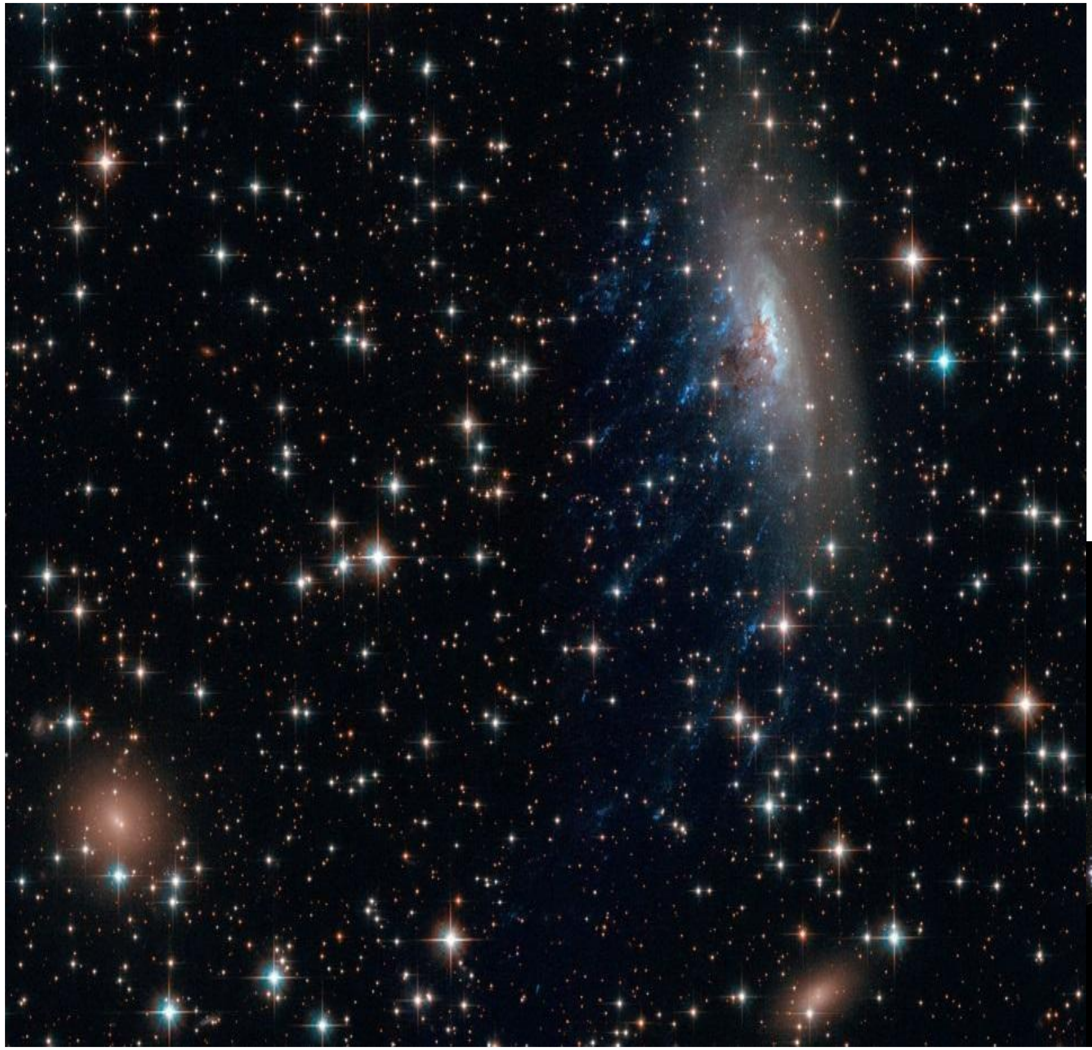
Institute for High Energy Physics
EXCELENCIA SEVERO OCHOA
Barcelona Institute of Science and Technology

Constraint on CP Violation in Neutrino Oscillations

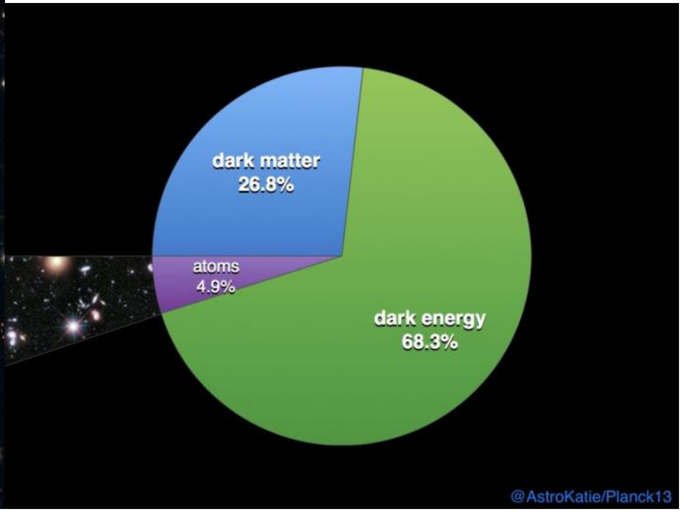
Thorsten Lux

The Universe

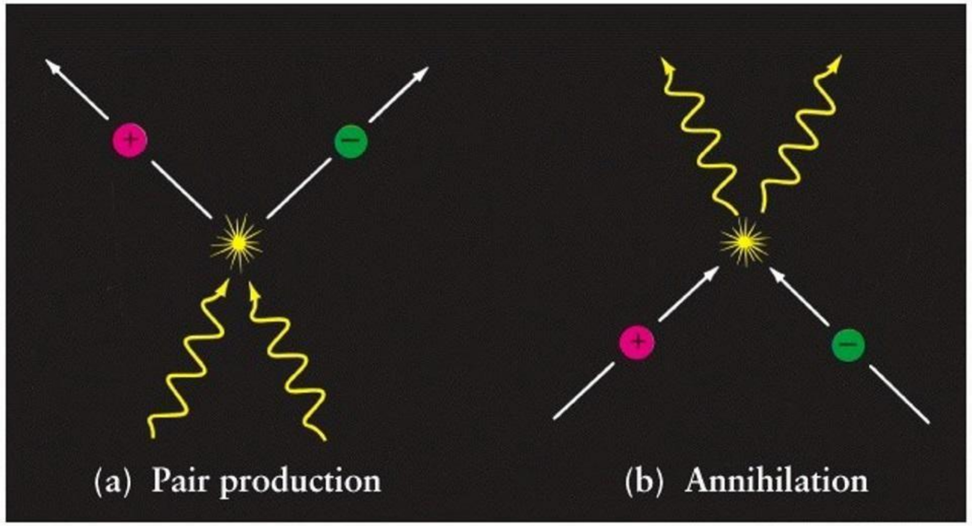


- Visible matter is only 5% of the Universe
- 25% is Dark Matter showing gravitational effects
- Rest is Dark Energy

Important question is not why matter is only 5% but why is there matter at all?



Why is there Matter at all?



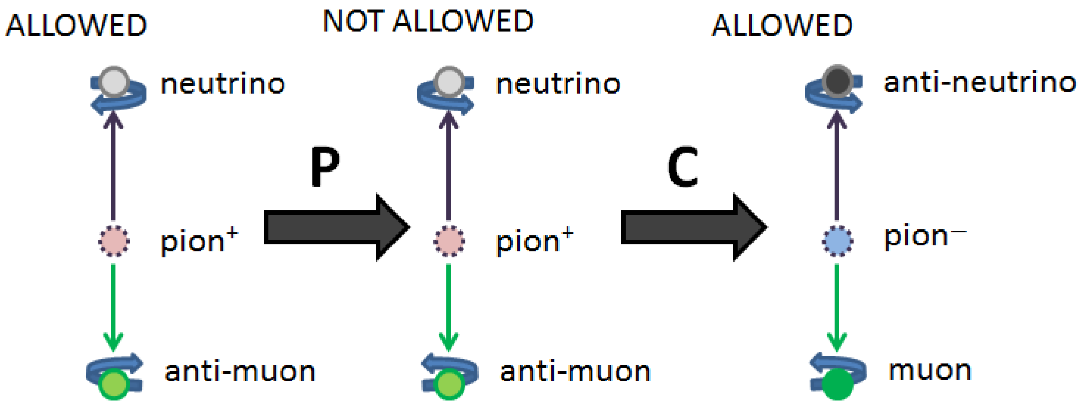
- Particles/anti-particles are always produced in pairs
- Particles/anti-particles are destroyed in pairs in annihalition

