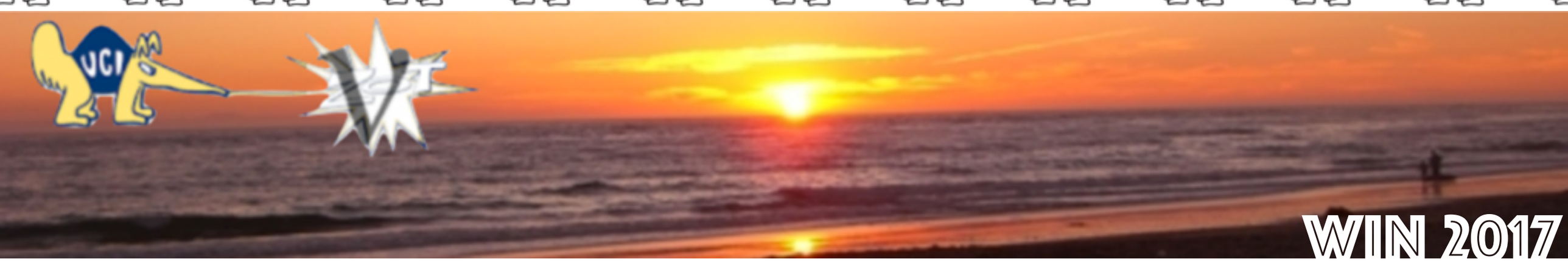
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Working group summary: Neutrino Physics Theory

Pedro A. N. Machado



Jun/2017

pmachado@fnal.gov

Neutrino Parallel Session

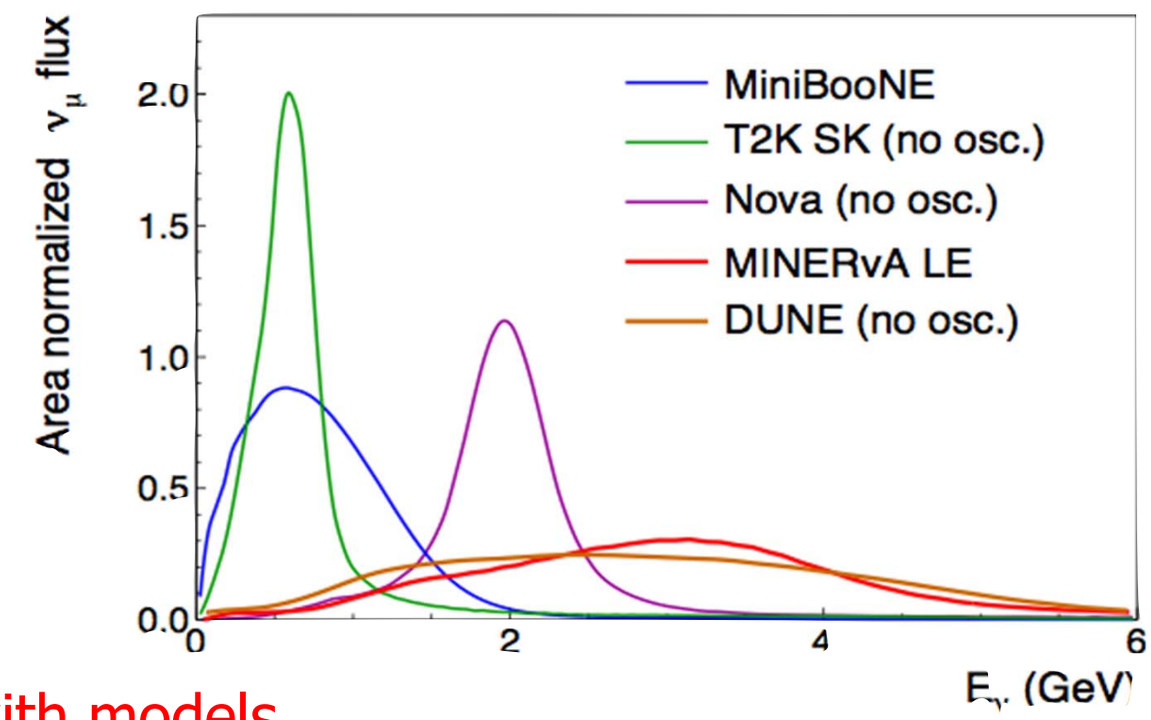
Theory

Featuring:
Neutrino mass models,
New interactions,
sterile neutrinos,
...

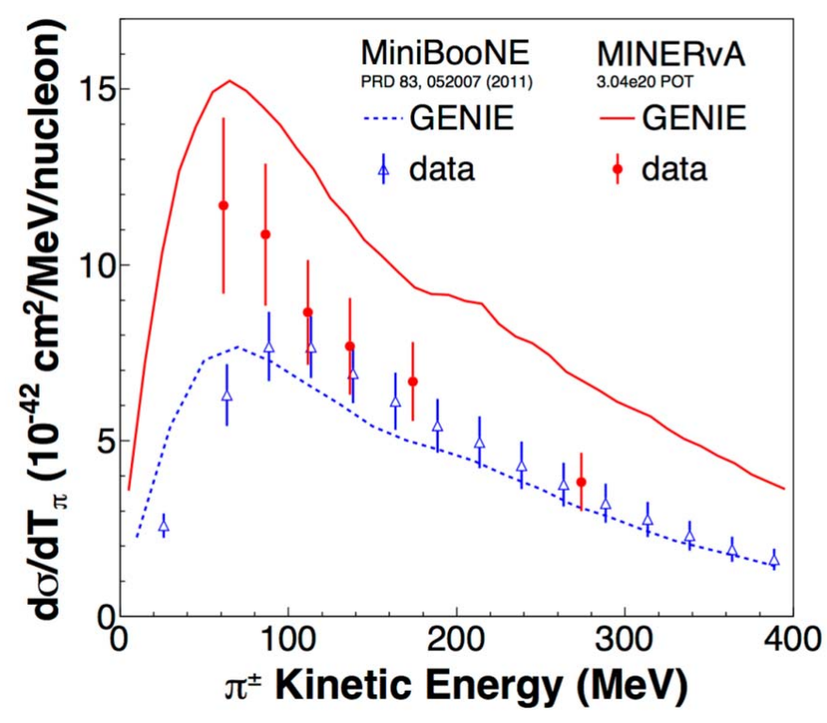
Neutrino Cross Sections

Steve Dytman, Univ. of Pittsburgh

- MiniBooNE (2011)
  - CCQE+'2p2h' (no 2p2h available)
  - CC0π (preferred)
- MINERvA (2014)
  - TrueCCQE+'true2p2h' +0π (no 2p2h available)
  - CC0π1p T_p<110 MeV
- T2K (2016)
  - CCQE+'2p2h'+0π (no 2p2h available)
- Very tricky to compare directly, must do it with models



- Tensions conclusions
  - Signals must be carefully chosen, described
  - Cuts should be on detected quantities (e.g. p_μ, T_p)
  - Avoid MC corrections from undetected kinematics (e.g. θ_μ)
  - Hard to imagine direct comparison between expts (signals)



Much progress has been made, but still long way to go

What is the mechanism behind neutrino masses?

Dark Gauge U(1) Symmetry for an Alternative Left-Right Model

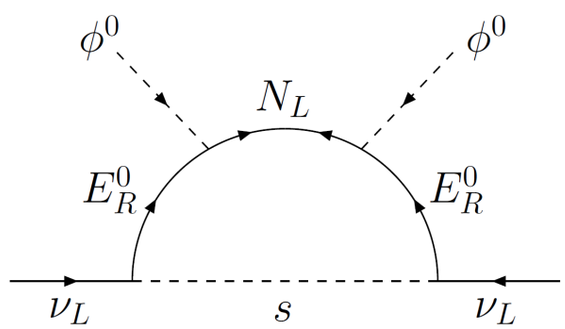
Oleg Popov

Restore symmetry between Left-Right sectors

Generate naturally small neutrino masses

Accomodate dark matter

$$\boxed{SU(3)_C \times SU(2)_L \times SU(2)_R \times \ldots}$$



particles	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$	$U(1)_S$
$(u,d)_L$	3	2	1	1/6	0
$(u,h)_R$	3	1	2	1/6	−1/2
d_R	3	1	1	−1/3	0
h_L	3	1	1	−1/3	−1
$(\nu,l)_L$	1	2	1	−1/2	0
$(n,l)_R$	1	1	2	−1/2	1/2
ν_R	1	1	1	0	0
n_L	1	1	1	0	1
(ϕ_L^+,ϕ_L^0)	1	2	1	1/2	0
(ϕ_R^+,ϕ_R^0)	1	1	2	1/2	1/2
η	1	2	2	0	−1/2
ζ	1	1	1	0	1
$(\psi_1^0,\psi_1^-)_R$	1	1	2	−1/2	2
$(\psi_2^+,\psi_2^0)_R$	1	1	2	1/2	1
χ_R^+	1	1	1	1	−3/2
χ_R^-	1	1	1	−1	−3/2
χ_{1R}^0	1	1	1	0	−1/2
χ_{2R}^0	1	1	1	0	−5/2
σ	1	1	1	0	3

M(Z')>4TeV

DM candidates

No tree level FCNC

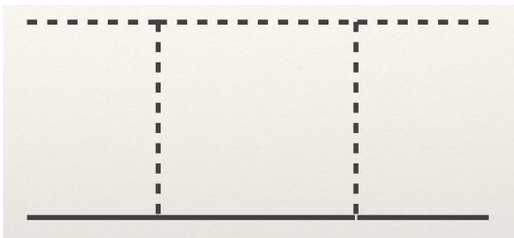
naturally small neutrino masses

Rich phenomenology accessable at LHC

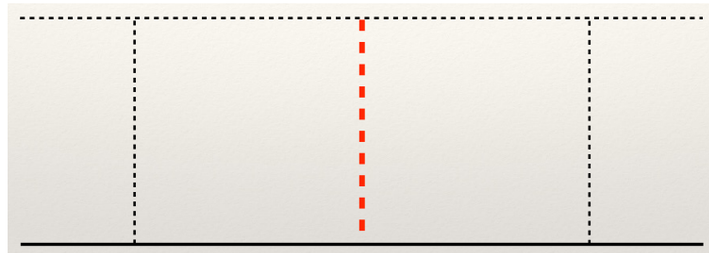
Fermilab
pmachado@fnal.gov

Deviations of symmetry-based exact neutrino structures using radiative neutrino masses.

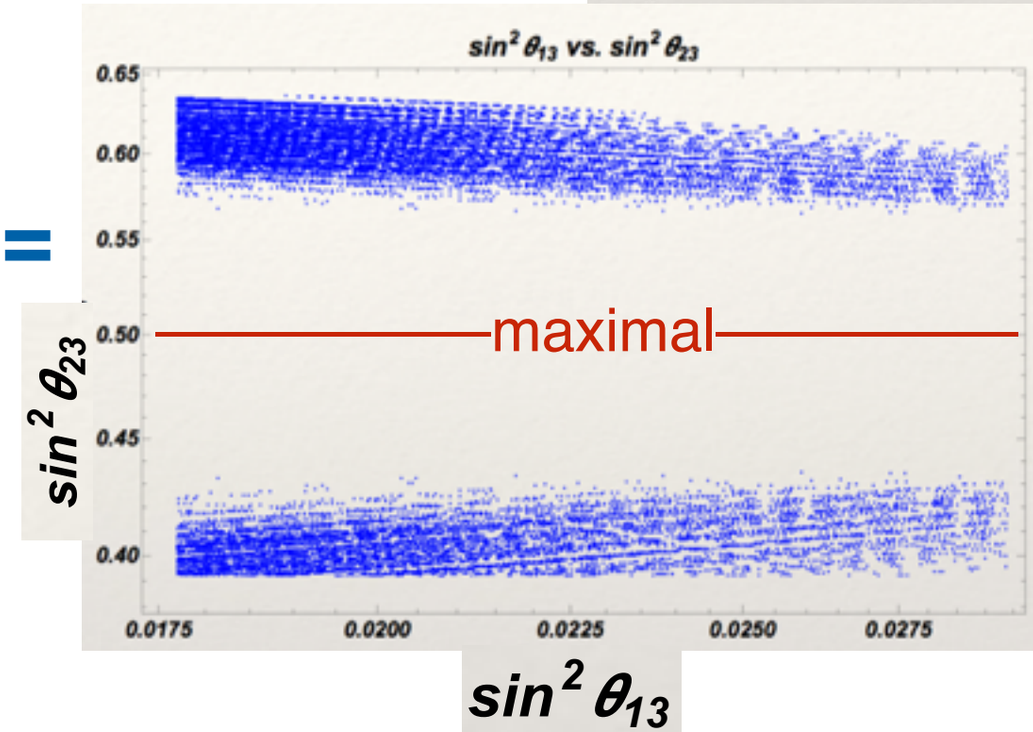
Daniel Wegman
ULg, Belgium



+



=



One loop diagram gives tribimaximal mixing

Two loop diagram gives corrections which reproduce observed neutrino mixing

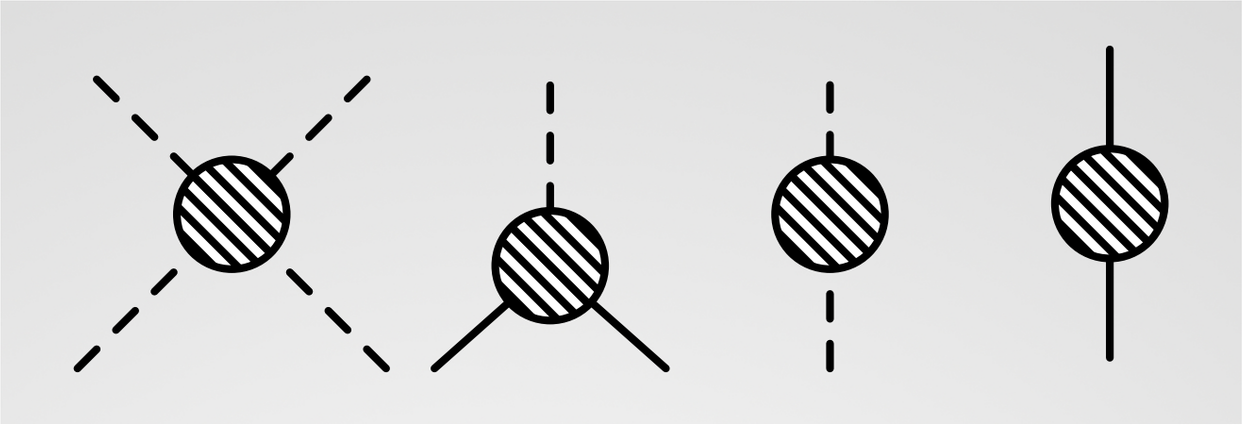
An exact mixing matrix (i.e tribimaximal, bimaximal, democratic, etc.) can be accomplished by using the Weinberg operator at one-loop level.

