WG III Summary

Poonam Mehta and Manimala Mitra

Manimala Mitra

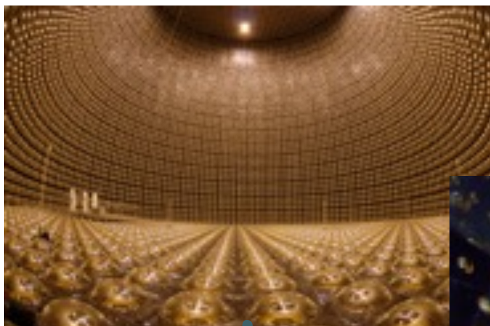
Institute of Physics (IOP), Bhubaneswar

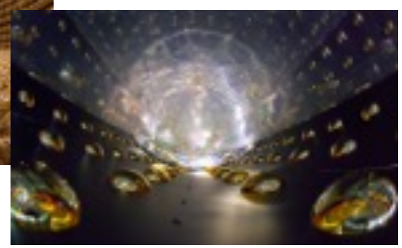
WHEPP XV, IISER Bhopal

23/12/2017

Neutrino Mass and Mixing:

eV neutrino mass and mixing from oscillation and non-oscillation experiments





$$\Delta m^2_{21} = (6.93 - 7.97) \times 10^{-5}\,\mathrm{eV}^2$$

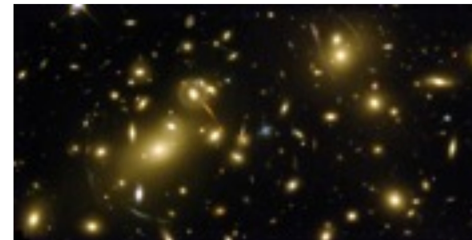
$$|\Delta m^2_{31}| = (2.37 - 2.63) \times 10^{-3}\mathrm{eV}^2$$

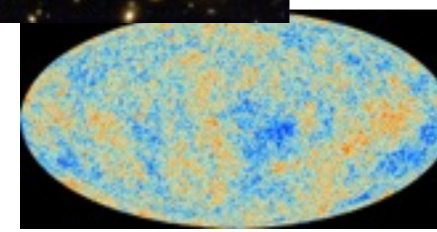
$$\sin^2\theta_{12} = 0.25 - 0.35, \sin^2\theta_{23} = 0.37 - 0.61$$

Large angle $\theta_{23} \sim 41^\circ - 48^\circ, \theta_{12} \sim 33^\circ$

Non-zero $\theta_{13} \sim 8.41^\circ$ **(DAYA BAY, RENO)**

(Fogli, Lisi, 2016)





Bound from cosmology

$$\Sigma m_i < \mathcal{O}(0.17 - 0.72)$$

(**Planck Collaboration, arXiv 1502.01589**)

Relaxed bound from β decay

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.3 \text{ eV}$$

(Mainz, Troitzk)

Major Puzzles

Beyond The Standard Model (BSM) theory is necessary

- **Underlying theory of neutrino mass generation!**

  At present no experimental evidence

- Neutrinos are electromagnetic charge neutral

  $\rightarrow$ **Dirac or Majorana ?** Majorana particle $\rightarrow$ it's own antiparticle.

Neutrino Oscillation

- Normal vs Inverted Mass hierarchy
- CP violation, Ambiguity in θ_{23}
- New physics

Neutrino oscillation

Neutrino mass models, experimental signatures

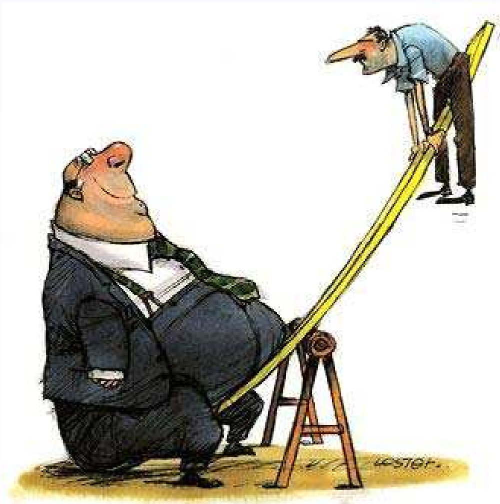
Neutrinos and astroparticle connection

By Suratna Das

Joint sessions with WG V, WG I, WG II

Origin of neutrino mass:

Neutrinos $\sim$ eV mass??



Seesaw

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979, Yanagida 1979, Mohapatra, Senjanovic 1980

Majorana mass of light neutrinos from d=5 operator

$$\mathcal{L}_f(\phi, N_R) \text{ at higher scale } \xrightarrow{N_R \text{ integrated out}} \mathcal{L}_{\rm eff}(\phi) \text{ at lower scale}$$

Lepton number violating operator $\Rightarrow \hat{O}_5 = \frac{LLHH}{M}$

Violates L and $B-L$ by 2 units

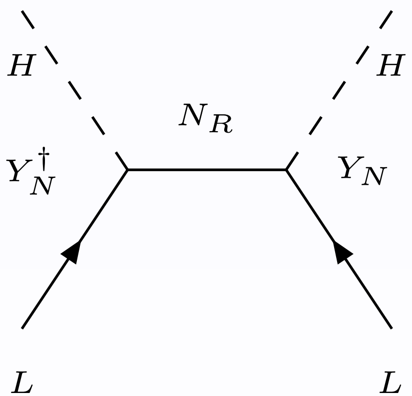
Weinberg *d=5* operator (Weinberg, PRL 43, 1979)

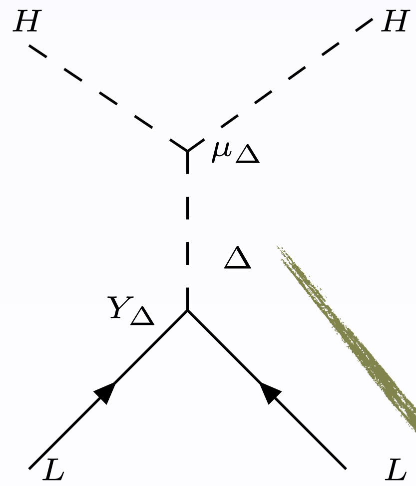
L and H are lepton and Higgs doublet. M is the mass of N_R.

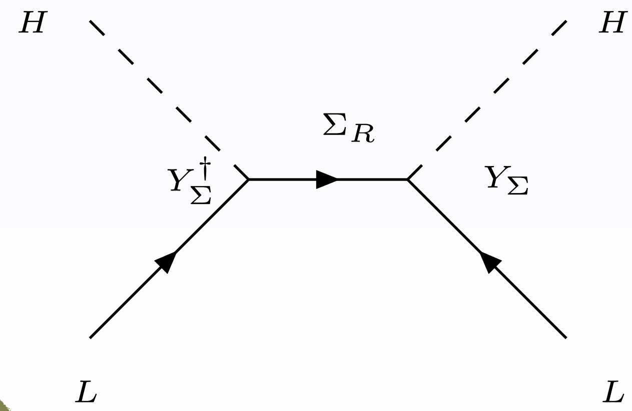
Contd:

Type-I	**Type-II**	**Type-III**
SM gauge singlet	$SU(2)$ Triplet, $Y = 2$	$SU(2)$ Triplet, $Y = 0$

Σ_R → Gauge interaction



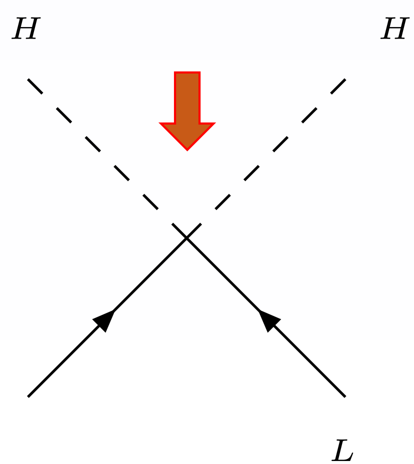




interaction of N with other SM particles is proportional to the active-sterile mixing

V_{lN}

Suppressed



H^{++} Doubly charged Higgs

Heavy modes integrate out

Minkowski, 1977; Gell-mann, Raymond, Slansky- 1979, Yanagida 1979, Mohapatra, Senjanovic 1980; Magg, Wetterich, 1980; Foot et al., 1989

Inverse Seesaw

Quasi-degenerate neutrinos

$M_{N_{1,2}} = M \pm \mu$

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

Unsupported mixing $\frac{m_D}{M} \to \sigma$ large

- For $\mu \ll m_D < M \to$ $m_\nu \sim \mu \frac{m_D}{M}^2$

Mohapatra, Valle, 1986

$\mu \sim 0$

enhances lepton number symmetry

- R-parity violating supersymmetry-(Masiero, 1982; Santamaria, Valle, 1987; Romao, Valle, 1992; Borzumati, 1996; B. Mukhopadhyaya, S Roy, F Vissani, PLB 1998, Anjan S Joshipura, Sudhir K Vempati, PRD 60, 1999...)

- Loop generated mass? Radiative inverse seesaw (A. Zee, 1980; A. Zee, K. S. Babu 1988; D, Choudhury et al., PRD 1994; Dev, Pilaftsis, 2012...)

- Others—dimension 7 $\frac{(LLHH)HH}{\Lambda^3}$ operators etc (K.S. Babu et al., 2009)

Left-Right symmetric theory

Type-I and Type-II

Pati; Salam; Mohapatra, Senjanović, 74,

Enlarged gauge sector $\rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

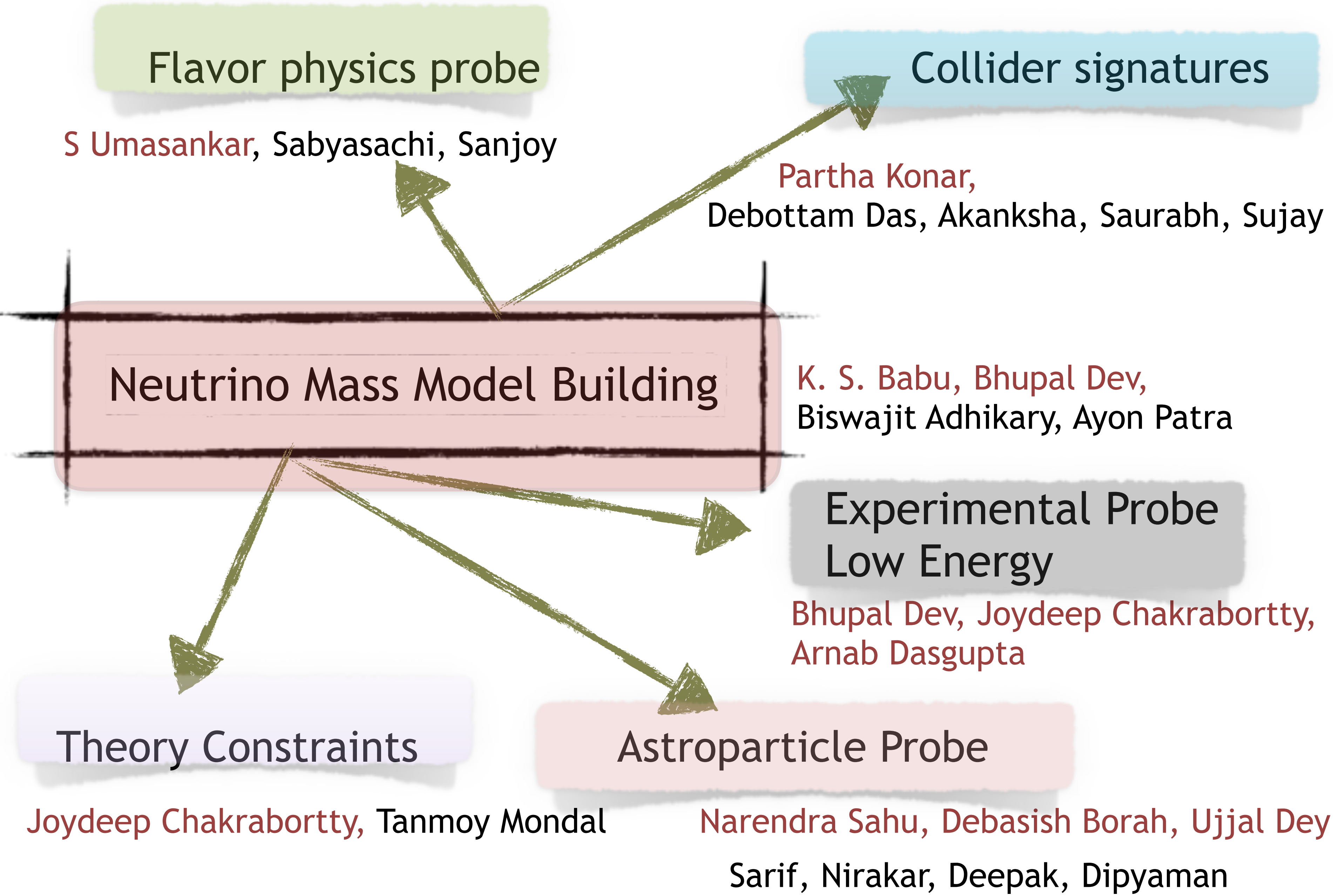
Parity symmetric theory $\rightarrow$ parity violating SM

