Unravelling the Neutrino Mysteries: Present & Future

Stephen Parke

Fermilab

Summary of the Important Issues:

- Confirming ν's are Majorana

(seesaw $\longrightarrow$ tiny masses, Leptogenesis)
$\mathbf{0\nu\beta\beta}$ decays

- Absolute ν Mass: quasi-degenerate OR hierarchical

Tritium decay, $0\nu\beta\beta$ decays, cosmology

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

- If hierarchical What is Mass of Lightest ν?
- Is the Spectrum Normal or Inverted ?
- How close is the Mixing Matrix to Tri-Bi-Maximal???

ν_e component in ν_3: $\mathbf{\sin^2\theta_{13}}$ $\Leftarrow$
ν_μ component in ν_3: $\mathbf{(\sin^2\theta_{23} - \frac{1}{2})}$
ν_e component in ν_2: $\mathbf{(\sin^2\theta_{12} - \frac{1}{3})}$

- What is the size and sign of CPV? $\mathbf{\sin\delta}$ $\cdots$ Long Baseline Experiments

Leptogenesis

- Is the Mixing Matrix Unitarity ?

  sterile neutrinos, Non-Standard Interactions, ...

- Neutrinos in Supernova

  Neutrino Properties $\Leftrightarrow$ Supernova Dynamics

- High Energy Neutrino Astronomy

  source of cosmic rays etc

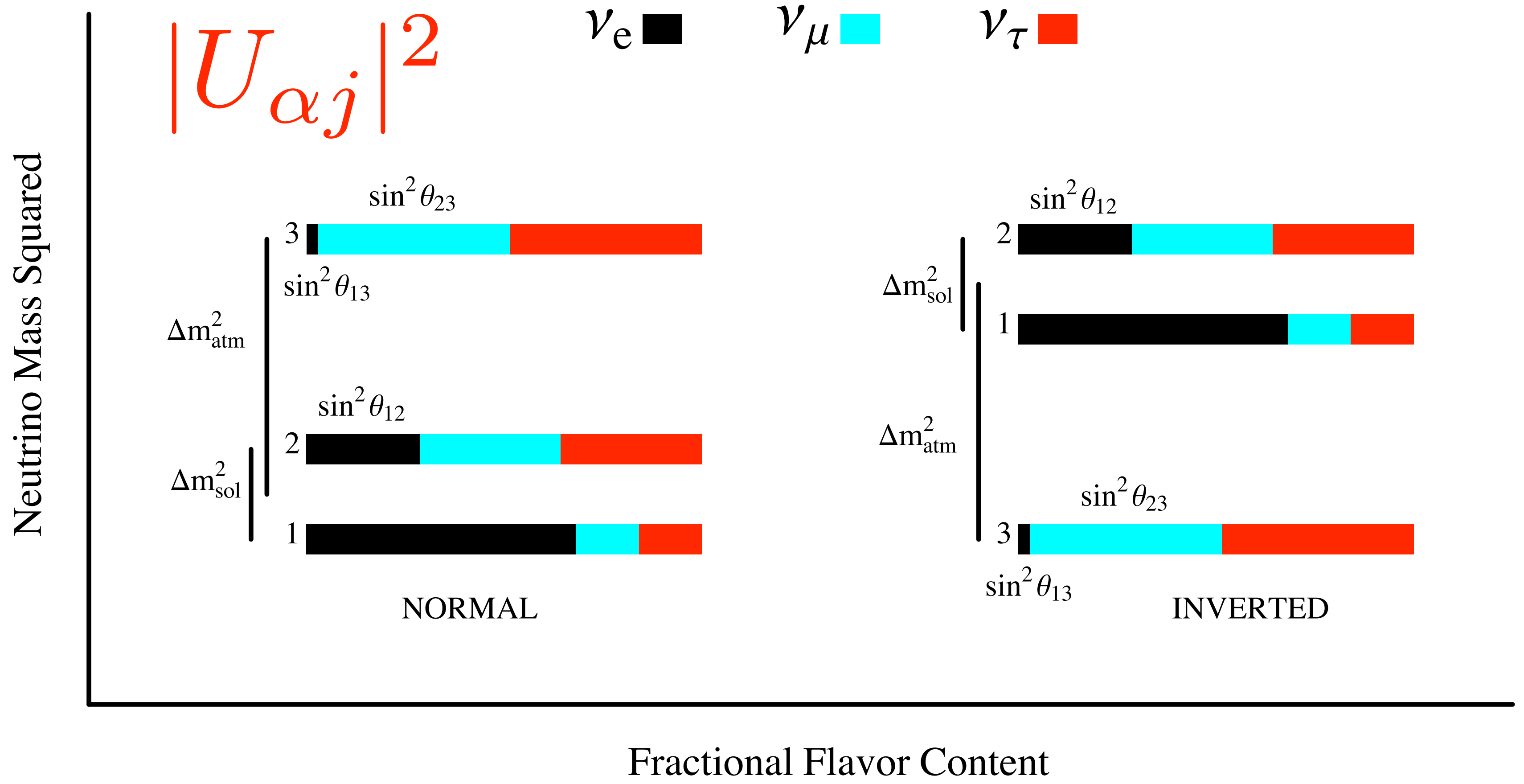
- How can we detect the Cosmic Neutrino Background ?

- Use of Neutrinos for other things:

  geo-neutrinos, reactor monitoring, ..., making euros

  Rupees

Masses and Mixings



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

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

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

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

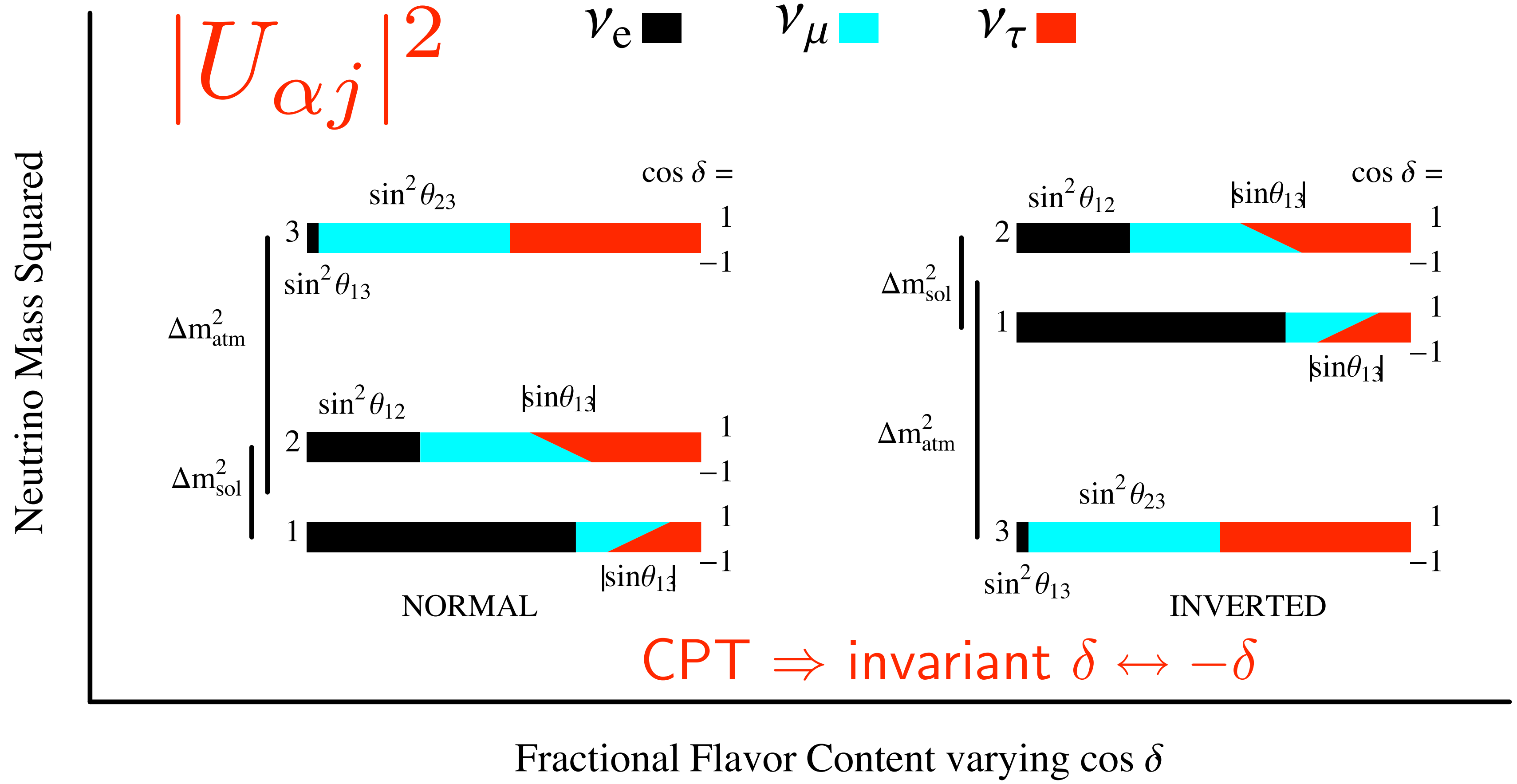
$\sin^2\theta_{12} \sim 1/3$

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

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

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

Masses and Mixings



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

Mixing Matrix:

$$|\nu_e,\ \nu_\mu,\ \nu_\tau\rangle^T_{flavor} = U_{\alpha i}\ |\nu_1,\ \nu_2,\ \nu_3\rangle^T_{mass}$$

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

Atmos. L/E $\mu \to \tau$ — Atmos. L/E $\mu \leftrightarrow e$ — Solar L/E $e \to \mu, \tau$ — $0\nu\beta\beta$ decay

500km/GeV — 15km/MeV

SNO/KamLAND $|U_{e2}|^2$

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

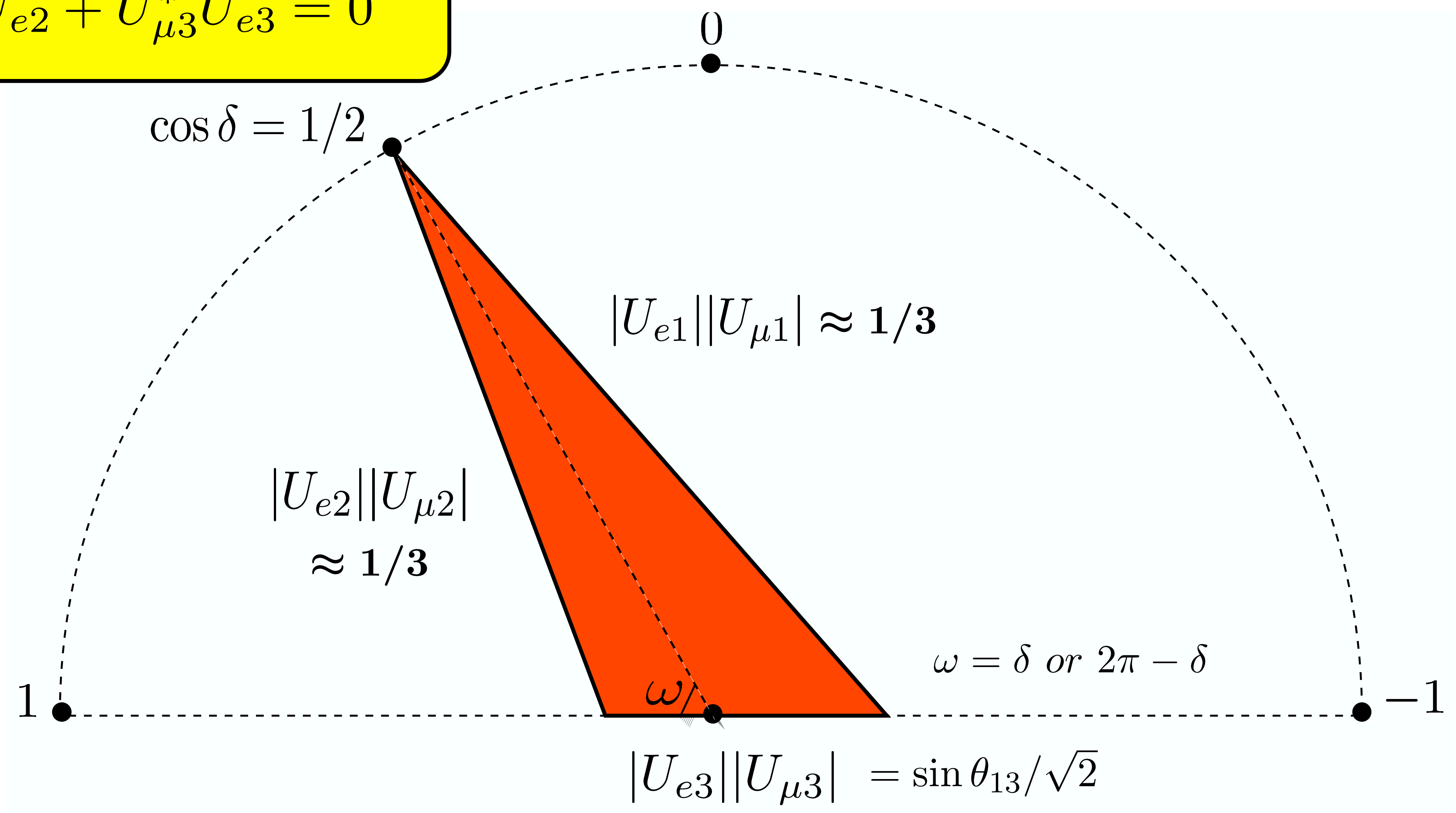
Atm Nus/LBL $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$