=> There should be no matter excess

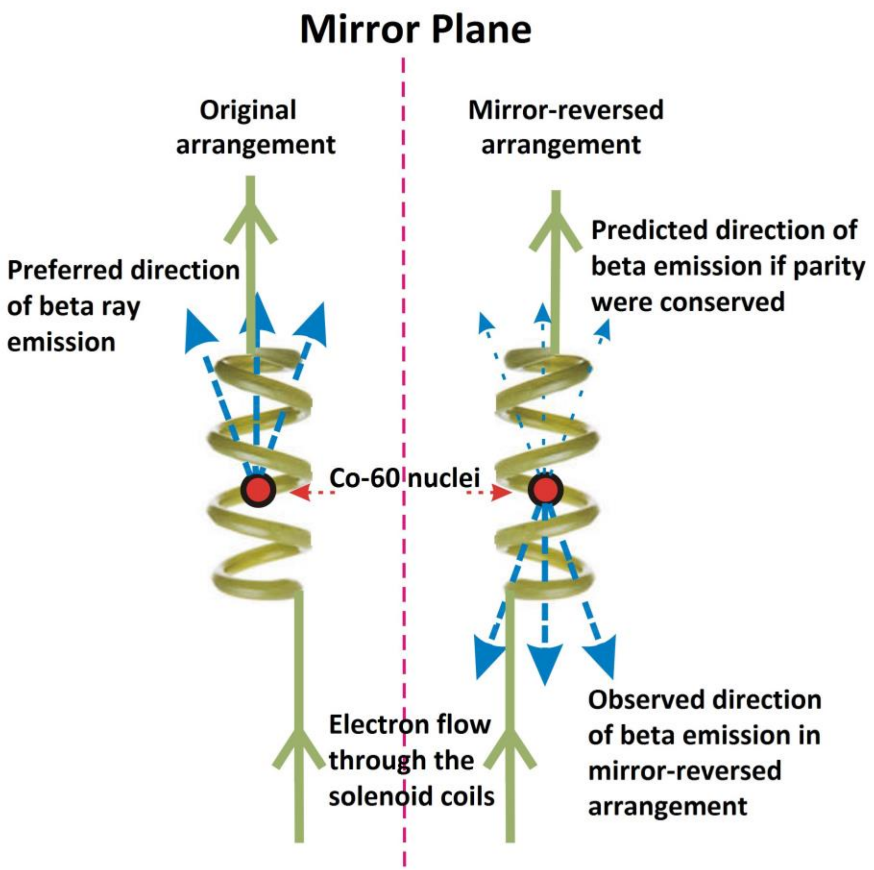
- Some anti-particles must have decayed before annihilation
- Tiny effect: only 1 of 6 billion particles survived
- What are the conditions to achieve this?

CP Symmetry/Violation

- Wu showed that Parity (mirroring) is not conserved in weak force (1956)
- Assumption was at least CP (Charge conjunction + Parity) is conserved
- Turned out that this is not true …



M. Strassler 2013



Sakharov Conditions

Andrei Sakharov defined 3 conditions which need to be fulfilled (1967):

1. Baryon number violation
2. System must go out of thermal equilibrium
3. C and CP violation

Sakharov Conditions

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1. Baryon number violation
2. System must go out of thermal equilibrium
3. **C and CP violation**

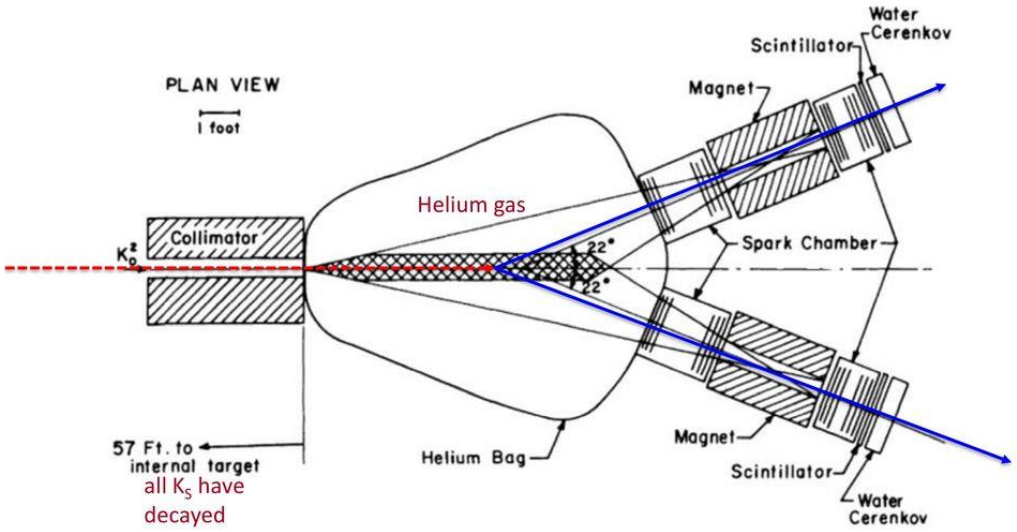
CP Violation in the Quark Sector

- Kaons are produced by the strong force and decay by the weak force
- 2 CP Eigenstates with different lifetimes and decay channels:
  - K_S -> 2π (CP = +1, $\tau \approx 0.9\ 10^{-10}$ s)
  - K_L -> 3π (CP = -1, $\tau \approx 0.5\ 10^{-7}$ s)
- Fitch-Cronin first test of CP violation (4 page proposal)
- Archieve pure K_L by producing K^0 beam in strong interaction and let K_S decay
- If CP is conserved one should only observe 3 π in final state
- In 0.2% of the case 2π were found

Conclusion:

CP is violated but effect too small to explain matter excess

The Fitch-Cronin experiment



Rev. Mod. Phys., Vol. 53, No. 3, July 1981

What else could cause the Asymmetry?

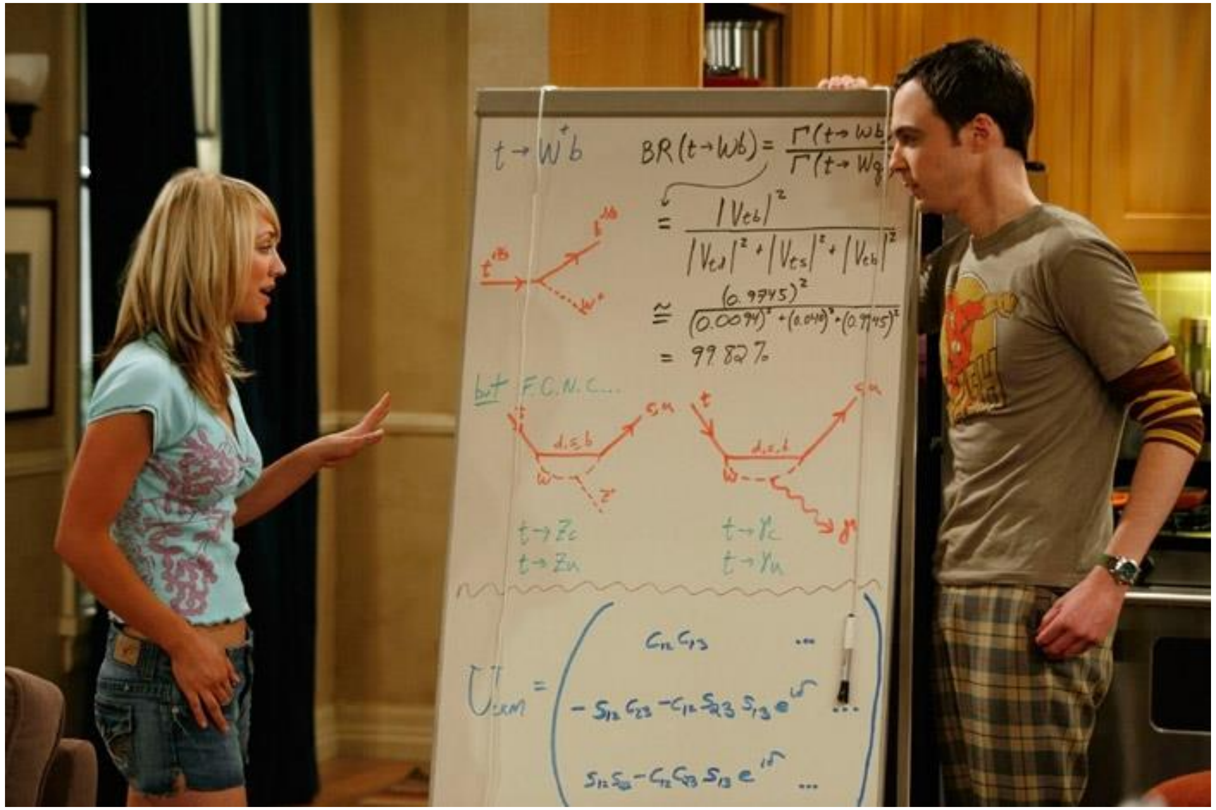
Theorist have many theories:

- GUT baryogenesis
- Leptogenesis
- Electroweak baryogenesis
- The Affleck-Dine mechanism
- More exotic ideas ….

