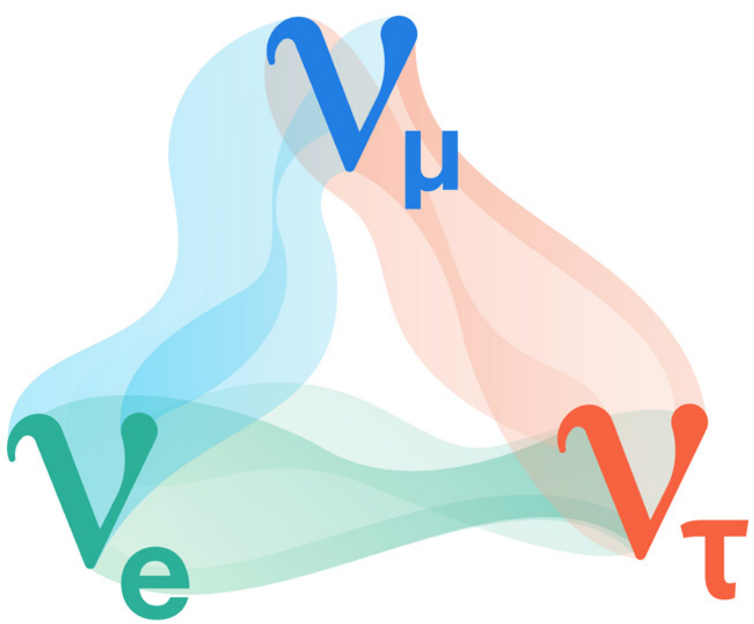
Tau Neutrinos and the Three-Flavor Model

Stephen Parke, Fermilab

Interactions:

simple

complicated



=U

unitarity ???

complicated

simple

Propagation:

PMNS matrix

flavor states

Mass Eigenstates

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

Mass Eigenstates
Labeled by
Decreasing
ν_e
content

PMNS matrix

flavor states

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Mass Eigenstates Labeled by Decreasing ν_e content

500 km/GeV

in vacuum

15,000 km/GeV

- $|\delta m^2_{31}| \approx 30\ \delta m^2_{21} > 0$ SNO

PMNS matrix

flavor states

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Mass Eigenstates Labeled by Decreasing ν_e content

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- Normal Ordering: $m_1^2 < m_2^2 < m_3^2$
and Inverted Ordering: $m_3^2 < m_1^2 < m_2^2$

NOνA, DUNE, HyperK
PINGU, ORCA $\cdots$, JUNO

Usual representation:

23	13	12	$0\nu\beta\beta$ Decay

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$$

Atmospheric	Reactor/Interference	Solar
$\mu \to \tau$ 500 Km/GeV	$\mu \leftrightarrow e$ 500 Km/GeV	$\mu \to e$ 15,000 Km/GeV

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$
$$\times\ \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

irrelevant for oscillations

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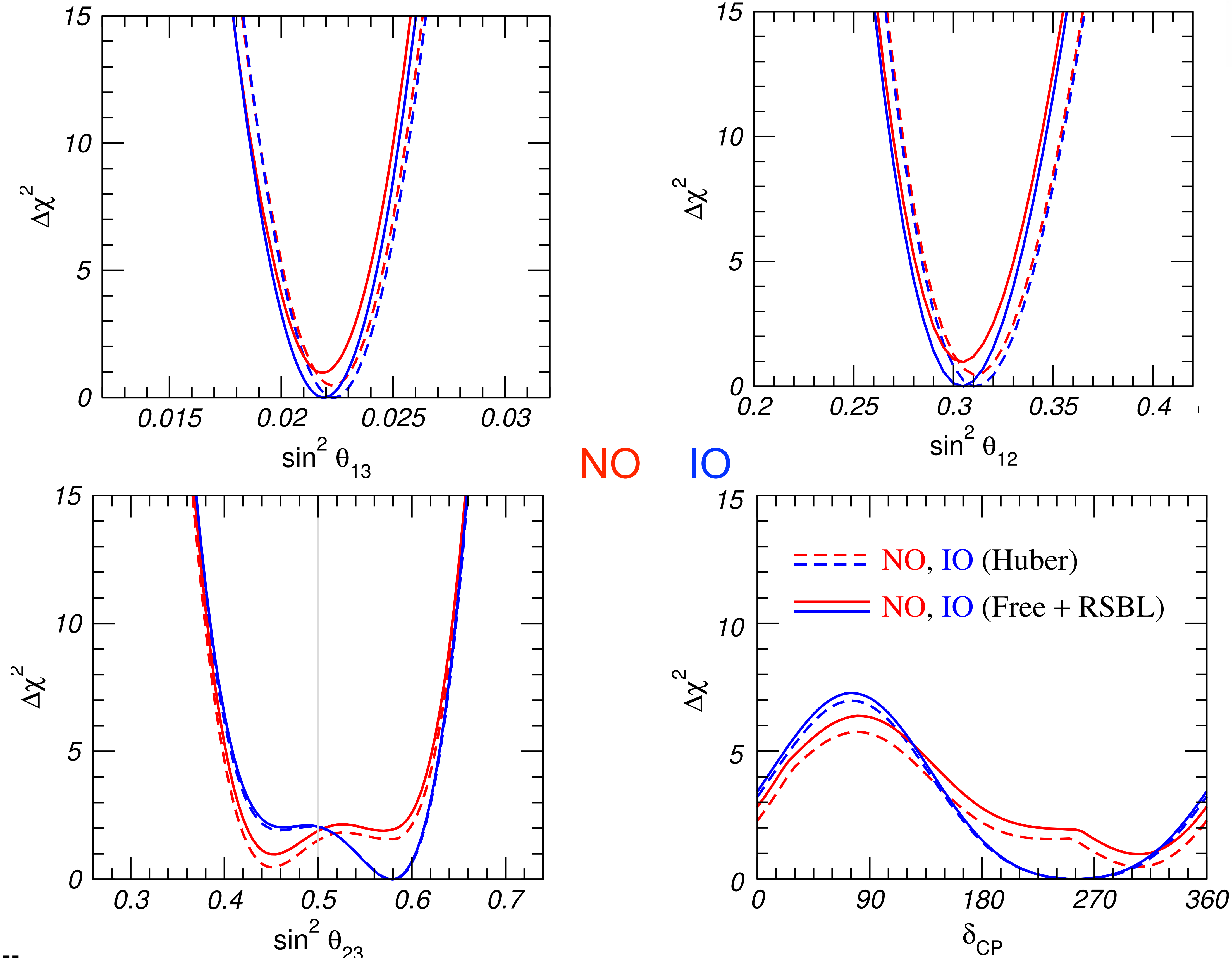
irrelevant for oscillations

UNITARITY IS BUILT IN: $U^\dagger U = 1$

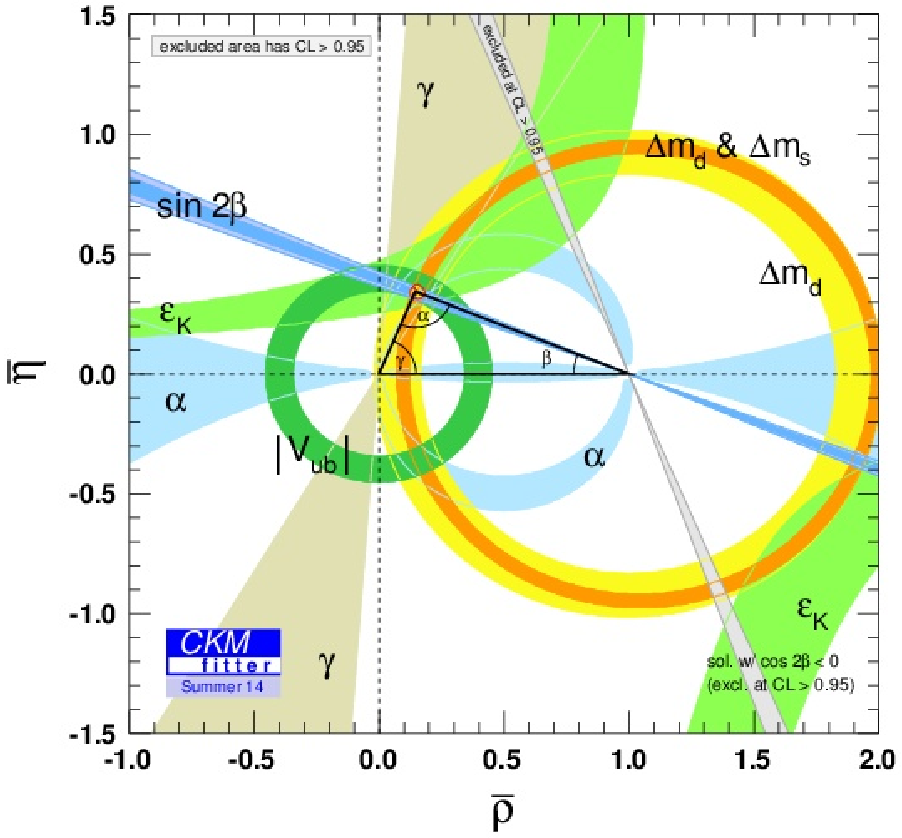
Global Fits:

2014



Unitarity Triangles:

Quarks:



Unitarity *Not* assumed

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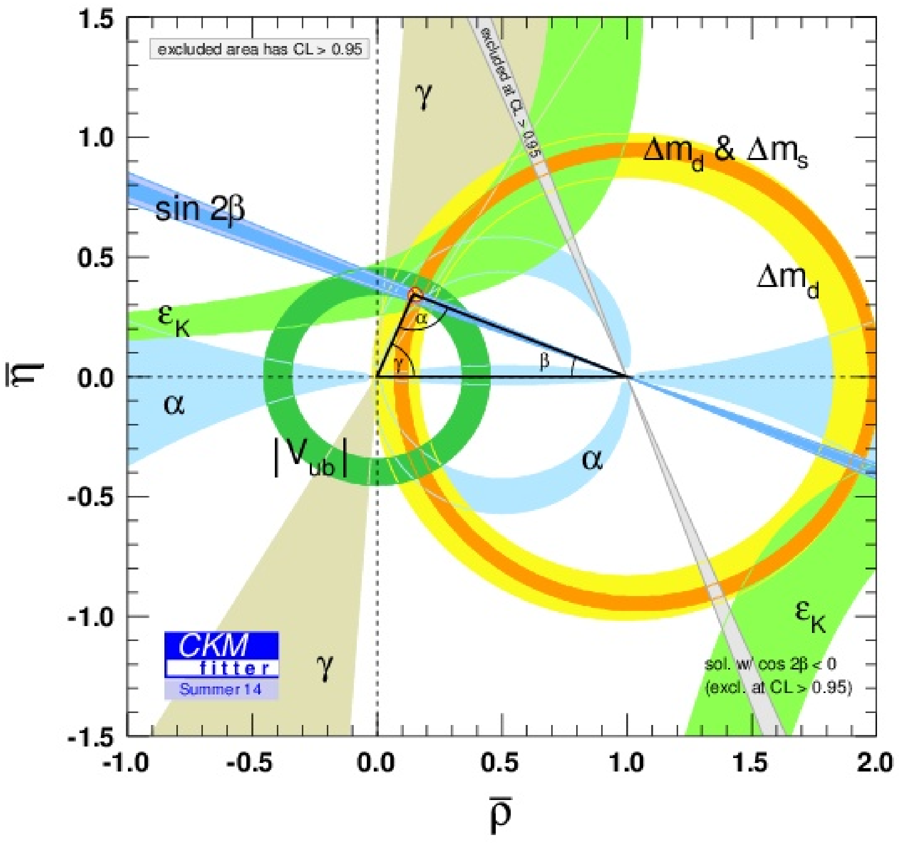
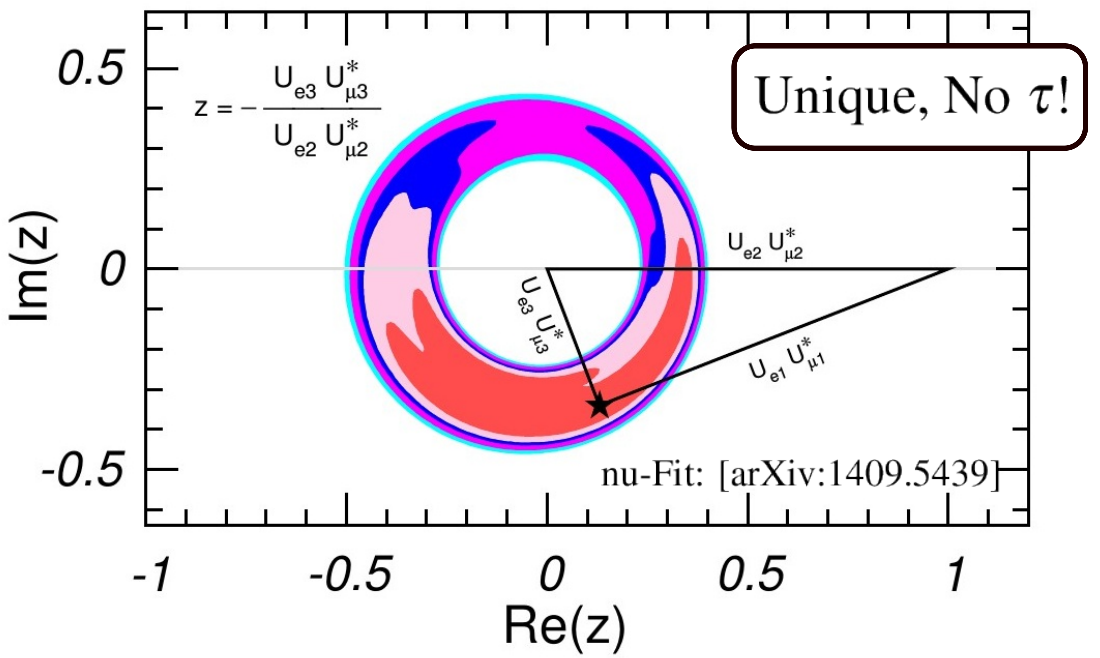