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

$$\frac{CC}{NC}\Big|_{sno} \approx |U_{e2}|^2$$

Unitarity Triangle:

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



$$|J| = 2 \times \mathcal{A}rea$$

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

Masses and Mixings

At 2σ we have the following limits:

$$\sin^2\theta_{13} < 0.04$$

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

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

Masses and Mixings

At 2σ we have the following limits:

$$\sin^2\theta_{13} \quad < \quad 0.04 \qquad \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^1$$

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

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

At 2σ we have the following limits:

$$\begin{aligned}
\sin^2\theta_{13} &< 0.04 && \approx \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^1 \\
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Near term goal to push to $\Longrightarrow \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \sim 0.001$

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Near term goal to push to $\Longrightarrow \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^2 \sim 0.001$

and eventually smaller to $\Longrightarrow \left(\frac{\delta m^2_{21}}{\delta m^2_{31}}\right)^3 \sim 3 \times 10^{-5}$ and beyond !

from Altarelli's talk at NuTheme's CERN last month:

The main question is

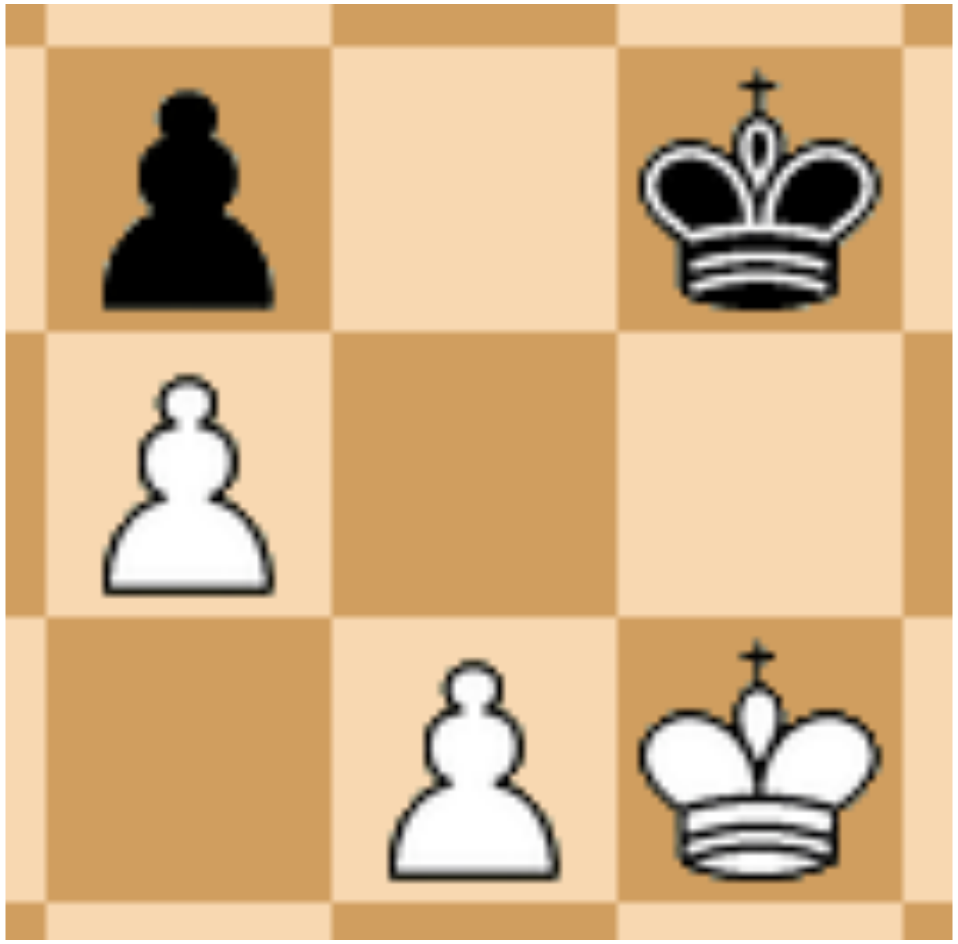
- is TB mixing accidental or a hint?

Anarchy
Lopsided models
$U(1)_{FN}$,
••••••

discrete groups

Value of θ_{13} important
for deciding

Given this end game:



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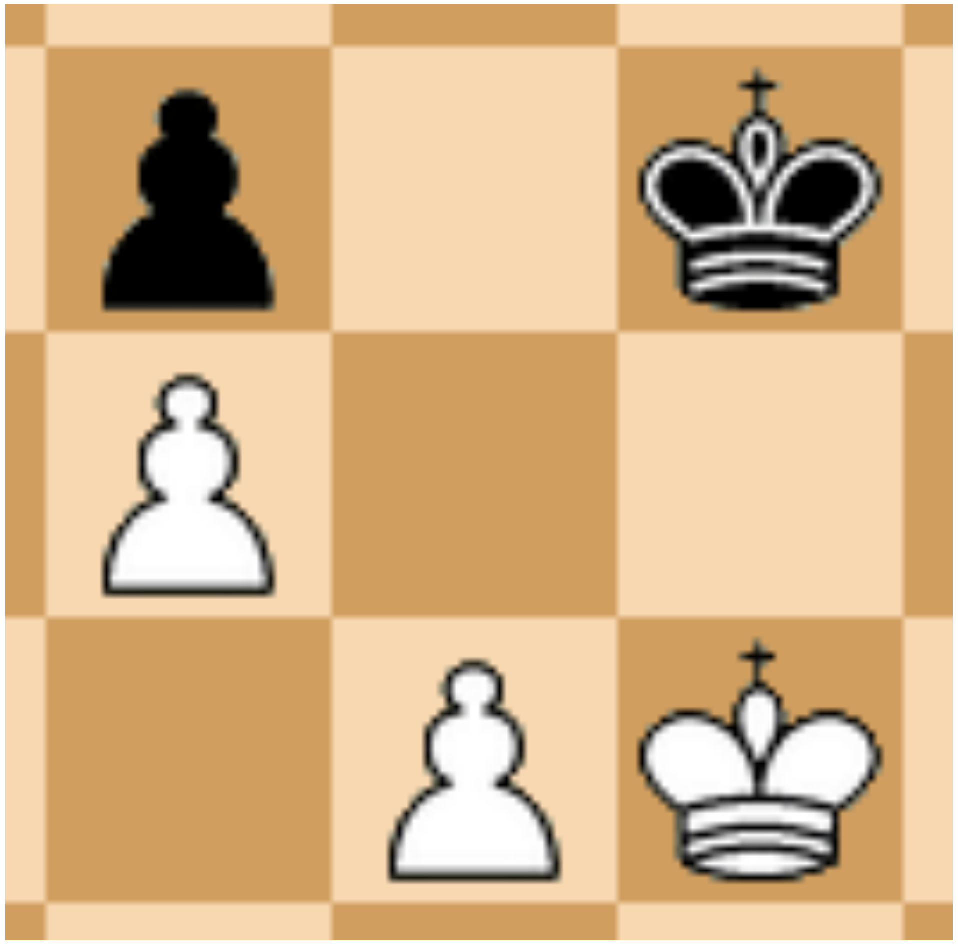
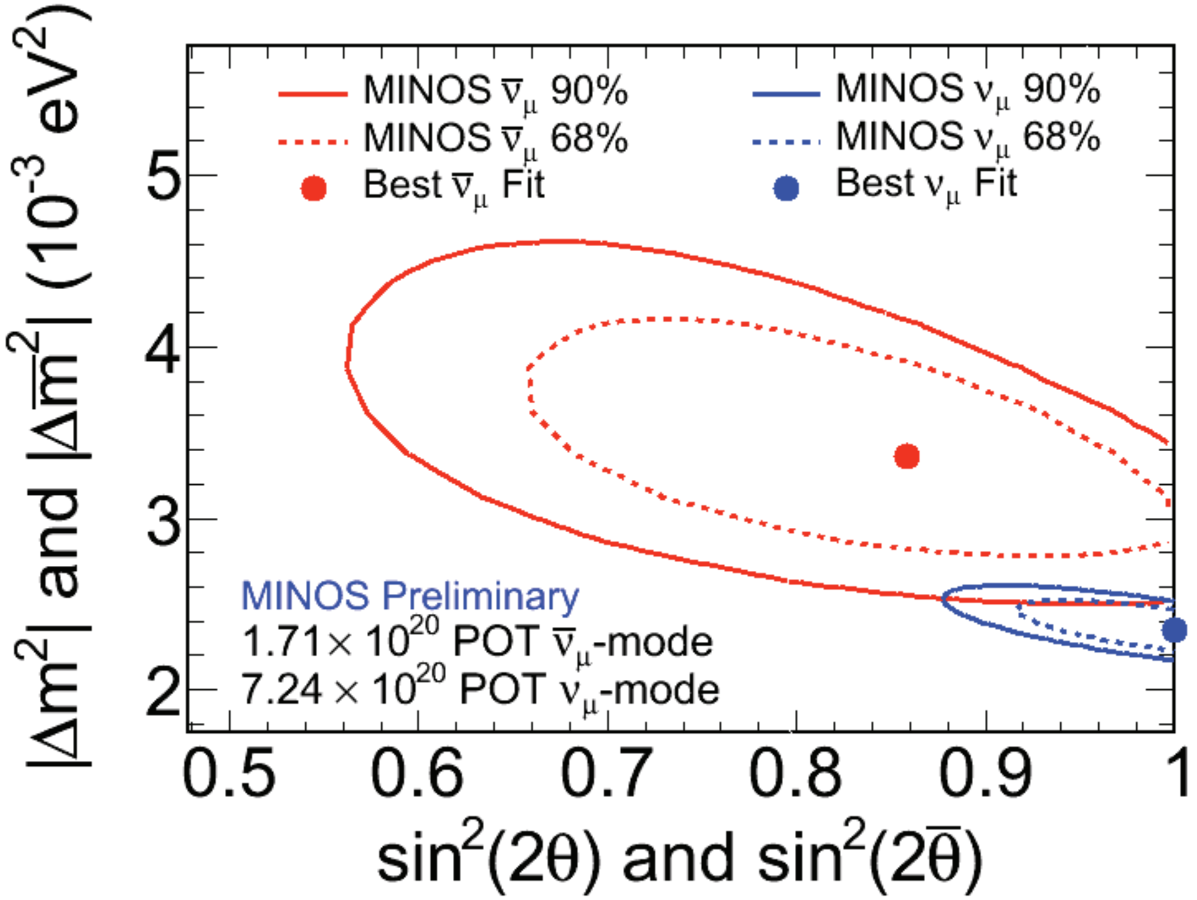


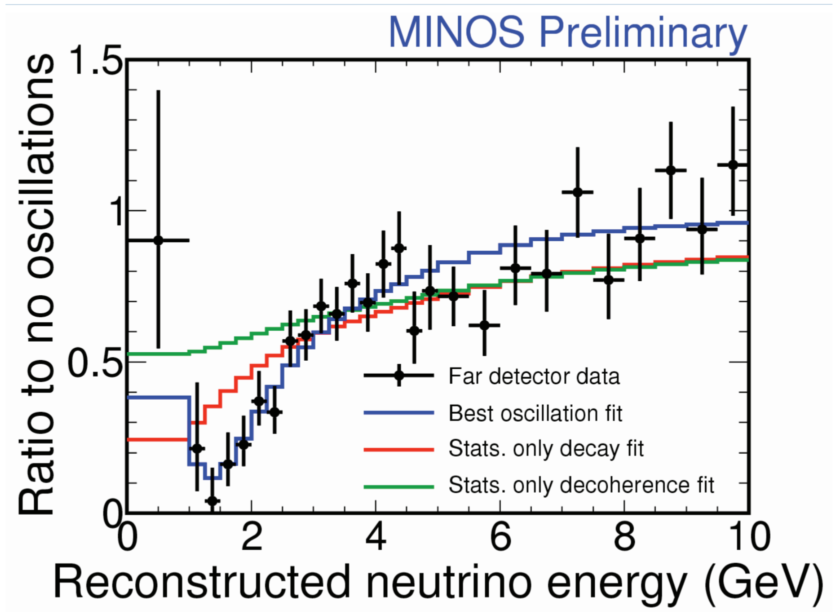
Deduce the rules of chess!!!

