SBNfit FC Update

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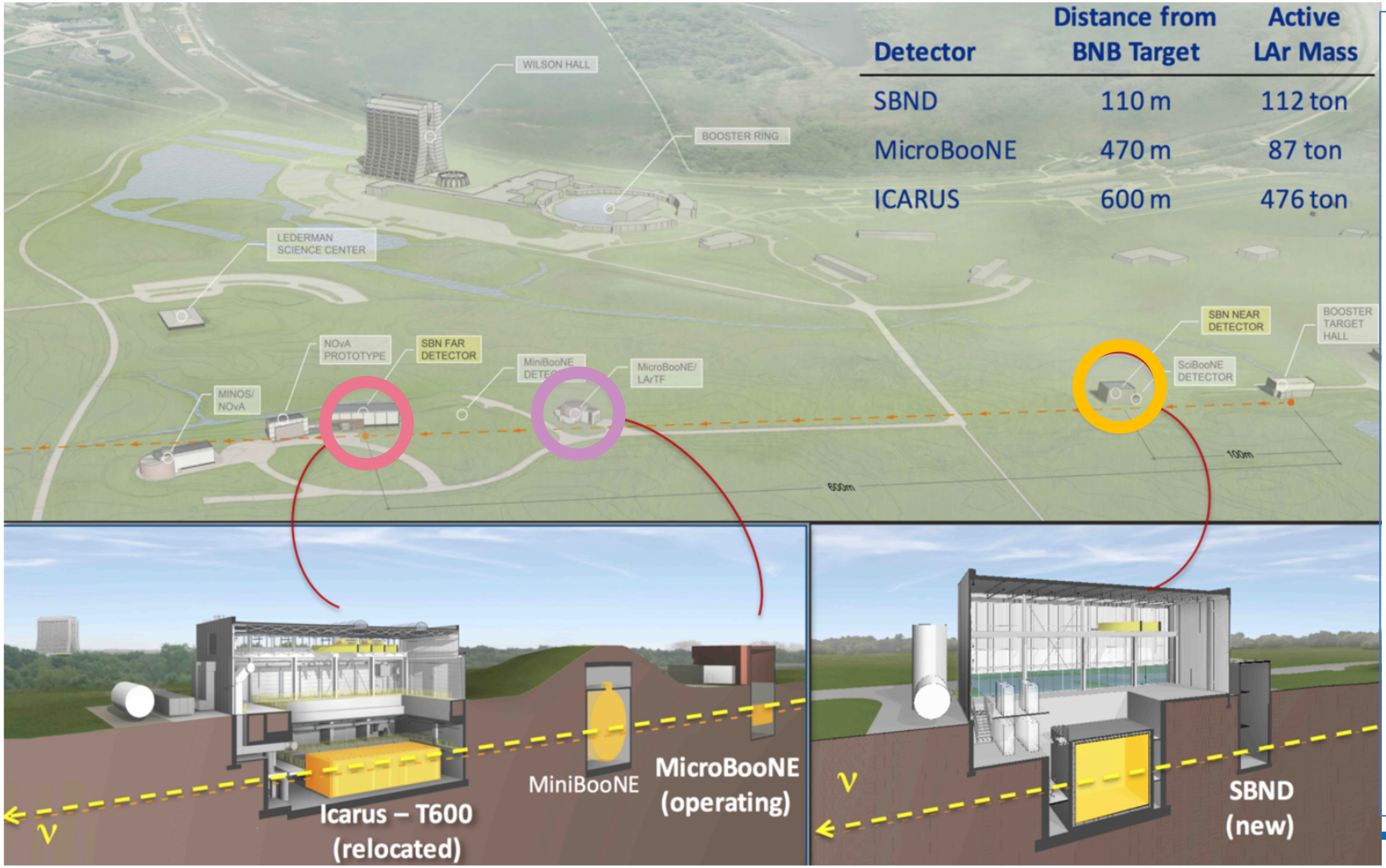
SBN Program



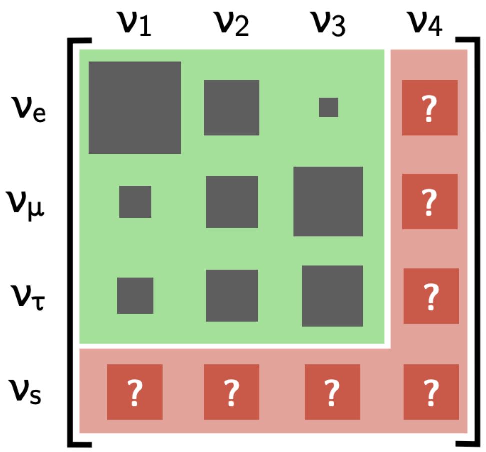
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

