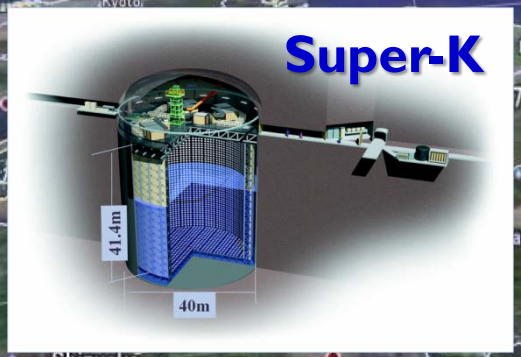
July 28th, 2010
@ICHEP2010, Paris

Long Baseline Accelerator ***Neutrino Experiments***

T. Nakaya (Kyoto)

Terrestrial Experiments



Super-K

295km

T2K

J-PARC

Kobe
Kyoto
Kanazawa
Nagano
Japan
Sado
Niigata
Awa-shima
Shizuoka
Hachioji
Kanagawa
Tokyo
Yokohama
Kawasaki
Honshu
Fukushima
Funabashi
Chiba
Mito
N35°
N37°
E135°
E141°
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

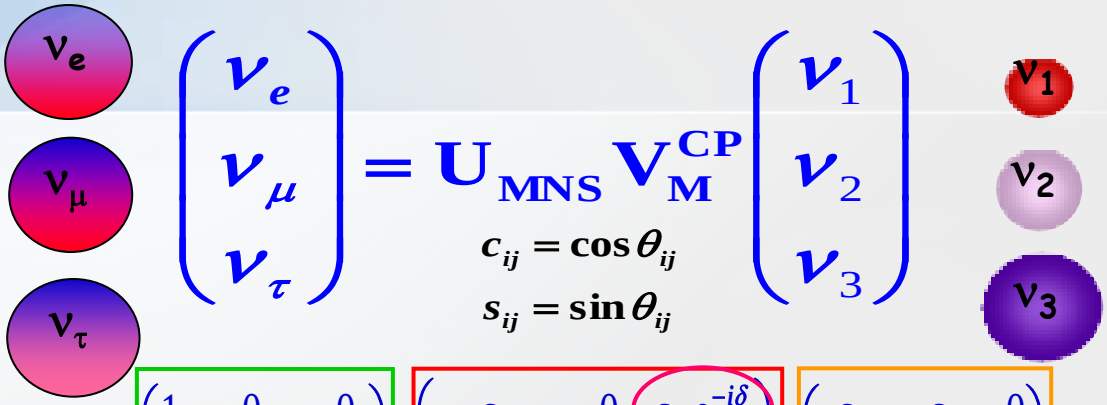
News (new results) in 2010

1. Observation of an oscillated tau neutrino candidate event in ***OPERA***.
2. Start of the Super-ν beam experiment, ***T2K***.
3. Precision measurements of neutrinos and anti-neutrinos oscillations in ***MINOS***.
4. Anomalies? LSND anti-neutrino oscillations still remains?

-- Outline --

1. ***Introduction***
2. ***ν_τ observation***
3. ***T2K starts***
4. ***Precision measurements***
5. ***Anomaly***
6. ***Future Prospects and Summary***

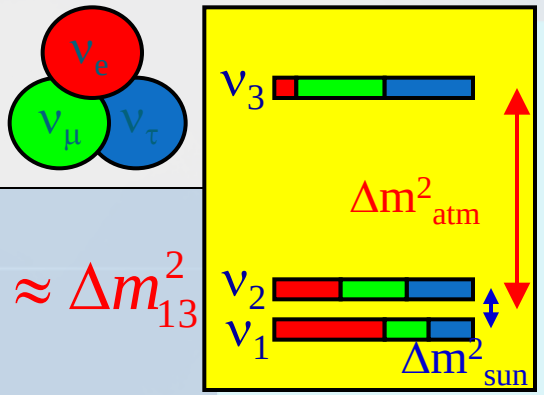
1. Introduction



- Precise measurements of ν oscillations ($\pm\Delta m_{23}^2$, θ_{23})
  - Test of the standard ν oscillation scenario (U_{MNS})
- Discover the last oscillation channel: θ_{13}
- CP violation in the lepton sector (ν, $\bar{\nu}$): δ
- Mass hierarchy : the sign of Δm_{23}^2

} Future exp.

Measurements



Oscillation Probabilities when $\Delta m^2_{12} << \Delta m^2_{23} \approx \Delta m^2_{13}$

- θ_{23} : ν_μ disappearance

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \underbrace{\cos^4\theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\Delta m^2_{23} L / E_\nu\right)$$

- θ_{13}: ν_e appearance

$$P_{\nu_\mu \to \nu_e} \approx \underbrace{\sin^2\theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m^2_{23} L / E_\nu\right)$$

common

- δ : CP violation (in future)

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \cdots \cdot \sin\delta$$

~0.18 ($\sin^2 2\theta_{13}$=0.1)

~0.58 ($\sin^2 2\theta_{13}$=0.01)

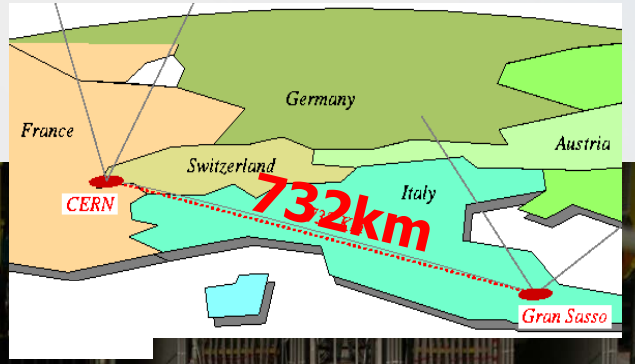
- $P(\nu_\mu \to \nu_e)$ at the 1st and 2nd osc. peaks could be different by δ!

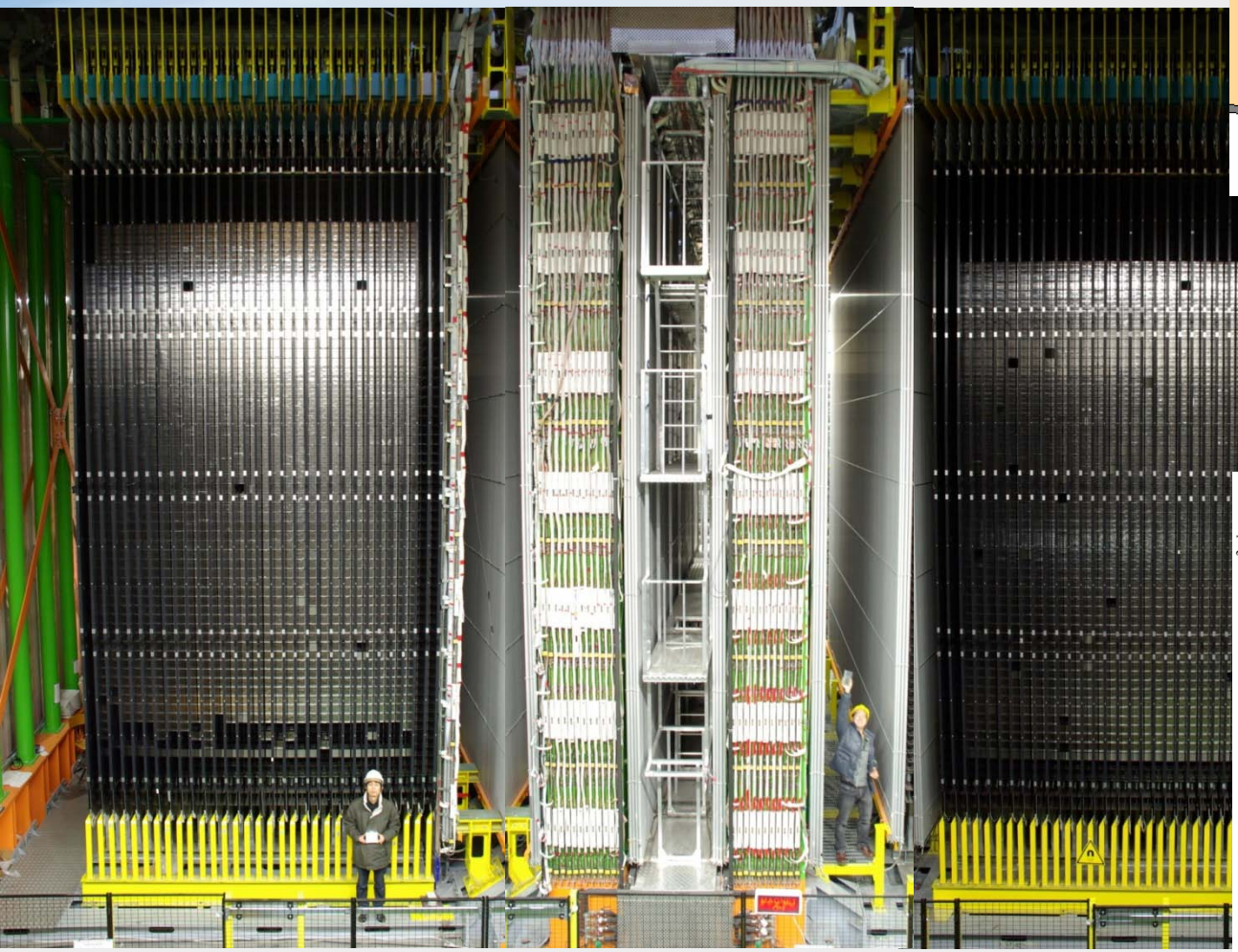
2. Tau neutrino observation

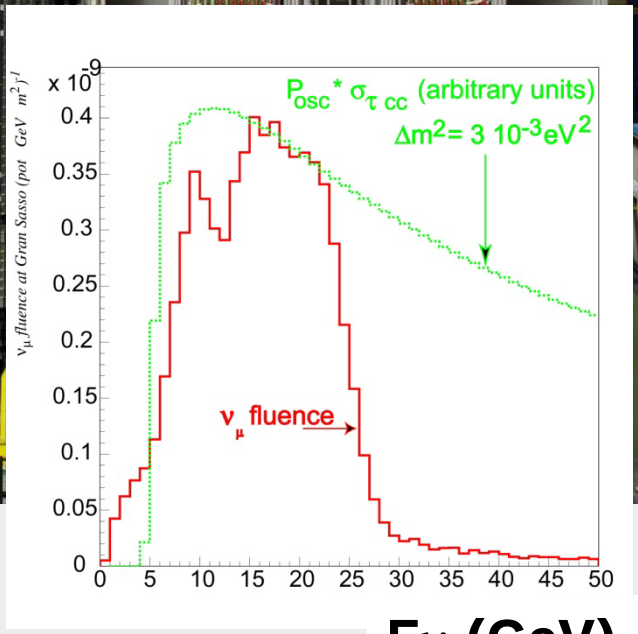
ν_μ ..... ν_τ

Phys.Lett.B691:138-145,2010.

ICHEP talk by Pasquale Migliozzi

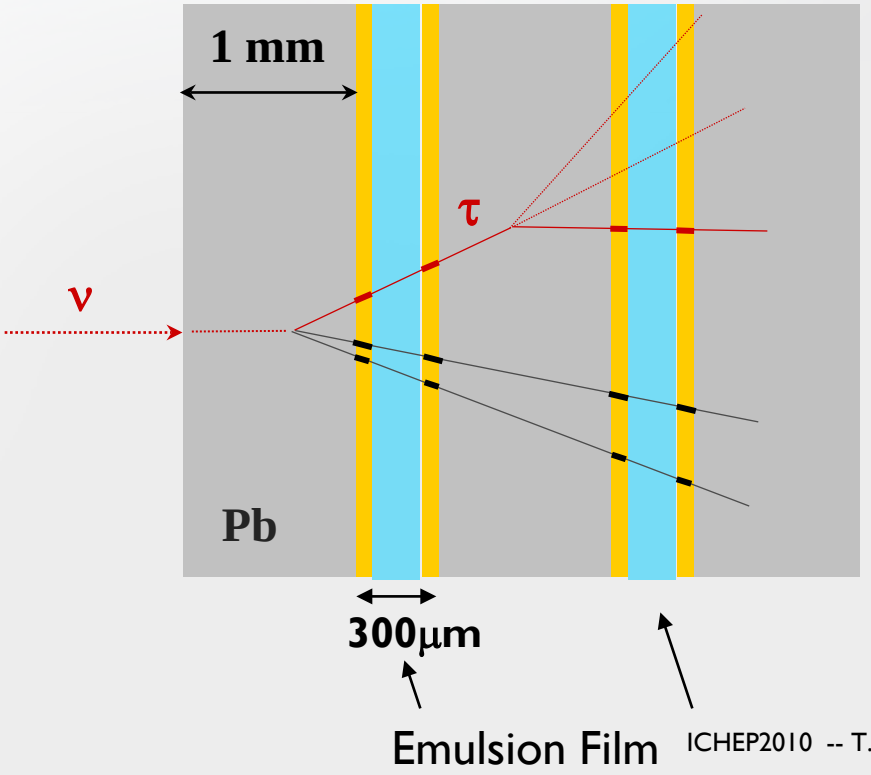


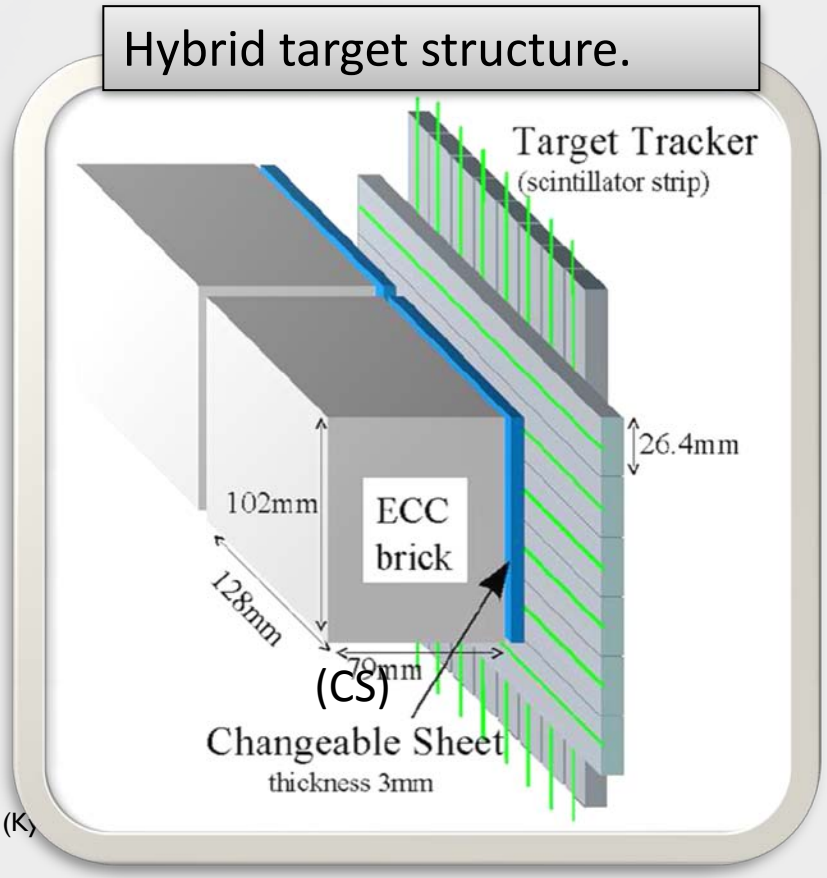




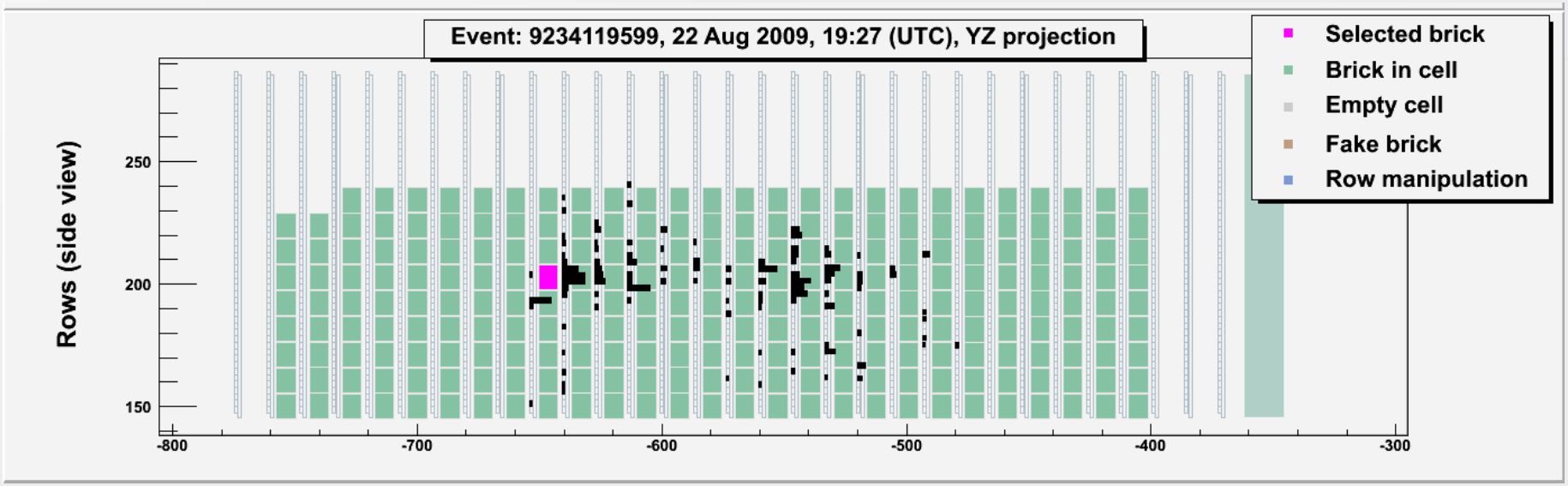
ECC TARGET BRICKS
-- Emulsion Cloud Chamber --