Unitarity *Not* assumed

Leptons:

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



Unitarity *Is* assumed.

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

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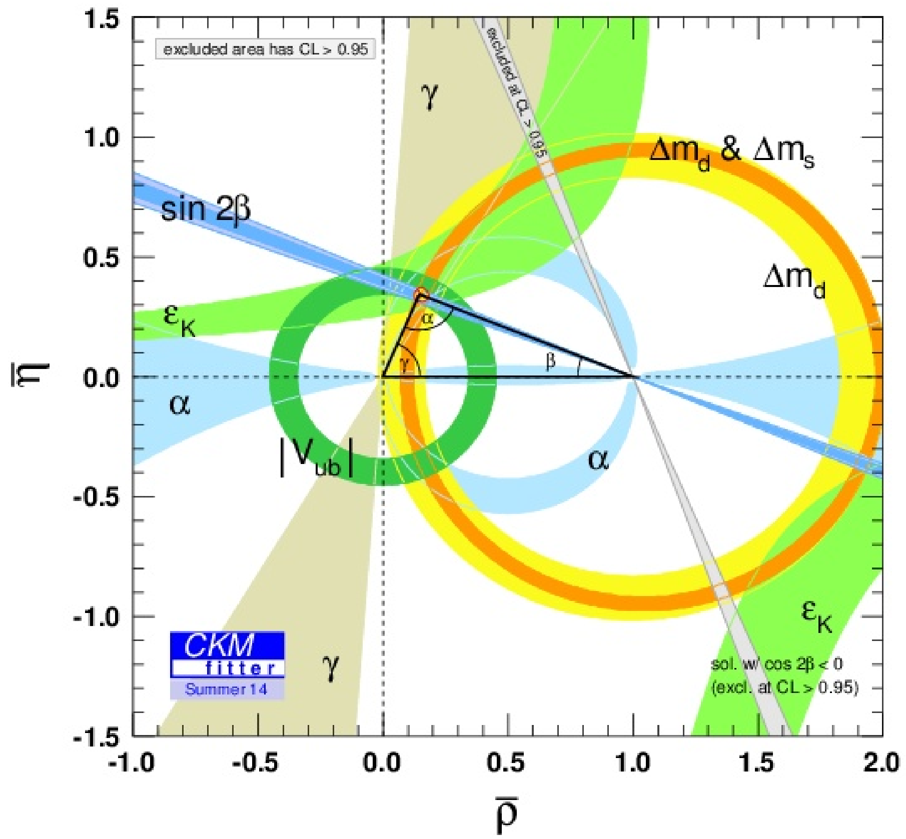

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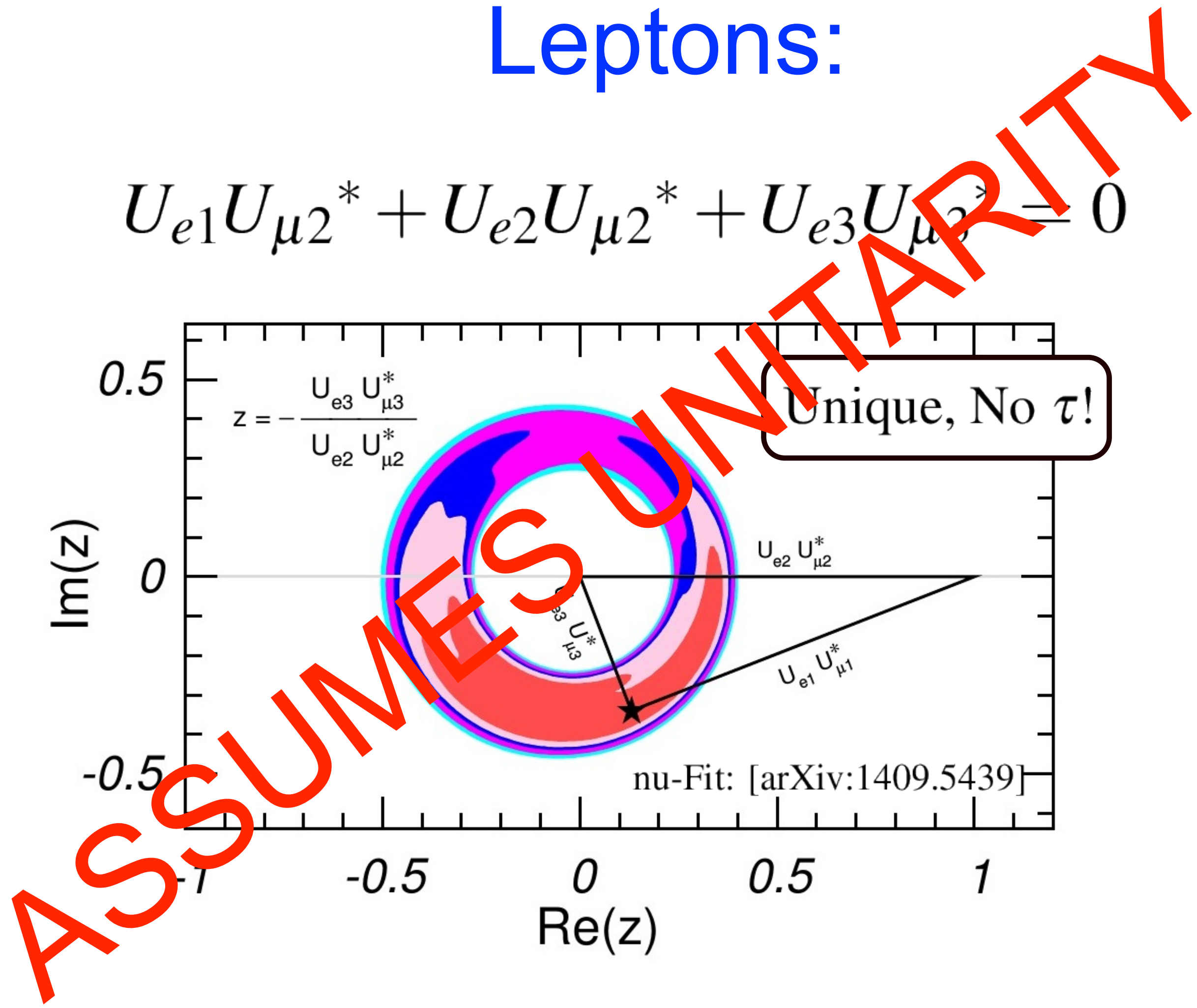