- Two Higgs triplet $\Delta_L = (3,1,2)$, $\Delta_R = (1,3,2)$.

  $\langle \Delta_R \rangle$ **breaks the** $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$
- Sterile neutrino N is part of the gauge multiplet $\begin{pmatrix} N \\ e \end{pmatrix}_R$
- Additional gauge bosons W_R and Z'. $M_{W_R} \propto \langle \Delta_R \rangle$

Natural way to embed the sterile neutrinos

N, W', Z', Δ^{++} $\longrightarrow$ Phenomenology



Joint sessions: WG3+WG1; WG3+WG5, WG3+WG2

Testing Type-I Seesaw Experimentally

The new particle in type-I seesaw is the SM singlet neutrino N

N has no direct interaction with the gauge bosons

Production of N must go through mixing or via Higgs coupling

Mixing of N with ν constrained by:

- Neutrino mass
- Lepton number violation
- Charged lepton flavor violation
- Lepton universality
- Direct searches for N

Similar signature for Inverse Seesaw, Type-III Seesaw

Majorana Nature

Neutrino mass and neutrinoless double beta decay most severe

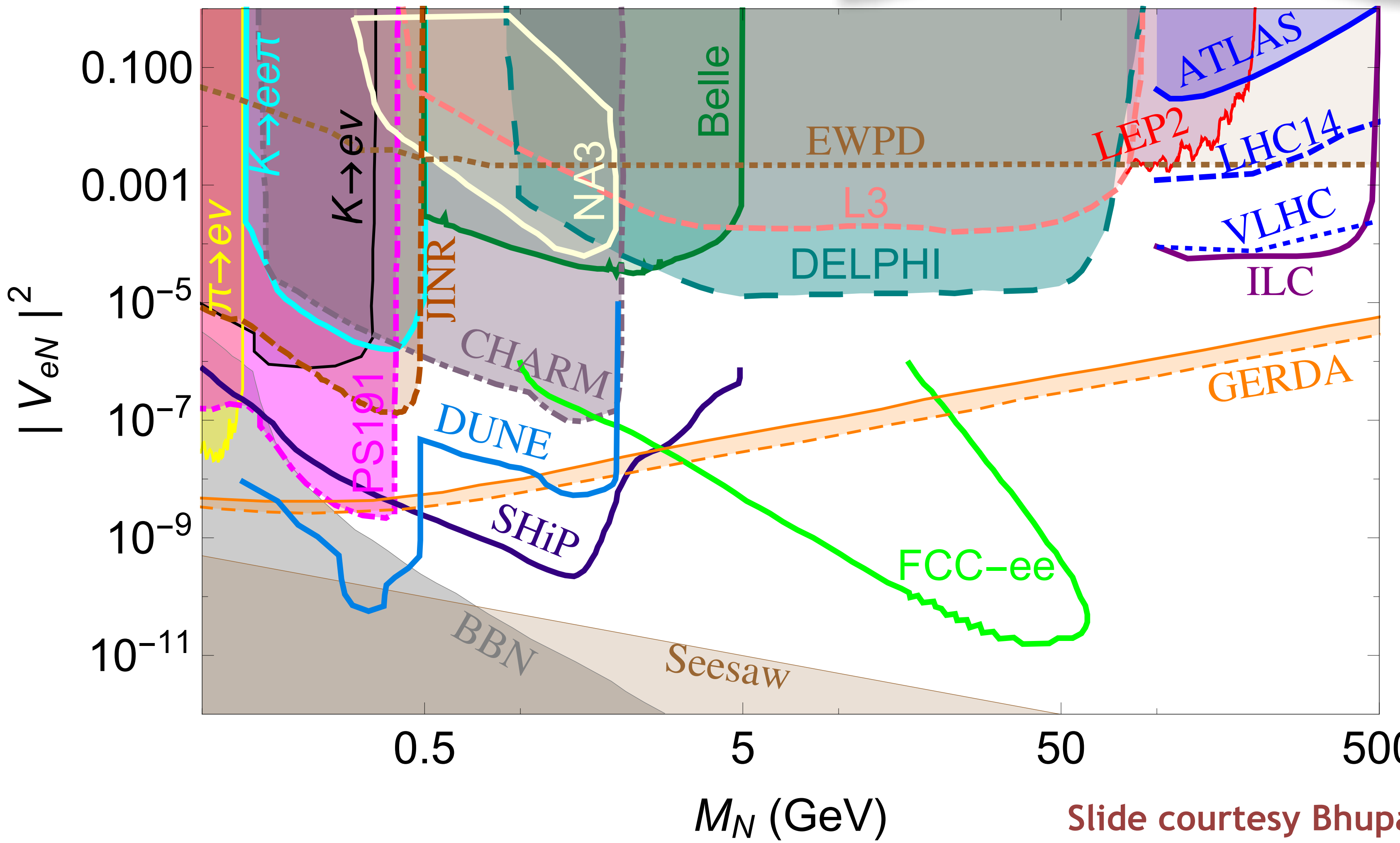
Simple way to avoid neutrino mass and $\beta\beta_{0\nu}$ constraints exists

Plenary talk by K. S. Babu

Slide courtesy K. S. Babu

Summary Plot (Electron Sector)

Sterile Neutrino



Slide courtesy Bhupal Dev

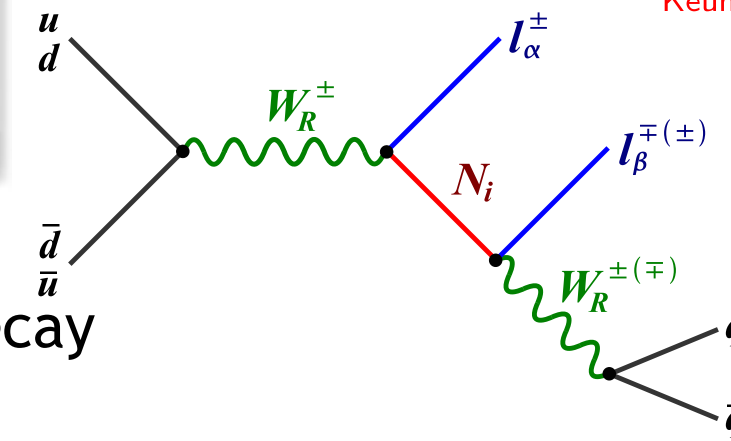
[Atre, Han, Pascoli, Zhang (JHEP '09); Deppisch, BD, Pilaftsis (NJP '15)]

