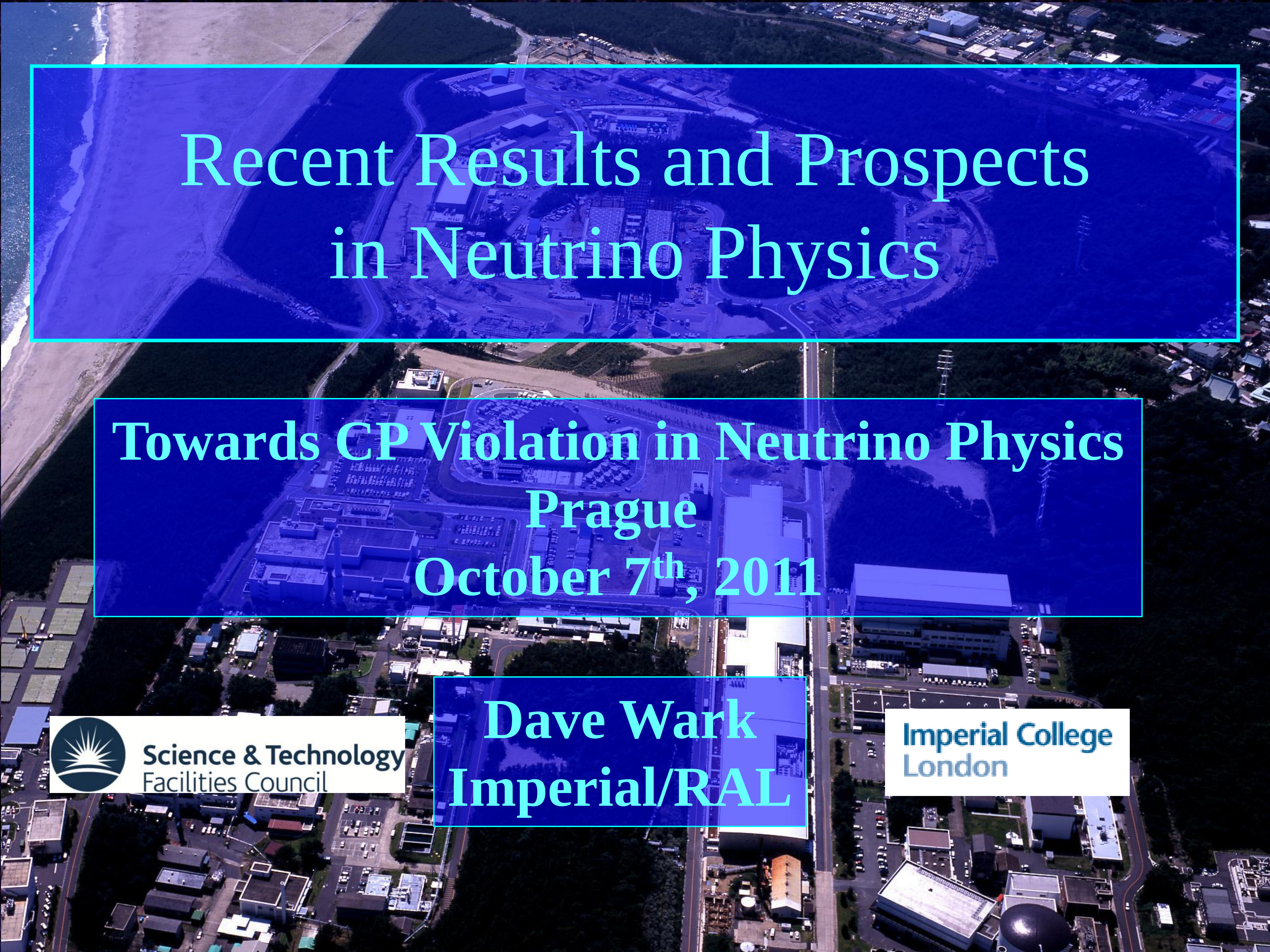


Recent Results and Prospects in Neutrino Physics

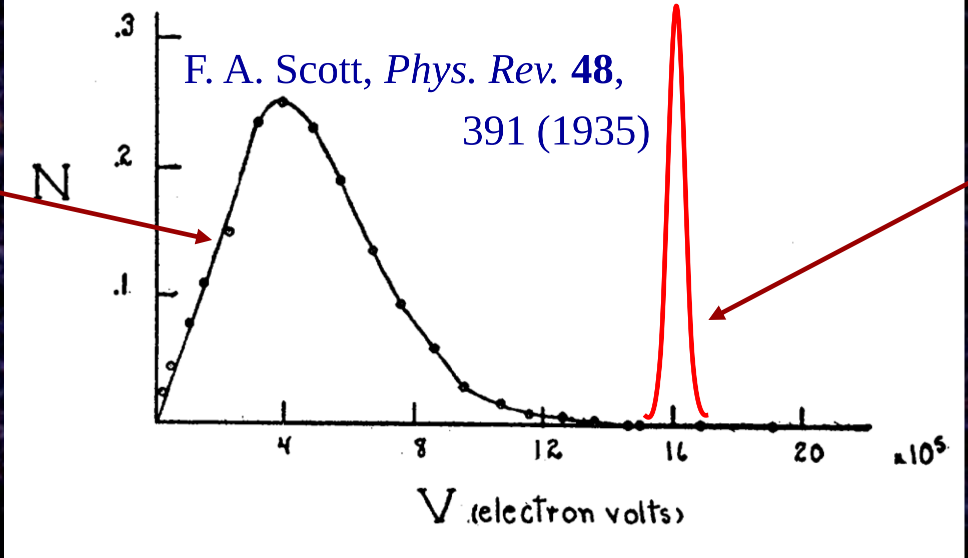
Towards CP Violation in Neutrino Physics
Prague
October 7th, 2011

Dave Wark
Imperial/RAL

Where did the idea of the neutrino come from?

There were problems in the early days of β decay.

β spectra were continuous



F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

FIG. 5. Energy distribution curve of the beta-rays.

Instead of discrete

And the spins didn't add up… $^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + e^{-}$

spin 0 spin 1 spin 1/2

Bohr: maybe energy/momentum not conserved in β decay?

Pauli's Solution…

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

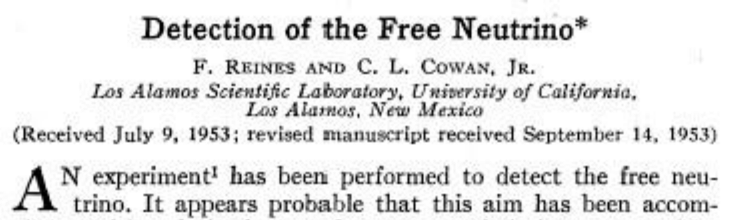
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like the new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
. W. Pauli

How to detect them?

- *The detection of neutrinos was an extreme challenge for the experiments of the mid-twentieth century – Pauli, in fact, apologized for hypothesizing a particle that could not be detected.*
- *In a Chalk River report in 1946, Bruno Pontecorvo pointed out the advantages of a radiochemical experiment based on* $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ *(and even mentioned solar neutrino detection using this method).*
- *However the first detection of neutrinos used another method…*

Towards CP Violation

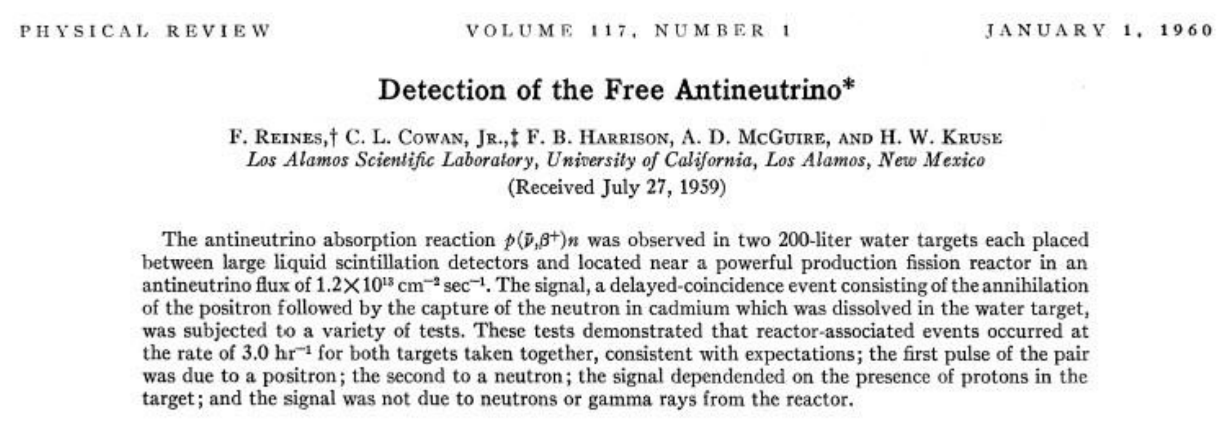


Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California,
Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

An experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The



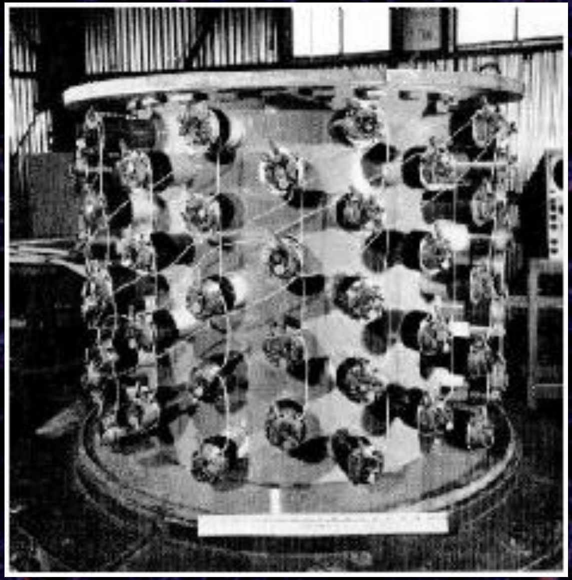
PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

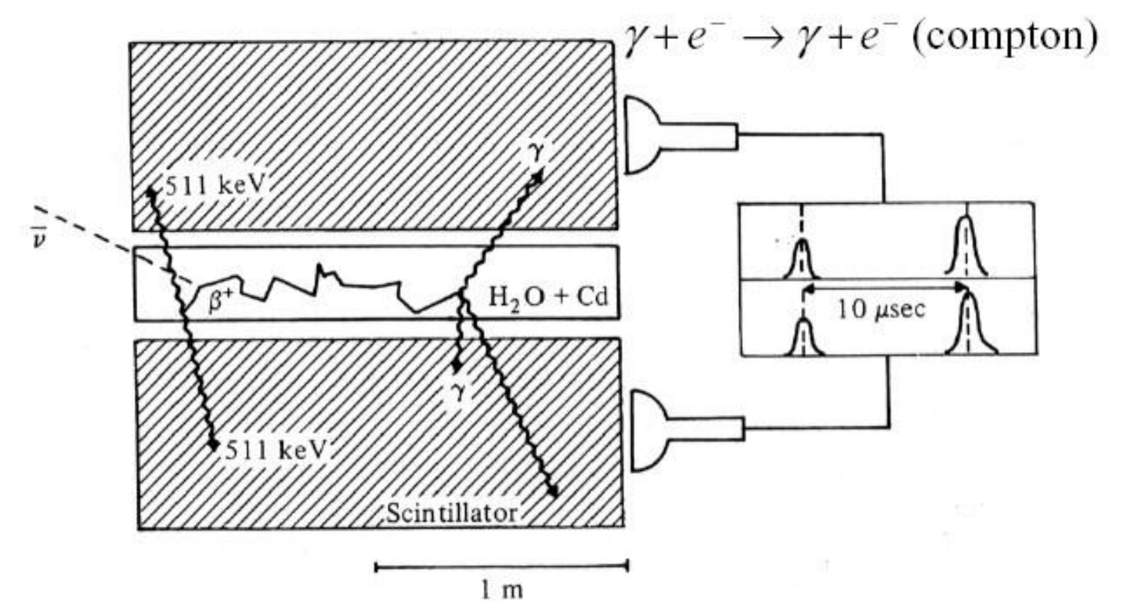
Detection of the Free Antineutrino*

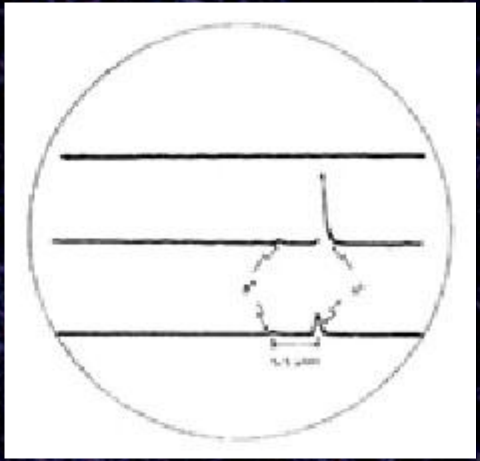
F. Reines,† C. L. Cowan, Jr.,‡ F. B. Harrison, A. D. McGuire, and H. W. Kruse
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.





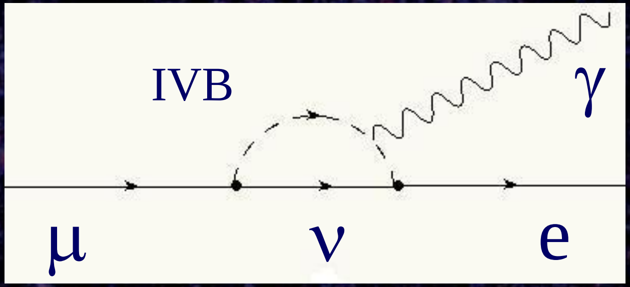


More Ancient History…

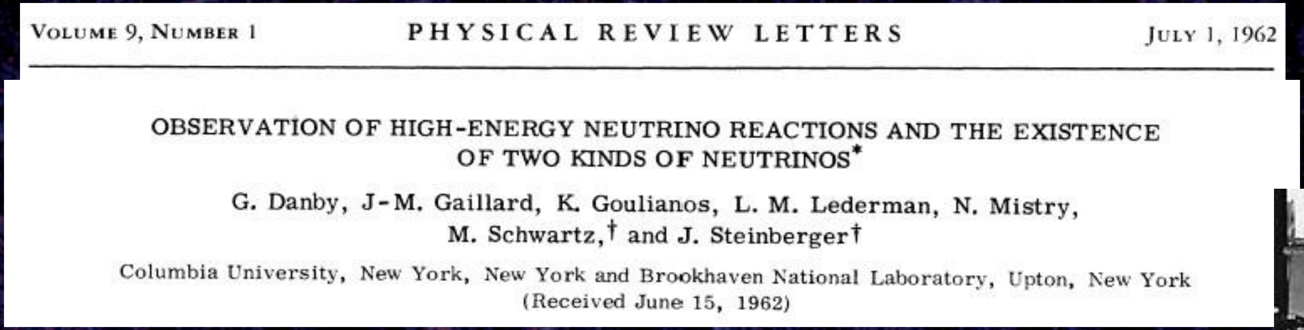
- Question in the late 50's: Are the neutrinos in these reactions the same thing?:

$n \rightarrow p + e + \nu \qquad \pi \rightarrow \mu + \nu \qquad \mu \rightarrow e + \nu + \nu$

- If so, why no $\mu \rightarrow e + \gamma$ via diagrams like?:



Towards CP Violation


VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

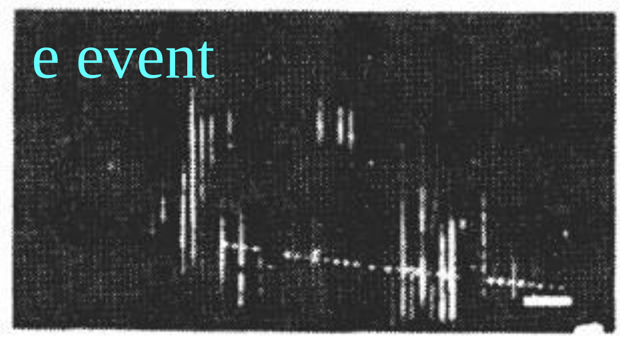
OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

Next year will be 50th anniversary!


μ event


e event

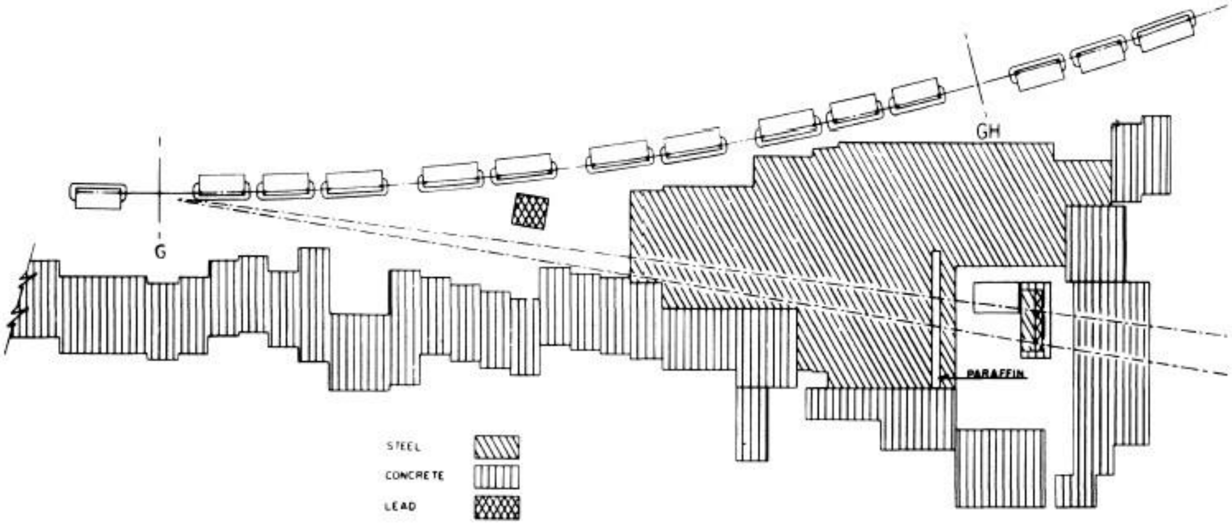


FIG. 1. Plan view of AGS neutrino experiment.

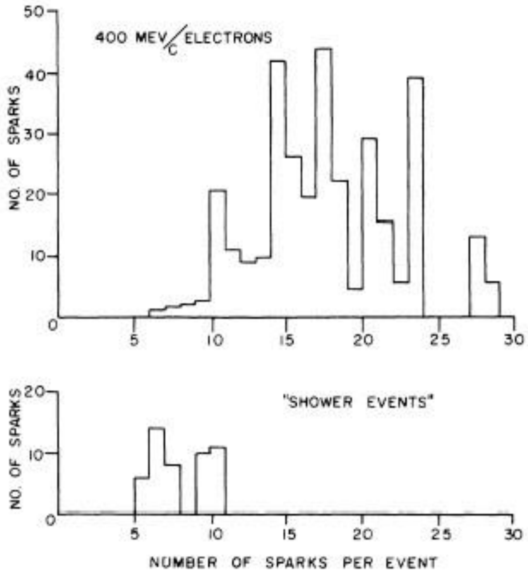
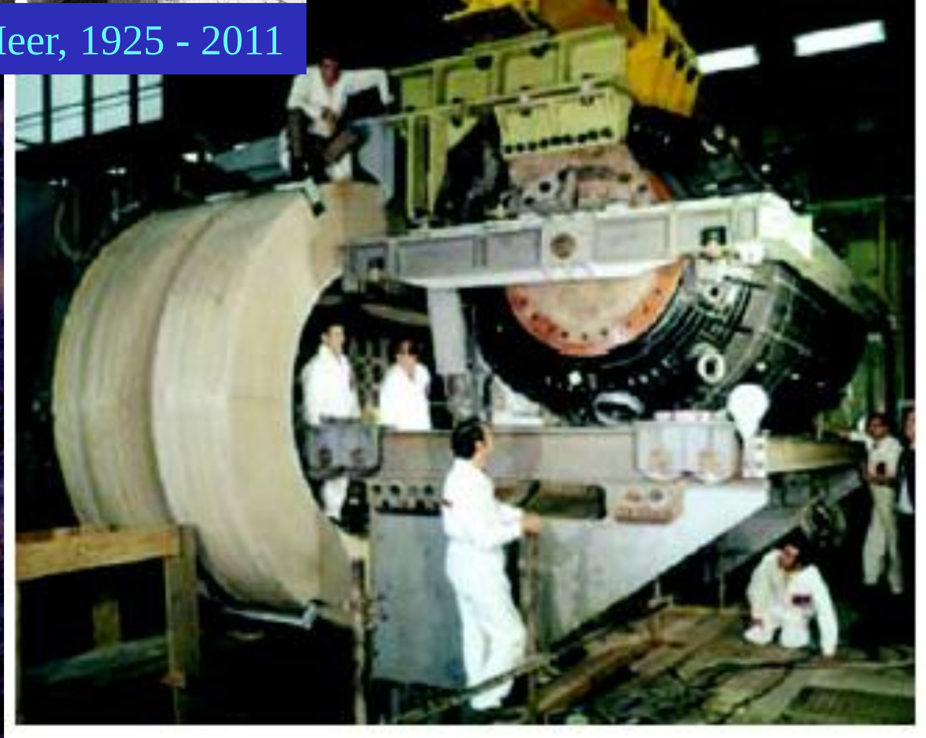


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

The Discovery of Neutral Currents

Simon van der Meer, 1925 - 2011

The 1st Neutrino Horn –
Van den Meer, CERN, 1961



The Gargamelle
CF_3Br Bubble Chamber

The Discovery of Neutral Currents

Most of the basic techniques were now in place, and since then we have built them bigger/faster/more sensitive. Learn from my advisor....

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle=\sum U_{li}|\nu_i\rangle$

$$U_{li}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

where $c_{ij}=\cos\theta_{ij}$, *and* $s_{ij}=\sin\theta_{ij}$

$$P(\nu_\mu\to\nu_e)=4C_{13}^2S_{13}^2S_{23}^2\sin^2\frac{\Delta m_{31}^2L}{4E}\times\left(1+\frac{2a}{\Delta m_{31}^2}\;(1-2S_{13}^2)\right)$$

$$+8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta-S_{12}S_{13}S_{23})\cos\frac{\Delta m_{32}^2L}{4E}\sin\frac{\Delta m_{31}^2L}{4E}\sin\frac{\Delta m_{21}^2L}{4E}$$

$$-8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\frac{\Delta m_{32}^2L}{4E}\sin\frac{\Delta m_{31}^2L}{4E}\sin\frac{\Delta m_{21}^2L}{4E}$$

$$+4S_{12}^2C_{13}^2\left\{C_{12}^2C_{23}^2+S_{12}^2S_{23}^2S_{13}^2-2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\}\sin^2\frac{\Delta m_{21}^2L}{4E}$$

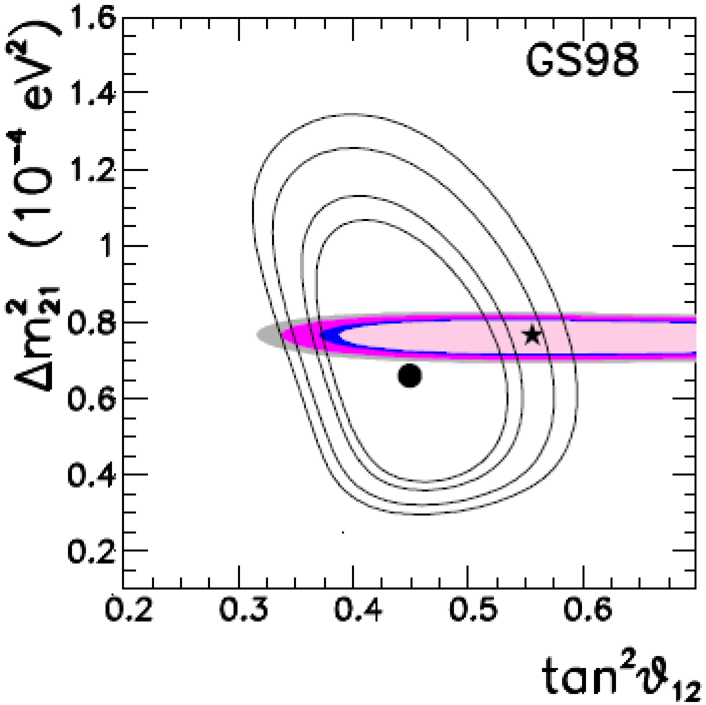
$$-8C_{13}^2S_{13}^2S_{23}^2\cos\frac{\Delta m_{32}^2L}{4E}\sin\frac{\Delta m_{31}^2L}{4E}\frac{aL}{4E}\;(1-2S_{13}^2$$

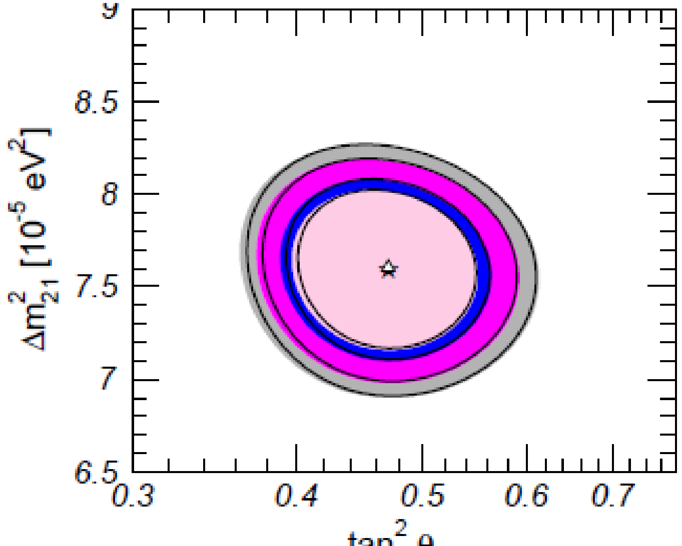
Remember degeneracies
And covariances!

How well do we know θ_{12}?

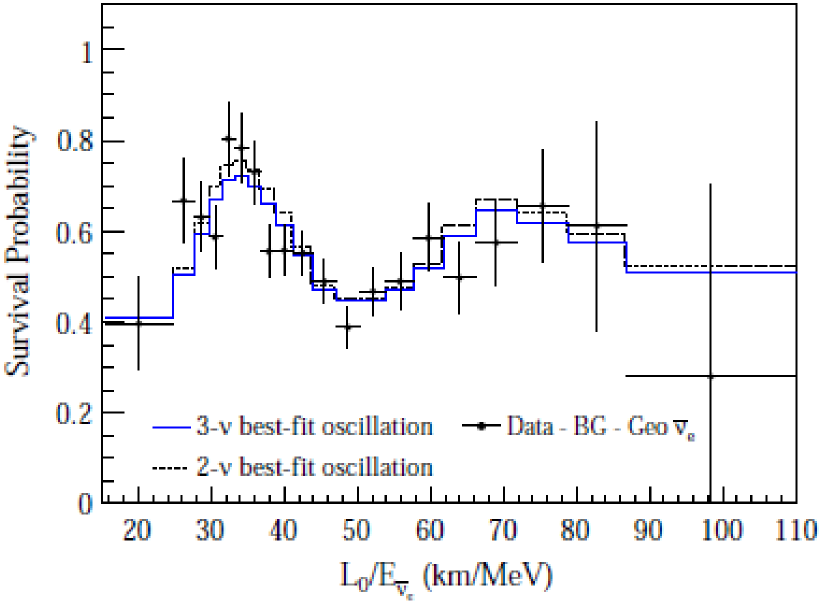
Gonzalez-Garcia, Maltoni, Salvado

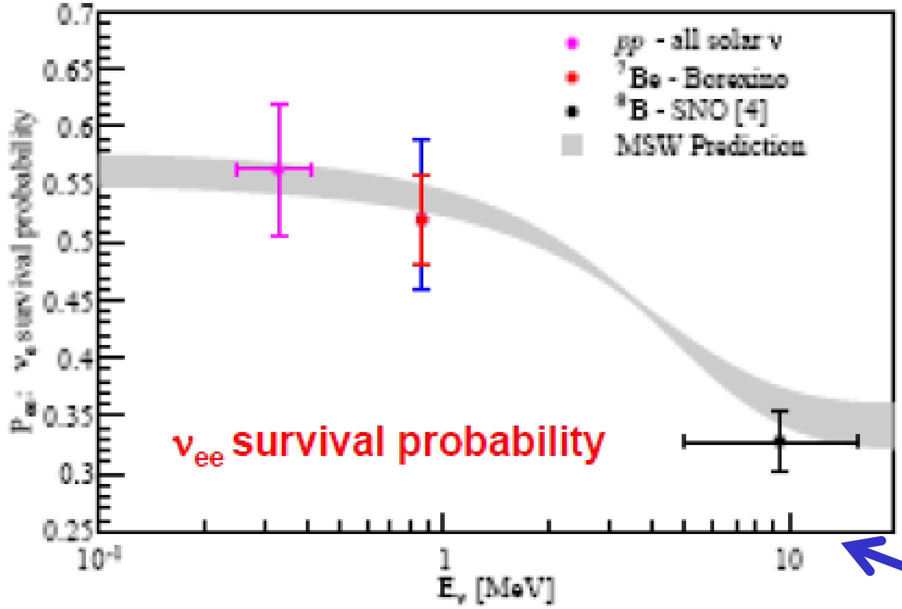
arXiv:1001.4524v4 [hep-ph] 16 Jun 2011





arXiv:1009.4771v3 [hep-ex] 25 Mar 2011



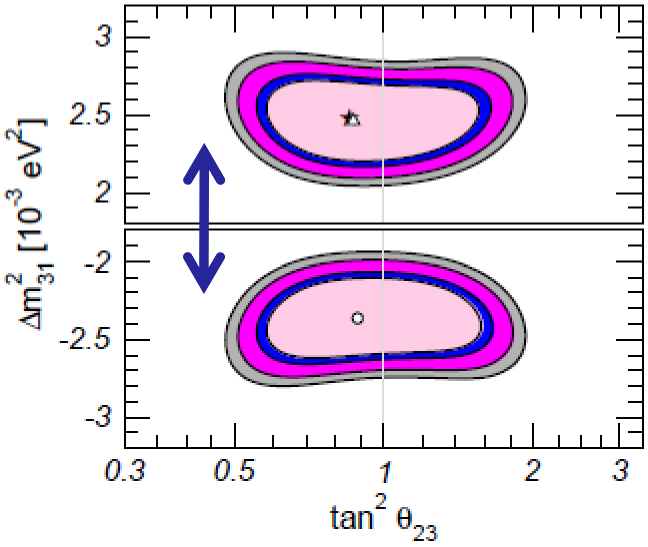


From Ranucci's BOREXINO talk at EPS 2011

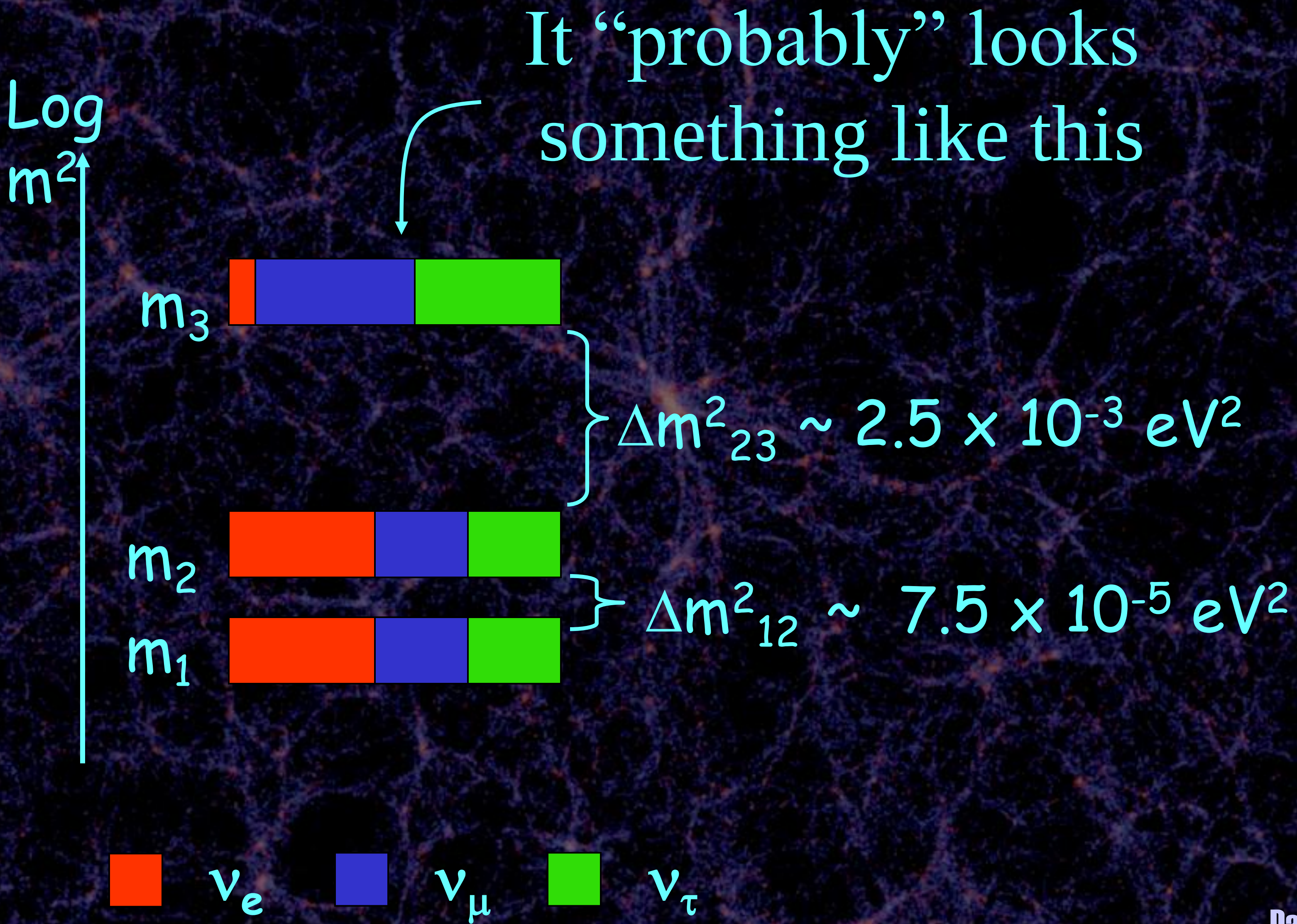
How well do we know θ_{23}?

Gonzalez-Garcia, Maltoni, Salvado

arXiv:1001.4524v4 [hep-ph] 16 Jun 2011



What is the pattern of neutrino masses?



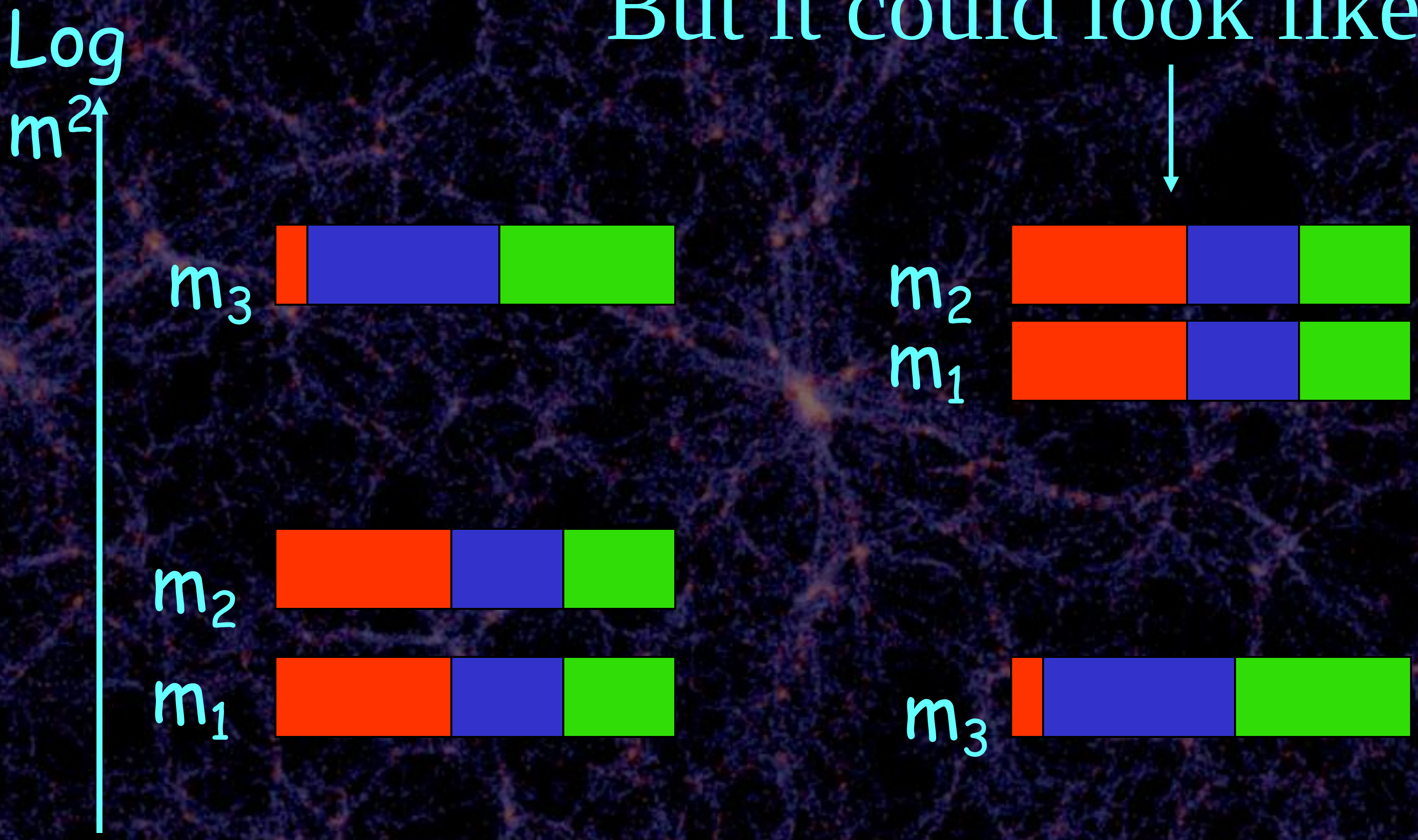
It "probably" looks something like this

$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{12} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$

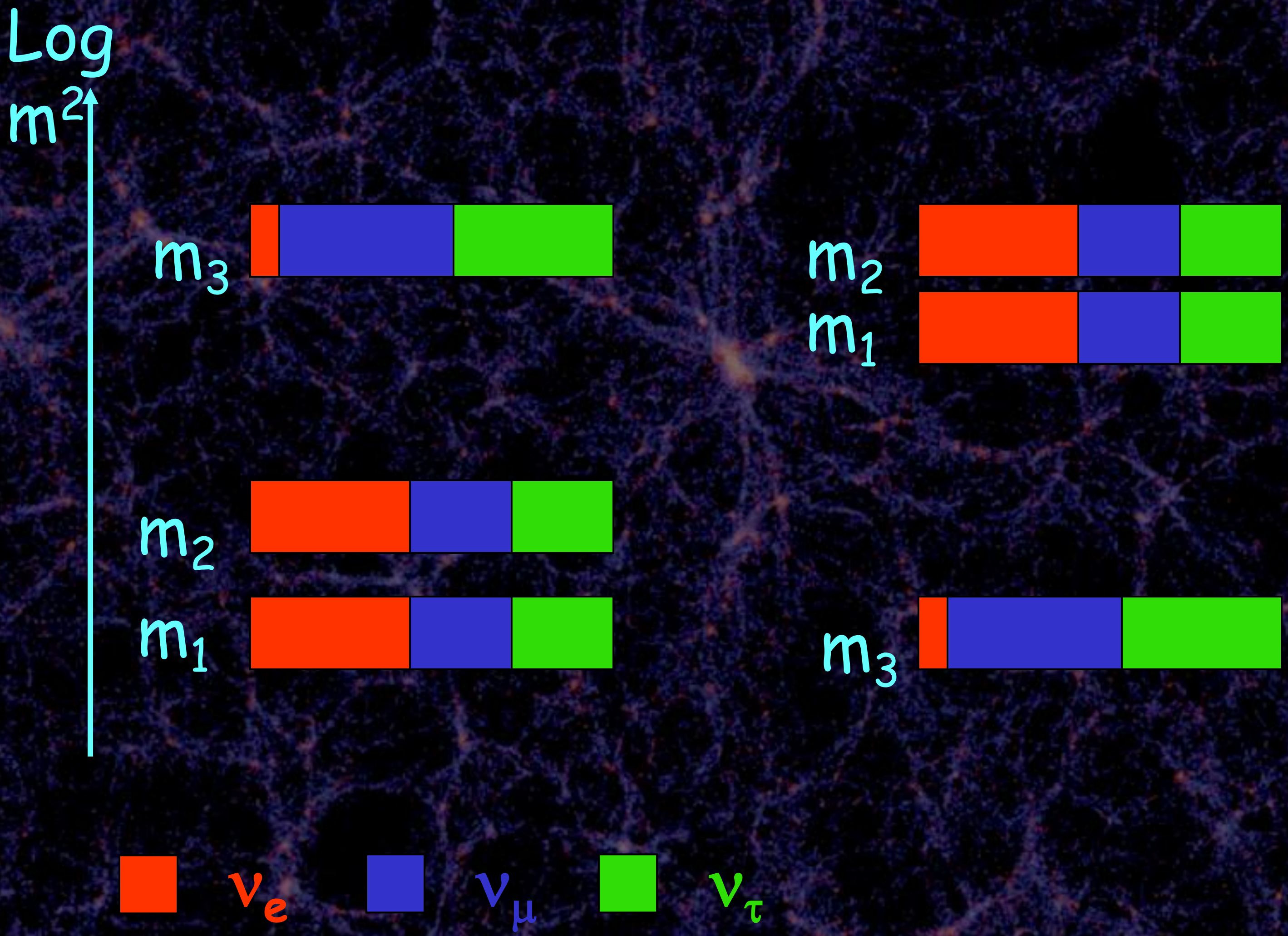
What is the pattern of neutrino masses?

But it could look like this

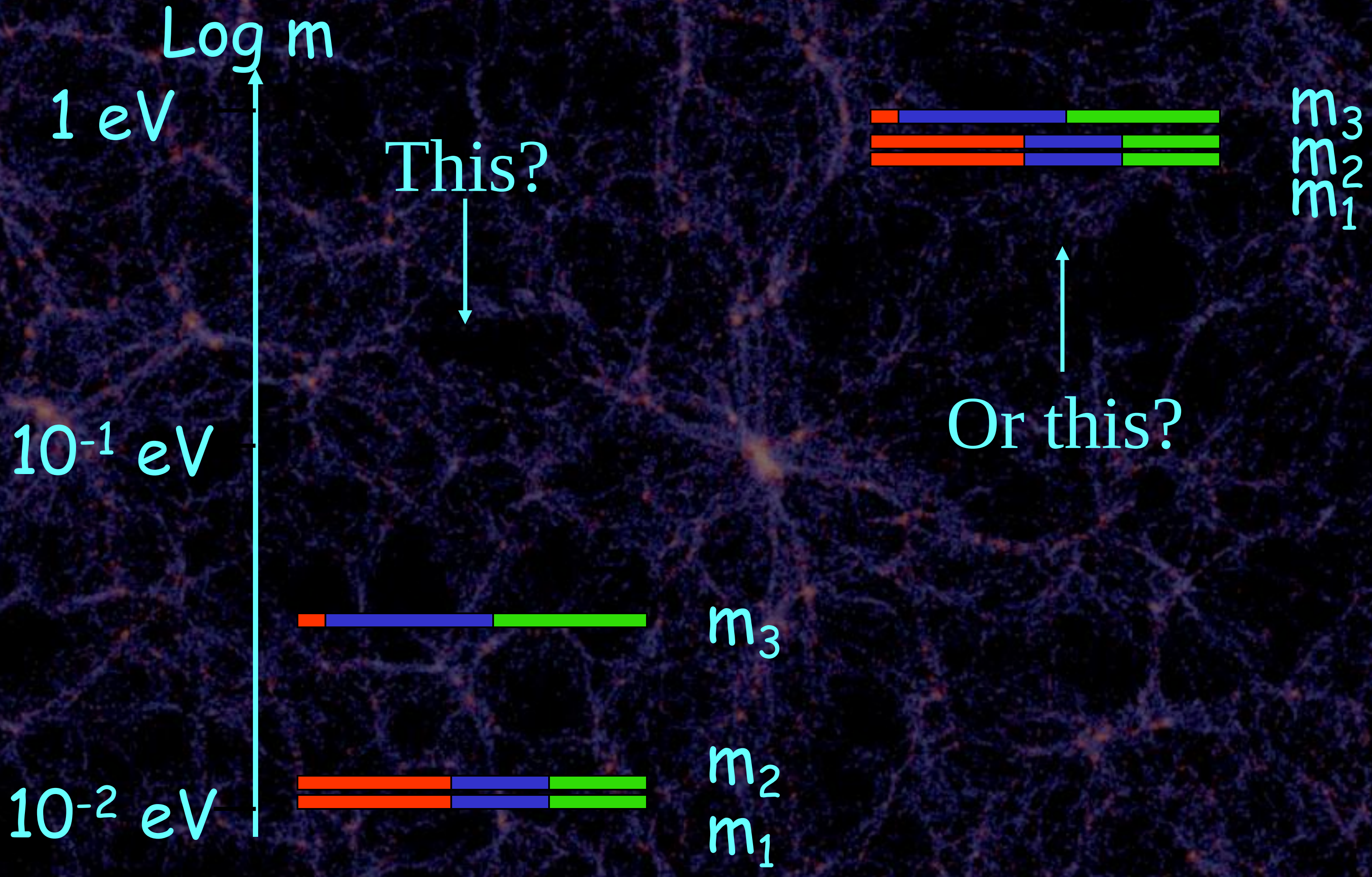


🟥 ν_e 🟦 ν_μ 🟩 ν_τ

This makes a factor of two difference in the cosmological contribution, but a factor of two on what?



Even more significant is the absolute scale.



This?

Or this?

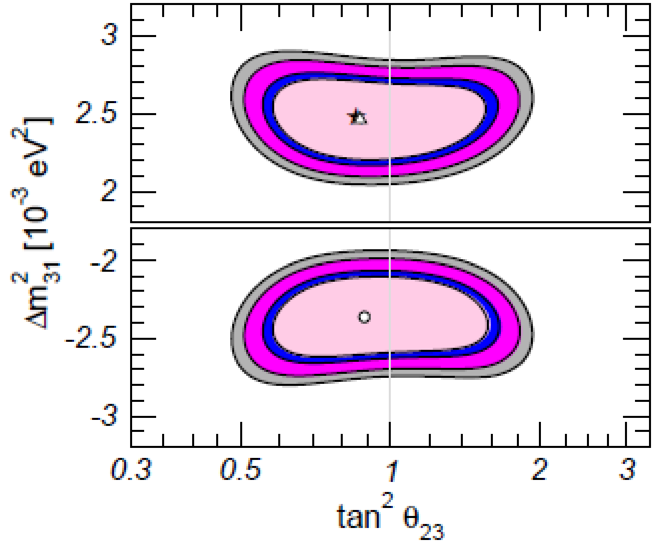
🟥 ν_e 🟦 ν_μ 🟩 ν_τ

Does this look natural?

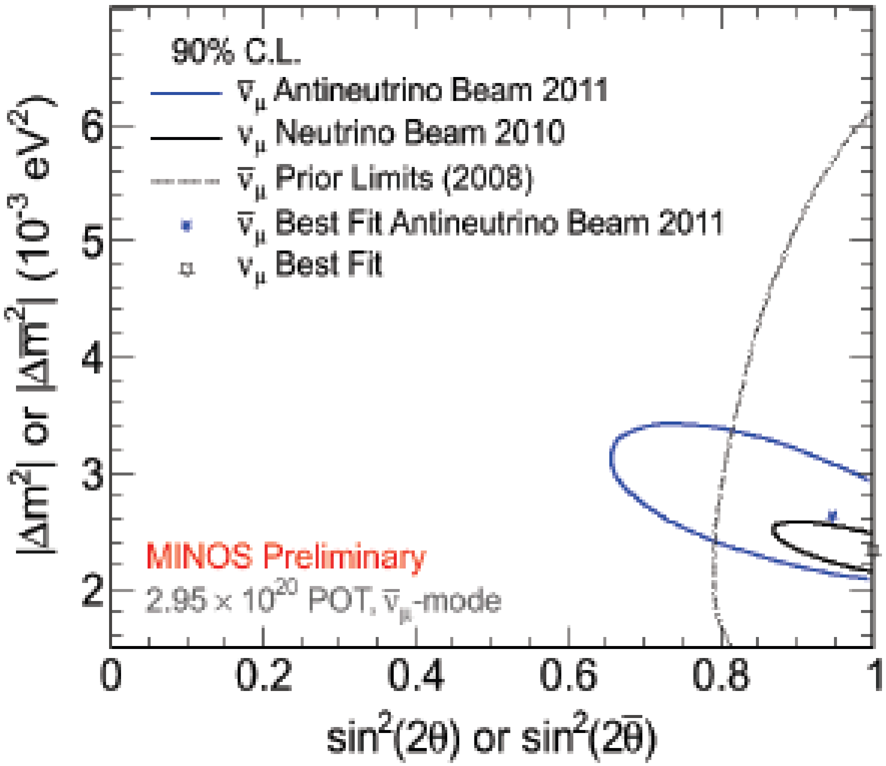
How well do we know θ_{23}?

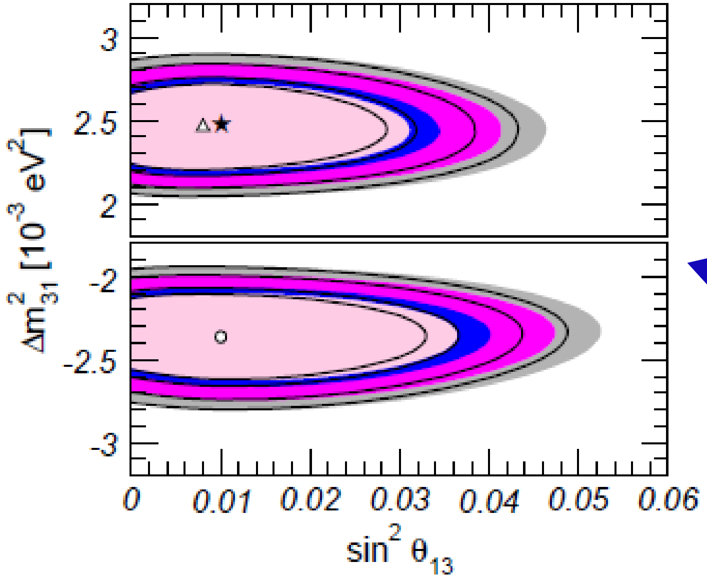
Gonzalez-Garcia, Maltoni, Salvado

arXiv:1001.4524v4 [hep-ph] 16 Jun 2011

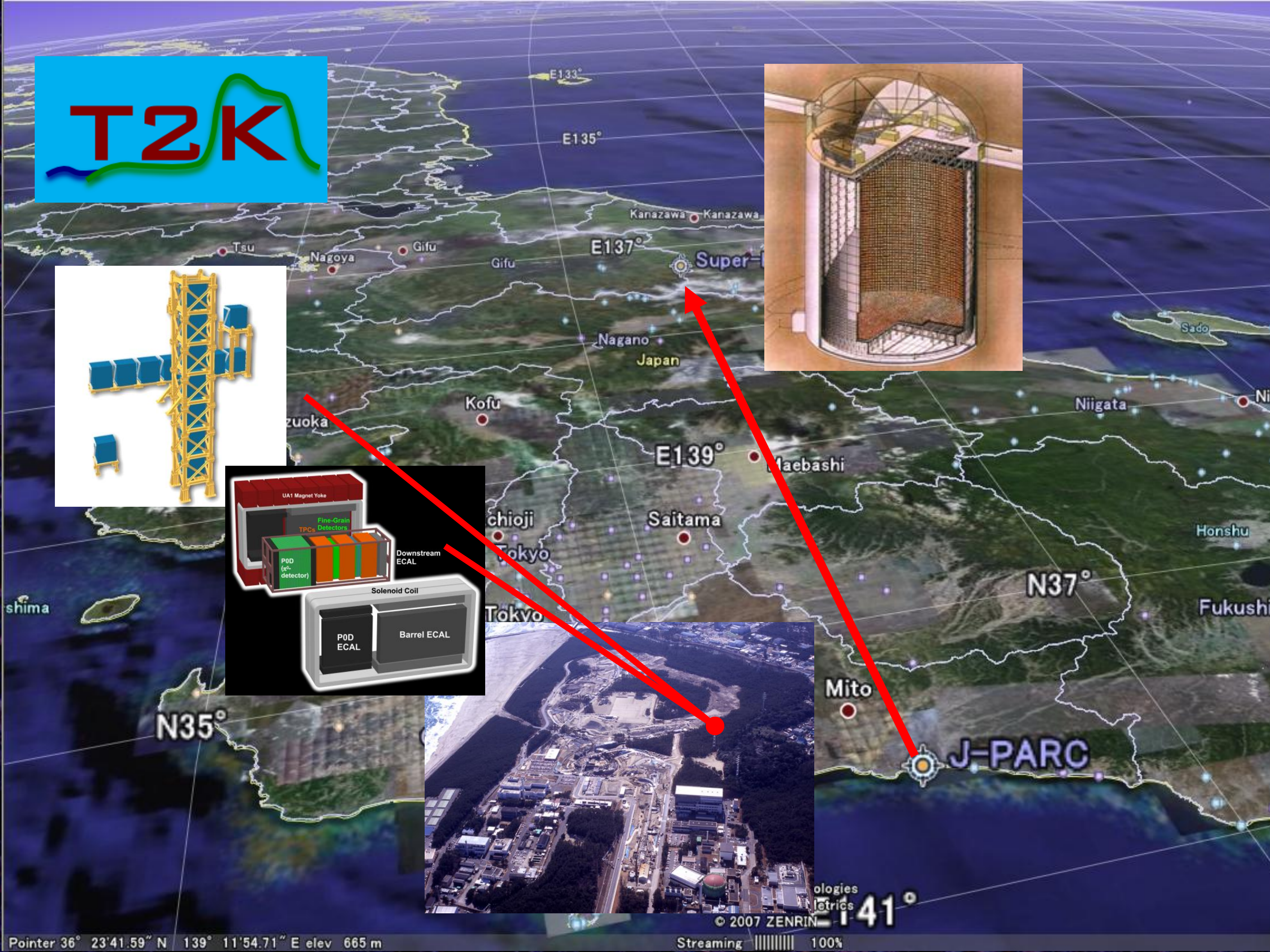


Tension between ν and $\bar{\nu}$ in MINOS relieved by new data....





But what about θ_{13}?


T2K
E133°
E135°
Kanazawa
Kanazawa
Tsu
Nagoya
Gifu
Gifu
E137°
Super-
Nagano
Japan
Sado
Kofu
zuoka
Niigata
Ni
E139°
Maebashi
UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π^0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL
chioji
Saitama
Tokyo
Tokyo
Honshu
N37°
Fukushi
shima
Mito
N35°
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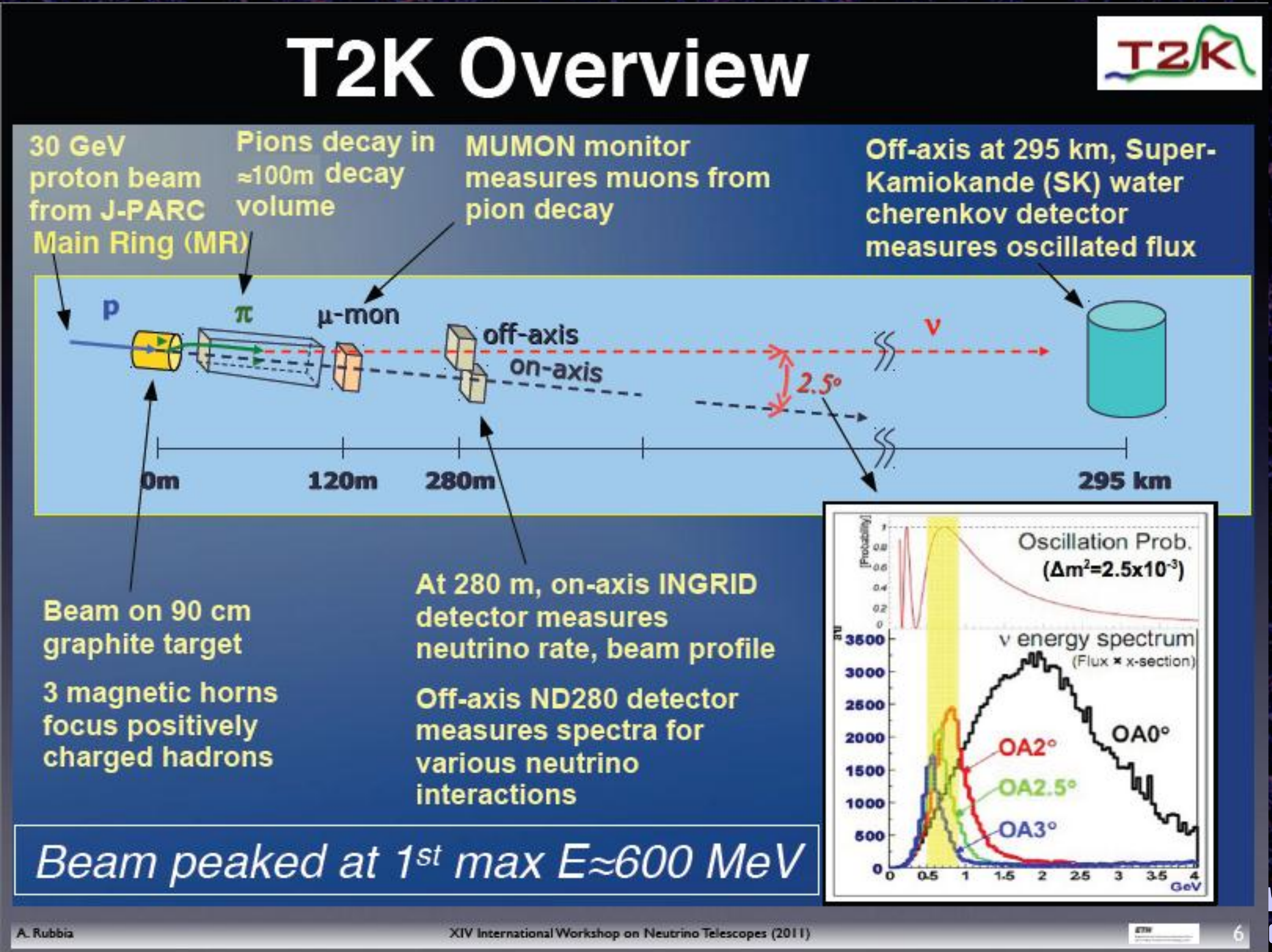
© 2007 ZENRIN
E141°
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%



T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in ≈100m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Off-axis ND280 detector measures spectra for various neutrino interactions

Beam peaked at 1st max E≈600 MeV

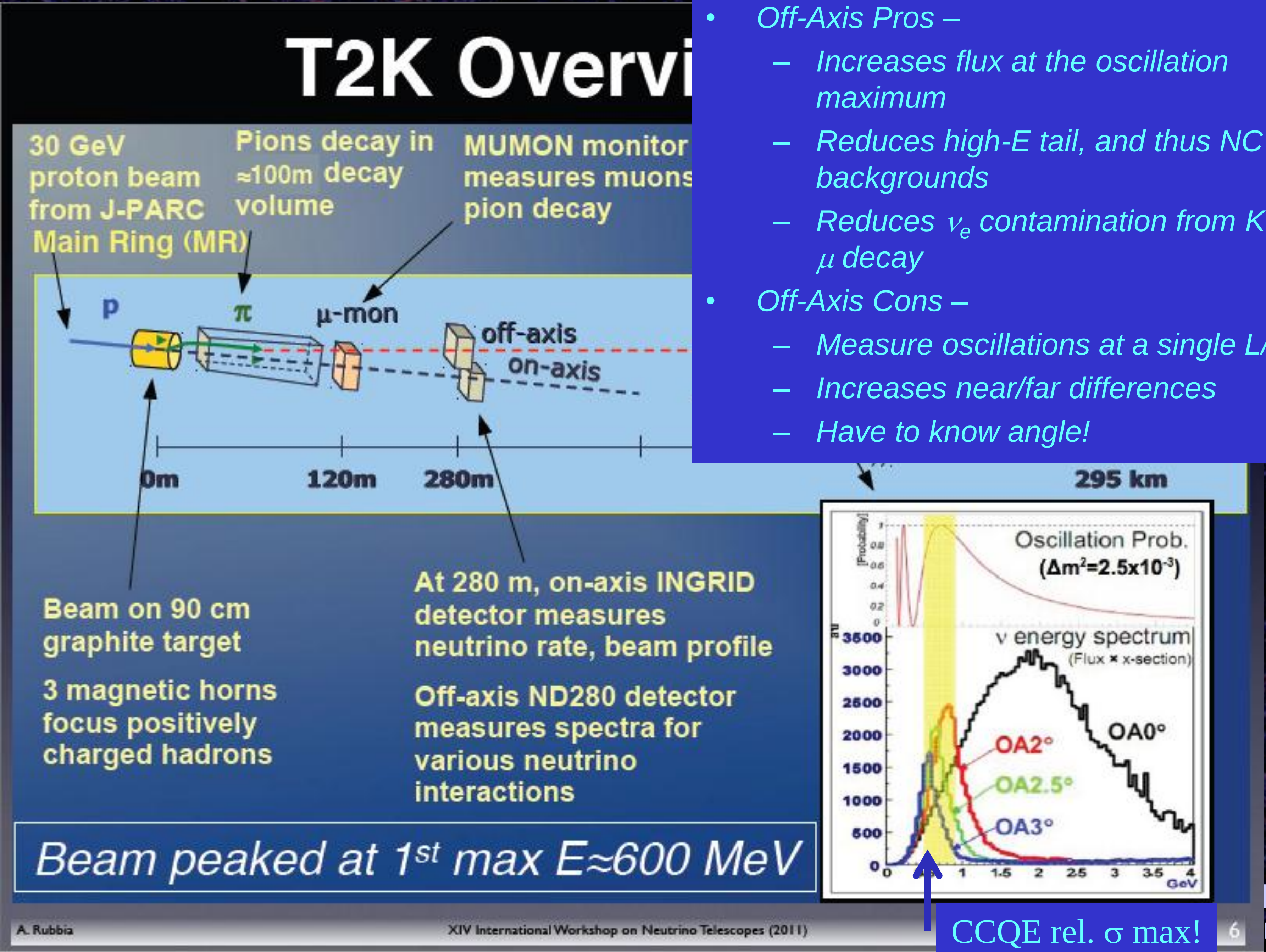
A. Rubbia

XIV International Workshop on Neutrino Telescopes (2011)

6

Towards CP Violation

- *Off-Axis Pros –*
  - *Increases flux at the oscillation maximum*
  - *Reduces high-E tail, and thus NC backgrounds*
  - *Reduces ν_e contamination from K and μ decay*
- *Off-Axis Cons –*
  - *Measure oscillations at a single L/E*
  - *Increases near/far differences*
  - *Have to know angle!*



T2K Overvi

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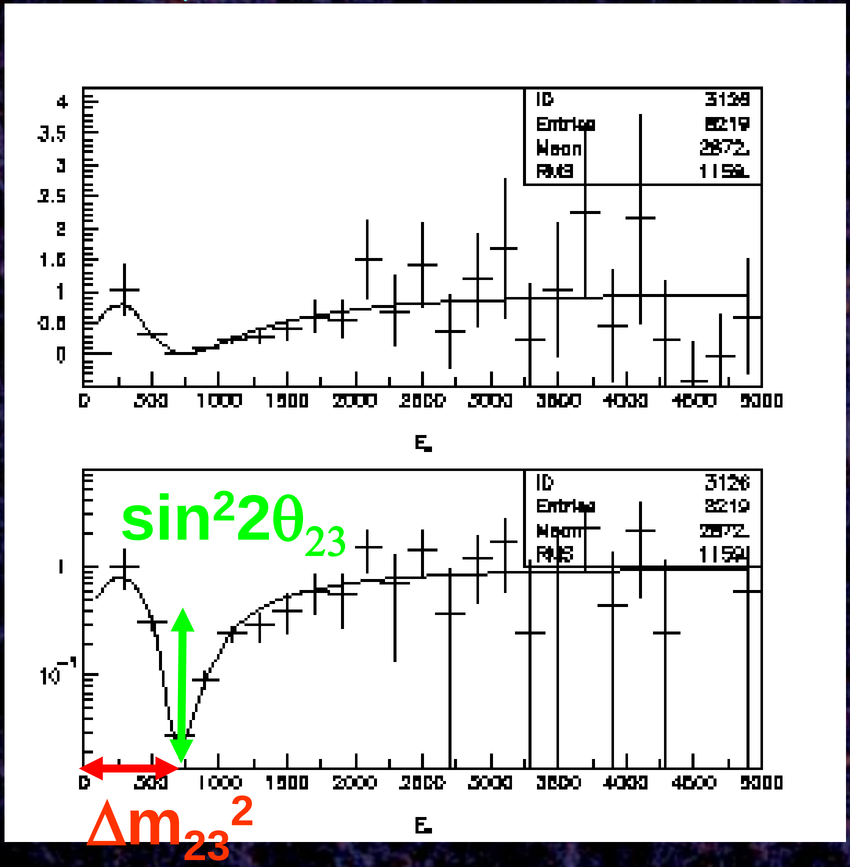
6

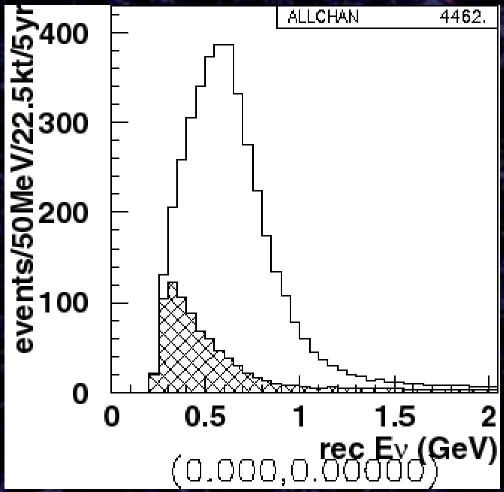
CCQE rel. σ max!

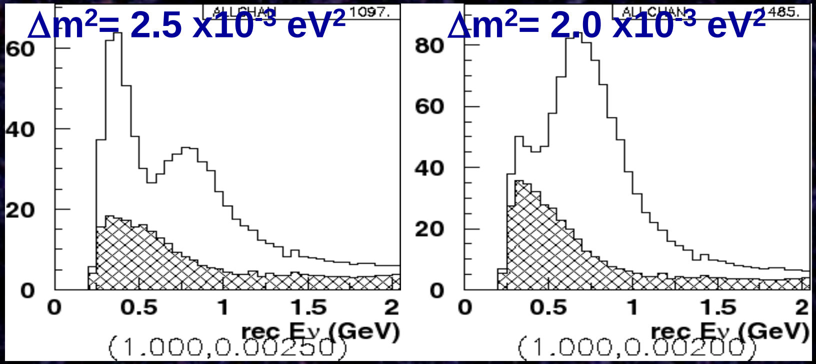
What are we trying to measure?

ν_μ disappearance



No oscillation



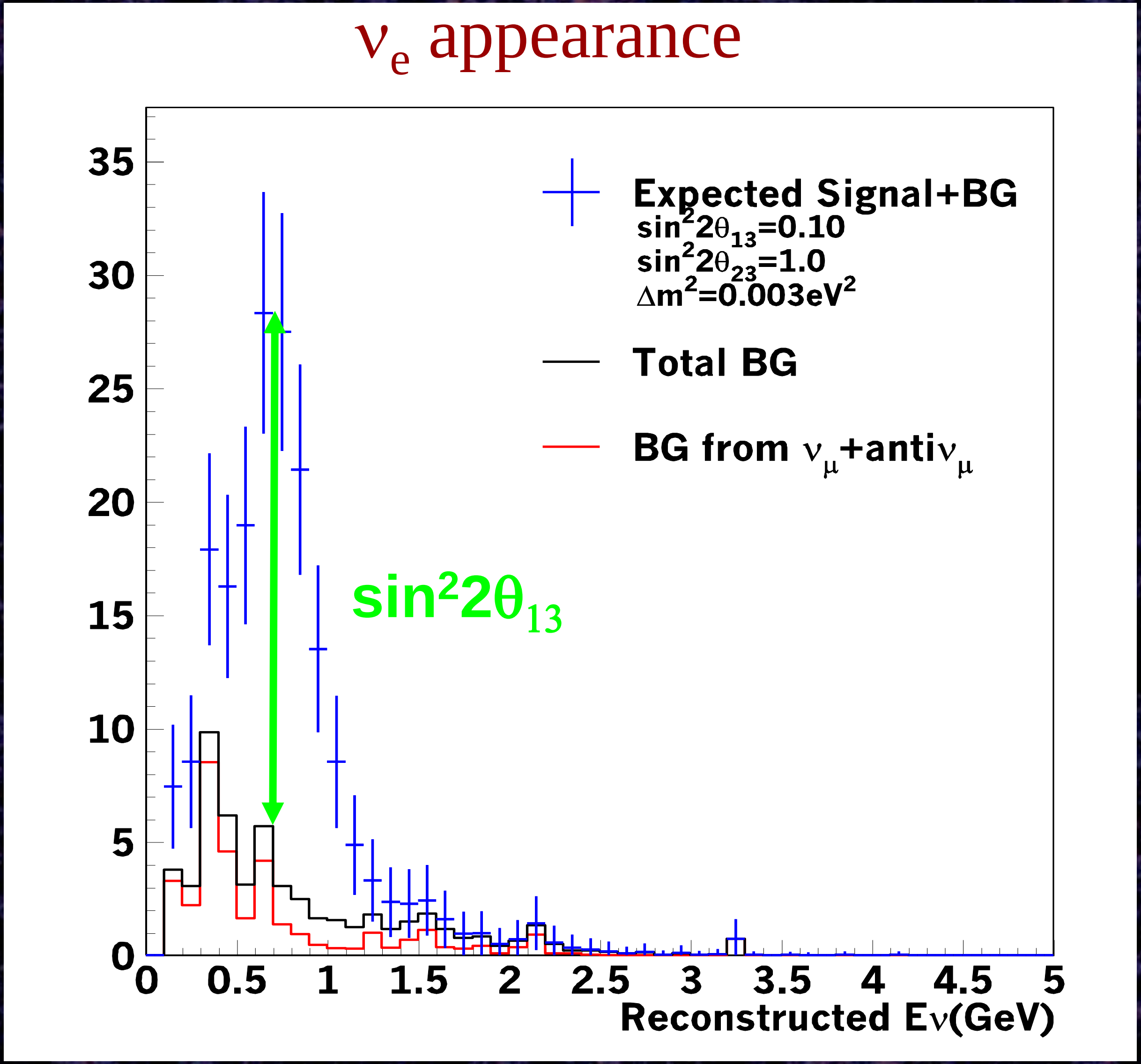


Precision measurements

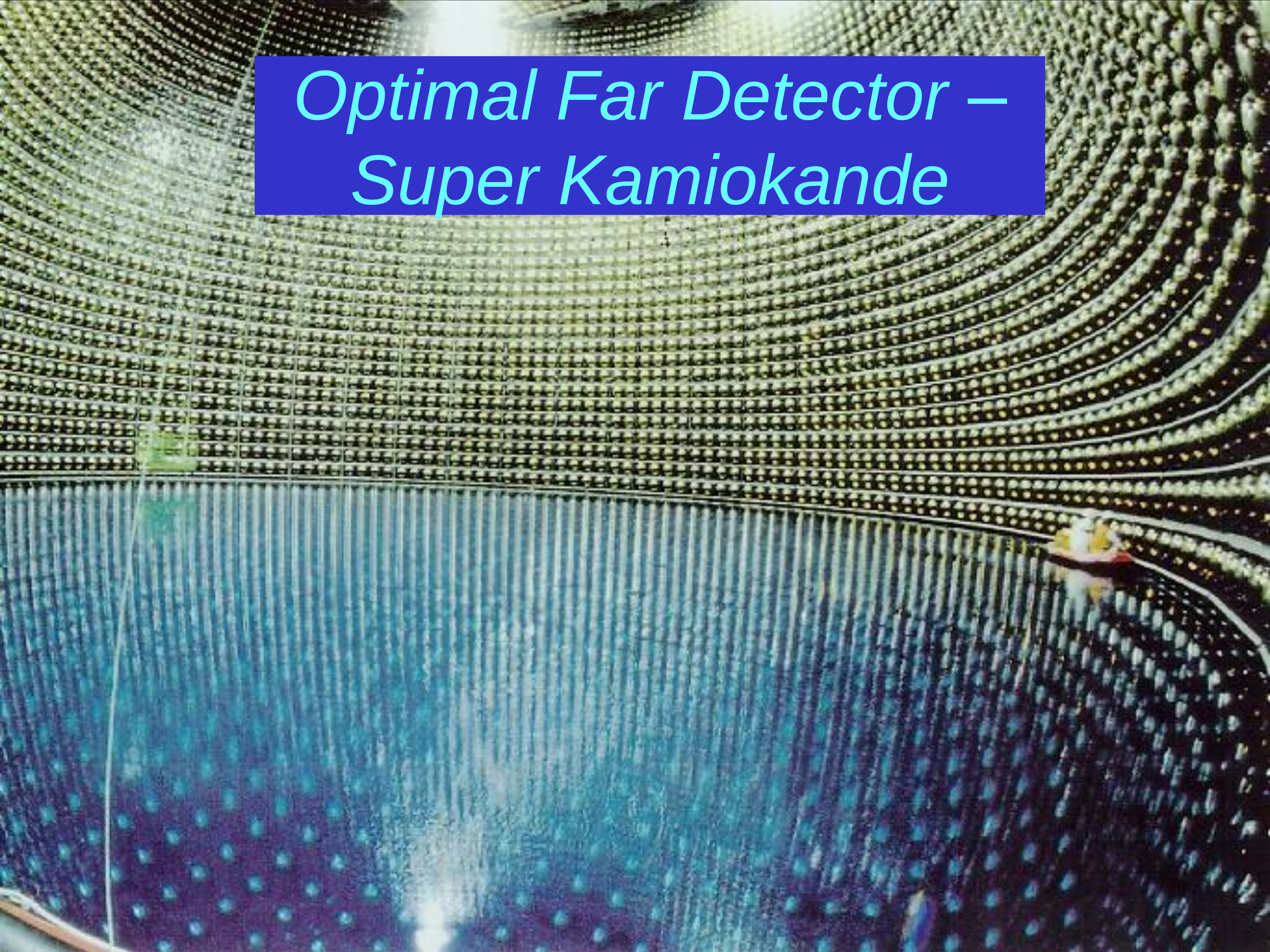
$\delta(\sin^2 2\theta)$ ~0.01

$\delta(\Delta m^2)$ $<1 \times 10^{-4}$(eV^2)

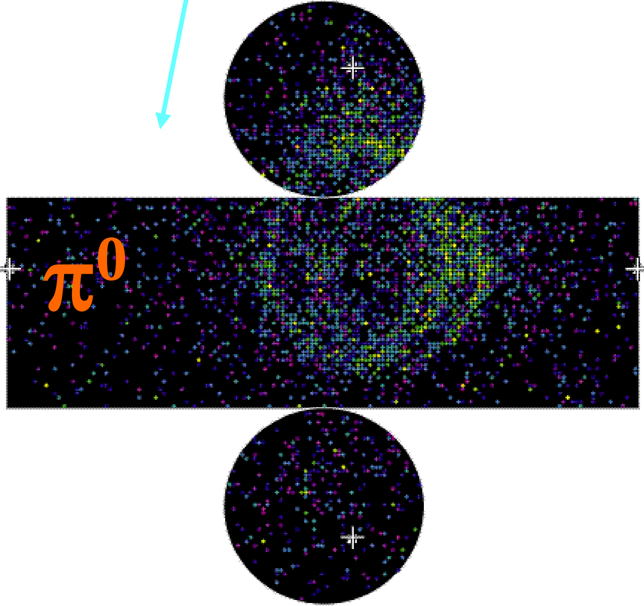
What are we trying to measure?



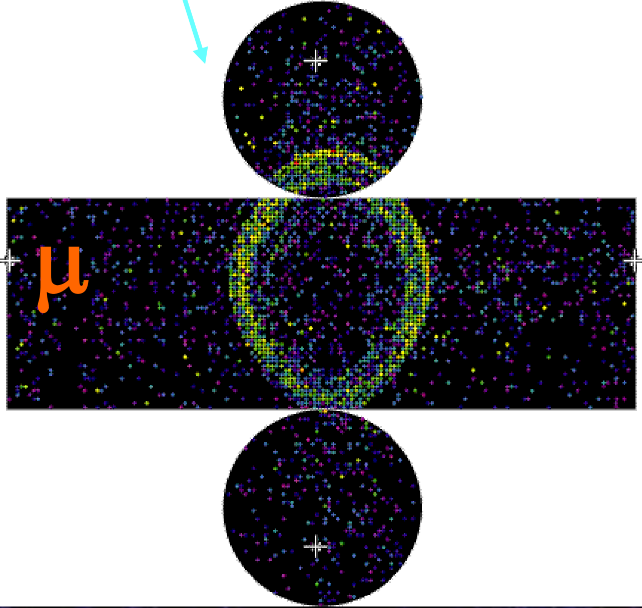
Optimal Far Detector – Super Kamiokande

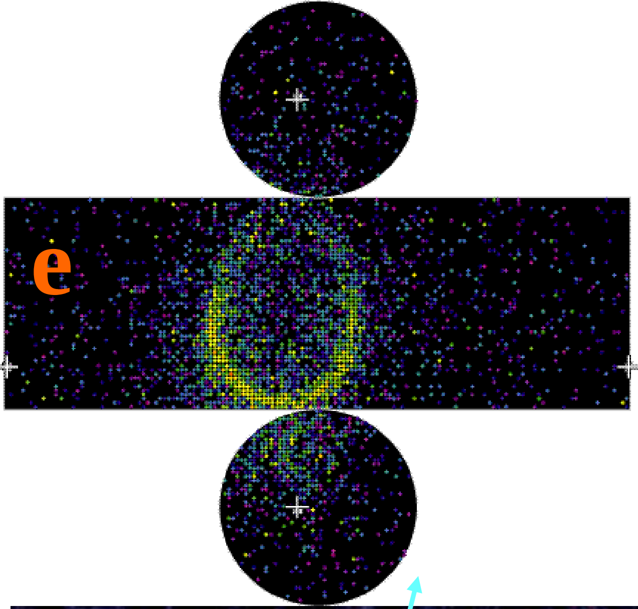


Background from NC interactions



ν_μ disappearance signal





ν_e appearance signal

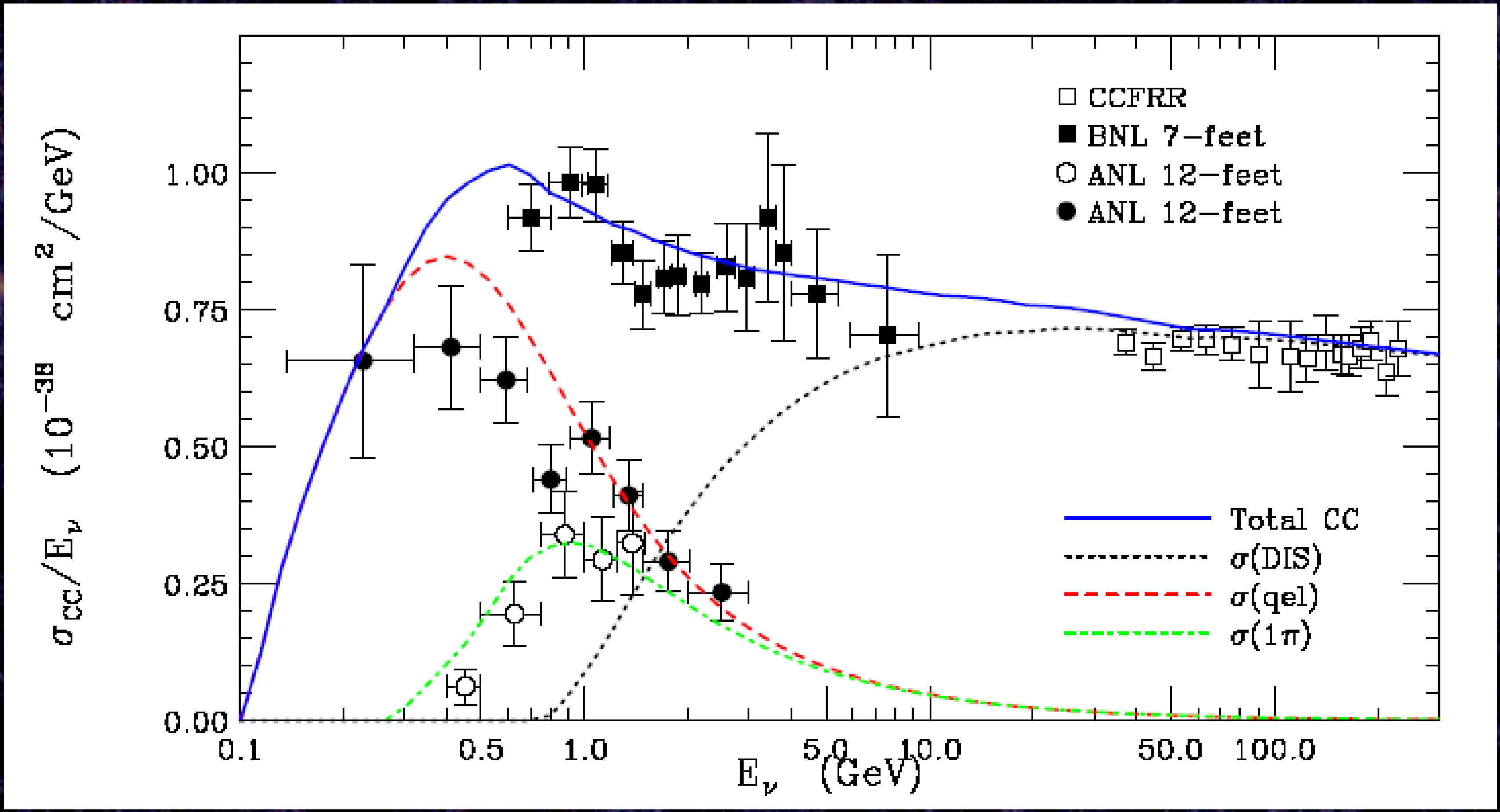
In this energy range, Super Kamiokande well understood, Excellent for separating electrons, μ, π^0

Optimal Near Detector (?)

- *Naively you would want the near and far detectors to be "identical", and then you just subtract.*
- *That was where we started out, but it was clear from very early that a water Cerenkov was not usable at the "near" site (280m).*
- *In fact near and far are never identical. There are differences in:*
  - *Size (and everything that goes with that)*
  - *Rate*
  - *Geometry with respect to the beam (a much more severe problem in an off-axis geometry)*
  - *Backgrounds*
- *For the appearance experiment it is even more complicated, because half your backgrounds arise from the* ν_μ, *and these oscillate into* ν_τ *at the far detector.*
- *So a straight subtraction is not possible, and you need to understand the beam and interactions in detail.*

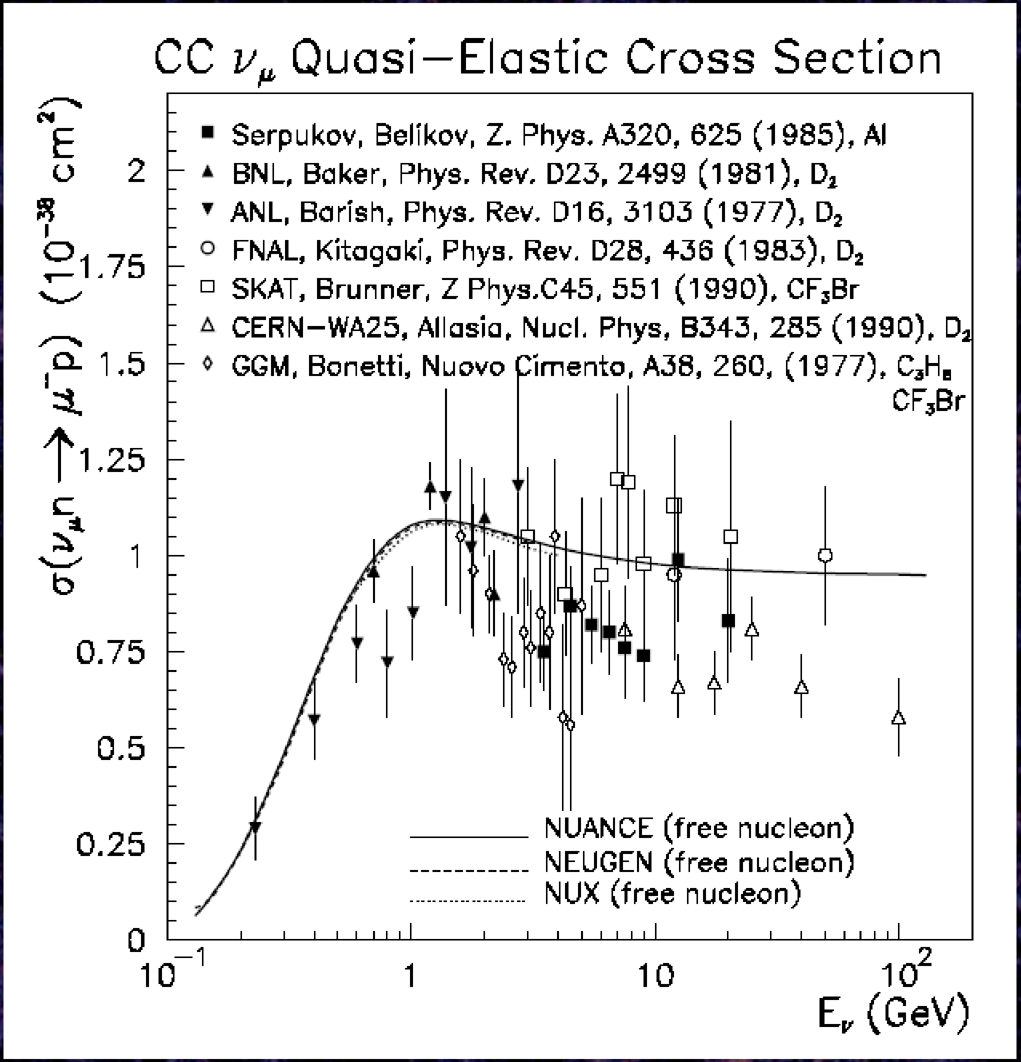
Critical σ's poorly known in range 0.1-10 GeV.

Total ν_μ CC cross section



Data compiled by G.Zeller, hep-ex/0312061

Cross sections are poorly known in range 0.1-10 GeV



Data compiled by G.Zeller, hep-ex/0312061

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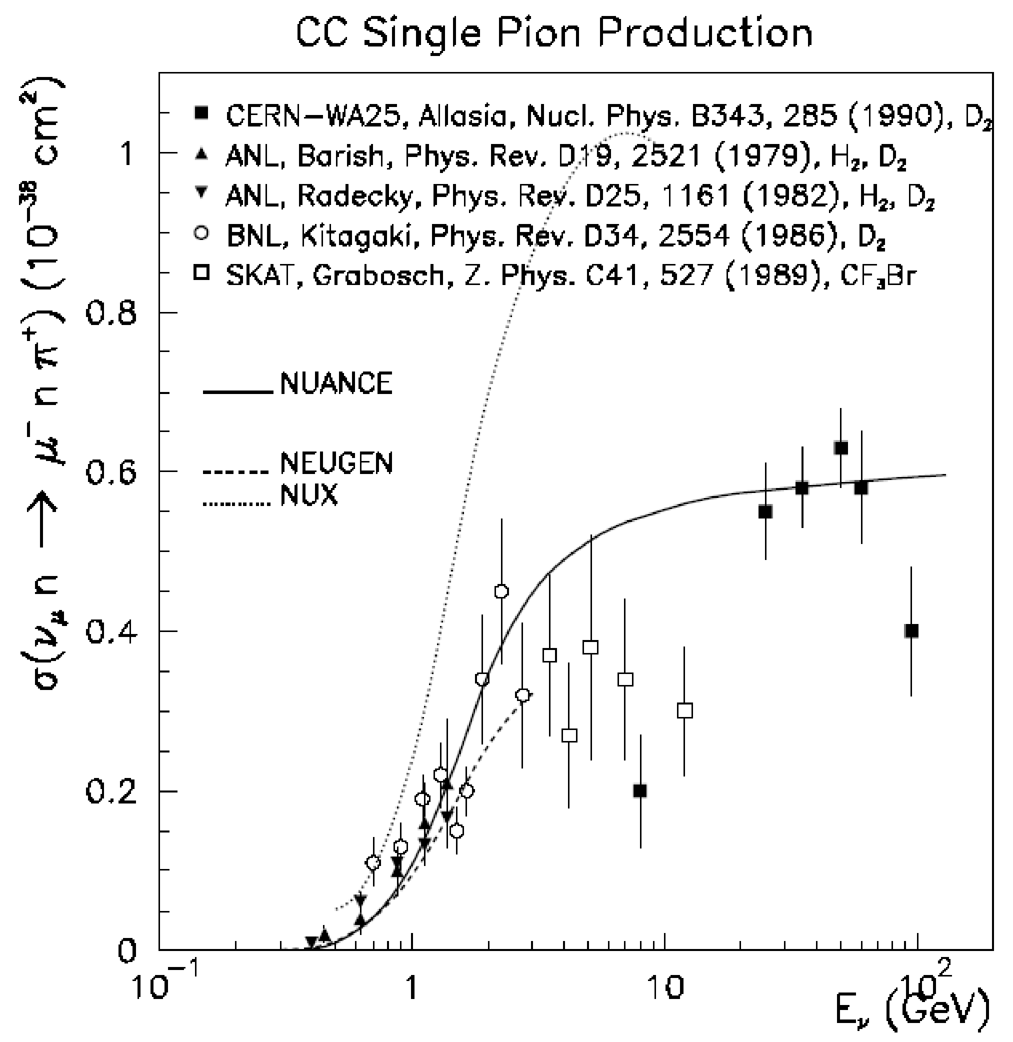
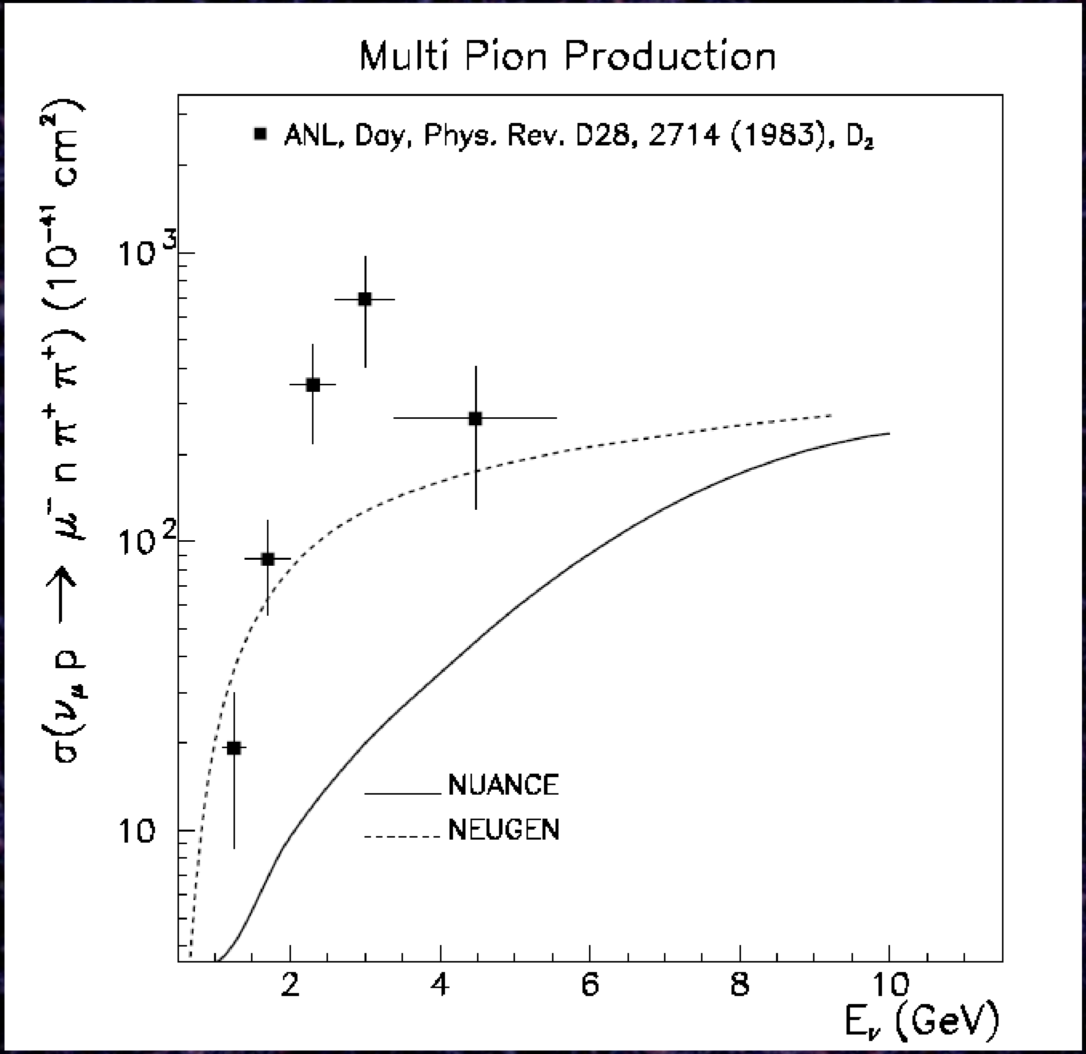


Data compiled by G.Zeller, hep-ex/0312061

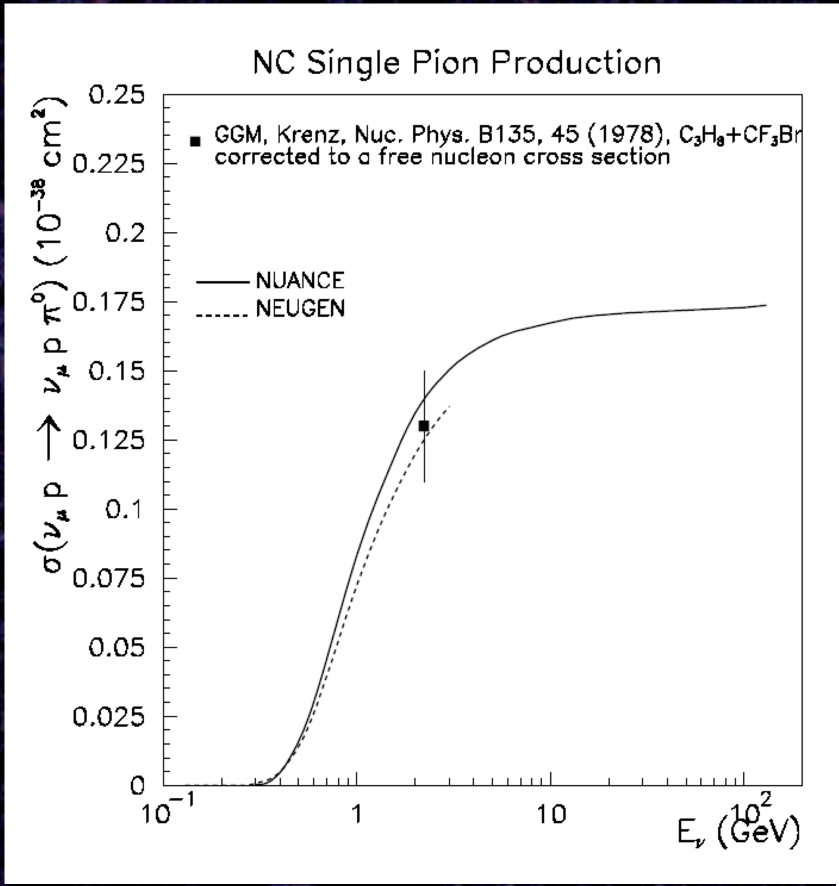
Cross sections are poorly known in range 0.1-10 GeV

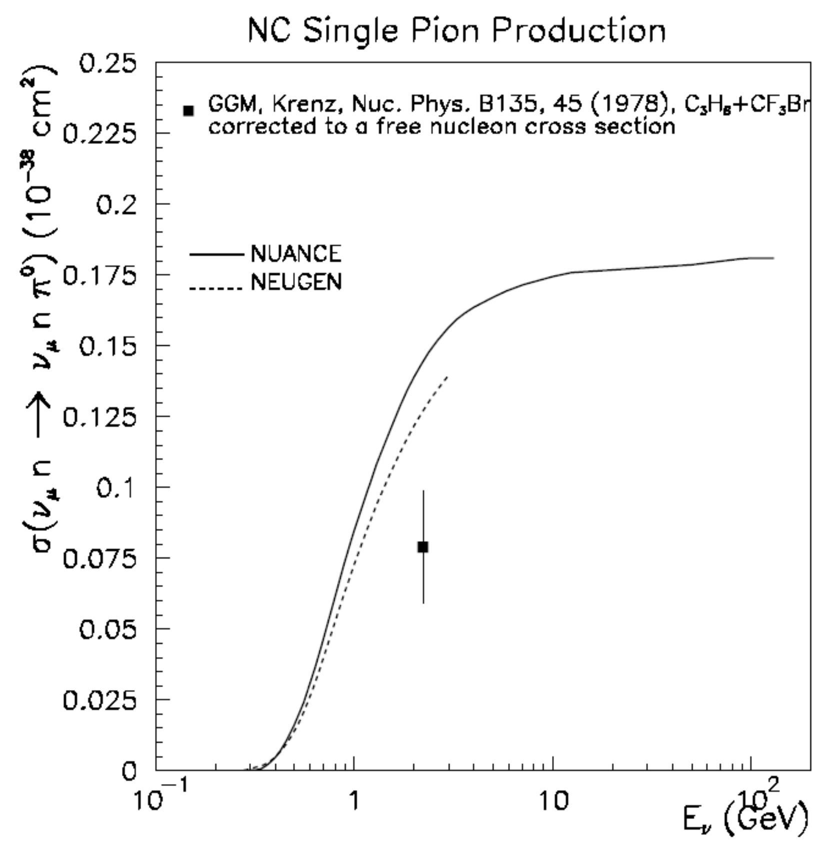


Data compiled by G.Zeller, hep-ex/0312061

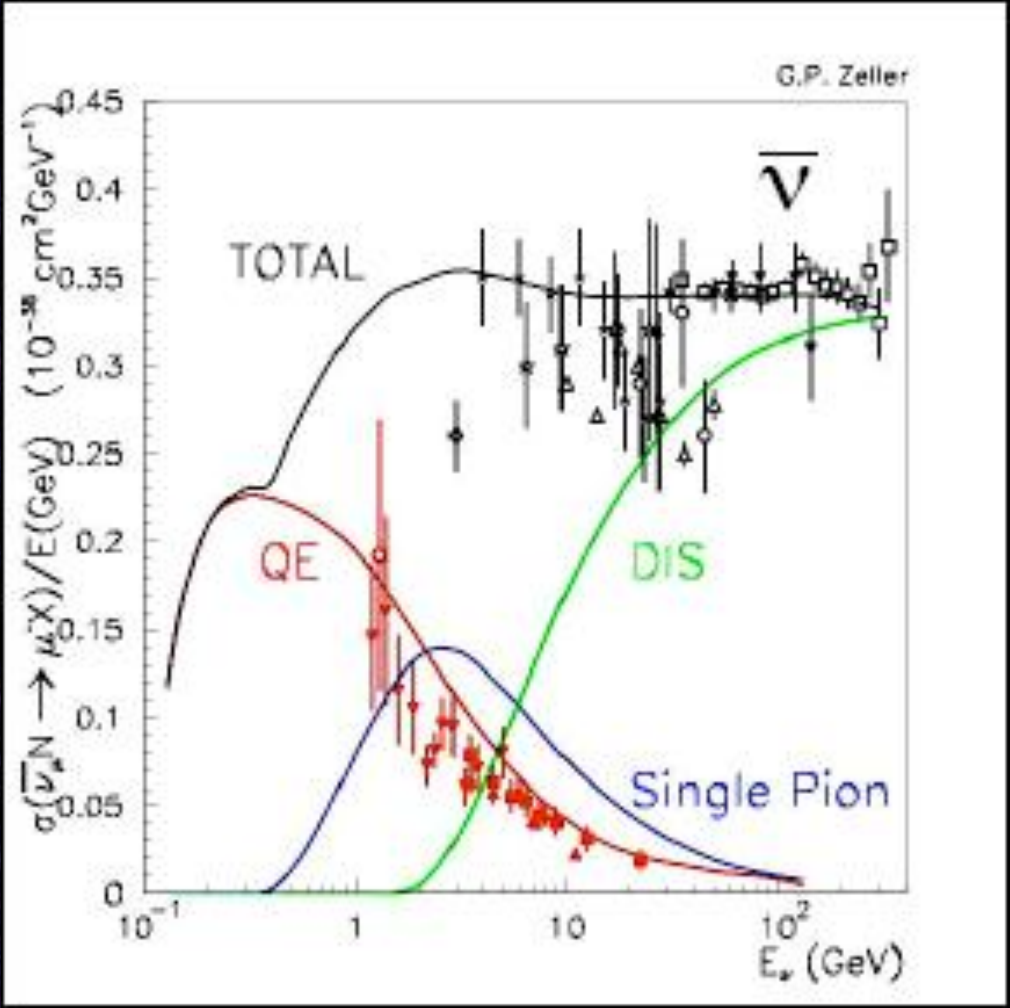
Some are worse than others…

Data compiled by G.Zeller, hep-ex/0312061





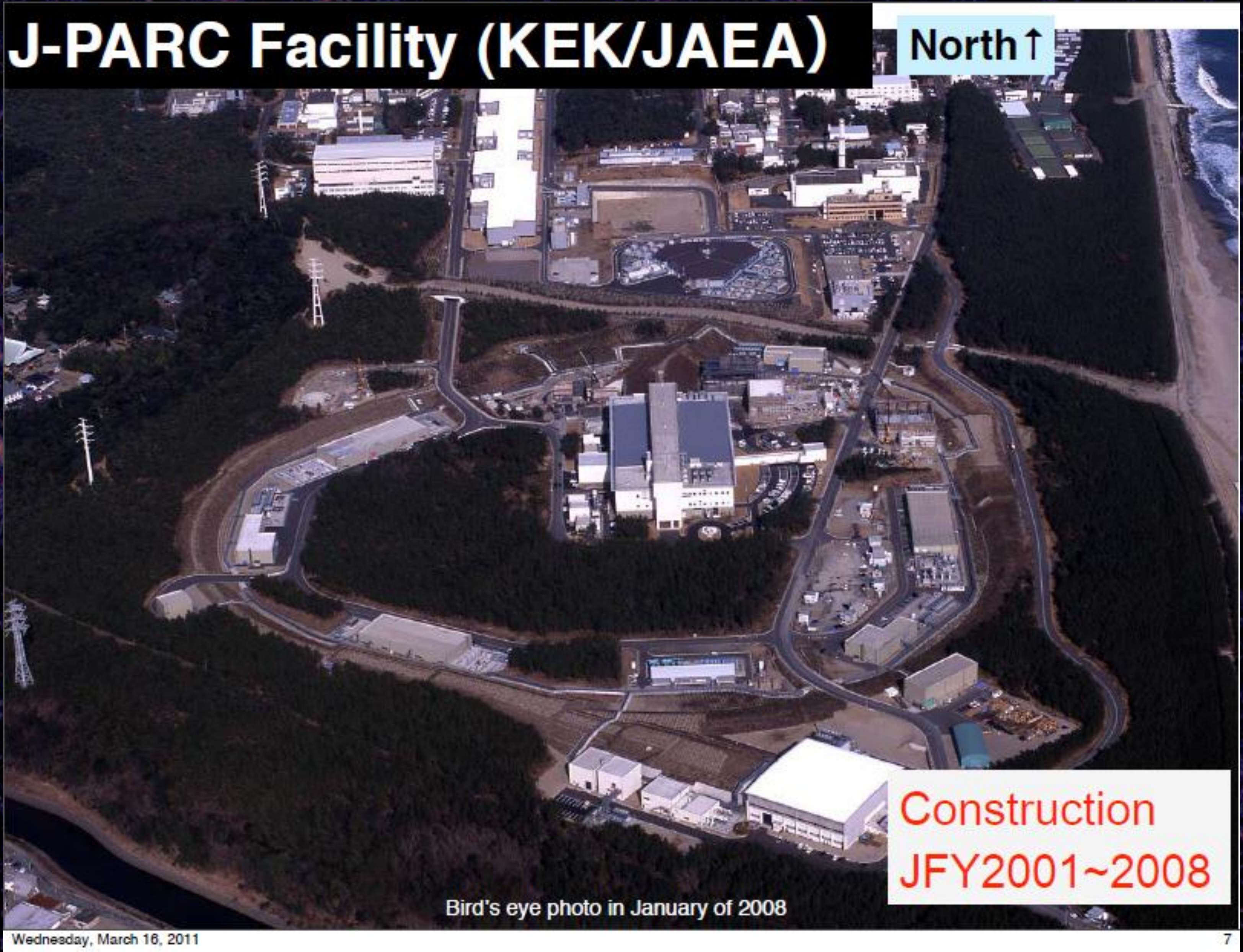
And lets not even talk about $\bar{\nu}$…



Optimal Near Detector (?)

- *Naively you would want the near and far detectors to be "identical", and then you just subtract.*
- *That was where we started out, but it was clear from very early that a water Cerenkov was not usable at the "near" site (280m).*
- *In fact near and far are never identical. There are differences in:*
  - *Size (and everything that goes with that)*
  - *Rate*
  - *Geometry with respect to the beam (a much more severe problem in an off-axis geometry)*
  - *Backgrounds*
- *For the appearance experiment it is even more complicated, because half your backgrounds arise from the ν_μ, and these oscillate into ν_τ at the far detector.*
- *So a straight subtraction is not possible, and you need to understand the beam and interactions in detail.*
- *The far detector must be huge, but the near detector doesn't need to be, so you can make it much more complex (and capable), if you are willing to go with a different technology.*

$\Rightarrow$ 280m near detectors



J-PARC Facility (KEK/JAEA)

North↑

Construction
JFY2001~2008

Bird's eye photo in January of 2008

Wednesday, March 16, 2011

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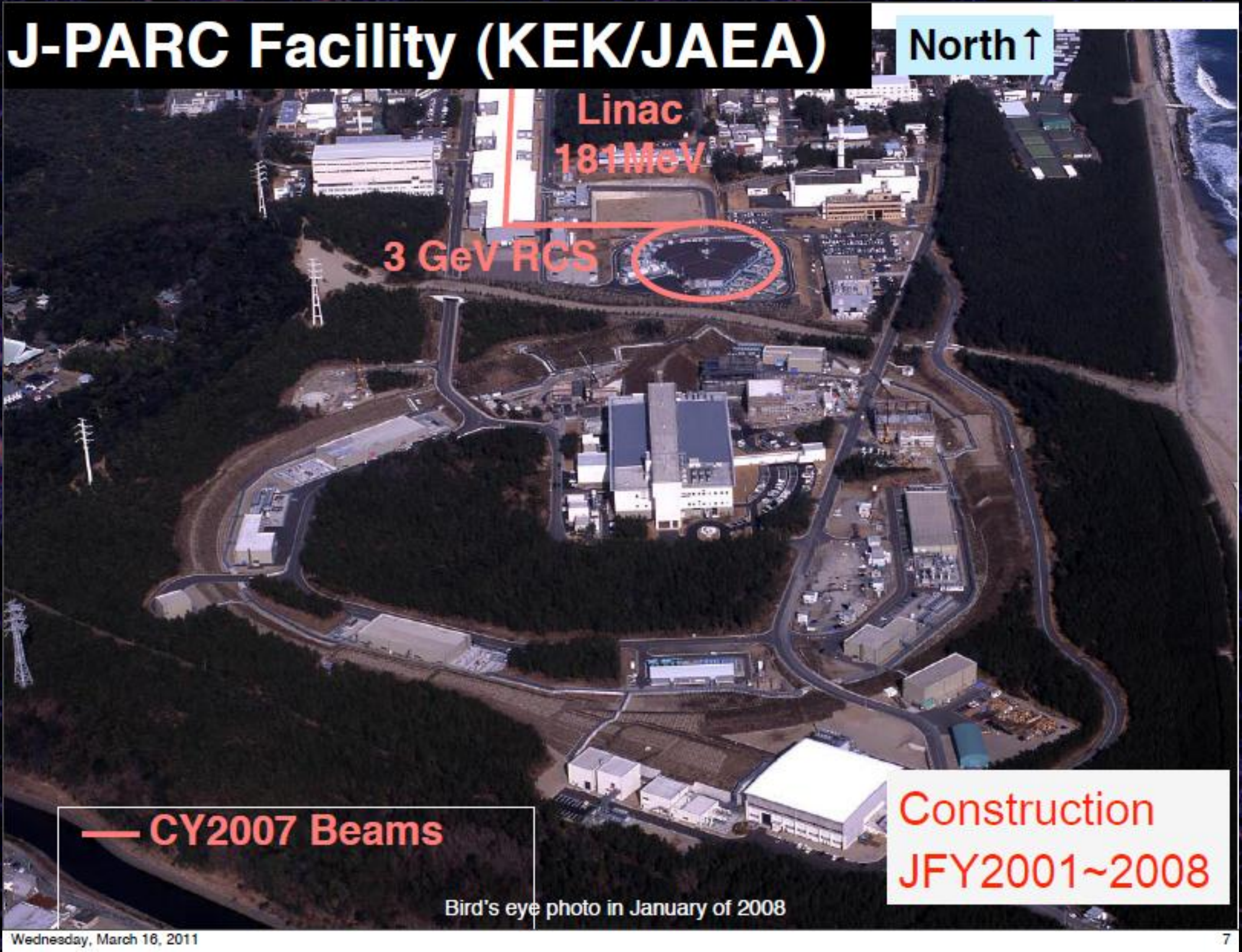


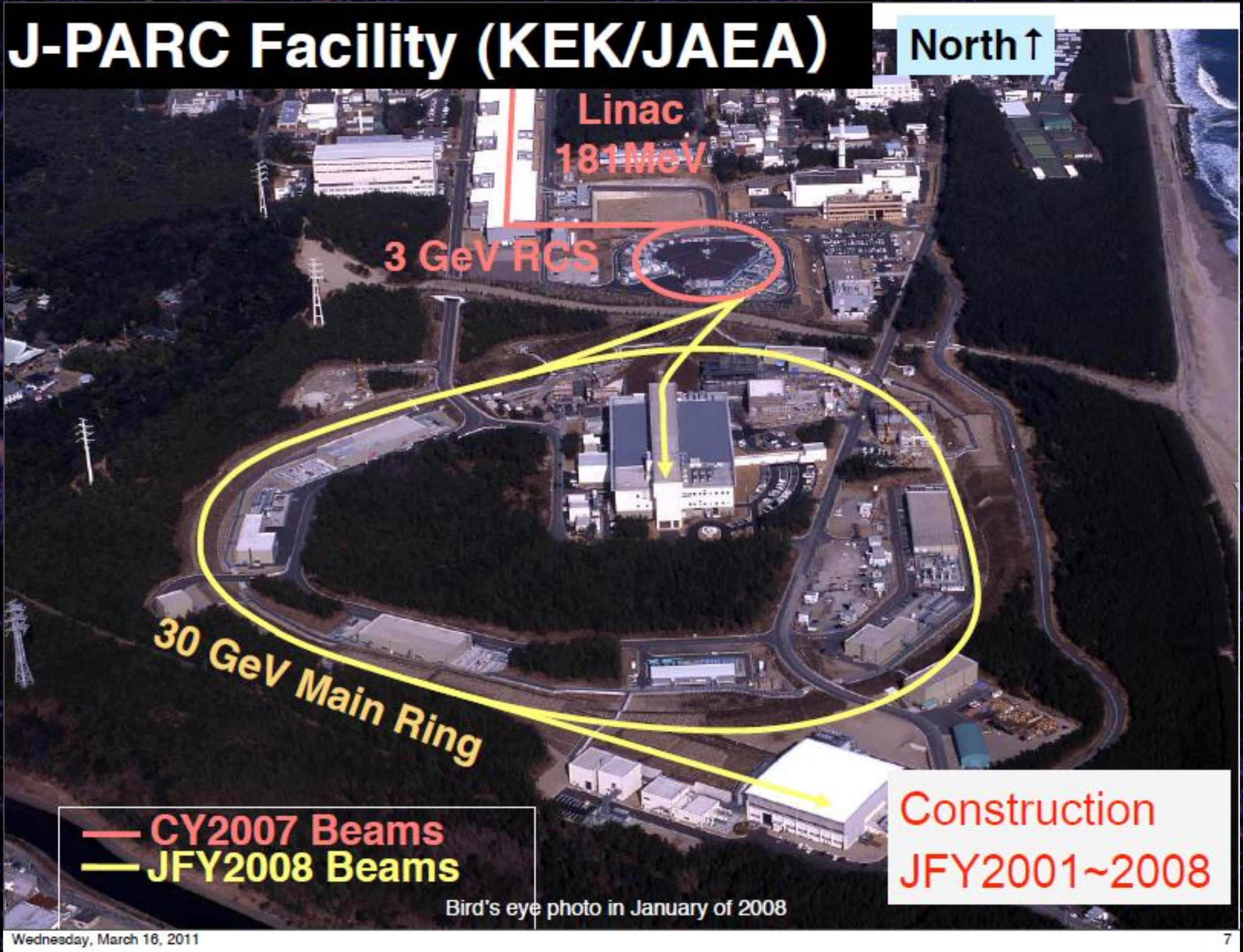
J-PARC Facility (KEK/JAEA)

— CY2007 Beams

Construction
JFY2001~2008

Bird's eye photo in January of 2008

J-PARC Facility (KEK/JAEA)



— CY2007 Beams
— JFY2008 Beams

Construction
JFY2001~2008

Bird's eye photo in January of 2008

Wednesday, March 16, 2011

7

J-PARC Facility (KEK/JAEA)

Construction
JFY2001~2008

- CY2007 Beams
- JFY2008 Beams
- JFY2009 Beams

Bird's eye photo in January of 2008

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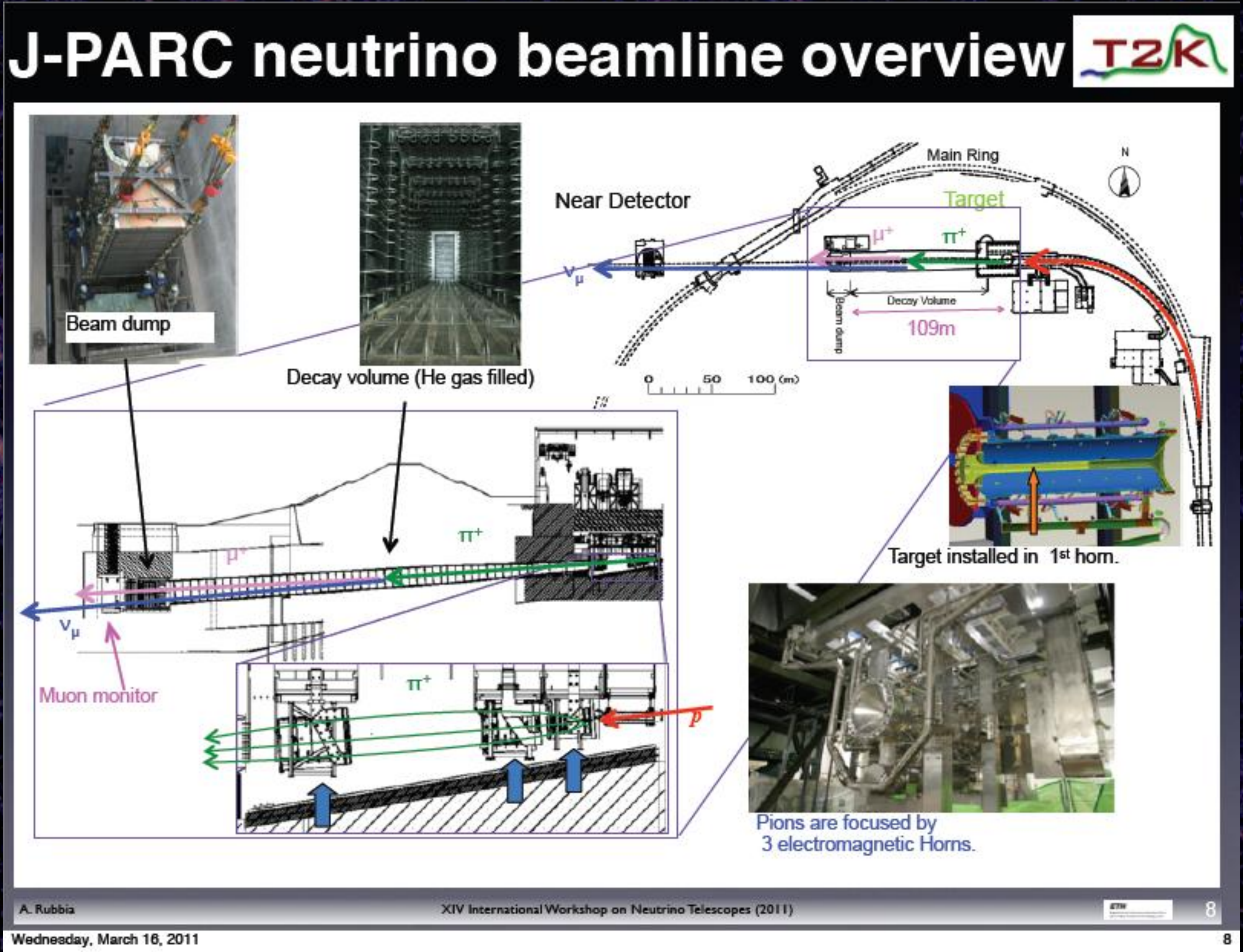

J-PARC neutrino beamline overview

Target installed in 1st horn.

Pions are focused by
3 electromagnetic Horns.

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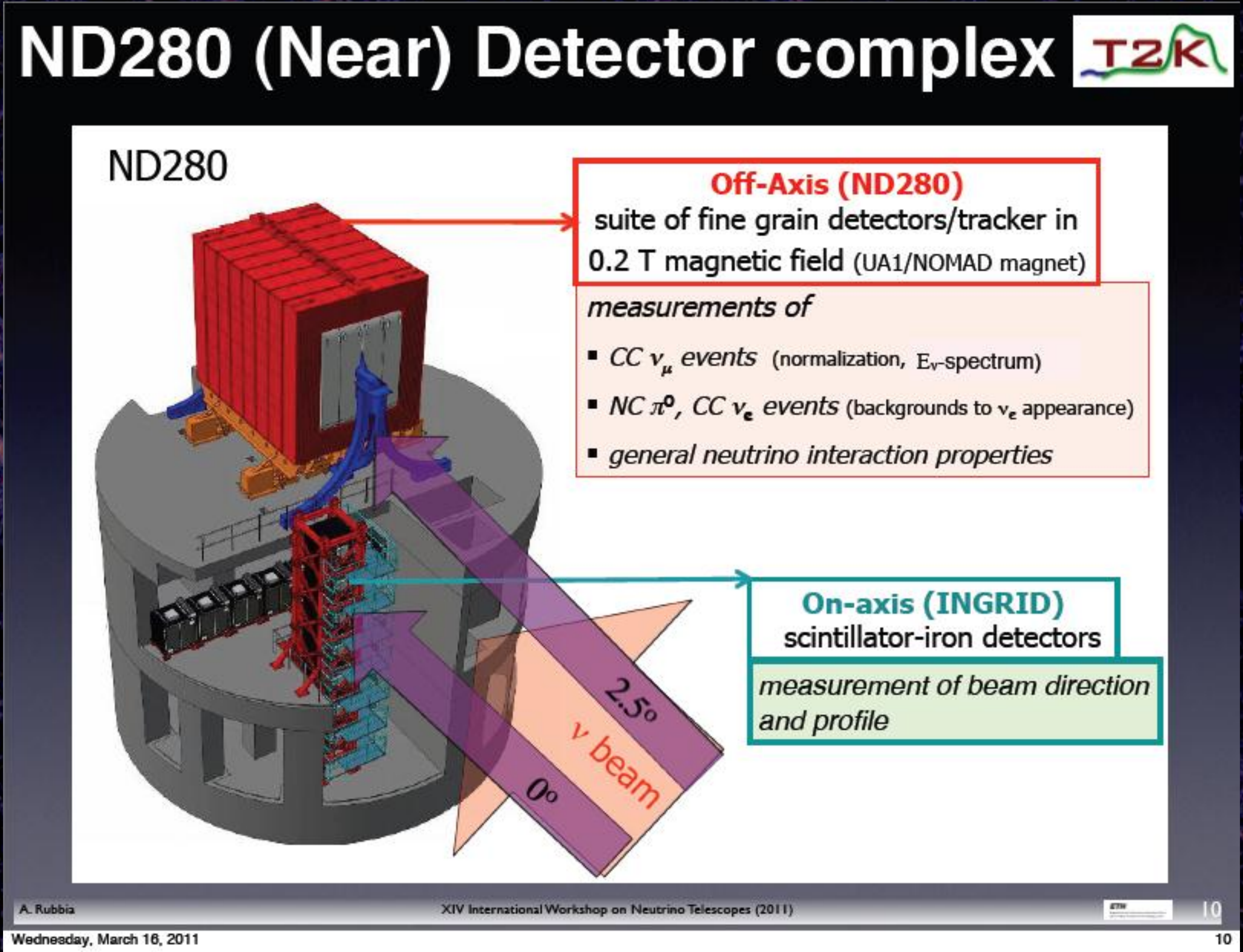


ND280 (Near) Detector complex

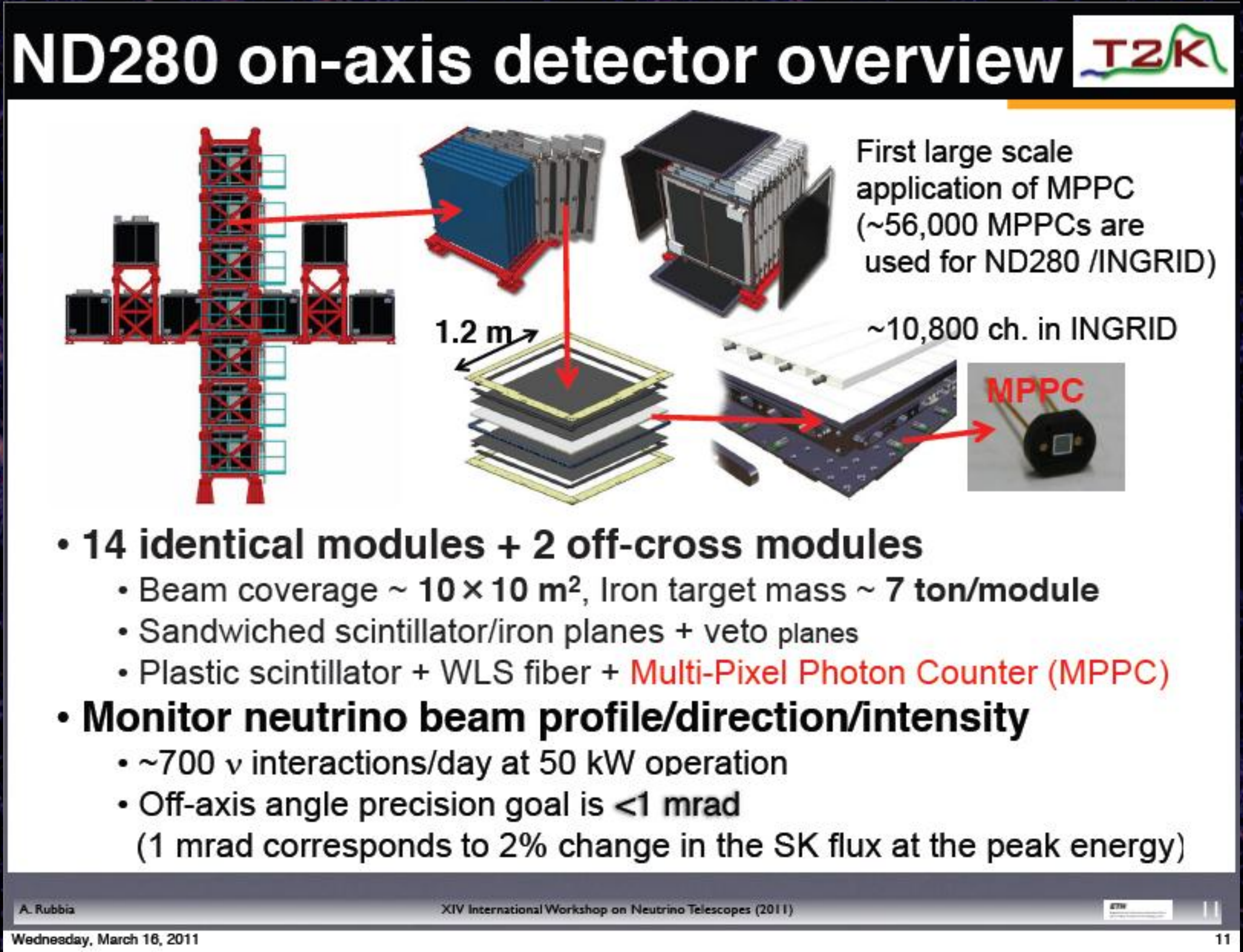
Off-Axis (ND280)
suite of fine grain detectors/tracker in 0.2 T magnetic field (UA1/NOMAD magnet)

measurements of

- *CC ν_μ events* (normalization, E_ν-spectrum)
- *NC π^0, CC ν_e events* (backgrounds to ν_e appearance)
- *general neutrino interaction properties*

On-axis (INGRID)
scintillator-iron detectors

measurement of beam direction and profile



ND280 on-axis detector overview

T2K

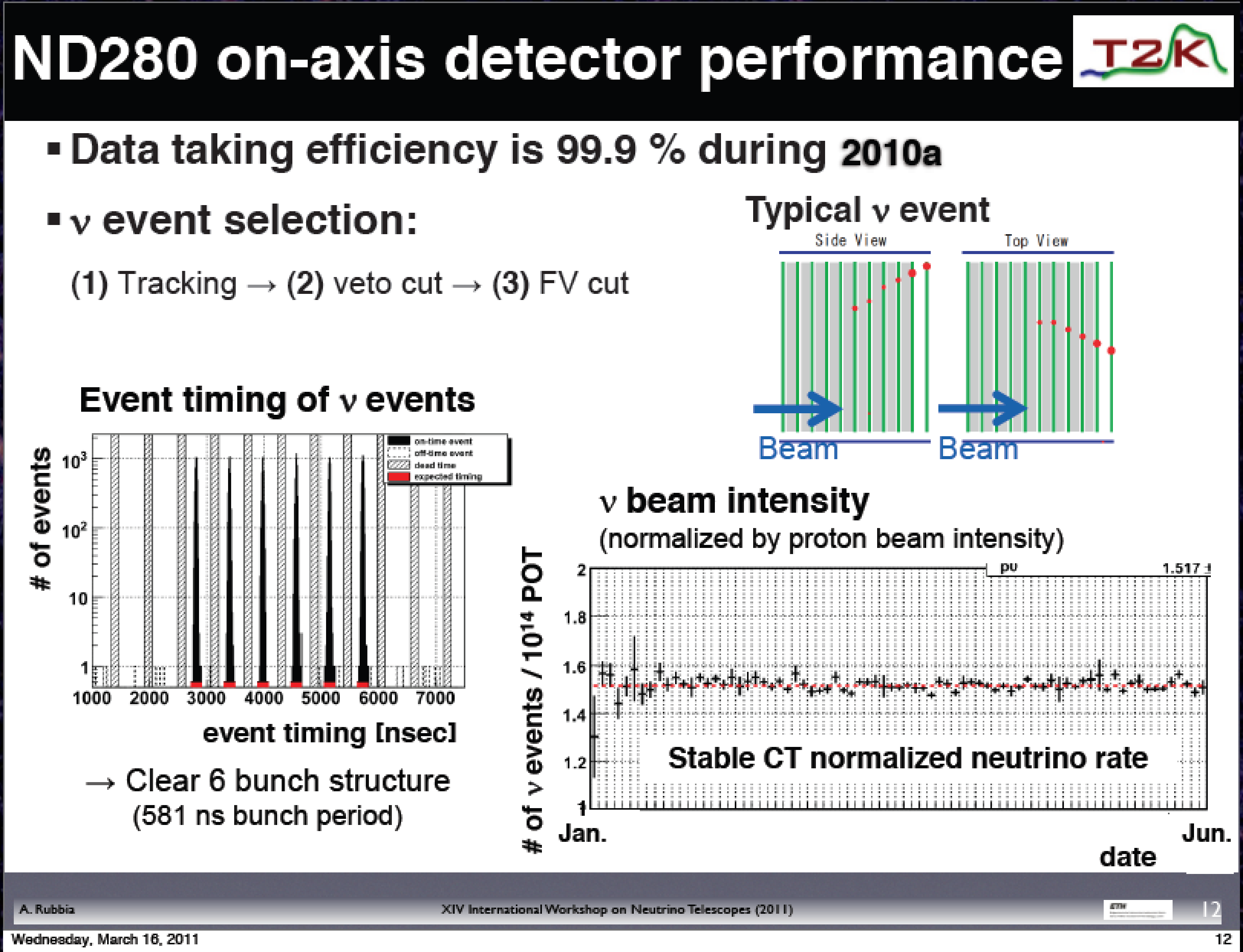
First large scale application of MPPC (~56,000 MPPCs are used for ND280 /INGRID)

1.2 m

~10,800 ch. in INGRID

MPPC

- **14 identical modules + 2 off-cross modules**
  - Beam coverage ~ **10 × 10 m^2**, Iron target mass ~ **7 ton/module**
  - Sandwiched scintillator/iron planes + veto planes
  - Plastic scintillator + WLS fiber + Multi-Pixel Photon Counter (MPPC)
- **Monitor neutrino beam profile/direction/intensity**
  - ~700 ν interactions/day at 50 kW operation
  - Off-axis angle precision goal is **<1 mrad**
    (1 mrad corresponds to 2% change in the SK flux at the peak energy)



ND280 on-axis detector performance

- **Data taking efficiency is 99.9 % during 2010a**
- **ν event selection:**

  (1) Tracking → (2) veto cut → (3) FV cut

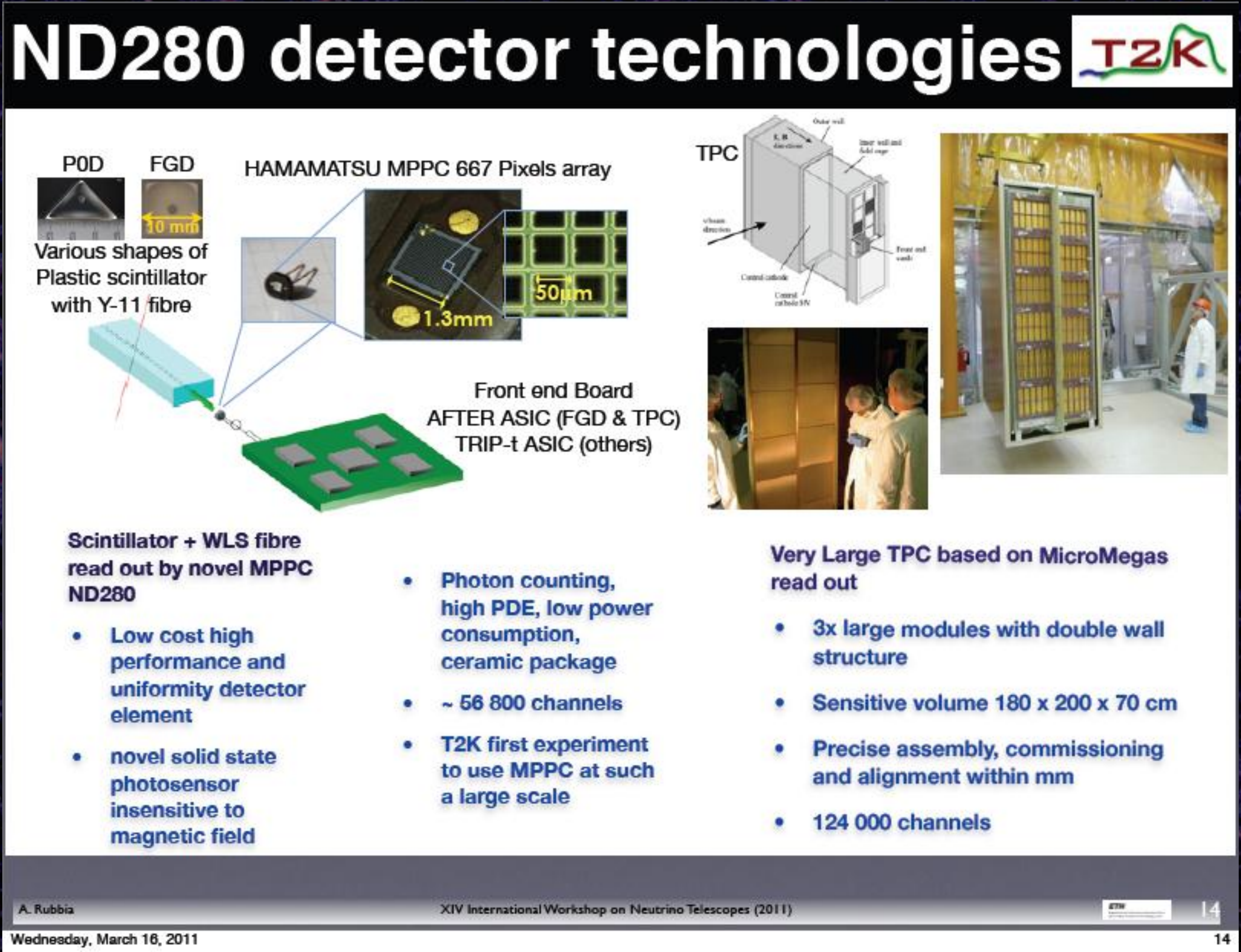
Typical ν event

Event timing of ν events

→ Clear 6 bunch structure
(581 ns bunch period)

ν beam intensity
(normalized by proton beam intensity)

Stable CT normalized neutrino rate



ND280 detector technologies

Various shapes of Plastic scintillator with Y-11 fibre

HAMAMATSU MPPC 667 Pixels array

Front end Board
AFTER ASIC (FGD & TPC)
TRIP-t ASIC (others)

Scintillator + WLS fibre read out by novel MPPC ND280

- Low cost high performance and uniformity detector element
- novel solid state photosensor insensitive to magnetic field

- Photon counting, high PDE, low power consumption, ceramic package
- ~ 56 800 channels
- T2K first experiment to use MPPC at such a large scale

Very Large TPC based on MicroMegas read out

- 3x large modules with double wall structure
- Sensitive volume 180 x 200 x 70 cm
- Precise assembly, commissioning and alignment within mm
- 124 000 channels

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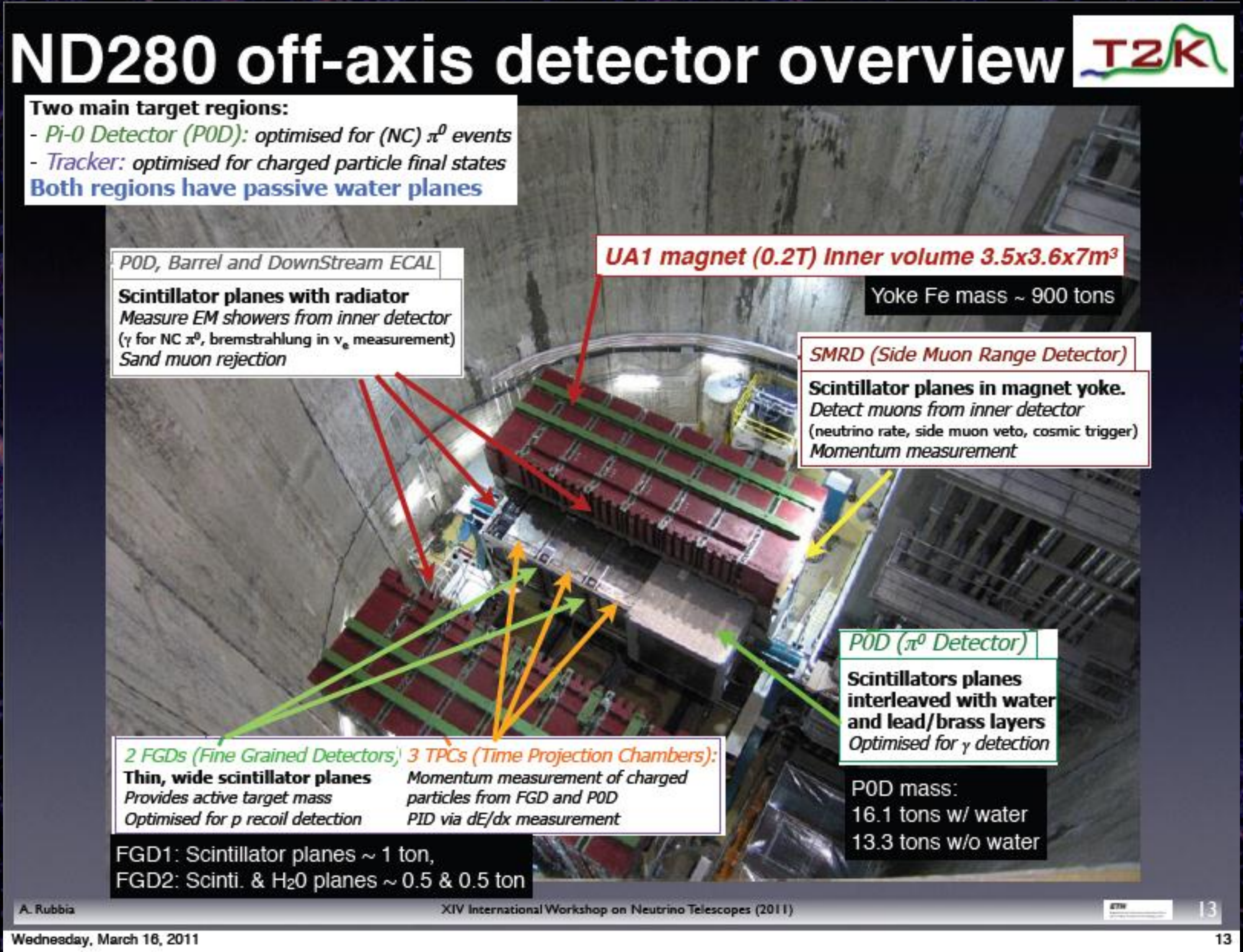

ND280 off-axis detector overview

Two main target regions:
- *Pi-0 Detector (P0D): optimised for (NC) π^0 events*
- *Tracker: optimised for charged particle final states*

Both regions have passive water planes

P0D, Barrel and DownStream ECAL

Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection

UA1 magnet (0.2T) Inner volume 3.5x3.6x7m^3

Yoke Fe mass ~ 900 tons

SMRD (Side Muon Range Detector)

Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement

P0D (π^0 Detector)

Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection

P0D mass:
16.1 tons w/ water
13.3 tons w/o water

2 FGDs (Fine Grained Detectors)

Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection

3 TPCs (Time Projection Chambers):

Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement

FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H_20 planes ~ 0.5 & 0.5 ton

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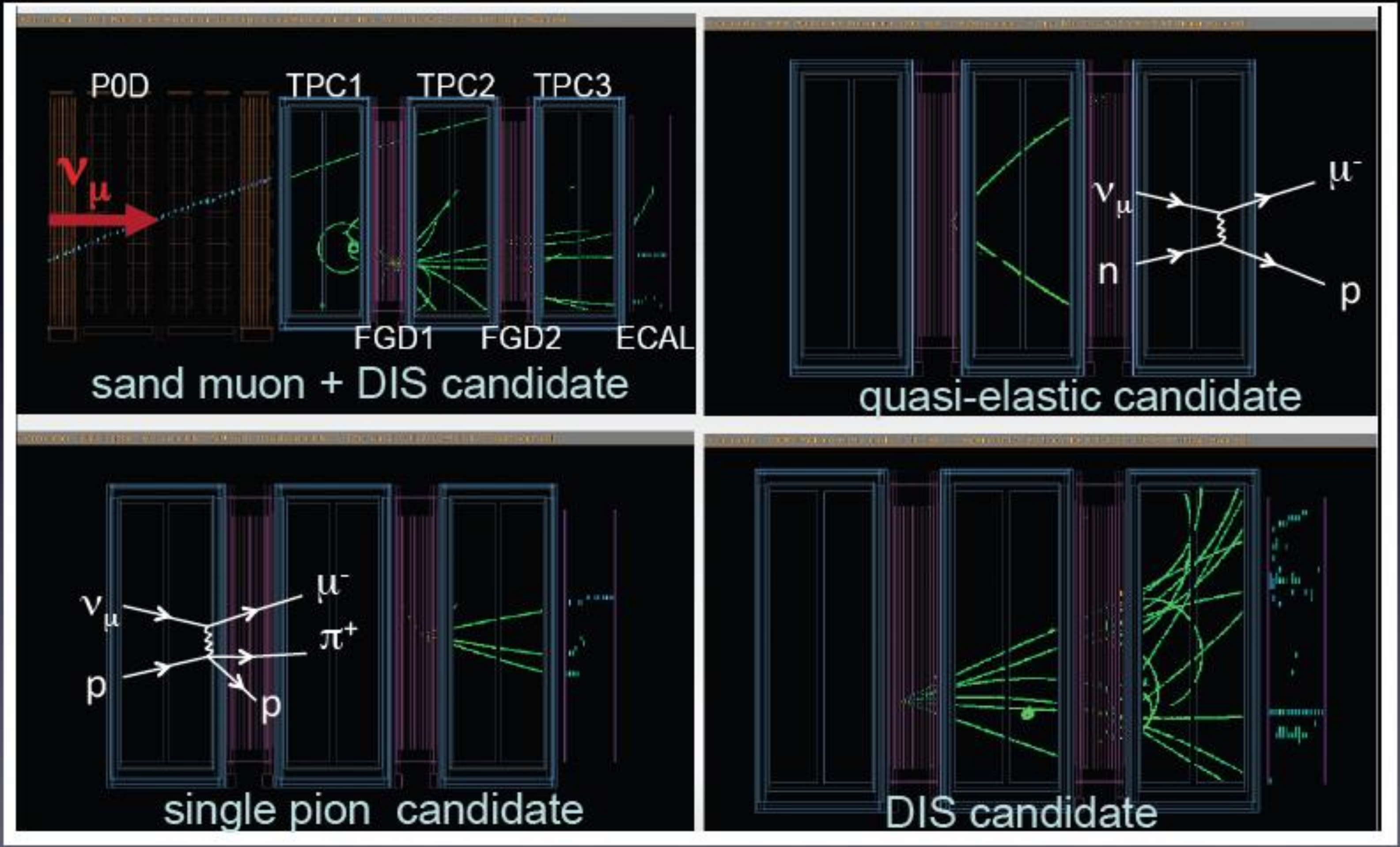
ND280 off-axis event gallery



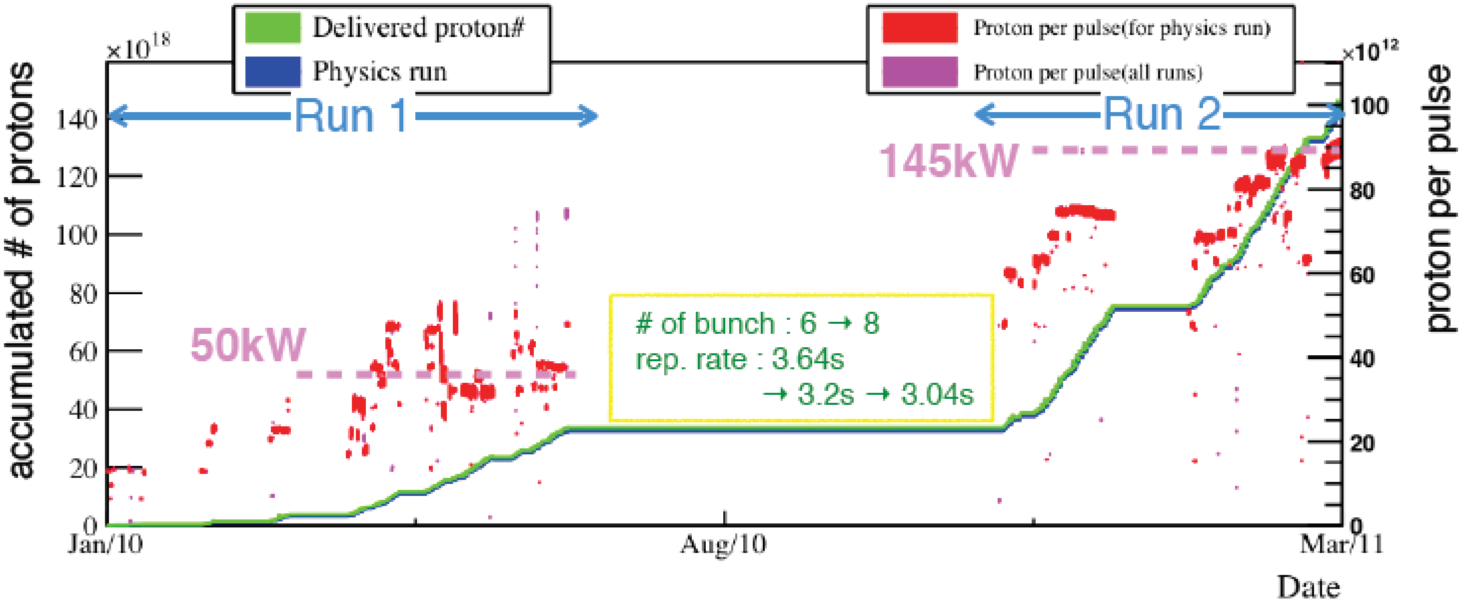
sand muon + DIS candidate

quasi-elastic candidate

single pion candidate

DIS candidate

Total # of protons used for analysis



Run 1 (Jan. '10 - June '10)

- 3.23 x 10^{19} p.o.t. for analysis
- 50kW stable beam operation

Run 2 (Nov. '10 - Mar. '11)

- 11.08 x 10^{19} p.o.t. for analysis
- ~145kW beam operation

Total # of protons used for this analysis is 1.43 x 10^{20} pot

2% of T2K's final goal and ~5 times exposure of the previous report

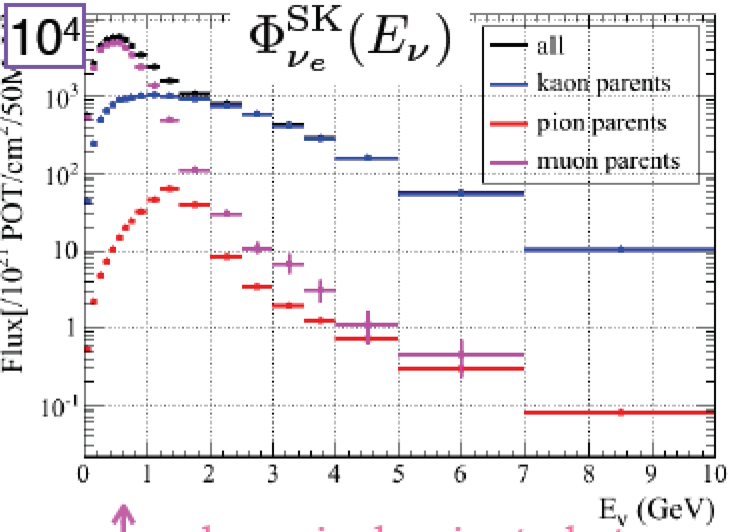
Number of events in on-timing windows (-2 ~ +10 μsec)

Class / Beam run	RUN-1	RUN-2	Total	non-beam background
POT (x 10^{19})	3.23	11.08	**14.31**	
Fully-Contained (FC)	33	88	**121**	0.023

$$N_{SK}^{exp} = R_{ND}^{\mu,\ Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\ MC}}$$

ND ν_μ event rate measurement

F/N ratio is estimated by using MC which is based on measurements

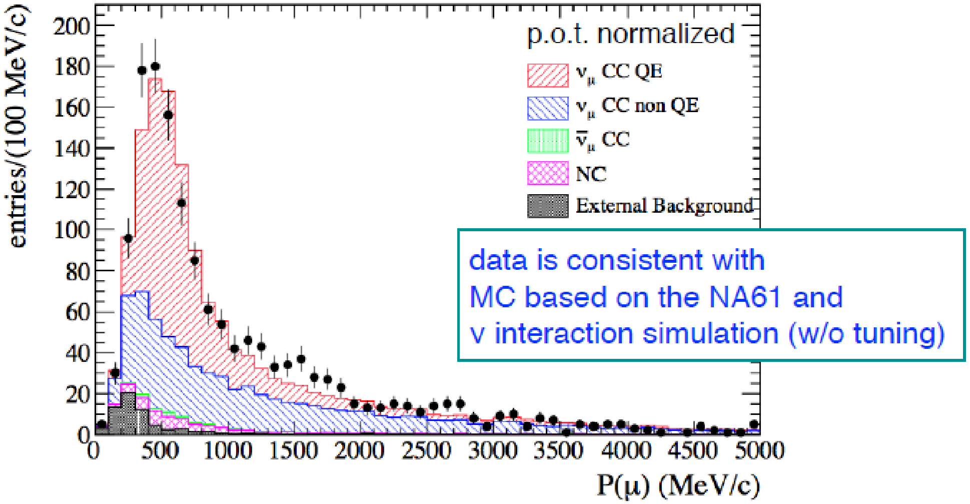


μ decay is dominated at low energy

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

NA61 pion measurement predicts the beam ν_e from pion origin

ND Measurement of muon momentum in inclusive ν_μ CC events ($\nu_\mu + N \rightarrow \mu^+ + X$)



data is consistent with MC based on the NA61 and ν interaction simulation (w/o tuning)

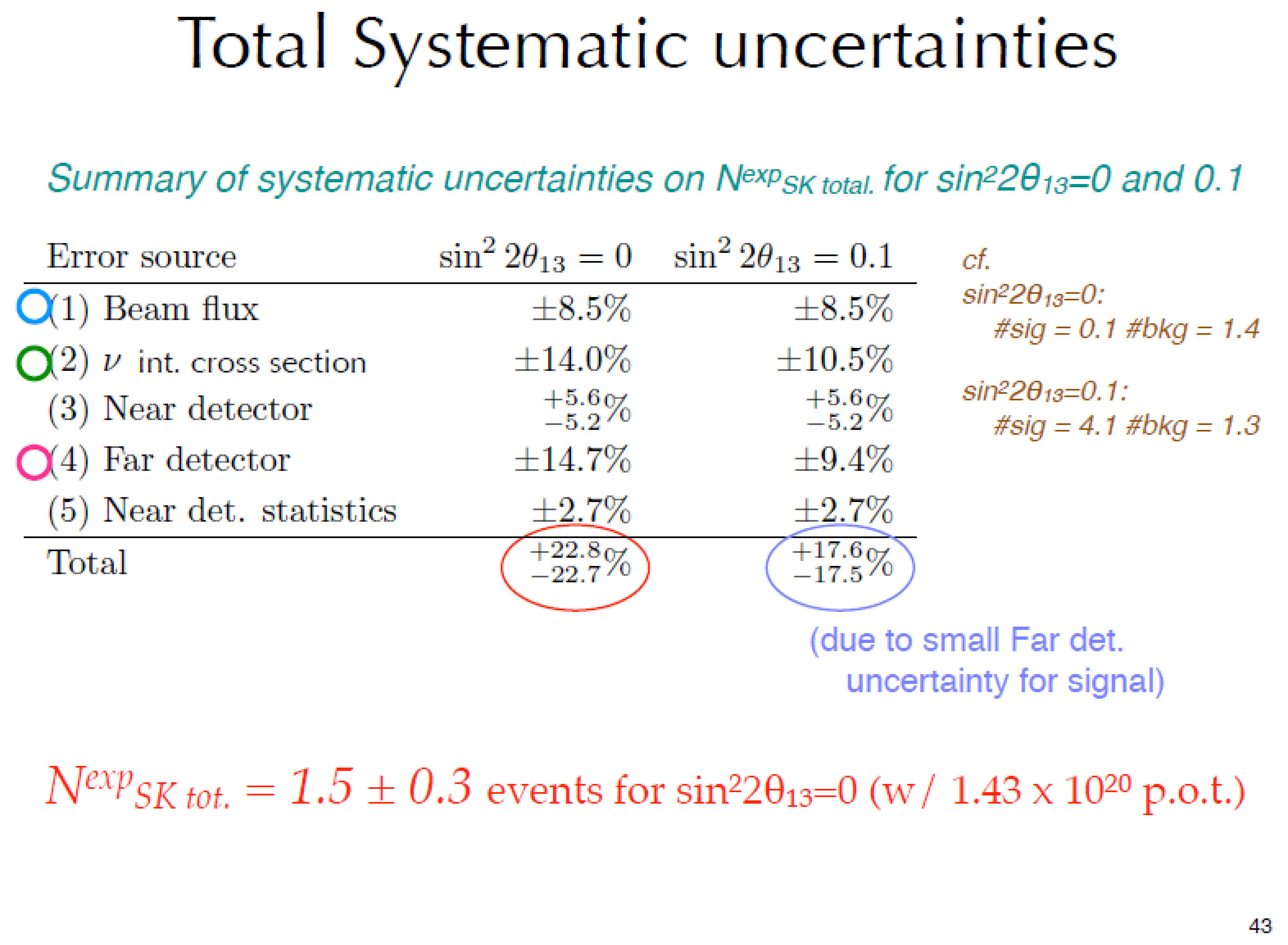
$$\frac{R_{ND}^{\mu,\ Data}}{R_{ND}^{\mu,\ MC}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

- **The number of beam ν_e background events at far detector is predicted using the ν beam simulation based on NA61 measurements (pion) and FLUKA (kaon)**
  - ND measurements (μ momentum and event rate) are consistent with MC based on the ν beam simulation

The expected number of events with 1.43 x 10^{20} p.o.t.

$N^{exp}_{SK\ tot.} = 1.5$ events for $\sin^2 2\theta_{13}=0$

	Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
The expected # of events at SK	**0.8**	**0.6**	**0.1**	**1.5**



Total Systematic uncertainties

Summary of systematic uncertainties on $N^{exp}_{SK\ total.}$ for $\sin^2 2\theta_{13}=0$ and 0.1

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
○ (1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
○ (2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
○ (4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

cf.

$\sin^2 2\theta_{13}=0$:
#sig = 0.1 #bkg = 1.4

$\sin^2 2\theta_{13}=0.1$:
#sig = 4.1 #bkg = 1.3

(due to small Far det.
uncertainty for signal)

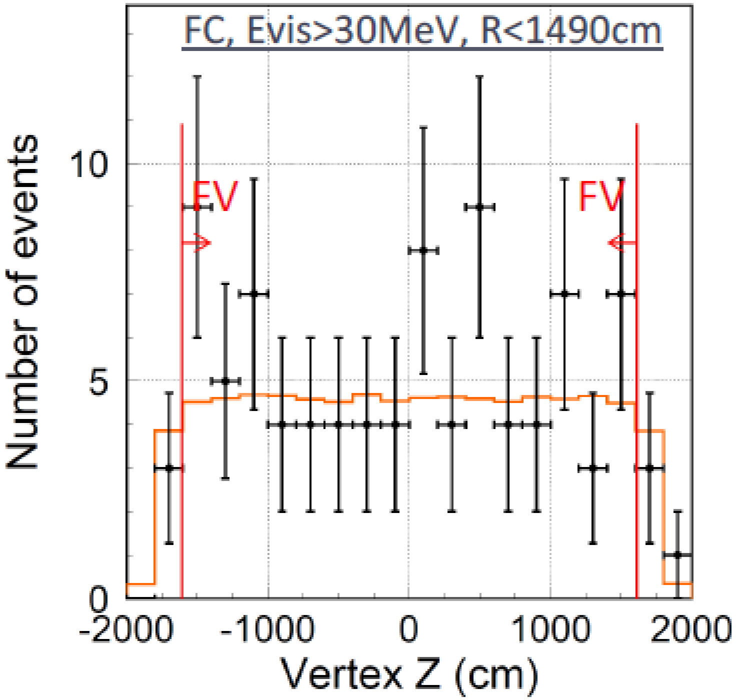
$N^{exp}_{SK\ tot.} = 1.5 \pm 0.3$ events for $\sin^2 2\theta_{13}=0$ (w/ 1.43 x 10^{20} p.o.t.)

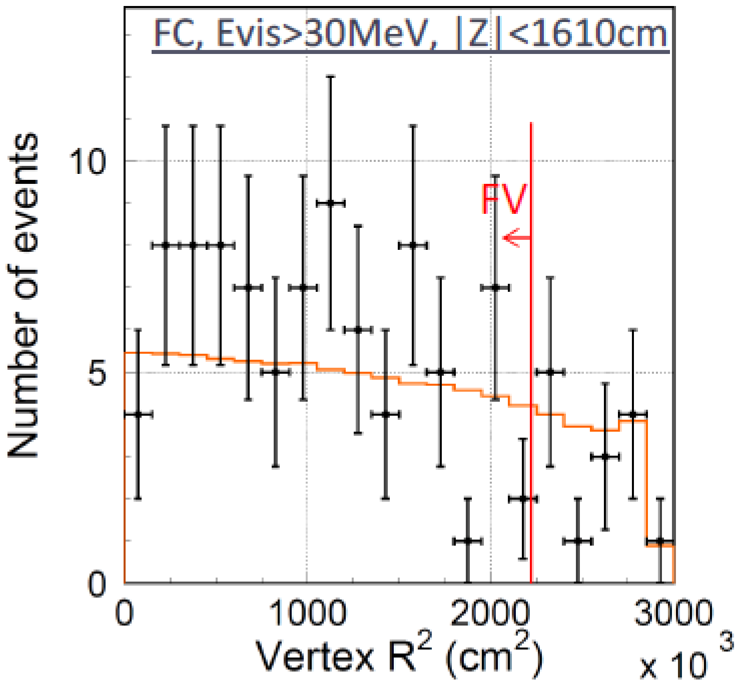
Apply ν_e event selection

defined before the data collection
6 selection cuts in addition FC cut

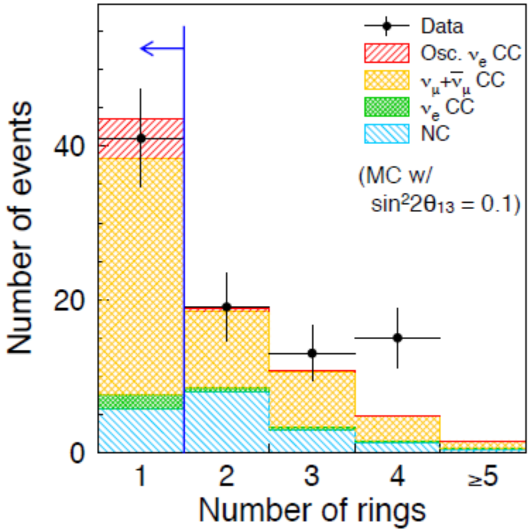
Fiducial volume cut

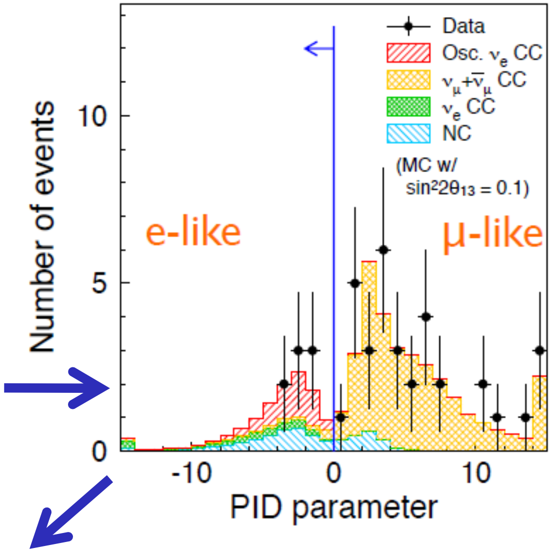
(distance between recon. vertex and wall > 200cm)

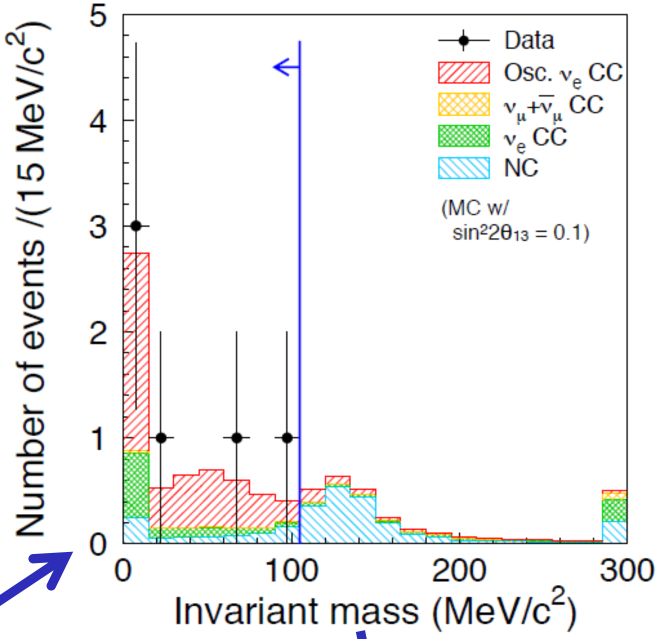


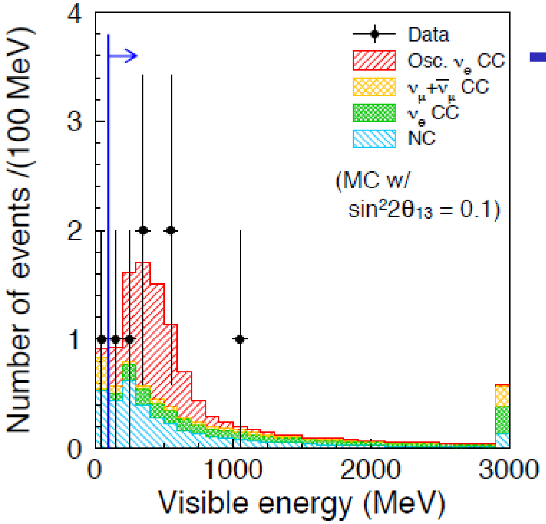


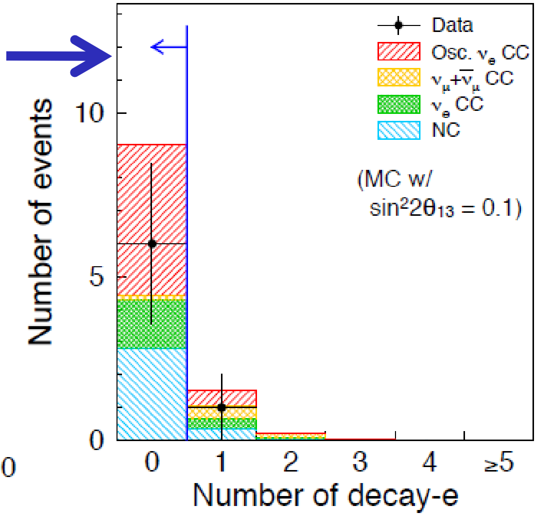
T2K ν_e Appearance Data Reduction

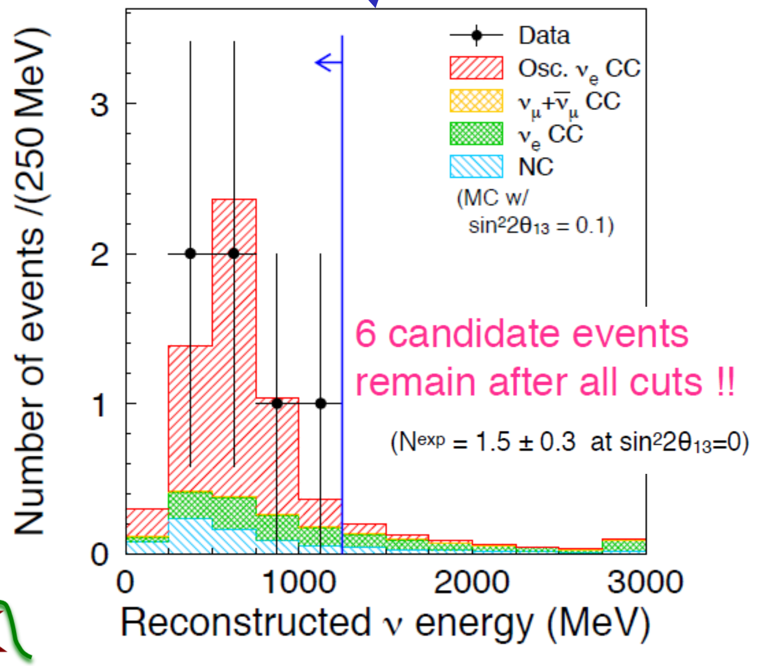










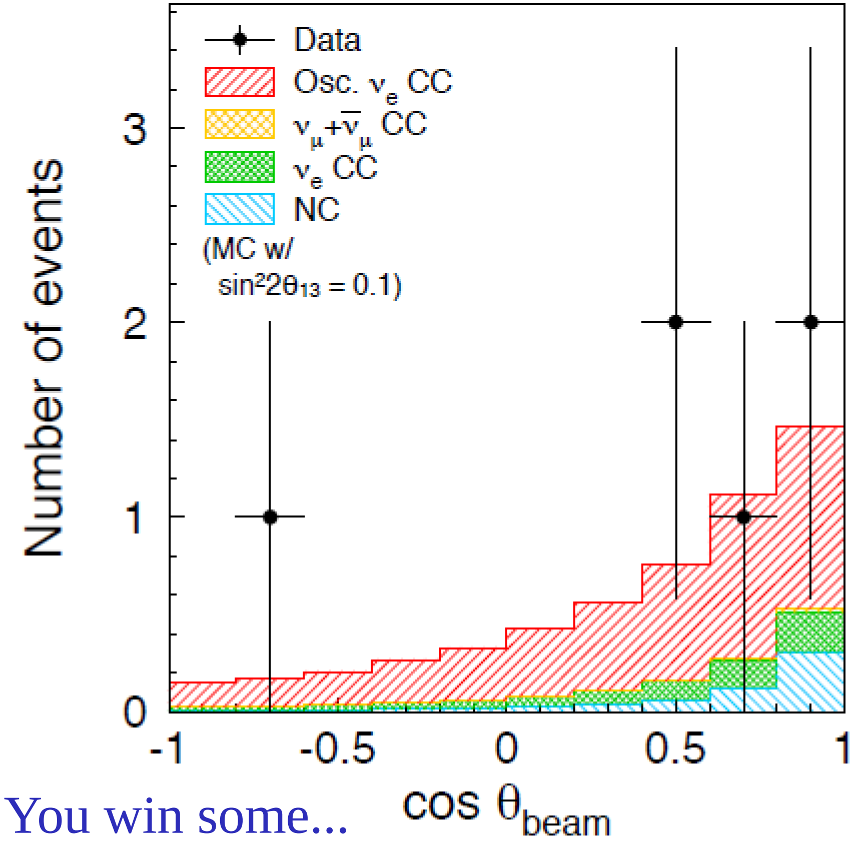


6 candidate events remain after all cuts !!

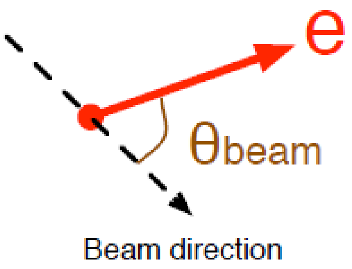
($N^{exp} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}=0$)

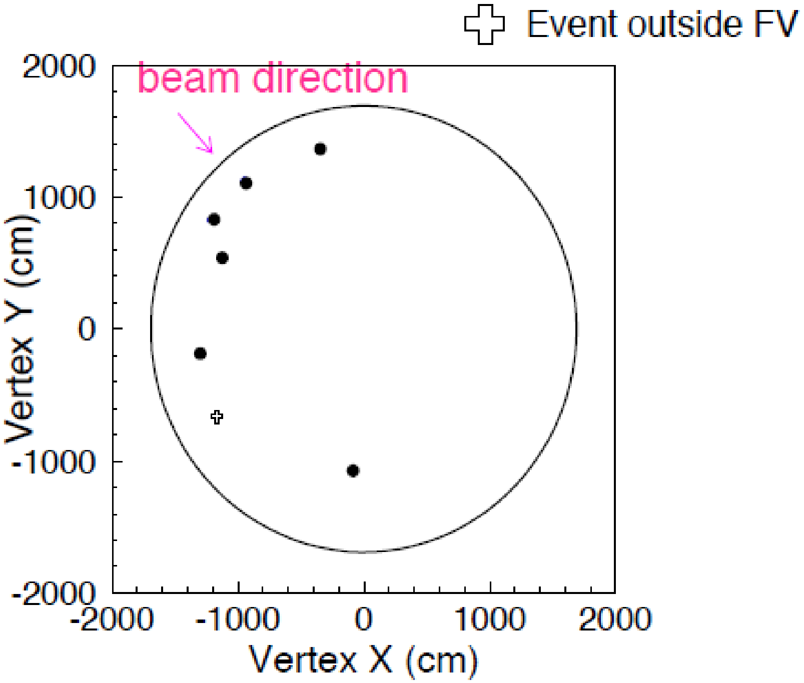
All cuts optimized for low statistics and fixed before data taken.

Check many distributions....

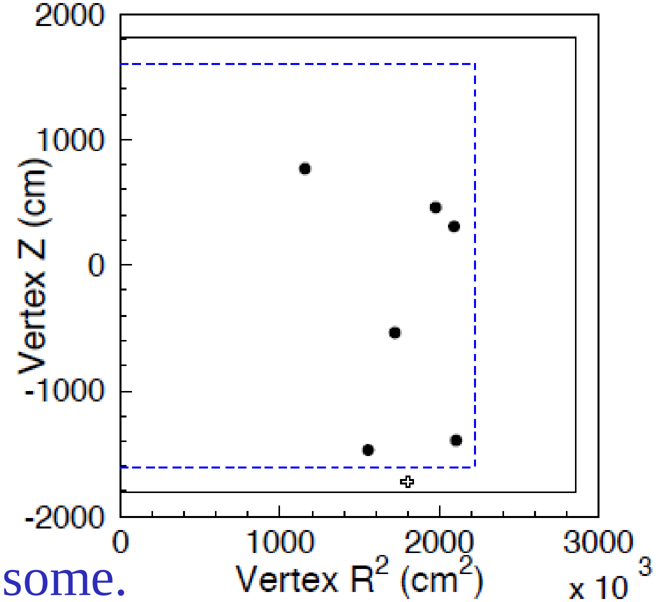


You win some...





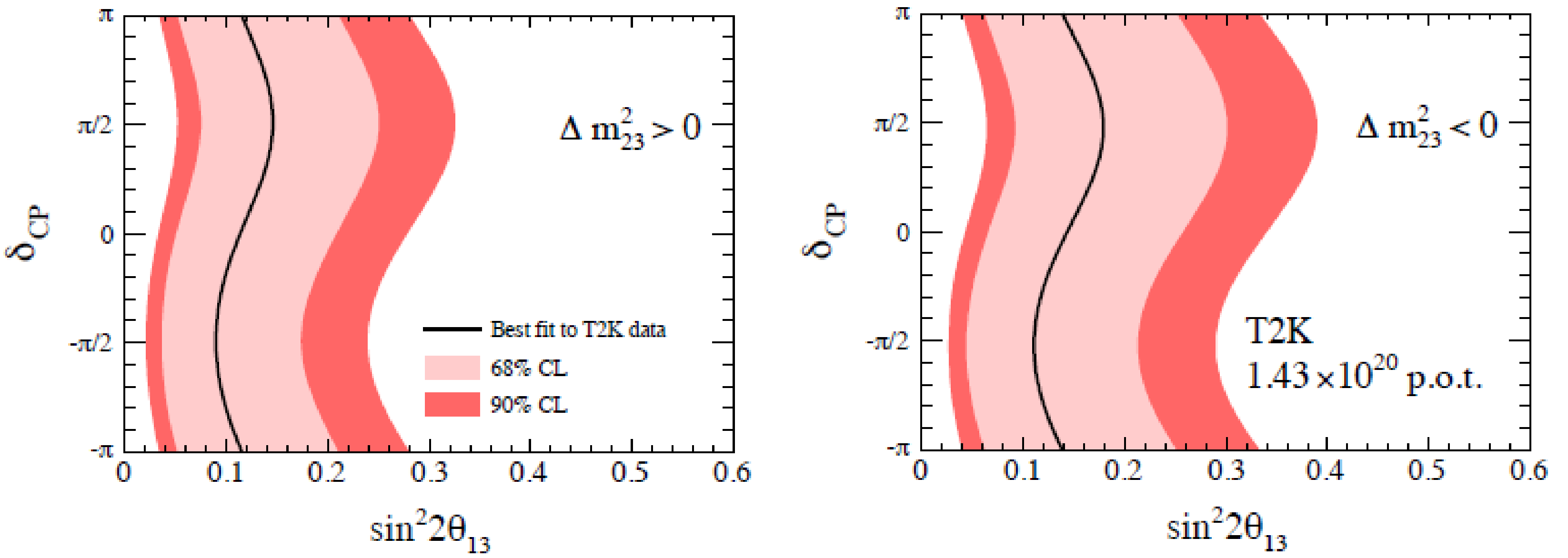
No excess outside FV or in OD, but KS prob. for R^2 is ~3%



You lose some.

Allowed region of $\sin^2 2\theta_{13}$ as a function of δ_{CP}

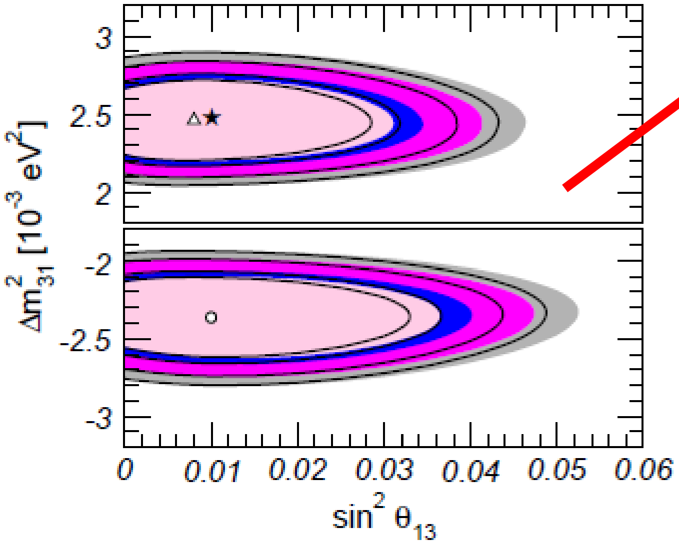
(assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)

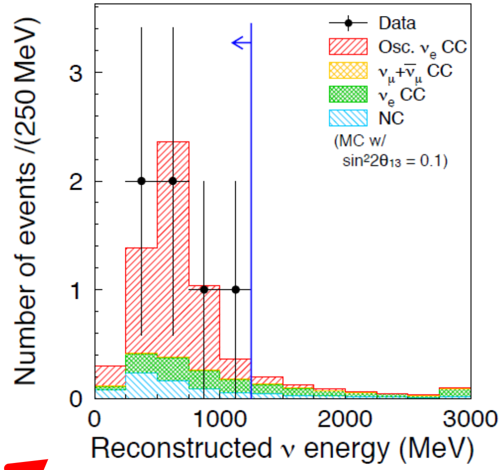


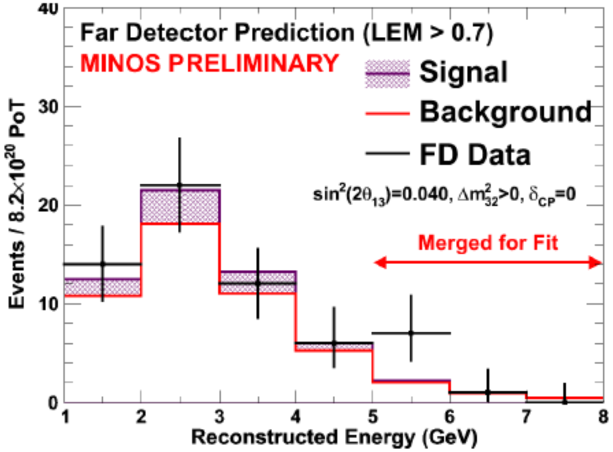
90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$	**$0.04 < \sin^2 2\theta_{13} < 0.34$**
$\sin^2 2\theta_{13} = 0.11$	**$\sin^2 2\theta_{13} = 0.14$**

What about θ_{13}?







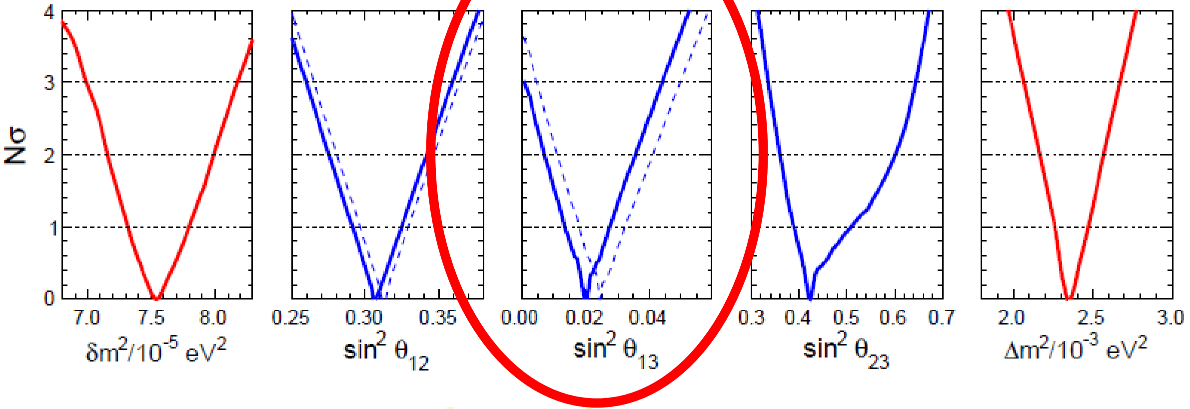
T2K (2.5σ) MINOS (1.7σ)

ν_e appearance, $\theta_{13} > 0$?

Evidence of $\theta_{13} > 0$ from global neutrino data analysis

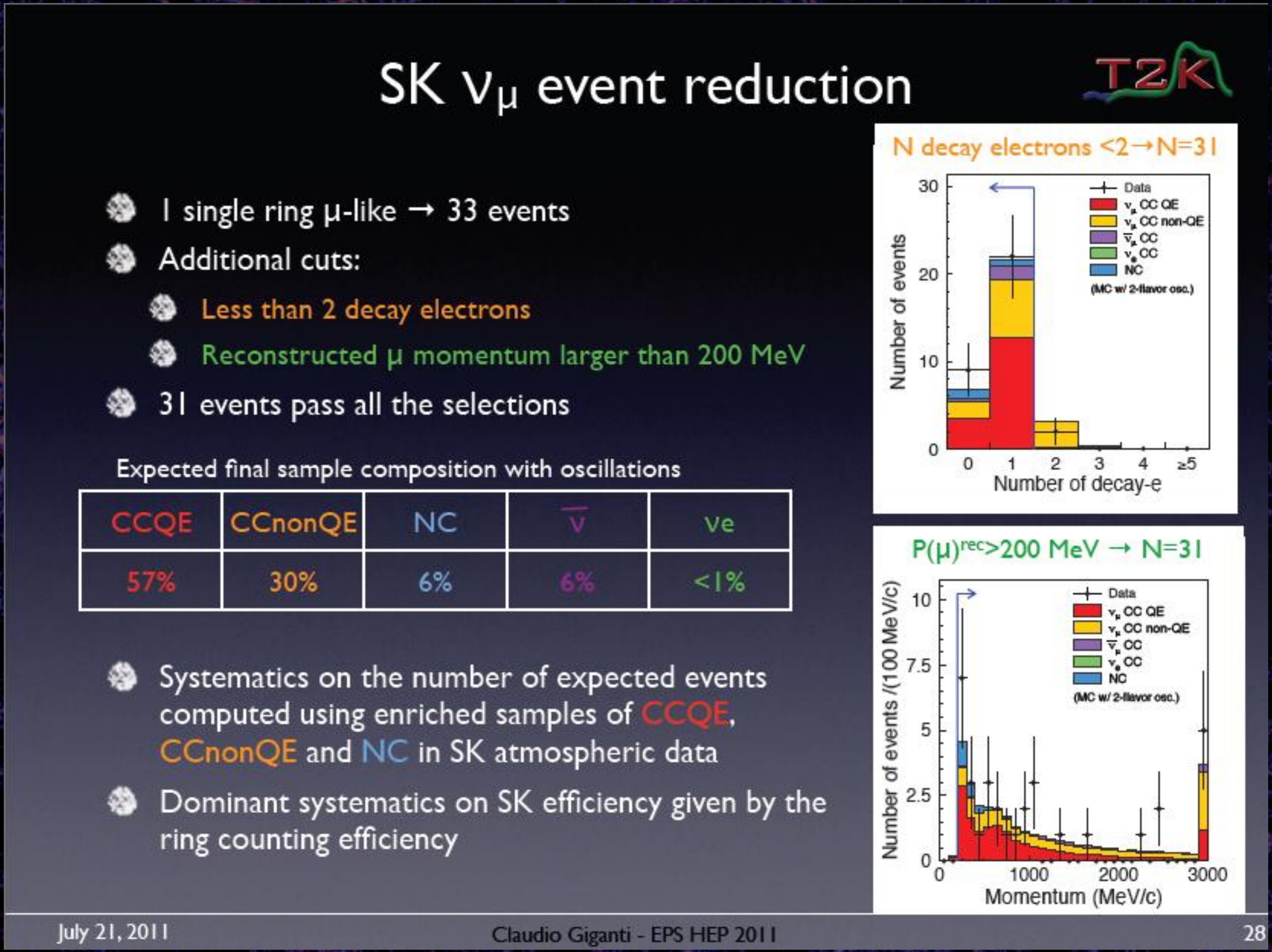
G.L. Fogli,[1,2] E. Lisi,[2] A. Marrone,[1,2] A. Palazzo,[3] and A.M. Rotunno[1]

Synopsis of global 3ν oscillation analysis



arXiv:1106.6028v1 [hep-ph] 29 Jun 2011

Interesting hints that $\theta_{13} > 0$, but clearly more data needed.



SK ν_μ event reduction

- 1 single ring μ-like → 33 events
- Additional cuts:
  - Less than 2 decay electrons
  - Reconstructed μ momentum larger than 200 MeV
- 31 events pass all the selections

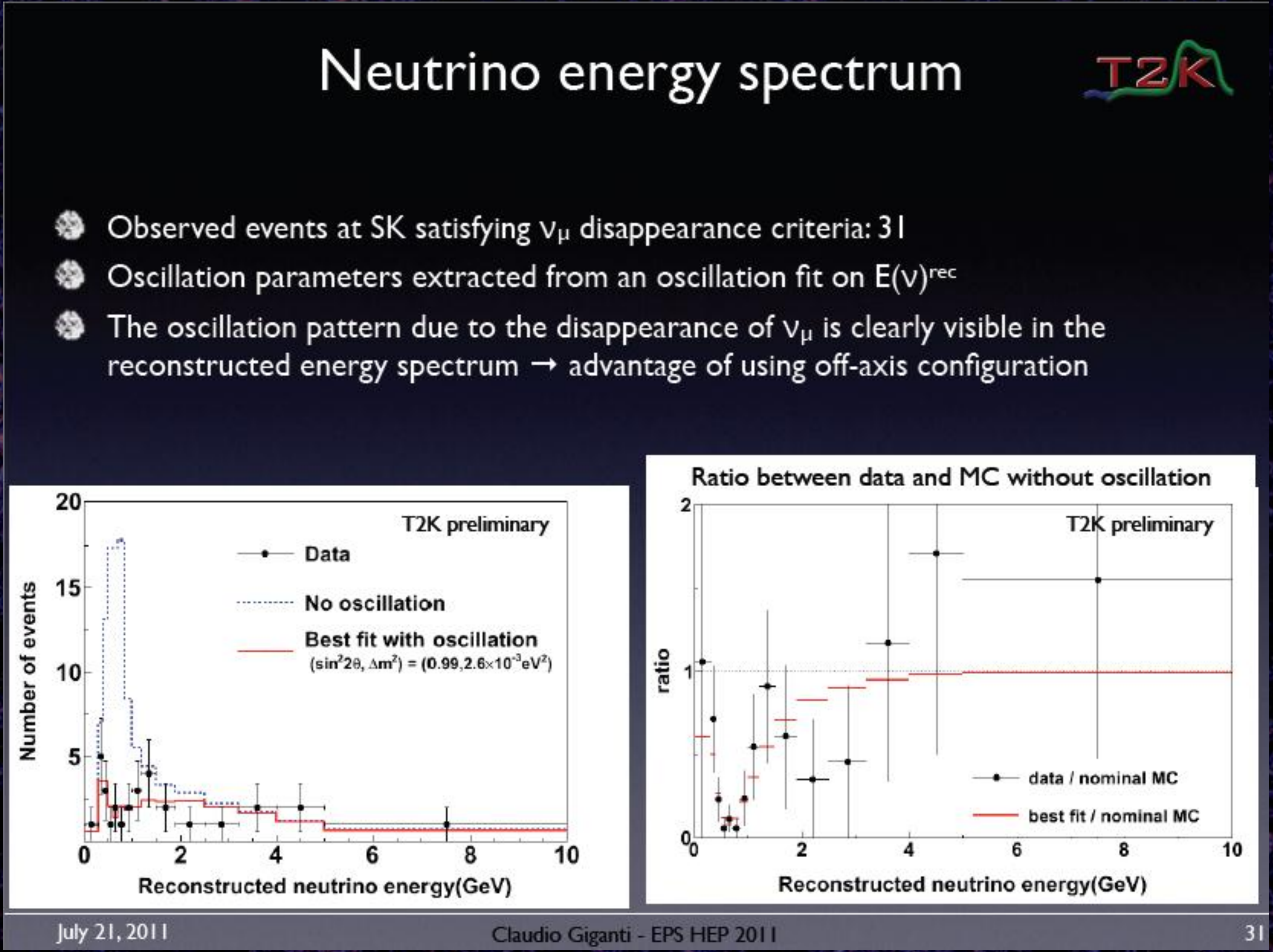
Expected final sample composition with oscillations

CCQE	CCnonQE	NC	$\overline{\nu}$	νe
57%	30%	6%	6%	<1%

- Systematics on the number of expected events computed using enriched samples of CCQE, CCnonQE and NC in SK atmospheric data
- Dominant systematics on SK efficiency given by the ring counting efficiency

N decay electrons <2→N=31

P(μ)^{rec}>200 MeV → N=31



Neutrino energy spectrum

- Observed events at SK satisfying ν_μ disappearance criteria: 31
- Oscillation parameters extracted from an oscillation fit on $E(\nu)^{rec}$
- The oscillation pattern due to the disappearance of ν_μ is clearly visible in the reconstructed energy spectrum → advantage of using off-axis configuration

July 21, 2011

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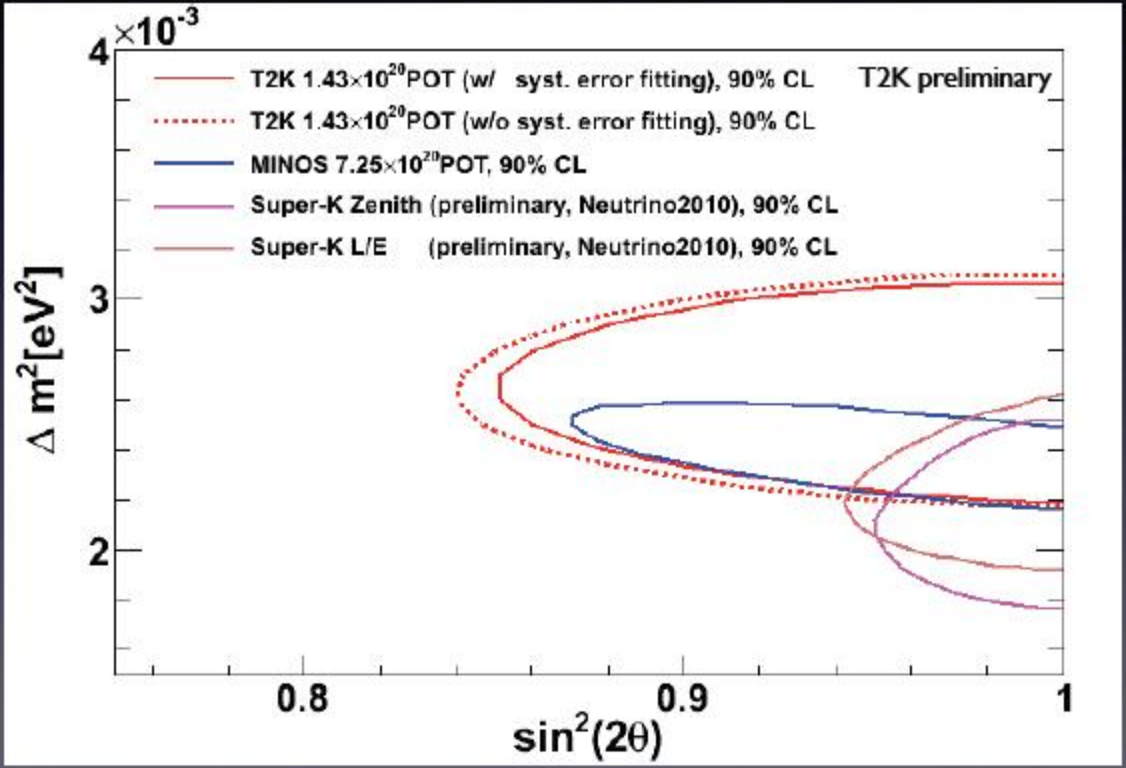
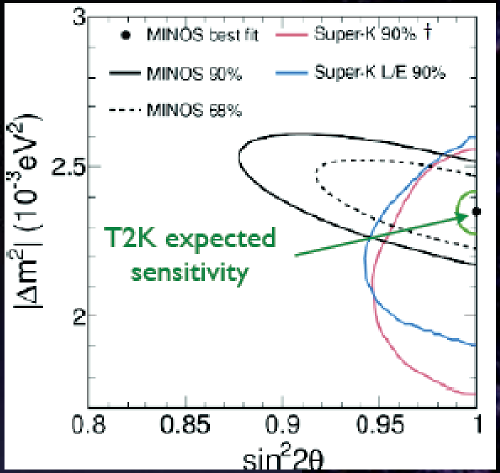
Comparison with SK and MINOS

- T2K results are in good agreement with results from SK and MINOS





T2K expected sensitivity

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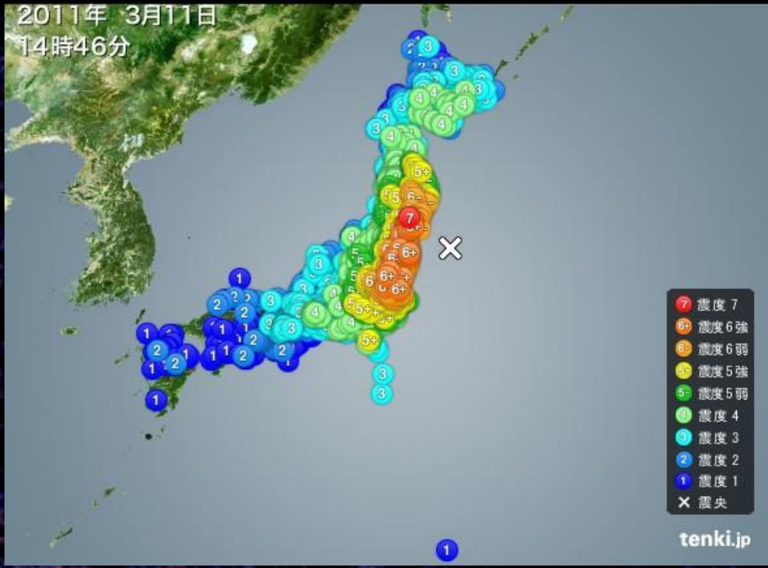
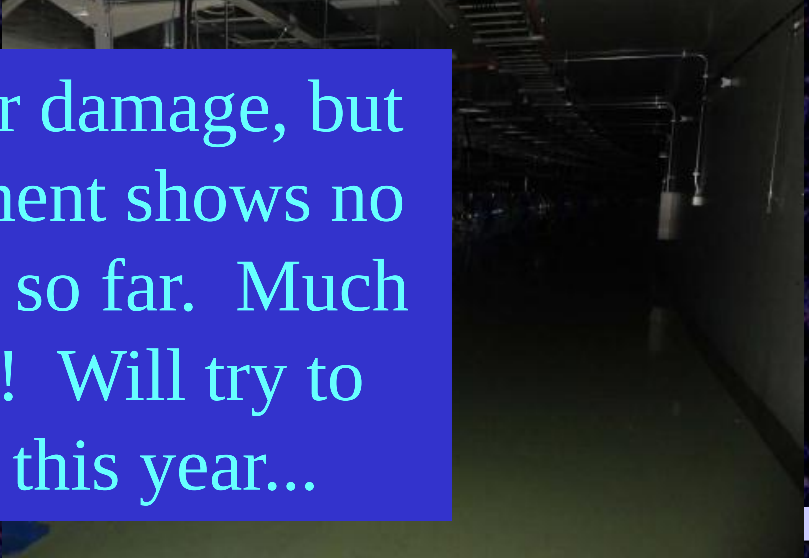
5/11, 14:46, all Hell broke loose...



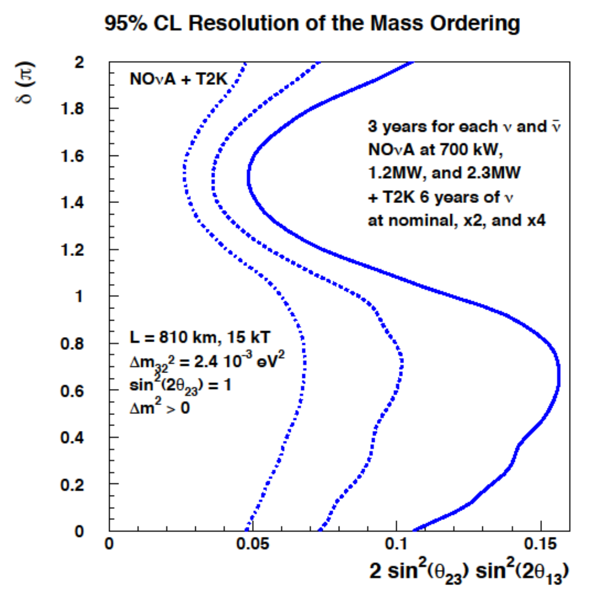


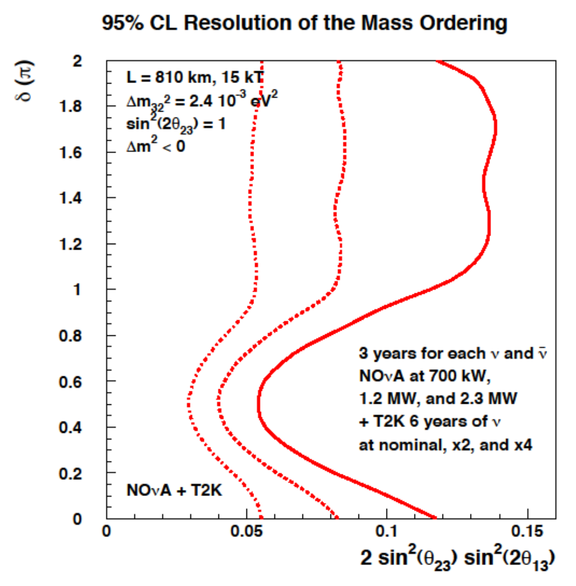
Much exterior damage, but inside equipment shows no major damage so far. Much to check yet! Will try to restart late this year...

What else to talk about?

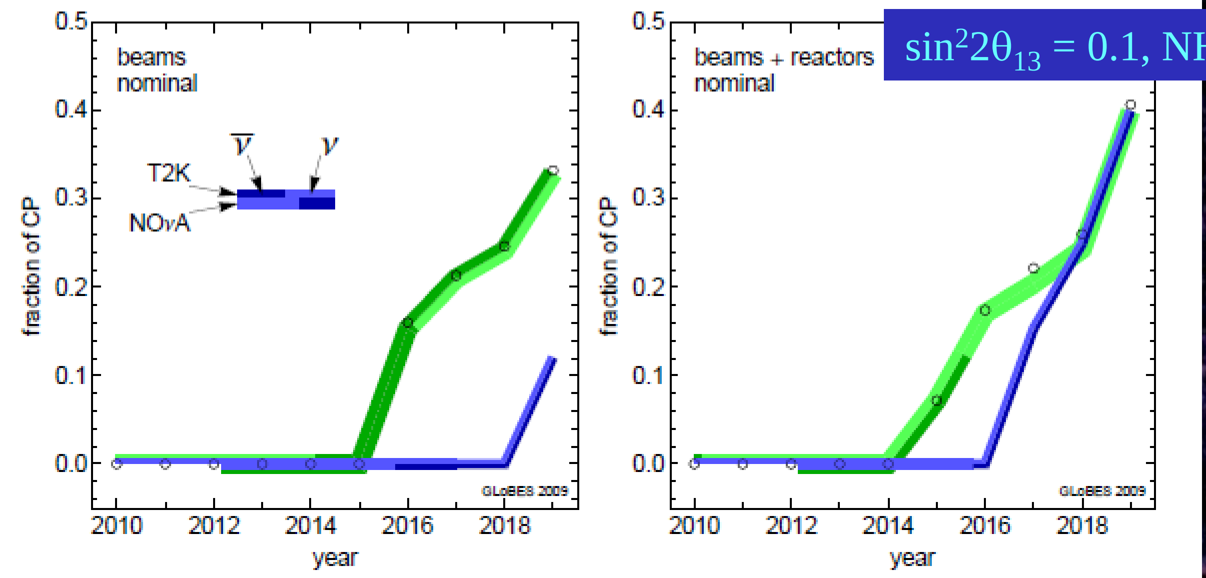
- Another round of supererbeams?:
    - Water Cerenkov or Liquid Argon?
    - Upgrade of T2K
    - LBNE
    - LBNO
- The further future?:
    - β beams
    - Neutrino Factory
- Cosmological ν
- Supernovae ν and the OPERA time anomaly
- Sterile neutrinos?
- Support Experiments...

What will existing experiments yield?





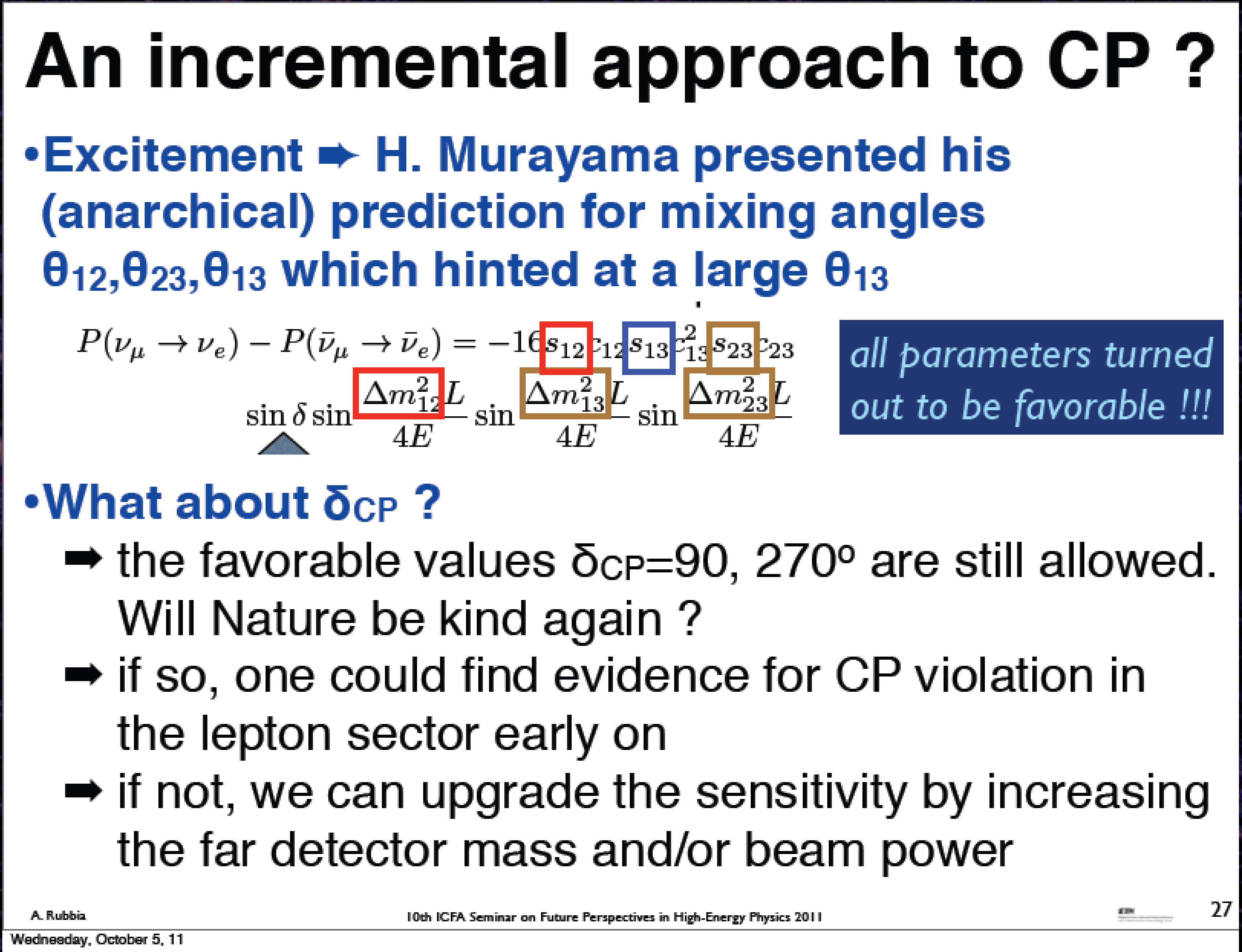
Even some 90% CP violation sensitivity…



$\sin^2 2\theta_{13} = 0.1$, NH

arXiv:0907.1896v1 [hep-ph] 10 Jul 2009

Dave Wark
Imperial College/RAL



An incremental approach to CP ?

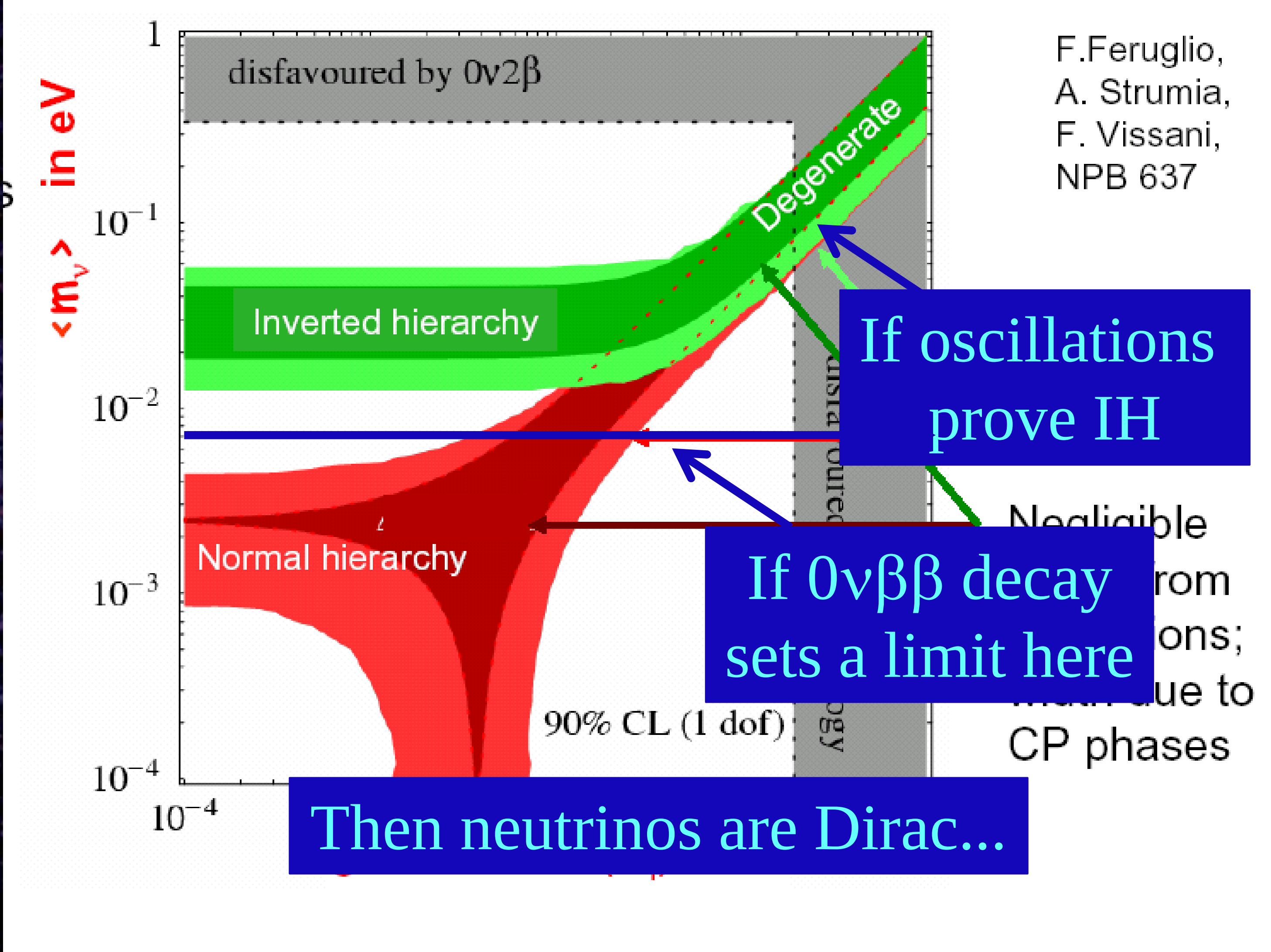
- **Excitement ➡ H. Murayama presented his (anarchical) prediction for mixing angles θ_{12},θ_{23},θ_{13} which hinted at a large θ_{13}**

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16\boxed{s_{12}}c_{12}\boxed{s_{13}}c_{13}^2\boxed{s_{23}}c_{23} \underset{\blacktriangle}{\sin\delta} \sin\frac{\boxed{\Delta m^2_{12}}L}{4E} \sin\frac{\boxed{\Delta m^2_{13}}L}{4E} \sin\frac{\boxed{\Delta m^2_{23}}L}{4E}$$

all parameters turned out to be favorable !!!

- **What about δ_{CP} ?**
  - ➡ the favorable values δ_{CP}=90, 270º are still allowed. Will Nature be kind again ?
  - ➡ if so, one could find evidence for CP violation in the lepton sector early on
  - ➡ if not, we can upgrade the sensitivity by increasing the far detector mass and/or beam power

Towards CP Violation



F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

Negligible
rom
ons;
ue to
CP phases

If oscillations prove IH

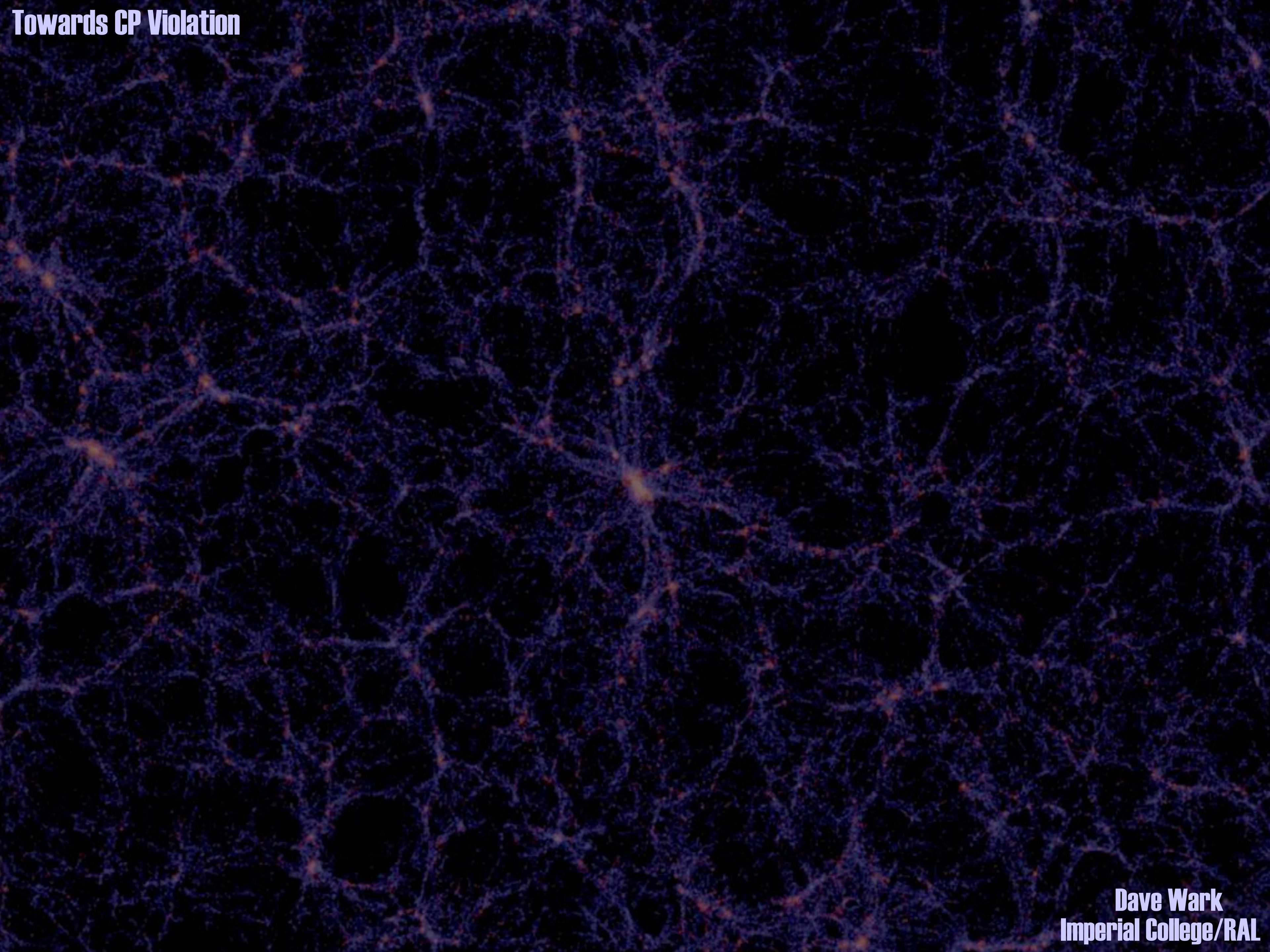
If $0\nu\beta\beta$ decay sets a limit here

Then neutrinos are Dirac…

Conclusions

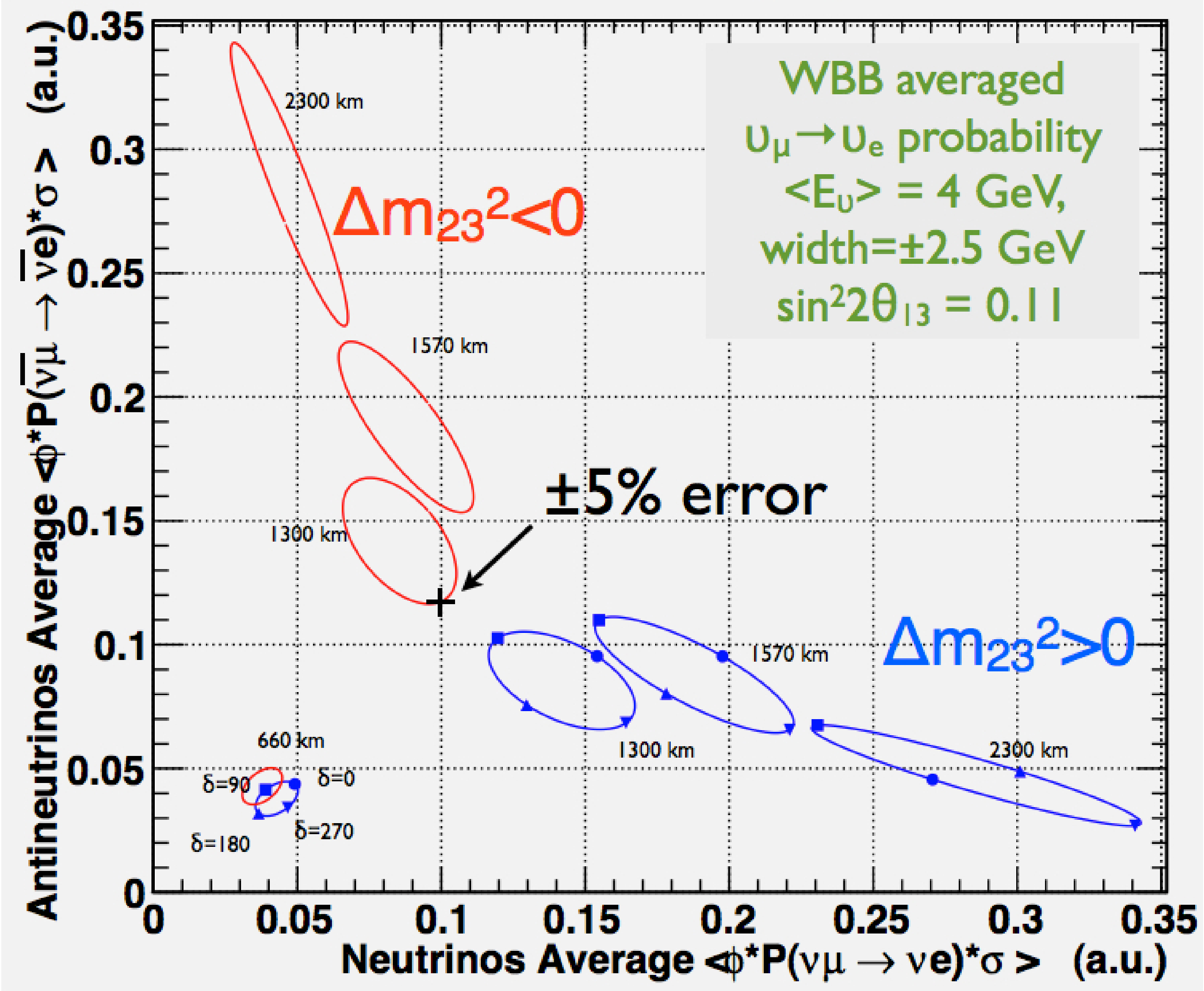
- Neutrino oscillations are the first confirmed physics beyond the SM!
- Current indications are that $\sin^2 2\theta_{13} \geq \sim 0.01$, which could give existing experiments the first sensitivity to CP violation in the neutrino sector.
- Do not assume we know everything that is going on – redundancy is essential!
- There are three next-generation superbeam projects, and I think the physics will justify at least two.
- In my opinion, a large LAr tracking calorimeter will be used in at least one experiment, making LAr development a high priority.
- There will be many other opportunities for smaller-scale involvement in cross-section, hadron production, and perhaps short-baseline projects.
- Neutrino experiments have a guaranteed future. JOIN US!

Towards CP Violation



Dave Wark
Imperial College/RAL

Simultaneous solution to CP and mass hierarchy problems

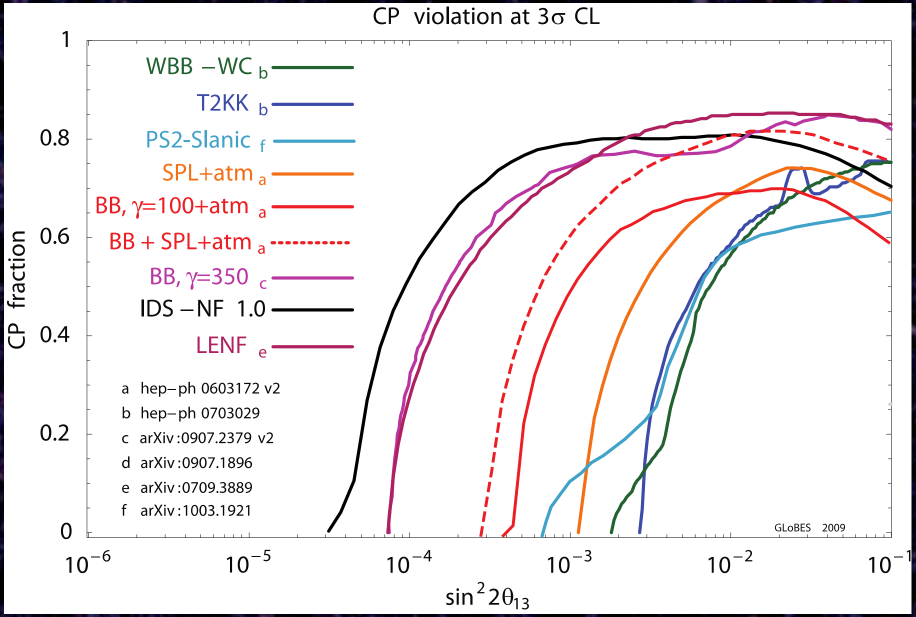


WBB averaged
$\upsilon_\mu \to \upsilon_e$ probability
$\langle E_\upsilon \rangle$ = 4 GeV,
width=±2.5 GeV
$\sin^2 2\theta_{13} = 0.11$

±5% error

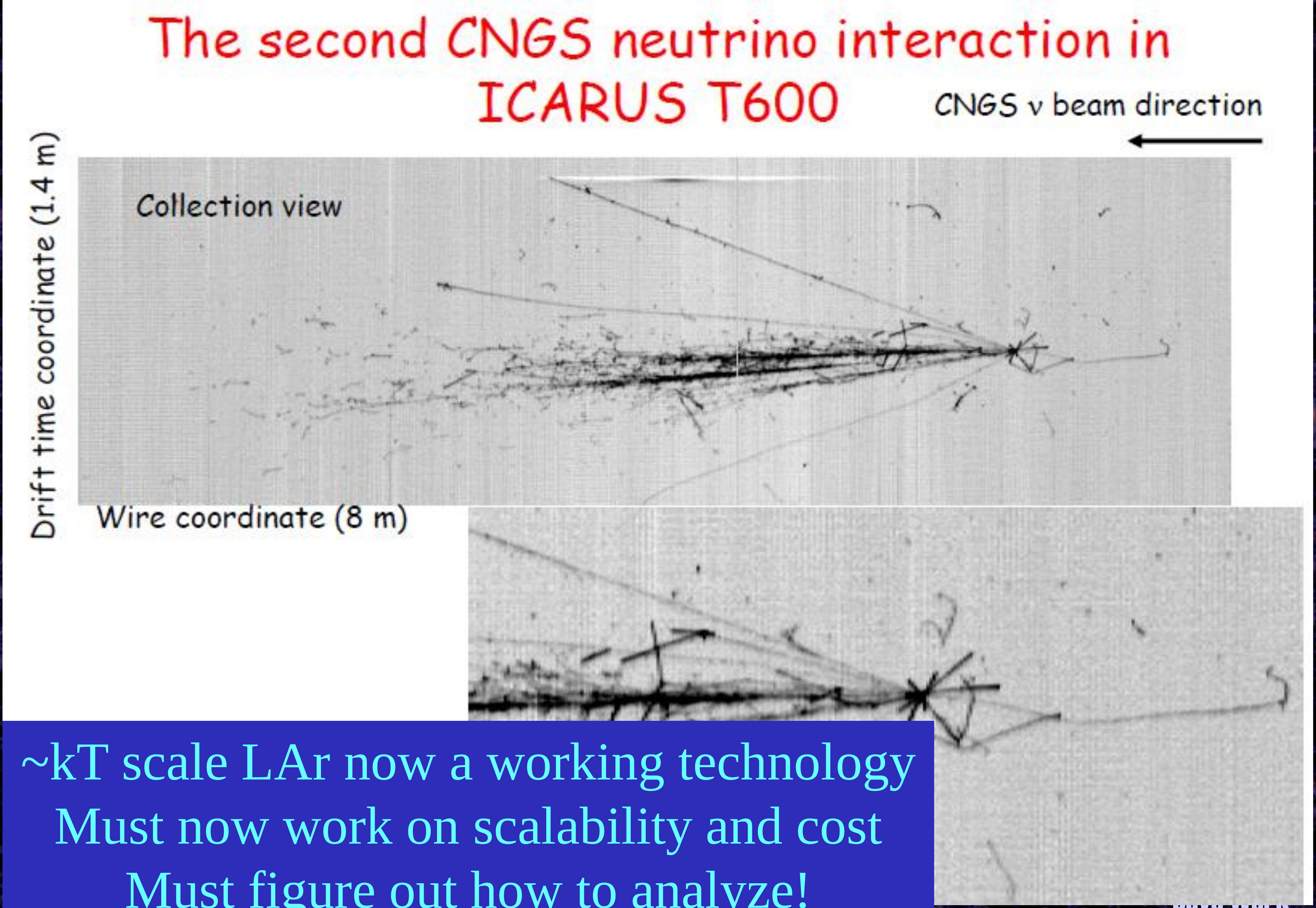
Longer baselines are better to determine mass hierarchy

OK, then what?



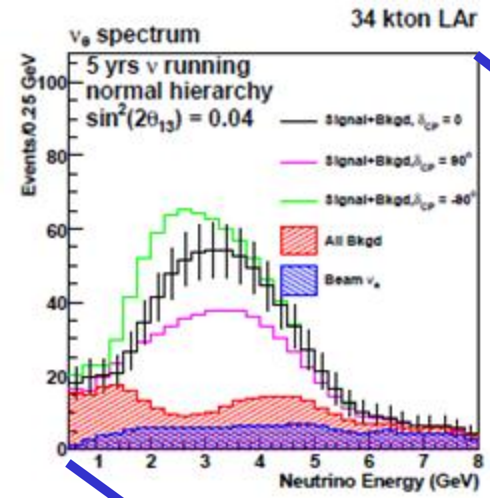
- Three “conventional” beam proposals:
  - – An upgrade of T2K based on reaching 1.6 MW beam power and a new far detector.
  - – LBNE – a plan to build a new neutrino beam at Fermilab aimed at Homestake, where either a large water Cerenkov detector or a LAr tracking calorimeter would be built.
  - – LAGUNA-LBNO – three different options for new long baseline in Europe.

Return ↑



The second CNGS neutrino interaction in ICARUS T600

~kT scale LAr now a working technology
Must now work on scalability and cost
Must figure out how to analyze!

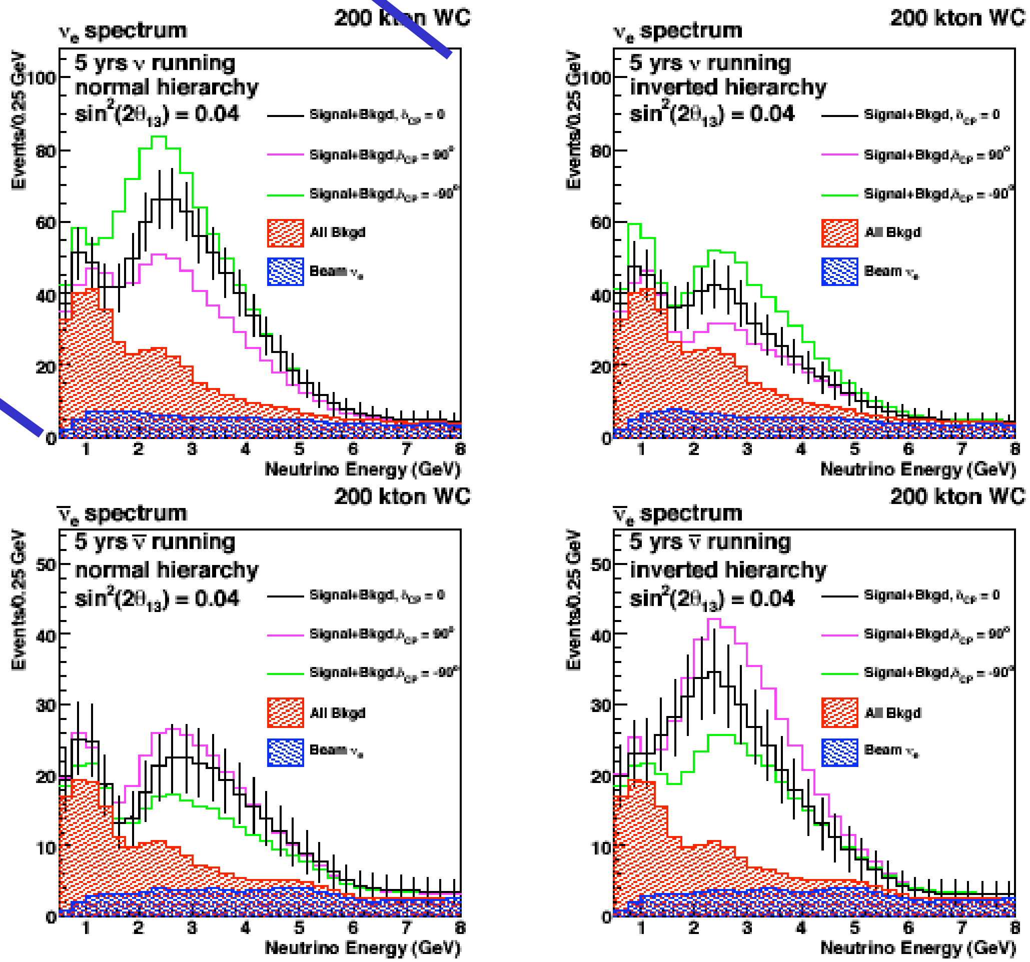


normal

inverted

nu

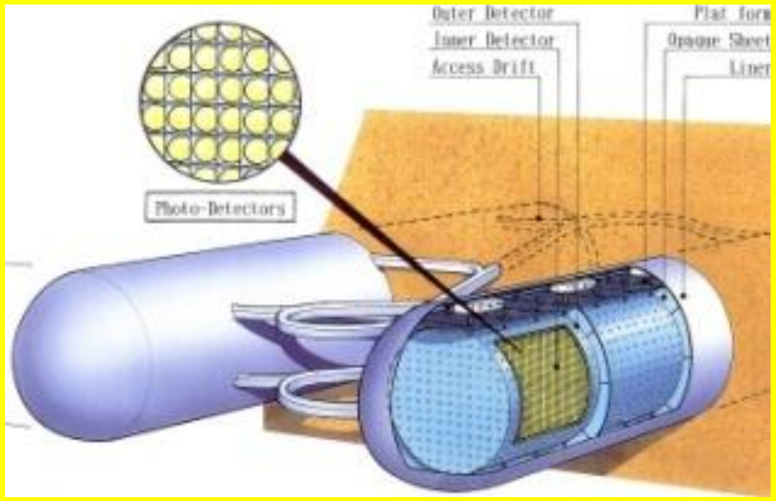
anti-nu



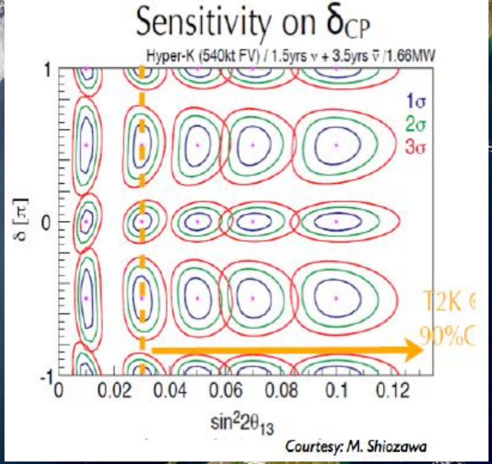
Return ↑

Lisa Whitehead

Scenarios in Japan

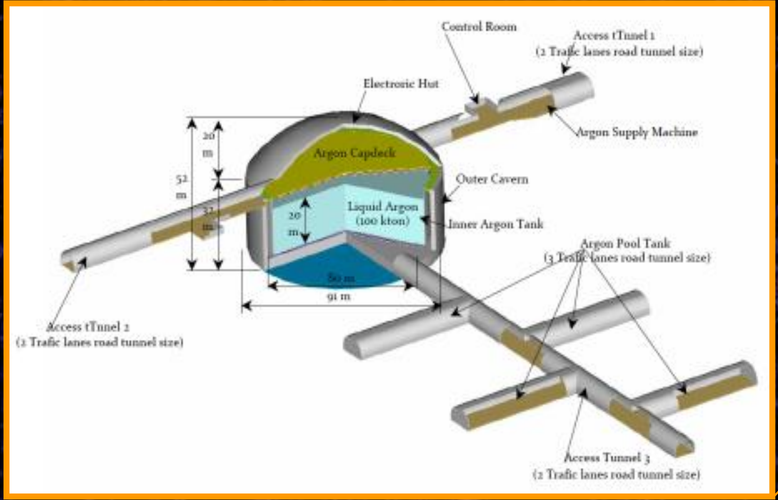


Kamioka L=295km OA=2.5deg



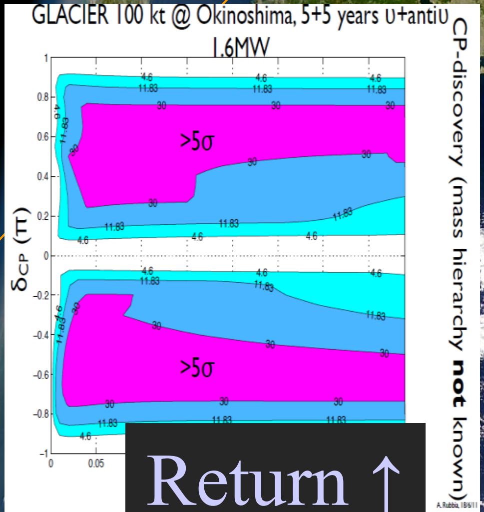
J-PARC

→1.7MW



Okinoshima L=658km OA=0.78deg

Almost On-Axis



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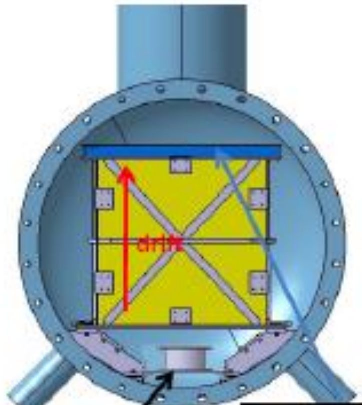
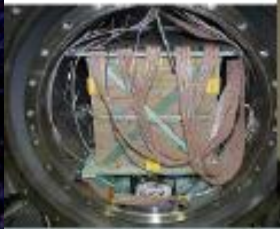
T32 test beam at J-PARC

Setup of Oct-2010 test-beam



Fiducial mass	170kg
Total LAr mass	~400kg
Field cage dimension	42cm x 42cm x 78cm
Fiducial volume	40cm x 40cm x 76cm
Typical Drift Field	~225V / cm
Maximum drift voltage	12kV
Readout method	single phase (temporary
Number of readout channels	76 strips (1cm)



76 strips (1cm) anode

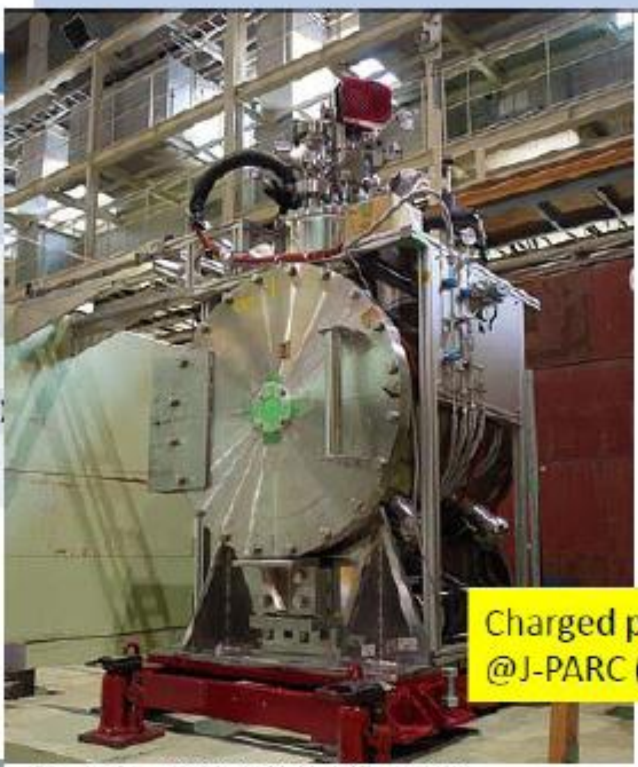
- Double phase component is under testing at CERN. (Unfortunately, not in time for the test-beam.)

◆ First beam data taken in Oct/Nov, 2010

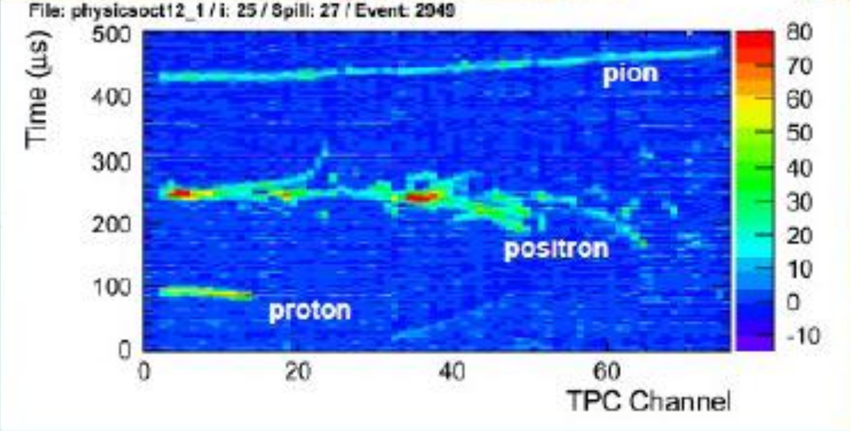
◆ Results will be presented in PAC (Jul.2011)

◆ Possible beam 2011(?)

◆ See Maruyama's talk

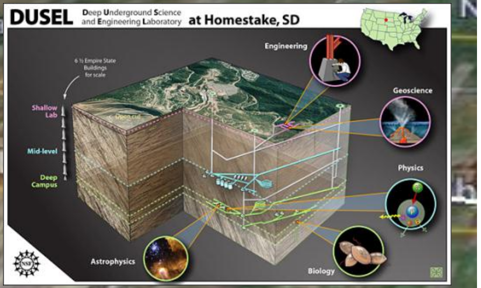


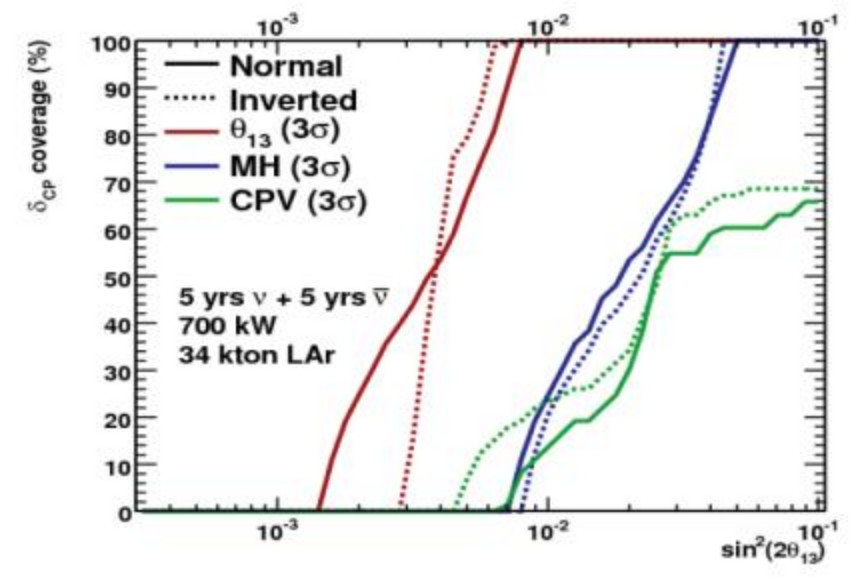
Charged particle test-bea
@J-PARC (Oct/24-31)

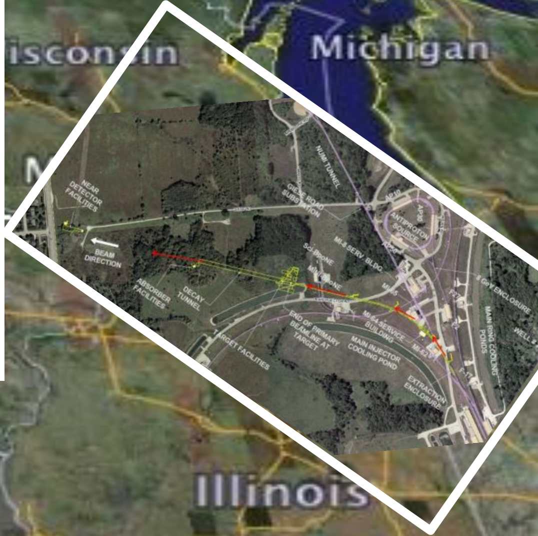


US: Long Baseline Neutrino Experiment

CD 0: January 2010







Collaboration:

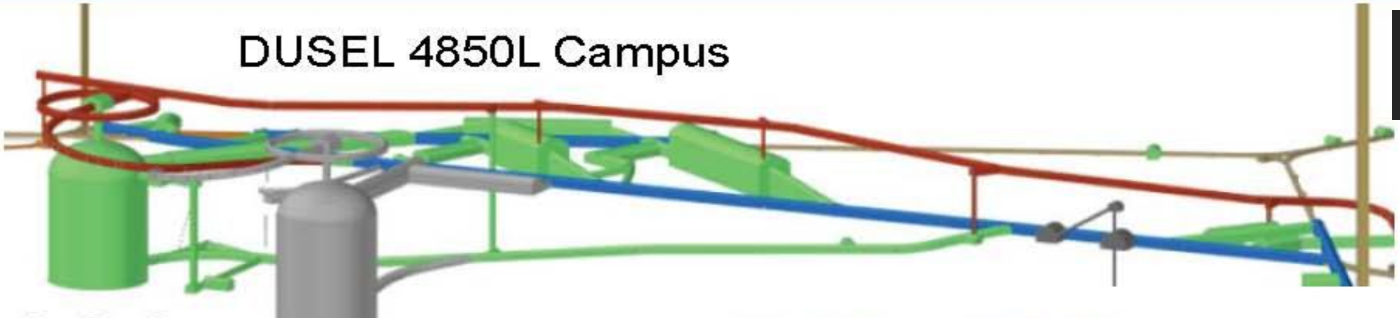
288 members from 54 institutions (India, Italy, Japan, UK, US)

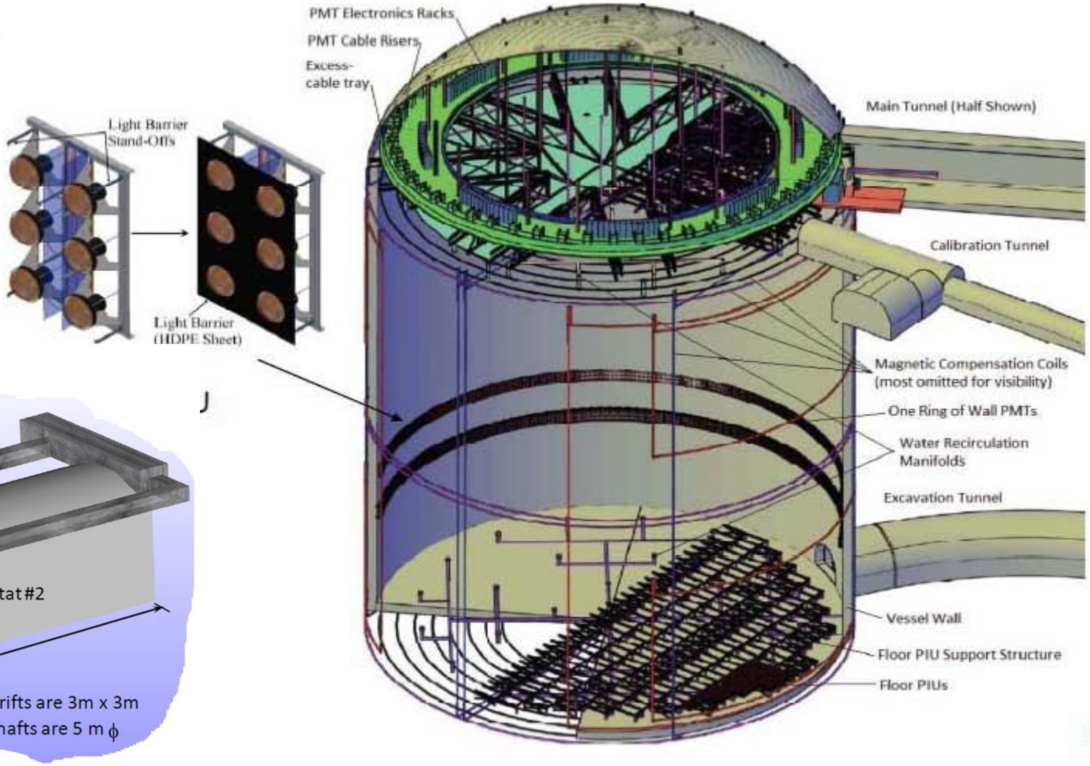
Continue to grow!

LAr Slight cheaper but riskier – Marx Committee

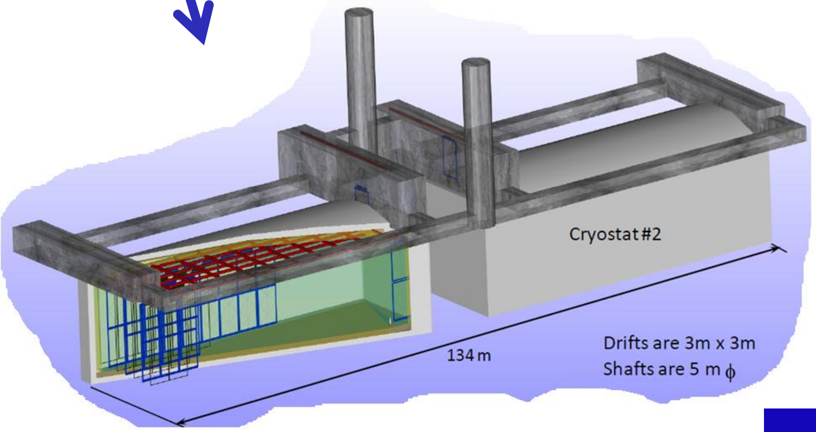
Conceptual Design Overview – Water Cherenkov

Return ↑



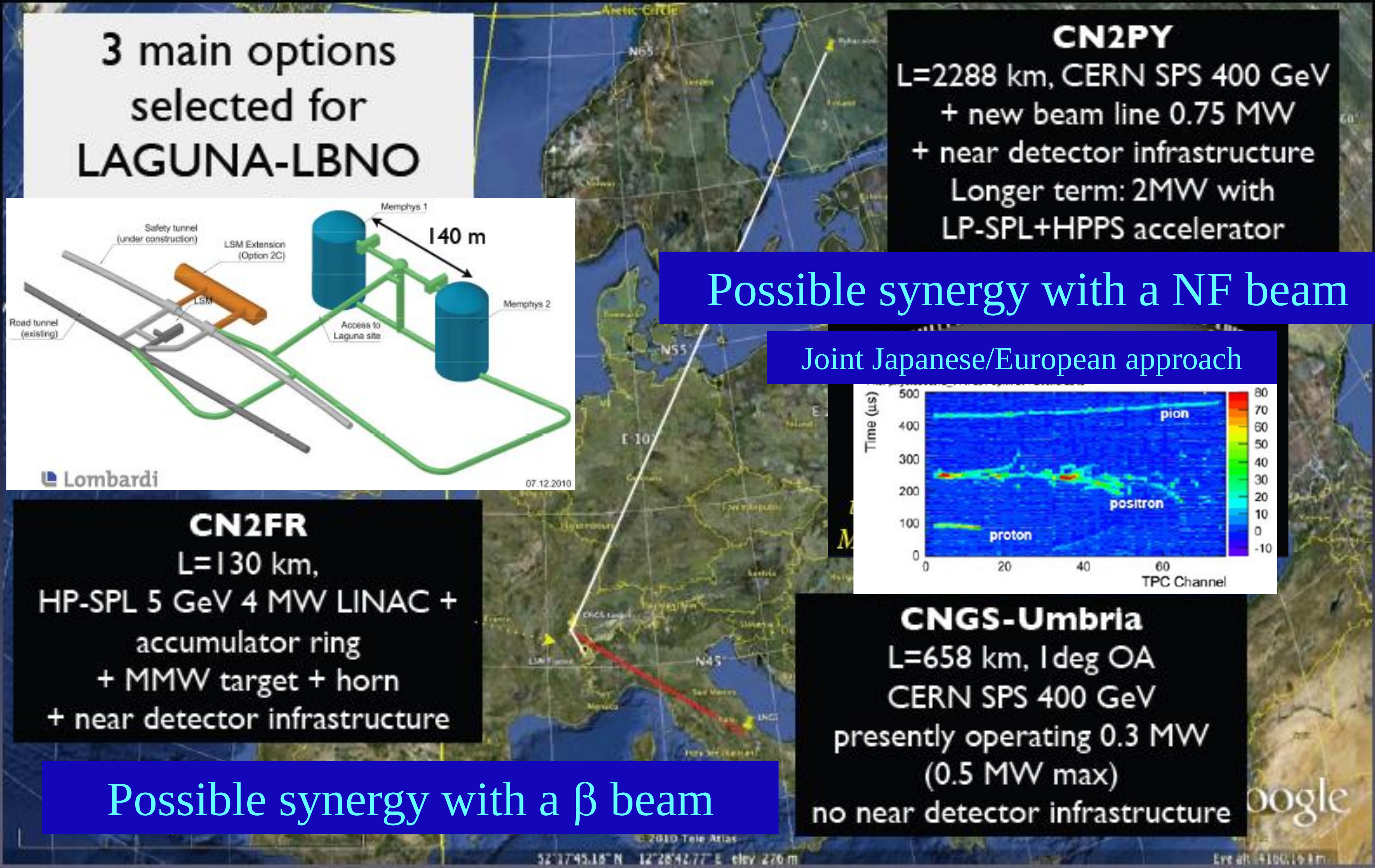


Alternative is 34 kT of LAr



Technology choice underway ....

Three main options



3 main options
selected for
LAGUNA-LBNO

CN2PY
L=2288 km, CERN SPS 400 GeV
+ new beam line 0.75 MW
+ near detector infrastructure
Longer term: 2MW with
LP-SPL+HPPS accelerator

Possible synergy with a NF beam

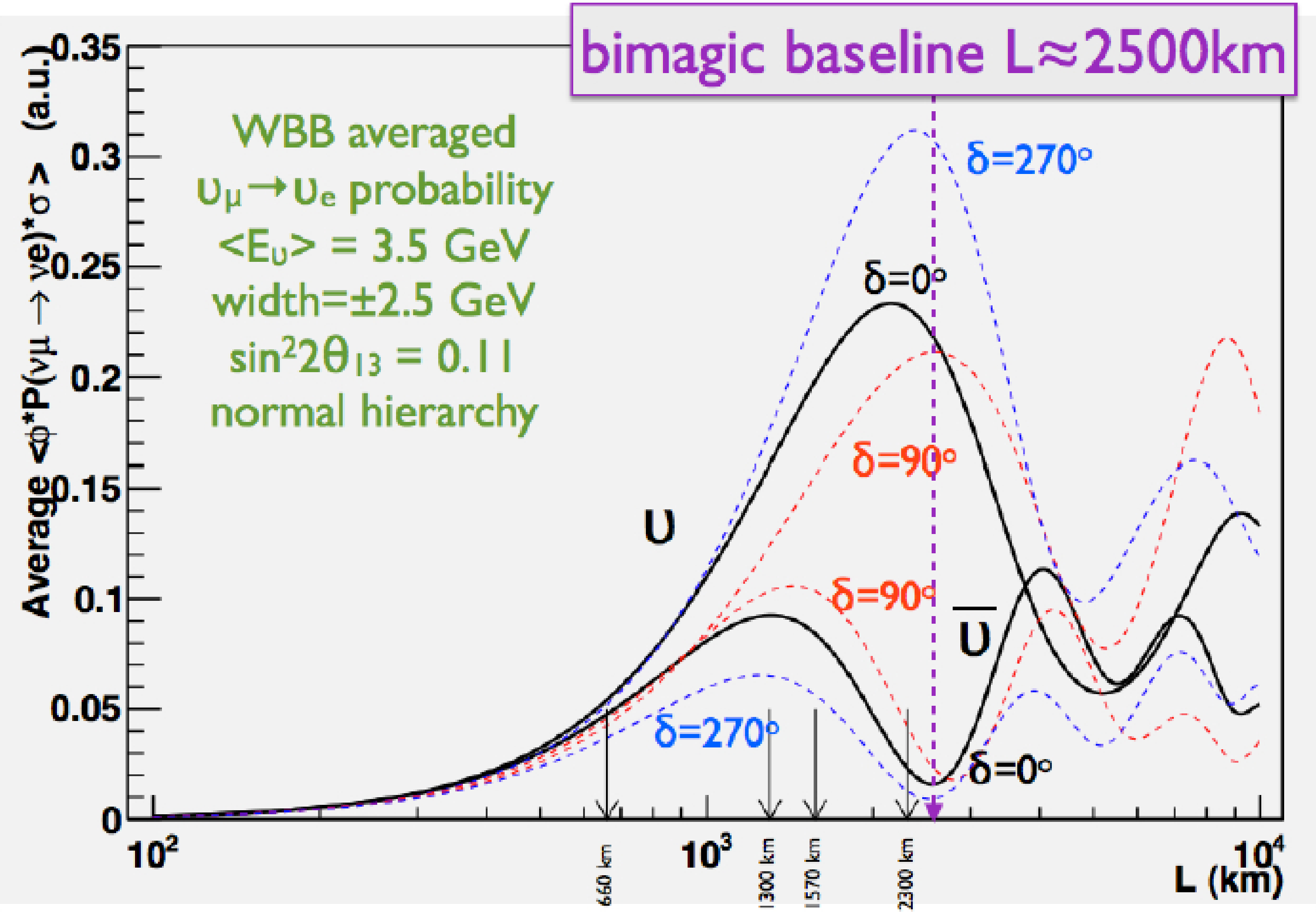
Joint Japanese/European approach

CN2FR
L=130 km,
HP-SPL 5 GeV 4 MW LINAC +
accumulator ring
+ MMW target + horn
+ near detector infrastructure

CNGS-Umbria
L=658 km, 1deg OA
CERN SPS 400 GeV
presently operating 0.3 MW
(0.5 MW max)
no near detector infrastructure

Possible synergy with a β beam

Baseline consideration

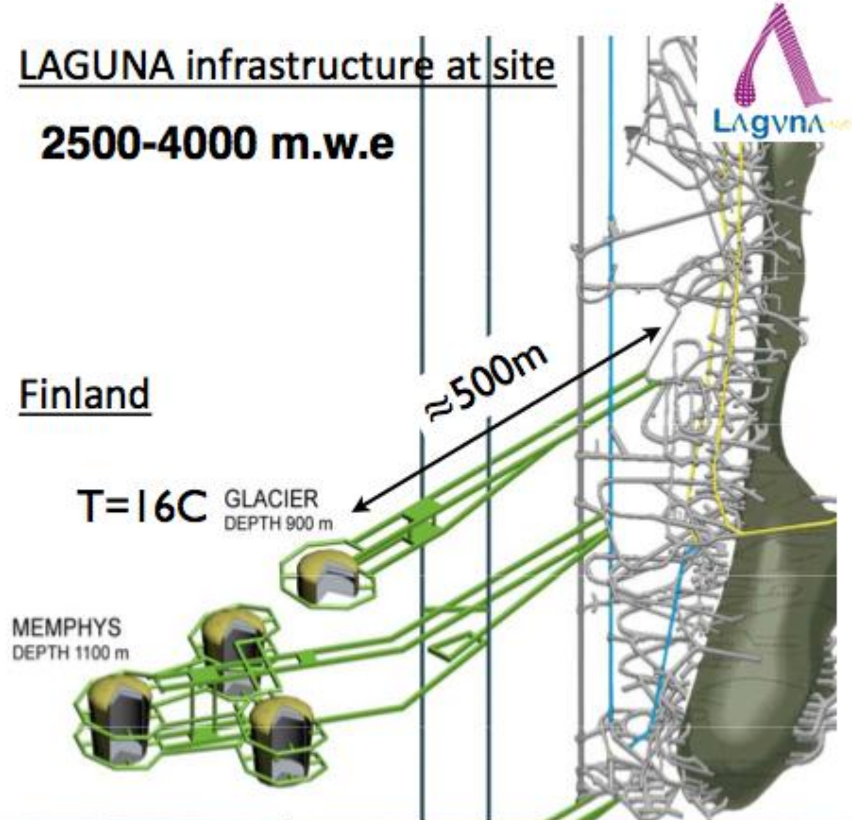


bimagic baseline L≈2500km

WBB averaged
$υ_μ \rightarrow υ_e$ probability
$<E_υ>$ = 3.5 GeV
width=±2.5 GeV
$\sin^2 2θ_{13} = 0.11$
normal hierarchy

The optimal baselines are in the range 1300-2500 km

LAGUNA Pyhäsalmi w/ GLACIER


LAGUNA infrastructure at site

2500-4000 m.w.e

Finland

T=16C

Main aspects of the infrastructure

- *existing working mine with very high standards*
- *existing decline tunnel access to deepest level*
- *excellent excavation strategy*
- *efficient rock disposal*
- *no disturbance with hosting site*
- *sufficient fresh air inlet*
- *effective outlet of return air*
- *safety*
- *supply routes for construction*
- *storage of material*
- *quality control of material at the vicinity*
- *supply route (pipe lines) for liquids*

