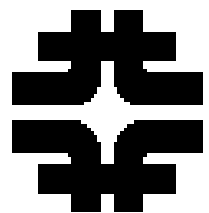


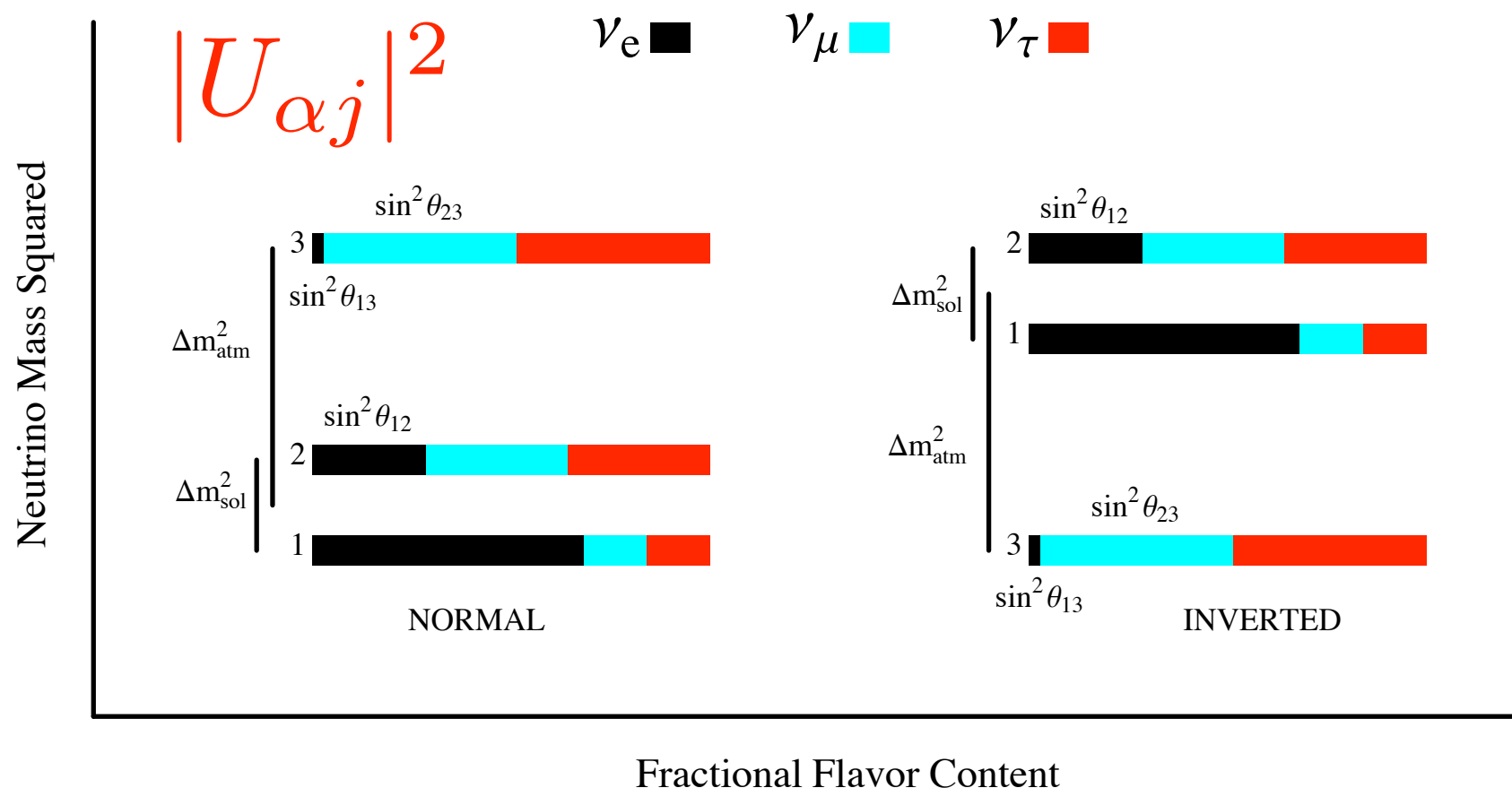
Neutrino Factory Physics Goals:

Stephen Parke
Fermilab

- Nu Standard Model
- Beyond Nu SM
- Staging & Conclusions



Nu Standard Model:



$$\sqrt{\delta m_{atm}^2} = 0.05 \text{ eV} < \sum m_{\nu_i} < 0.5 \text{ eV} = 10^{-6} * m_e$$

$$\delta m_{sol}^2 = +7.6 \times 10^{-5} \text{ eV}^2$$

$$|\delta m_{atm}^2| = 2.4 \times 10^{-3} \text{ eV}^2$$

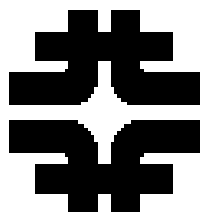
$$|\delta m_{sol}^2| / |\delta m_{atm}^2| \approx 0.03$$

$$\sin^2 \theta_{12} \sim 1/3$$

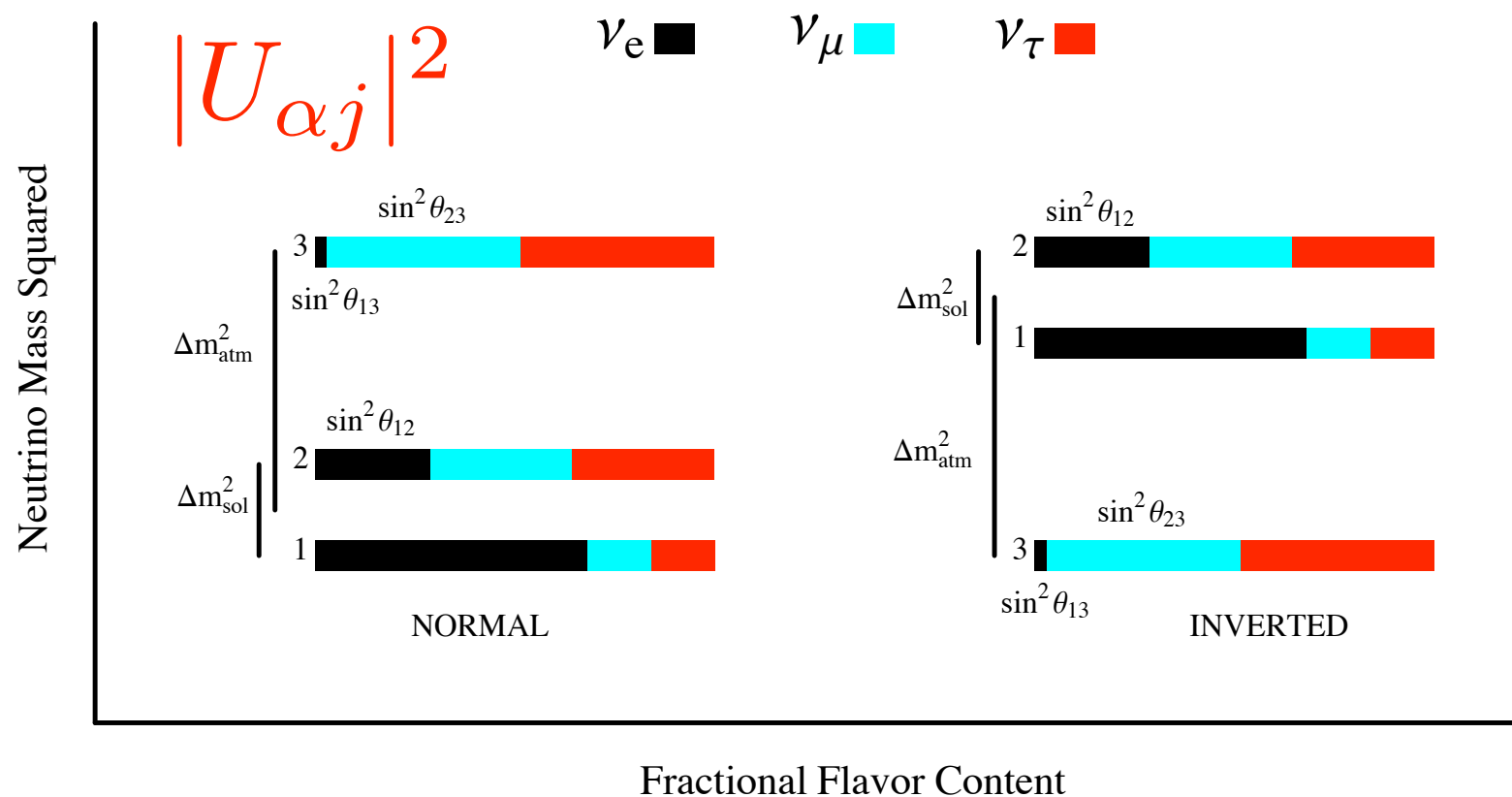
$$\sin^2 \theta_{23} \sim 1/2$$

$$\sin^2 \theta_{13} < 3\%$$

$$\sin^2 \theta_{13} \equiv |U_{e3}|^2, \quad \sin^2 \theta_{12} \equiv \frac{|U_{e2}|^2}{(1 - |U_{e3}|^2)}, \quad \sin^2 \theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1 - |U_{e3}|^2)}$$



Masses & Mixings:



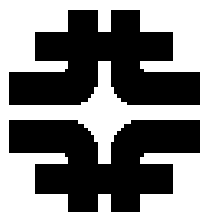
$$\sin^2 \theta_{13} \approx 0.02 \pm 0.01$$

$$\left| \sin^2 \theta_{12} - \frac{1}{3} \right| < 0.04$$

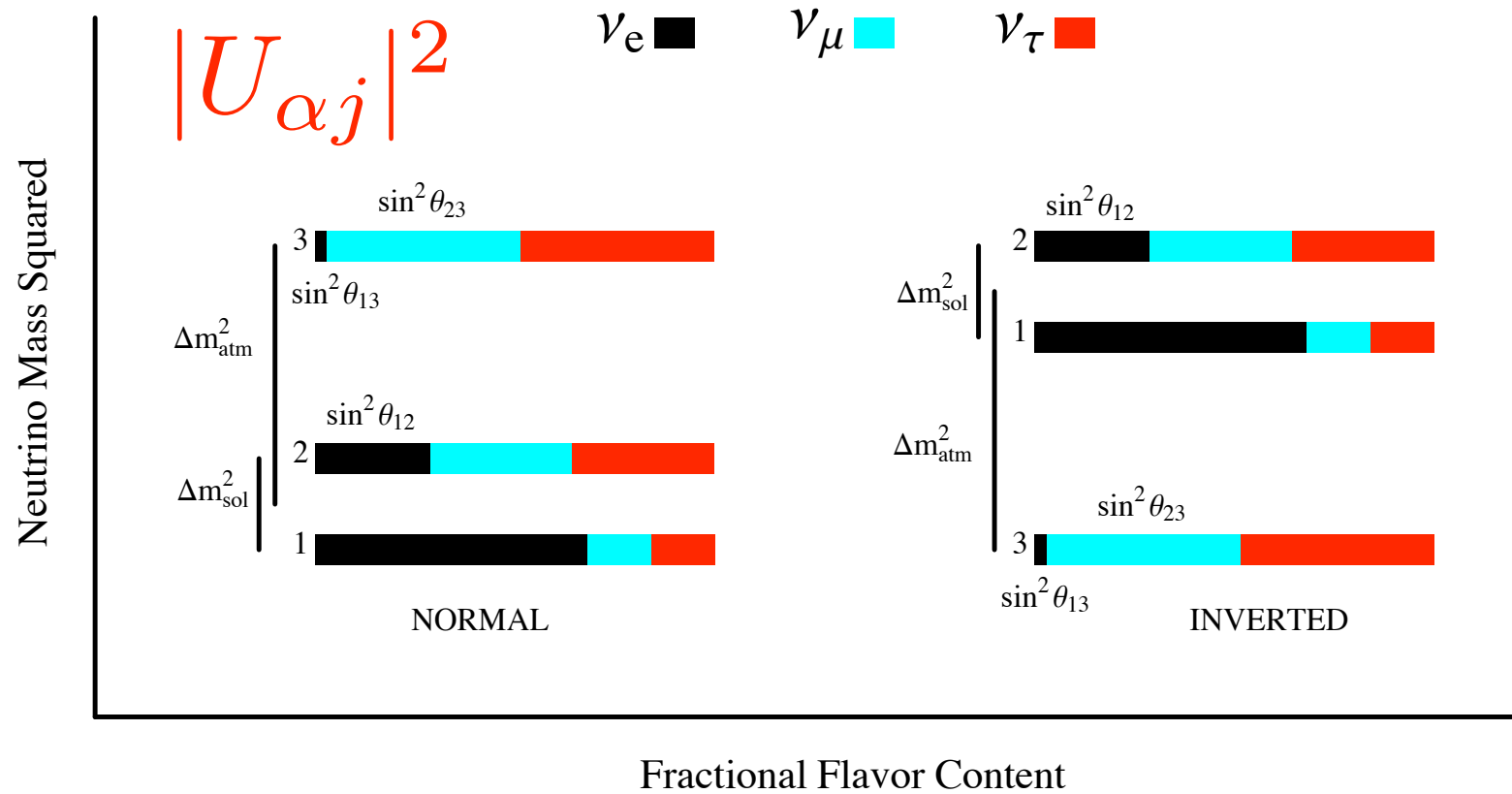
$$\left| \sin^2 \theta_{23} - \frac{1}{2} \right| < 0.12$$

Close to Tri-Bi-Maximal: Accident or Symmetry ?

$$\sin^2 \theta_{13} \equiv |U_{e3}|^2, \quad \sin^2 \theta_{12} \equiv \frac{|U_{e2}|^2}{(1 - |U_{e3}|^2)}, \quad \sin^2 \theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1 - |U_{e3}|^2)}$$



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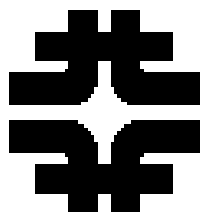
Are the deviations
from TBM related?