Experimental signatures by Bhupal Dev

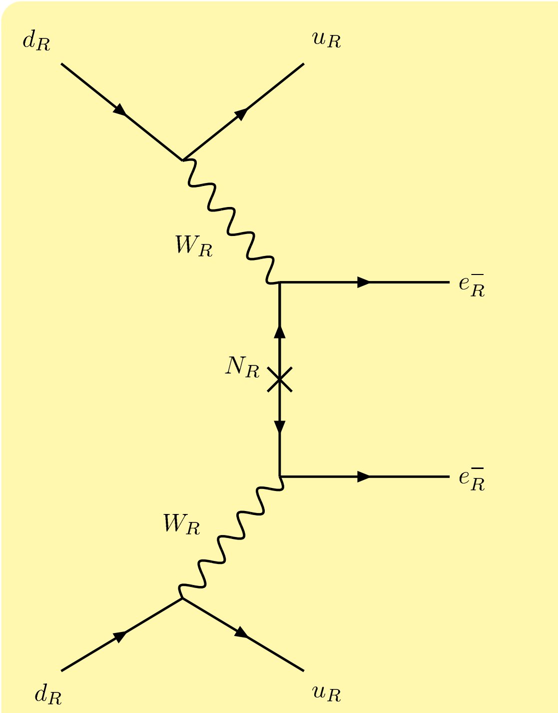
By Partha Konar, Akanksha Bhardwaj

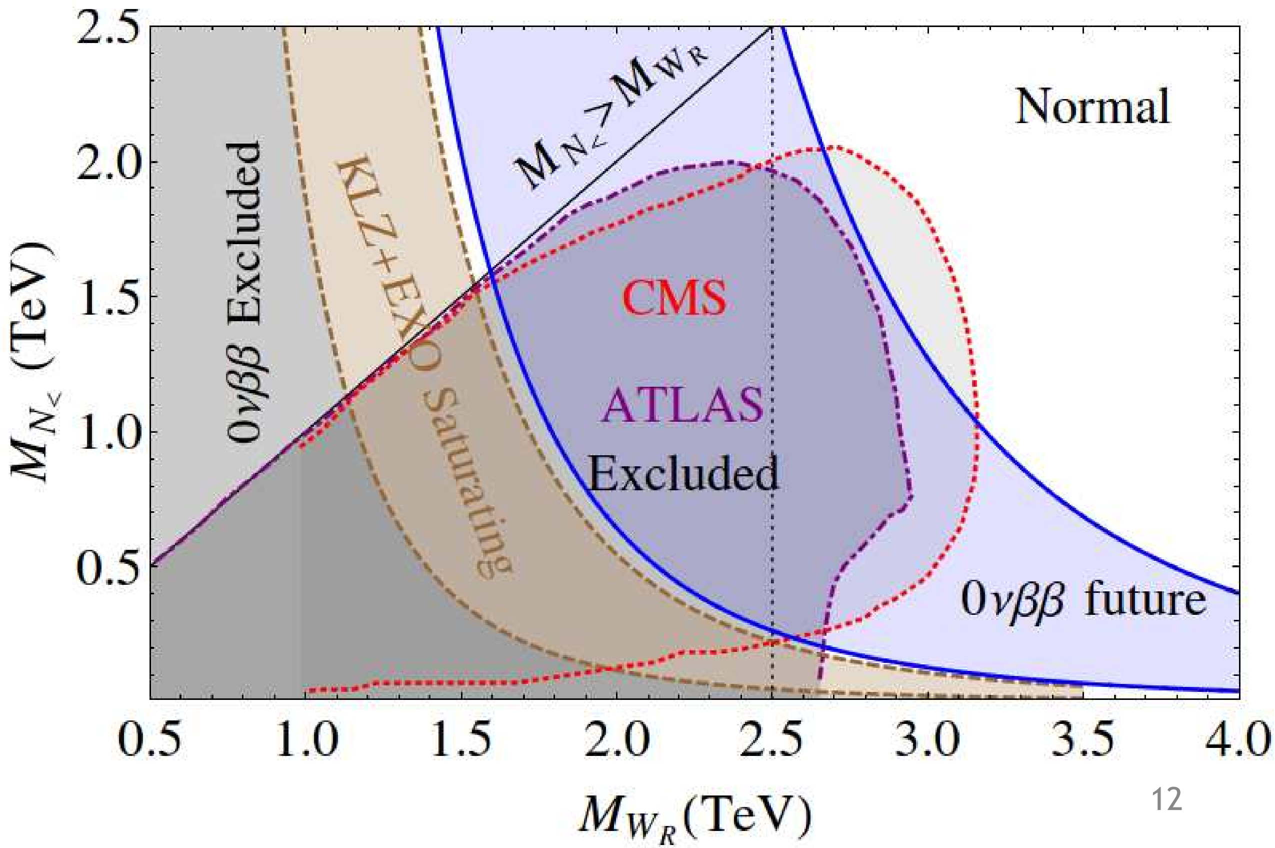
Left Right Symmetry

Keung, Senjanović, PRL, 83



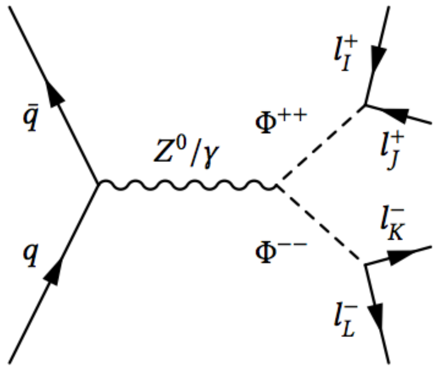
- Collider
- Neutrinoless Double Beta Decay
- Meson Decays
- charged lepton flavor violation



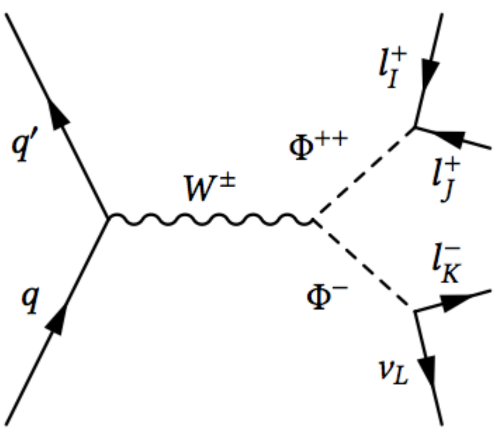


Type-II Seesaw at the LHC

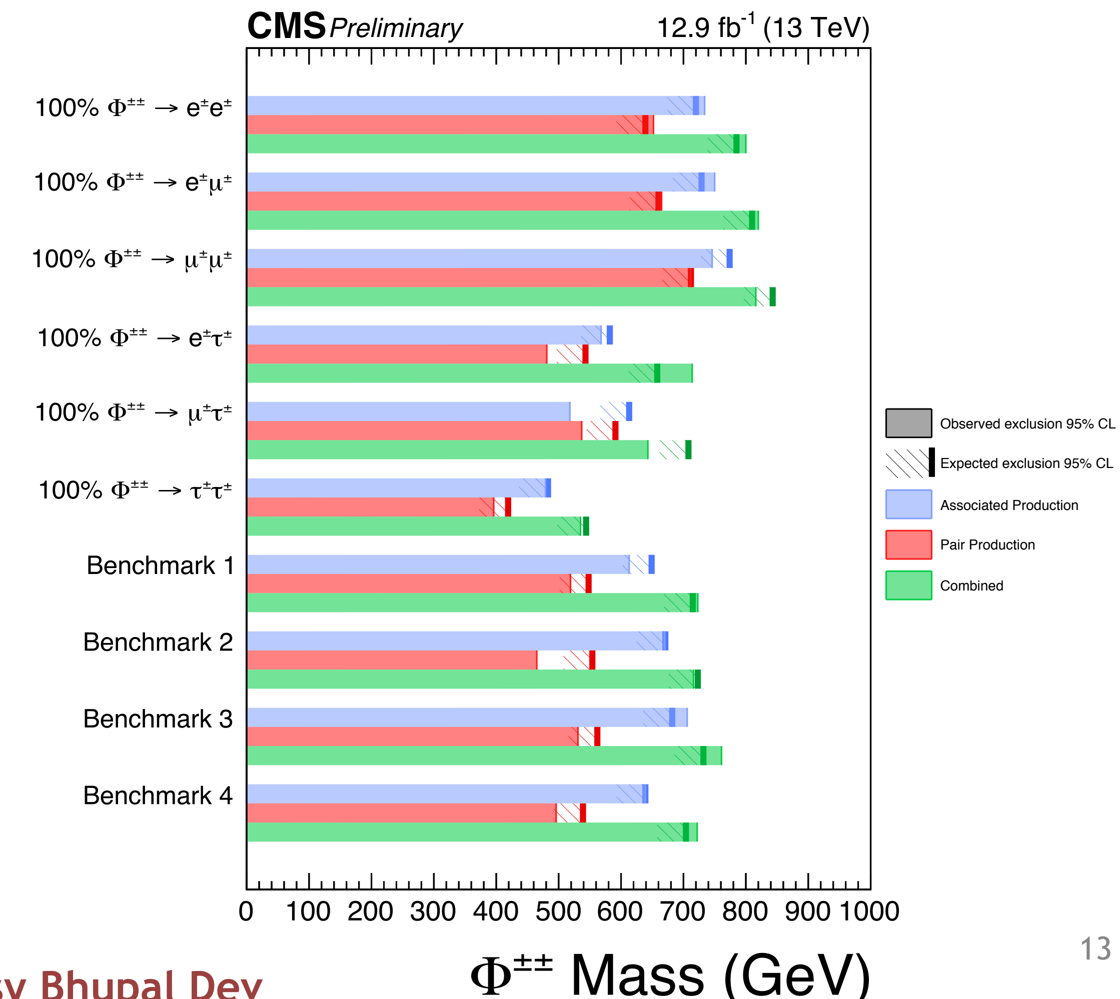
- $SU(2)_L$-triplet scalar $(\Phi^{++}, \Phi^{+}, \Phi^{0})$. [Schechter, Valle (PRD '80); Magg, Wetterich (PLB '80); Cheng, Li (PRD '80); Lazarides, Shafi, Wetterich (NPB '81); Mohapatra, Senjanović (PRD '81)]
- Multi-lepton signatures. [Akeroyd, Aoki (PRD '05); Fileviez Perez, Han, Huang, Li, Wang (PRD '08); del Aguila, Aguilar-Saavedra (NPB '09); Melfo, Nemevsek, Nesti, Senjanović, Zhang (PRD '12)]



(a) 4ℓ



(b) 3ℓ



Slide courtesy Bhupal Dev

LFV signatures $\mu \to 3e, \mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$

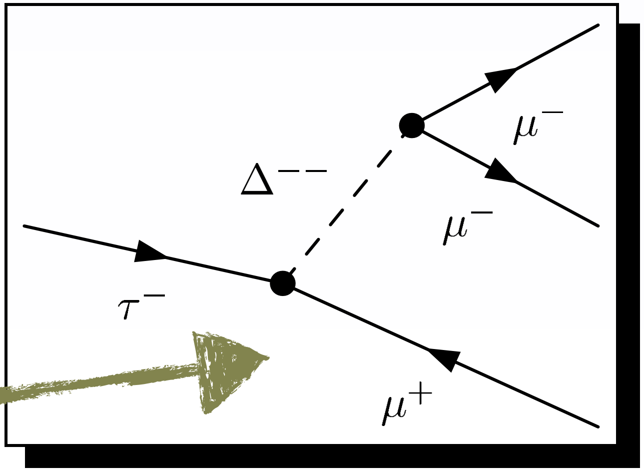
- Branching ratio of $\mu \to 3e \leq 10^{-12}$
- Branching ratio of $\mu \to e\gamma \leq 5.7 \times 10^{-13}$

Tightly constrained

τ sector is less constrained $\tau \to 3\mu, e\mu\mu, e\gamma, \mu\gamma$.

$$\boxed{\tau \to 3\mu, e\mu\mu \sim 10^{-8}}$$

- $\Gamma(\tau^{\mp} \to \mu^{\pm}\mu^{\mp}\mu^{\mp}) = \frac{m_\tau^5}{192\pi^3}|C_{\tau\mu\mu\mu}|^2$
- $C_{\tau\mu\mu\mu} = \frac{Y_{\tau\mu}Y_{\mu\mu}}{m^2_{\Delta^{\pm\pm}}} = \frac{M_\nu(\tau,\mu)M_\nu(\mu,\mu)}{2v^2_\Delta m^2_{\Delta^{\pm\pm}}}$



Higgs triplet

Contd:

$$\tau^\pm \to \mu^\pm\mu^\mp\mu^\mp$$

Experiment	Current	Projected
Belle	2.1×10^{-8}	$(4.7 - 10) \times 10^{-10}$
BaBar	3.3×10^{-8}	–
FCC-ee	–	$(5 - 10) \times 10^{-12}$
LHCb	4.6×10^{-8}	$(1.5 - 11) \times 10^{-9}$
ATLAS	3.8×10^{-7}	$(1.8 - 8.1) \times 10^{-9}$
FCC-hh	–	$(3 - 30) \times 10^{-10}$

$$\tau^\pm \to e^\mp\mu^\pm\mu^\pm$$

	$\tau^\mp \to e^\pm\mu^\mp\mu^\mp$		$\tau^\mp \to e^\mp\mu^\mp\mu^\pm$	
Experiment	Current	Projected	Current	Projected
Belle	1.7×10^{-8}	$(3.4 - 5.1) \times 10^{-10}$	2.7×10^{-8}	$(5.9 - 12) \times 10^{-10}$
BaBar	2.6×10^{-8}	–	3.2×10^{-8}	–
FCC-ee	–	$(5 - 10) \times 10^{-12}$	–	$(5 - 10) \times 10^{-12}$

The present limit $\sim 10^{-8}$. LHCb limit similar to Belle. The future sensitivity $\sim 10^{-10} - 10^{-12}$. 13 TeV LHC can give stringent limit.

LHC limits $\to$ 8 TeV. Future limits with 13 TeV, 3 ab^{-1} for ATLAS and 50 ab^{-1} with LHCb.