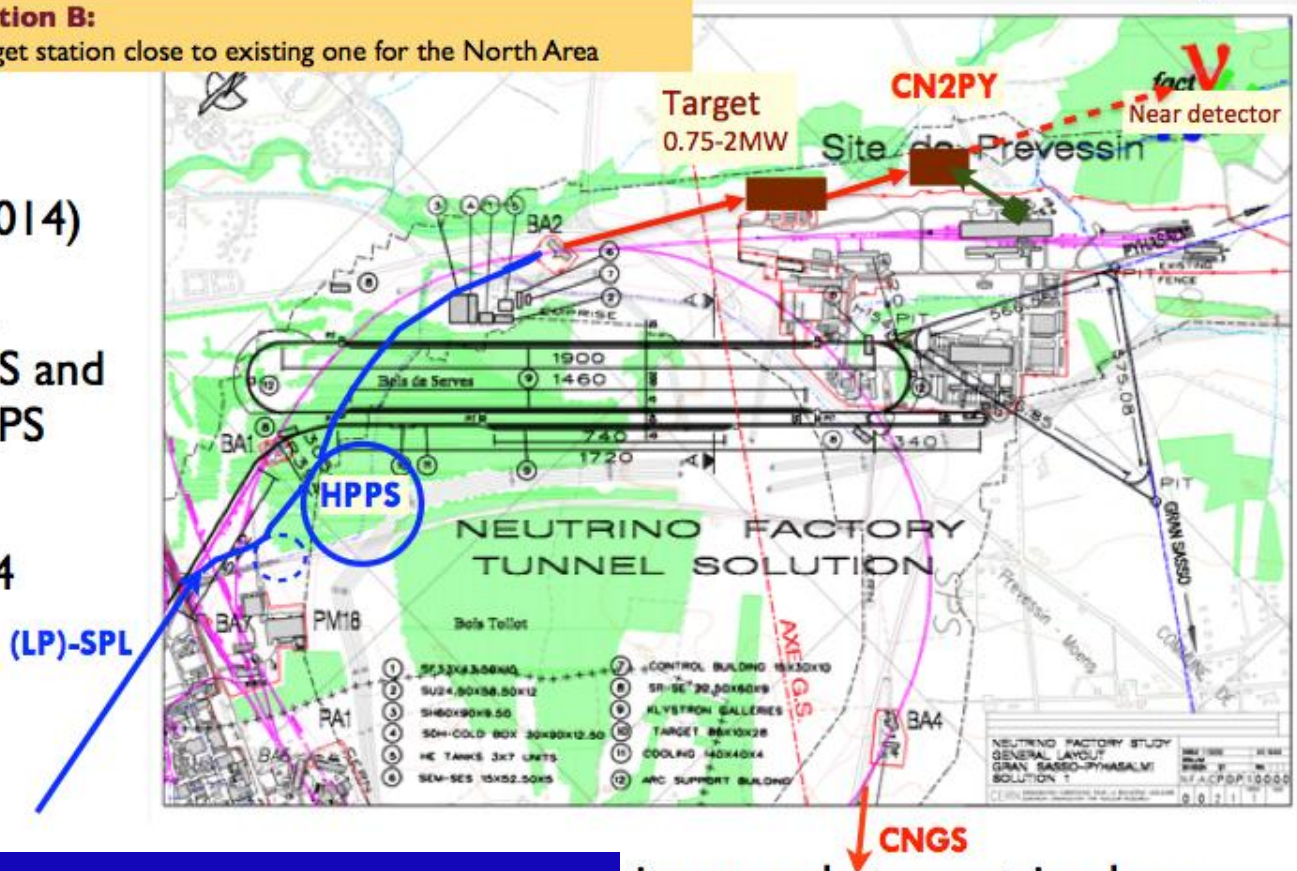

Cafeteria, meeting room and sauna at 1400 m below ground


250 m long tunnel and a cavern at 1400m excavated for LAGUNA R&D

CERN new conventional beams option

- Feasibility of new beams approved by CERN study (LAGUNA-LBNO/2011-2014)
- New beam facility accepts protons from 400 GeV SPS and eventual new 50 GeV HP-PS
- Will produce conceptual design reports within 2014

Option B:
Target station close to existing one for the North Area

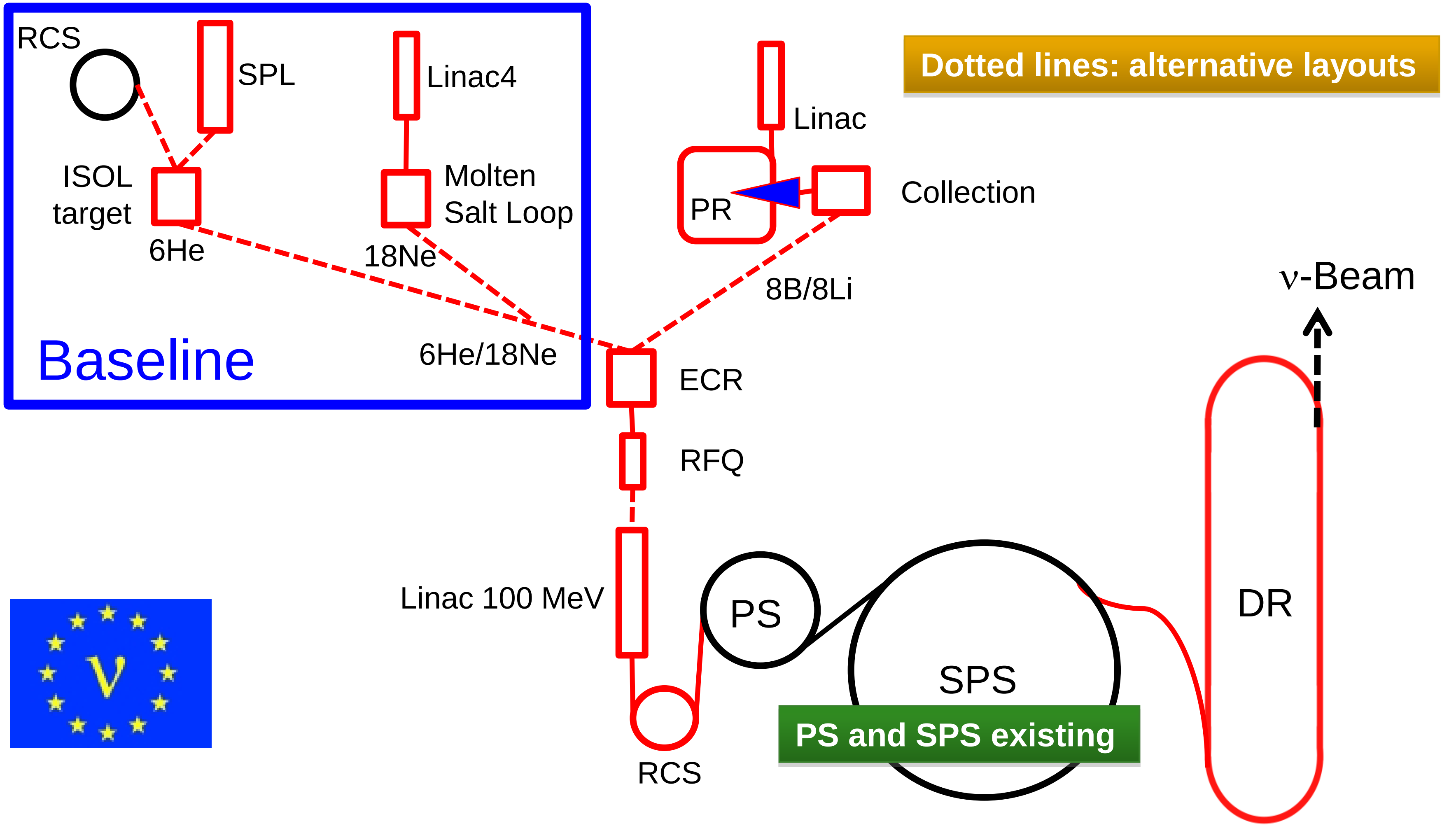


Exploring within LAGUNA an LoI for a 10 kT LAr with a muon ranger combined with a new beam in the NA.

- **Tas**… sity upgrade to neutrino beams
- **Tas**…
- **Tas**… m
- **Tas**…
- **Task 4.5** Definition of the accelerators and beamlines layout at CERN
- **Task 4.6** Study of the Magnetic Configuration for the LAGUNA detector
- **Task 4.7** Definition of near detector requirements and development of conceptual design

Return ↑

CERN Beta Beams, Synoptic



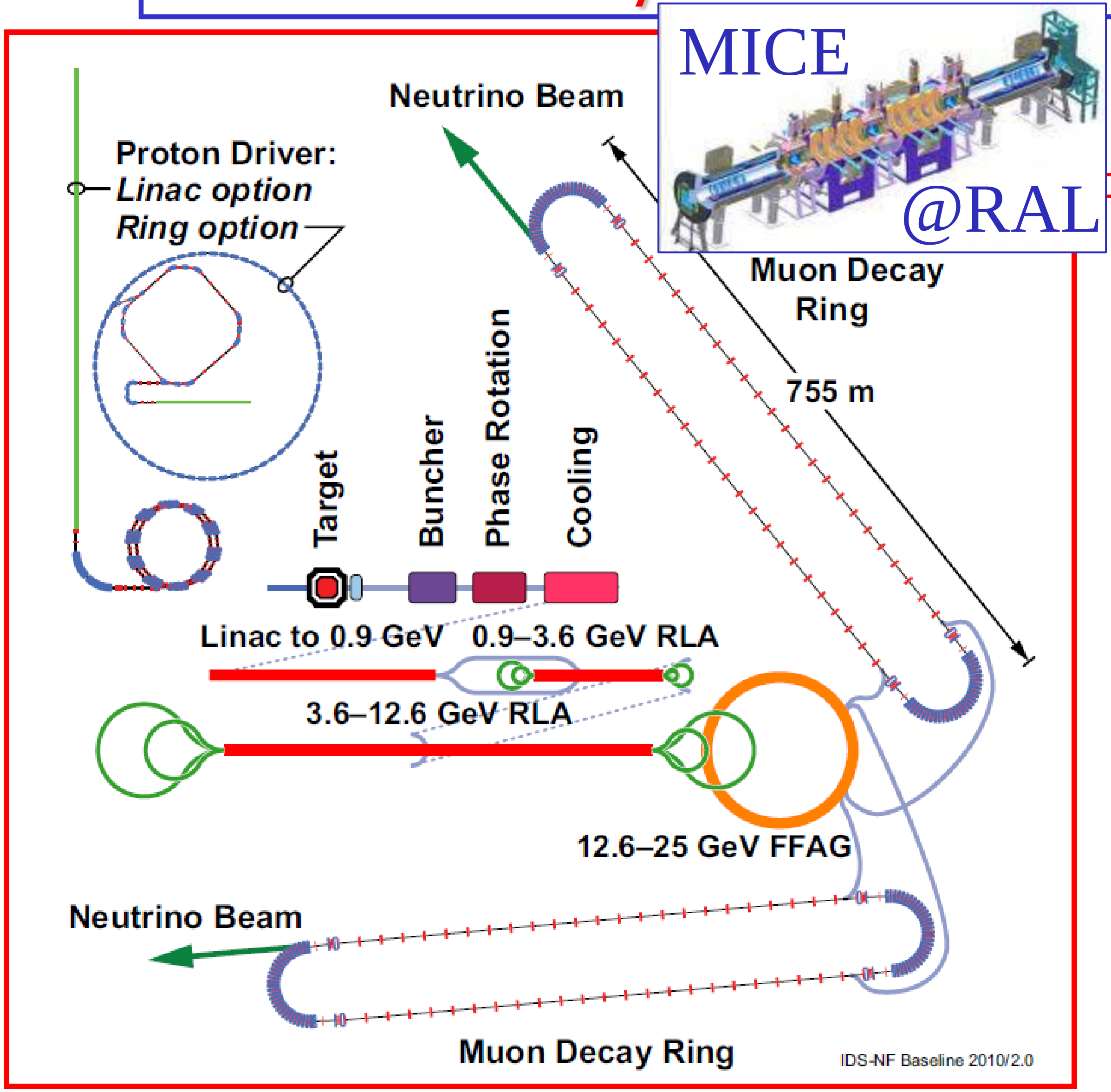
Dotted lines: alternative layouts

PS and SPS existing

Decay Ring: Bρ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

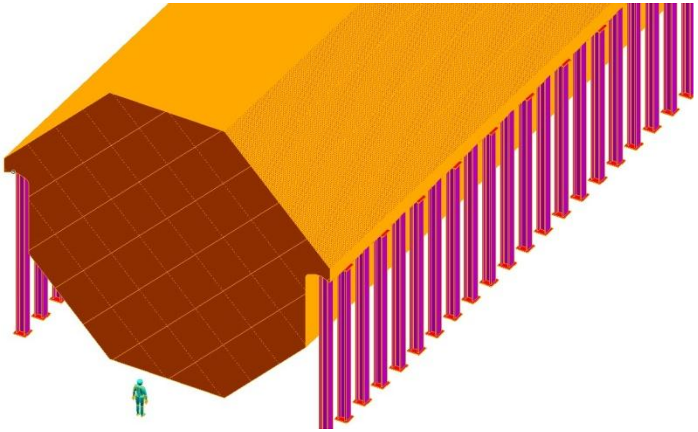
Return ↑

Neutrino Factory Baseline



Two Magnetised Iron Neutrino Detectors (MIND):

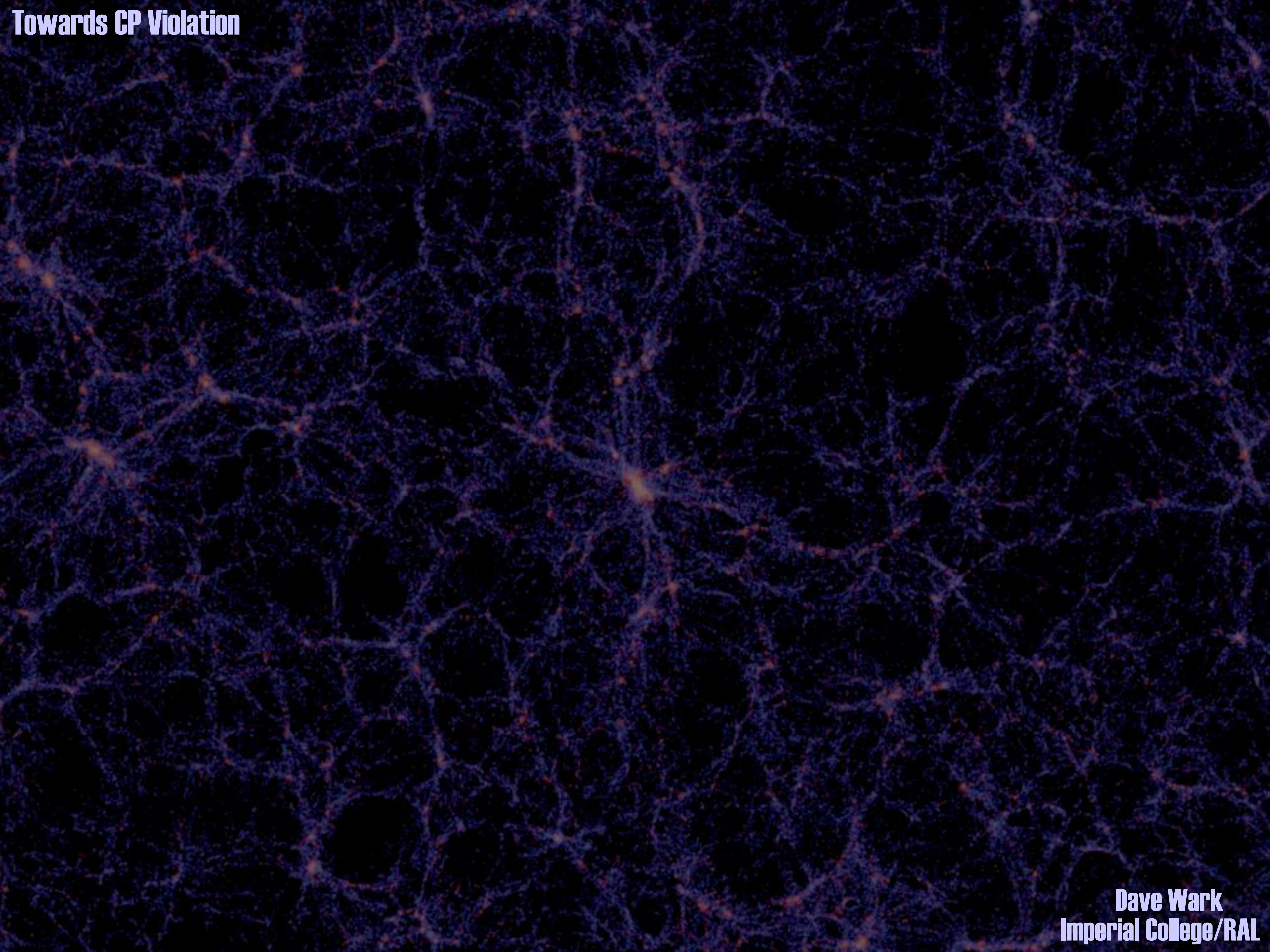
- 100 kton at 2500-5000 km
- 50 kton at 7000-8000 km



Baseline constantly under review in light of new physics results

Return ↑

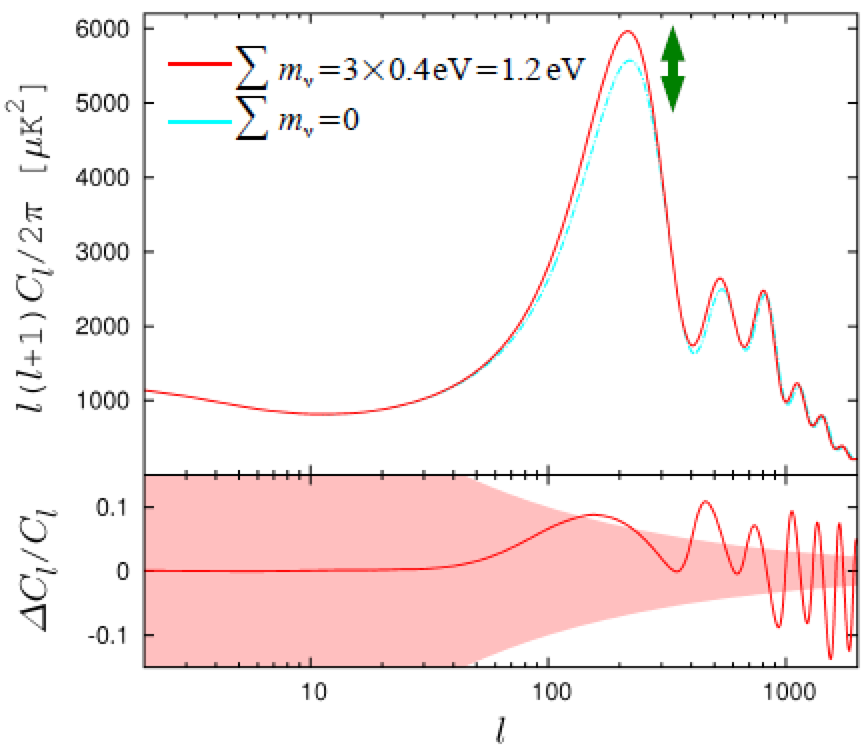
Towards CP Violation

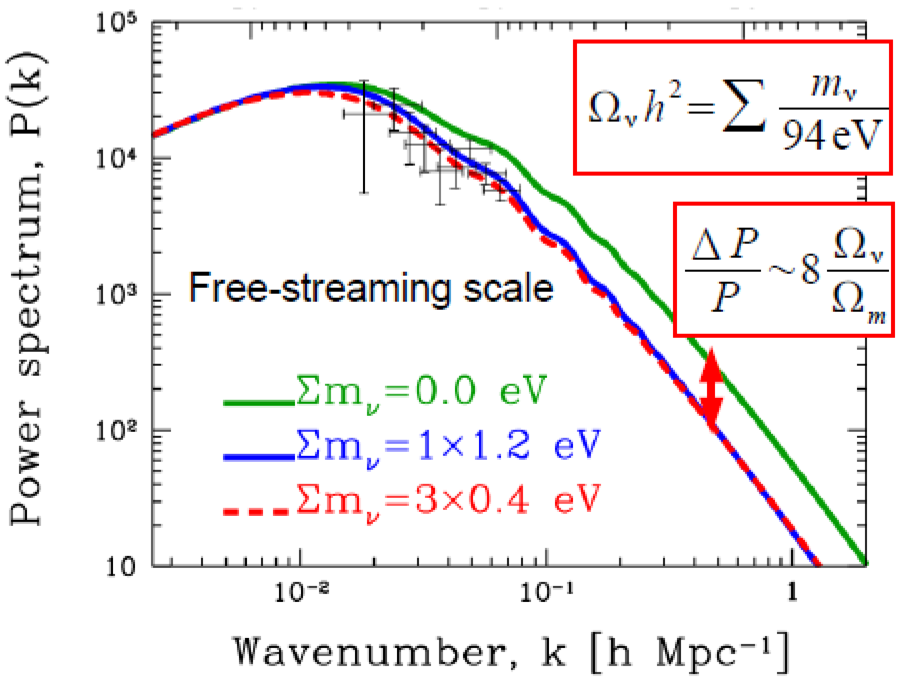


Dave Wark
Imperial College/RAL

Towards CP Violation

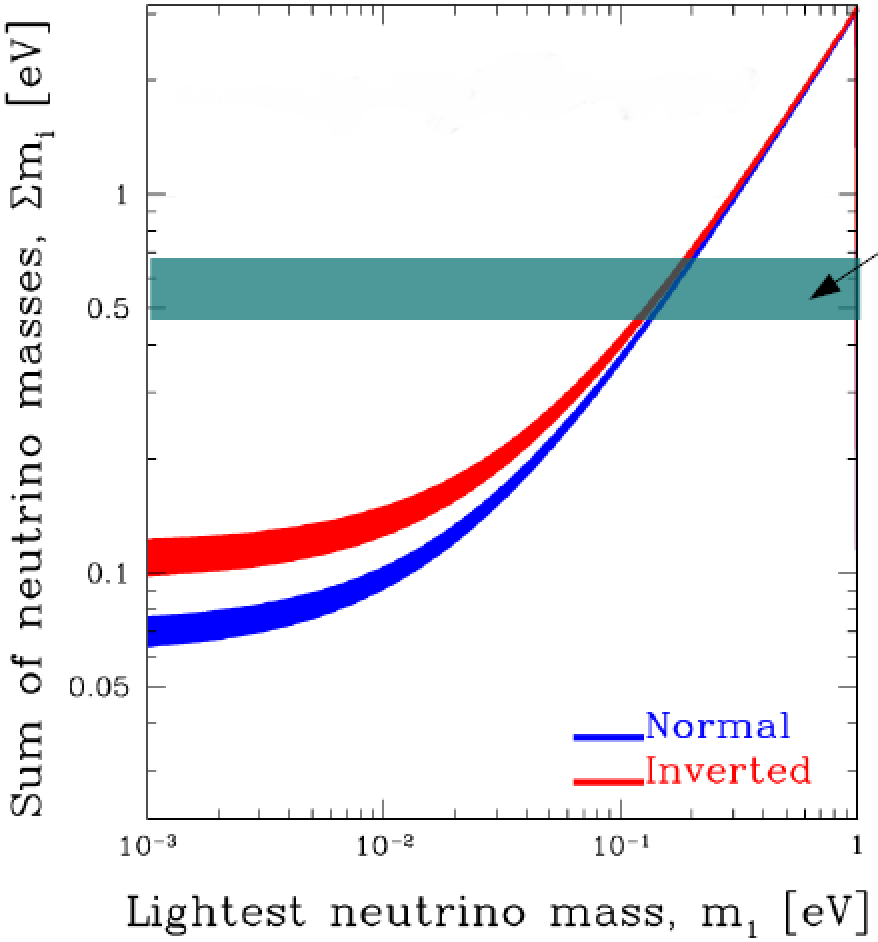
- **CMB** probes the relativistic to non-relativistic transition of neutrinos via the early ISW effect.
- **LSS** measures suppression of power on small scales due to non-clustering neutrinos.





Slide from Yvonne Wong's talk at TAUP '11

Present constraints...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

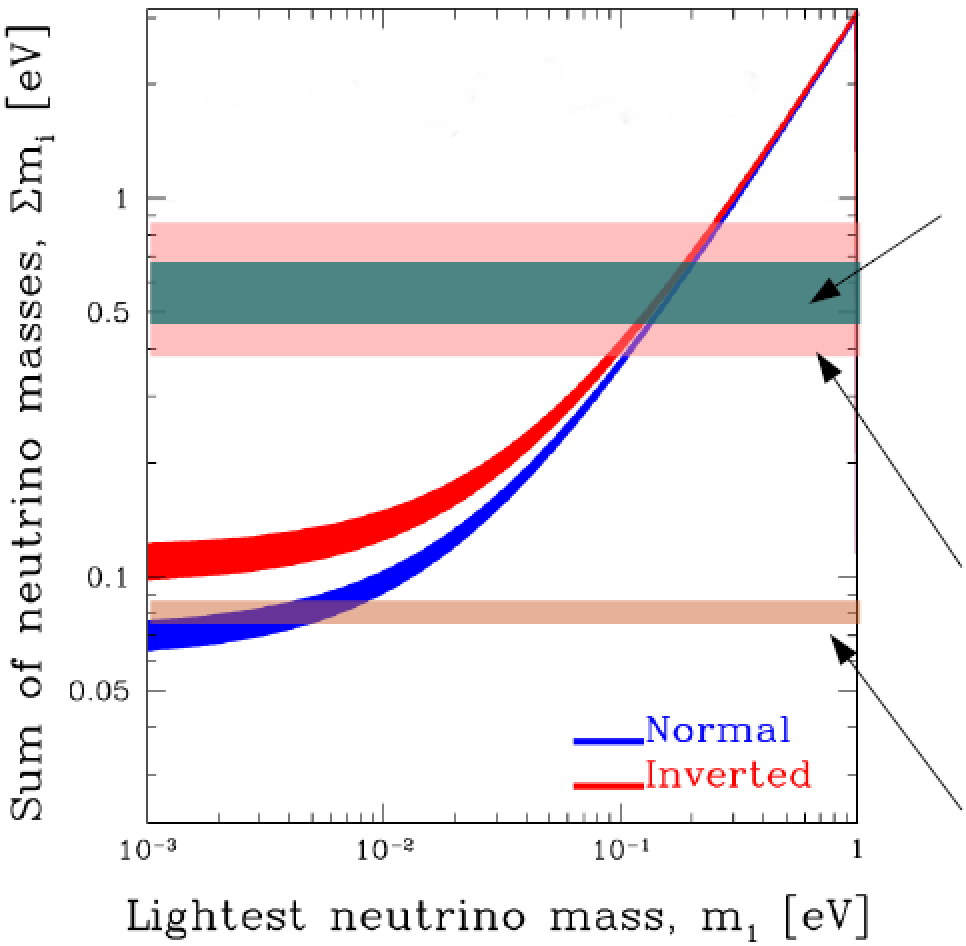
$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y^{3}W 2010
Gonzalez-Garcia et al. 2010, etc.

Slide from Yvonne Wong’s talk at TAUP ‘11

Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
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$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y³W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

Perotto et al. 2006

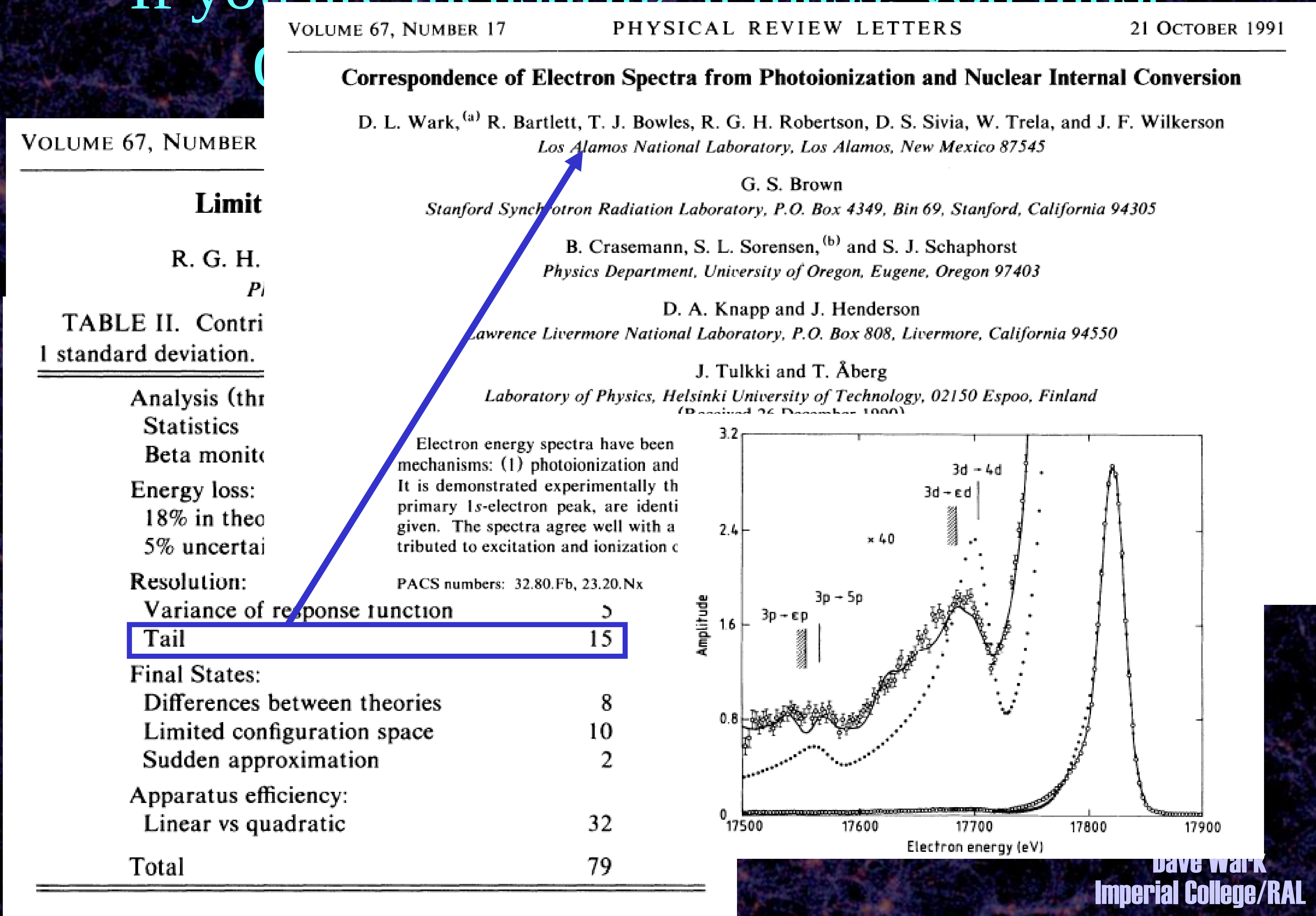
Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\,\%\,\mathrm{CI})$$

Hannestad, Tu & Y³W 2006

Slide from Yvonne Wong's talk at TAUP '11

If you are measuring a mass, you must



VOLUME 67, NUMBER

Limit

R. G. H.

P

TABLE II. Contri
1 standard deviation.

Analysis (thr	
Statistics	
Beta monit	
Energy loss:	
18% in theo	
5% uncertai	
Resolution:	
Variance of response function	5
Tail	15
Final States:	
Differences between theories	8
Limited configuration space	10
Sudden approximation	2
Apparatus efficiency:	
Linear vs quadratic	32
Total	79

VOLUME 67, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1991

Correspondence of Electron Spectra from Photoionization and Nuclear Internal Conversion

D. L. Wark,[a] R. Bartlett, T. J. Bowles, R. G. H. Robertson, D. S. Sivia, W. Trela, and J. F. Wilkerson
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G. S. Brown
Stanford Synchrotron Radiation Laboratory, P.O. Box 4349, Bin 69, Stanford, California 94305

B. Crasemann, S. L. Sorensen,[b] and S. J. Schaphorst
Physics Department, University of Oregon, Eugene, Oregon 97403

D. A. Knapp and J. Henderson
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

J. Tulkki and T. Åberg
Laboratory of Physics, Helsinki University of Technology, 02150 Espoo, Finland

(Received 26 December 1990)

Electron energy spectra have been
mechanisms: (1) photoionization and
It is demonstrated experimentally th
primary 1*s*-electron peak, are identi
given. The spectra agree well with a
tributed to excitation and ionization c

PACS numbers: 32.80.Fb, 23.20.Nx

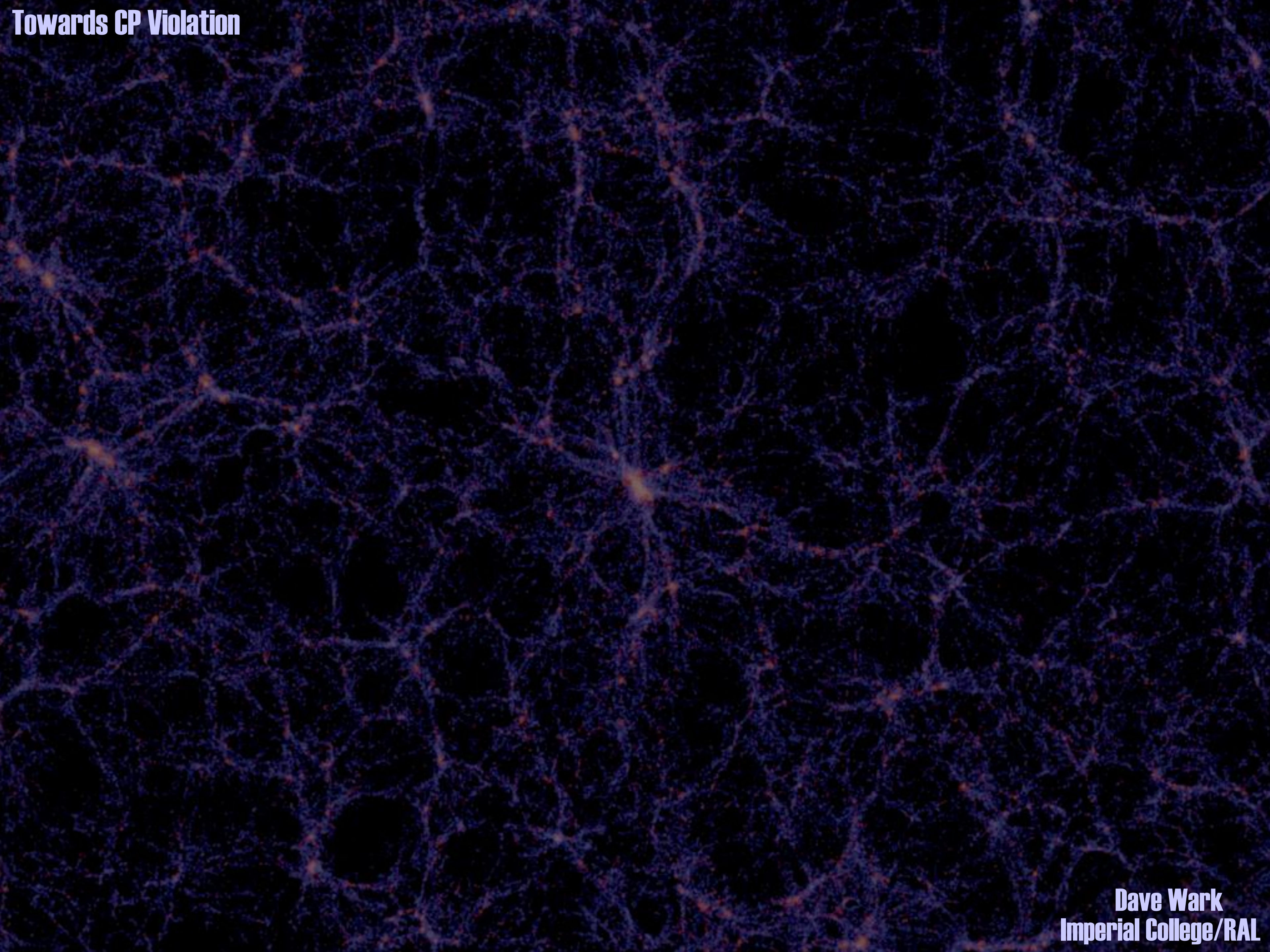
SNO Systematic Flux Uncertainties

Error Source	CC error (%)	ES error (%)
Energy scale	-5.2, +6.1	-3.5, +5.4
		±0.3
		±0.4
		±3.3
		±0.4
		±2.2
		-1.9, +0.0
Low energy background	-0.2, +0.0	-0.2, +0.0
Instrumental background	-0.2, +0.0	-0.6, +0.0
Trigger efficiency		
Live time		
Cut acceptance		
Earth orbit eccentricity		
^{17}O, ^{18}O	0.0	0.0
Experimental uncertainty	-6.2, +7.0	-5.7, +6.8
Cross-section	3.0	0.5
Solar Model	-16, +20	-16, +20

Unless a real error analysis is done for astrophysical mass “limits” they cannot really be considered equivalent to laboratory limits.

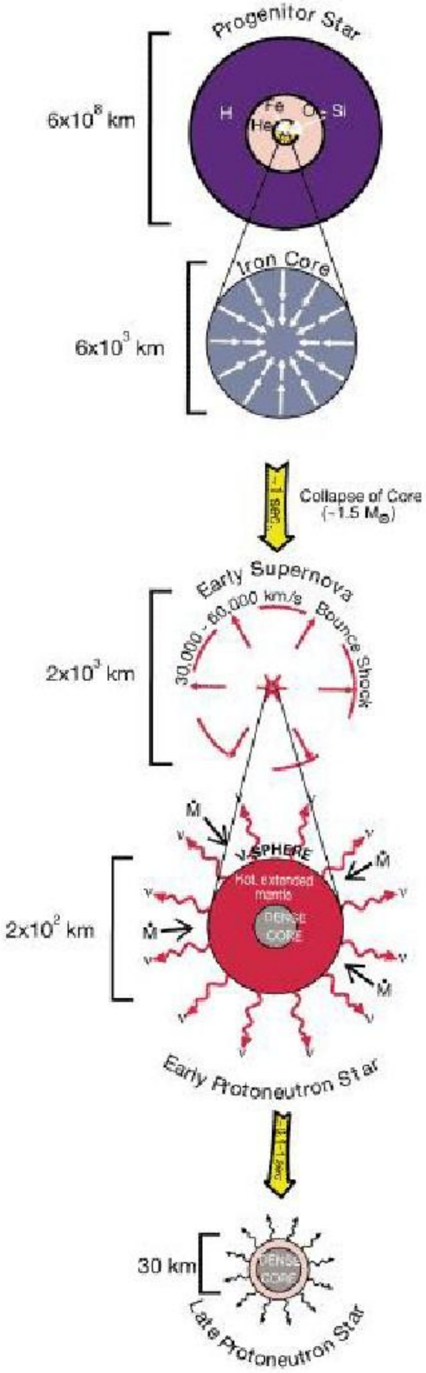
In any case why would you waste precious cosmological data constraining m_ν?