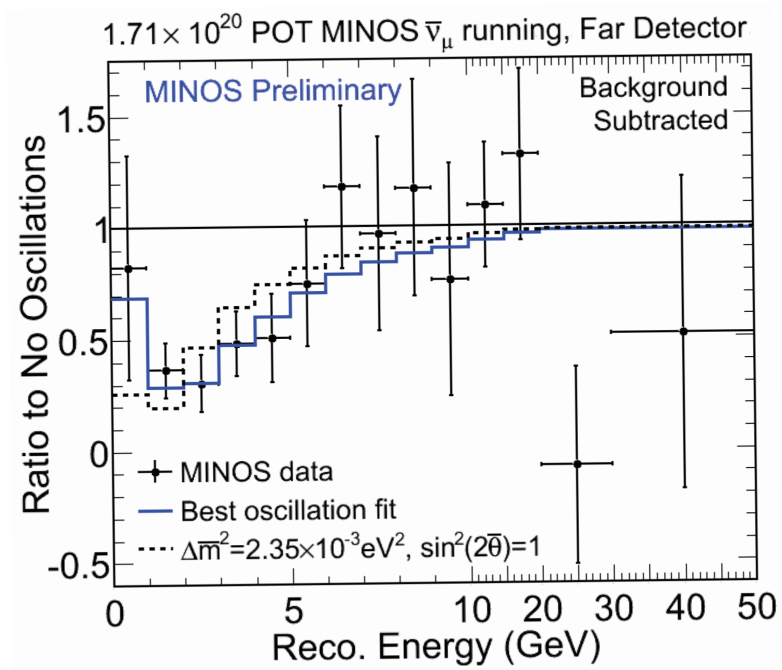
Current Anomalies!!

from P. Vahle, Neutrino 2010



P. Vahle, Neutrino 2010





CPT violation ?

One Example: Charge Current NSI

$$\nu_\tau + N \to X + \mu\,,$$

J. Kopp, P. Machado and SP **arXiv:1009.0014**

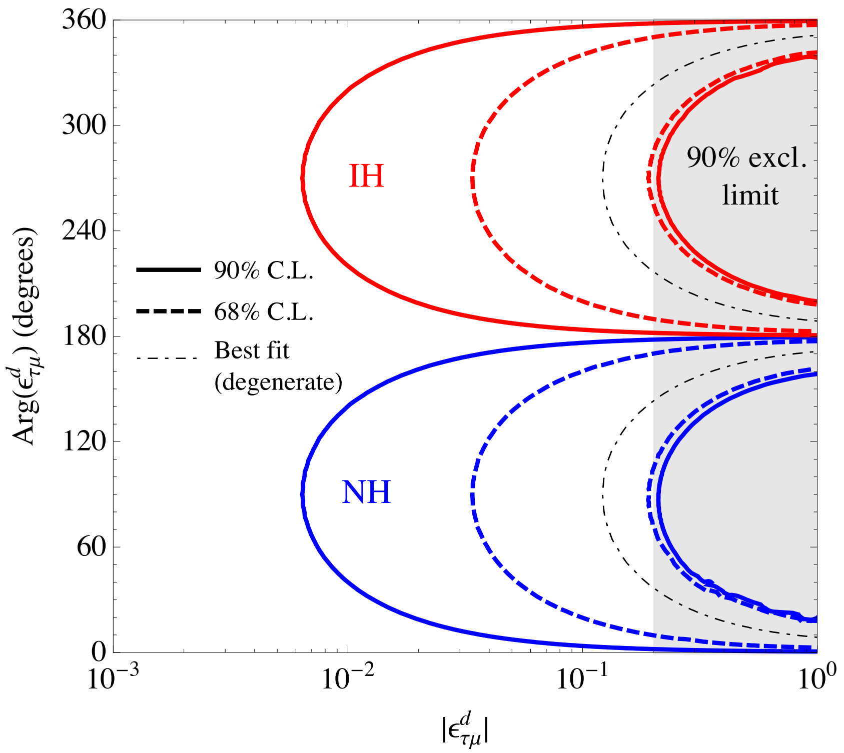
$$\mathcal{L}_{\rm NSI} \supset -2\sqrt{2} G_F \epsilon^d_{\tau\mu} V_{ud}\, [\bar{u}\gamma^\rho d]\, [\bar{\mu}\gamma_\rho P_L \nu_\tau] + h.c.\,,$$

Vector only; not axial vector!

gauge invariance?

$$\nu_\mu + N \to X + \mu$$

$$\nu_\mu \xrightarrow{\text{osc.}} \nu_\tau + N \to X + \mu$$



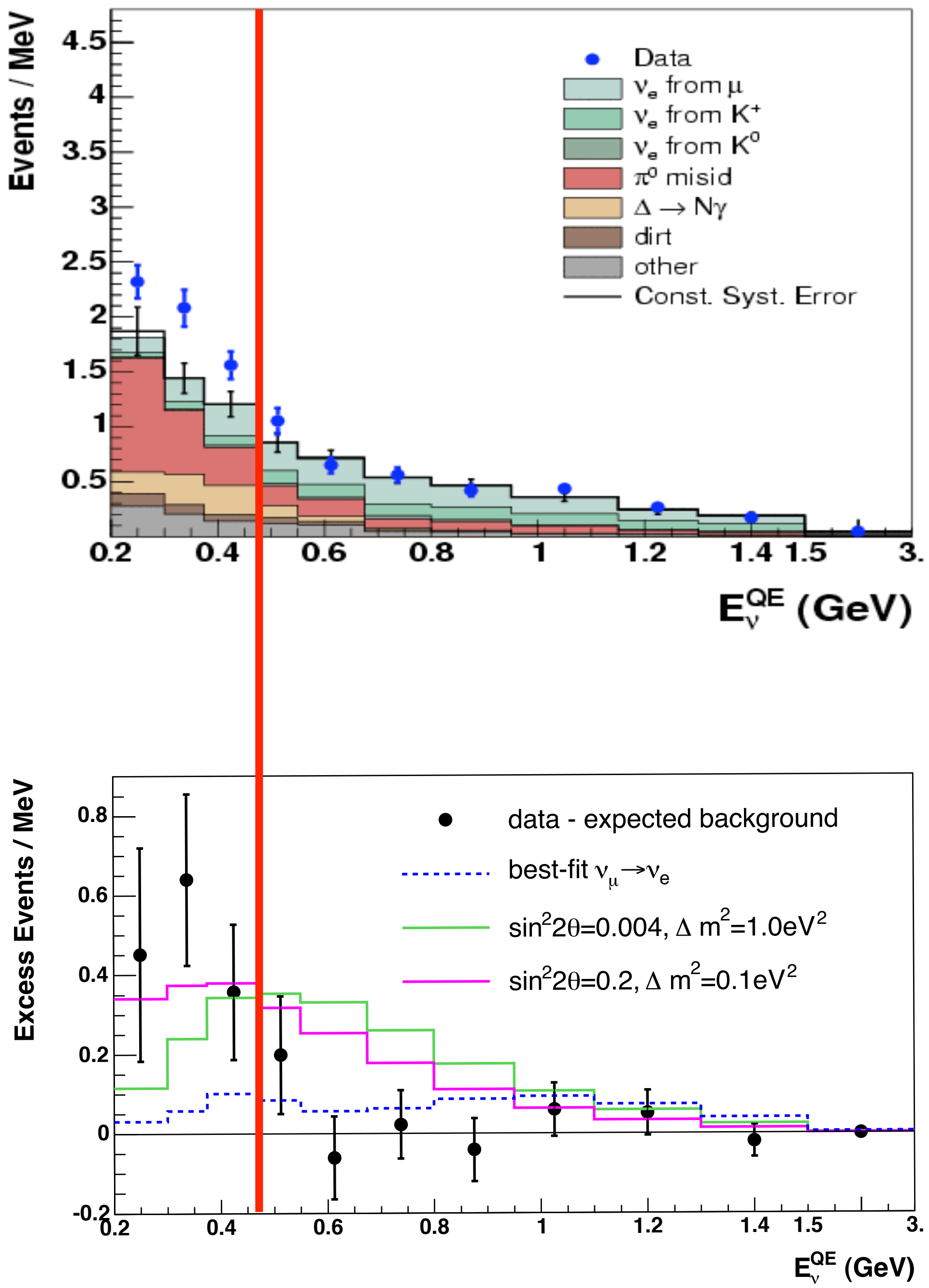
$$\tilde{P}(\nu_\mu \to \nu_\mu) = 1 - \left[1 + 2\,|\epsilon^d_{\tau\mu}| \cot 2\theta_{23} \cos\left[\arg(\epsilon^d_{\tau\mu})\right] - |\epsilon^d_{\tau\mu}|^2\right] \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$
$$+ 2\,|\epsilon^d_{\tau\mu}| \sin 2\theta_{23} \sin\left[\arg(\epsilon^d_{\tau\mu})\right] \sin\left(\frac{\Delta m^2_{32} L}{4E}\right) \cos\left(\frac{\Delta m^2_{32} L}{4E}\right)\,.$$

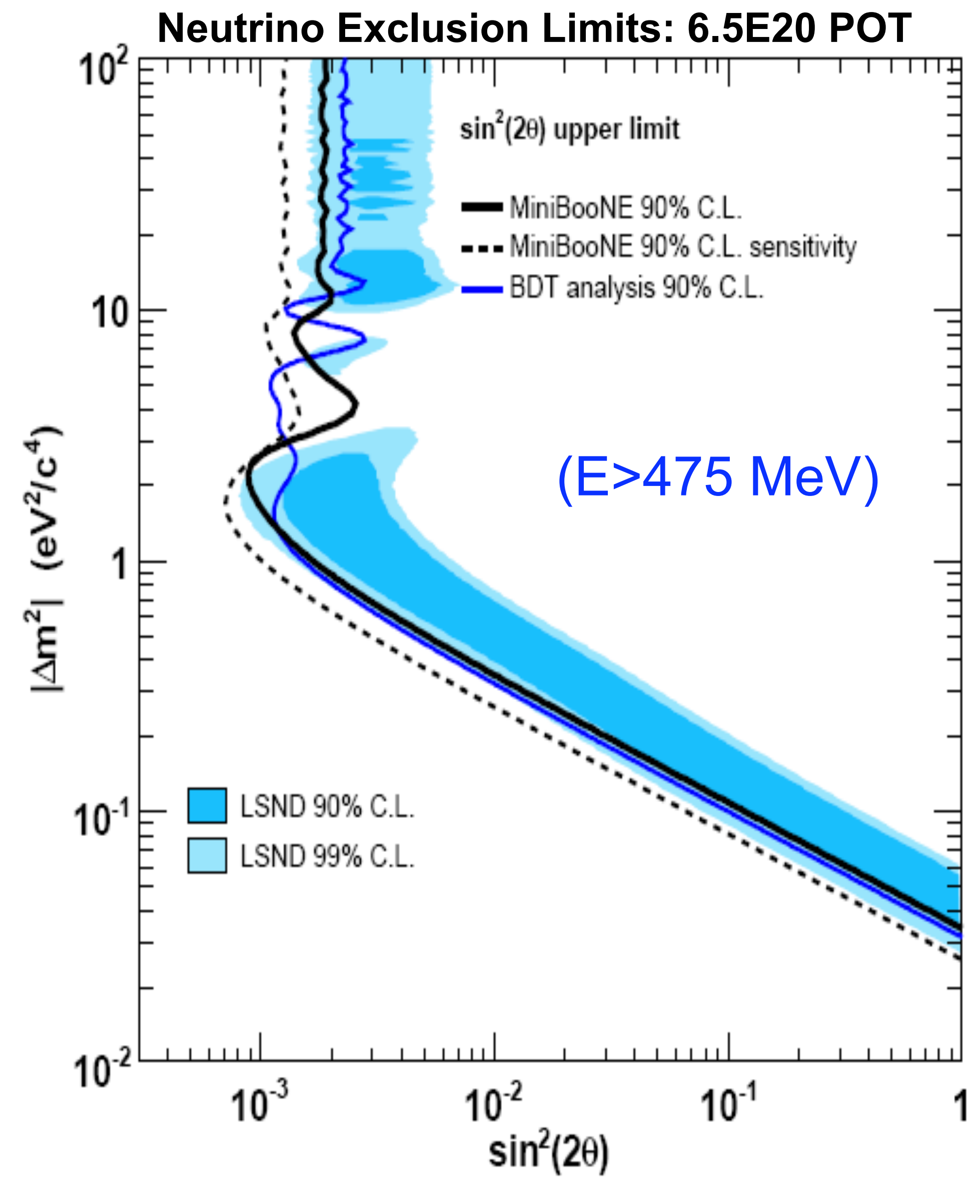
For anti-neutrinos, the sign of $\arg(\epsilon^d_{\tau\mu})$ has to be reversed, and thus

$$\tilde{P}(\nu_\mu \to \nu_\mu) \neq \tilde{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu)\,.$$