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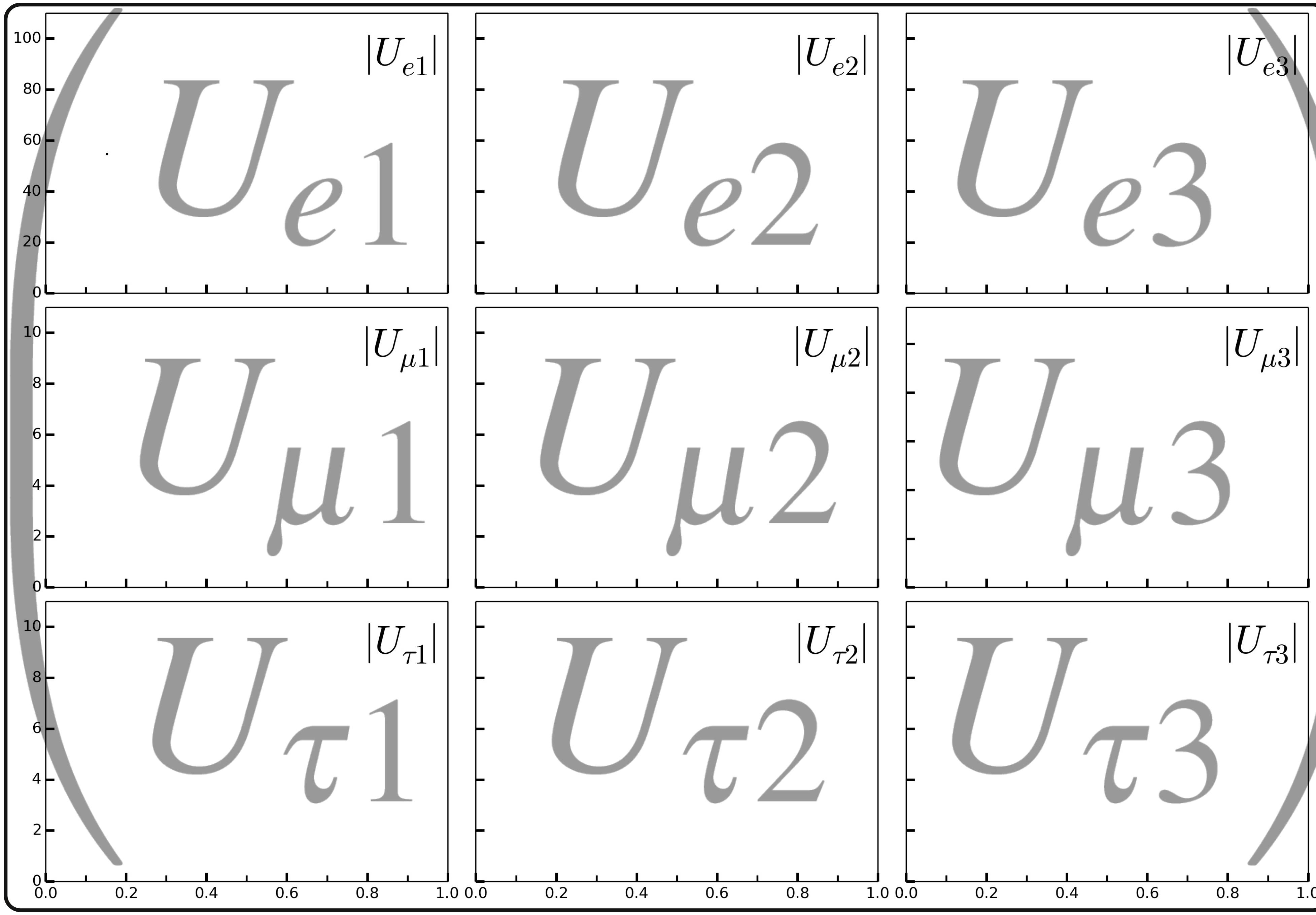
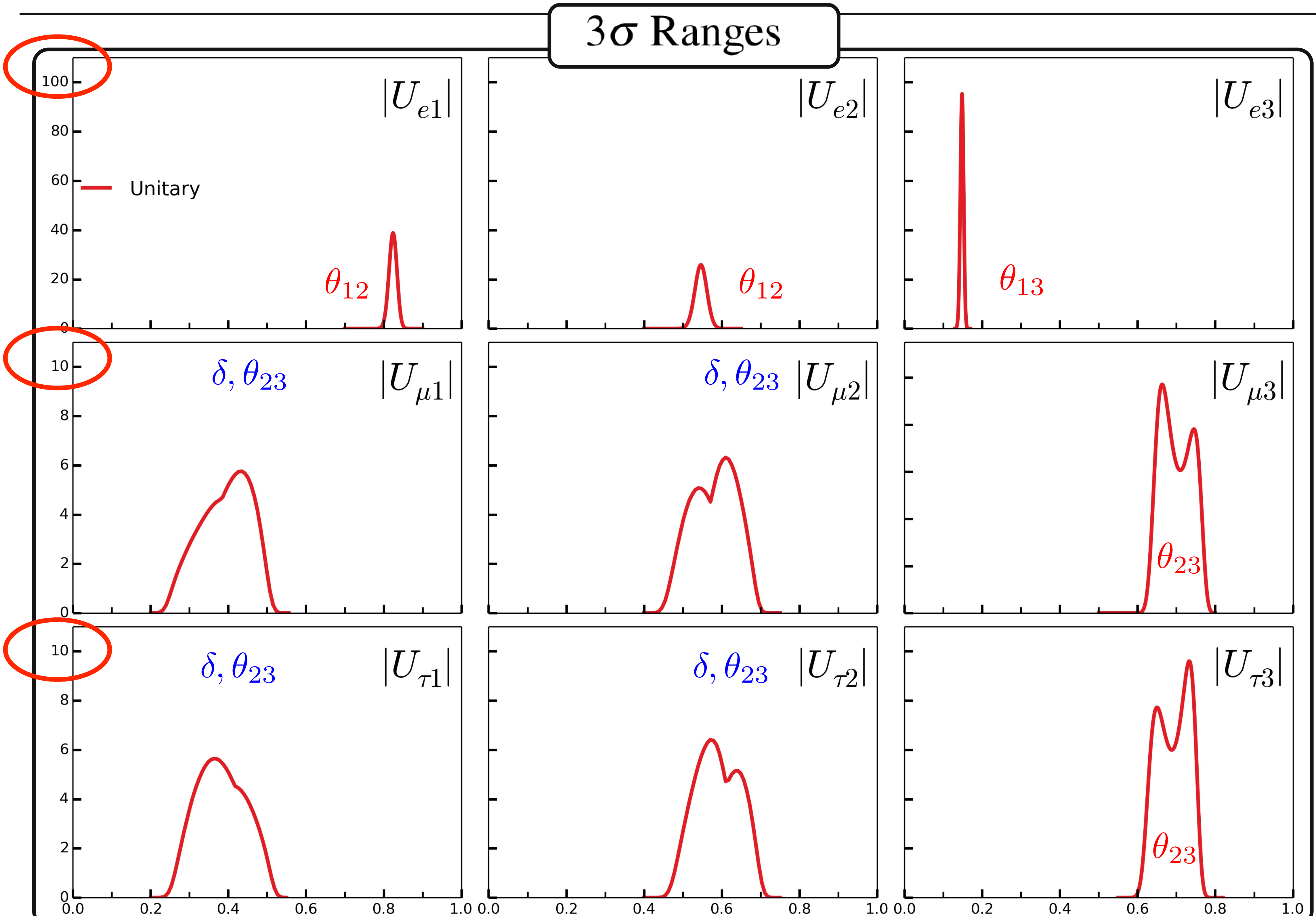
Visualisation of precision



Probability Distribution for |U|

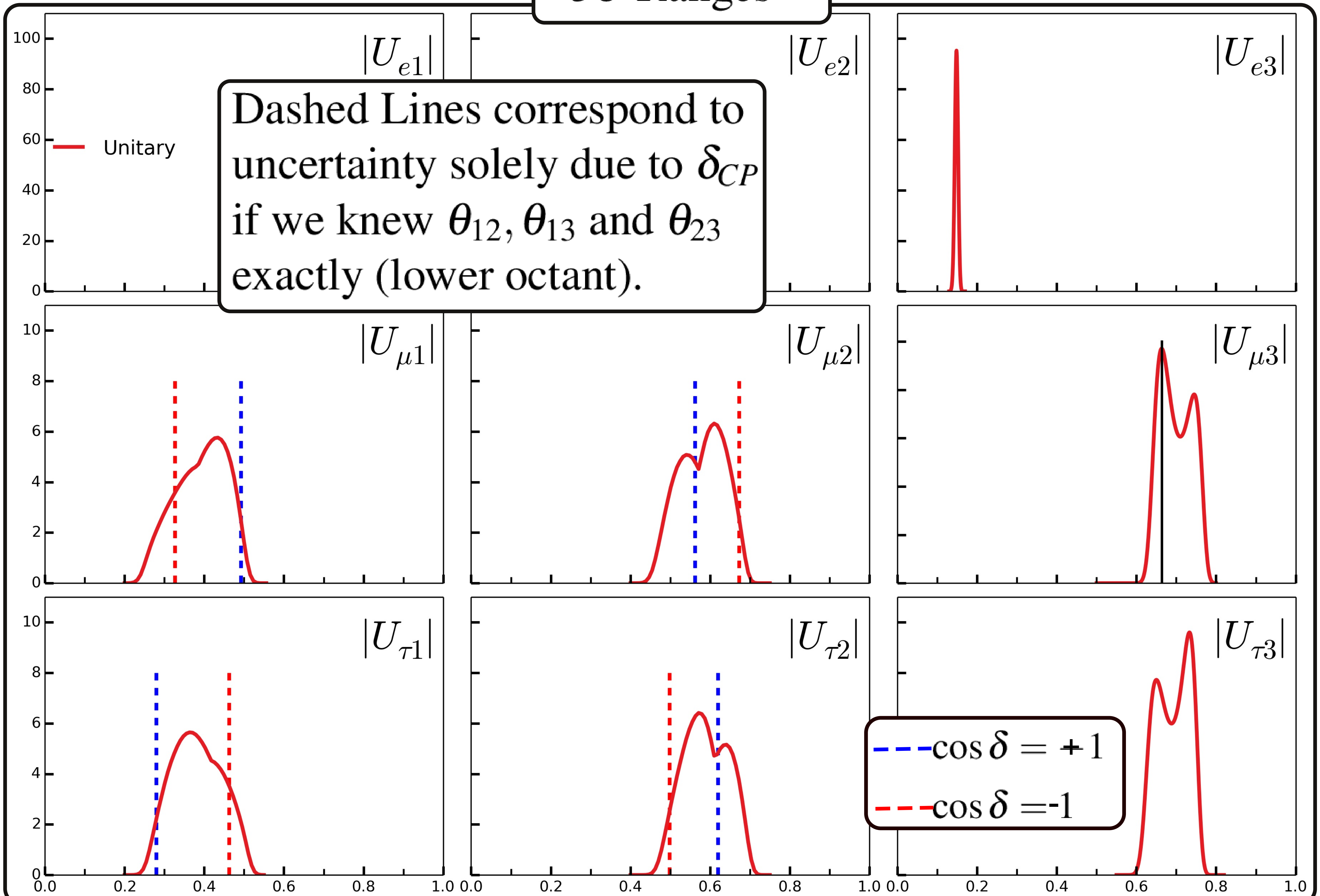
note scales

1508.05095 SP+Ross-Lonergan



*Agrees with contemporary global fits to within $\mathcal{O}(1\%)$ precision at 3 σ.

3σ Ranges



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Atmospheric: $\boxed{\mu \to \tau}$ 500 Km/GeV

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UNITARITY IS BUILT IN: $U^\dagger U = 1$

Unitarity Conditions:

ROWS: $\alpha = (e, \mu, \tau) \qquad j = (1, 2, 3)$

$$UU^\dagger = 1$$

$$\sum_j |U_{\alpha j}|^2 = 1$$ row normalizations

$$\sum_j U_{\alpha j} U^*_{\beta j} = 0 \quad \alpha \neq \beta$$ row orthogonality

All must be satisfied if U is unitary !

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9 conditions (real):
with 4 not involving τ
$(e^2, \mu^2$ and $\Delta_{e\mu})$
AND 5 involving τ's !

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COLUMNS:

$$U^\dagger U = 1$$

$$\sum_\alpha |U_{\alpha j}|^2 = 1 \quad \text{column normalizations}$$

$$\sum_\alpha U_{\alpha j} U^*_{\alpha k} = 0 \quad j \neq k \quad \text{column orthogonality}$$

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COLUMNS:

$$U^\dagger U = 1$$

ALL 9 conditions involve τ's !

$$\sum_\alpha |U_{\alpha j}|^2 = 1$$ column normalizations

$$\sum_\alpha U_{\alpha j} U^*_{\alpha k} = 0 \quad j \neq k$$ column orthogonality

All must be satisfied if U is unitary !

Non-Unitary 3x3

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

note: 13 - 9 = 4

Non-Unitary 3x3

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

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- 13 real parameters after rephrasing the leptonic fields !
- compared to 4 real parameters for unitary case.

note: 13 - 9 = 4

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ν_μ disappearance: L/E ~ 500 km/GeV

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

SK, K2K,
MINOS, T2K,
NOvA, ...

$$|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)$$

ν_μ disappearance: L/E ~ 500 km/GeV

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

SK, K2K,
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$$|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \quad \Rightarrow \quad \frac{|U_{\mu 3}|^2(\ |U_{\mu 1}|^2 + |U_{\mu 2}|^2\ )}{(\ |U_{\mu 1}|^2 + |U_{\mu 2}|^2 + |U_{\mu 3}|^2\ )}$$

Solar:

SNO (CC/NC ratio), ...

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$|\boldsymbol{U_{e2}}|^{\mathbf{2}}$$

Solar:

SNO (CC/NC ratio), ...

$$\begin{pmatrix} U_{e1} & \boxed{U_{e2}} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$|U_{e2}|^2 \quad \Rightarrow \quad \frac{|U_{e2}|^2}{(\ |U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2\ )}$$

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SNO (CC/NC ratio), ...