<u>Interesting Alternatives</u>

Baryogenesis from
- → Cosmic Strings
- → Magnetic Fields
- → Black Holes

Dissipative Baryogenesis
Warm Baryogenesis
Cloistered Baryogenesis
Cold Baryogenesis
Planck Baryogenesis
Post-Sphaleron Baryogenesis
WIMPy Baryogenesis
Dirac Leptogenesis
Non-Local Electroweak Baryogenesis
Magnetic-Assisted EW Baryogenesis
Singlet-Assisted EW Baryogenesis



What else could cause the Asymmetry?

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- GUT baryogenesis
- **Leptogenesis**
- Electroweak baryogenesis
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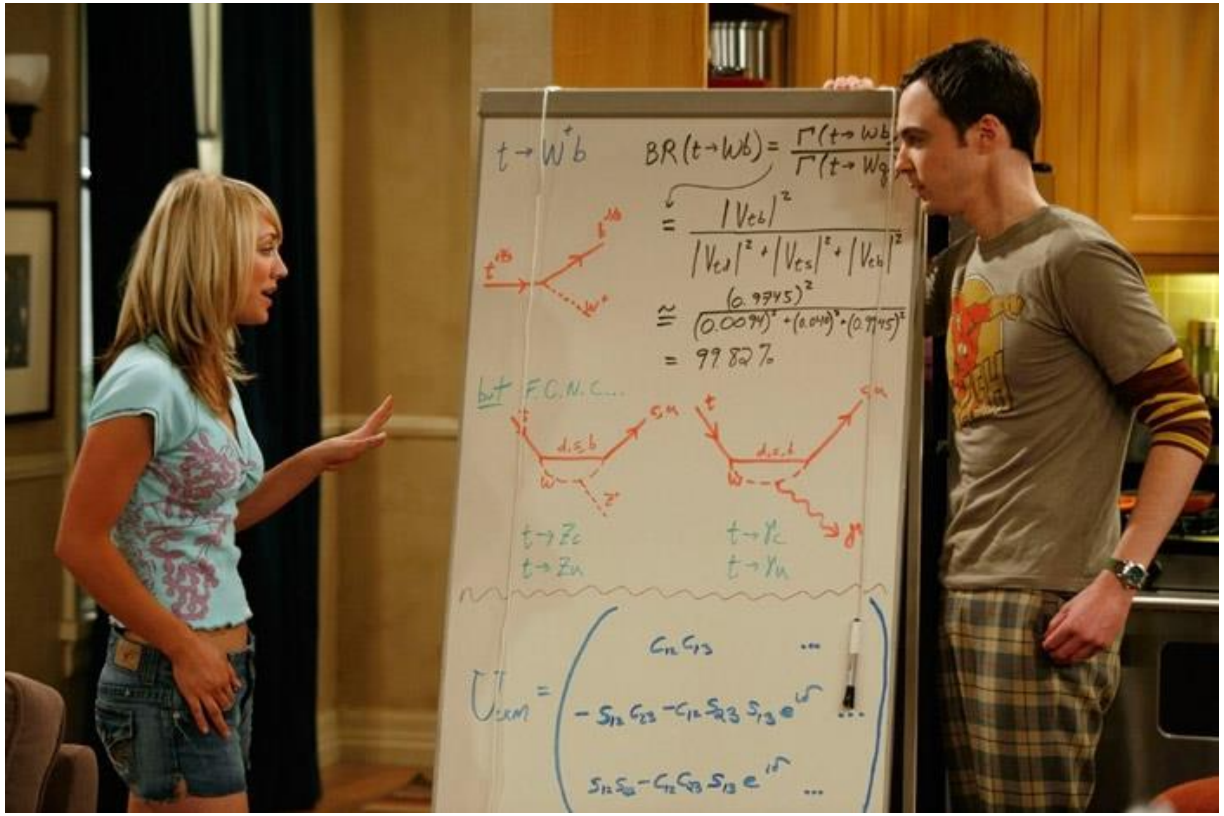
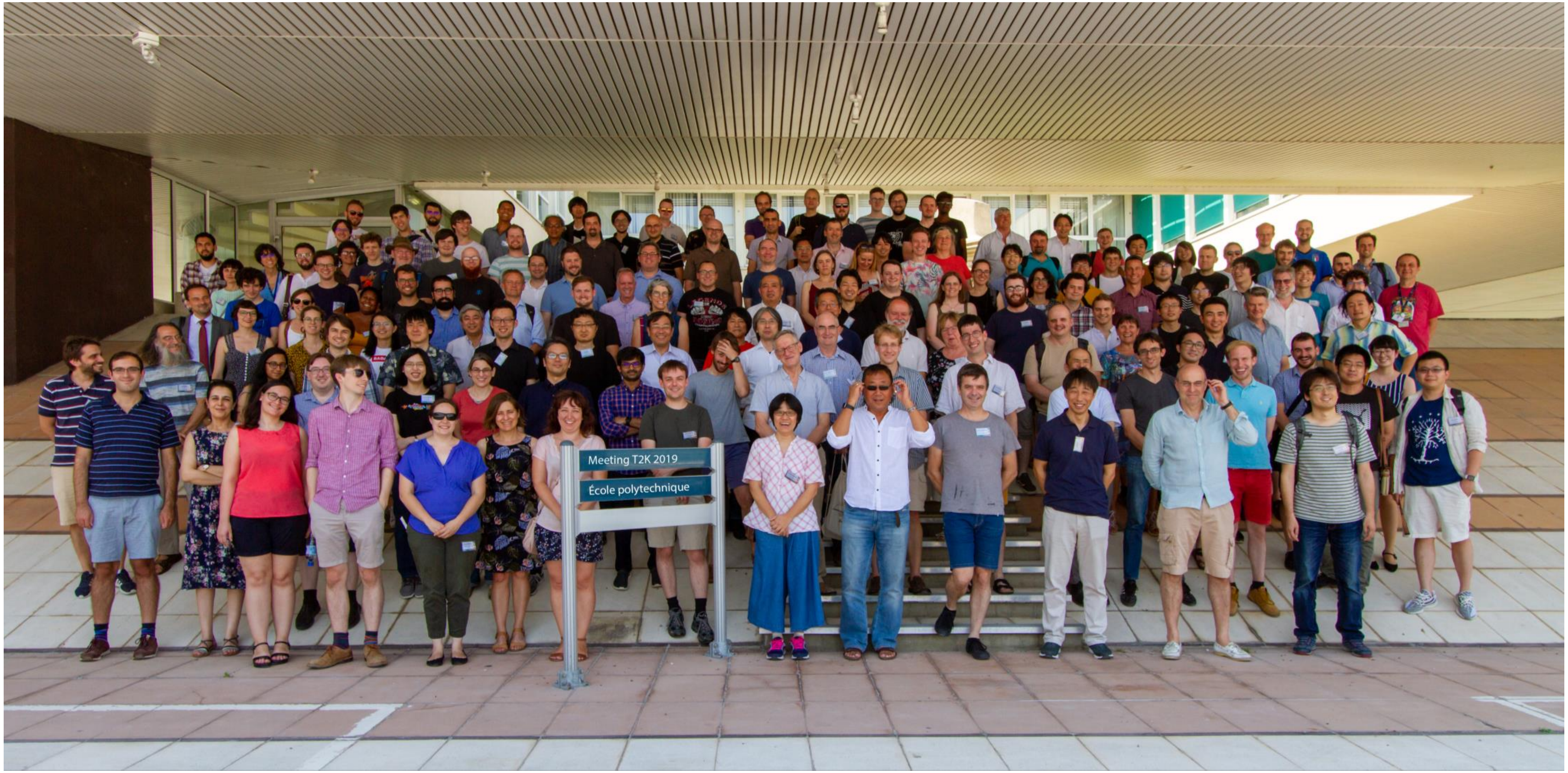
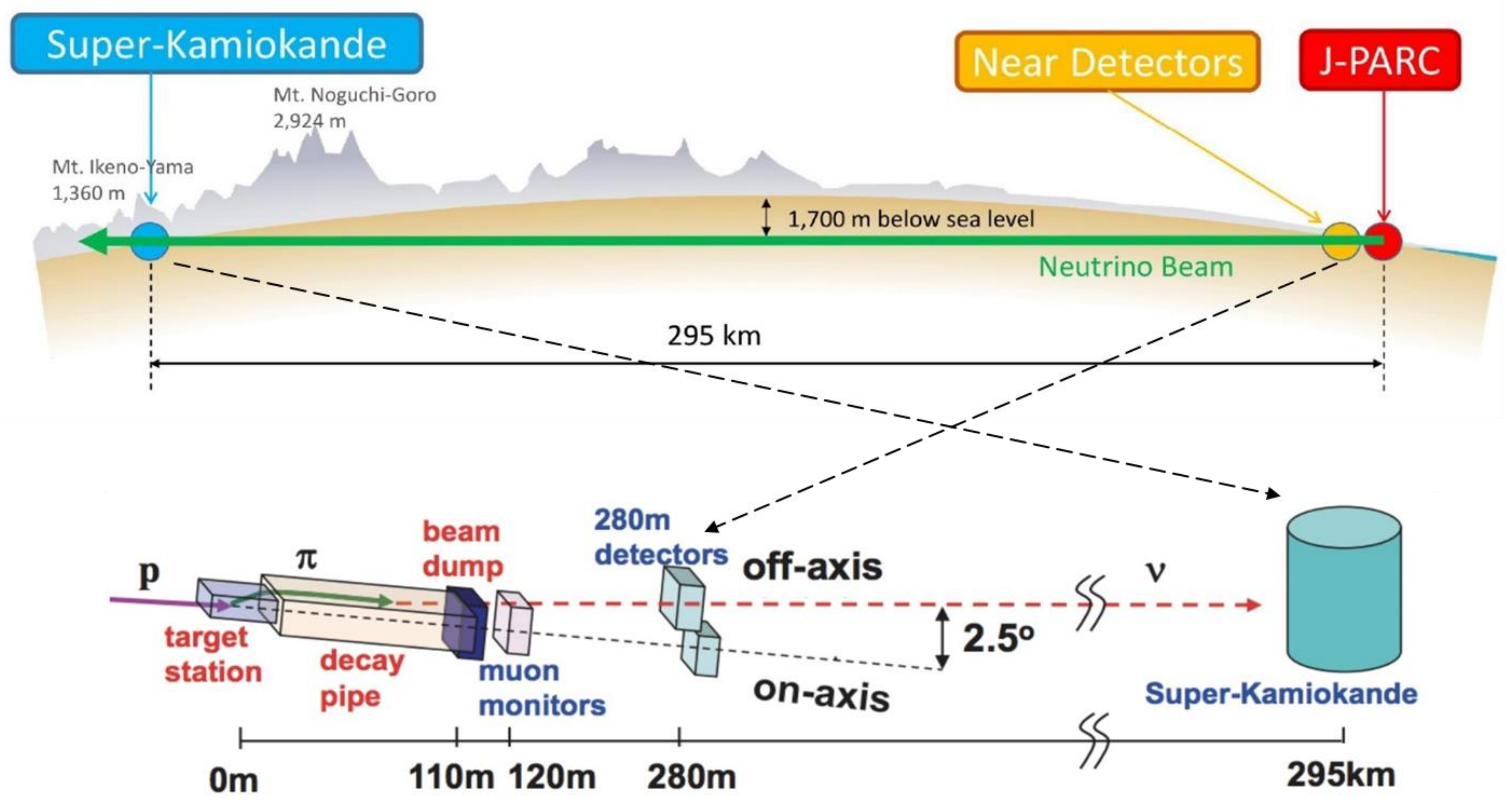