WG III Projects - Mass Models

Higher Dimensional Probe of Seesaw

Babu-Nandi-Tavartkiladze (BNT) Model

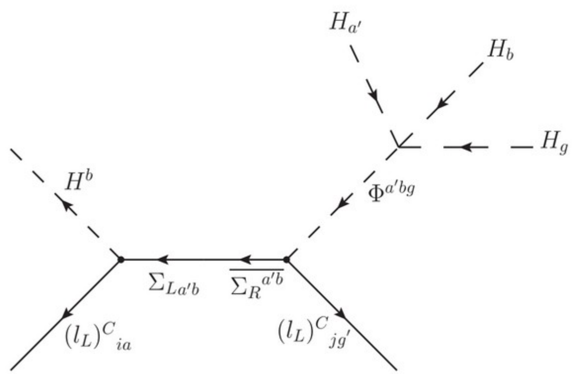
Scalar isospin 3/2 quadruplet (Φ)

$$\Phi = \left(\Phi^{+++} \quad \Phi^{++} \quad \Phi^{+} \quad \Phi^{0} \right)_{Y=3}$$

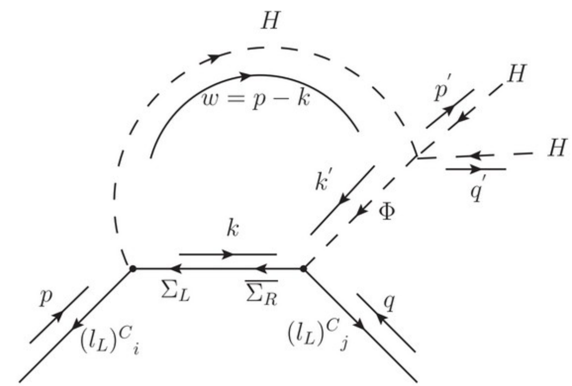
Vecor like triplet (Σ)

$$\Sigma_{R,L} = \left(\Sigma^{++}_{R,L} \quad \Sigma^{+}_{R,L} \quad \Sigma^{0}_{R,L} \right)_{Y=2}$$

Tree level (d=7)



1-loop level (d=5)



$$V = \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^\dagger \Phi)^2 + \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \tau_a H)(\Phi^\dagger T_a \Phi) + \{\lambda_5 H^3 \Phi^* + \text{H.c.}\},$$

$$(m_\nu)_{ij} = -\frac{\lambda_5 (Y_i Y_j' + Y_i' Y_j) v^4}{(M_\Sigma M^2_{\Phi^0})}$$

Rich Phenomenology with **"Multi-lepton"** final states

$$pp \xrightarrow{Z/\gamma} \Phi^{\pm\pm\pm}\Phi^{\mp\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm}\Phi^{\mp};$$

$$pp \xrightarrow{W^\pm} \Phi^{\pm\pm\pm}\Phi^{\mp\mp},\ \Phi^{\pm\pm}\Phi^{\mp},\ \Phi^{\pm}\Phi^{0}.$$

3ℓ, 4ℓ, 5ℓ and 6ℓ events

Same-sign-tri-lepton events

Lepton flavour violating (LFV) 4 lepton events

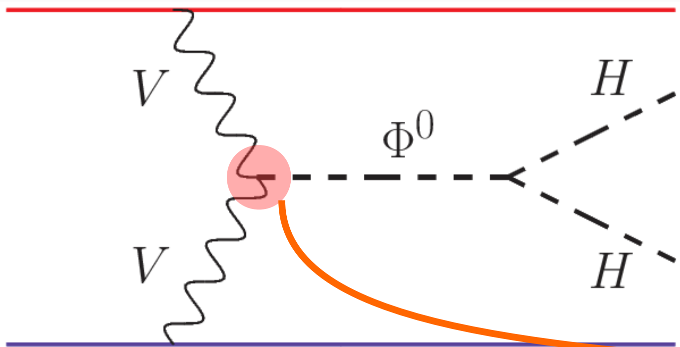
Small v_Φ

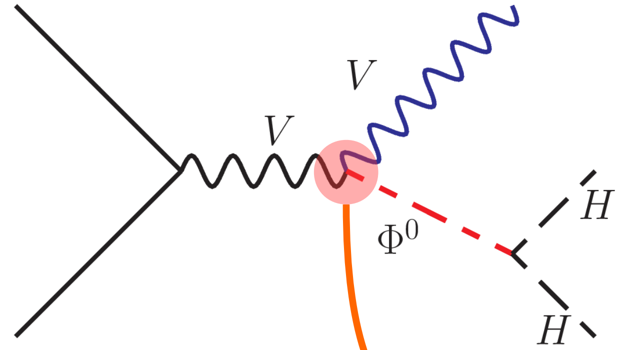
K. S. Babu, S. Nandi, and Zurab Tavartkiladze, PRD (Rap Comm) 80, 071702(R) (2009)

Gulab Bambhaniya, Joydeep Chakrabortty, Srubabati Goswami, and Partha Konar, PRD, 88, 075006 (2013)

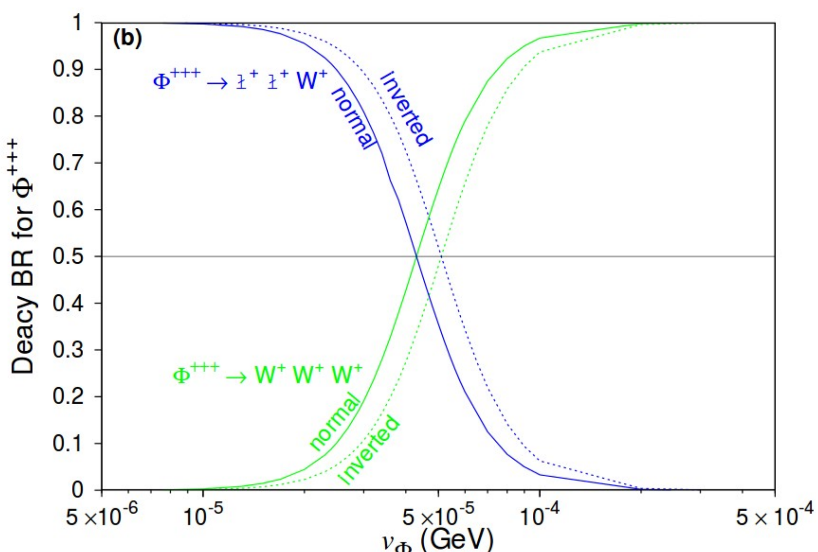
Possible studies with large vev of the quadruplet :

- Enhannced Di-Higgs production





- Charged scalar in multi W final state



multi W final state domintes for large V_Φ

$\Phi^{+++} \to W^+ W^+ W^+$

Tanmoy Modal, Saurabh Niyogi, Joydeep Chakrabortty

Manimala, Bhupal, Sujay, others

Stability of Potential, Unitarity

- Scalars in the model:
  (i) $\Phi = (\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^{0})$, isospin 3/2, $(Y = 3)$
  (ii) $H = (H^{+}, H^{0})$, SM doublet
- Scalar potential:

$$
\begin{aligned}
V(H,\Phi) = &\mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^\dagger \Phi)^2 \\
&+ \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \tau_a H)(\Phi^\dagger T_a \Phi) \\
&+ \{\lambda_5 H^3 \Phi^* + \mathrm{h.c.}\}
\end{aligned}
$$

- We want to study the stability of the potential as well as the unitarity constraints on the physical scalars present in the model

Ujjal, Triparno,Tripurari, Bharti

Flavor and DM constraints on Minimal LRSUSY

$$\Delta^c(1,1,3,-2)=\begin{bmatrix}\frac{\delta^{c-}}{\sqrt{2}} & \delta^{c0}\\ \delta^{c--} & -\frac{\delta^{c-}}{\sqrt{2}}\end{bmatrix},\quad \bar{\Delta}^c(1,1,3,2)=\begin{bmatrix}\frac{\bar{\delta}^{c+}}{\sqrt{2}} & \bar{\delta}^{c++}\\ \bar{\delta}^{c0} & -\frac{\bar{\delta}^{c+}}{\sqrt{2}}\end{bmatrix},\quad \Delta(1,3,1,2)=\begin{bmatrix}\frac{\delta^{+}}{\sqrt{2}} & \delta^{++}\\ \delta^{0} & -\frac{\delta^{+}}{\sqrt{2}}\end{bmatrix},$$

$$\bar{\Delta}(1,3,1,-2)=\begin{bmatrix}\frac{\bar{\delta}^{-}}{\sqrt{2}} & \bar{\delta}^{0}\\ \bar{\delta}^{--} & -\frac{\bar{\delta}^{-}}{\sqrt{2}}\end{bmatrix},\quad \Phi_a(1,2,2,0)=\begin{bmatrix}\phi_1^{+} & \phi_2^{0}\\ \phi_1^{0} & \phi_2^{-}\end{bmatrix}_a,\quad S\,(1,1,1,0)$$

- Fermionic superpartner of the triplet Higgs can give a viable Dark matter along with possible lepton flavor violating signals.
- Long-standing excess in the anomalous muon magnetic moment measurement can also be addressed.

Ayon, Joydeep, Manimala, others

Alternate Left Right Model

Different realisation of W'

$\mathcal{G}_{SM} \otimes SU(2)_N$

An 'Alternate' LR Model

$E6 \to 333 \to 32211 \to 321 \cdot 2 \to 321 \to 31$ SM

Hypercharge

V1 V2 V3

Broken SU(2) gen. **but** (electrically) uncharged

- 27 Fermions (E6) → SM + 11 Fermions
  - Sterile Neutrinos
  - Multi-TeV Exotic colored objects
- $SU(2)_N$ vector bosons not directly bounded by current searches for HVT
- Theoretical bounds will also change from normal LR models
- Dark gauge bosons etc.

• Detailed study of the model •

- Joydeep, Manimala, Triparno, Ujjal ??? Sanjoy

To reconcile the LSND, MinoBoone anomaly with dark Matter, neutrino mass, and cosmological constraint on extra light degrees of freedom.

Problem: Want to address LSND and MiniBoone anomalies by considering an eV scale sterile neutrino with mixing angle $\sin^2(2\theta_{41}) \sim 0.1$ and also a sterile neutrino dark matter candidate in the same framework.

Plan to tackle the problem: We will consider a model where one can naturally explain the tiny neutrino masses, LSND, MiniBoone anomalies and at the same time the model will also contain a suitable dark matter candidate. We will consider all kinds of experimental and theoretical bounds to constrain the parameter space of the proposed model.

Progress: Rodejohan et. al. (1105.3911) and Heeck et. al. (1211.0538) and many others have shown that they can simultaneously explain two above mentioned issues. But the major drawback of most of the earlier works in this direction is that they are unable to satisfy the cosmological bound on the sum of the neutrino masses ($\sum_i m_{\nu_i} \leq 0.23$) as well as the bound on N_{eff}.

Anirban, Sarif, Manimala, Suprabh, Aritra, Debasish, Sandhya, Arnab

Connection between flavour structure and 'alignment limit'

(Biswajit Adhikary, Siddhartha Karmakar, Subhendu Rakshit)

- Models with additional doublets are eventually getting pushed to 'alignment limit'. Imposing some global symmetry on 2HDM potential can dictate alignment naturally. (Pilaftsis et al 1408.3405)
- Discrete symmetries are used in order to explain the pattern of neutrino masses and mixings. New Higgs doublets are often an integral part of such models. (Altarelli et al 1002.0211)
- Discrete symmetries will be explored to reconcile the flavour structure and 'alignment limit' under a single framework. Leptogenesis and the phenomenology of additional scalars in such a model will also be studied.