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$$|U_{e2}|^2 \quad \Rightarrow \quad \frac{|U_{e2}|^2}{(\ |U_{e2}|^2 + |U_{\mu 2}|^2 + |U_{\tau 2}|^2\ )}$$

- also SNO's NC fluxes constrains $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2$

ν_e disappearance: L/E ~ 500 m/MeV

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Daya Bay,
RENO,
Double Chooz

$$|U_{e3}|^2(1-|U_{e3}|^2)$$

ν_e disappearance: L/E ~ 500 m/MeV

$$\begin{pmatrix} \boxed{U_{e1} \quad U_{e2} \quad U_{e3}} \\ U_{\mu 1} \quad U_{\mu 2} \quad U_{\mu 3} \\ U_{\tau 1} \quad U_{\tau 2} \quad U_{\tau 3} \end{pmatrix}$$

Daya Bay,
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$$|U_{e3}|^2(1 - |U_{e3}|^2) \qquad \Rightarrow \qquad \frac{|U_{e3}|^2(\ |U_{e1}|^2+|U_{e2}|^2\ )}{(\ |U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2\ )}$$

ν_e disappearance: L/E ~ 15 km/MeV

= 15,000 km/GeV

KamLAND wiggles

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$|U_{e1}|^2 |U_{e2}|^2$$

JUNO will do much better here !

ν_e disappearance: L/E ~ 15 km/MeV

= 15,000 km/GeV

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$$|U_{e1}|^2 |U_{e2}|^2 \quad \Rightarrow \quad \frac{|U_{e1}|^2 |U_{e2}|^2}{(\ |U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2\ )}$$

JUNO will do much better here !

ν_τ appearance: L/E ~ 500 km/GeV

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Opera and SK

$$|U_{\tau 3}|^2 |U_{\mu 3}|^2$$

ν_τ appearance: L/E ~ 500 km/GeV

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ \boxed{\begin{matrix} U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}} \end{pmatrix}$$

Opera and SK

$$|U_{\tau 3}|^2 |U_{\mu 3}|^2$$

$$\Rightarrow \mathcal{R}\{-U^*_{\tau 3} U_{\mu 3} \left(U_{\tau 1} U^*_{\mu 1} + U_{\tau 2} U^*_{\mu 2}\right)\}$$

ν_e appearance: L/E ~ 500 km/GeV

T2K, MINOS
NOvA,
LBNF, HyperK,
SuperPINGU, ...

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$|U_{e3}|^2 |U_{\mu 3}|^2 + \cdots$$

ν_e appearance: L/E ~ 500 km/GeV

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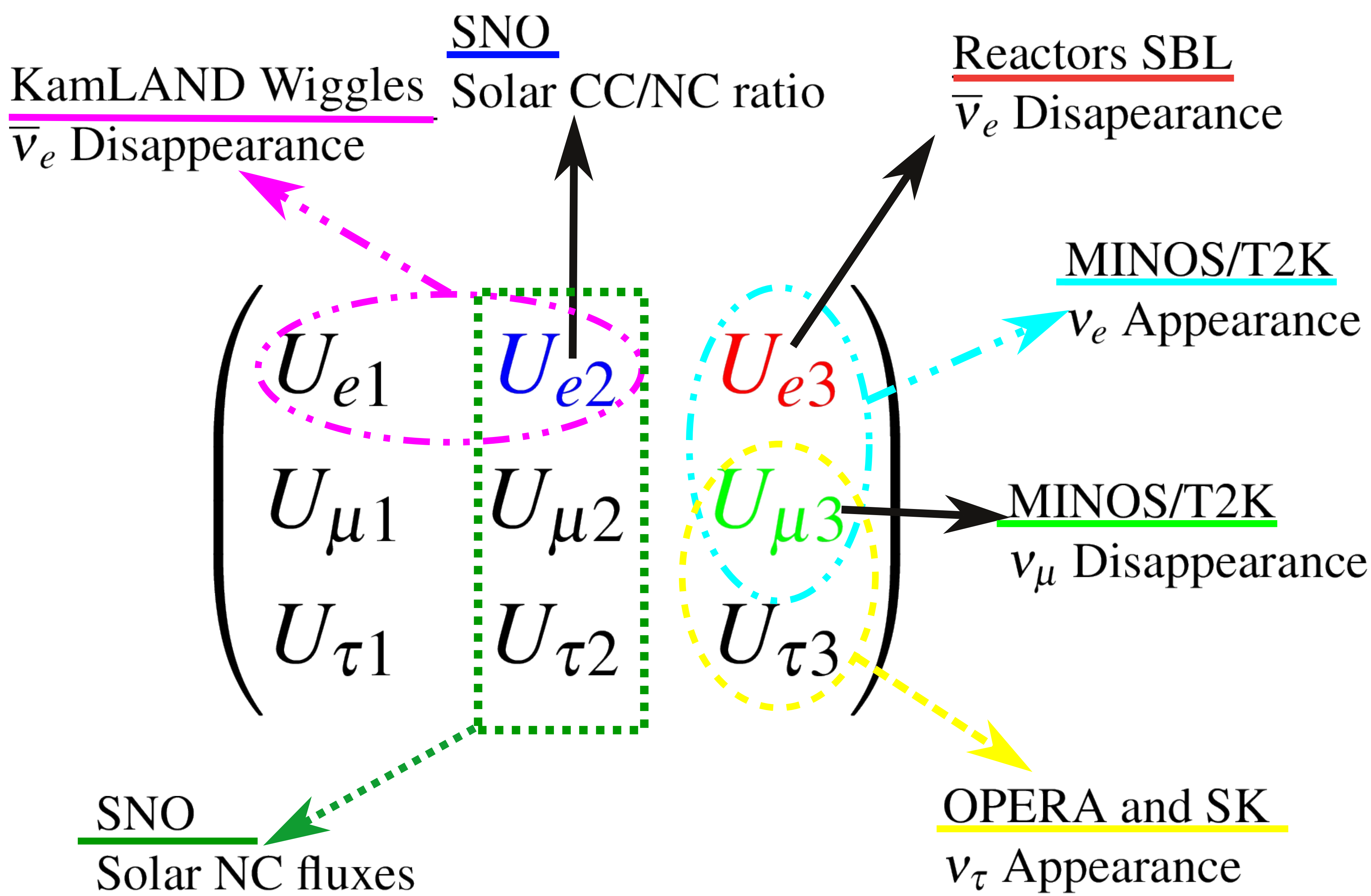
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$|U_{e3}|^2 |U_{\mu 3}|^2 + \cdots$$

$$\Rightarrow \mathcal{R}\{-U_{e3}^* U_{\mu 3} \left(U_{e1} U_{\mu 1}^* + U_{e2} U_{\mu 2}^*\right)\} + \cdots$$

Summary (unitary case):



where is our information ?
non-unitary case:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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- Only places the degeneracy is broken between $|U_{\alpha 1}|$ and $|U_{\alpha 2}|$:

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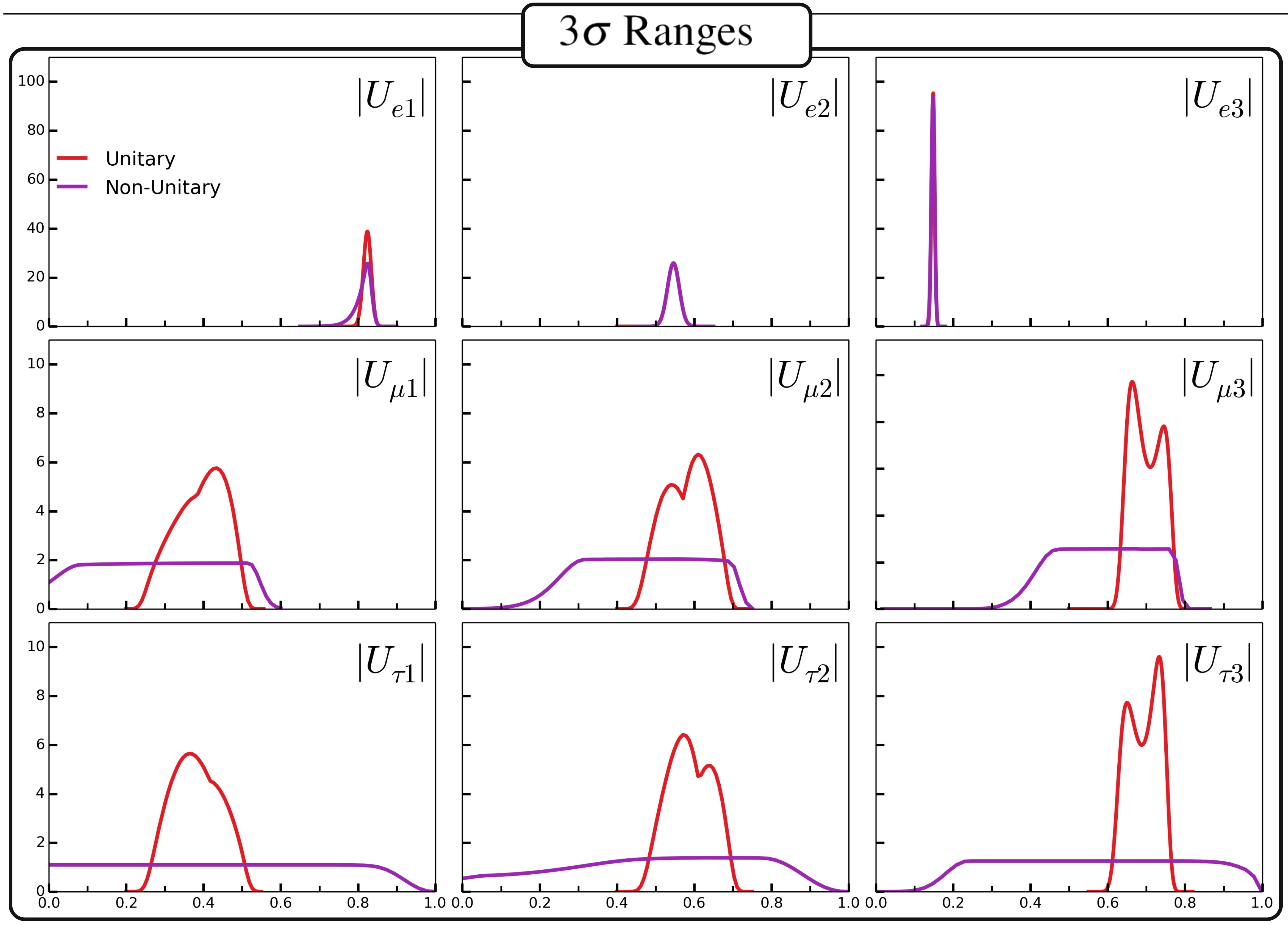
- Only places the degeneracy is broken between $|U_{\alpha 1}|$ and $|U_{\alpha 2}|$:
- KamLAND wiggles and SNO's NC flux plus feed through ! ! !

Non-Unitary ! ! !

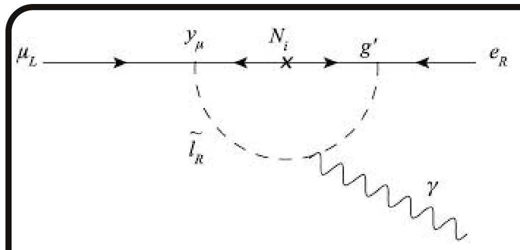
1508.05095 SP+Ross-Lonergan



OPERA ?

What about Theory ? ? ?

