Constraining Non-Unitarity in the Neutrino Sector using the SBN Facility

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Based on work with Georgia Karagiorgi

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MANCHESTER 1824
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Motivation: Current Status of Neutrino Oscillation

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric — Reactor/Interference — Solar

Three angles, θ_{13}, θ_{23}, θ_{12}

One Phase, δ_{CP}

Two Mass Differences, Δm^2_{sol} , Δm^2_{atm}

A Mass Ordering IO or NO?

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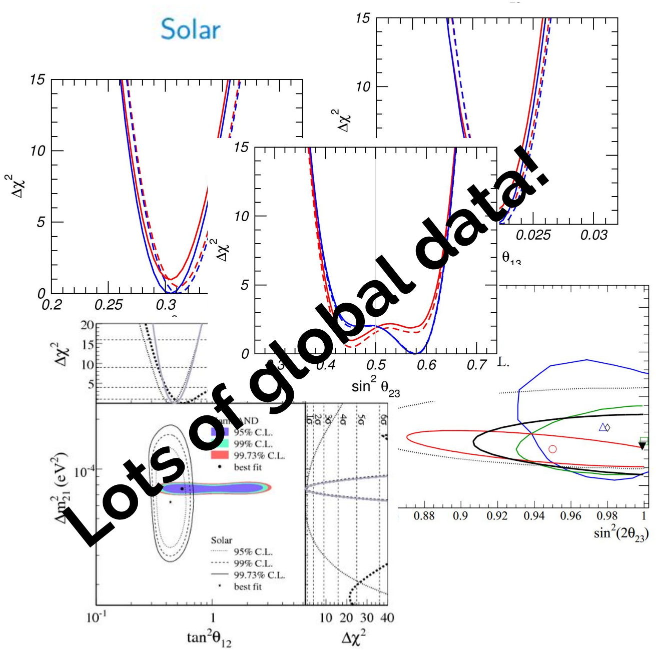

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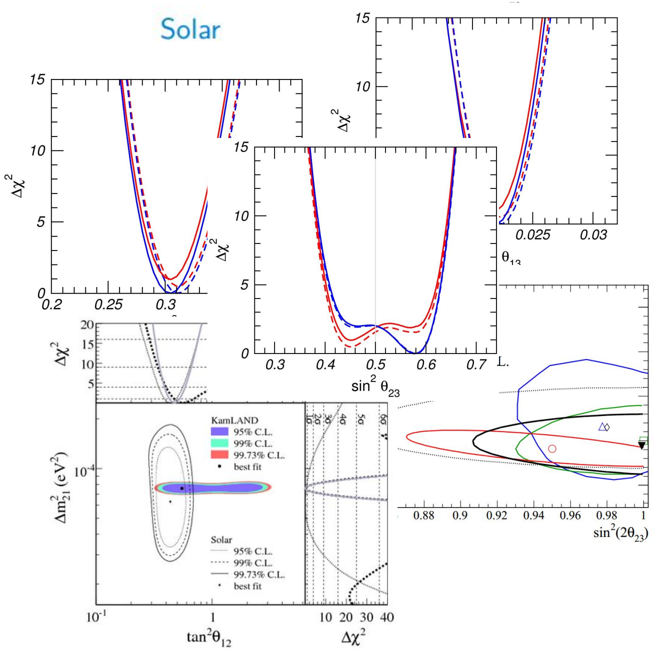
Atmospheric | Reactor/Interference | Solar



Three angles, θ_{13}, θ_{23}, θ_{12}

One Phase, δ_{CP}

Two Mass Differences, Δm^2_{sol} , Δm^2_{atm}

A Mass Ordering IO or NO?

+

An Assumption of Unitarity!

Parameterisation in terms of mixing angles is only valid if mixing matrix is unitary!

What do we actually measure?

