FUTURE NEUTRINO FACILITIES

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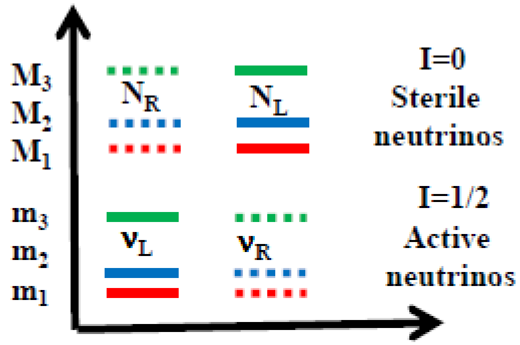
Why future neutrino facilities ?

Recently an american colleague having measured θ_{13} was talking to hisfunding agency about a future neutrino project and was told:

what more do you want ? dont you know all these angles now?

➔ IMPORTANT TO STATE THE BIG PICTURE:

Neutrinos : the New Physics there is… and a lot of it!

SM	Dirac mass term only	Majorana mass term only	Dirac AND Majorana Mass terms
ν_L $\bar{\nu}_R$ I= ½ ½	ν_L ν_R $\bar{\nu}_R$ $\bar{\nu}_L$ ½ 0 ½ 0	ν_L ‘ $\bar{\nu}_R$ ‘ ½ ½	
X 3 Families	X 3 Families	X 3 Families	
6 massless states **wrong**	3 masses 12 states 3 active neutrinos 3 active antinu’s **6 sterile neutrinos…** 3 mixing angles 1 CP violating phase **$0\nu\beta\beta = 0$**	3 masses 6 active states **No steriles** 3 mixing angles 3 CP violating phases **$0\nu\beta\beta \neq 0$**	6 masses 12 states 6 active states **6 sterile neutrinos…** More mixing angles and CPV phases **$0\nu\beta\beta \neq 0$** → Leptogenesis and Dark matter

Mass hierarchies are all unknown except $m_1 < m_2$

Preferred scenario has both Dirac and Majorana terms …

… many physics possibilities and experimental challenges

Any of the following would be a fundamental breakthrough or discovery:

Q.1 Determination of the absolute mass scale of neutrinos.

Q.2 Determination of the mass hierarchy of the active neutrinos.

Q.3 CP violation in neutrino oscillations.

Q.4 Violation of unitarity of the neutrino mixing matrix.

Q.5 Observation of fermion number violation by neutrinoless double beta decay.

Q.6 Discovery of effects implying unambiguously the existence of sterile neutrino(s)

Where do we stand?

Present situation of neutrino mixing:

1. **We know that there are three families of active, light neutrinos**

   (LEP-1989)

2. **Solar neutrino oscillations are established**

   (Homestake+Gallium+Kamland+SK+SNO-1968-2002)

3. **Atmospheric neutrino (ν_μ –> …) oscillations are established**

   (IMB+Kam+Macro+Sudan+SK) (1986-1998)

3. **At the atmospheric frequency, electron neutrino oscillations are smaller** *(CHOOZ)* **but not that small** *(T2K, MINOS, DoubleChooz, Daya Bay, Reno 2011-2012)*

This allows a consistent picture with 3-family oscillations preferred:

$\theta_{12} \sim 30^0$ $\Delta m_{12}^2 \sim 8\ 10^{-5} eV^2$, $\theta_{23} \sim 45^0$, $\Delta m_{23}^2 \sim \pm 2.5\ 10^{-3} eV^2$, $\theta_{13} = 9^0$

5. **There is indication of possible higher frequency oscillations**

   (LSND, miniBooNE, reactor, source anomaly) (1993-2011)

   This is not consistent with three families of active neutrinos oscillating, and is not supported (nor is it completely contradicted) by other experiments.

   This could be a series of unconvincing results with poor experimental methods…

   or a sign of the existence of light sterile neutrino(s)?

***)to set the scale: CP violation in quarks was discovered in 1964 and there is still an important program (K0pi0, B-factories, Neutron EDM, BTeV, LHCb..) to go on for 10 years…(superB etc…) i.e. a total of ~60 yrs.**

and we have not discovered leptonic CP yet!

Бруно Понтекорво

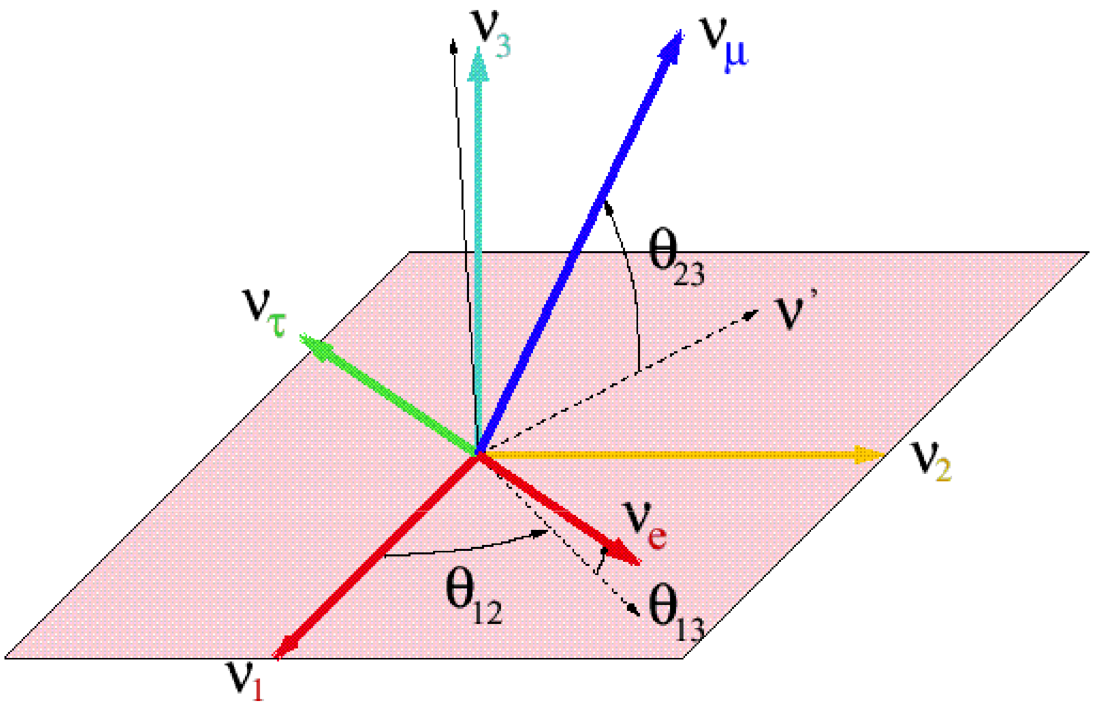
THE NEUTRINO MIXING MATRIX

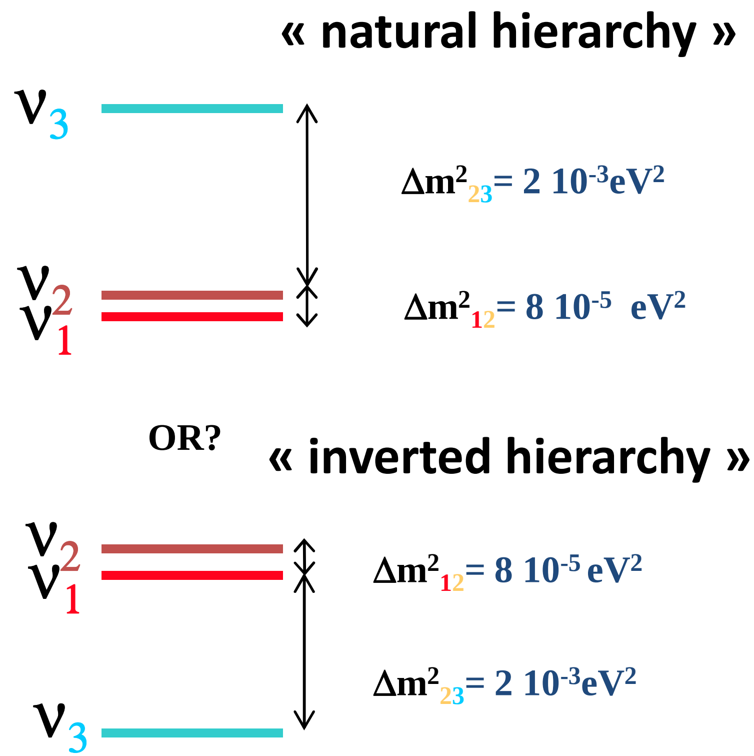
or
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

From Wikipedia, the free encyclopedia:

In particle physics, the **Pontecorvo–Maki–Nakagawa–Sakata matrix** (**PMNS matrix**), **Maki–Nakagawa–Sakata matrix** (**MNS matrix**), **lepton mixing matrix**, or **neutrino mixing matrix**, is a unitary matrix[note 1] which contains information on the mismatch of quantum states of leptons when they propagate freely and when they take part in the weak interactions. It is important in the understanding of neutrino oscillations. This matrix was introduced in 1962 by Ziro Maki, Masami Nakagawa and Shoichi Sakata,[1] to explain the neutrino oscillations predicted by Bruno Pontecorvo.[2][3]

Active neutrino mixing parameters:





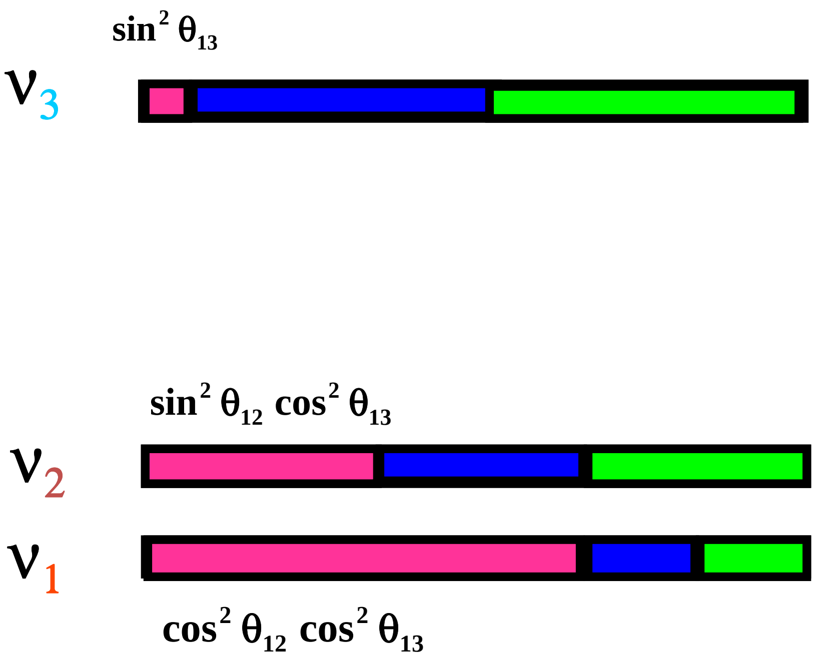
θ_{23} (atmospheric) = 45^0, θ_{12} (solar) = 32^0, θ_{13} = 9^0

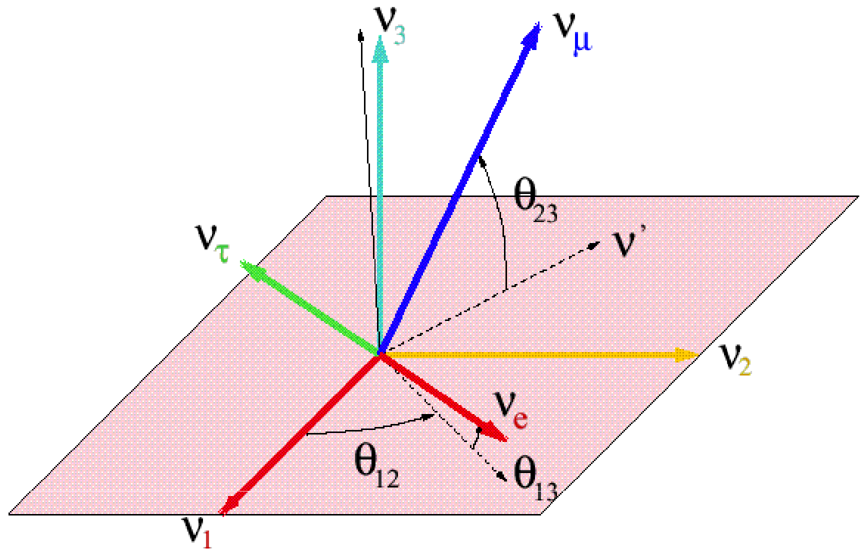
$$U_{PMNS} \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Crucial role played by θ_{13} !
Next: phase δ, sign of Δm^2_{13}

2

neutrino mixing





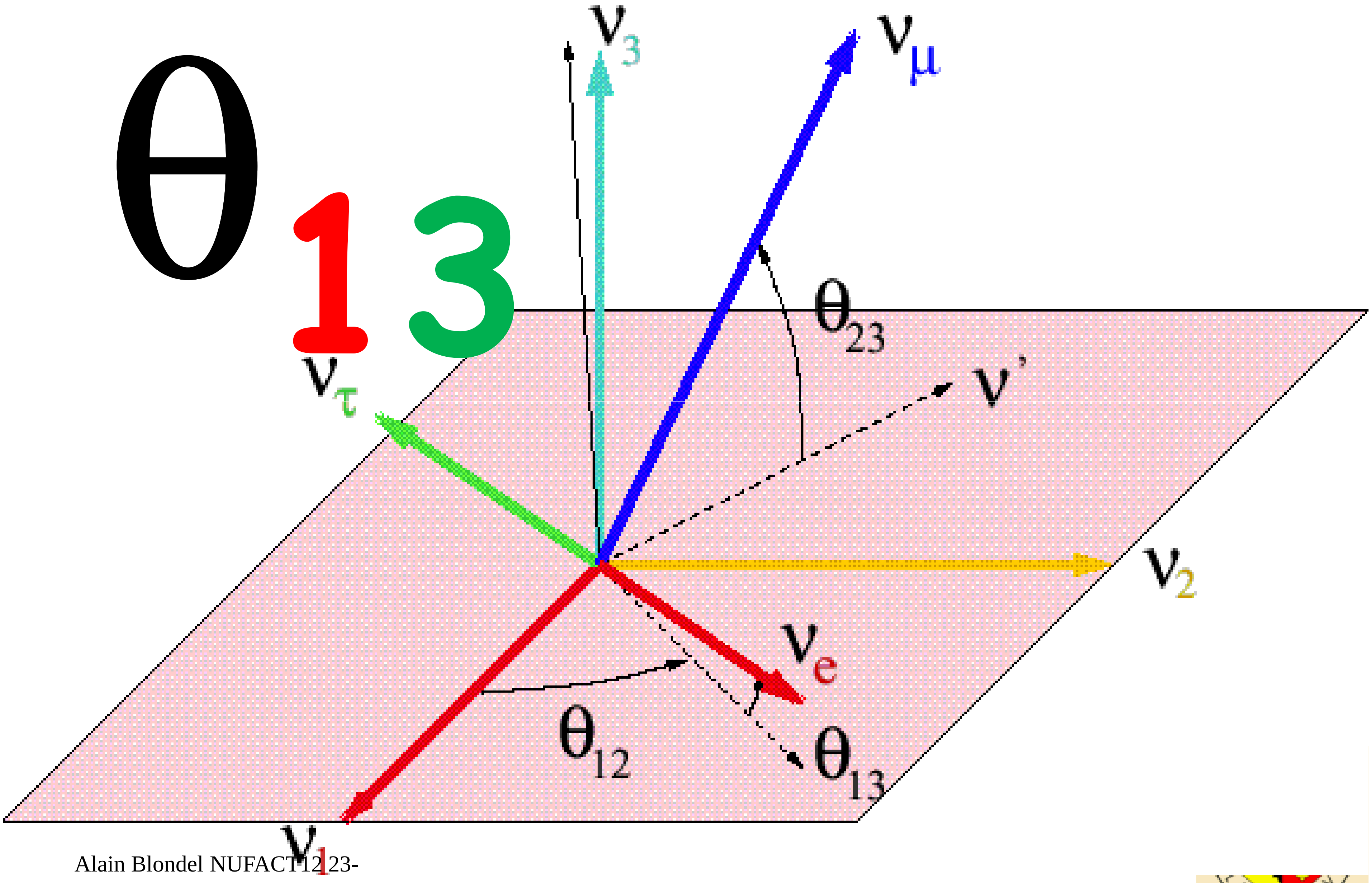
$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

ν_e is a (quantum) mix of

ν_1 (majority, 65%) and ν_2 (minority 30%)

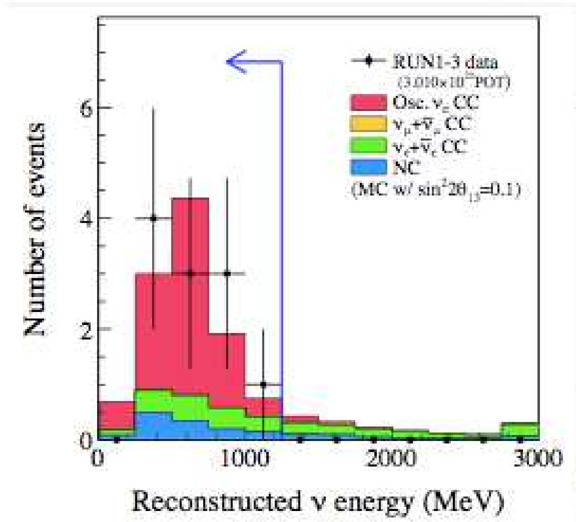
with a small admixture of ν_3 (< 13%) (CHOOZ)

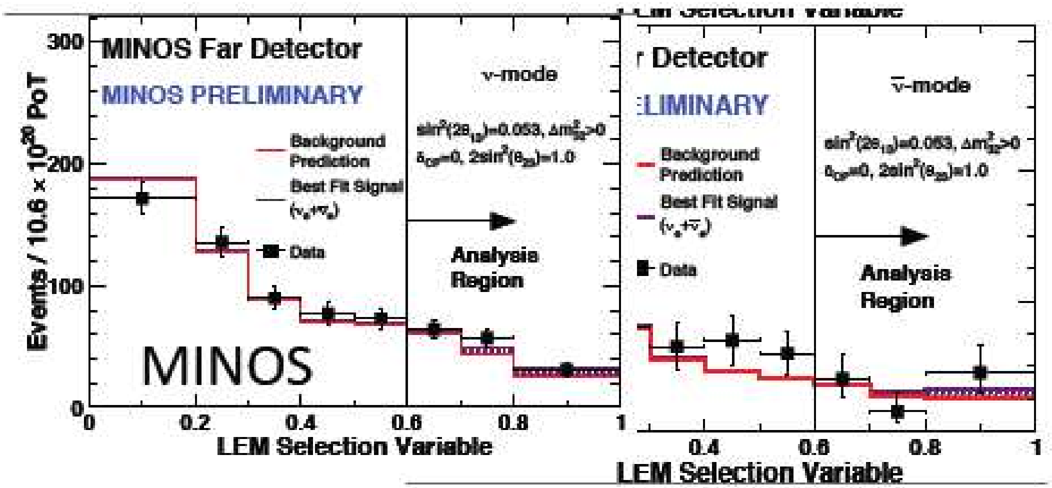
θ13

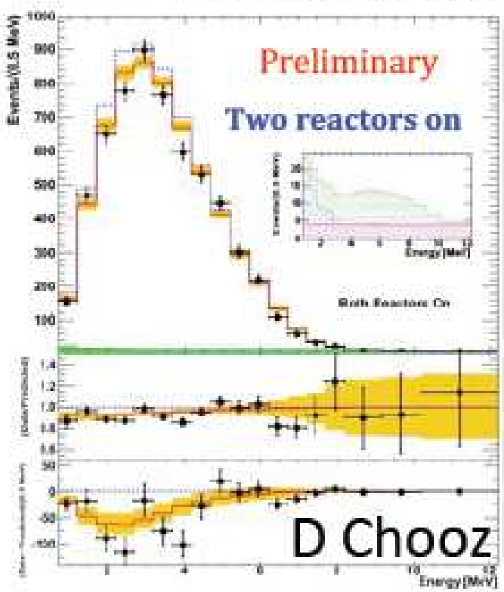


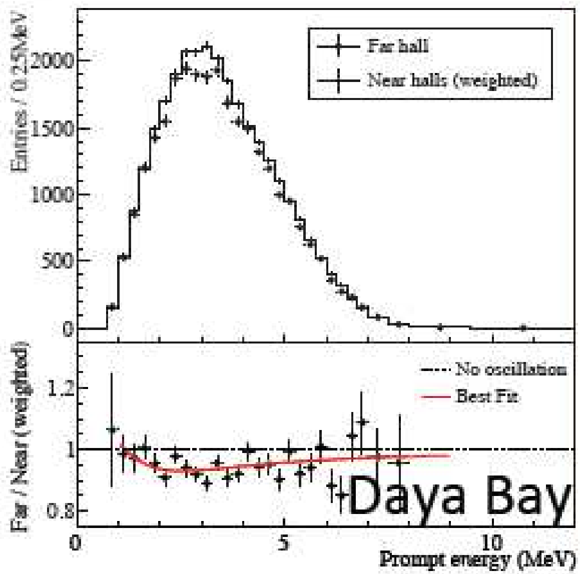
Situation today:

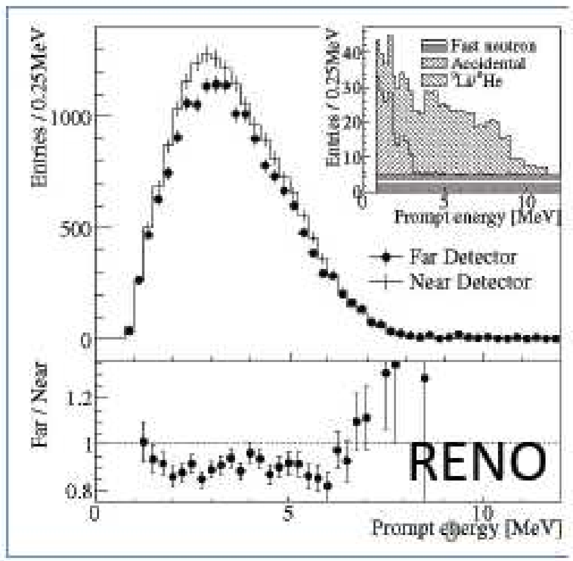
accelerator ν_μ beam ➔ appearance : $\nu_\mu \rightarrow \nu_e$











reactor $\bar{\nu}_e$ disappearance

Reactors

Double Chooz $\sin^2 2\theta_{13} = 0.109 \pm 0.03$ (stat) ± 0.025(sys)