Rare Lepton Decays MEG Experiment : $\mu \to e\gamma$



$BR < 5.7 \times 10^{-13}$

$$|U_{e1}U_{\mu 2}{}^* + U_{e2}U_{\mu 2}{}^* + U_{e3}U_{\mu 3}{}^*| < 1.5 \times 10^{-5}$$

Post Neutrino 2014 results, at the 90 % C.L, the bounds on the unitarity violation of U_{PMNS} is given by

Experimentally unitary at $\mathcal{O}(0.1\%)$ level!

$$|U^\dagger U| = \begin{pmatrix} 0.9978 - 0.9998 & < 10^{-5} & < 0.0021 \\ < 10^{-5} & 0.9996 - 1.0 & < 0.0008 \\ < 0.0021 & < 0.0008 & 0.9947 - 1.0 \end{pmatrix}$$

S. Antusch and O. Fischer, (2014), arXiv:1407.6607 [hep-ph]

ARE THERE LIGHT STERILE

$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\rm PMNS}^{\rm 3x3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

ARE THERE LIGHT STERILE

$$U_{\text{PMNS}}^{\text{Extended}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\text{PMNS}}^{\text{3x3}}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

Cauchy-Schwartz

$$\left| \sum_{i=1}^{3} U_{ei} U_{\mu i}{}^{*} \right|^2 \leq \left(1 - \sum_{i=1}^{3} |U_{ei}|^2 \right) \left(1 - \sum_{i=1}^{3} |U_{\mu i}|^2 \right)$$

ARE THERE LIGHT STERILE

$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\mathrm{PMNS}}^{3\mathrm{x}3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

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- ν_μ Disappearance

- ν_μ Disappearance

MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

ARE THERE LIGHT STERILE

$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\rm PMNS}^{\rm 3x3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

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- ν_e Disappearance
- ν_μ Disappearance

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MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

- ν_e Disappearance

Daya Bay, RENO, many $\sim$10m Reactor experiments & source experiments.

ARE THERE LIGHT STERILE

$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\rm PMNS}^{\rm 3x3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

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- $\nu_\mu \to \nu_e$ Appearance
- ν_e Disappearance
- ν_μ Disappearance

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MINOS+, NOvA, T2K, atmospheric neutrinos (SK and ICECUBE)

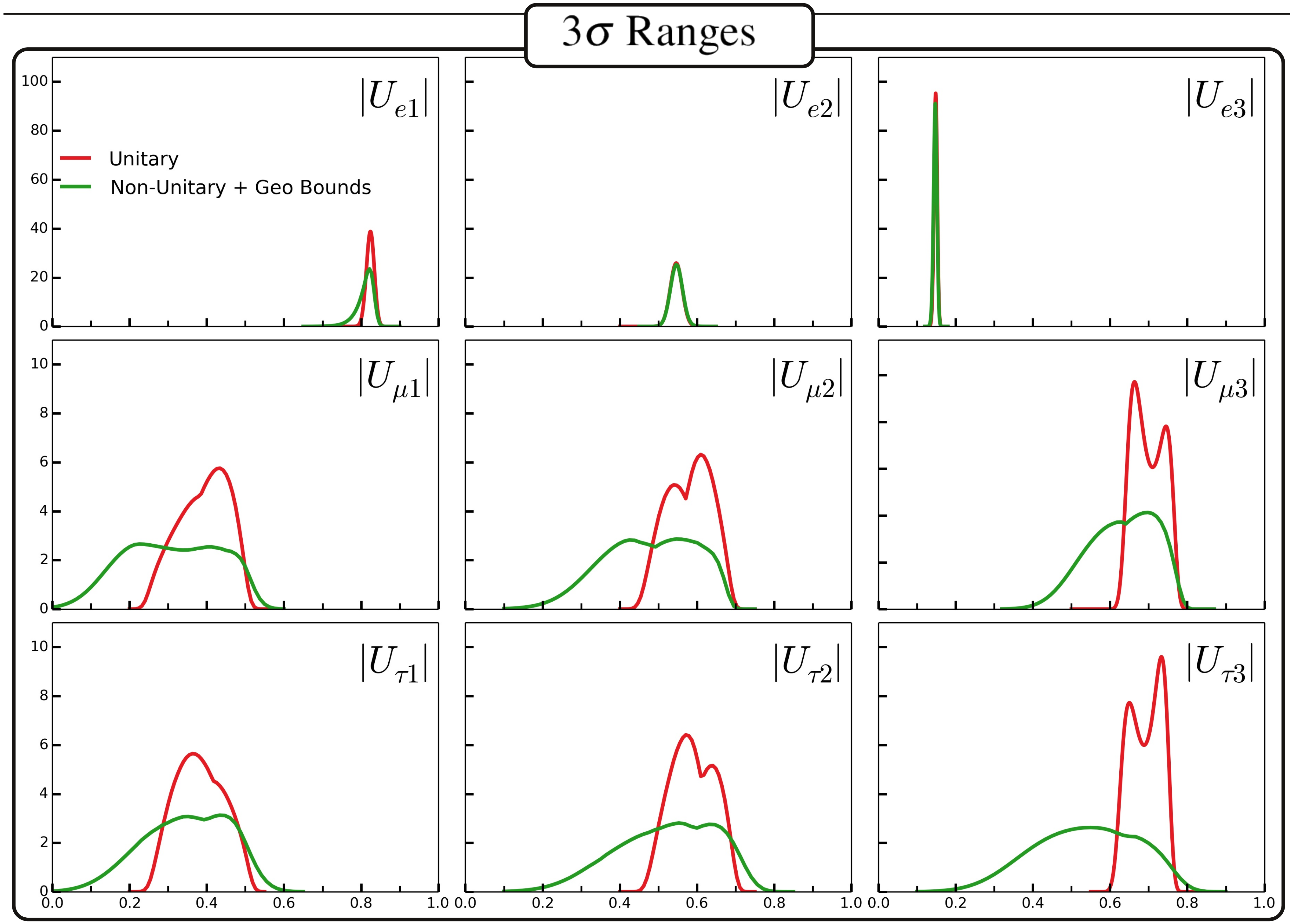
- ν_e Disappearance

Daya Bay, RENO, many $\sim$10m Reactor experiments & source experiments.

- $\nu_\mu \to \nu_e$ Appearance

Fermilab SBN Program, T2K and NOvA: DUNE & HyperK

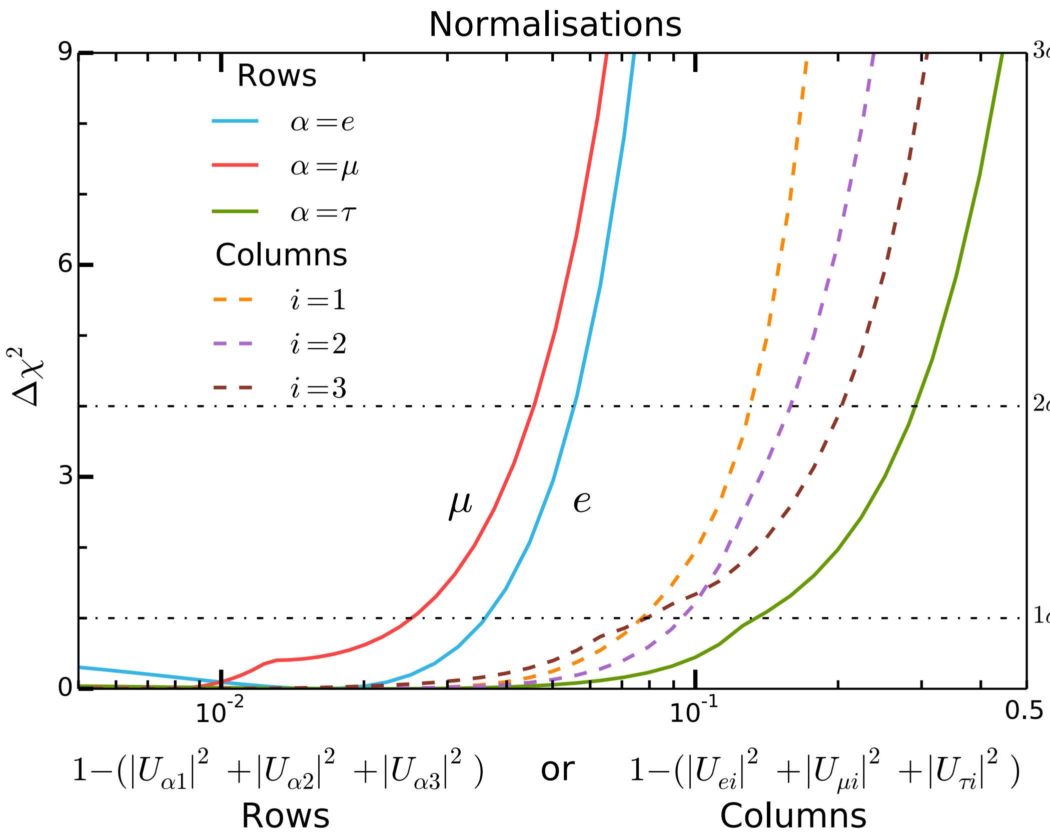
Theoretical Geometric Bounds:

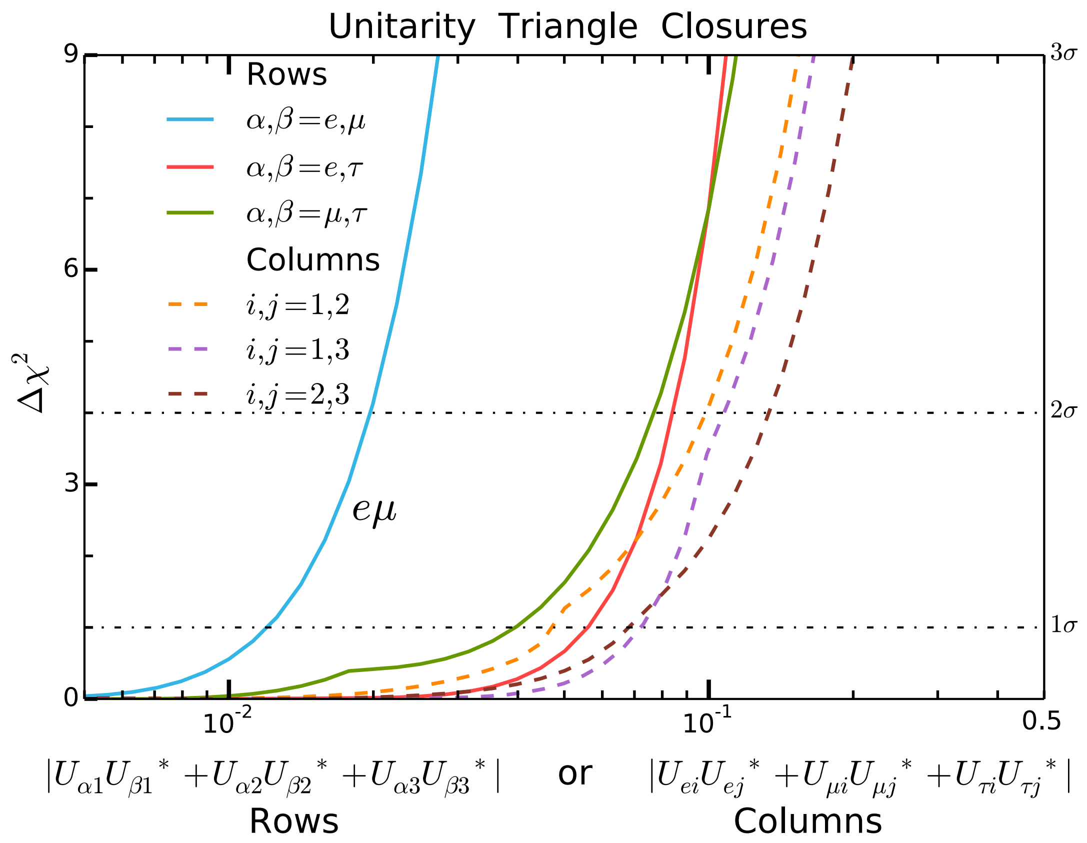


Most Assumption Independent that is theoretically motivated !