Flavor Puzzle

Overview talk by S. Umasankar, Sabyasachi on models

Anomaly in R_K, R_K^* have observable consequence

$$B_s \to \mu^+\mu^-, B_s \to \mu^+\mu^-\gamma, B_s^* \to \mu^+\mu^-$$

$(\bar{s}\Gamma b)(\bar{\mu}\Gamma\mu)$ → Effect in other observables

$R_\eta, R_{\eta'}$

$$R_K = \frac{Br(B \to K\mu^+\mu^-)}{Br(B \to Ke^+e^-)} \qquad R_{K^*} = \frac{Br(B \to K^*\mu^+\mu^-)}{Br(B \to K^*e^+e^-)}$$

Deviation from SM prediction

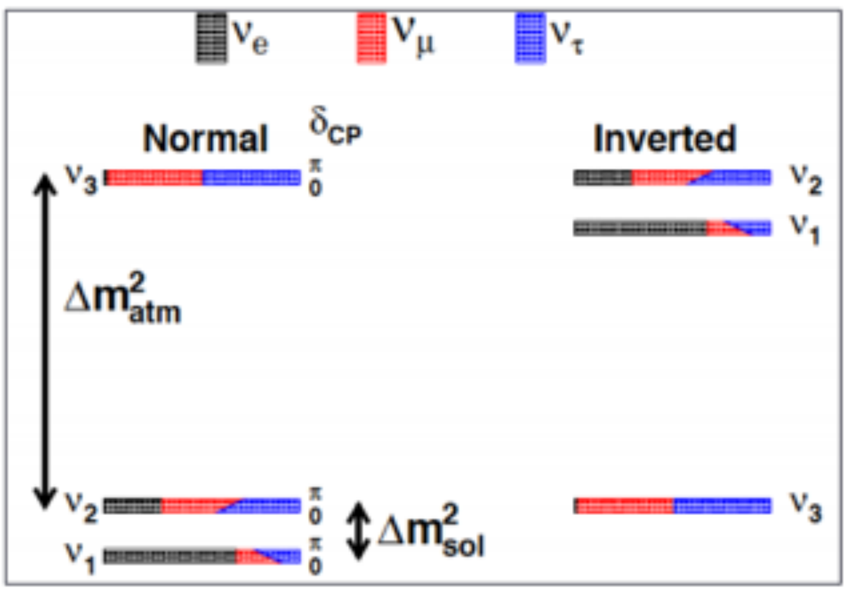
WG III – Neutrino physics
Oscillation phenomenology

Overview of neutrino oscillations: Recent developments in neutrino oscillations and future outlook

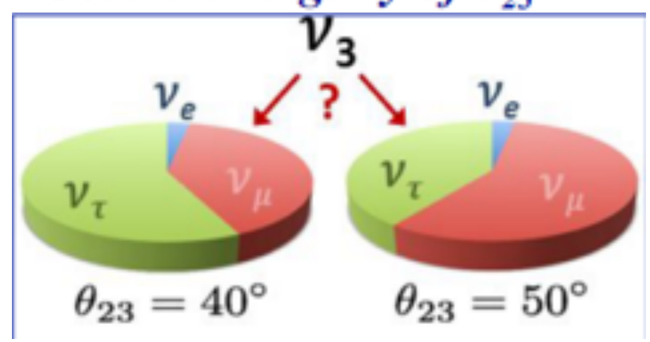
Sanjib Agarwalla

Open questions:

The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known



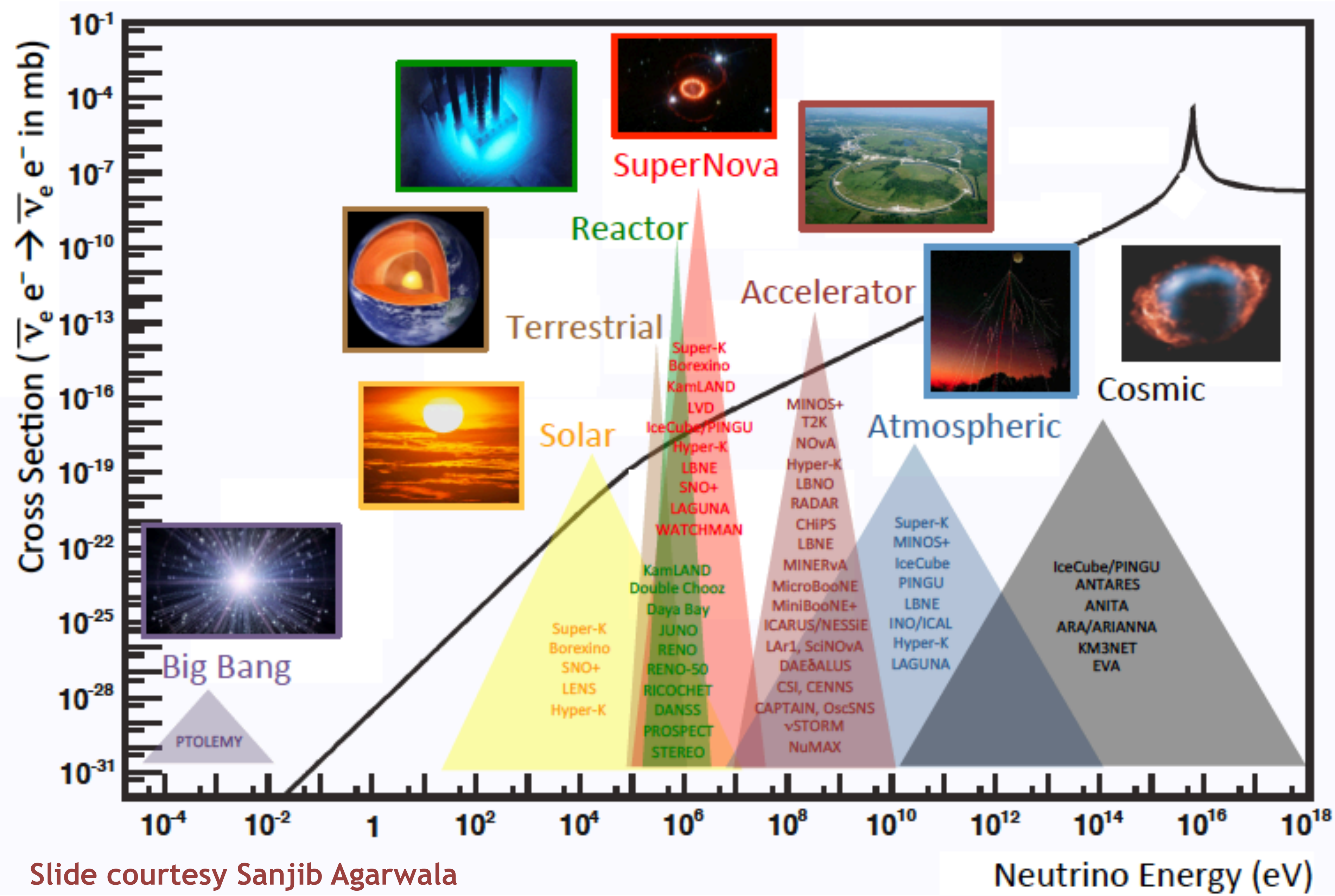
Octant ambiguity of θ_{23}



Is CP violated in the neutrino sector, as in the quark sector?

Several extensions of the Standard Model give rise to new effects in neutrino oscillations

Neutrinos are omnipresent: Friends across 23 orders of magnitude



Slide courtesy Sanjib Agarwala

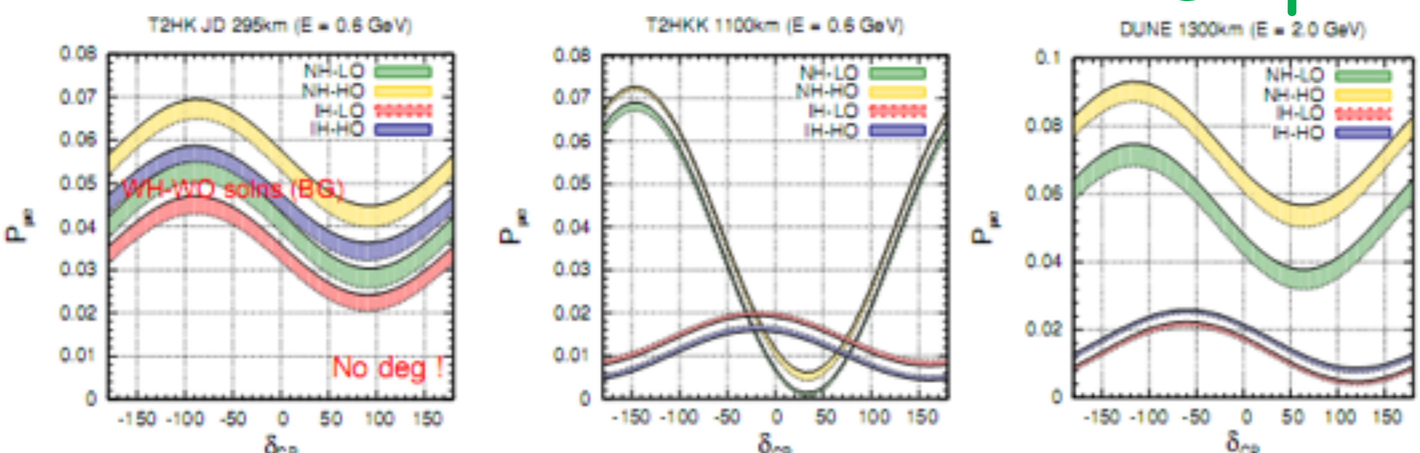
J. L. Hewett et al., arXiv:1310.4340v1, Snowmass 2013 Neutrino Working Group

Long-baseline neutrino oscillations

- Overview **Sandhya Choubey**

T2K Sample	Predicted Rates				Observed Rates
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	
CCQE 1-Ring e-like ν-mode	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like ν-mode	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like $\bar{\nu}$-mode	7.93	9.04	10.04	8.93	7

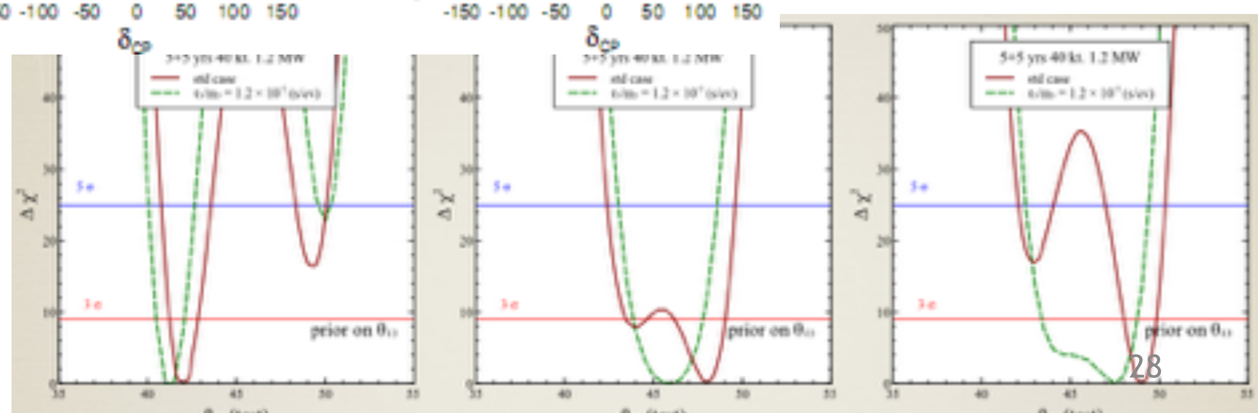
- T2HK, T2HKK, DUNE sensitivity **Deepthi Kuchibhatla**



Parameter degeneracies relevant for sensitivity, for each experiment

- Invisible ν-decay

Dipyaman Pramanik



Slide courtesy: Sushant Raut

Long-baseline neutrino oscillations

- Non-standard interactions **Rathin Adhikari**
  - Additional scalars: In R violating supersymmetry there are L violating interactions:

$$\lambda_{ijk} L_i L_j E^c_k, \quad \lambda'_{ijk} L_i Q_j D^c_k$$

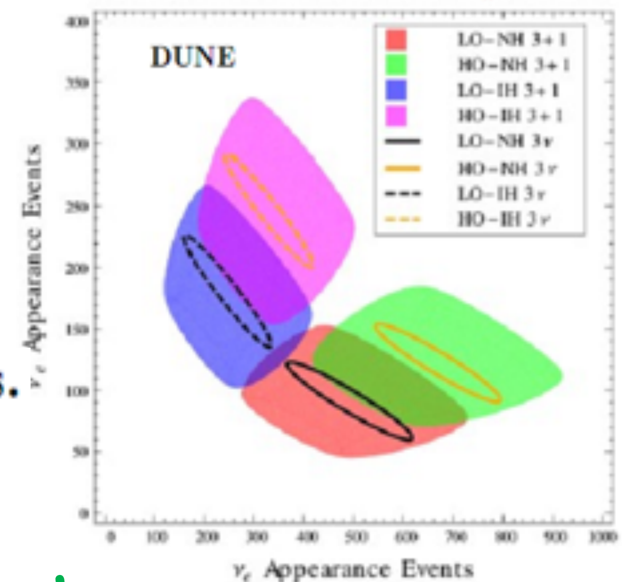
$$\varepsilon^{dR}_{\mu\mu} = \sum_j \frac{|\lambda'_{2j1}|^2}{4\sqrt{2}G_F m^2_{\tilde{q}_{jL}}} \quad \text{and} \quad \varepsilon^{dR}_{\mu\tau} = \sum_j \frac{\lambda'_{3j1}\lambda'_{2j1}}{4\sqrt{2}G_F m^2_{\tilde{q}_{jL}}}$$

- Sterile neutrino searches

Sabya Sachi Chatterjee

In 3+1, ellipses becomes blobs.

Bi-events convoluted plot



- Neutral current sterile searches

Suprabh Prakash

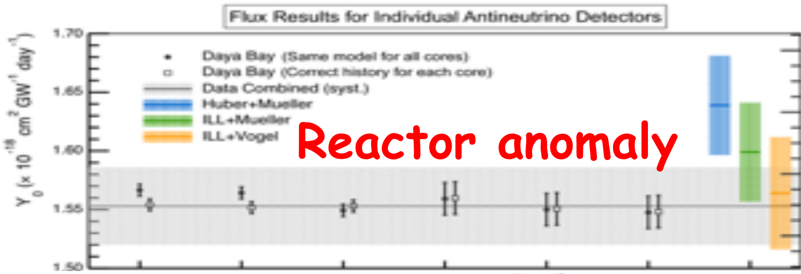
$$D_{NC} \propto Im\left[U^*_{\mu 5}U_{\mu 4}(U_{s_1 5}U^*_{s_1 4} + U_{s_2 5}U^*_{s_2 4})\right] \sin\Delta_{54}\sin\Delta_{43}\sin\Delta_{53}$$

$$D_{CC} \propto Im\left[U^*_{\mu 5}U_{\mu 4}U_{e5}U^*_{e4}\right] \sin\Delta_{54}\sin\Delta_{43}\sin\Delta_{53}$$

the NC measurements will provide a qualitatively and quantitatively different window into the CP violating and mixing sectors of a new physics scenario compared to the CC measurements.

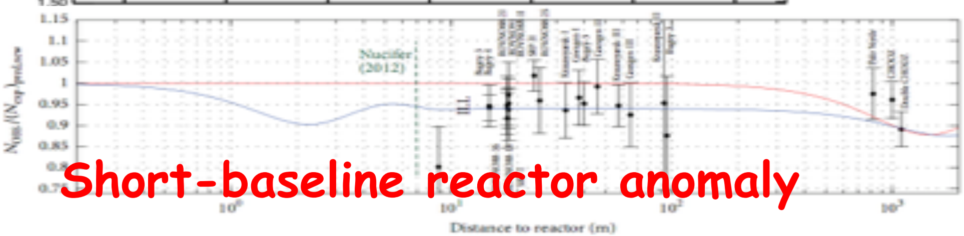
Short-baseline neutrino physics

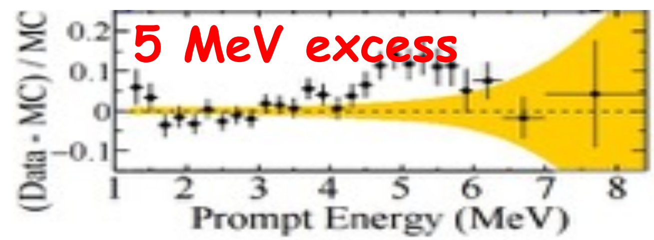
- Overview of reactor neutrinos **Sushant Raut**



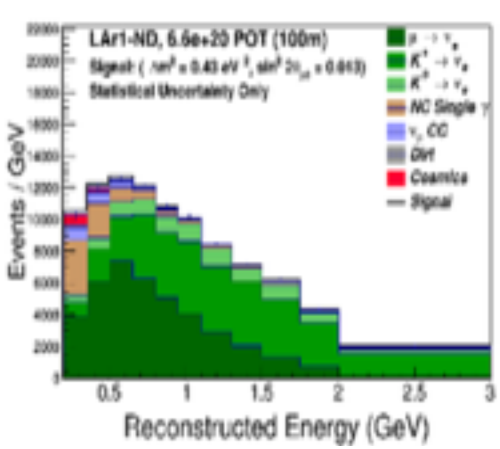
Gallium anomaly

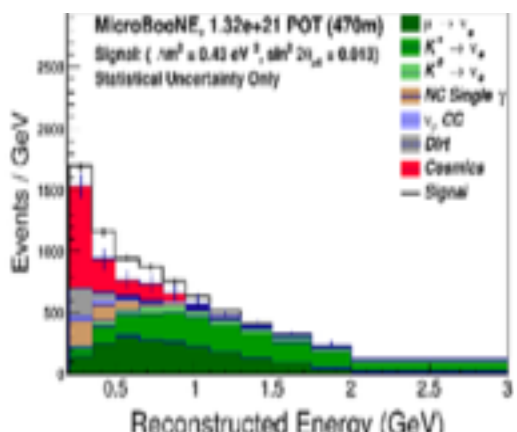
	GALLEX	
k	G1	G2
source	^{51}Cr	^{51}Cr
R^k_B	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$
R^k_H	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$

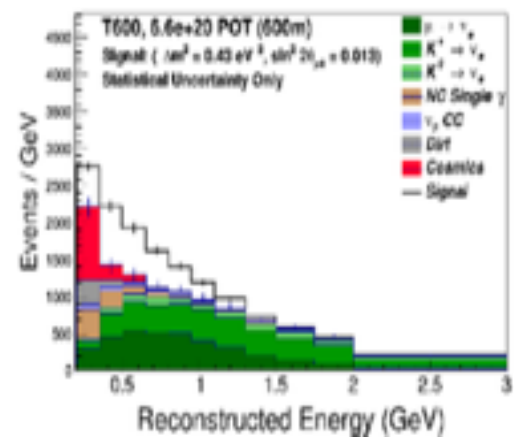




- Short-baseline appearance experiments **Samiran Roy**







SBN setup proposed to test LSND anomaly

Slide courtesy: Sushant Raut

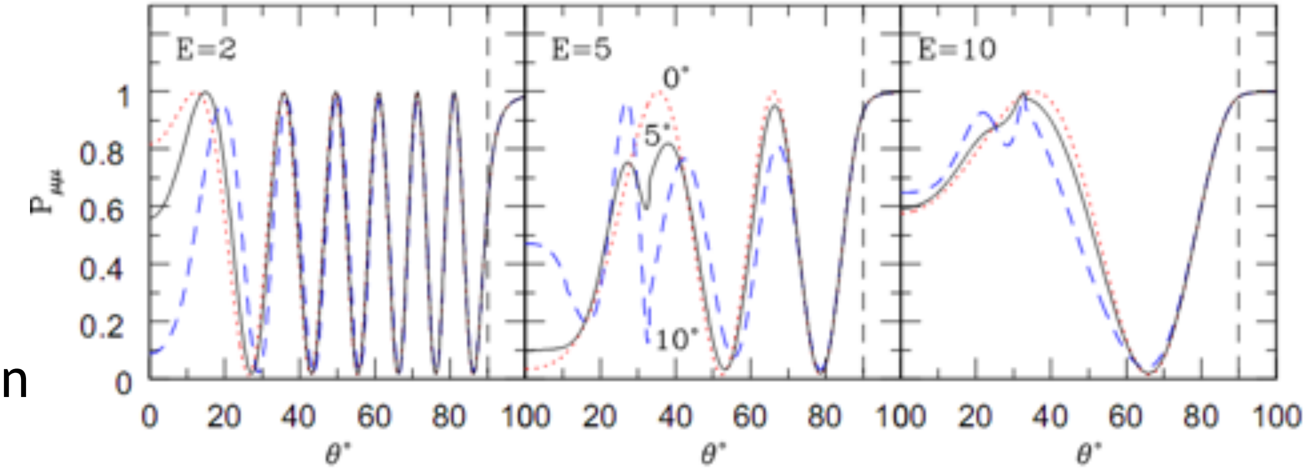
Slide courtesy: Sushant Raut

Atmospheric neutrinos

- Overview

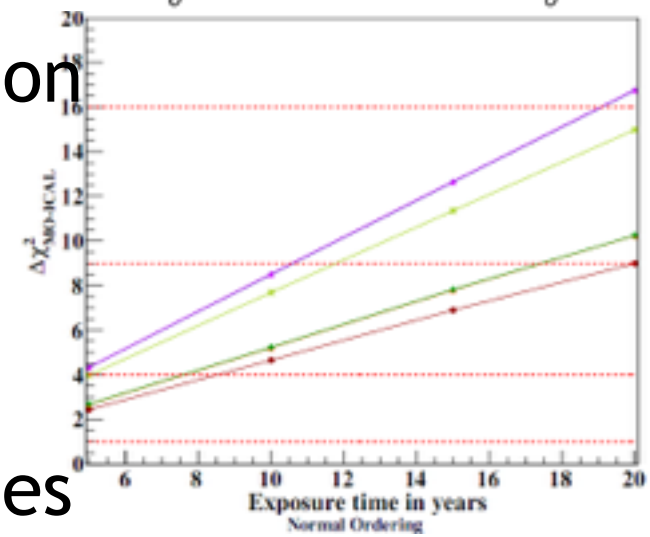
  D. Indumathi

  Neutrinos with a wide variety of energy and direction



- Parameter estimation using ICAL@INO

  Lakshmi Mohan



Mass hierarchy sensitivity of ICAL@INO

- New physics searches at ICAL@INO

  Amina Khatun

  Standard vs flavoured U(1)’ potential in ν-osc

L (km) ($\cos\theta_\nu$)	E (GeV)	$\frac{\Delta m^2_{31}}{2E}$ (eV)	V_{CC} (eV)	$V_{e\mu/e\tau}$ (eV) ($\alpha_{e\mu/e\tau} = 10^{-52}$)
5000 (-0.39)	5	2.5×10^{-13}	1.5×10^{-13}	1.3×10^{-13}
8000 (-0.63)	15	0.84×10^{-13}	1.6×10^{-13}	1.3×10^{-13}

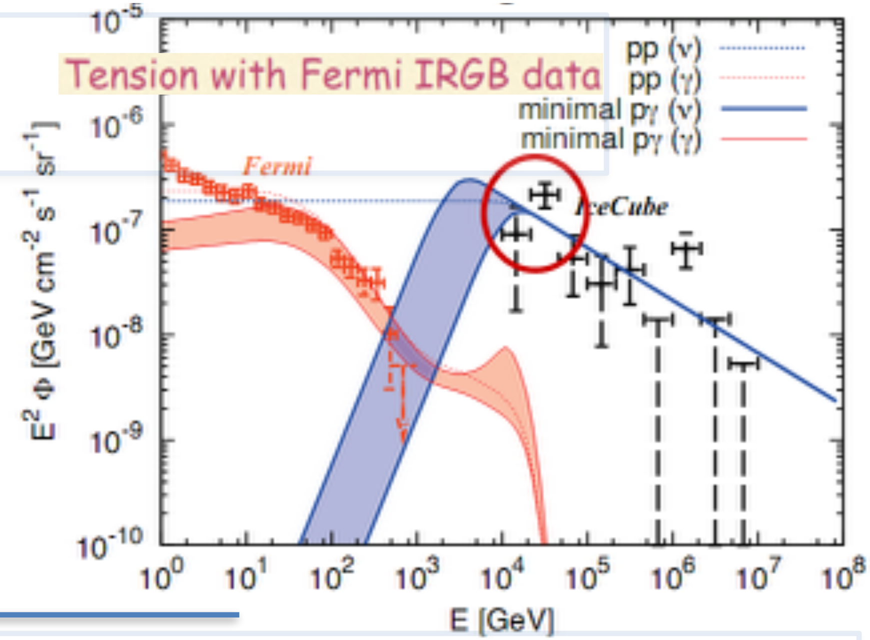
Ultra high energy neutrinos

Raj Gandhi

Danny Marfatia

- UHEν and CPT violation

Arita Gupta, Ujjal Dey



- Supernova neutrinos **Amol Dighe, Manibrata Sen**

- Self-induced collective flavor conversions in SN are undergoing a paradigm shift.
- Fast conversions could be possible near the SN core, leading to a quick flavor equilibration. Much more conclusive work is needed, both from theory and numerics.

Decoherence in neutrino oscillations

Legget-Garg inequalities and quantum decoherence in oscillation

by Poonam Mehta, Ashutosh K Alok, and Moon Moon Devi

Ajit M Srivastava, D Indumathi on Bell's inequality

WG III projects- Oscillation

Is the 'tension' between T2K and NOνA just a statistical fluctuation?

Deepthi K, D. Indumathi, Suprabh Prakash, Sushant Raut

Some preliminary statistical analysis by Deepthi

Flux uncertainties in atmospheric neutrinos

Moon Moon Devi, D. Indumathi, Amina Khatun, Lakshmi Mohan

Preliminary discussions

Phenomenological impact of exotic sources of ultra high energy neutrinos with ν_τ production at source

D. Indumathi, Deepak Tiwari

Preliminary literature review by Deepak

Impact of high energy/low energy extension on DUNE and ICAL

D. Indumathi, Lakshmi Mohan

Preliminary discussions

Various problems on new physics scenarios:

(a) Probing new physics at very short baseline reactor experiments

(b) Probing new physics models with coherent elastic neutrino-nucleus scattering

(c) Generalizing unitarity triangles and invariants in new physics scenarios

(d) Impact of new physics on standard measurements

Sandhya Choubey, Moon Moon Devi, D. Indumathi, Deepthi K, Amina Khatun, Lakshmi Mohan, Poonam Mehta, Suprabh Prakash, Dipyaman Pramanik, Ushak Rahaman, Sushant Raut, Jogesh Rout, Samiran Roy, Manibrata Sen, Jyotsna Singh, Deepak Tiwari

Preliminary discussions and calculations

Decoherence in neutrino oscillations:
(a) distinguishing environment-induced vs wavepacket decoherence
(b) testing the decoherence explanation of LSND

Sandhya Choubey, Moon Moon Devi, D. Indumathi, Deepthi K, Amina Khatun, Poonam Mehta, Lakshmi Mohan, Dipyaman Pramanik, Ushak Rahaman, Sushant Raut, Manibrata Sen, Jyotsna Singh, Deepak Tiwari

Preliminary discussions

Summary

Mass hierarchy, CP Violation, octant sensitivity, NSI, sterile neutrino

Quantum decoherence

Connection with mass models and experimental probes

Astroparticle connection

Flavor puzzles

Open questions, projects

Thank You

Flux uncertainties in atmospheric neutrinos

Moon Moon Devi, D. Indumathi, Amina Khatun, Lakshmi Mohan

Preliminary discussions

Type-I and Type-III

Type-I

Majorana neutrino $N_R \to$ Gauge singlet

$$-\mathcal{L}_f = Y_\nu \overline{L} \tilde{H} N_R + \frac{1}{2} \overline{N_R^c} M N_R + \text{h.c}$$

- **Active-sterile mixing**

$$V = m_D M^{-1}$$

suppressed production

Type-III

$SU(2)$ triplet with hypercharge $Y = 0$, $\Sigma^+, \Sigma^-, \Sigma^0$

$$-\mathcal{L}_Y = \left[Y_{\Sigma ij} \tilde{H}^\dagger \overline{\Sigma}_{R_i} L_j + h.c. \right]$$

$$+\frac{1}{2} M_{\Sigma_{ij}} Tr \left[\overline{\Sigma}_{R_i} \Sigma_{R_j}^{C'} + h.c. \right] + \bar{\Sigma} \not{D} \Sigma$$

- Σ **has gauge interaction**

$$W^\mp \Sigma^\pm \Sigma^0, Z \Sigma^\pm \Sigma^\mp$$

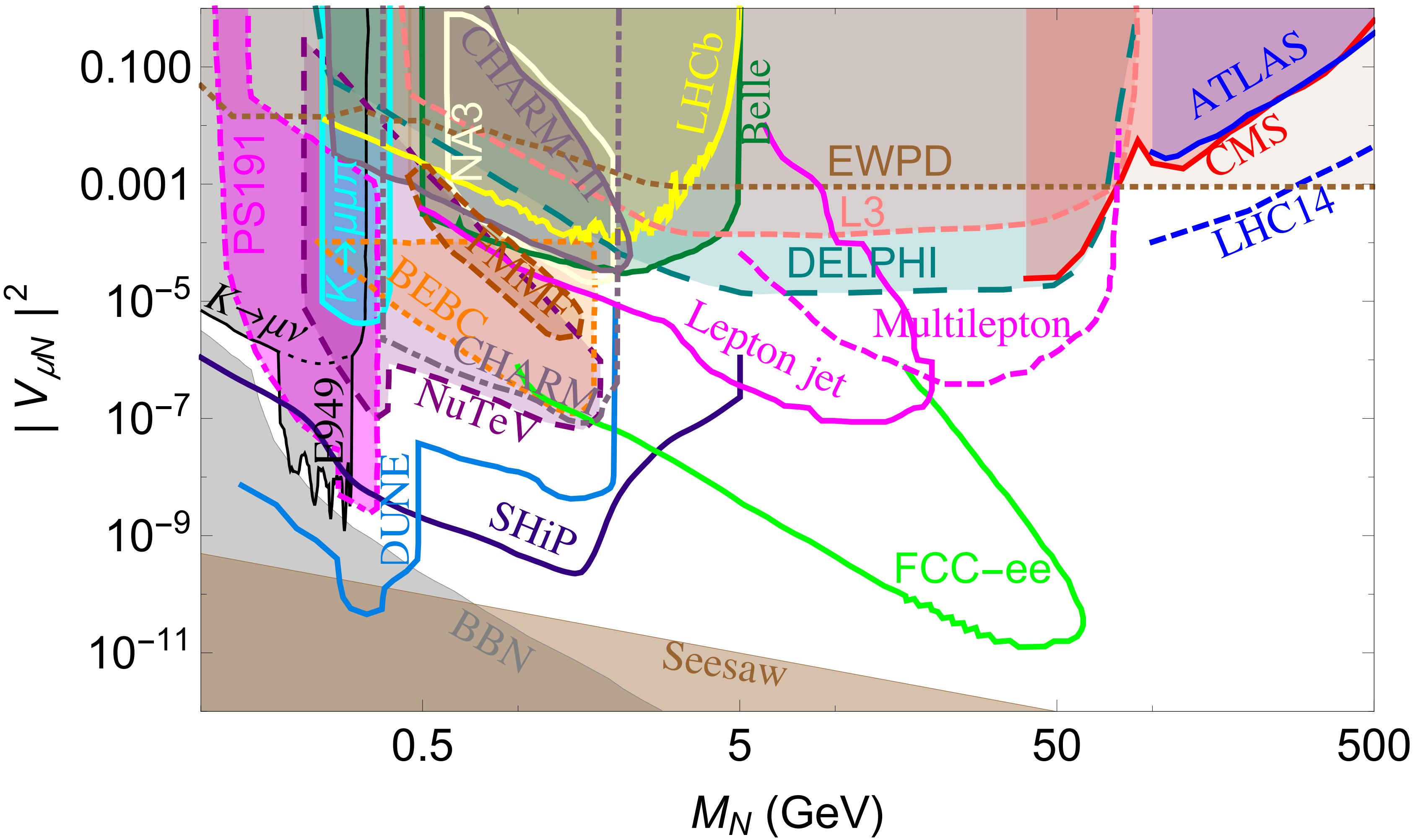
Unsuppressed production

M, M_Σ **are Lepton Number Violating**

For $M \gg M_D = Y_\nu v$ **Light neutrino mass** $m_\nu \sim m_D^T M^{-1} m_D$

For $M \to 100\text{GeV} \to V \sim 10^{-6}$

Summary Plot (Muon Sector)

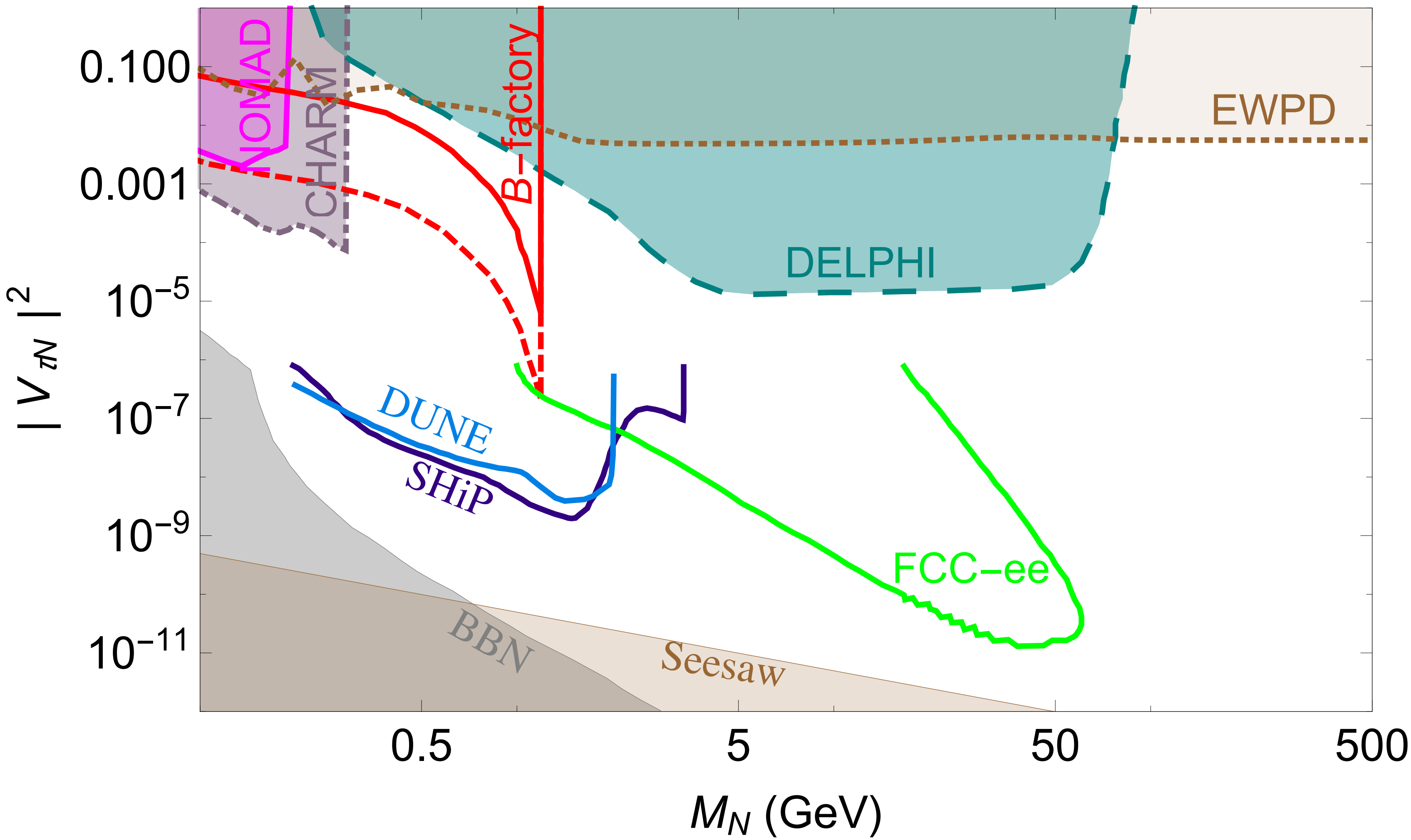


[Atre, Han, Pascoli, Zhang (JHEP ’09); Deppisch, BD, Pilaftsis (NJP ’15)]

New limits from NA48/2

Slide courtesy Bhupal Dev

Summary Plot (Tau Sector)



[Atre, Han, Pascoli, Zhang (JHEP ’09); Deppisch, BD, Pilaftsis (NJP ’15)]

Slide courtesy Bhupal Dev

Overview of neutrino oscillations: Recent developments in neutrino oscillations and future outlook Sanjib Agarwalla

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

Three mixing angles: θ_{23}, θ_{13}, θ_{12} and one CP violating (Dirac) phase δ_{CP}

Over a distance L, changes in the relative phases of the mass states may induce flavor change

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j}\mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

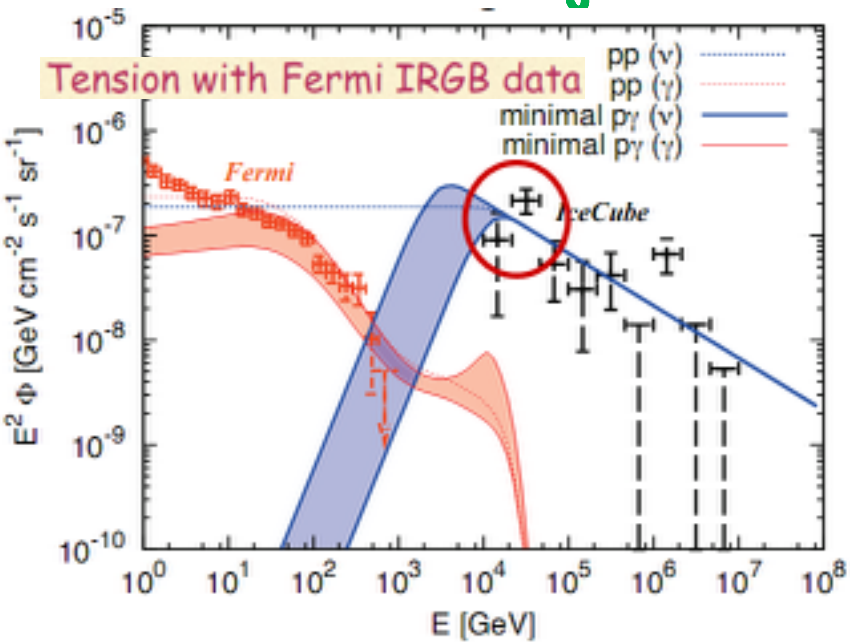
2 independent mass splittings Δm^2_{21} and Δm^2_{32}, for anti-neutrinos replace δ_{CP} by $-\delta_{CP}$

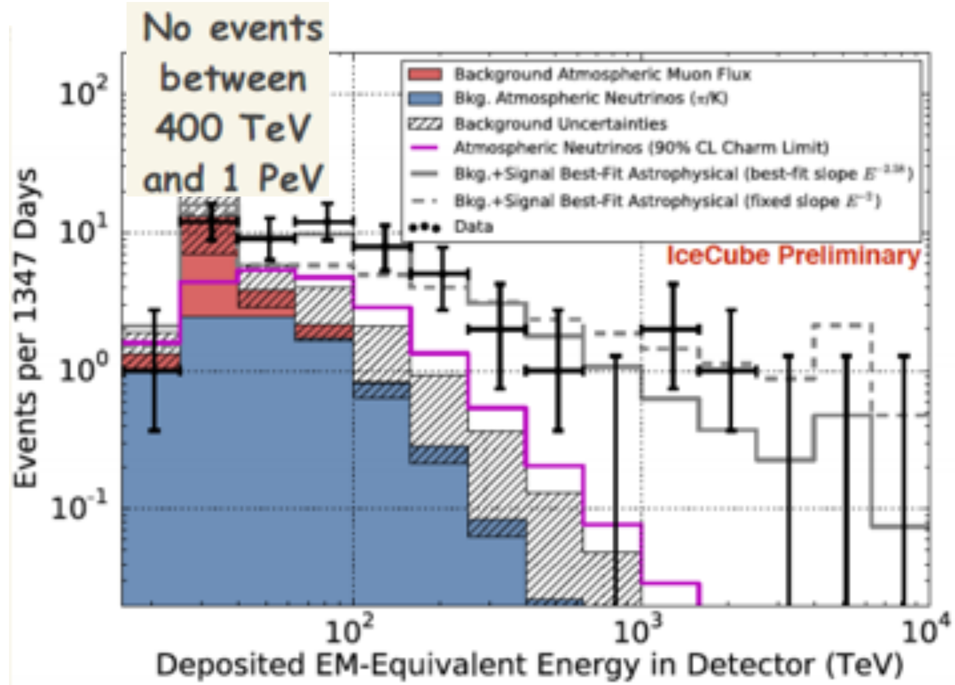
Stability and unitarity analysis

- Stability analysis
  - We shall use co-positivity criteria to find the stability conditions
  - Possible issue of basis dependency due to the presence of λ_5 coupling
- Unitarity analysis
  - We have to define the q-charged ($q = 0, 1, 2, \ldots$) 2-particle states
  - Construct the scattering matrix with possible basis states
  - Determine (analytic expression or numerical evaluation) the eigenvalues of the matrix to get the unitarity constraints

Ultra high energy neutrinos

- Overview **Raj Gandhi**





- UHEν and CPT violation

Danny Marfatia

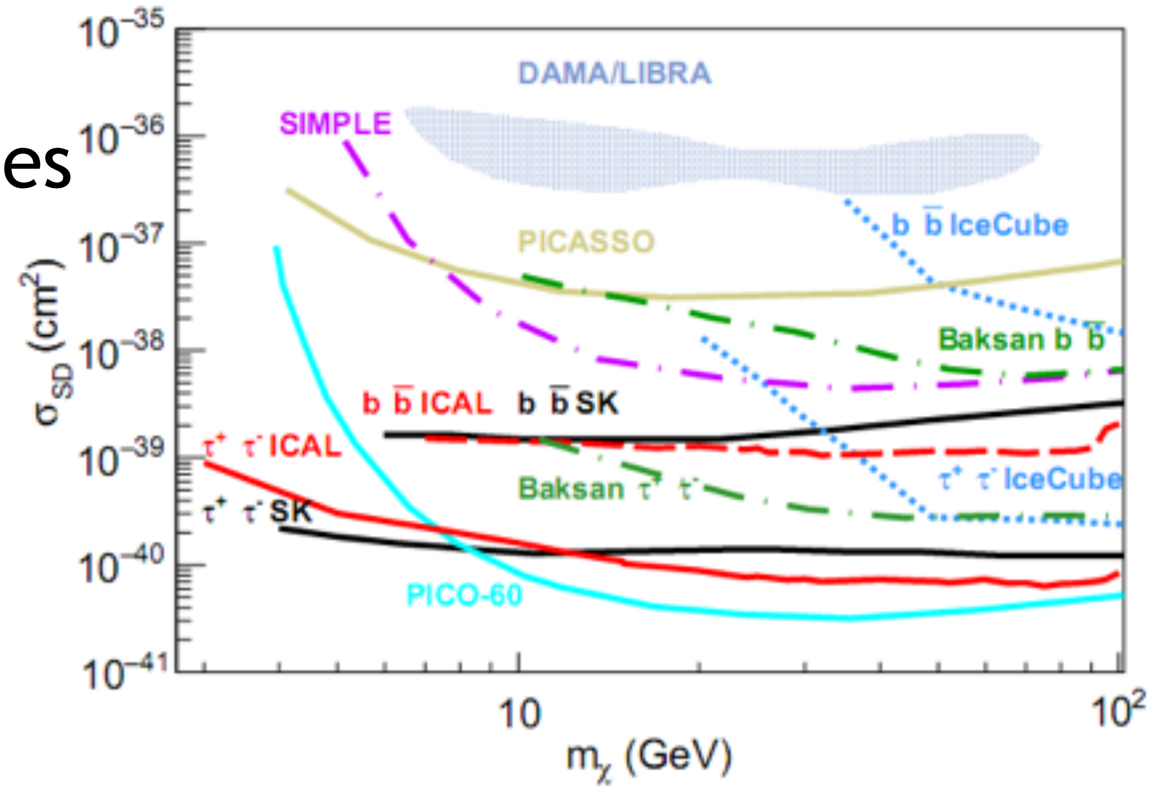
No energy gap in upgoing muon neutrinos below PeV

- Multicomponent neutrino flux not required if neutrino interactions violate CPT
- Excess below 200 TeV explained by event pile-up from superluminal neutrino decay

- Supernova neutrinos **Amol Dighe, Manibrata Sen**
  - Self-induced collective flavor conversions in SN are undergoing a paradigm shift.
  - Self-interacting neutrinos can spontaneously break space-time symmetries. This could lead to instabilities at all length scales.
  - Fast conversions could be possible near the SN core, leading to a quick flavor equilibration. Much more conclusive work is needed, both from theory and numerics.
  - Effect of new physics presents a plethora of new phenomenology.

- Indirect DM searches

  Deepak Tiwari



Decoherence in neutrino oscillations

- Legget-Garg inequalities **Ashutosh Alok**

Goals of LGI tests: To test "realism", the notion that physical systems possess complete sets of definite values for various parameters prior to, and independent of, measurement and *to demonstrate that QM applies on macroscopic scales up to the level at which many-particle systems exhibit decoherence.*

- Quantum decoherence in ν-osc **Poonam Mehta**

$$\frac{\partial \rho}{\partial t} = -i\,[H,\,\rho] + \mathcal{D}\,[\rho]$$

H, is responsible for the usual unitary evolution, $\mathcal{D}\,[\rho]$, for non-unitary evolution, i.e., decoherence.

$$P \;=\; \frac{1}{2}\sin^2(2\theta)\left[1 - e^{-d^2 L}\cos\left(\frac{\delta m^2}{2E}L\right)\right]$$

- Decoherence effects **Moon Moon Devi**

System–environment type interactions: Even if initial state is a pure quantum mechanical state, the system–environment coupling would produce a mixed quantum mechanical state. Wave packet decoherence introduces exponential damping factors which multiply the oscillatory terms in the oscillation transition probabilities

Impact of high energy/low energy extension on DUNE and ICAL

D. Indumathi, Lakshmi Mohan

Preliminary discussions