Neutrino Physics: Status and Outlook

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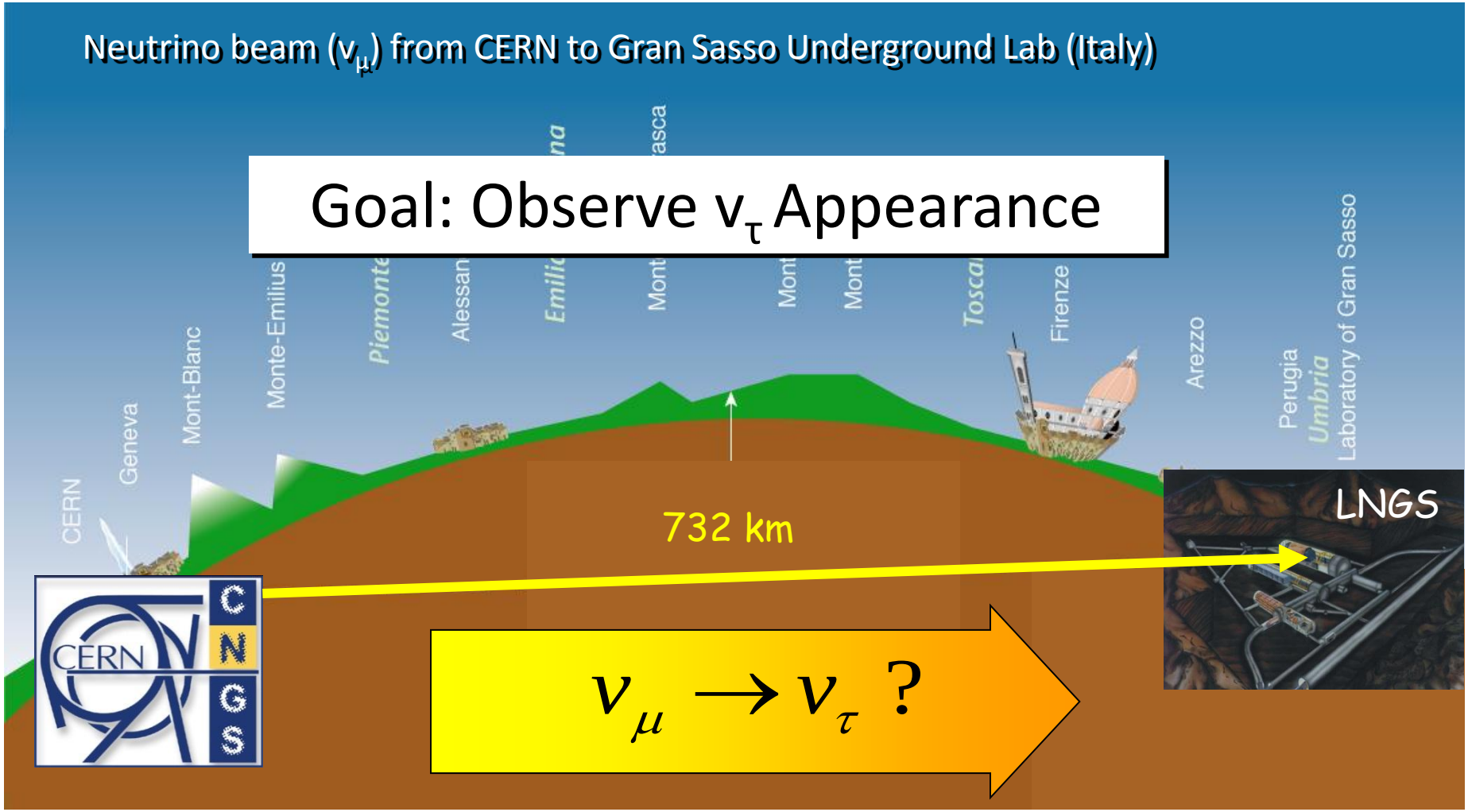
Contents:

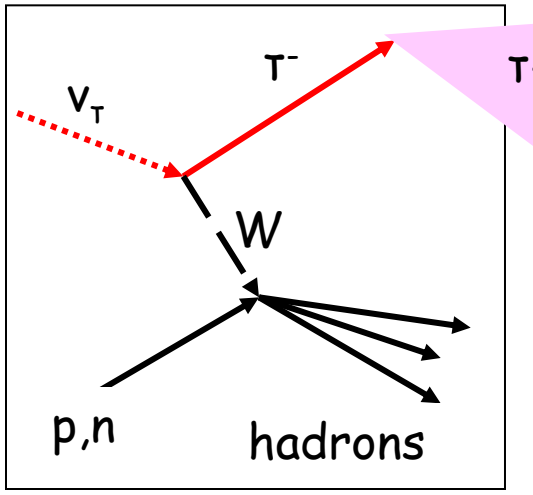
- Neutrino Oscillation: Confirming the Standard Picture
  - Direct Tau Appearance
  - Matter/Vacuum transition
  - Measurement of θ_{13}
- Neutrino Oscillation: The Future
  - Mass Hierarchy and CP Phase
  - Longbaseline
  - Atmospheric & Reactor
- Neutrino Oscillation: Anomalies
- Double Beta Decay

OPERA:
Oscillation Project with Emulsion tRacking Apparatus



Physics runs: 2008, 2009, 2010, 2011, 2012 until 3rd Dec

OPERA: Detection of ν_τ



τ-decay:

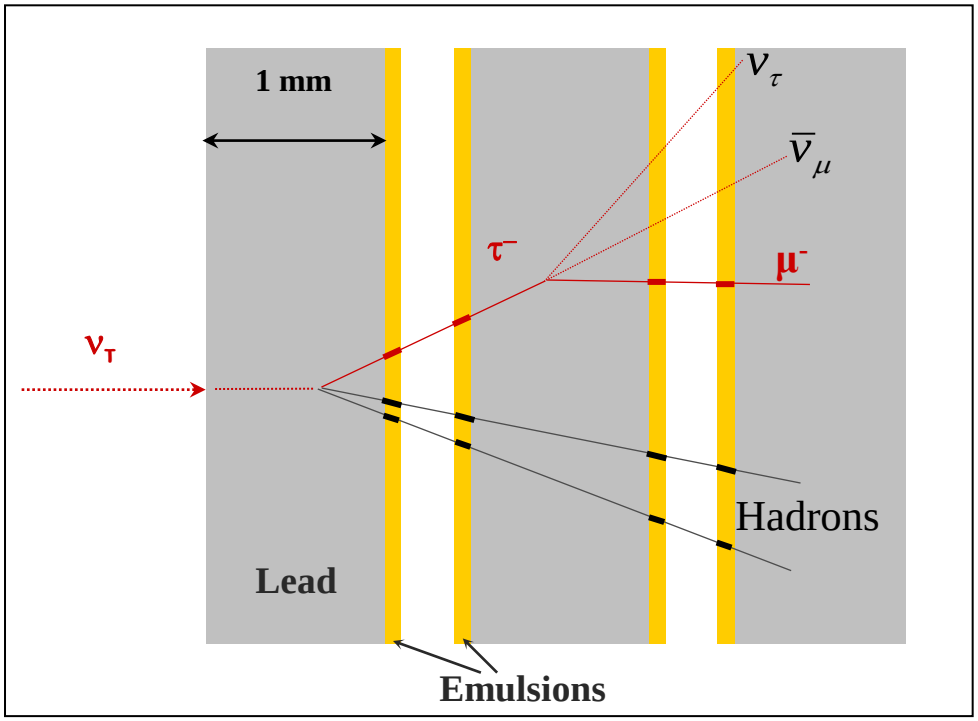
$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \quad 18\%$$

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \quad 18\%$$

$$\tau^- \to \pi^-(n\pi^0) + \nu_\tau \quad 48\%$$

$$\tau^- \to \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau \quad 15\%$$

Typical topology of τ-decay:
"Kink" within 1mm from vertex



Expected Signal

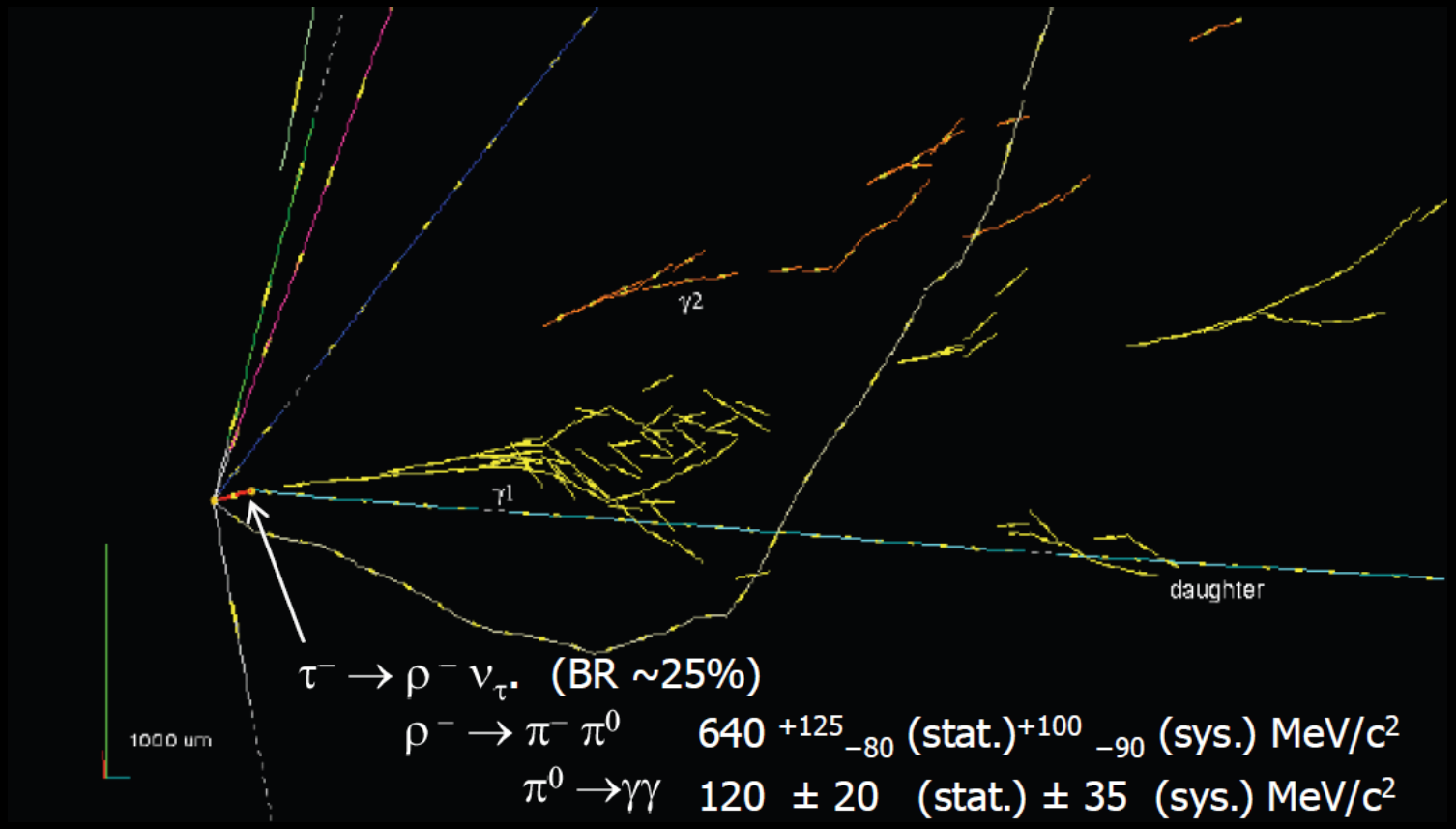
Assume: Maximal mixing, 22.5×10^{19}pot (= 5years @ 4.5×10^{19}pot/year)

τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background
$\tau \rightarrow \mu$	17.7	2.9	0.17
$\tau \rightarrow e$	17.8	3.5	0.17
$\tau \rightarrow h$	49.5	3.1	0.24
$\tau \rightarrow 3h$	15.0	0.9	0.17
Total		**10.4**	**0.75**

Expected events:

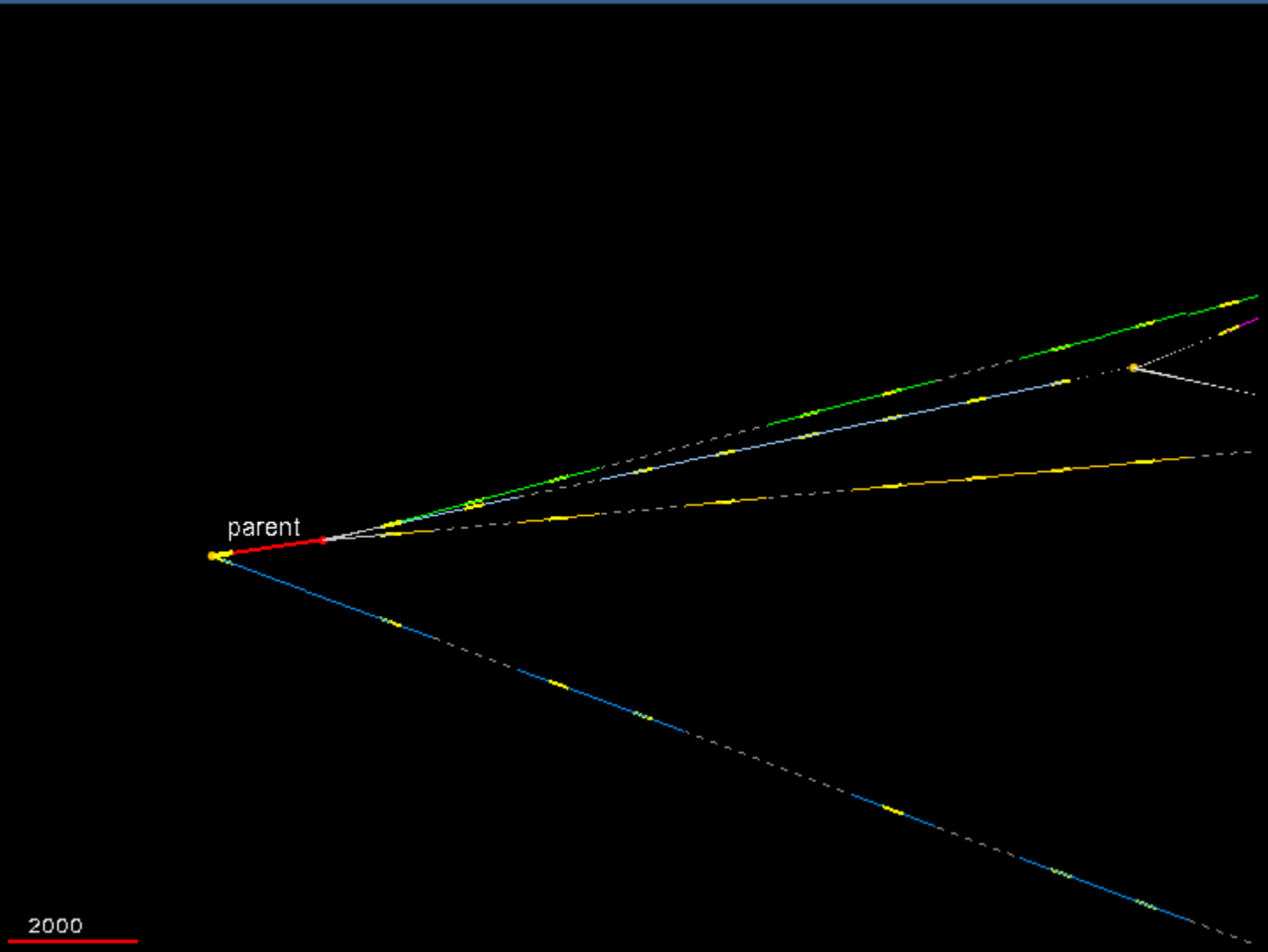
~ 23600 ν_μ CC+NC interactions
~ 160 ν_e interactions
~ 115 ν_τ CC interactions
~ 10 identified ν_τ
< 1 background

1st ν_τ candidate

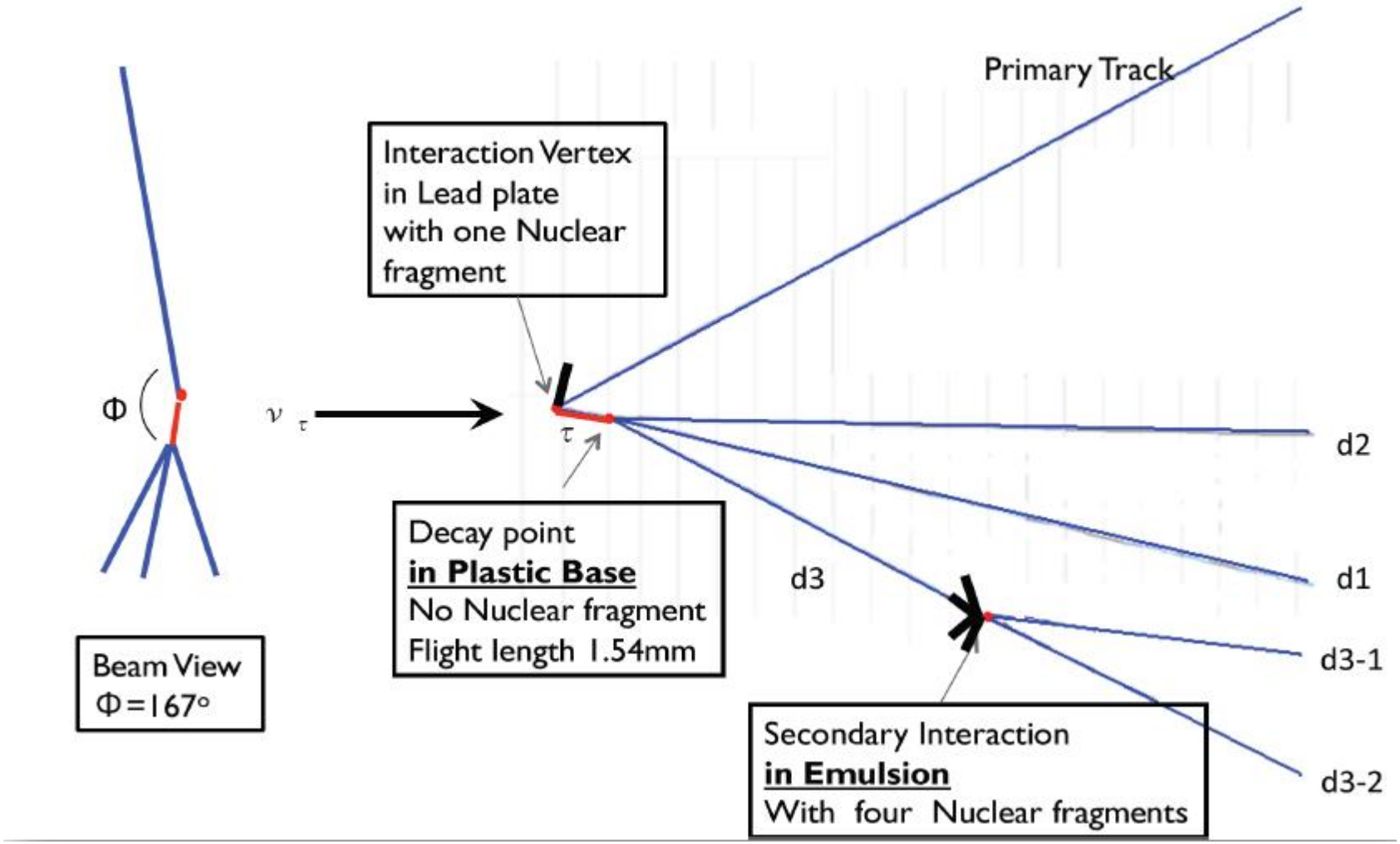


Data sample: 2008-2009 as published in Phys. Lett. B 691 (2010) 138.

2nd ν_τ candidate



2nd ν_τ candidate



Status of Data Taking and Analysis

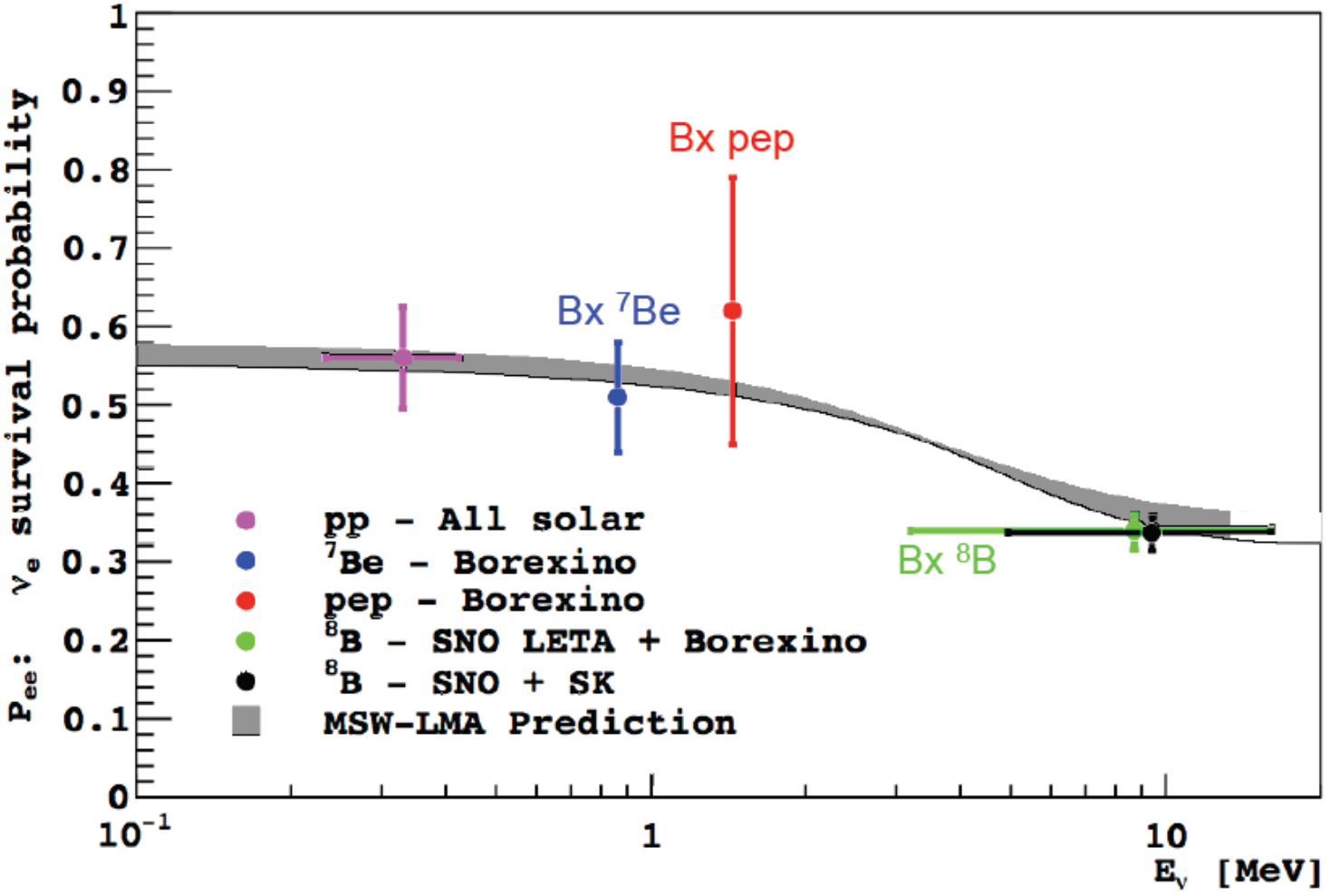
Run	Protons on target	In-targets events	Integrated POT / Proposed value
2008	1.78×10^{19}	1698	7.9 %
2009	3.52×10^{19}	3557	23.6 %
2010	4.04×10^{19}	3912	41.5 %
2011	4.84×10^{19}	4210	63.0 %
2012	(~ 4.3×10^{19})	(~ 3700)	(~ 82%)

Years	Status	Number of analysed events	Expected ν_τ events (Preliminary)	Observed ν_τ Candidate Events	Expected BG (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

Preliminary

Expected: improvement in statistics (analysed events) by factor 3

Transition Matter-Vacuum Oscillations: BOREXINO



Main features of oscillation in matter model confirmed

More data points in transition region needed! (BSM and/or solar physics)

Parametrisation of Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac-phase (CP violating): δ
- (if Majorana: 2 additional phases)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} θ_{13}, δ θ_{12}

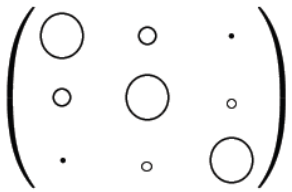
$\theta_{23} \approx 34^o$ (accuracy 5%)

$\theta_{13} \approx 9^o$, **δ?** (accuracy 13%)

$\theta_{12} \approx 45^o$ (accuracy 13%)

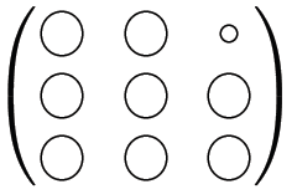
Comparison to Quark Mixing

Quarks::



$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Leptons (PMNS)



Why is this so different?

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.795 \to 0.841 & 0.517 \to 0.584 & 0.141 \to 0.179 \\ 0.213 \to 0.543 & 0.425 \to 0.728 & 0.575 \to 0.802 \\ 0.213 \to 0.541 & 0.411 \to 0.720 & 0.576 \to 0.802 \end{pmatrix}$$

Gonzalez-Garcia ICHEP2012

Goal: Measure PMNS matrix with same precision as CKM matrix

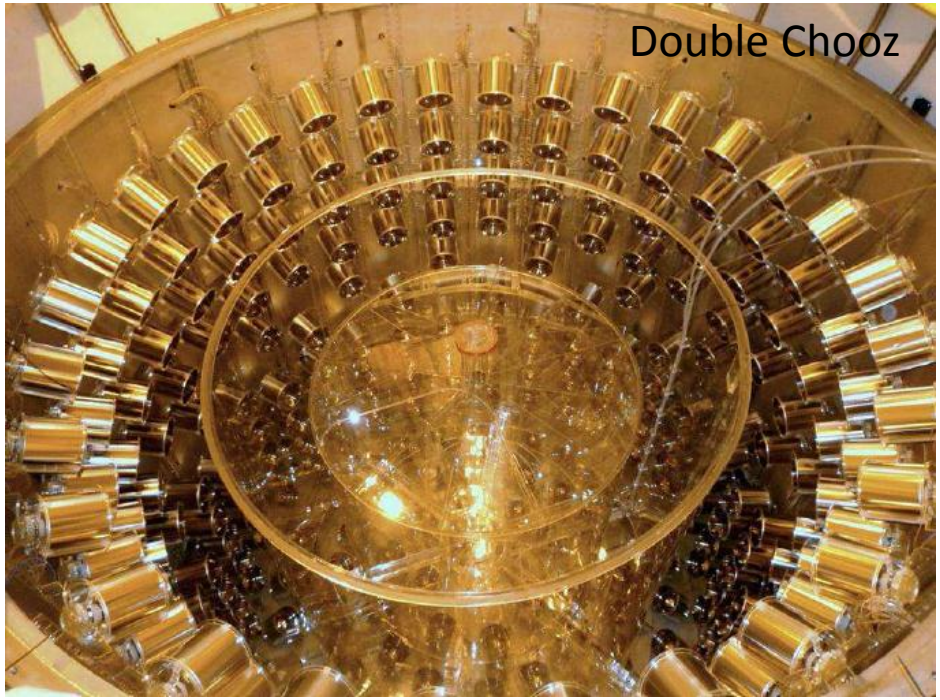
The θ_{13} Revolution

CBS comedy “The Big Bang Theory”

How to measure θ_{13} with reactor neutrinos

Search for **disappearance of anti electron neutrinos** from nuclear reactors

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2\left(1.267 \frac{\Delta m^2_{atm}(\text{in eV}^2) \cdot L(\text{in m})}{E(\text{in MeV})}\right)$$



Detect anti-neutrinos with Gd loaded scintillator

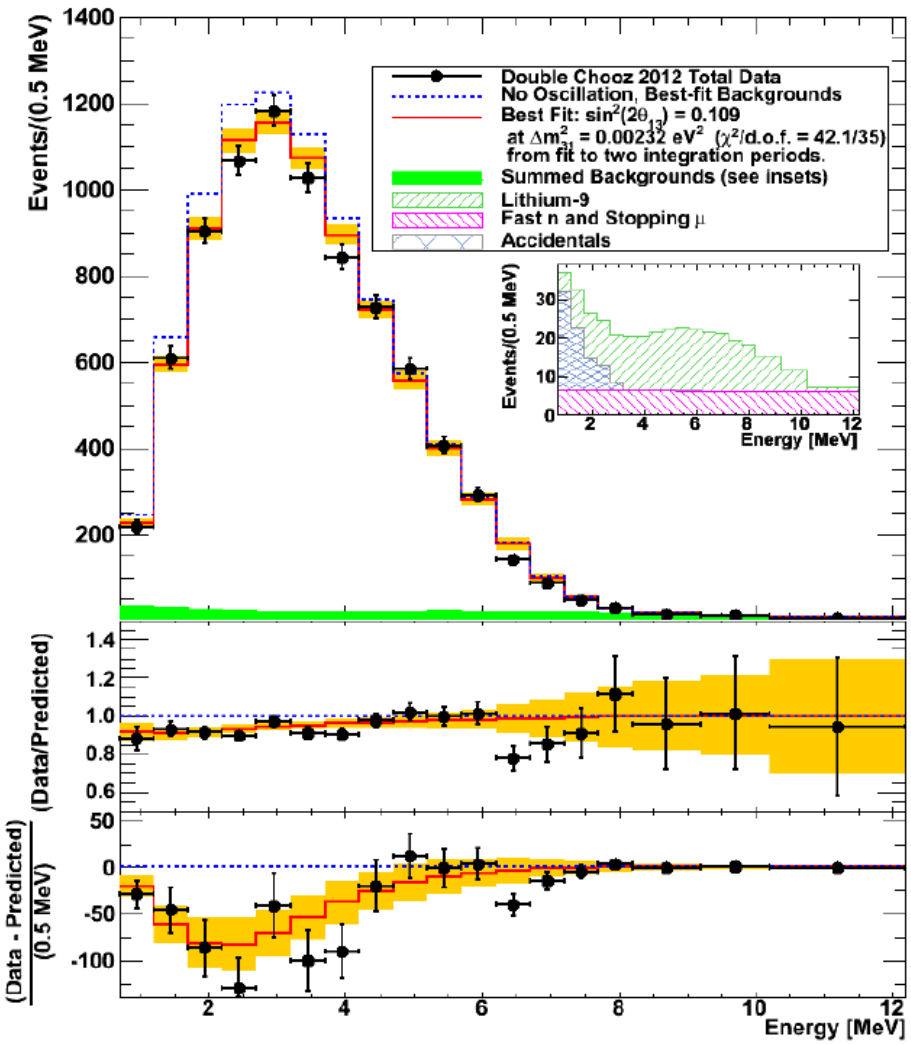
Compare Neutrino Rates at „Near“ Detector (100m) and „Far“ Detector (1km)

Several Experiments running:

- Double Chooz (France)
- Daya Bay (China)
- RENO (South Korea)

Double Chooz experiment

Double Chooz Result



Double Chooz Prompt Spectrum

Data w/ Stat. Error Bars

Best Fit Prediction

(w/ Syst. Errors)

Null Oscillation Prediction

Backgrounds

Improvement with Near Detector in 2014

Double Chooz Coll.,
"Reactor anti ν_e Disappearance in the Double Chooz experiment",
arXiv:1207.6632v2 (14 Aug 2012),
accepted by PRD

Rate & Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

The Daya Bay Experiment

Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

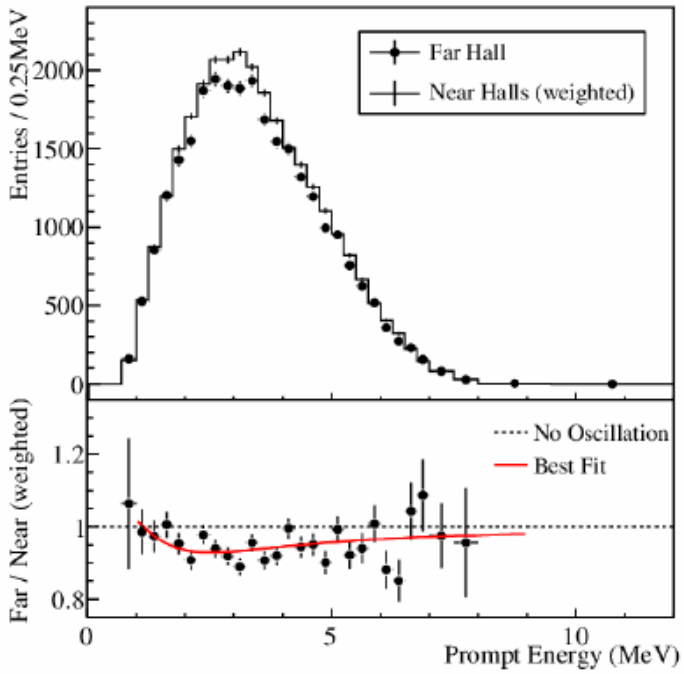
6 commercial reactor cores with 17.4 GW_{th} total power.

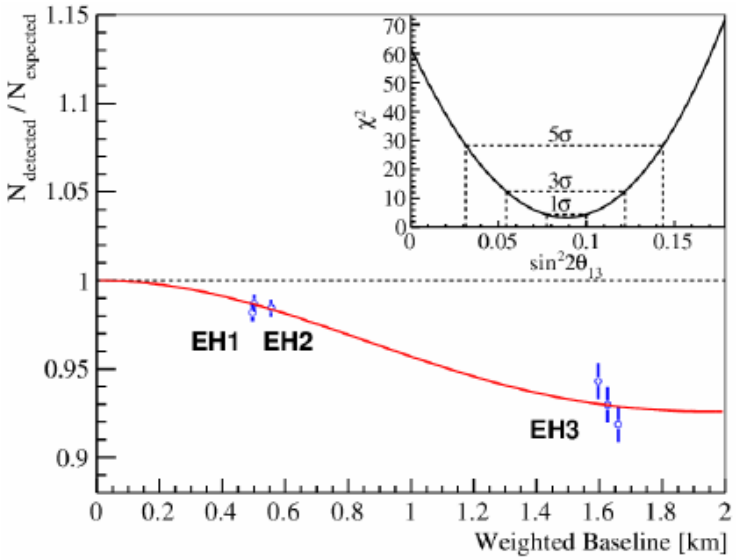
6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.

Daya Bay Latest Update

Improved results



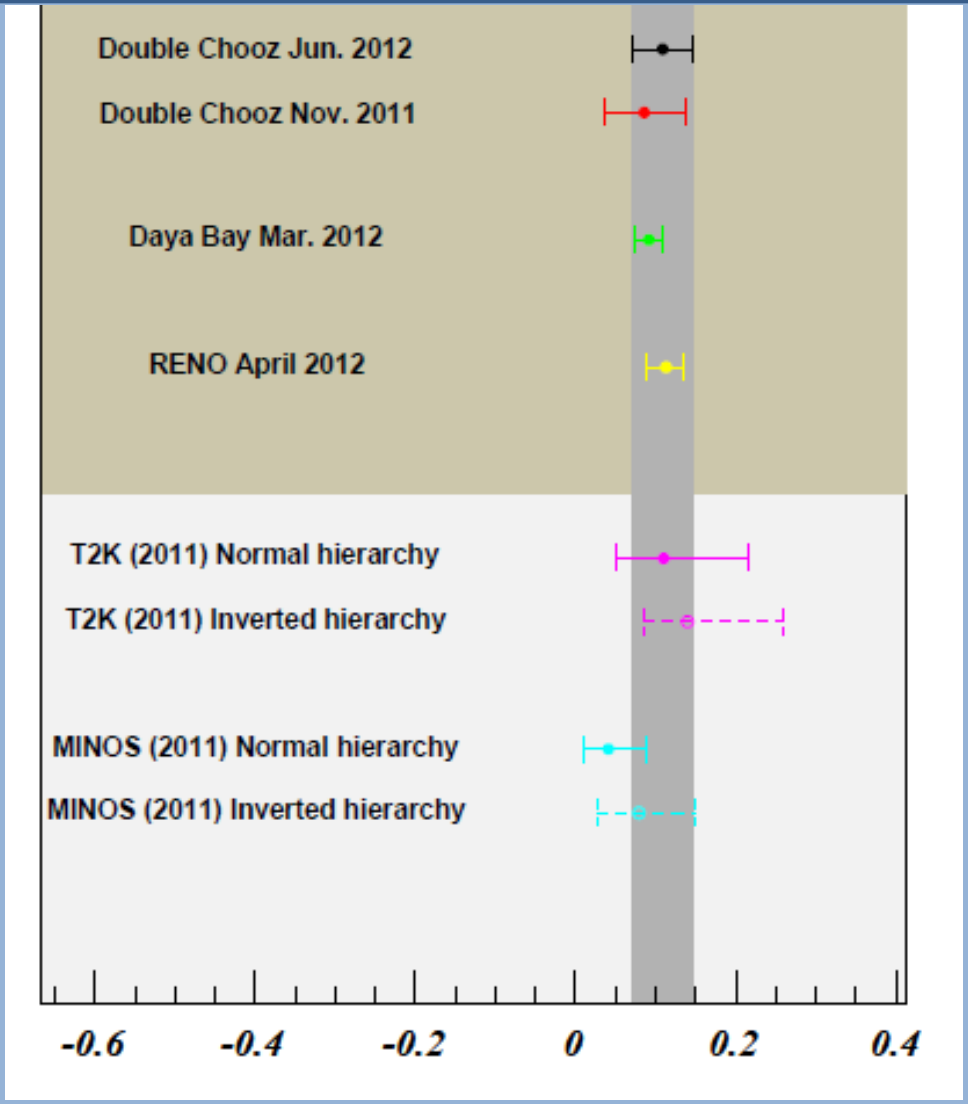


- $R = 0.944 \pm 0.007\ (stat) \pm 0.003\ (syst)$
- $\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat) \pm 0.005(syst)$

- **With 2.5x more statistics, an improved measurement to θ_{13}**

Xiaonan Li at NOW2012 (September)
to be submitted to Chinese Physics C

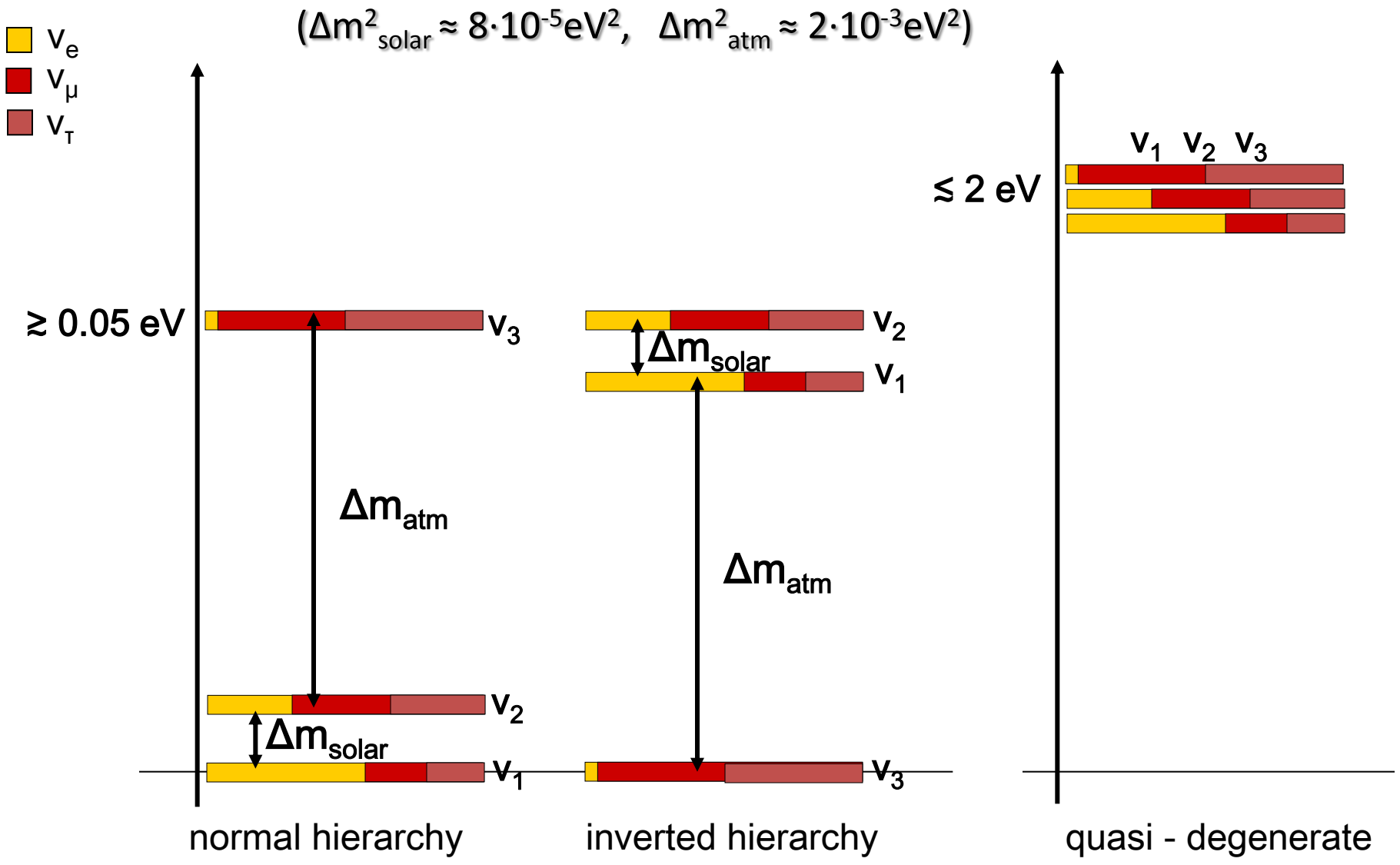
Overview θ_{13}



Open Questions for Neutrino Oscillations

- What is the mass hierarchy?
- What is the value of the CP phase?
- Are there “sterile” neutrinos?
- (Are there non-standard interactions?)

What is the Mass Hierarchy?



How to measure MH and δ_{CP} with Longbaseline

Search for **appearance of electron neutrinos** in a beam of muon neutrinos

The Oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is approximately given by:

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \approx\ & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\
& \mp\alpha\frac{\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha\frac{\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)
\end{aligned}
$$

for anti-ν → $\mp$

with:

$$\alpha = \Delta m^2_{21} / \Delta m^2_{31} << 1$$

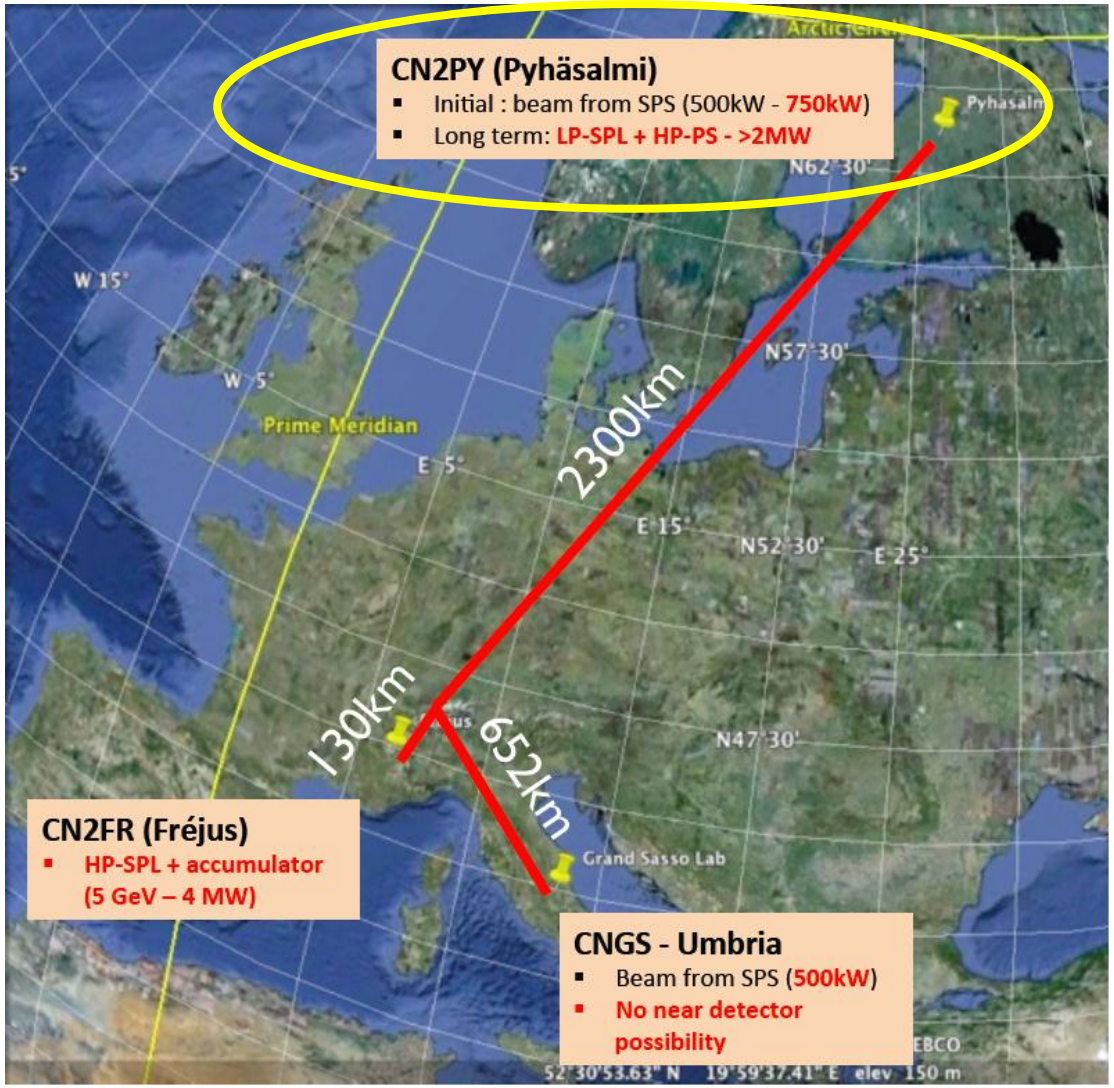
$$\Delta = \Delta m^2_{31} L / 4E$$

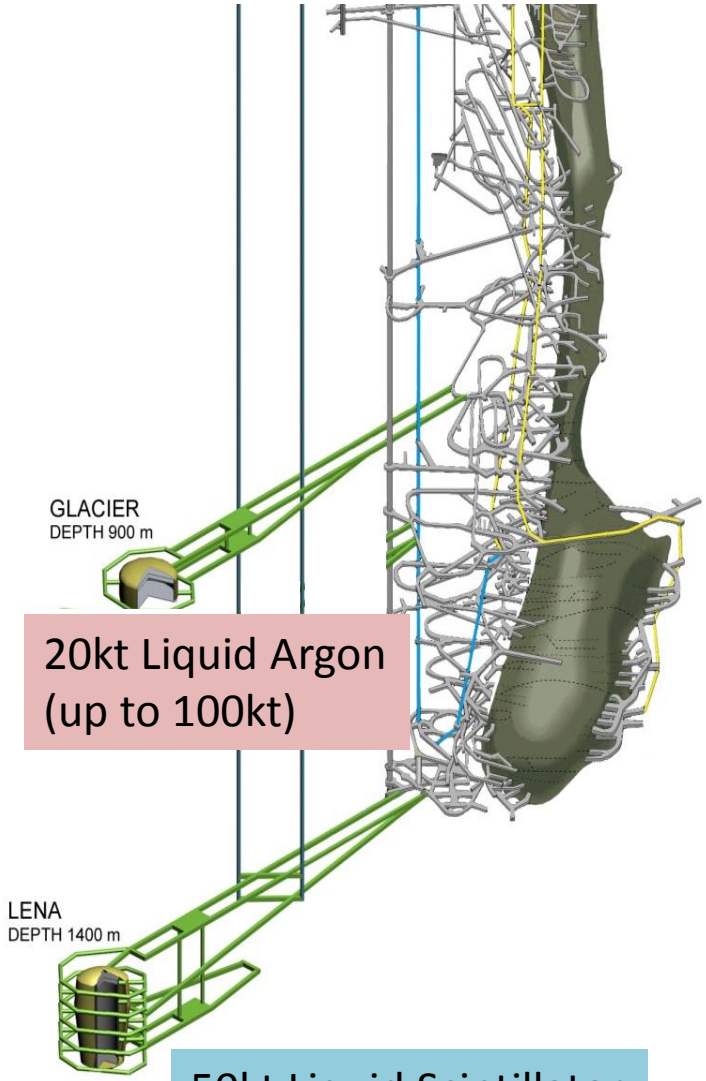
matter dependent quantities:

$$\hat{A} = 2VE / \Delta m^2_{31}$$

$V = \sqrt{2} G_F n_e$, with electron density n_e (assumed constant)

LAGUNA-LBNO Design Study FP7 (2011-2014)





DESY - Pyhäsalmi (1500km), Protvino – Pyhäsalmi (1100km)

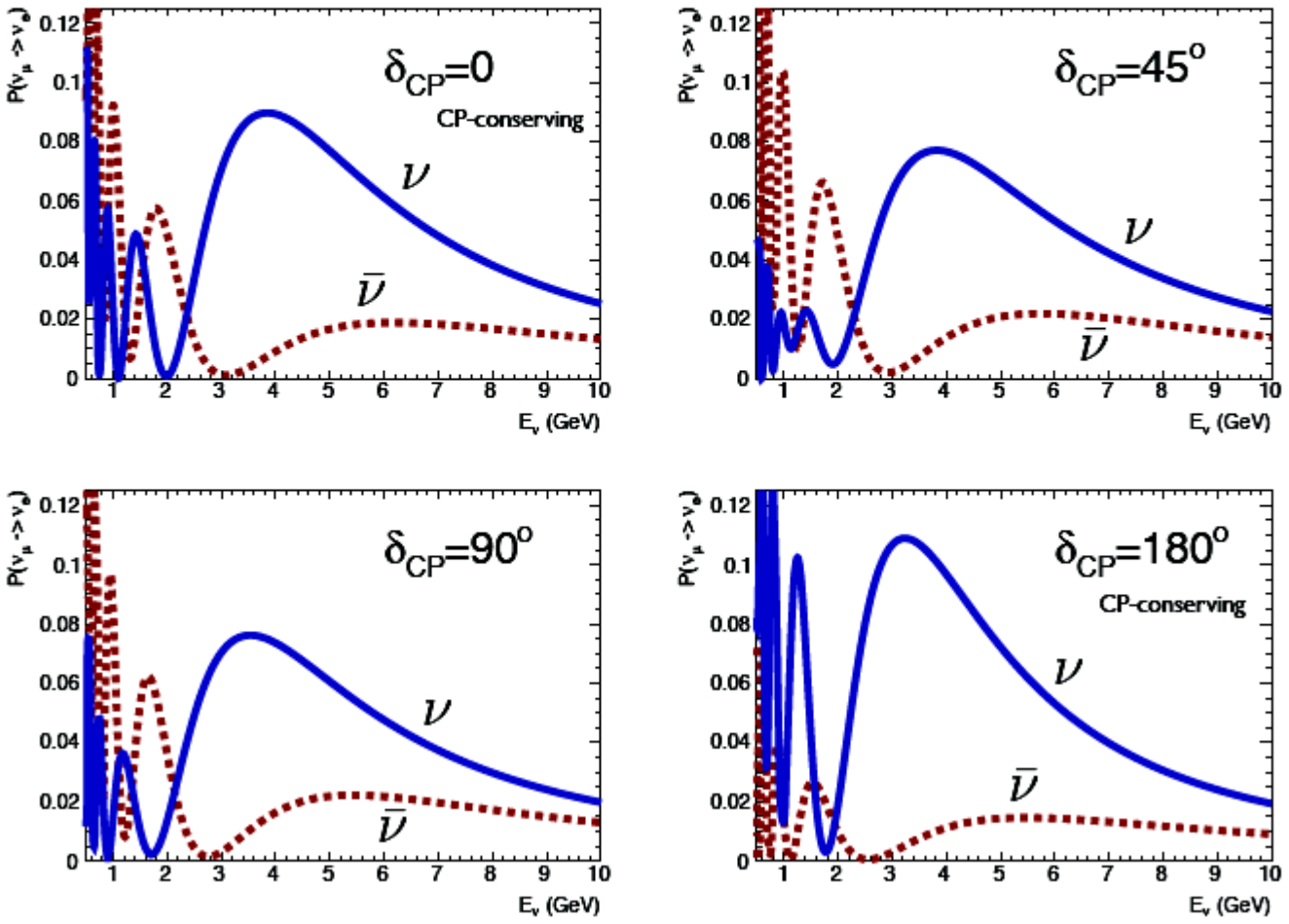
LAGUNA-LBNO

CERN-Pyhäsalmi: oscillations

★Normal mass hierarchy

L=2300 km

$\sin^2(2\theta_{13}) = 0.09$



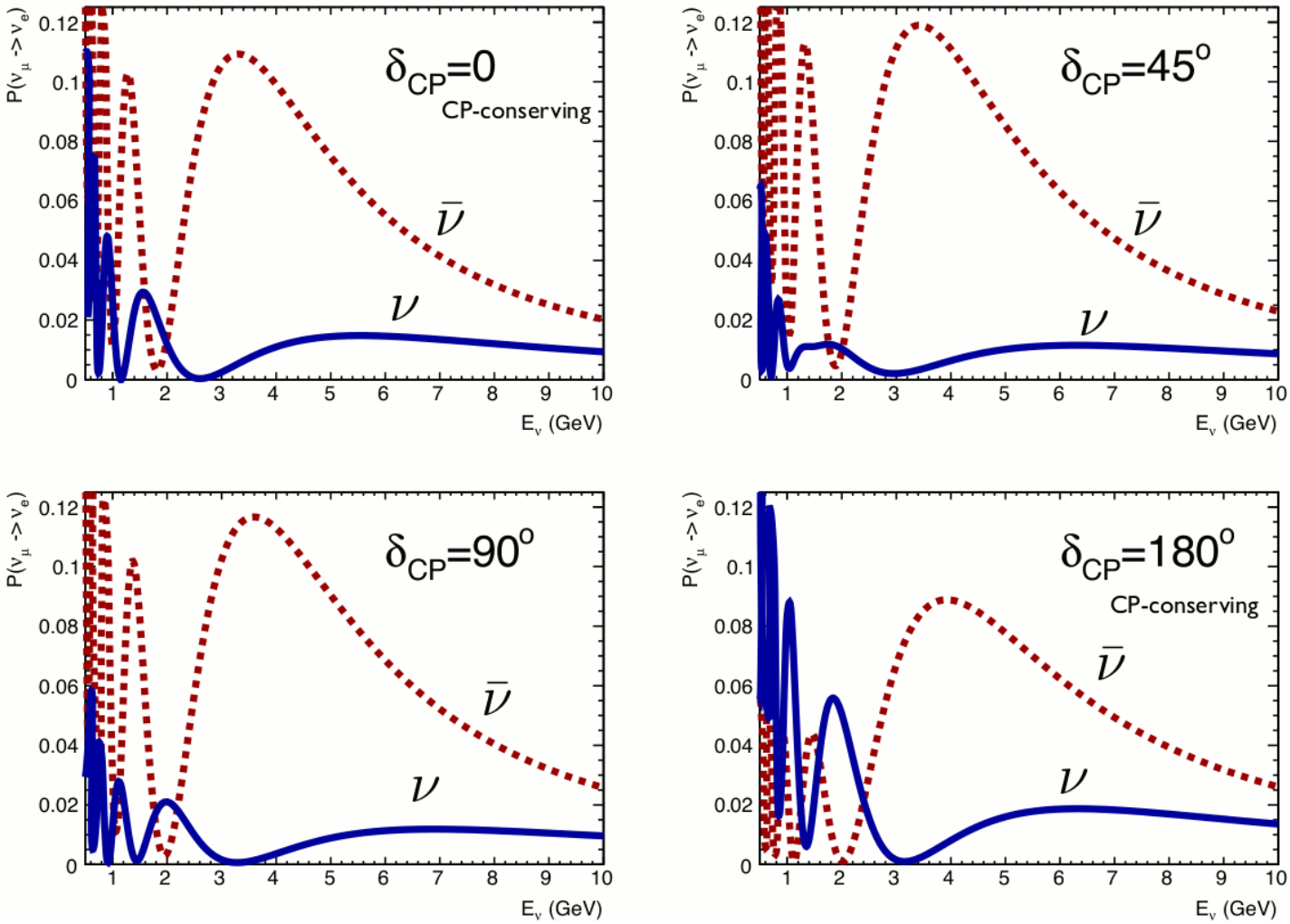
DiLudovico NNN2012

LAGUNA-LBNO

★Inverted mass hierarchy

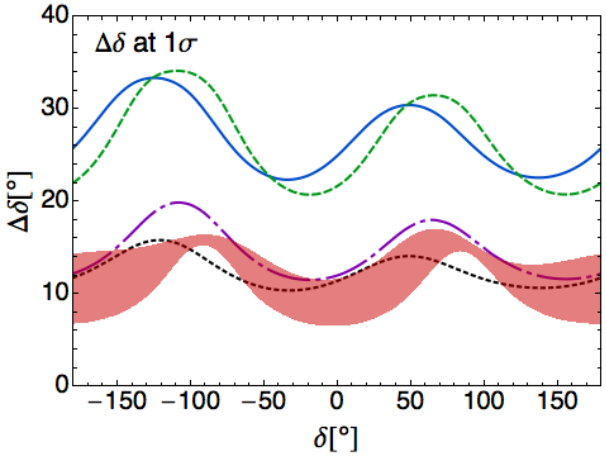
L=2300 km

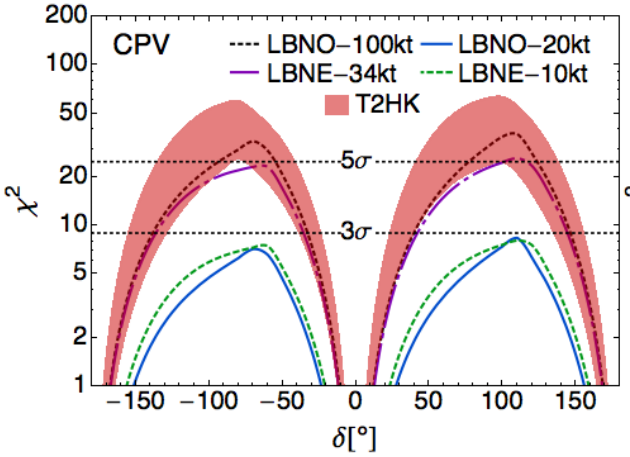
$\sin^2(2\theta_{13}) = 0.09$

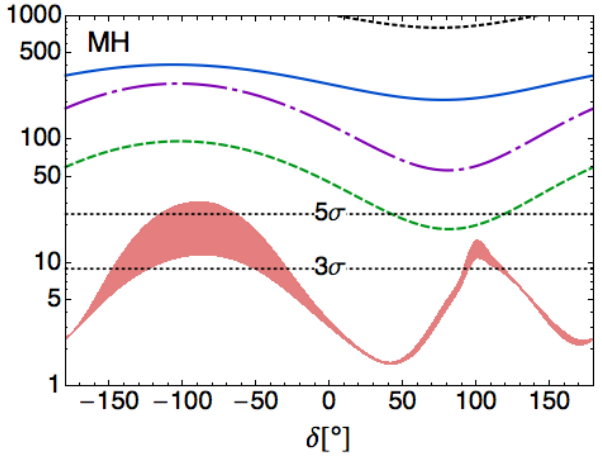


Longbaseline with Superbeams: δ, CPV, MH

Timescale: 20 years from now







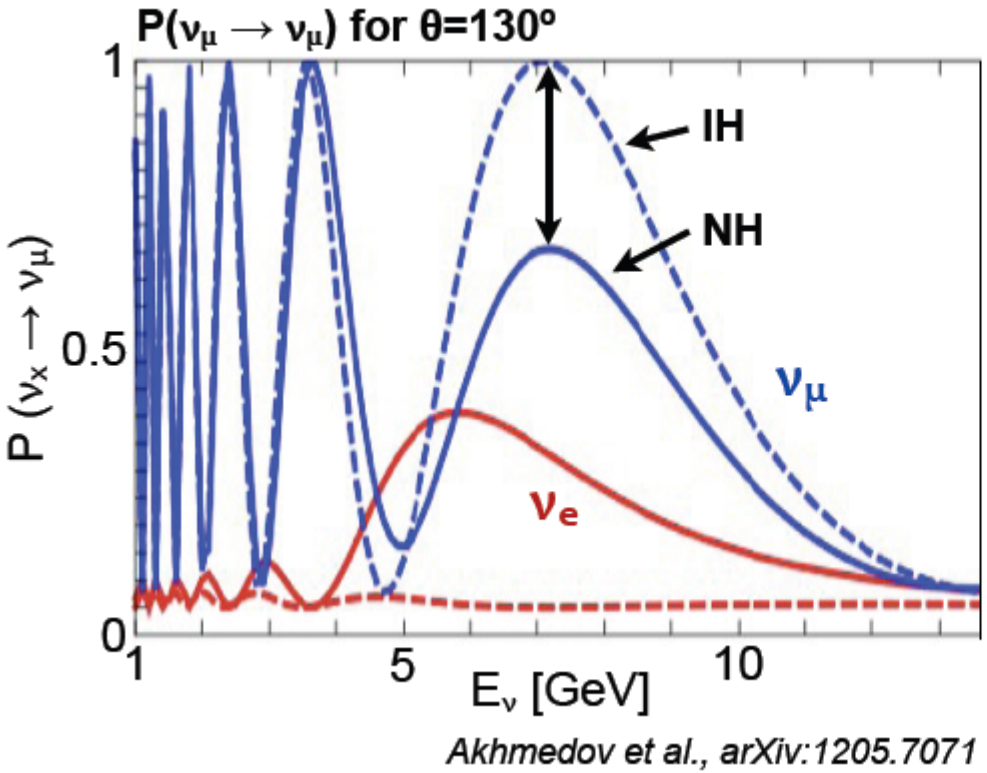
from talk of P. Hernandez at ESPP2012
systematics as in Coloma, Huber, Kopp, Winter (to appear)

Potential to measure Mass Hierarchy with 5σ : very high
Potential to measure CPV with > 3σ: very challenging

Mass Hierarchy with Atmospheric Neutrinos

ORCA PINGU

PINGU (example):
add 20 lines with 60 optical modules each
to IceCube and DeepCore



- Maximum effect NH ↔ IH for θ=130° at 7 GeV
- For $\bar{\nu}$ NH and IH approximately swapped
  → effect cancels if detected N(ν) = N($\bar{\nu}$)
- Fortunately, flux(ν_{atm}) ≈ 1.3 × flux($\bar{\nu}_{atm}$)
  and xsec(ν) ≈ 2 × xsec($\bar{\nu}$)

⟹ Count $N_\mu(E,\theta)$ from $\nu_\mu + N \rightarrow \mu + X$
and compare with NH / IH predictions

slide from A. Kappes
(Astroteilchen, Zeuthen, Sept2012)

Detailed studies ongoing

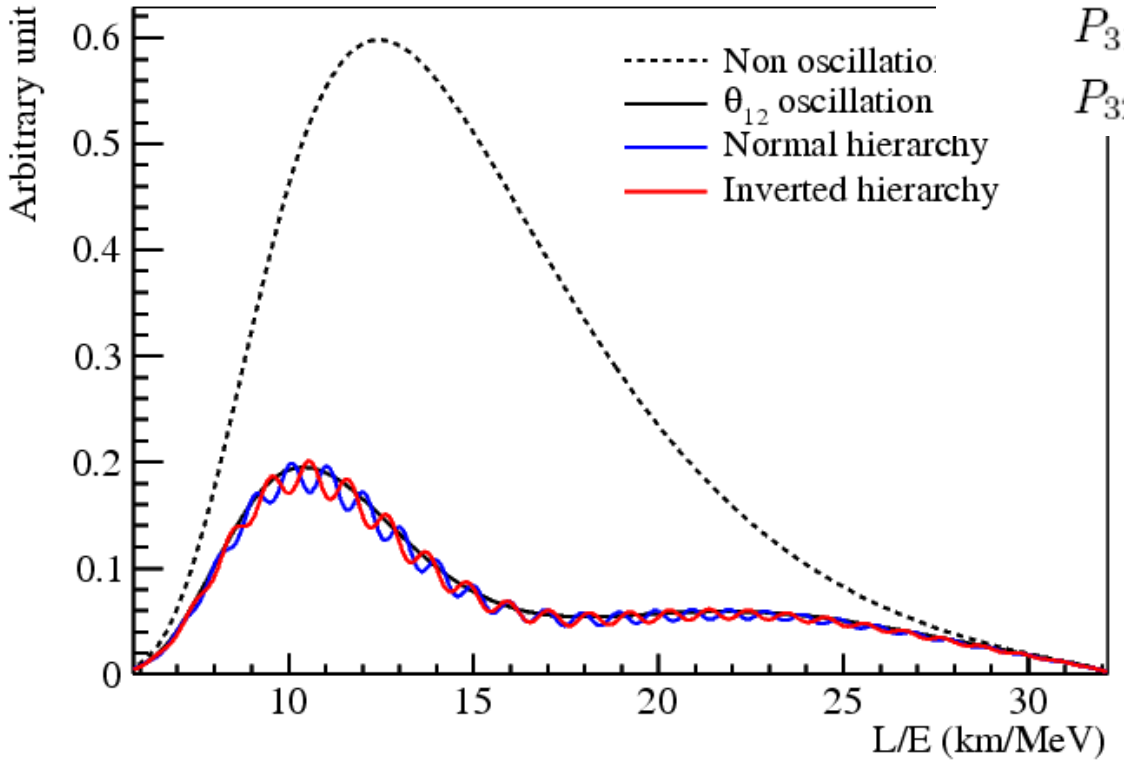
Other alternative Method for Mass Hierarchy (with Reactor Experiments)

S.T. Petcov et al. PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008 PRD79:073007, 2009

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \text{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32}) \end{aligned}$$



Daya Bay II
20kt,
baseline should be 45-60km

Extremely challenging for 20kt:
Energy resolution 3%/√E

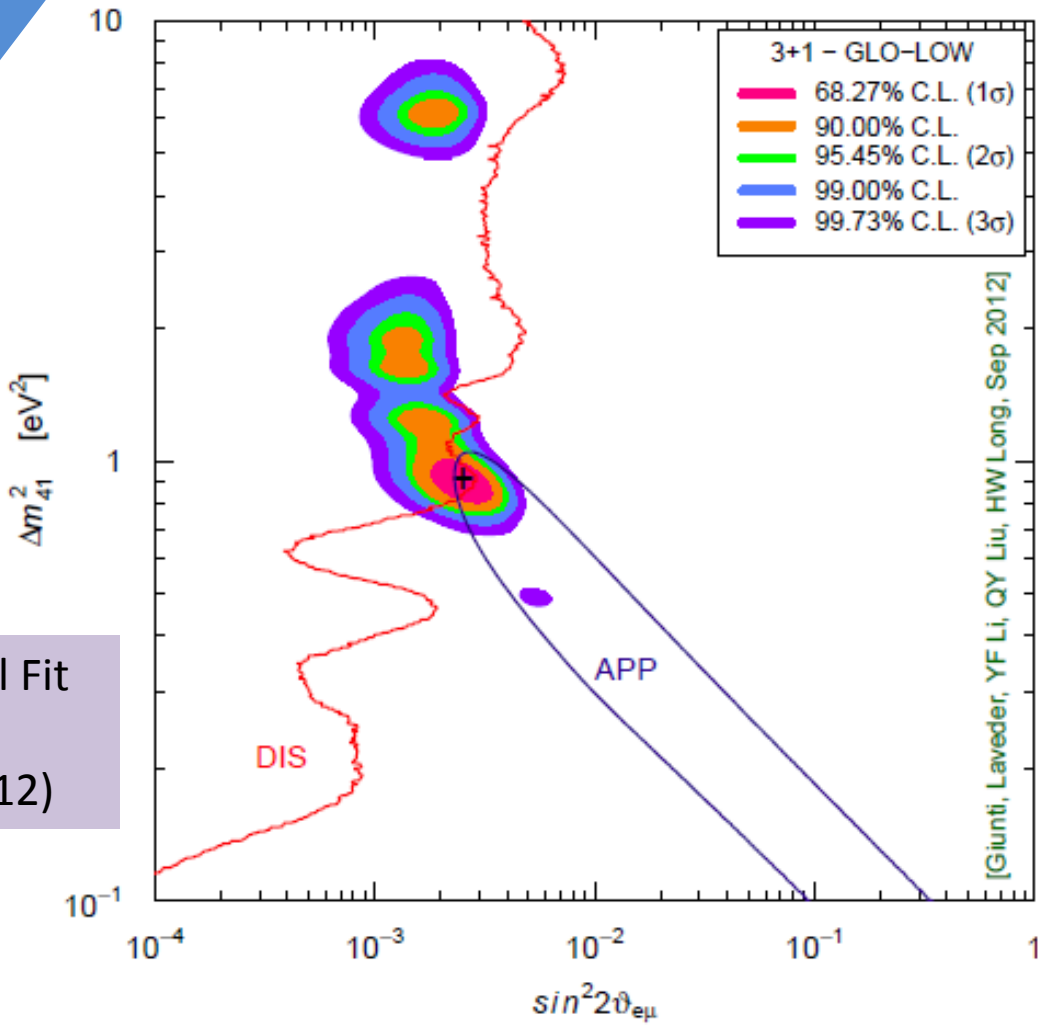
Neutrino Anomalies

LSND
MiniBooNE
Reactor Neutrino Anomaly
Gallium Anomaly

Sterile Neutrinos with mass scale 1eV ?

Need New Experiments !

Example of Global Fit in 3+1 Scheme (C.Giunti NOW2012)

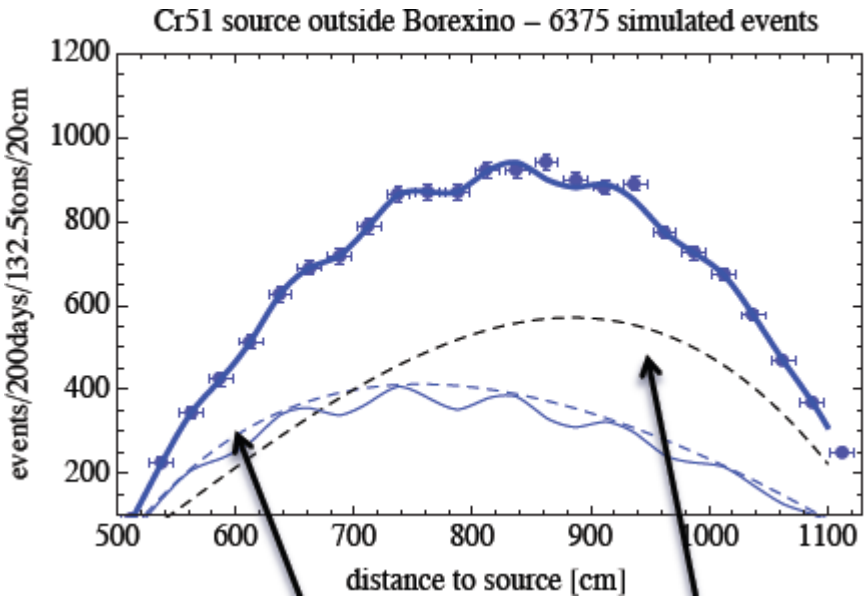


Many Shortbaseline ν_e Experiments proposed

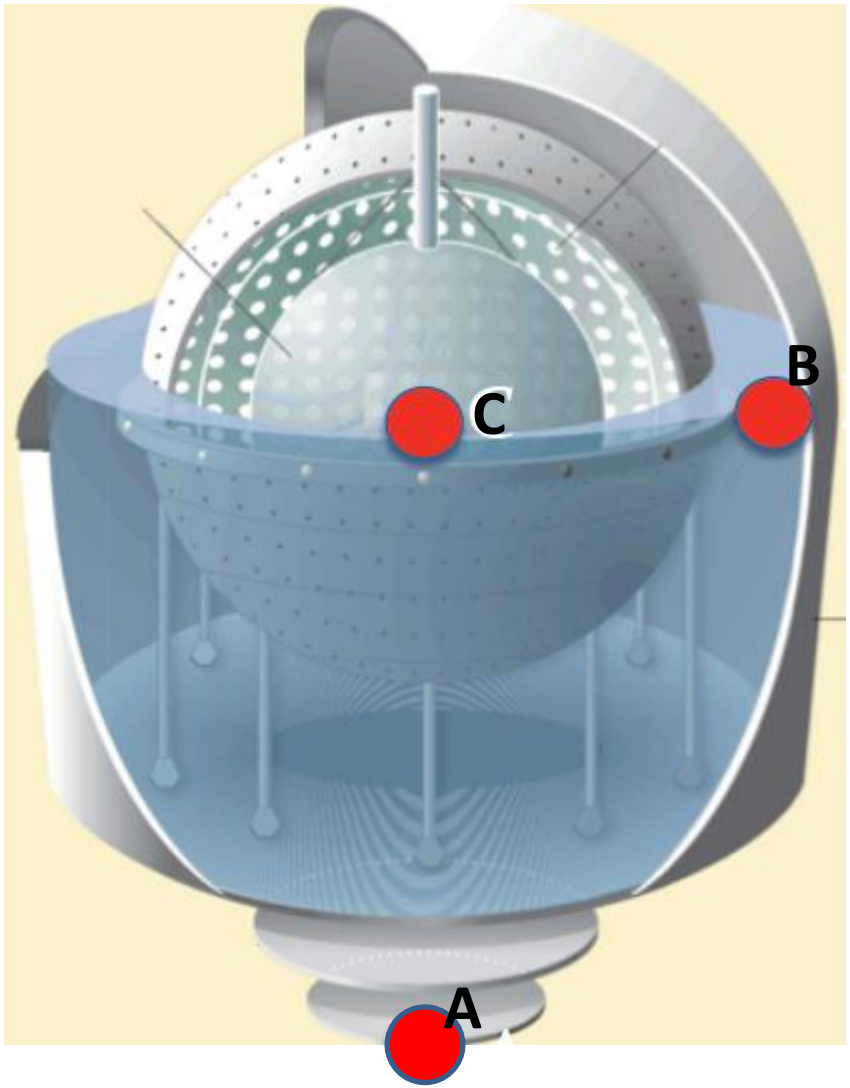
One Example: ^{51}Cr Source in Borexino

e-capture (Eγ=0.32MeV 10%),
$T_{1/2}$ = 40 days,
185 PBq

$(\Delta m^2, \sin^2 2\theta_{SBL}) = (2eV^2, 0.15)$, Source at A



Signal without oscillation background



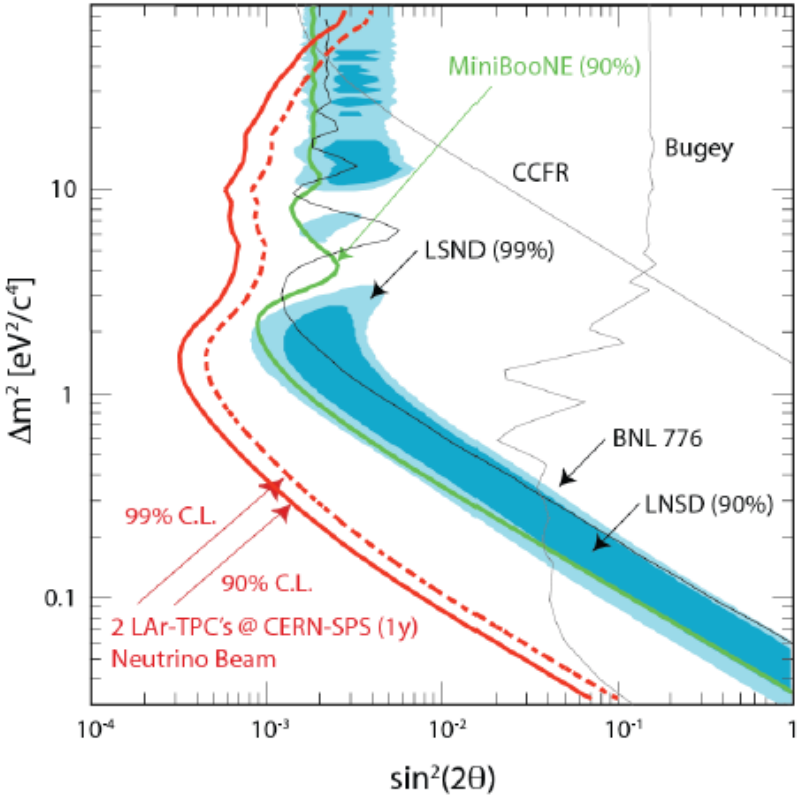
A. Ianni NOW2012

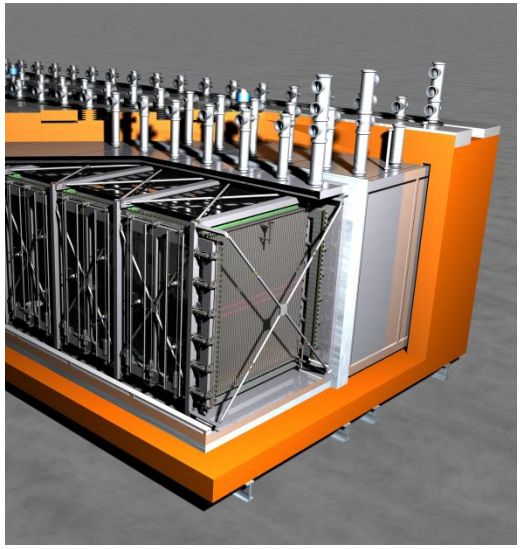
Proposal for ν_μ Shortbaseline at CERN

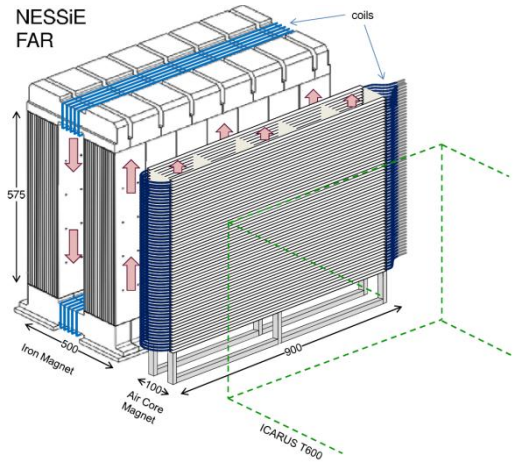
"Search for "anomalies" from neutrino and anti-neutrino oscillations at $\Delta m^2 \approx 1eV^2$ with muon spectrometers and large LAr–TPC imaging detectors."

Technical proposal (CERN-SPSC-2012-010 and SPSC-P-347) by ICARUS & NESSIE Collaborations

CERN v-beam E_p=100GeV → Near Detector (330m): Liquid Argon (Icarus) 150t → Far Detector (1600m): Liquid Argon (Icarus) 600t → NESSIE: Magnetic Spectrometer

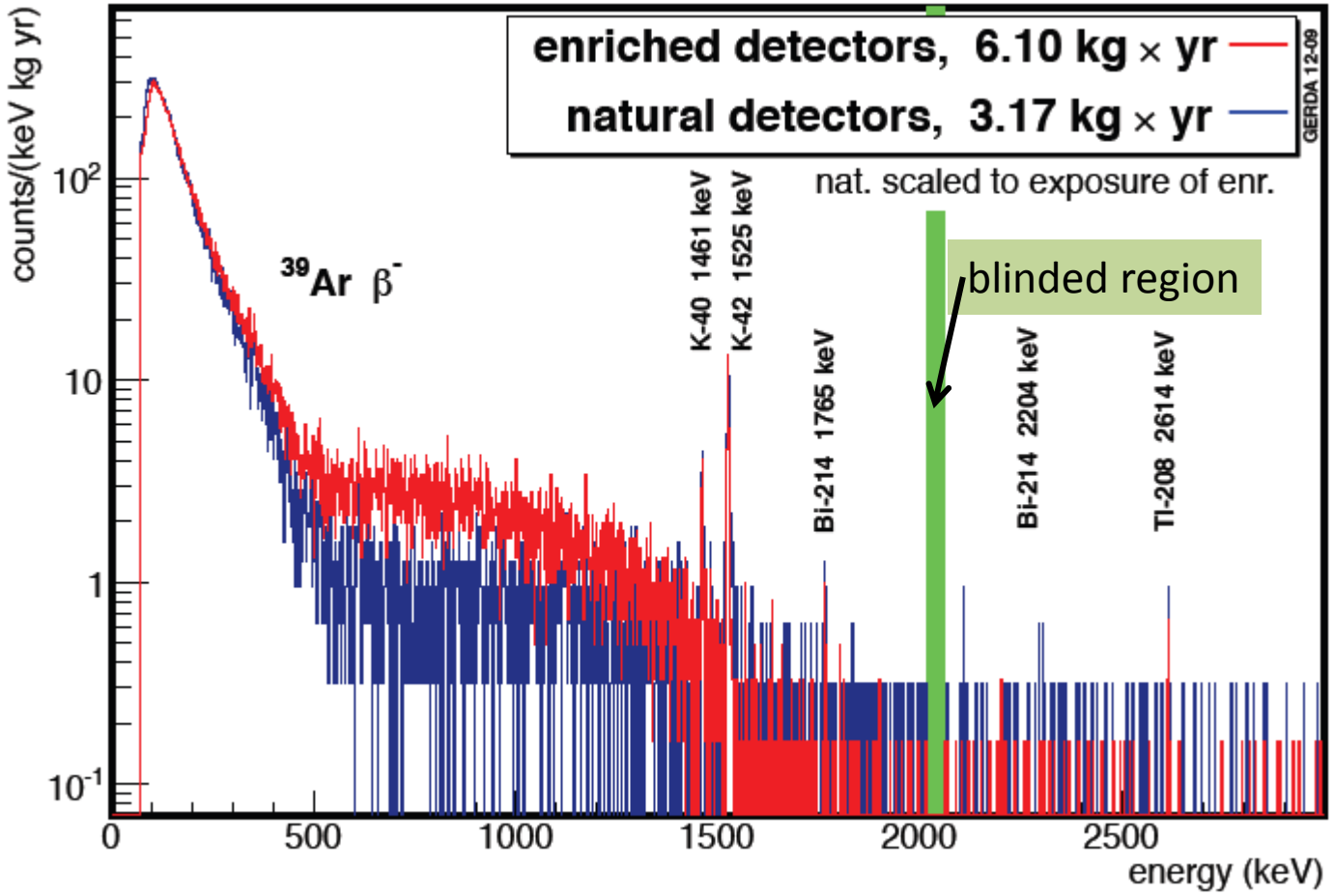






Double Beta Decay

GERDA is taking data, has acquired 10kg x years of data (Sept2012),
expect completion phase I in spring 2013, → unblind data & analysis.
Enough data to test Heidelberg/Moscow claim.



Summary

- Standard picture of neutrino oscillations is confirmed
- 2 mass differences and 3 angles measured
  $\theta_{13} = 9^o$!
- Next:
  mass hierarchy and CP ciolation
  (longbaseline … or atmospheric/reactor)
  Neutrino Factory best for CP phase
- 20-100kton detectors for Astrophysics/Geophysics/Proton-Decay possible
- Many experiments to clarify anomalies planned
- Next Generation of Double Beta Experiments is taking data