$$\left| \sin^2 \theta_{12} - \frac{1}{3} \right| < 0.04$$

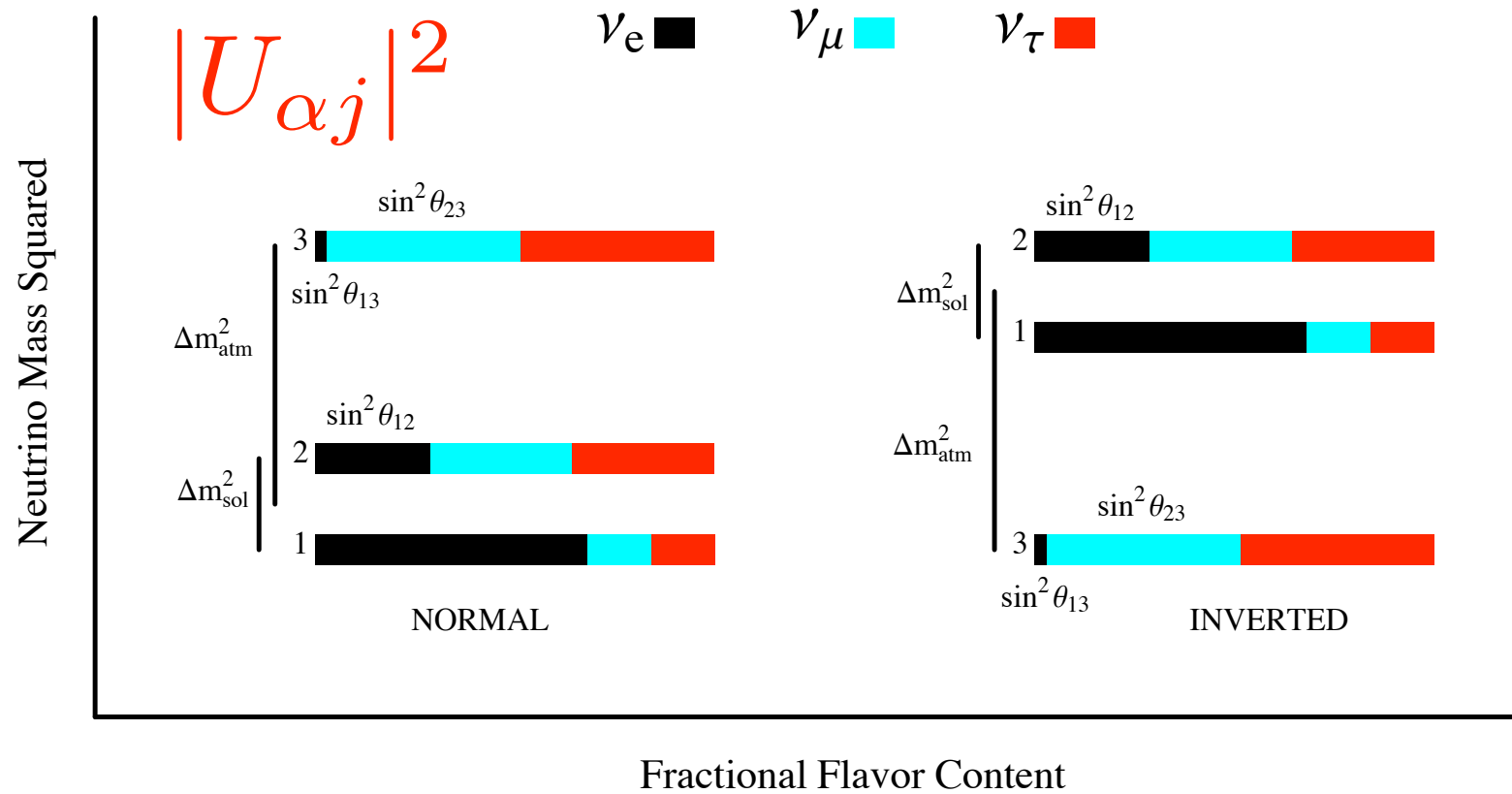
$$\left| \sin^2 \theta_{23} - \frac{1}{2} \right| < 0.12$$

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Masses & Mixings:



$$\sin^2 \theta_{13} \approx 0.02 \pm 0.01$$

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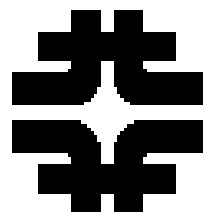
$$\left| \sin^2 \theta_{12} - \frac{1}{3} \right| < 0.04$$

$$\left| \sin^2 \theta_{23} - \frac{1}{2} \right| < 0.12$$

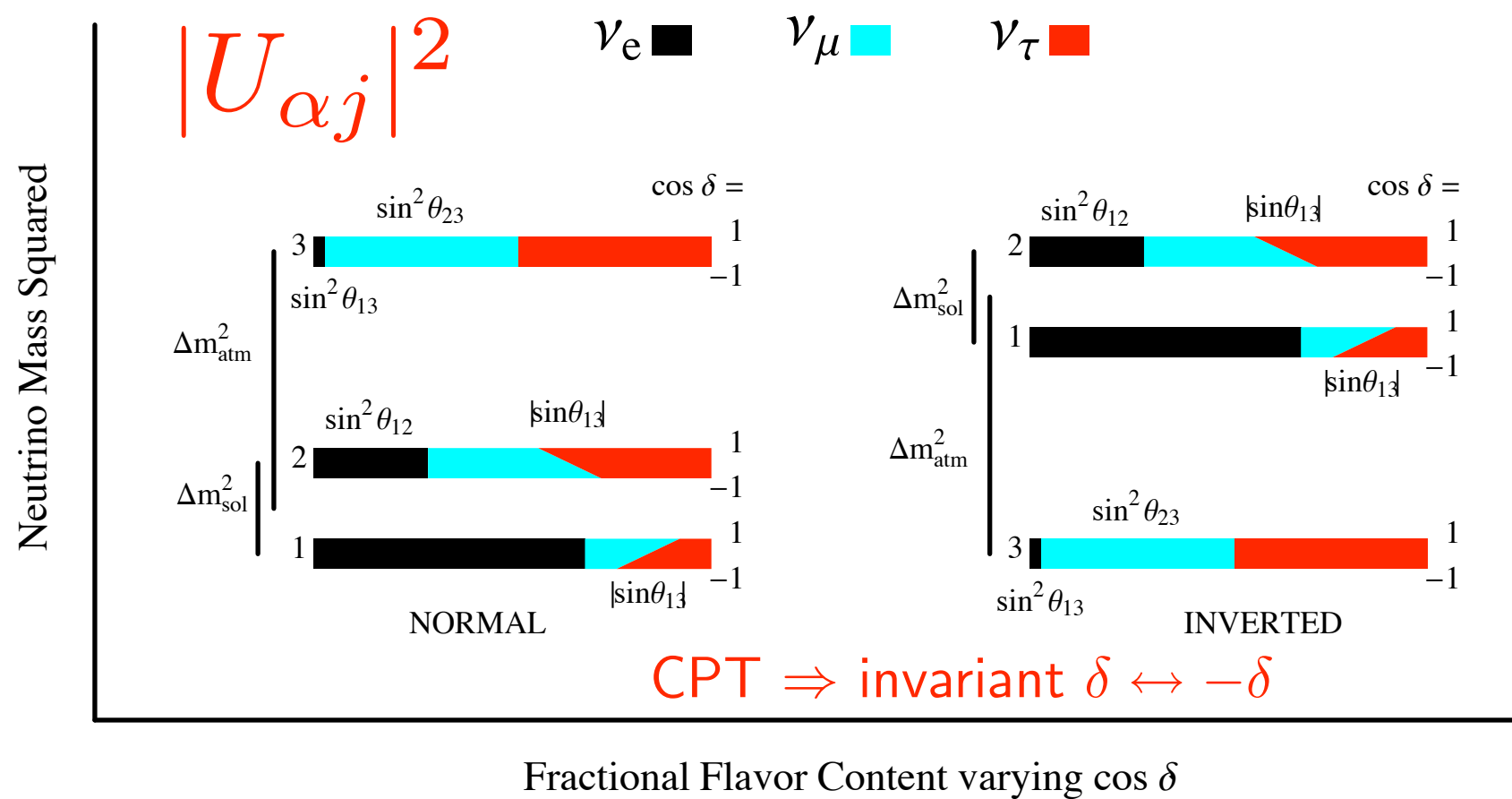
Yes, of course!!!
(except HM et al)

Close to Tri-Bi-Maximal: Accident or Symmetry ?

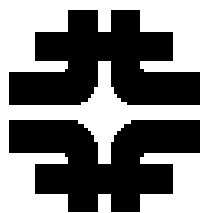
$$\sin^2 \theta_{13} \equiv |U_{e3}|^2, \quad \sin^2 \theta_{12} \equiv \frac{|U_{e2}|^2}{(1 - |U_{e3}|^2)}, \quad \sin^2 \theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1 - |U_{e3}|^2)}$$



Masses & Mixings



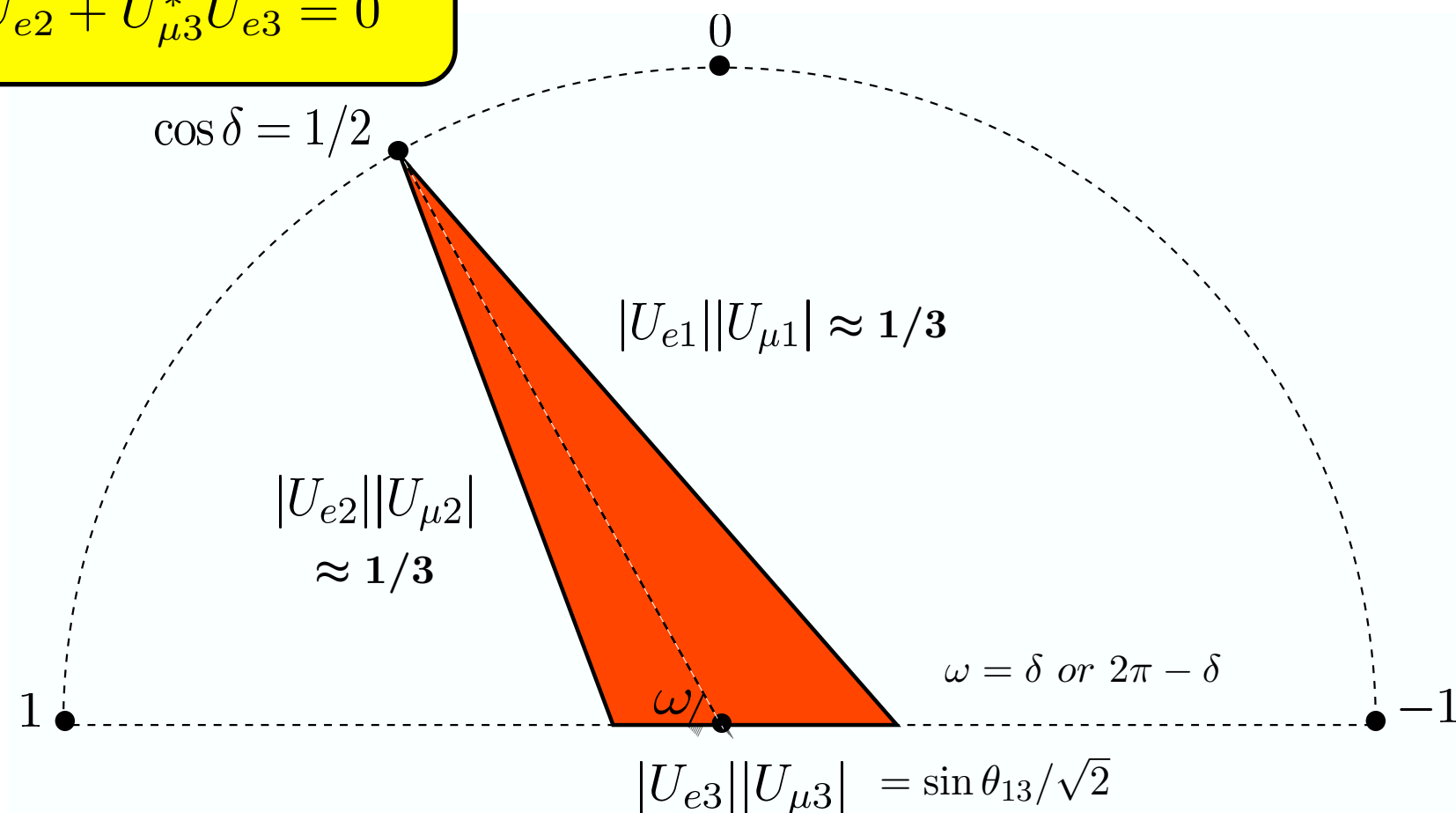
$$0 \leq \delta < 2\pi$$



Unitarity Triangle:

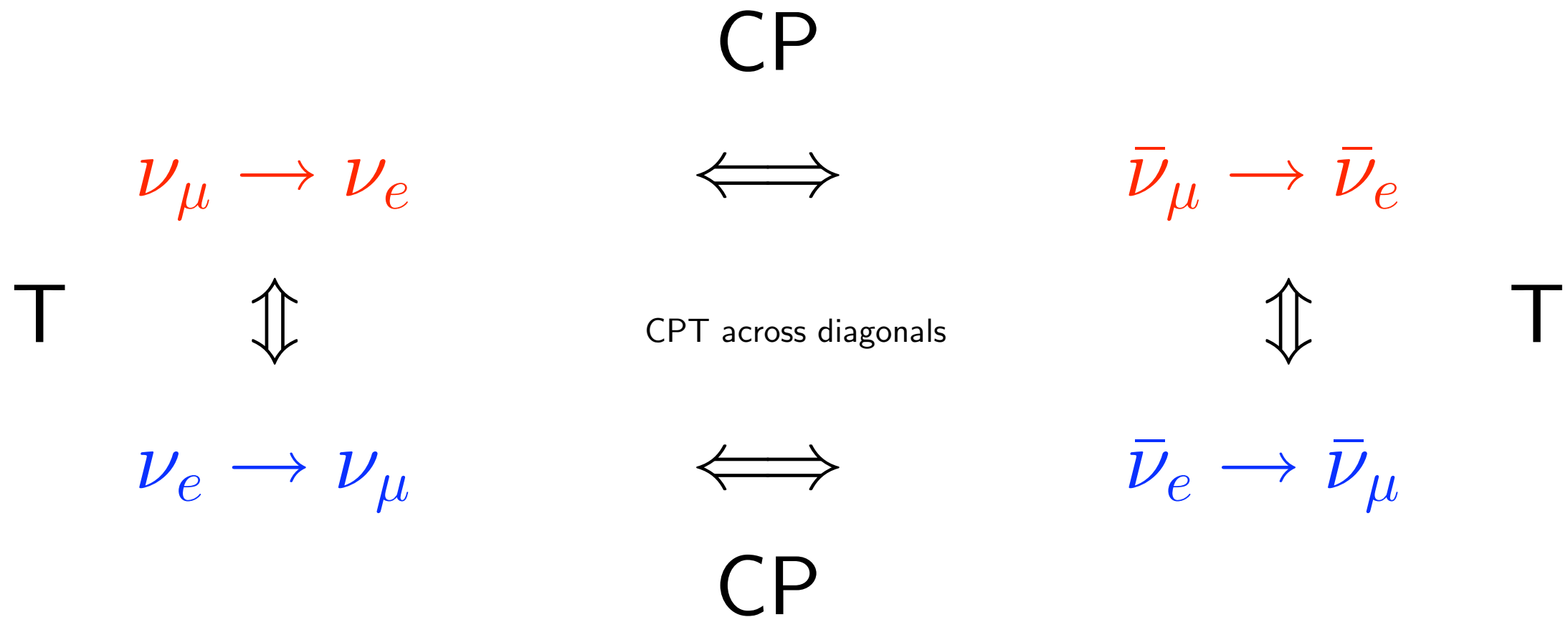
Unitarity Triangle:

$$U_{\mu 1}^* U_{e 1} + U_{\mu 2}^* U_{e 2} + U_{\mu 3}^* U_{e 3} = 0$$

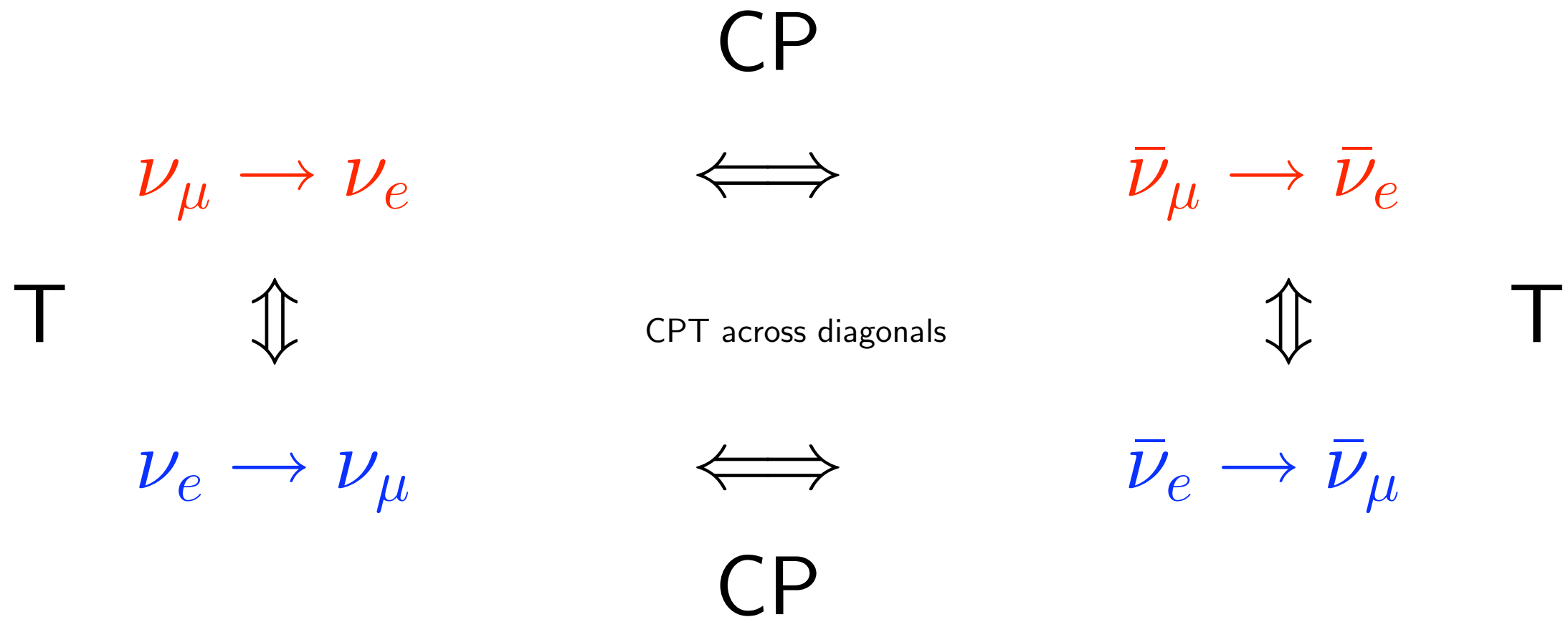


$$|J| = 2 \times Area$$

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin \delta$$



- First Row: Superbeams where ν_e contamination $\sim 1\%$
- Second Row: ν -Factory or β -Beams, no beam contamination