Daya Bay $\sin^2 2\theta_{13} = 0.089 \pm 0.010$(stat) ± 0.005(sys)

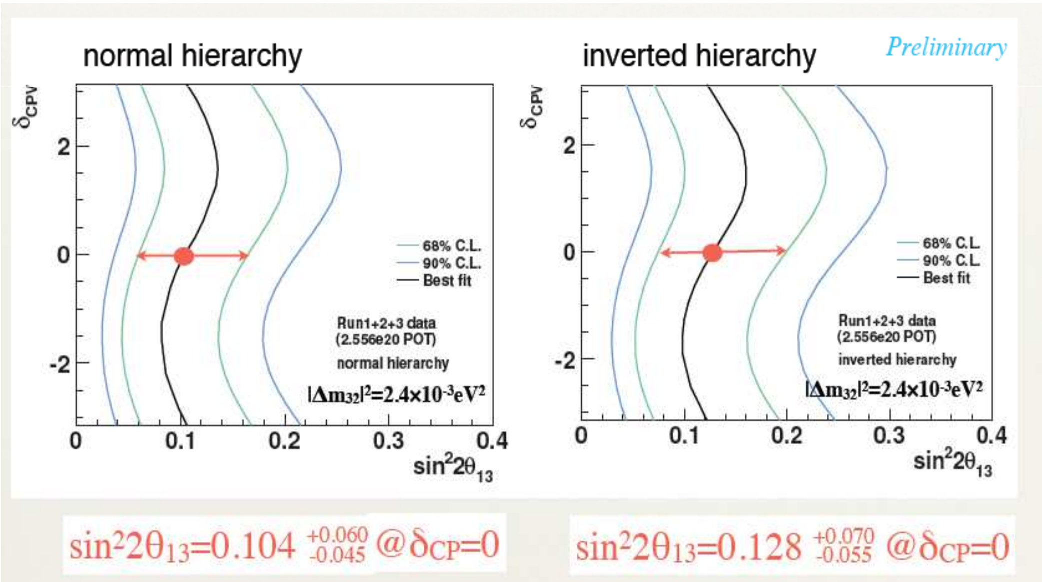
RENO $\sin^2 2\theta_{13} = 0.113 \pm 0.013$(stat) ± 0.019 (sys)

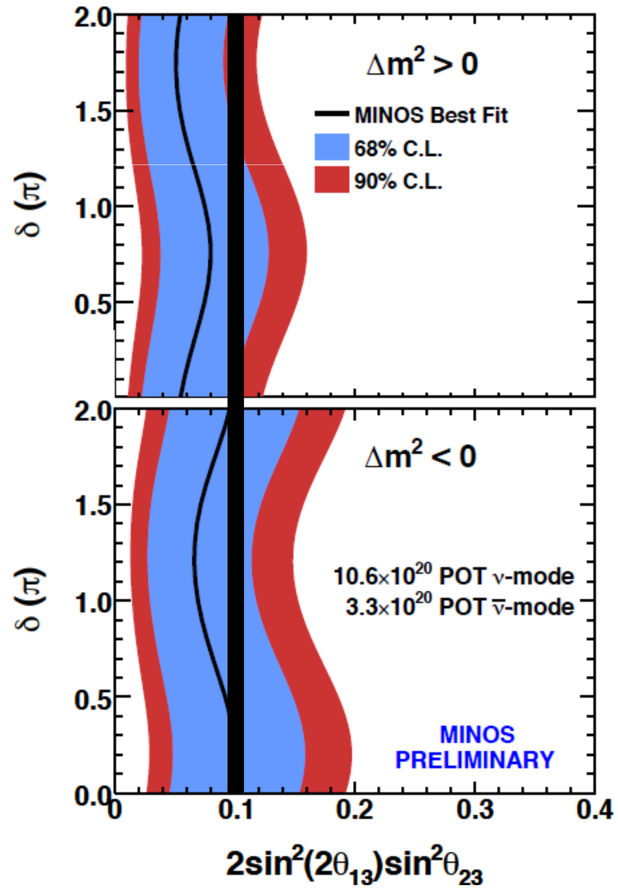
$\sin^2 2\theta_{13} \approx 0.095 \pm 0.011$

I believe that ultimate precision will be ≤ 0.005

MINOS 2012

T2K 2012





MINOS *very* slight preference for $\Delta m^2_{32} < 0$...

Our colleagues of Dchooz had it all right

-- detector concept and design

-- importance of two detectors for cancellation of systematics
(L. Mikaelyan & V. Sinev)

Disappearance and appearance are not the same thing!

-- we don't know into what do $\bar{\nu}_e$ disappear!
(in the 3x3 unitary mixing it's a nearly equal mix of $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$)

-- even in 3x3 mixing the effects are different

appearance

directly measures $\nu_\mu \rightarrow \nu_e$ neutrino transition,
CP violation by interference of atmospheric and solar oscillation
mass hierarchy through matter effects at long distances (level shift)

disappearance

at short distance (1.5km) pure θ_{13}-driven disappearance
mass hierarchy via solar/atmospheric interference around 50km
at very large distances (200km, KAMLAND) θ_{12}-driven disappearance

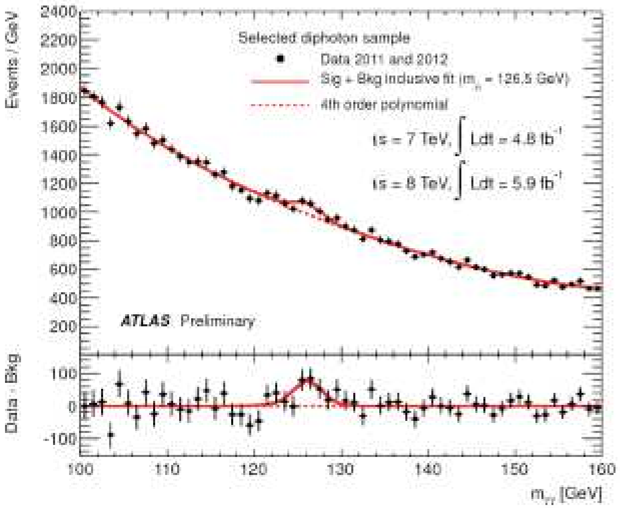
This is the big neutrino news.

We now know all three mixing angles!
and
the interplay of appearance and disappearance experiments will give us access to
sign(Δm^2_{32})
and to CP violation

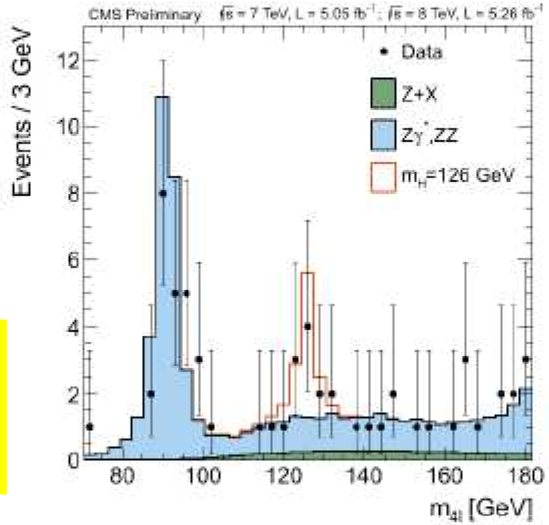
Meanwhile,

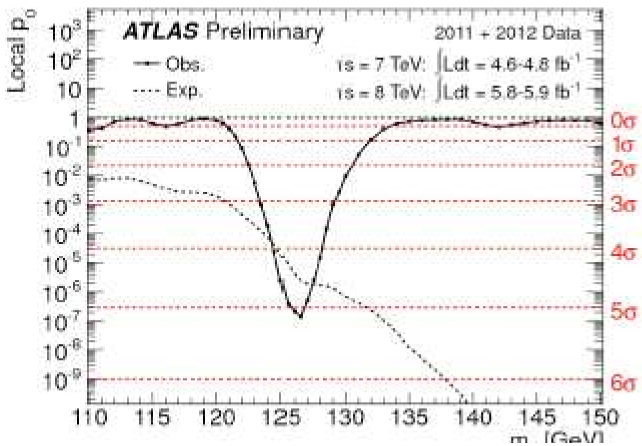
IN ANOTHER WORLD…

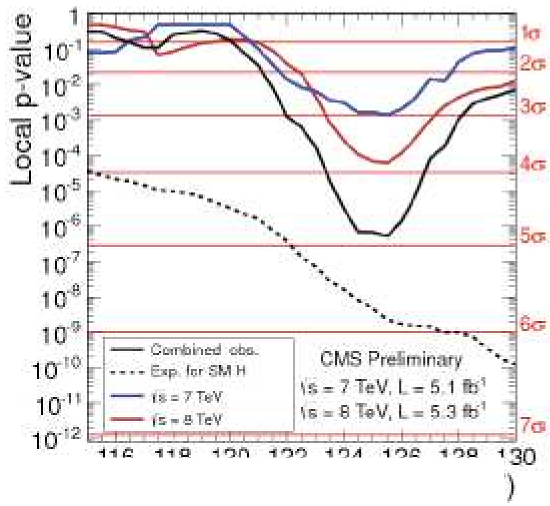
While looking for the SM Higgs boson,
LHC discovered a new boson!



2 expts
5σ each



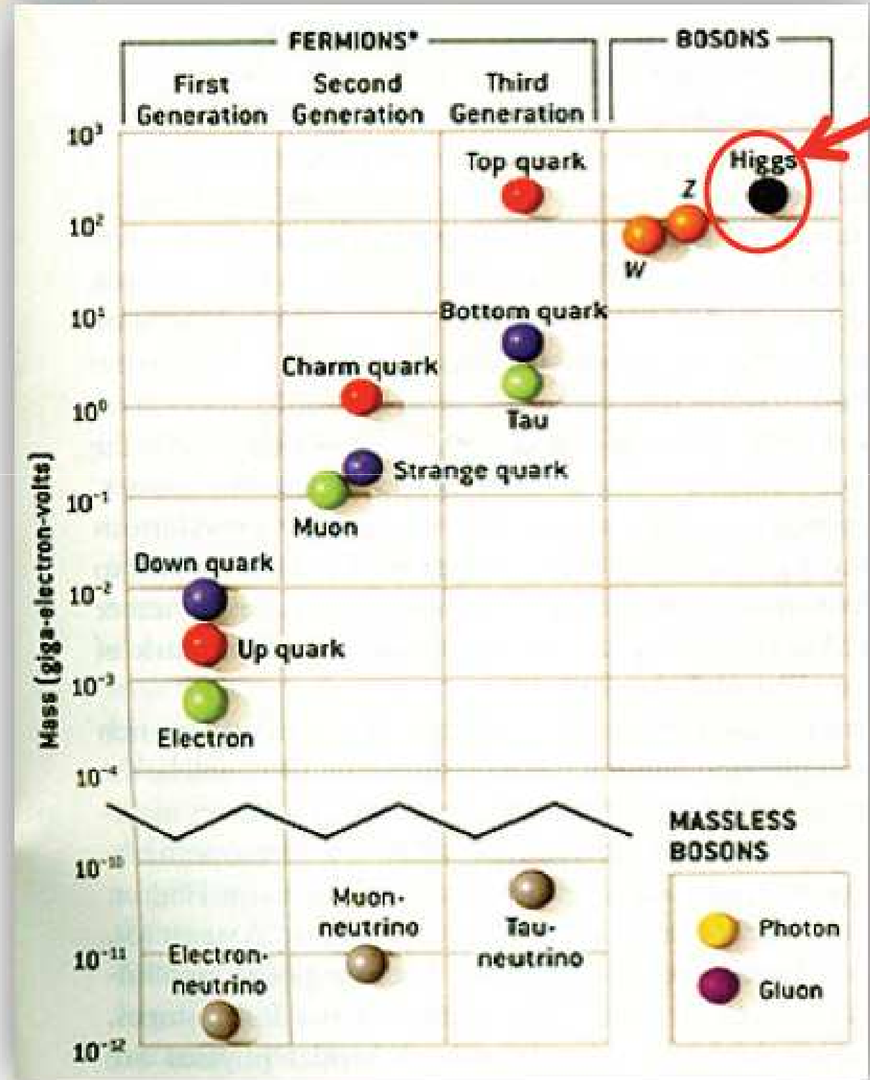




Mass=125.3+-0.4(stat)+-0.5(syst) GeV

The Standard Model

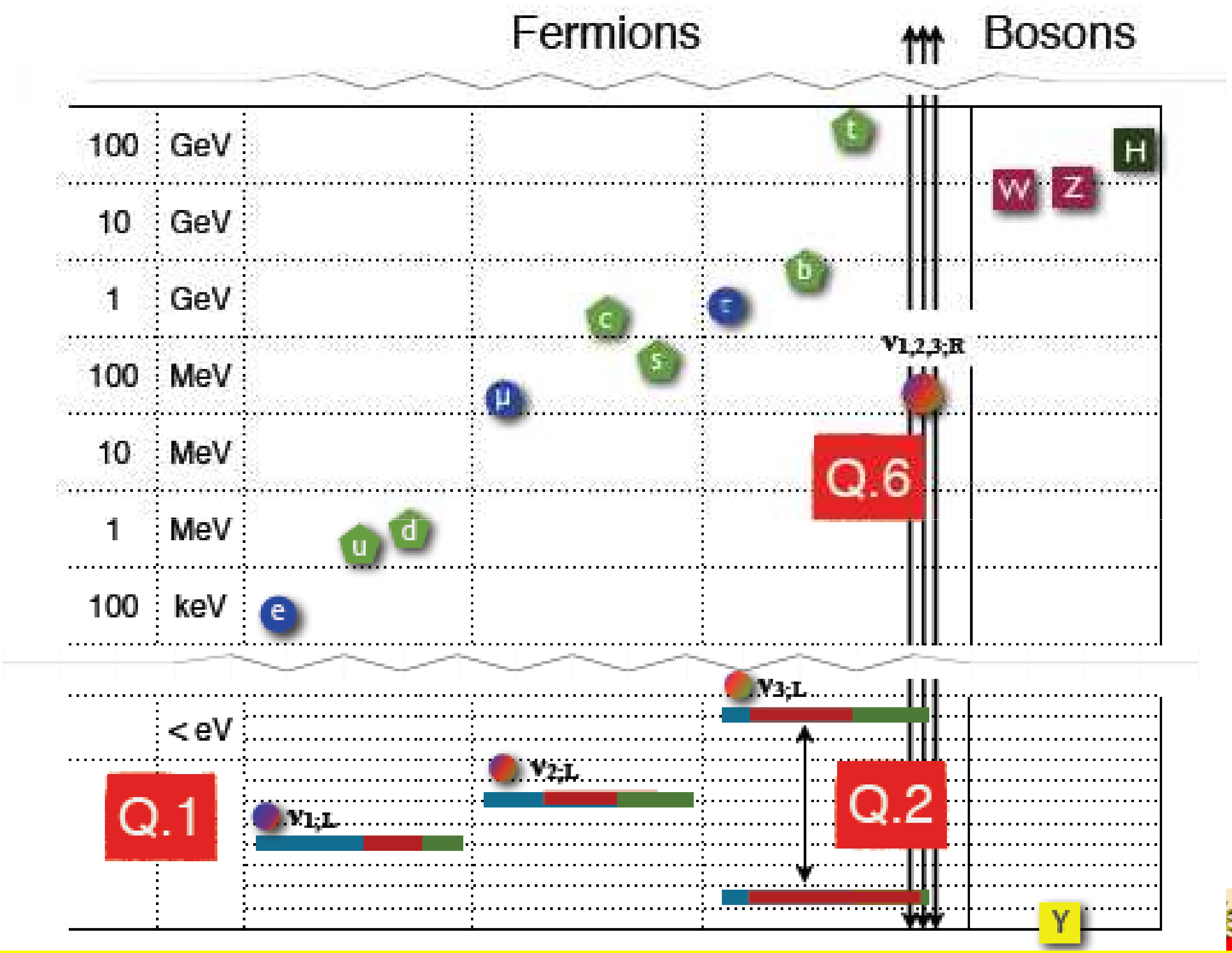
1 Missing piece: Higgs



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$ (0 1 2 3)
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^{0} [nb]	41.540 ± 0.037	41.479	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.3 ± 1.1	173.4	

July 2010

Confirmed to better than 1 % uncertainty by 100's of precision measurements



The SM is « complete »… but the neutrino questions remain…

Sterile neutrinos

Sterile neutrinos can have masses extending from (essentially 0) all the way to GUT-inspired 10^{10} GeV!

We have many hints for 'something that could be indications for sterile neutrinos ' in the ~ few eV^2 range

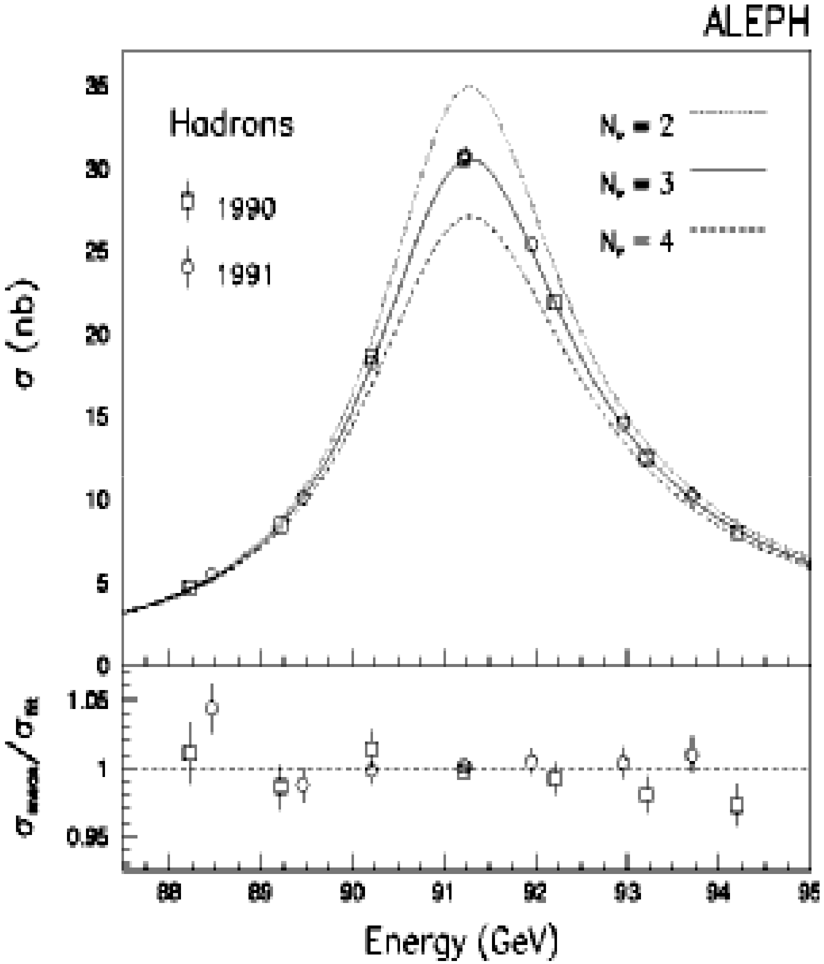
In general these hints are not performed with the desired methodological quality

-- no near detector
-- no direct flux measurement
-- no long target hadroproduction with full acceptance
-- etc.. etc…
-- none is 5 sigma

-- need decisive experiments (> 5σ significance)
-- look wide! other ranges than LSND 'effect'

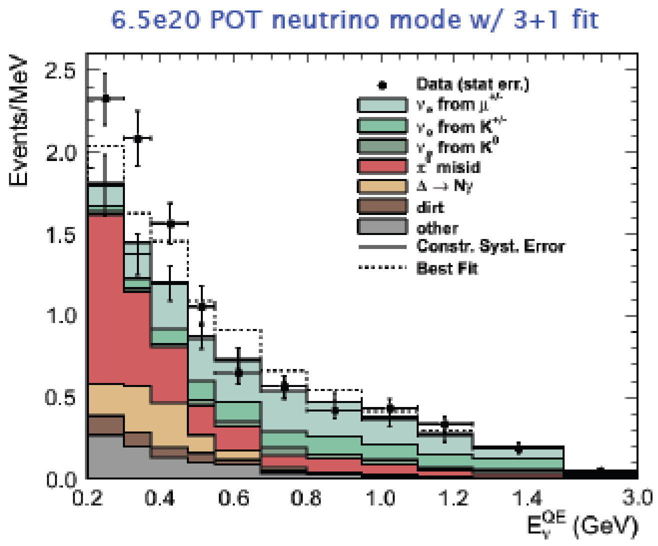
1989 The Number of light neutrinos

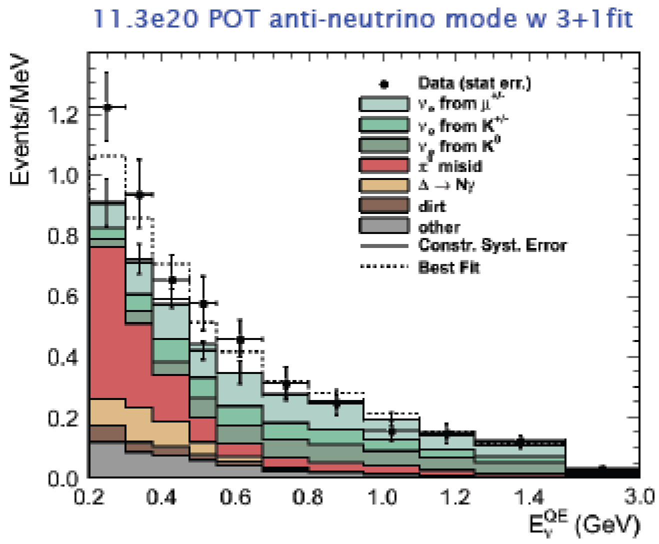
$e^+e^- \rightarrow Z \rightarrow q\bar{q}$, vs $e^+e^- \rightarrow Z \rightarrow \nu\bar{\nu}$



ALEPH+DELPHI+L3+OPAL in 2001 N_ν = 2.984 ±0.008

Error dominated by systematics on luminosity.





MiniBooNE observes an excess of νe candidates in the 200-1250 MeV energy range in neutrino mode (3.0σ) and in anti-neutrino mode (2.5σ).
The combined excess is 240.3 ± 34.5 ± 52.6 events (3.8σ)
It is not yet known whether the MiniBooNE excesses are due to oscillations.