1508.05095 SP+Ross-Lonergan

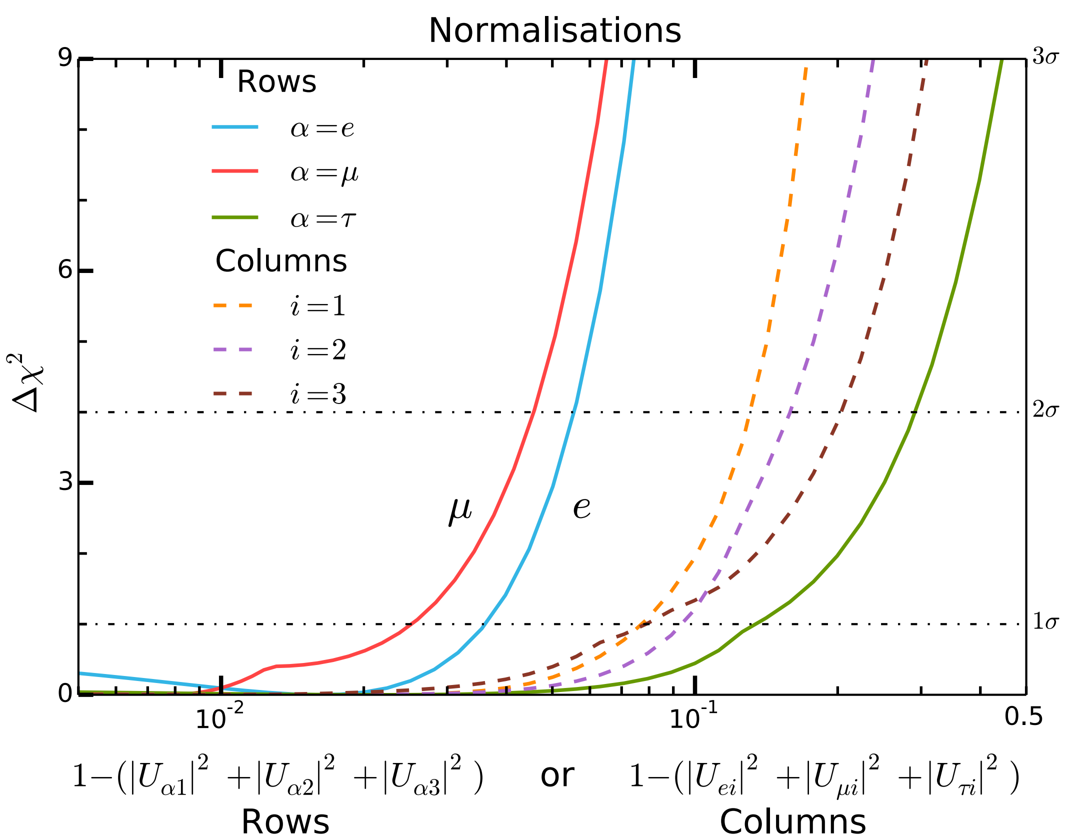
Constraints on Unitarity Conditions:

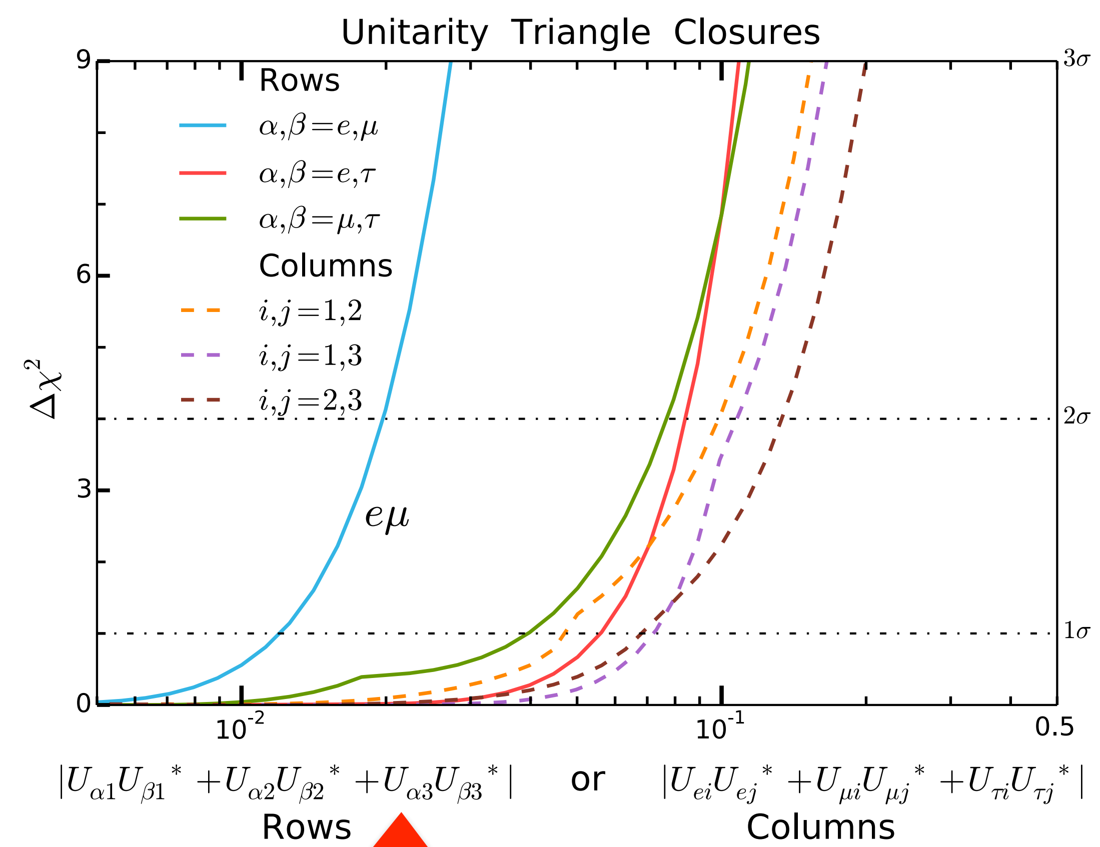




1508.05095 SP+Ross-Lonergan

Constraints on Unitarity Conditions:





LSND

1508.05095 SP+Ross-Lonergan

UPDATES:

UPDATES:

10/1 4pm Fermilab JETP Seminar:

Search for anomalous single-photon production in MicroBooNE as a first test of the MiniBooNE low-energy excess

Mark Ross-Lonergan, Columbia U.

→ **If steriles heavier than electroweak scale:**

$$\widetilde{U} = (\mathbf{1} - \eta)\, U$$

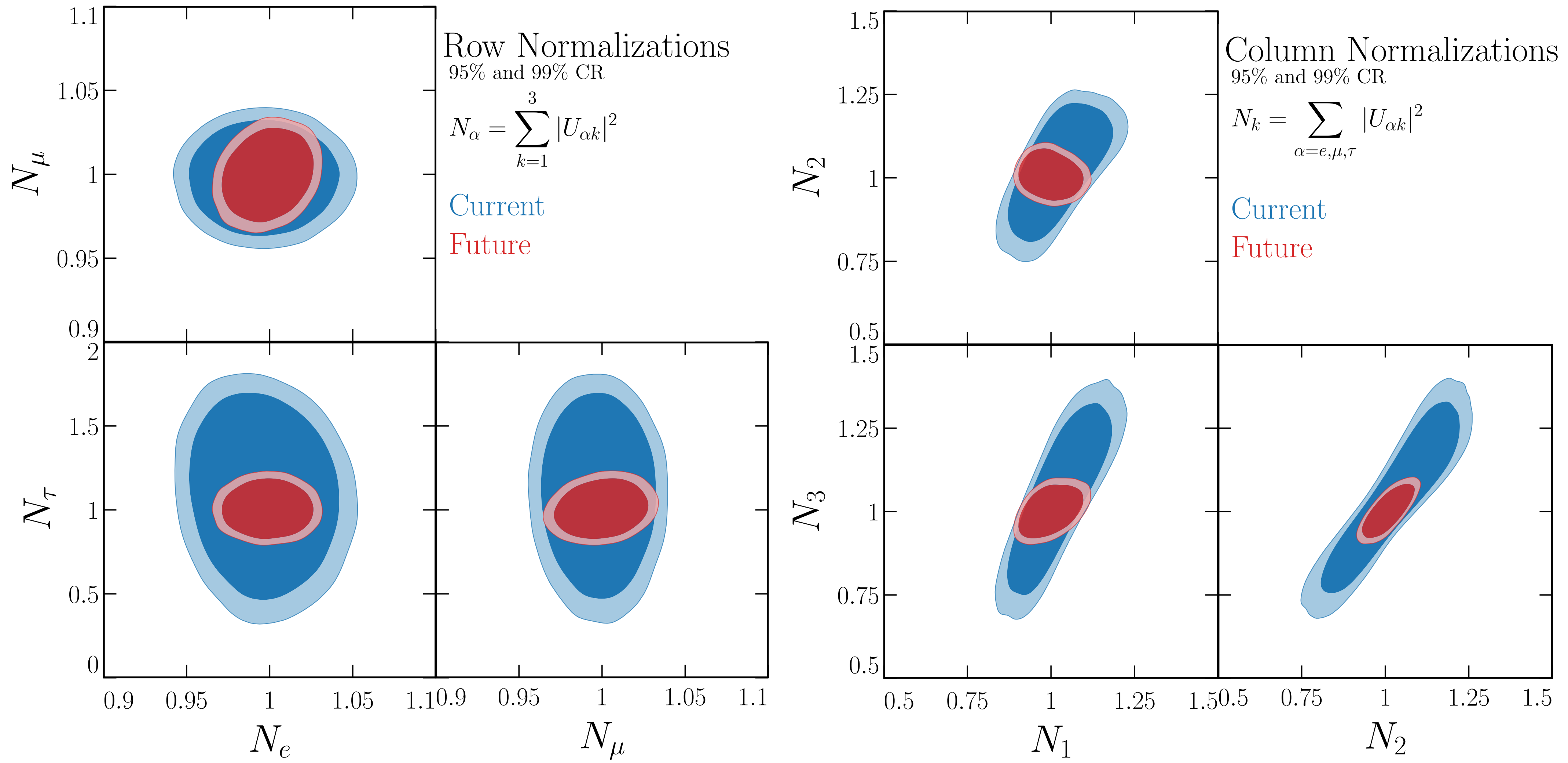
$$2|\eta| \leq \begin{pmatrix} 2.5 \times 10^{-3} & 2.4 \times 10^{-5} & 2.7 \times 10^{-3} \\ 2.4 \times 10^{-5} & 4.0 \times 10^{-4} & 1.2 \times 10^{-3} \\ 2.7 \times 10^{-3} & 1.2 \times 10^{-3} & 5.6 \times 10^{-3} \end{pmatrix} \quad \text{at } 2\sigma$$

[Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, PLB 649 (2007) 427]
[Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, arXiv:1605.08774]

U is Unitary and $\eta \neq 0$ makes $\tilde{U}$ non-unitary:

Ellis, Kelly and Li: 2008.01088

Normalisations:



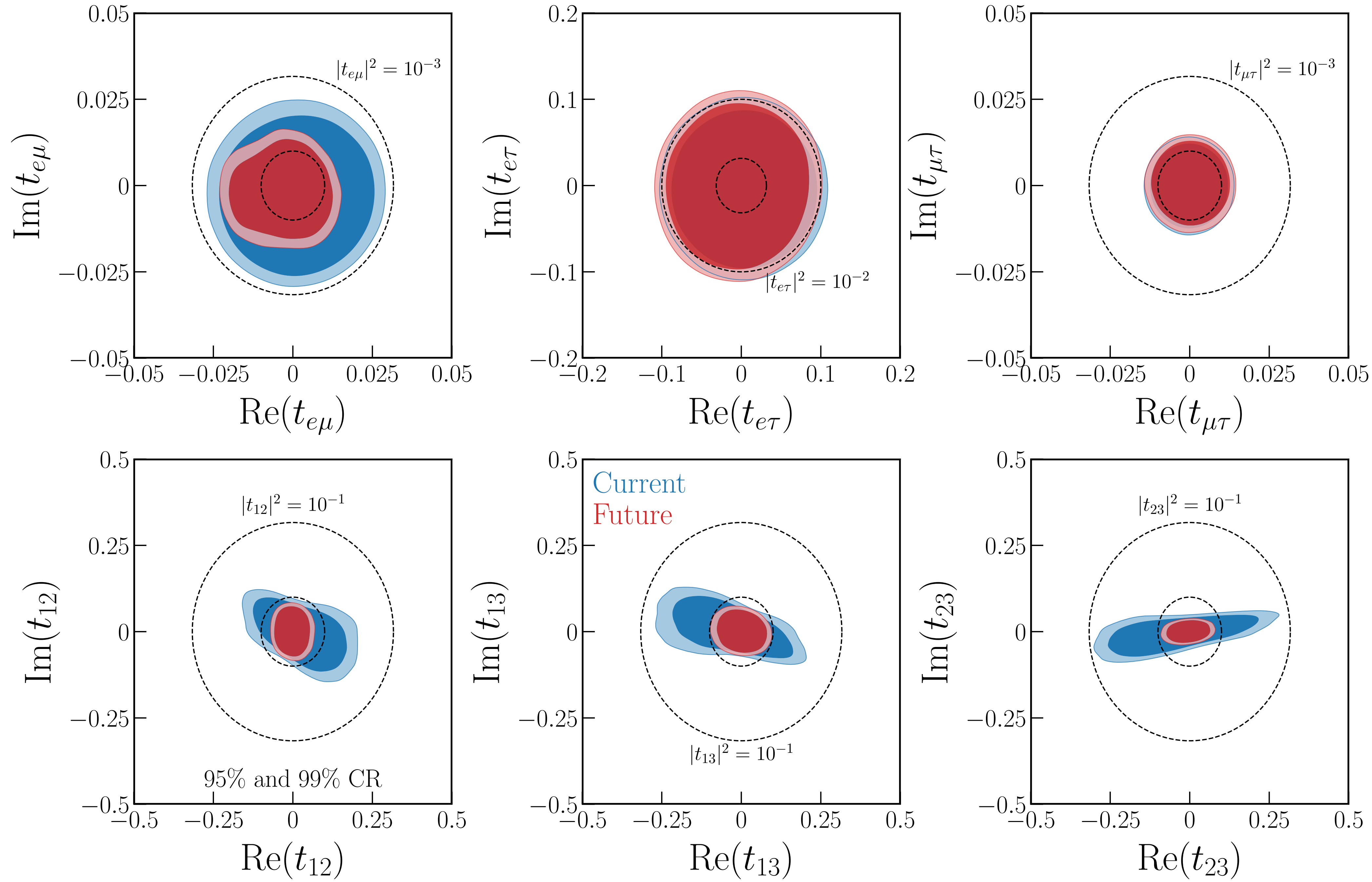
Ellis, Kelly and Li: 2008.01088

Triangles:

IMPORTANT NOTE: SCALE CHANGES !

$$t_{\alpha\beta} \equiv U^*_{\alpha 1}U_{\beta 1} + U^*_{\alpha 2}U_{\beta 2} + U^*_{\alpha 3}U_{\beta 3}$$

$$t_{kl} \equiv U^*_{ek}U_{el} + U^*_{\mu k}U_{\mu l} + U^*_{\tau k}U_{\tau l}$$



See Kevin Kelly and Julia Gehrlein talks

Wednesday

Issues for Discussion Session:

Current Limits:

	Current 3σ Upper Limit
$\lvert t_{e\mu}\rvert$	3.2×10^{-2}
$\lvert t_{e\tau}\rvert$	1.3×10^{-1}
$\lvert t_{\mu\tau}\rvert$	1.6×10^{-2}
$\lvert t_{12}\rvert$	2.5×10^{-1}
$\lvert t_{13}\rvert$	3.2×10^{-1}
$\lvert t_{23}\rvert$	3.3×10^{-1}

Ellis, Kelly and Li: 2008.01088

Current Limits:

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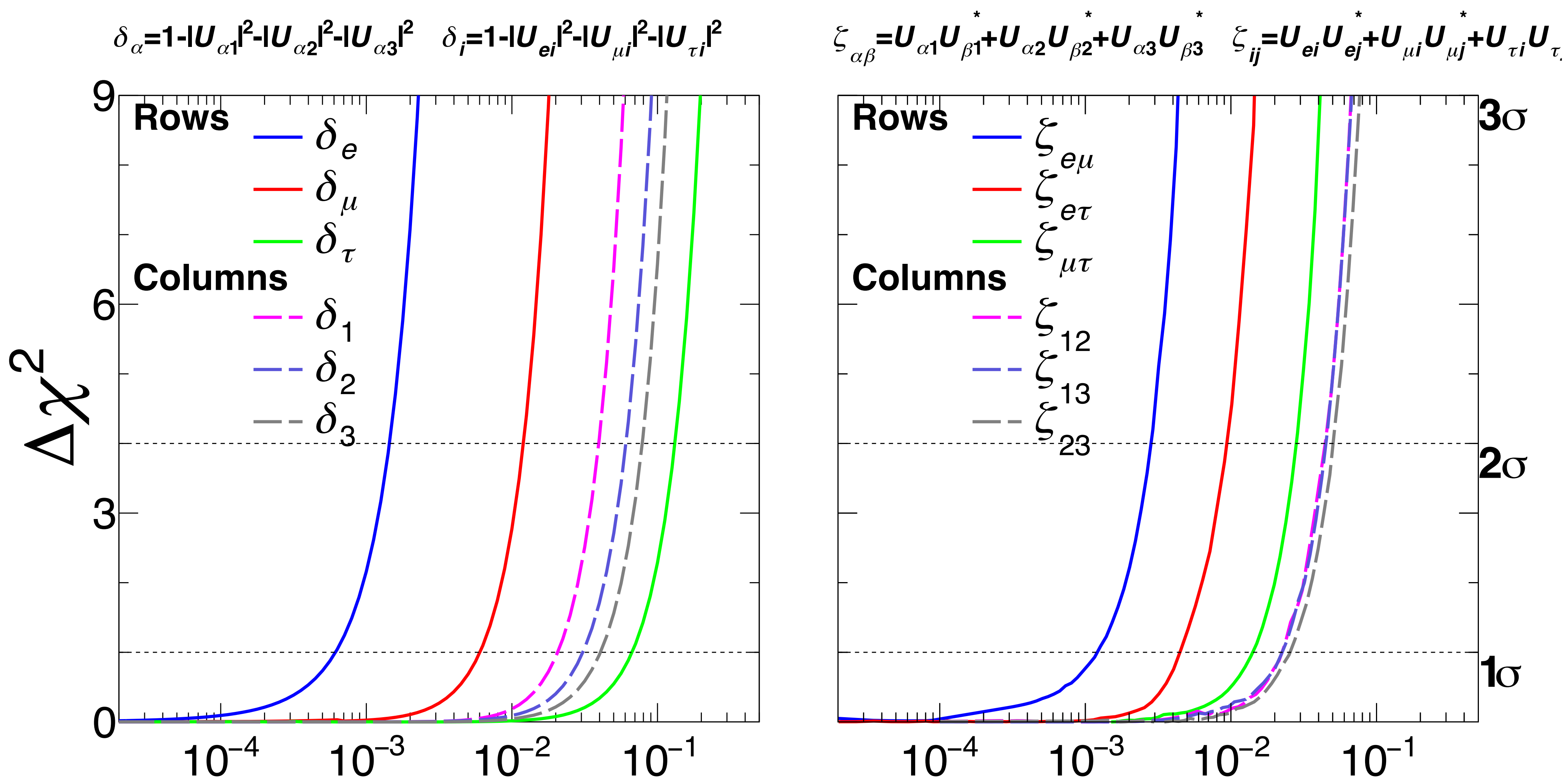
$\lvert t_{13}\rvert$	3.2×10^{-1}
$\lvert t_{23}\rvert$	3.3×10^{-1}

How/Why so good ?

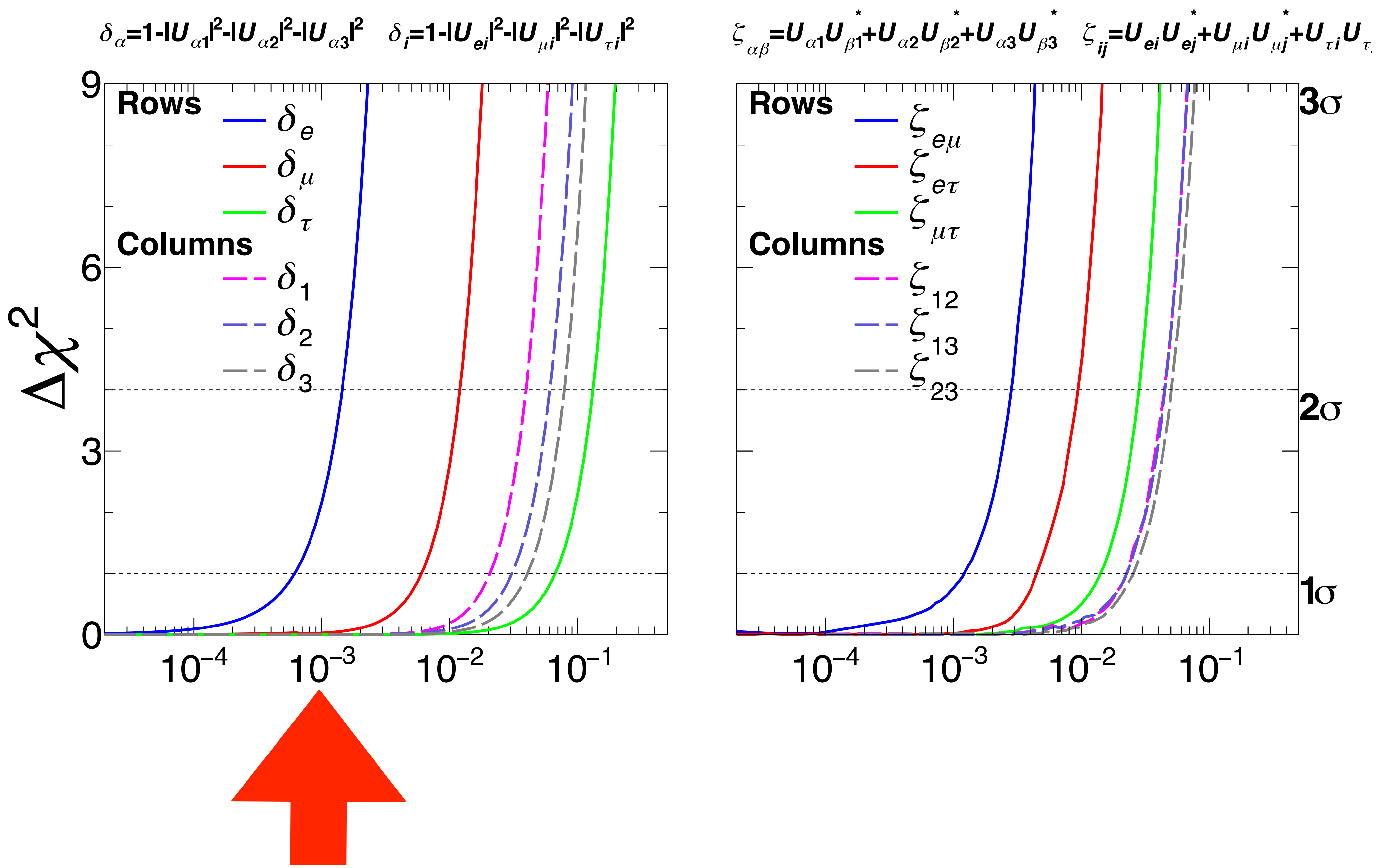
What's the physics here?