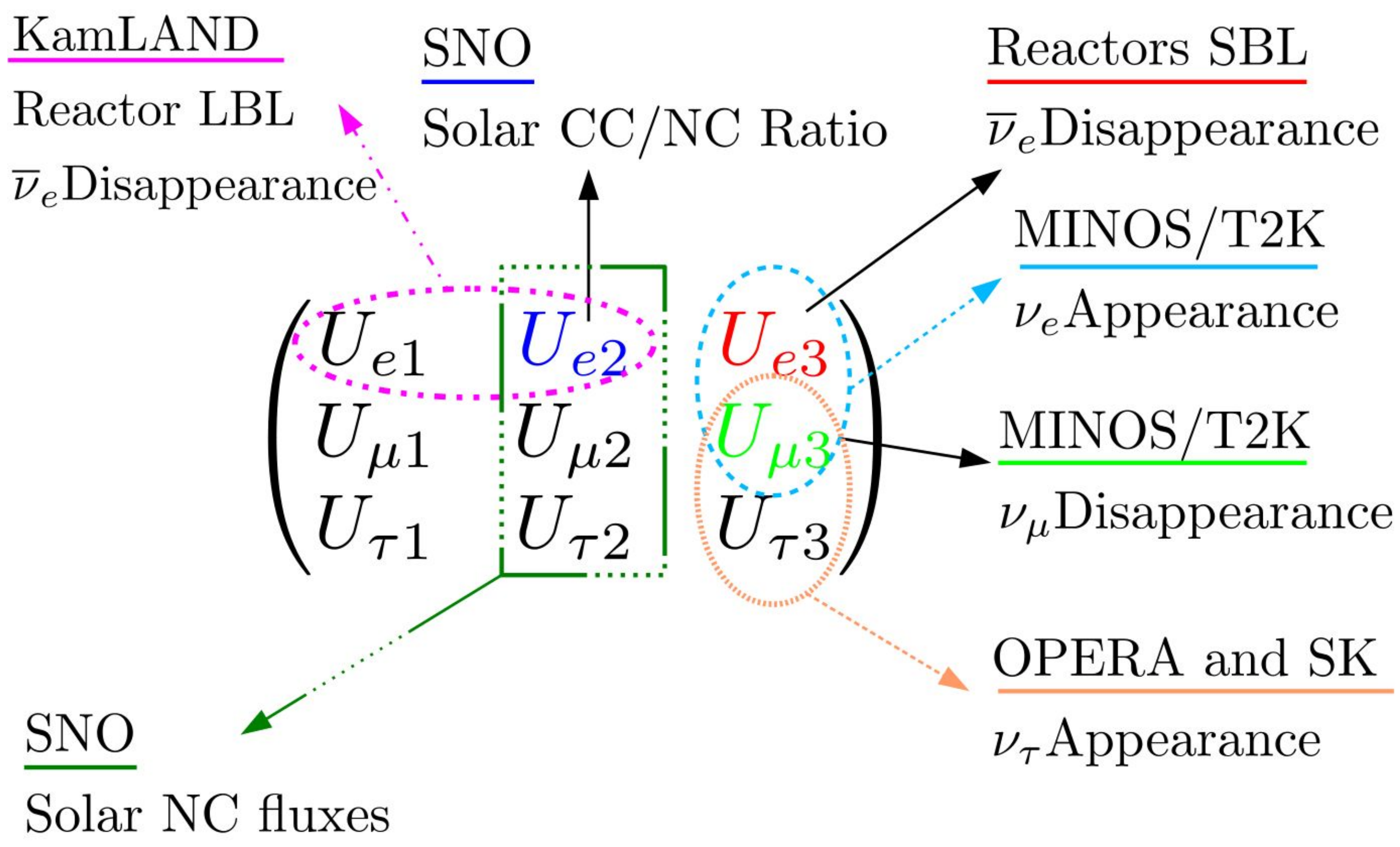
$$U_{\text{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass Eigenstates Labeled by Decreasing ν_e Content

$$|U_{e1}| \geq |U_{e2}| \geq |U_{e3}|$$

What do we actually measure?



Unitarity Conditions

$$U^{\dagger}_{\mathrm{PMNS}} U_{\mathrm{PMNS}} = 1 = U_{\mathrm{PMNS}} U^{\dagger}_{\mathrm{PMNS}}$$

6 Normalisations

3 Row

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$

$$|U_{\mu 1}|^2 + |U_{\mu 2}|^2 + |U_{\mu 3}|^2 = 1$$

$$|U_{\tau 1}|^2 + |U_{\tau 2}|^2 + |U_{\tau 3}|^2 = 1$$

and 3 Column

$$|U_{e1}|^2 + |U_{\mu 1}|^2 + |U_{\tau 1}|^2 = 1$$

$$|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2 = 1$$

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$

6 Unitarity Triangle Closures

3 Row

$$|U_{e1} U^*_{\mu 1} + U_{e2} U^*_{\mu 2} + U_{e3} U^*_{\mu 3}| = 0$$

$$|U_{e1} U^*_{\tau 1} + U_{e2} U^*_{\tau 2} + U_{e3} U^*_{\tau 3}| = 0$$

$$|U_{\mu 1} U^*_{\tau 1} + U_{\mu 2} U^*_{\tau 2} + U_{\mu 3} U^*_{\tau 3}| = 0$$

and 3 Column

$$|U_{e1} U^*_{e2} + U_{\mu 1} U^*_{\mu 2} + U_{\tau 1} U^*_{\tau 2}| = 0$$

$$|U_{e1} U^*_{e3} + U_{\mu 1} U^*_{\mu 3} + U_{\tau 1} U^*_{\tau 3}| = 0$$

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Unitarity Conditions

$$U^\dagger_{\text{PMNS}} U_{\text{PMNS}} = 1 = U_{\text{PMNS}} U^\dagger_{\text{PMNS}}$$

6 Normalisations

3 Row

$(U^\dagger U)_{ee}$ $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$

$(U^\dagger U)_{\mu\mu}$ $|U_{\mu 1}|^2 + |U_{\mu 2}|^2 + |U_{\mu 3}|^2 = 1$

$|U_{\tau 1}|^2 + |U_{\tau 2}|^2 + |U_{\tau 3}|^2 = 1$

and 3 Column

$|U_{e1}|^2 + |U_{\mu 1}|^2 + |U_{\tau 1}|^2 = 1$

$|U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2 = 1$

$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$

6 Unitarity Triangle Closures

3 Row

$(U^\dagger U)_{e\mu}$ $|U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2} + U_{e3}U^*_{\mu 3}| = 0$

$|U_{e1}U^*_{\tau 1} + U_{e2}U^*_{\tau 2} + U_{e3}U^*_{\tau 3}| = 0$

$|U_{\mu 1}U^*_{\tau 1} + U_{\mu 2}U^*_{\tau 2} + U_{\mu 3}U^*_{\tau 3}| = 0$

and 3 Column

$|U_{e1}U^*_{e2} + U_{\mu 1}U^*_{\mu 2} + U_{\tau 1}U^*_{\tau 2}| = 0$

$|U_{e1}U^*_{e3} + U_{\mu 1}U^*_{\mu 3} + U_{\tau 1}U^*_{\tau 3}| = 0$

$|U_{e2}U^*_{e3} + U_{\mu 2}U^*_{\mu 3} + U_{\tau 2}U^*_{\tau 3}| = 0$

Where does this non-unitarity come from?