C. Polly

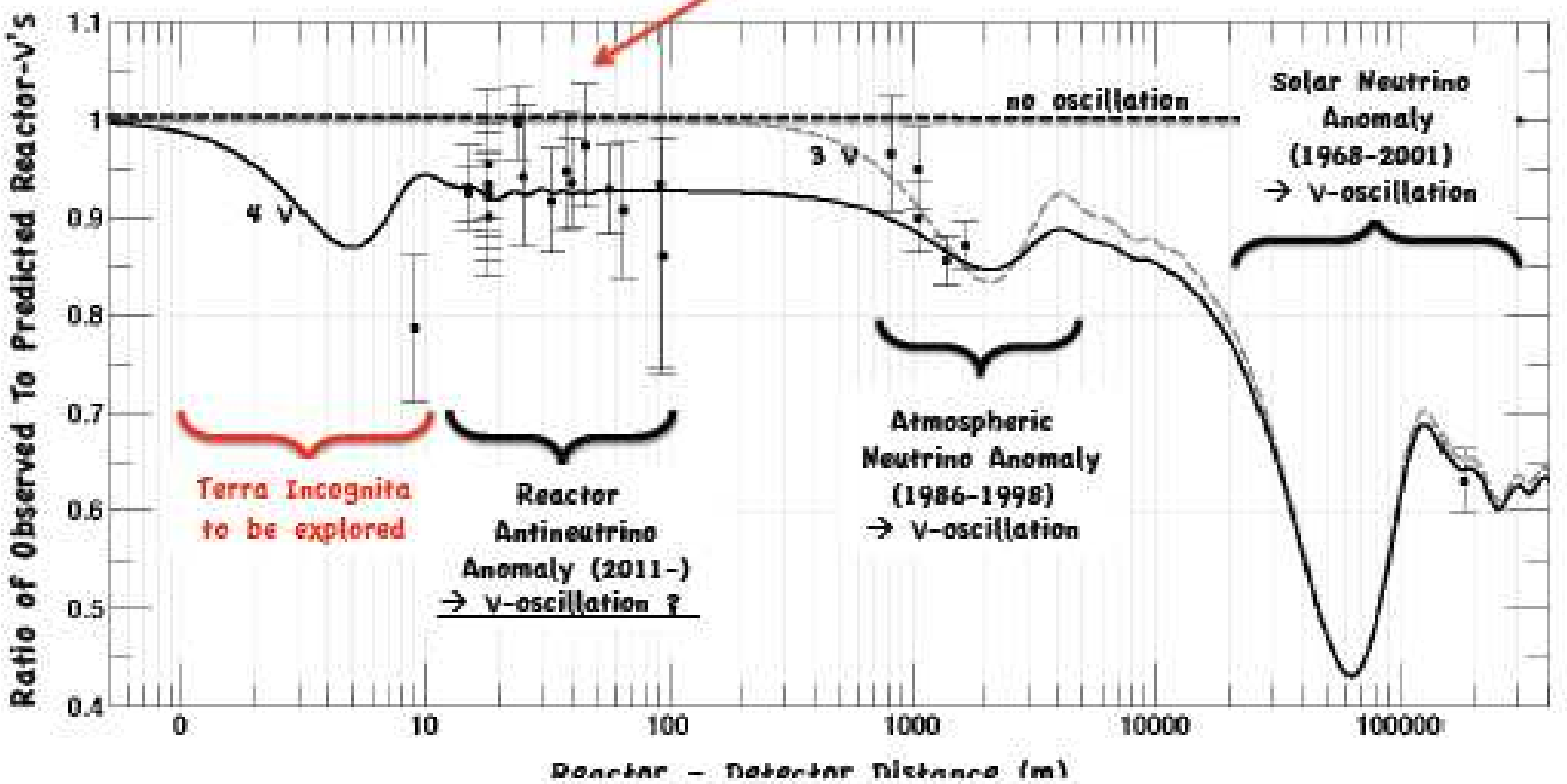
Anomaly	Type	Channel	Significance
LSND	DAR	$\bar{\nu}$ CC	3.8 σ
MiniBooNE	SBL accelerator	ν CC	3.0 σ
MiniBooNE	SBL accelerator	$\bar{\nu}$ CC	1.7σ
Gallium/Sage	Source - e capture	ν CC	2.7σ
Reactor	Beta-decay	$\bar{\nu}$	3.0σ

New MiniBooNE
Combined ν + $\bar{\nu}$
Now 3.8 σ

M. Shaevitz

The Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Thierry Lasserre

Future Experimental Oscillation Proposals

Type of Exp	App/Disapp	Osc Channel	Experiments
Reactor Source	Disapp	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	See K. Heeger Talk
Radioactive Sources	Disapp	$\bar{\nu}_e \rightarrow \bar{\nu}_e$ ($\nu_e \rightarrow \nu_e$)	See T. Lasserre Talk
Isotope Source	Disapp	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator $\overset{(-)}{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \rightarrow \nu_\mu$, $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$	νSTORM at Fermilab

Shaewitz Neutrino 2012

Sterile neutrino search a global view:

Detected by mixing between sterile and active neutrino

ideal experiments:

source

known process

$\nu_{active,\,\alpha}$

$\nu_{sterile}$

$\nu_{active,\,\beta}$

detector

known process

0. if $\nu_{sterile}$ cannot be produced (too heavy) apparent **deficit in decay rate**

1. disappearance, not necessarily oscillatory best is **NC disappearance**

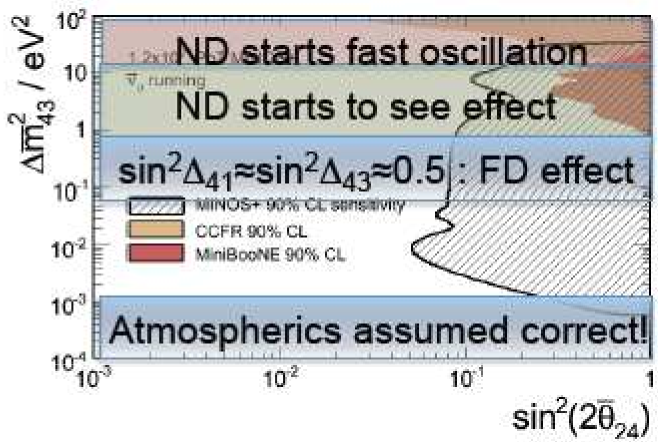
2. $\nu_\alpha \rightarrow \nu_\beta$ **appearance** (at higher order)

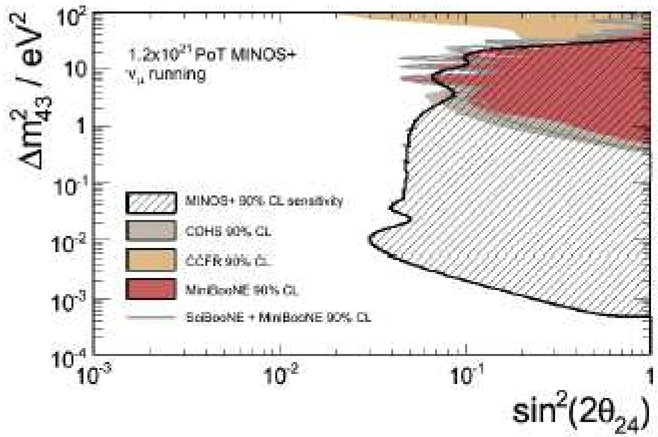
MINOS+ sterile reach

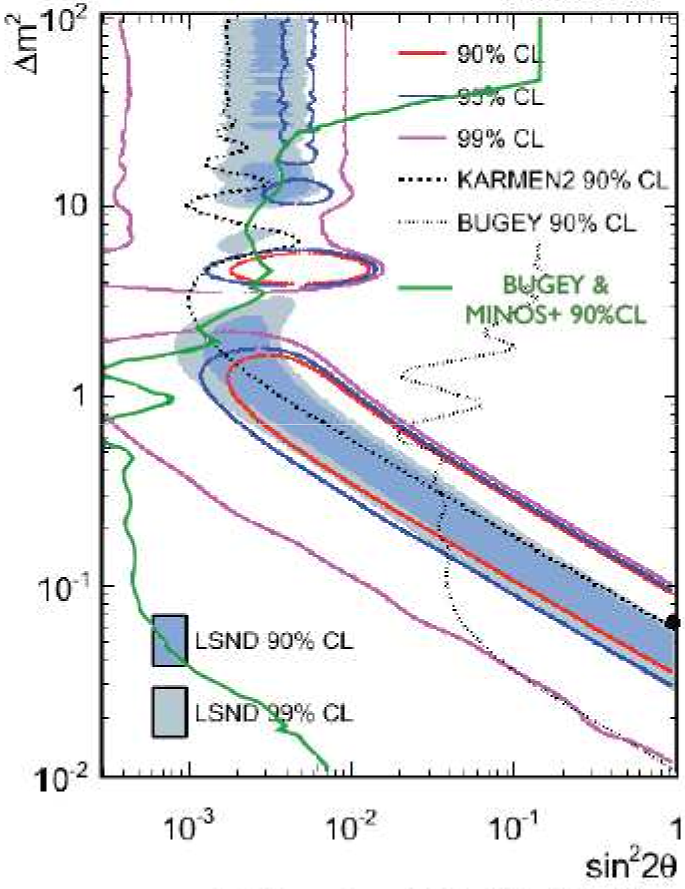
$|U_{e4}|^2 = \sin^2\theta_{14}$
$|U_{\mu4}|^2 = \cos^2\theta_{24} * \sin^2\theta_{24}$
$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu4}|^2$

(http://lanl.arxiv.org/abs/1109.4033)

A.Sousa



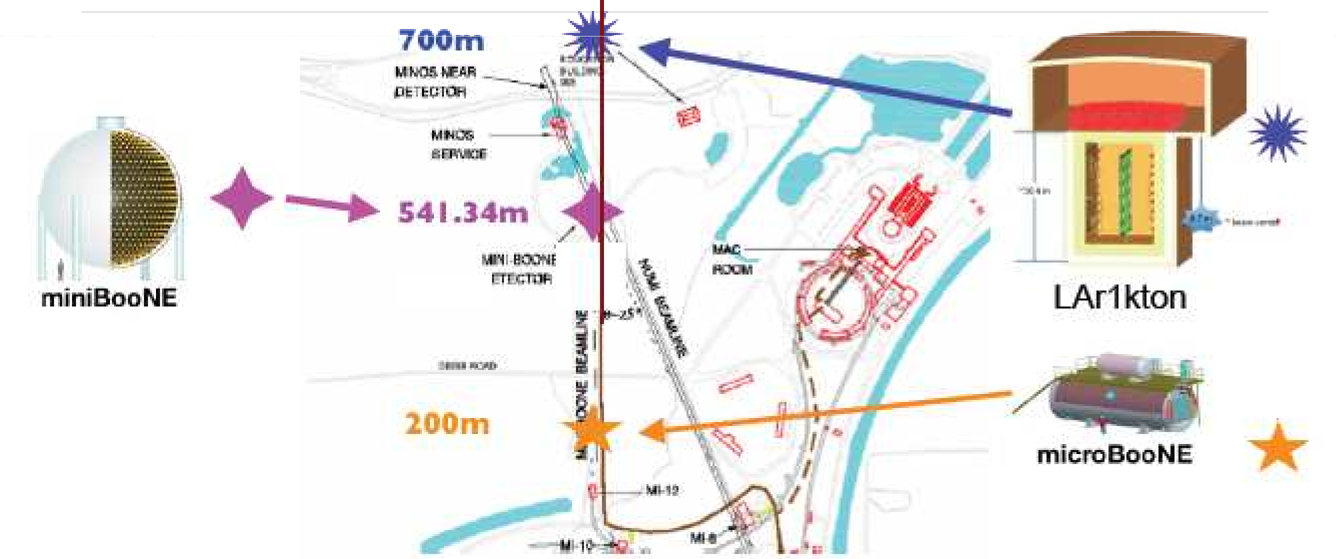




$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu4}|^2$

LAr1kton at Fermilab Booster ν Beamline (BNB)

- To directly address LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal, use multiple detectors in the Fermilab BNB
- Large (1 kton fiducial) LAr detector at 700m plus MicroBooNE at 200m (also maybe MiniBooNE with scintillator at 540 m)
- LAr capabilities significantly reduces gamma and other backgrounds



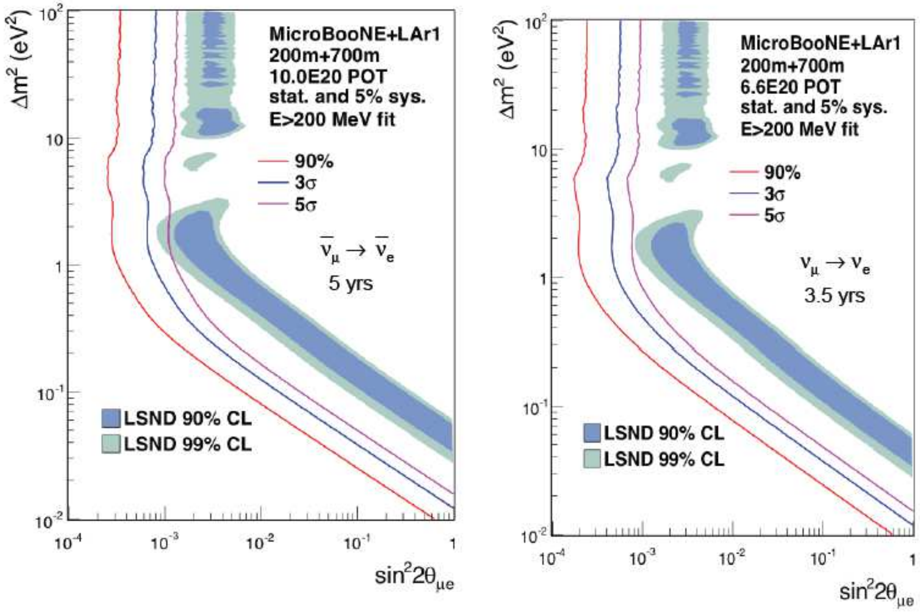
CERN SPS: Two (or Three) Detector Proposal using Liquid Argon and Iron Spectrometers

- Combined ICARUS and NESSiE Collaborations

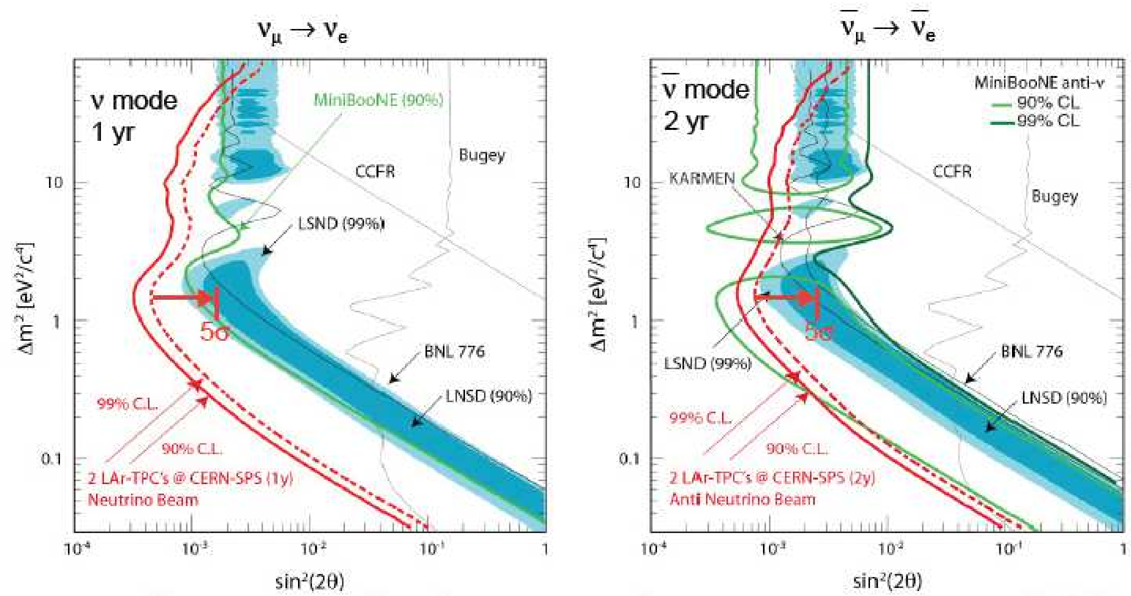
New Neutrino Facility in the CERN North Area

100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.

LAr1kton Sensitivity

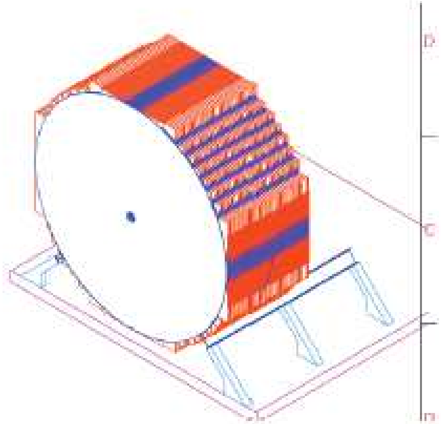


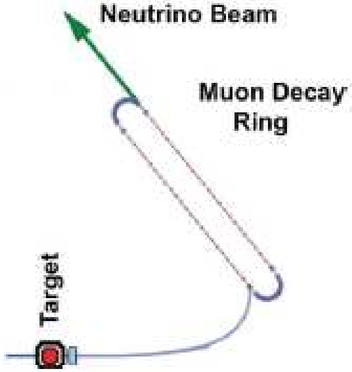
CERN SPS Appearance Sensitivity



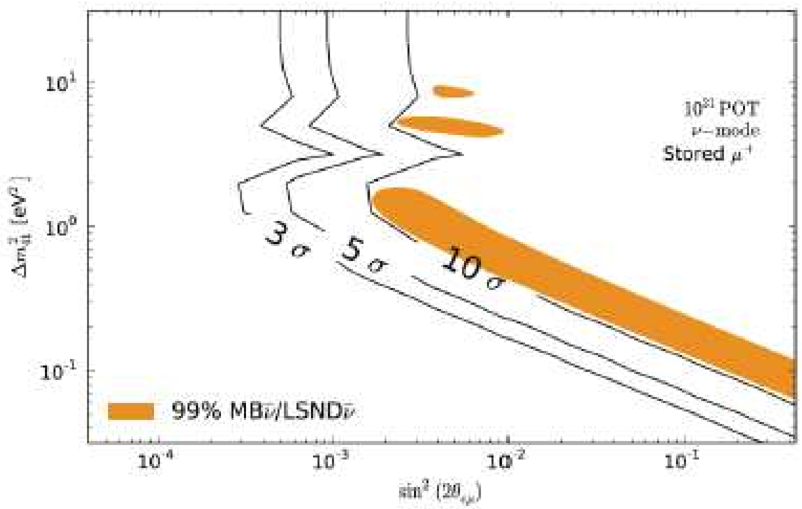
Neutrinos from STORed Muons - νSTORM

- Simplest implementation of the NF concept
  - 60 GeV protons on solid target (100 kW)
  - Horn capture and π transfer
  - Decay ring
- No new technology is required
  - Little R&D is needed
    ≈"Technology" ready





$\nu_e \rightarrow \nu_\mu$: CPT Invariant mode of LSND/MinBooNE



See posters 110 & 111 (Tunnell, Bross)

- Performance assumptions:
  - 10^{21} 60 GeV/c POT
- Yields ≈ $2\text{X}10^{18}$ useful ν
- ≈ 2000 m baseline
- 1.3 kT Minos-like detector: SuperB IND
  - Thinner plates
  - 2T B

why magnetized iron, and not Larg, TASD etc…?

Future experiments

-- determination of mass hierarchy

-- determination of CP violation or CP phase

-- verification of 3x3 framework
and search for sterile neutrinos

Oscillation maximum $1.27\,\Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}$ eV^2 L = 500 km @ 1 GeV
Solar $\Delta m^2 = 7\ 10^{-5}$ eV^2 L = 18000km @ 1 GeV

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_e$ oscillation at L_{atm}

$$P(\nu_\mu \leftrightarrow \nu_e)_{max} =\sim \tfrac{1}{2} \sin^2 2\theta_{13} + \ldots$$

(small)

II There will be CP or T violation

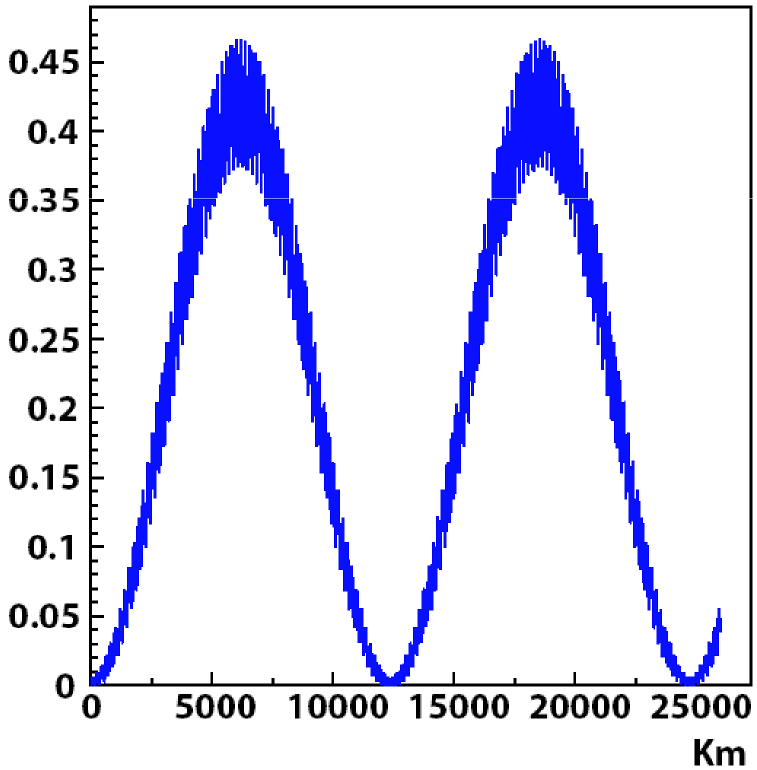
CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

T : $P(\nu_\mu \leftrightarrow \nu_e) \neq P(\nu_e \leftrightarrow \nu_\mu)$

III we do not know if the neutrino ν_1 which contains more ν_e is the lightest one (natural?) or not.

Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



$$P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\ \sin\delta$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\ \sin\delta$$

$$\frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} = A_{CP} \ \alpha \ \frac{\sin\delta \ \ \sin(\Delta m^2_{12} L/4E) \ \ \sin\theta_{12} \sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}\ldots}$$

… need large values of $\sin\theta_{12}$, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

… need APPEARANCE … $P(\nu_e \rightarrow \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (30%) for suppressed channel (one small angle vs two large)

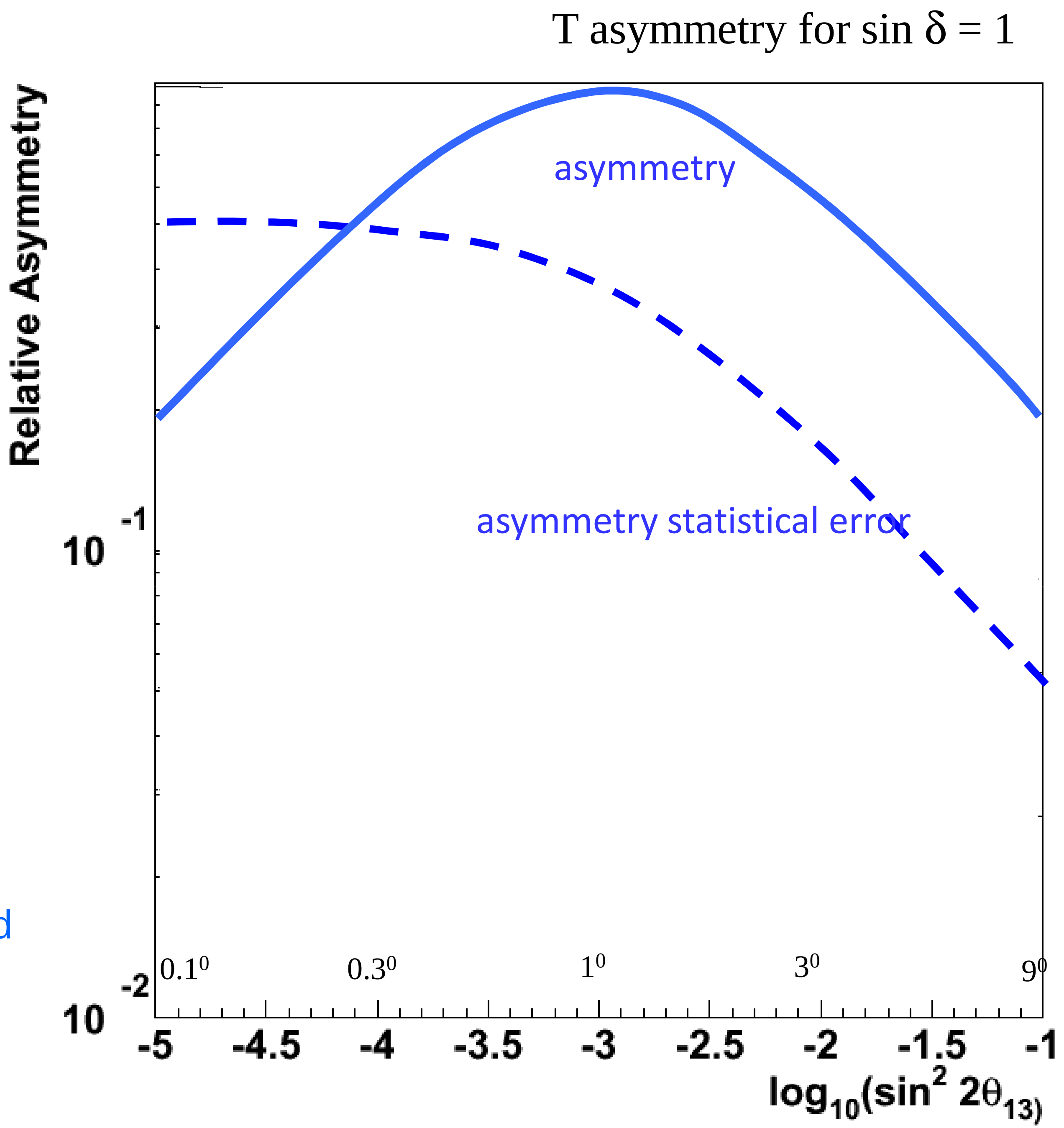
at wavelength at which ‘solar’ = ‘atmospheric’ and for $\nu_e \rightarrow \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$

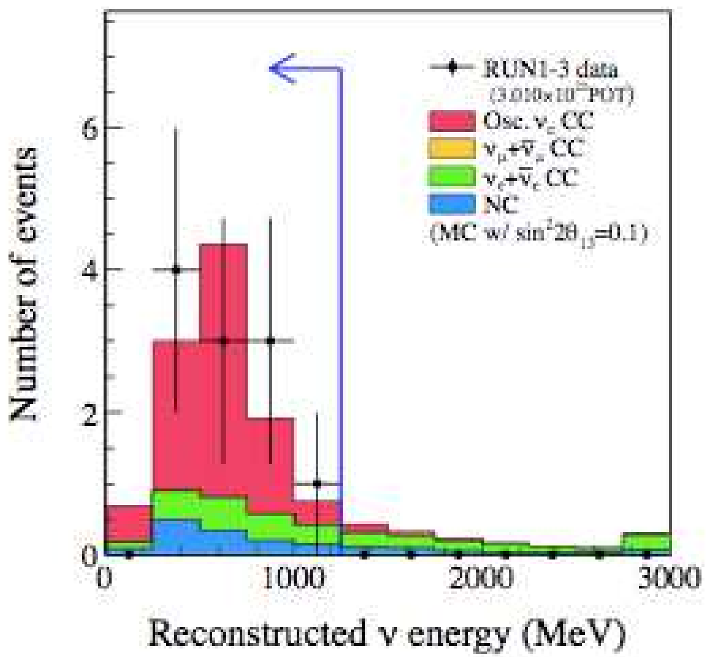
!

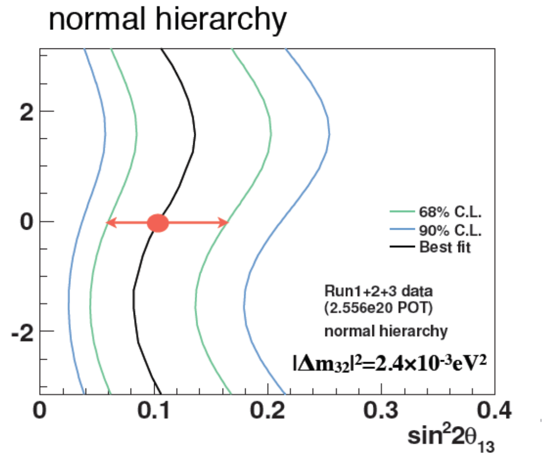
large θ_{13} ➔ asymmetry is a few % and requires excellent flux normalization (neutrino fact., beta beam or excellent near/far detector

NOTE:
This is at first maximum!
Sensitivity at low values of θ_{13} is better for short baselines, sensitivity at large values of θ_{13} may be better for longer baselines (2d max or 3d max.)

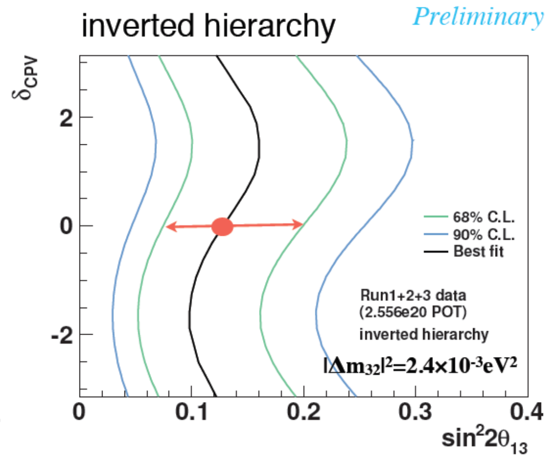


All the plots here are preliminary.





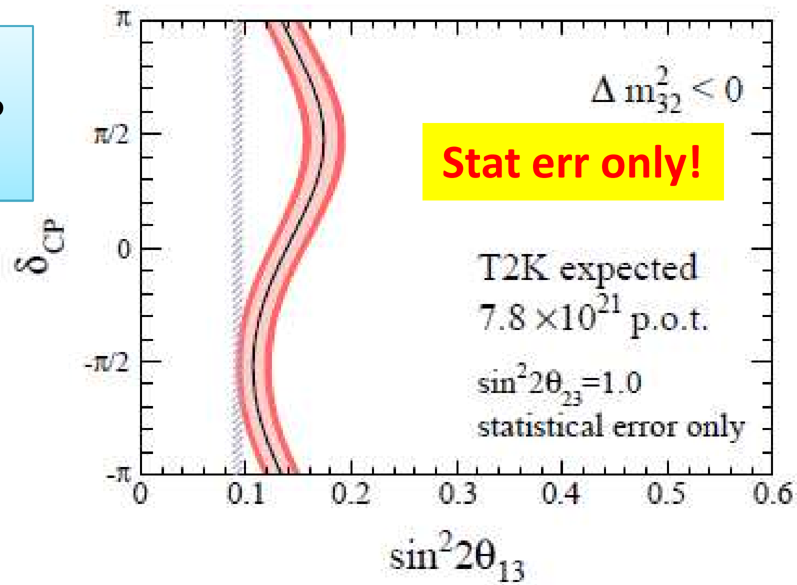
$\sin^2 2\theta_{13}=0.104\ ^{+0.060}_{-0.045}$ @$\delta_{CP}=0$



$\sin^2 2\theta_{13}=0.128\ ^{+0.070}_{-0.055}$ @$\delta_{CP}=0$

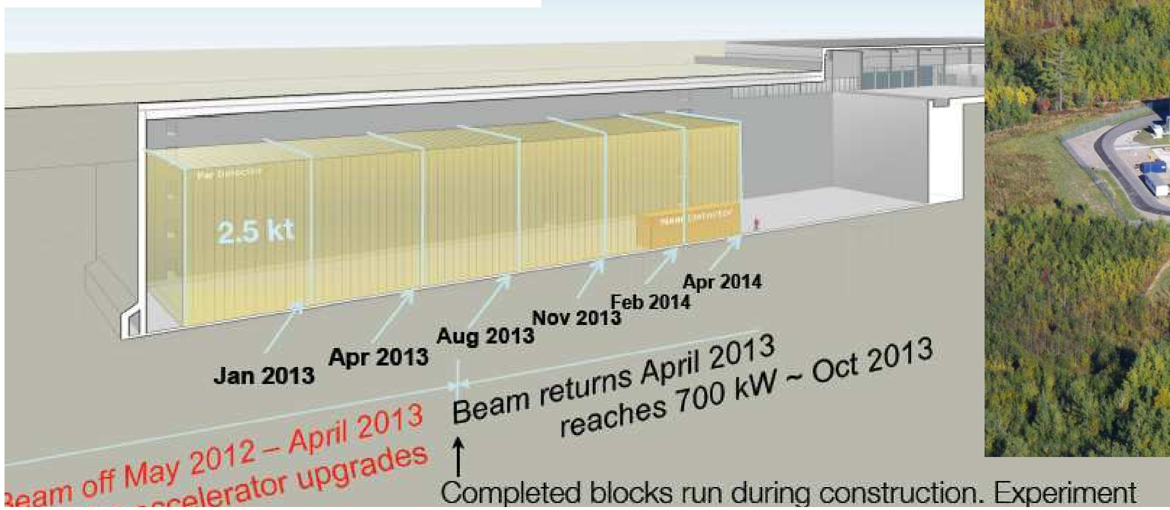
Improvement of both reactor and accelerator experiments will provide first handle on the CP violating complex phase δ_{CP}.

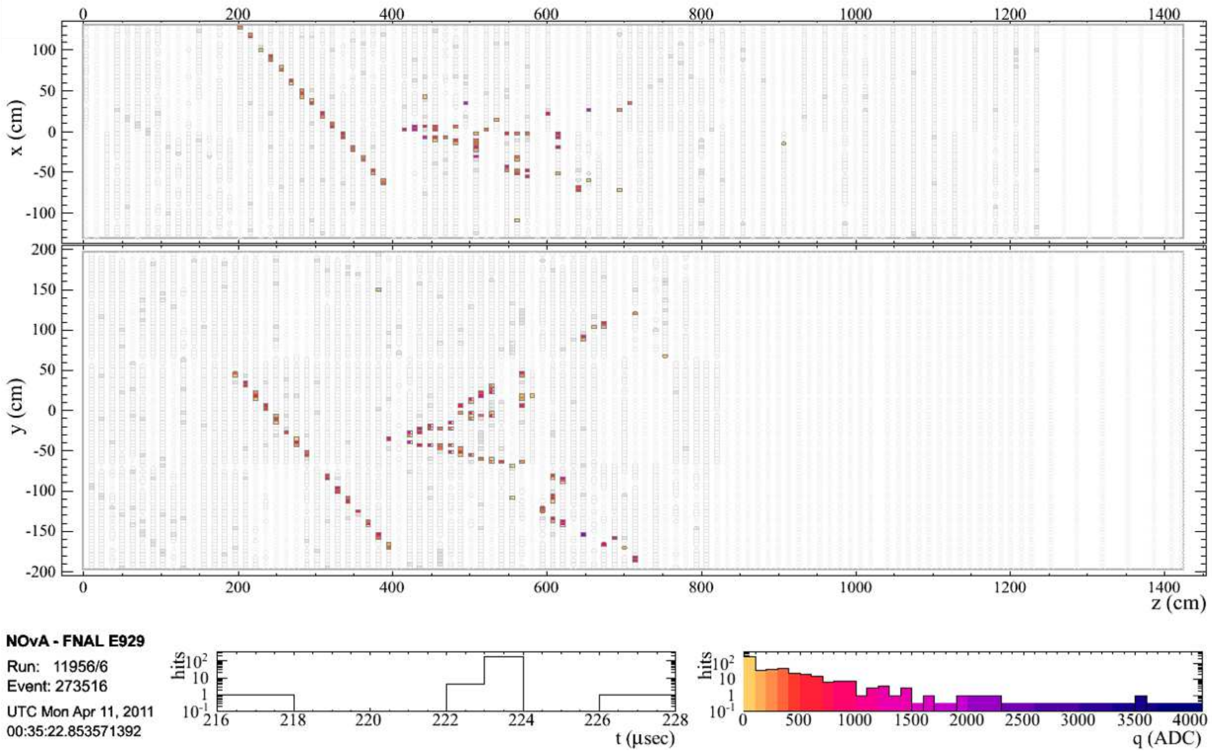
Expectation with ~50 times more data
(750kWx 5x10^7s)



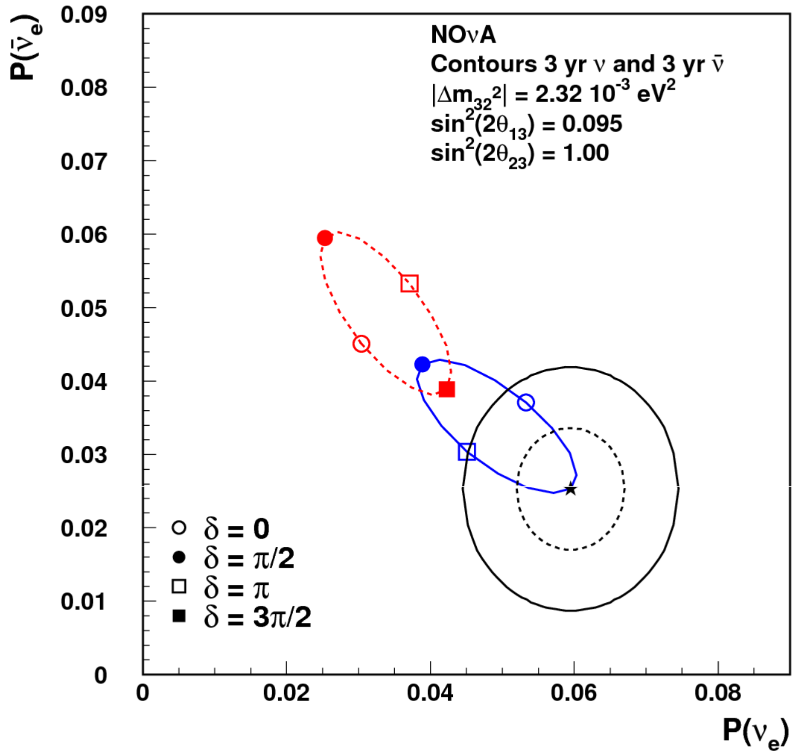
Expected beam power	May 2012	2014	2018
	190kW	300kW	750kW

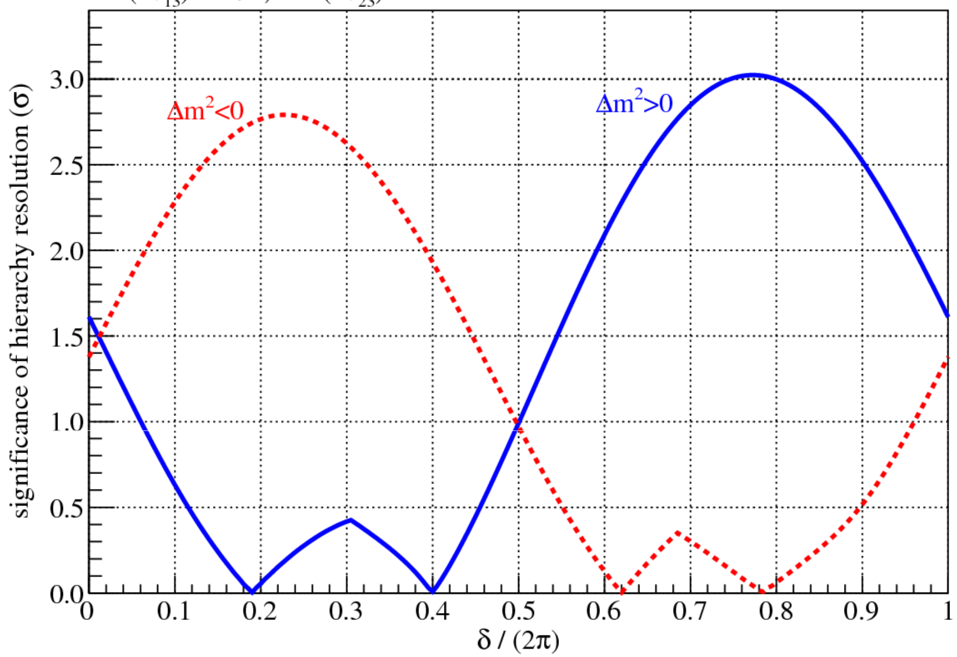
NOvA


2.5 kt
Jan 2013
Apr 2013
Aug 2013
Nov 2013
Feb 2014
Apr 2014
Beam off May 2012 – April 2013
accelerator upgrades
Beam returns April 2013
reaches 700 kW ~ Oct 2013
Completed blocks run during construction. Experiment


x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11956/6
Event: 273516
UTC Mon Apr 11, 2011
00:35:22.853571392
hits
t (μsec)
q (ADC)

1 and 2 σ Contours for Starred Point

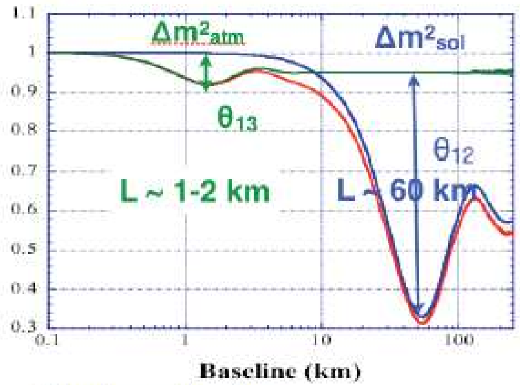




in some regions will be able to determine mass hierarchy at 3σ in 6 years

mass hierarchy with reactor?

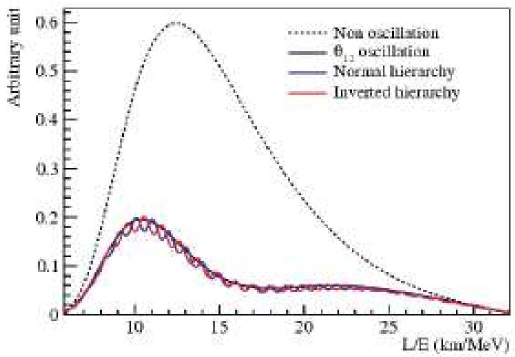
Daya Bay II



Site Investigation

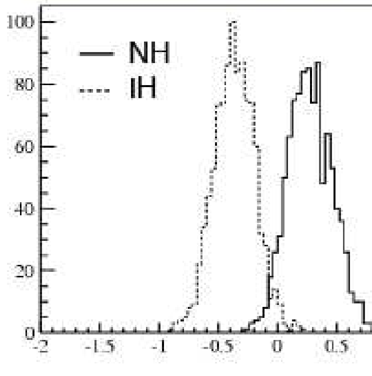
K. Heeger

With reactor



$\sin^2\theta_{12}$ to ~2% from dedicated reactor experiment at optimized L~60km

Mass Hierarchy Sensitivity



50k events = 20 kton, 3 years
→ 96%
100k events
→ 3σ

Ref: Y. Wang, J. Cao, et al
nuTurn 2012

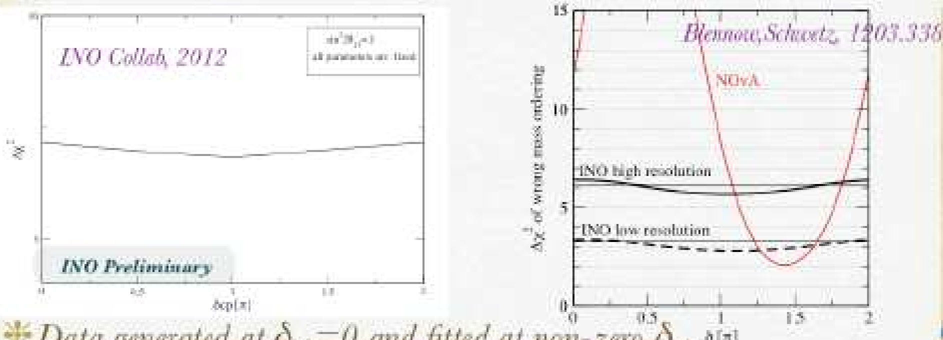
16

need resolution < separation between peaks <~ 2% at 3 MeV

mass hierarchy with atmospherics?

