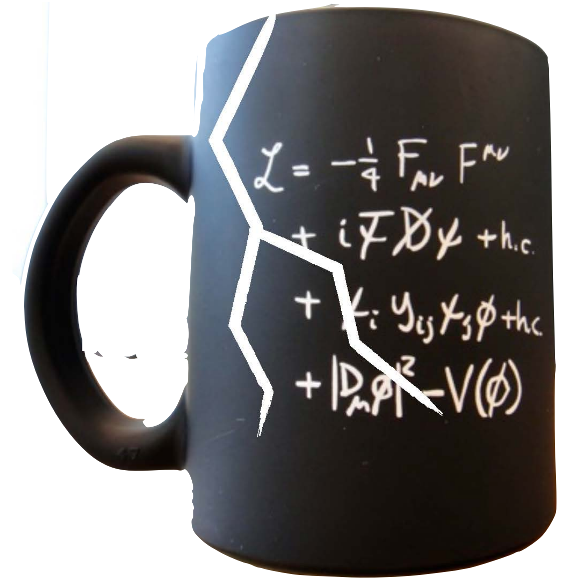


Beyond the Standard Model Physics TDR Discussion

Alex Sousa and Jaehoon Yu
for the BSM Physics Working Group

DUNE Conveners Meeting
Dec. 13, 2016

BSM Physics WG Scope and Goals

- **Enrich DUNE Physics case by studying sensitivities to a wide variety of non-Standard Model phenomena**
  - Looking into both Two-Detector and ND-only topics
  - Explore high-intensity beam, large FD detector mass, and high resolution of both ND and FD
  - Collaborate with Long-Baseline Physics group on topics that may affect standard oscillation measurements
- **Develop code framework to carry out these studies and provide tools for others to test new ideas/models**
- **Inform beamline and/or detector design by reporting how sensitivities are modified by different designs or potential enhancements**
- **Contribute to physics capabilities section of DUNE TDR by FY19**

CDR Table of Contents - DocDB-181

DUNE BSM Physics WG

BSM Physics TDR Proposal

- **Ch. 3: "Long-Baseline Neutrino Oscillation Physics"** remains, but **Sec. 3.8: "Testing the 3-flavor paradigm(…)"** is removed
- **Sec. 6.5: "New Physics Searches"** of **Ch.6: "Near Detector Physics"** removed
- **New Chapter: "Beyond the Standard Model Physics Searches"**
  - **Sec.: "Long-Baseline Searches"**
    - **SubSec.** for each item
  - **Sec.: "Near Detector Searches"**
    - **SubSec.** for each item
  - **Sec.: "Beam and Detector Requirements"** (if any)
    - **SubSec.** for Beam
    - **SubSec.** for Far Detector
    - **SubSec.** for Near Detector
  - **Sec.: "Potential Impact of New Physics on Neutrino Oscillation Measurements"**

LBL (FD+ND) BSM Physics Topics

- **Light Sterile Neutrinos**
  - L/E plots using DUNE/LBNF fluxes (AS), sensitivities from Phenomenology/Theory groups (e.g. André de G. et al.). Exercise GloBES framework and interface with official DetSim, include reco inefficiencies, and include effects of syst. uncertainties.
- **Large Extra Dimensions**
  - MINOS-based model ported to GloBES framework (Animesh C. and Simon DeR.), able to reproduce probabilities, sensitivities with DUNE/LBNF fluxes next.
- **Non-Standard Interactions**
  - Large amount of interest from Pheno/Theory groups (Brazil, China, Colombia, Fermilab, Spain), including NC and CC NSI, and non-unitarity models. NC NSI model ported to GLoBES (Animesh C.), preliminary sensitivities produced.
- **Boosted Dark Matter**
  - DM interactions with relativistic particles in final state. Interest from Yue Zhao and collaborators (U. Michigan), Yanou Cui (UC Riverside), and Yun-Tse Tsai (SLAC). Incorporating Boosted DM models in GENIE. Need to understand low-energy tracking efficiencies and backgrounds
- **Lorentz Violation, CPT Violation -** Not started (interest from Kostelecky group)

SBL (ND-only) BSM Physics Topics

- **Light Dark Matter**
  - Studying optimized configuration of ND and sensitivities with ND reference and Ar designs (Garret B., Animesh C., and Jae Y.). Have LDM MC generator need to interface with DUNE simulation, produce realistic sensitivities as a function of LDM mass

- **Heavy Neutral Leptons**
  - Closely following work being done for NOvA (Athans H., Sergey K. Filip J., and Biao W.). Currently working on generating simulated sample of HNL signals to understand EM signal efficiency. Comparisons between DUNE, NOvA, and ShiP will follow

- **Neutrino Tridents**
  - Sensitive to SM process, which is enhanced in presence of BSM Z'. Computed expected rates using LBNF/DUNE ND flux (Stefania G., Wolfgang A., and AS). Creating C++ MC generator to be interfaced with DUNE simulation. Need BG studies with existing DUNE files to understand feasibility (π vs. μ separation crucial).

- **Sterile-driven ν_e, ν_τ Appearance**
  - Same L/E plots can be generated to show how 3-flavor oscillation probabilities change in the presence of sterile mixing. Can in principle use GloBE framework to produce sensitivities

BSM Physics Milestones in Sept.

- End of 2016: Complete the initial list of topics and people
  - Will review the overall BSM tasks at the CERN meeting
  - Clearly identify existing MC tools and the needs for missing tools
  - Include completed initial studies on sensitivities on various topics
  - Assess necessary detector enhancement and potential measurements at PtotoDUNE
- May 1, 2017: Complete more systematic discovery potential and sensitivity studies and determine further studies necessary
  - Must include design limitations vs impact to physics
- Jan. 1, 2018: Identify missing elements for TDR
- July 1, 2018: Complete the missing studies

J. Yu, U. Texas at Arlington

Sept. 15, 2016

- Will have a BSM Sub-Group leaders meeting Tuesday, Dec. 20, to take stock of progress in different topics, and refine and adjust milestones above
  - Will need to attract more people within DUNE, if the above is to be realized

Backup

What LBL Expts. and Others Measure

- Different experiments are sensitive to different angles (3+1 model)
  - Reactor experiments ($\bar{\nu}_e$ disappearance): θ_{14}

$$P_{ee} \approx 1 - 2\sin^2 2\theta_{14} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \qquad |U_{e4}|^2$$

  - MiniBooNE, LSND, and KARMEN, T2K ND (ν_e, $\bar{\nu}_e$ appearance): θ_{14}, θ_{24}

$$P_{\mu e} \approx 2\sin^2 2\theta_{14} \sin^2 \theta_{24} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \qquad 4|U_{e4}|^2|U_{\mu 4}|^2$$

  - MiniBooNE, CDHS, CCFR (ν_μ, $\bar{\nu}_\mu$ disappearance): θ_{24}

$$P_{\mu\mu} \approx 1 - 2\sin^2 2\theta_{24} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \qquad |U_{\mu 4}|^2$$

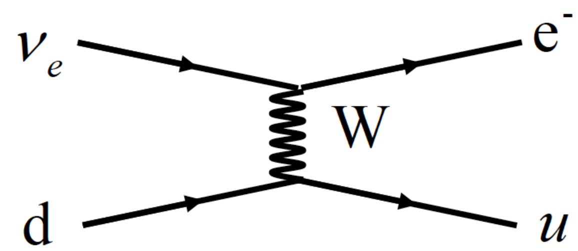
  - MINOS/MINOS+, SuperK, NOvA, DUNE (ν_μ, $\bar{\nu}_\mu$ disappearance and NC): θ_{24}, θ_{34}

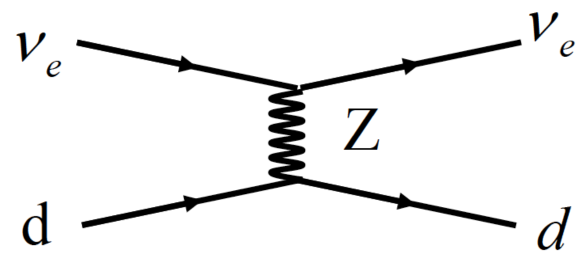
$$1 - P_{\mu s} \approx \cos^2 \theta_{24} \sin^2 \theta_{34} \times \sin^2 \frac{\Delta m^2_{41} L}{E} \sin^2 \frac{\Delta m^2_{31} L}{E} \qquad |U_{\mu 4}|^2,\ |U_{\tau 4}|^2$$

Non-Standard Interactions

Célio Moura

- In the Standard Model,





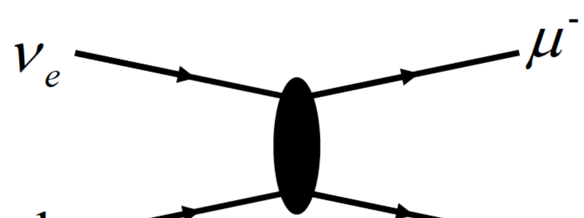
$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f')$$

$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\alpha)(\bar{f}\gamma_\mu P_L f')$$

- Focusing on ability to constrain NC NSI parameters

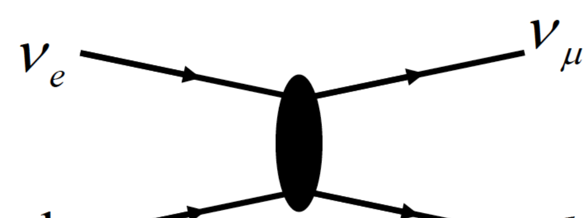
- With new physics, we could have

$$\mathcal{L}_{CC} = (\overline{\ell_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$



CC NSI
production, detection

$$\mathcal{L}_{NC} = (\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_{L,R} f')$$

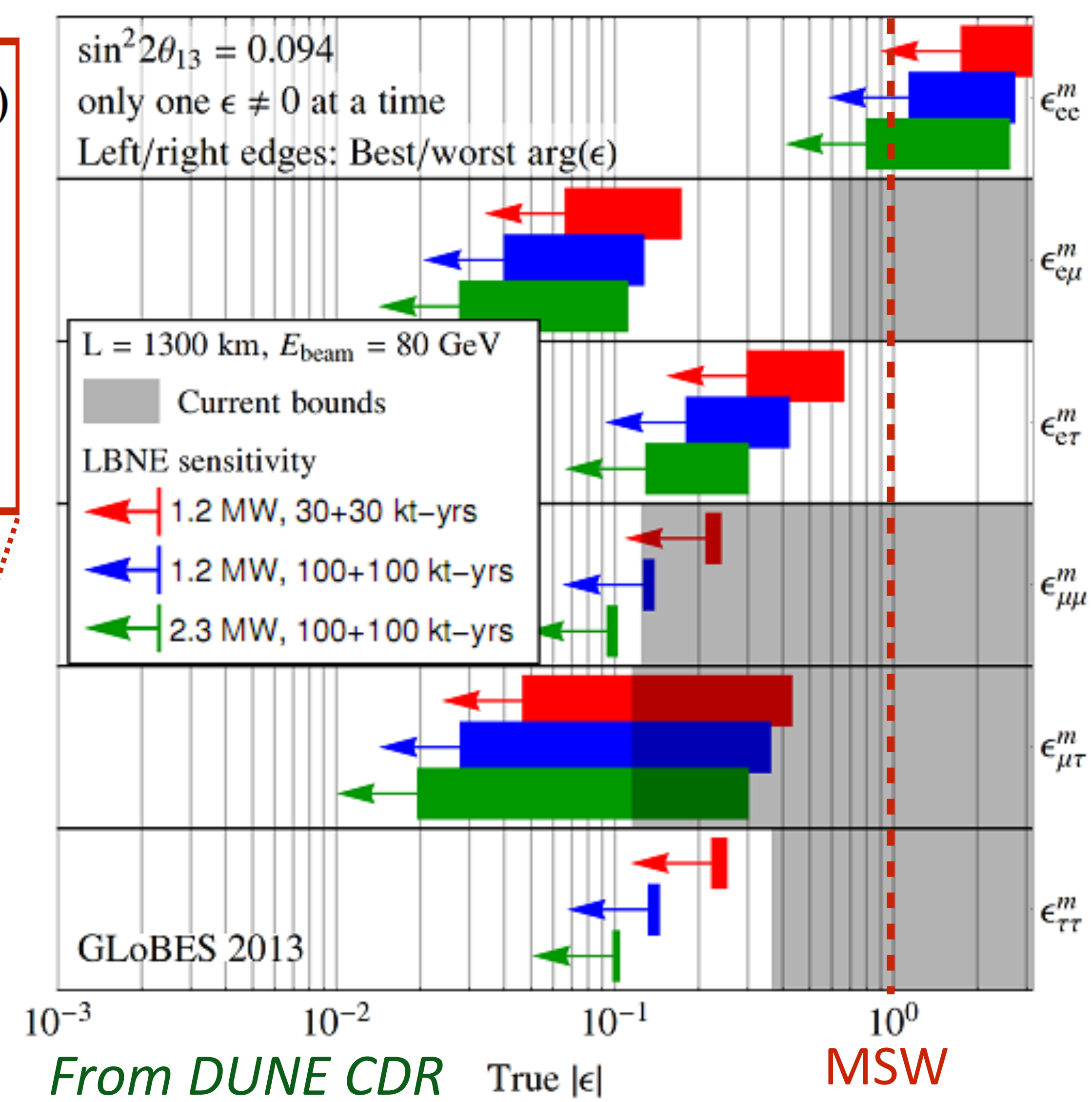


NC NSI
propagation

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\rm MSW}$$

$$\tilde{V}_{\rm MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

NC NSI discovery reach (3σ C.L.)

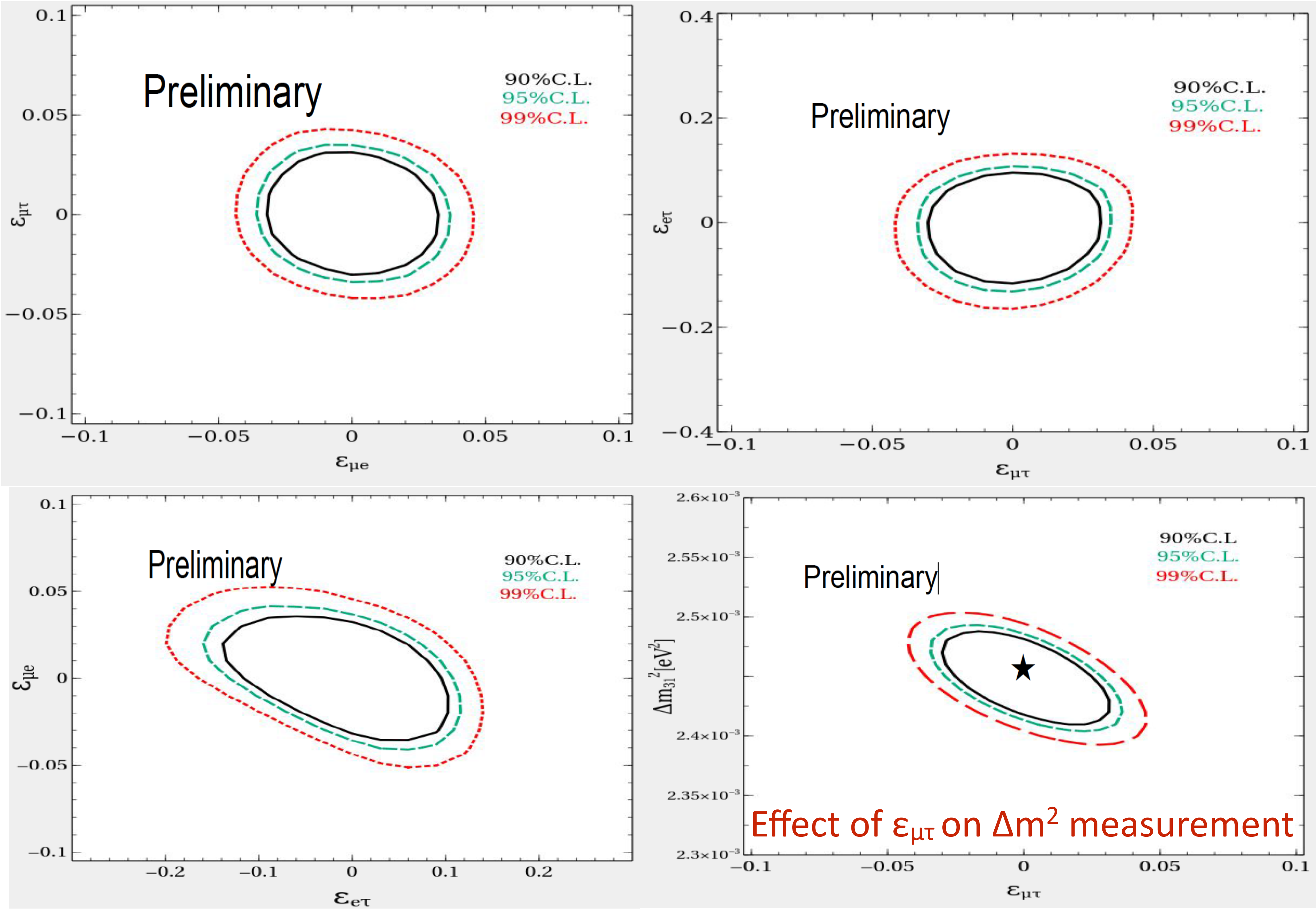


From DUNE CDR

Preliminary NSI Results

- Using BSM code framework (more later), Animesh produced preliminary sensitivities

Animesh Chatterjee



DUNE constraints on NSI parameters more stringent when compared to current results (arXiv:1307.3092).