- The micron-resolution with one kilo-ton mass scale.
  - $c\tau_\tau = 87\mu m$

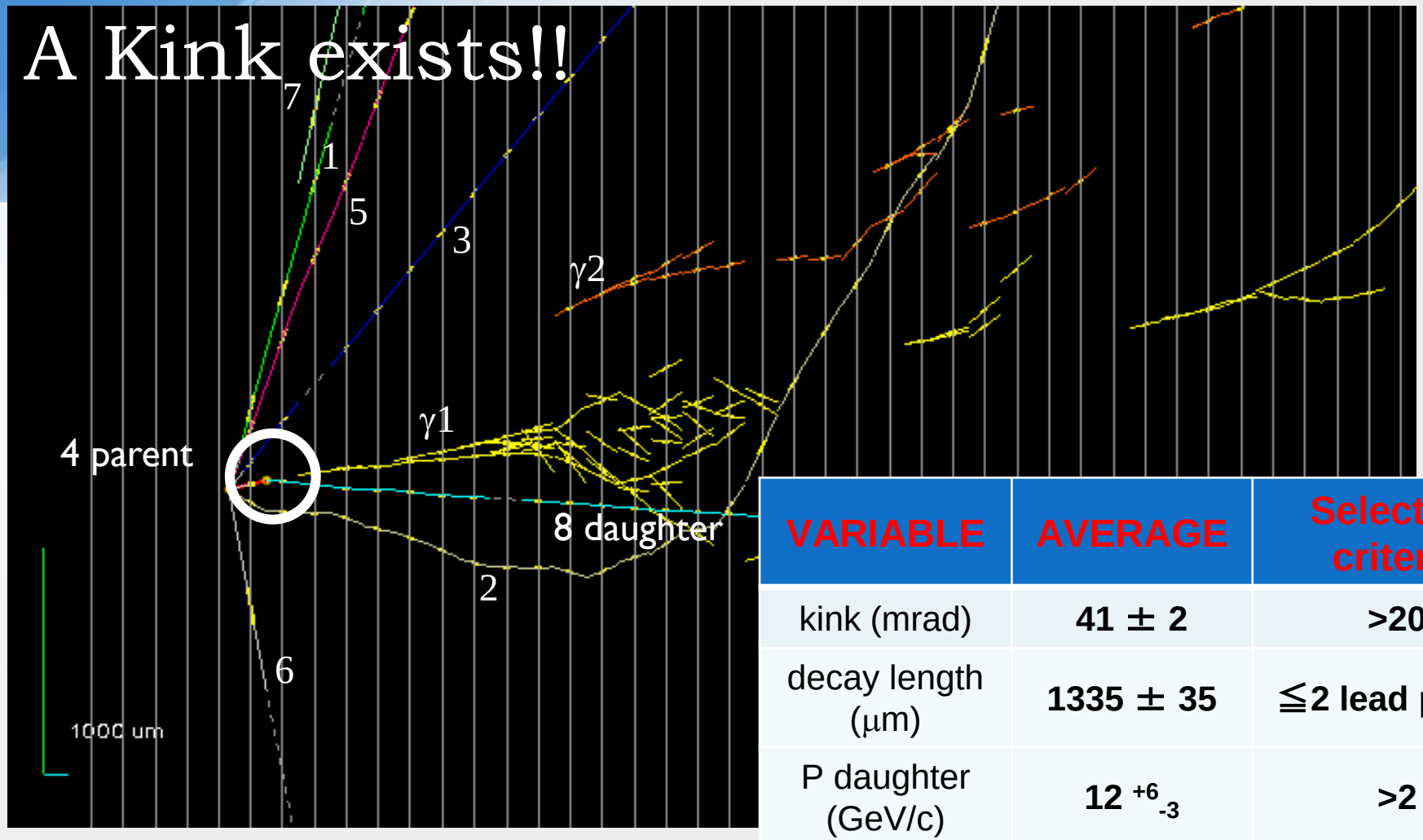




- OPERA analyze 35% of 2008-2009 data, corresponding to 1.89 x 10^{19} POT (Protons On Target).
  - ~0.5 tau events are expected.
  - Muonless event 9234119599 (22 August 2009, 19:27)
    - NC events or CC-tau hadoronic decay?



A Kink exists!!



VARIABLE	AVERAGE	Selection criteria
kink (mrad)	**41 ± 2**	**>20**
decay length (μm)	**1335 ± 35**	**≦2 lead plates**
P daughter (GeV/c)	**12^{+6}_{-3}**	**>2**
Pt (MeV/c)	**470^{+230}_{-120}**	**>300**
missing Pt (MeV/c)	**570^{+320}_{-170}**	**<1000**
Azimuth angle (deg)	**173 ± 2**	**>90**

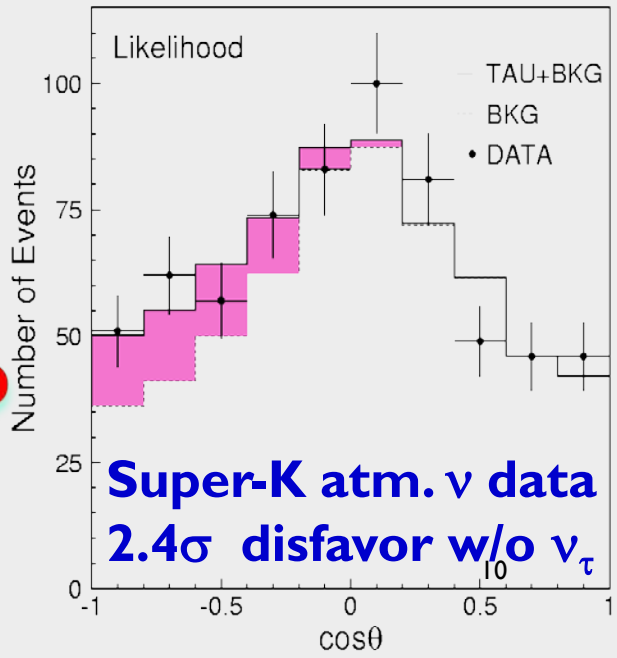
- $\tau \rightarrow \rho \nu_\tau$ candidate
  - $\rho \rightarrow \pi\pi^0 (\pi^0 \rightarrow \gamma\gamma)$

Tau Neutrino Candidate event

- The Expected Number of BG
  - 0.018 ± 0.007 for the 1 prong tau selection
  - 0.045 ± 0.020 for all kinds of tau selections
- The expected Signal events
  - 0.54 ± 0.13 (syst.) @ $\sin^2 2\theta_{23}=1.0$, $\Delta m_{23}^2=2.5\times10^{-3}eV^2$

- The statistical Significance
  - 2.36 σ with 0.018 ± 0.007 BG events
  - 2.01 σ with 0.045 ± 0.020 BG events

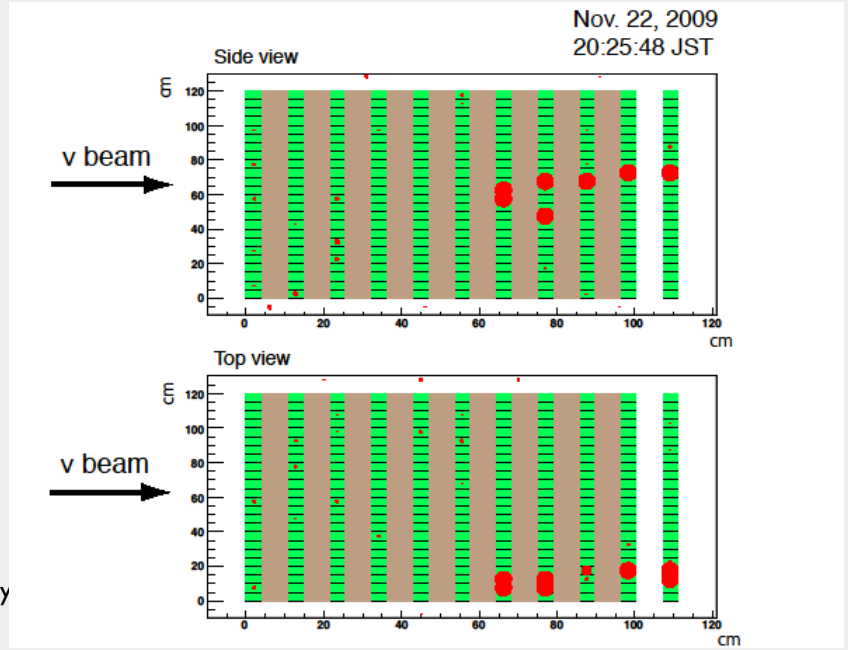
We are looking forward to more data for OPERA



What happened in November 2009?

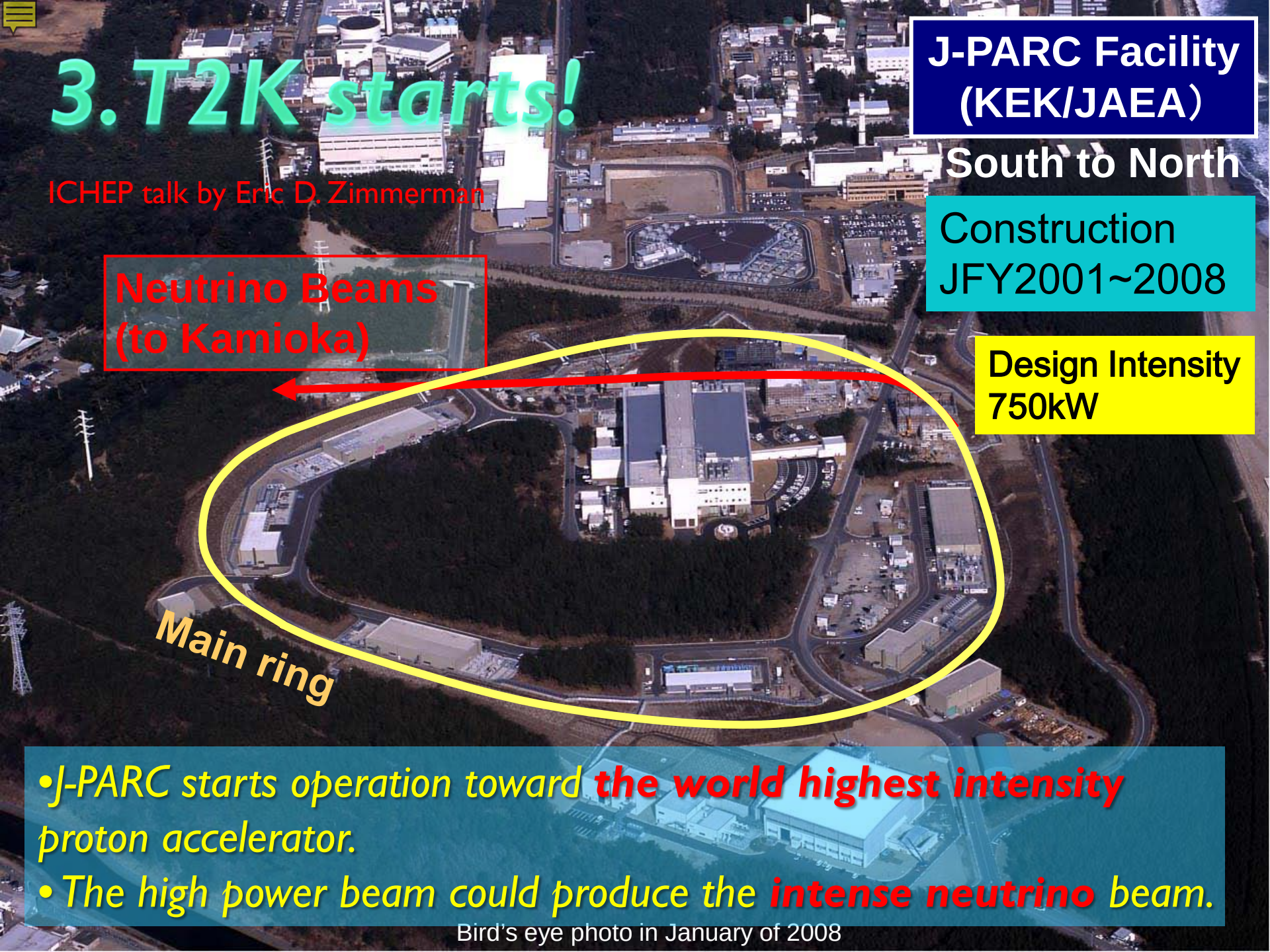
- November 20th, 2009.
  - First Beams in LHC
- **November 22nd, 2009.**
  - **First Observation of T2K neutrino events in J-PARC.**
- November 23rd, 2009.
  - First Collision in LHC

akay



3. T2K starts!

ICHEP talk by Eric D. Zimmerman

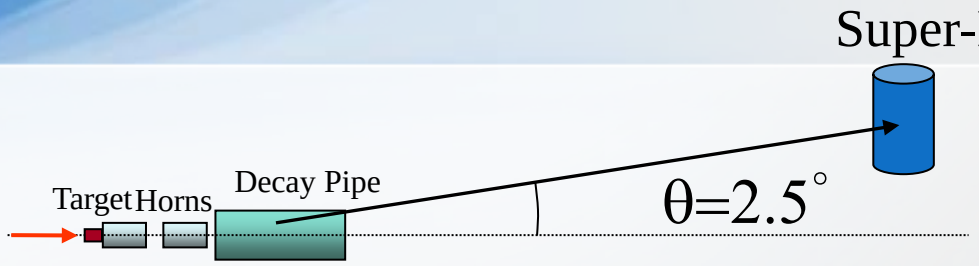


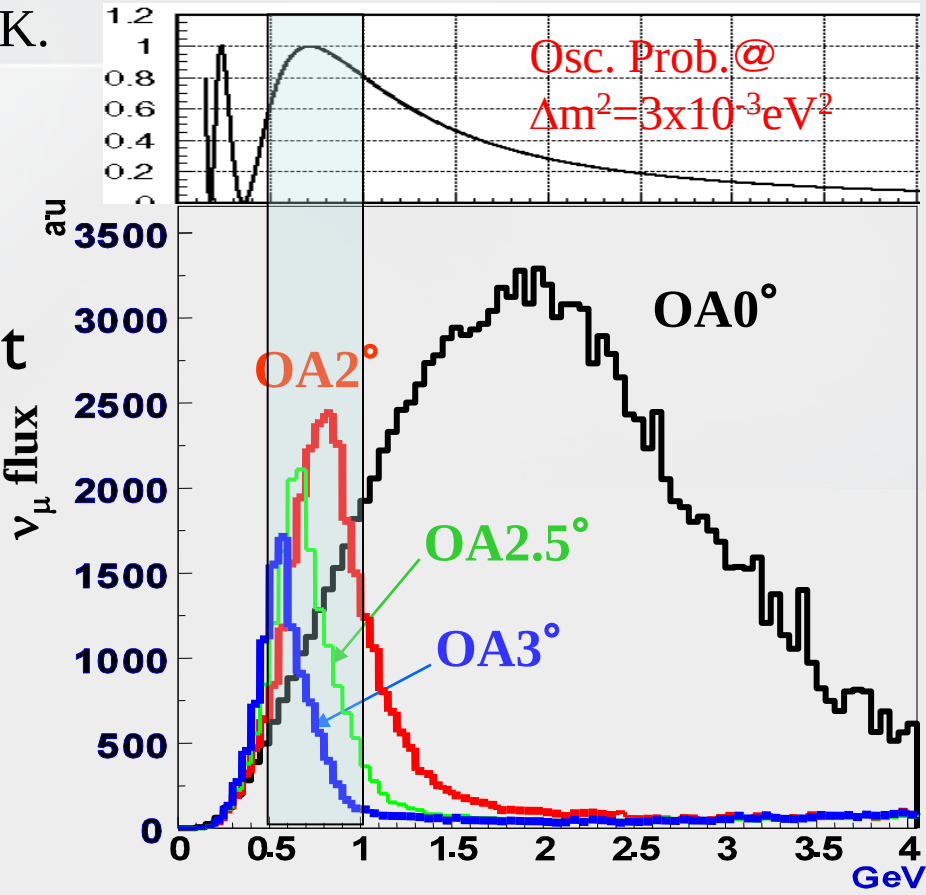
- *J-PARC starts operation toward **the world highest intensity** proton accelerator.*
- *The high power beam could produce the **intense neutrino** beam.*