Is there a CP violation in the leptonic sector?

T2K Collaboration



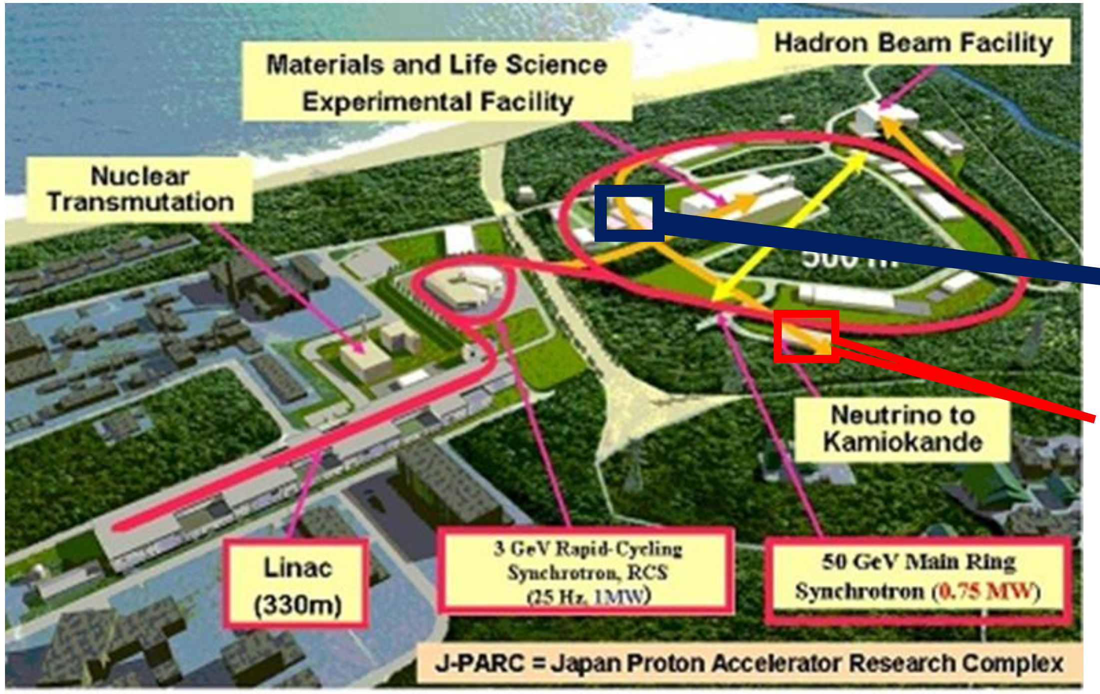
Tokai-to-Kamiokande (T2K)



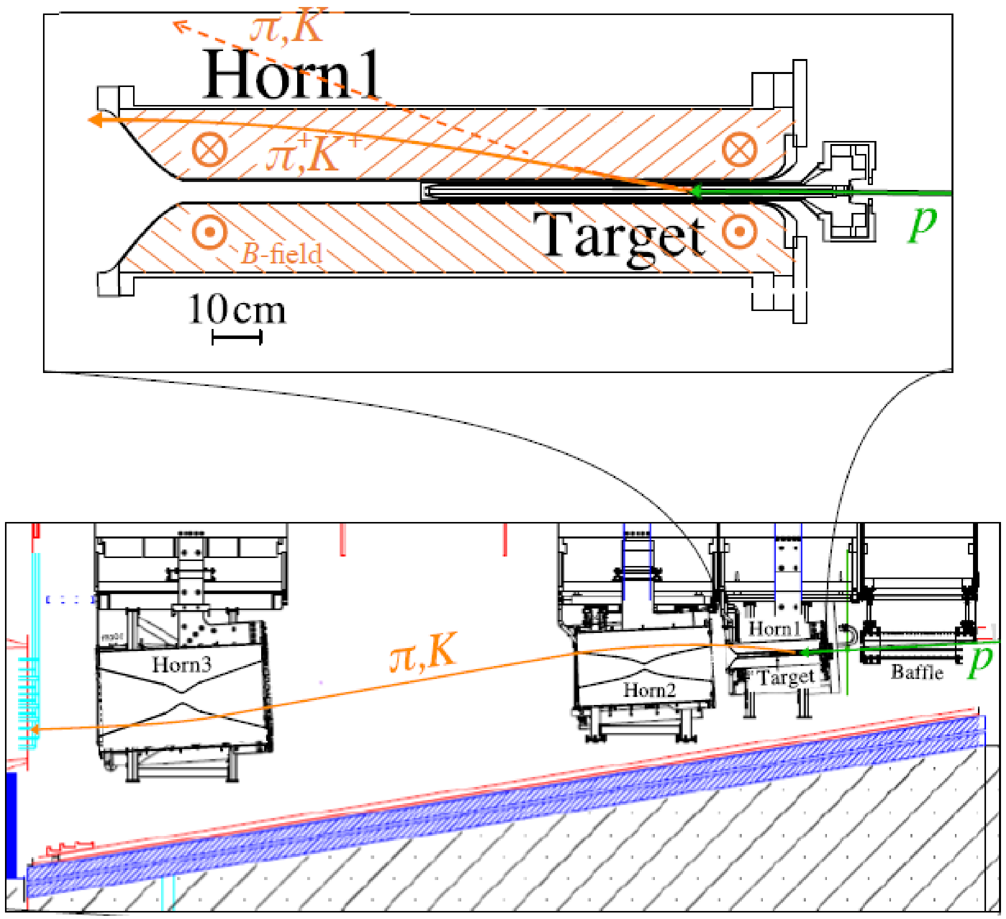
- Neutrino beam produced in Tokai
- Measured with near detector on site
- And with far detector 295 km away

Neutrino Beam

- 30 GeV proton beam collides with graphite target
- Magnetic horn system allows to select either π^-/K^- or π^+/K^+
- 100 m long decay tunnel to produce ν or $\bar{\nu}$



Near detector complex



Beam composition

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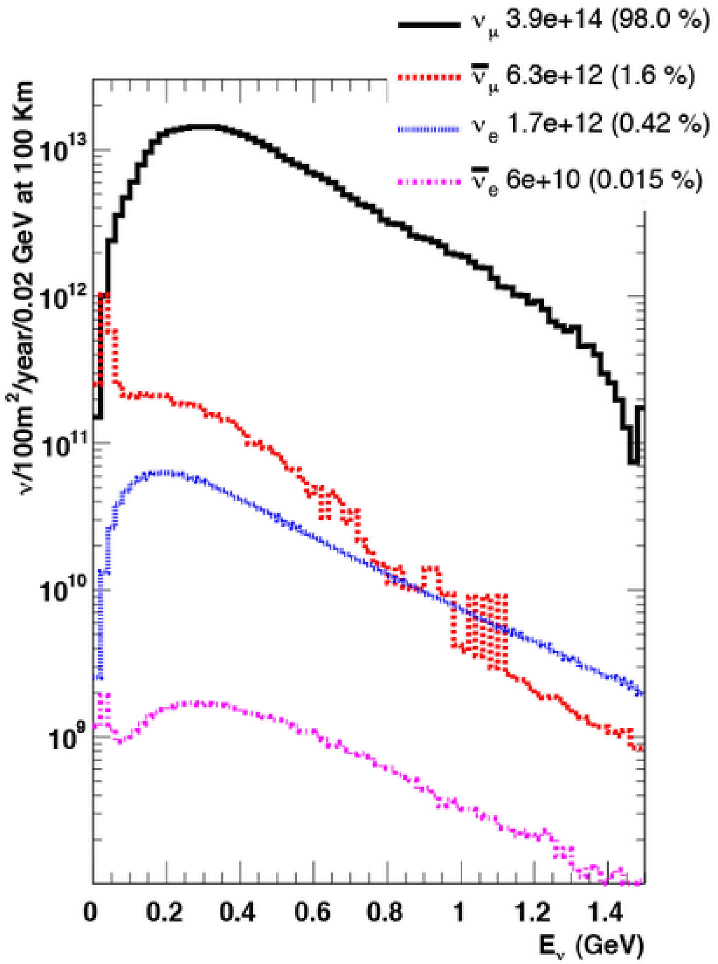
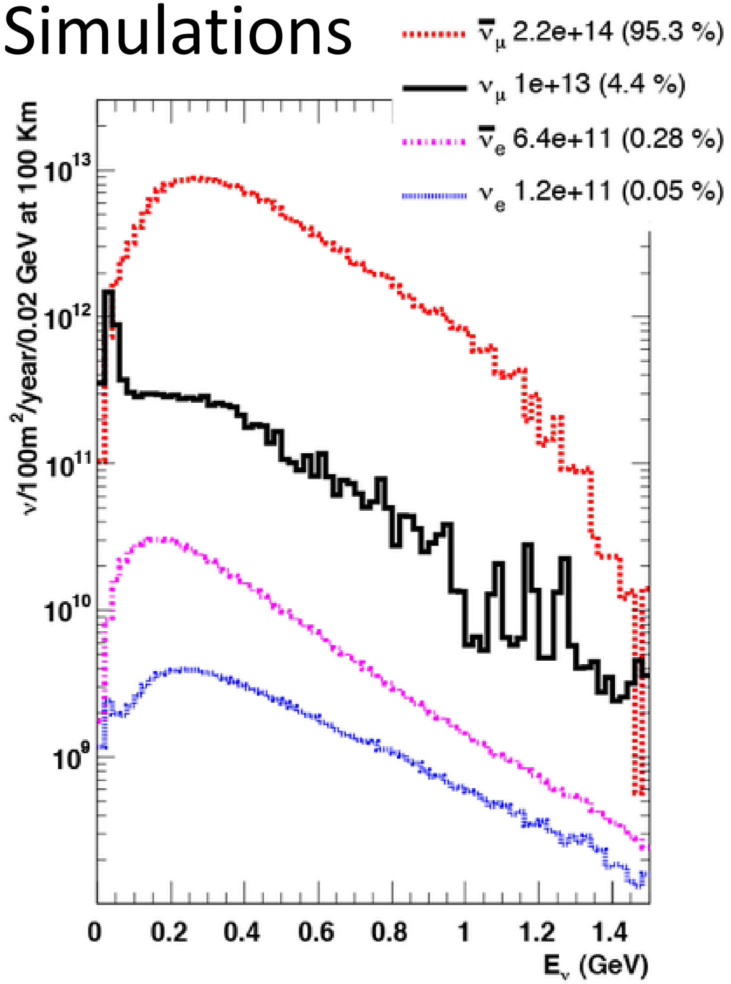
- Ideally one would like to have pure (anti-)neutrino beam
- But unfortunately in reality background present

Simulations

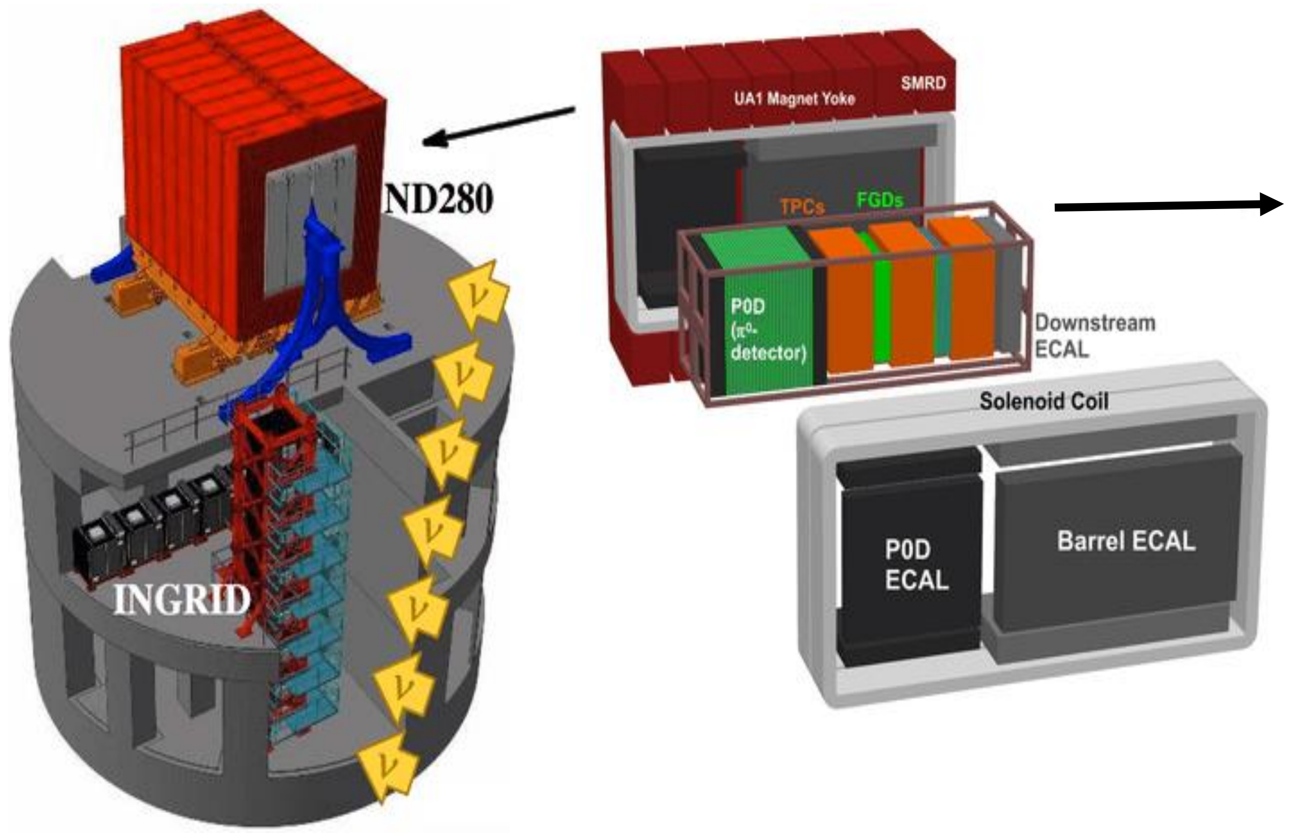


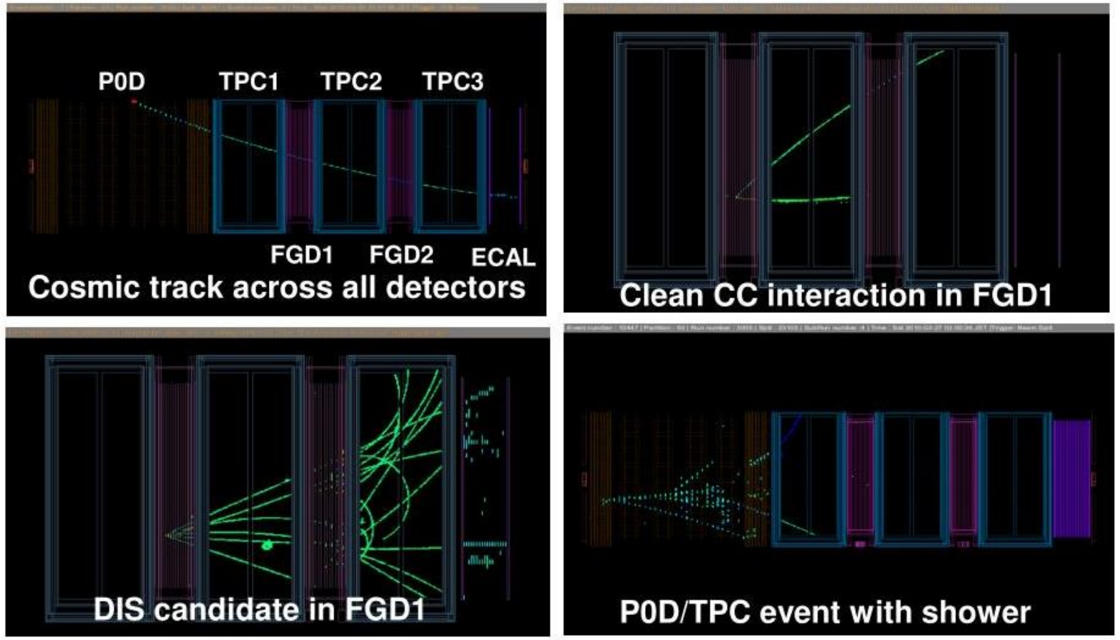
Neutrino mode



Anti-neutrino mode

Near Detectors: INGRID + ND280

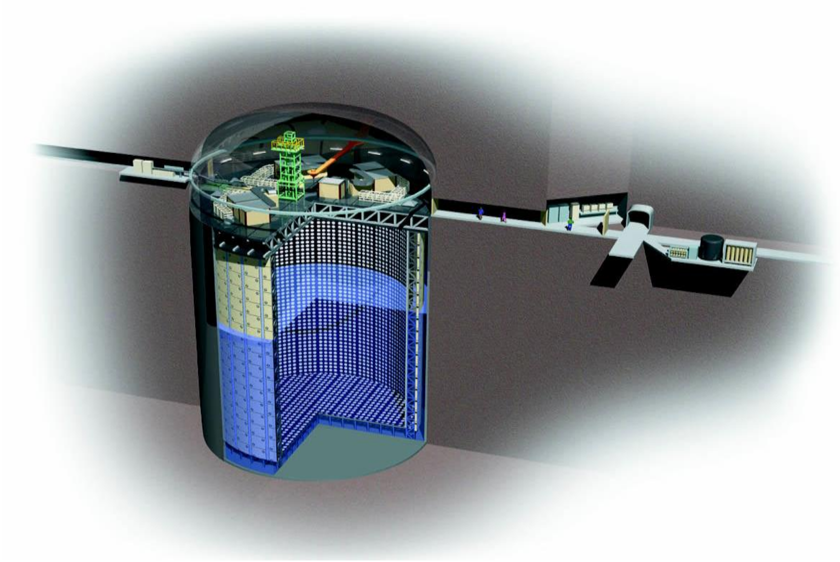


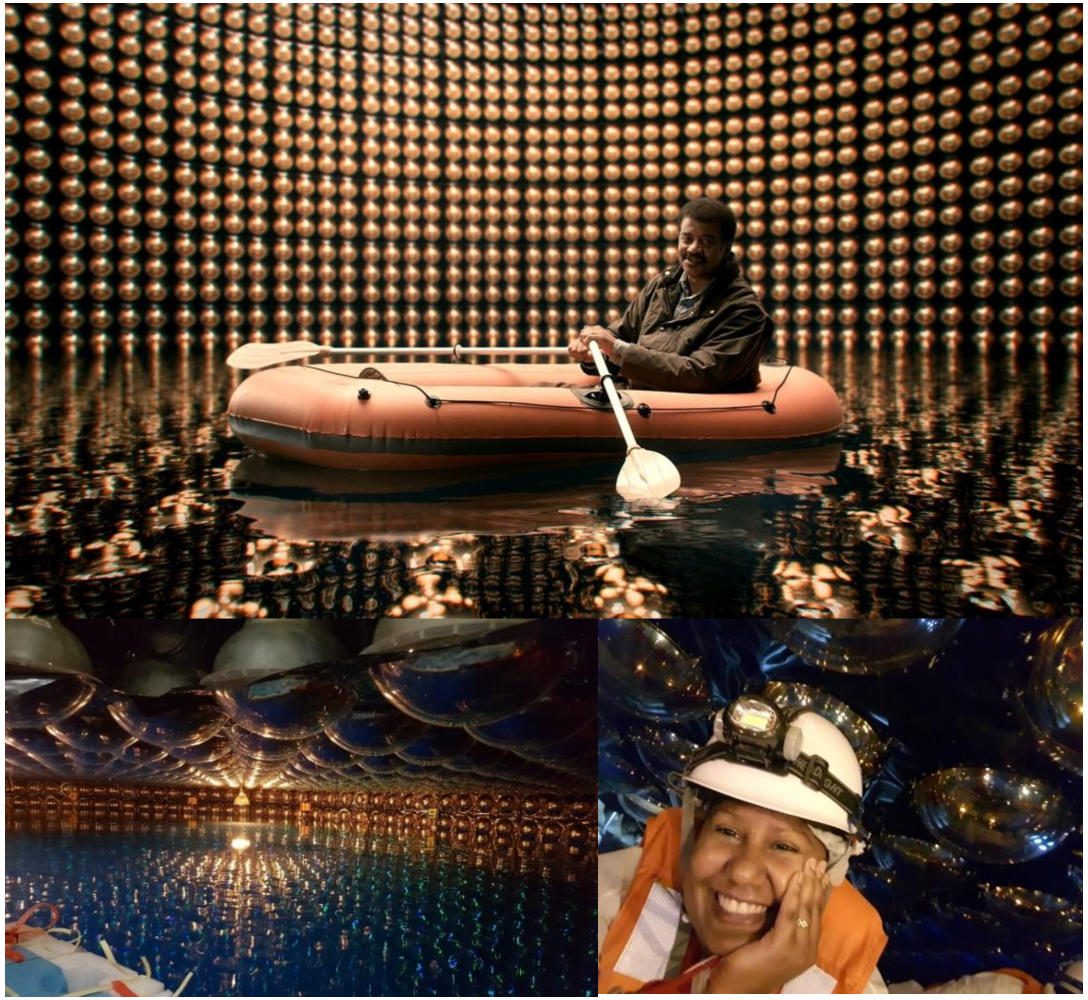


- INGRID: non-magnetized on-axis detector => direction and rate
- ND280: magnetized off-axis detector => flux/composition, cross sections