Additional $SU(3) \times SU(2) \times U(1)$ singlets a generic feature of many BSM scenarios.

$$U_{PMNS}^{\text{extended}} = \begin{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} & \begin{matrix} \cdots & U_{eN} \\ \cdots & U_{\mu N} \\ \cdots & U_{\tau N} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \end{matrix} & \begin{matrix} \ddots & \vdots \end{matrix} \\ \begin{matrix} U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \cdots & U_{s_n N} \end{matrix} \end{pmatrix}$$

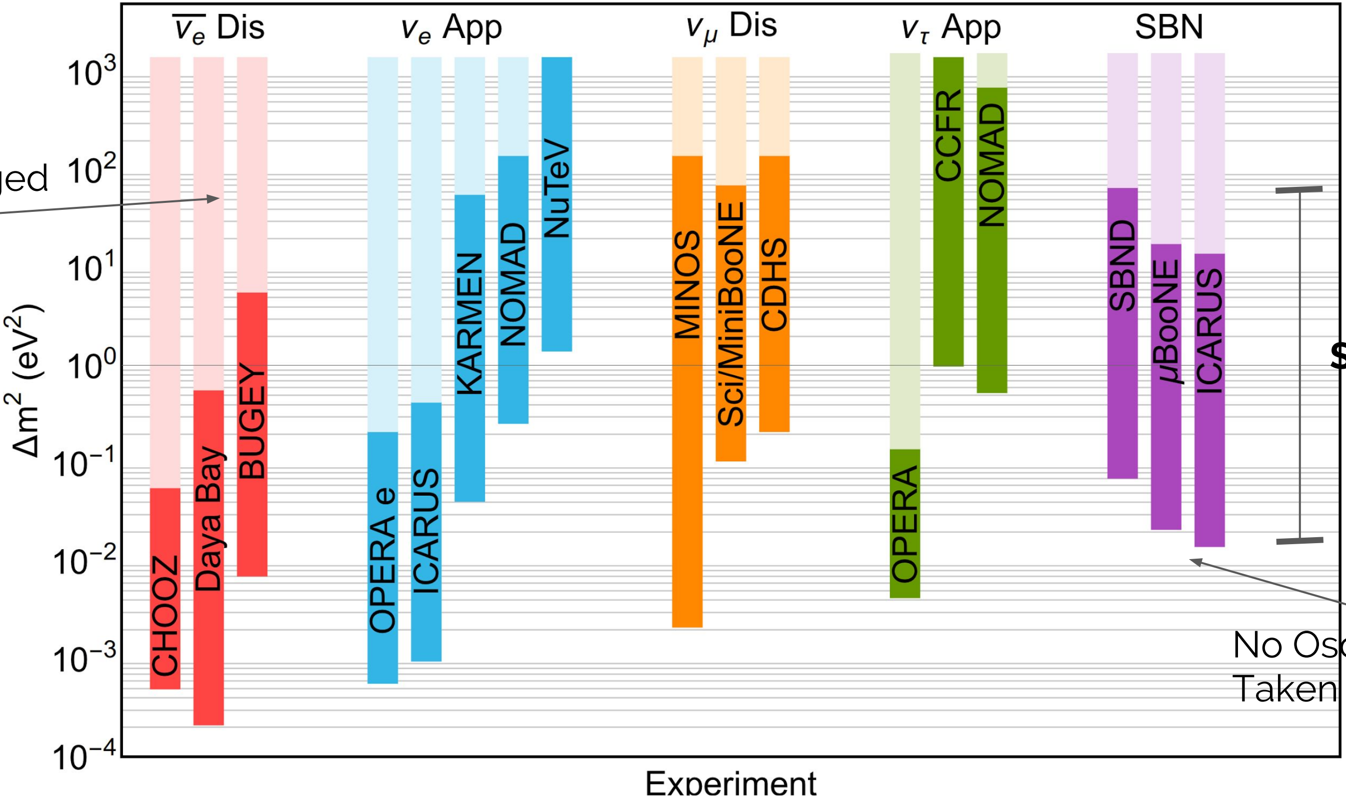
Any arbitrary subset not necessarily unitary.

$$U_{PMNS}^{3\times 3} = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}|e^{i\delta_{\mu 1}} & |U_{\mu 2}|e^{i\delta_{\mu 2}} & |U_{\mu 3}| \\ |U_{\tau 1}|e^{i\delta_{\tau 1}} & |U_{\tau 2}|e^{i\delta_{\tau 2}} & |U_{\tau 3}| \end{pmatrix}$$

Not necessarily oscillating steriles, masses can be eV, keV, MeV... TeV... all the way up to GUT scales ~ 10^{16} eV.

Measuring Sterile Neutrinos at short baselines

Oscillations fully averaged out



SBN

No Oscillations Taken place yet

Non-Unitary approach valid (for steriles) in SBN from ~ 50 eV^2 upwards

Effects of non-unitarity at Short Baselines

Non-unitarity can arise from sterile neutrinos, but these are either integrated out or averaged out. The analysis is from a three active neutrino standpoint only.