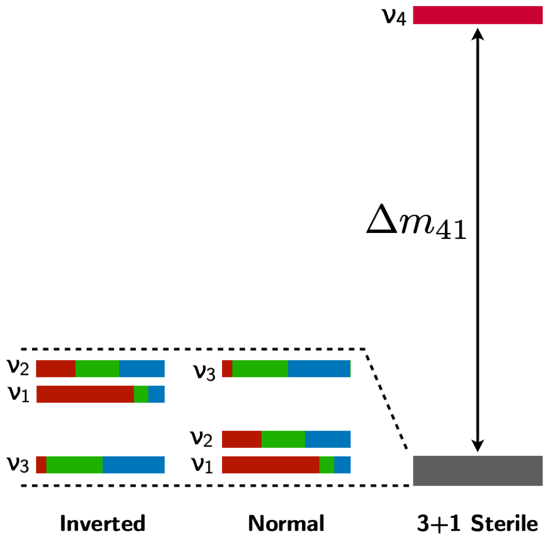
- **SBN**: **3 liquid argon detectors** located in the **Fermilab Booster Neutrino Beamline** with main goal to search for short baseline anomaly:
  - **ICARUS**
  - **MicroBooNE**
  - **SBND**
- Each detector shares the **same neutrinos source** and **same detector material/technology**-> measurement is **highly correlated -> reduce systematics**

Extra Neutrinos

Minimal extension to the Three-Neutrino Paradigm is if there is an additional sterile neutrino.
This is referred to as the **3+1 paradigm** and currently what the current project is benchmarking against.

$U =$





$$P_{\alpha\rightarrow\beta} = sin(2\theta)^2 sin\left(\frac{\Delta m^2 L}{4E}\right)^2$$

Δm^2: frequency of oscillation

$\sin^2(2\theta)$: amplitude of oscillation

Oscillation probability via this mixing:

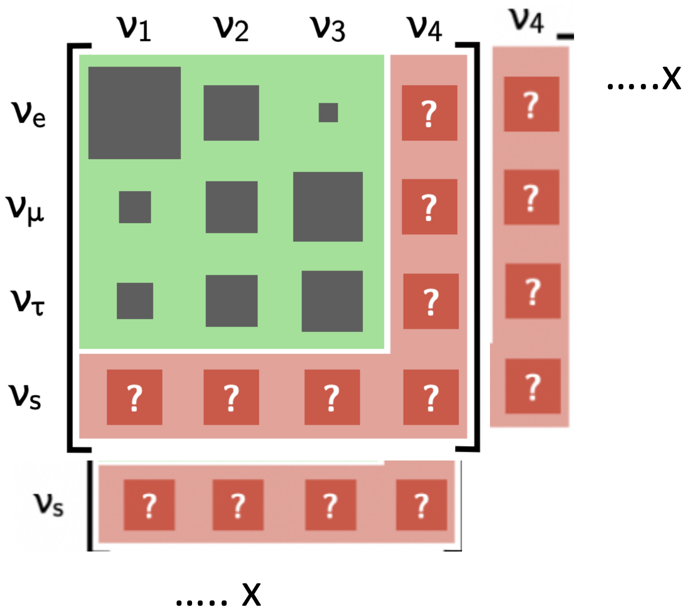
$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(1.27\frac{\Delta m^2_{41}L}{E}\right)$$

Only depends on 2 parameters!

More Neutrinos?

We will have to expand the U matrix seen previously to account these additional sterile neutrinos (3+x).

$U =$



depends on more parameters!

3N+2: 7 parameters
3N+3: 12 parameters

Oscillation probability via this mixing will need to be expanded as well:

$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(1.27\frac{\Delta m^2_{41}L}{E}\right)$$

Motivates improvement to the grid-based scanning method

Objective: Provide FC correction to the Sensitivity Curves

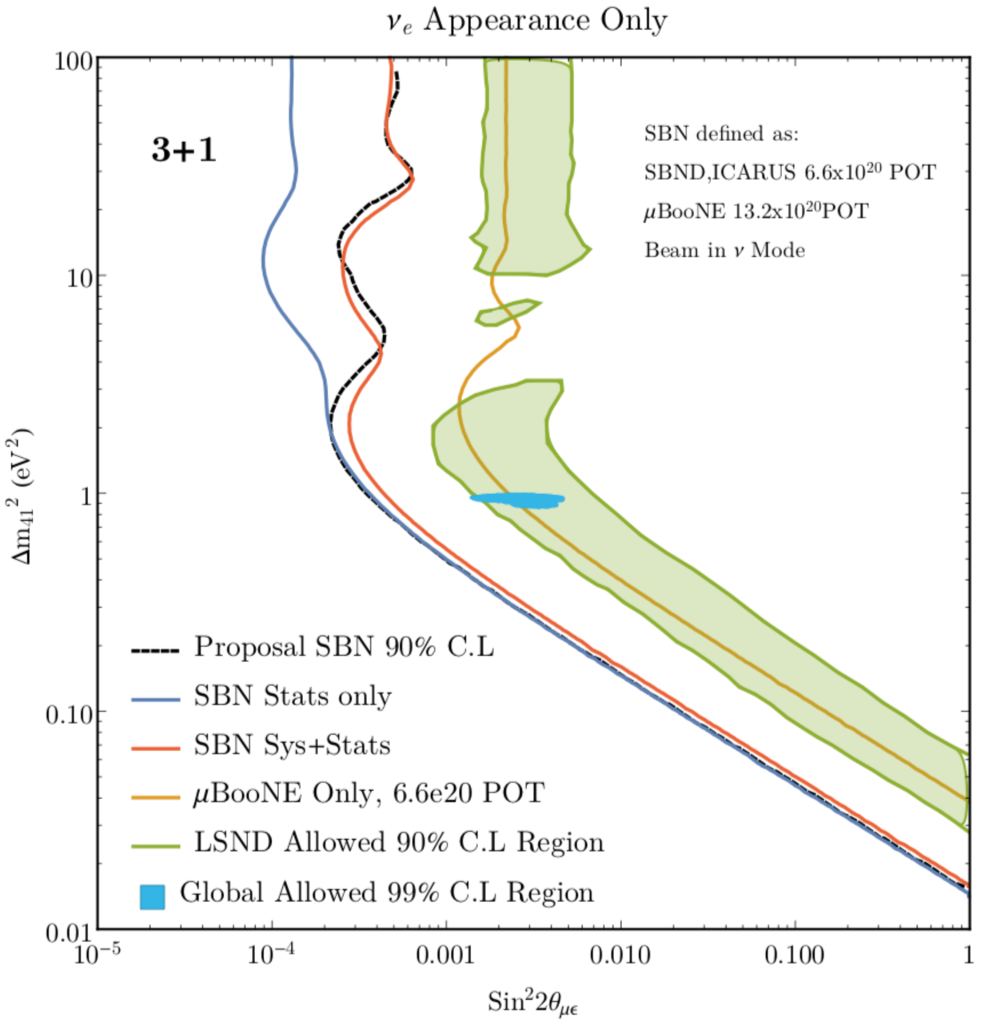
This is the (3+1) paradigm:

$$P_{\alpha\to\beta} = sin(2\theta)^2 sin\left(\frac{\Delta m^2 L}{4E}\right)^2$$

Δm^2: frequency of oscillation

$\sin^2(2\theta)$: amplitude of oscillation

Only depends on 2 parameters!



FC curves from this study will be added into this plot to increase the precision of the fits

χ^2 Calculation for υ Oscillation Sensitivity

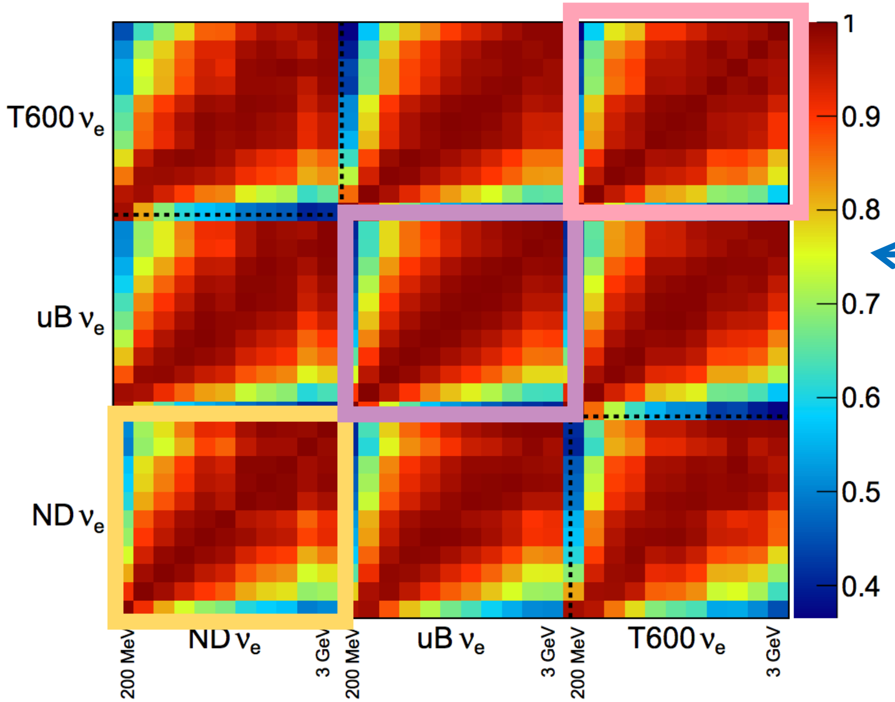
- Benchmarking:
  - SBNfit framework: one of the fitting framework used by SBN collaboration (Physics Group at Nevis Lab at Columbia University)
- The core of this procedure is to calculate a χ^2 surface in the $(\Delta m^2_{41}, \sin^2(2\theta))$ oscillation parameter plane:

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

Covariance Matrix

Sensitivity is calculated by computing a χ^2 surface in the $(\Delta m^2_{41}, \sin^2(2\theta))$ oscillation parameter plane:

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$



Systematics uncertainties are computed in form of combined covariance matrix of the 3 detectors **(56x56 matrix):** SBND, MicroBooNE, ICARUS

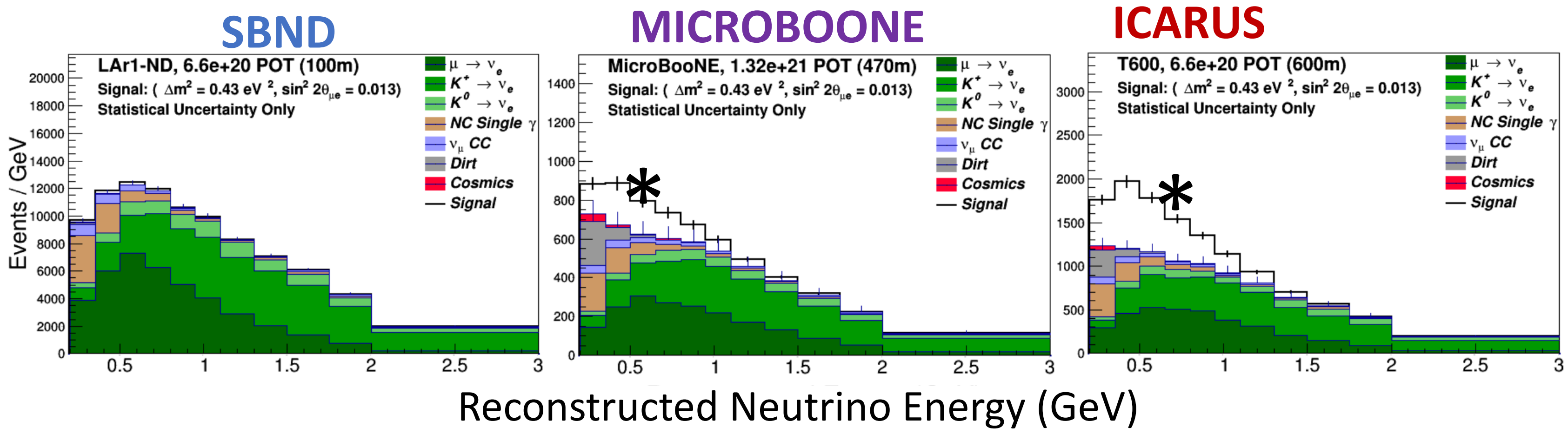
[arXiv:1503.01520v1]

Spectrum/Input Data

Sensitivity is calculated by computing a χ^2 surface in the $(\Delta m^2_{41}, \sin^2(2\theta))$ oscillation parameter plane:

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc*}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

$$P^{*}_{\alpha\to\beta} = sin(2\theta)^2 sin\left(\frac{\Delta m^2 L}{4E}\right)^2$$



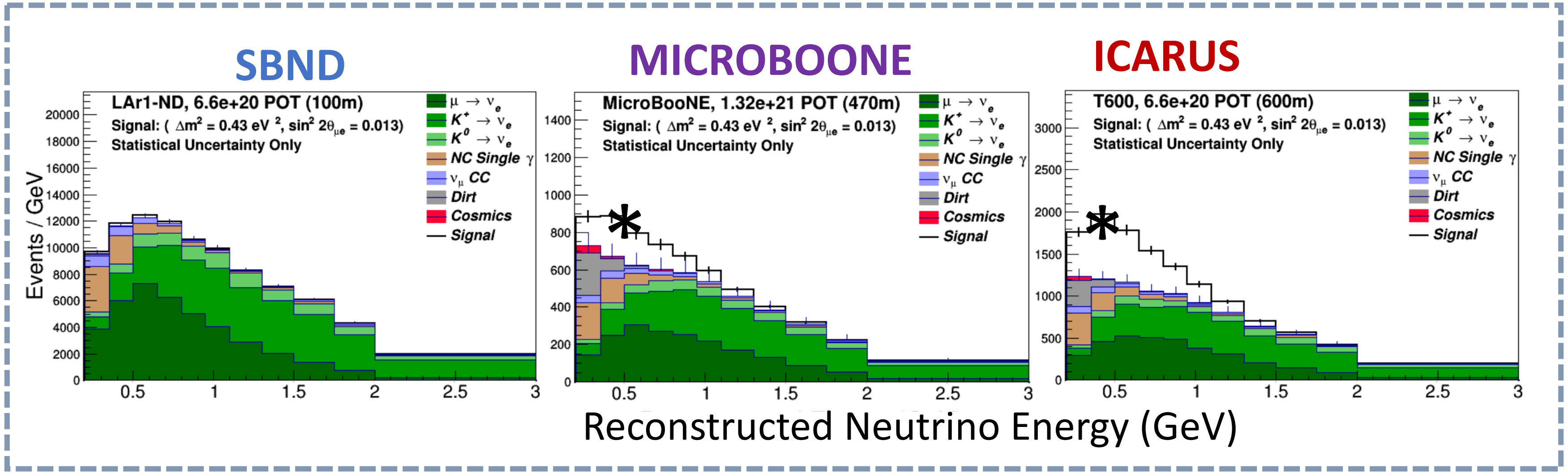
Δm^2: frequency of oscillation

$\sin^2(2\theta)$: amplitude of oscillation

*Oscillation spectrum at Best Fit Point

[arXiv:1503.01520v1]

Bringing in MFA Model (Tom, David)



We calculate the oscillated spectrum (*) at each grid point that depends on the frequency (mass) and the amplitude (angle)

↓

Bin contents of these oscillated spectrum at each grid point are concatenated into a 56 length size vector

↓

Create MFA model which field-geometry dimension depends on the grid size (Ngridpoints).
Bin content represents the science variable -> 56 science variables.

Still ongoing: validating the model. Accuracy of the MFA model not as good as previous implementation

χ^2 Calculation for υ Oscillation Sensitivity

SBND — Neutrino energy spectrum

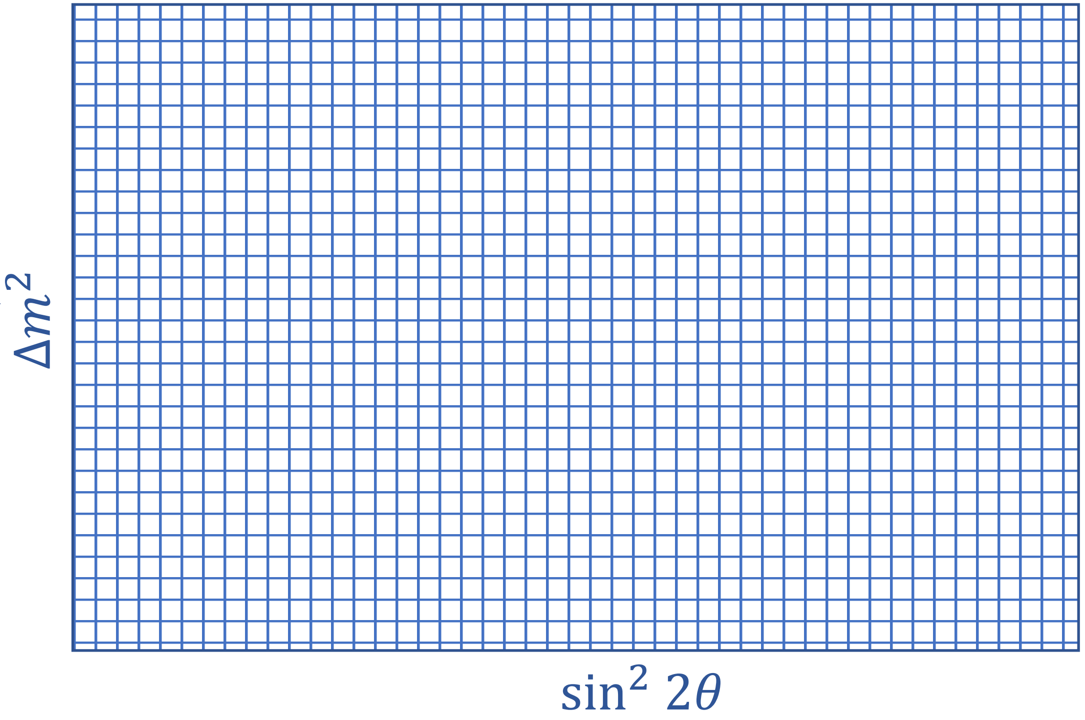
MicroBooNE — Neutrino energy spectrum

ICARUS — Neutrino energy spectrum

→ Covariance Matrix

Input

Perform χ^2 calculation at each **oscillation parameter space point** where we generate *N* number of toy experiments (Nuniv) – Feldman Cousins procedure



Output

ROOT Ntuples

↓

n-dimensional contour plot

FC Procedure Pseudo Code (old implementation)

Given number of universes $N_{\text{univ}} > 0$, discretized grid $\mathcal{G} = \{\mathbf{p}_k \ : \ k = 1, \ldots, N_{\text{gridpoints}}\}$, and given fixed covariance $\mathbf{M}$.

for $\mathbf{p}_k \in \mathcal{G}$ **do**

  for $i = 1, \ldots, N_{univ}$ **do**

    Fluctuate: $\mathbf{d}_i \leftarrow \mathcal{P}(\mathbf{c}_k)$ pswеudo-experiment sample of central data $\mathbf{c}_k := \vec{\mathcal{S}}(\mathbf{p}_k)$

    Initialize: $\chi^2_{\text{min}} \leftarrow \infty$, and $\mathbf{q}_{\text{min}} \leftarrow \mathbf{p}_k$

    for $\mathbf{q}_l \in \mathcal{G}$ **do**

      Evaluate: $\chi^2(\mathbf{q}_l) := \chi^2(\mathbf{d}_i, \vec{\mathcal{S}}(\mathbf{q}_l), \mathbf{M})$

      if $\chi^2(\mathbf{q}_l) < \chi^2_{\text{min}}$ **then**

        Update: $\chi^2_{\text{min}} \leftarrow \chi^2(\mathbf{q}_l)$ and $\mathbf{q}_{\text{min}} \leftarrow \mathbf{q}_l$

      end

    end

    Record: $\Delta\chi^2(\mathbf{p}_k) \leftarrow \chi^2(\mathbf{d}_i, \mathbf{c}_k, \mathbf{M}) - \chi^2(\mathbf{d}_i, \vec{\mathcal{S}}(\mathbf{q}_{\text{min}}), \mathbf{M})$ distance to mean.

  end

end

Algorithm 1: Classical Feldman-Cousins Algorithm.

From: Sven's overleaf document
https://www.overleaf.com/project/5f7205a341ace1000189420d

- calculate the chi2 at each grid point for Nuniv
- find which grid point will give the minimum chi2 and assign that grid point as the best fit point.