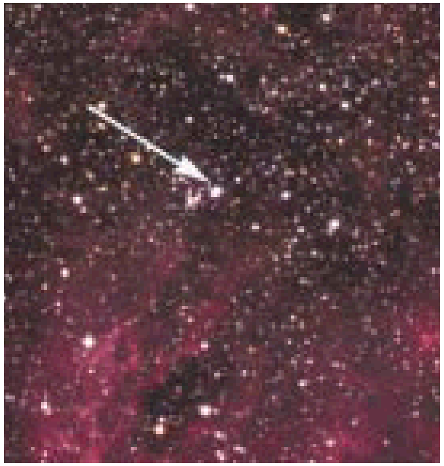
Return ↑



Towards CP Violation

Dave Wark
Imperial College/RAL



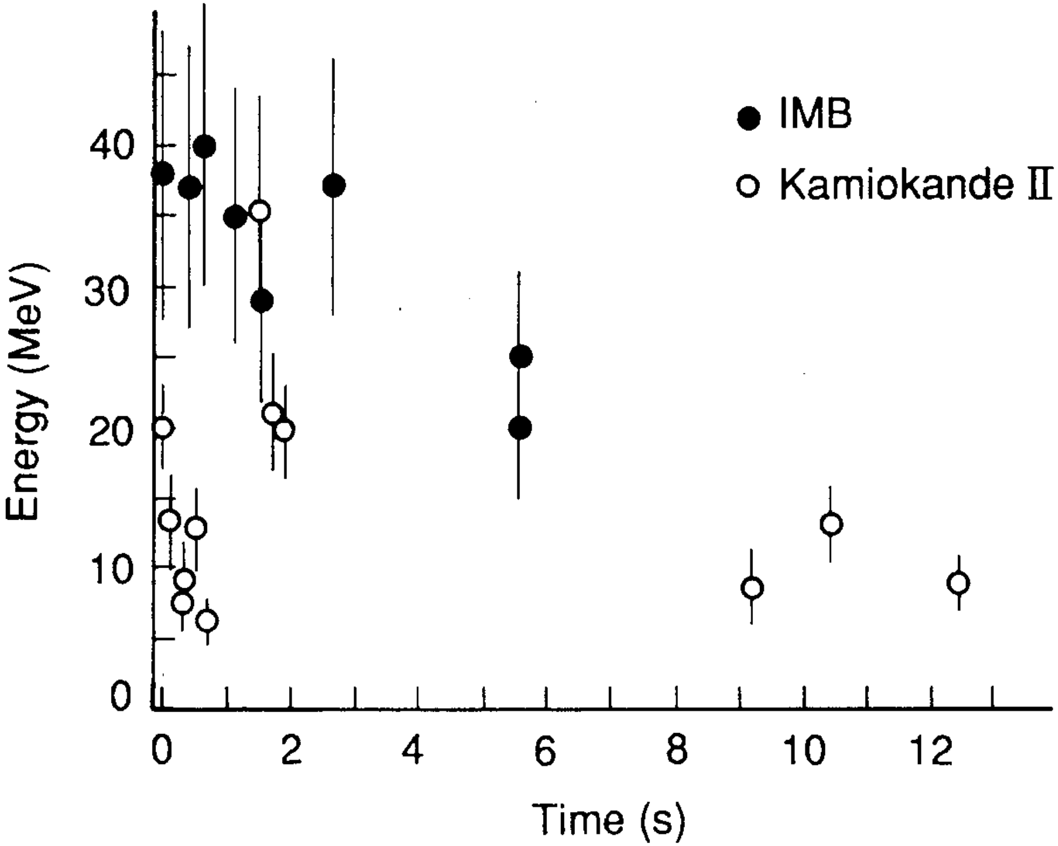


February 1984

March 8,1987

A supernova
converts
~ 1 $M_\odot$ to ν

$$|\Delta t| = \frac{1}{2} L m_{\nu}^{2} \frac{|E_1^2 - E_2^2|}{E_1^2 E_2^2}$$

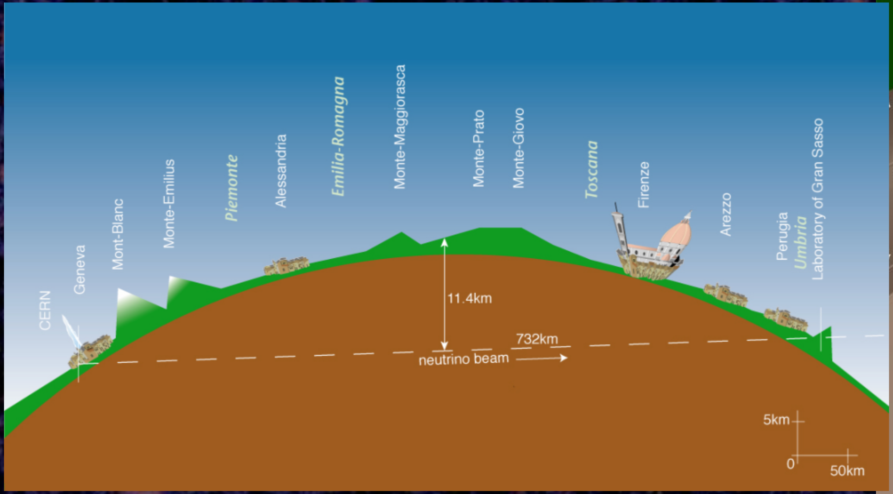


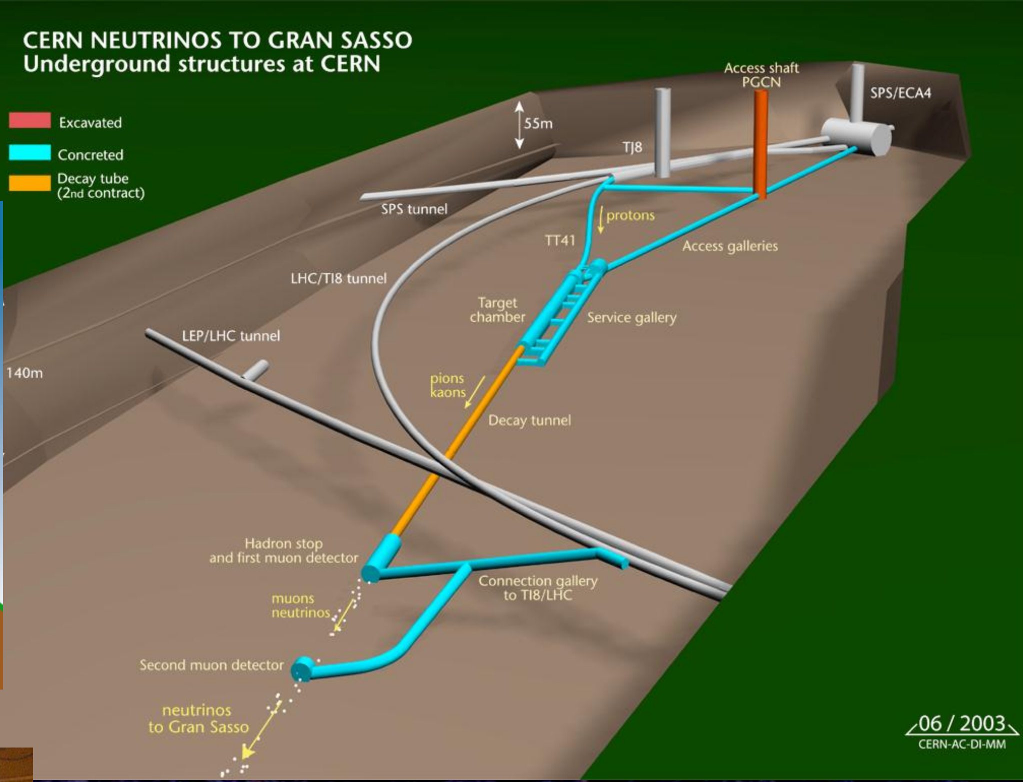
Limit from SN1987a is $m_{\nu_e} > 23$ eV (PDG)

Best you can do is ~5-10 eV, which isn’t good enough

Light and neutrinos got here on the same day after travelling for ~160k yrs, so $|v_\nu - c|/c < 2\times10^{-9}$ at $E_\nu \sim 10$ MeV

Towards CP Violation





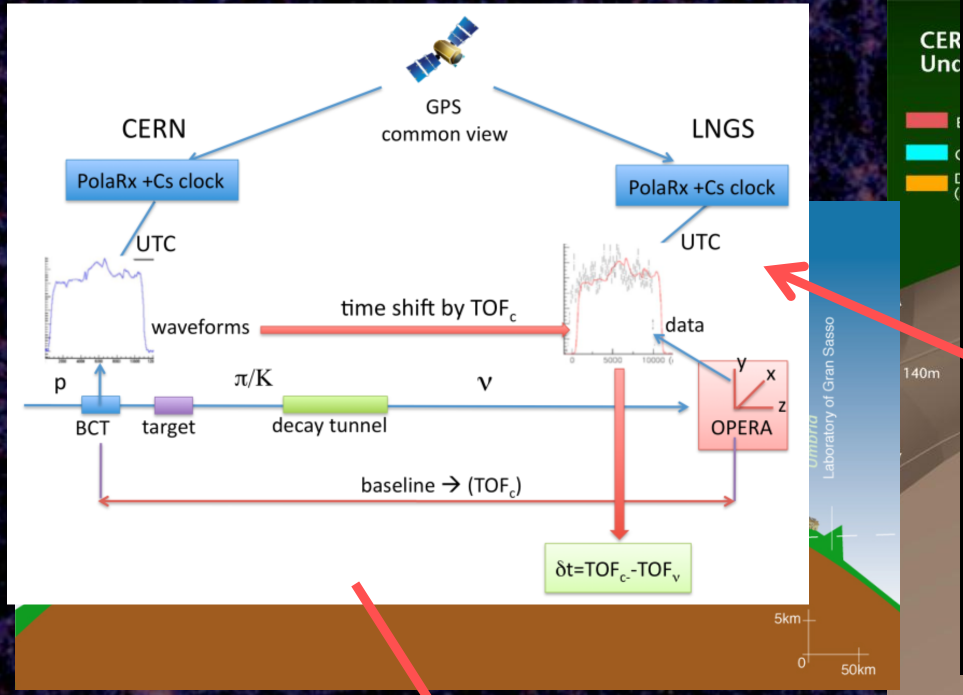
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

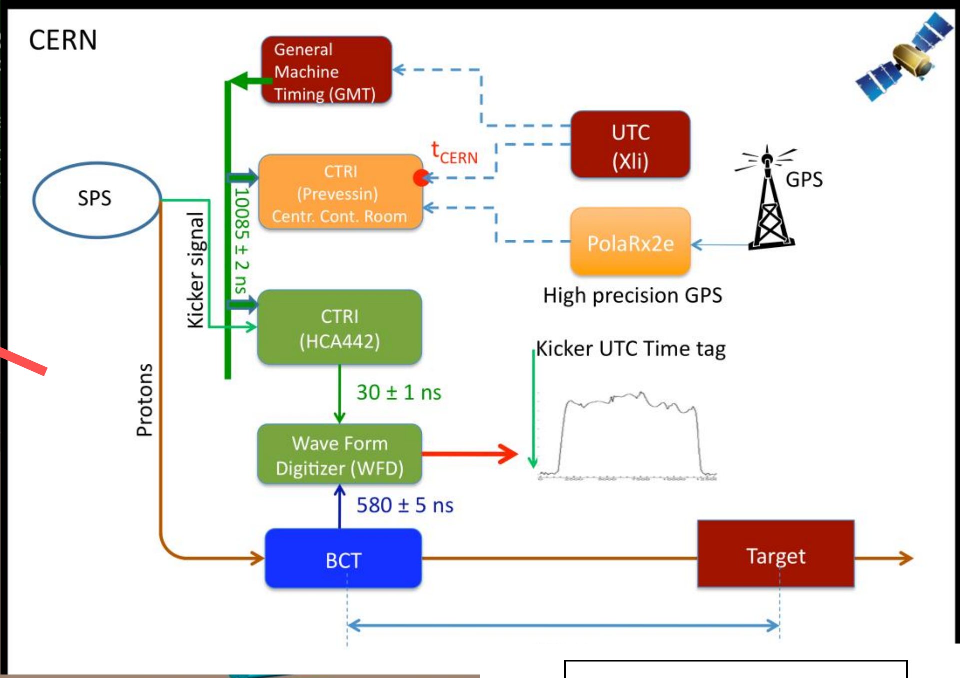
Dusini at EPS

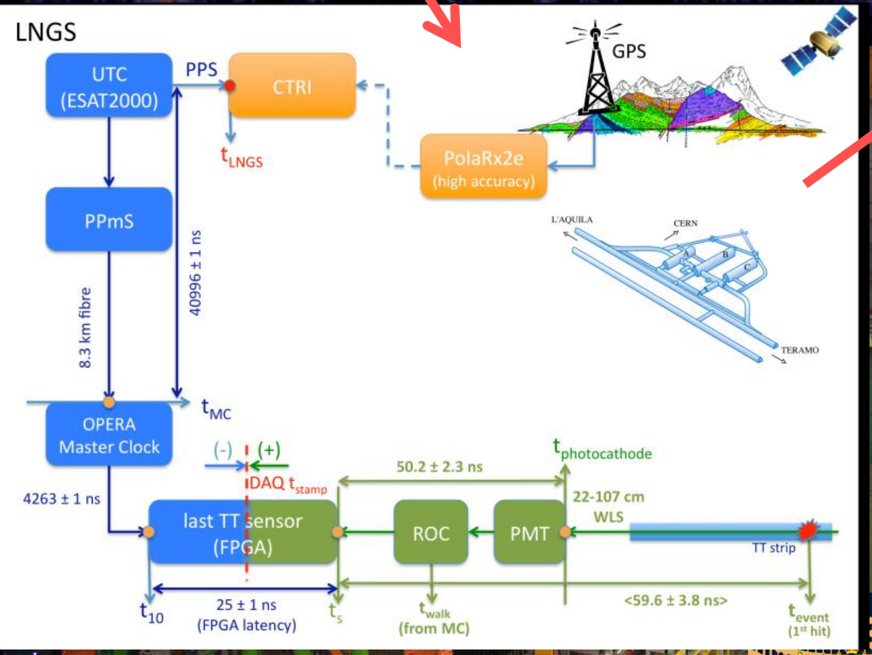
OPERA τ appearance event....

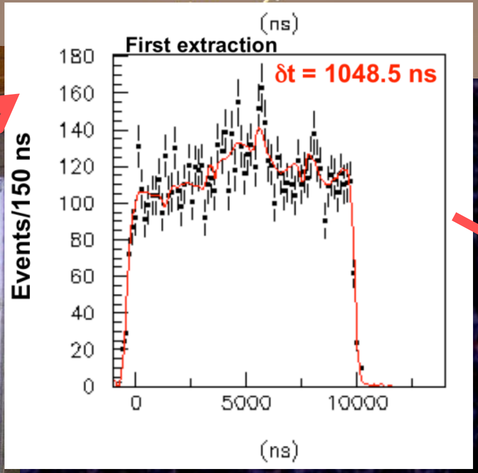
.... has no friends yet. Expect 1.65±0.16

Phys. Lett. B 691 (2010) 138-145

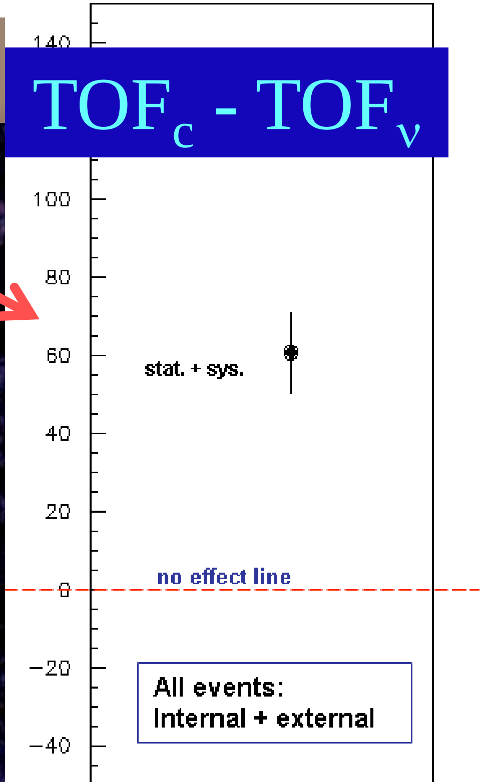






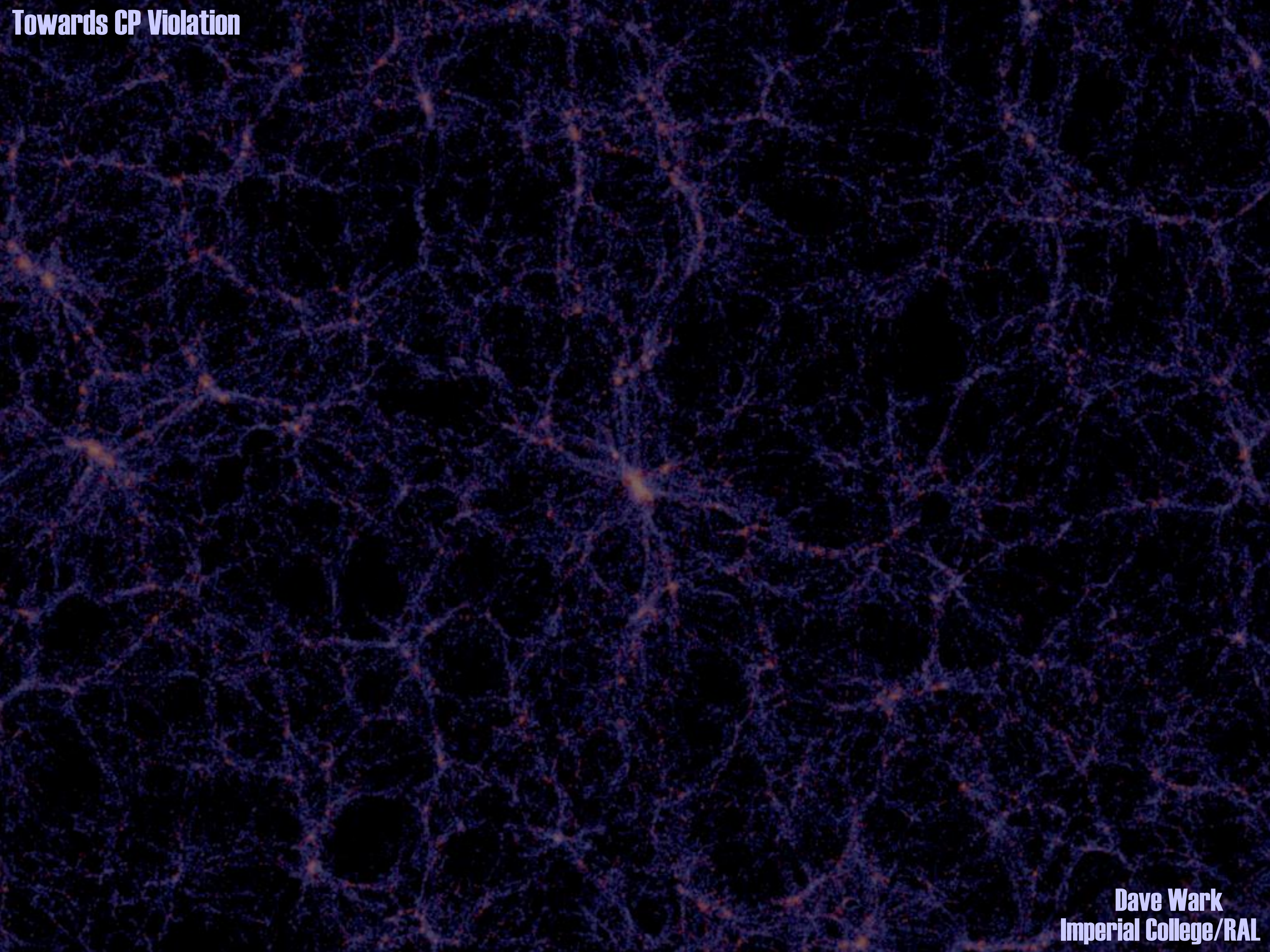


TOF$_c$ - TOF$_ν$



$$|v_\nu - c|/c = (2.48 \pm 0.28 \pm 0.30) \times 10^{-5}$$

Return ↑



Towards CP Violation

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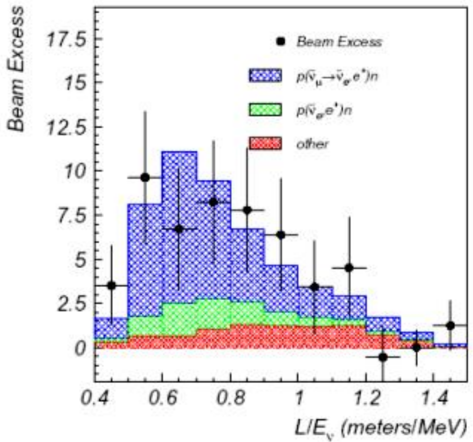
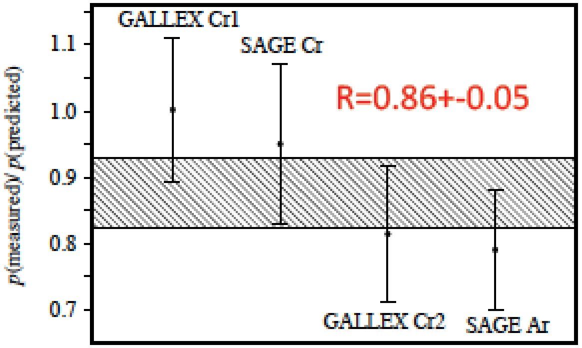
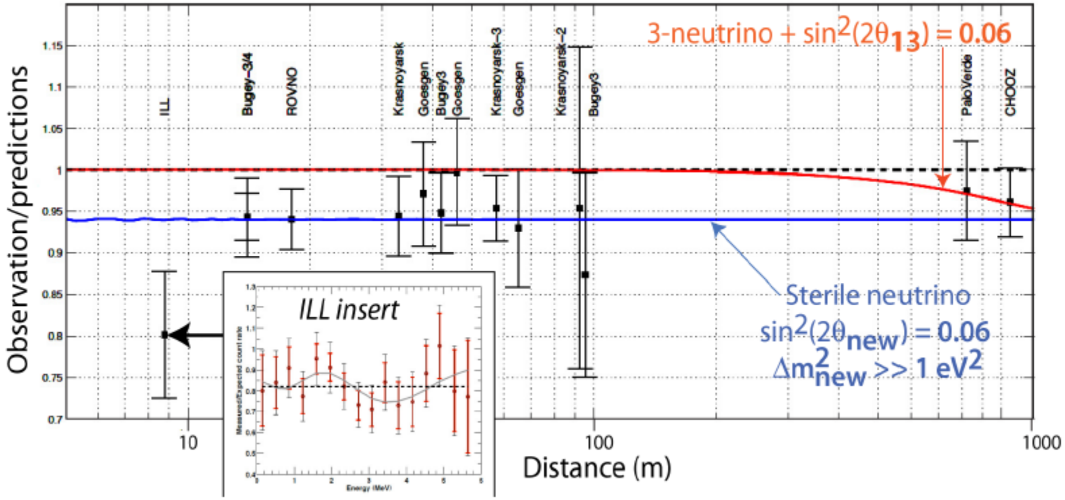
LSND Starts it all…

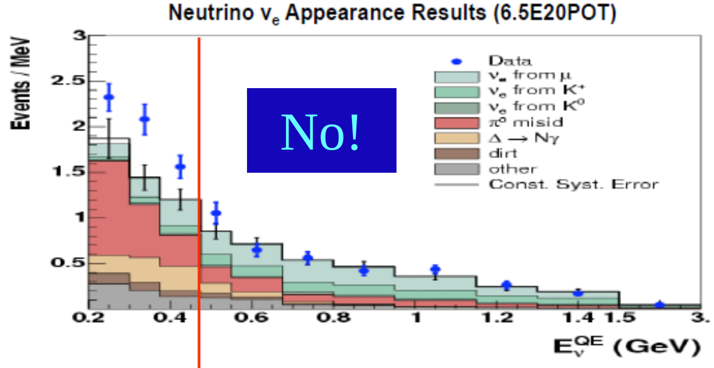


Short baselines (L/E ~ 1) and sterile ν.

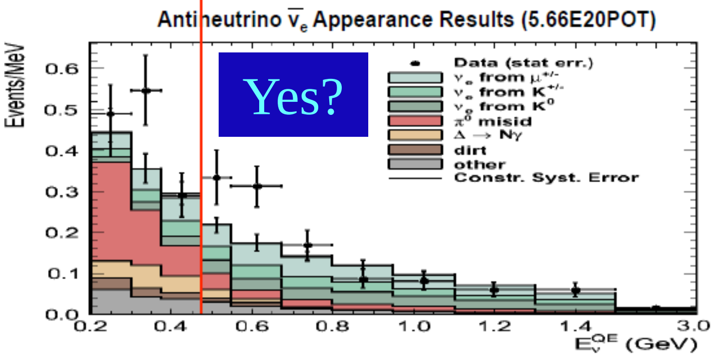




MiniBooNE says….



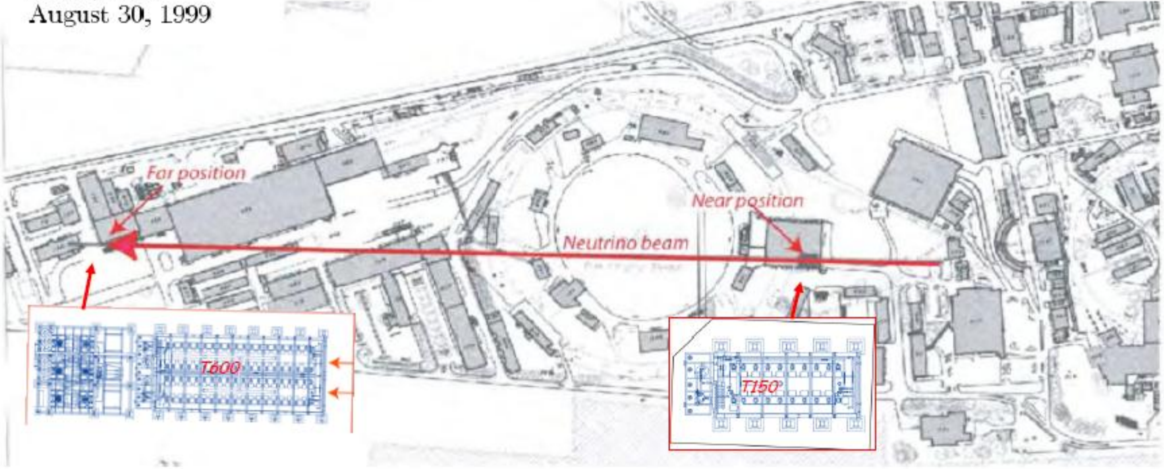
No!

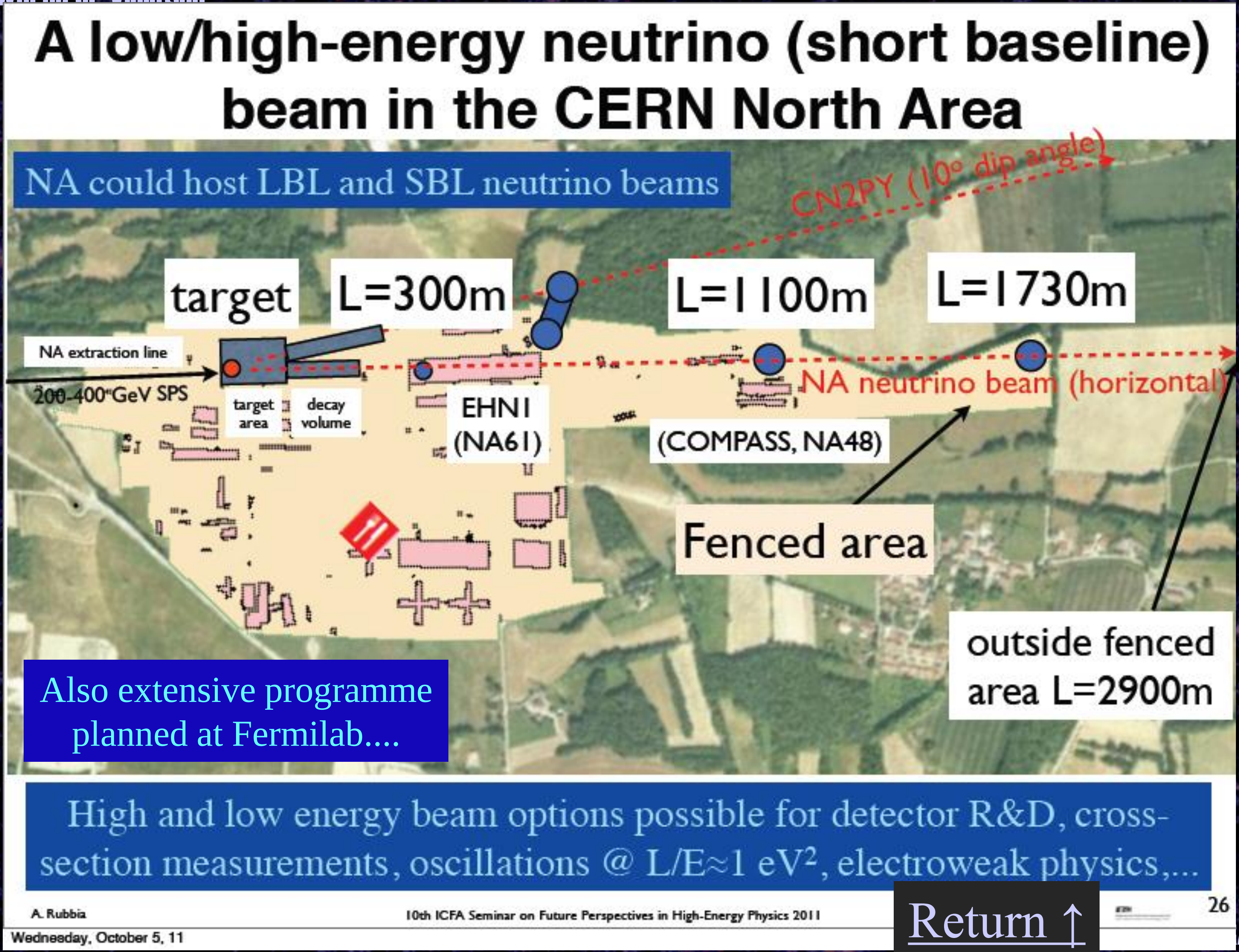


Yes?

CERN-SPSC/99-26
SPSC/P311
August 30, 1999

SEARCH FOR $\nu_\mu \to \nu_e$ OSCILLATION
AT THE CERN PS





A low/high-energy neutrino (short baseline) beam in the CERN North Area

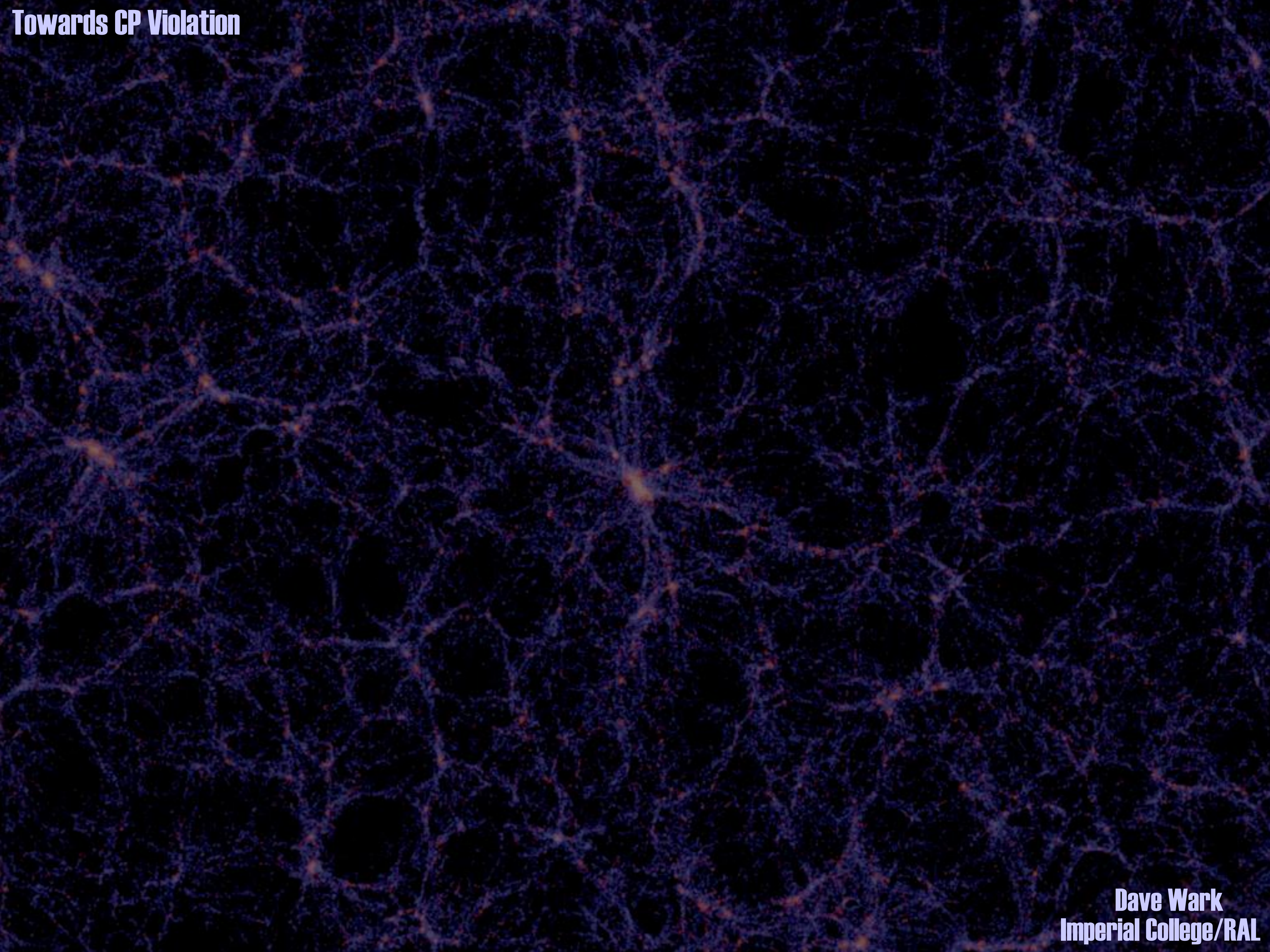
NA could host LBL and SBL neutrino beams

Also extensive programme planned at Fermilab....

High and low energy beam options possible for detector R&D, cross-section measurements, oscillations @ $L/E \approx 1\ \mathrm{eV}^2$, electroweak physics,...

Return ↑

Towards CP Violation



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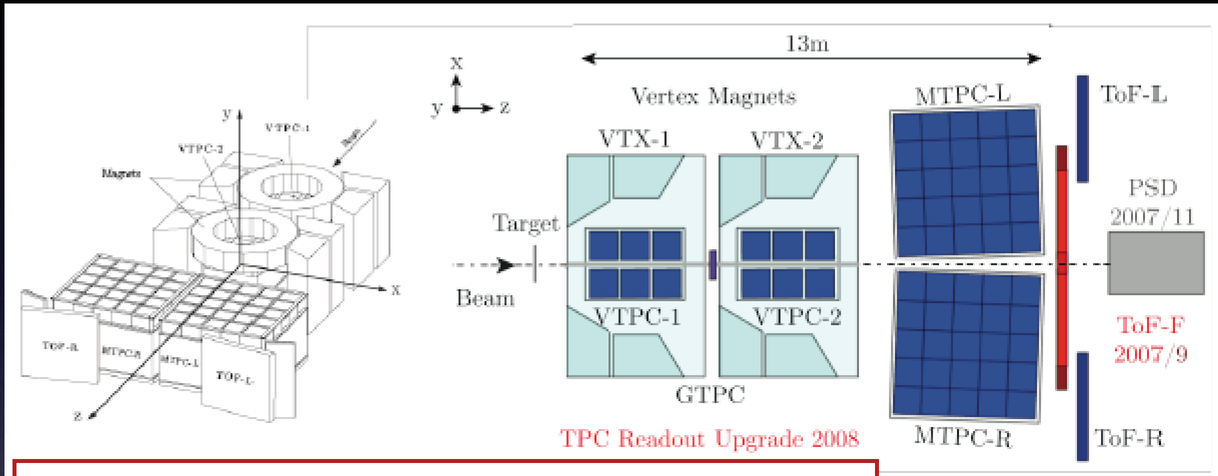
Tow

In the systematics dominated era support measurements are essential!

CERN NA61 measurements

Evaluation of Particle Yields in 30 GeV p+C Inelastic Interacti
and in the T2K replica target



La

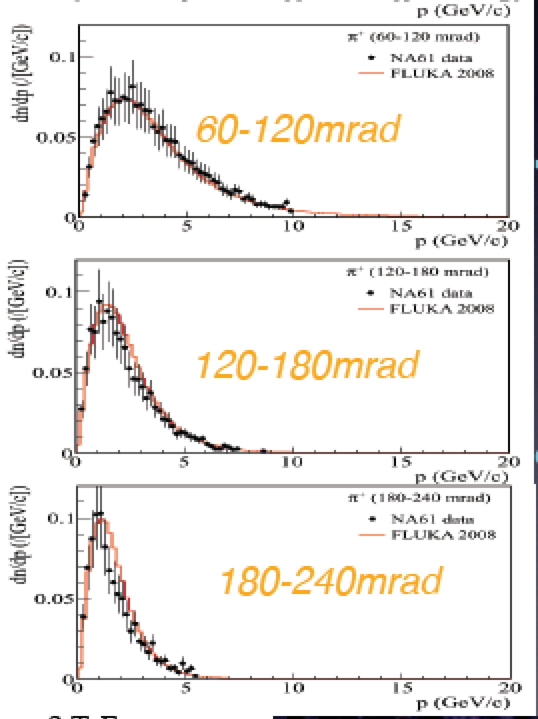
2

σ(p)/
σ(dE/

3 ToFs
σ(ToF-F) ≈ 120 ps
σ(ToF-L/R) ≈ 60 ps

Full Coverage of T2K phase space

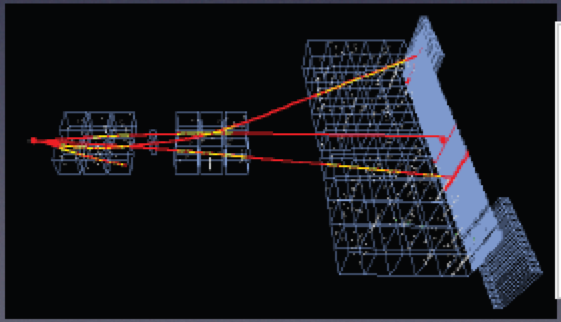
thin target: 2.5x2.5x2 cm^3 int. length ~ 0.04 ~600k triggers in 2007

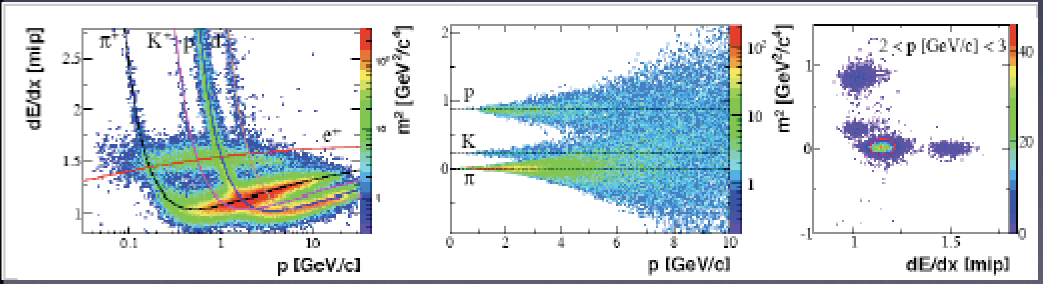


p+C @ 31 GeV/c

Particle ID methods used:

1) dE/dx (p < 1 GeV/c, p > 4 GeV/c)
2) Combined dE/dx + ToF (1 < p [GeV/c] < 4)
3) Negatively charged hadron h- analysis (π- only)





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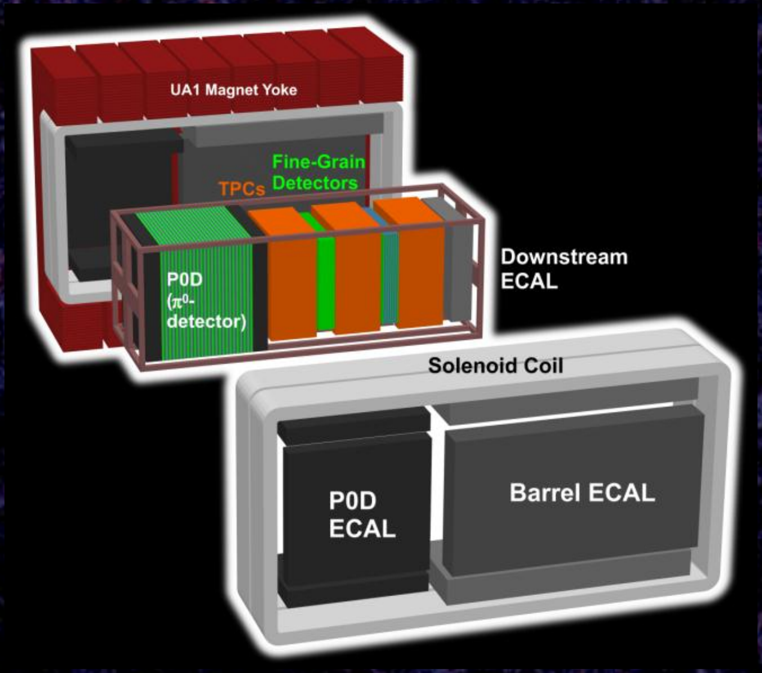
Neutrino interaction properties must also be measured...

SciBooNE

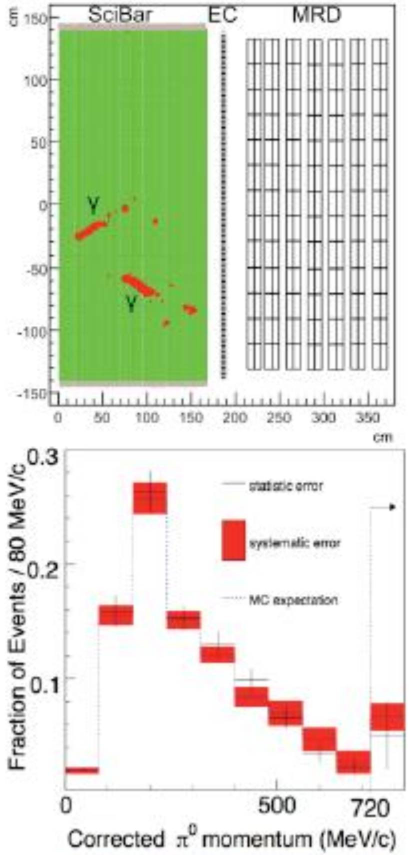
http://www-sciboone.fnal.gov/

But also need....

Near Detectors....



NCπ0 xsecs



Phys. Rev. D 81, 033004 (2009)

Phys. Rev. D 81, 111102(R) (2009)

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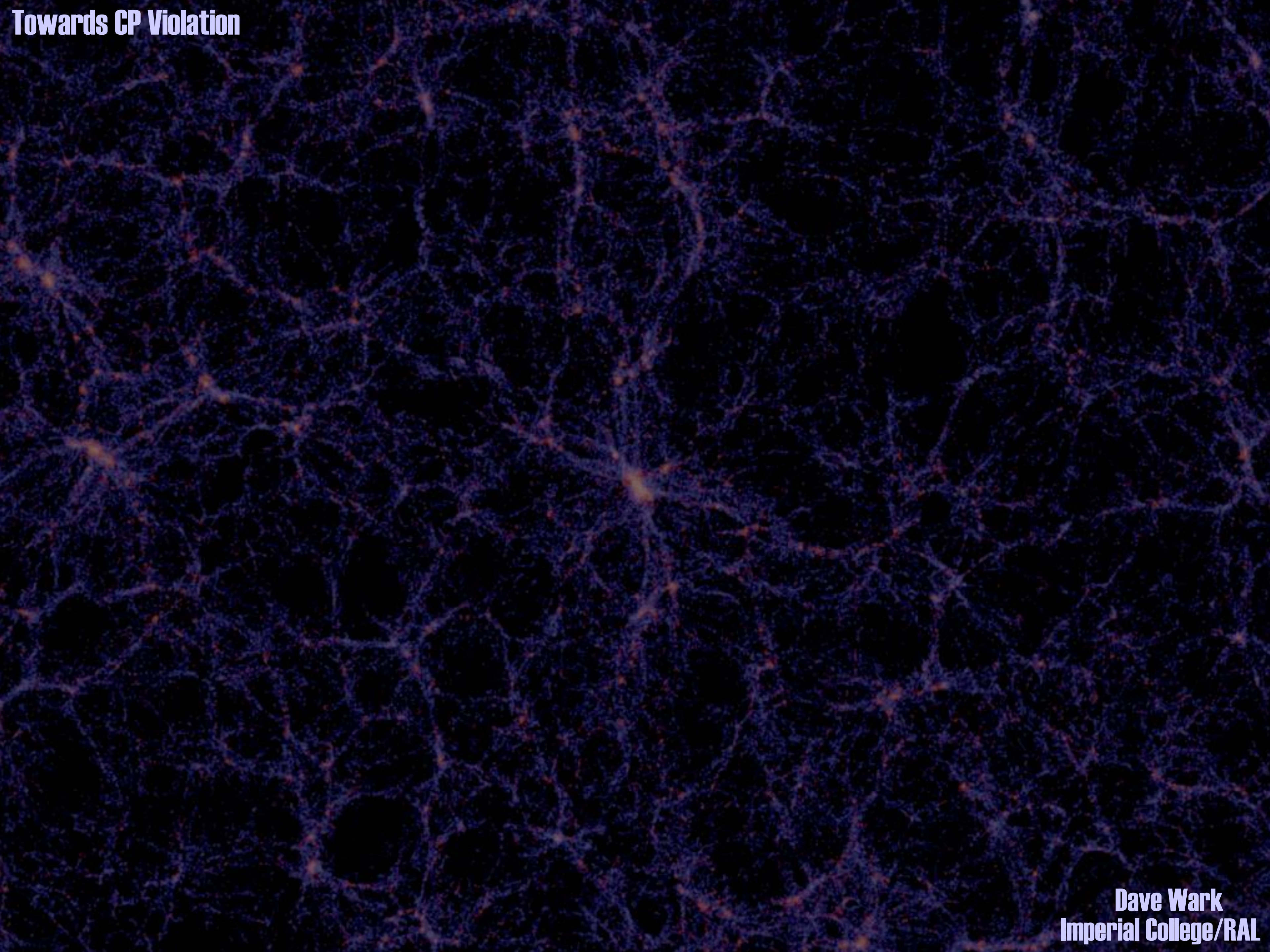

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