Far Detector: Super-Kamiokande

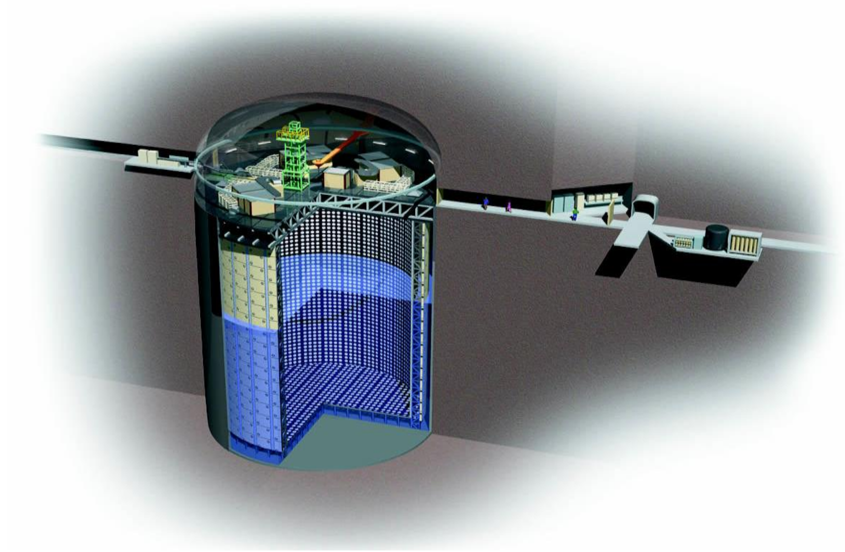
- 50 kt water Cherenkov detecot
- 22.5 kt fiducial mass
- 40 m diameter and ~ 50 m height
- 11200 PMTs
- Operational desde el 31 de Mayo del 1996

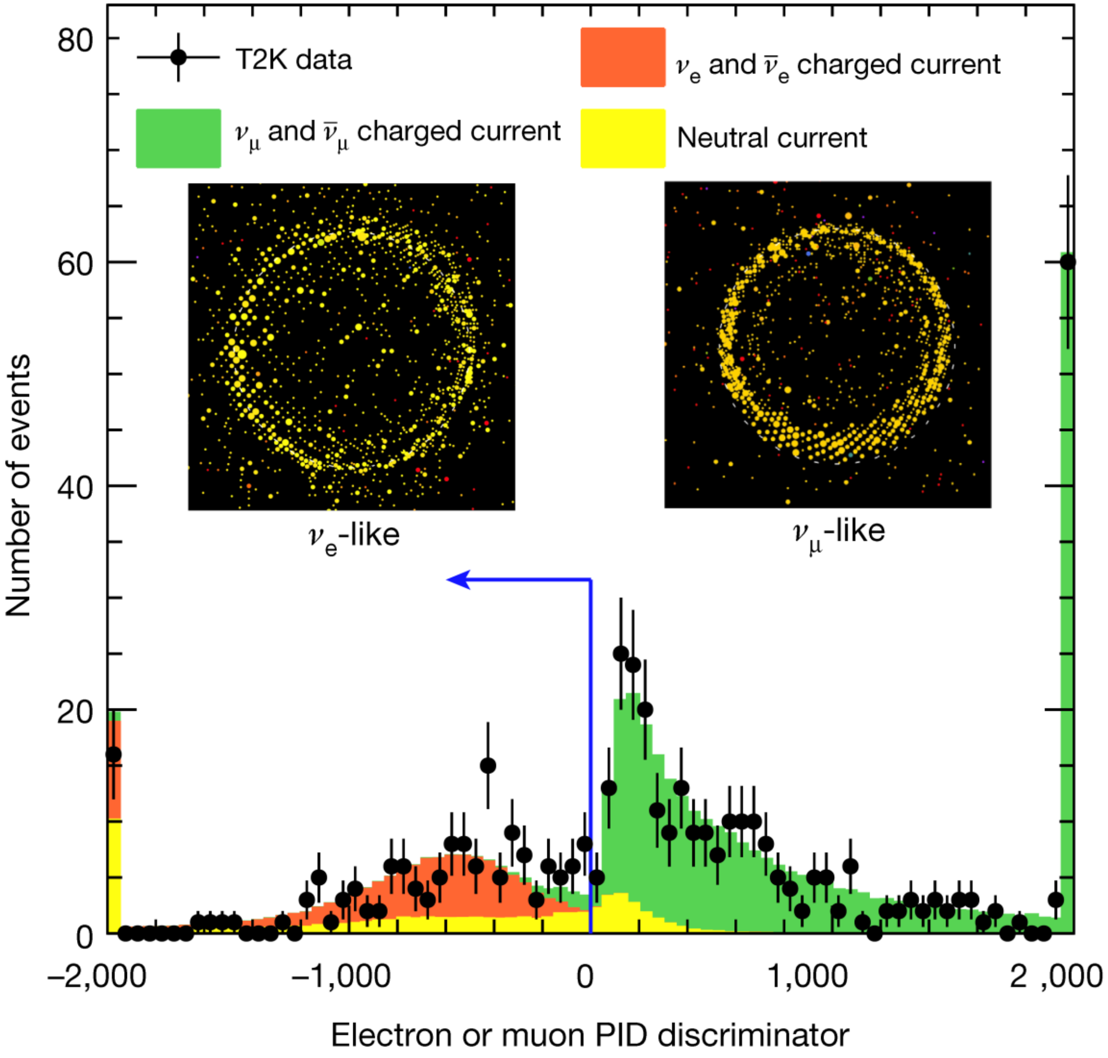




Far Detector: Super-Kamiokande

- Shape of Cherenkov ring depends strongly on particle type
- Excellent electron/muon seperation
- But not charge sensitive
- Threshold: some particles might be undetected





Neutrino Oscillation: 2ν case

Why this near and far detector configuration?

Flavor, $\nu_{e,\mu}$, and mass, $\nu_{1,2}$, Eigenstates are not identical but connected via a mixing angle, Θ:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Starting with pure ν_μ beam we might detect after distance, L, ν_e in the beam

Probability:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m_{12}^2 L}{4E_\nu}\right)$$

$m_1^2 - m_2^2$

Neutrino energy

Neutrino Oscillation: 2ν case

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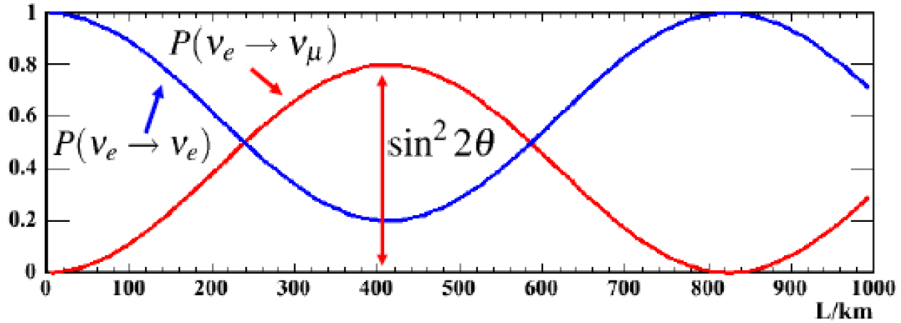
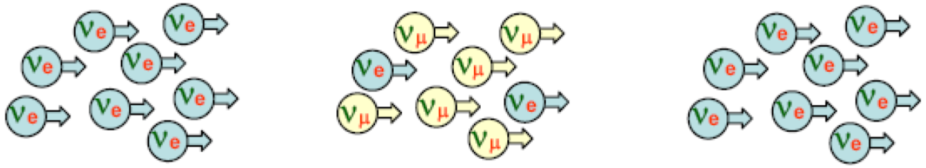
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m_{12}^2 L}{4E_\nu}\right)$$

•e.g. $\Delta m^2 = 0.003\,\mathrm{eV}^2, \quad \sin^2 2\theta = 0.8, \quad E_\nu = 1\,\mathrm{GeV}$





What would CP Violation imply?

$$P(\vartheta_\mu^L \to \vartheta_e^L) \neq P(\overline{\vartheta_\mu^R} \to \overline{\vartheta_e^R})$$