With the addition of only one more particle to the model, one can generate a two-loop diagram that is ***naturally surpassed*** and explains the deviations.

Radiative Corrections in ν-mass models

Maximilian Löschner

How do radiative corrections to masses and mixing angles behave in ν-mass models?



General treatment of radiative corrections to neutrino masses

General idea: build a tool for studying radiative corrections to masses and mixing angles in neutrino mass models with flavor symmetries

Exact Neutrino Mixing Angles from Three Subgroups of SU(2)

Franklin Potter

Show that the 3 lepton families represent 3 special and related subgroups of SU(2), therefore remaining within the realm of the SM EW gauge group.

$2T = [3,3,2] \Rightarrow (\nu_e, e^-) \quad \theta_1 = 52.660°$

$2O = [4,3,2] \Rightarrow (\nu_\mu, \mu^-) \quad \theta_2 = 18.379°$

$2I = [5,3,2] \Rightarrow (\nu_\tau, \tau^-) \quad \theta_3 = 61.238°$

Neutrino mixings from symmetry arguments

Fermilab
pmachado@fnal.gov

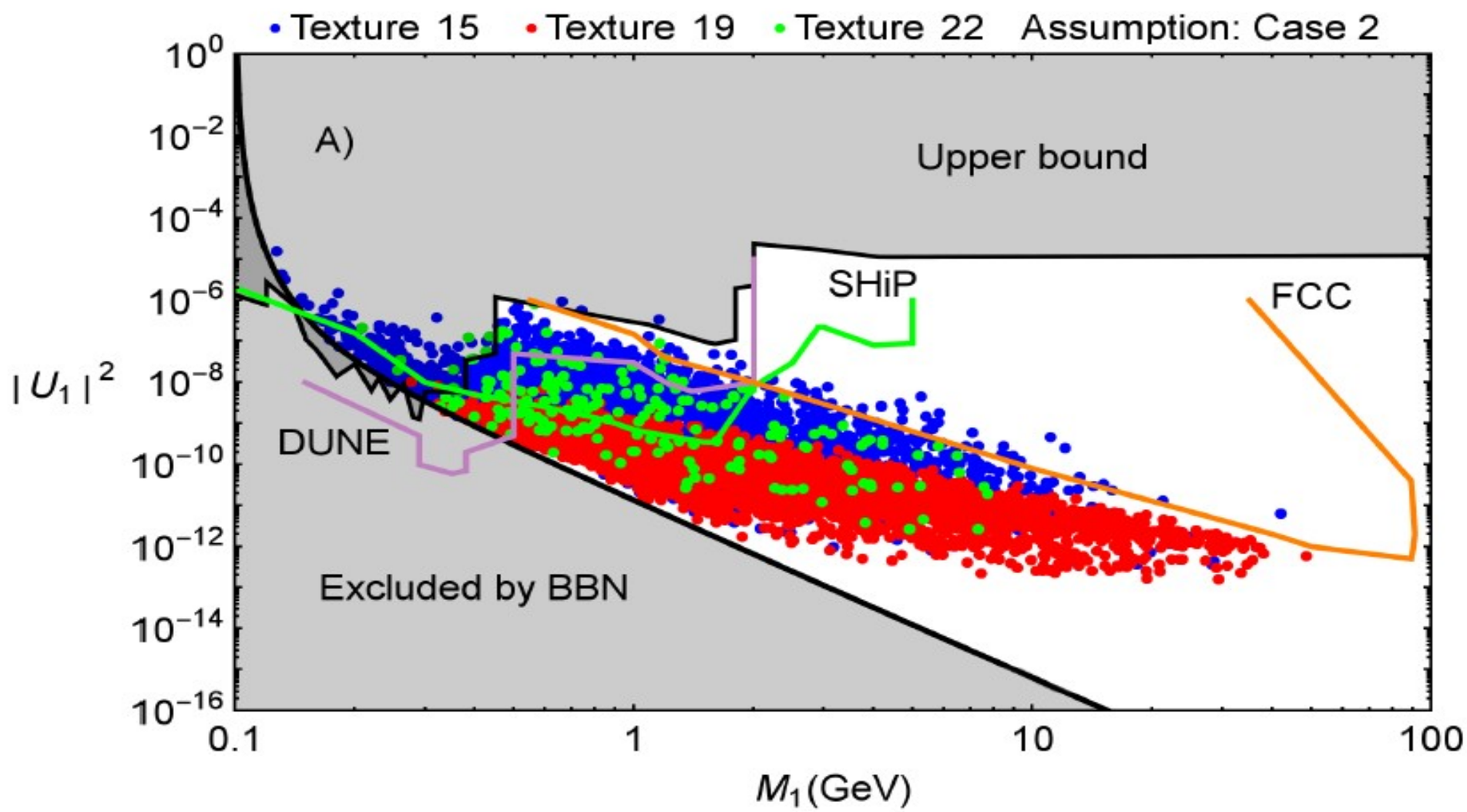
What are the physical impacts of these mechanisms?

GeV neutrino mass models: Experimental reach vs. theoretical predictions

Rasmus W. Rasmussen

All realizations have to obey experimental constraints: Neutrino oscillation data, LFV, neutrinoless double beta decay, direct searches, loop corrections and Big Bang nucleosynthesis

Model-independent approach generates the whole parameter space

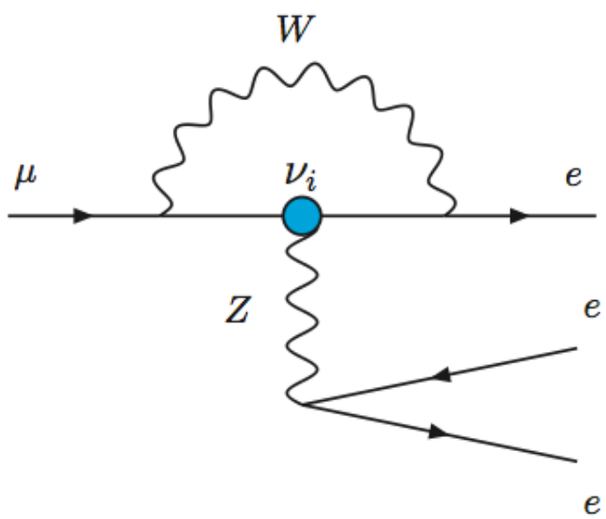


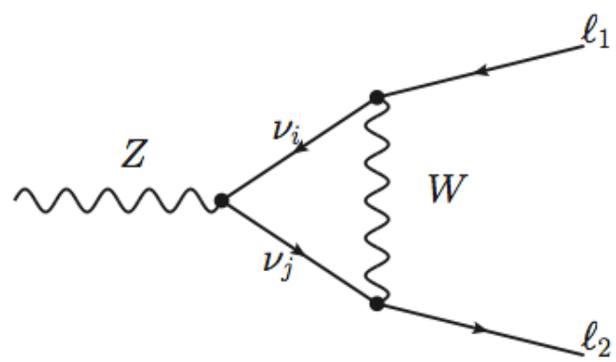
pmachado@fnal.gov

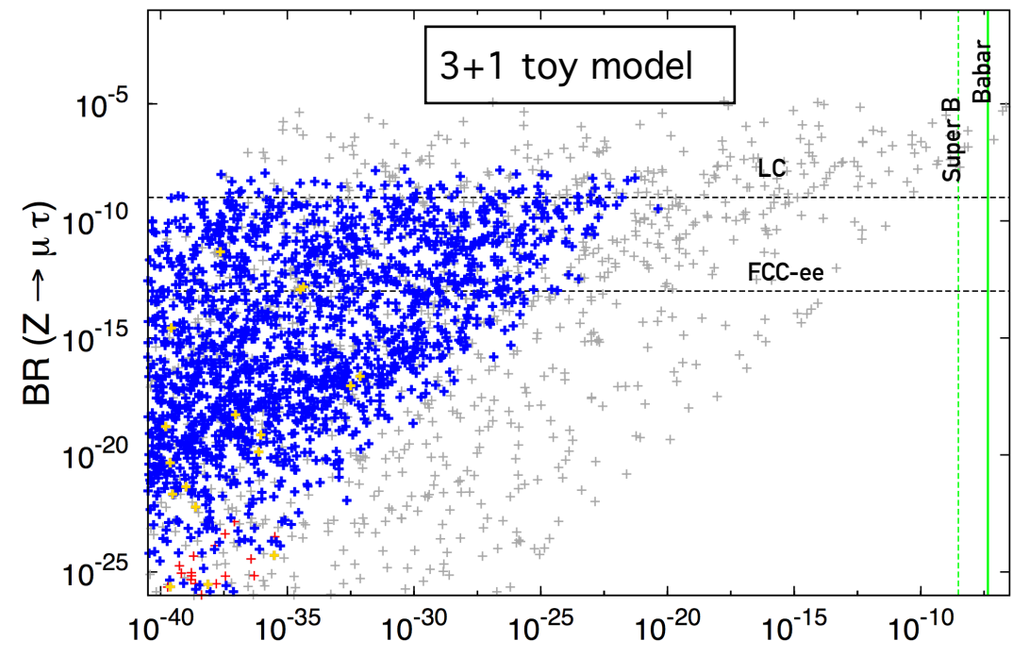
Impact of sterile neutrinos on cLFV processes

Valentina De Romeri

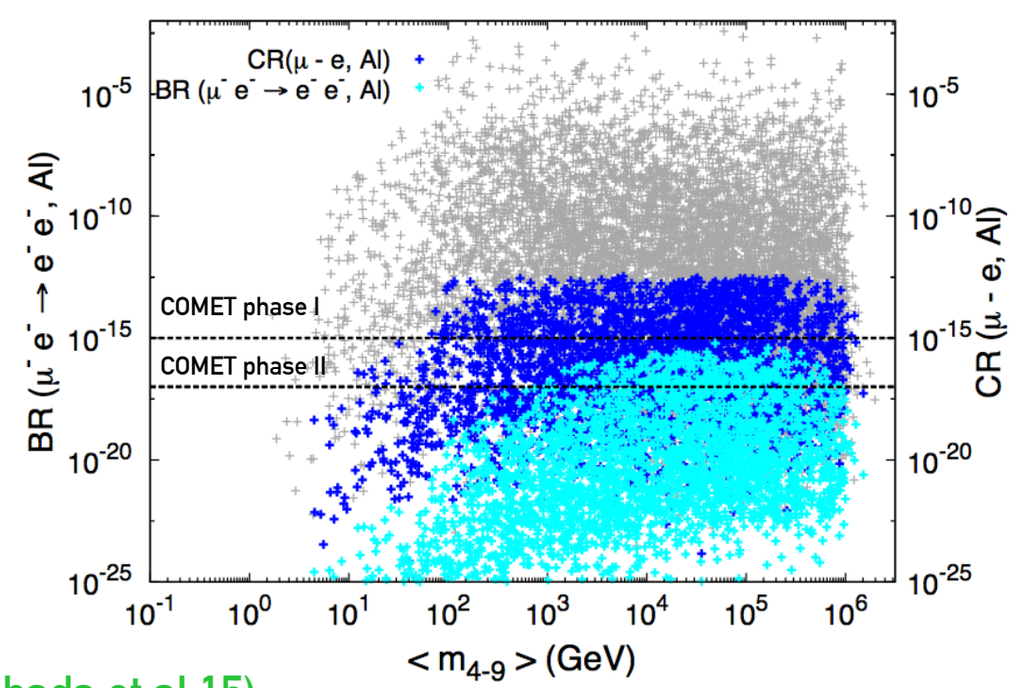
Are neutral and charged LFV (cLFV) related? Does cLFV arise from ν-mass mechanism?