Observable non-unitarity can also arise from non-sterile sources such as extra-dimensions, new interactions or perhaps something we have never thought of (new new physics)

$$\begin{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} & \begin{matrix} \cdots & U_{eN} \\ \cdots & U_{\mu N} \\ \cdots & U_{\tau N} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n N} \end{matrix} \end{pmatrix}$$

The new physics is encoded in the degree of non-unitarity of the 3x3 mixing matrix

Effects of non-unitarity at Short Baselines

Non-unitarity effects the oscillation probability we know and love;

$$
\begin{aligned}
P\left(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta\right) = & \left| \sum_{i=1} U^*_{\beta i} U_{\alpha i} \right|^2 \\
& - 4 \sum_{i<j} \mathrm{Re}(U_{\beta i} U^*_{\beta j} U_{\alpha i} U^*_{\alpha j}) \sin^2\left(\Delta m^2_{ji} \frac{L}{4E_\nu}\right) \\
& \overset{(-)}{+} \; 2 \sum_{i<j} \mathrm{Im}(U_{\beta i} U^*_{\beta j} U_{\alpha i} U^*_{\alpha j}) \sin\left(\Delta m^2_{ji} \frac{L}{2E_\nu}\right),
\end{aligned}
$$

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$$\cancel{-4\sum_{i<j} \mathrm{Re}(U_{\beta i}U^*_{\beta j}U_{\alpha i}U^*_{\alpha j}) \sin^2\left(\Delta m^2_{ji}\frac{L}{4E_\nu}\right)}$$

$$\cancel{\overset{(-)}{+}\ 2\sum_{i<j} \mathrm{Im}(U_{\beta i}U^*_{\beta j}U_{\alpha i}U^*_{\alpha j}) \sin\left(\Delta m^2_{ji}\frac{L}{2E_\nu}\right)},$$

At baselines we are interested in, solar and atmospheric mass splittings are insignificant. These terms vanish*

*non-unitarity only affects amplitudes, not frequencies so we can fix Δm^2 at global b.f.

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Not necessarily 0 or 1.
Independent of E_ν and L !
"Zero-Distance" or
"Instantaneous" Oscillation
Probability.

At baselines we are interested in, solar and atmospheric mass splittings are insignificant.
These terms vanish*

Can be due to averaged oscillations, or heavier non-oscillating steriles

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Effects of non-unitarity at Short Baselines

Non-unitarity effects the oscillation probability we know and love;

$$P\left(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta\right) = \left|\sum U^*_{\beta i} U_{\alpha i}\right|^2$$

$$\cancel{- 4 \sum_{i<j} \mathrm{Re}(}$$

$$\cancel{\overset{(-)}{+} \; 2 \sum_{i<j} \mathrm{I}}$$

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Independent of E_ν and L !
“Zero-Distance” or
s” Oscillation

we are interested
atmospheric mass
insignificant.
vanish*

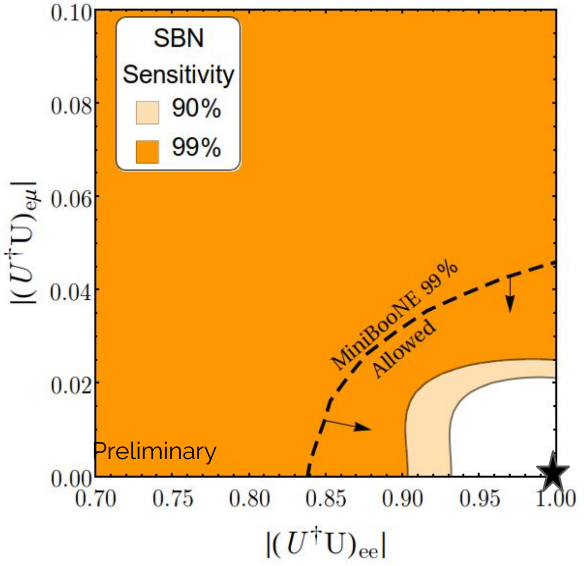
$$\text{“}P\text{”}(\nu_e \to \nu_e) = \left|(U^\dagger U)_{ee}\right|^2 ,$$
$$\text{“}P\text{”}(\nu_\mu \to \nu_\mu) = \left|(U^\dagger U)_{\mu\mu}\right|^2 ,$$
$$\text{“}P\text{”}(\nu_\mu \to \nu_e) = \left|(U^\dagger U)_{e\mu}\right|^2 .$$

Can be due t ... cillating steriles

Fit using full SBND, μBooNE and ICARUS **ν**-mode with a combined appearance and disappearance analysis, method as outlined in Davio Cianci’s talk, (right before this talk).

*non-unitarity only affects amplitudes, not frequencies so we can fix Δm^2 at global b.f.

Preliminary Results



Orange color shows region SBN is sensitive to violations of unitarity.

Black dashed line shows previous SBL **allowed** regions interpreted from MiniBooNE
(G.Karagiorgi FERMILAB-THESIS-2010-39)

There is overlap!

★Indicates Unitary PMNS

Perform a global scan of parameter space

Joint ν_e appearance and ν_μ disappearance fit

SBN has potential to significantly improve on previous MiniBooNE non-unitarity bounds.

Assuming neutrino mode only
SBND/ICARUS with 6.6e^{20} POT
MicroBooNE with 13.2e^{20} POT

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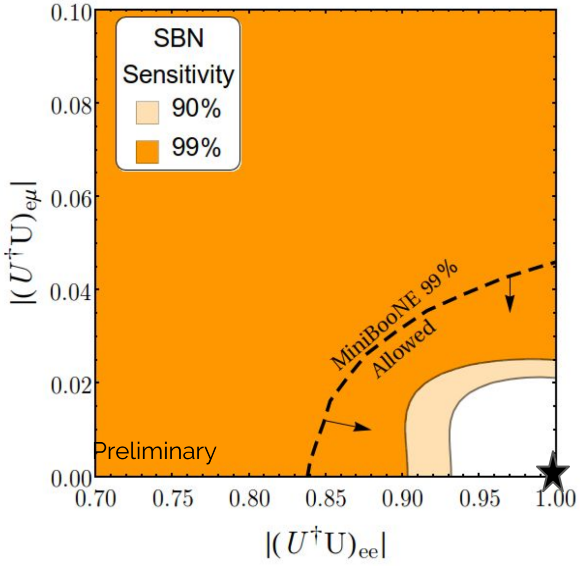

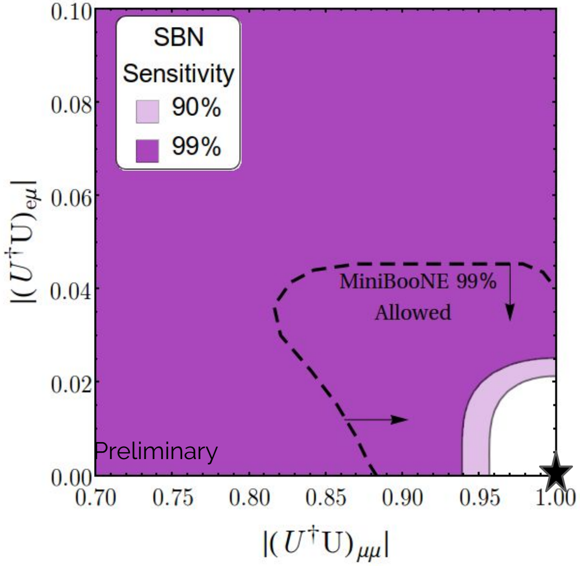

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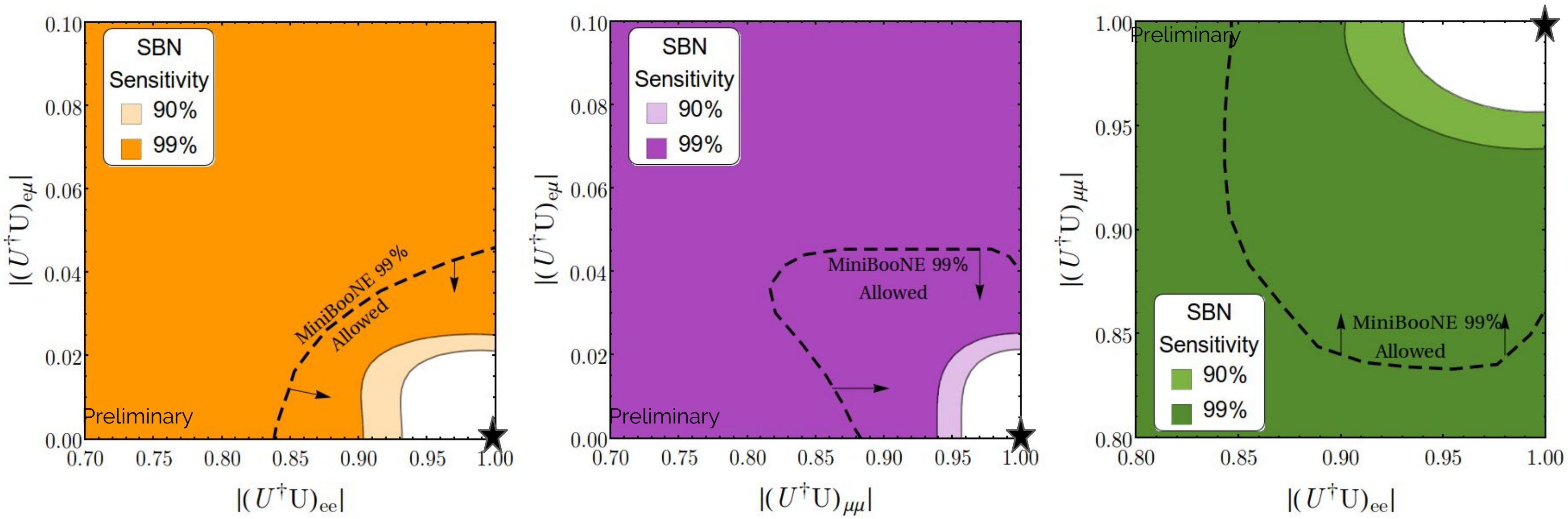

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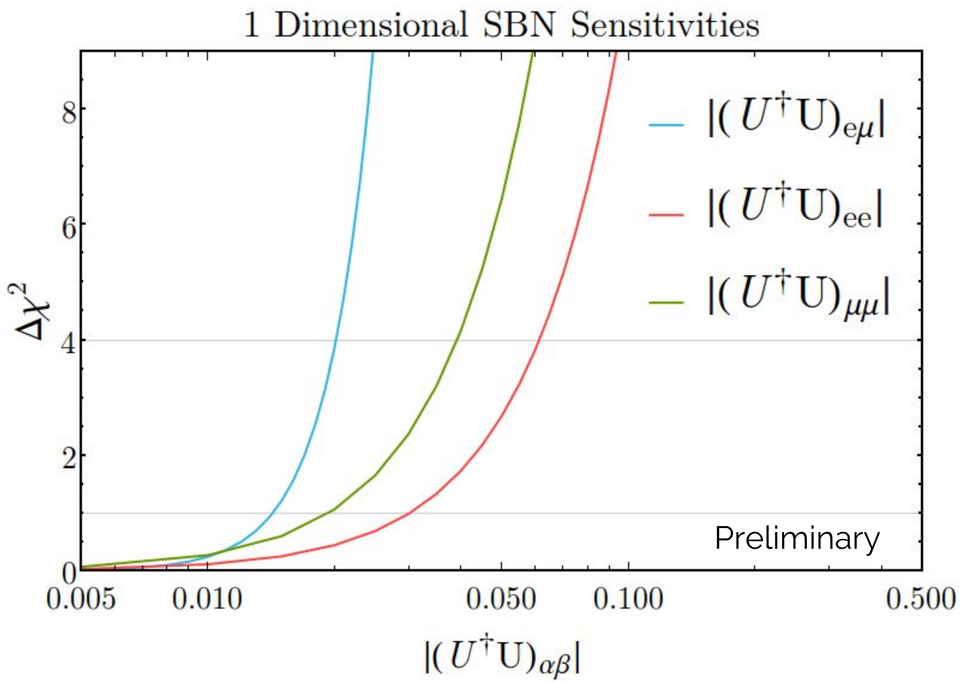

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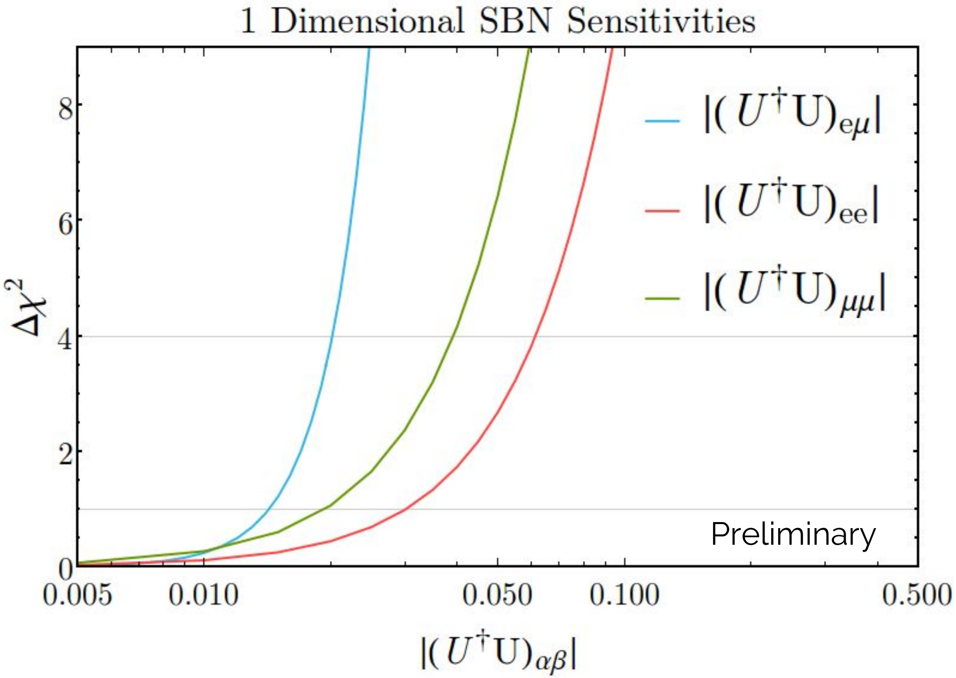

Assuming neutrino mode only
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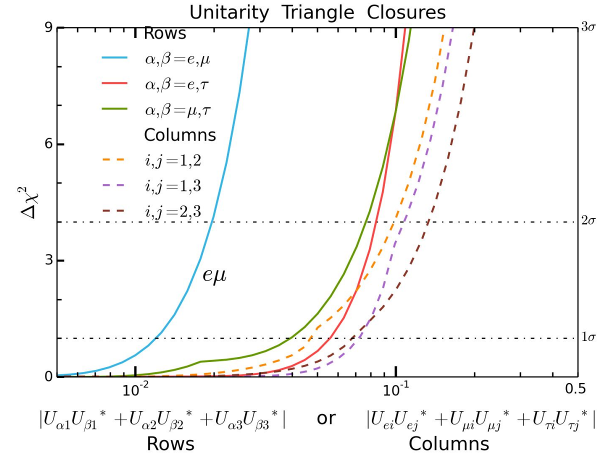
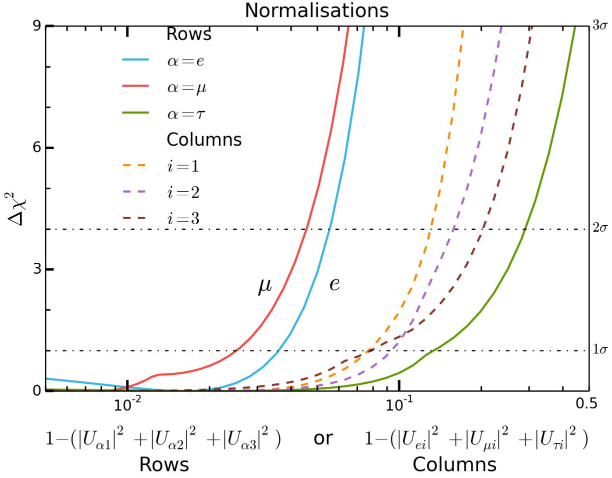
Global Constraints, valid ~ m_N > 0.1 eV





M.R-L, S.Parke **[hep-ph]** arXiv:1508.05095

Conclusions

Unitarity remains an initial theoretical assumption inherent in many analyses, but is the basis for the validity of the 3ν paradigm.

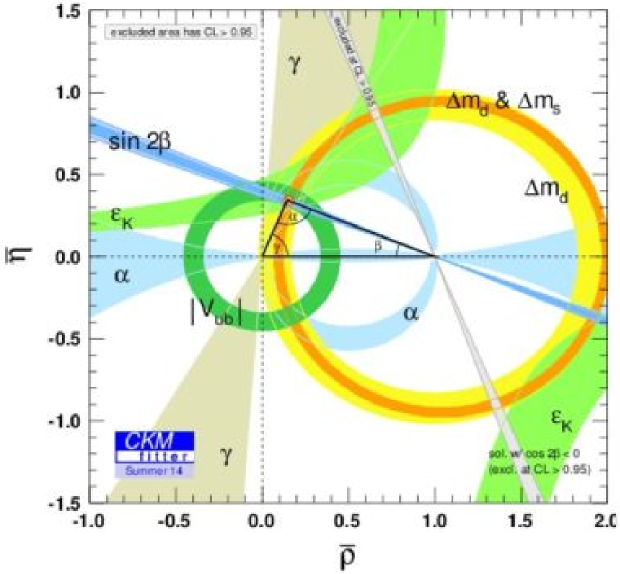
If the U_{PMNS} matrix is indeed non-unitarity, SBN will be sensitive to a wide region of parameter space not excluded by MiniBooNE, and if nothing is observed should be able to significantly improve the Short Baseline bounds.

The addition of a full high statistics NC analysis will show potential sensitivity to $|(U^{\dagger}U)_{\tau\tau}|$ and $|(U^{\dagger}U)_{\alpha\tau}|$, by far the worst known parameters, and any future anti-neutrino running will give information on the CP violating phases possibly introduced by such non-unitarity.


Thank You!

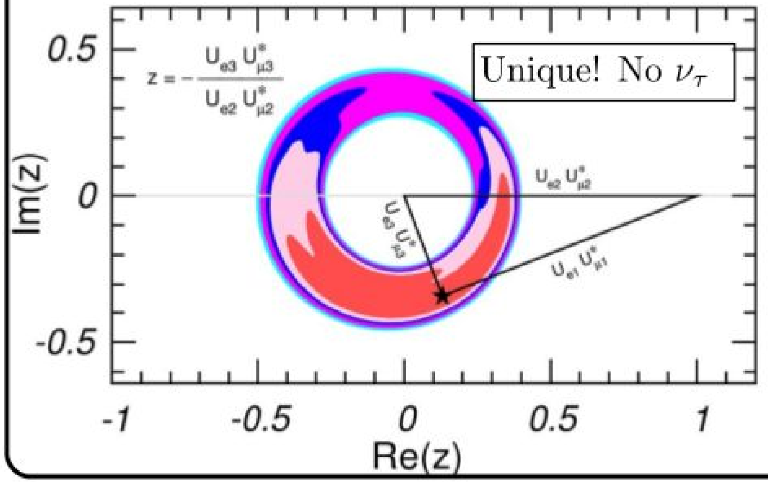
Backup Slides?

Unitarity Triangles in the neutrino sector: quite a way to go.



$\nu_e \nu_\mu$ Triangle

$$U_{e1}U_{\mu 1}^* + U_{e2}U_{\mu 2}^* + U_{e3}U_{\mu 3}^* = 0$$



Quark Sector

High precision without assuming unitarity

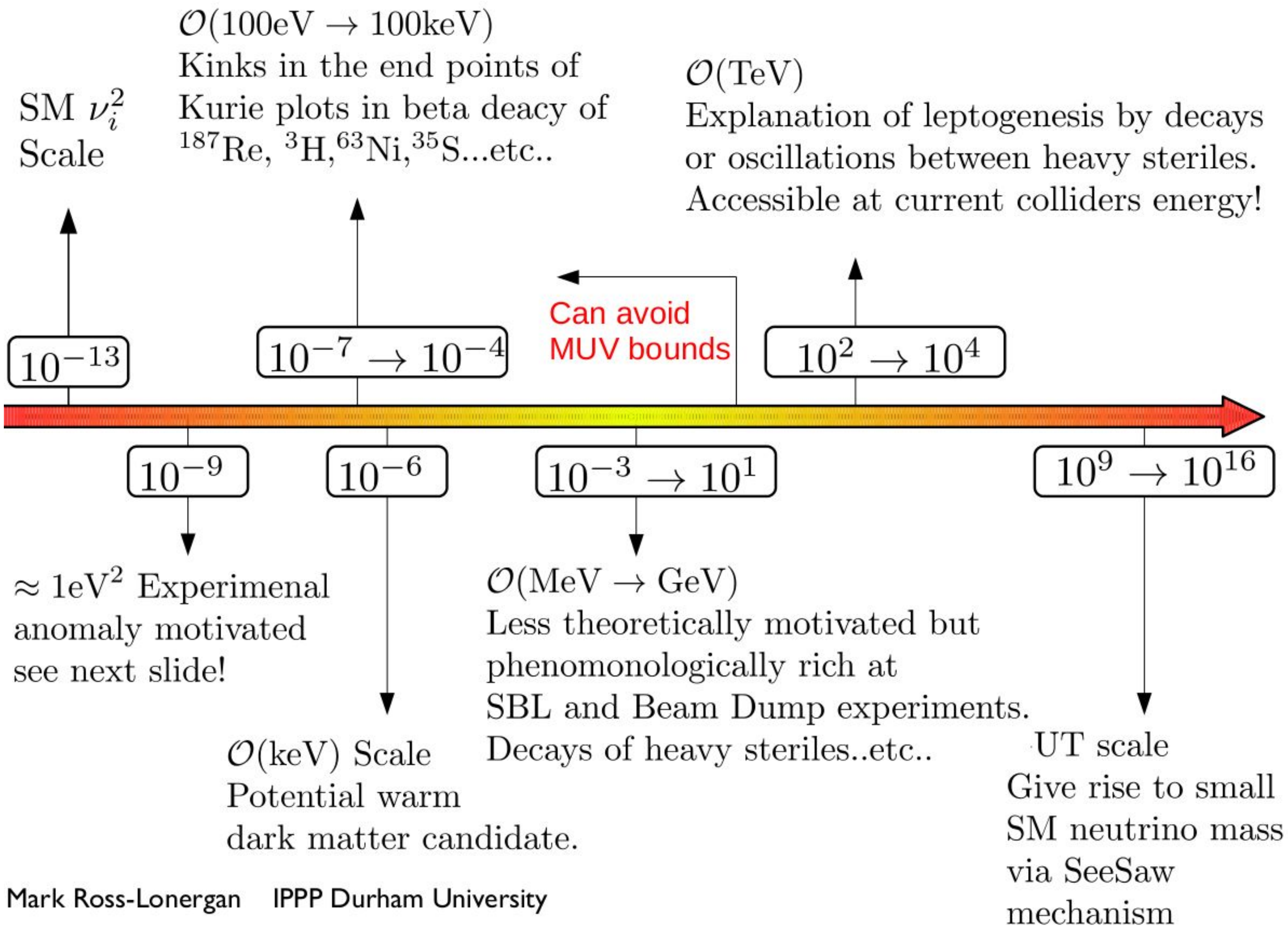
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$$
$$= 0.99999 \pm 0.0006$$