INO

✻ *What is the impact of δ_{cp} on the MH sensitivity of ICAL@INO*

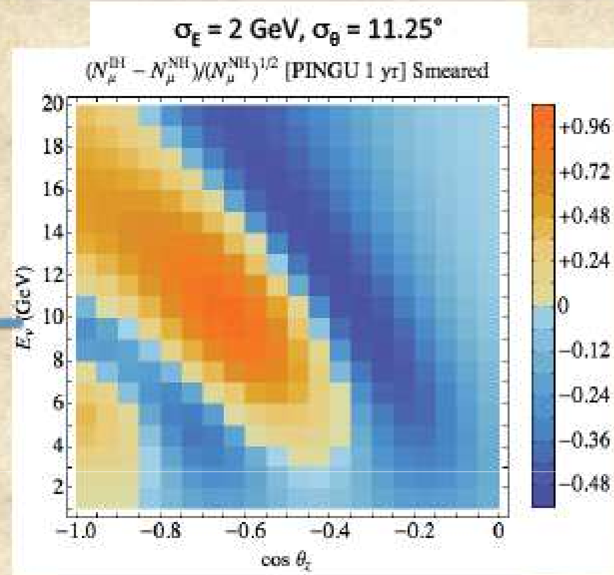


✻ *Data generated at δ_{cp}=0 and fitted at non-zero δ_{cp}*

✻ *INO will give MH sensitivity almost indep of δ_{cp}*

S. Choubey

PINGU



3σ – 11σ in 5 Years of running

Includes systematic error ≤ 10%

requirements on:

1) Energy Resolution
2) Angular Resolution
3) Systematic Errors

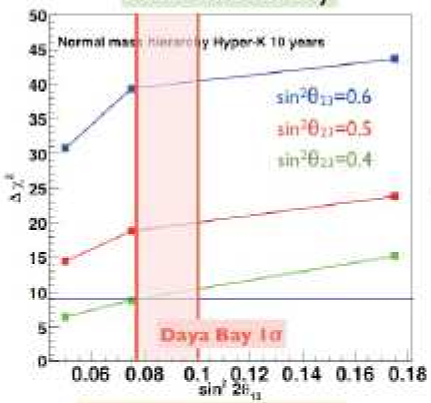
Being studied

G. Sullivan

15

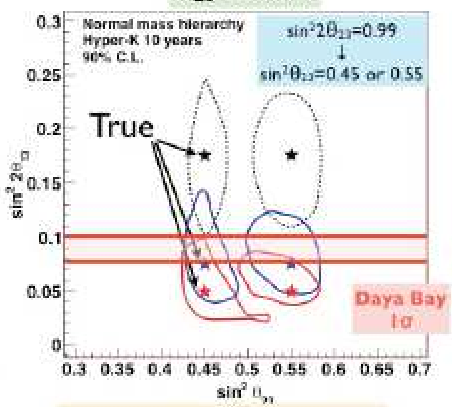
Atmospheric ν (Hyper-K)

Mass hierarchy



>3σ with 5-10 years

θ_{23} octant



Resolved if $\sin^2 2\theta_{23}$<0.99

M. Yokoyama

DayaBay II	reactor 60km	20 kt LS	3 σ in 6 years	R&D on E-reso. my guess 2020	Karsten Heegner	
ICAL@INO	atmos.	50 kt MID (RPCs)	2.7 σ in 10 years	2027	Sandhya Choubey	
HyperK	atmos.	1 Mt Water Cerenkov	3 σ in 5 years 4 σ in 10 years	2027/28 2033/34	Sandhya Choubey	LoI submitted
T2HK	LBL accel. 295 km	1 Mt Water Cerenkov	0..3 σ in 10 years	2028	Masashi Yokoyama	
PINGU	atmos.	Ice (South pole)	3...11 σ in 5 years	feasibility study ongoing.	Sandhya Choubey Poster	Systematics ?
MINOS+	LBL accel. 735 km	MID 5.4 kt	no claim on mass hierarchy	---	speaker on question	
GLADE	LBL accel. 810 km	LAr 5 kt	In combination with NOνA and T2K $\leq 2\,\sigma$	Letter-of-Intent	André Rubbia, Poster	
NOνA	LBL AshRiver 810 km	TASD 14 kt	0...3 σ in 6 years depending on δ	2020	Ryan Patterson	under construction starts 2014
LBNE	LBL Homestake LBL Soudan LBL AshRiver	LAr 10 kt LAr 15 kt LAr 30 kt	1.5...7 σ in 10 y 0...3 σ in 10 y 0.5...5σ in 10 y	2030	Bob Swoboda	range gives dependence on δ
LBNO LArg	LBL accel. 2300 km	LAr 20 kt	> 5σ in a few y.	2025 + number of years to the decision	André Rubbia	
LBNO- Lsc	LBL accel. 2300 km	Liq. Scint. 50 kt	5 σ in 10 years	2028 + number of years to the decision	Lothar Oberauer	
ν-factory	LBL accel. ? km	LAr ? kt	$\gg 5\,\sigma$	?		

The information is collected from talks given at the NEUTRINO2012 conference in Kyoto in June 2012.
The following transparencies are extracted from the corresponding talks (speakers listed in the 6th column).

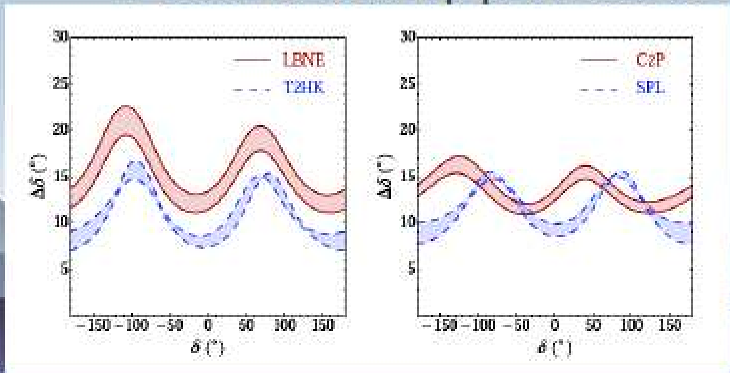
red =~ approved

Long baseline projects

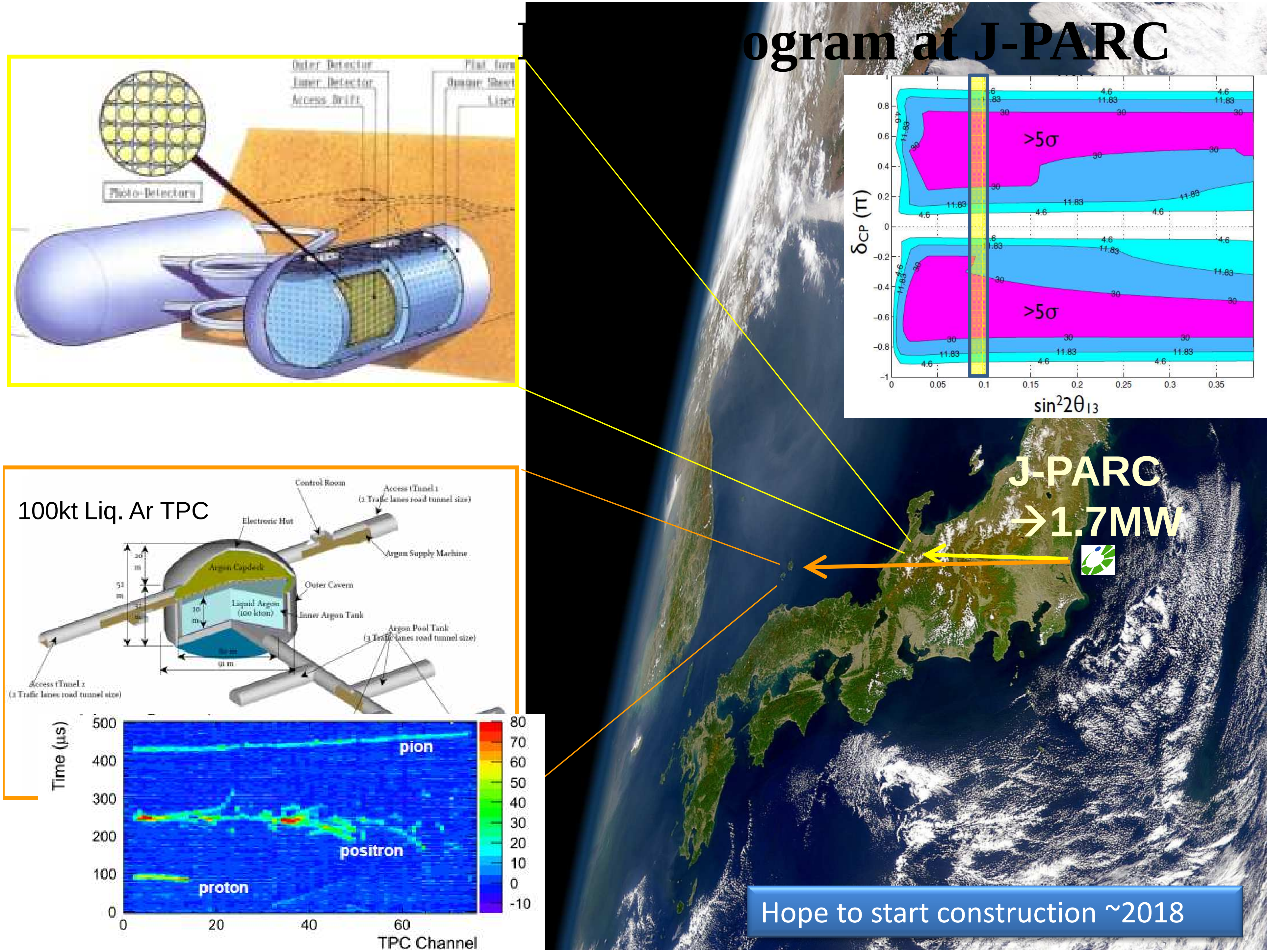
Project	Beam power MW	Fiducial Mass kt	Baseline km	MH	CPV 90%CL, (3σ)	Physics starts	Astrophysical program
LBNO	0.8	20->100	2300	Excellent	71 (44)	2023	Yes
T2HK	0.75	500	295	No	86 (74)*	2023	Yes
LBNE	0.7	10	1300	OK	69 (43)	2022	No
Lund	5	440	365	Some	86 (70)	>2019	Yes
CERN-Canfranc	0.8-4	440	650	Some	80-88(80)	>2020	Yes

*: if mass hierachy is known

P. Coloma et al.hep-ph:1203.5651



T2HK: 4MW, 500 kt
LBNE: 0.8 MW,33 kt
C2P=LBNO : 0.8 MW, 100 kt



ogram at J-PARC
Outer Detector
Inner Detector
Access Drift
Photo-Detectors
100kt Liq. Ar TPC
Control Room
Access Tunnel 1
(2 Traffic lanes road tunnel size)
Electronic Hut
Argon Supply Machine
Argon Capdeck
Outer Cavern
Liquid Argon
(100 kton)
Inner Argon Tank
Argon Pool Tank
Access Tunnel 2
(2 Traffic lanes road tunnel size)
Time (μs)
pion
positron
proton
TPC Channel
δCP (π)
sin²2θ13
>5σ
>5σ
J-PARC
→1.7MW
Hope to start construction ~2018

Tricky business… Lots of maybe's and no definite assurance that with approved or non accelerator expts we will determine (i.e. 5σ) sign(Δm^2_{32})

Should we propose a new definitive experiment?

Some risk, so needs to be able to do CPV too…

In the following I restrict to a European view given the upcoming upgrade of the European Strategy for particle physics

Getting our feet on (under) the ground:

CERN EOI

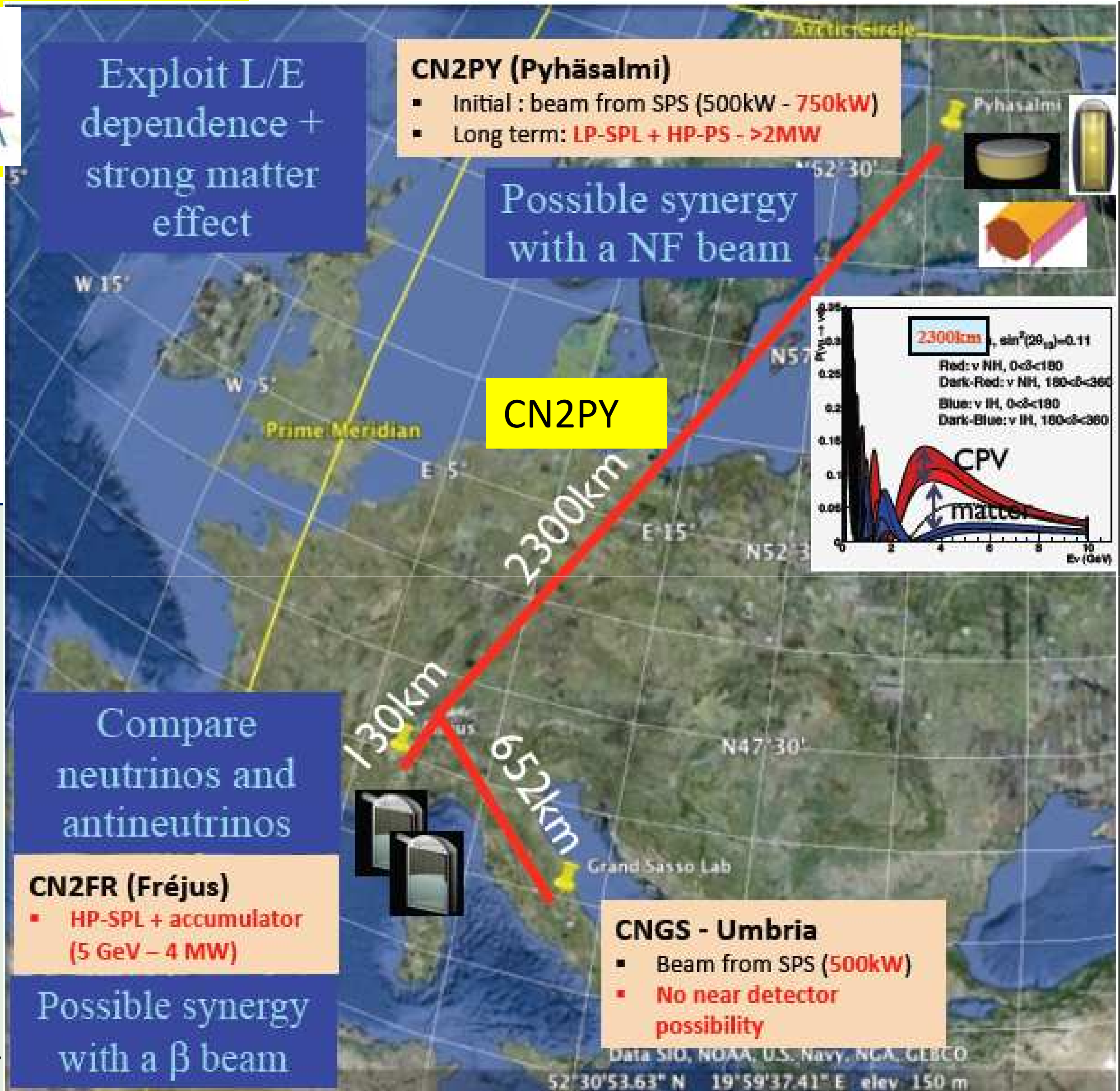
LAGUNA –LBNO
new FP7 design study
2011-2014

2 main options

Short distance: 130km
Memphys at Frejus
SPL+beta beam
CP and T violation

Long distance: 2300km
Pyhasalmi
Fine grain detector
e.g. 20kton fid. Larg
+ Magnetized detector
Long distance allows
rapid sensitivity to
$sign(\Delta m^2_{13})$

1st step easier: SPS C2PY
➔ consortium 1st priority
Nextsteps: HP 50 GeV PS …
…or neutrino factory



Medium term plans include long term plans!

CERN-SPSC-2012-021 (SPSC-EOI-007)

aim at
start date
(2023)

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Expression of Interest

for a very long baseline neutrino oscillation experiment

(LBNO)

A. Stahl,[1] C. Wiebusch,[1] A. M. Guler,[2] M. Kamiscioglu,[2] R. Sever,[2] A.U. Yilmazer,[3] C. Gunes,[3] D. Yilmaz,[3] P. Del Amo Sanchez,[4] D. Duchesneau,[4] H. Pessard,[4] E. Marcoulaki,[5] I. A. Papazoglou,[5] V. Berardi,[6] F. Cafagna,[6] M.G. Catanesi,[6] L. Magaletti,[6] A. Mercadante,[6] M. Quinto,[6] E. Radicioni,[6] A. Ereditato,[7] I. Kreslo,[7] C. Pistillo,[7] M. Weber,[7] A. Ariga,[7] T. Ariga,[7] T. Strauss,[7] M. Hierholzer,[7] J. Kawada,[7] C. Hsu,[7] S. Haug,[7] A. Jipa,[8] I. Lazanu,[8] A. Cardini,[9] A. Lai,[9] R. Oldeman,[10] M. Thomson,[11] A. Blake,[11] M. Prest,[12] A. Auld,[13] J. Elliot,[13] J. Lumbard,[13] C. Thompson,[13] Y.A. Gornushkin,[14] S. Pascoli,[15] R. Collins,[16] M. Haworth,[16] J. Thompson,[16] G. Bencivenni,[17] D. Domenici,[17] A. Longhin,[17] A. Blondel,[18] A. Bravar,[18] F. Dufour,[18] Y. Karadzhov,[18] A. Korzenev,[18] E. Noah,[18] M. Ravonel,[18] M. Rayner,[18] R. Asfandiyarov,[18] A. Haesler,[18] C. Martin,[18] E. Scantamburlo,[18] F. Cadoux,[18] R. Bayes,[19] F.J.P. Soler,[19] L. Aalto-Setälä,[20] K. Enqvist,[20] K. Huitu,[20] K. Rummukainen,[20] G. Nuijten,[21] K.J. Eskola,[22] K. Kainulainen,[22] T. Kalliokoski,[22] J. Kumpulainen,[22] K. Loo,[22] J. Maalampi,[22] M. Manninen,[22] I. Moore,[22] J. Suhonen,[22] W.H. Trzaska,[22] K. Tuominen,[22] A. Virtanen,[22] I. Bertram,[23] A. Finch,[23] N. Grant,[23] L.L. Kormos,[23] P. Ratoff,[23] G. Christodoulou,[24] J. Coleman,[24] C. Touramanis,[24] K. Mavrokoridis,[24] M. Murdoch,[24] N. McCauley,[24] D. Payne,[24] P. Jonsson,[25] A. Kaboth,[25] K. Long,[25] M. Malek,[25] M. Scott,[25] Y. Uchida,[25] M.O. Wascko,[25] F. Di Lodovico,[26] J.R. Wilson,[26] B. Still,[26] R. Sacco,[26] R. Terri,[26] M. Campanelli,[27] R. Nichol,[27] J. Thomas,[27] A. Izmaylov,[28] M. Khabibullin,[28] A. Khotjantsev,[28] Y. Kudenko,[28] V. Matveev,[28] O. Mineev,[28] N. Yershov,[28] V. Palladino,[29] J. Evans,[30] S. Söldner-Rembold,[30] U.K. Yang,[30] M. Bonesini,[31] T. Pihlajaniemi,[32] M. Weckström,[32] K. Mursula,[32] T. Enqvist,[32] P. Kuusiniemi,[32] T. Räihä,[32] J. Sarkamo,[32] M. Slupecki,[32] J. Hissa,[32] E. Kokko,[32] M. Aittola,[32] G. Barr,[33] M.D. Haigh,[33] J. de Jong,[33] H. O'Keeffe,[33] A. Vacheret,[33] A. Weber,[33,34] G. Galvanin,[35] M. Temussi,[35] O. Caretta,[34] T. Davenne,[34] C. Densham,[34] J. Ilic,[34] P. Loveridge,[34] J. Odell,[34] D. Wark,[34] A. Robert,[36] B. Andrieu,[36] B. Popov,[36,14] C. Giganti,[36] J.-M. Levy,[36] J. Dumarchez,[36] M. Buizza-Avanzini,[37] A. Cabrera,[37] J. Dawson,[37] D. Franco,[37] D. Kryn,[37] M. Obolensky,[37] T. Patzak,[37] A. Tonazzo,[37] F. Vanucci,[37] D. Orestano,[38] B. Di Micco,[38] L. Tortora,[39] O. Bésida,[40] A. Delbart,[40] S. Emery,[40] V. Galymov,[40] E. Mazzucato,[40] G. Vasseur,[40] M. Zito,[40] V.A. Kudryavtsev,[41] L.F. Thompson,[41] R. Tsenov,[42] D. Kolev,[42] I. Rusinov,[42] M. Bogomilov,[42] G. Vankova,[42] R. Matev,[42] A. Vorobyev,[43] Yu. Novikov,[43] S. Kosyanenko,[43] V. Suvorov,[43] G. Gavrilov,[43] E. Baussan,[44] M. Dracos,[44] C. Jollet,[44] A. Meregaglia,[44] E. Vallazza,[45] S.K. Agarwalla,[46] T. Li,[46] D. Autiero,[47] L. Chaussard,[47] Y. Déclais,[47] J. Marteau,[47] E. Pennacchio,[47] E. Rondio,[48] J. Lagoda,[48] J. Zalipska,[48] P. Przewlocki,[48] K. Grzelak,[49] G. J. Barker,[50] S. Boyd,[50] P.F. Harrison,[50] R.P. Litchfield,[50] Y. Ramachers,[50] A. Badertscher,[51] A. Curioni,[51] U. Degunda,[51] L. Epprecht,[51] A. Gendotti,[51] L. Knecht,[51] S. Di Luise,[51] S. Horikawa,[51] D. Lussi,[51] S. Murphy,[51] G. Natterer,[51] F. Petrolo,[51] L. Periale,[51] A. Rubbia,[51,*] F. Sergiampietri,[51] and T. Viant[51]