Abada, VDR et al.,15



(Abada et al.15)

1. Neutrino oscillation parameters (mixing angles and Δm^2)
2. Unitarity constraints $U_{3\times3} = (1-\eta)U_{PMNS}$ effective theory approach
3. Electroweak precision data e.g. invisible and leptonic Z-decay widths, the Weinbe
4. LHC data (invisible decays) decay modes of the Higgs boson $h \to \nu_R\, \nu_L$ relevant for sterile neutrino masses ~100 G
5. Leptonic and semileptonic meson decays (K,B and D) $\Gamma(P \to l\nu)$ with P = K,D two neutrinos in the fi
6. Laboratory bounds: direct searches for sterile neutrinos e.g. $\pi^\pm \to \mu^\pm \nu_S$, th spectrum would s monochromatic li
7. Lepton flavor violation ($\mu \to e\,\gamma$, $\mu \to eee$ ...)
9. Neutrinoless double beta decay $m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (140-700) meV$
10. Cosmological bounds on sterile neutrinos Large scale structure, Lyman-α, BB ray constraints (from $\nu_i \to \nu_j \gamma$),SN19

Important sterile contributions to CR(μ – e, N) and BR($\mu^- e^- \to e^- e^-$), potentially within COMET and Mu2e reach

Fermilab
omachado@fnal.gov

Distinguish between Dirac&Majorana neutrinos in the presence of new interactions

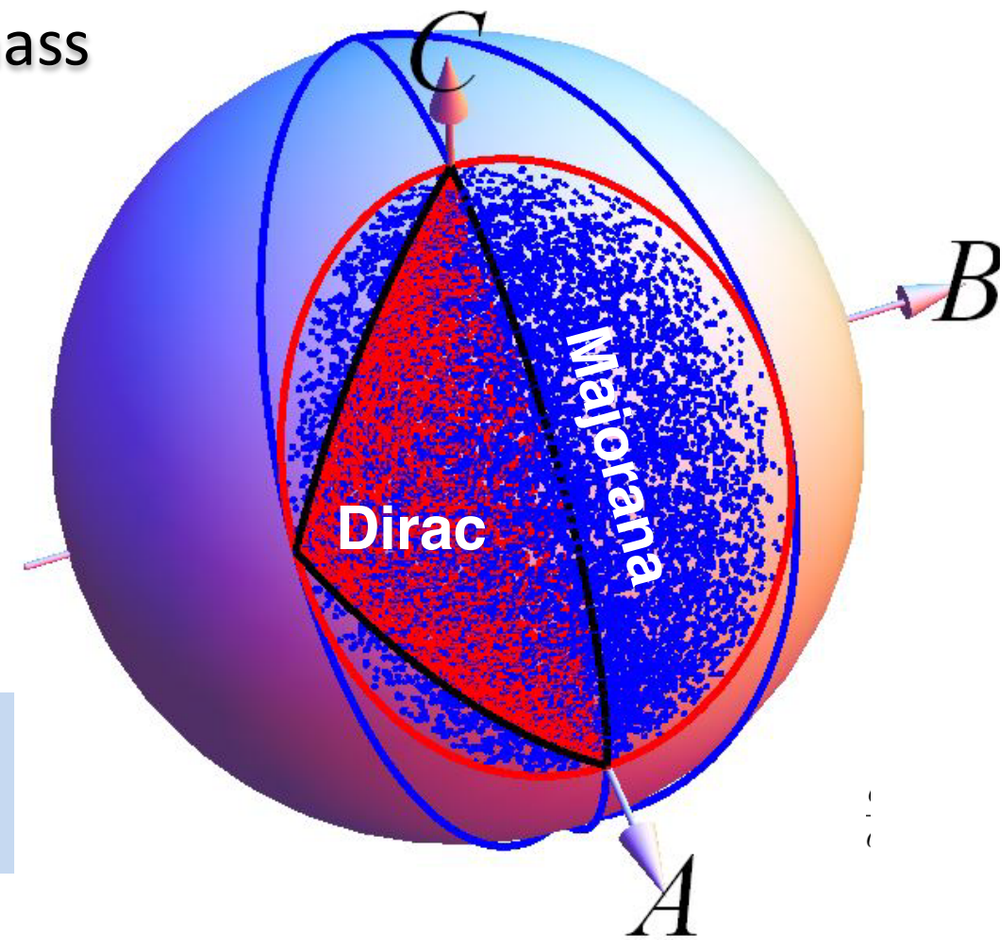
Xun-Jie Xu

Only SM interactions: difference suppressed by mass

$$\text{Dirac}-\text{Majorana} \propto m_\nu$$

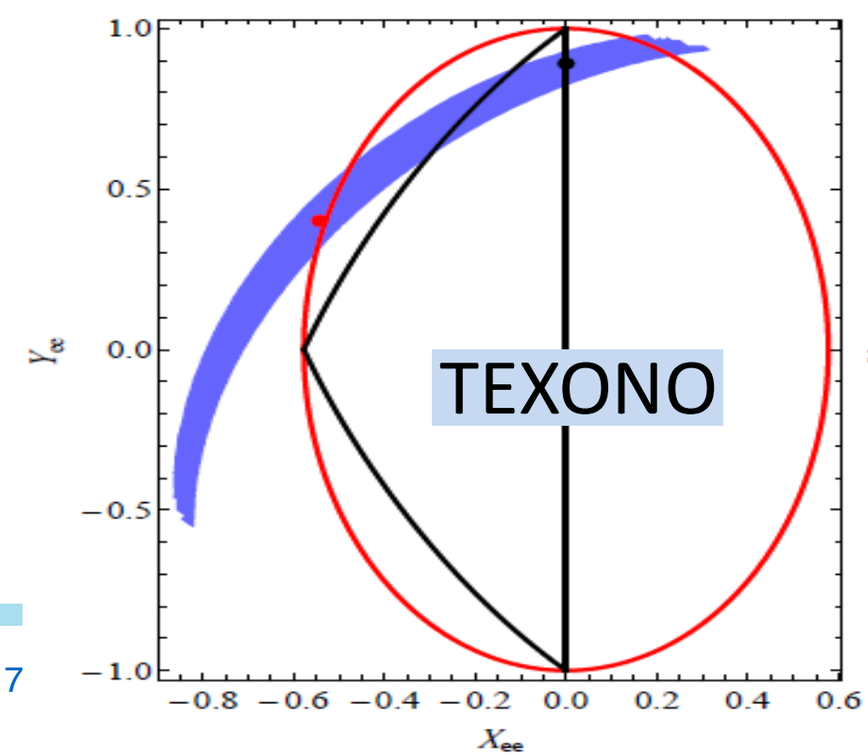
New interactions: difference NOT suppressed

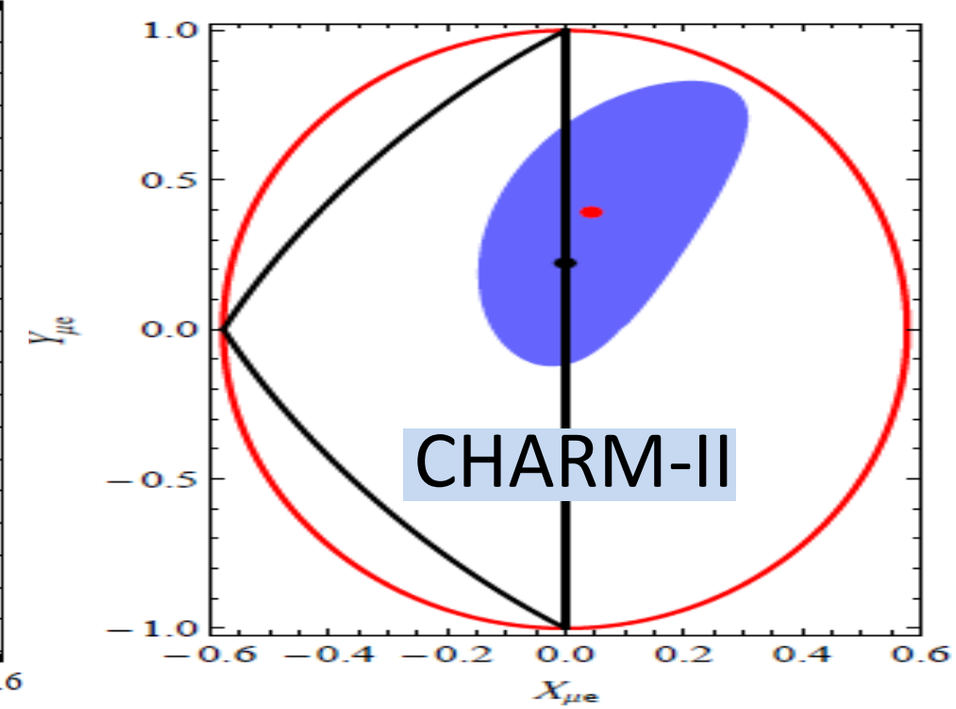
$$\text{Dirac}-\text{Majorana} \propto \text{new int.}$$



Scalar, **P**seudo-scalar, **V**ector, **A**xial-vector, **T**ensor

$$\frac{d\sigma}{dT}(\nu+\ell) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1-\frac{T}{E_\nu}\right) + C\left(1-\frac{T}{E_\nu}\right)^2\right]$$

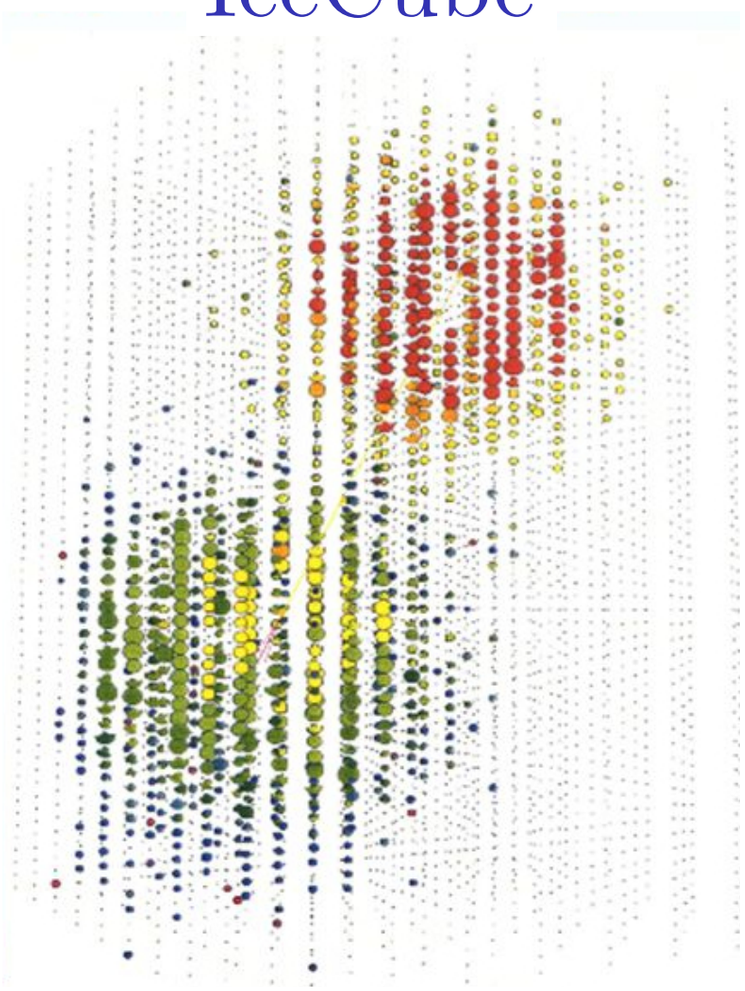


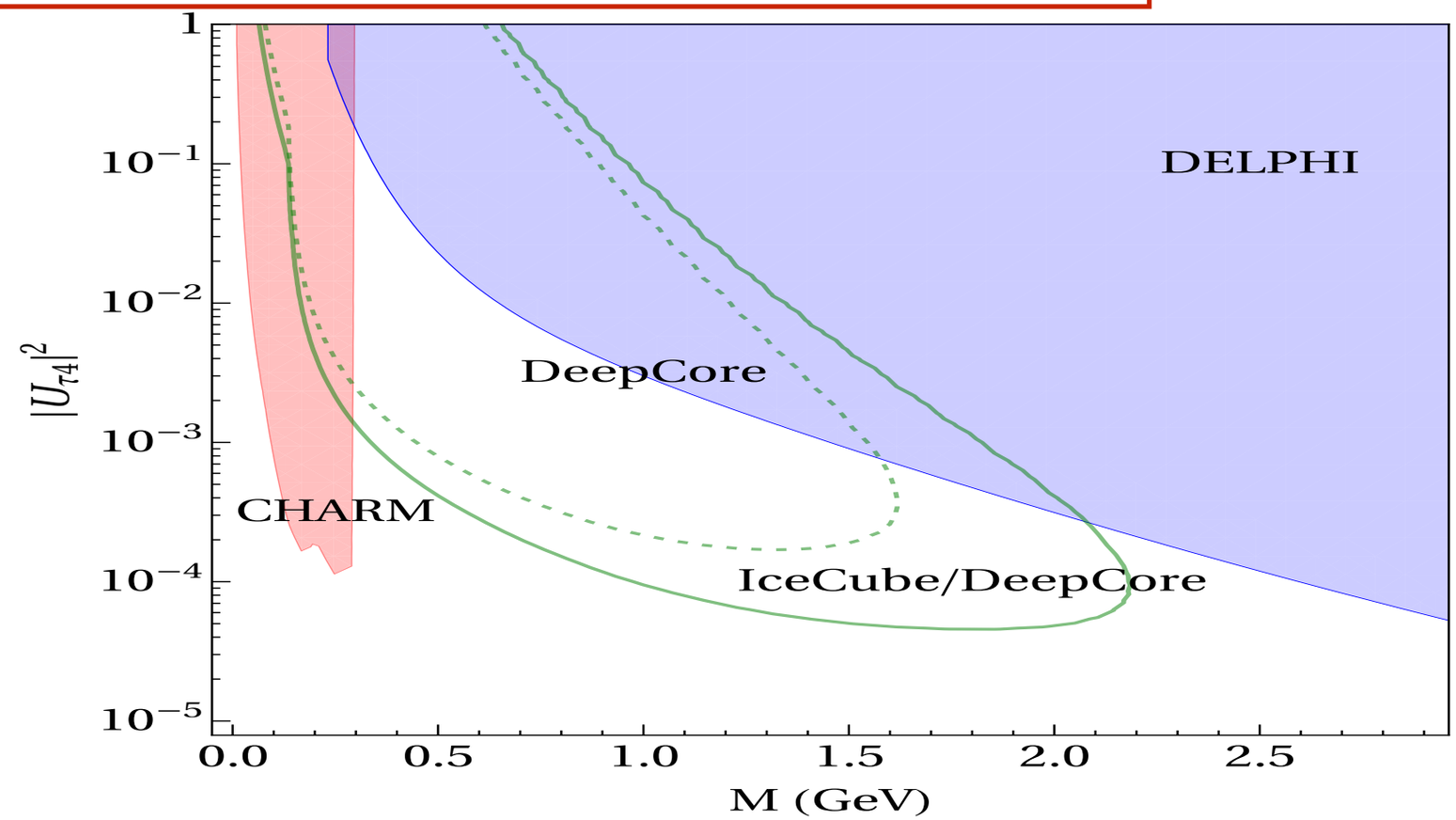


Fermilab
pmachado@fnal.gov

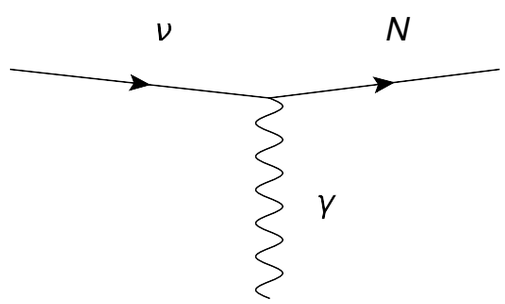
Double Bang signals can probe new physics