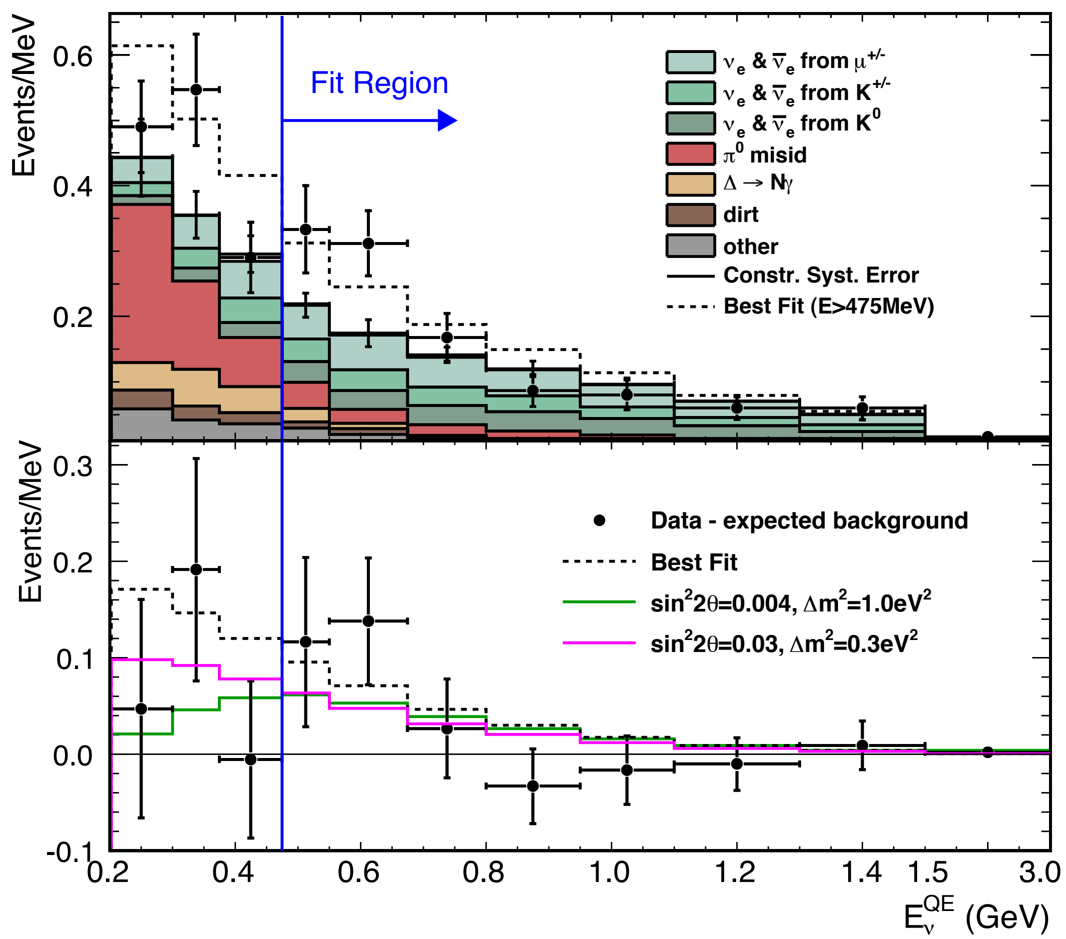
Neutrinos

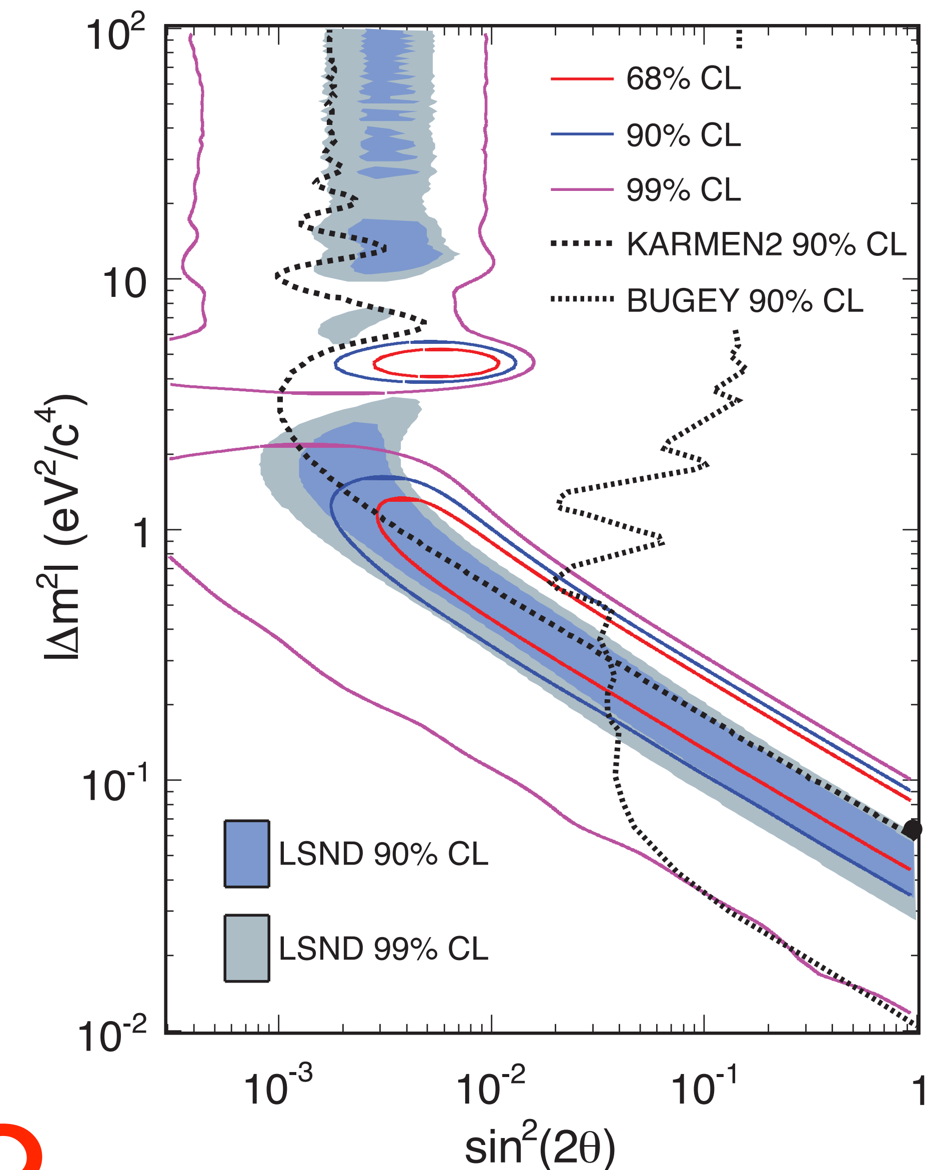
Published PRL 102,101802 (2009)





MiniBooNE Anti-Neutrinos





CP violation ???

Sterile Neutrinos PLUS CC NSI Akhmedov and Schwetz arXiv:1007.4171

MiniBooNE's Summary

Robertson: Nu 2010

- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:
  1) **Neutrino Mode**:
     a) E < 475 MeV: An unexplained 3σ electron-like excess.
     b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.
  2) **Anti-neutrino Mode**:
     a) E < 475 MeV: A small 1.3σ electron-like excess.
     b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
- **Clearly we need more statistics!**
  – MiniBooNE is running to double antineutrino data set for a total of ~10×10^{20} POT.
  – If signal continues at current rate, statistical error will be ~4σ and two neutrino best fit will be >3σ.

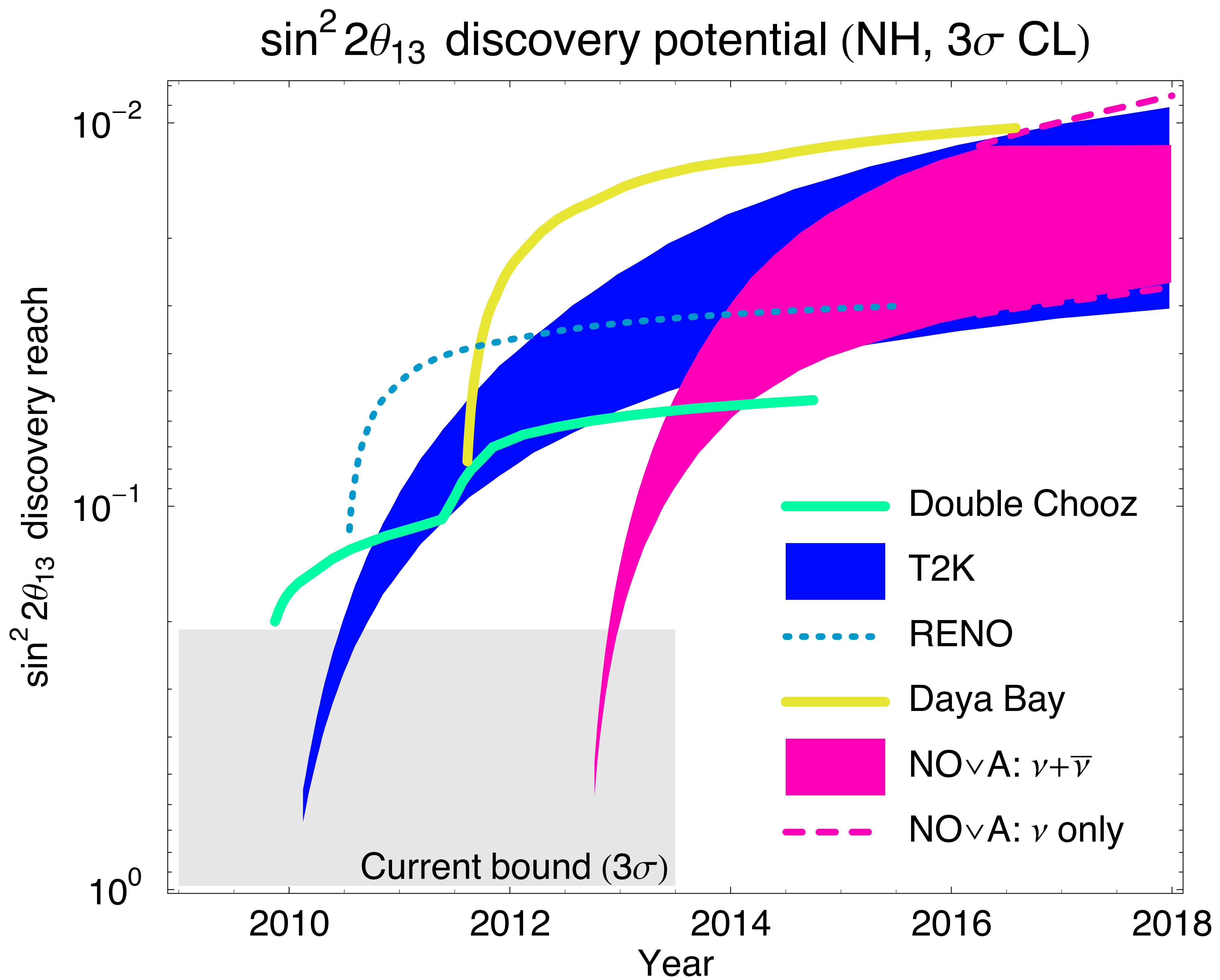
Asked for total 15e20 POT about double current exposure

Now What?

If your experiment needs better statistics, you need a better experiment.

