2\cos\theta_W}Z_\mu\left(\sum_{\ell=e}^{\tau}\sum_{m=1}^{3}U_{\ell m}^*\;\overline{\nu_m}\gamma^\mu P_L\;\nu_\ell + \sum_{\ell=e}^{\tau}\sum_{m'=4}^{3+n}V_{\ell m'}^*\overline{N_{m'}^c}\gamma^\mu P_L\;\nu_\ell\right) + \text{h.c.}$$

Sterile Neutrino

FASER collaboration, arXiv:1811.12522

- MeV-GeV scale Heavy Neutral Lepton Searches
  - Without new Z' interaction



- Decay channels are induced by CC/NC
- Decay Width is suppressed by $|U_{l4}|^2$ as well as G_F^2.
- This mixing can be proved by beam-dump experiments, IceCube, rare meson decays…

LSND

LSND collaboration, PRL 77, 1996

- Liquid Scintillator Neutrino Detector
  - measured the number of neutrinos being produced by an accelerator neutrino source
  - results conflict with the standard model expectation of only three neutrino flavors

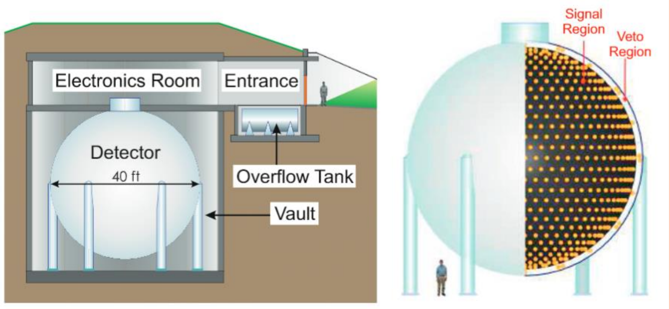
Oscillation Channel	Class	Experiments
ν_e appearance	Short Baseline Experiments	LSND ($\bar{\nu}$)

- The controversial LSND result was tested by the MiniBooNE experiment
  - found similar evidence for oscillations

MiniBooNE

MiniBooNE collaboration, PRD 103, 2021

- 8GeV protons from the Fermilab Booster interacting on a beryllium target
- Neutrino mode @ the detector
  - ν_μ: 93.5%
- Antineutrino mode @ the detector
  - $\bar{\nu}_\mu$: 83.7%



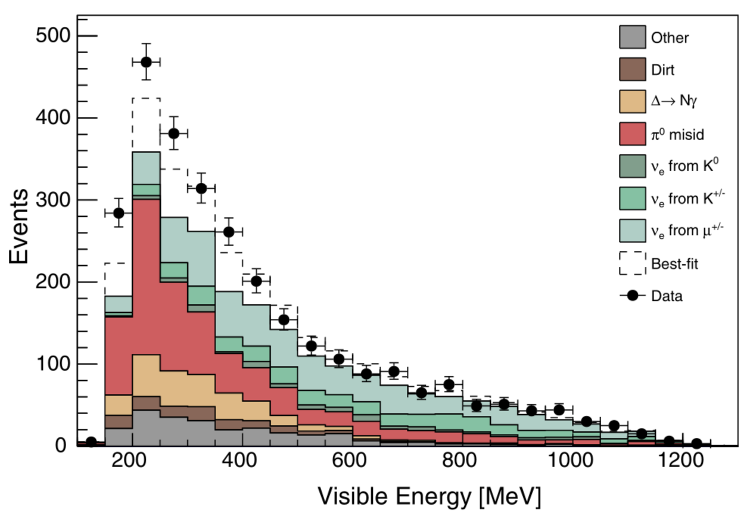
- ν_μ & $\overline{\nu}_\mu$ fluxes peak @ 600 MeV and 400 MeV
- Detector consists of a 12.2m diameter sphere filled with 818 tonnes of pure mineral oil (CH_2)
  - Located 541m from the beryllium target
  - Covered by 152 PMTs

MiniBooNE

MiniBooNE collaboration, PRD 103, 2021

- Long-standing anomaly
  - 4.8σ discrepancy
  - 460 low-energy electronlike events
- Muon-to-electron flavor appearance

Oscillation Channel	Class	Experiments
ν_e appearance	Short Baseline Experiments	MiniBooNe $(\nu, \bar{\nu})$