Ellis, Kelly and Li: 2008.01088

Hu, Ling, Tang, Wang: 2008.09730 see JHEP

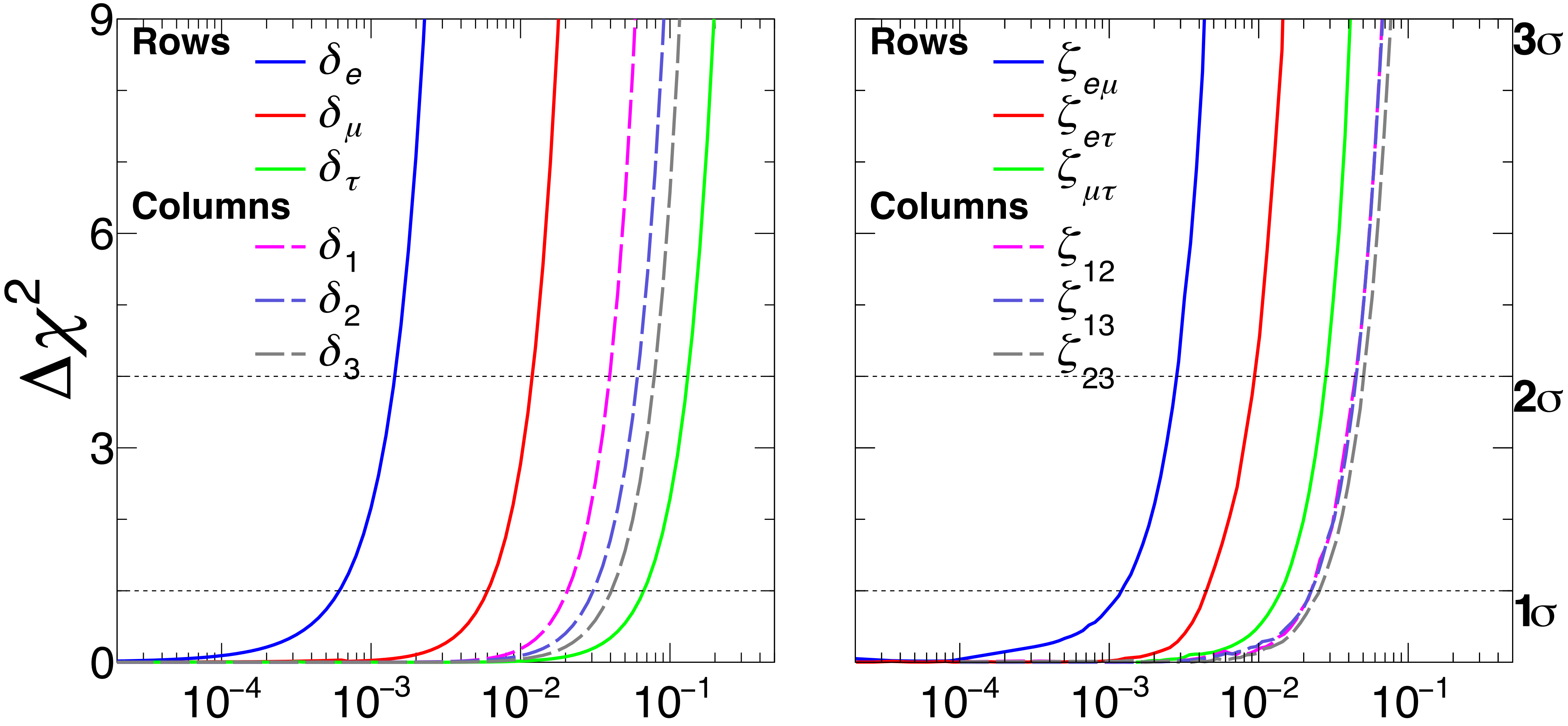


Hu, Ling, Tang, Wang: 2008.09730 see JHEP



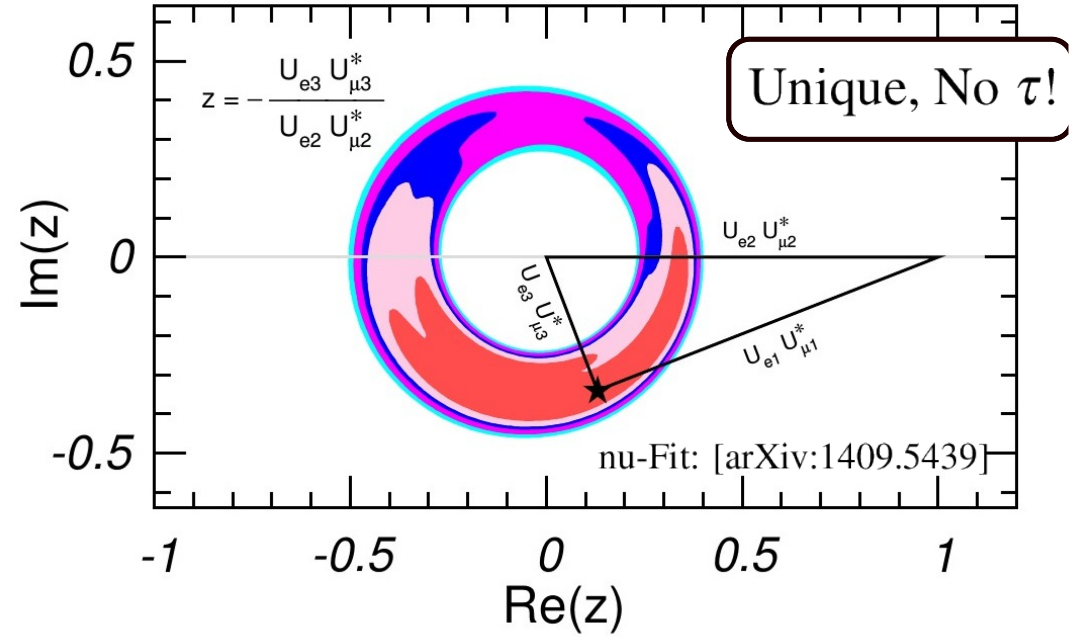
Hu, Ling, Tang, Wang: 2008.09730 see JHEP

$\delta_\alpha = 1 - |U_{\alpha 1}|^2 - |U_{\alpha 2}|^2 - |U_{\alpha 3}|^2$ $\delta_i = 1 - |U_{ei}|^2 - |U_{\mu i}|^2 - |U_{\tau i}|^2$ $\zeta_{\alpha\beta} = U_{\alpha 1}U^*_{\beta 1} + U_{\alpha 2}U^*_{\beta 2} + U_{\alpha 3}U^*_{\beta 3}$ $\zeta_{ij} = U_{ei}U^*_{ej} + U_{\mu i}U^*_{\mu j} + U_{\tau i}U_{\tau}$

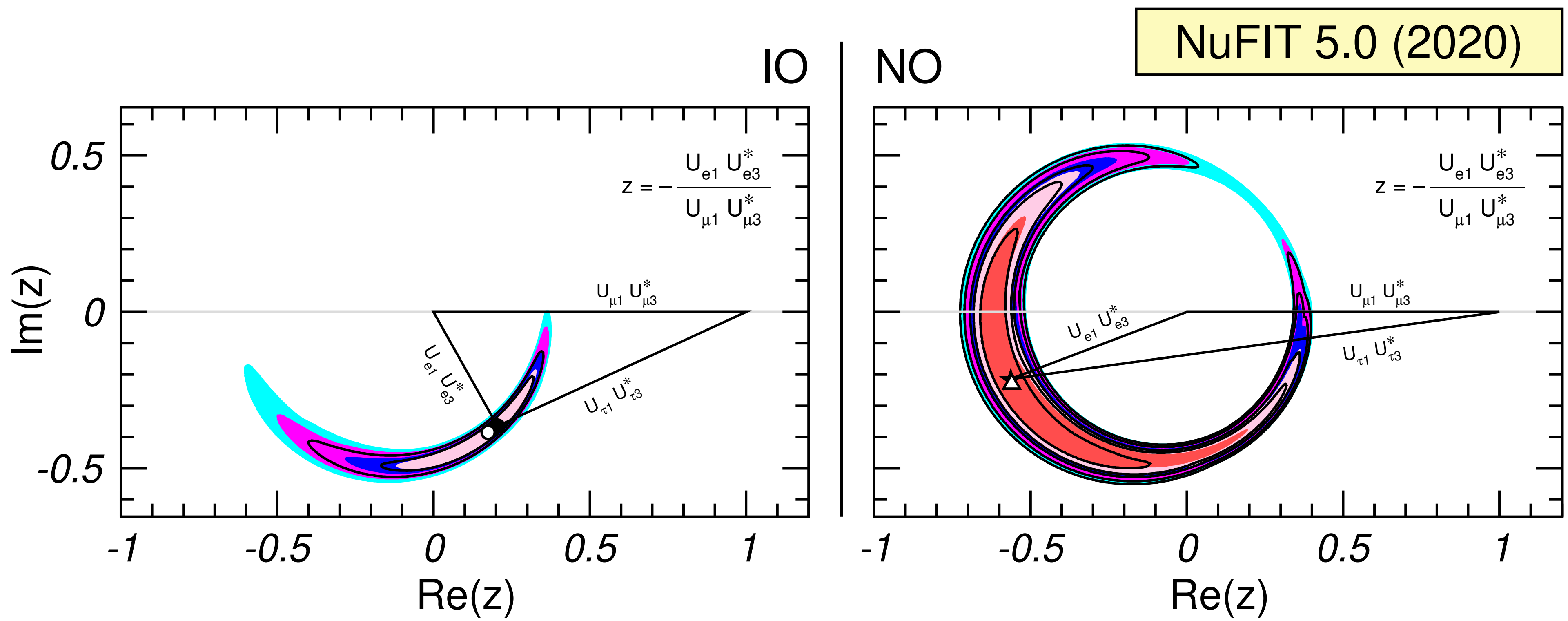


HOW / WHY ?

Which Triangle ?



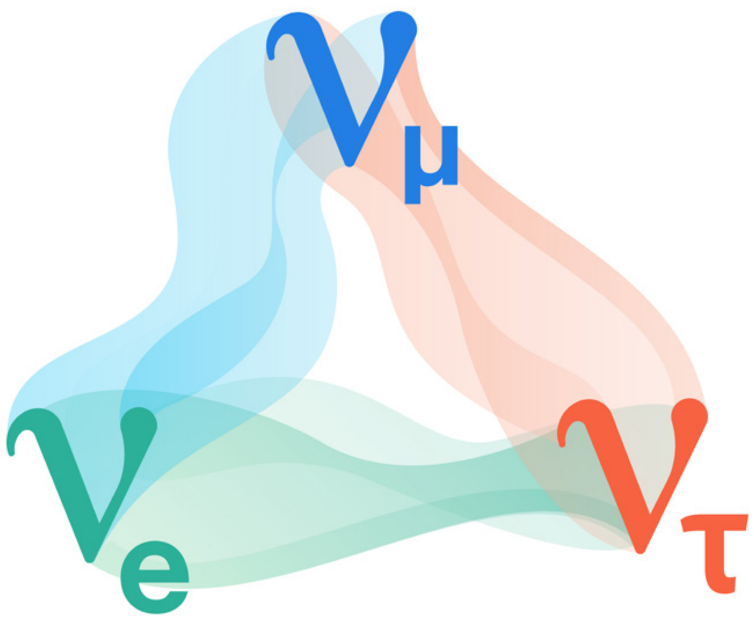
Unitarity *Is* assumed.



Thank You !

Interactions:

simple — complicated



$$= U$$

unitarity ???

complicated — simple

Propagation: