NuFact10 Mumbai, India

Oscillation Physics WG Summary

Thomas Schwetz

(Sandhya Choubey, Patricia Vahle)

WG1 statistics

- 8 WG1 sessions + 2 joint WG1/WG2 sessions
- 28 + 8 talks (29 speakers)
  → 15 theory/phenomenology
  → 13 + 8 experimental
- + 7 accepted abstracts for posters

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I will give a very biased summary and appologize for those talks which I will mention only briefly!

Session topics

- Status reports (OPERA, T2K, NOvA, reactors, LBNE)
- MiniBooNE/LSND (explanations/tests)
- MINOS (neutrino/antineutrino „anomaly)
- LBL phenomenology (2540 km / tau decays)
- neutrino mass models
- NSI and exotics
- Daedalus / LENA / thousand suns
- ND/LAr/WC R&D (joint WG1/2)
- near-far extrapolation (joint WG1/2)

Status reports from ...

- **OPERA** T. Ariga

  hope for $4.5x10^{19}$ pot end of 2010 (out of $22.5x10^{19}$ pot total) analysis of $1.85x10^{19}$ pot completed: 1 tau candidate (0.5 expected) / full 2008/09 data set analysis: early next year

- **T2K** A. Blondel

  -- T2K experiment is now fully operational and data taking
  -- superb detector performance
  -- proton intensity increasing steadily (reach 750 kW in 2014)
  -- First data taking period in 2010 accumulated $3.23\ 10^{19}$ 30 GeV p.o.t.
  -- Preparing first physics result for end 2010

- **NOvA** B. Rebel

  NDOS running now / FD constr. begins July 2011 / acceler. shutdown March 2010 / 700 kW beam turns on Feb. 2013 (FD 2/3 built) / FD complete fall 2013

... and reactor experiments

- **DoubleChooz** filling started 13th Oct, first neutrino early 2011

  M. Dracos

  2011-2012, phase I : FD only $\sin^2(2\theta_{13}) < 0.06$ @ 90% C.L.

  2012-2014, phase II : both detectors $\sin^2(2\theta_{13}) < 0.03$ @ 90% C.L.

- **RENO** PMT inst. completed, prep. of liquid handling/DAQ systems

  RENO is suitable for measuring **sin2(2θ13) > 0.02**

  J.S.Jang

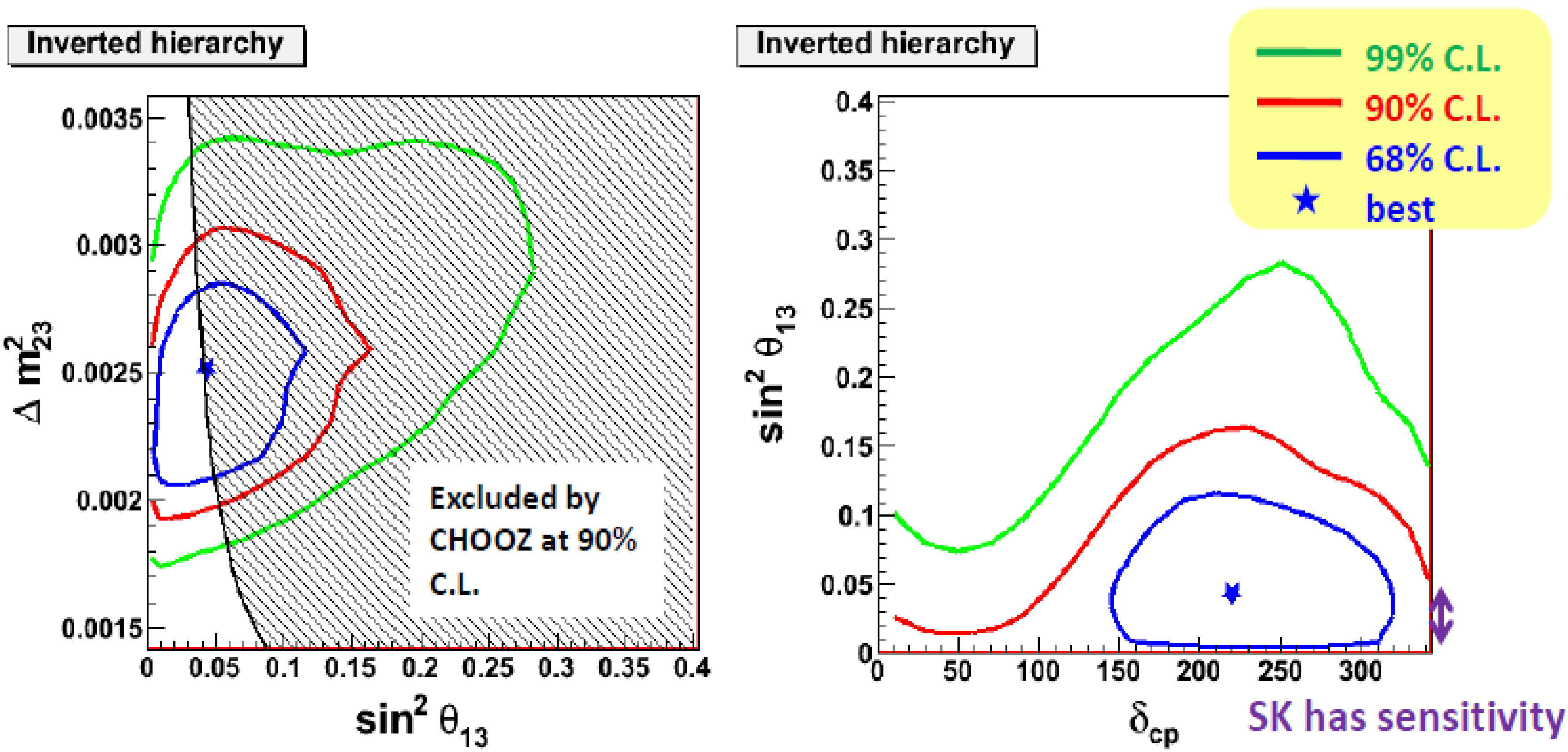
- **DayaBay** civil constr. near hall: finished, far hall: excavation, two detectors assambled: dry run, fall 2012 all near/far hall physics ready

  ➢ Goal: sensitivity to $\sin^2 2\theta_{13} < 0.01$;

  H. Lu

SK atmospheric neutrinos

- "full" 3-flavour analysis H. Kaji



SK has sensitivity to δ_{CP} when large θ_{13}.

SK atmospheric neutrinos

- "full" 3-flavour analysis H. Kaji

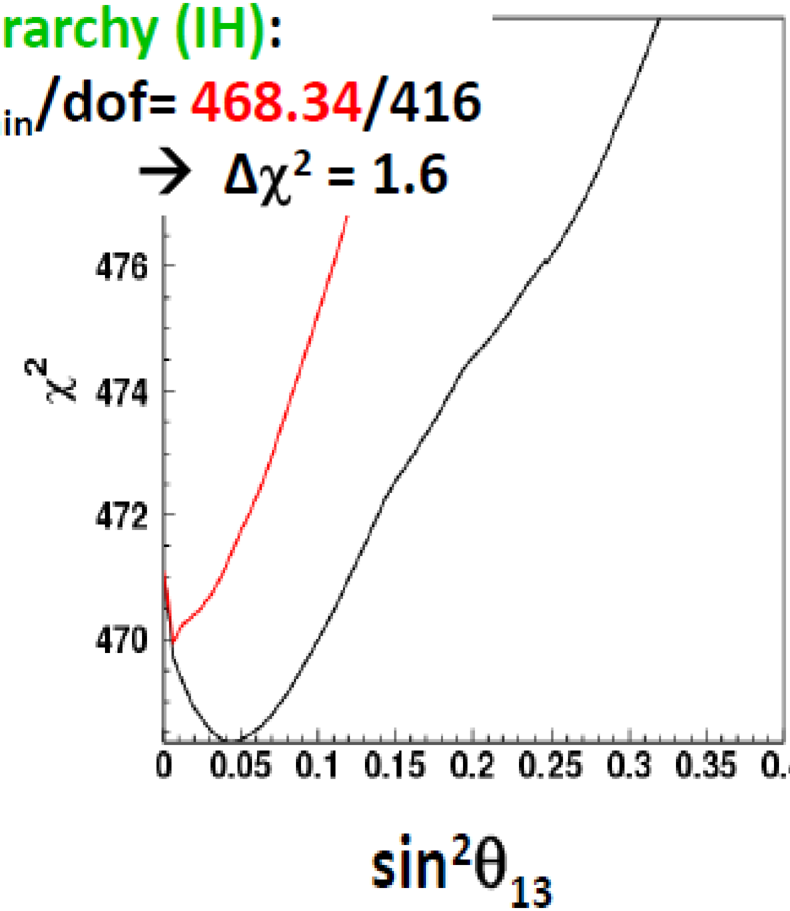
Normal hierarchy (NH):

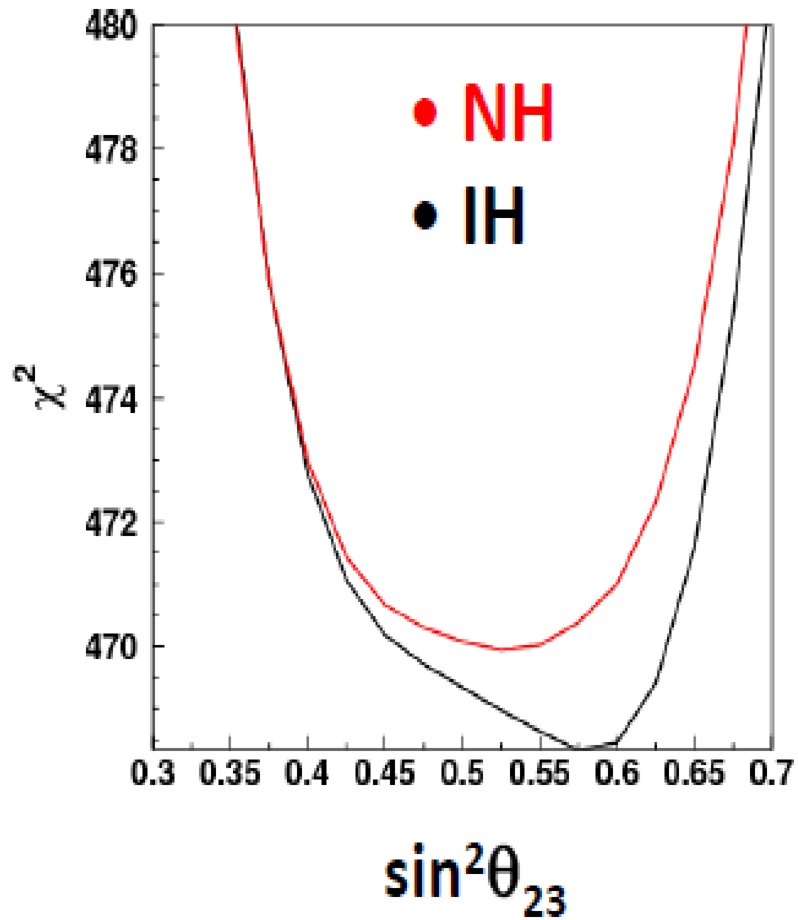
χ^2_{min}/dof= 469.94/416

Inverted hierarchy (IH):

χ^2_{min}/dof= 468.34/416

→ $\Delta\chi^2$ = 1.6

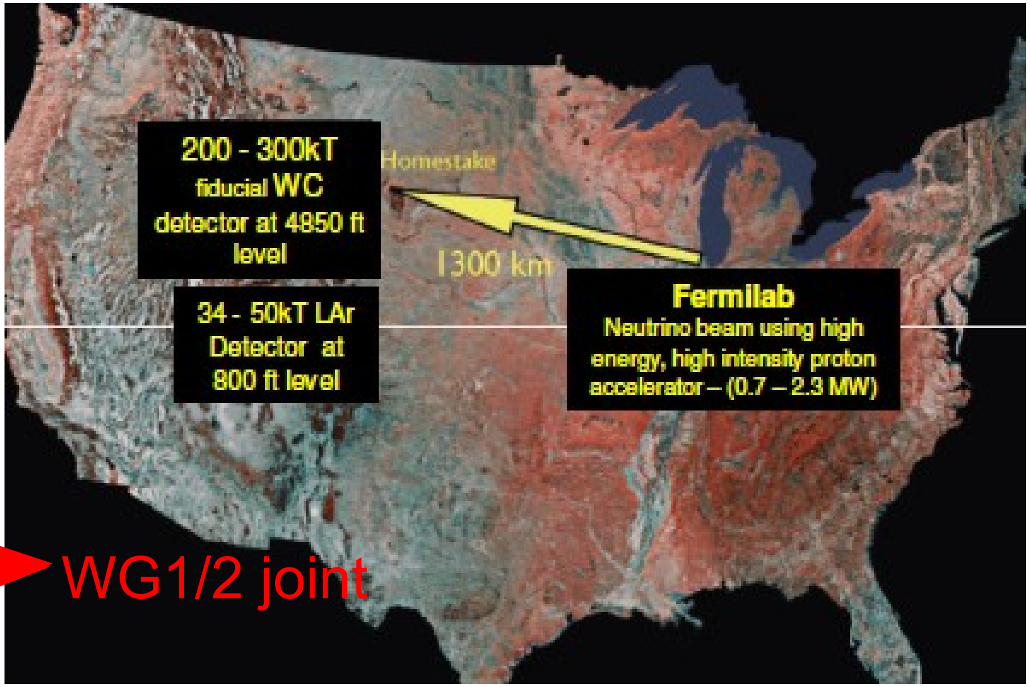




LBNE program

- LBNE status
  Choudhary
- ND plans Mishra
- LAr R&D Rebel
- large WC detector
  Whitehead

WG1/2 joint

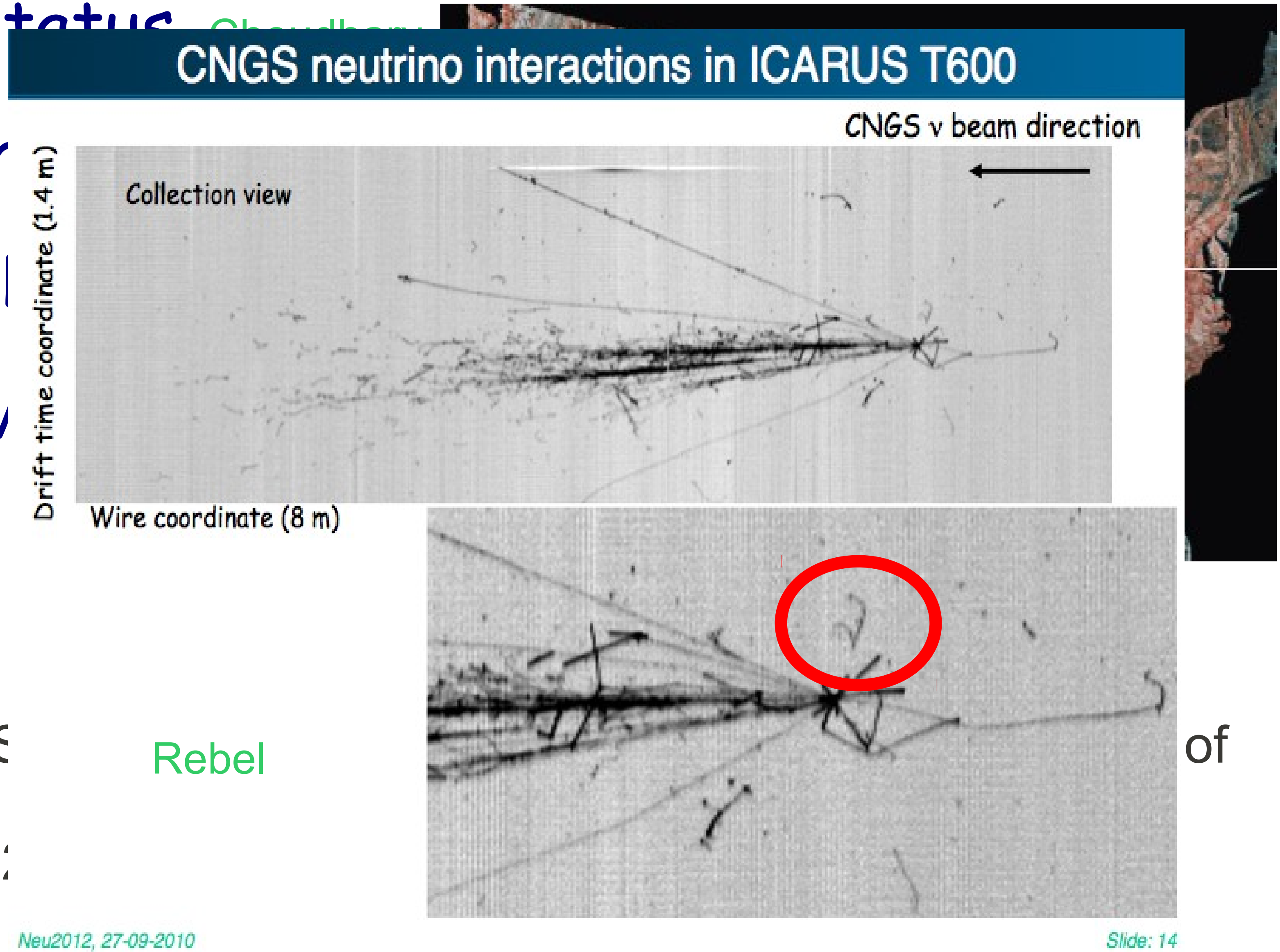


Det. @ DUSEL: 200 kt WC or 34 kt LAr or a combination thereof

Det constr. 2014/15, physics by the end of the decade

LBNE program

- LBNE status
- ND plar
- LAr R&
- large W
  Whitehead



Det. @ DUS Rebel of

Det constr. :

Joint WG1/2 session

on near → far extrapolation

- on-axis (MINOS) L. Whitehead
- off-axis (NOνA) Z. Djurcic
- off-axis (T2K) K. McFarland
- reactor experiments L. Whitehead

GeV neutrinos in LENA

use huge scintillation detetector for LBL experiment:
track reconstruction by light front propagation

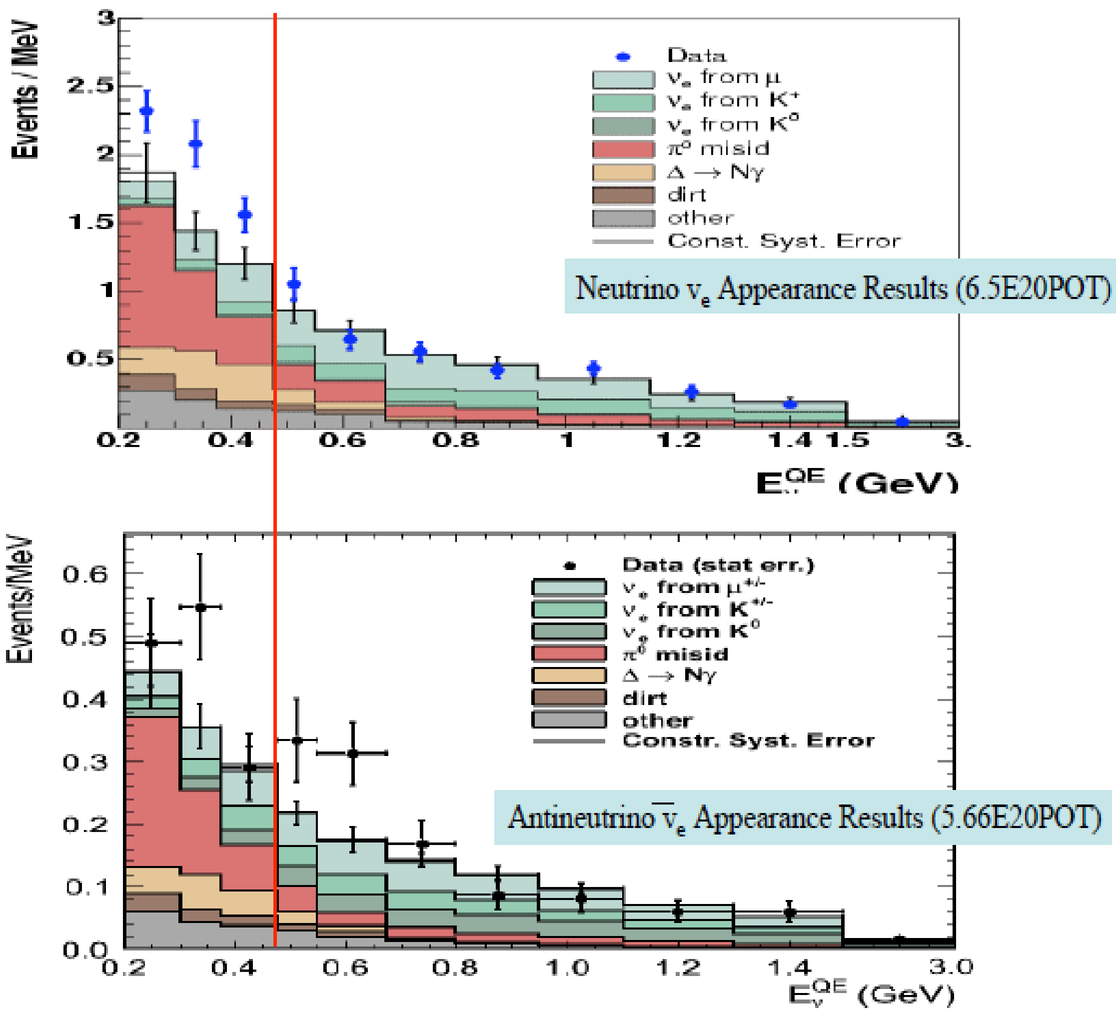
- Two possible baselines for LENA, 130 km (CERN-Frejus) and 2300 km (CERN-Pyhäsalmi)
- Single particle tracks can be reconstructed precisely at low energies (0.2 GeV-1 GeV)
- At high energies (1 GeV-5 GeV) up to 3 tracks in one event can be reconstructed
- Good lepton energy resolution at low energies (0.5%)
- Good neutrino energy resolution at high energies (1% to 5%)
- Good lepton flavour identification at low and high energies
- Background from NC events, needs to be analyzed in future Monte-Carlo studies

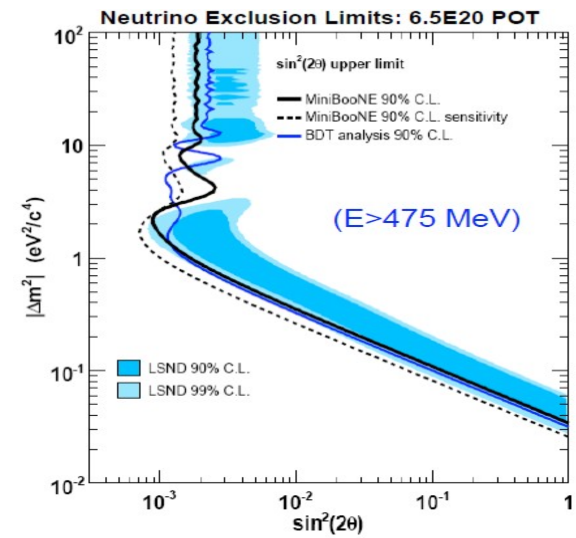
R. Möllenberg

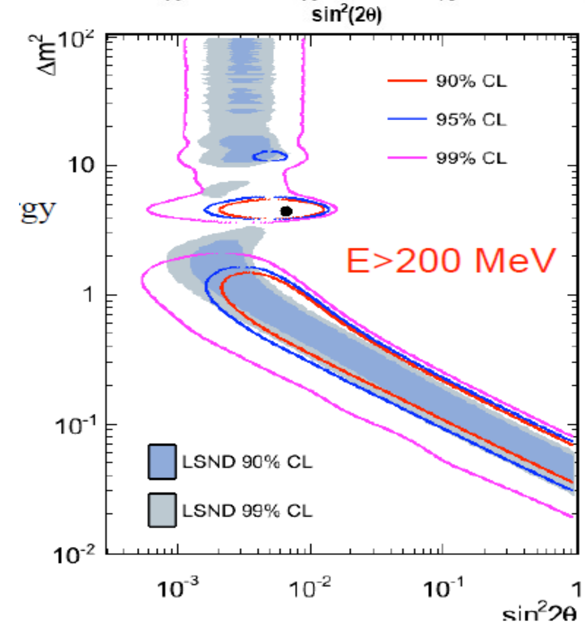
MiniBooNE results

Z. Djurcic

Comparison of ν_e and $\bar{\nu}_e$ Appearance Results



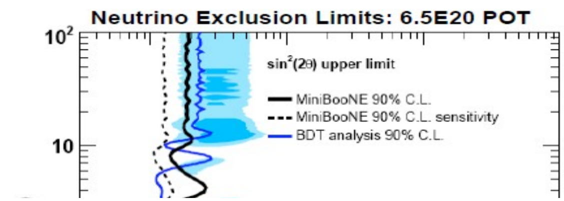




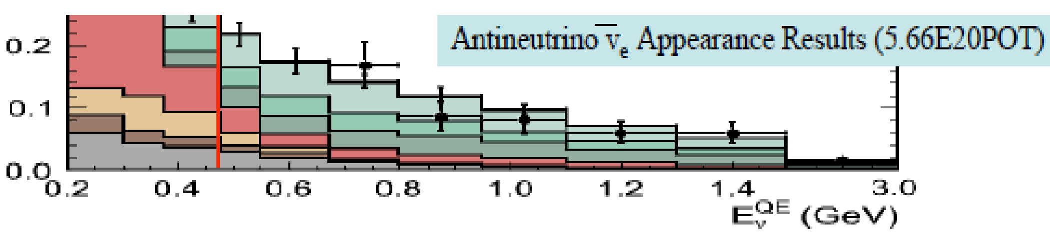
MiniBooNE results

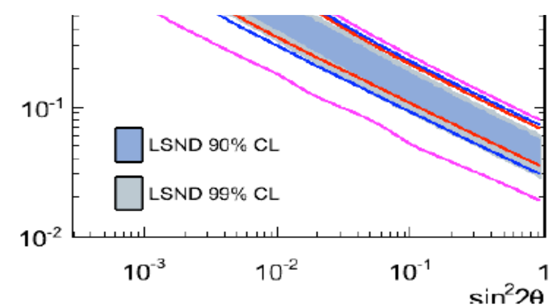
Z. Djurcic

Comparison of ν_e and $\bar{\nu}_e$ Appearance Results



- Need more statistics
  - MiniBooNE is running to double antineutrino data set for a total of ~10×10^{20} POT by Spring 2011.
  - If signal continues at current rate, two neutrino best fit will be ~3σ (with >8×10^{20} POT).
  - Requested ~15×10^{20} POT to achieve ~4σ evidence.





How to explain LSND/MB?

- Oscillations involving one [(3+1)] or more [(3+n)] sterile neutrinos does not provide a satisfactory fit to global data
- Severe constraints from null-result experiments, in particular e and μ disappearance experiments

More exotic proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation
  Kostelecky, Mews, 04; Gouvea, Grossman, 06; Katori, Kostelecky, Tayloe, 06
- mass varying neutrinos
  Kaplan, Nelson, Weiner 04; Zurek 04; Barger, Marfatia, Whisnant 05
- shortcuts of sterile neutrinos in extra dimensions
  Paes, Pakvasa, Weiler 05
- 1 decaying sterile neutrino Palomares-Riuz, Pascoli, Schwetz 05
- 2 decaying sterile neutrinos with CPV
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS, 07

More exotic proposals

- 3-neutri... ...ation Murayama, Yanagida 01; Barenboim, Bo..., Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
  KamLAND+atmospheric antineutrino data
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-dec... ...02
  KARMEN, TWIST
- CPT viol. ...ence Barenboim, Mavromatos 04
  KamLAND spectral data
- Lorentz vi... Kostelecky, ...Grossman, 06; Katori, Kostelecky, Tayloe, 06
  energy dependence, MiniBooNE?
- mass varyin... Kaplan, Nelson, Wei..., Zurek 04; Barger, Marfatia, Whisnant 05
  CDHS+atmospheric data?
- shortcuts of sterile ...extra dimensions Paes, Pakvasa, We...
  MiniB+KamL+atmospheric?
- 1 decaying sterile... Palomares-Riuz, Pascoli, Schwetz 05
  MiniBooNE
- 2 decaying sterile neutrinos with CPV
- sterile neutrin... ...gauge boson Nelson, Walsh 07
  KamL+atmospheric?
- sterile ν with ener... ...mass or mixing TS, 07
  MiniBooNE $\bar{\nu}$?

(3+1) + NSI TS

- a 4th neutrino with $\Delta m^2_{41} \sim 1$ eV^2
- a new type of CC-like interaction

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon^{ff'}_{\alpha\beta} (\bar{f} P_{L,R} \gamma^\mu f')(\bar{l}_\alpha P_L \gamma_\mu \nu_\beta) + h.c.$$

f, f' fermions depending on production or detection process

- need ε's ~ 0.01, in agreement with phenomenological bounds
- Can decouple LSND/KARMEN from rest of data (the only experiments using muon decay as neutrino source)
- CP violation due to oscillation-NSI interference
- Tension between appearance and disappearance resolved
- Cannot explain low-energy MiniBooNE excess

How to test LSND/MiniBooNE?

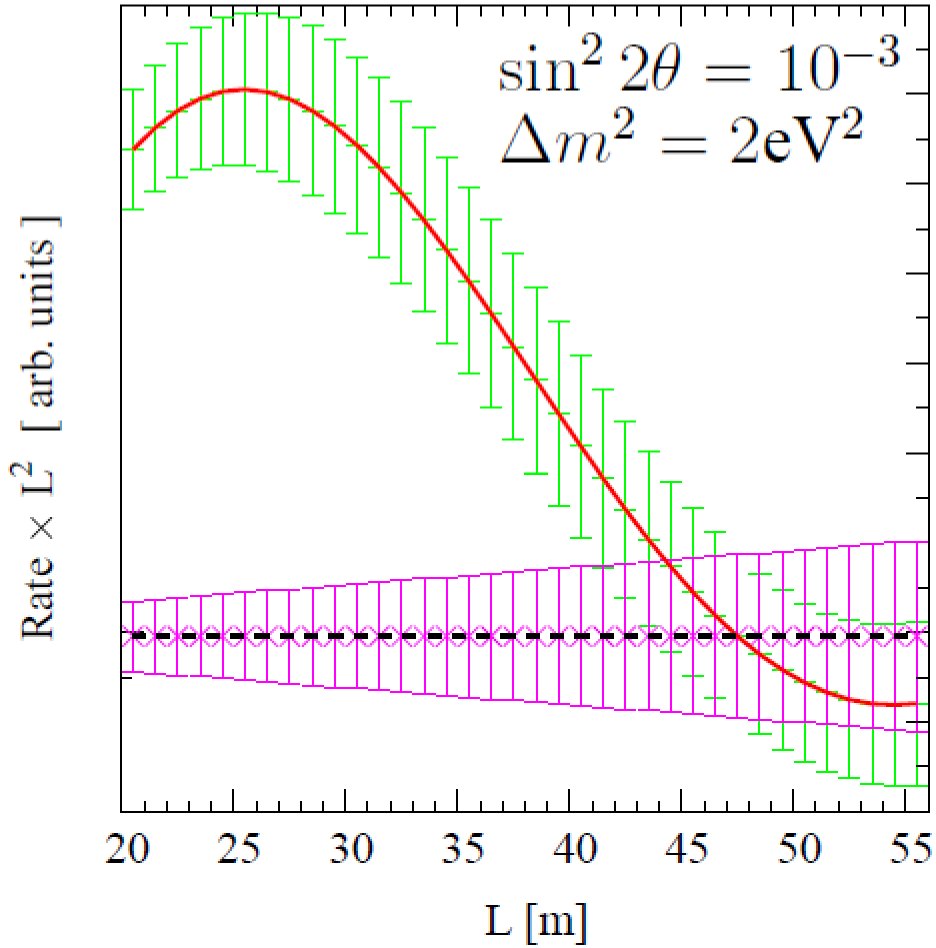
- MicroBooNE?, BooNE?
- LAr detectors at CERN PS beam?
- NOvA or LBNE near detectors (S. Mishra)

Can we use any of the many near/R&D/cross section detectors (maybe with some minor adjustment) to search for high Dm^2 oscillations?

We will need to sort out these anomalies once we want to do oscillation experiments at sub-percent precision

Pions, Protons, Gadolinium P.Huber

- Stopted pion source
- 300 kW proton beam
- Gd doped SK
- Beamstop 20 m from SK surface



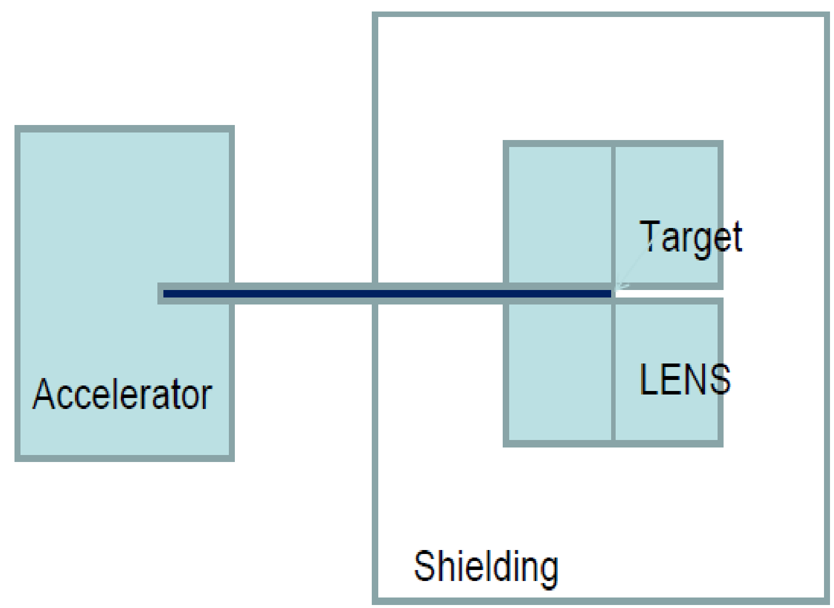
New physics with MeV ν sources

...brighter than a thousand suns

R.S. Raghavan

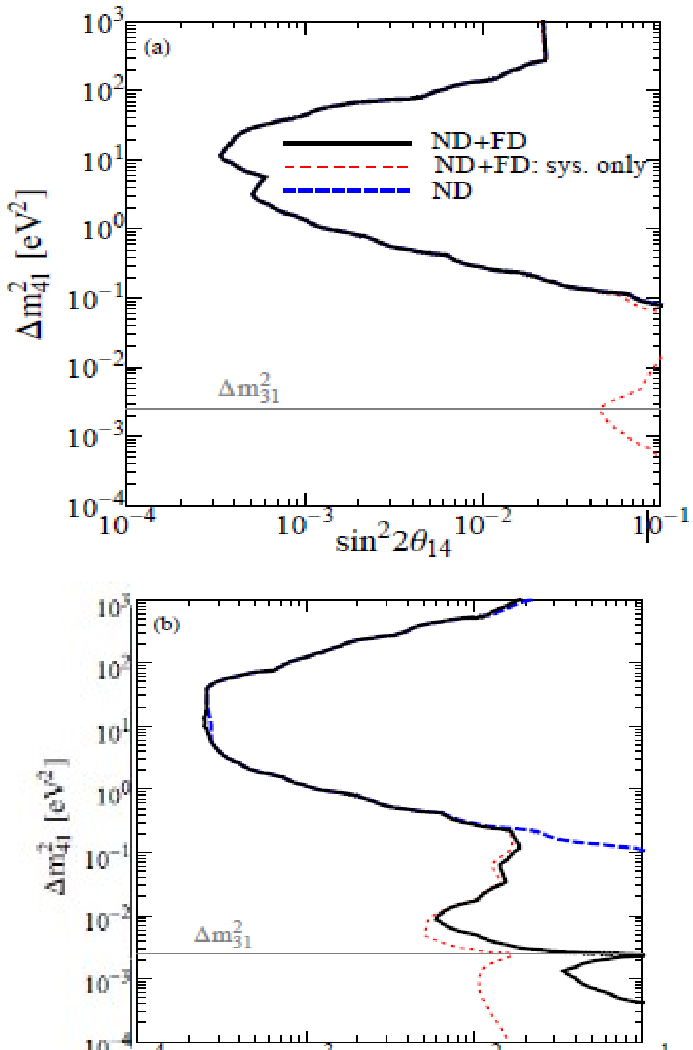
in-line production of radio active source → search for sterile neutrino oscillations inside the LENS detector

Example already exists: SK calibrator
On-line source for LENS modular detector

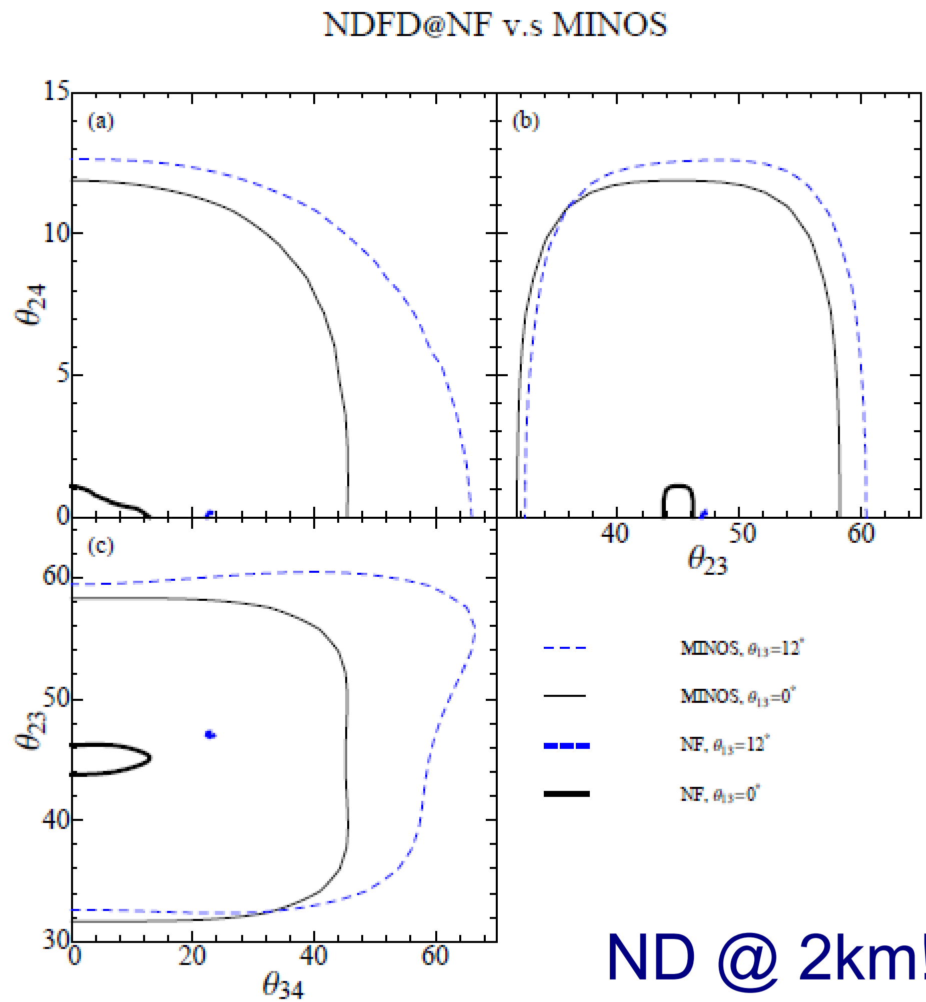


Sterile Nu's @ NuFact J. Tang

arb. mass



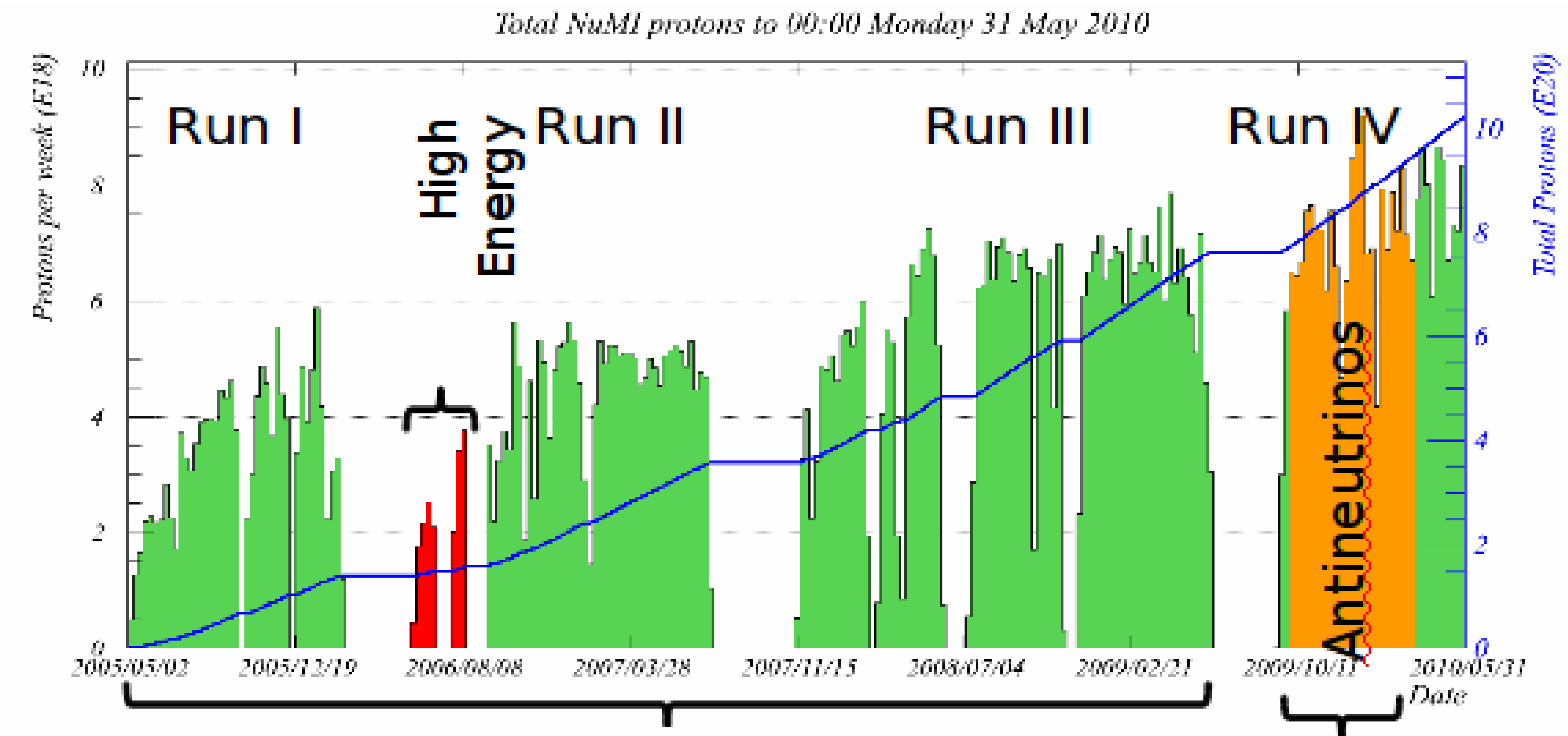
eV mass



ND @ 2km!

MINOS results
S. Childress

Data Sets for Current CC Results



7.24×10^{20} POT ν_μ mode

Current ν_μ Analysis

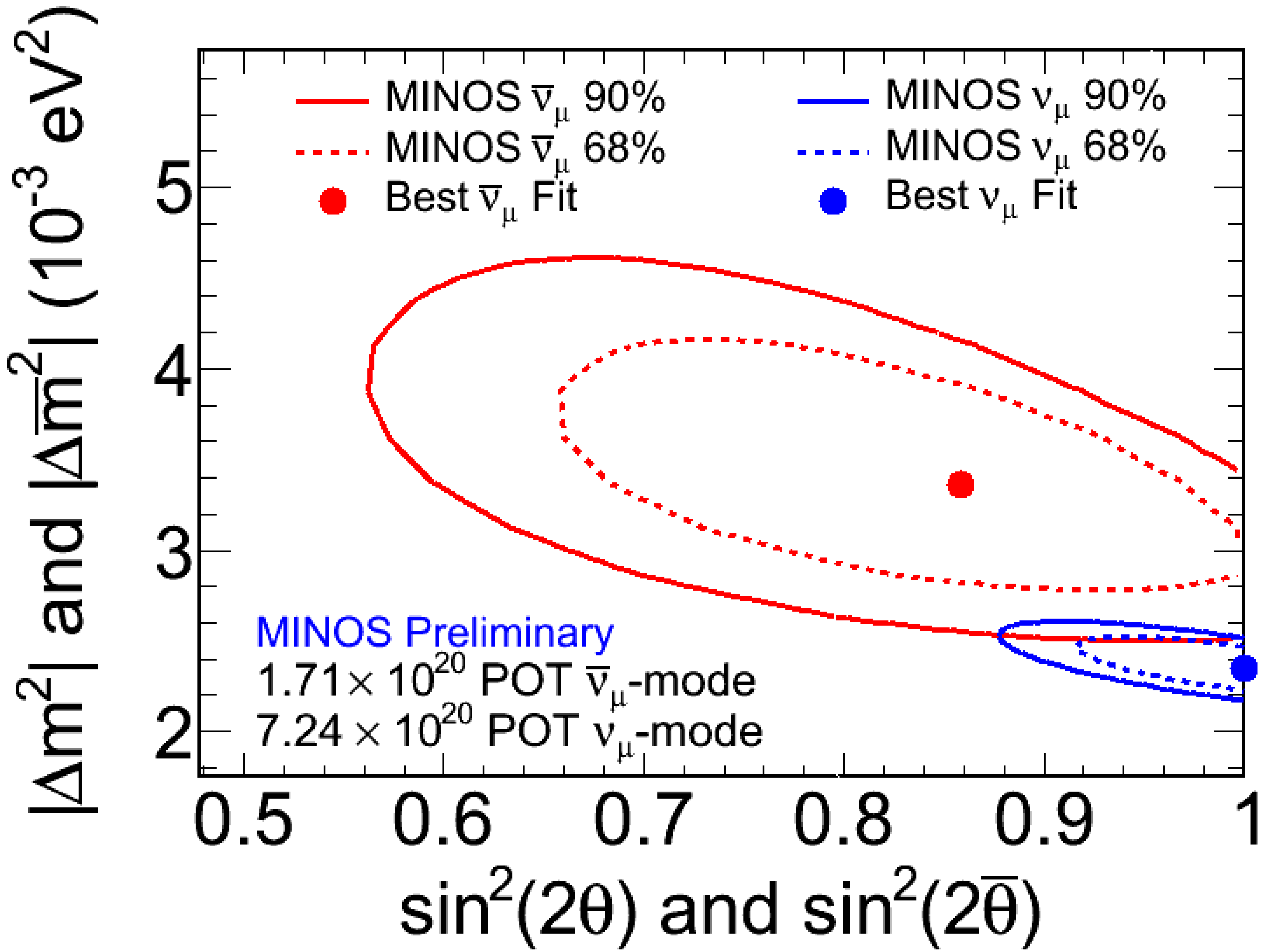
1.71×10^{20} POT

$\overline{\nu}_\mu$ mode

MINOS results

S. Childress

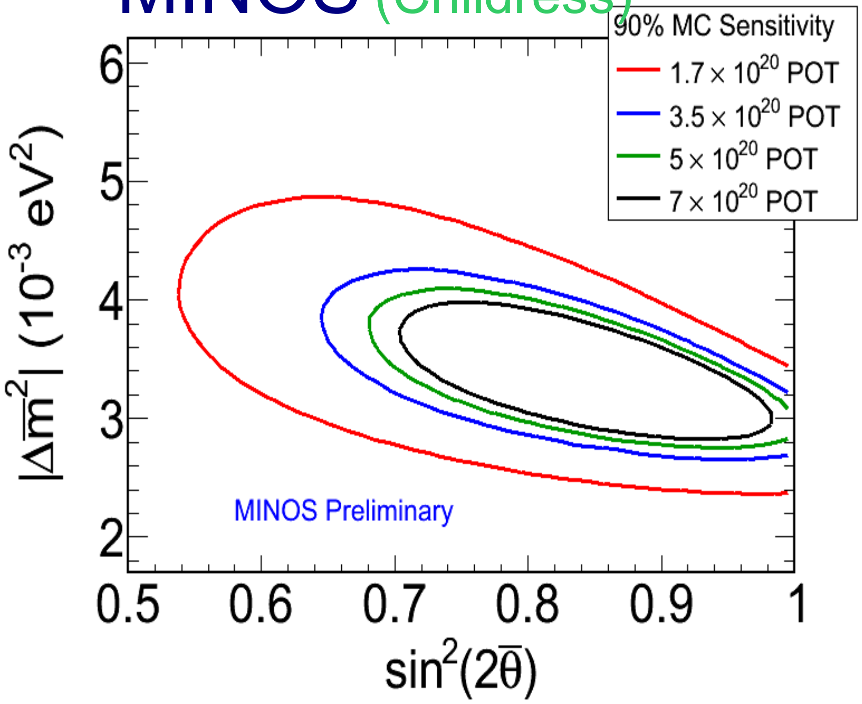
Tension between neutrinos and anti-neutrinos?



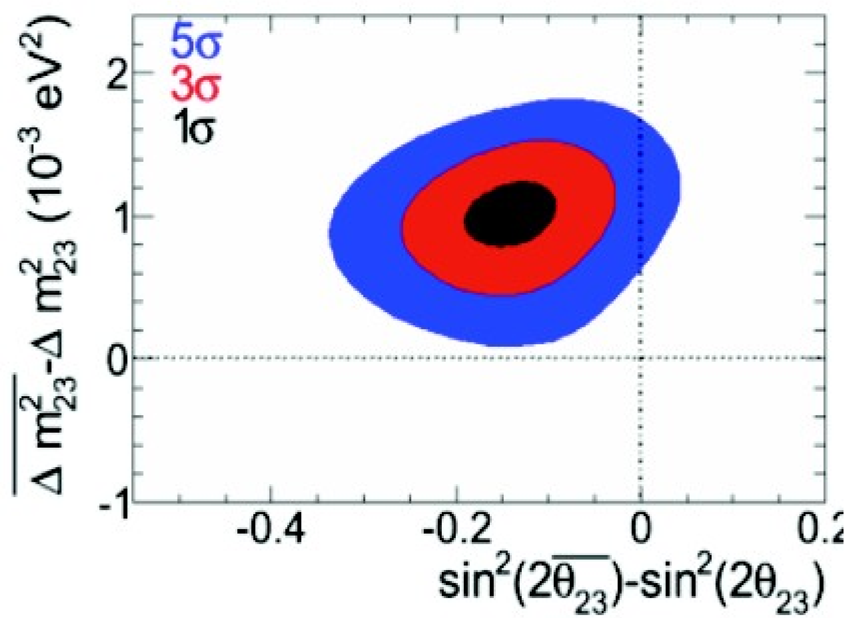
How to improve on anti-nu's?

- MINOS more powerful to measure Dm² for anti-neutrinos than NOvA (nu-contamination in anti-nu beam → magnetic field)

MINOS (Childress)



NOvA (3yrs full) (Rebel)



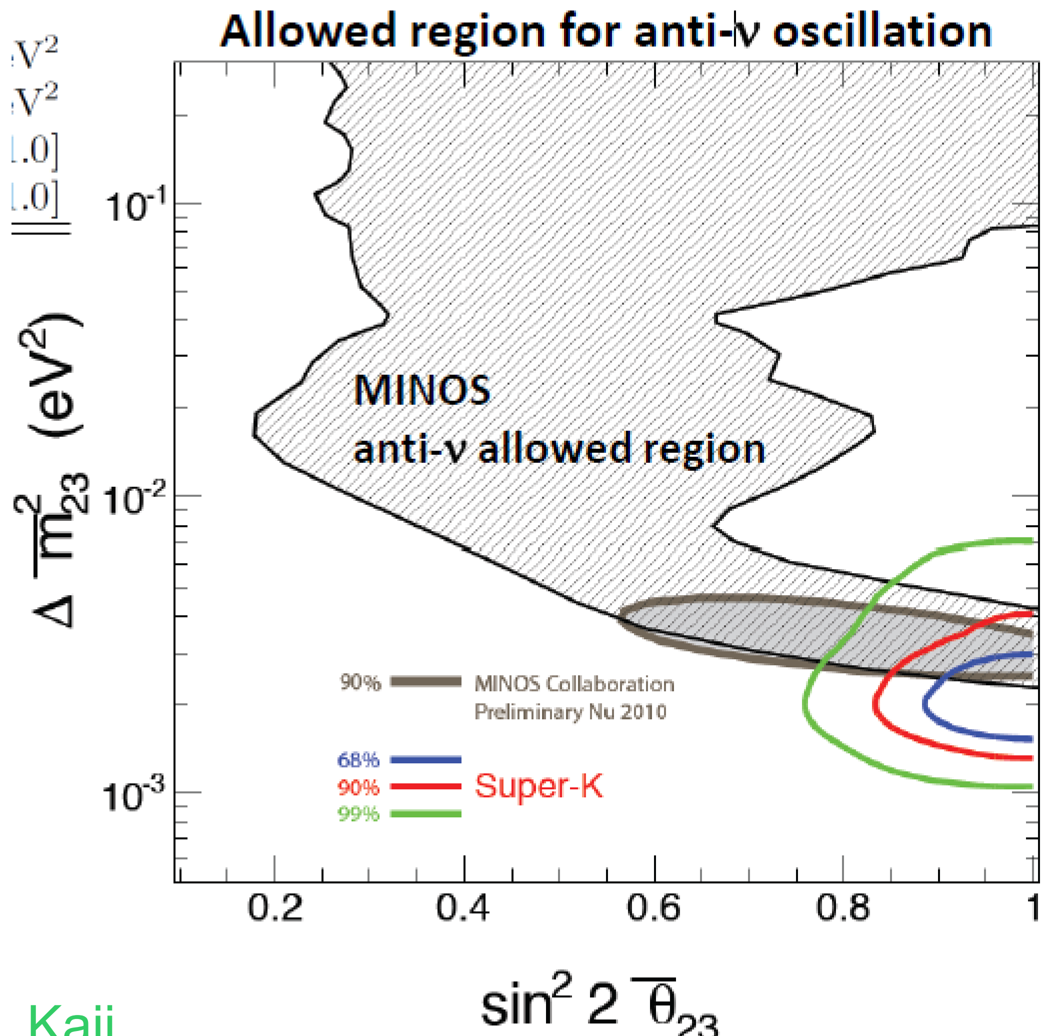
How to improve on anti-nu's?

- MINOS more powerful to measure Dm^2 for anti-neutrinos than NOvA (nu-contamination in anti-nu beam → magnetic field)
- Run MINOS longer → delay NOvA?
- MINERvA wants neutrinos → conflict with longer anti-nu running for MINOS?
- Can we use CNGS for this? (probably no)
- Should we base our strategy on 2σ effects?

discussion session on MINOS anti-nu results

SK atmospheric neutrinos?

- using different zenith angle distr. of single- and multi-ring events for neutrinos and antineutrinos →
- statistical separation
- no hint for CPT violation

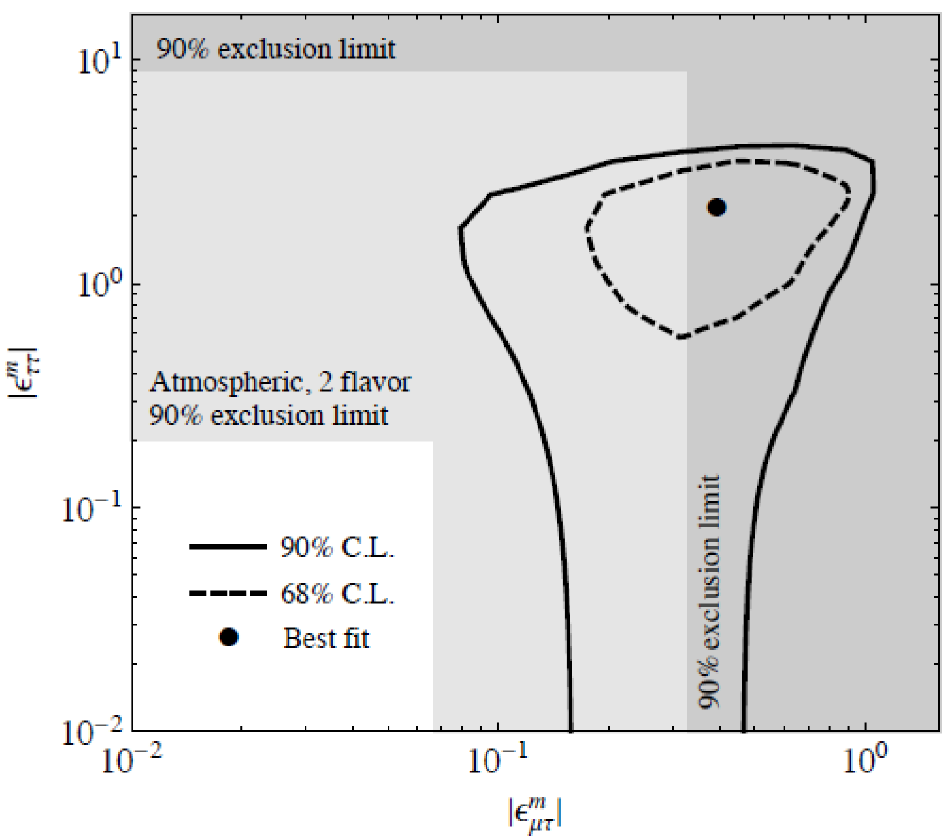


H. Kaji

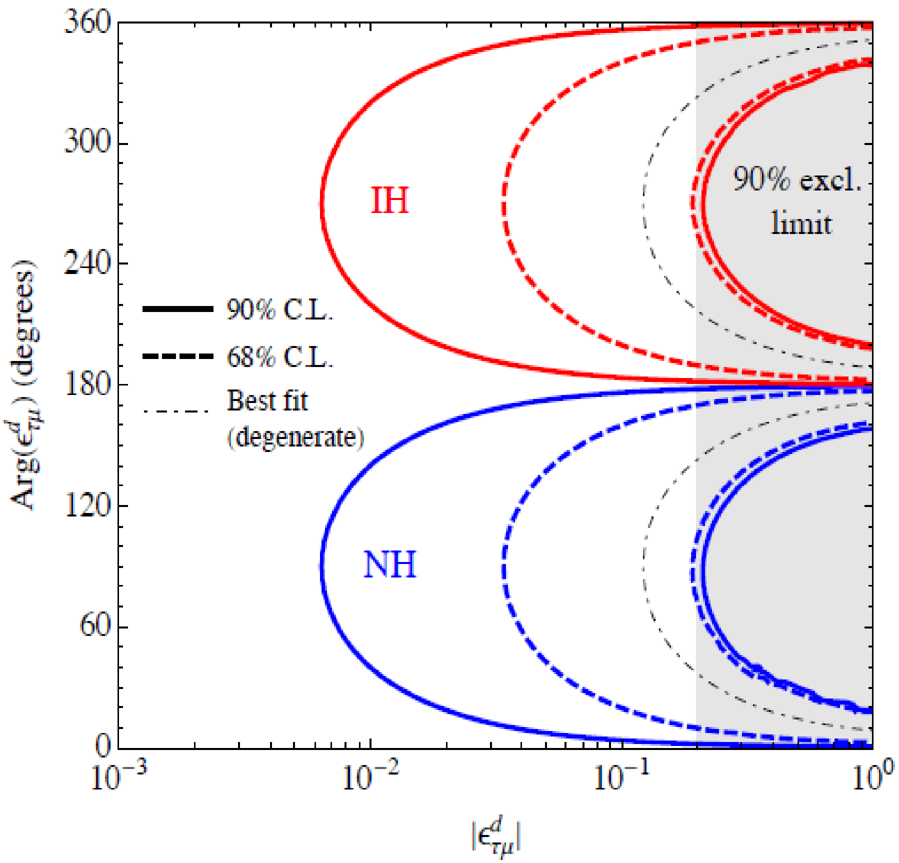
Can we explain nu/anti-nu diffs?

- non-standard neutrino interactions? S. Parke

NC-like NSI: exlcuded!



CC-like NSI



Can we explain nu/anti-nu diffs?

O. Yasuda

- NSI in the e-τ channel, where limits are O(1) when correlated with the $\tau\tau$ element
- sterile neutrinos at the atmosph Dm ^{2} scale

W. Rodejohann

- gauged L_μ-L_τ Z' long-range force + Z-Z' mixing → effective potential between ν_μ-ν_τ

Can we explain nu/anti-nu diffs?

all these ideas do not really improve the neutrino/antineutrino problem and/or are excluded by other constraints

O. Yasuda, W. Rodejohann

Summary

It's very hard to explain MINOS data[a]

[a] Also see Osamu's talk why all solutions presented so far probably don't work...

2540 km (bi)magic baseline

S. Raut (superbeam)

S. Goswami (LENF)

the magic baseline ~7500 km

$$P_{\mu e} = C_0 \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} + \alpha^2 C_2 \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

$$+ \alpha C_1 \cos(\Delta + \delta_{cp}) \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \frac{\sin(\hat{A}\Delta)}{\hat{A}}$$

Barger et al. 01; Huber, Winter 03; Smirnov 06

$A\Delta = \pi$ independent of osc params and energy!

2540 km (bi)magic baseline

$$P_{\mu e} = C_0 \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} + \alpha^2 C_2 \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

$$+ \alpha C_1 \cos(\Delta + \delta_{cp}) \frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})} \frac{\sin(\hat{A}\Delta)}{\hat{A}}$$

- IH no CP $\Longrightarrow \sin[(1-\hat{A})\Delta] = 0$

  $\Longrightarrow (1+|\hat{A}|)\cdot|\Delta| = n\pi$

  For NH $\sin[(1-\hat{A})\Delta] = 1$

  $\Longrightarrow (1-|\hat{A}|)\cdot|\Delta| = (m-1/2)\pi$

- For $n=1$ and $m=1$

  $L \approx 2540$ km $E_\nu \equiv E_{IH} \approx 3.3$ GeV, Raut, Singh, UmaShankar, 2009

2540 km (bi)magic baseline

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- NH No CP $\Longrightarrow \sin[(1-\hat{A})\Delta]$ = 0

  $\Longrightarrow (1-|\hat{A}|)\cdot|\Delta| = n\pi$

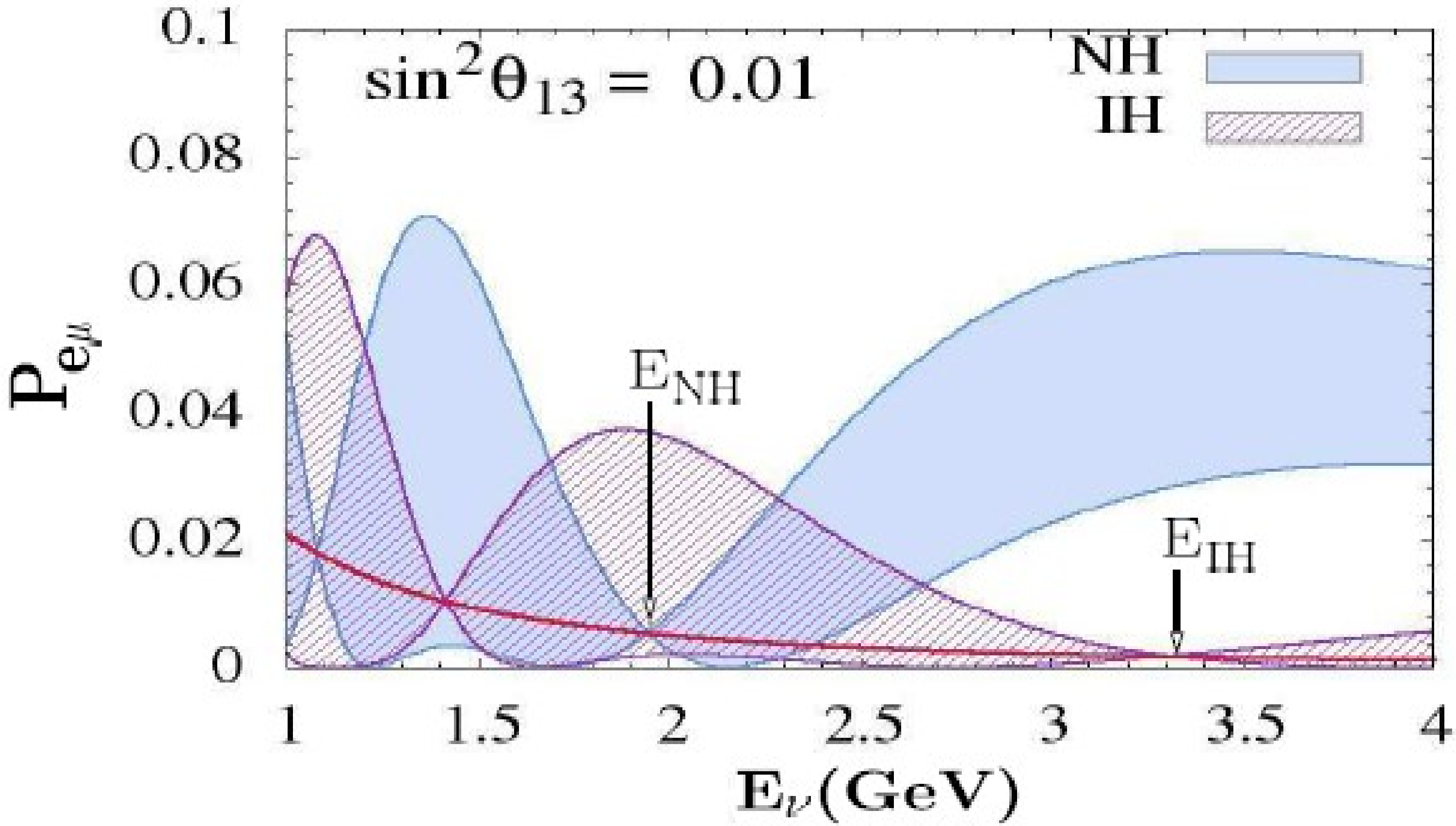
  For IH $\sin[(1+\hat{A})\Delta]$ = 1

  $\Longrightarrow (1+|\hat{A}|)\cdot|\Delta| = (m-1/2)\pi$

- For $n=1$ and $m=2$,

  $L \approx 2540$ km $E_\nu \equiv E_{NH} \approx 1.9$ GeV. Dighe,Goswami,Ray, 2010

2540 km (bi)magic baseline



Goswami

L = 2540 km

magic energies: E_{NH} = 1.9 GeV, E_{IH} = 3.3 GeV

2540 km (bi)magic baseline

$\sin^2 2\theta_{13}$	Run time (years), NH	Run time (years), IH
0.10	0.022	0.048
0.09	0.026	0.057
0.08	0.031	0.068
0.07	0.040	0.082
0.06	0.051	0.105
0.05	0.070	0.137
0.04	0.104	0.195
0.03	0.180	0.420
0.02	0.425	2.600
0.01	2.950	4.800

S. Raut

Runtime required in years for 3σ hierarchy distinction, for the specified setup, combined with T2K, NOvA and the reactor expts.

NOvA-like det. @ 2540 km with 10 x kt pot/yr
NuMI beam (med. E) 7mrad off-axis (→ peak @ 3.3 GeV)

2540 km (bi)magic baseline ?

Is it „magic“ or is it just the increase of the matter effect?

Barger et al., hep-ph/0607177

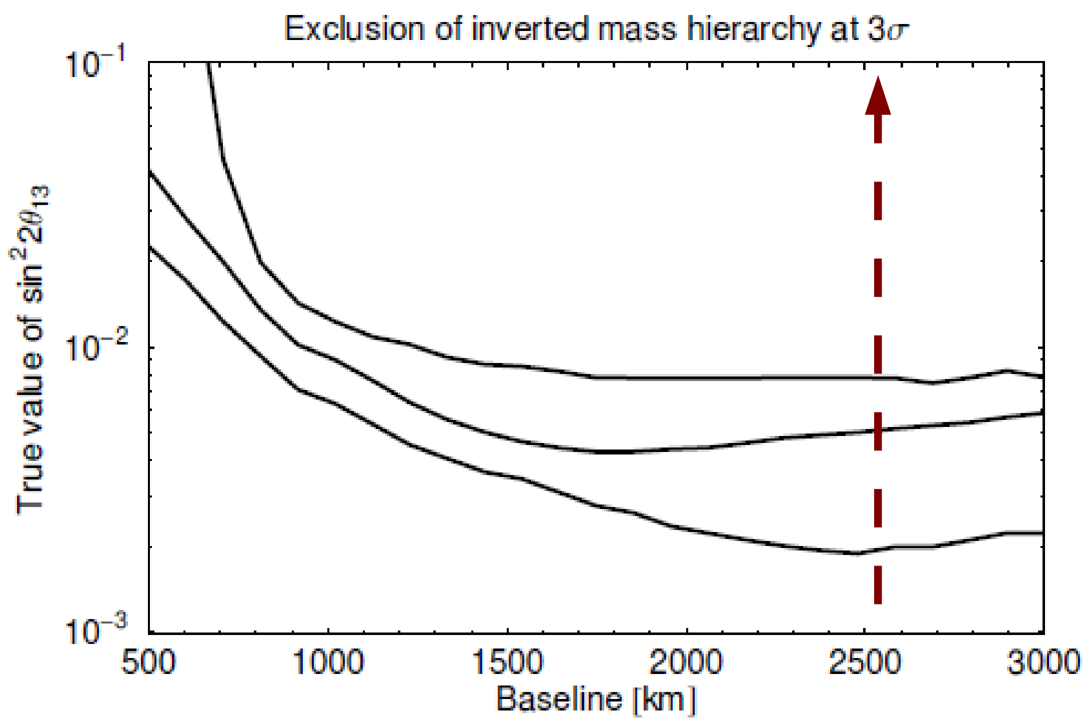


Figure 6: Discovery reach for a normal mass hierarchy at 3σ for CP fractions 0 (lowermost line, best case), 0.5 (middle line) and 1 (uppermost line, worst case) as a function of the baseline. The detector mass, beam power and exposure are kept the same for all baselines.

2540 km (bi)magic baseline ?

Is it „magic" or is it just the increase of the matter effect?

Barger et al., hep-ph/0607177

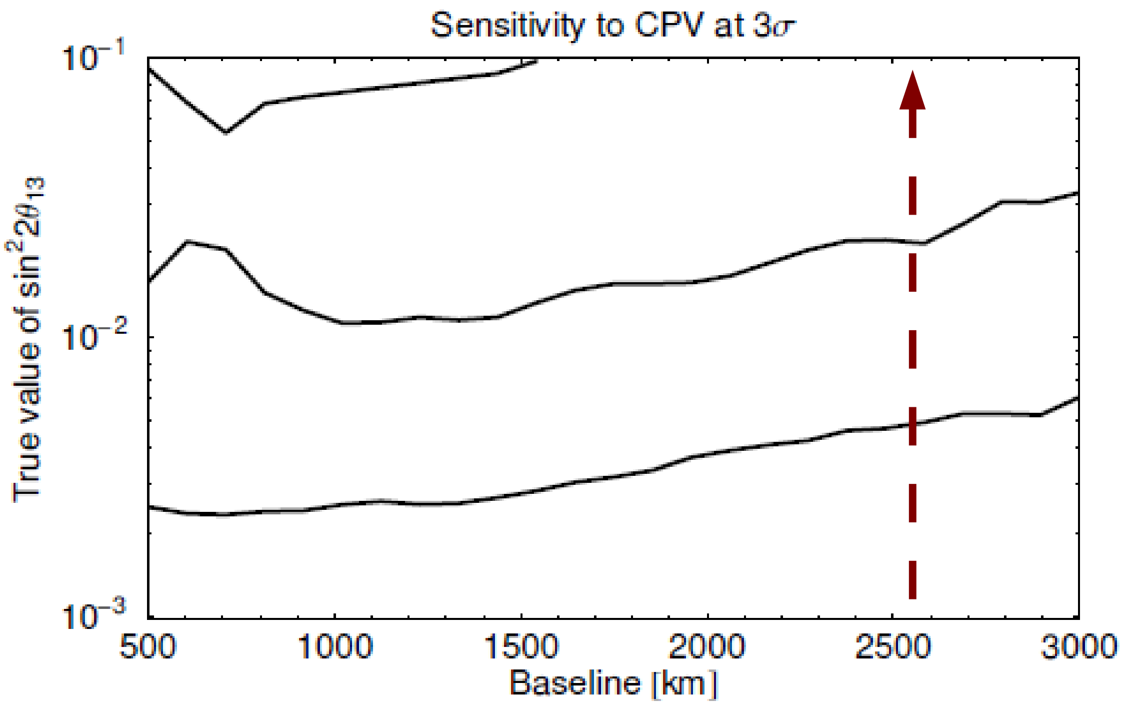


Figure 8: Discovery reach for CP violation at 3σ for CP fractions 0 (lowermost line, best case), 0.5 (middle line) and 0.75 (uppermost line) as a function of the baseline. The detector mass, beam power and exposure are kept the same for all baselines.

μ's from τ decays at NuFact

μ^-

$e^- \bar{\nu}_e \nu_\mu$

$\rightarrow \nu_\mu \rightarrow \mu^-$

$\rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^-$

right-sign muons
N. Sinha

$\rightarrow \bar{\nu}_\mu \rightarrow \mu^+$

$\rightarrow \bar{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$

wrong-sign muons
P. Coloma

μ's from τ decays at NuFact

μ^-

$e^- \bar{\nu}_e \nu_\mu$

$\rightarrow \nu_\mu \rightarrow \mu^-$

$\rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^-$

right-sign muons
N. Sinha

$\rightarrow \bar{\nu}_\mu \rightarrow \mu^+$

$\rightarrow \bar{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$

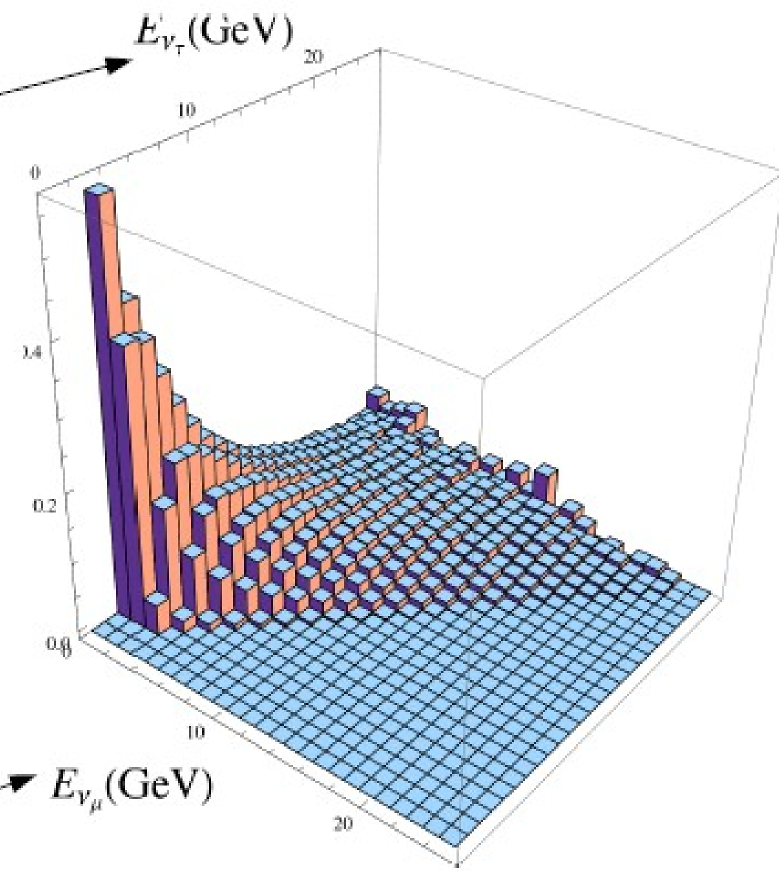
wrong-sign muons
P. Coloma

finally alchemy succeeded: making gold out of silver!

μ's from τ decays at NuFact

Migration matrix

True energy



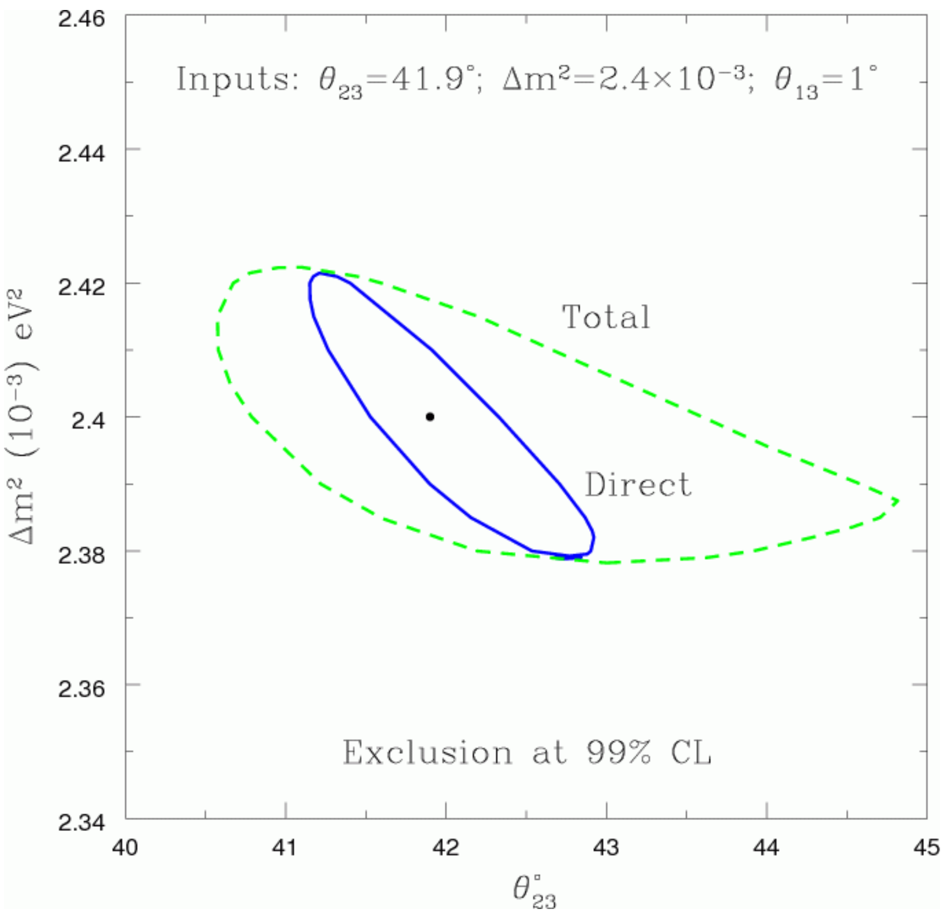
- 10^6 ν_τ per energy bin
- Cross section and differential decay width $\tau \to \mu$ with GENIE

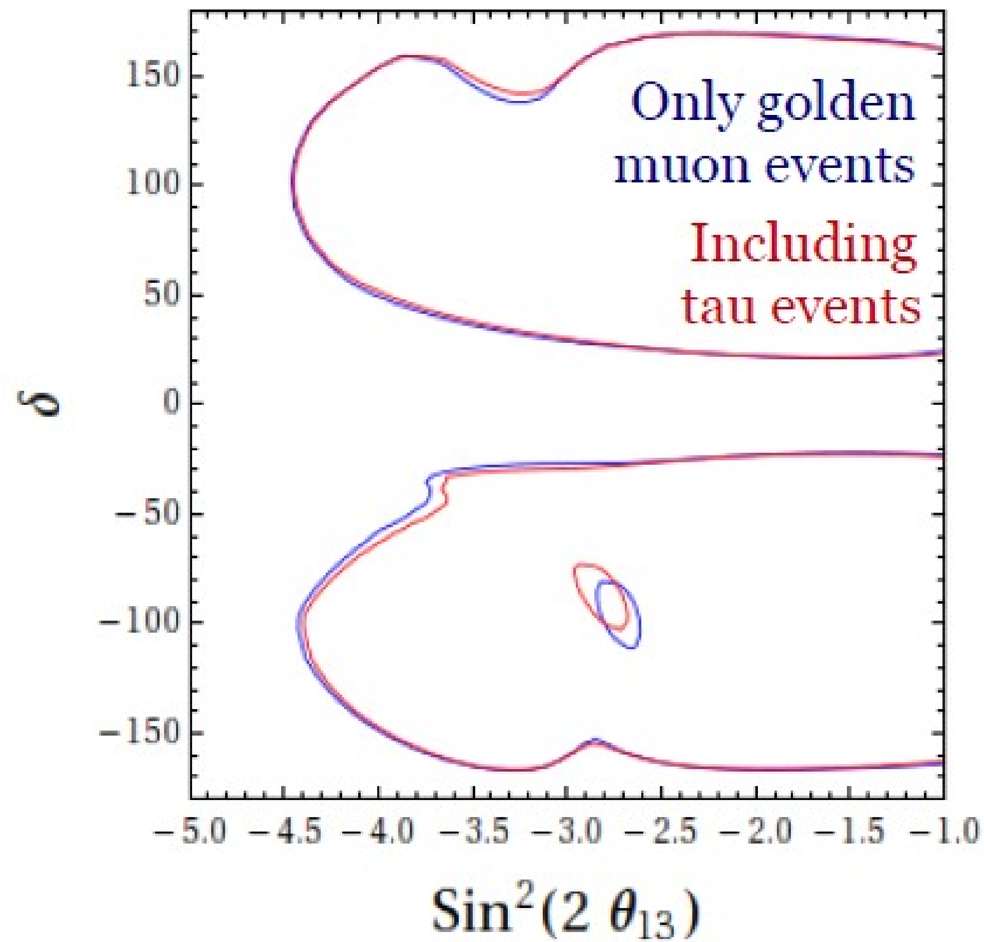
(Andreopopoulos *et al*, arXiV:0905.2517)

Fake energy

P. Coloma – NuFact10

μ's from τ decays at NuFact





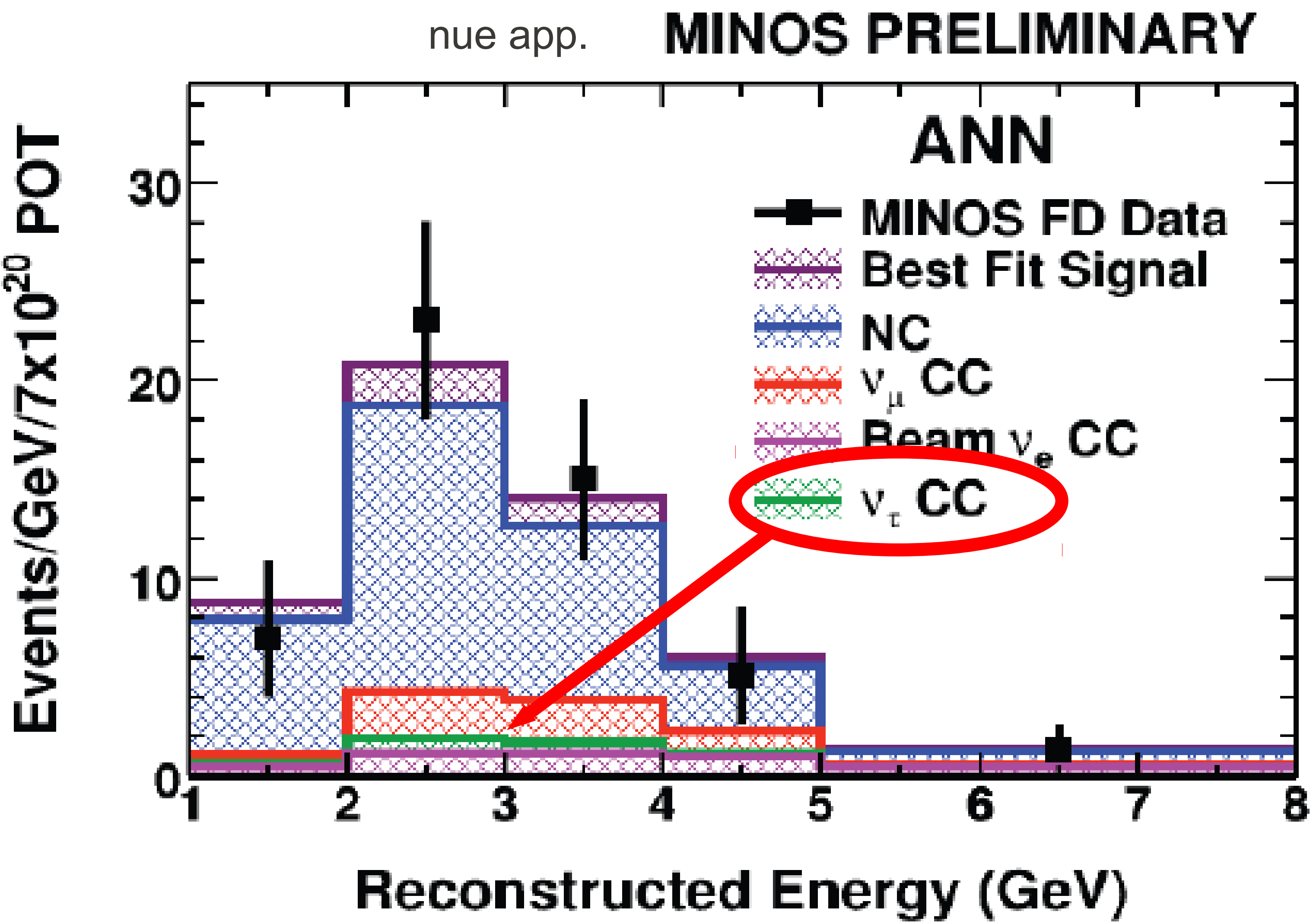
right-sign muons N. Sinha
important for Dm32, θ23 measurment

wrong-sign muons P. Coloma
small impact for CPV sens.

e's from τ decays at MINOS

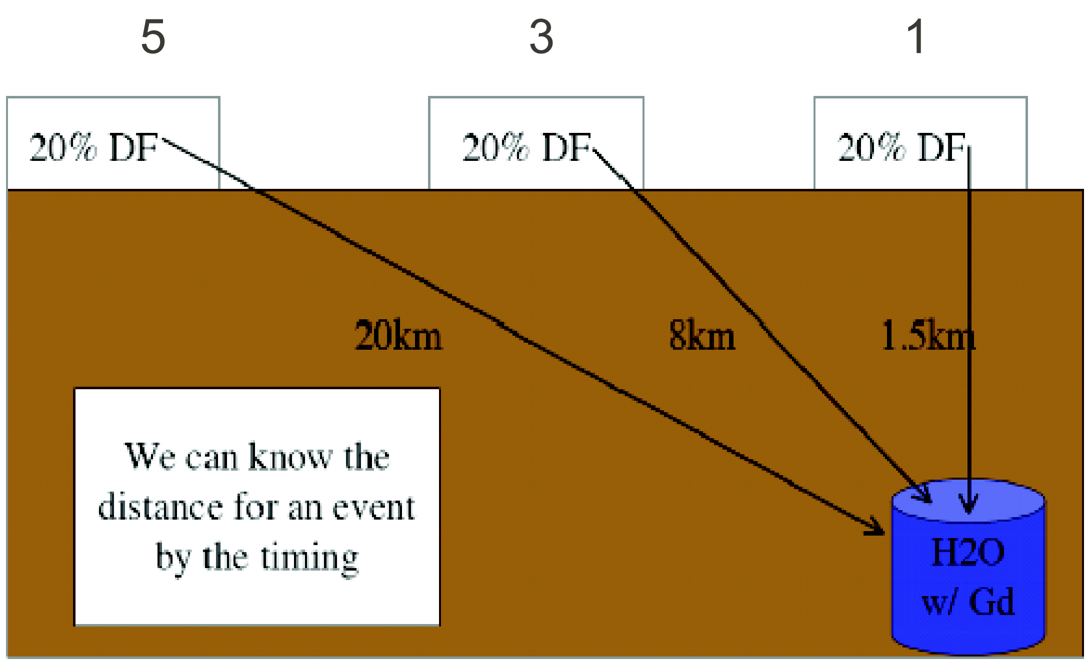
taus are included in the MINOS analysis

nue app.



Daedalus

- "low-cost" high-power (~MW) cynclotrons + ~100 kt WC + Gd (DUSEL)



Z. Djurcic

Daedalus

- “low-cost“ high-power (~MW) cynclotrons + ~100 kt WC + Gd (DUSEL)
- measure θ_{13} and δ by spectral fit
- combine with LBNE beam

Z. Djurcic, P. Huber

Session on neutrino mass models

- Neutrino mass generation from higher dimensional operators T. Ota
- Four Zero neutrino Yukawa textures, mu-tau symmetry and baryogenesis P. Roy
- Quasi-degenerate neutrinos in SO(10) K. Patel

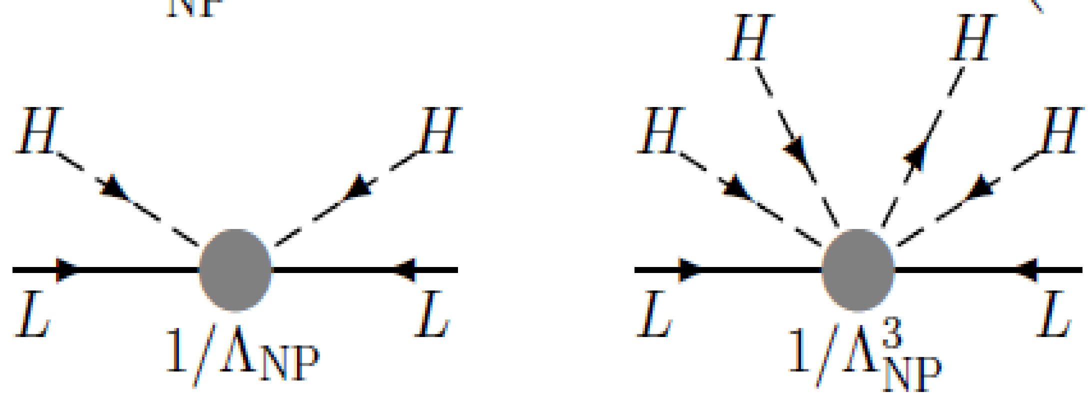
nu mass from higher dim ops

T. Ota

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \delta\mathscr{L}^{d=5} + \delta\mathscr{L}^{d=6} + \delta\mathscr{L}^{d=7} + \cdots$$

$$\delta\mathscr{L}^{d=5} = \frac{1}{\Lambda_{\rm NP}}(\overline{L^c} i\tau^2 H)(H^{\sf T} i\tau^2 L) \to v\frac{v}{\Lambda_{\rm NP}}\overline{\nu^c}\nu,$$

$$\delta\mathscr{L}^{d=7} \ni \frac{1}{\Lambda_{\rm NP}^3}(\overline{L^c} i\tau^2 H)(H^{\sf T} i\tau^2 L)(H^\dagger H) \to v\left(\frac{v}{\Lambda_{\rm NP}}\right)^3\overline{\nu^c}\nu,$$



"Higher d" = "Lower $\Lambda_{\rm NP}$"

If Weinberg op. ($d = 5$) is forbidden and m_ν is induced from $d = 7$ op., $\Lambda_{\rm NP}$ is lowered → Collider testability is recovered

non-standard nu interactions

- CC-like (source and detector)

  T. Ota (M. Blennow) tau appearance at near detectors

- NC-like (matter/propagation)

  J. Lopez neutrino factory

non-standard nu interactions

- general basis of dim-6 operators
- bounds from charged LFV

Operator	$(\mathcal{C}^1_{LQ})_\alpha^{\tau}$	$(\mathcal{C}^3_{LQ})_\alpha^{\tau}$	$(\mathcal{C}_{ED})_\alpha^{\tau}$	$(\mathcal{C}_{EU})_\alpha^{\tau}$	$(\mathcal{C}^\dagger_{ED})_\alpha^{\tau}$	$(\mathcal{C}^\dagger_{EU})_\alpha^{\tau}$
$\alpha = \mu$	$2.1 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$6.2 \cdot 10^{-4}$	$6.2 \cdot 10^{-4}$
$\alpha = e$	$2.4 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$6.9 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$	$6.1 \cdot 10^{-4}$

- Bounds are generally $\mathcal{O}(10^{-4})$
- Implies reach for probability must generally be $\mathcal{O}(10^{-6}\text{–}10^{-8})$

T. Ota (M. Blennow)

non-standard nu interactions

matter NSI at IDS-inspired NuFact setups:

- Sensitivity to off-diagonal NSI parameters:
  - $\epsilon_{e\mu}$: higher energies are the key
  - $\epsilon_{e\tau}$: the MB is the key (stronger correlations)
  - $\epsilon_{\mu\tau} < 10^{-3} - 10^{-2}$. Independent of the set up.

$\Big\} \mathcal{O}(10^{-3})$

- CP violation exclusively due to NSI could be measured for reasonable input values of the NSI parameters. Even for $\theta_{13} = 0$

J. Lopez

Questions for Next NuFact

- Is there really a synergy between Neutrino Oscillation Expts, LFV expts, Neutrino-less double beta decay expts, direct mass search experiments, SN, LHC....?
- What is the case for precision in neutrino expts? Does it lead to better theoretical understanding?
- What value of $\sin^2 2\theta_{13}$ is uninterestingly small?
- Is it really possible to measure NSI in neutrino oscillation expts?

Thank you

SANDHYA CHOUBEY   WG1 SUMMARY: THEORY   NuFact09, IIT, CHICAGO, 25.07.09

WG1 tasks for NuFact 2011

- Sensitivity and optimization studies

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- Write down a consistent model which gives observable non-standard neutrino interactions

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Thank you!