Bird's eye photo in January of 2008

Off-axis ν beam configuration

- **Quasi Monochromatic Beam**



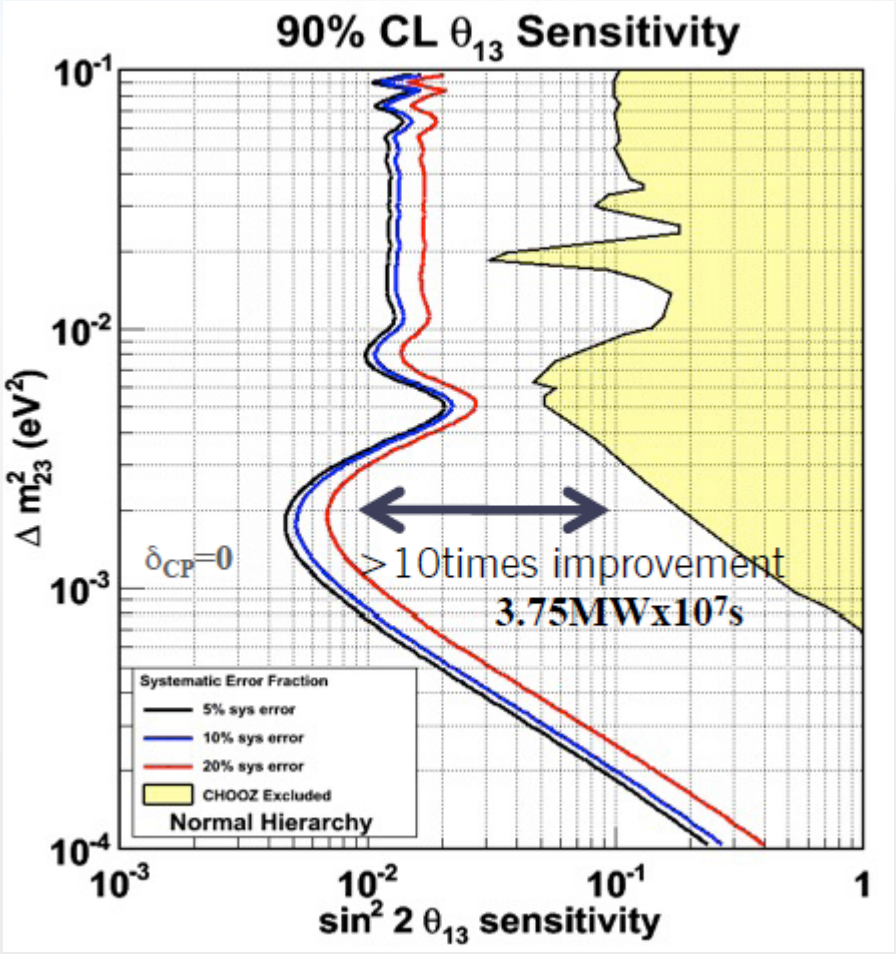


- The ν beam energy is tuned at the oscillation maximum.
  - **Higher signal yield.**
  - **Less background from high energy neutrinos.**

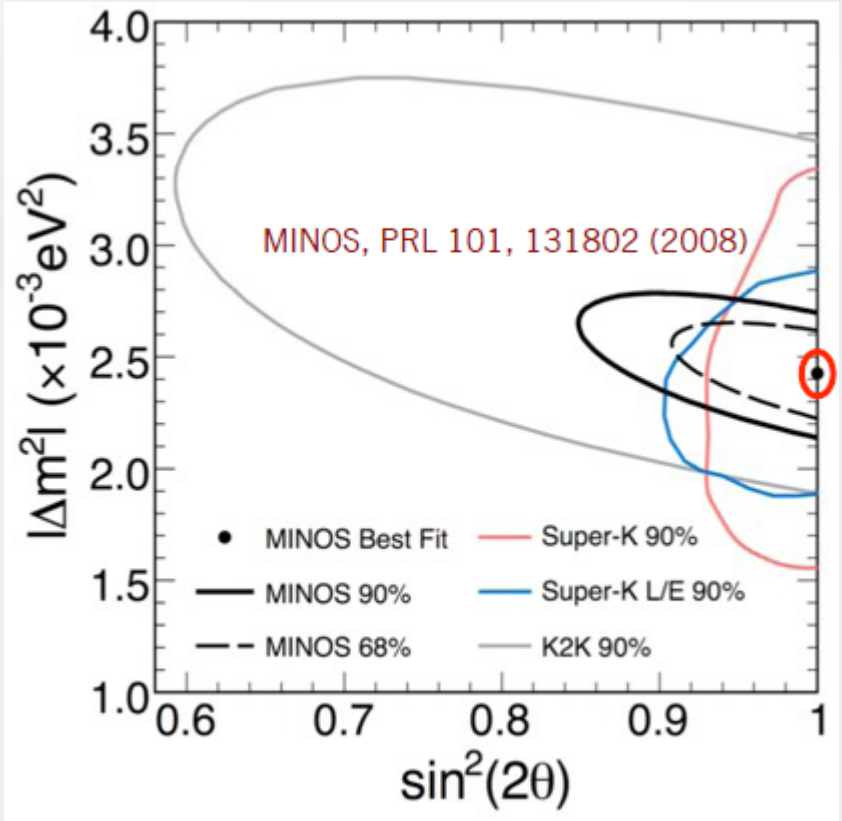
Intense and high-quality neutrino beam

Expected Sensitivity of T2K

$\nu_\mu \rightarrow \nu_e$ appearance

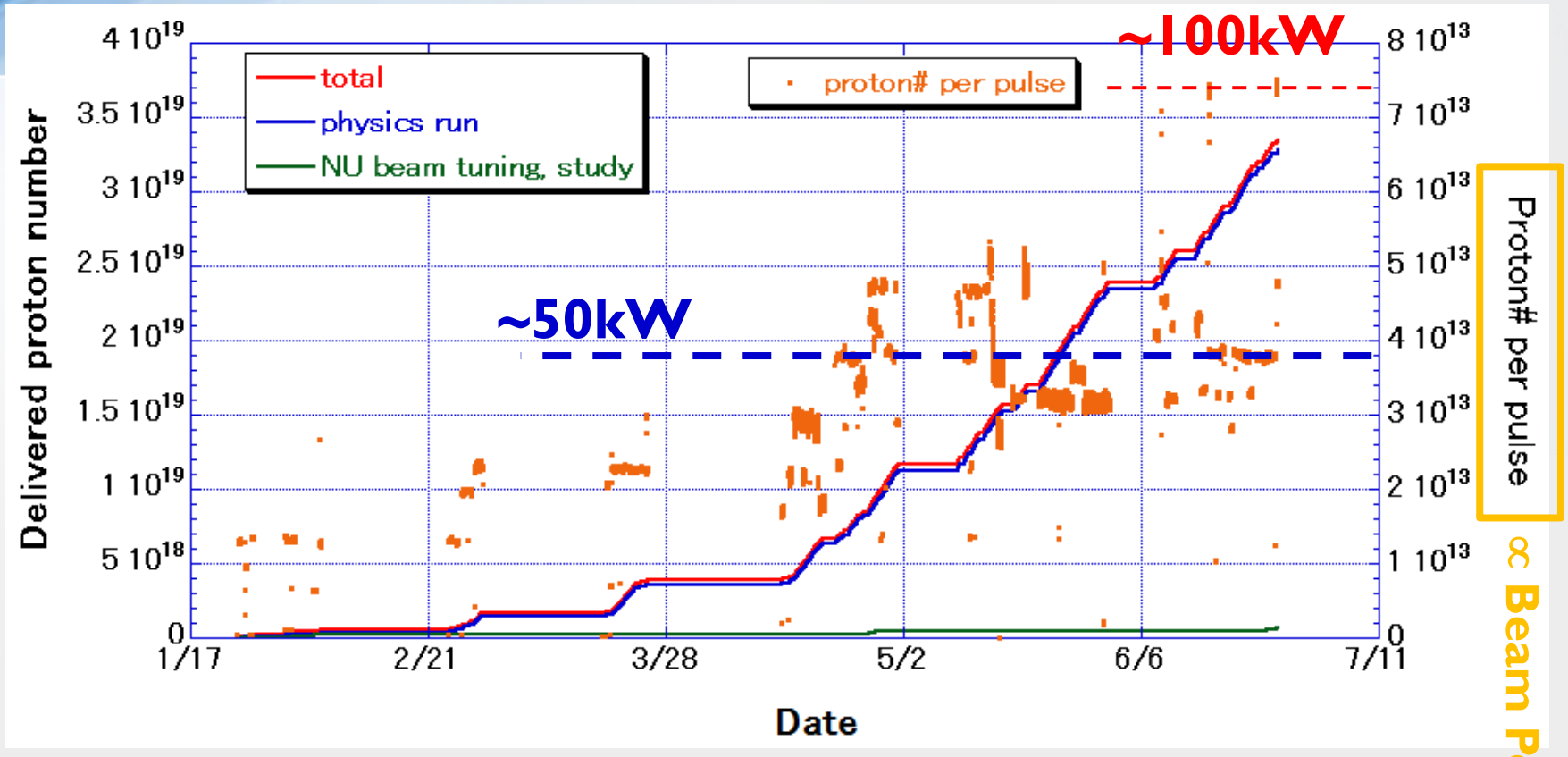


$\nu_\mu \rightarrow \nu_\mu$ disappearance



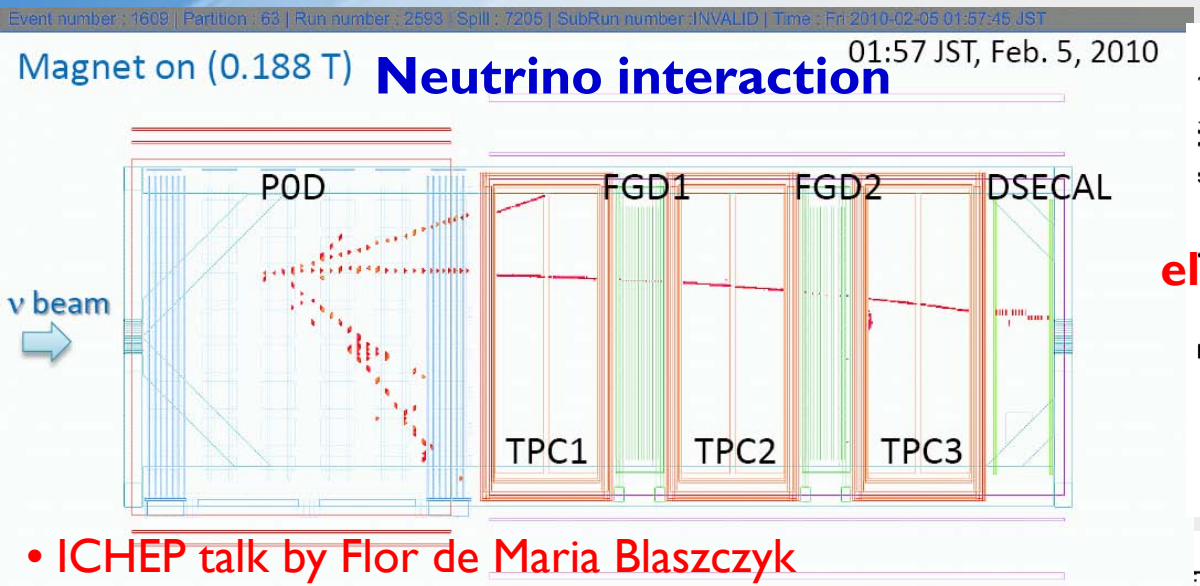
T2K Full Statistic goal:
3.75MW × 10^7 sec.

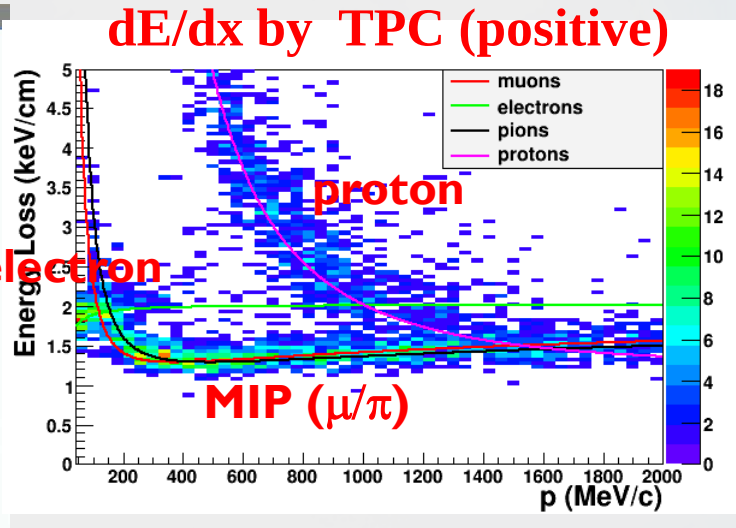
T2K Physics Run begins in 2010.



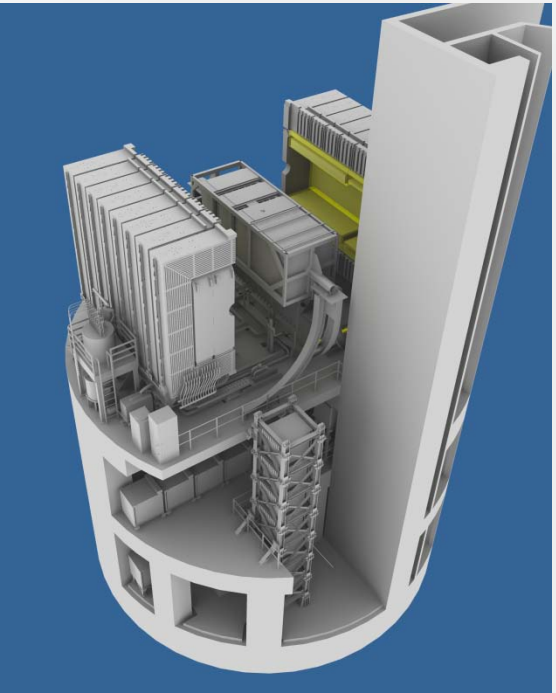
- Delivered POT: 3.35×10^{19} (3.28×10^{19} for physics)
- Continuous run @ ~50kW level
- Trial up to 100kW successful.