Neutrino Sector

Unitarity is assumed

$$|J| = 2 \times \text{Area}$$
$$= |s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta_{CP}|$$

Scale of new physics (in GeV)



Theoretical Geometric Bounds

If non-unitarity originated from an extended sector, extra correlations exist between parameters

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu N} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} & \cdots & U_{s_n N} \end{pmatrix}$$

- Form Cauchy Schwarz inequalities using new sterile elements

$$|U_{e4}U^*_{\mu 4} + \cdots U_{eN}U^*_{\mu N}|^2 \leq (|U_{e4}|^2 + \cdots |U_{eN}|^2)(|U_{\mu 4}|^2 + \cdots |U_{\mu N}|^2)$$

and as total $N \times N$ mixing matrix is unitary,

$$|U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2} + U_{e3}U^*_{\mu 3}|^2 \leq (1 - |U_{e1}|^2 - |U_{e2}|^2 - |U_{e3}|^2)(1 - |U_{\mu 1}|^2 - |U_{\mu 2}|^2 - |U_{\mu 3}|^2)$$
$$\leq \mathcal{O}(\epsilon^2)$$

Physically interesting subclass
$\sum_i |U_{\alpha i}|^2 \leq 1, \alpha = e, \mu, \tau$
$\sum_\alpha |U_{\alpha i}|^2 \leq 1, i = 1, 2, 3$

Analagous to how disapearance experiments can bound appearance rates in 3+1 sterile scenarios.

3 σ Ranges

$$|U|_{3\sigma}^{\substack{\textbf{w/o Unitarity} \\ \text{(with Unitarity)}}} =$$

$$\begin{pmatrix} \begin{matrix} 0.76 \to 0.85 \\ \scriptstyle (0.79 \to 0.85) \end{matrix} & \begin{matrix} 0.50 \to 0.60 \\ \scriptstyle (0.50 \to 0.59) \end{matrix} & \begin{matrix} 0.13 \to 0.16 \\ \scriptstyle (0.14 \to 0.16) \end{matrix} \\ \begin{matrix} 0.21 \to 0.54 \\ \scriptstyle (0.22 \to 0.52) \end{matrix} & \begin{matrix} 0.42 \to 0.70 \\ \scriptstyle (0.43 \to 0.70) \end{matrix} & \begin{matrix} 0.61 \to 0.79 \\ \scriptstyle (0.62 \to 0.79) \end{matrix} \\ \begin{matrix} 0.18 \to 0.58 \\ \scriptstyle (0.24 \to 0.54) \end{matrix} & \begin{matrix} 0.38 \to 0.72 \\ \scriptstyle (0.47 \to 0.72) \end{matrix} & \begin{matrix} 0.40 \to 0.78 \\ \scriptstyle (0.60 \to 0.77) \end{matrix} \end{pmatrix}.$$

The ranges for the individual elements, assuming unitarity (bracketed numbers in above expression), are in good agreement with published results in contemporary global fits such as ν-fit

CC Production: $$\frac{d\Phi_\alpha(E)}{dE} = \frac{d\Phi_\alpha^{CC}(E)}{dE} = \frac{d\Phi_\alpha^{CC(SM)}(E)}{dE}|(UU^\dagger)_{\alpha\alpha}|,$$

CC Detection: $$\sigma_\beta(E) = \sigma_\beta^{CC}(E) = \sigma_\beta^{CC(SM)}(E)|(UU^\dagger)_{\beta\beta}|,$$

$$P_{\alpha\beta}(L/E=0) = \frac{|(UU^\dagger)_{\beta\alpha}|^2}{|(UU^\dagger)_{\beta\beta}||(UU^\dagger)_{\alpha\alpha}|}.$$

Observed Events:

$$n = \int dE \quad \frac{d\Phi_\alpha^{CC}(E)}{dE} \quad P_{\alpha\beta} \quad \sigma_\beta^{CC}(E)\epsilon(E).$$

$$n = \int dE \quad \frac{d\Phi_\alpha^{CC(SM)}(E)}{dE} \quad \underbrace{|(UU^\dagger)_{\beta\alpha}|^2}_{\text{“}P_{\alpha\beta}\text{”}} \quad \sigma_\beta^{CC(SM)}(E)\epsilon(E).$$