- DUNE NSI measurements should help resolve ambiguities with mass hierarchy, octant, and CP
  - *e.g.* Coloma, Schwetz, *arXiv:1604.05772*; Masud, Mehta, *arXiv:1603.01380*

Non-Unitary Mixing

Omar Miranda
Mariam Tórtola

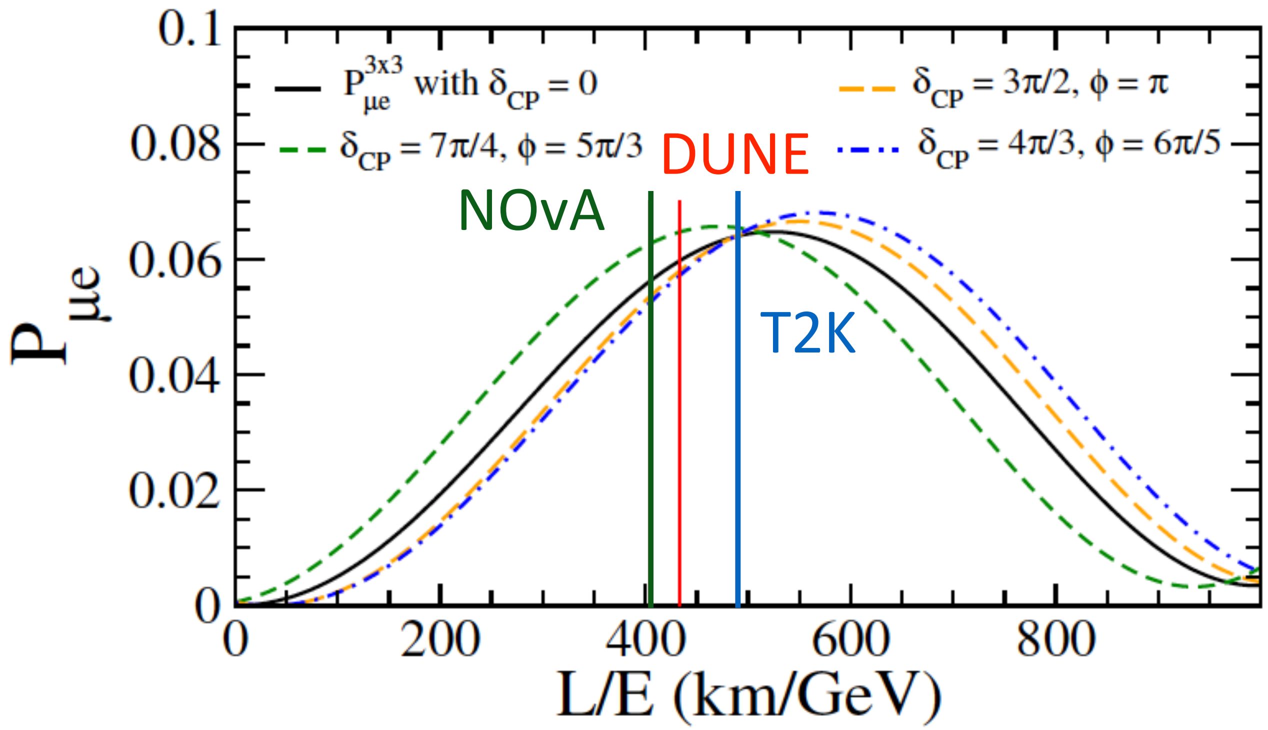
- If neutrinos acquire mass through (type I) seesaw mechanism, extra heavy state(s) mean mixing matrix need not be unitary

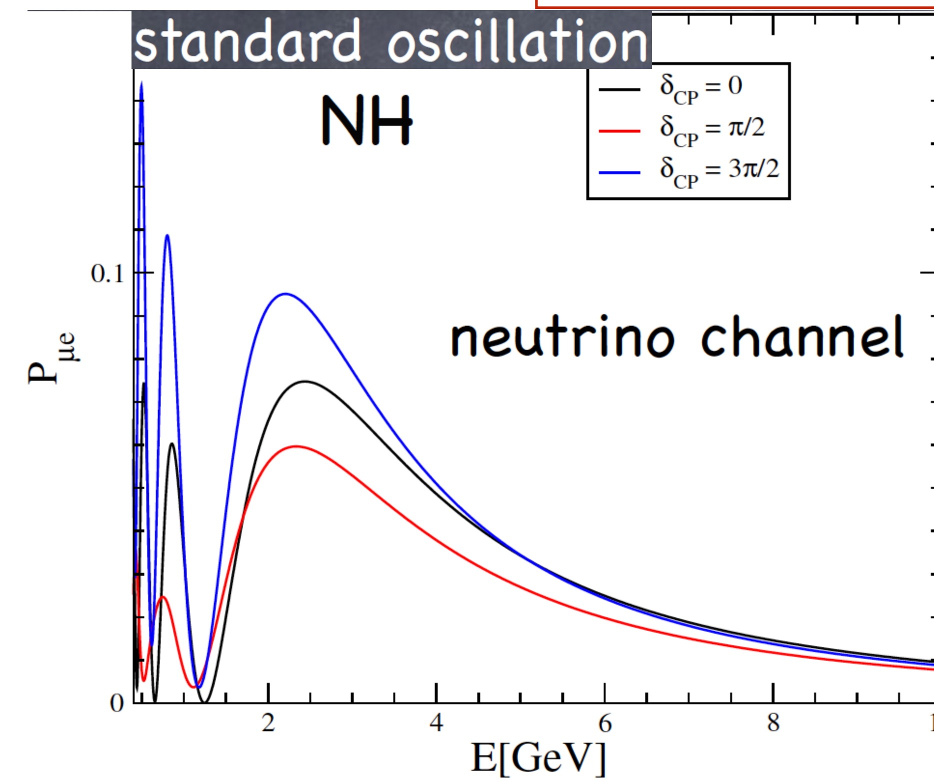
$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times3}$$

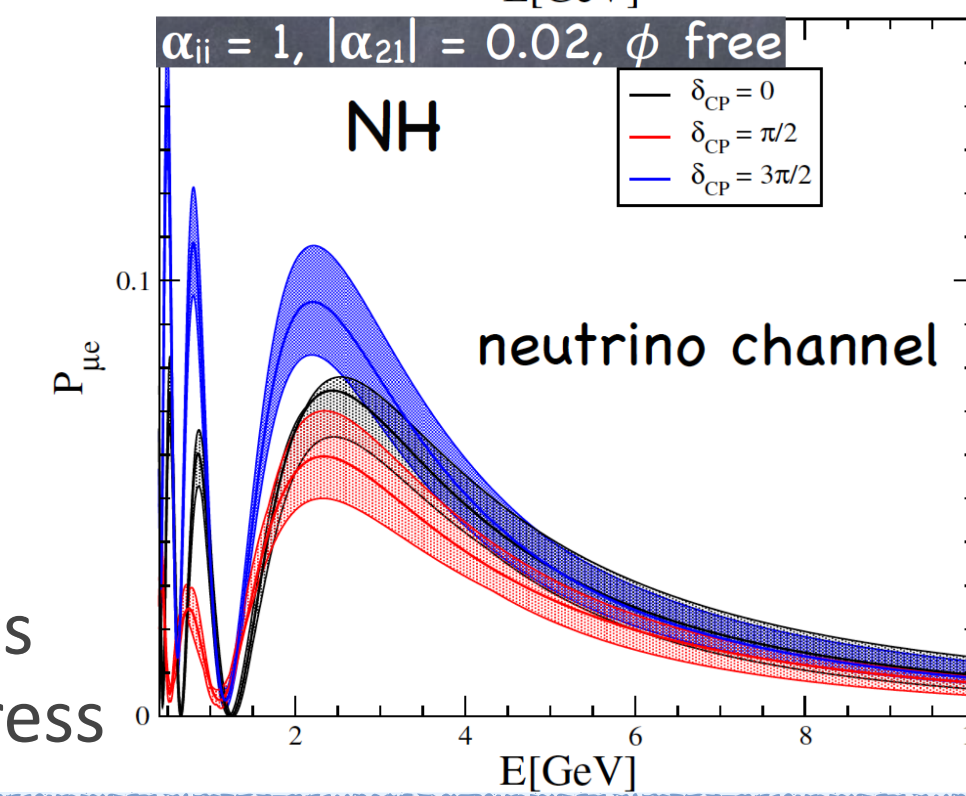
Miranda, Tórtola, Valle, arXiv:1604.05690

- $P_{\mu e}$ then depends on new parameters

$$\alpha_{11} \quad \alpha_{22} \quad |\alpha_{21}| \qquad \phi = \phi_{12} - \mathrm{Arg}(\alpha_{21})$$







- DUNE requires analysis of NU with matter effects
- Full simulation of DUNE with NU mixing in progress

Non-Standard Interactions

Célio Moura

- NSI Sub-Group holds satellite meeting and summarizes them at BSM Physics WG meetings
- Large number of expressions of interest

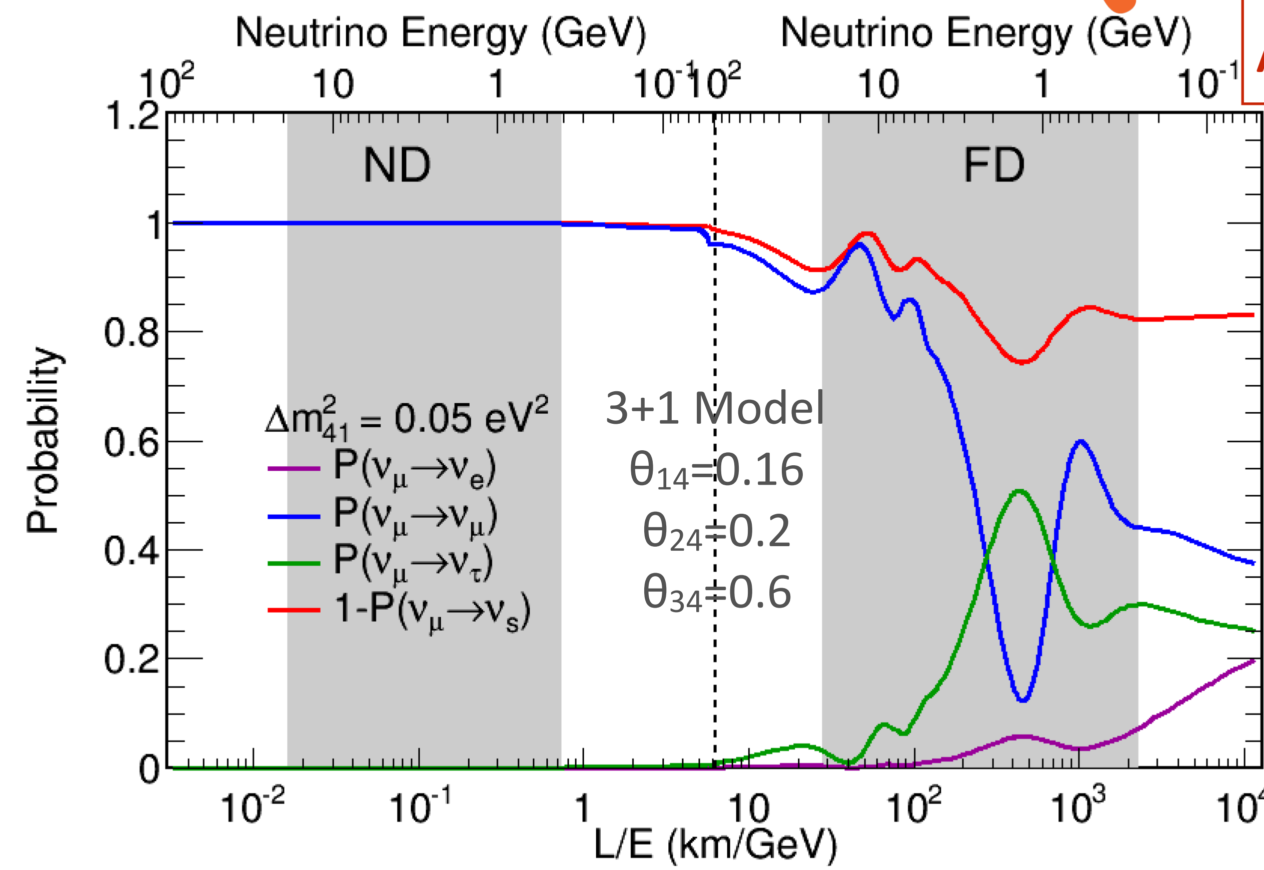
  - Omar Miranda (Cinvestav – Mexico); Mariam Tortola (IFIC – Spain) → **Non-Unitarity**
  - D.Aristizabal (moving to Chile) and A.Bhattacharya (Univ. Liege – Belgium) → **μ-τ neutrino oscillation interplay with IceCube Deepcore**
  - A.Chatterjee (UTA – USA) → **Computing Tools**
  - M.Guzzo, F.Rossi-Torres, C.Moura (Gefan – UNICAMP – Brazil) → **Matter density variation effects on NSI**
  - A.Khan ("JUNO" - China)
  - O.Zapata and D.Restrepo (Univ. de Antioquia - Colombia)
  - A.Gago and M.Delgado (PUC – Peru)

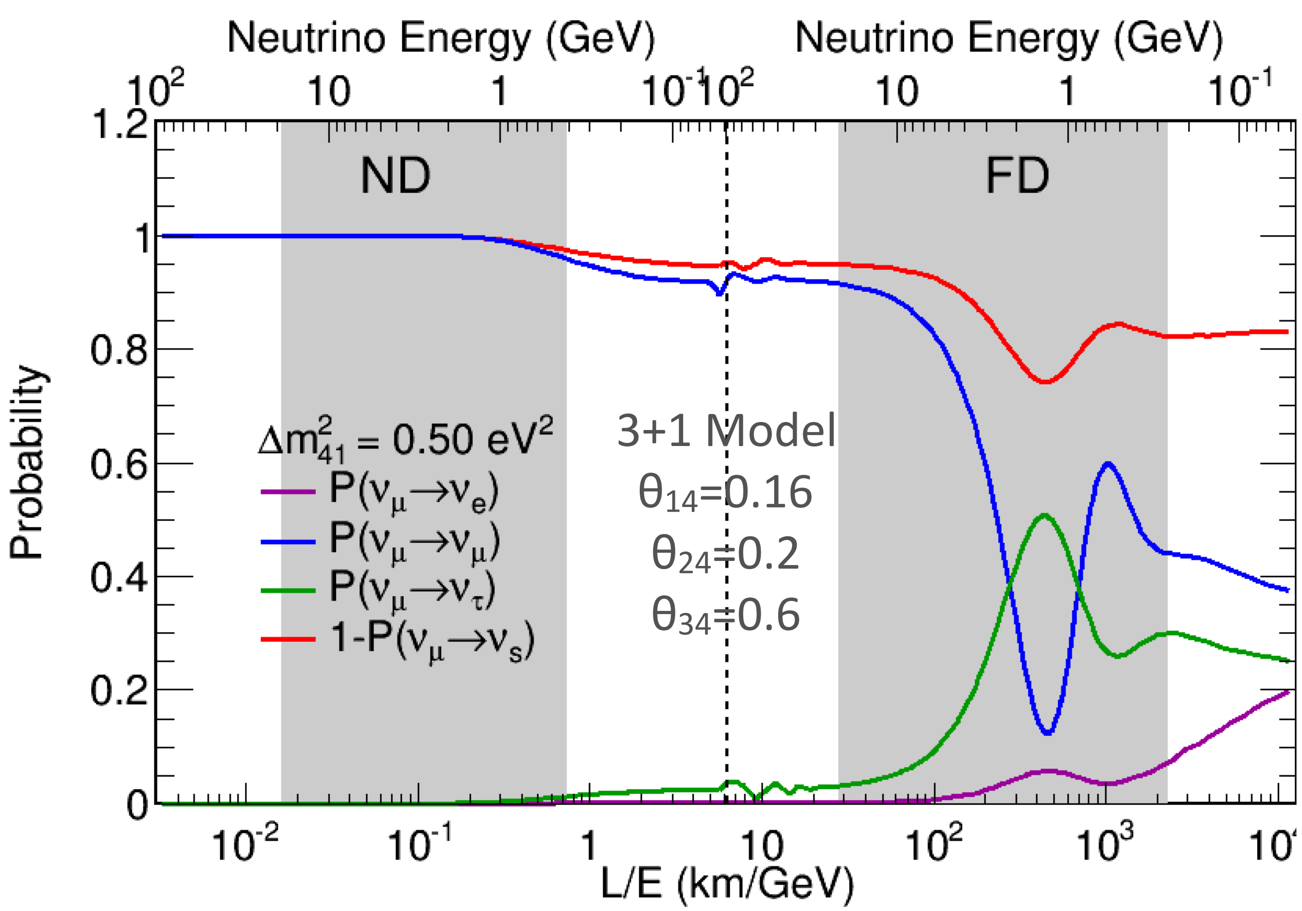
- Also contributed in NSI meetings: Pilar Coloma (FNAL), Mary Bishai (BNL), and André de Gouvêa (Northwestern)

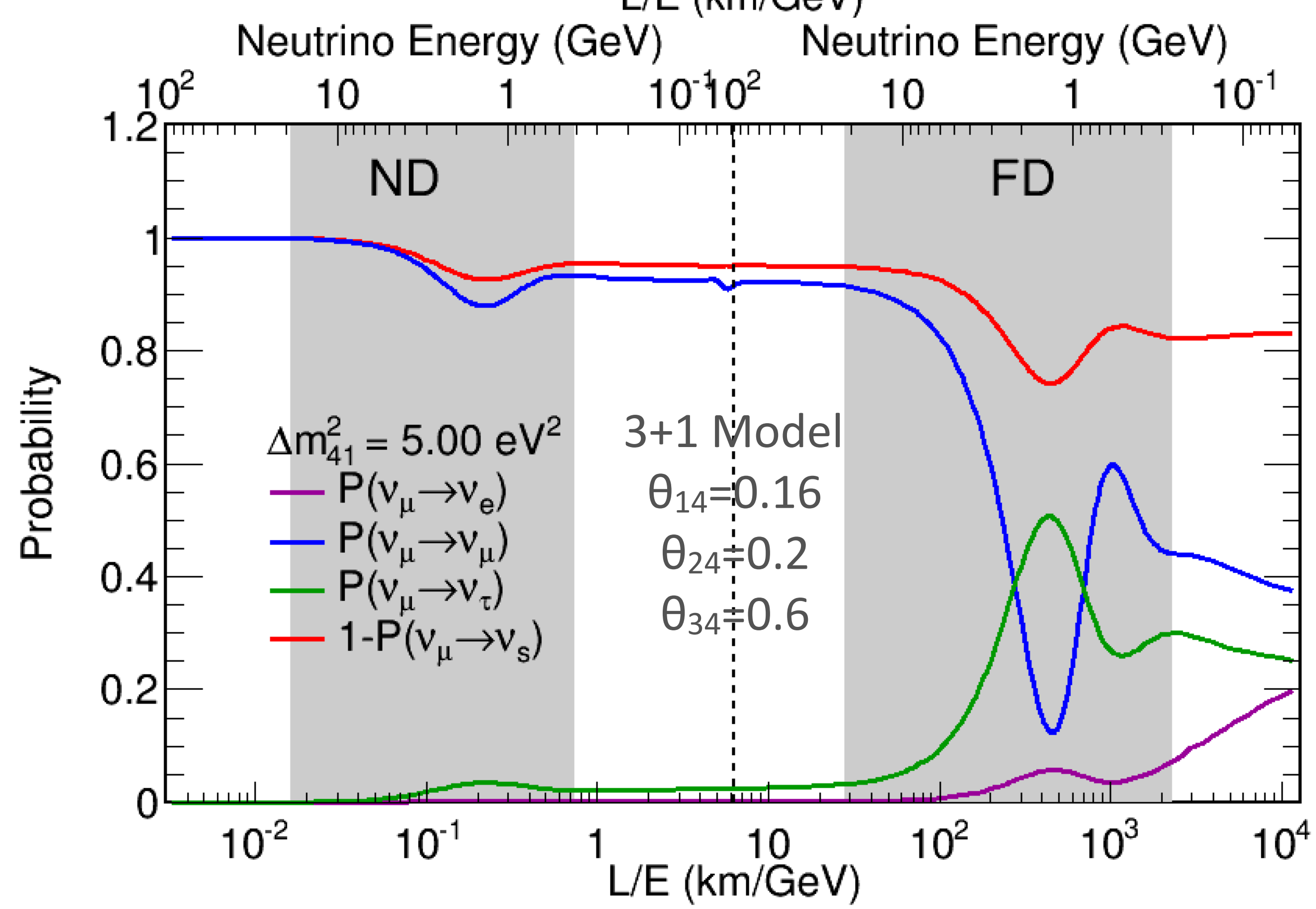
Sterile Neutrinos

AS

- DUNE should have powerful sensitivity to sterile mixing:
  - **Look for CC and NC disappearance between ND and FD** (also anomalous ν_e appearance like ICARUS and OPERA)
  - SuperK and IceCube type of searches using FD's atmospheric sample
  - Should also have sensitivity to SBL ν_e appearance at the ND



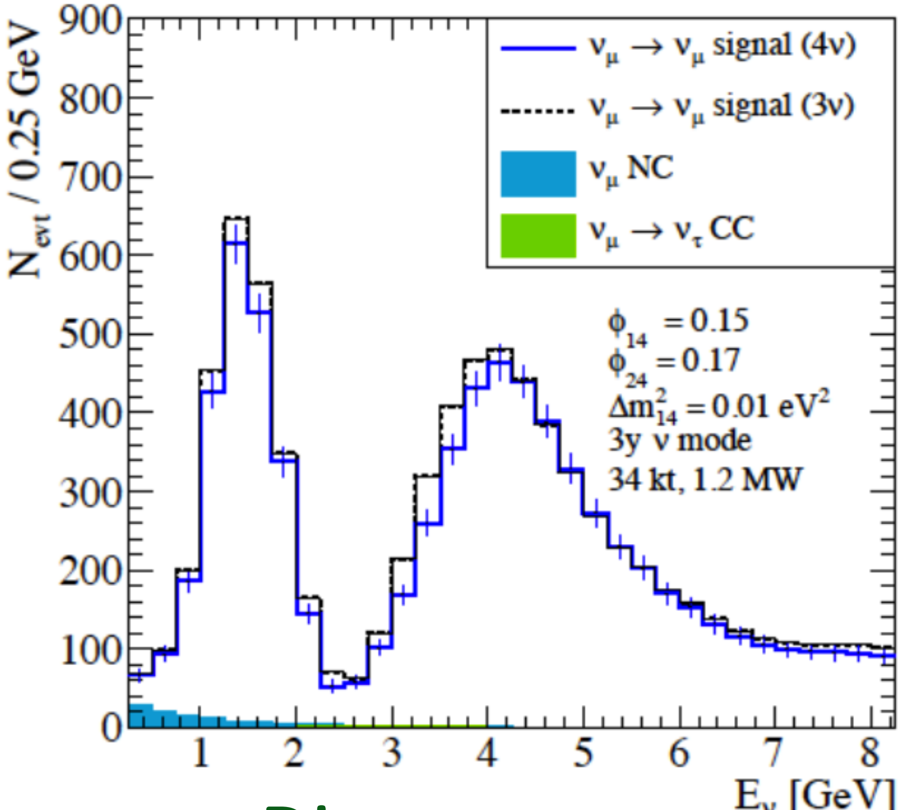


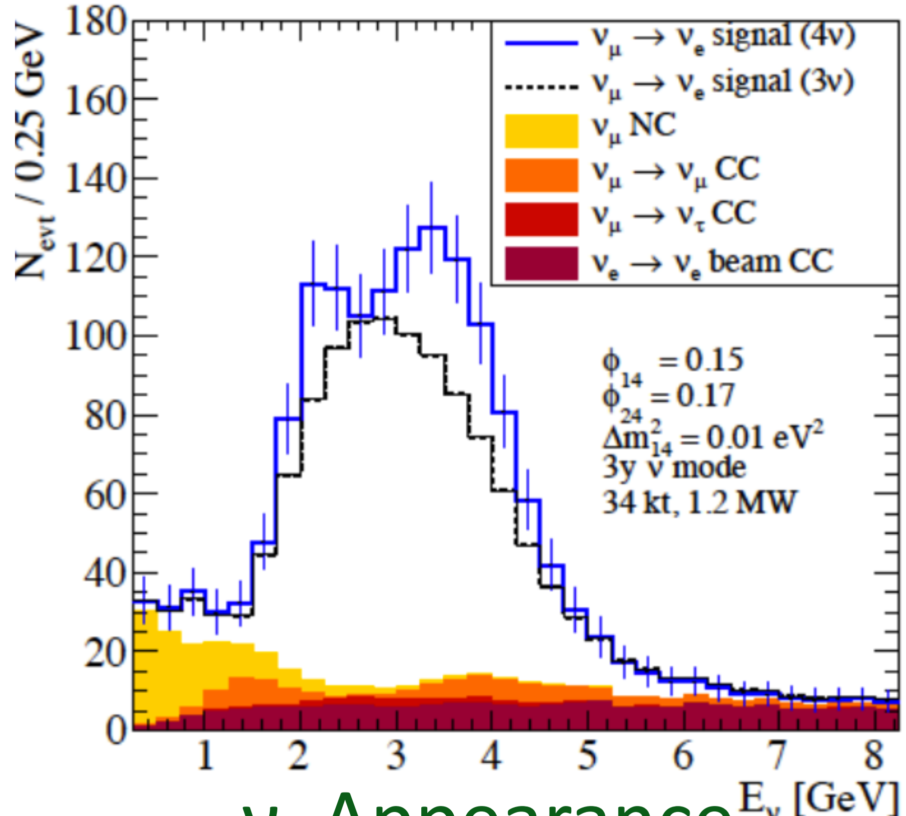


Sterile Neutrinos

André de Gouvêa

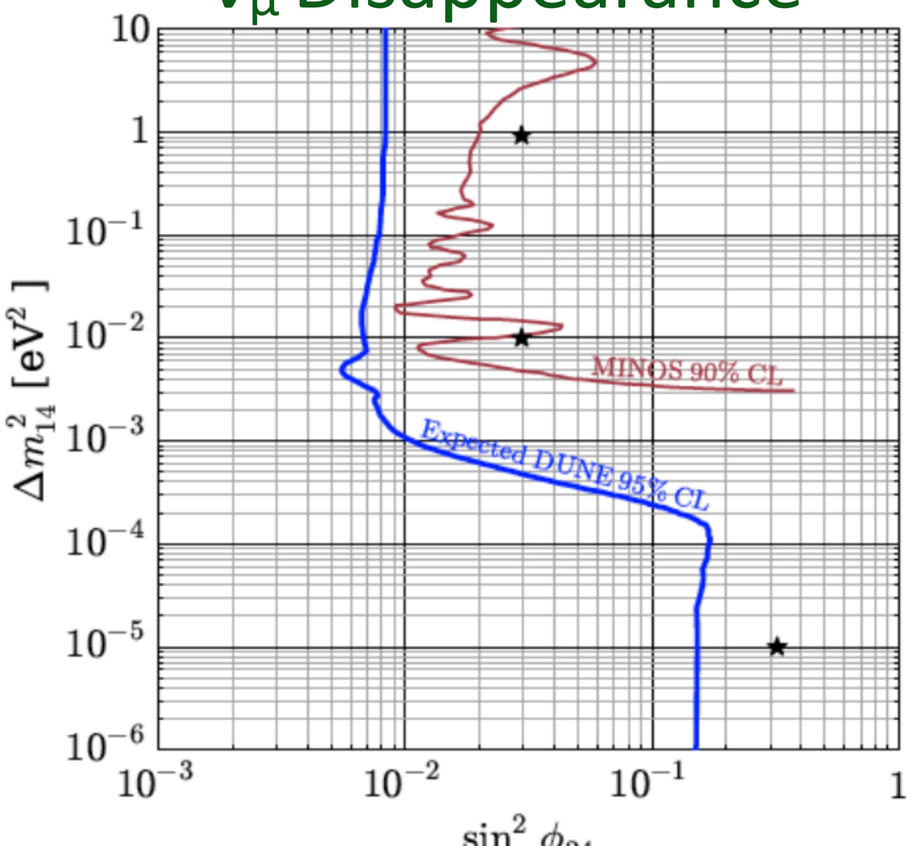
[Berryman et al, arXiv:1507.03986]



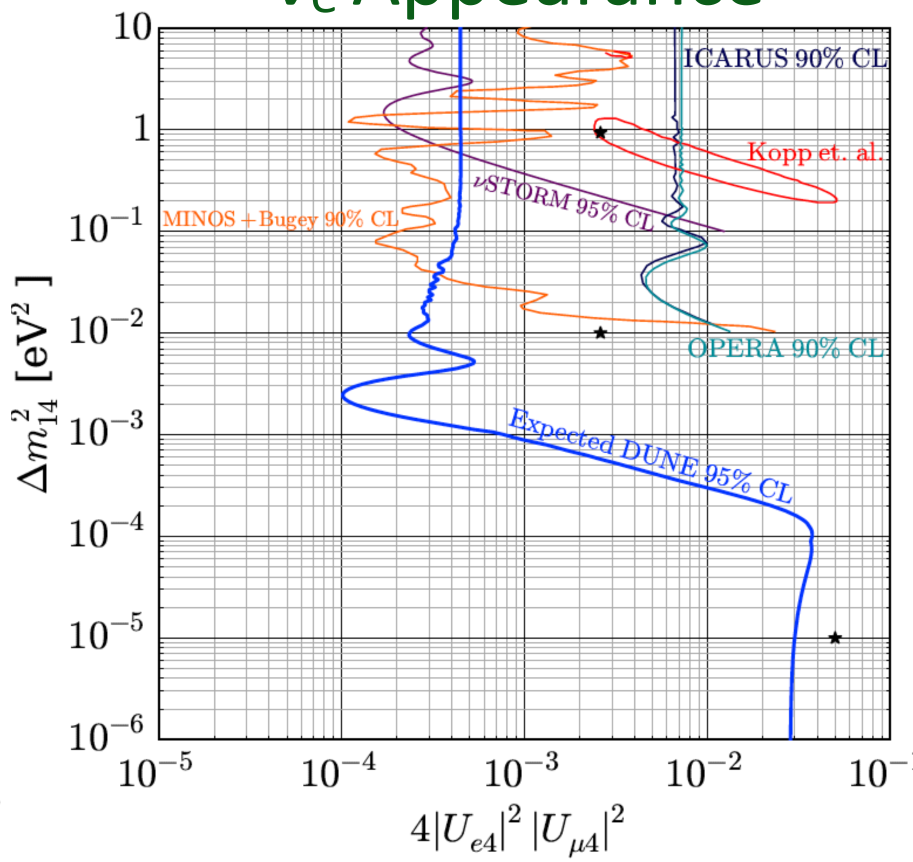


- Immediate Plans
  - Compute sensitivities using BSM framework
  - Start incorporating det. efficiencies, backgrounds, systs.

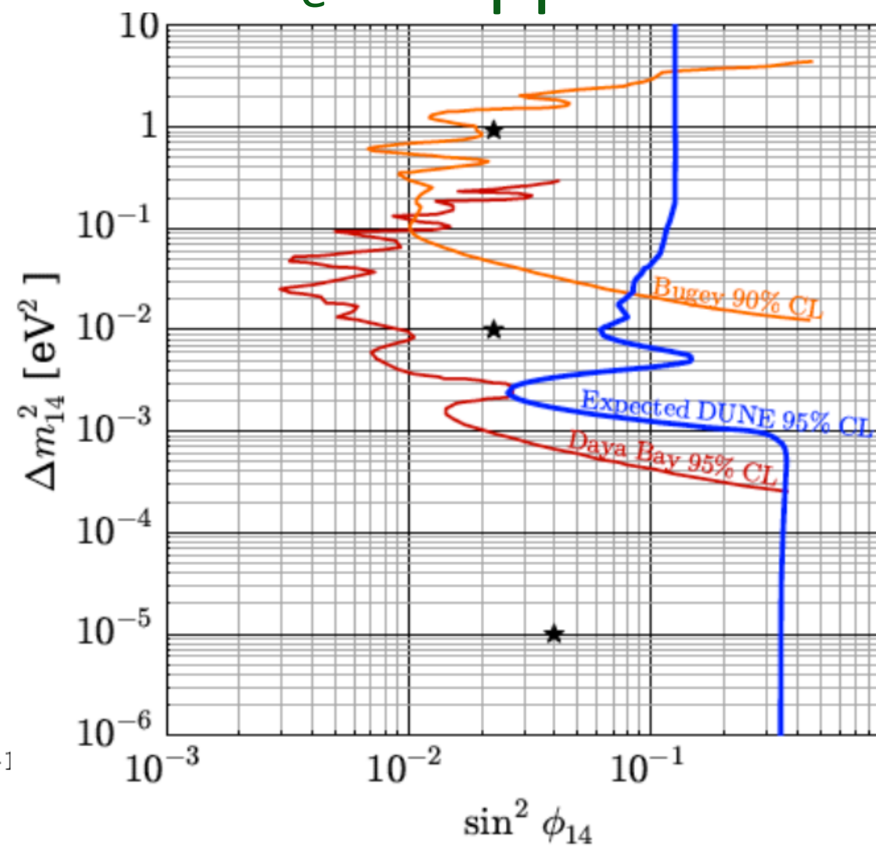
ν_μ Disappearance



ν_e Appearance



ν_e Disappearance



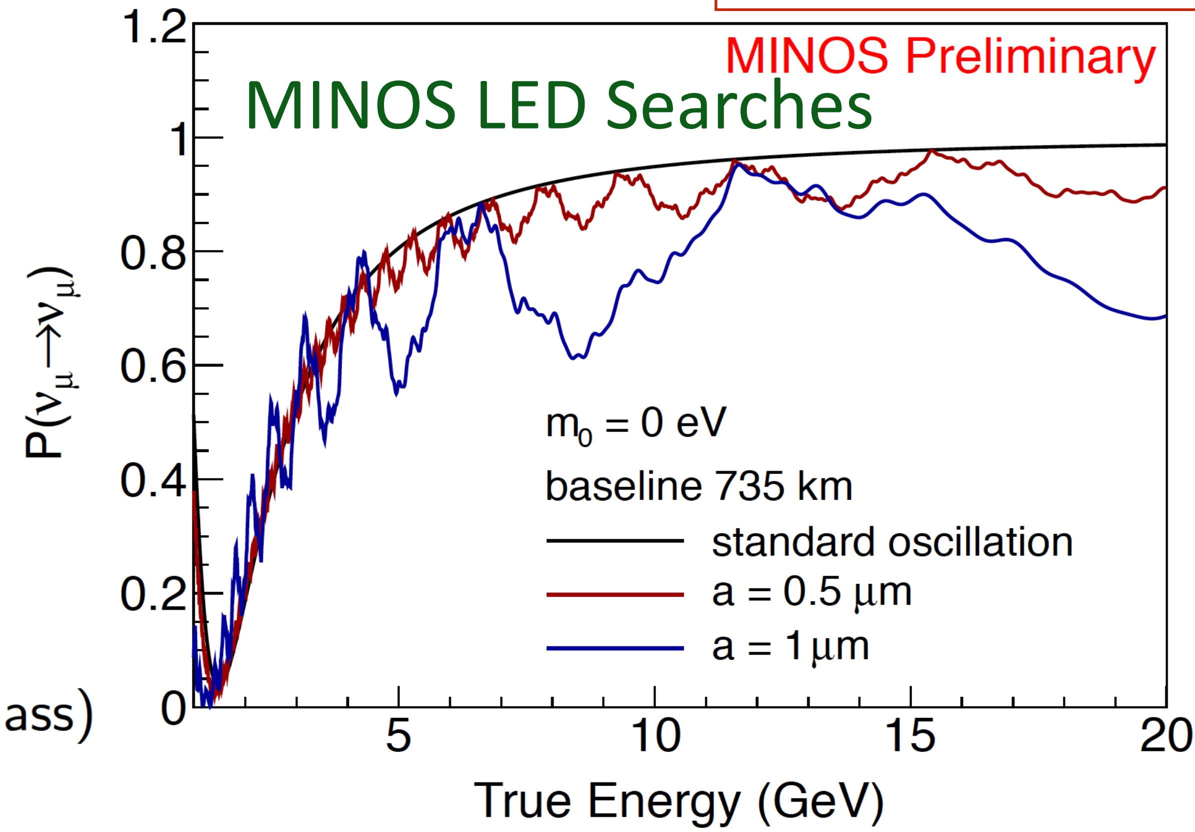
- Note: Disentangling ν_s from NSI may require multiple expts. [AdG and Kelly, arXiv:1511.05562]

Large Extra-Dimensions

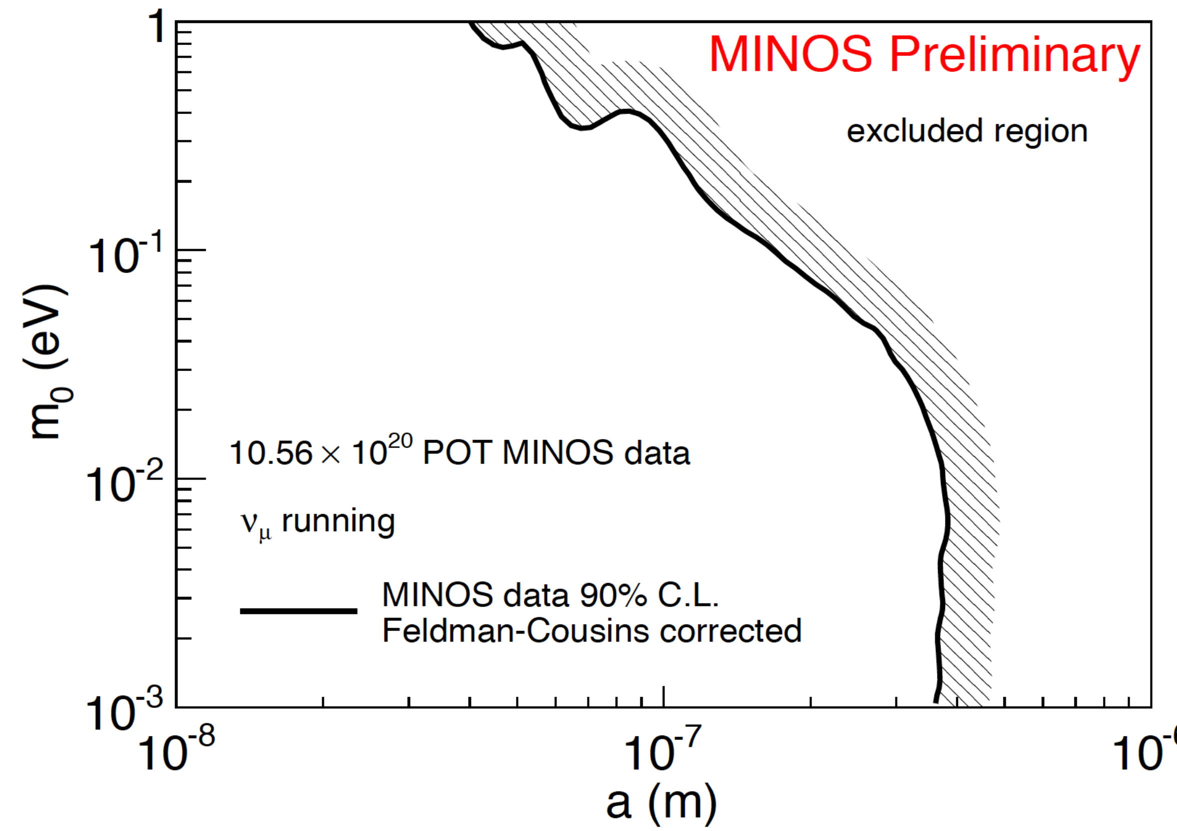
Simon De Rijck, AS

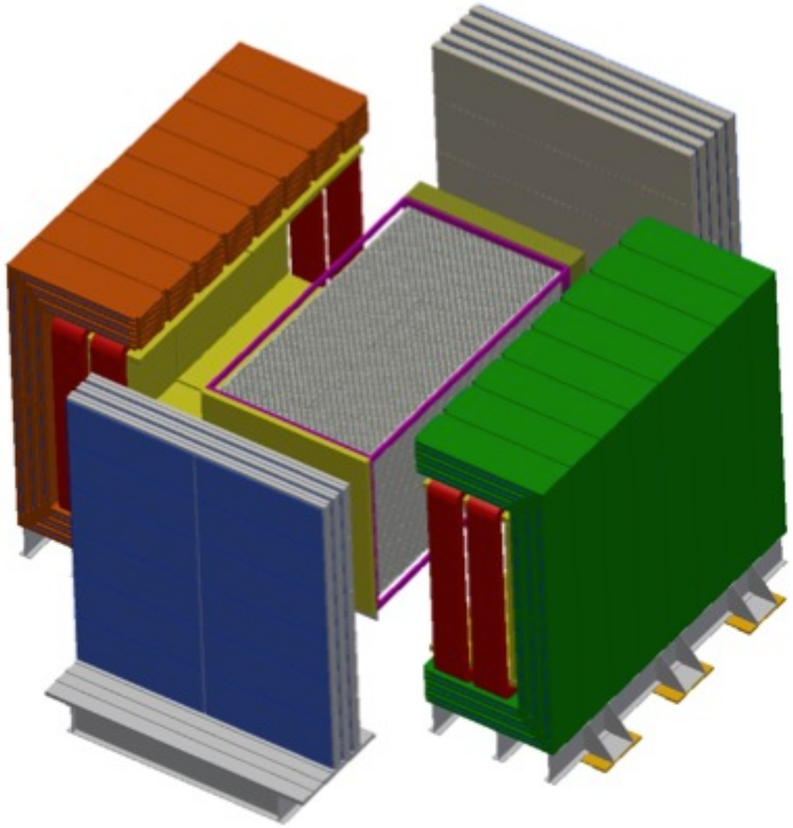
- For model by Arkani-Hamed, Dimopolous and Dvali [Phys.Lett. B **429**, 263-272 (1998)], assuming one large extra-dimension (LED) in the *bulk*, Kaluza-Klein (KK) modes in 3+1 *brane* behave like sterile neutrinos
  - **Can reuse the sterile neutrino mixing framework with LED model**

- Extra model parameters: a and m_0 (smallest neutrino mass)
  - NH: $m_3 > m_2 > m_1 \equiv m_0$
  - IH: $m_2 > m_1 > m_3 \equiv m_0$

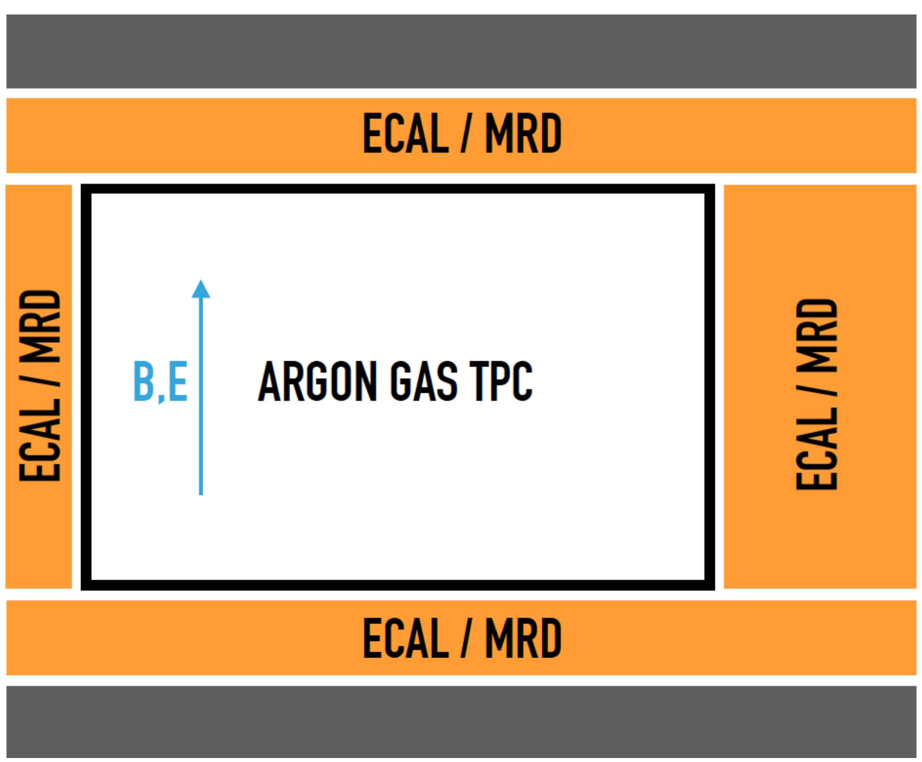


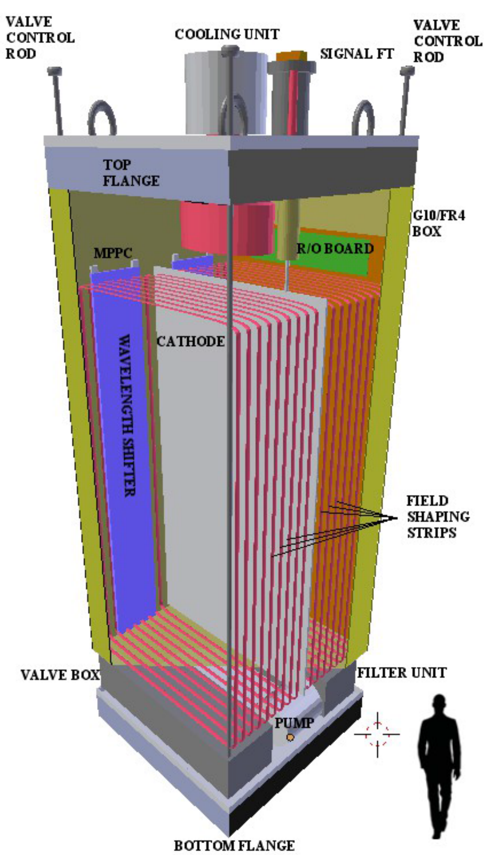
- For extensive detail on LBL sterile ν and extra-dimension searches see:
  - Talk by AS at https://indico.fnal.gov/conferenceDisplay.py?confId=10732
  - Talk by Simon De Rijck at https://indico.fnal.gov/conferenceDisplay.py?confId=11137





ND-Only BSM Physics

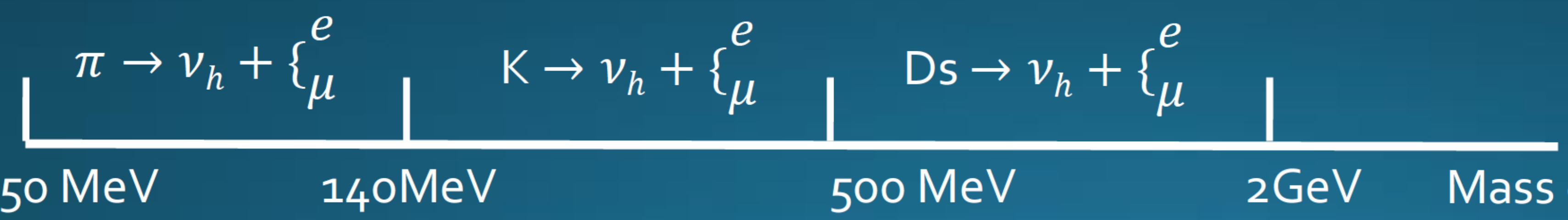




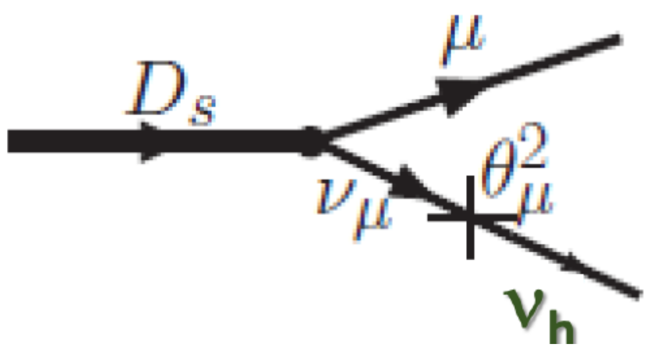
Heavy Neutral Leptons - Neutrinos

Athans Hatzikouteilis

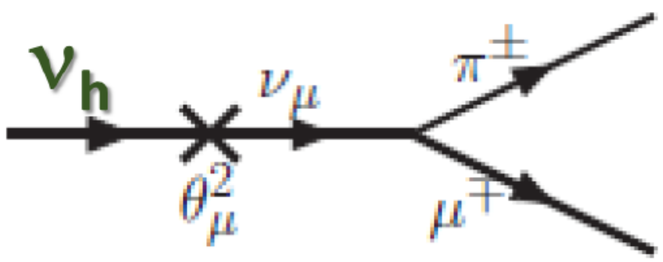
- Neutrino portal to Heavy Neutrino.
  - The HNL coupling to SM "should not" be more than $U^2 \sim 10^{-7}$.



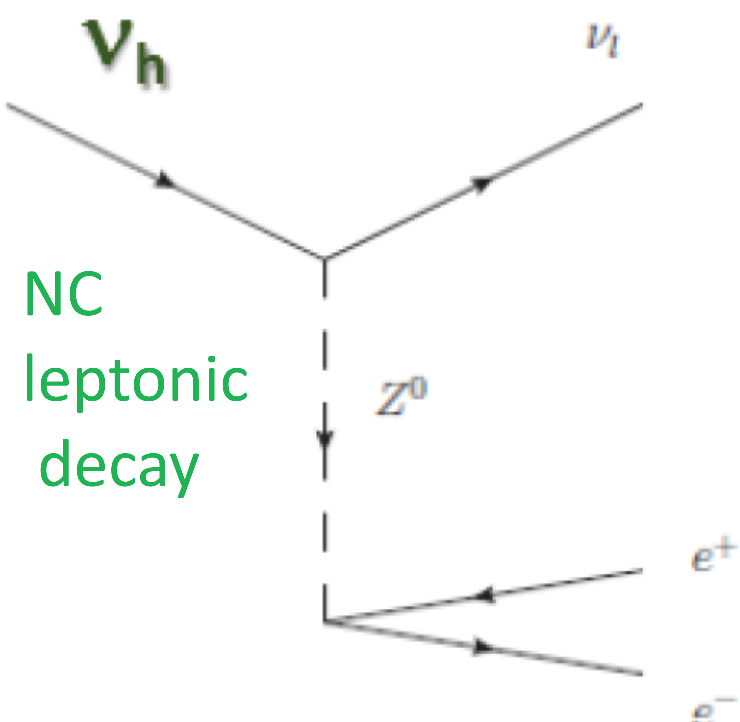
Appelquist and Shrock, PLB548,(2002) & PRL90,(2003), & PRD 69,(2004)



Semi-leptonic decay

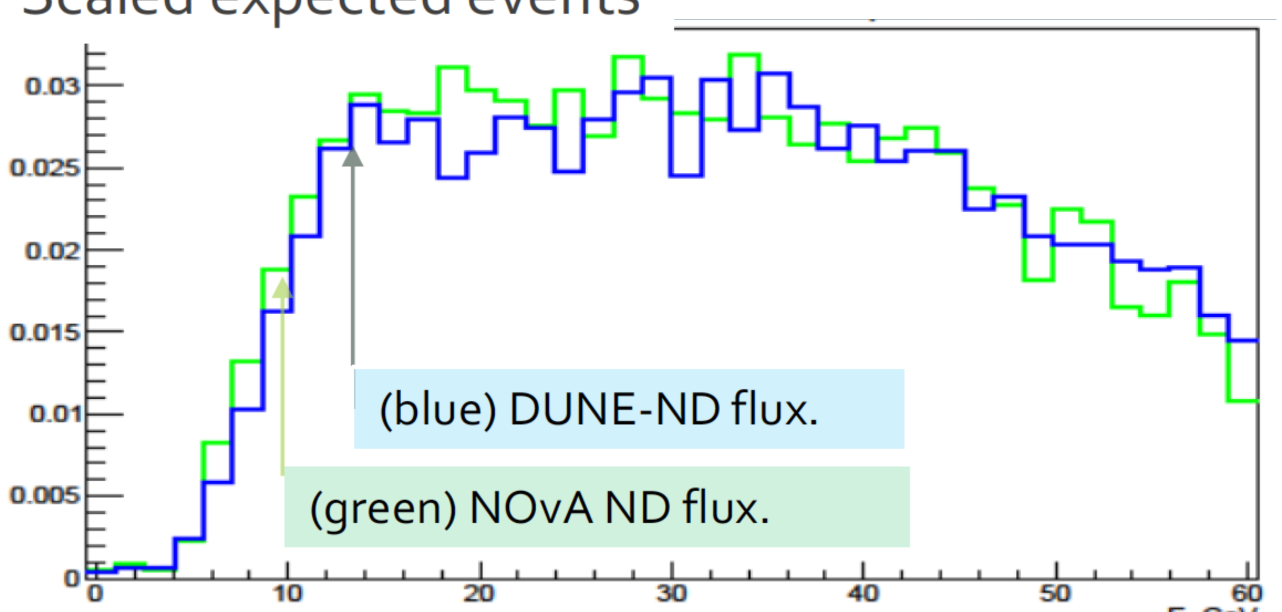


NC leptonic decay



- D_s production of 1μb in NuMI target, likely similar to LBNF target
- DUNE ND geometry favorable for GeV masses and ~1μs lifetimes

Scaled expected events



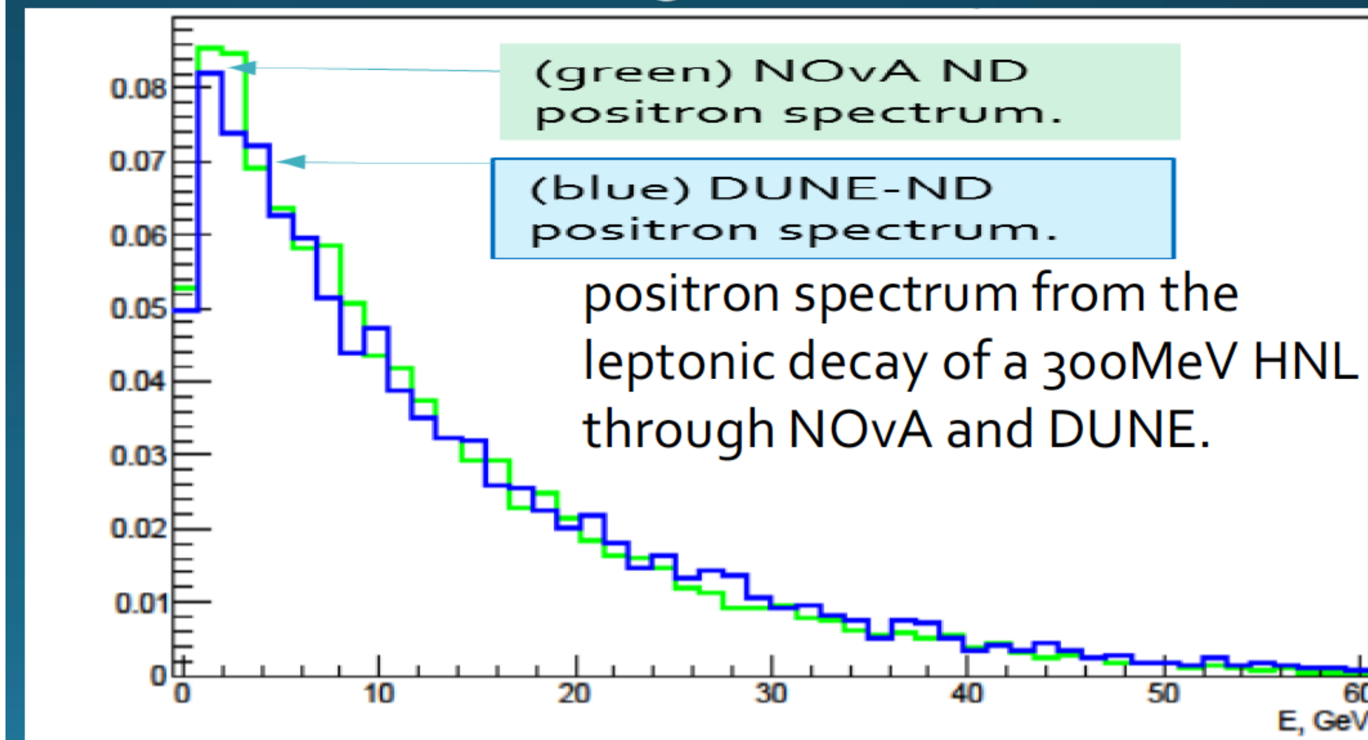
- Work being developed for NOvA ND analysis
- People:
  - A. Hatzikoutelis, UTK
  - S. Kotelnikov, FNAL
  - Filip Jediny, CTU
  - Biao Wang, SMU

Heavy Neutral Leptons - Neutrinos

Athans Hatzikouteilis

- Possible signal topologies to look for
  - e-showers surrounded by pion-showers.
  - combinations of an e-shower with a muon tracks of high energy.
  - multi-pion signatures.
  - one muon plus a jet (may be the strongest channel).
    - PID may indiscriminately categorize all such channels into a neutrino interaction of summed energy deposited in the ND.

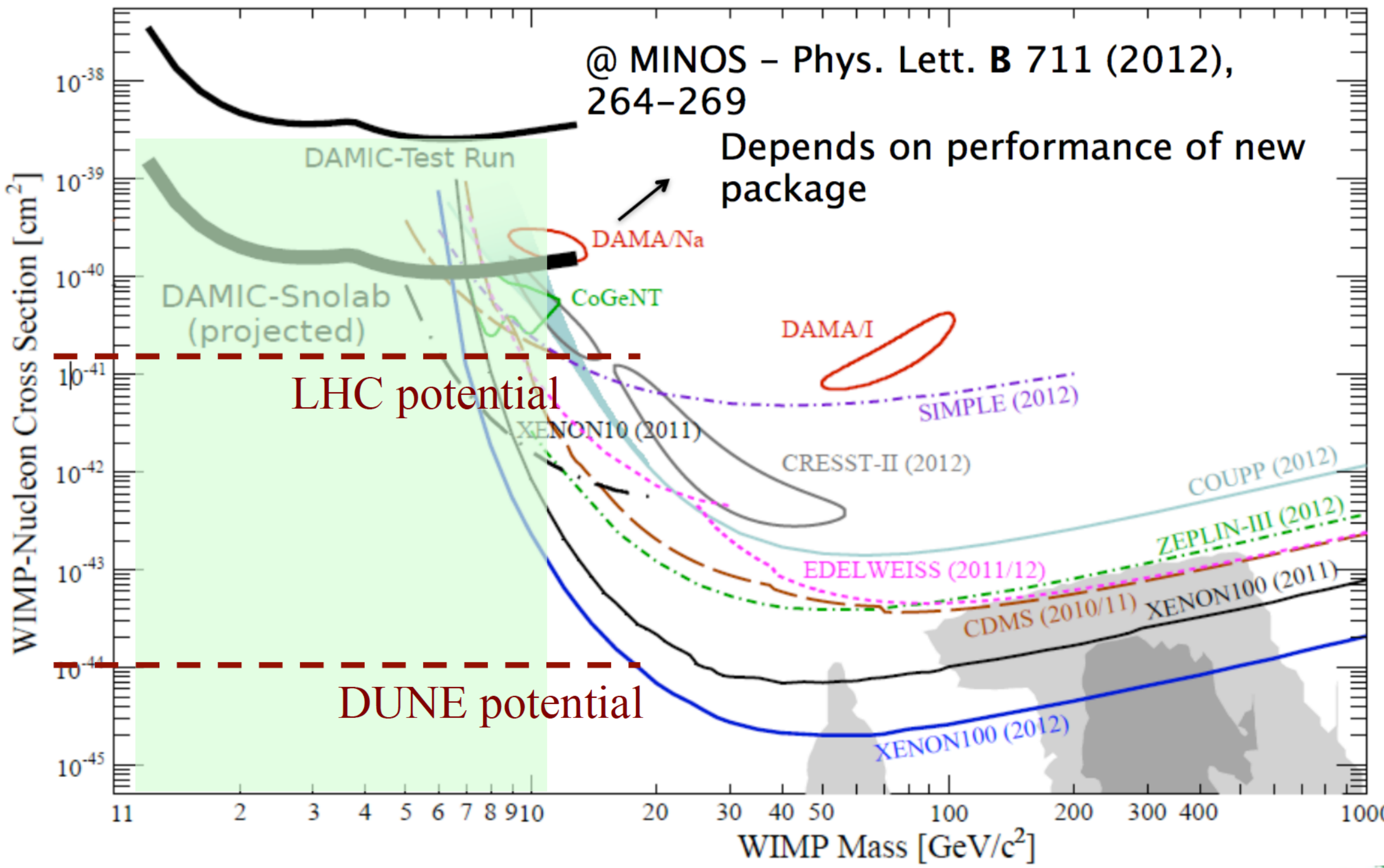
Comparing the spectrum of the flux of a 300MeV HNL through NOvA and DUNE.



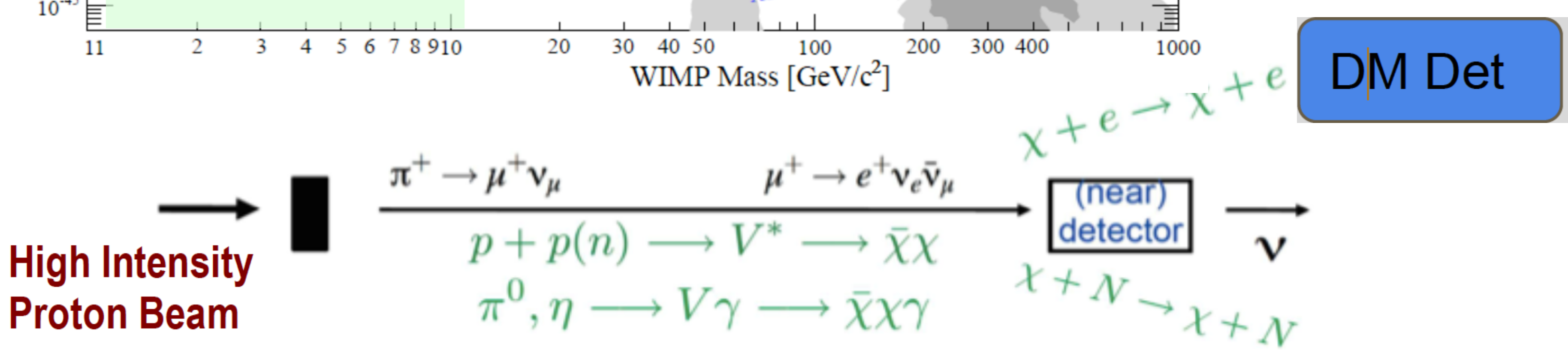
- Plans
  - Take advantage of the experience with NOvA.
    - Learn from the NOvA-LDM-search challenges in order to anticipate DUNE-ND-PID needs in the s/w.
    - Constrain model rates from searches in the NOvA data, currently being collected.
  - Study backgrounds, the neutrino interactions.
- Working on generating a simulated sample of HLNs signals
- Understand EM signal reconstruction efficiencies
- Develop a comparison study on HNL searches at DUNE, NOvA, and SHiP in the Summer

Low-Mass Dark Matter

Jae Yu, Animesh Chatterjee



- Look for dark matter decays at off-axis angles
- Strong probe of m<10 Gev/c[2] dark matter
- Requires dedicated DM detector next to DUNE ND



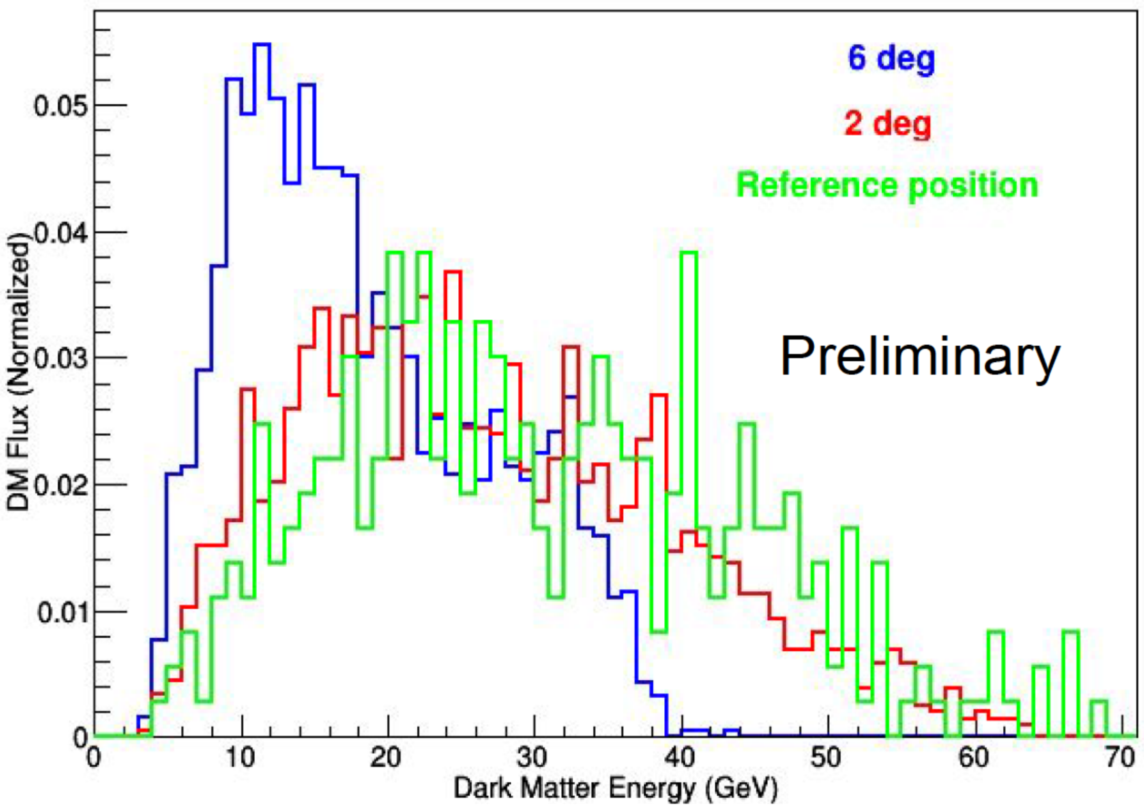
- Main Background for the DM signal is the neutrino neutral current events.
  - In the case of pions, neutrinos emitted with a sizable angle have very low energies regardless of the parent pion energy because of the low pion mass.
  - Main background is going to come from the neutrinos produced from kaon decay.

Low-Mass Dark Matter

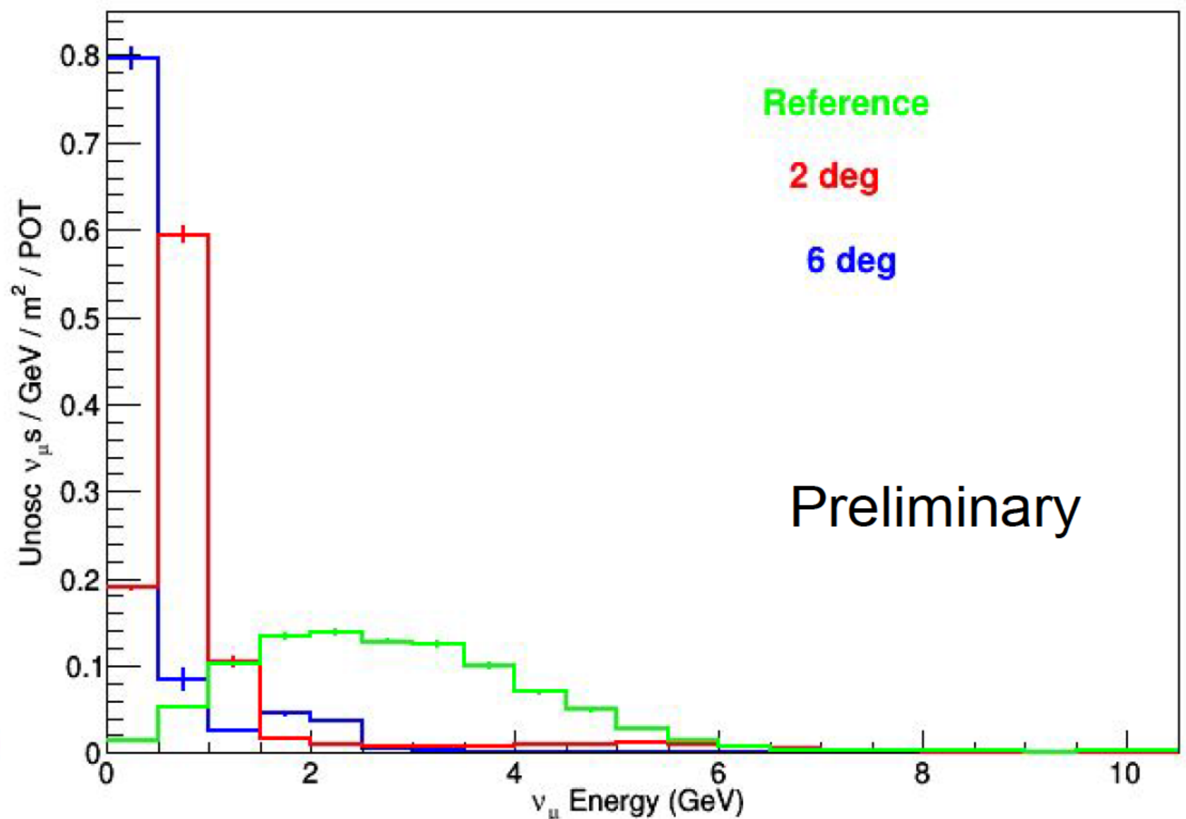
Jae Yu, Animesh Chatterjee

- Expecting good neutrino background separation for 2° angle

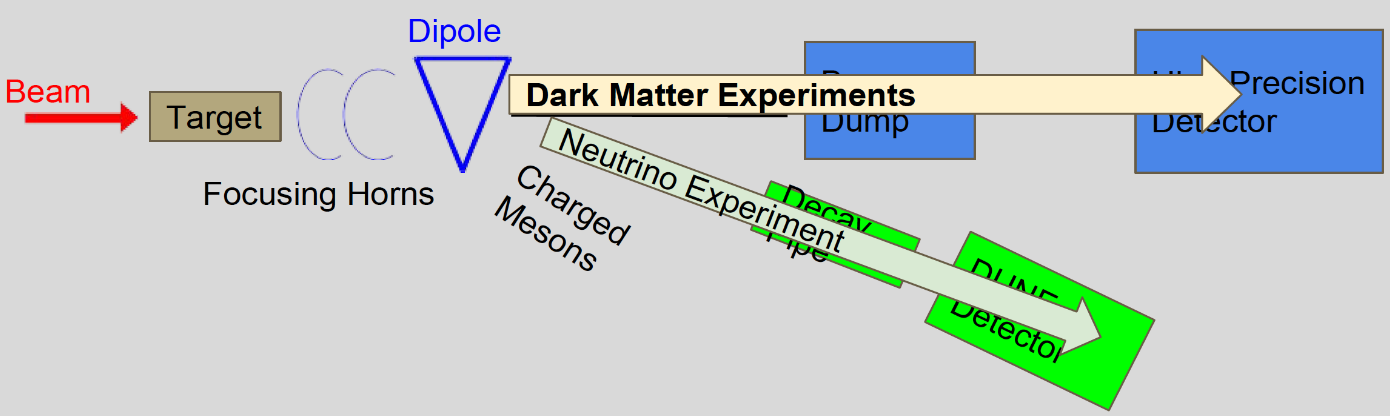
DM Energy Spectrum for different off axis angles



Neutrino Energy Spectrum for different off axis angles



- Beam dump experiment would be another option, since beam dump can be made to absorb all the mesons which are the source of neutrinos.
- Separate neutrino and antineutrino from DM.



- Plans:
  - Developing LDM MC generator to be interfaced with DUNE simulations
  - Interest from SLAC Theory Group in participating DUNE LDM Searches (Matt Graham, JoAnne Hewett).
  - Collaborating with SLAC in writing PRD describing potential

- Possible dedicated experiment using Doubly-Sign-Selected Horn System and beam stop

Neutrino Tridents

Wolfgang Altmannshofer, Stefania Gori

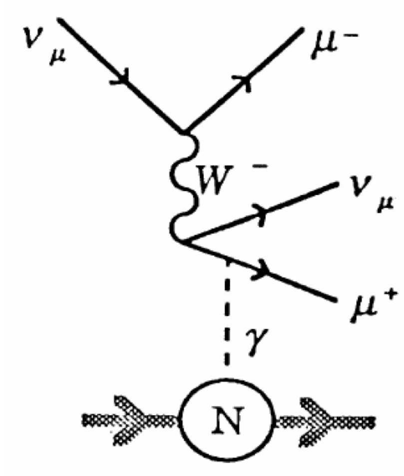
- Rare SM process. Has been observed with measured cross section in good agreement with SM

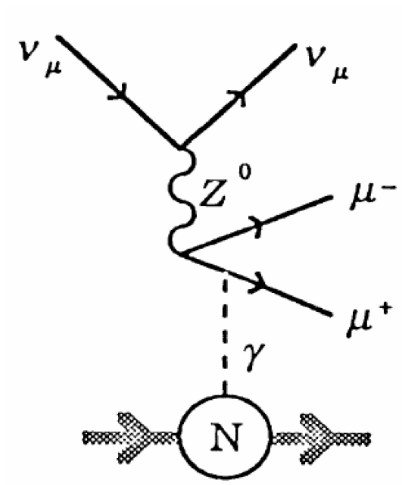
production of a muon anti-muon pair
in the scattering of a muon neutrino
in the Coulomb field of a heavy nucleus

probes the electro-weak interactions
of 2nd generation leptons

a rare process:
cross section is many orders of magnitude smaller than the inclusive neutrino-nucleus scattering cross section

see talk on Feb. 16, 2016
https://indico.fnal.gov/conferenceDisplay.py?confId=11408





first signal claimed at CHARM II:
neutrinos with average energy
$\sim$ 20 GeV on glass
Phys.Lett. B245, 271 (1990)

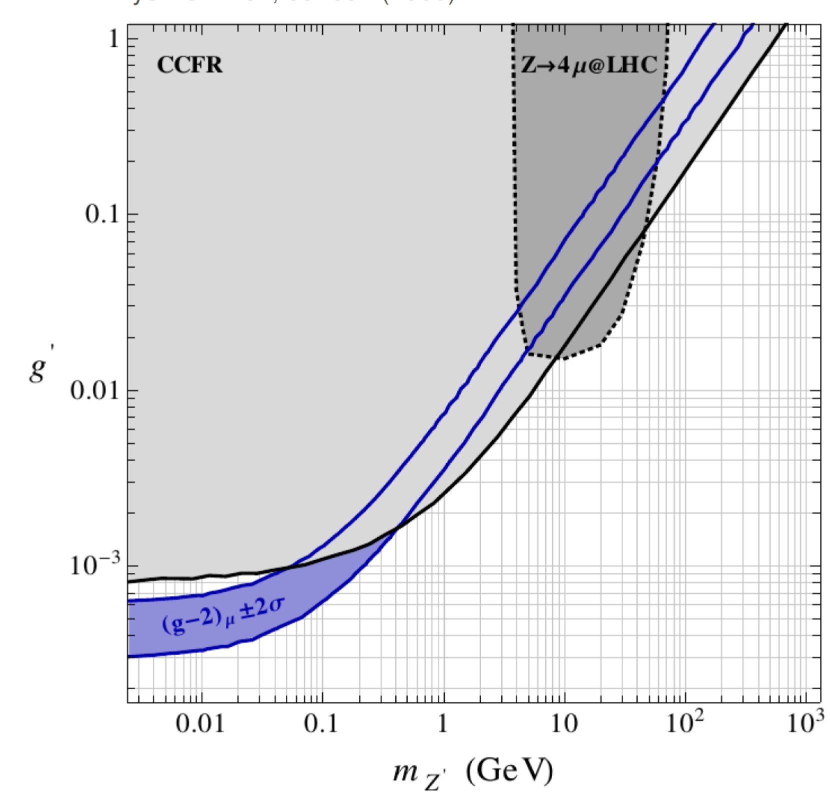
$\sigma_{\text{CHARM II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57$

demonstration of the destructive W interference at CCFR:
neutrinos with average energy
$\sim$ 160 GeV on iron
Phys.Rev.Lett. 66, 3117 (1991)

$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28$

no conclusive signal at NuTeV:
neutrinos with average energy
$\sim$ 160 GeV on iron
Phys.Rev.D 61, 092001 (2000)

$\sigma_{\text{NuTeV}}/\sigma_{\text{SM}} = 0.72^{+1.73}_{-0.72}$



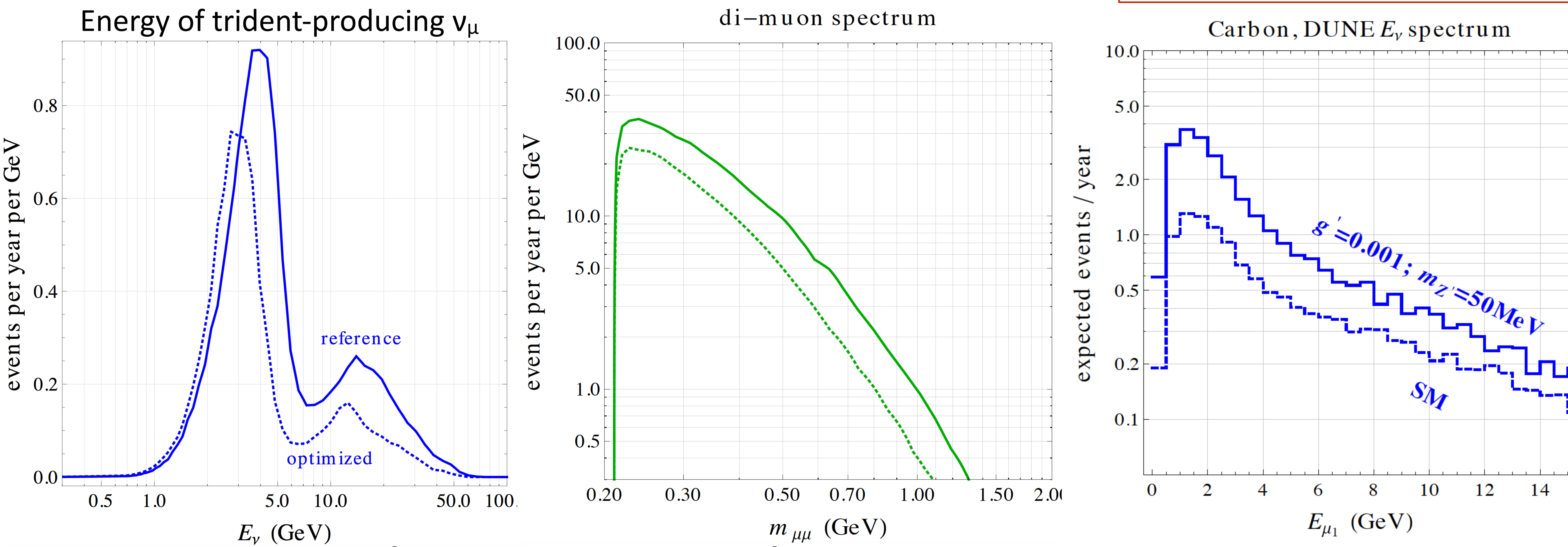
WA, Gori, Pospelov, Yavin, Phys.Rev.Lett. 113 (2014) 091801

- Strong probe of potential new Z' boson advanced as explanation for (g-2) anomaly
  - Z' couples to muons, but also to muon neutrinos. Enhances trident production w.r.t. SM
  - DUNE can probe still-allowed $m_{Z'} < 0.4$ GeV region

Neutrino Tridents

- Using *reference* and *optimized* beam fluxes provided by Laura Fields and assuming 8 ton Fine-Grained-Tracker ND design

Wolfgang Altmannshofer, Stefania Gori



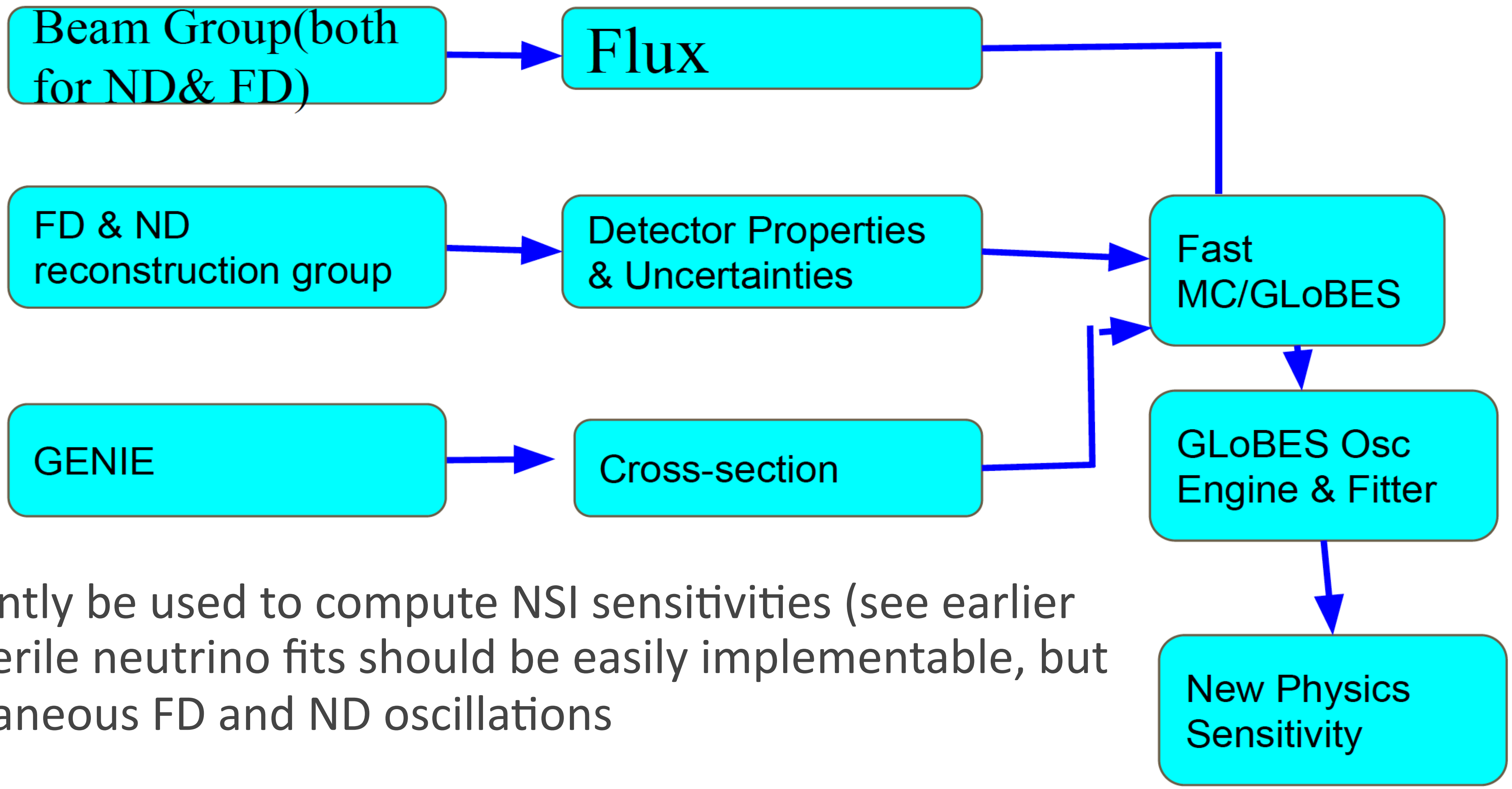
- Reference: **8.2 evts/year** (Carbon) + **2 evts/year** (Nitrogen)
- Optimized: **6.5 evts/year** (Carbon) + **1.5 evts/year** (Nitrogen)
- Assuming 8 ton Ar, **16.5 evts/year** (reference) and **12.7 evts/year** (optimized)
- Close to a factor of 3 increase in event rate from Z' contribution
- Working on producing trident MC generator - will need to interface with Det. simulation to evaluate trident detection efficiency
- Background studies (in particular of ν_μ CC with single pion production) would likely benefit from input by Reconstruction group

Other Potential Topics

- Boosted Dark Mater, see talk by Yanou Cui (Perimeter Institute):
  - https://indico.fnal.gov/conferenceDisplay.py?confId=11814
- Lorentz-violation/CPT-violation in the context of the Standard Model Extension (SME). *Colladay, Kostelecky, Phys. Rev. D **58** 116002 (1998)*
- Neutrino->antineutrino transitions
- **Your idea here!**

BSM Physics Code Framework

- Presently based on GloBES
- Exists in repository in dunebsm redmine https://cdcvs.fnal.gov/redmine/projects/dunebsm/repository **Thanks Tom!**

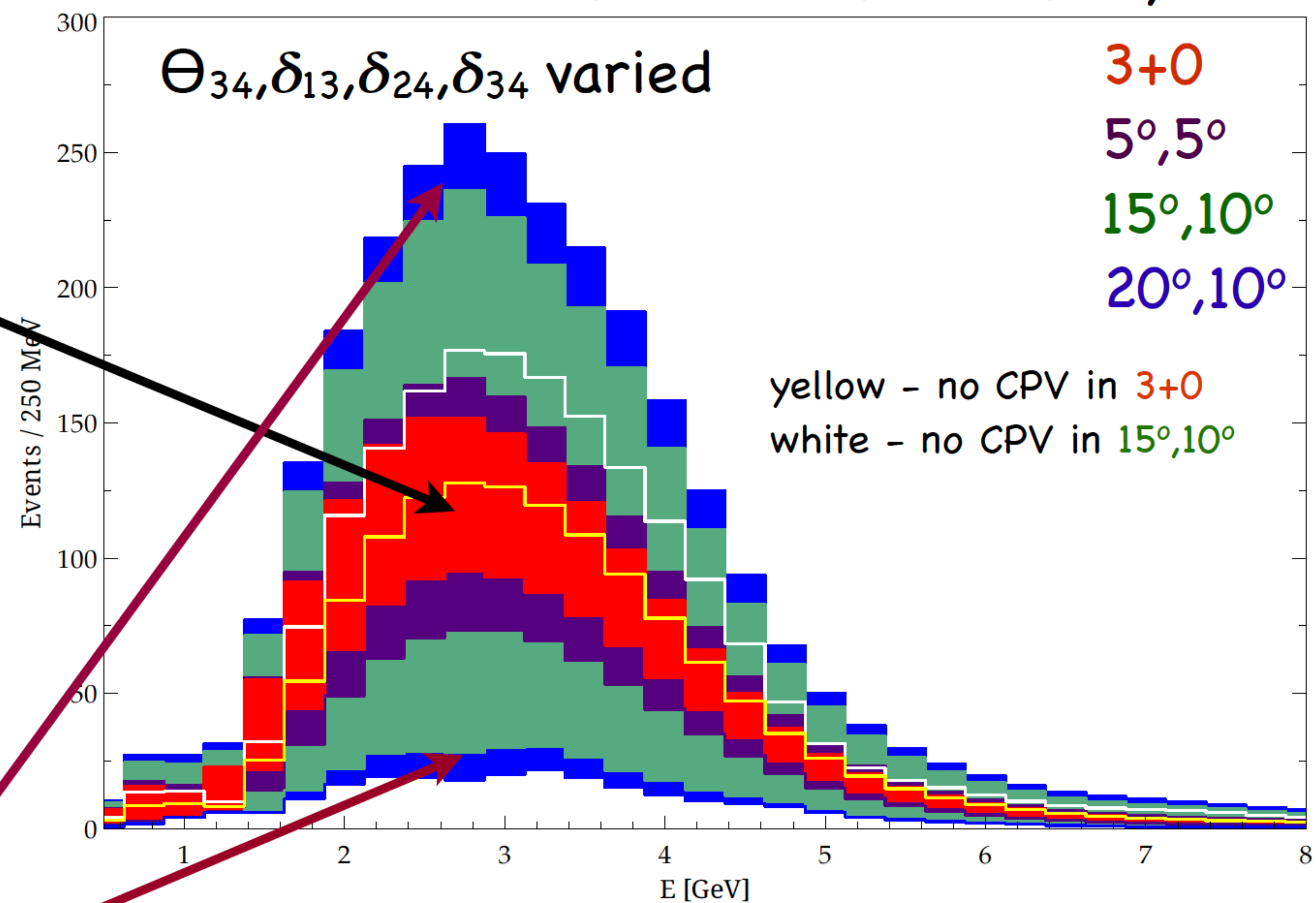


- Can currently be used to compute NSI sensitivities (see earlier slides), sterile neutrino fits should be easily implementable, but no simultaneous FD and ND oscillations
- Will need development to allow non-GENIE MC generators (*e.g.* Low-Mass DM, neutrino trident searches)
- Working on interfacing with FastMC in very near future

ν_s and Osc. Param. Measurement

The 3+1 band can potentially encompass the 3+0 band, leading to substantial degeneracy.

For large active-sterile mixings, an excess or shortage of events, esp. at osc. max. will be pointers to the existence of new physics.

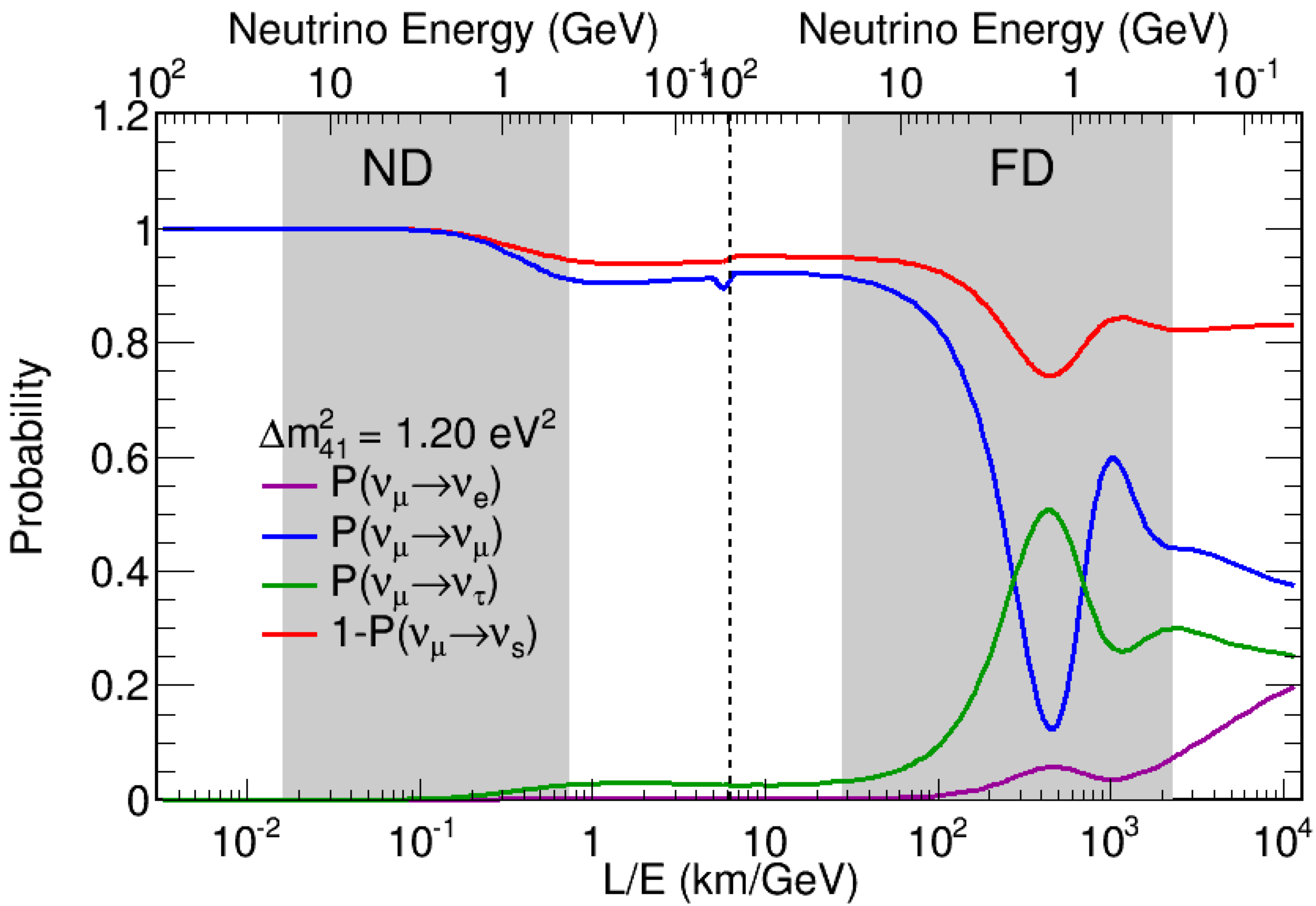


$\Theta_{12} = 33.48^\circ$, $\Theta_{13} = 8.5^\circ$, $\Theta_{23} = 45^\circ$

$\Delta m^2_{31} = +2.457e\text{-}3\ eV^2$, $\Delta m^2_{21} = 7.5e\text{-}5\ eV^2$

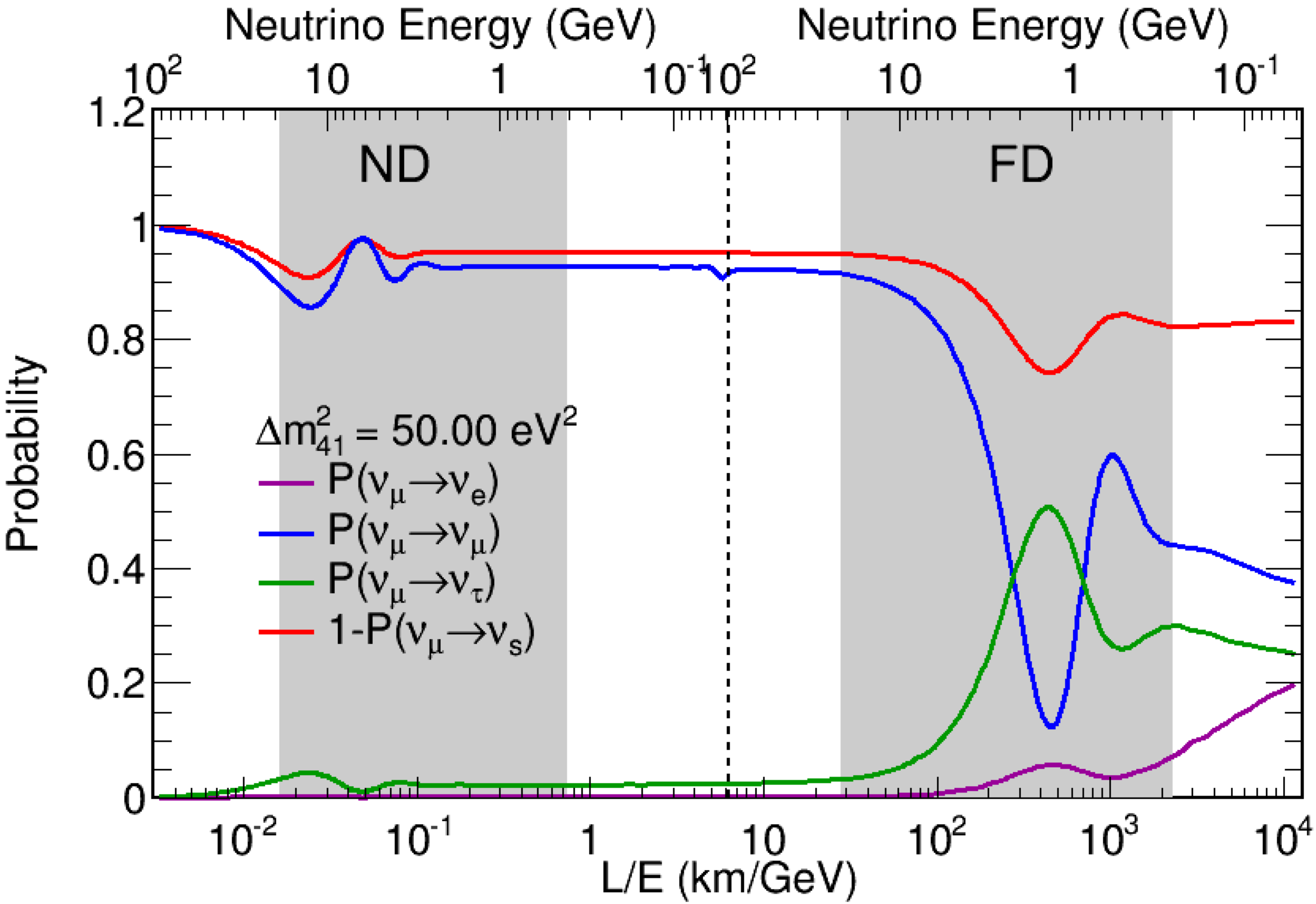
R. Gandhi, B. Kayser, M. Masud, S. Pakrash, arXiv:1508.06275

Sterile Sensitivity @LSND



- 3+1 oscillation probabilities at the LSND best fit point for Δm^2_{41}

Large-Mass Sterile-driven ND Oscillations



NSI and Osc. Param. Measurements

LMA dark solution

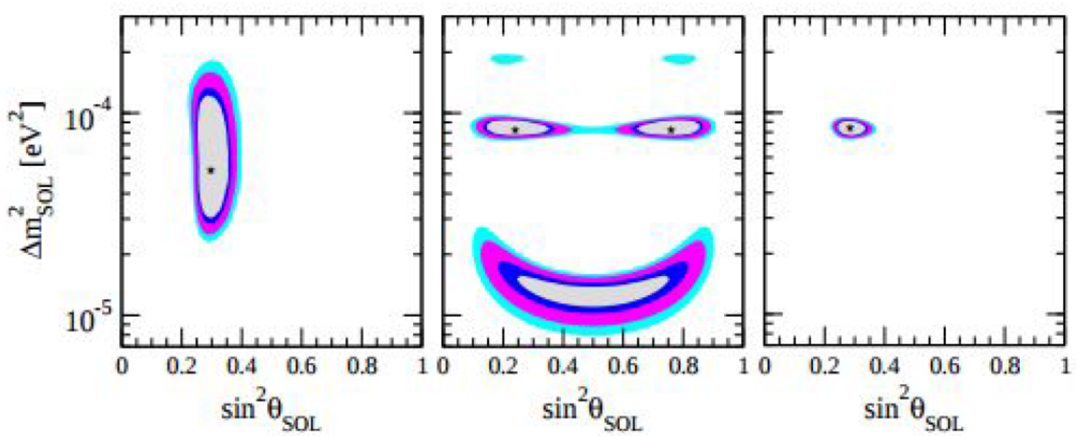


FIG. 1: 90%, 95%, 99% and 99.73% C.L. allowed regions of the neutrino oscillation parameters from the analysis of the latest solar data (left panel), the 766.3 ton-yr KamLAND data (middle panel) and from the combined analysis (right panel).

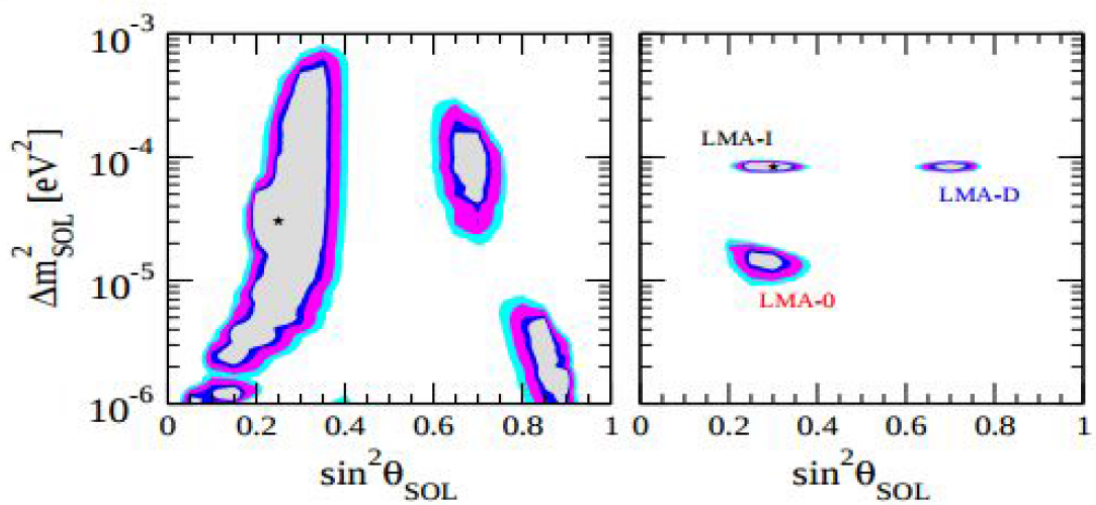
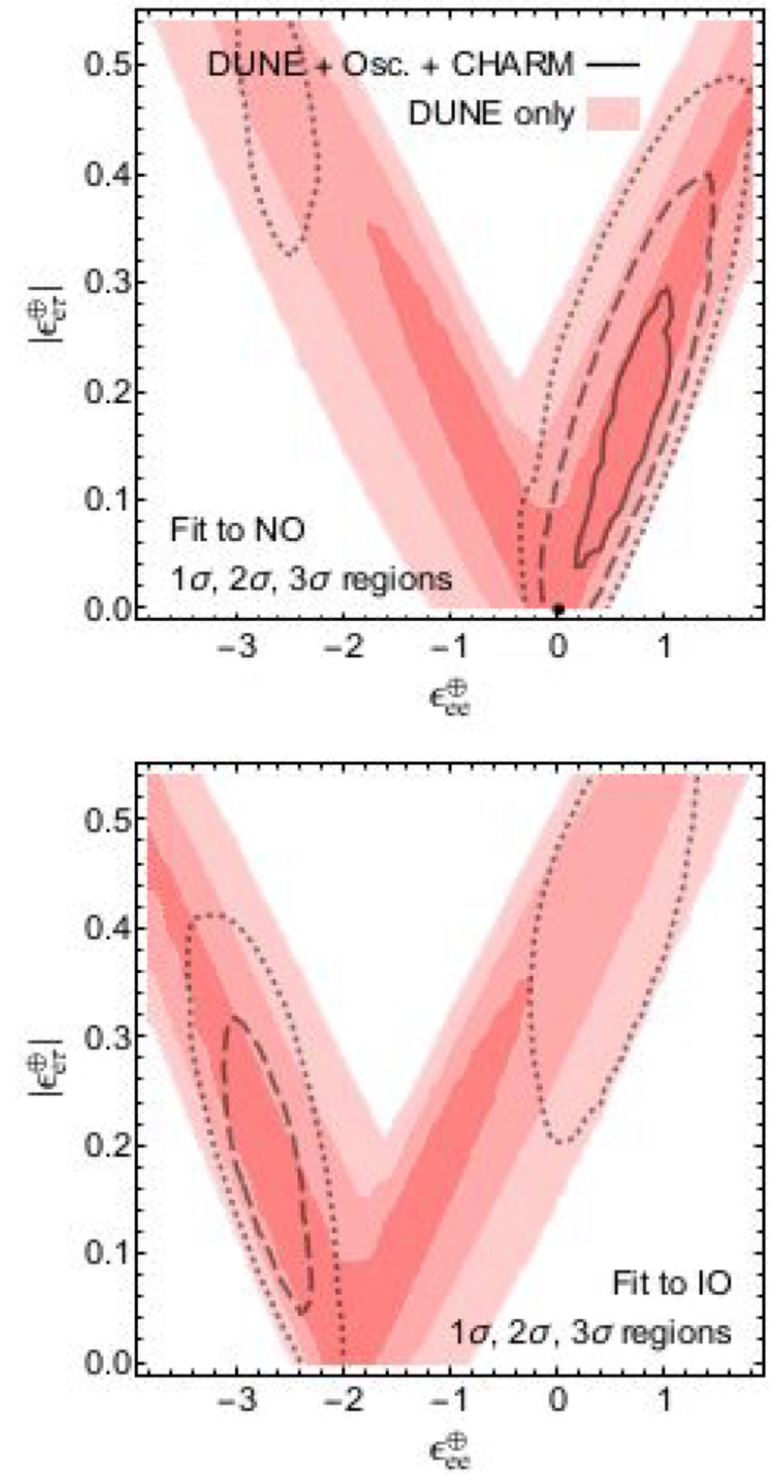


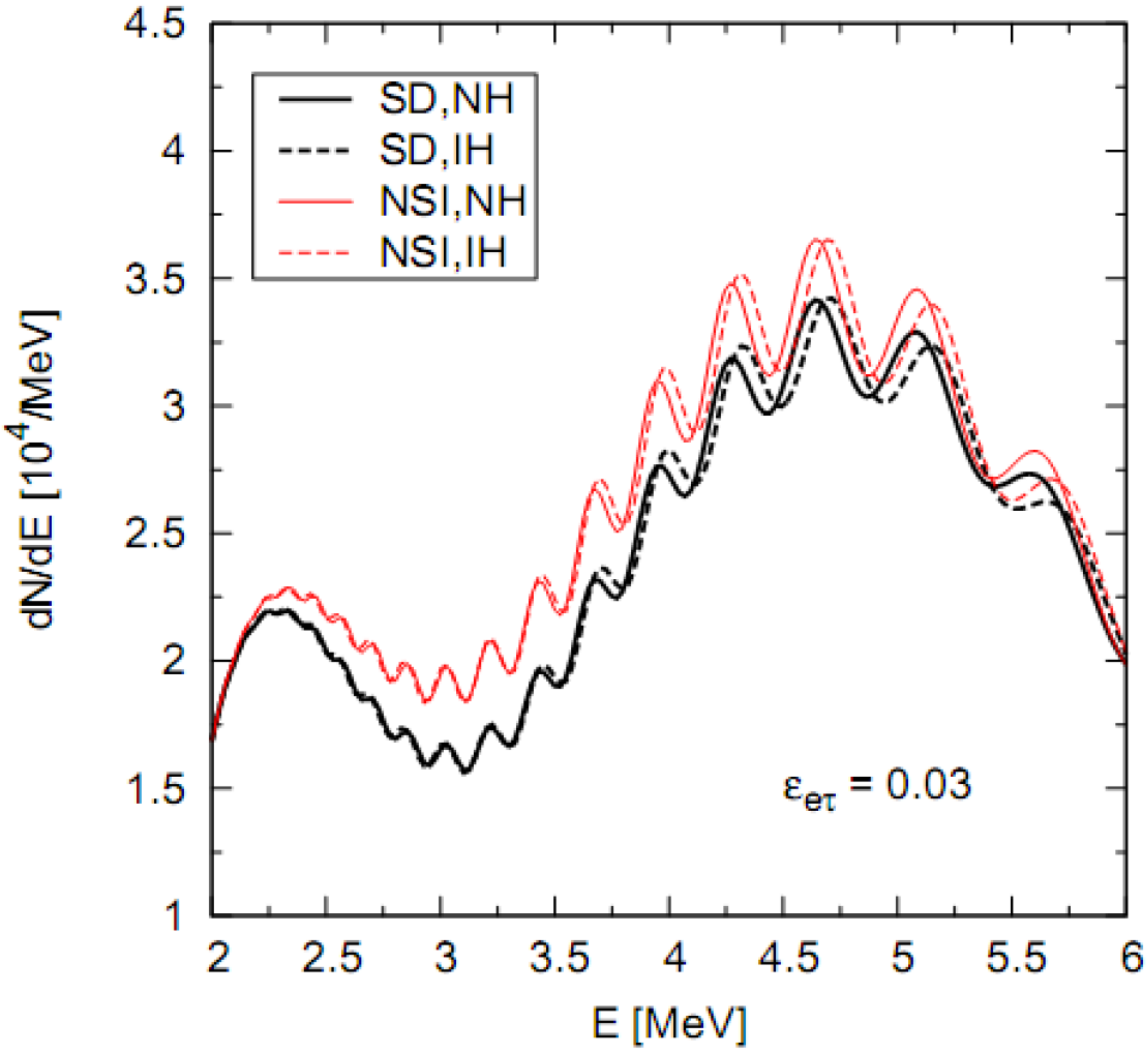
FIG. 2: Same as in Fig. 1 for the generalized OSC + NSI case, showing the modification of the allowed region in the light side as well as the new LMA-D solution.

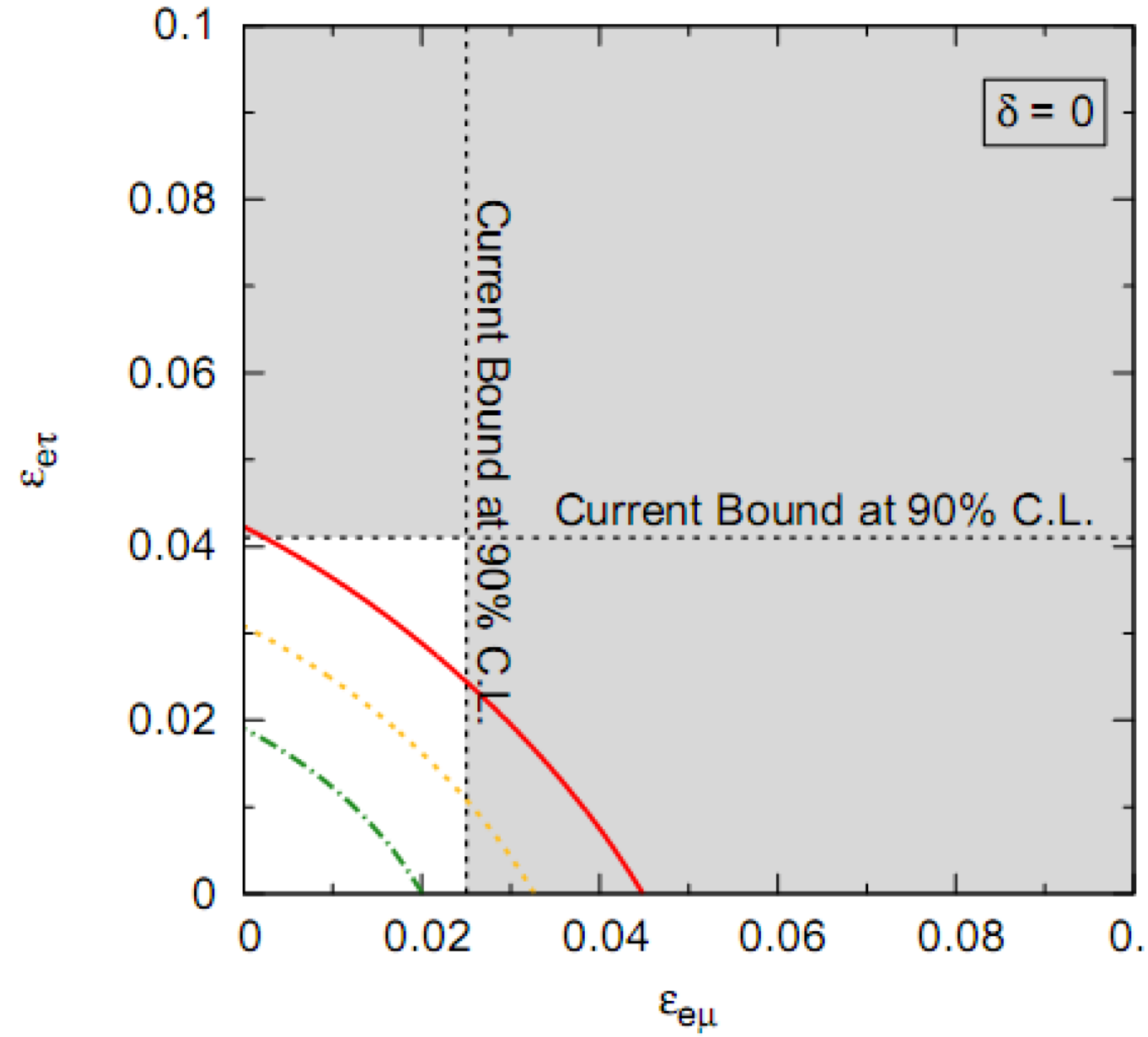
Miranda, Tortola, Valle



Coloma

NSI and Osc. Param. Measurements





Medium baseline reactors: JUNO

1310.5917: Ohlsson, Zhang, Zhou