- This best fit grid point and the chi2 minimum will then be used to build the sensitivity curves

BF point is limited to the input grid point

FC Procedure Pseudo Code (new implementation)

Given number of universes $N_{\text{univ}} > 0$, discretized grid $\mathcal{G} = \{\mathbf{p}_k \ : \ k = 1, \ldots, N_{\text{gridpoints}}\}$, and given fixed covariance $\mathbf{M}$.

for $\mathbf{p}_k \in \mathcal{G}$ **do**

  for $i = 1, \ldots, N_{univ}$ **do**

    Fluctuate: $\mathbf{d}_i \leftarrow \mathcal{P}(\mathbf{c}_k)$ sample of central data $\mathbf{c}_k := \overrightarrow{\mathcal{S}}(\mathbf{p}_k)$

    Optimize: Find the (global) minimizer over $\mathbf{q} \in \mathbb{R}^D$ of:

$$\mathbf{q}_{\min} \leftarrow \min_{\mathbf{q}} \ F(\mathbf{q}) \equiv \chi^2(\mathbf{d}_i, \overrightarrow{\mathcal{M}}(\mathbf{q}), \mathbf{M}) = \left(\mathbf{d}_i - \overrightarrow{\mathcal{M}}(\mathbf{q})\right)^T \mathbf{M} \left(\mathbf{d}_i - \overrightarrow{\mathcal{M}}(\mathbf{q})\right)$$

    Record: $\Delta\chi^2(\mathbf{p}_k) \leftarrow \chi^2(\mathbf{d}_i, \mathbf{c}_k, \mathbf{M}) - \chi^2(\mathbf{d}_i, \overrightarrow{\mathcal{M}}(\mathbf{q}_{\min}), \mathbf{M})$ distance to mean.

  end

end

Algorithm 2: Optimization-Based Feldman-Cousins Algorithm.

BF point is not limited to the input grid point!

From: Sven's overleaf document
https://www.overleaf.com/project/5f7205a341ace1000189420d

- In new procedure, use optimization to find the chi2 minimum and BF point
- The data is now encoded as MFA model
- Currently using cppoptlib libraries for the optimizer
- Exploring the **LBfgsbSolver** to set the constraint for the minimization point

Complete Workflow

SBND — Neutrino energy spectrum
MicroBooNE — Neutrino energy spectrum
ICARUS — Neutrino energy spectrum

Covariance Matrix

Encoded in MFA model

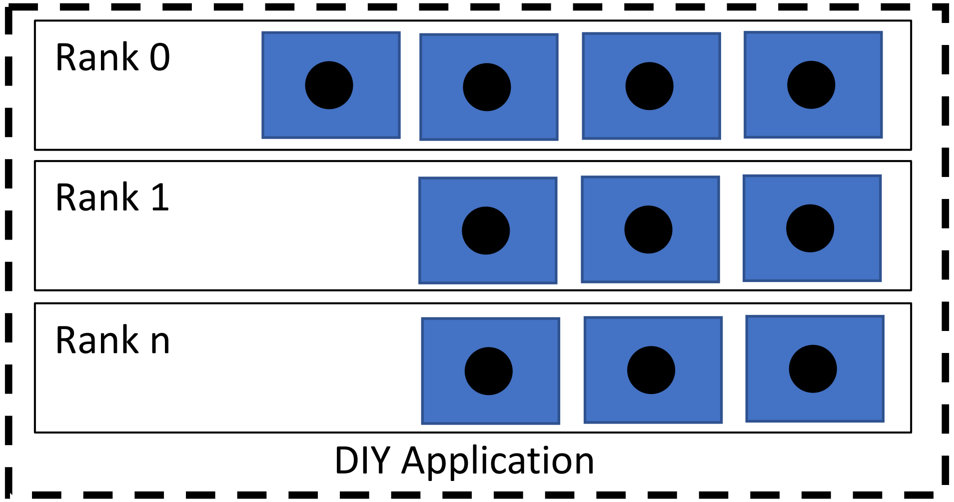
Input

Perform χ^2 calculation at each **oscillation parameter space point per toy experiments per rank in a node** – **Optimization-based Feldman Cousins procedure**

Read once

HPC tools: MPI to distribute the work load to all ranks through memory

*MPI: Message Passing Interface



HPC tools: MPI to merge

Machine	Cori phase 1 (Haswell)	Cori phase 2 (KNL)
CPU	Intel Xeon E5-2698 v3	Intel Xeon Phi 7250
Clockspeed	2.3 GHz	1.4 GHz
Cores per node	32	68