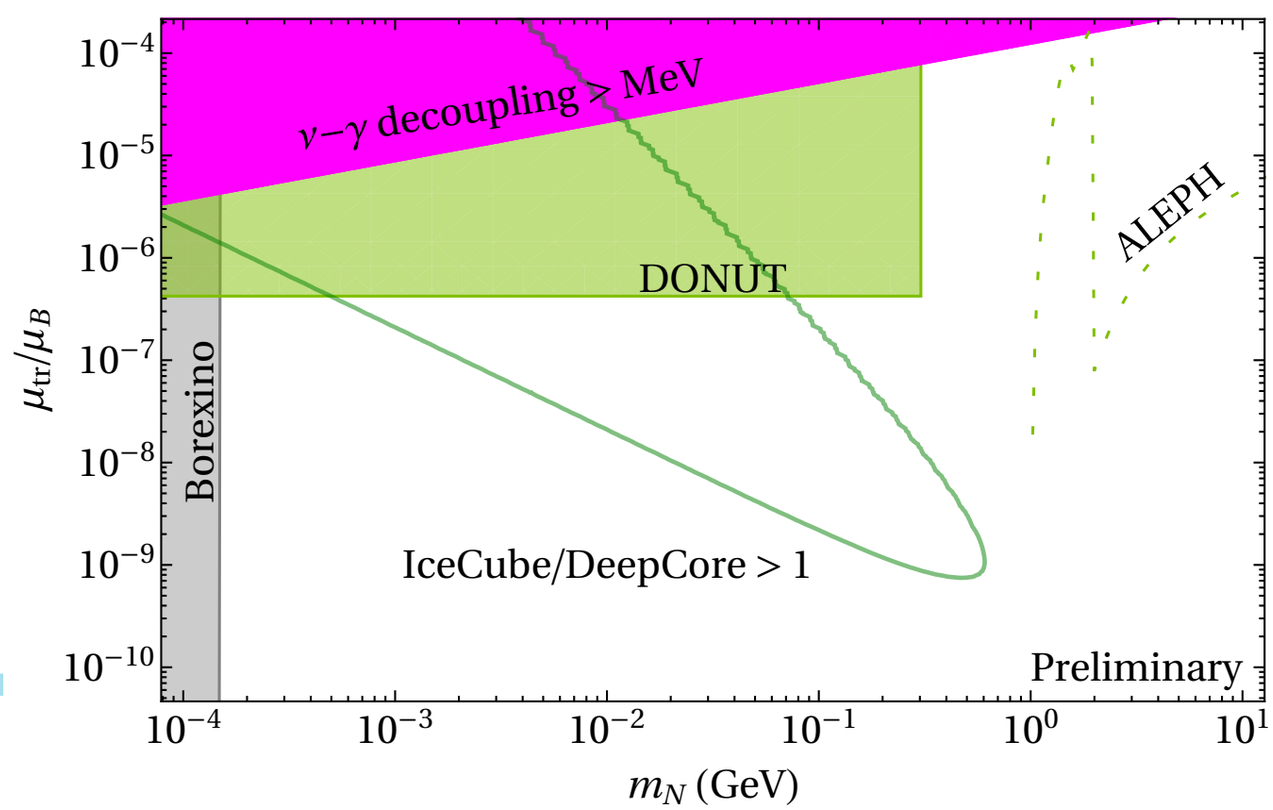
IceCube





$$\mathcal{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$





Fermilab
chado@fnal.gov

Bounds on heavy Majorana neutrinos in type-I seesaw and implications for collider searches

Arindam Das

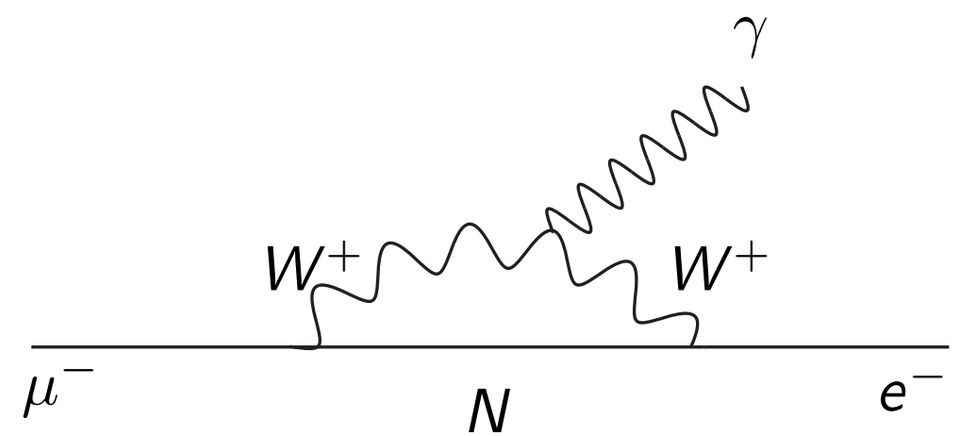
Production of the heavy neutrino at the LHC

$$q\bar{q}' \to \ell N_i \; (u\bar{d} \to \ell_\alpha^+ N_i \text{ and } \bar{u}d \to \ell_\alpha^- \overline{N_i})$$

$$M_N = 100 \text{ GeV}.$$

Experiments	Mixning angles	Upper Bounds
EWPD-e[62–64]	$\lvert V_{eN}\rvert^2$	1.7×10^{-3}
EWPD-μ[62–64]	$\lvert V_{\mu N}\rvert^2$	9.0×10^{-3}
EWPD-τ[62–64]	$\lvert V_{\tau N}\rvert^2$	4.2×10^{-3}
L3[65]	$\lvert V_{\ell N}\rvert^2$, $\ell = e, \mu$	2.2×10^{-3}
Higgs-LHC[66]	$\lvert V_{\ell N}\rvert^2$, $\ell = e, \mu$	3.4×10^{-3}
LHC-e(ATLAS, 8 TeV)[67]	$\lvert V_{eN}\rvert^2$	4.1×10^{-2}
LHC-μ(ATLAS, 8 TeV)[67]	$\lvert V_{\mu N}\rvert^2$	1.9×10^{-3}
LHC-e(CMS, 8 TeV)[68]	$\lvert V_{eN}\rvert^2$	1.1×10^{-2}
LHC-μ(CMS, 8 TeV)[68]	$\lvert V_{eN}\rvert^2$	4.6×10^{-3}
LHC-e, μ(CMS, 8 TeV)[68]	$\frac{\lvert V_{eN}V_{\mu N}^*\rvert^2}{\lvert V_{eN}\rvert^2+\lvert V_{\mu N}\rvert^2}$	2.4×10^{-3}

LFV processes



To constrain the analysis we use neutrino oscillation data, LFV and LEP results. Hence we obtain indirect limits on the light-heavy mixing angle which are stronger than the current experimental bounds.

Fermilab
pmachado@fnal.gov

Low-Energy vs. High-Energy Leptonic Unitarity Violation

Hisakazu Minakata

Paradigm Test !

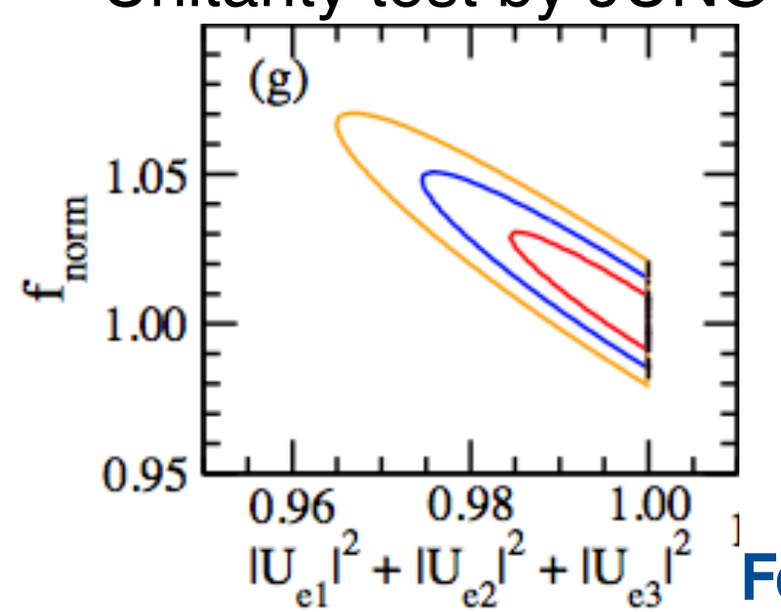
Low-energy UV	High-energy UV
lepton flavor universality: YES	lepton flavor universality: NO
zero distance neutrino flavor transition: NO	zero distance neutrino flavor transition: YES
Kinematical effect of sterile nu emission: YES	Kinematical effect of sterile nu emission: YES (if kinematically allowed)

3+N

$$P(\nu_\alpha \to \nu_\alpha) = \mathcal{C}_{\alpha\alpha} + \left(\sum_j^3 |U_{\alpha j}|^2\right)^2 - 4\sum_{k>j}^3 |U_{\alpha j}|^2 |U_{\alpha k}|^2 \sin^2 \frac{(\Delta_k - \Delta_j)x}{2},$$

A constant **leaking term** $C_{\alpha\beta}$
(=distinguishes between low-E vs high-E unitarity violation !!)

Unitarity test by JUNO



Question: Does this model allow us to write active nu oscillation probability in a manner independent of details of the N sterile sector?

pmachado@fnal.gov

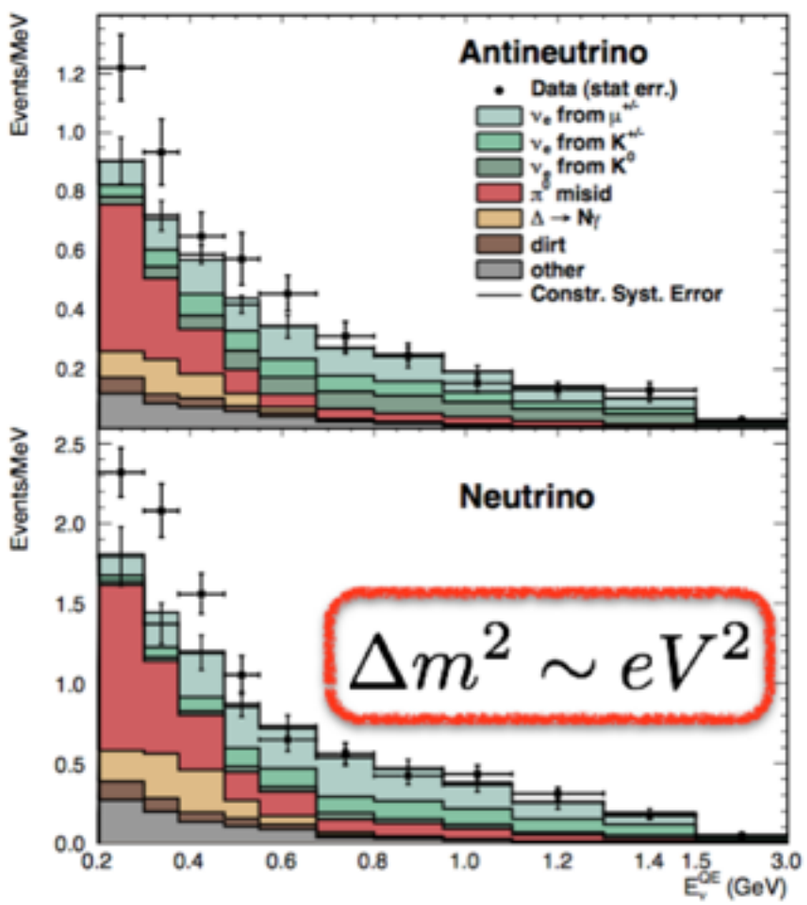
Neutrinos In Large Extra Dimensions and the LSND/MiniBooNE anomalies

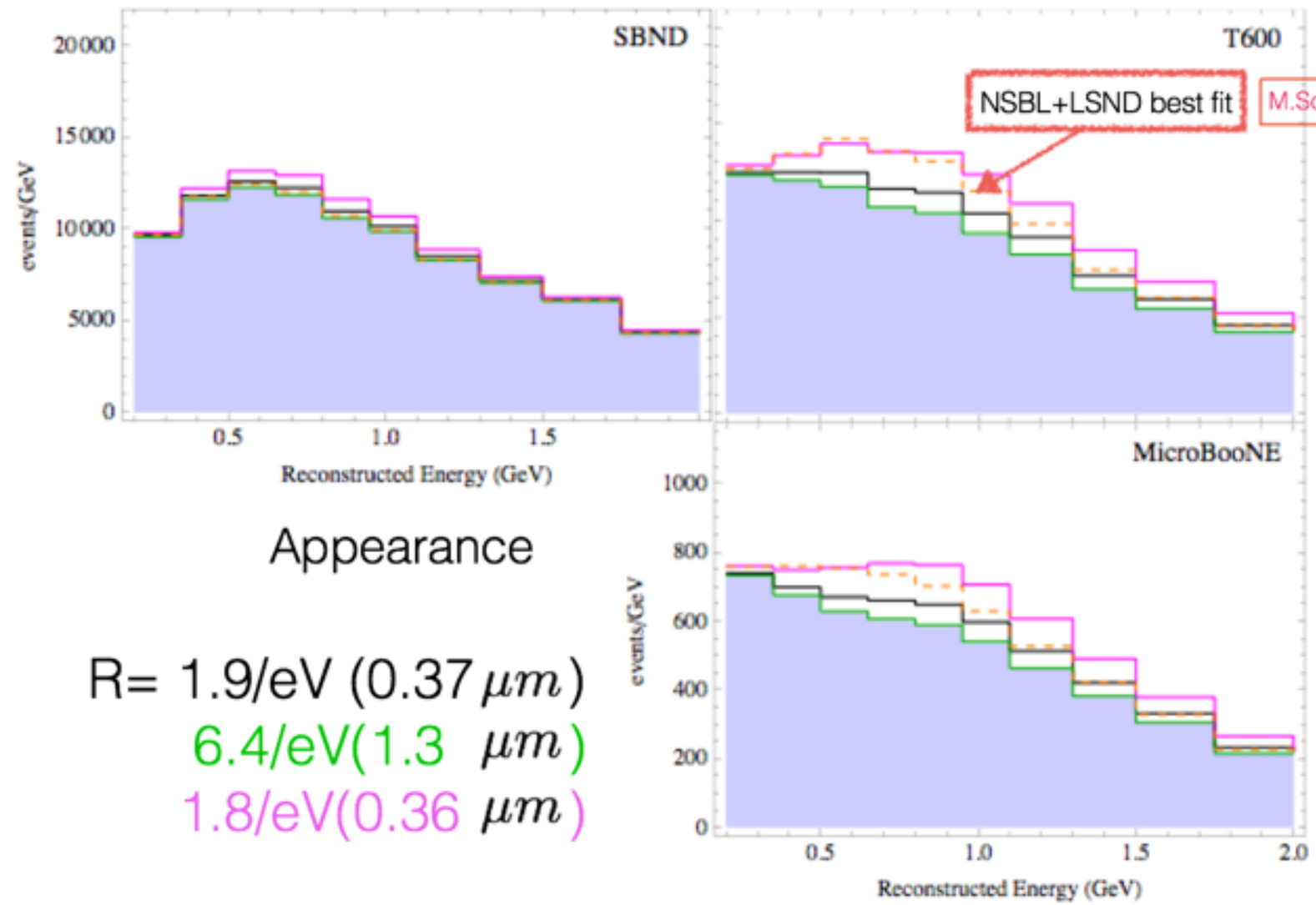
Ying-Ying Li

LED model + bulk mass could explain LSND/MinibooNE anomaly

$$S_f = \int d^4x\, dz \left[i\bar{\Psi}_i \Gamma^A \overleftrightarrow{\partial}_A \Psi_i - c_i \bar{\Psi}_i \Psi_i \right]$$

$$S_Y = -\int d^4x \sum_{i=1}^{3} \left(y^i \bar{L}_i \tilde{H} \Psi_i^R(x^\mu, 0) + \text{h.c.} \right)$$





Appearance

R= 1.9/eV (0.37 μm)
6.4/eV(1.3 μm)
1.8/eV(0.36 μm)

pmachado@fnal.gov

Astro neutrinos

pmachado@fnal.gov

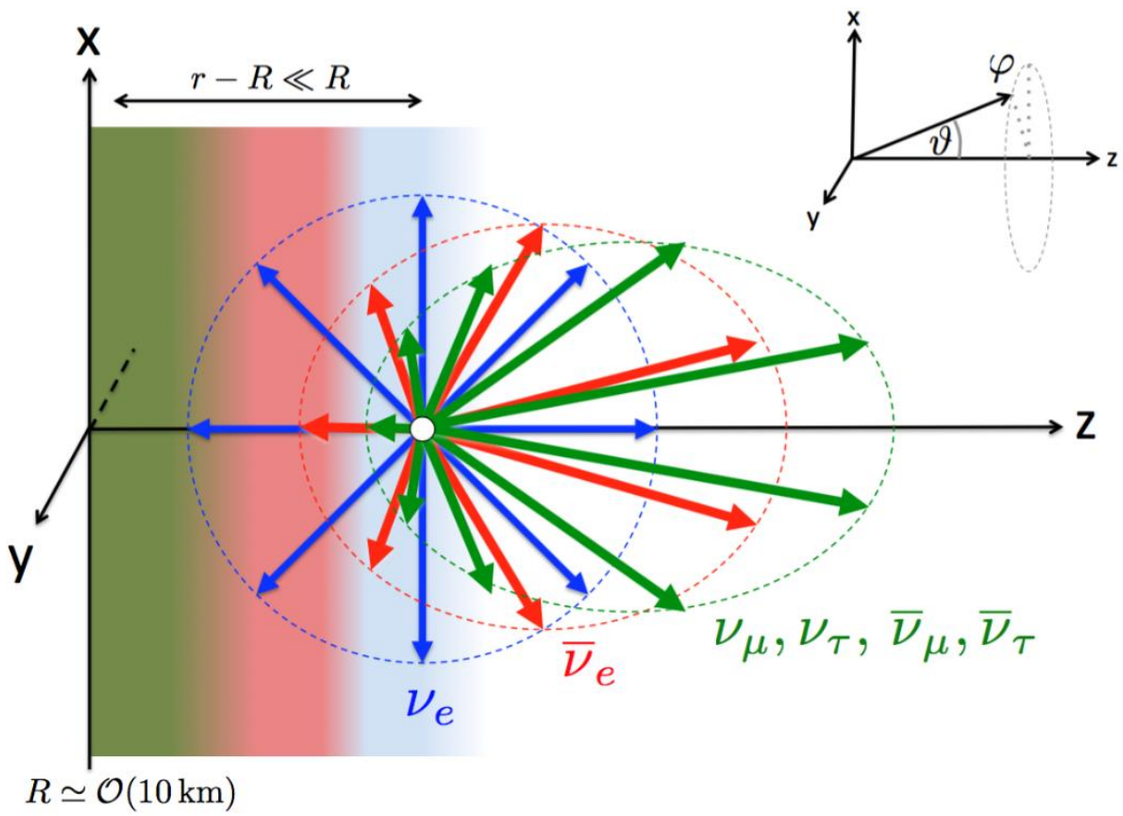
FAST NEUTRINO FLAVOR CONVERSIONS NEAR THE SN CORE

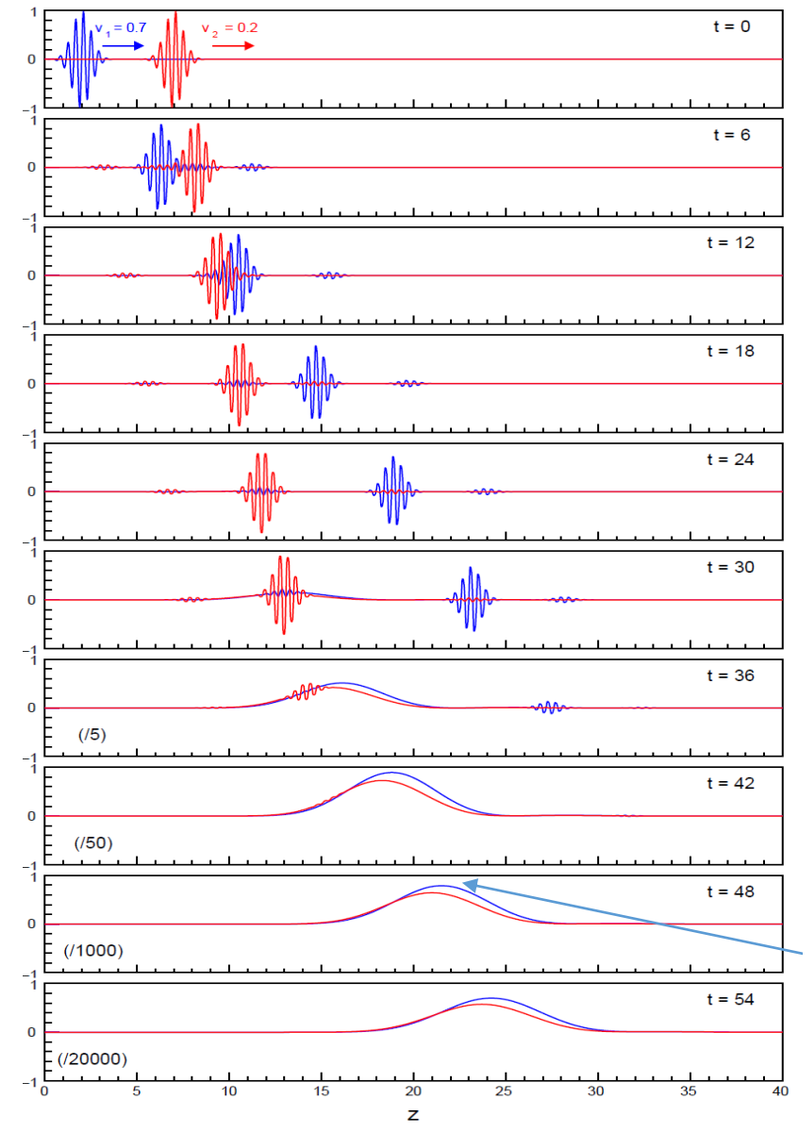
Alessandro MIRIZZI

Linearized equations of motion for $\Delta m^2=0$

$$i(\partial_t + \vec{v}\cdot\vec{\nabla})S_{\vec{v}}(t,\vec{x}) = (\Lambda_0 + \Phi_0 - \vec{v}\cdot\vec{\Phi})S_{\vec{v}}(t,\vec{x}) - \int \frac{d^3\vec{v}'}{4\pi}(1-\vec{v}\cdot\vec{v}')G_{\vec{v}'}S_{\vec{v}'}(t,\vec{x})$$

$$\rho = \begin{pmatrix} f_{\nu_e} & f_{\langle\nu_e|\nu_x\rangle} \\ f_{\langle\nu_x|\nu_e\rangle} & f_{\nu_x} \end{pmatrix} = \frac{f_{\nu_e}+f_{\nu_x}}{2} + \frac{f_{\nu_e}-f_{\nu_x}}{2}\begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$





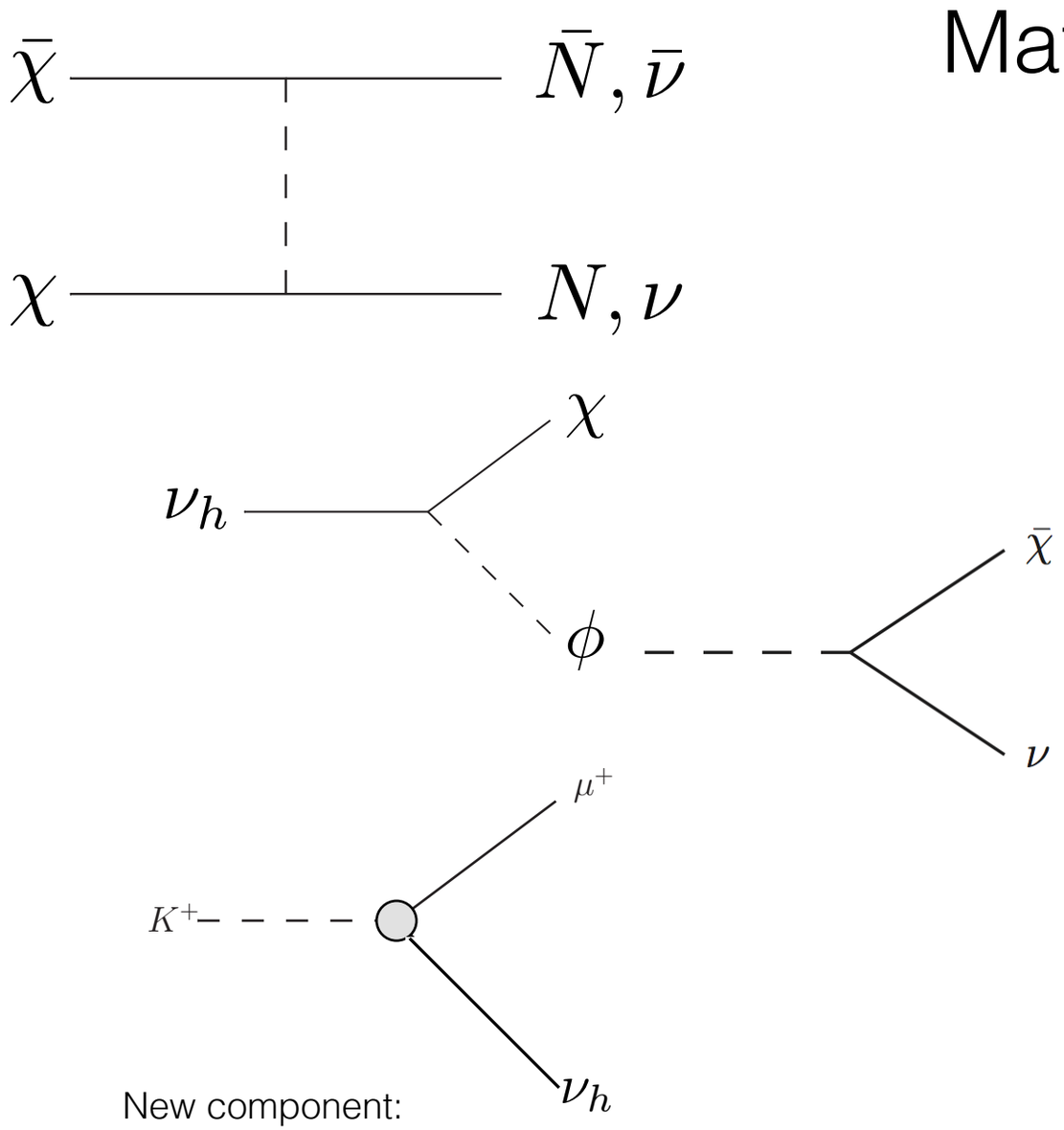
Non-linear simulations of the flavor evolution are mandatory to determine if fast conversions lead to flavor equilibrium.

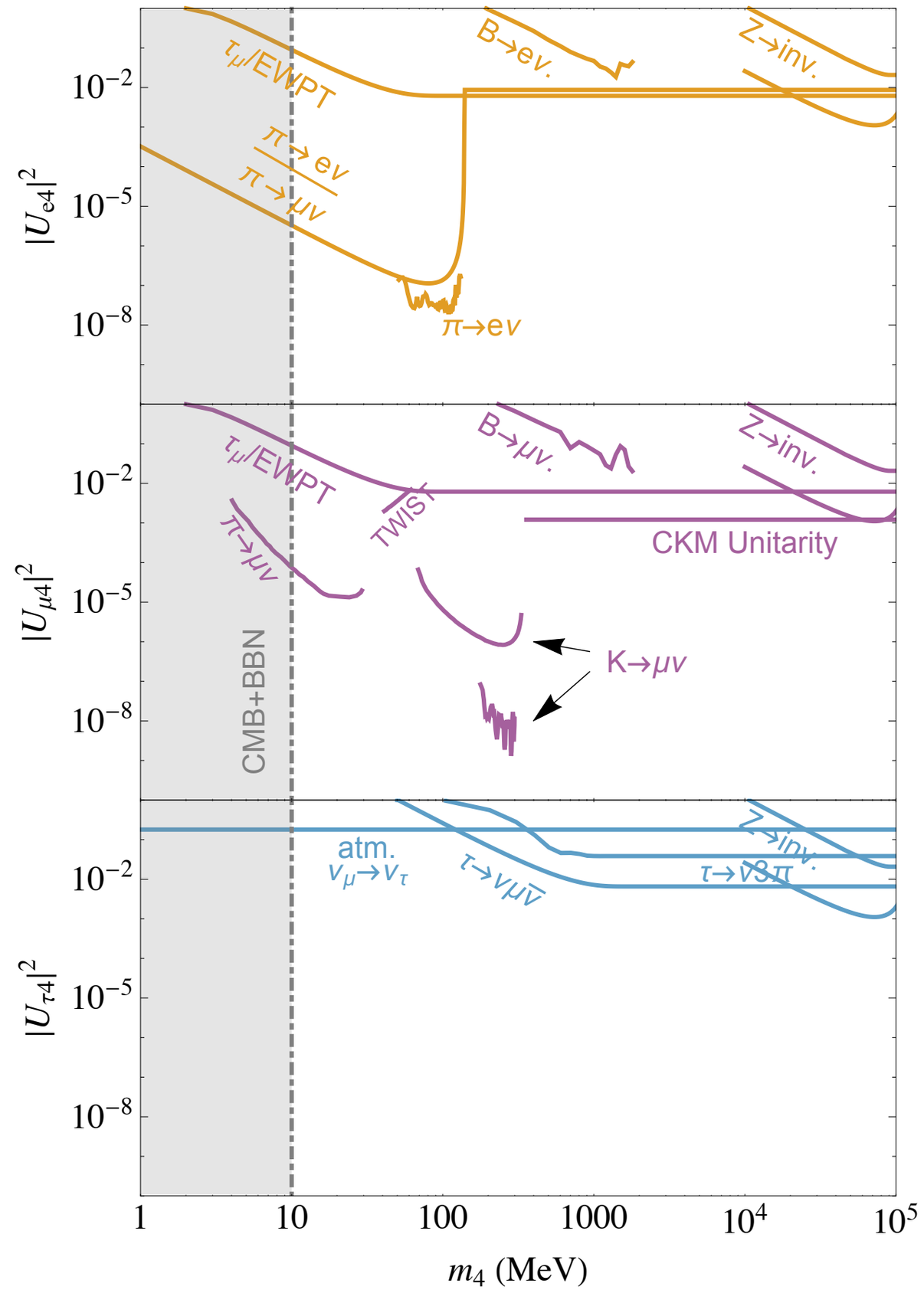
LOT OF WORK STILL ON THE AGENDA!

Fermilab
pmachado@fnal.gov

Neutrino Portal Dark Matter

David McKeen





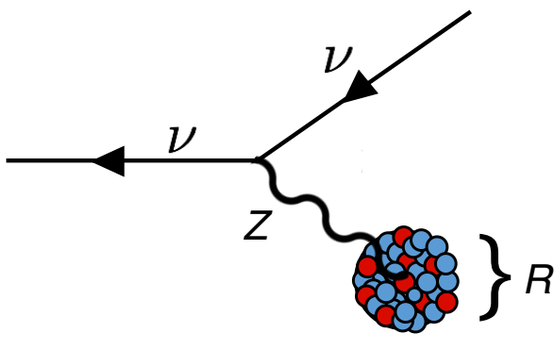
Neutrino portal relatively less well studied

Interesting new probes

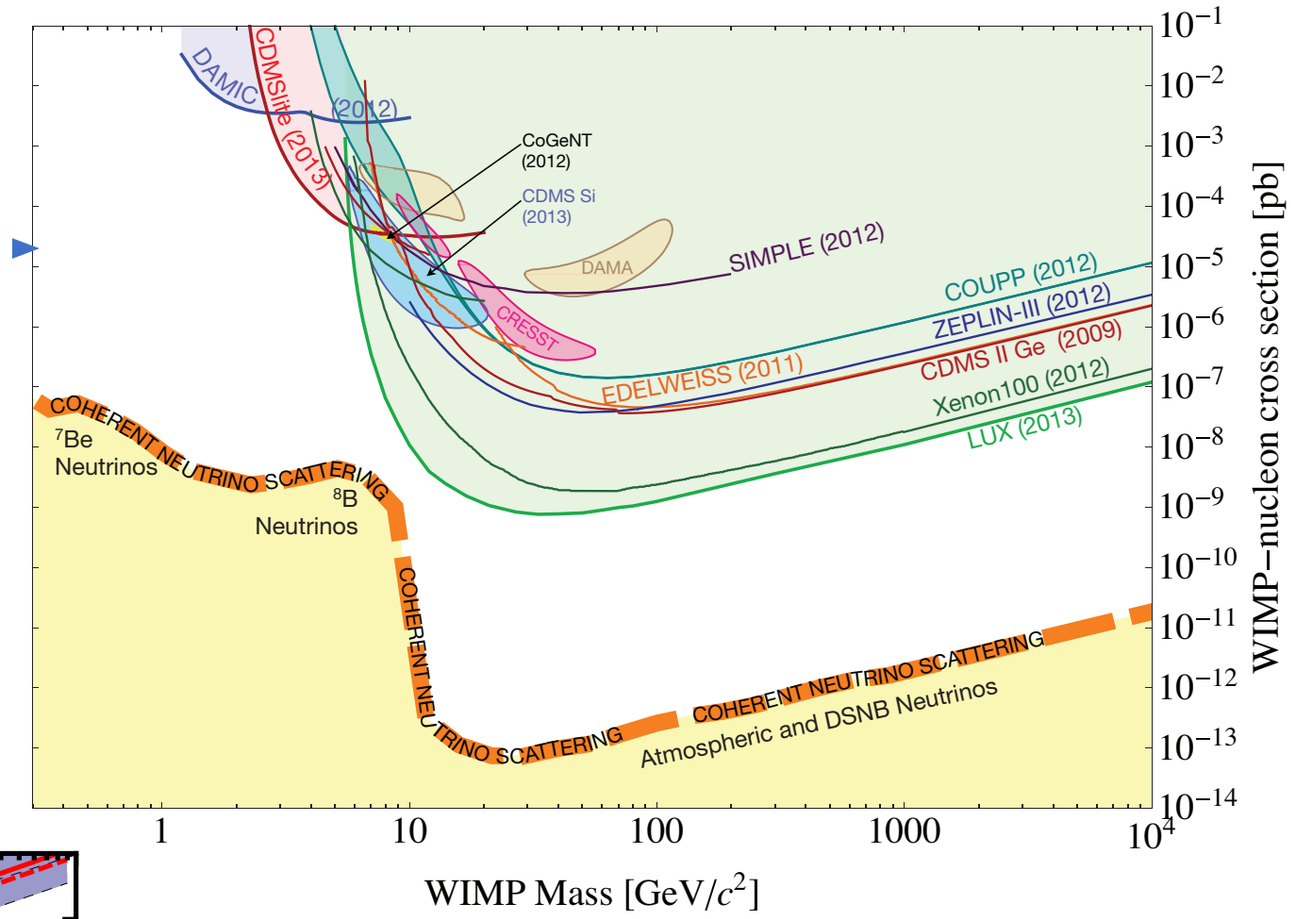
lots of connections across fields!

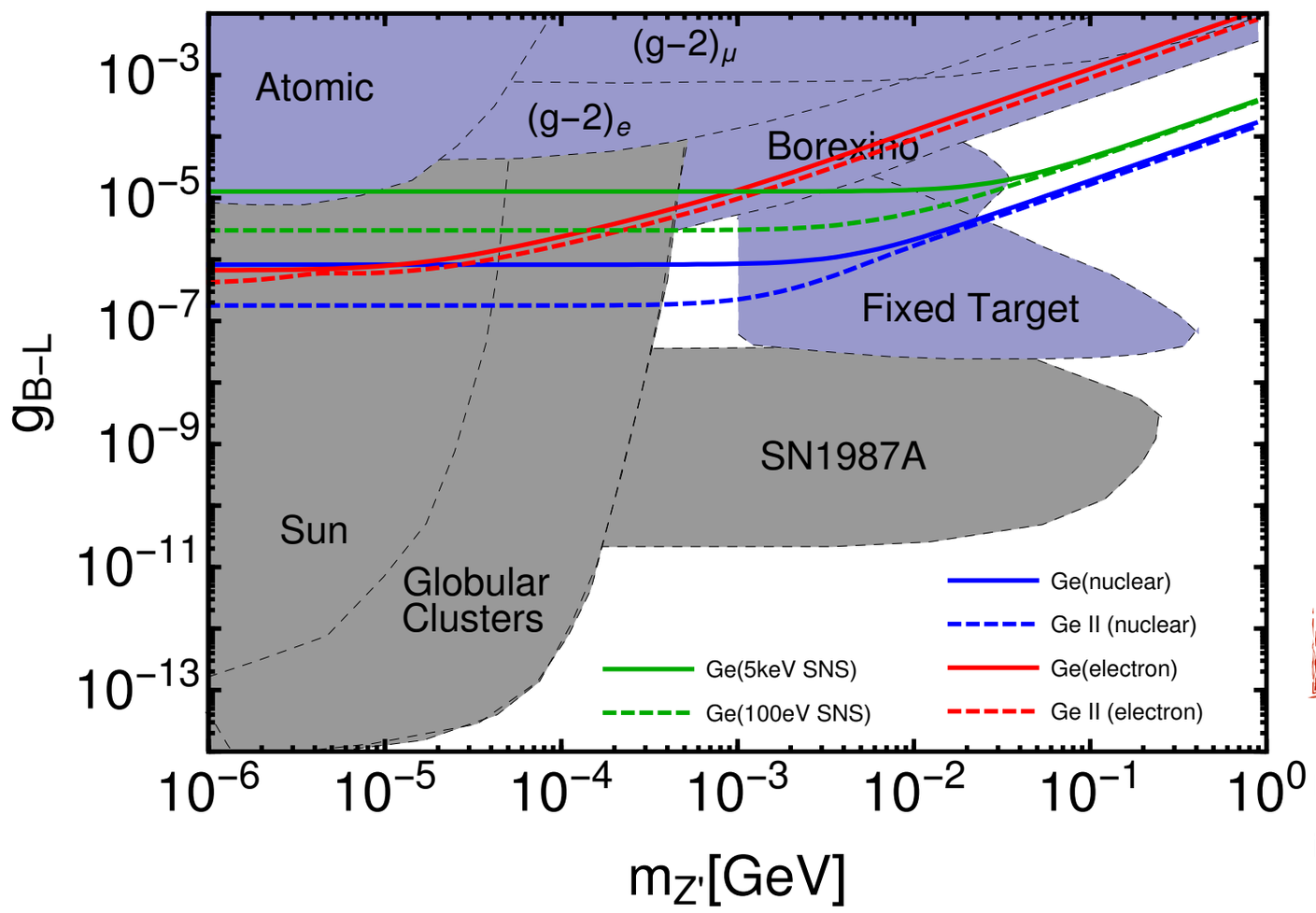
CEνNS

James Dent



$$\frac{d\sigma}{dE_r}(E_r, E_\nu) = \frac{G_F^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$





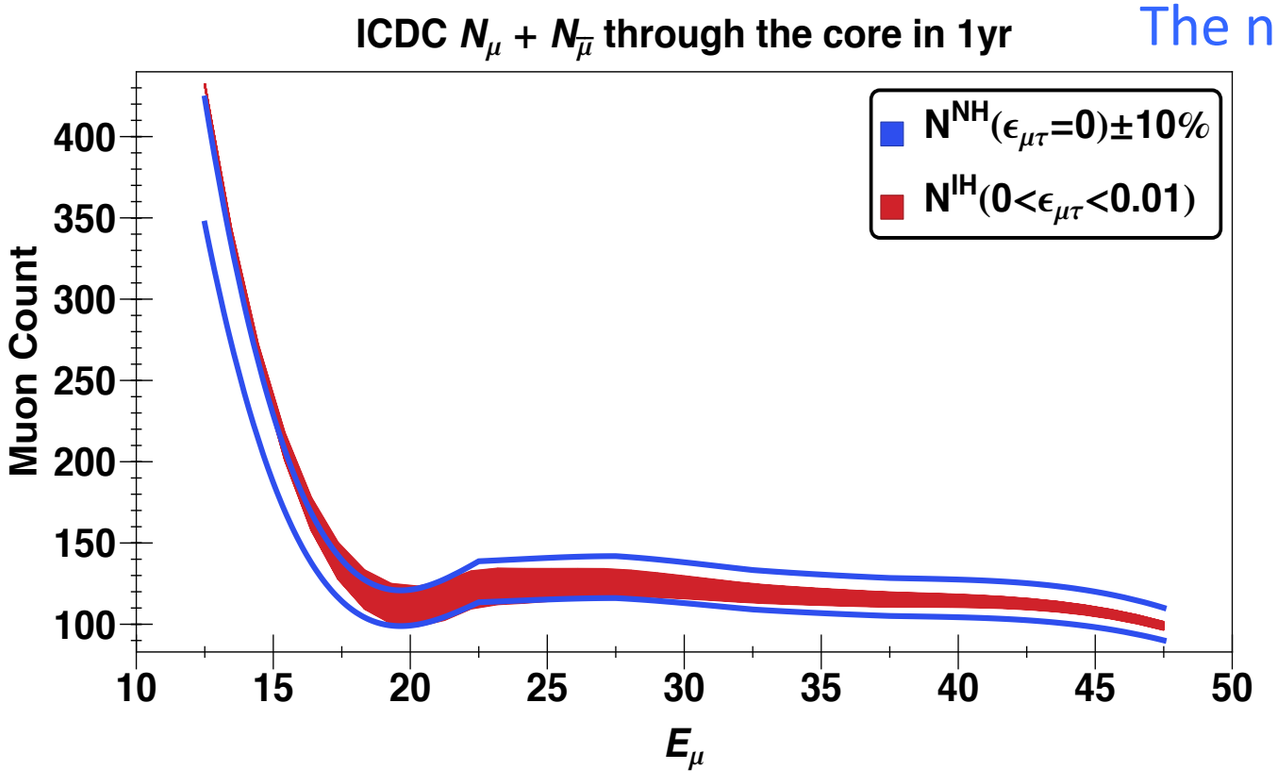
MIνER

NSI, the weak mixing angle, sterile neutrinos, electromagnetic form factors, new dark sectors, etc…

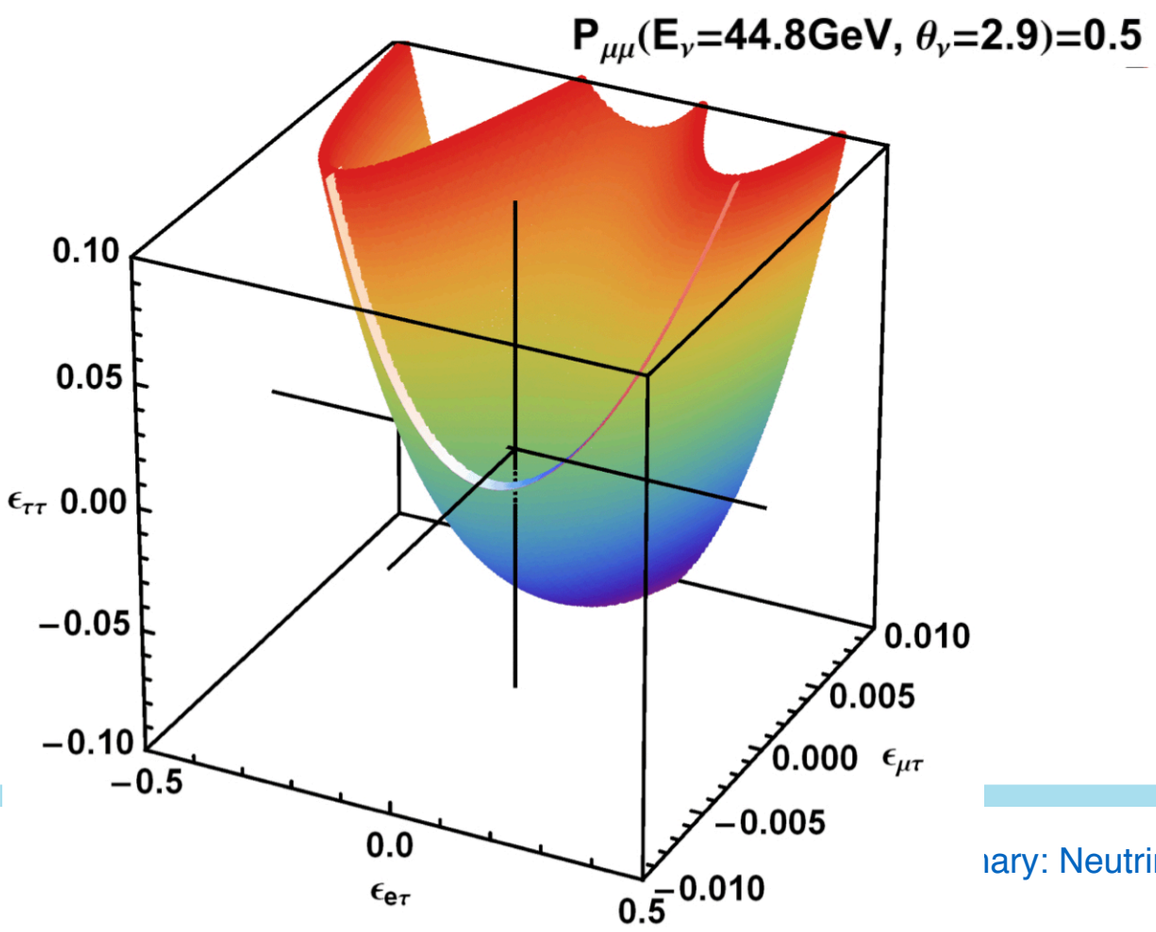
There is great physics potential

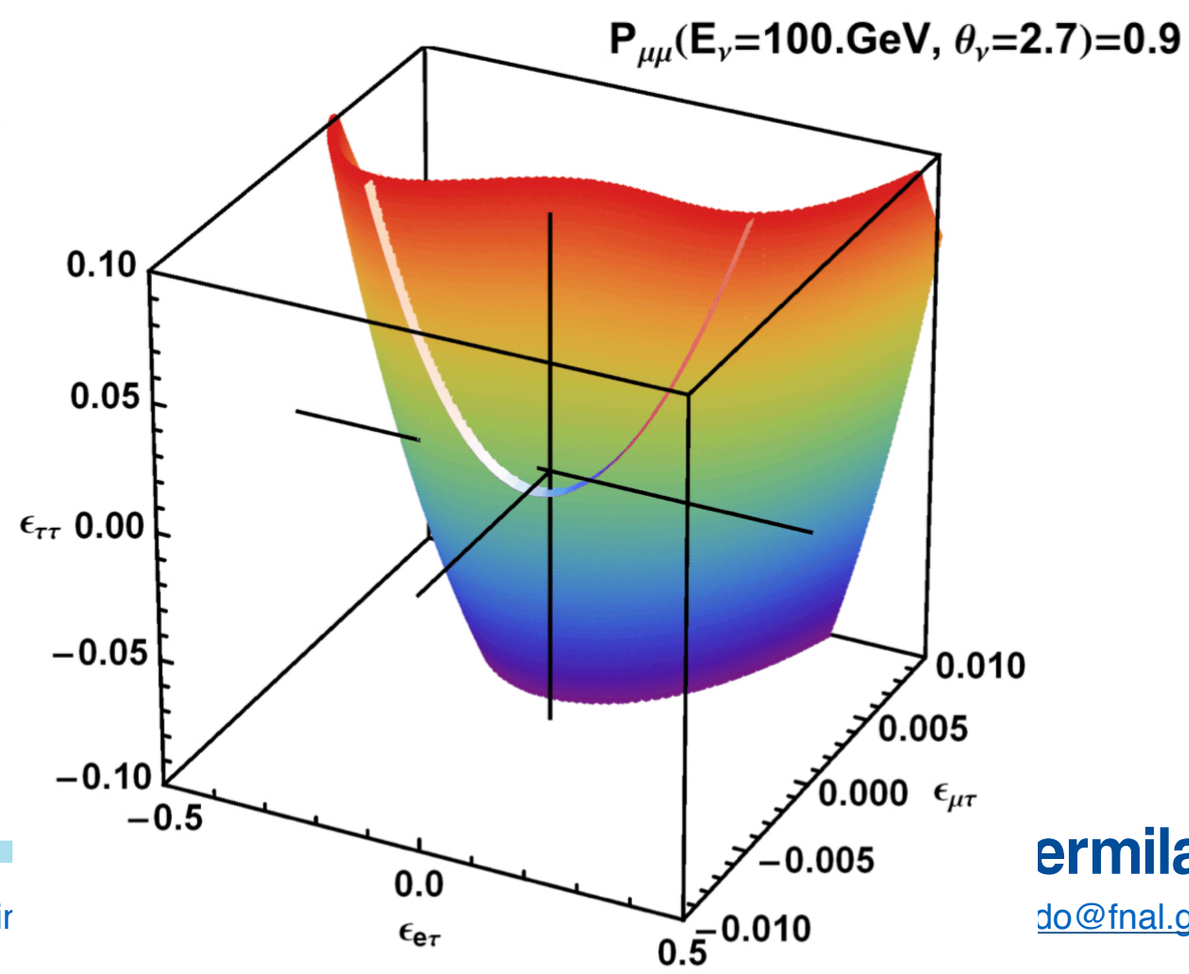
New physics in the neutrino sector

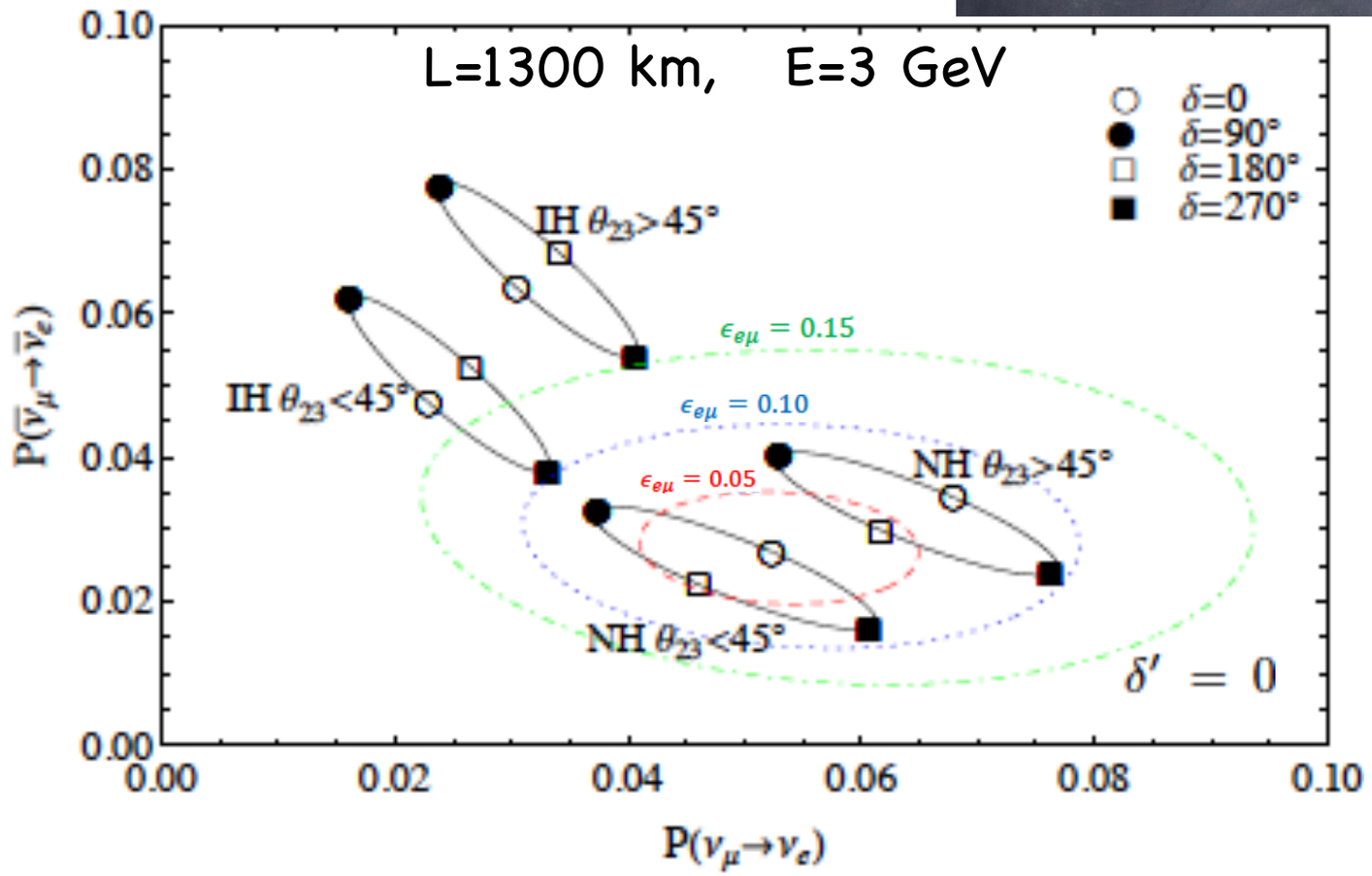
The new physics is there! (somewhere)



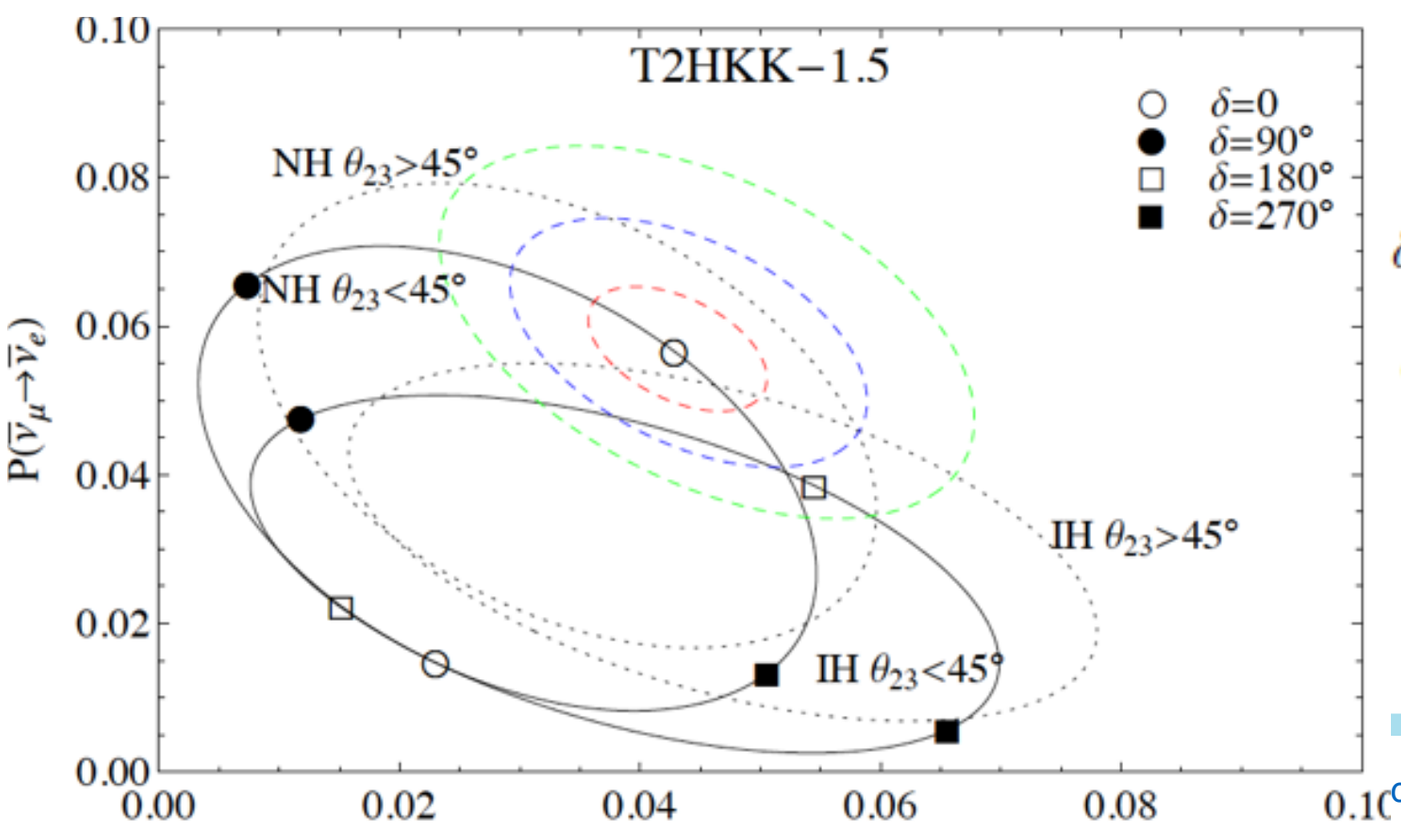
Degeneracies!
Need different energies and baselines to break them







Degeneracies!
Need different energies and baselines to break them



Degeneracy at Hamiltonian level:

$$\delta m^2_{31} \to -\delta m^2_{32}, \quad \theta_{12} \to 90^\circ - \theta_{12}, \quad \delta \to 180^\circ - \delta$$

$$\epsilon_{ee} \to -\epsilon_{ee} - 2, \quad \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \to -\epsilon_{\alpha\beta} e^{-i\phi_{\alpha\beta}} (\alpha\beta \neq ee)$$

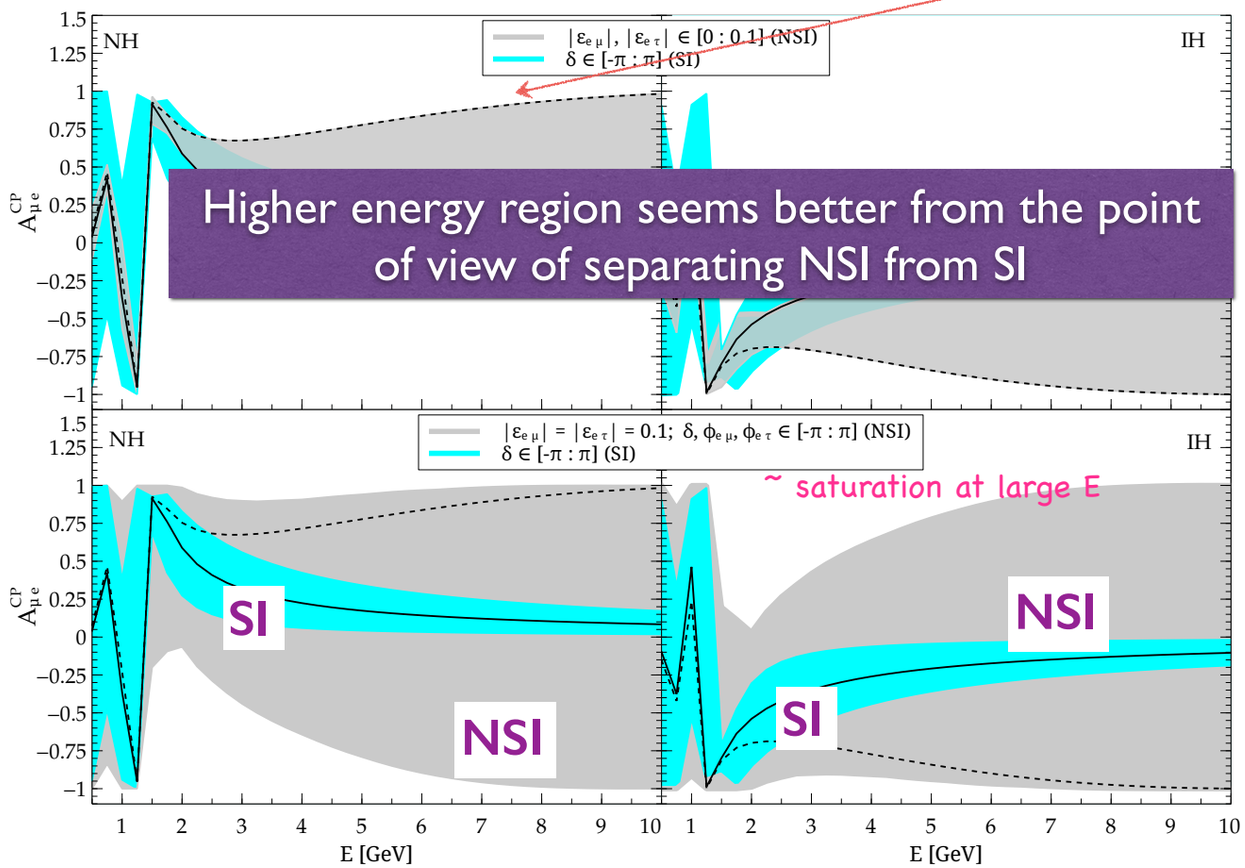
1604.05772

Extricating new physics scenarios at DUNE with high energy beams

Poonam Mehta

Large value implies new physics

CP ASYMMETRY

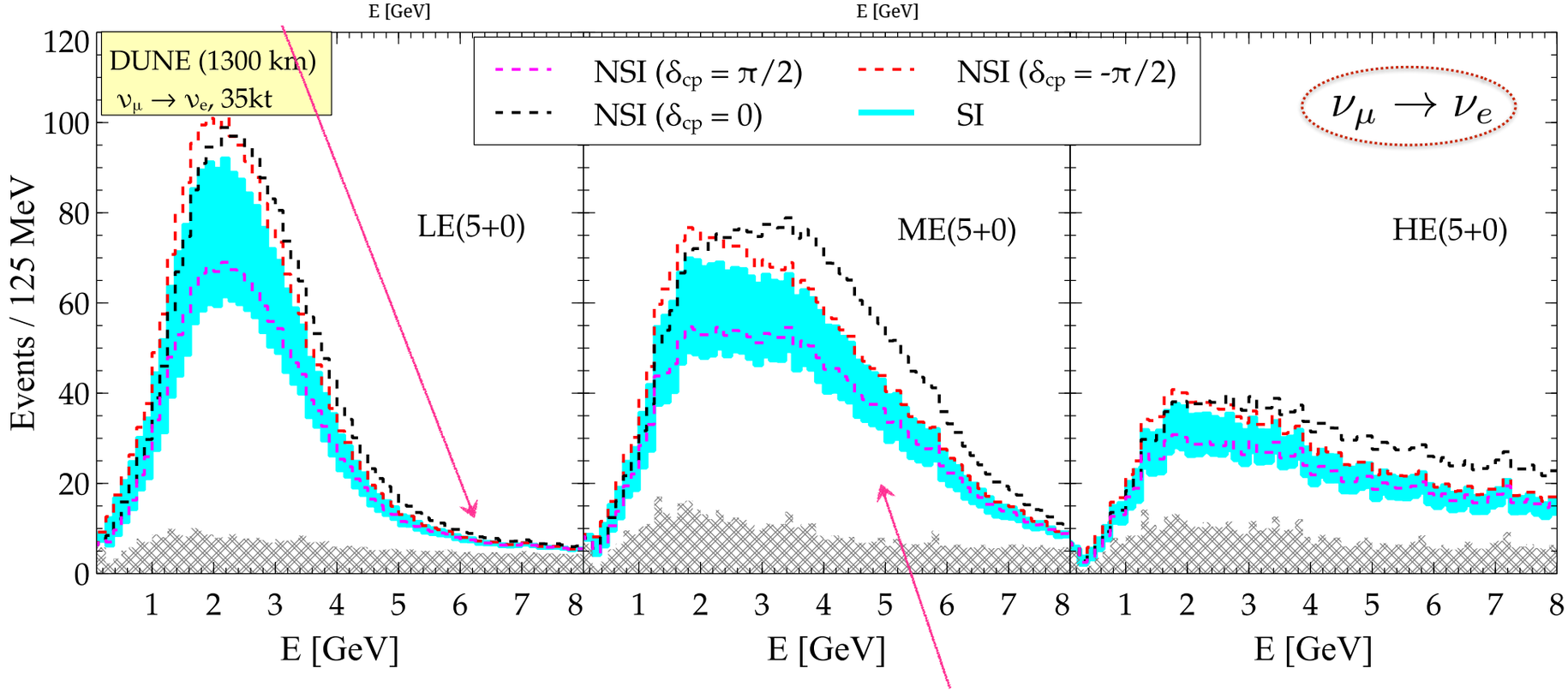


Higher energy region seems better from the point of view of separating NSI from SI

~ saturation at large E

Degeneracies!
Need different energies and baselines to break them

Run DUNE in different beam energy configuration?



Better ability to separate black curve from cyan band

Fermilab
pmachado@fnal.gov

BSM in the neutrino sector

$$\mathcal{L} = -2\sqrt{2}G_F \epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f}\gamma_\rho P f)$$

Non Standard Interactions (NSI)

Neutrino matter potential actually probes the EW symmetry breaking scale

$$V_{CC} = \sqrt{2}G_F N_e, \quad G_F = \frac{1}{\sqrt{2}v^2}$$

NSI: $2\sqrt{2}G_F \varepsilon^f_{\alpha\alpha} \left(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$ → 1% NSI translates into v' ~ 10v

few % NSI ~ TeV scale!

Fermilab
pmachado@fnal.gov

Efforts in many directions

Neutrino scattering cross sections:

Lots of progress, but still long way to go

Neutrino masses:

colliders, LFV, cosmology, neutrino scattering, …

3 neutrino paradigm:

Non-unitarity tests (model dependent and independent)

eV sterile neutrinos (UV models)

New interactions in the neutrino sector:

Degeneracies and impact on determination of oscillation parameters

New experimental signals

My personal view

Neutrinos are NOT an isolated sector of the SM

Neutrino scattering cross sections:

Necessary for precision neutrino physics

Neutrino masses:

Many connections and synergies among vastly different experiments

Broad approach is necessary!

3 neutrino paradigm:

Sterile neutrinos would be a revolution,

crucial to finally settle the LSND/reactor anomalies

New interactions in the neutrino sector:

Can neutrino experiments probe *"reasonable"* new physics?

UV complete models to be able to compare with other experiments

Coherent neutrino scattering will be a precious tool