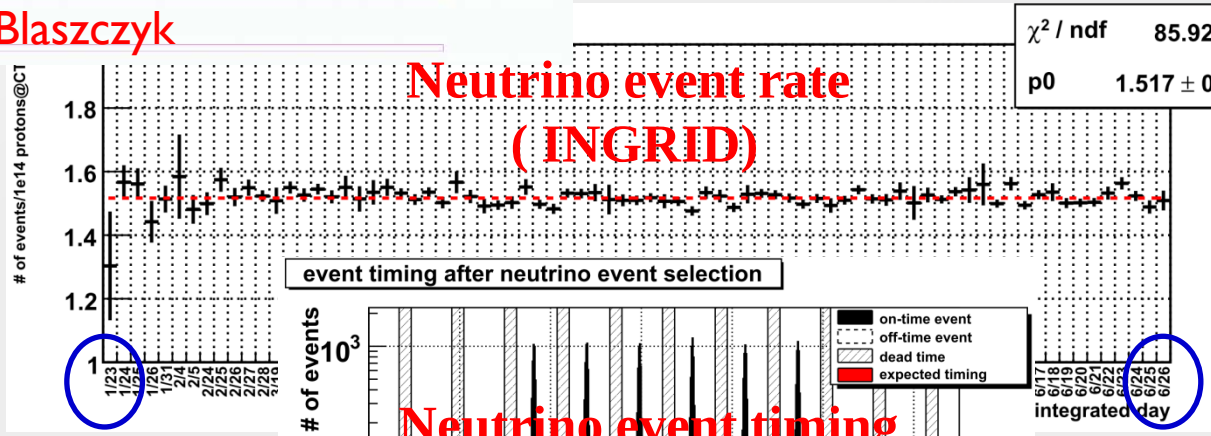
Near Detector Neutrino Measurements

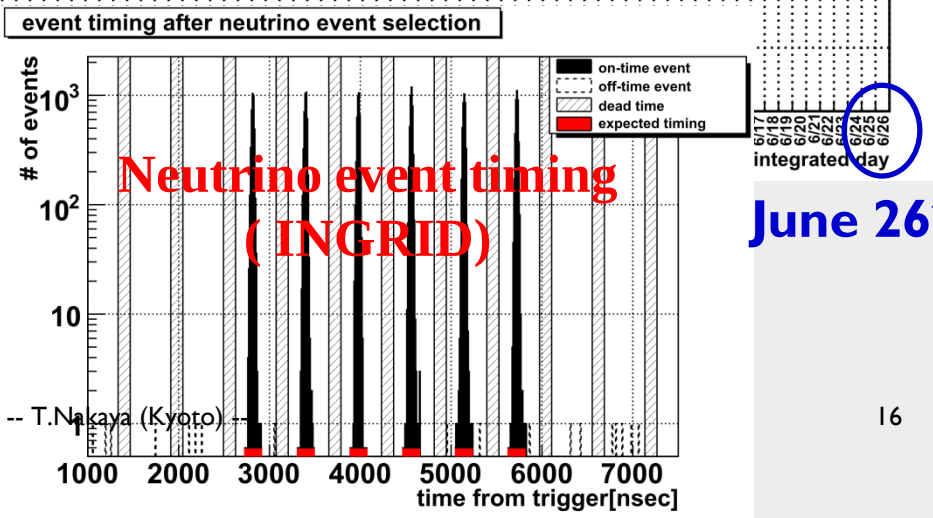




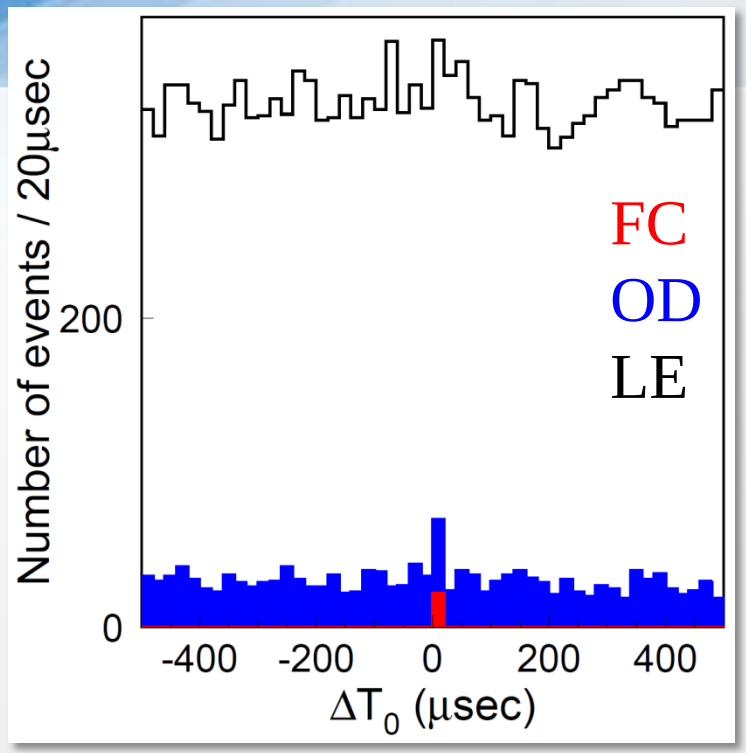
- ICHEP talk by Flor de Maria Blaszczyk







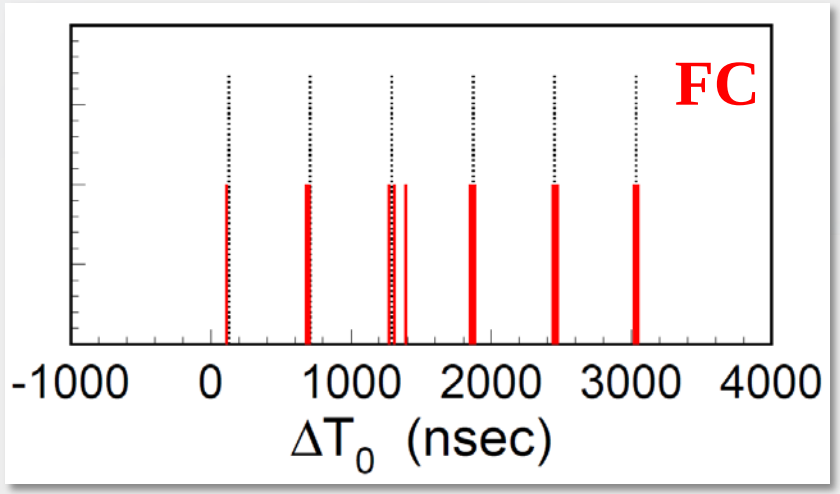
Super-K(Far detector) neutrino events



LE: Low energy triggered events

OD: Outer detector events

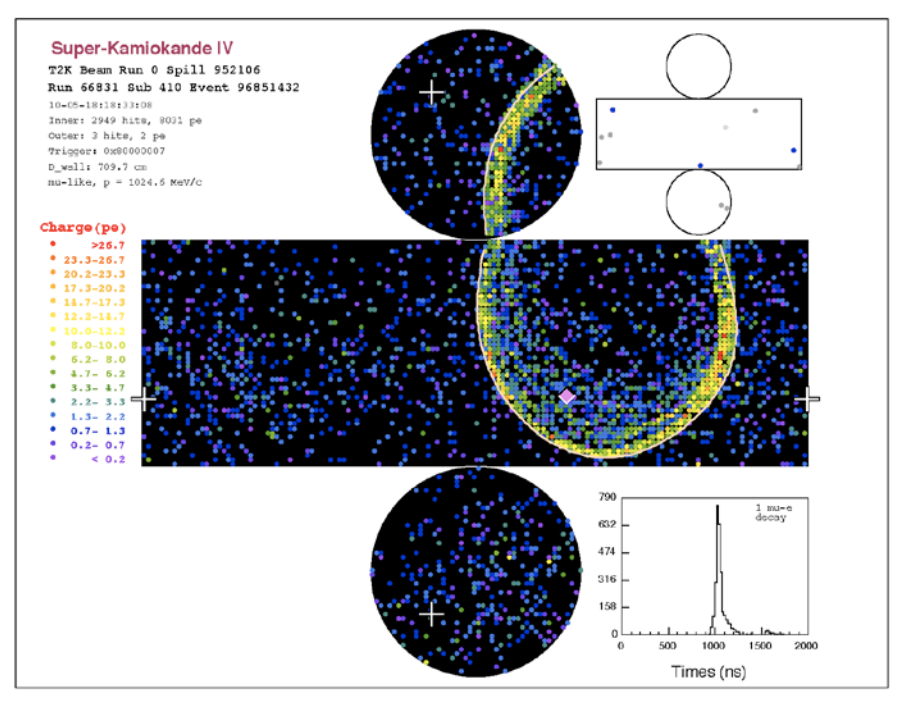
FC: Fully contained events



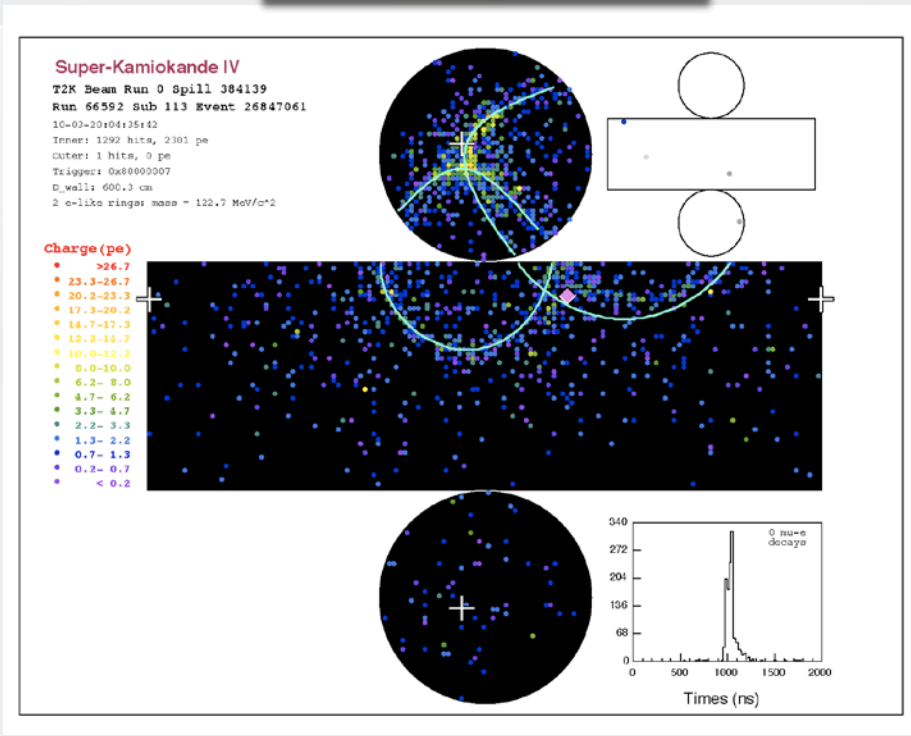
- Clean beam timing structure confirmed in FC events
- Twenty-two FC events observed by Mid. May
- Non-beam BG estimated to be $<10^{-3}$evts

Super-K events and T2K Status

Single-ring μ-like event



Two-ring event



Pink diamonds are placed on the wall in the beam direction starting from the reconstructed vertex.

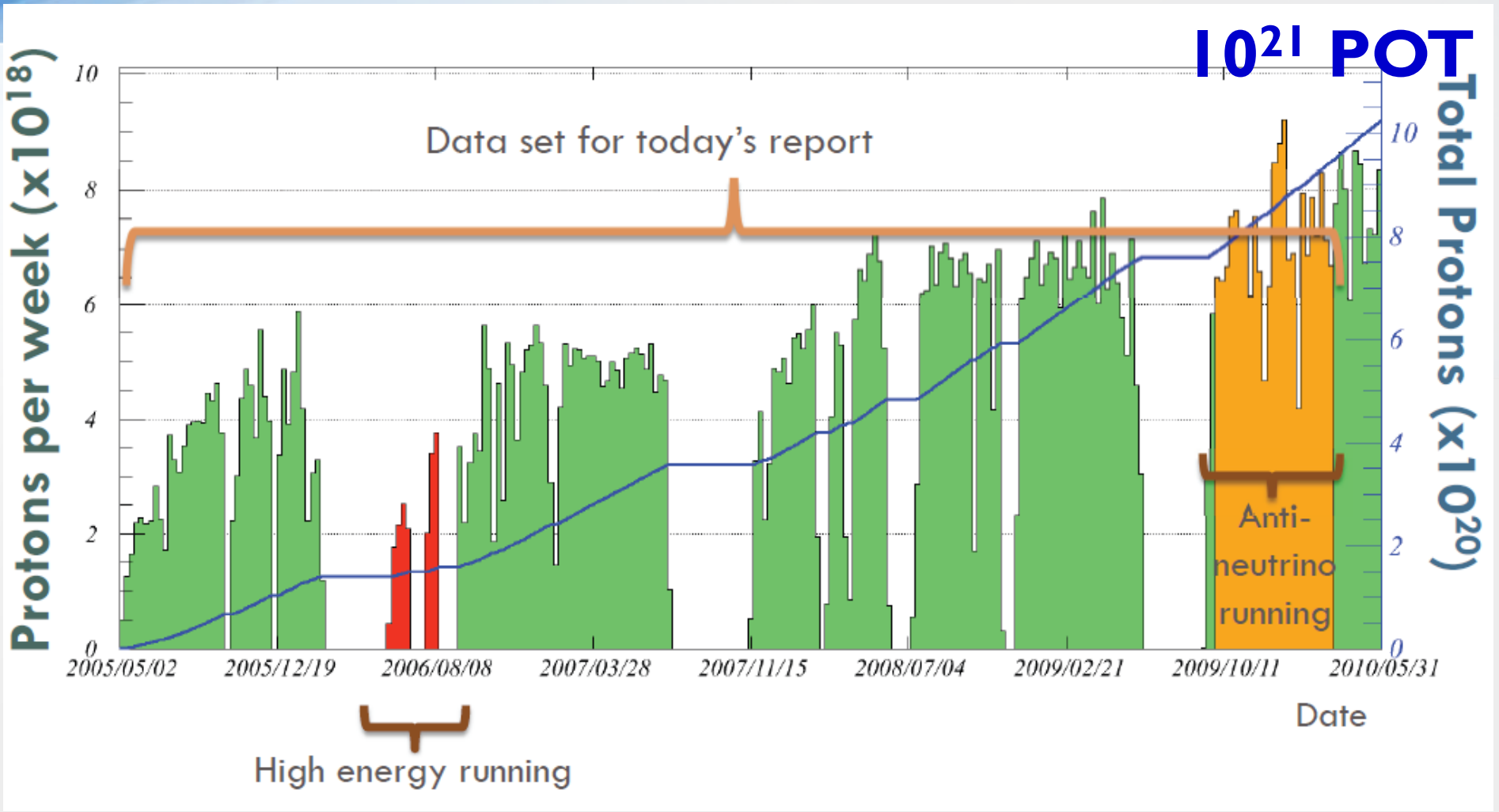
- We are accumulating more and more beam data from now on.
  - Will significantly improve the sensitivity of neutrino oscillations.

4. Precision Measurements

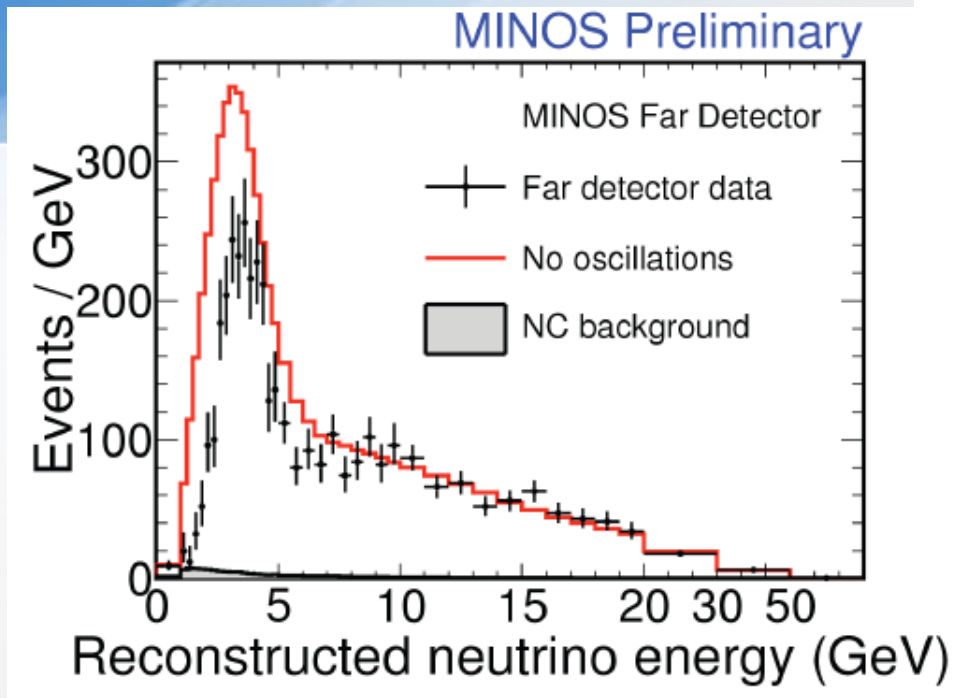
ICHEP talk by Justin Evans

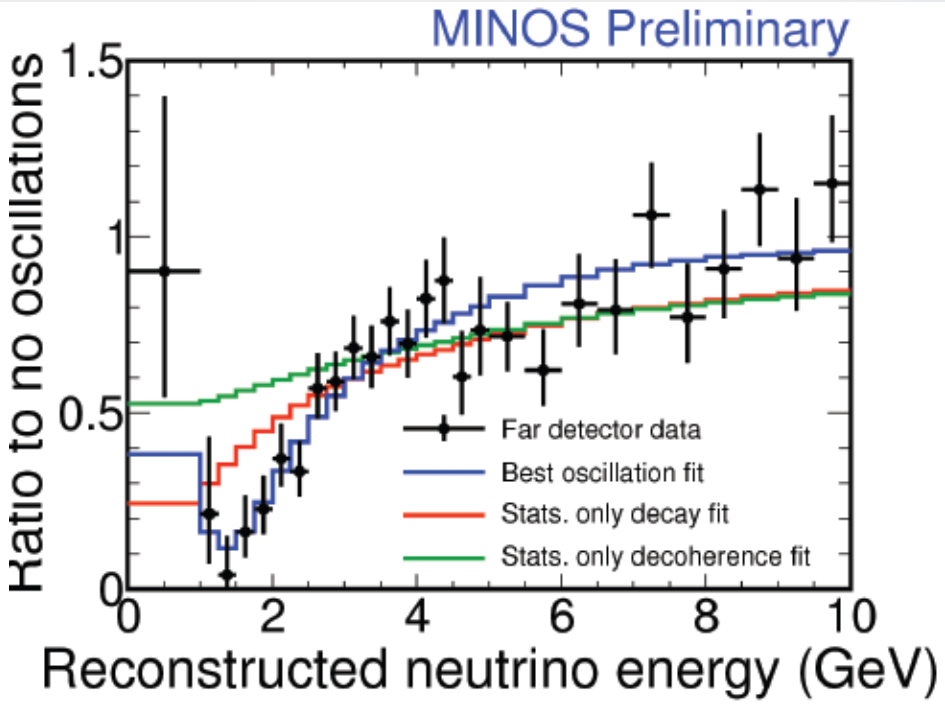
FNAL NuMI (Neutrino beam at Main Injector)

-- Today's highest power neutrino beam --

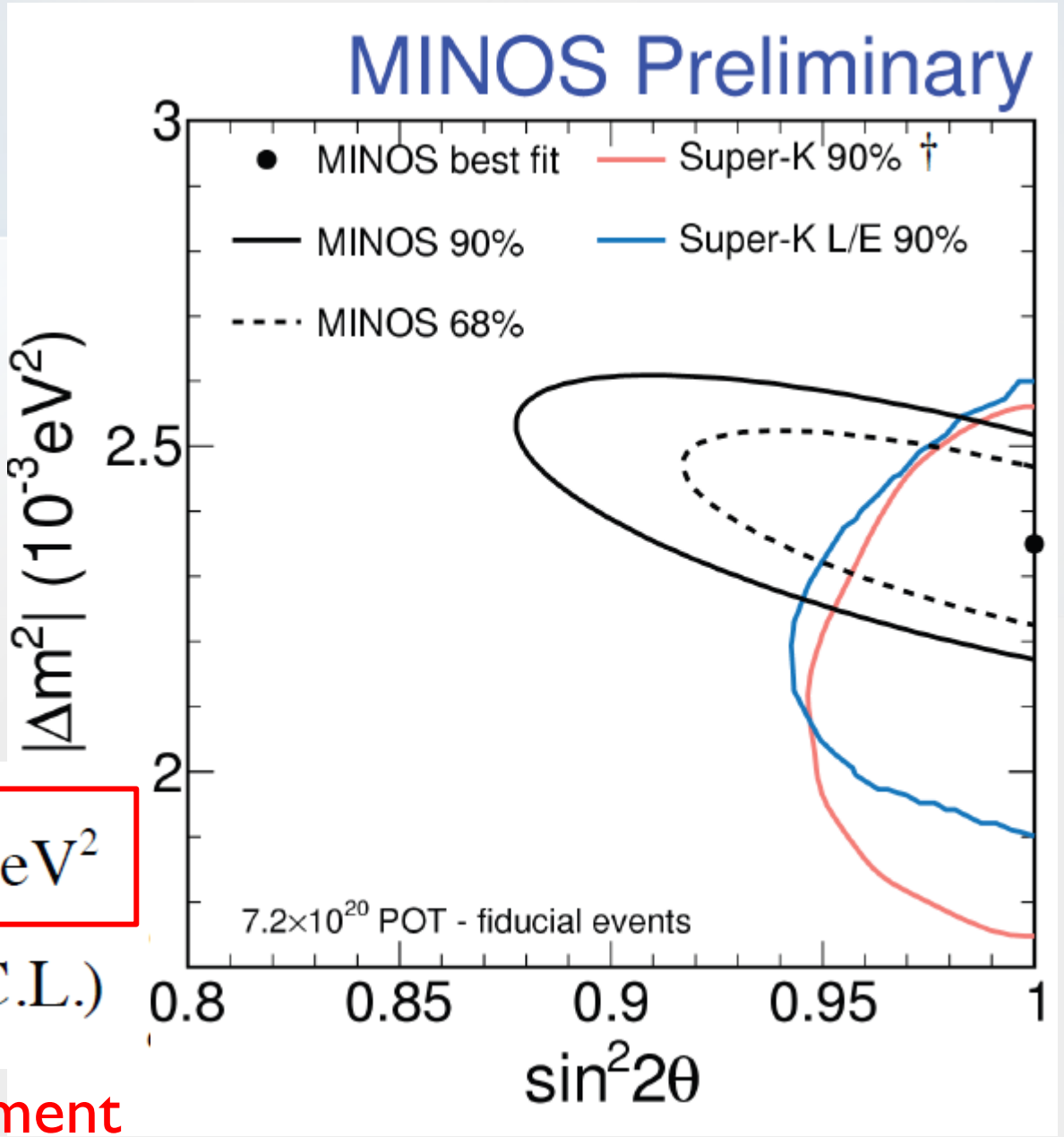


Precision Oscillation Parameter Measurements





- $\nu_\mu \rightarrow \nu_\mu$ measurement w/ 7.2×10^{20} POT.
- **1986 events** observed for **2451 events** expected without oscillation.
  - **Best fit with neutrino oscillations.**
  - Decoherence disfavored: $> 8\sigma$
  - Pure decay disfavored: $> 6\sigma$ (7.8σ if including NC)

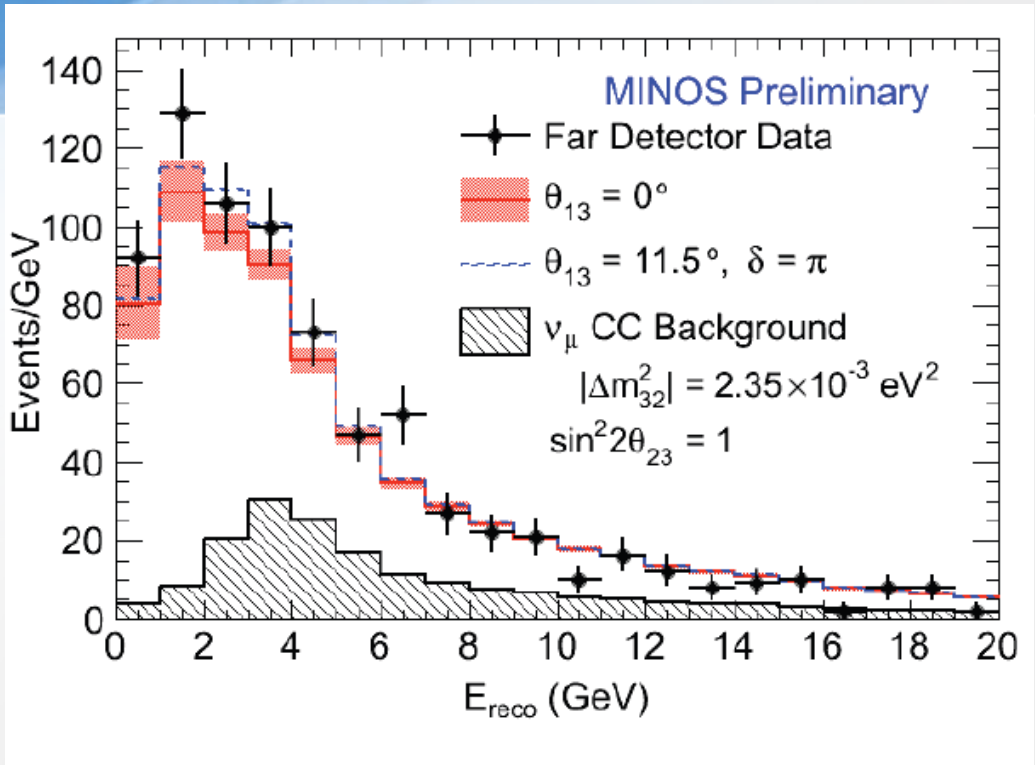


$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\,(90\%\,\mathrm{C.L.})$$

World Best Measurement

NC (Neutral Current) Events



- Observation: 850 events
- Expectation: 757 events

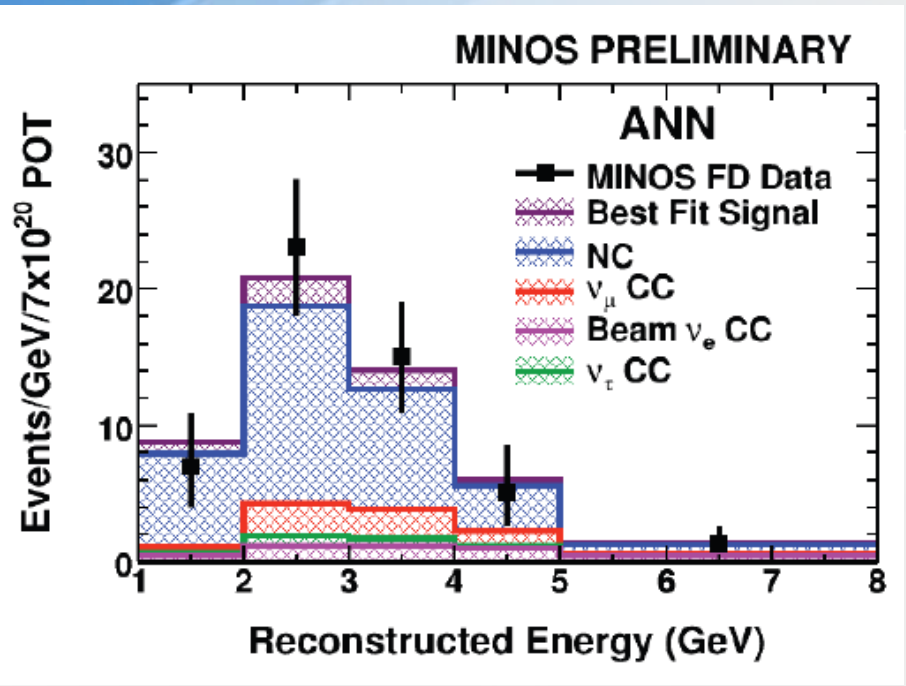
$$f_s \equiv \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} < 0.22 \ \ (0.40)$$

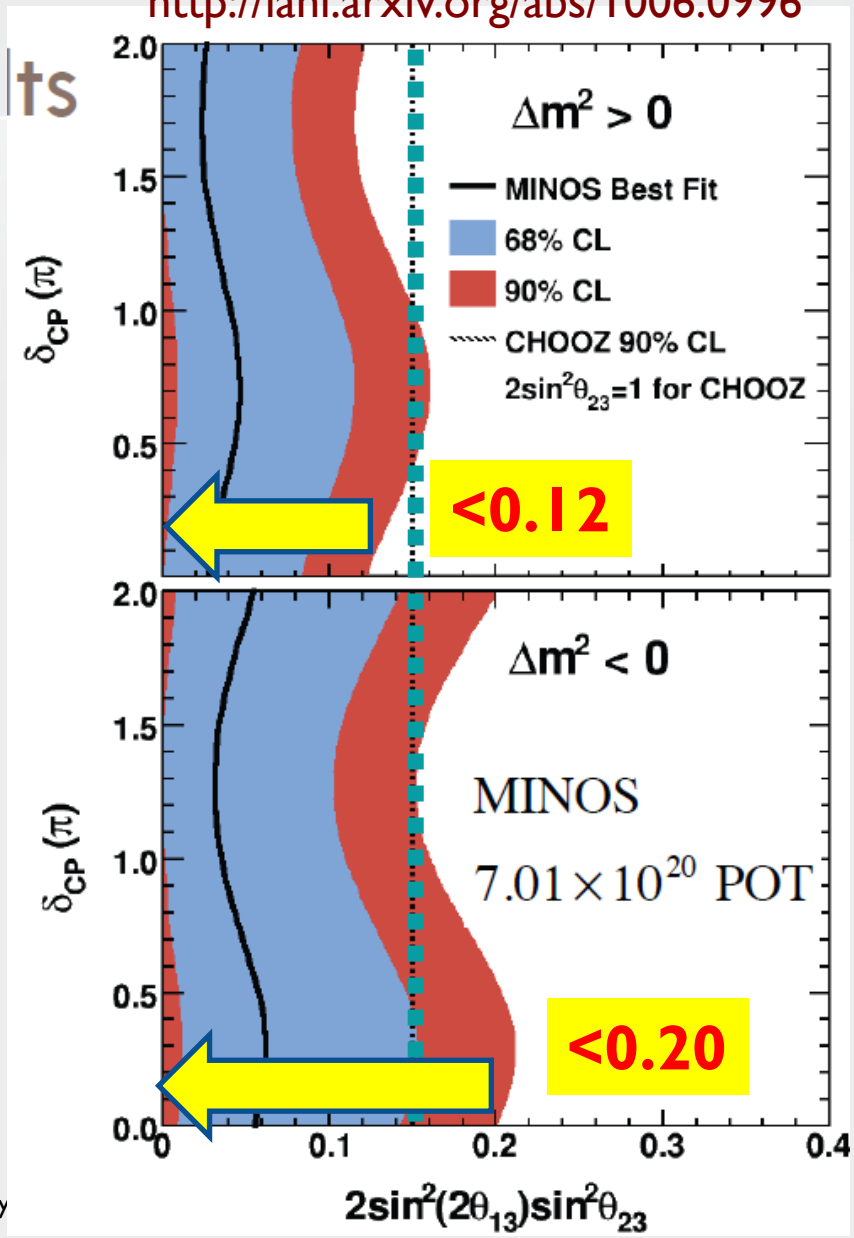
90% C.L. for
no (with) ν_e appearance

- NC events are as expected.
  - Neutrinos do not disappear. No oscillations to sterile neutrinos.
  - ν_μ changes the flavor to ν_τ or ν_e.

ν_e appearance ($\nu_\mu \rightarrow \nu_e$) -- *$\theta_{13}$ hunting* --

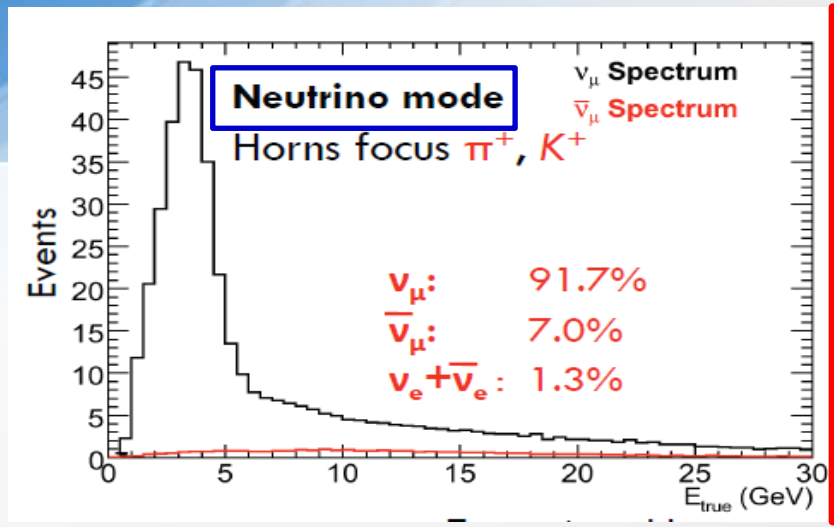
http://lanl.arxiv.org/abs/1006.0996

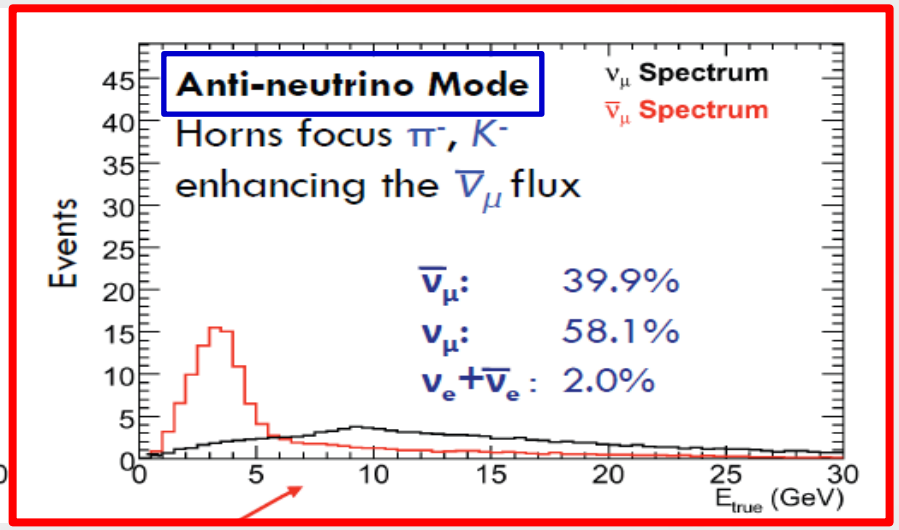


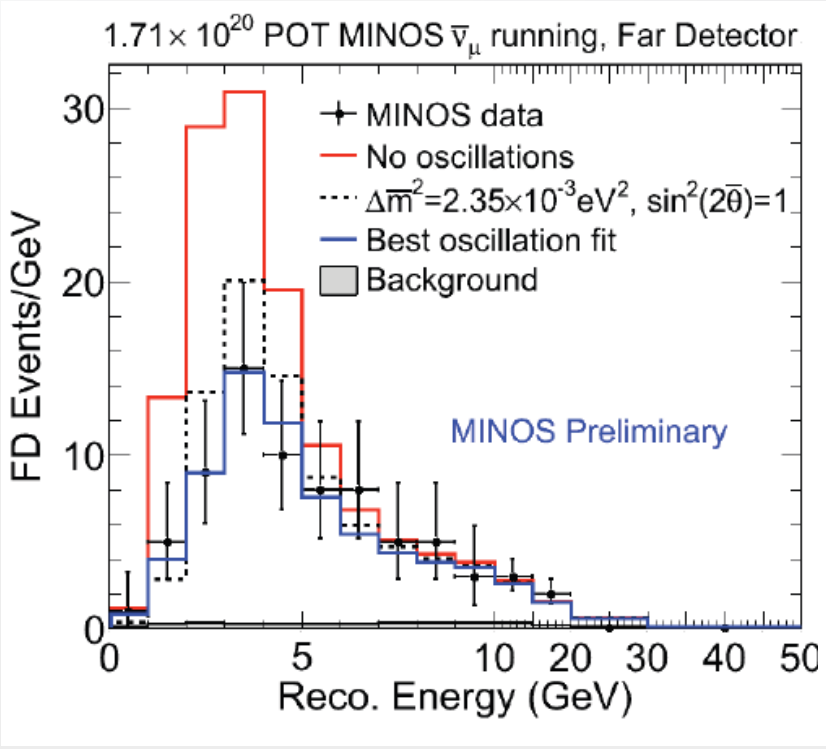


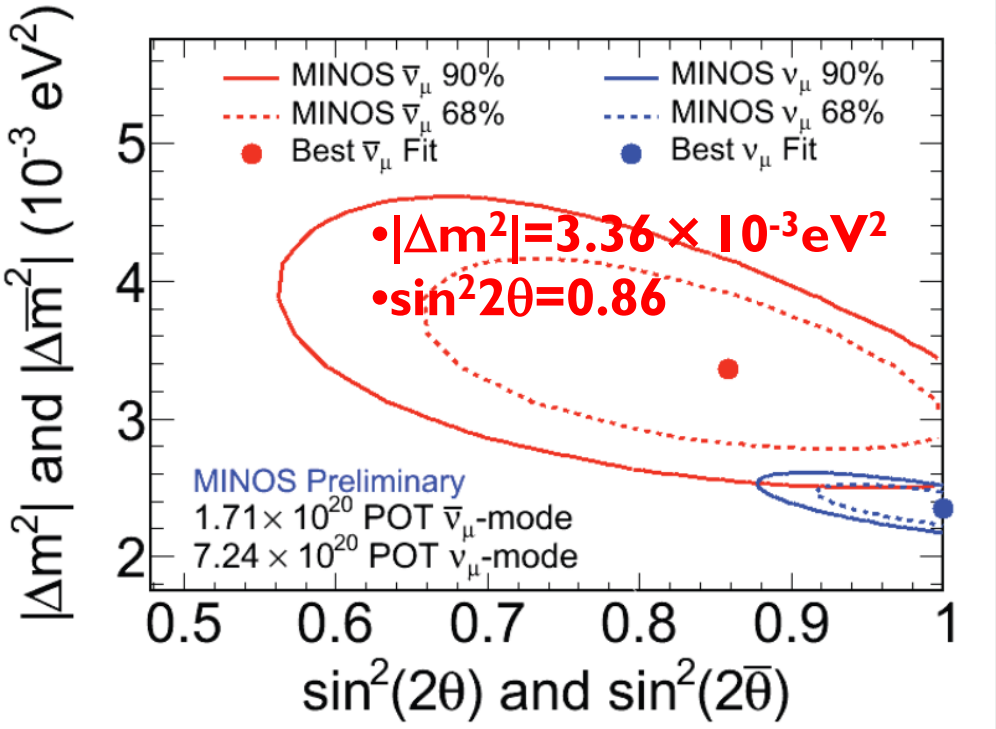
- 54 events observed for 49.1±7.0±2.7 expect: 0.7σ excess.
- For δ_{CP}=0, $\sin^2 2\theta_{23}$=1, $|\Delta m_{23}^2|$=2.43×10^{-3}eV^2 ,
  - **$\sin^2 2\theta_{13}$<0.12 (90%CL for Δm^2>0)**
  - **$\sin^2 2\theta_{13}$<0.20 (90%CL for Δm^2<0)**

Measurements with Anti-neutrinos









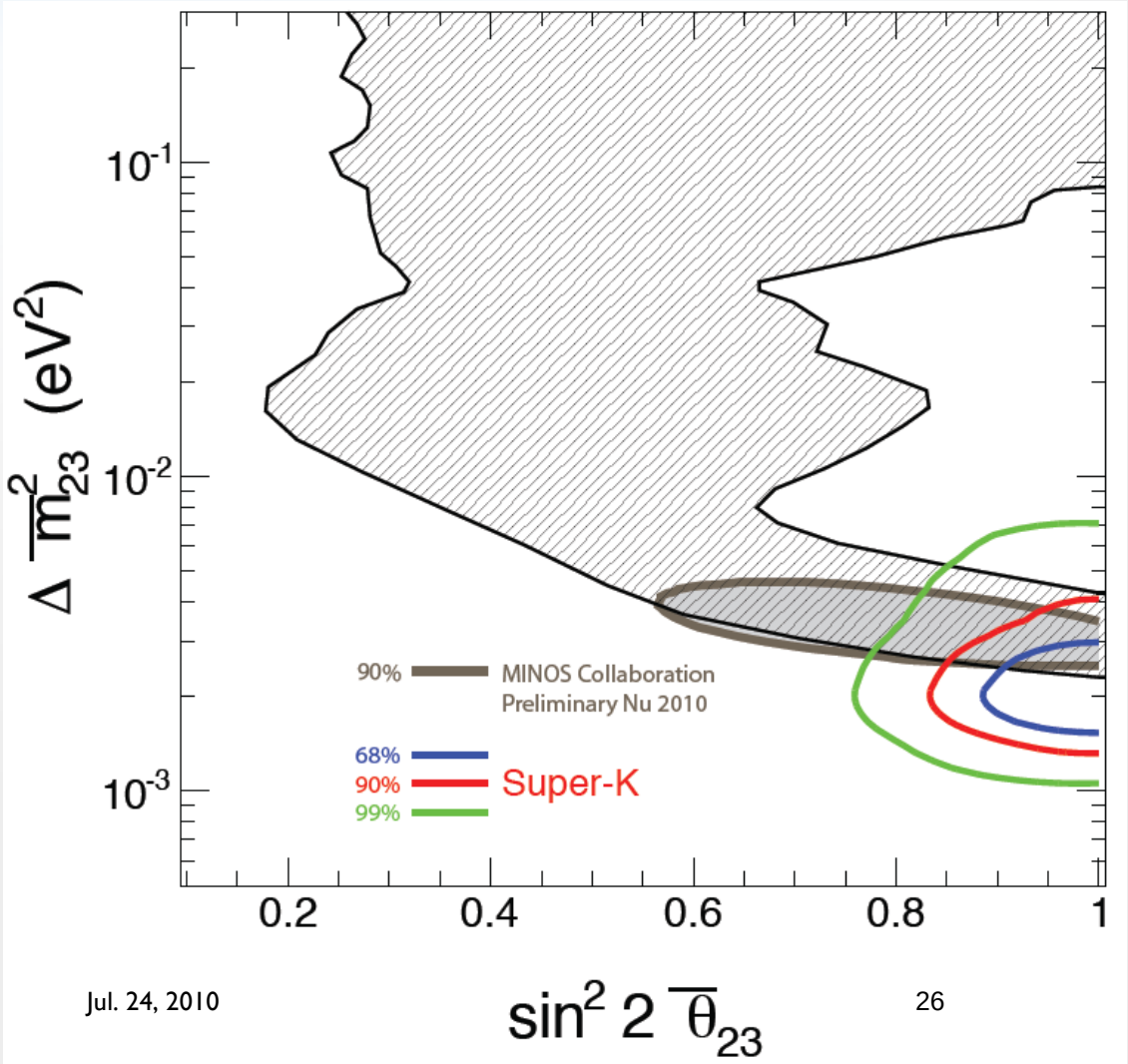
Super-K: Search for CPT violation in atm. ν

ICHEP talk by Yoshihisa Obayashi

- Under the CPT theorem, $P(\nu \rightarrow \nu)$ and $P(\bar{\nu} \rightarrow \bar{\nu})$ should be same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.

SK-I+II+III

Preliminary



Neutrino:

$\Delta m_{23}^2 = 2.2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

$\Delta \overline{m}_{23}^2 = 2.0 \times 10^{-3} eV^2$

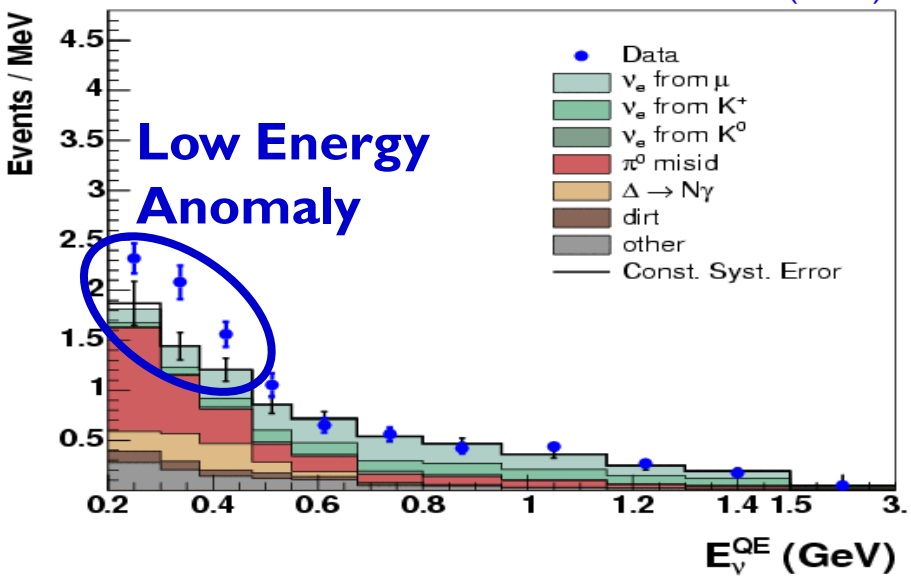
$\sin^2 2\overline{\theta}_{23} = 1.0$

No evidence for CPT violating oscillations is found.

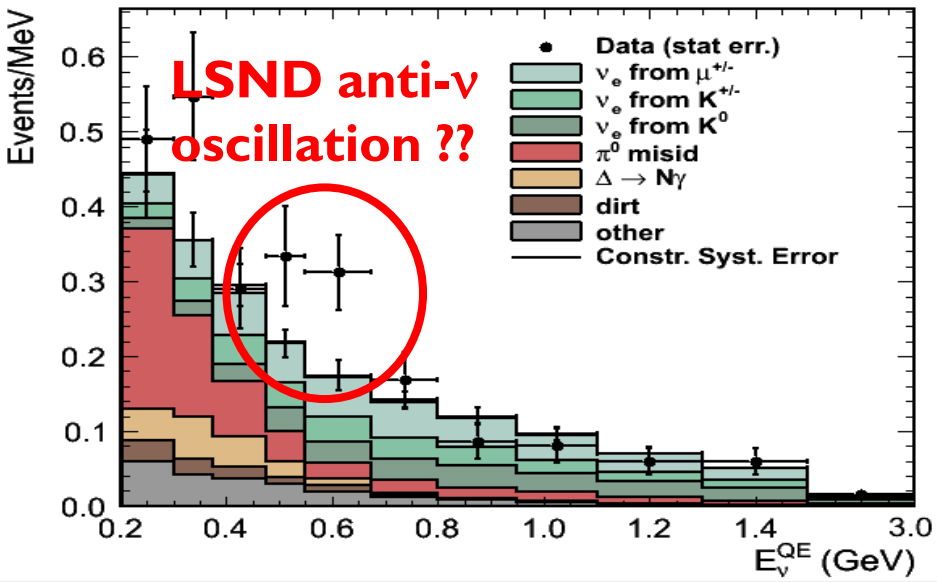
5. Anomaly -- MiniBooNE results --

ICHEP talk by Geoffrey Mills

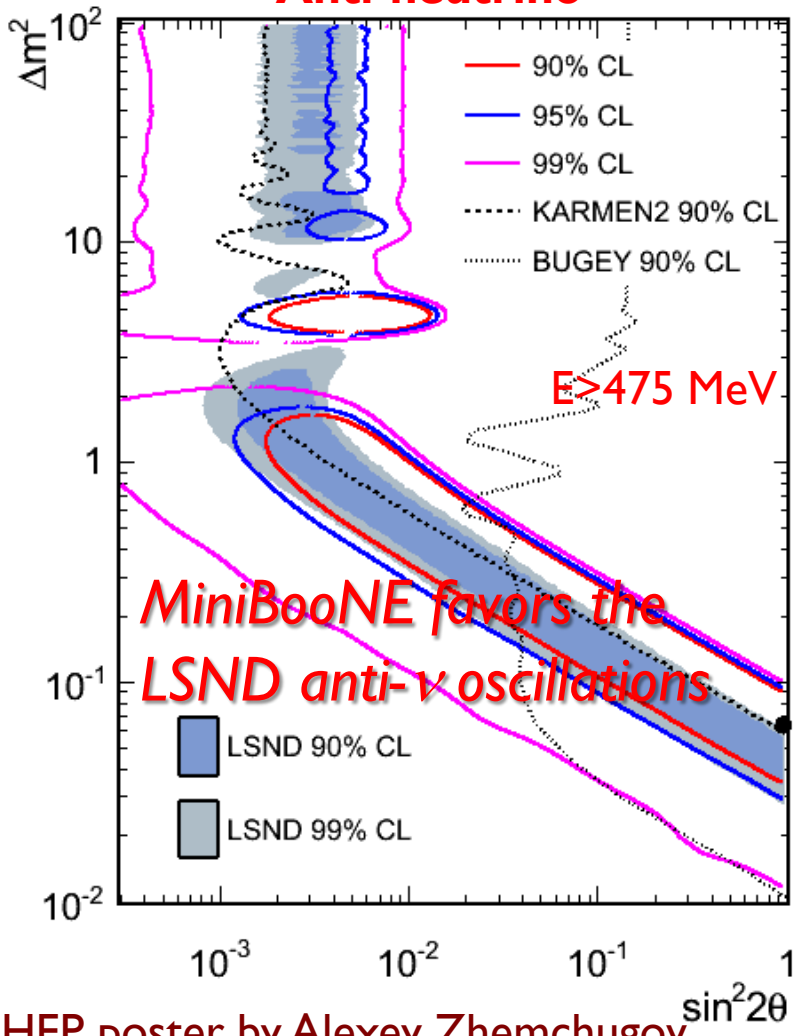
Neutrino Published PRL 102,101802 (2009)



Anti-neutrino

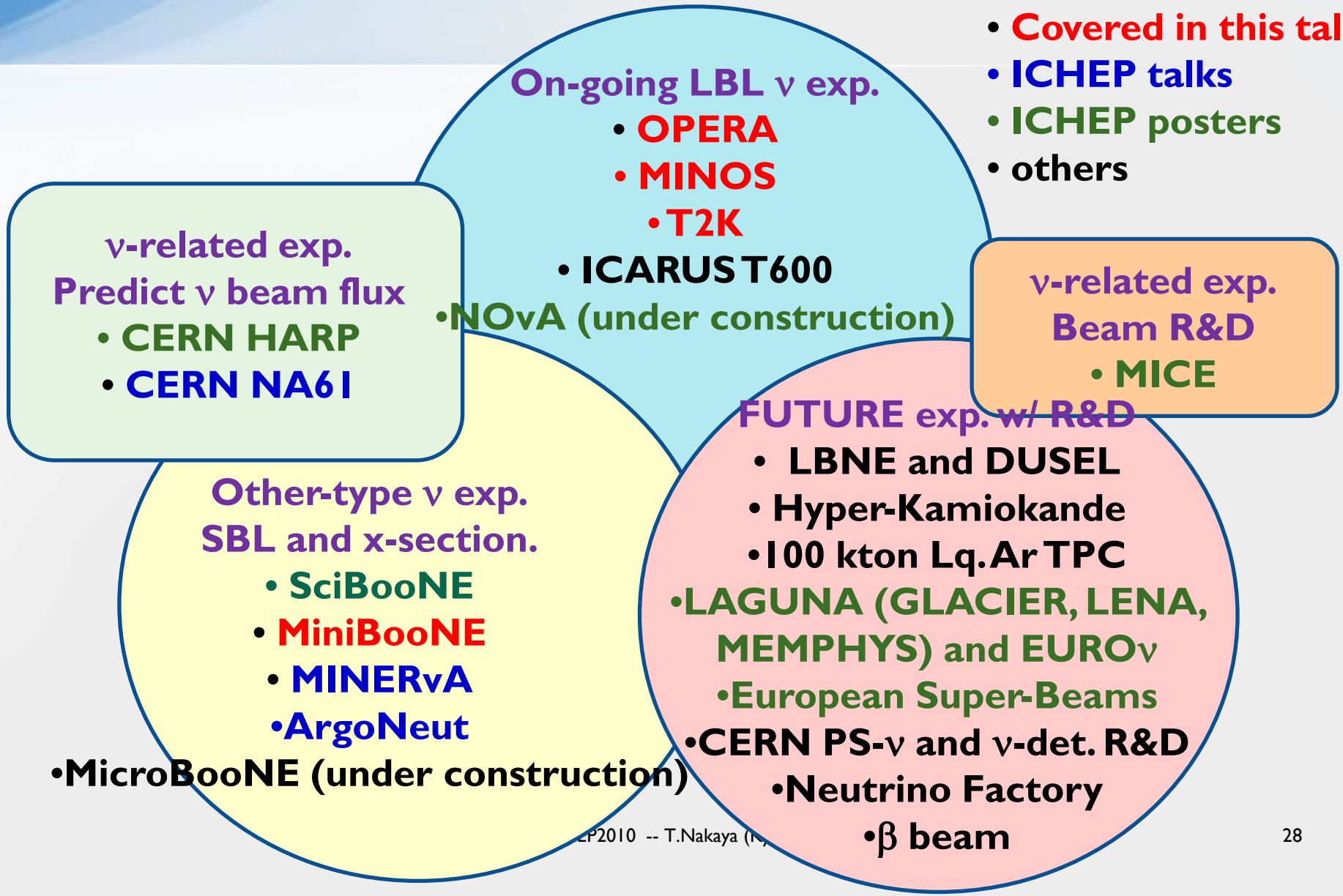


Anti-neutrino

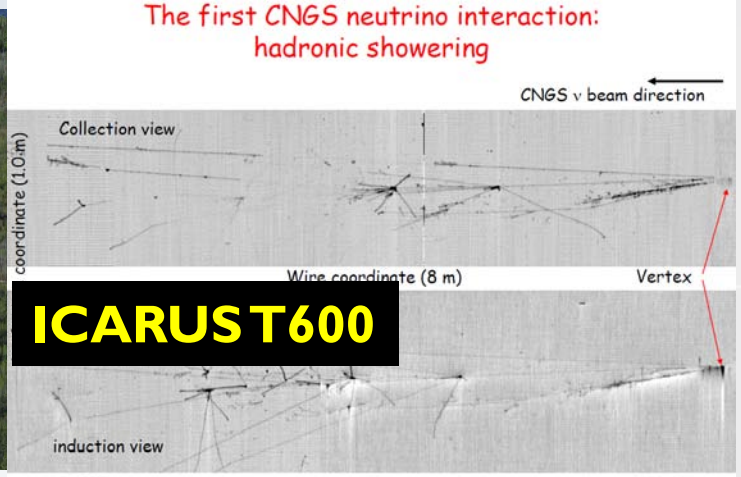


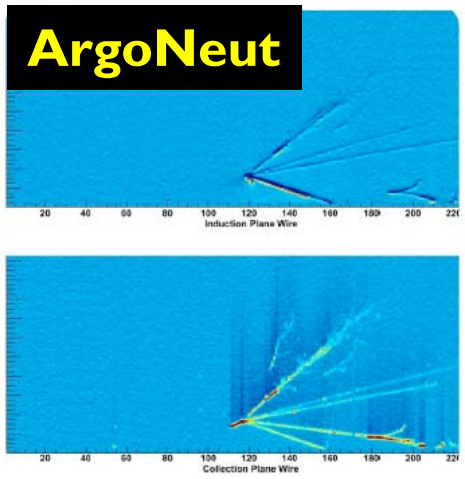
ICHEP poster by Alexey Zhemchugov.
"Is there any "LSND" anomaly" Due to π production cross section uncertainties.

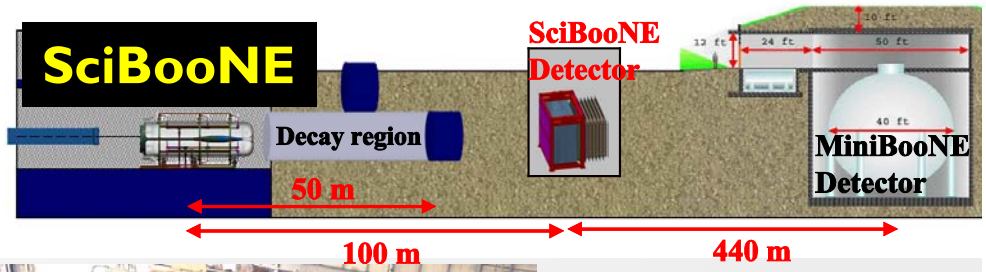
6. Future Prospects and Summary

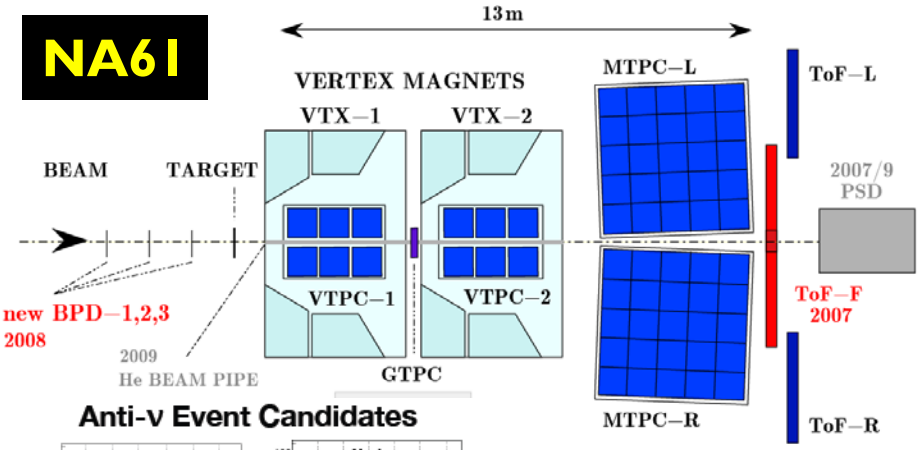



NOvA
Receiving building
Detector hall
Concrete factory

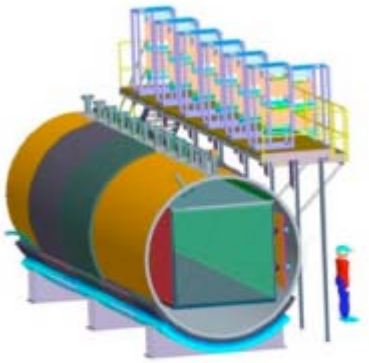

The first CNGS neutrino interaction:
hadronic showering
CNGS ν beam direction
Collection view
coordinate (1.0 m)
Wire coordinate (8 m)
Vertex
induction view
ICARUS T600

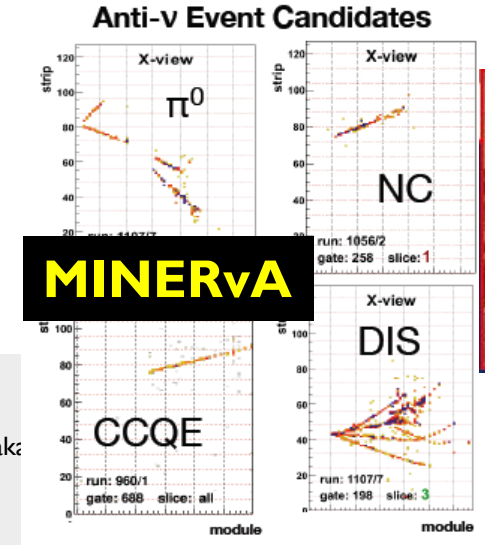

ArgoNeut
Induction Plane Wire
Collection Plane Wire


SciBooNE
SciBooNE Detector
Decay region
MiniBooNE Detector
50 m
100 m
440 m


NA61
13 m
VERTEX MAGNETS
VTX−1
VTX−2
MTPC−L
ToF−L
BEAM
TARGET
2007/9
PSD
new BPD−1,2,3
2008
VTPC−1
VTPC−2
ToF−F
2007
2009
He BEAM PIPE
GTPC
MTPC−R
ToF−R

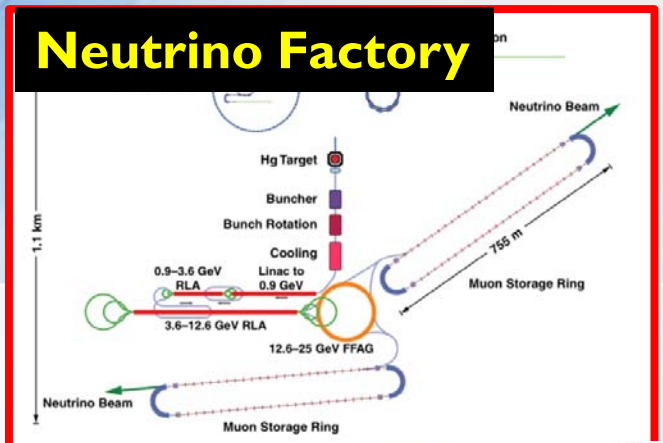

HARP


MicroBooNE

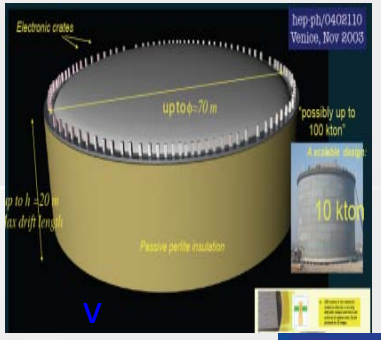

Anti-ν Event Candidates
X-view
π0
NC
run: 1056/2
gate: 258 slice: 1
MINERvA
CCQE
DIS
run: 960/1
gate: 688 slice: all
run: 1107/7
gate: 198 slice: 3
module


MICE

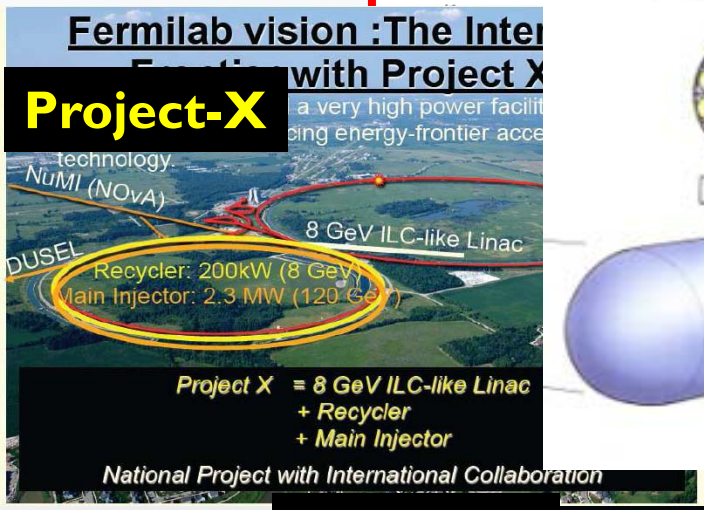
Neutrino Factory



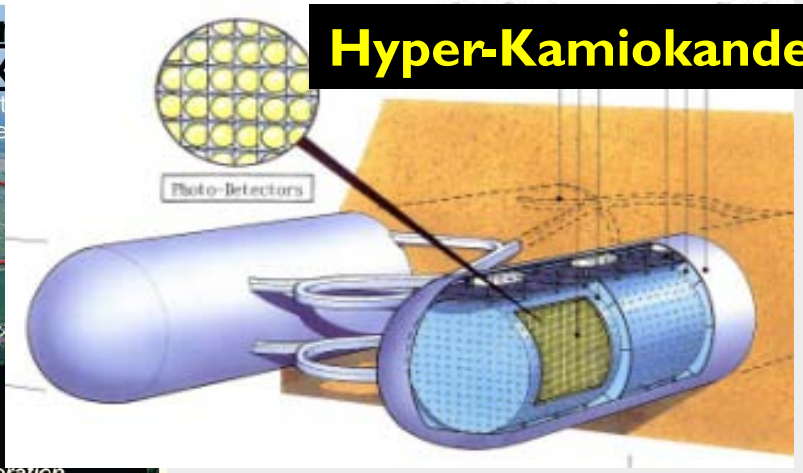
100 kton Lq.Ar.TPC



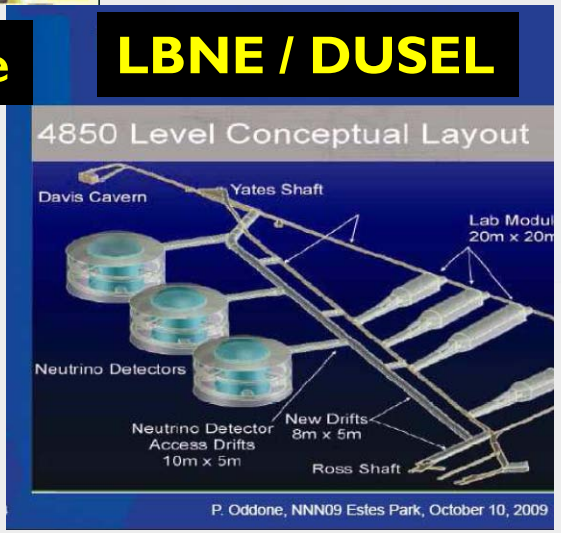
Project-X



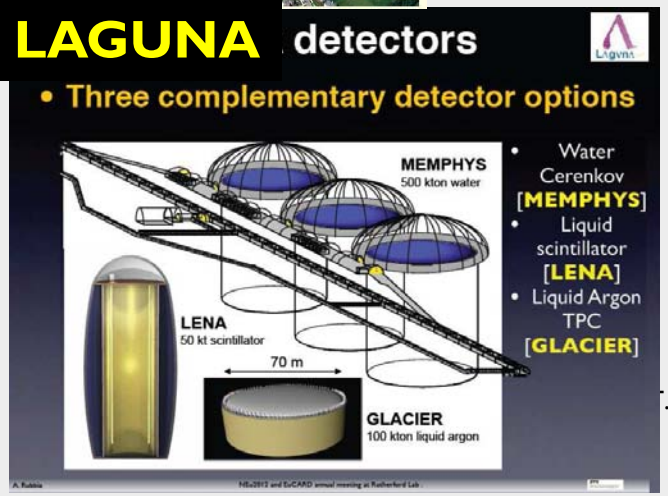
Hyper-Kamiokande



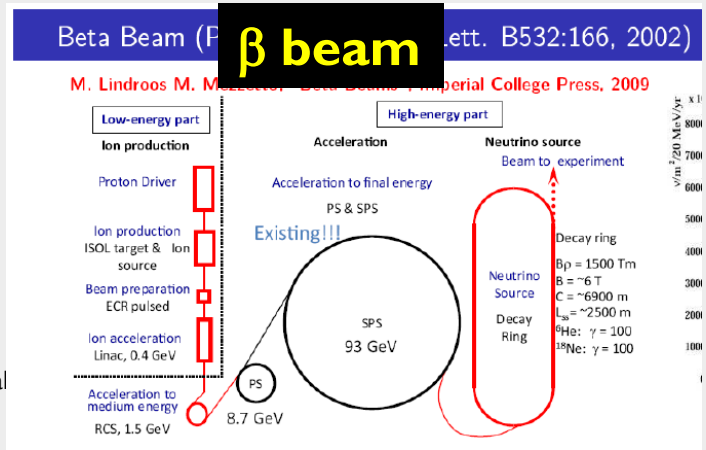
LBNE / DUSEL



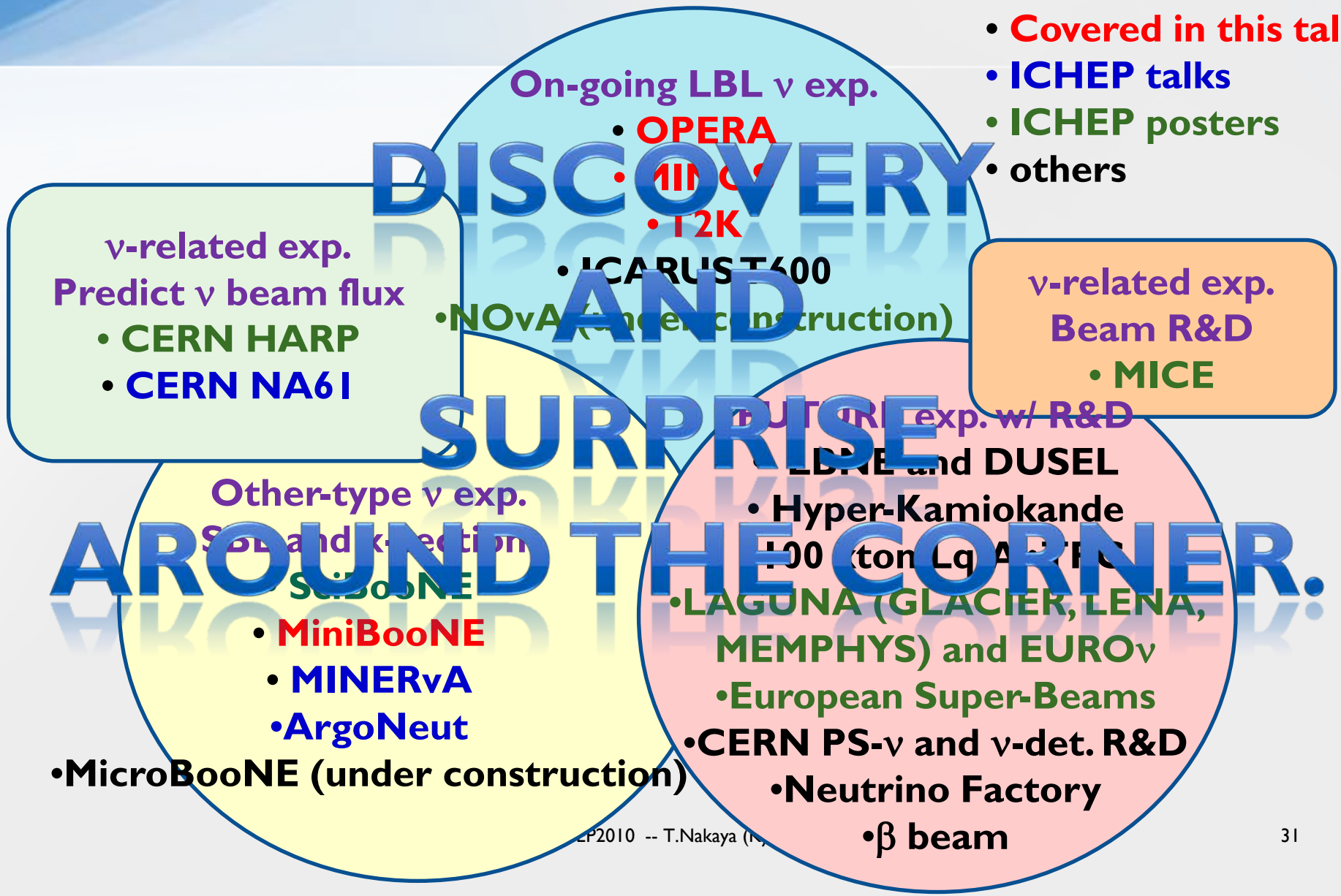
LAGUNA



β beam



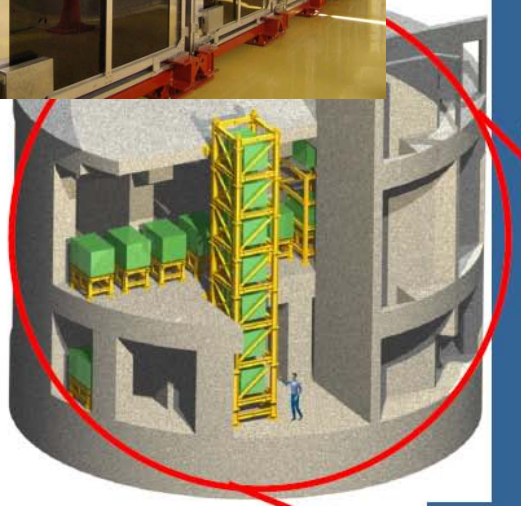
6. Future Prospects and Summary

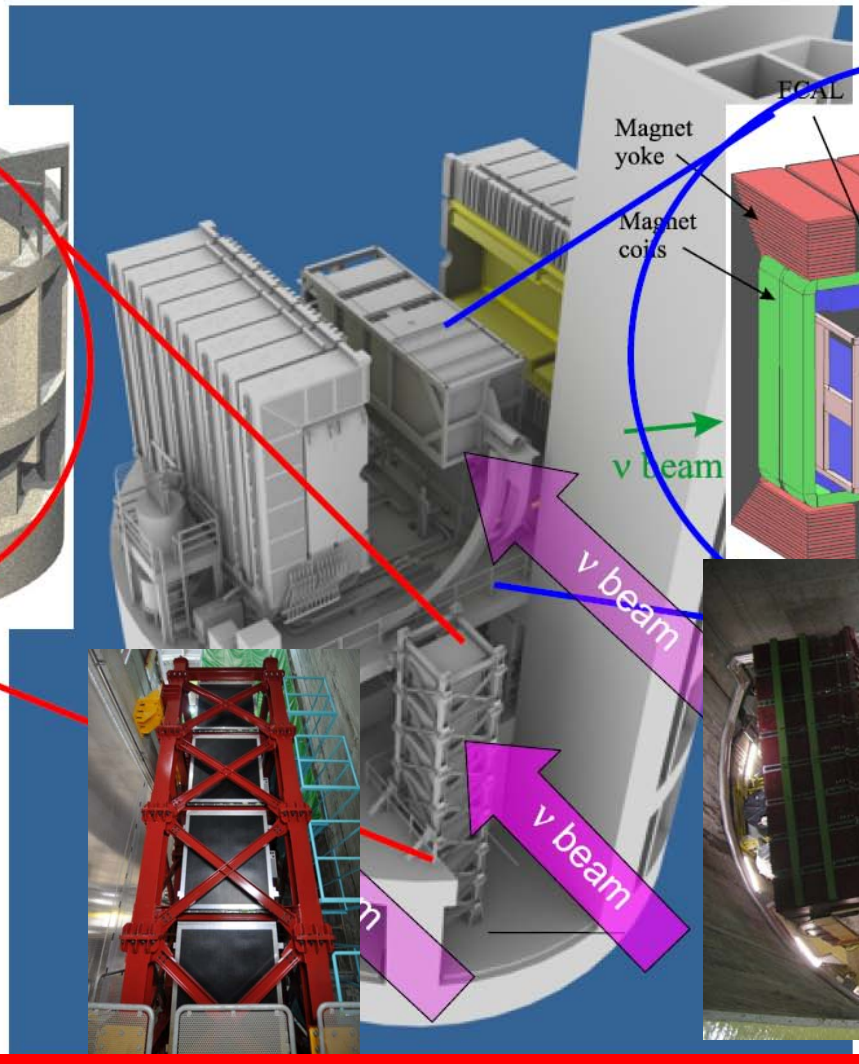


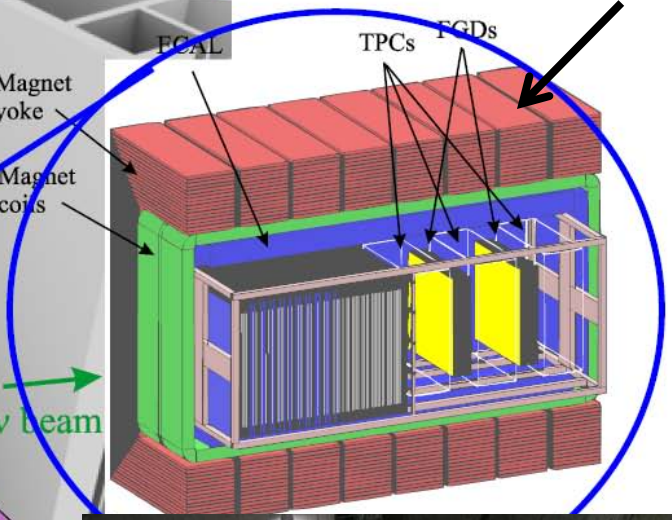
Supplement

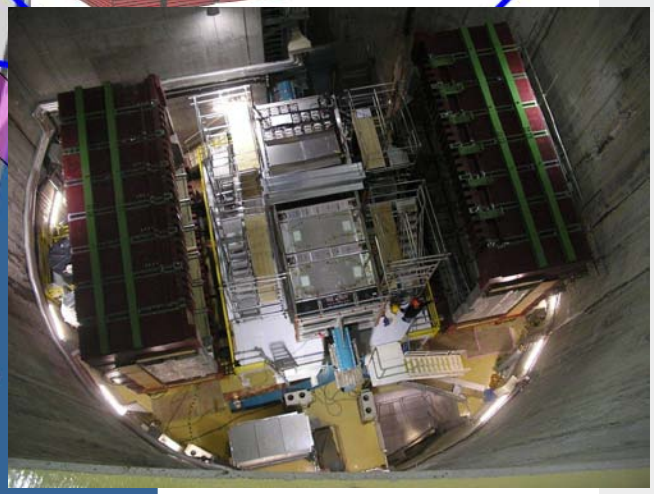
2 Near Detectors

UA1 magnet (Donated From CERN)









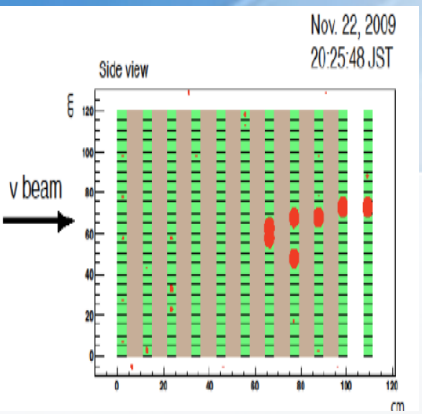
On-Axis Neutrino Monitor (INGRID)

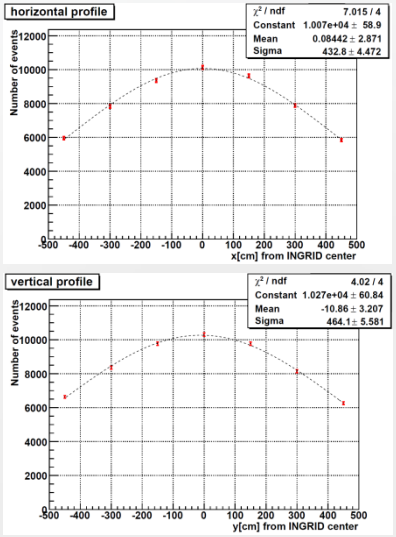
Monitor: ν beam direction

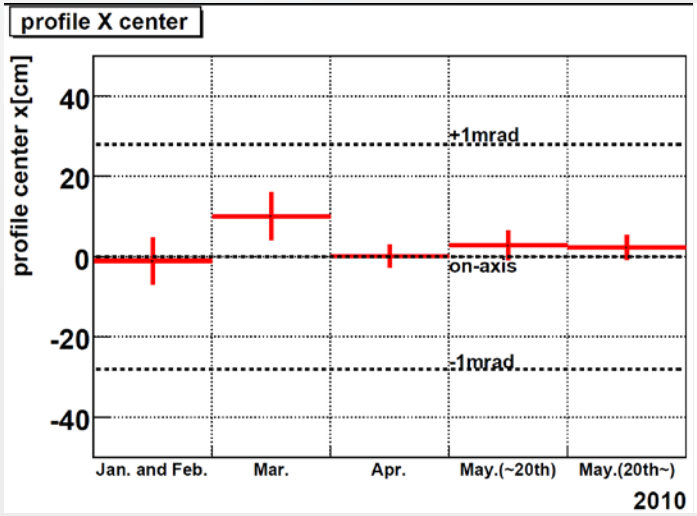
Scintillator tracker & Iron sandwich

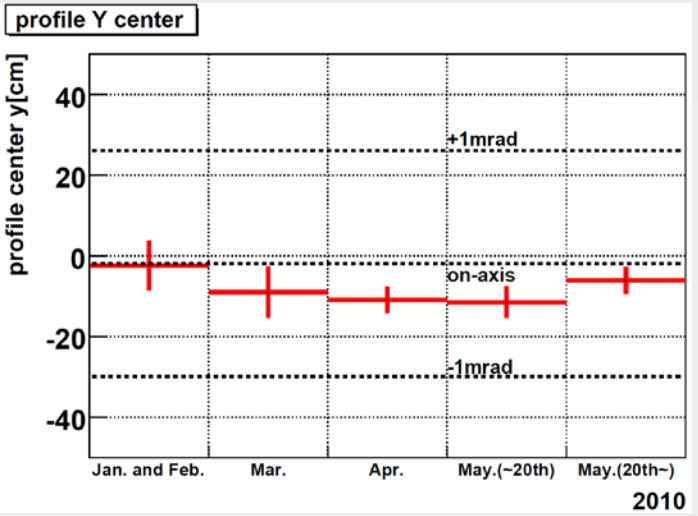
- **INGRID & off-axis completed in 2009 (Except side ECAL)**
  - **Side ECAL installation in Summer 2010**
- **Commissioning completed**

INGRID measurements



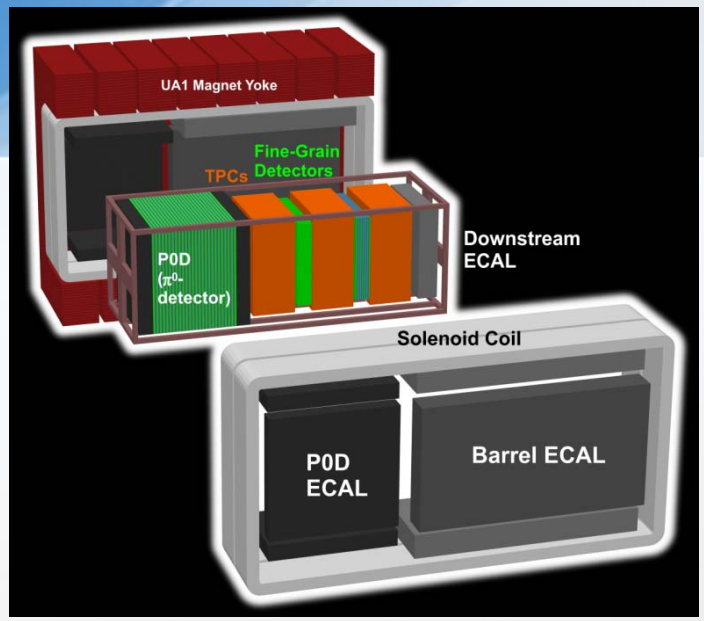






- Bunch structure clearly seen as expected
- Event rate is stable
- Beam direction well controlled within requirement (<1mrad)

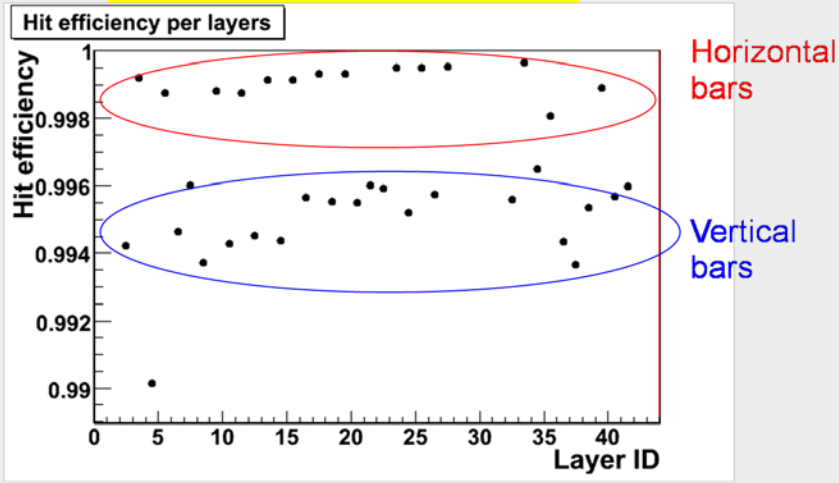
Off-axis detector performances

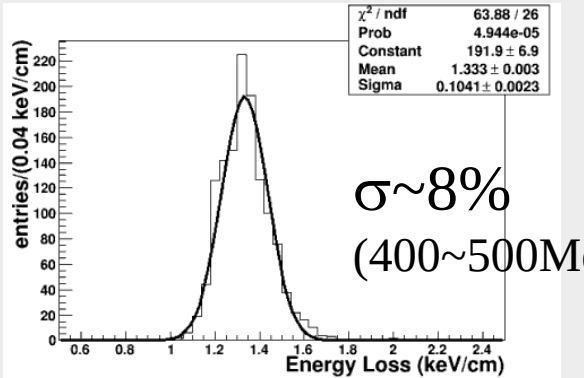


System	Channels	Bad chan.	Fraction
DSECAL	3400	11	0.3%
SMRD	4016	3	0.07%
P0D	10400	7	0.07%
INGRID	8360	8	0.1%
TPC	124416	12	0.01%
FGD	8448	32	0.4%

Very small number of bad channels

Hit Efficiencies >99%
For all layers (FGD)





σ~8%
(400~500MeV/c)

Super-Kamiokande Event Selection

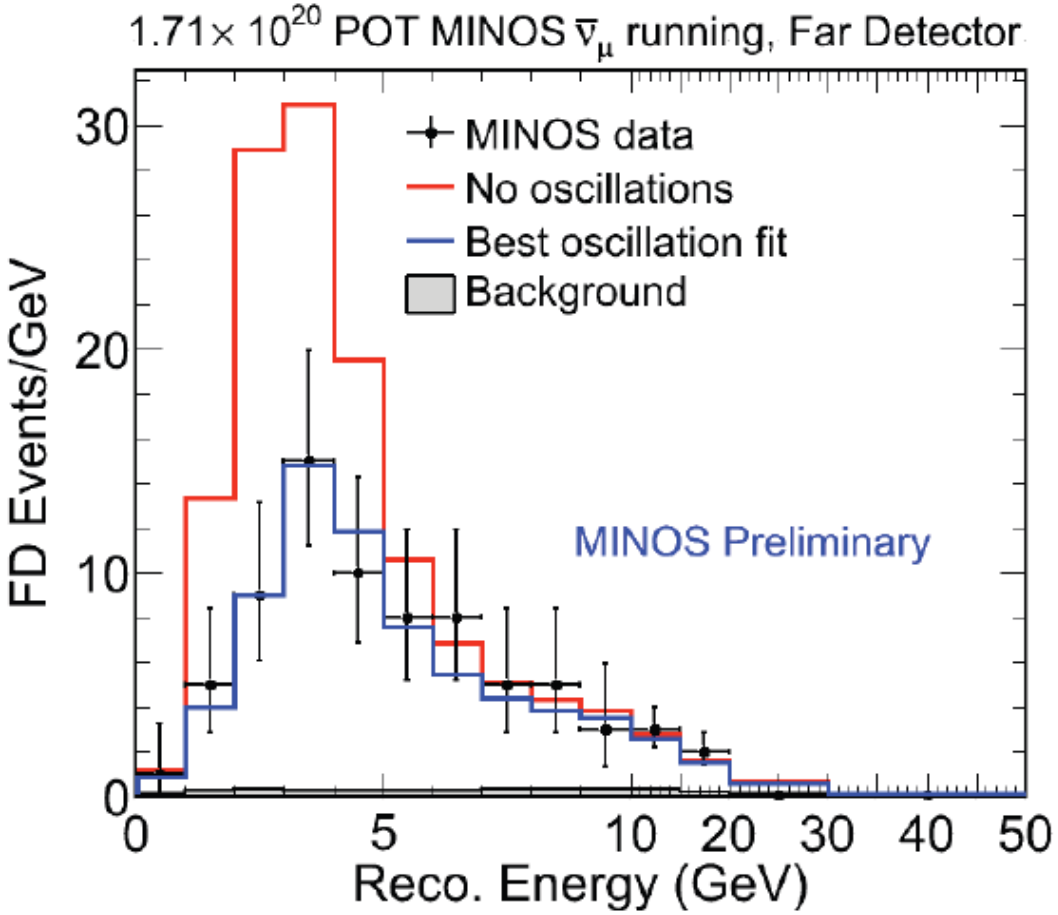
- J-PARC neutrino events selected by event timing using GPS
- SK analysis is very well established
  - >20yrs of experiences w/ Water Cherenkov detector
- Event selection & cut values are fixed already

UNBIASED SELECTON

- Selection criteria

For ν_μ disappearance analysis	**For ν_e appearance search**
Timing coincidence w/ beam timing (+TOF)	
Fully contained (No OD activity)	
Vertex in fiducial volume (Vertex >2m from wall)	
Evis > 30MeV	Evis > 100MeV
# of ring =1	
μ-like ring	e-like ring
	No decay electron
	Inv. mass w/ forced-found 2nd ring < 105MeV
	E_ν^{rec} < 1250MeV

FD Data



- No oscillation Prediction: **155**
- Observe: **97**
- No oscillations disfavored at 6.3σ

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$