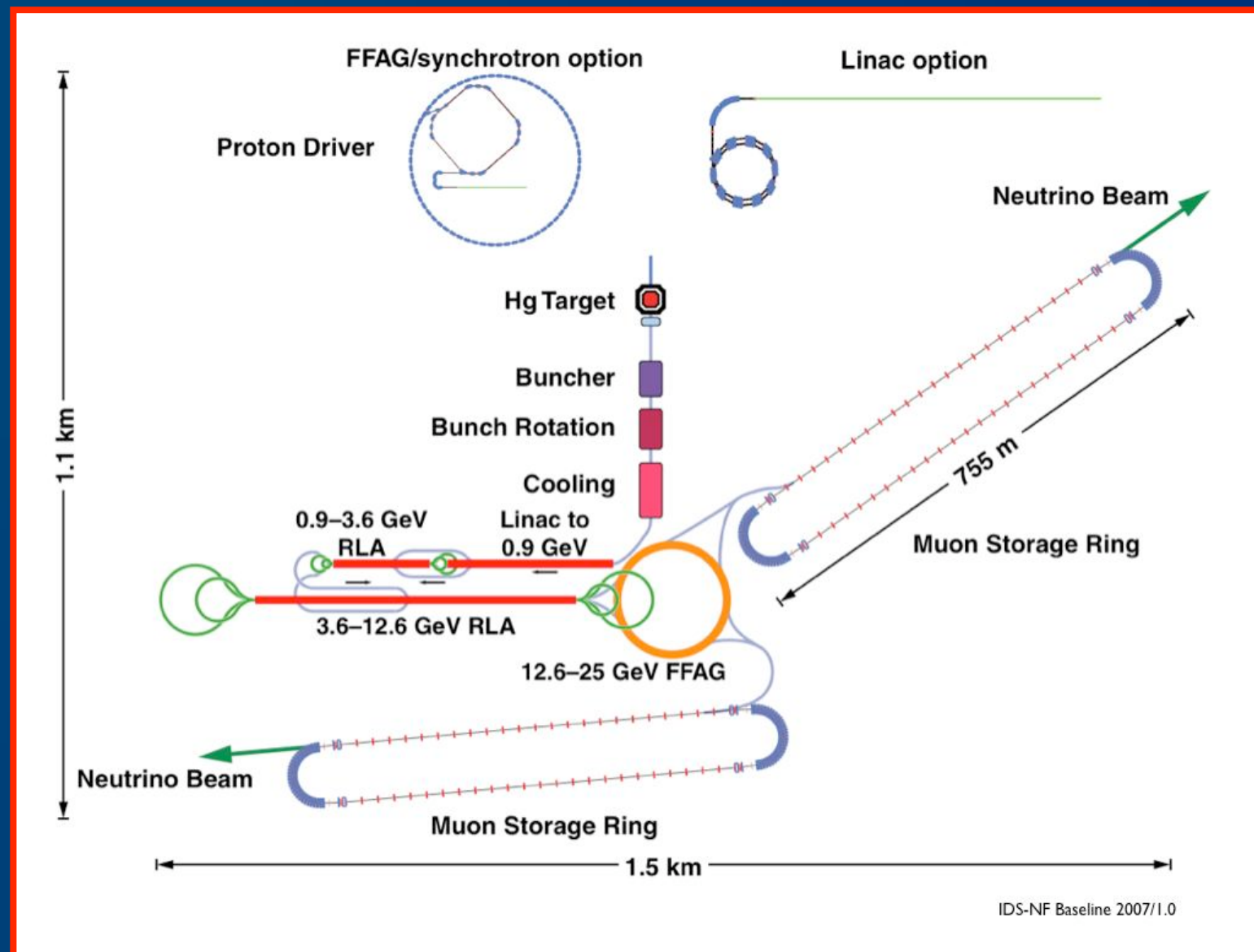
- First Row: Superbeams where ν_e contamination $\sim 1\%$
- Second Row: ν -Factory or β -Beams, no beam contamination

However

for ν -Factory: Distinguish μ^+ from μ^- at 10^{-4}

for β -Beam: Distinguish μ from e in Water Cerenkov or LAr

Neutrino Factory: accelerator facility:



IDS-NF-002: <https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=view&target=IDS-NF-002-v1.1.pdf>

Also Low Energy Nu Factory option
plus a very Low Energy Muon Storage ring.

Vacuum LBL:

$$\nu_{\mu} \rightarrow \nu_e$$

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

$$\Delta_{ij} = \delta m_{ij}^2 L / 4E$$

CP violation !!!

where $\sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$

and $\sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \sin \Delta_{21}$

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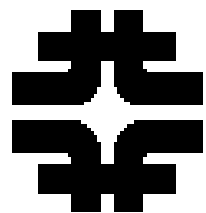
and $\sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \sin \Delta_{21}$

$$P_{\mu \rightarrow e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}} \cos(\Delta_{32} \pm \delta) + P_{sol}$$

only CPV

$$\cos(\Delta_{32} \pm \delta) = \cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta$$

$$\Delta P_{cp} = 2 \sin \delta \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \cos \theta_{13} \sin \Delta_{21} \sin \Delta_{31} \sin \Delta_{32}$$



$$\nu_{\mu} \rightarrow \nu_e$$

In Matter:

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

$$\text{where } \sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$$

$$\text{and } \sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

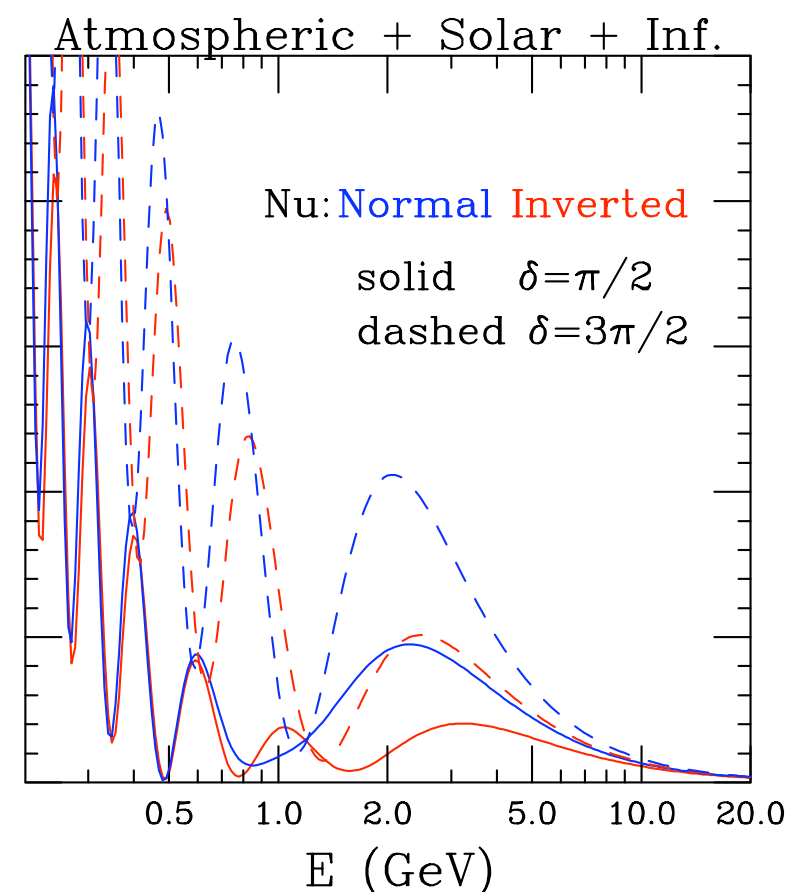
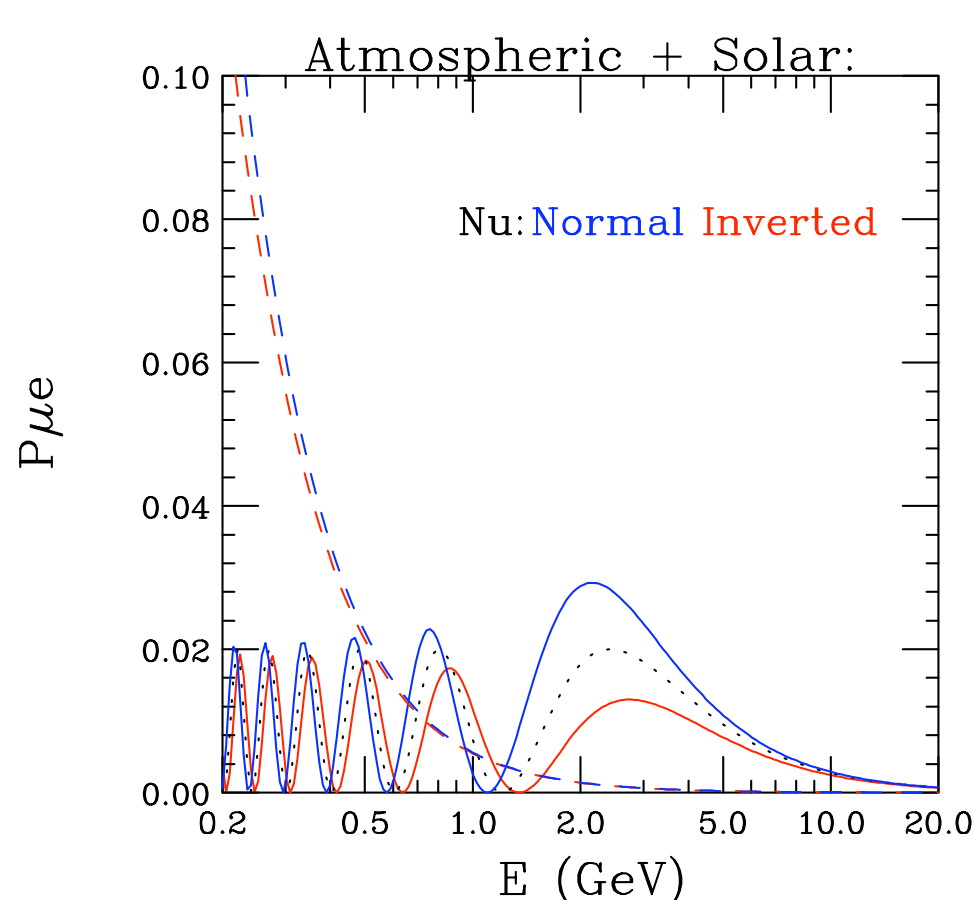
For $L = 1200 \text{ km}$
and $\sin^2 2\theta_{13} = 0.04$

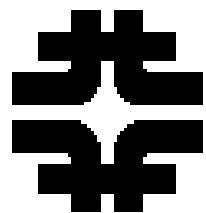
$$a = G_F N_e / \sqrt{2} = (4000 \text{ km})^{-1},$$

Anti-Nu: Normal Inverted

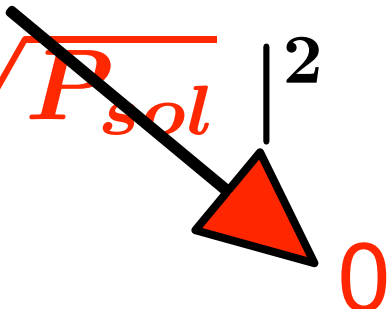
dashes $\delta = \pi/2$

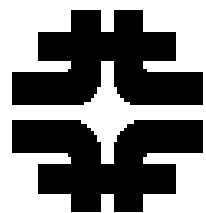
solid $\delta = 3\pi/2$



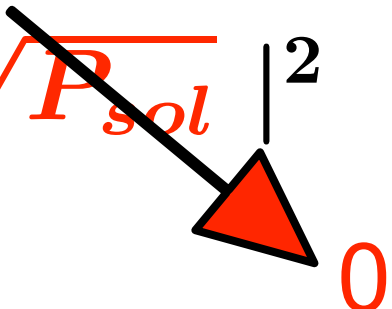


Special Baselines:

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$
A red arrow points from the $\sqrt{P_{sol}}$ term in the equation to a red '0' below it, indicating that this term is zero.