Output

Convert to HDF5

n-dimensional contour plot

Adding the FC curves to the Sensitivity Plot

Output

Convert to HDF5

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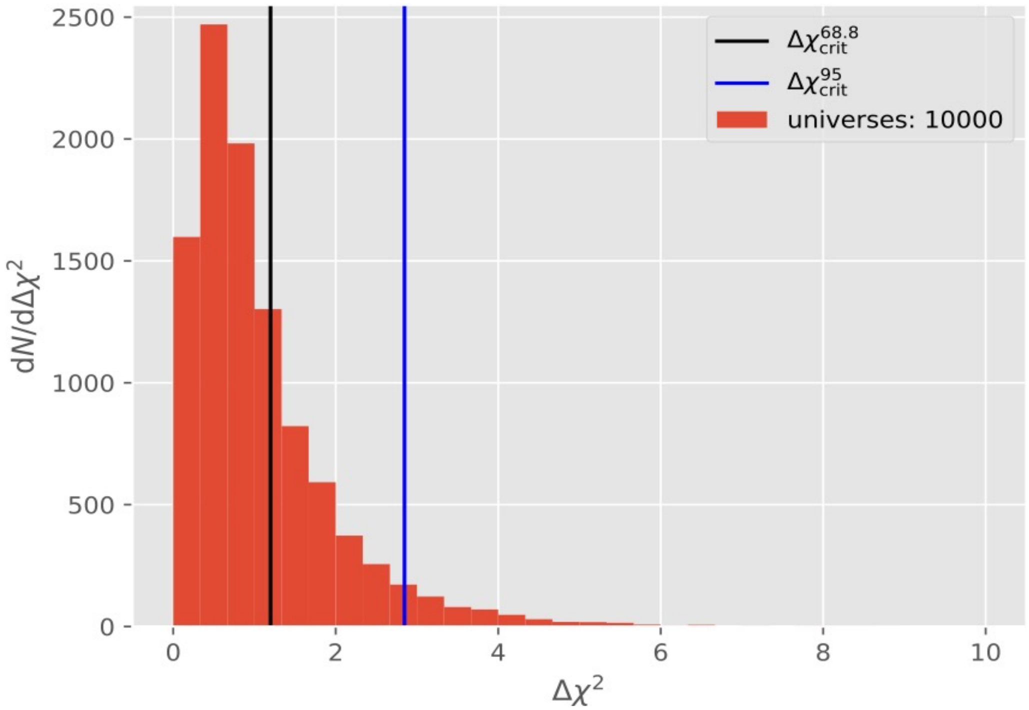
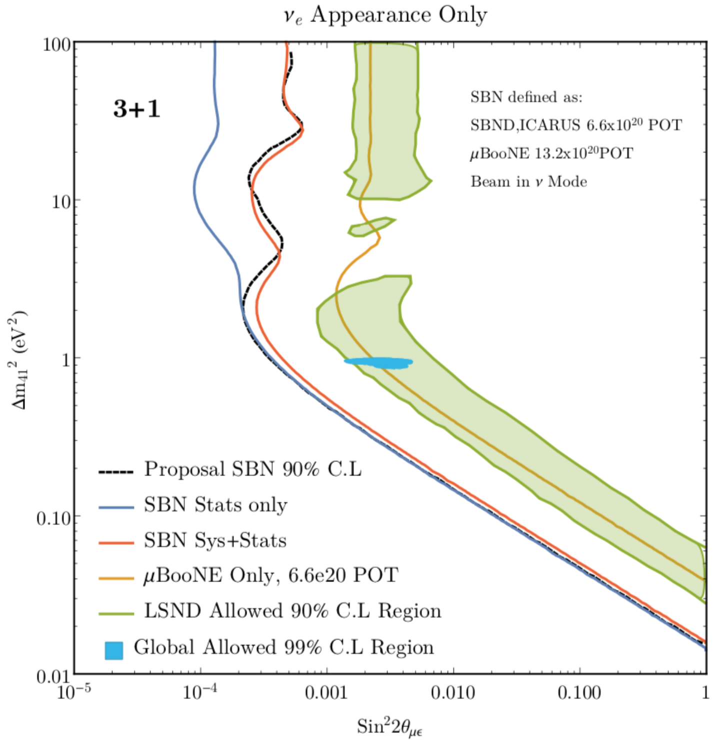
n-dimensional contour plot



[arXiv:2002.07858v1]

FC calculation



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Summary

- A lot of progress made since last All Hands Meeeting.
- In the process of implementing alternate approach to the grid scanning for higher dimensionality (7 parameters for 3N+2 → 3.2 mil grid points!).
  - Implementation of **MFA model**
  - Replacing grid scanning method with optimization using **libraries** from **cppoptlib**
  - Validation work for the MFA modeling and minimization are ongoing