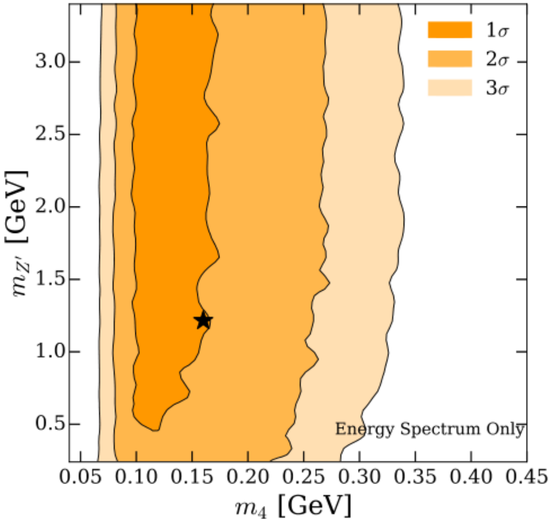


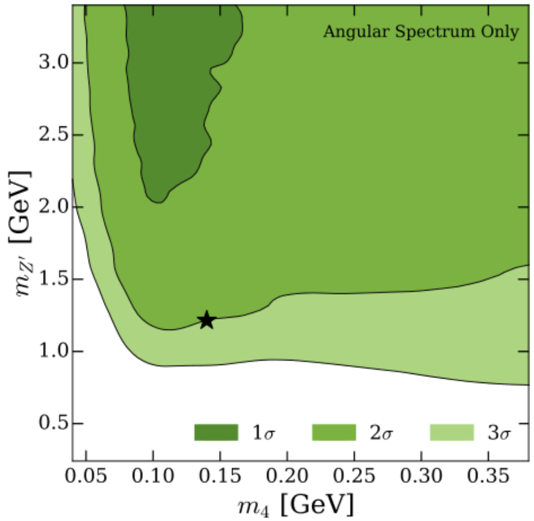
Process	Neutrino mode	Antineutrino mode
ν_μ and $\bar{\nu}_\mu$ CCQE	107.6 ± 28.2	12.9 ± 4.3
NC π^0	732.3 ± 95.5	112.3 ± 11.5
NC $\Delta \to N\gamma$	251.9 ± 35.2	34.7 ± 5.4
External events	109.8 ± 15.9	15.3 ± 2.8
Other ν_μ and $\bar{\nu}_\mu$	130.8 ± 33.4	22.3 ± 3.5
ν_e and $\bar{\nu}_e$ from $\mu^\pm$ decay	621.1 ± 146.3	91.4 ± 27.6
ν_e and $\bar{\nu}_e$ from $K^\pm$ decay	280.7 ± 61.2	51.2 ± 11.0
ν_e and $\bar{\nu}_e$ from K^0_L decay	79.6 ± 29.9	51.4 ± 18.0
Other ν_e and $\bar{\nu}_e$	8.8 ± 4.7	6.7 ± 6.0
Unconstrained bkgd.	2322.6 ± 258.3	398.2 ± 49.7
Constrained bkgd.	2309.4 ± 119.6	400.6 ± 28.5
Total data	2870	478
Excess	560.6 ± 119.6	77.4 ± 28.5
0.26% (LSND) $\nu_\mu \to \nu_e$	676.3	100.0

MiniBooNE

P. Ballet et al PRD 99, 2019

- Z' boson + sterile neutrino with $m_4 = 100 - 500$ MeV
- Lagrangian
  - $\mathcal{L} \supset -eq_f \cos\theta_W \chi \bar{f}\gamma^\mu f Z'_\mu$, $\quad \mathcal{L} \supset U^*_{\alpha 4} g' \bar{\nu}_\alpha \gamma^\mu P_L \nu_4 Z'_\mu + U^*_{\alpha 4} U_{\beta 4} g' \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta Z'_\mu + g' \bar{\nu}_4 \gamma^\mu P_L \nu_4 Z'_\mu,$
  - Upscatter to produce the heavy neutrinos inside the detector via the Z'-mediated production process $\nu_\mu + N \to \nu_4 + N$
  - Subsequent decay: $\nu_4 \to \nu_\alpha e^+ e^-$

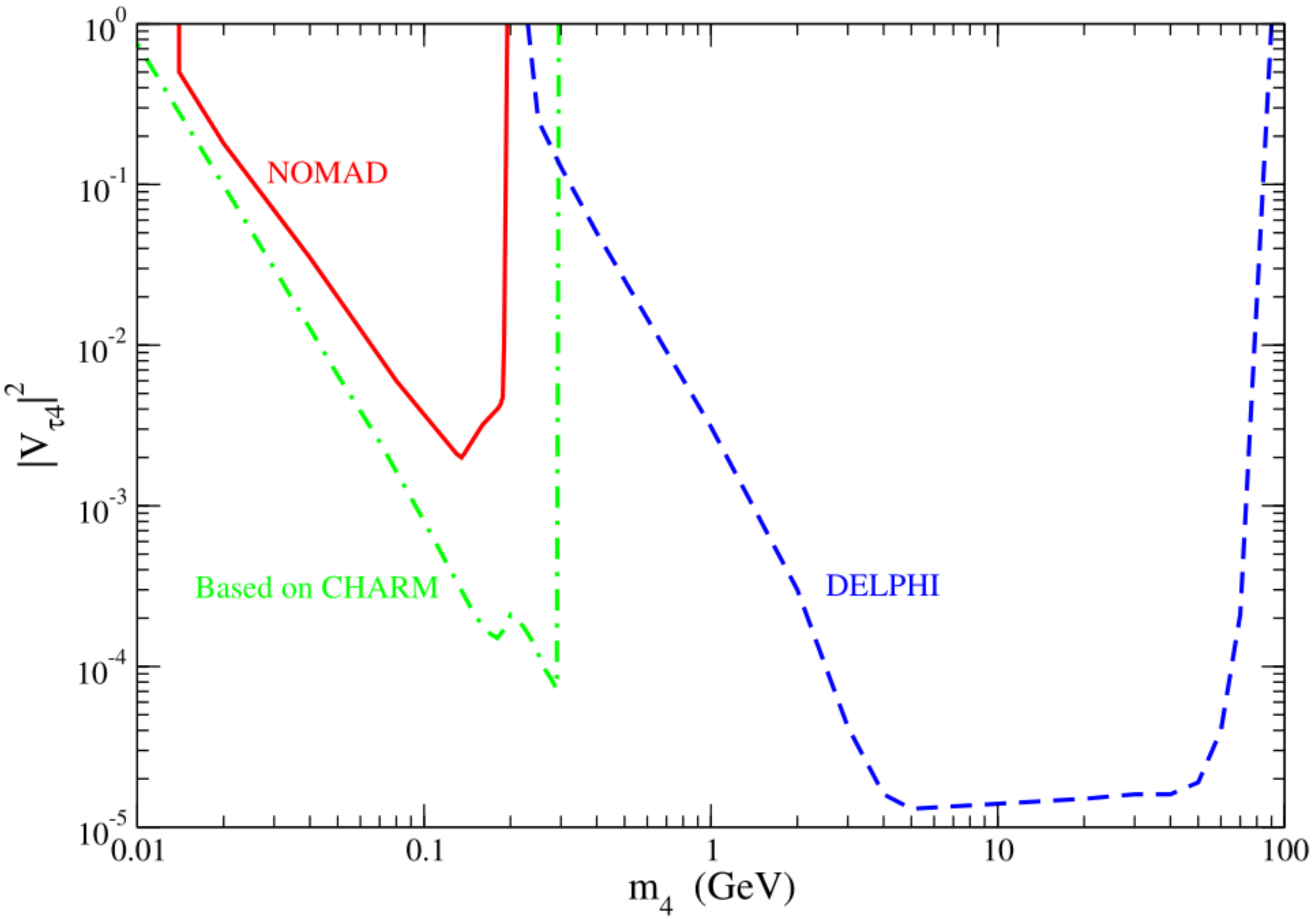




Sterile Neutrino

A. Atre et al, 0910.3589

- Tau-Sterile neutrino mixing



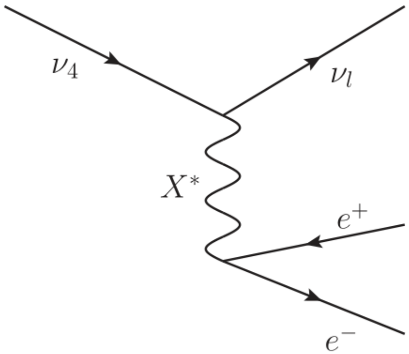
Sterile ν-specific $U(1)_s$ P. Ko et al, PLB 739, 2014

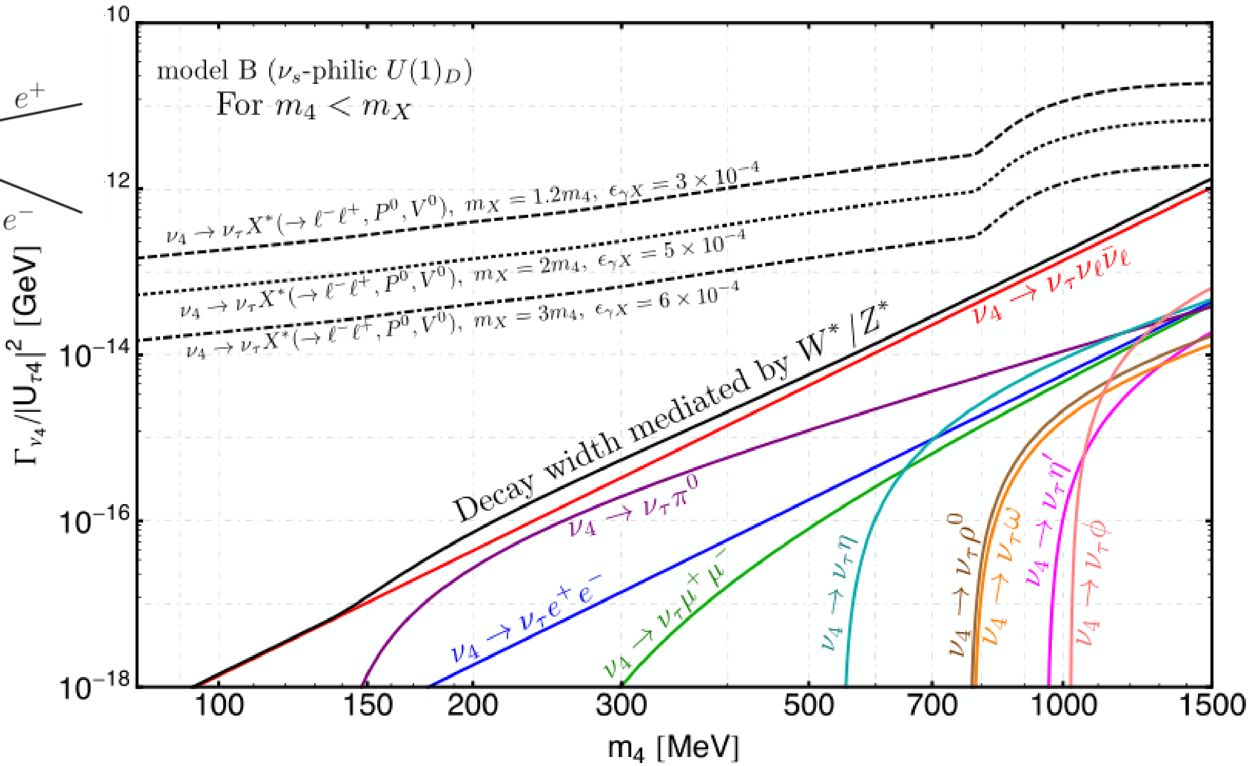
- Dark `sterile neutrino-specific' gauge interaction
- $U(1)_S$ symmetry
  - No SM particles are charged
  - Introduce gauge singlet RH neutrinos, SM-singlet Dirac neutrino, new scalar field
- $$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{m_X^2}{2} X_\mu X^\mu - \frac{\epsilon_{\gamma X}}{2} X_{\mu\nu} B^{\mu\nu} - g_X \bar{\nu}_s \gamma^\mu \nu_s X_\mu - m_s \overline{\hat{\nu}_s} \hat{\nu}_s - \left(\hat{y}^j_{\nu_s} \overline{\hat{N}_{Rj}} \hat{\nu}_s \phi^\dagger + \hat{y}^{ij}_\nu \overline{\hat{L}_i} \tilde{H} \hat{N}_{Rj} + \text{h.c.} \right).$$
- Active-sterile neutrino mixing & kinetic mixing
  - $\mathcal{L} \supset -g_X U_{\ell 4} \bar{\nu}_\ell \gamma^\mu \nu_4 X_\mu - g_X \epsilon_{\gamma X} \cos\theta_W Q_f \bar{f} \gamma^\mu f X_\mu$

Sterile ν-specific $U(1)_s$

- Decay width:

$$\Gamma_{\nu_4 \to \nu_\tau e^- e^+} = \frac{G_X^2 \epsilon_{\gamma X}^2}{48\pi^3} |U_{\tau 4}|^2 m_4^5$$





(b) model B, $m_4 < m_X$

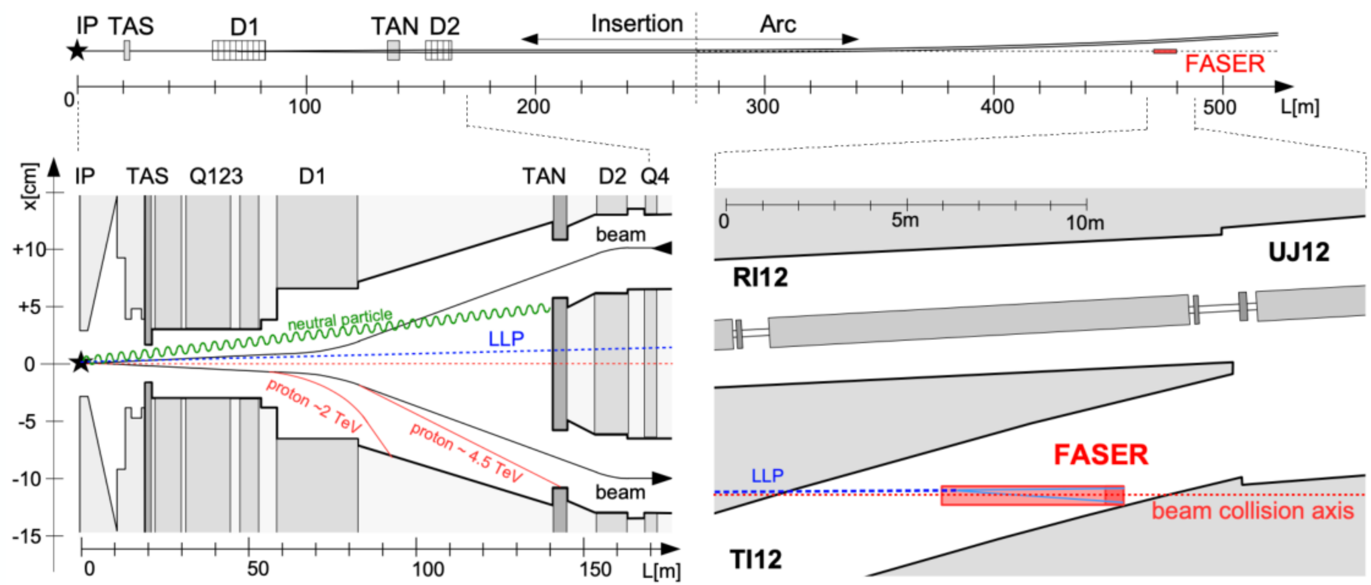
CHARM / NOMAD

J. Orloff et al, PLB 550 2002,
NOMAD collaboration, PLB 506, 2001

- Beam-dump searches using proton beams
  - CHARM: 400 GeV/c proton beam
  - NOMAD: 450 GeV/c & beryllium target
- CHARM
  - $m_4 = 10 - 290\ \mathrm{MeV}$
- NOMAD
  - $m_4 = 10 - 190\ \mathrm{MeV}$
- Without X boson effect, the largish parameter space up to $|U_{\tau 4}|^2 \geq 10^{-4}$ were probed.
  - With X boson, $|U_{\tau 4}|^2 \sim 10^{-8} - 10^{-4}$ can be reached

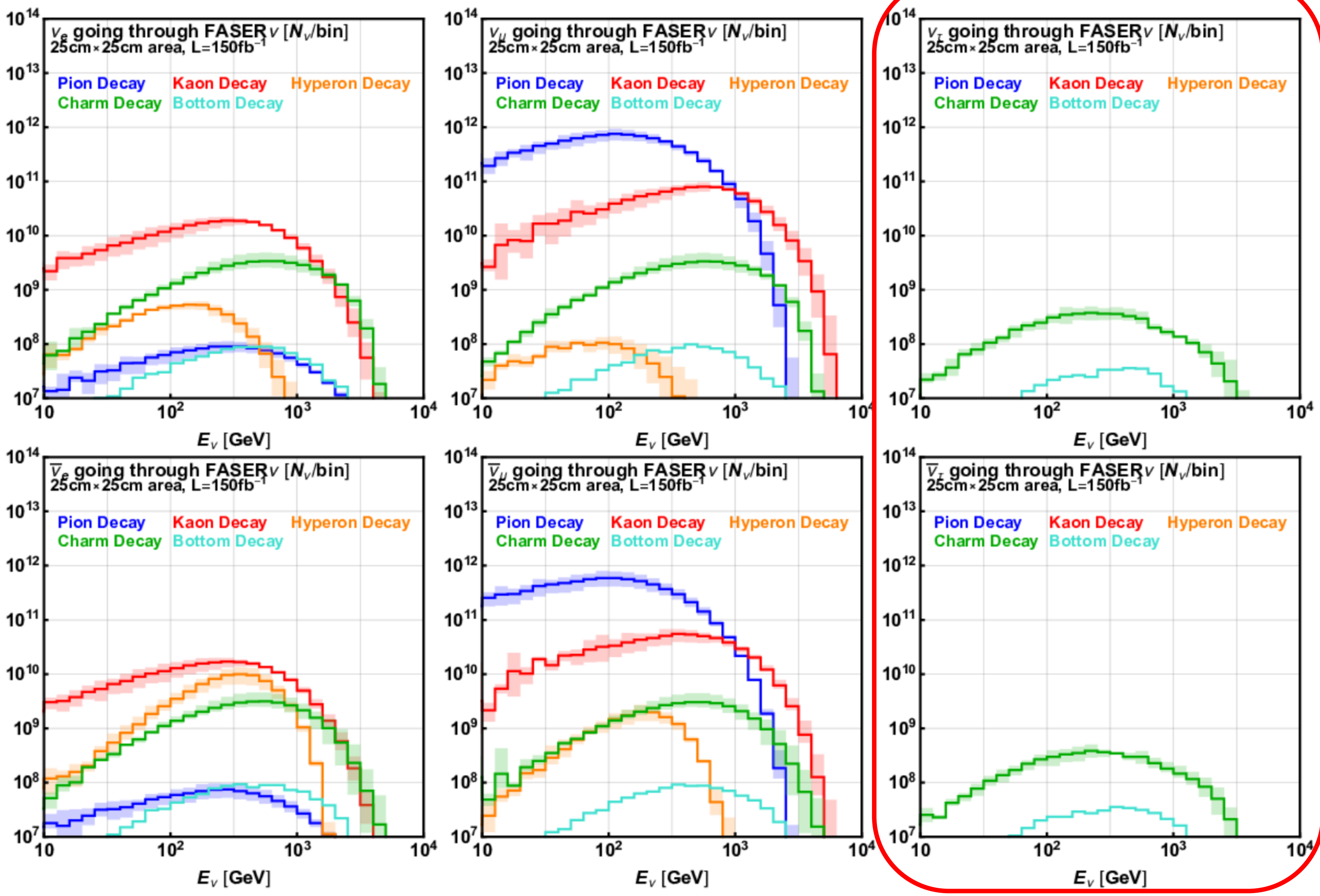
FASER

- ForwArd Search ExpeRiment
- Designed to search for new light & long-lived particles
- If these particles are sufficiently light, they can be produced in rare decays of hadrons.
  - dominantly produced in the forward direction along the collision axis



FASER

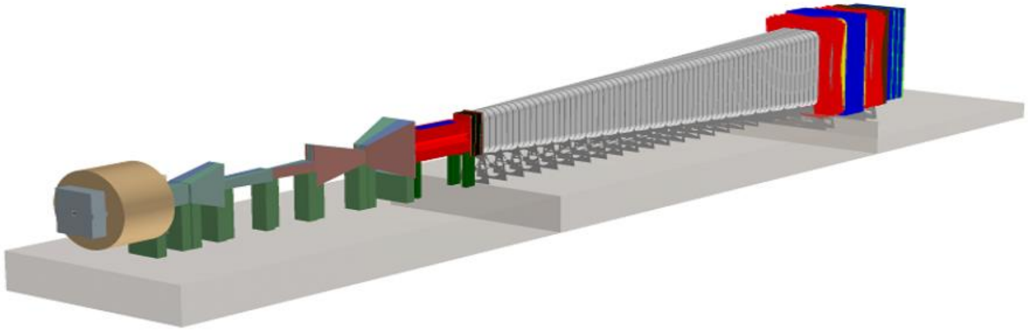
FASER collaboration, EPJC 80 2020

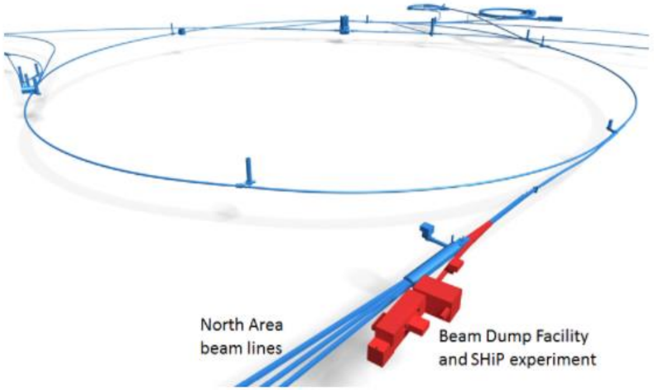


SHiP

S. Alekhin et al,
Rept. Prog. Phys. 79, 2016

- Search for Hidden Particles
- Search for LLP using CERN SPS proton beam of 400 GeV & the molybdenum target.
  - Proton on target: $\sim 10^{20}$ (in 5 years)
  - Distance: 110m, Δ=50m
  - $\langle E_{\nu_4} \rangle \sim 50$ GeV





LLP searches

- LLP searches @ ground experiments

Experiment	$N_{\rm POT}$ or $\int \mathcal{L}\, dt$	$\sqrt{s}$	$E_{p\text{ beam}}$	L	Δ	$\langle E_{\nu_4} \rangle$	95% C.L. limit
FASER (LHC Run 3)	$\int \mathcal{L}\, dt = 150\ \text{fb}^{-1}$	14 TeV	7 TeV	480m	1.5m	~ 1 TeV	$N_{\rm sig} \geq 3$
FASER2 (HL-LHC)	$\int \mathcal{L}\, dt = 3\ \text{ab}^{-1}$						
SHiP	$N_{\rm POT} = 2 \times 10^{20}$	27.4 GeV	400 GeV	110m	50m	~ 50 GeV	
CHARM	$N_{\rm POT} = 2.4 \times 10^{18}$			515m	35m		
NOMAD	$N_{\rm POT} = 4.1 \times 10^{19}$	29 GeV	450 GeV	835m	290m		

- The number of events

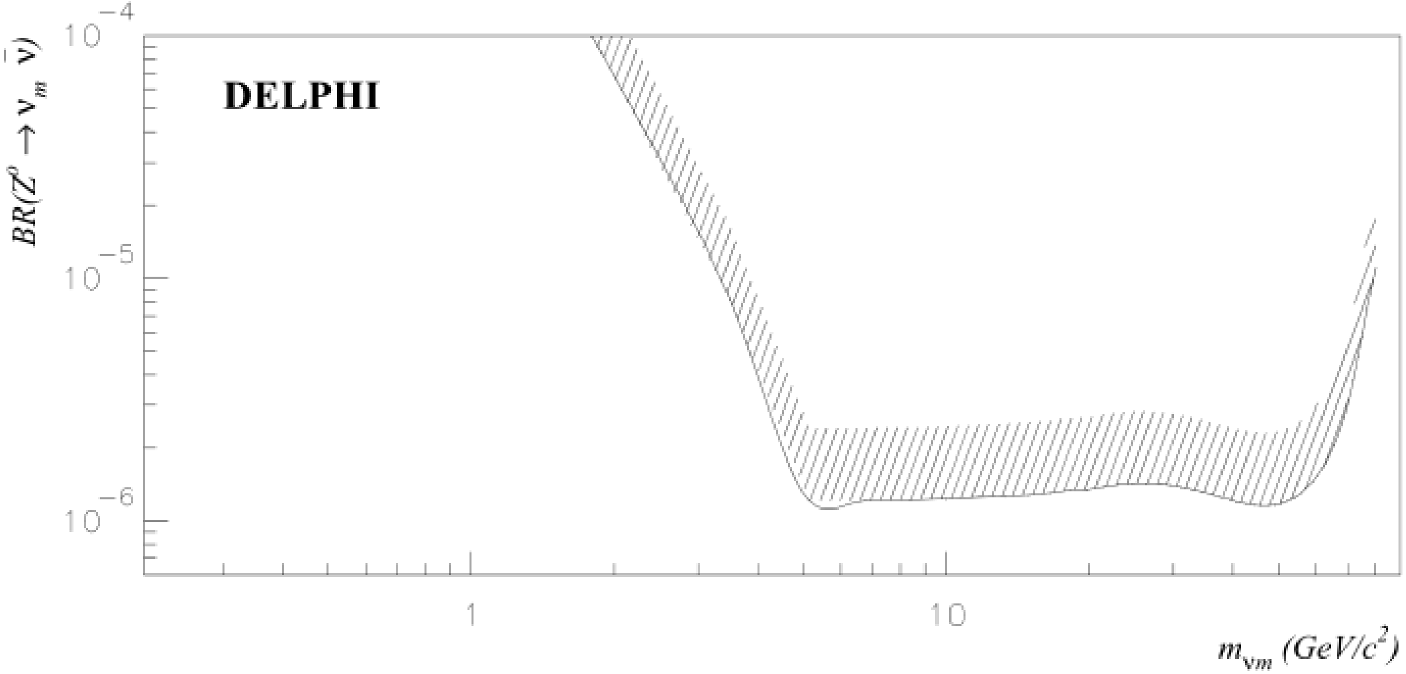
$$N_{\rm sig.} = \int_{E_{\rm min}}^{E_{\rm max}} dE_{\nu_4} \left[\frac{dN_{\nu_4}(E_{\nu_4})}{dE_{\nu_4}} \times \left(e^{-\frac{L-\Delta}{d}} - e^{-\frac{L}{d}} \right) \times {\rm Br}(X/\nu_4 \to \text{visible}) \times A_{\rm eff}(E_{\nu_4}) \right]$$

$$\frac{dN_{\nu_4}}{dE_{\nu_4}} \approx \frac{dN_{\nu_\tau}}{dE_{\nu_\tau}} \times |U_{\tau 4}|^2 \times (\text{phase space suppresion})$$

LEP monojet search

DELPHI Collaboration, Z. Phys. C 74, 1997

- DELPHI reported the weak isosinglet neutral heavy lepton search with 3.3×10^6 Z bosons @ LEP
  - $\nu_4 \rightarrow \text{monojet} : m_4 \geq 6\text{GeV}$
  - $\text{Br}(Z \to \nu\nu_4) < 1.3 \times 10^{-6}$ (95% C.L.)



Z invisible decay

S. Schael et al, Phys. Rept. 427, 2006

- Measurement of invisible Z decay

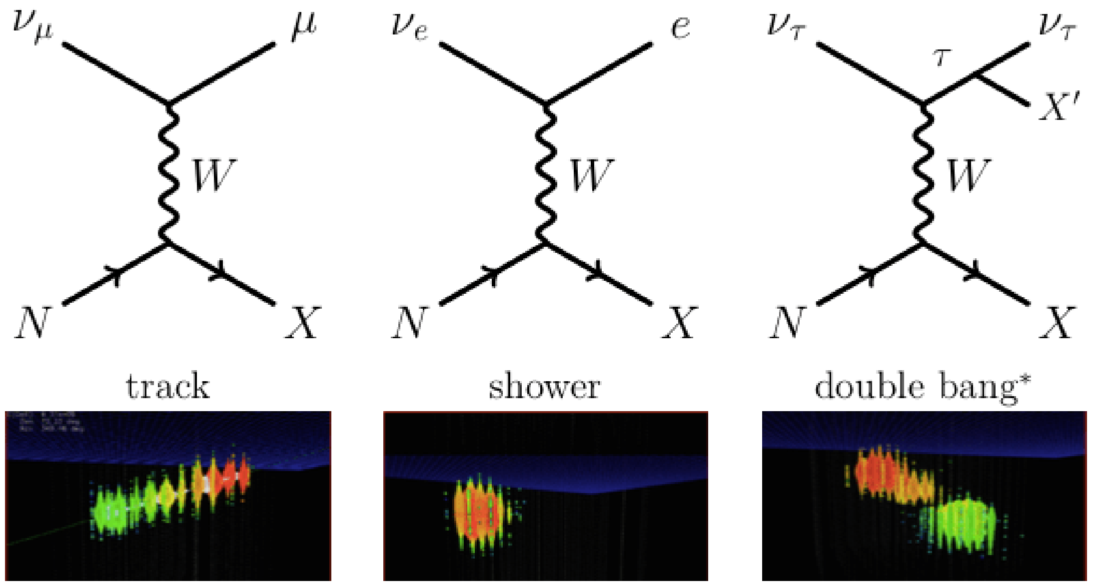
$$\Gamma^{\text{Exp.}}_{Z\to\text{invisible}} = 499.0 \pm 1.5 \text{ MeV},$$
$$\Gamma^{\text{SM}}_{Z\to\text{invisible}} = 501.69 \pm 0.06 \text{ MeV}.$$

- Conveniently, the experimental measurement of Z invisible width can be expressed in terms of the number of light neutrino species
  - $N_\nu = 2.9963 \pm 0.0074$
- To get our limits we set the confidence level to 3σ

$$|U_{l4}|^2 < \frac{1}{\text{Br}(X \to \text{invisible})} \cdot \left(\frac{\Gamma^{\text{Exp.}}_{Z\to\text{invisible}}}{\Gamma^{\text{SM}}_{Z\to\text{invisible}}} - 1 \right)$$

IceCube Telescope

- IceCube can distinguish flavors by observing event topology.



<u>Charged Current (CC)</u>

- electrons → shower
- muons → **track**
- taus → shower, track, double-bang

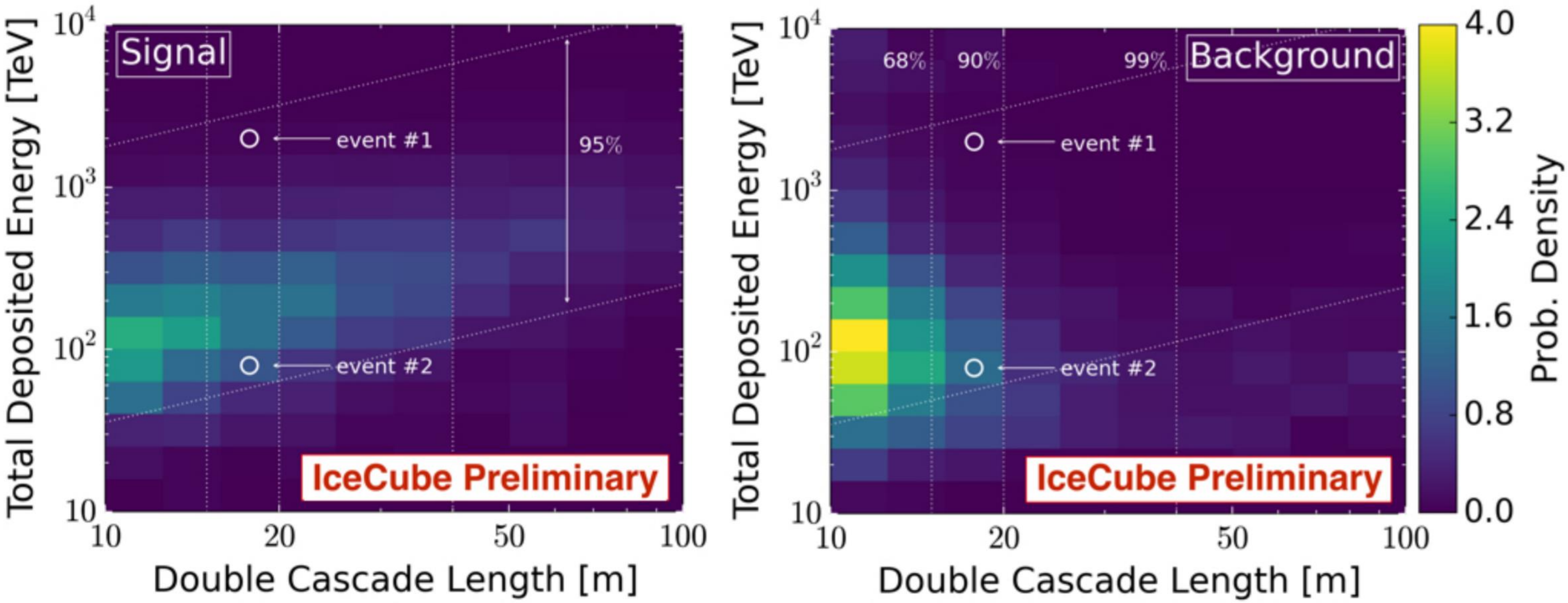
<u>Neutral Current (NC)</u>

hadronic shower
for
all flavors

IceCube

1908.05506

- Distribution of tau-DB & Non-DB events



- 2 candidates of tau-DB @ the IceCube

- $L^{\tau}_{\text{dec.}} = \gamma_\tau c\tau_\tau = 49.04\text{m}\left(\frac{E_\tau}{\text{PeV}}\right)$

IceCube

- GeV-energy tau-sterile probe by (Earth-penetrating) atmospheric neutrinos

$$P(\nu_\mu \to \nu_\tau) = \sum_{j,k} U_{\mu j} U^*_{\tau j} U^*_{\mu k} U_{\tau k} \exp\left(i \frac{\Delta m^2_{jk} L}{2E_\nu}\right) \approx \cos^4\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{jk} L}{4E_\nu}\right)$$

- TeV(~PeV)-energy tau-sterile probe by almost isotropic astrophysical neutrinos

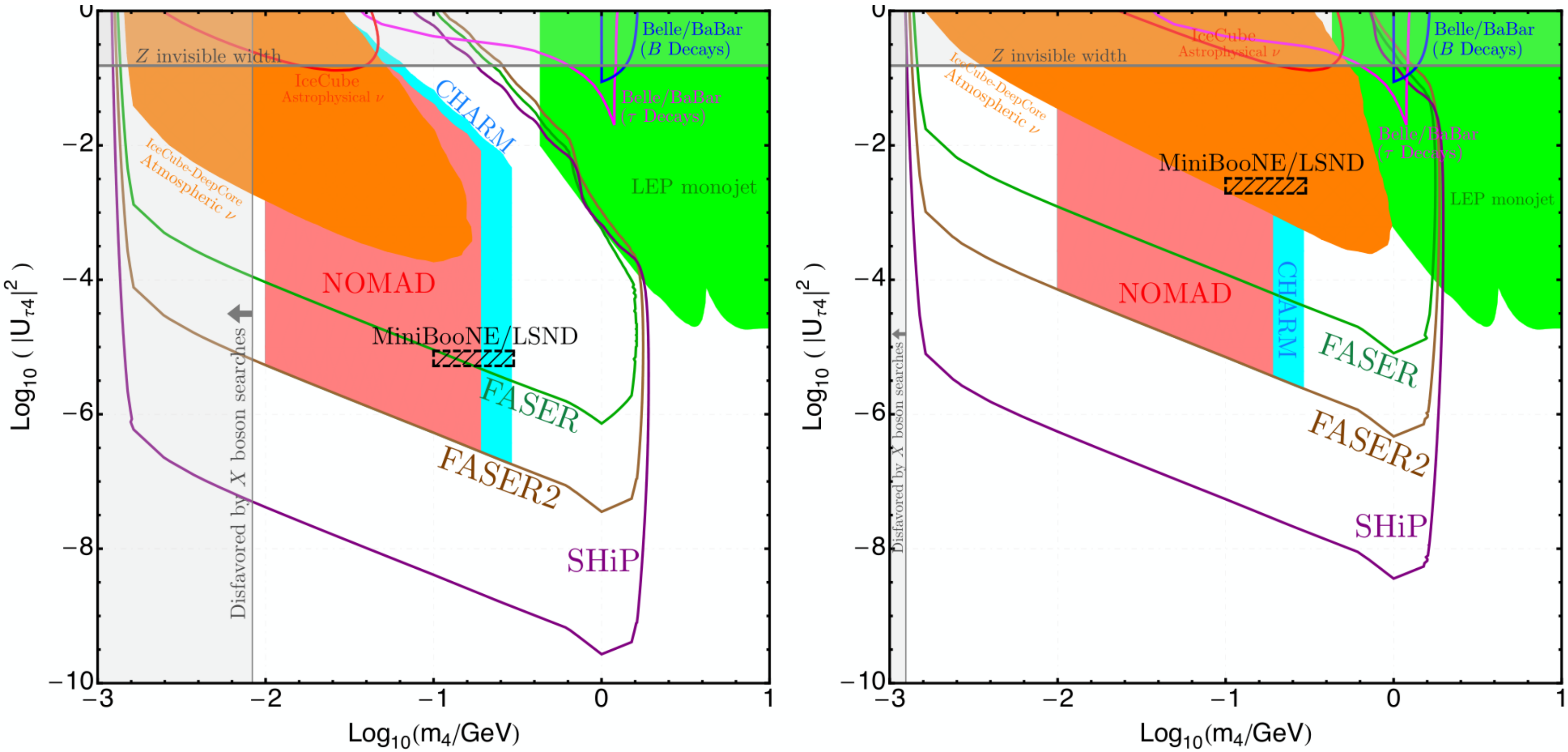
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \Phi_0 \times 10^{-18} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma} [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$$

- Double-Bang event rate at IceCube

$$N_{\mathrm{sig.}} \simeq \int dE_\nu \left[\frac{dN^{\nu_\tau}_{\mathrm{NC}}}{dE_\nu} \times \left(e^{-\frac{L-\Delta}{d}} - e^{-\frac{L}{d}}\right) \times \mathrm{Br}(X/\nu_4 \to \mathrm{visible})\right]$$

Numerical Analysis

- Sterile ν-specific $U(1)_s$ model



$$(m_X, g_X) = (1.2 m_4, 3 \times 10^{-4}) \qquad (m_X, g_X) = (8 m_4, 10^{-3})$$

Conclusions

- We consider MeV-GeV Neutral Lepton in the presence of light gauge interactions in the neutrino sector.
- Due to the different kinematics and decay channels of HNL, the signatures @ LLP searches and neutrino telescopes can be significantly changed.
- Future beam-dump experiments, IceCube telescope are expected to probe even very small tau-sterile mixing region near future.

Conclusions

- We consider MeV-GeV Neutral Lepton in the presence of light gauge
- Due to HNL, the telescopes
- Future beam-dump experiments, IceCube telescope are expected to probe even very sm mixing region near future.

Thank you very much

Question?