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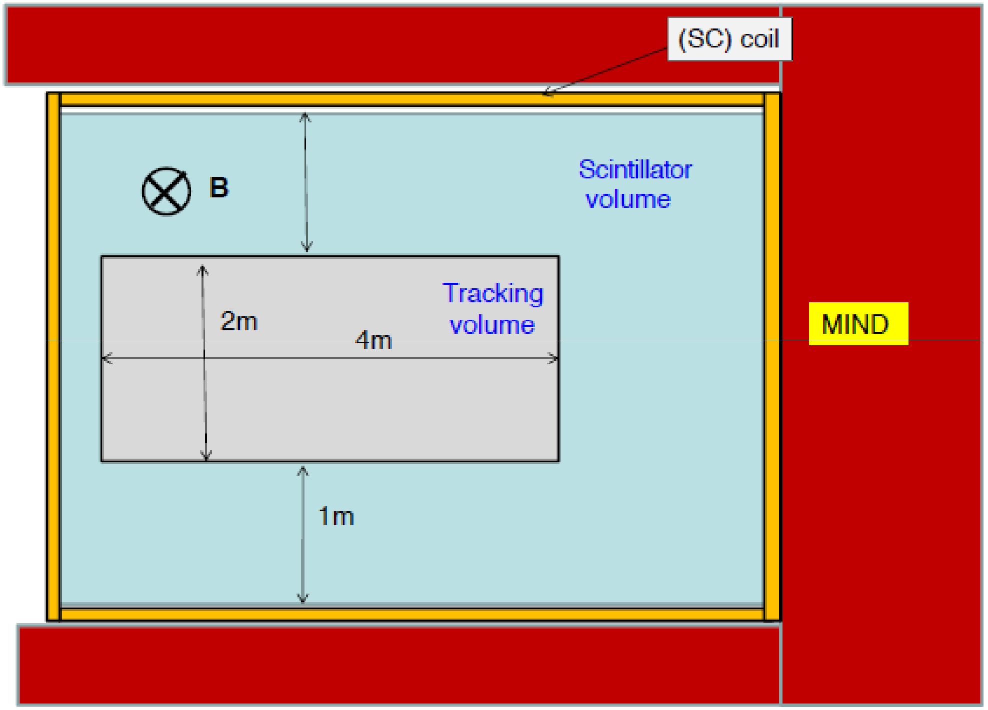
[51] ETH Zurich, Institute for Particle Physics, Zurich, Switzerland

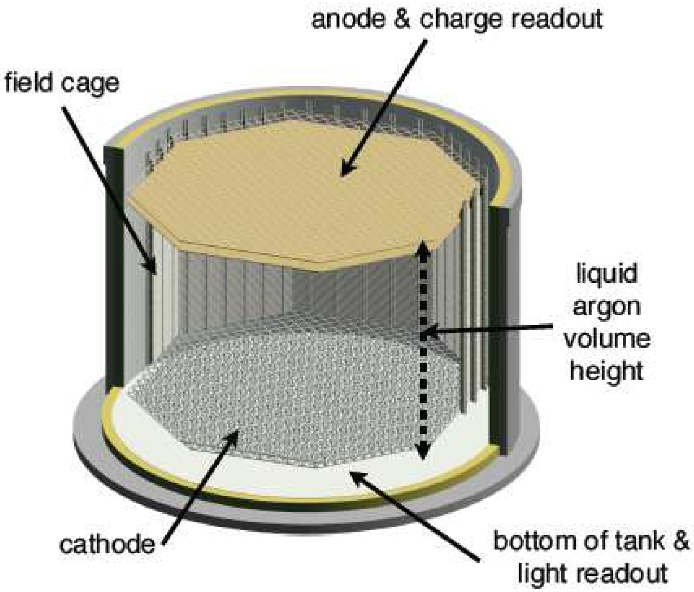
(Dated: June 28, 2012)

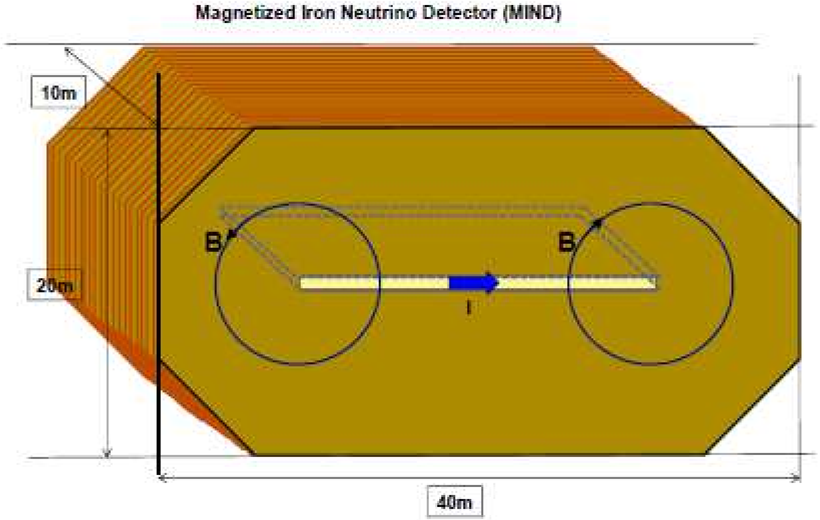
LBNO near detector 500m from target
(> 100m underground)

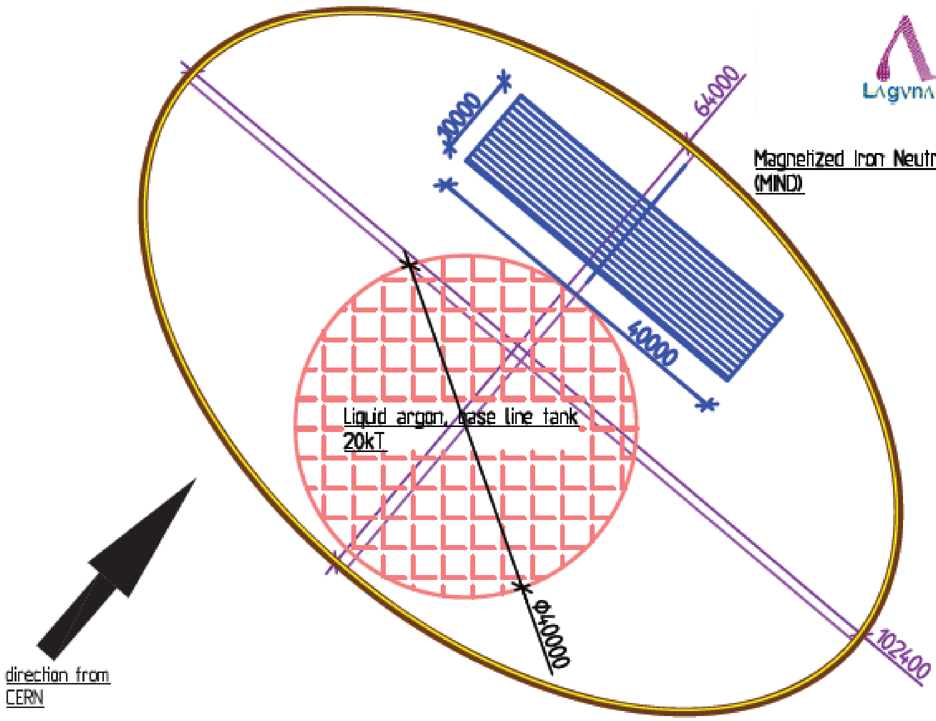


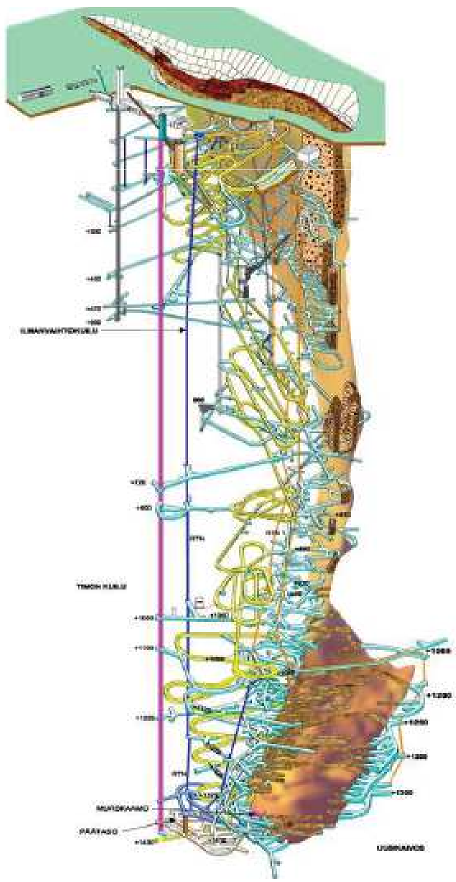
High pressure Ar gas TPC surrounded by TASD and MIND → 100k events/year avoid pile-up and allows charge determination of electrons

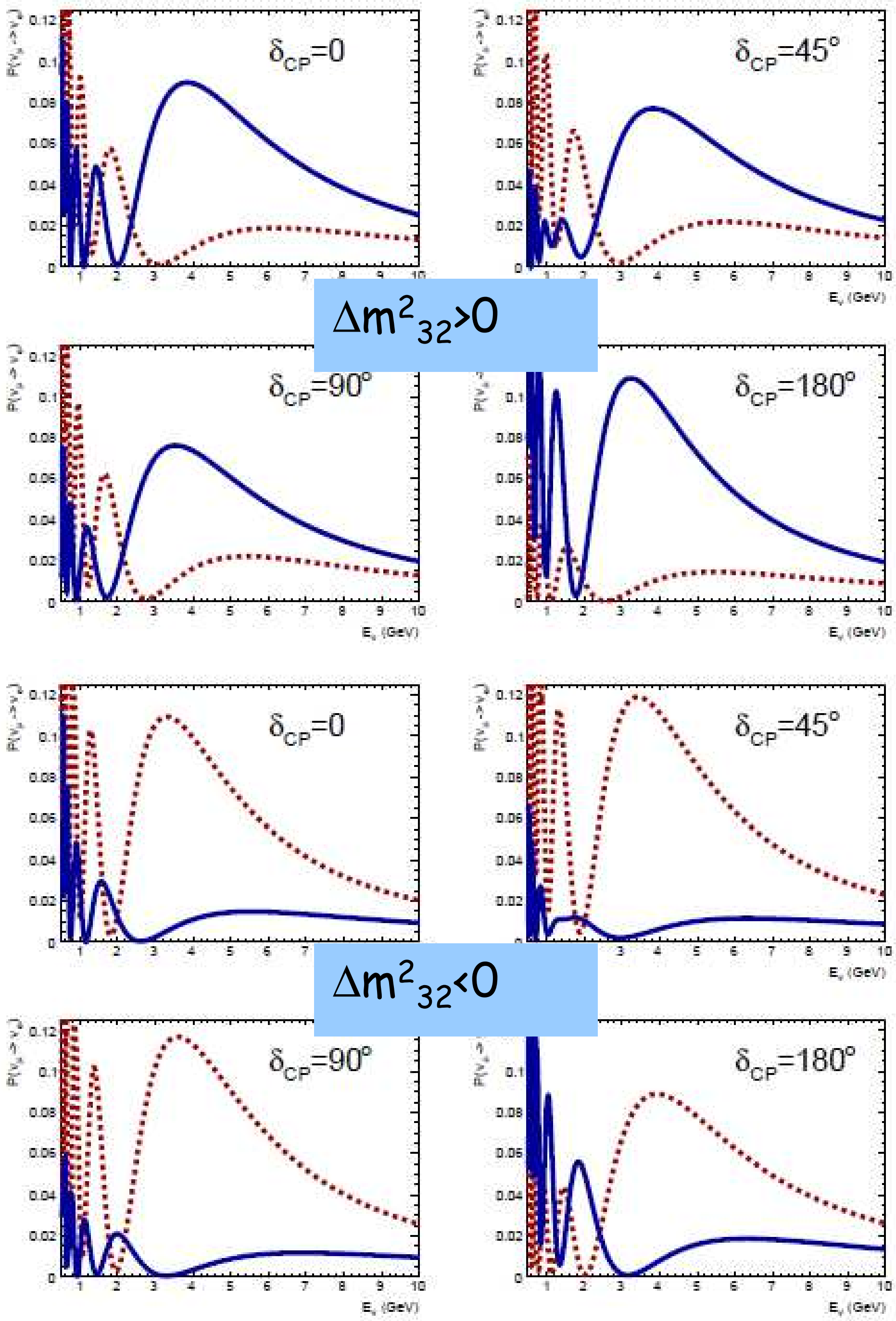
FAR DETECTOR











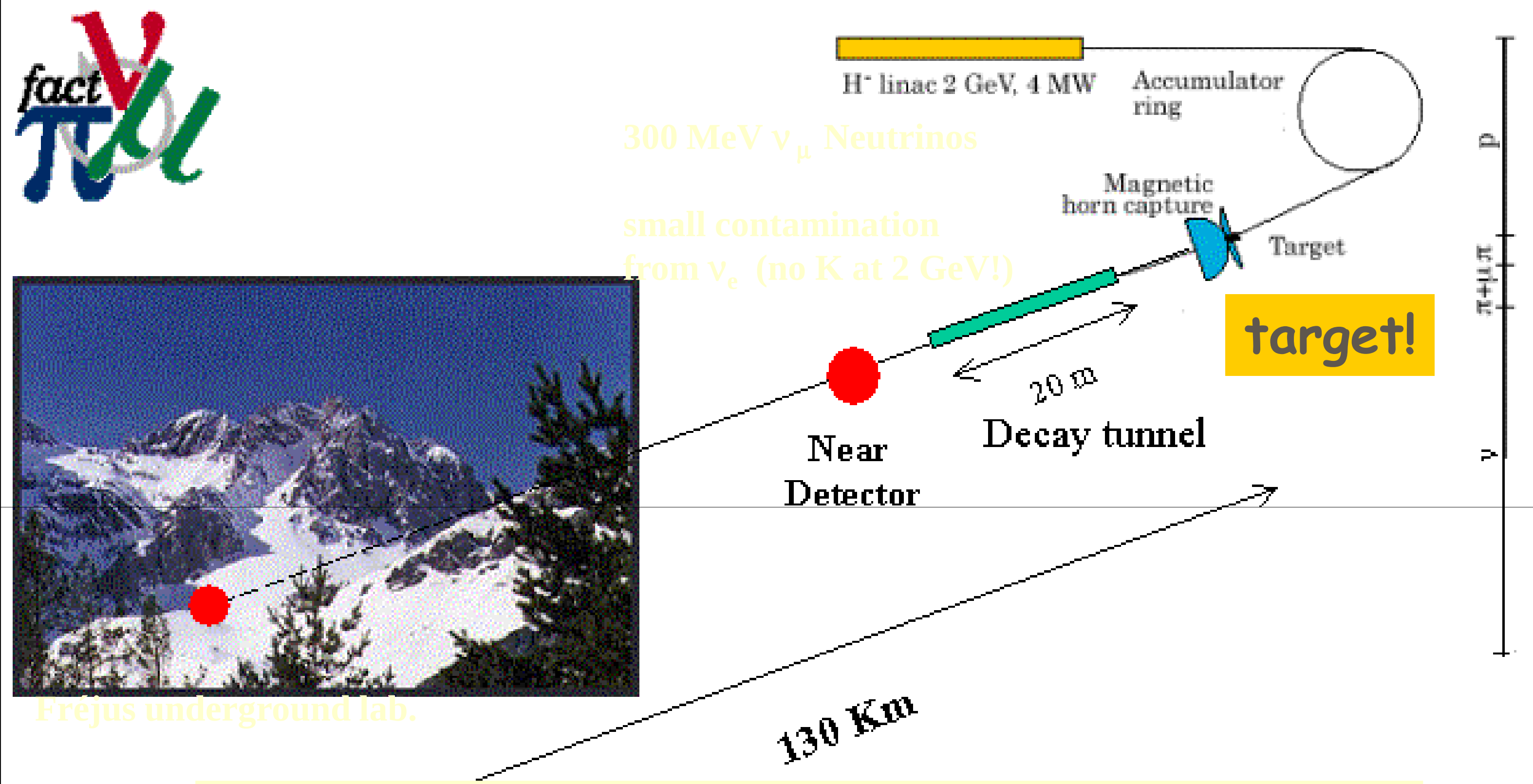
1. rate dramatically affected by mass hierarchy.
➔ 5sigma in 2 years

First goal of experiment

both rate and spectrum of appearance sensitive to CPV

➔ longer term plans
-- upgrade to stronger proton source
-- upgrade to neutrino factory

CERN-SPL-based Neutrino **SUPERBEAM**

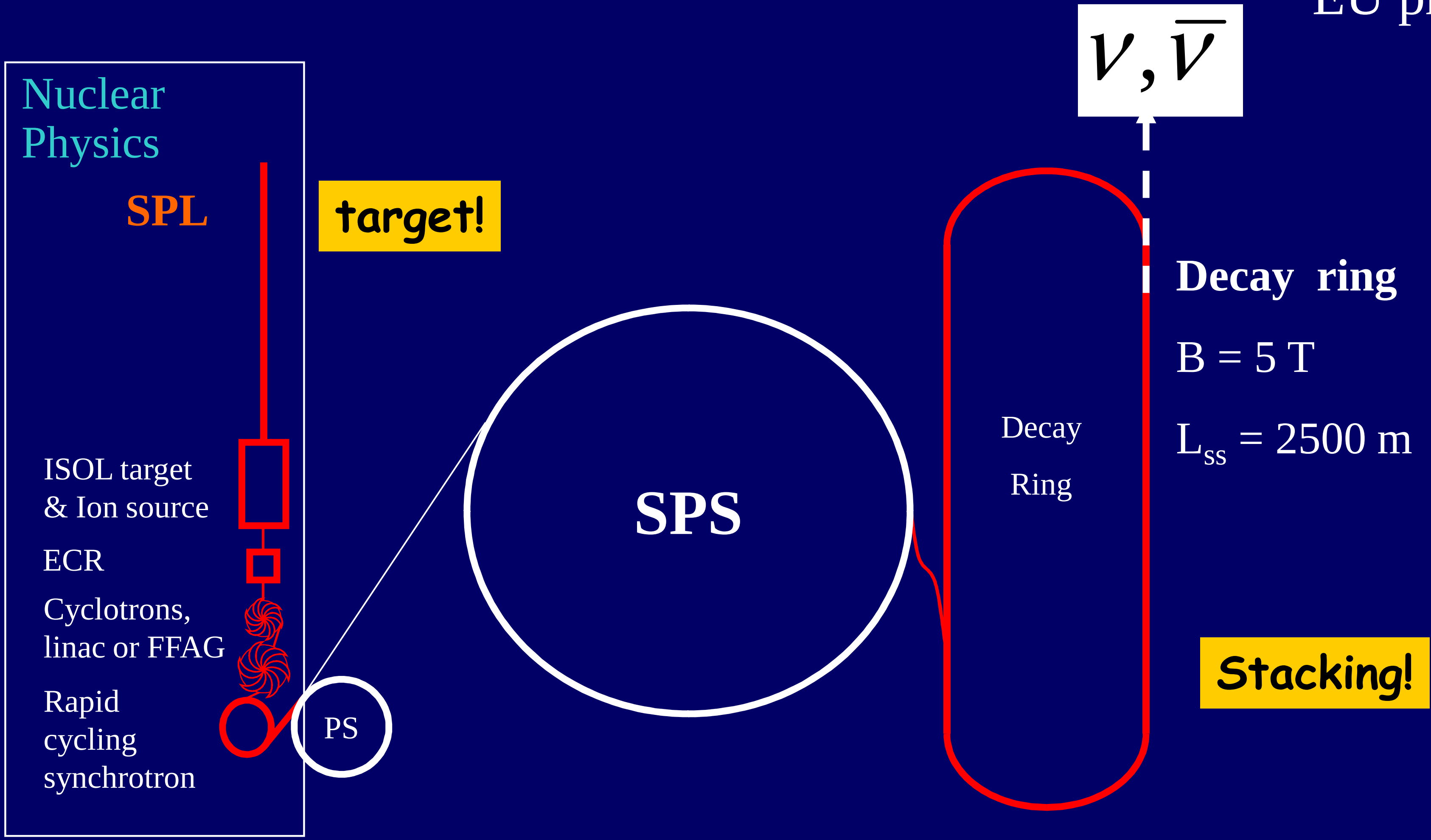


A large underground water Cerenkov (400 kton) UNO/HyperK or/and a large L.Arg detector.
also : proton decay search, supernovae events solar and atmospheric neutrinos. Performance similar to J-PARC II
There is a window of opportunity for digging the cavern stating in 2008 (safety tunnel in Frejus)

CERN: β-beam baseline scenario

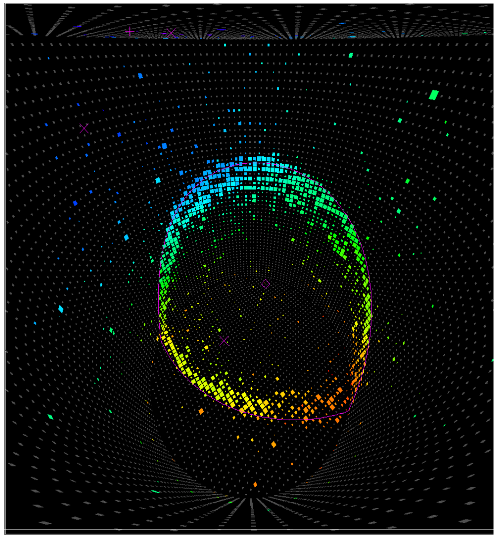
neutrinos of E_{max}=~600MeV

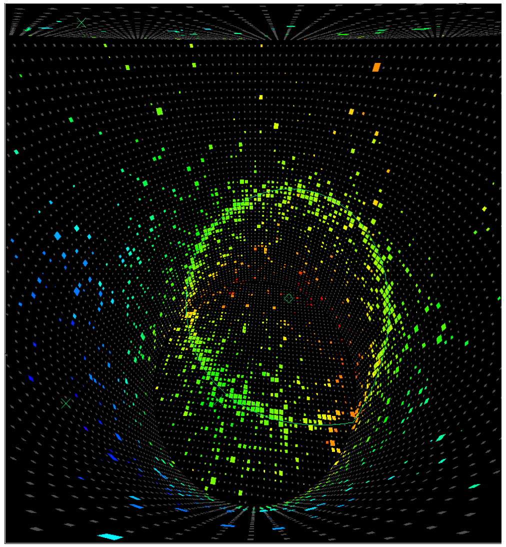
EU pride..



Same detectors as Superbeam !