-- Sir Ernest Rutherford

ν_e component in ν_3: $\sin^2\theta_{13}$



sin²2θ₁₃ discovery potential (NH, 3σ CL)
10⁻²
10⁻¹
10⁰
sin²2θ₁₃ discovery reach
2010
2012
2014
2016
2018
Year
Double Chooz
T2K
RENO
Daya Bay
NOνA: ν+ν̄
NOνA: ν only
Current bound (3σ)

Huber

In Matter:

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

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

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

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

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

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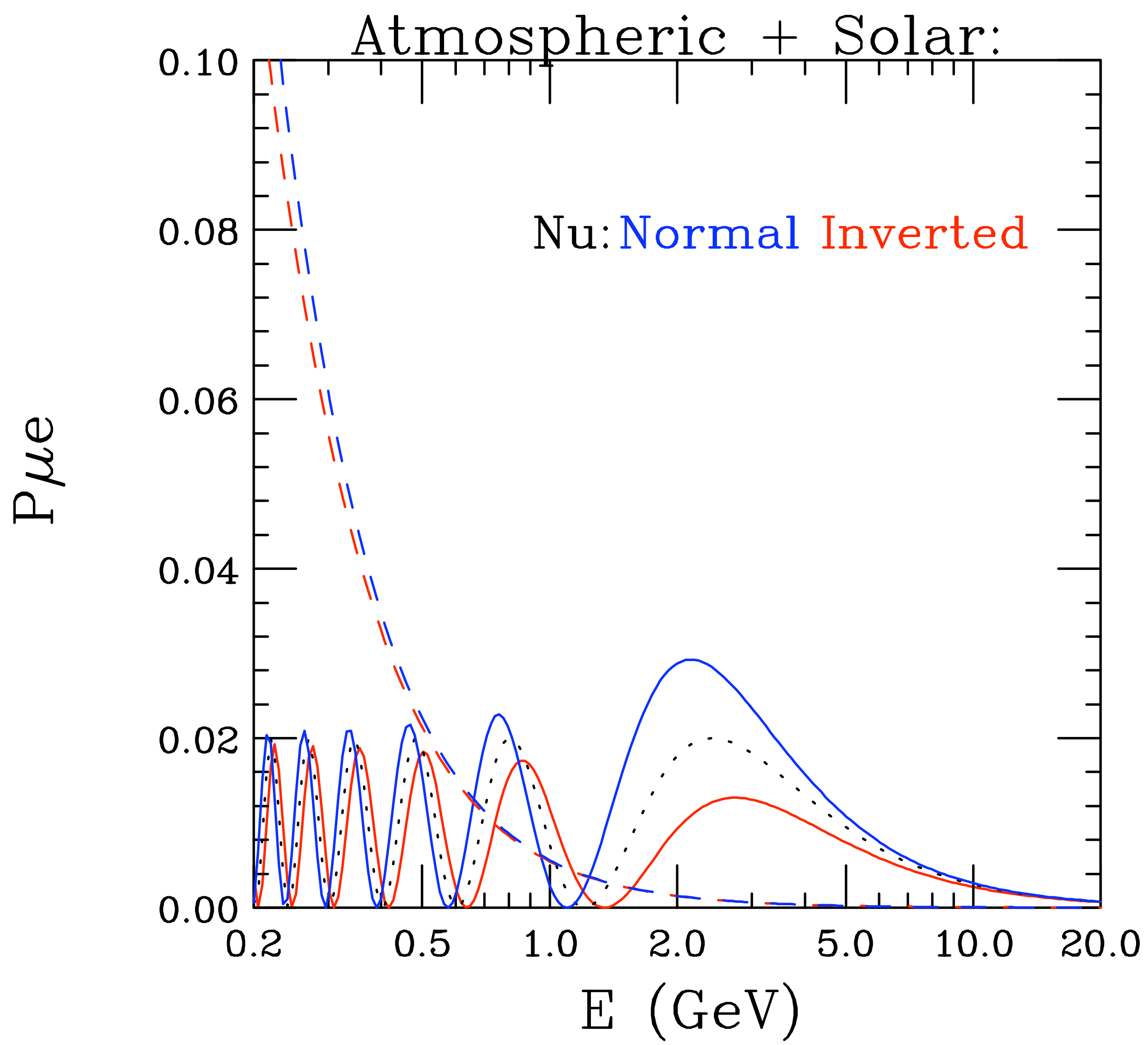

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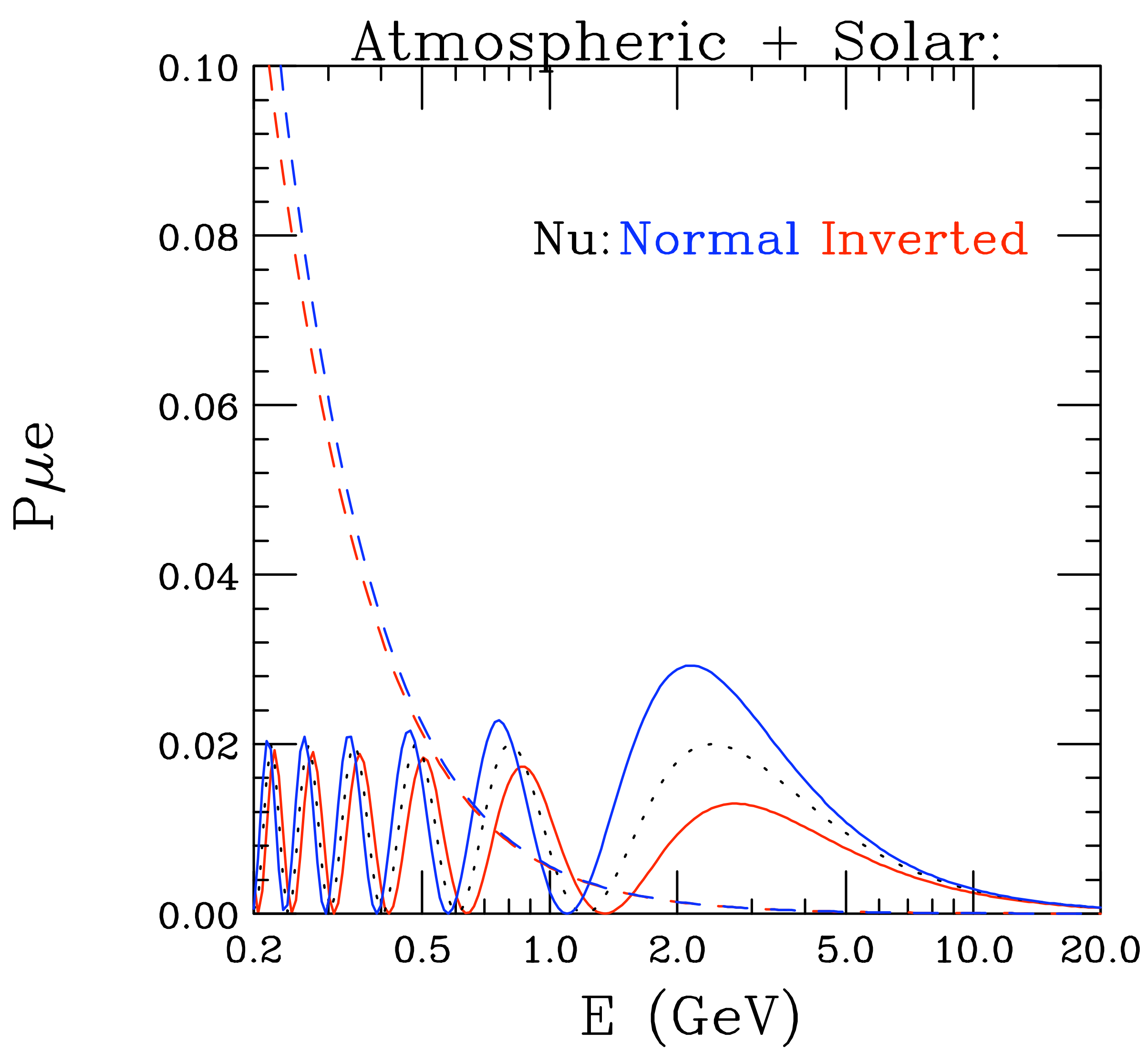
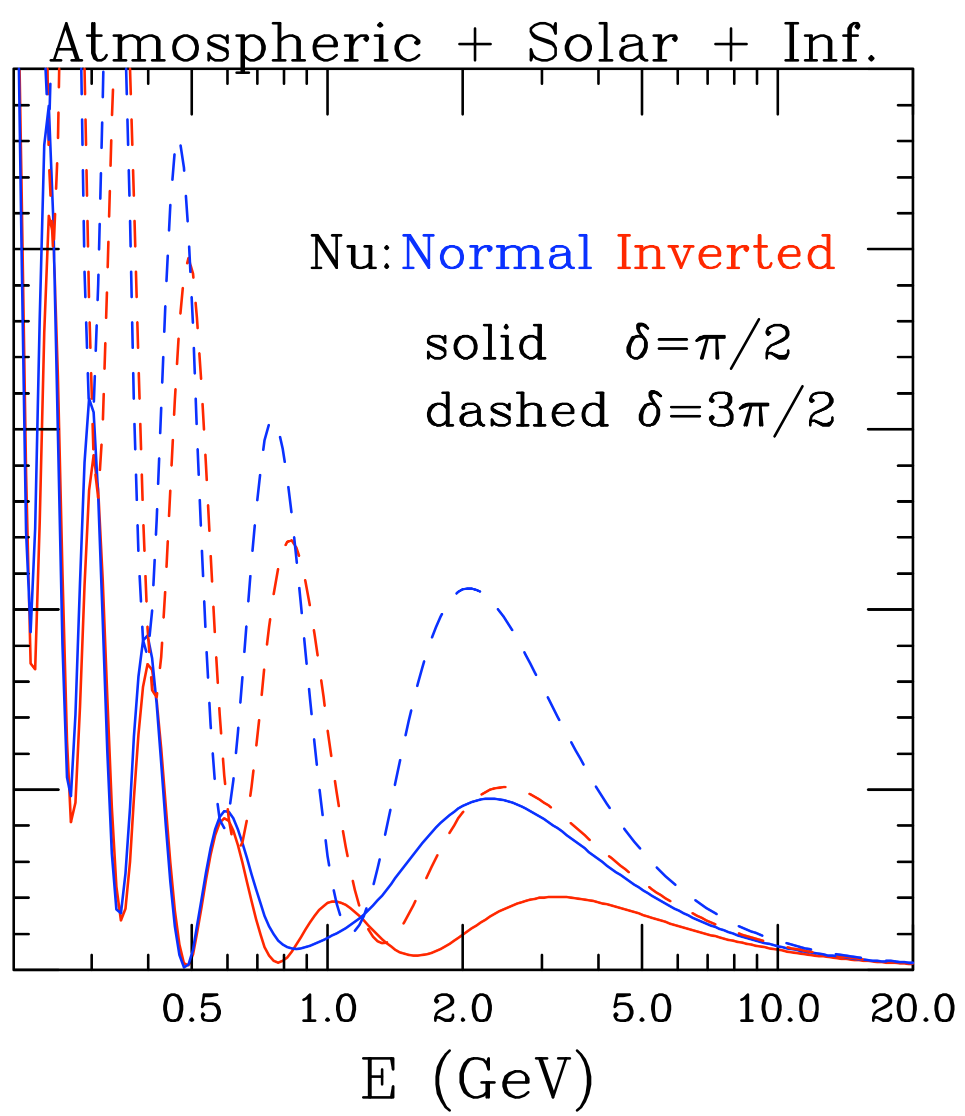
and $\sin^2 2\theta_{13} = 0.04$

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

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





"Bi-Magic" Baseline

Capabilities of a 2540km Superbeam Experiment

Sushant K. Raut
IIT Bombay

(to be submitted)

Aniket Joglekar, Suprabh Prakash, Sushant K. Raut, S. Umasankar

NuFact2010 (TIFR), October 2010

2540 km: Bimagic baseline for ν parameters

Srubabati Goswami +Dighe and Ray

Physical Research Laboratory, Ahmedabad, India

NuFact10, TIFR, Mumbai
October 22, 2010

“Magic” Baseline

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"Magic" Baseline

=0

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"Magic" Baseline

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

in earth this happens for L≈7500 km

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)

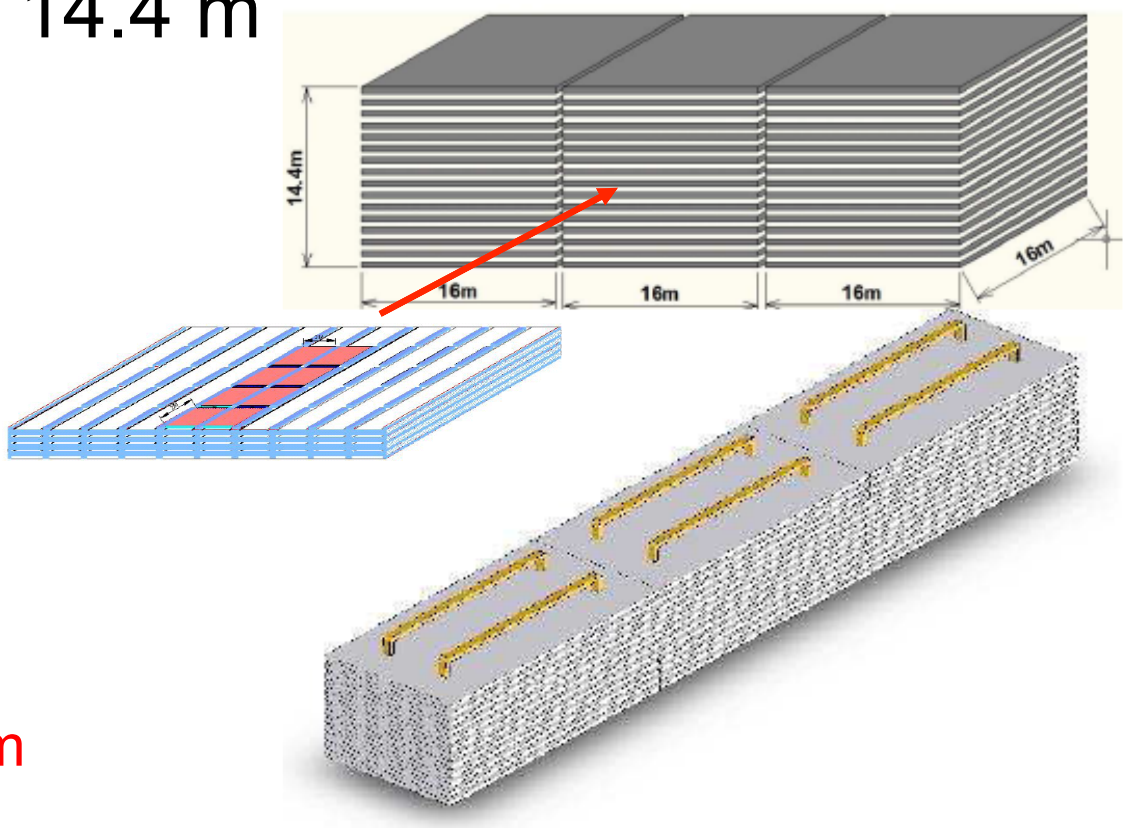
CERN to INO

JPARC to INO

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

INO: the magic baseline MIND?

- Indian Neutrino Observatory is the great opportunity for a 50 kton magnetised detector (Indumathi)
  - Main purpose: sign selected atmospheric neutrinos
  - Can be used for beam neutrinos (magic baseline for Europe, Japan)
- Detector size: 48 m x 16 m x 14.4 m
- 5.6 cm plate thickness
- Readout: RPCs
- B=1.5 T
- Far detector at magic baseline of neutrino factory:
  - CERN to INO: distance = 7152 km
  - JPARC to INO: distance = 6556 km
  - RAL to INO: distance = 7653 km
- Scope for collaboration on R&D: software, testbeam, technology



“Bi-Magic” Baseline and Energy

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In Matter:

Max for one Hierarchy and 0 other

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

"Bi-Magic" Baseline and Energy

Choose L such that

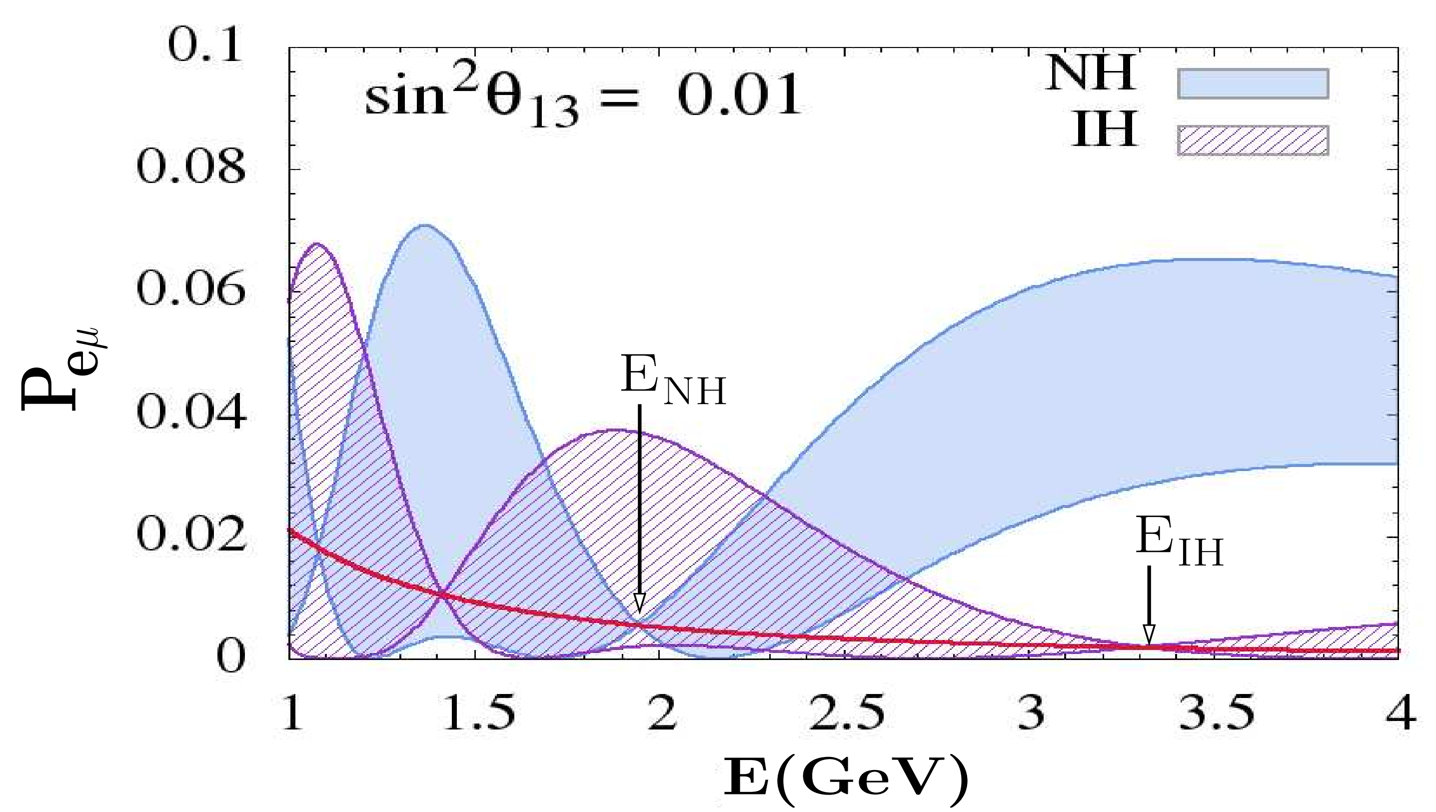
$P_{atm}|_{IH} = 0$ and $P_{atm}|_{NH}$ is max. at E_{IH}

and

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

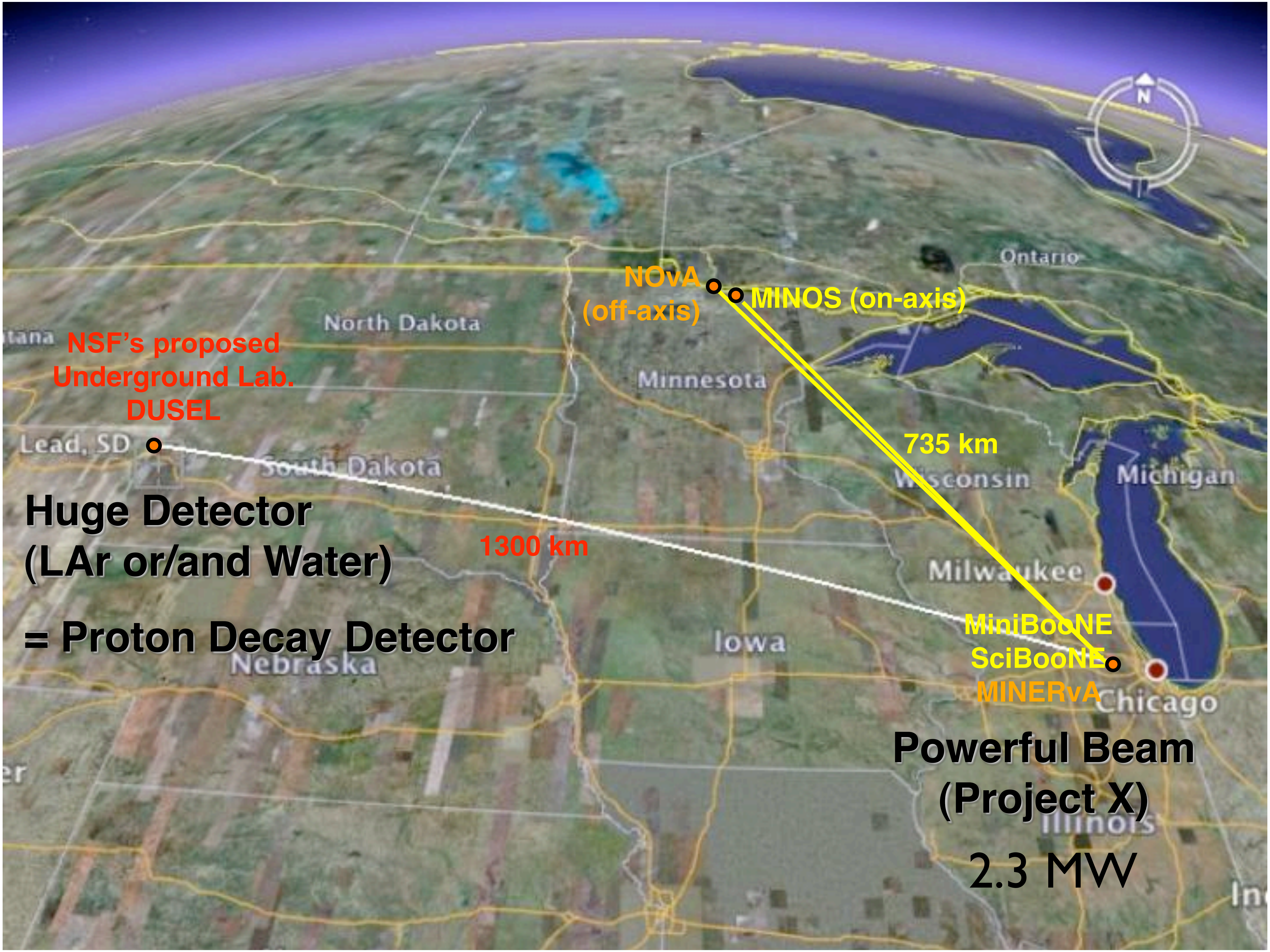
L=2540 km and E_{IH}=3.3 GeV and E_{NH}=1.9 GeV

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

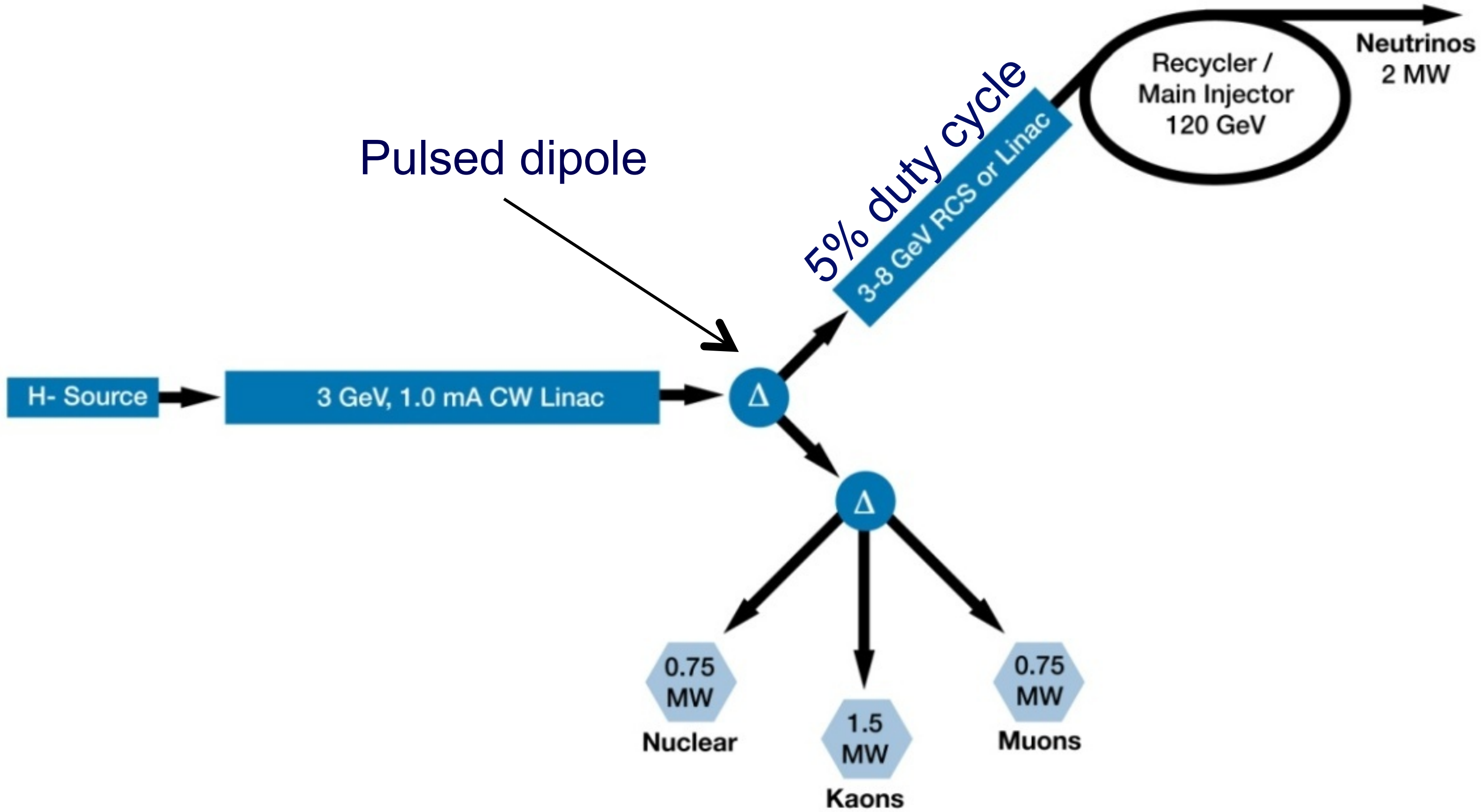


CERN to Pyhasalami and BNL to DUSEL

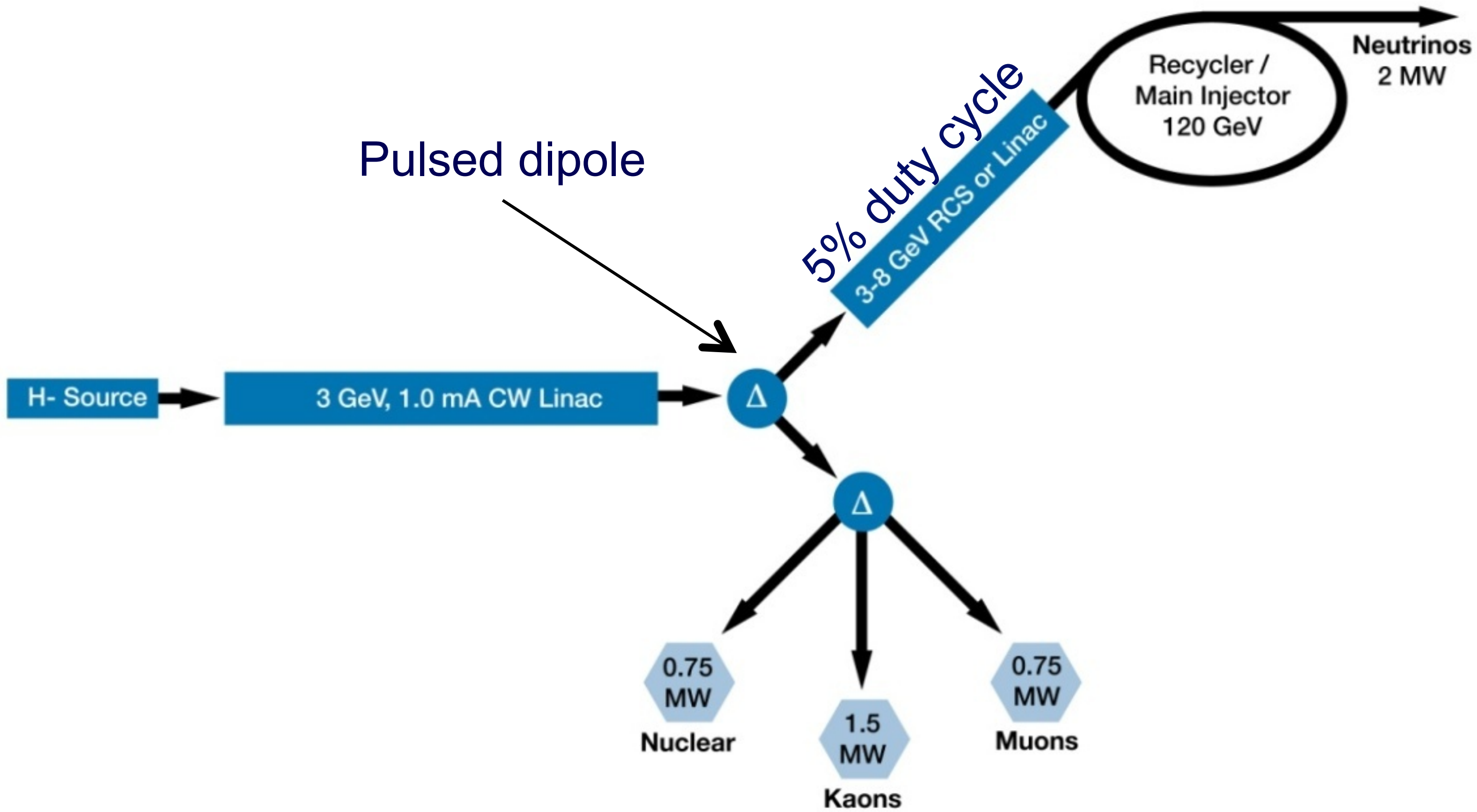
Proposed Accelerator/Detector Combination:


NOvA
(off-axis)
MINOS (on-axis)
Ontario
North Dakota
NSF's proposed
Underground Lab.
DUSEL
Minnesota
Lead, SD
South Dakota
735 km
Wisconsin
Michigan
Huge Detector
(LAr or/and Water)
1300 km
Milwaukee
= Proton Decay Detector
Nebraska
Iowa
MiniBooNE
SciBooNE
MINERvA
Chicago
Powerful Beam
(Project X)
Illinois
2.3 MW

Project X @ Fermilab



Project X @ Fermilab



India is involved in this Project

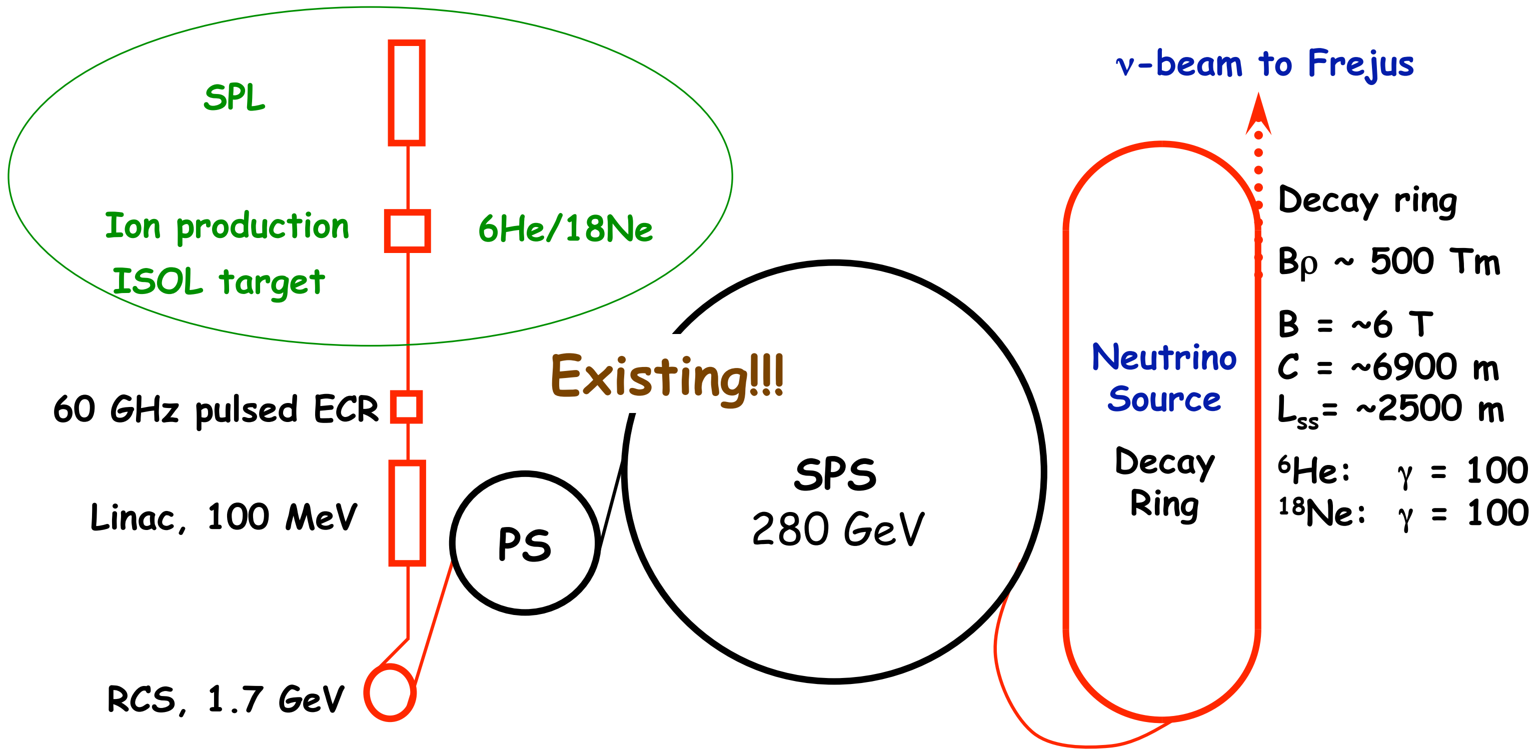
Three Possible Scenario Studied at NP08 Workshop

Comparison of Each Scenario

	Scenario 1 Okinoshima	**Scenario 2 Kamioka**	**Scenario 3 Kamioka Korea**
Baseline(km)	660	295	295 & 1000
Off-Axis Angle(°)	0.8(almost on-axis)	2.5	2.5 1
Method	ν_eSpectrum Shape	Ratio between ν_e $\bar{\nu}_e$	Ratio between 1st 2ndMax Ratio between ν_e $\bar{\nu}_e$
Beam	5Years ν_{μ}, then Decide Next	2.2 Years ν_{μ}, 7.8 Years $\bar{\nu}_{\mu}$,	5 Years ν_{μ}, 5 Years $\bar{\nu}_{\mu}$,
Detector Tech.	Liq. Ar TPC	Water Cherenkov	Water Cherenkov
Detector Mass (kt)	100	2×270	270+270

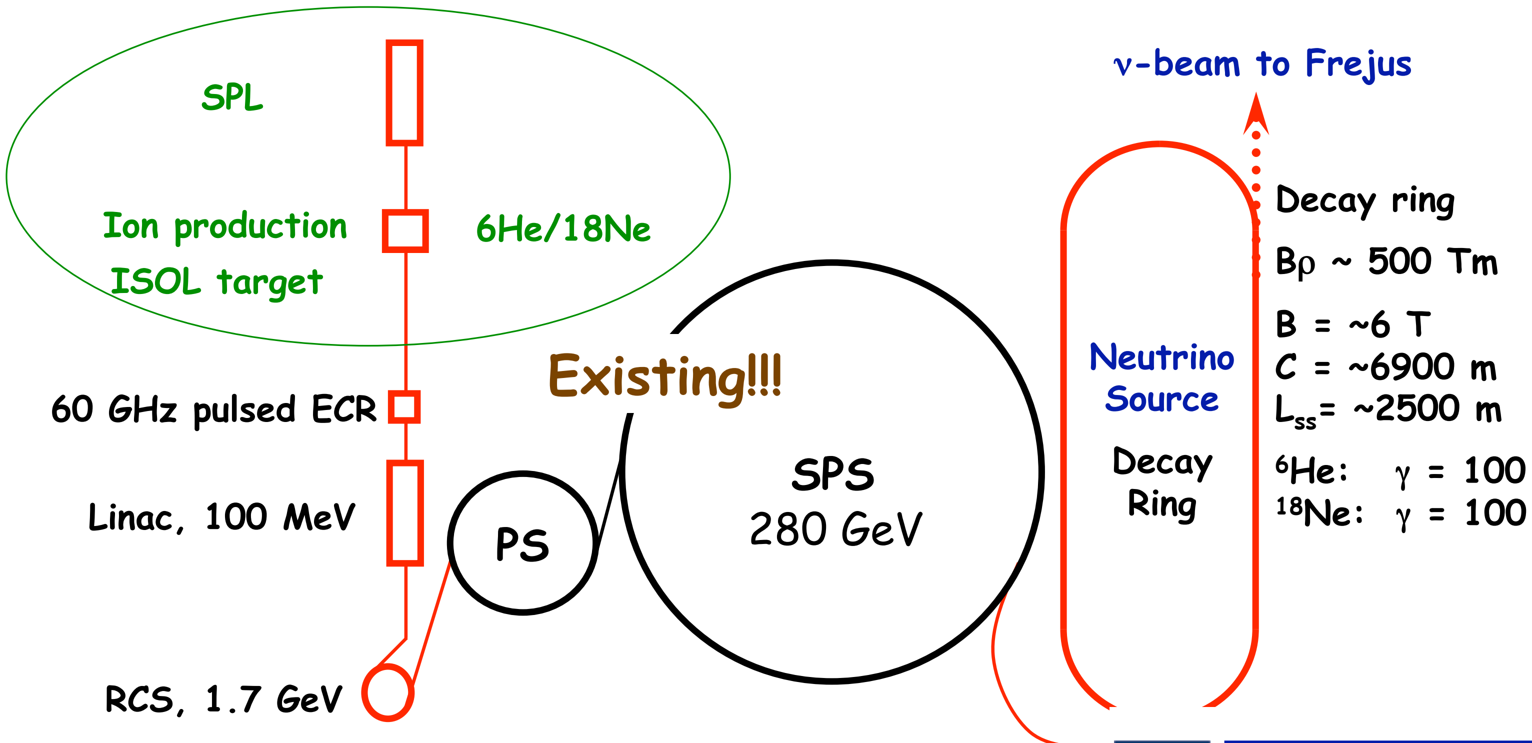
Low Energy:

Beta Beam scenario 6He/18Ne



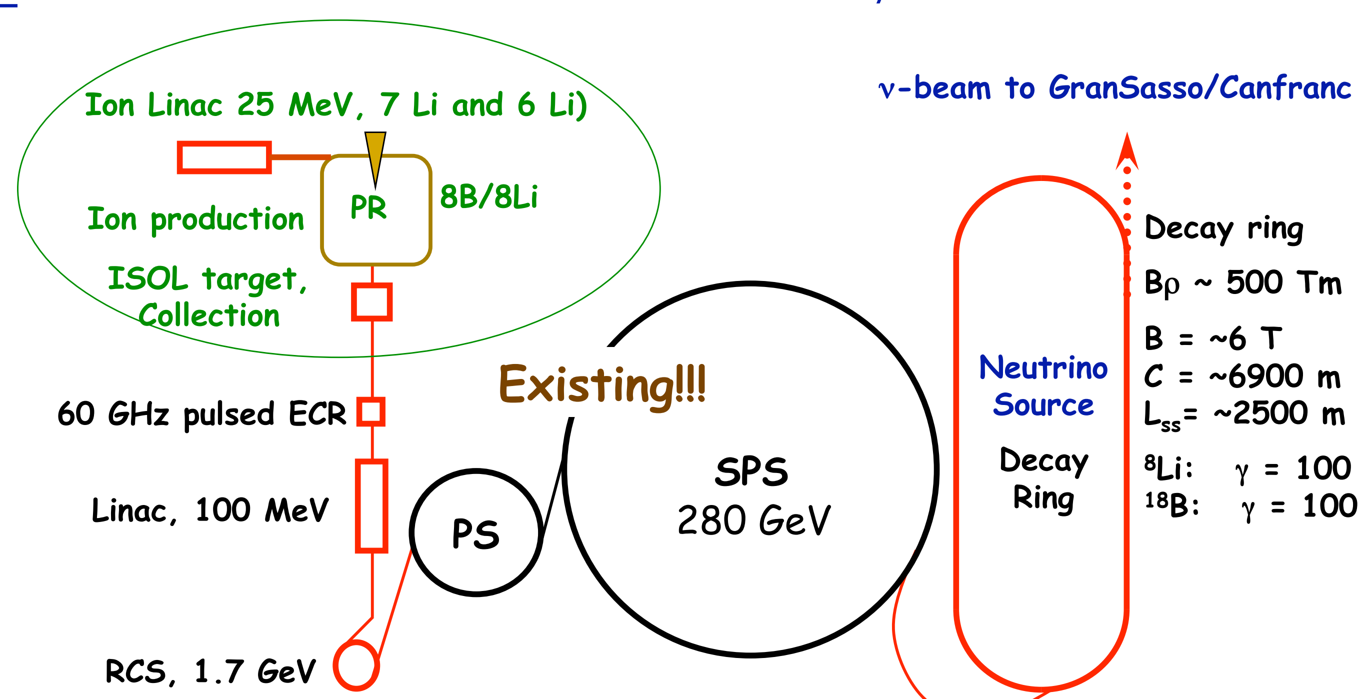
Low Energy:

Beta Beam scenario 6He/18Ne

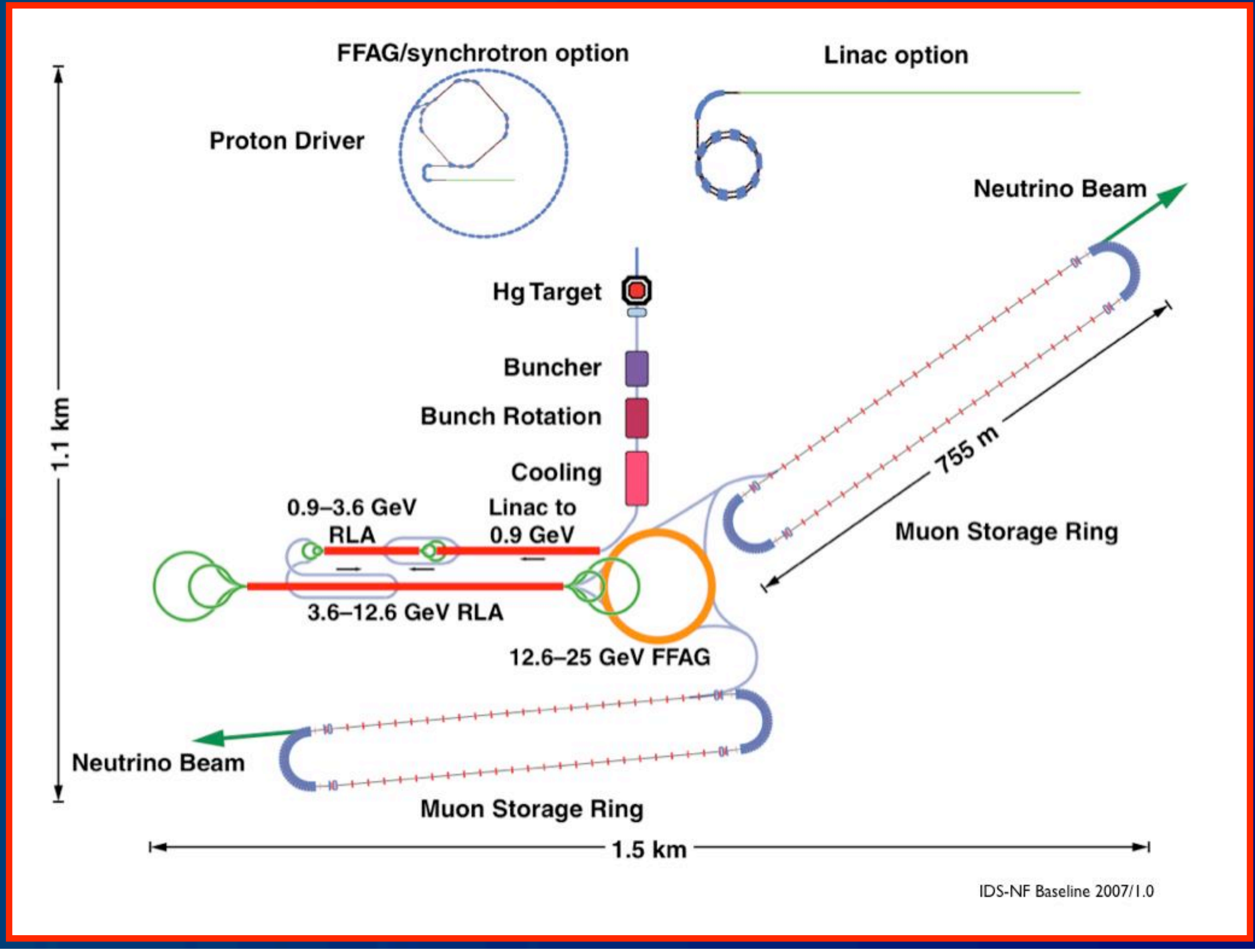


High Energy:

Beta Beam scenario 8Li/8B



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.

EFFECT OF TAU NEUTRINO CONTRIBUTION TO MUON SIGNALS AT NEUTRINO FACTORIES

Nita Sinha
The Institute of Mathematical Sciences
Chennai

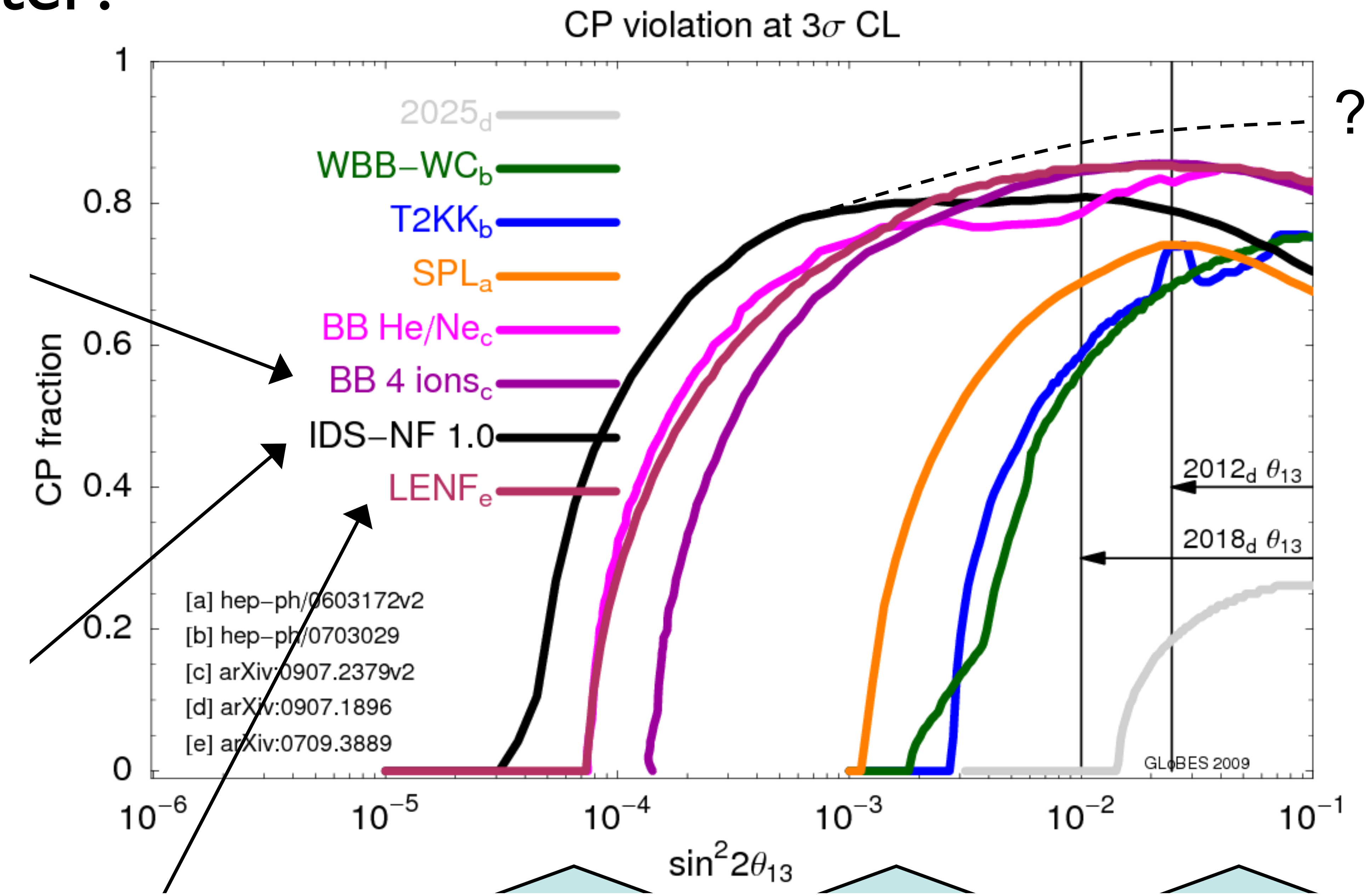
Tau-Contamination in the golden channel at the Neutrino Factory

Pilar Coloma

Universidad Autónoma de Madrid (Spain)
&
IPPP, University of Durham (UK)

Based on the work of
A. Donini, D. Meloni and J.J. Gómez Cadenas
arXiV: 1005.2275 [hep-ph]

Winter:



What will happen when we have knowledge of $\sin^2\theta_{13}$?

- SuperBeams (WC, LAr,....)
- Beta Beams (WC, LAr,.....)
- Neutrino Factories (MIND, TASD,....)
- Other

- SuperBeams (WC, LAr,....)
- Beta Beams (WC, LAr,.....)
- Neutrino Factories (MIND, TASD,....)
- Other

What will be needed??????

- SuperBeams (WC, LAr,....)
- Beta Beams (WC, LAr,.....)
- Neutrino Factories (MIND, TASD,....)
- Other

What will be needed??????

The answer depends on the SURPRISES the neutrino has for us !!!!!

Such as NC-NSI, CC-NSI, sterile neutrinos, etc etc.

1966

1966

``And yet the nothing-particle is not a nothing at all"

1966

``And yet the nothing-particle is not a nothing at all"

Far from it!!!

Extras:

Communications via Neutrinos:

Communications via Neutrinos:

$$\Delta Time = 20 - 30\ msec$$