Special Baselines:

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$


“Magic” Baseline

$$P_{sol} = 0 \text{ when } aL = \pi, 2\pi, \dots$$

in earth this happens for $L \approx 7500$ km

CERN to INO

JPARC to INO

then $P_{\mu e} \approx P_{atm} = \sin^2 \theta_{23} \sin^2 \theta_{13} \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} \Delta_{31}^2$

No sensitivity to CPV (δ)

Good for measuring $\sin^2 \theta_{13}$ and Mass Hierarchy

In Matter:

Bi-Magic Baseline:

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

$$\text{where } \sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$$

$$\text{and } \sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

$$a = G_F N_e / \sqrt{2} = (4000 \text{ km})^{-1},$$

In Matter:

Max for one Hierarchy and 0 other

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$$a = G_F N_e / \sqrt{2} = (4000 \text{ km})^{-1},$$

Sushant K. Raut, Ravi Shanker Singh, S.Uma Sankar [arXiv:0908.3741](#)

Amol Dighe, Srubabati Goswami, Shamayita Ray [arXiv:1009.1093](#)

“Bi-Magic” Baseline and Energy

Choose L such that

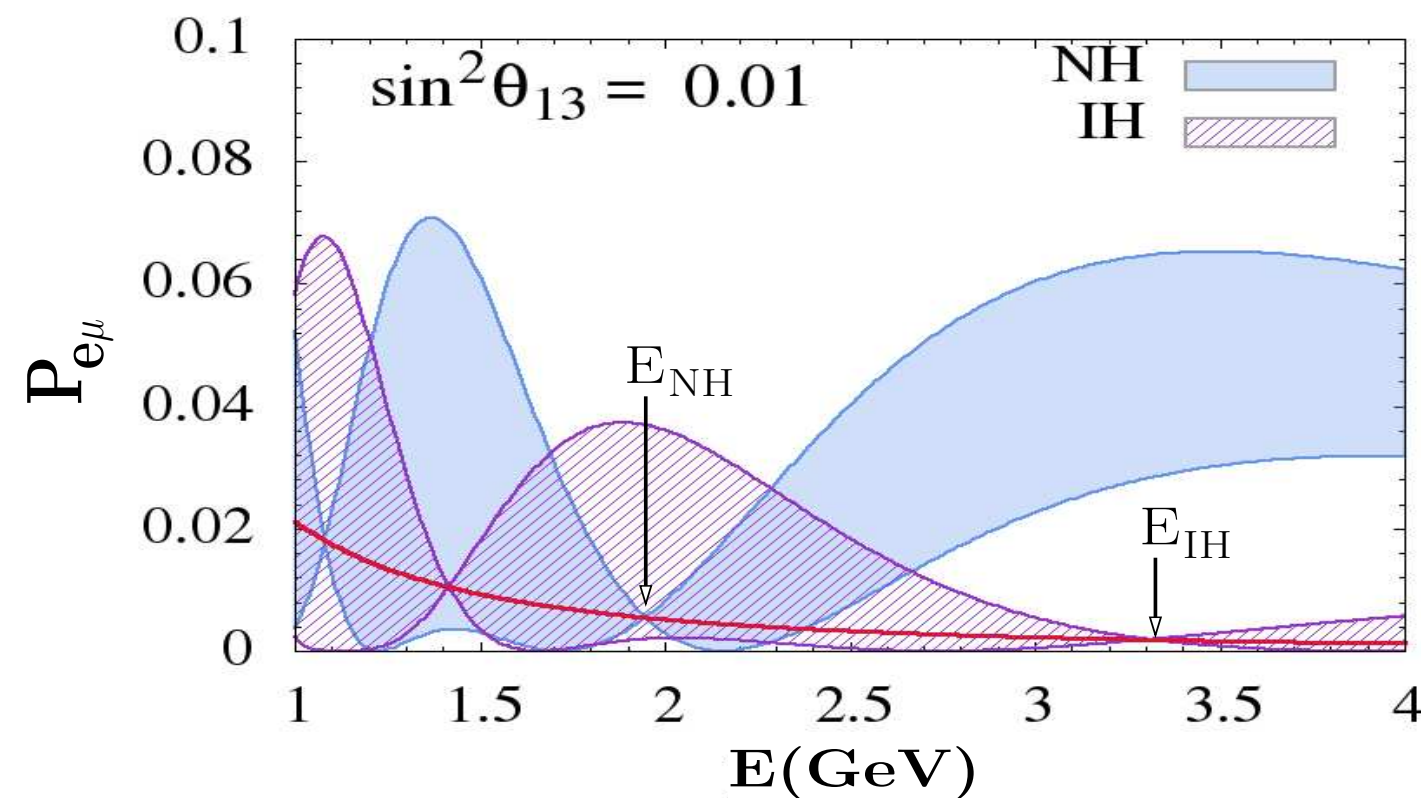
$$P_{atm}|_{IH} = 0 \text{ and } P_{atm}|_{NH} \text{ is max. at } E_{IH}$$

and

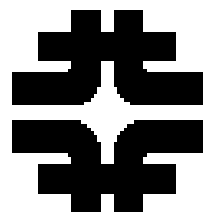
$$P_{atm}|_{NH} = 0 \text{ and } P_{atm}|_{IH} \text{ is max. at } E_{NH}$$

$L=2540 \text{ km}$ and $E_{IH}=3.3 \text{ GeV}$ and $E_{NH}=1.9 \text{ GeV}$

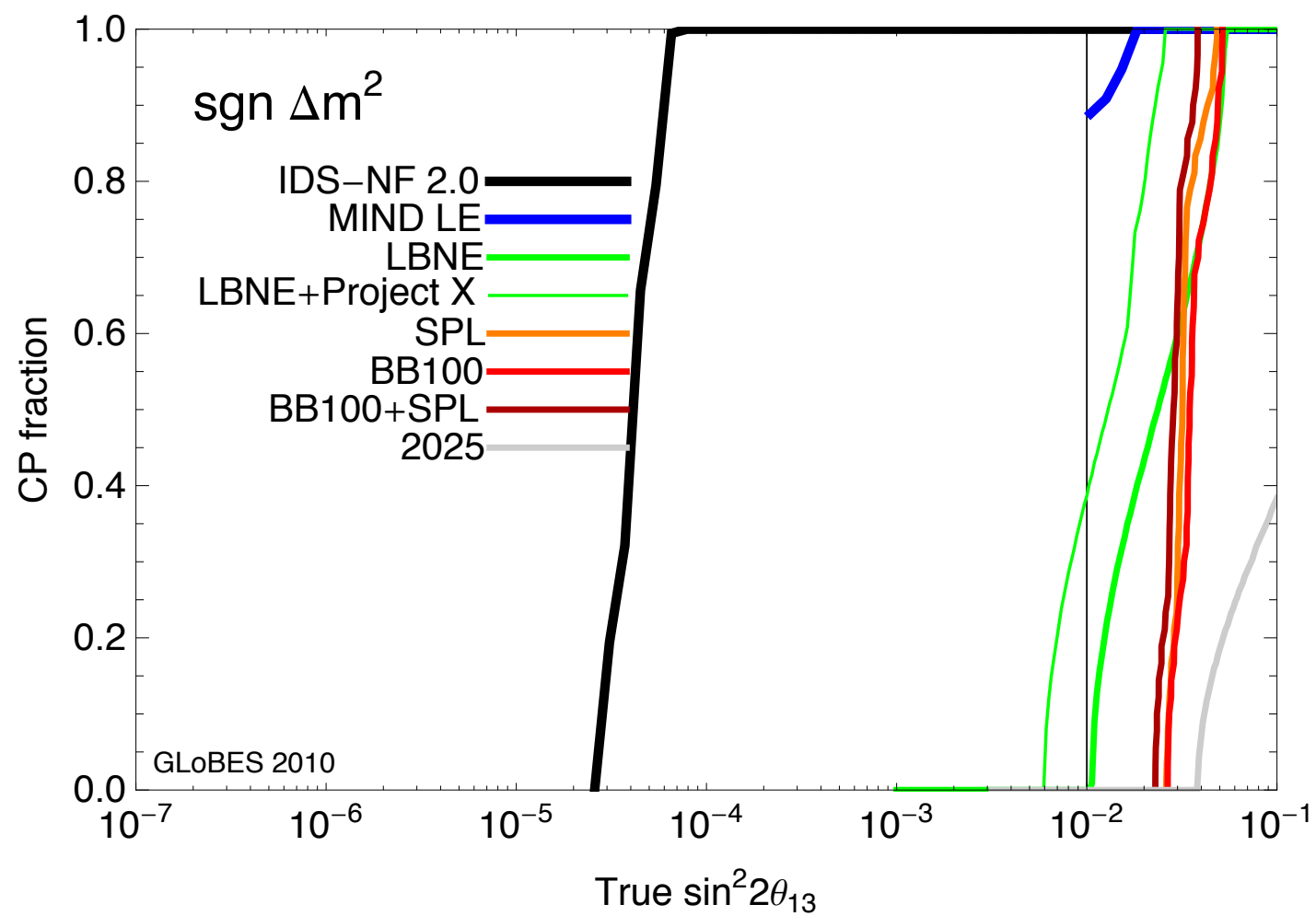
flip when ν and $\bar{\nu}$ interchange

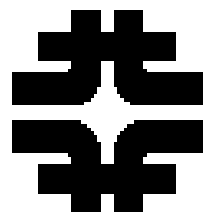


Approx. Fermilab to Yucca Mtn:

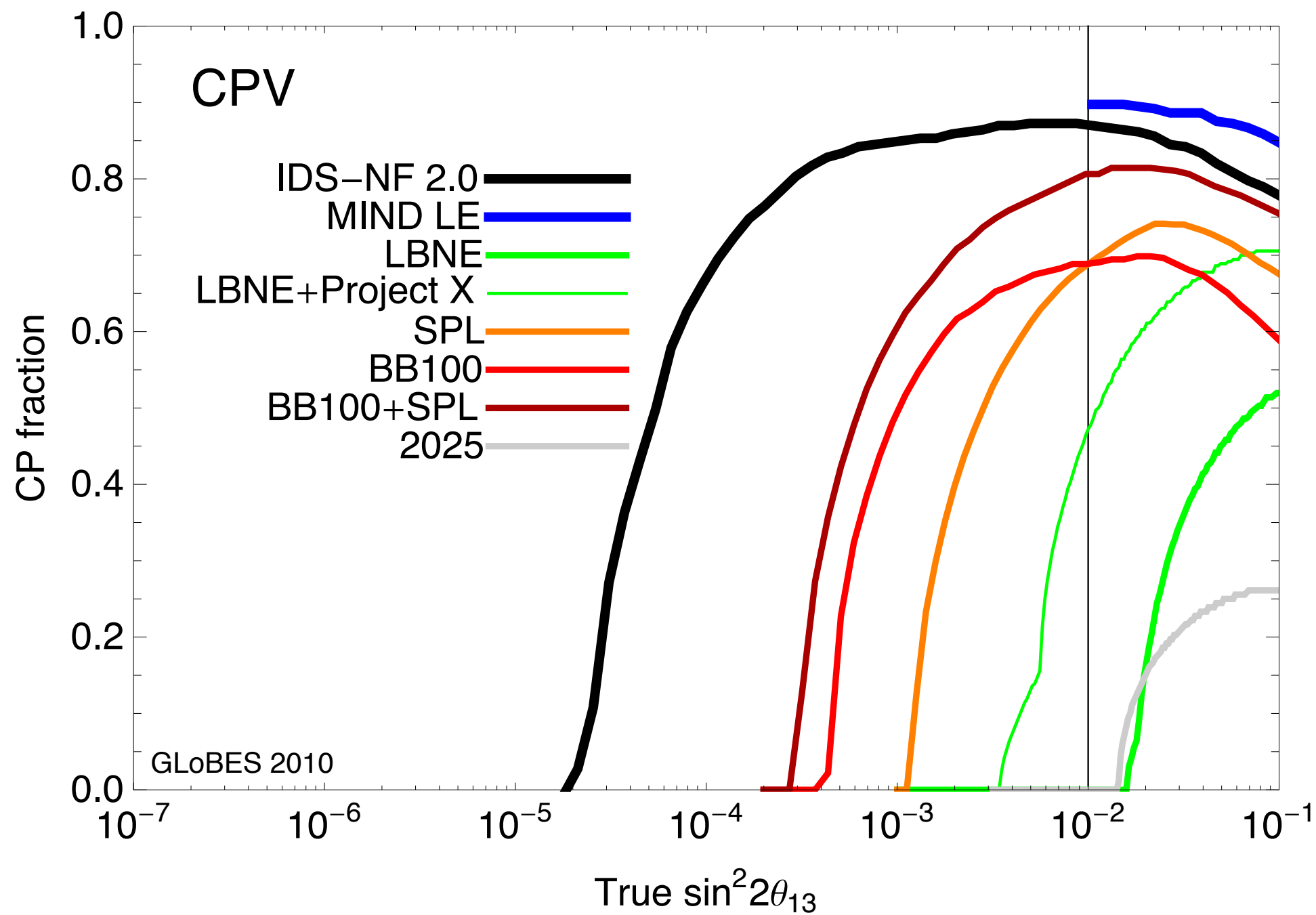


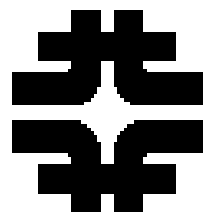
Mass Hierarchy:





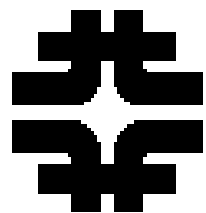
CP Violation:



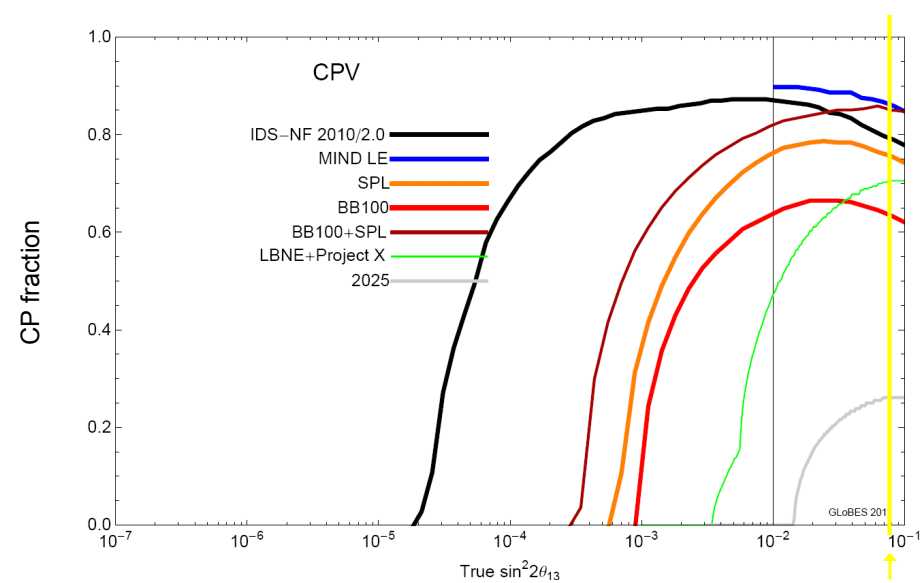


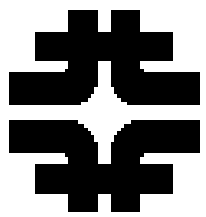
Large Theta_13

- Large Theta_13, if confirmed
 - wonderful opportunity for all !!!
 - Double Chooz, Daya Bay and Reno, T2K, NOvA
 - precision determination of Theta_13
 - exclude wrong Hierarchy at high CL
 - CPV, precision dominated by systematic effects!
 - New Physics less likely to be entangled with Theta_13 effects !
- More at or before Nu 2012 (June) !!!
especially RENO and T2K

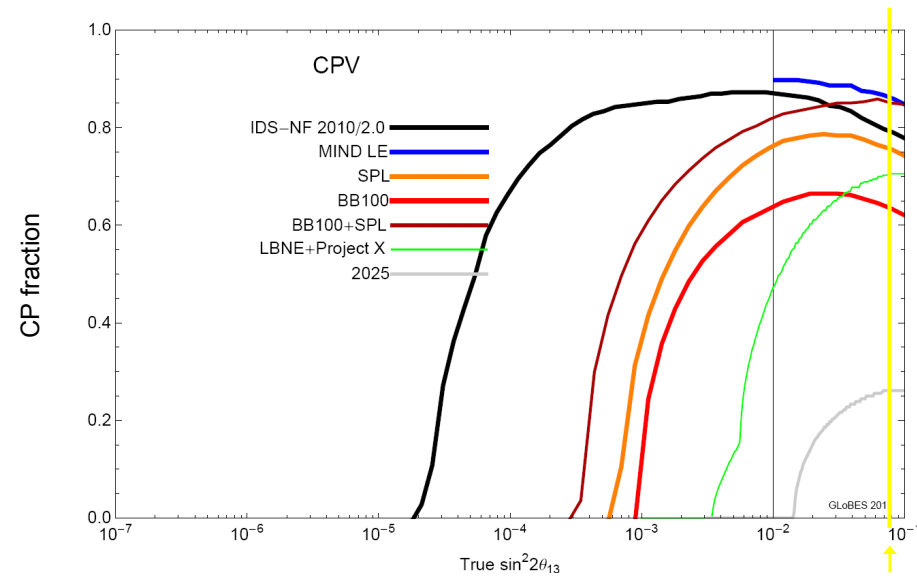


Asymmetry:



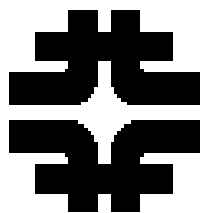


Asymmetry:

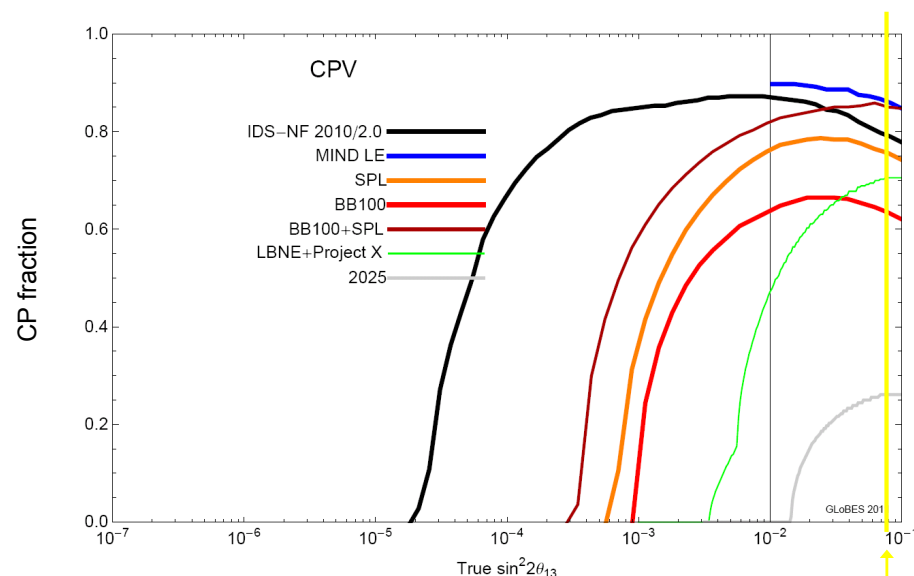


$$A_{vac} \approx \frac{1}{11} \frac{\sin 2\theta_{13} \sin \delta}{(\sin^2 2\theta_{13} + 0.002)}$$

$$[A_{vac} \equiv \frac{P - \bar{P}}{P + \bar{P}} = \frac{P_\delta - P_0}{P_0} \text{ at } \Delta_{31} = \frac{\pi}{2} \text{ (VOM)}]$$



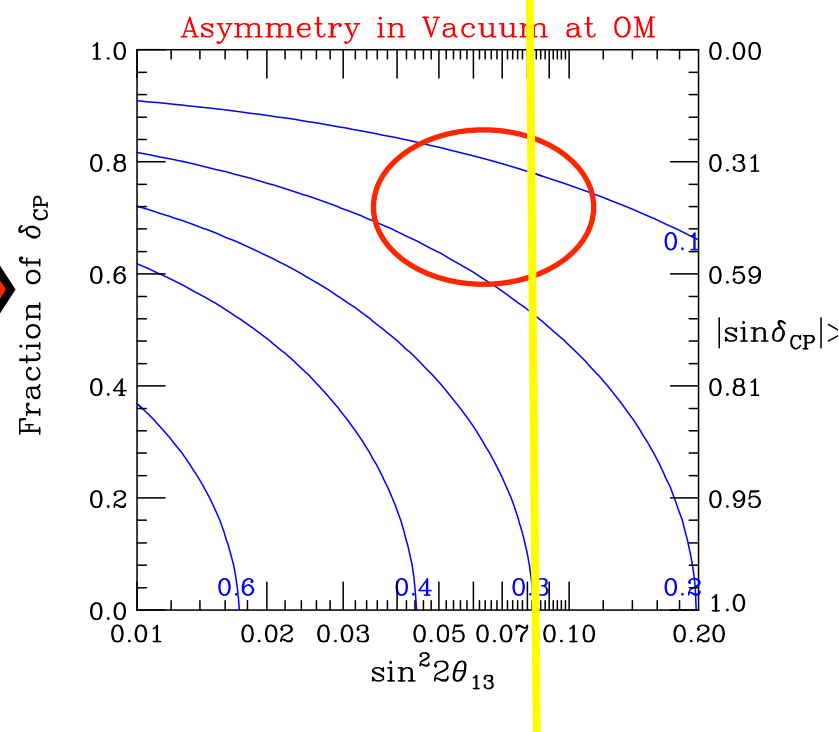
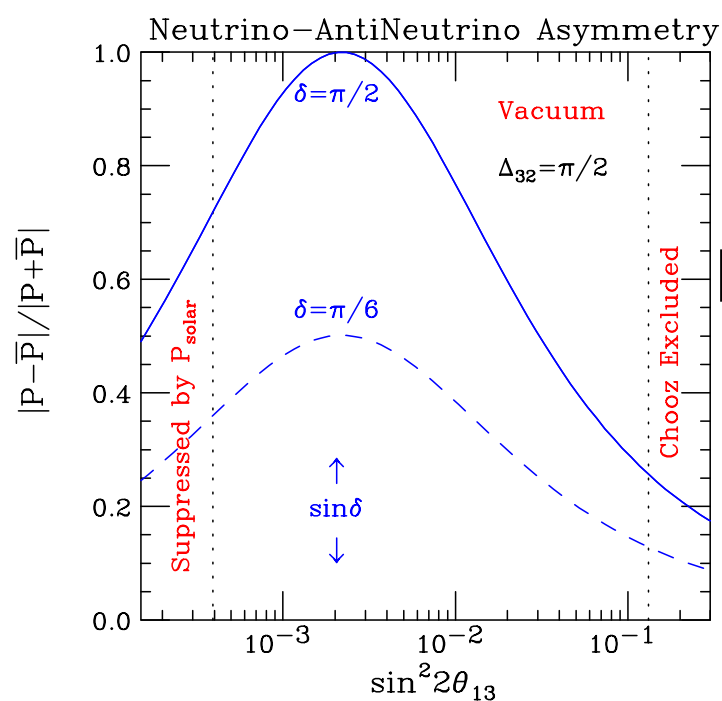
Asymmetry:

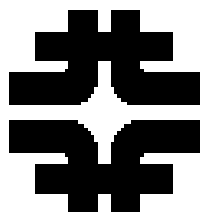


$$A_{vac} \approx \frac{1}{11} \frac{\sin 2\theta_{13} \sin \delta}{(\sin^2 2\theta_{13} + 0.002)}$$

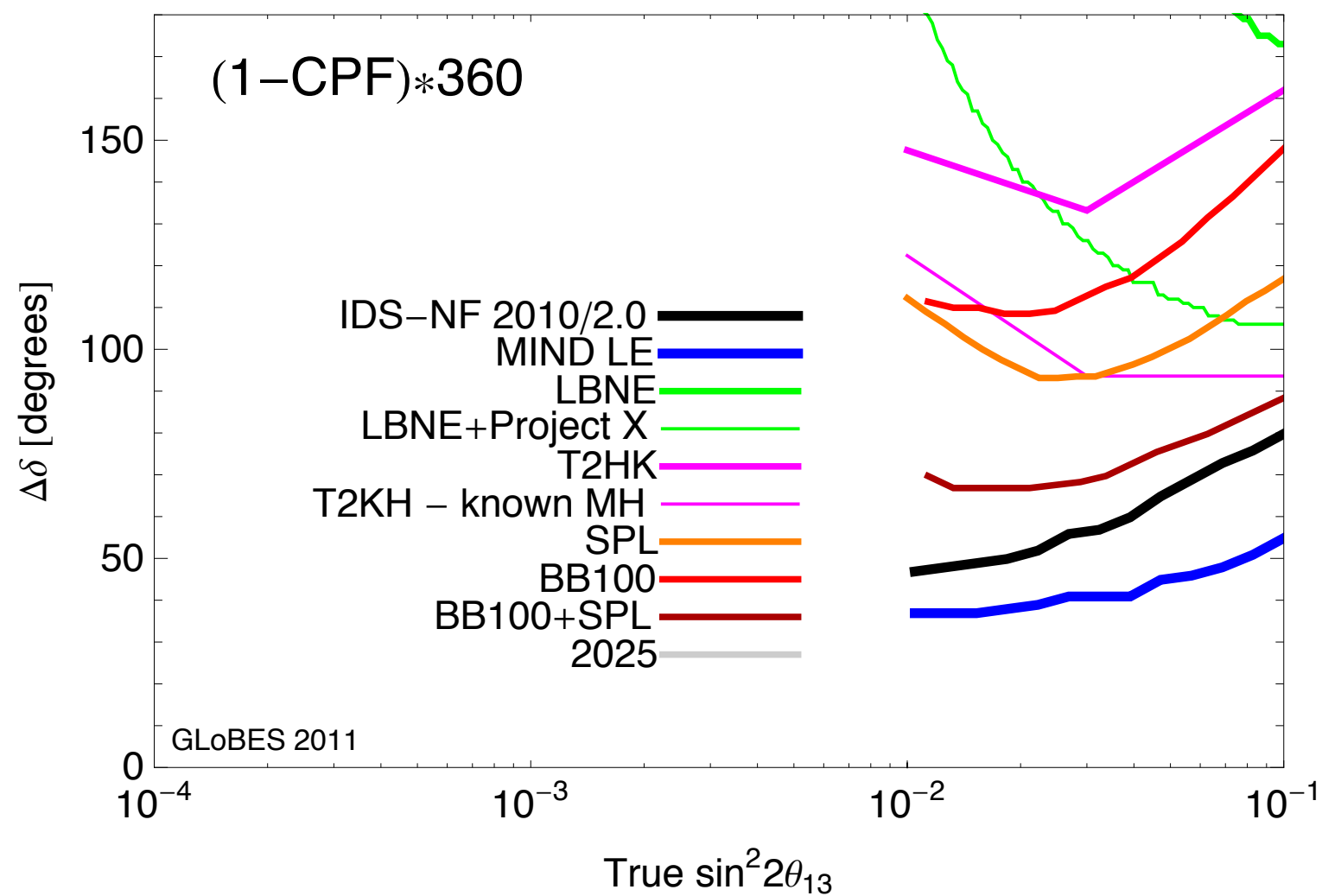
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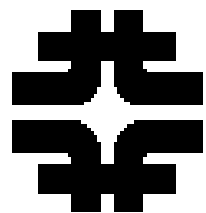
Vacuum, at 1st oscillation maximum





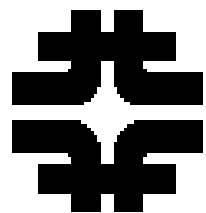
CPV





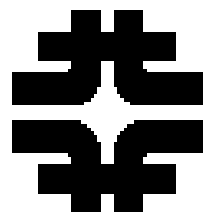
Beyond Nu SM

- Sterile
- Non-Standard Interactions (NSI)
- Surprises !



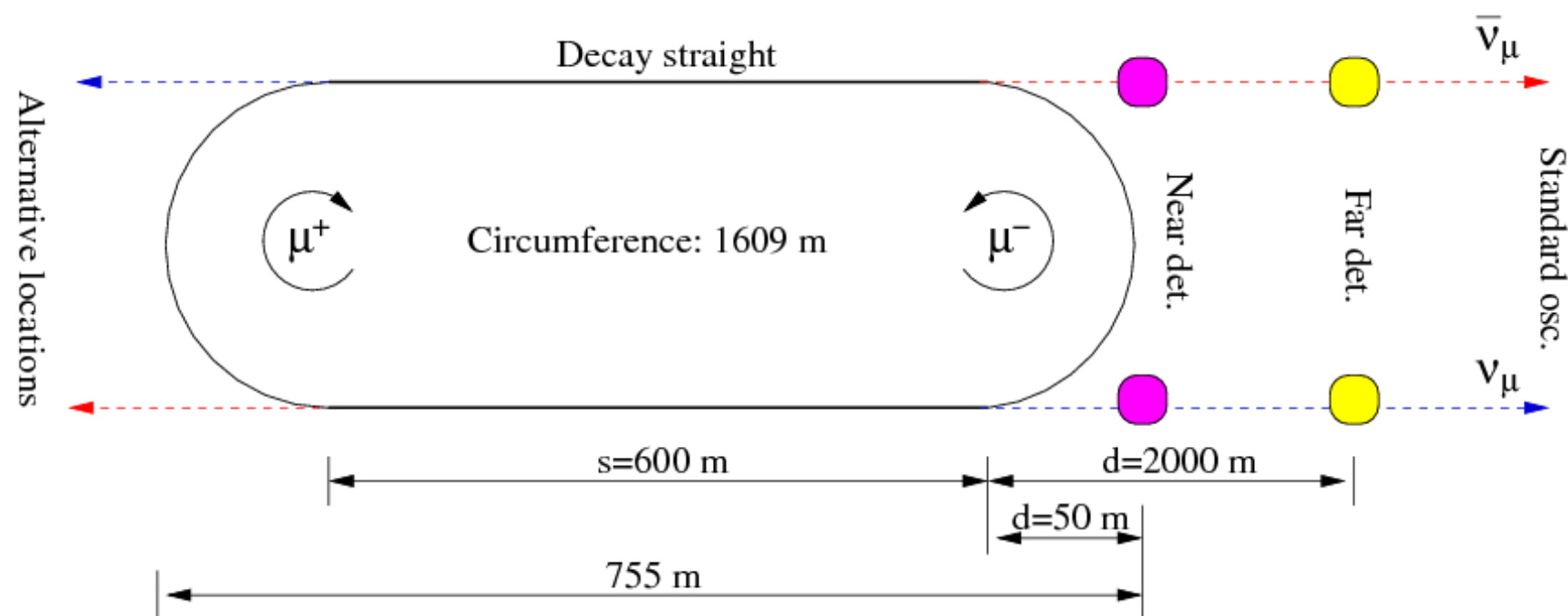
Sterile Neutrinos:

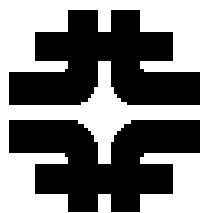
- hints of Sterile Neutrinos
 - LSND (3.8 sigma)
 - miniBooNE anti-neutrinos (?)
 - Reactor Anomaly
 - Gallium Anomaly



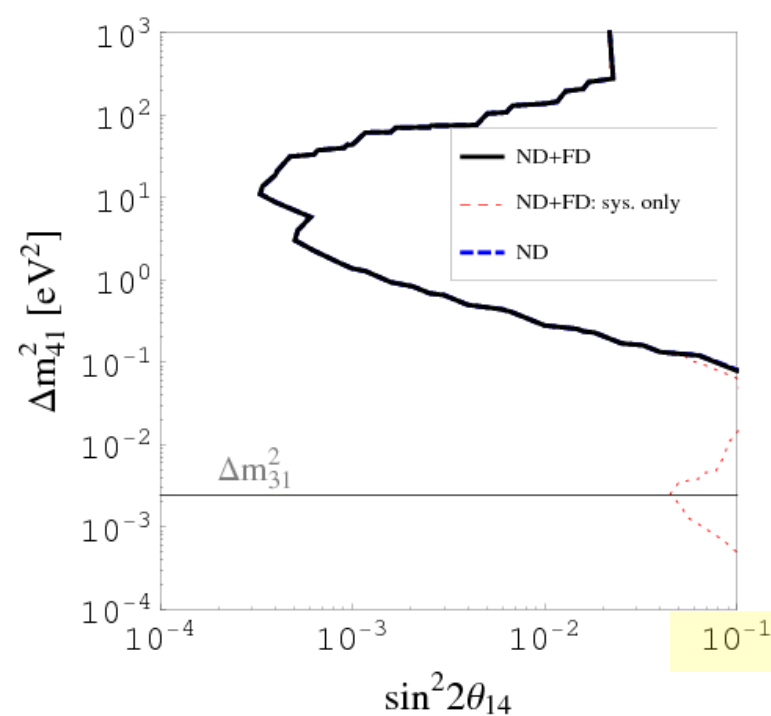
Sterile Neutrinos:

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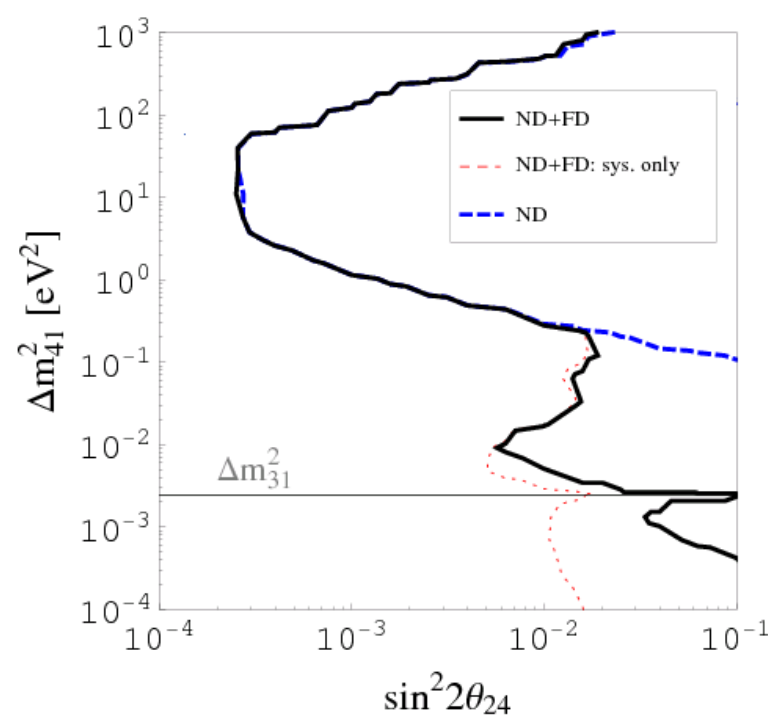




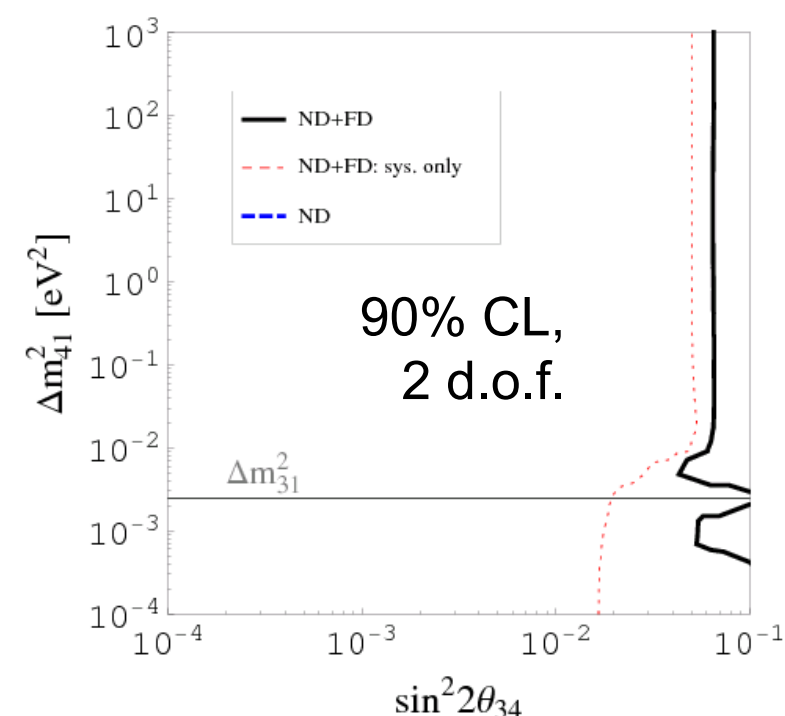
... without any constraints on Δm_{41}^2



From ν_e
disappearance

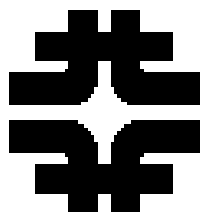


From ν_μ
disappearance



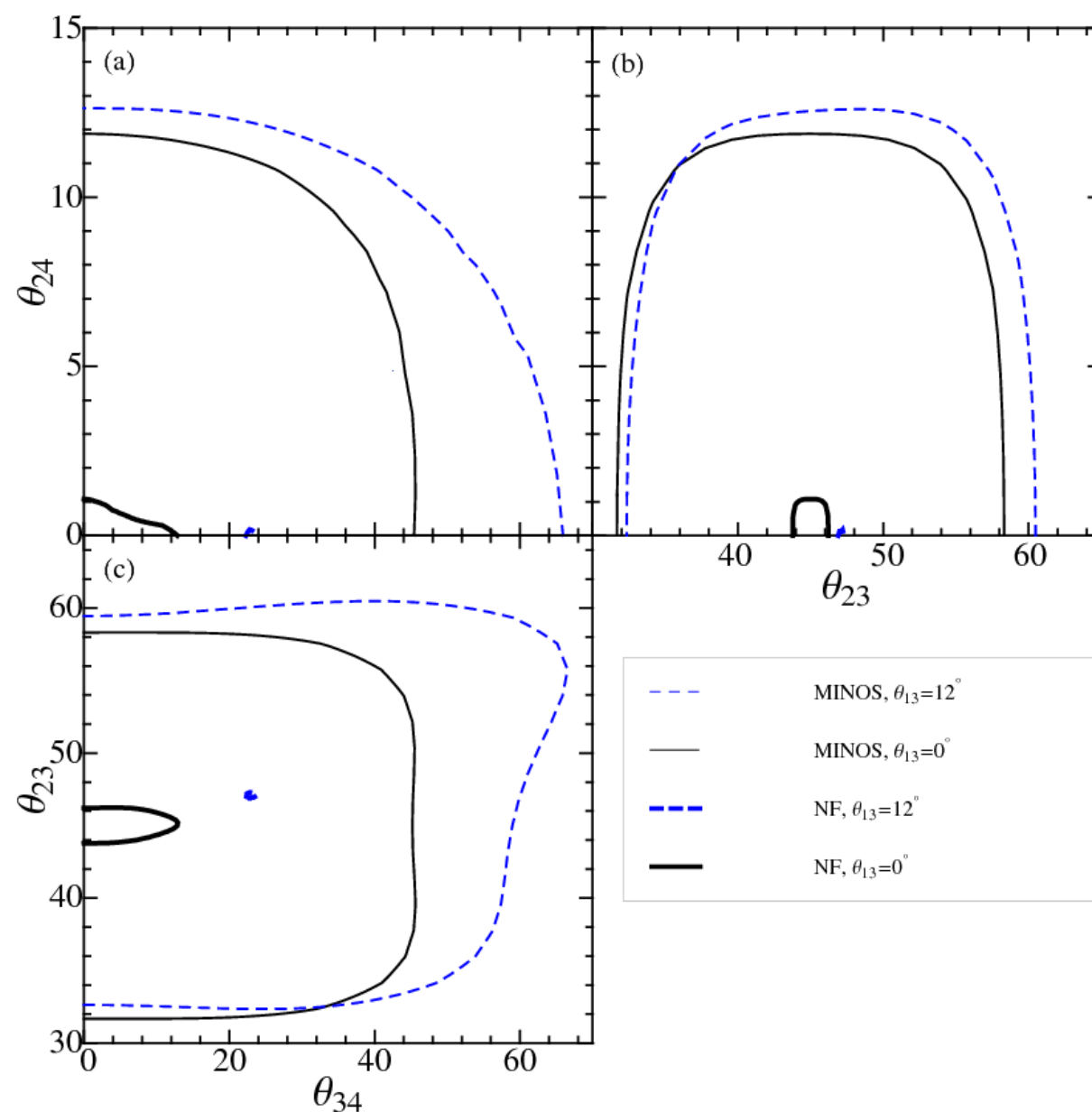
From LBL- ν_μ
disappearance
(higher order effect)

(Meloni, Tang, Winter, arXiv:1007.2419)

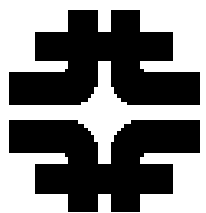


- Comparison to MINOS: Tremendous increase of sensitivity, especially for large θ_{13}

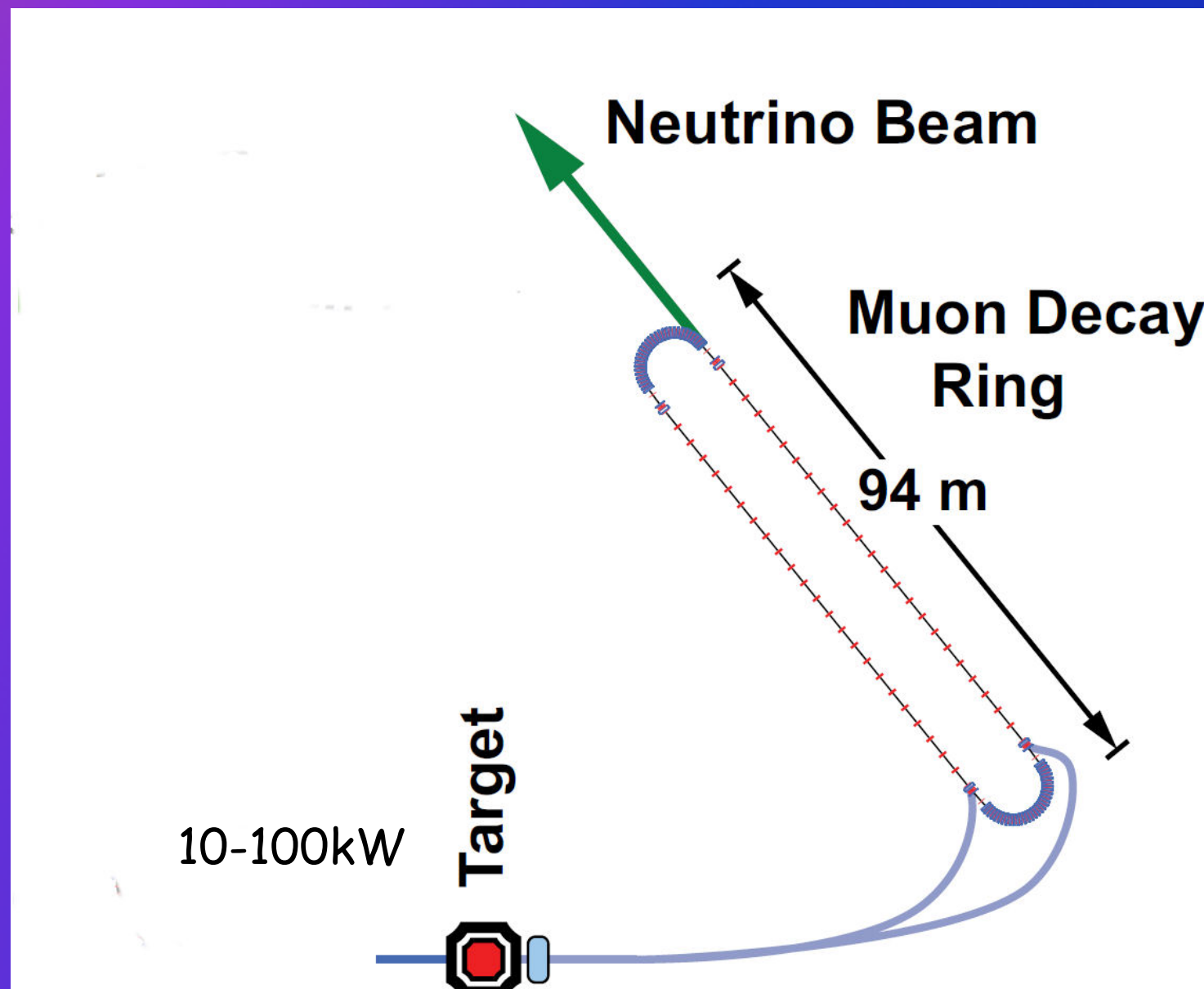
NDFD@NF v.s MINOS



(Meloni, Tang, Winter, arXiv:1007.2419;
compared to MINOS, Adamson et al, arXiv:1003.0336)

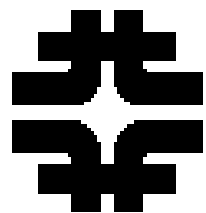


Very Low Energy NF (VLENF):



- **Motivation:**

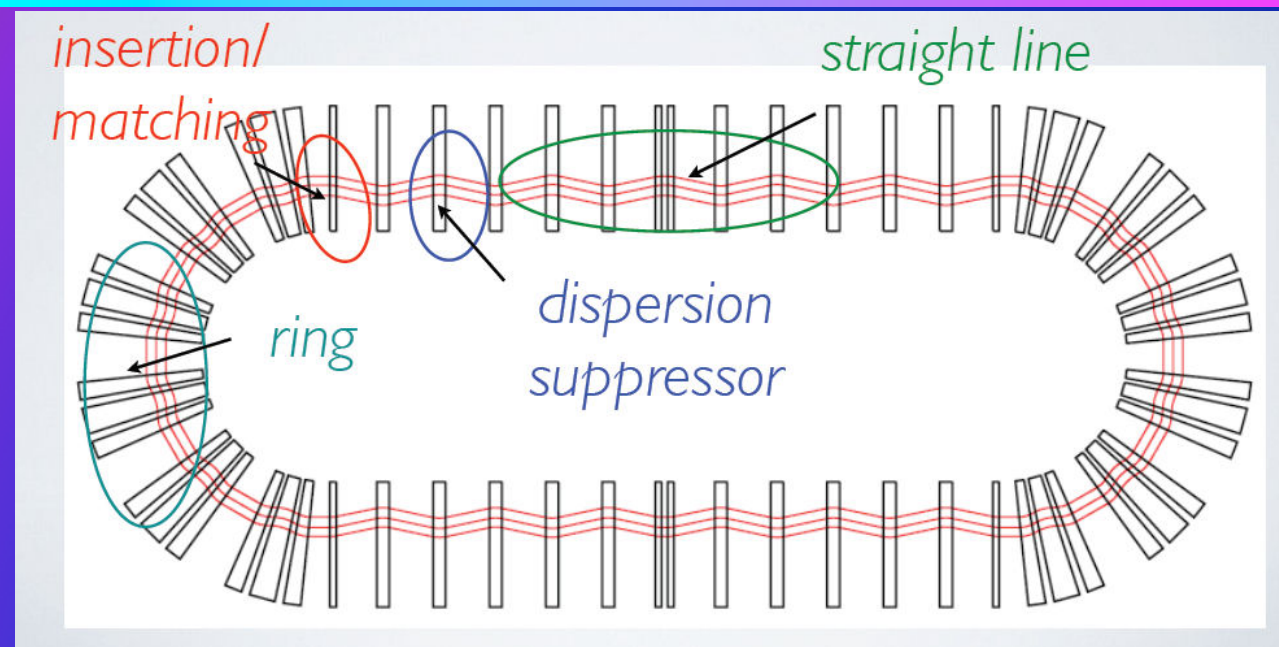
- ◆ Address large δm^2 regime (LSND, MiniBooNE)
- ◆ Reactor flux anomaly (ν_e disappearance)
- ◆ Cross-section measurements
 - ▲ μ storage ring presents only way to measure ν_μ & ν_e x-sections in same experiment
 - ▲ Supports future long-baseline experiments
- ◆ A technology proving ground and a test bed for μ storage ring instrumentation (Goal of flux normalization to 1% or better)
 - ▲ BCT
 - ▲ Polarimeter
 - ▲ Beam divergence monitor



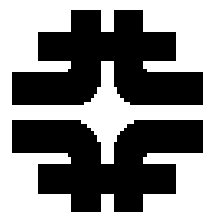
VLENF (conti)

Yoshi Mori
Kyoto

FFAG Racetrack



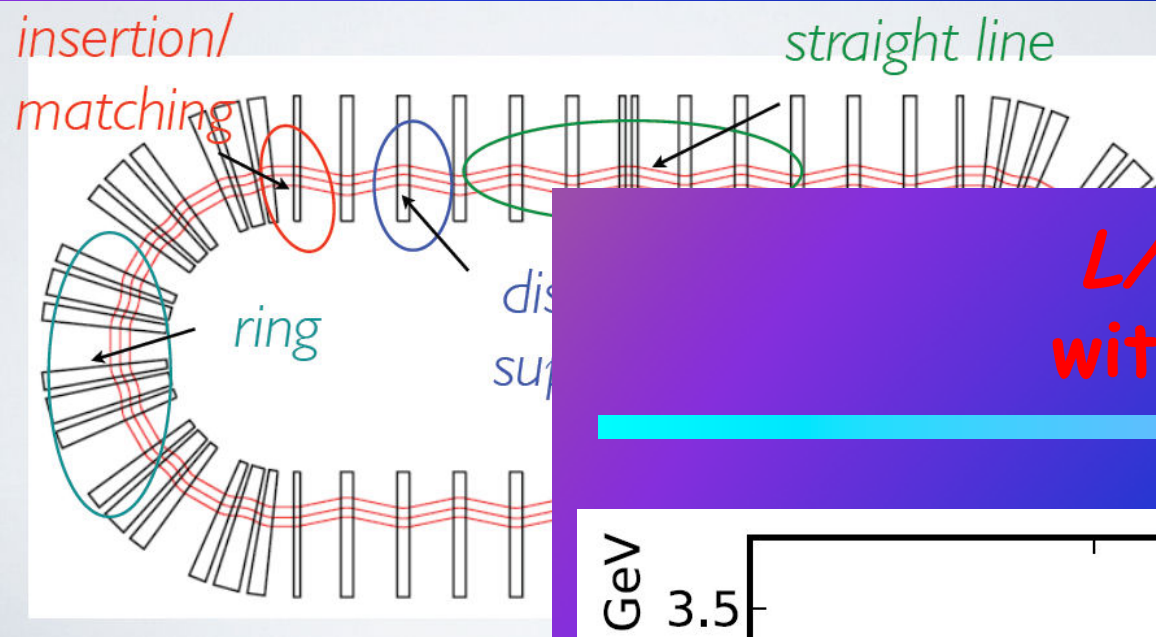
$$\delta p/p \approx 20\%$$



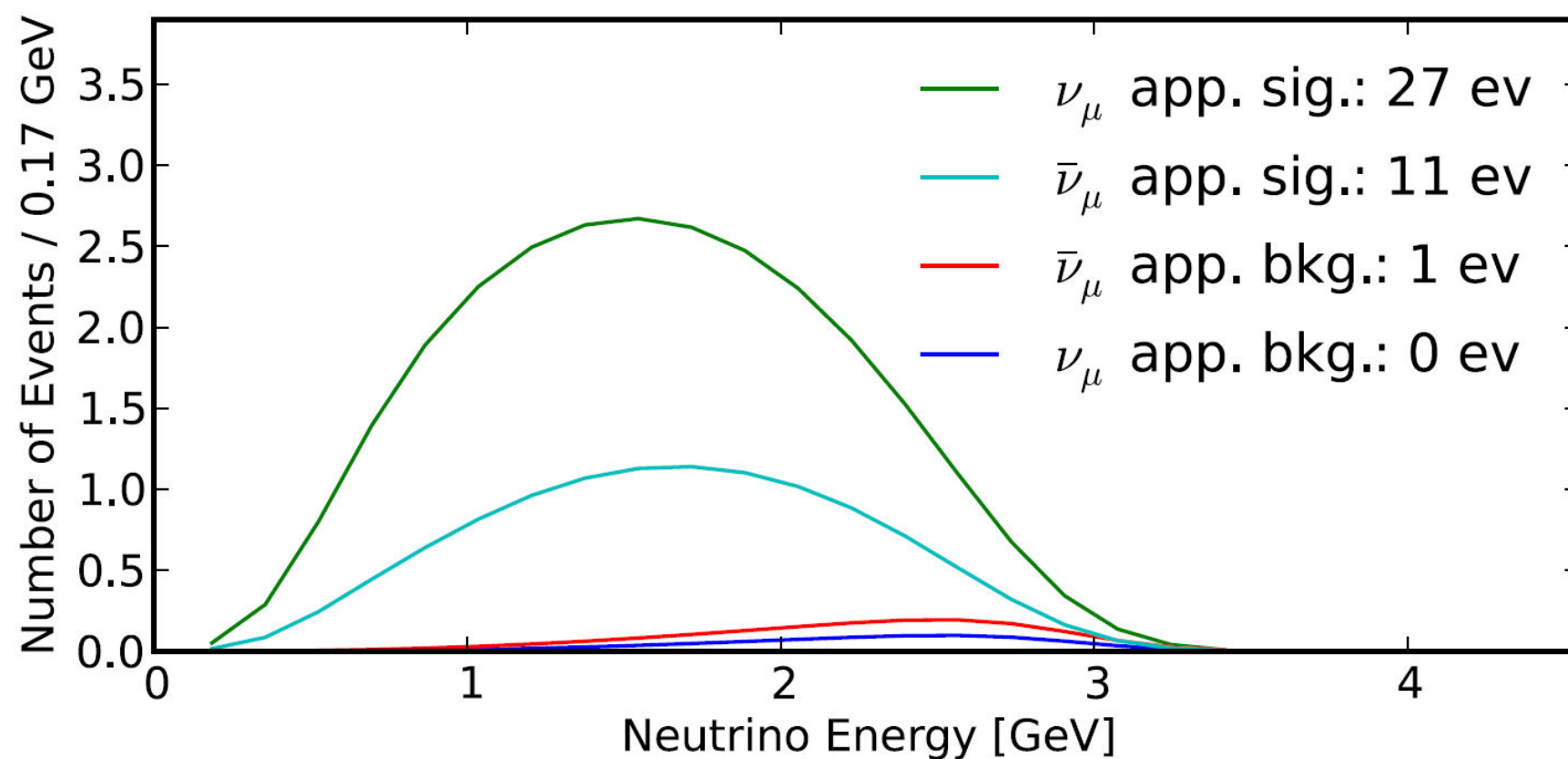
VLENF (conti)

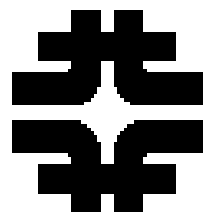
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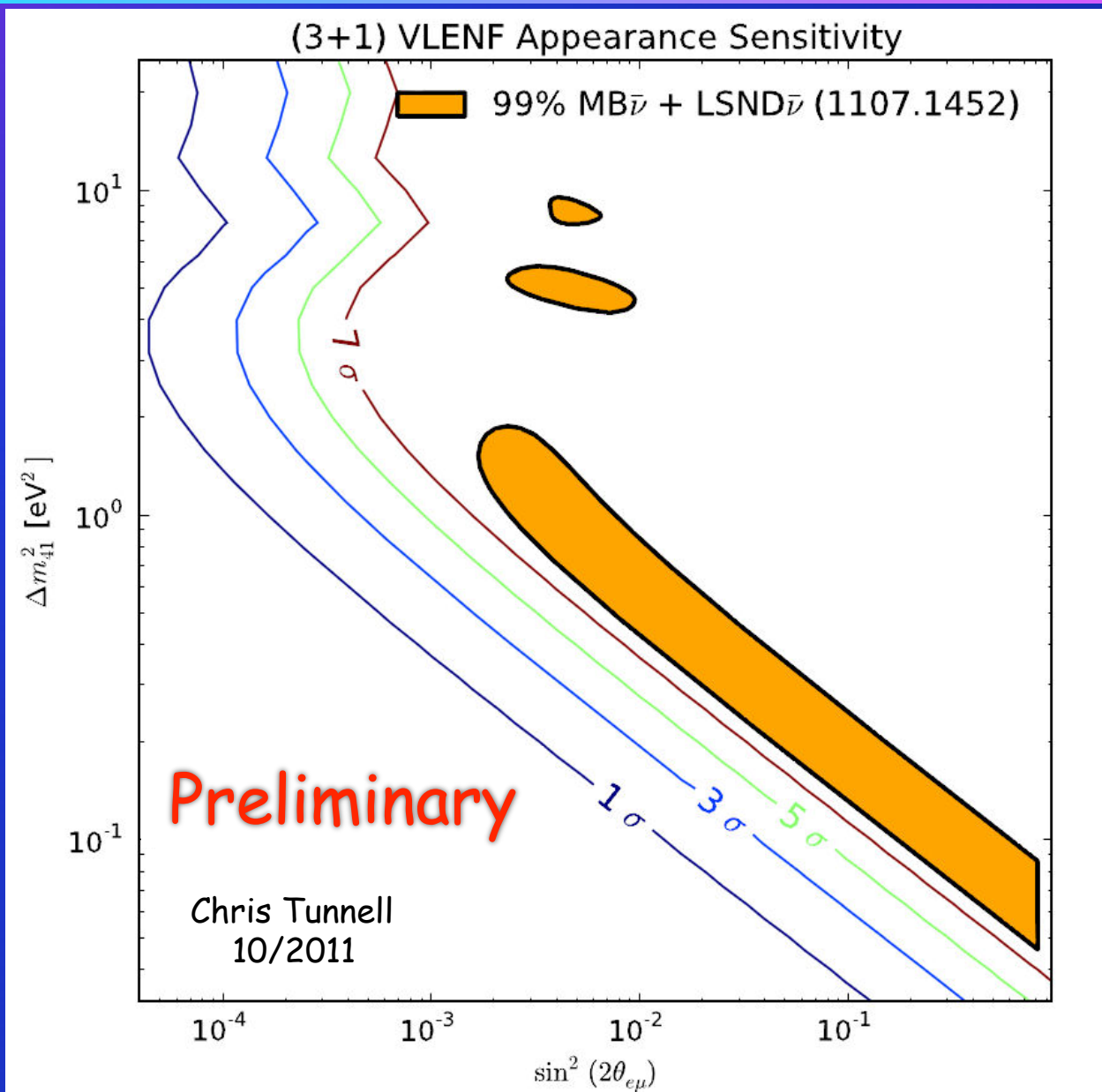
**$L/E \approx 1$ Oscillation reach
with FFAG $E_{\mu}^{\text{center}} = 2 \text{ GeV}$**



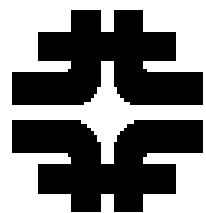


VLENF (conti)

**$L/E \approx 1$ Oscillation reach
Exclusion contours**



MUST be DEFINITIVE !!!



Beyond Nu SM

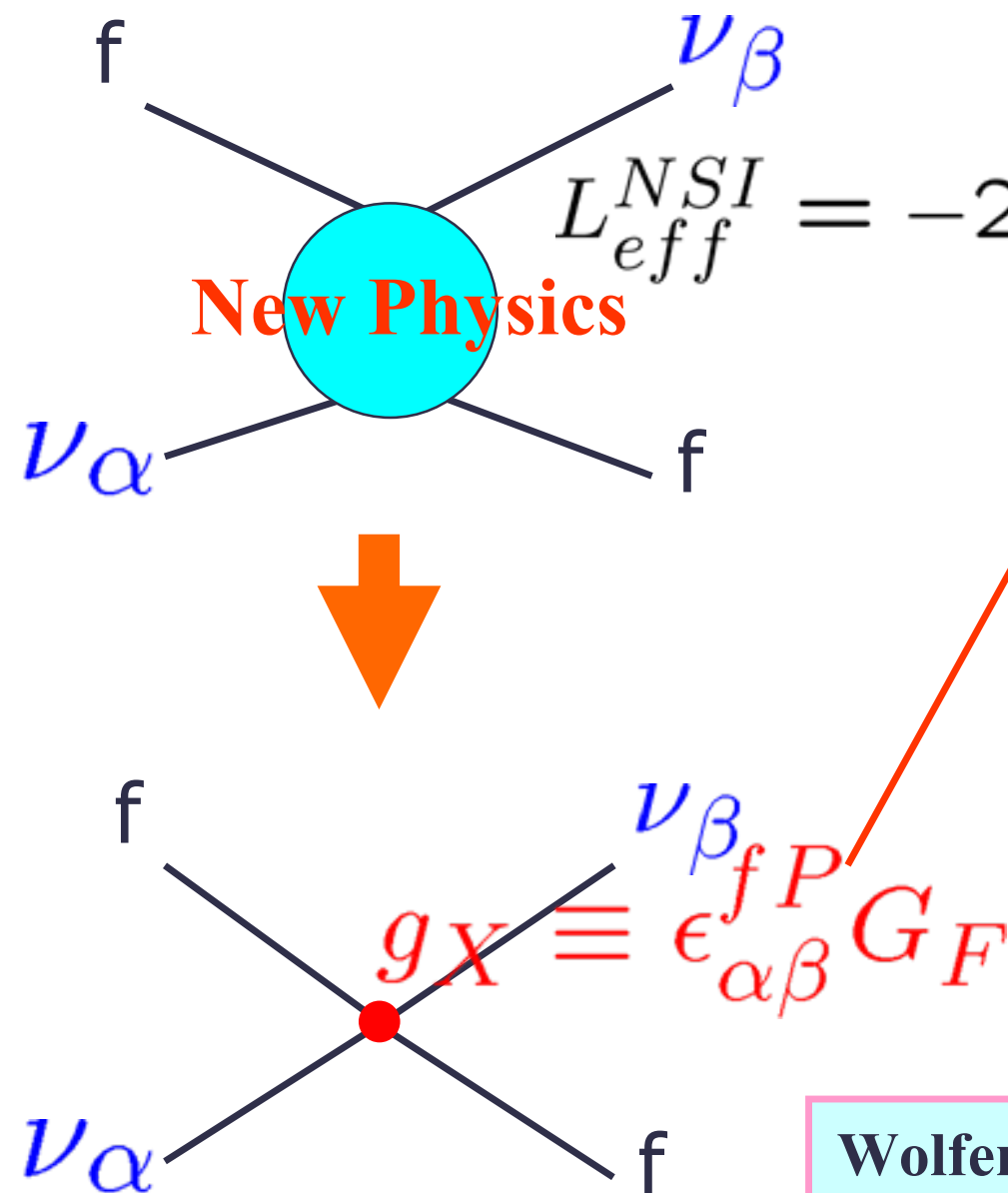
- Sterile
- Non-Standard Interactions
(NSI)
- Surprises !