Combination of beta beam with low energy super beam





Unique to CERN:

need few 100 GeV accelerator (PS + SPS will do!)
experience in radioactive beams at ISOLDE

many unknowns: what is the duty factor that can be achieved? (needs $< 10^{-3}$)

combines CP and T violation tests

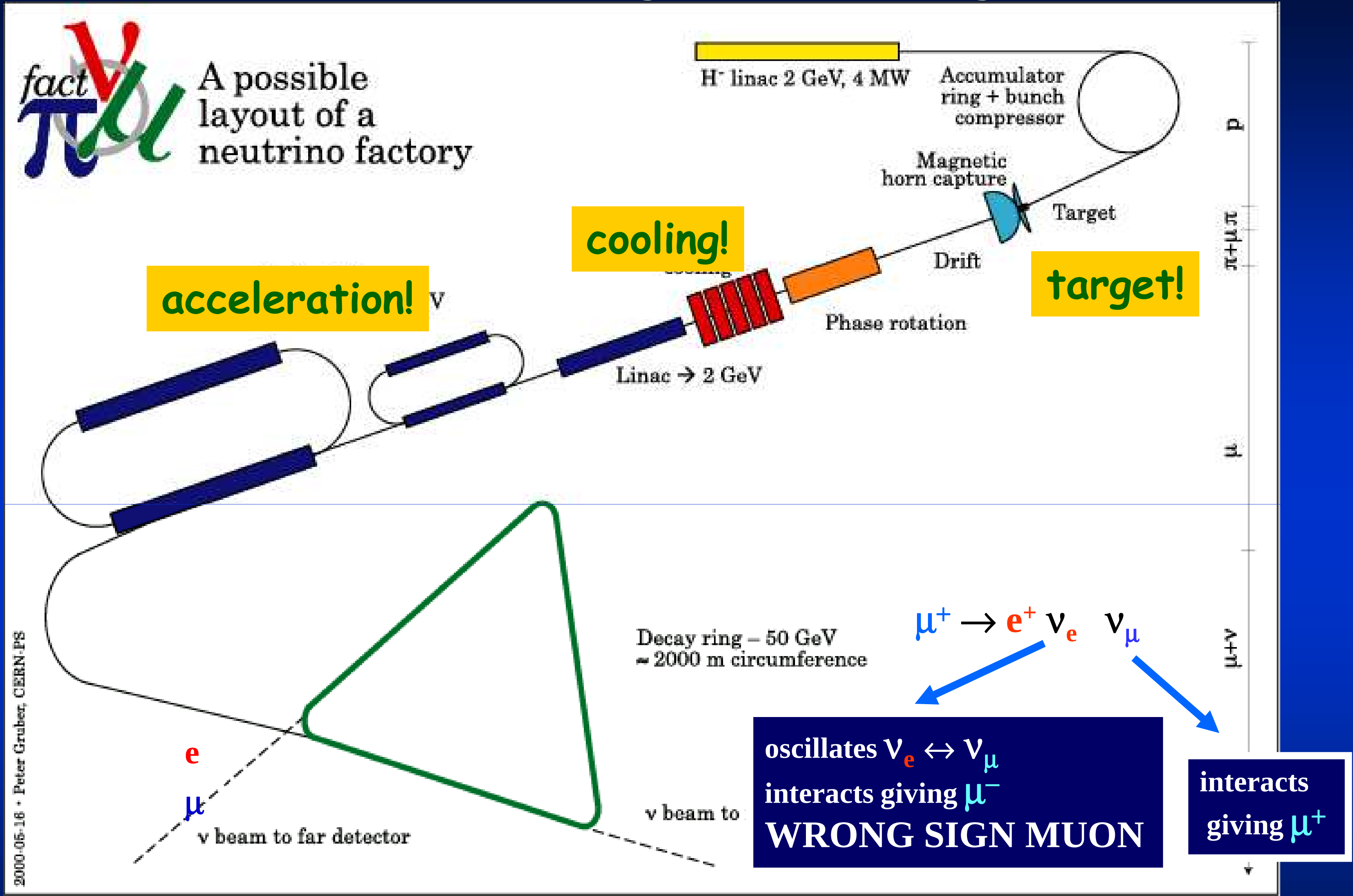
$\nu_e \rightarrow \nu_\mu$ (β+) **(T)** $\nu_\mu \rightarrow \nu_e$ (π^+)

(CP)

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (β-) **(T)** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (π^-)

Can this work???? **theoretical studies now on beta beam**
+ SPL target and horn R&D → design study together with EURISOL

-- Neutrino Factory -- CERN layout --



Where do you prefer to take shifts?

Golden MEASUREMENTS at ν- FACTORY

$$\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$$

$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$ is the golden measurement at Nufact:
appearance of wrong-sign muons

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

$$\downarrow$$

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

$$\mu^+ \rightarrow \bar{\nu}_\mu \quad \nu_e \quad e^+$$

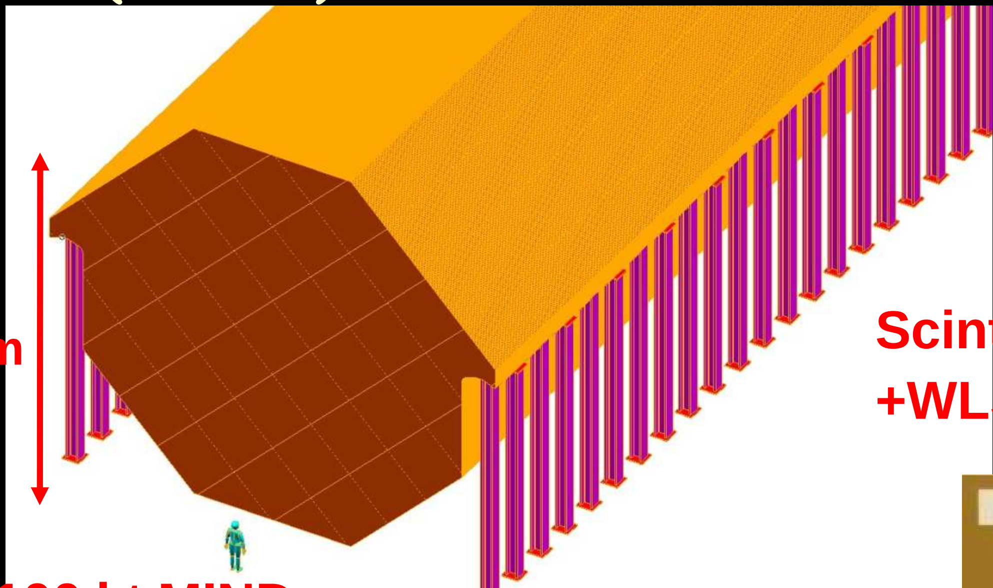
$$\downarrow$$

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

Neutrino Factory detectors

Neutrino Factory has demonstrated best performance

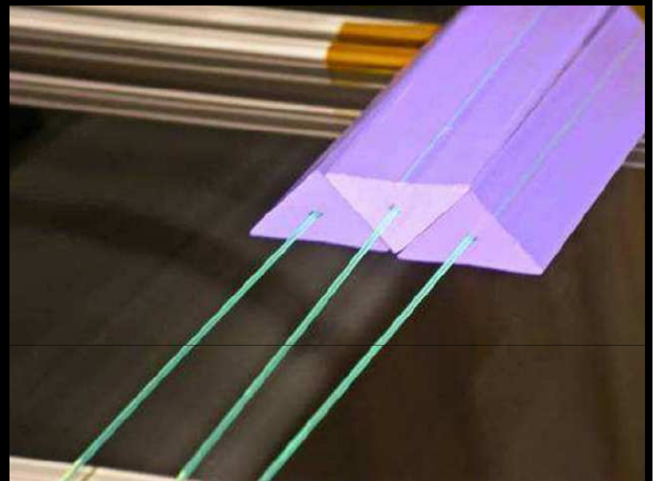
Neutrino detector: Magnetised Iron Neutrino Detector (MIND): iron+scintillator

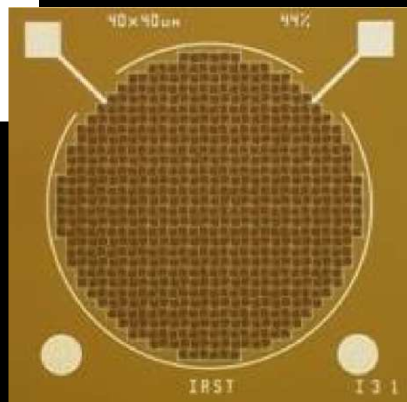


14 m

50-100 kt MIND

Scintillator +WLS fibre





Multi Pixel Photon Counter (MPPC)

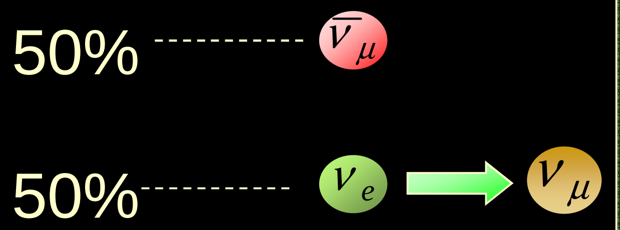
Toroidal B-field: 1-2.2 T

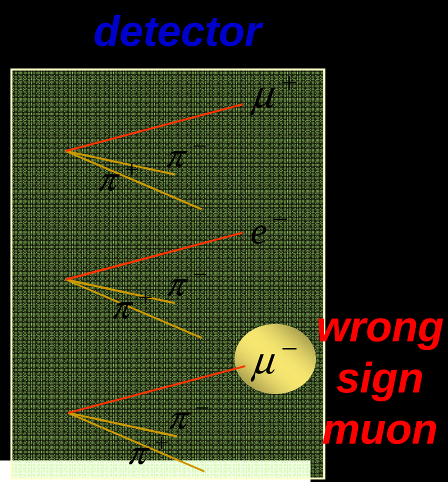
Neutrino Factory detectors

Neutrino Factory with MIND

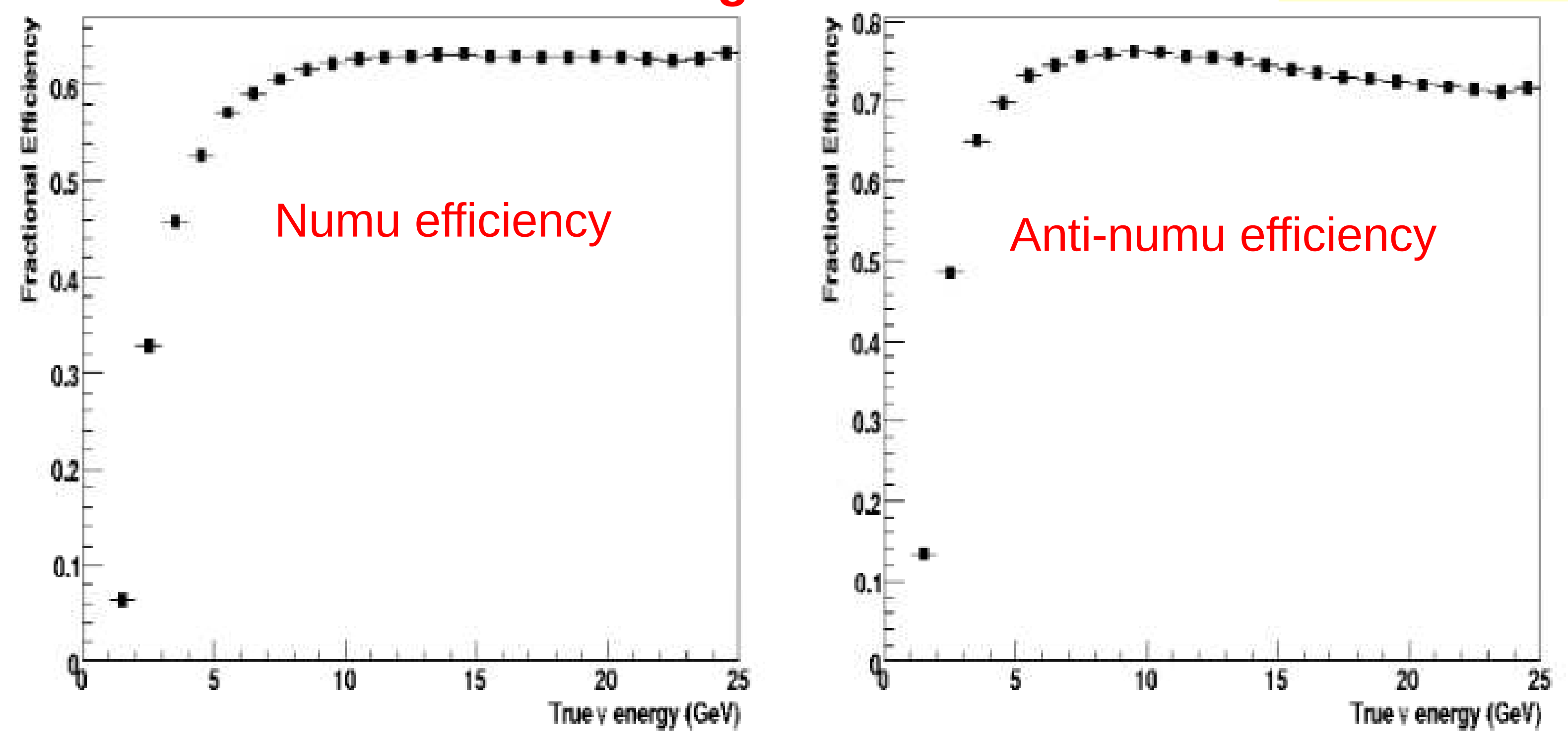
Wrong-sign muon identification

Test muon charge identification capabilities in MIND test beam.



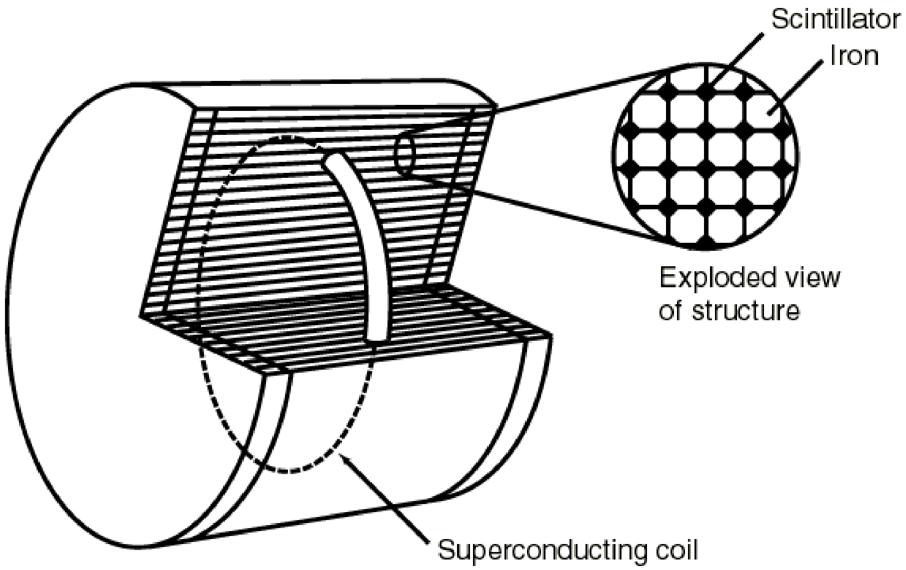


Background: 10^{-4}



Detector

LARGE MAGNETIC DETECTOR



Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

Iron calorimeter

Magnetized

- Charge discrimination
- B = 1 T

R = 10 m, L = 20 m

Fiducial mass = 40 kT

Also: L Arg detector: magnetized ICARUS
Wrong sign muons, electrons, taus and NC evts *->

Events for 1 year

Baseline	$\overline{\nu}_\mu$ CC	ν_e CC	ν_μ signal ($\sin^2\theta_{13}=0.01$)	
732 Km	3.5 x 10^7	5.9 x 10^7	1.1 x 10^5	(J-PARC I → SK = 40)
3500 Km	1.2 x 10^6	2.4 x 10^6	1.0 x 10^5	

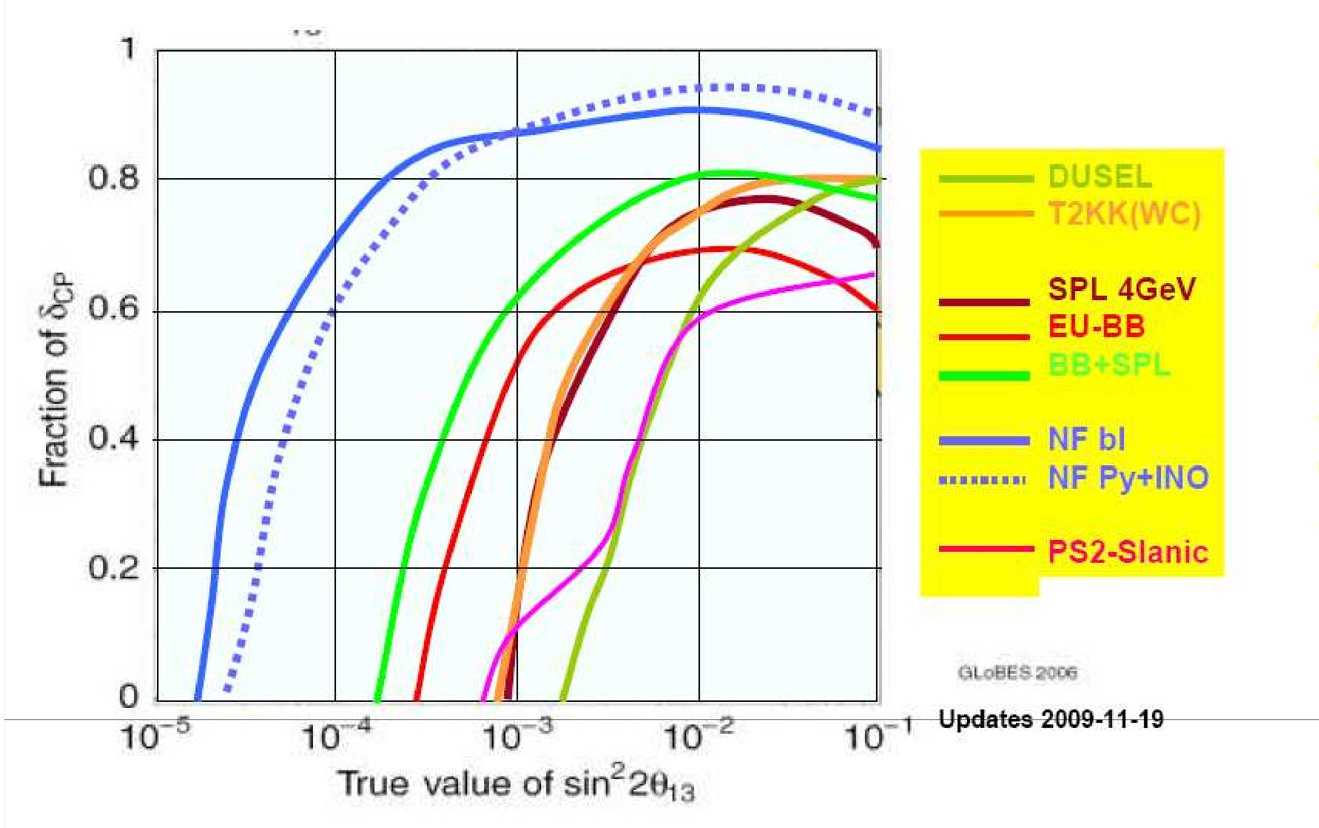


Figure 2 A representative compilation of sensitivities of some future long baseline projects. Here the fraction of δ_{CP} where CP violation can be observed at 3 standard deviations is plotted as a function of θ_{13}.

T2KK: *T2K 1.66 MW beam to 270 kton fid volume Water Cherenkov detectors in Japan (295km) and in Korea (1050 km);*
DUSEL*: a WBB from Fermilab to a 300 kton WC in Dusel (1300km);*
SPL 4 GeV, EU-BB and BB+SPL: *CERN to Fréjus (130km) project;*
NF bl *is the Neutrino Factory baseline (4000km and 7000km baselines) and*
NF Py+INO *represents the concrete baseline from CERN to Pyhasalmi mine in Finland (2285 km) and to INO in India (7152 km);*
PS2-Slanic *is a preliminary superbeam study at 1500km based on an upgrade of PS2 to 1.66MW and a 100kton Liquid Argon TPC*

SPC meeting, 16.03.2010

Neutrino fluxes $\mu^+ \to e^+ \nu_e \nu_\mu$

ν_μ/ν_e ratio reversed by switching μ^+/μ^-
ν_e ν_μ spectra are different
No high energy tail.

Very well known flux ($\pm 10^{-3}$)

-- E&σ_E calibration from muon spin precession

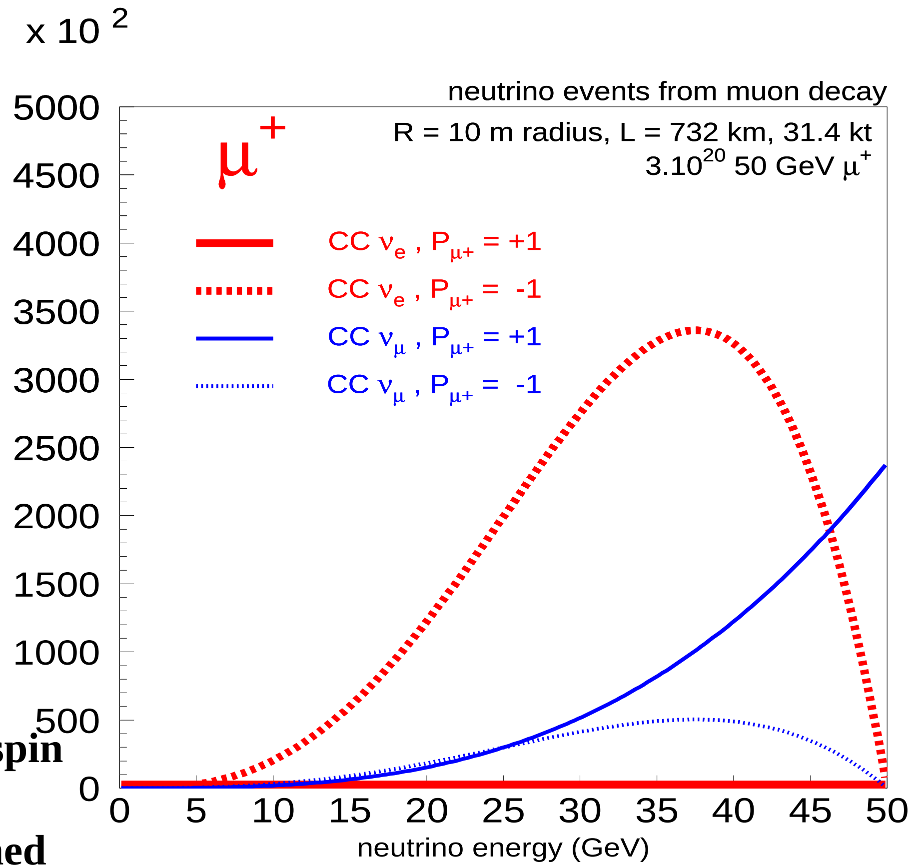
-- angular divergence: small effect if $\theta < 0.2/\gamma$,

-

- **absolute flux measured** from muon current
or by $\nu_\mu e^- \to \mu^- \nu_e$ in near expt.

-- similar comments apply to beta beam, except spin 0

→ Energy and energy spread have to be obtained from the properties of the storage ring (Trajectories, RF volts and frequency, etc…)



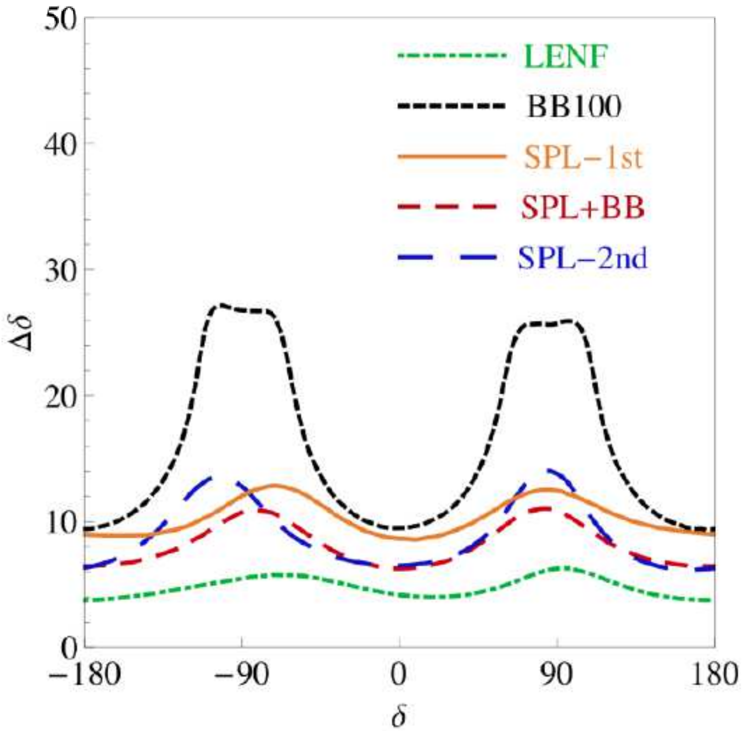
μ polarization controls ν_e flux:

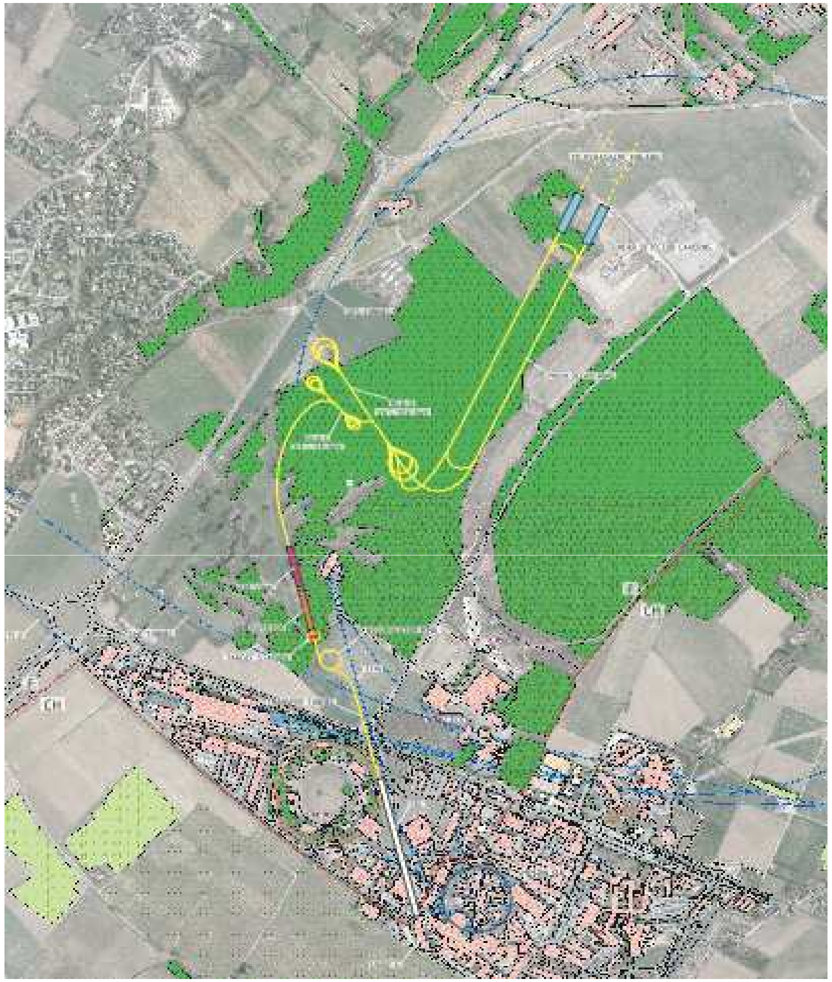
μ^+ -X> ν_e in forward direction

Neutrino Factory

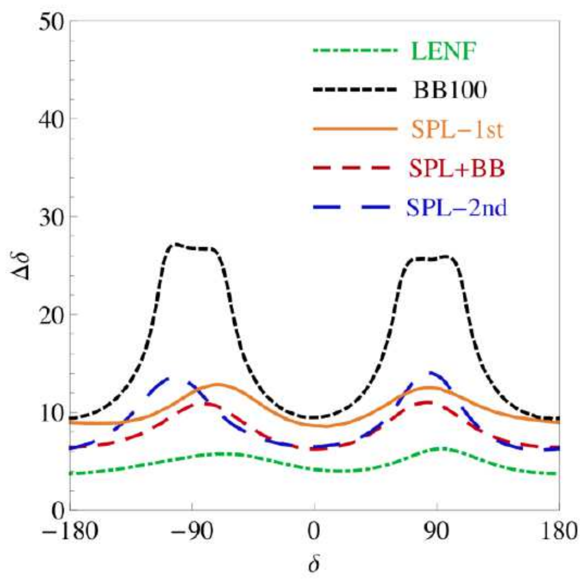
Given $\sin^2 2\theta_{13} \approx 0.1$, the optimal energy and distance for the neutrino factory are 2200km, 10 GeV muons

Pyhasalmi (2300km) OKOK





a 10 GeV neutrino factory on the CERN site aiming at the Pyhasalmi site



explanation of higher precision of Neutrino Factory (LENF=10 GeV NF) to delta_CP:

existence of **$\cos\delta \cos \Delta m^2_{23}L/4$** term

in addition to **$\sin\delta \sin \Delta m^2_{23}L/4$** term

which manifest itself between first and second oscillation maximum.

Short baseline (BB100) experiment is completely insensitive to this.

NF will be able to measure independently $\sin\delta$ and $\cos\delta$!

$$p(\nu_\mu \to \nu_e) =$$

$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13}\ \text{driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \mathrm{CP-even}$$

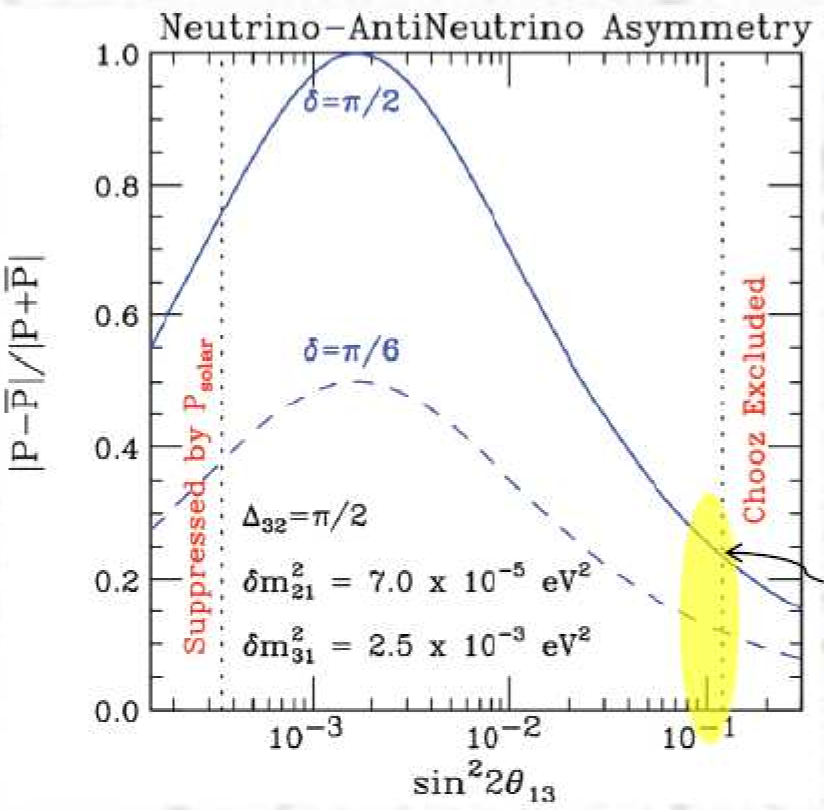
$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \mathrm{CP-odd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$- 8c_{13}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)} \tag{1}$$

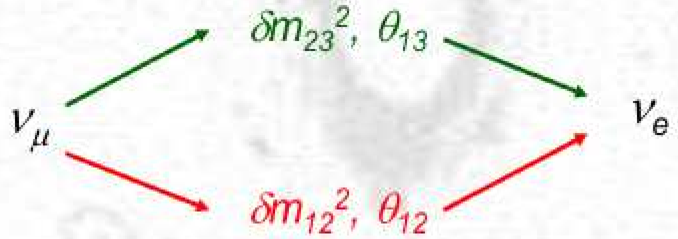
A last word on cross-sections

Implications of Large θ_{13}



(Parke 2003, arXiv:0710.554)

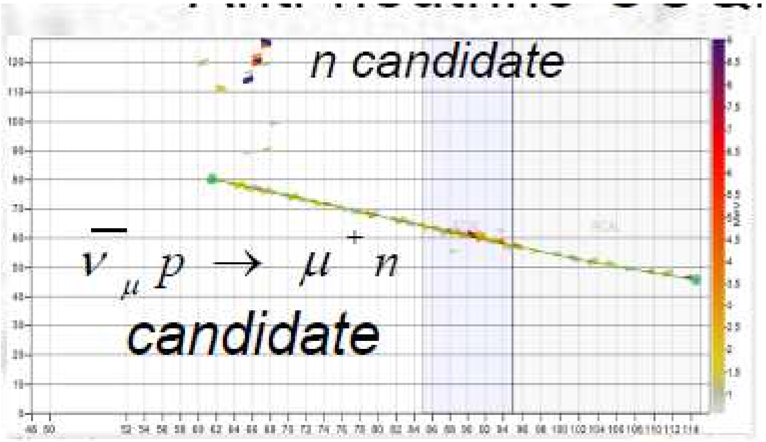
- Large θ_{13} means high rate of $\nu_\mu \rightarrow \nu_e$…
  - But fractional CP asymmetry decreases as θ_{13} increases

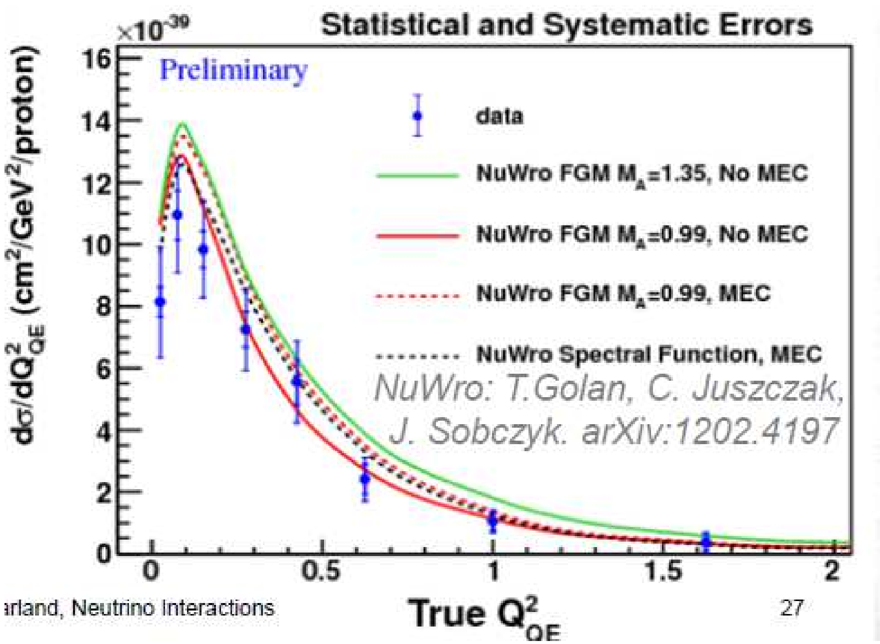


- Nature put us here
- Relatively high statistics, so the challenge will be controlling systematic uncertainties.

New results

MINERvA





07- 2012

T2K ND280

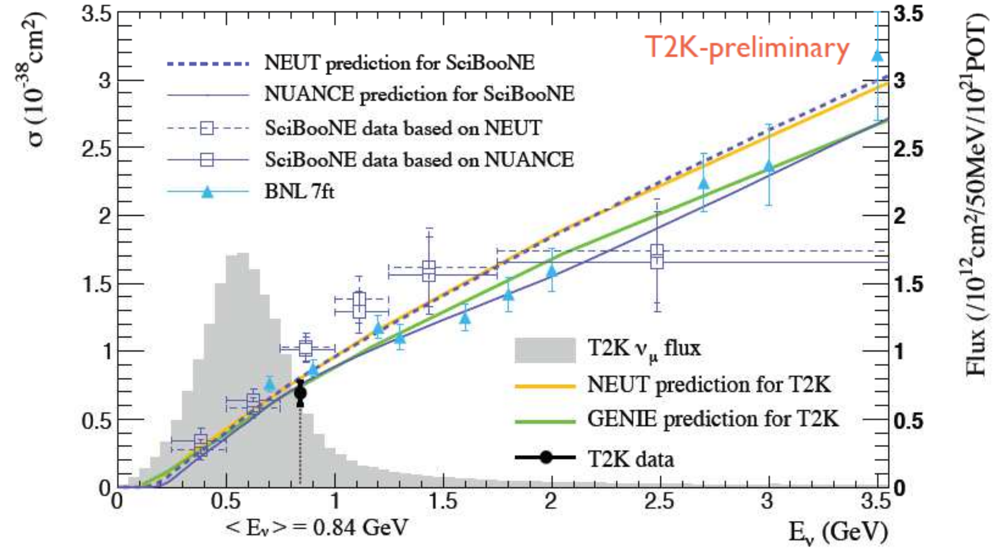
data

$$\langle\sigma_{CC}\rangle_\phi = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39}\,\frac{\text{cm}^2}{\text{nucleons}}$$

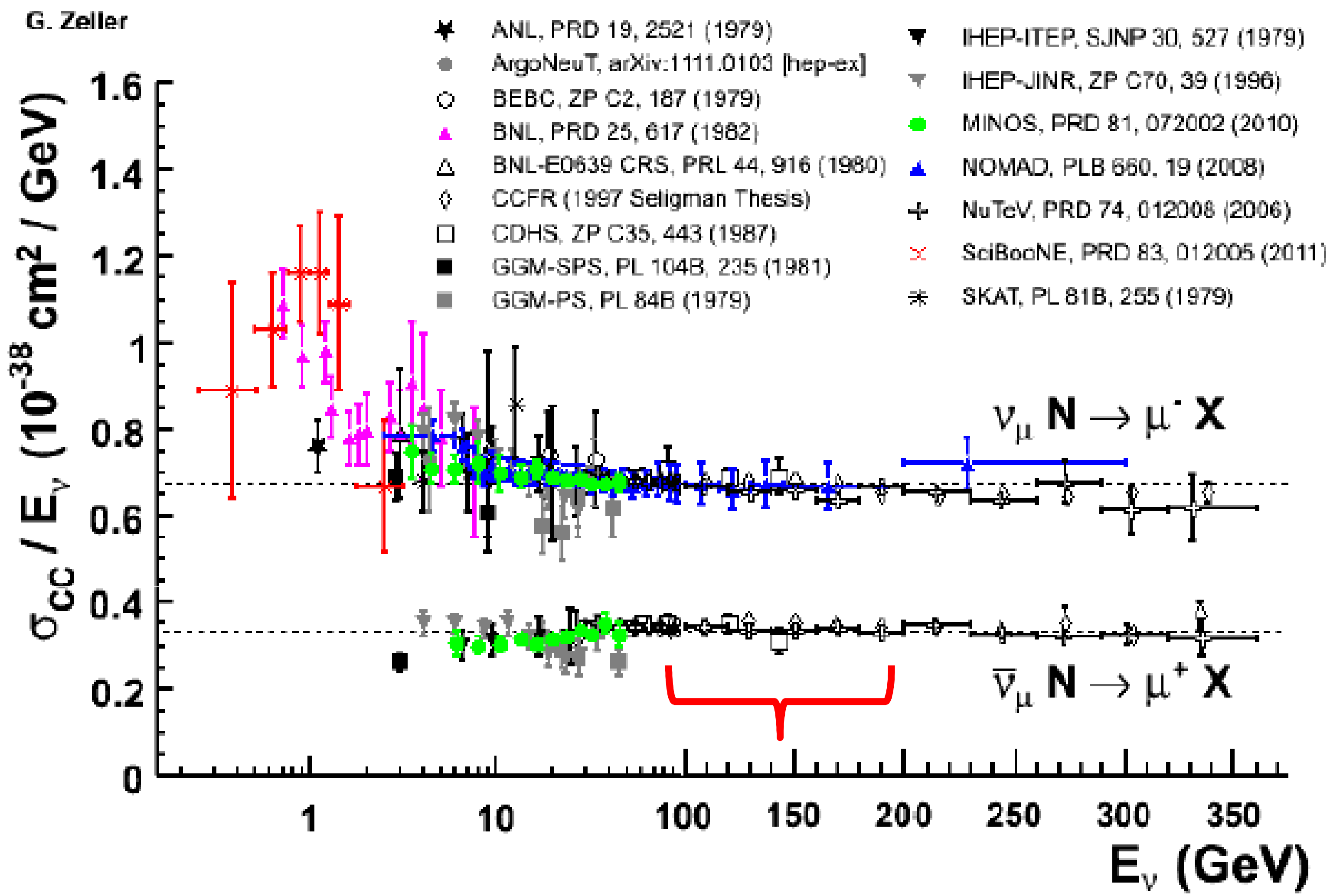
predicted from generators

$$\langle\sigma_{CC}^{NEUT}\rangle_\phi = 7.26 \times 10^{-39}\,\frac{\text{cm}^2}{\text{nucleons}}$$

$$\langle\sigma_{CC}^{GENIE}\rangle_\phi = 6.68 \times 10^{-39}\,\frac{\text{cm}^2}{\text{nucleons}}$$

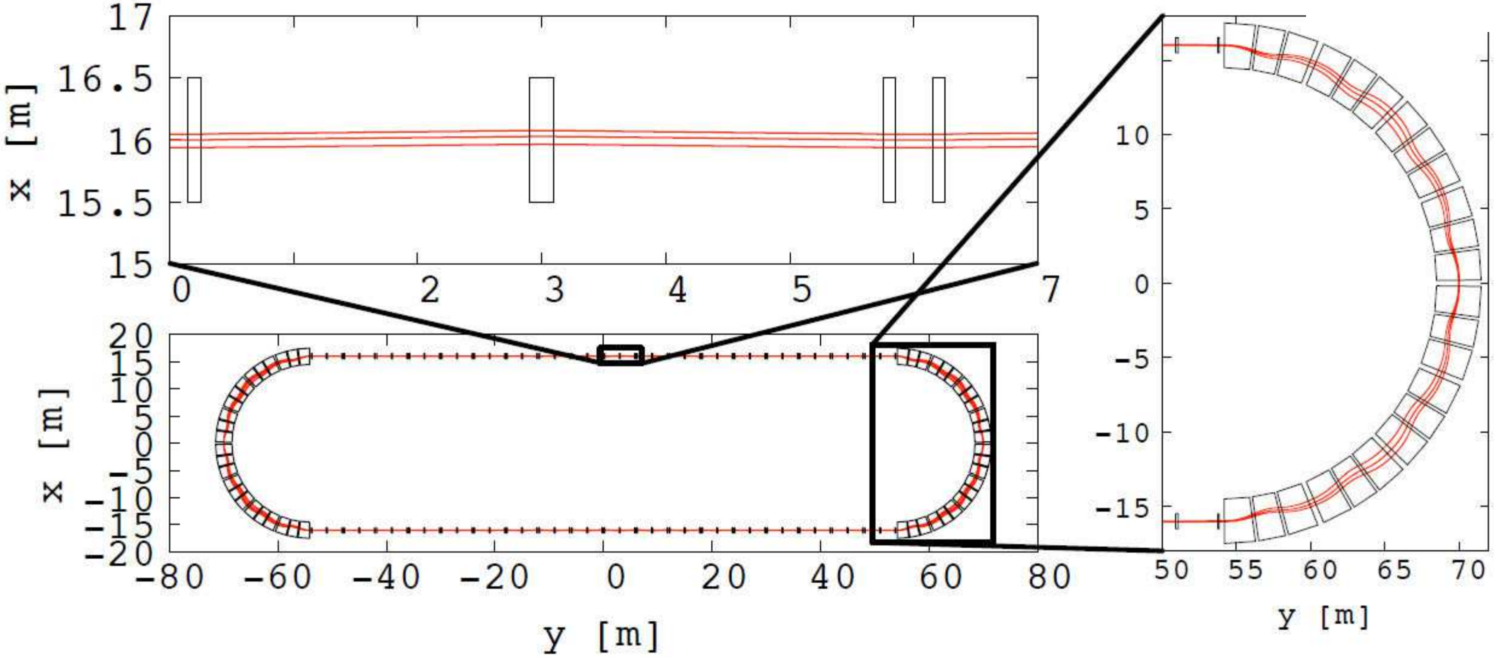


Thursday, July 5, 2012



the best, 2-3 % measurements were made with narrow-band beams (count decaying pions)

A first NUFACT step: cross-section measurements



muon storage ring with absolute count of muons
and nearly perfect knowledge of muon decay
➔ flux to (few) permil precision for all four of ν_e $\bar{\nu}_\mu$ $\bar{\nu}_e$ ν_μ

by running at nearby energies can extract nearly monochromatic beam of these flavours. ➔ calibrate energy reconstruction etc...

Conclusions

The last year has seen neutrinos in the forefront of particle physics – even for good reasons

What difference to have 5σ with a near/far detector methodology!

We now know all three angles of the active neutrino mixing matrix

We can plan for the next steps.

-- clean the sterile neutrino claims
-- search for sterile neutrinos everywhere we can
-- determine the mass hierarchy MH
    -- it does make sense to propose a 5σ MH determination
-- determine the CP violation and verify the 3x3 framework
    -- systematics will be crucial;
    -- cross-sections in particular
    -- nuSTORM as a first step towards nuFACT!

A very exciting middle term and long term future!