Non-Standard neutrino Interaction

Shoichi Uchinami

Nei Cipriano Ribeiro^{*1}, Hisakazu Minakata^{*2}, Hiroshi Nunokawa,^{*1} and Renata Zukanovich Funchal^{*3}

Non-Standard Interaction



$$L_{eff}^{NSI} = -2\sqrt{2}\epsilon_{\alpha\beta}^f P G_F (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) (\bar{f} \gamma^\mu P f)$$

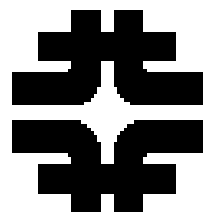
$$P_L \equiv \frac{1}{2}(1 - \gamma_5), P_R \equiv \frac{1}{2}(1 + \gamma_5)$$

Naive Estimation $\epsilon_{\alpha\beta} \propto \frac{m_W^2}{m_X^2}$

If new physics scale $\sim 1(10)$ TeV

$$\epsilon_{\alpha\beta} \sim 0.01(0.0001)$$

Wolfenstein '78, Grossman '95, Berezhiani-Rossi '02 and many people...



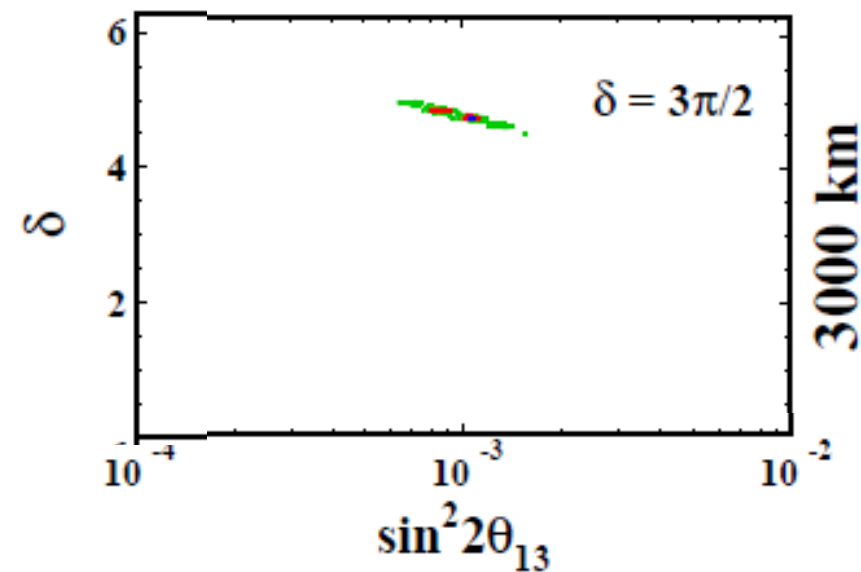
NF constraints on NSI

Model independent approach. Mild experimental constraints:

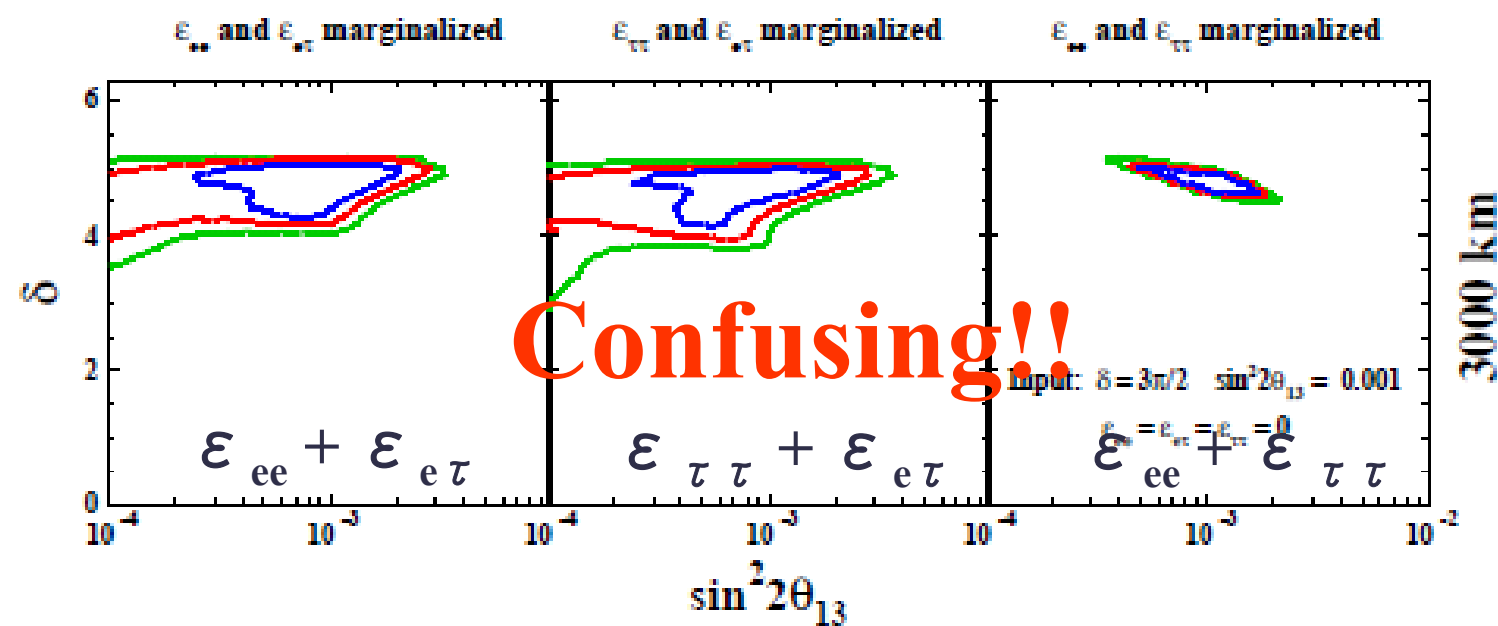
$$|\varepsilon_{\alpha\beta}^{\oplus}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

relative to G_F

standard case



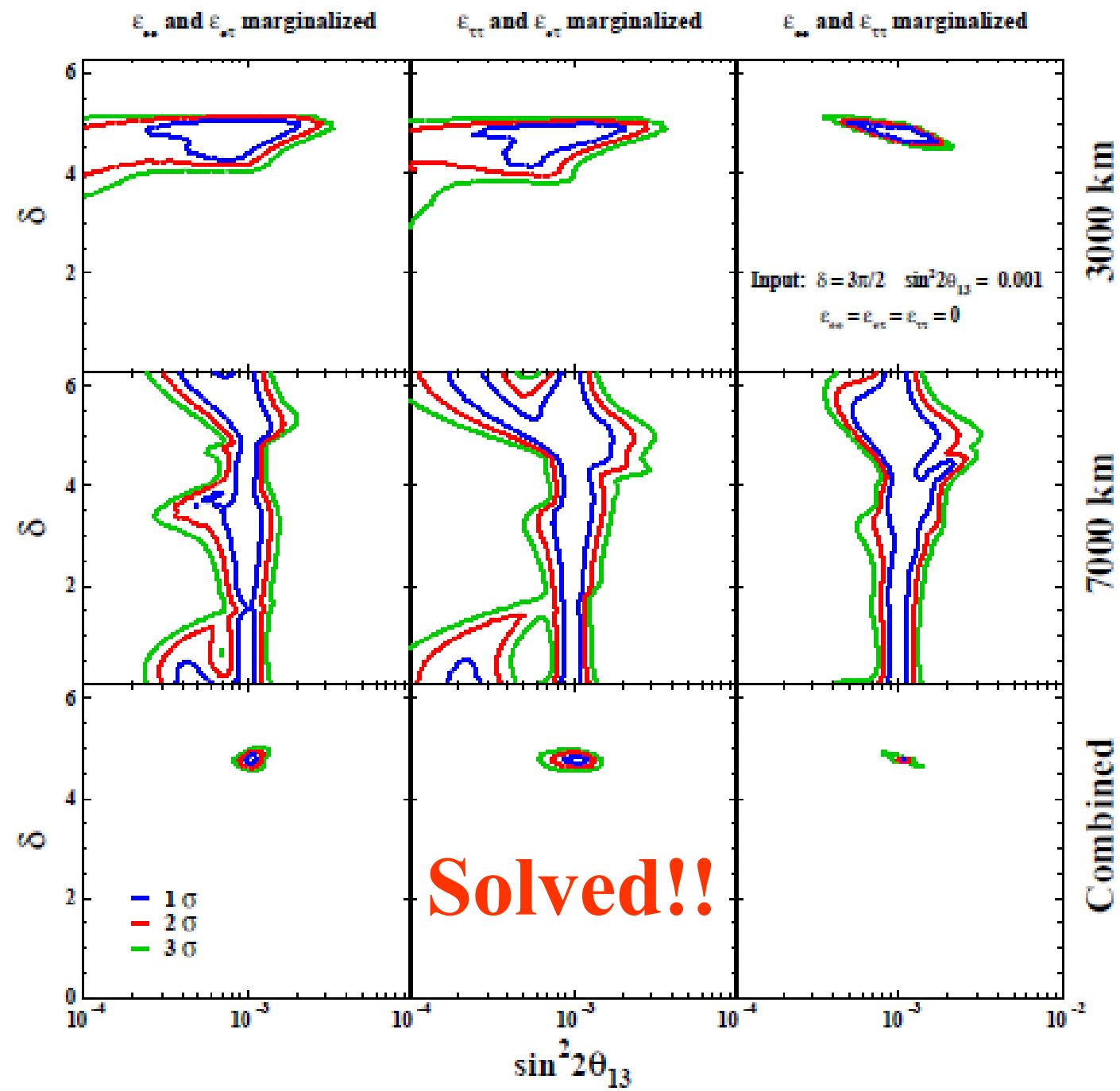
If we take account of the possible existence of NSI



all $\epsilon = 0$

our setting

2 detector setting



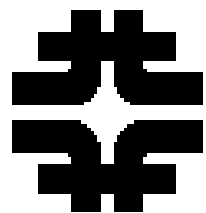
Neutrino factory with two detectors at $L=3000\text{km}$ and 7000km

1. solves the problem that the presence of NSI confuses the precision measurement of θ_{13} and δ
2. is powerful enough to probe into extremely small values of the NSI parameters.

$$\varepsilon_{e\tau} \sim O(10^{-3})$$

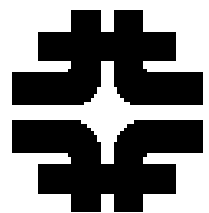
$$\varepsilon_{e\mu} \sim O(10^{-4})$$

(2 σ)

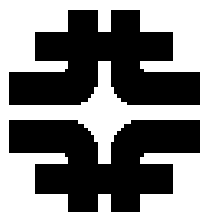


Beyond Nu SM

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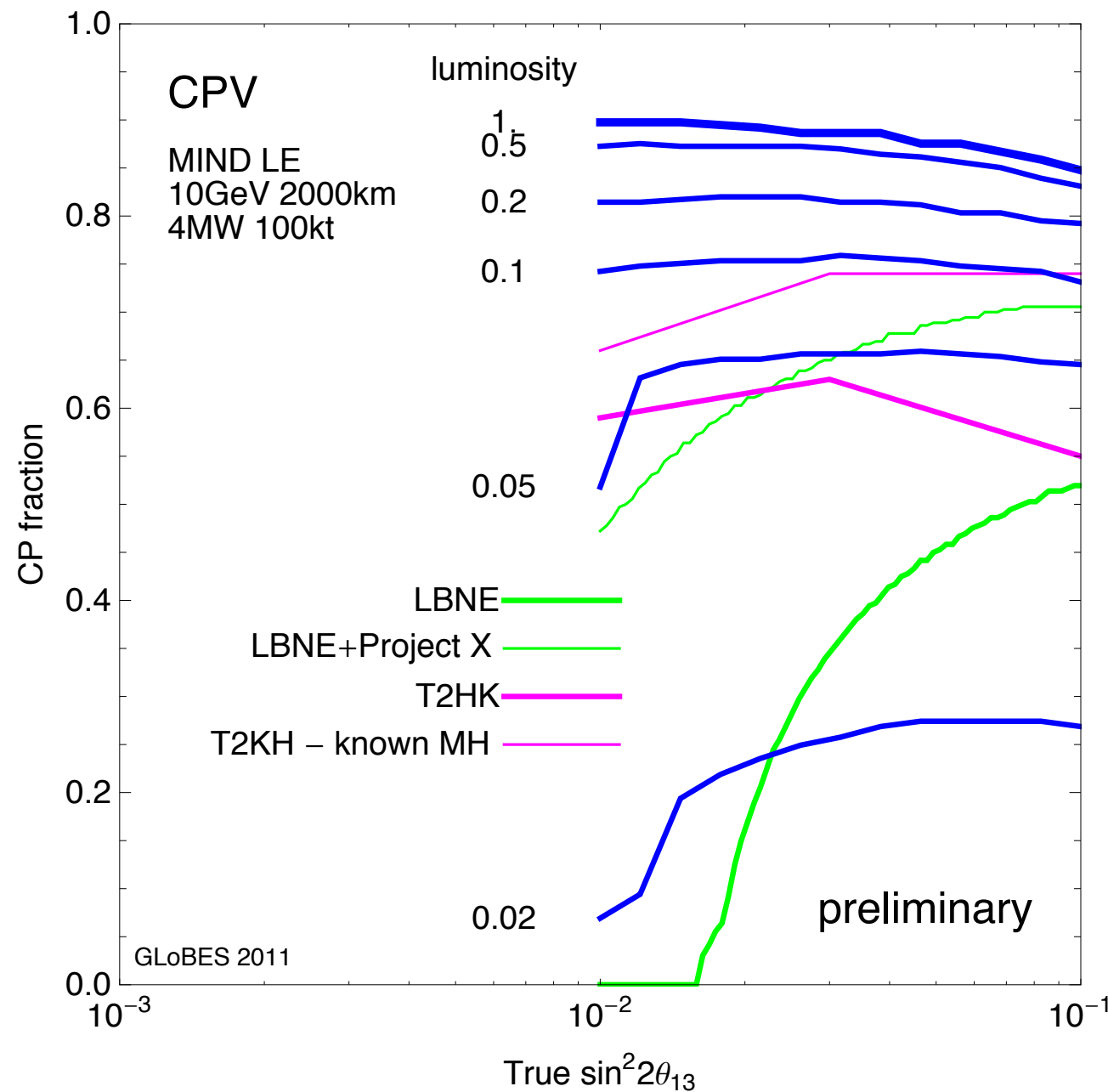
STAGING & CONCLUSIONS



STAGING & CONCLUSIONS

- Very Low Energy NF
 - technology, Xsections, steriles
- Low Luminosity Low Energy NF
 - comparable to SuperBeam exp.

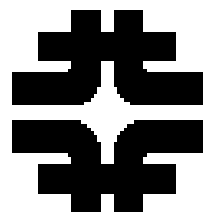
Staging – luminosity



1/20-1/10 of luminosity
- NF as good as the best SB

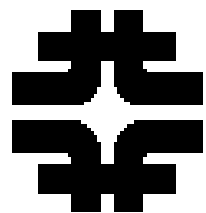
1/50-1/20 of luminosity
- NF on par with LBNE

⇒ Start somewhere between 1/50 and 1/20 and work your way to full luminosity



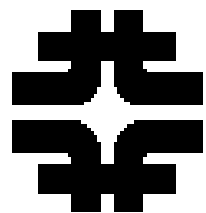
STAGING & CONCLUSIONS (conti)

- Low Energy NF
 - precision measurements
- Two Baseline NF (NSI etc)
- Muon Collider



- Accelerator Physics/Technology
- Bread & Butter Physics Measurements
- Possibilities for New Physics

at Every Stage:



- Accelerator Physics/Technology
- Bread & Butter Physics Measurements
- Possibilities for New Physics

at Every Stage:

deserves much, much more support IMHO !