=> Measure oscillations with neutrinos and anti-neutrinos

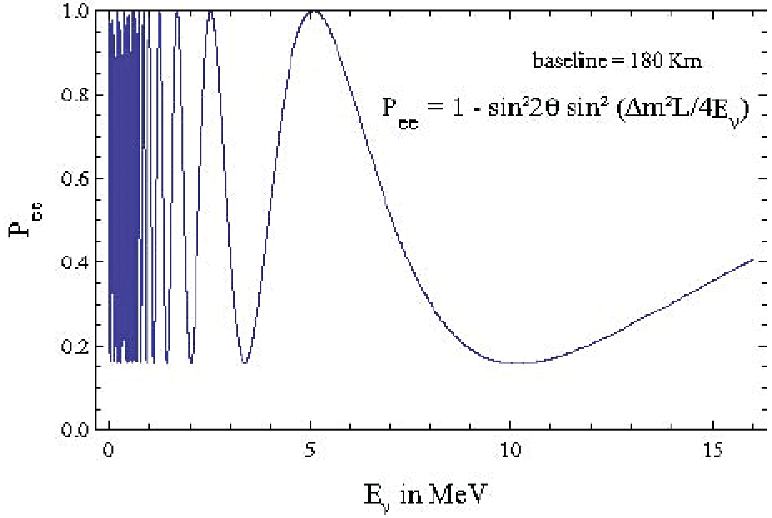


Fig. 1: An illustration [4] of neutrino oscillation of two flavors with baseline L=180Km.

More complicated: 3ν

- In reality we have 3 neutrino families
- Mixing is described by PMNS matrix, U (3 mixing angles, 1 CP violating phase)

Flavour Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass Eigenstates

Pontecorvo-Maki-Nakagawa-Sakata

$\theta_{23} \sim 45°$ $\theta_{13} \sim 9°$ $\theta_{12} \sim 30°$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \; ; \; c_{ij} = \cos\theta_{ij}$$

Atmospheric **Reactor/accelerator** **Solar**

More complications: Matter Effects

- Even without CP violation:

$$P\left(\vartheta_\mu^L \rightarrow \vartheta_e^L\right) \neq P\left(\overline{\vartheta_\mu^R} \rightarrow \overline{\vartheta_e^R}\right)$$

- Neutrinos cross the Earth and there are only electrons but no positrons!
- Corresponds to additional potential V:

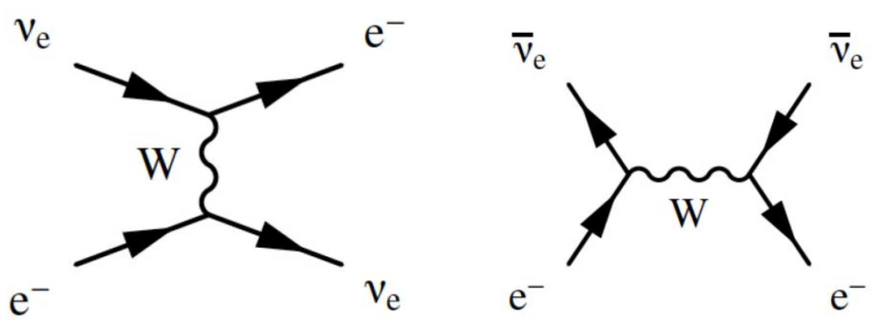
$$V = \pm\sqrt{2} G_F n_e$$

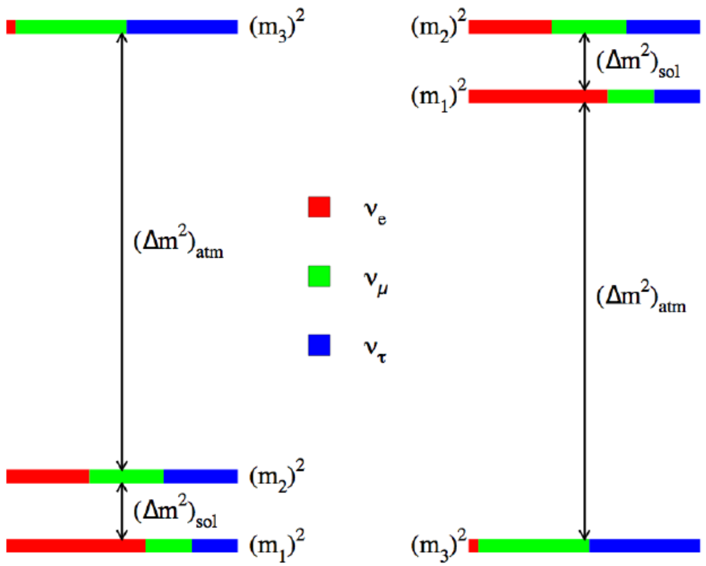
GF: Fermi const., ne: electron number, sign depends on neutrinos or anti-neutrinos

- Depends on mass hierarchy in addition: normal preferred at 3σ level by SK atmospheric neutrinos

How to disentagle matter from CP violation effects?

Weak forward scattering

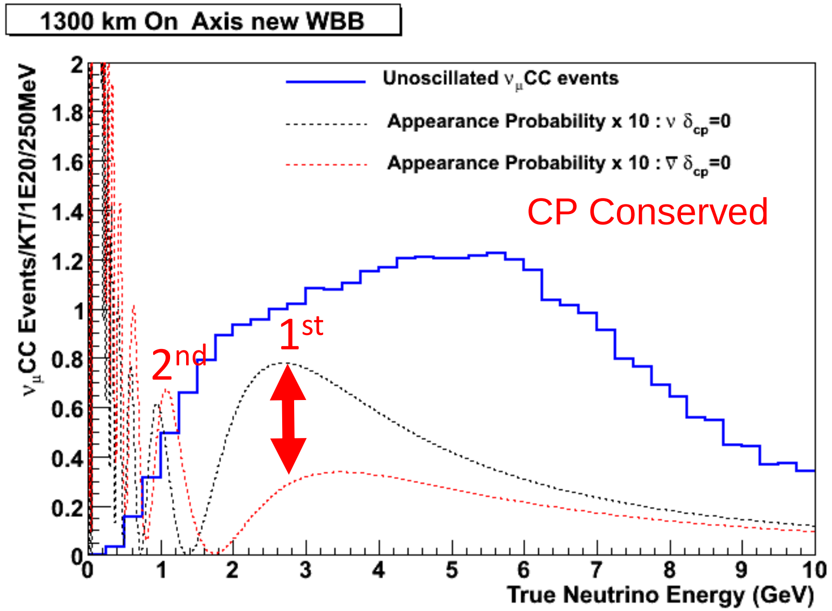


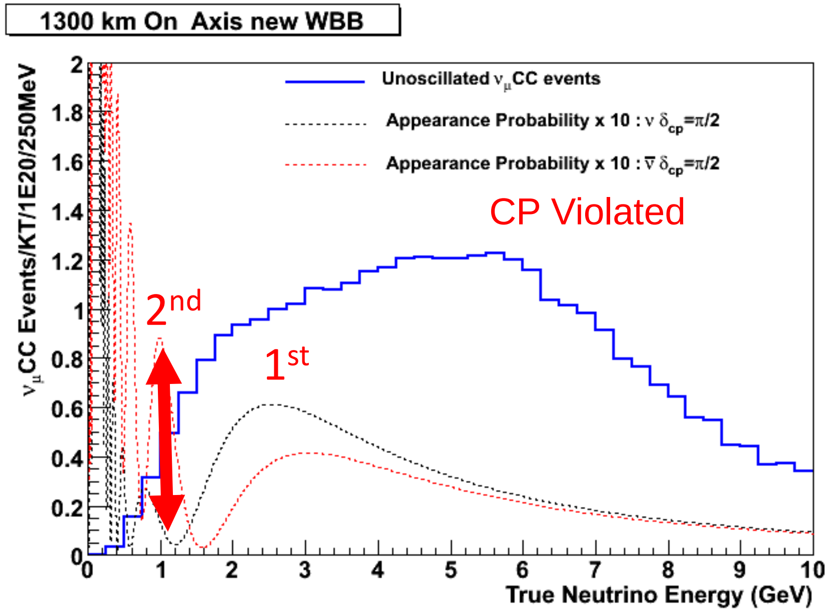


2 Approaches: Longer Long Baseline

L > 1000 km

- Use wideband neutrino energy beam => on-axis
- Use high energy (E_ν>2 GeV) 1st maximum for mass hierarchy
- Use low energy 2nd maximum for CP violation

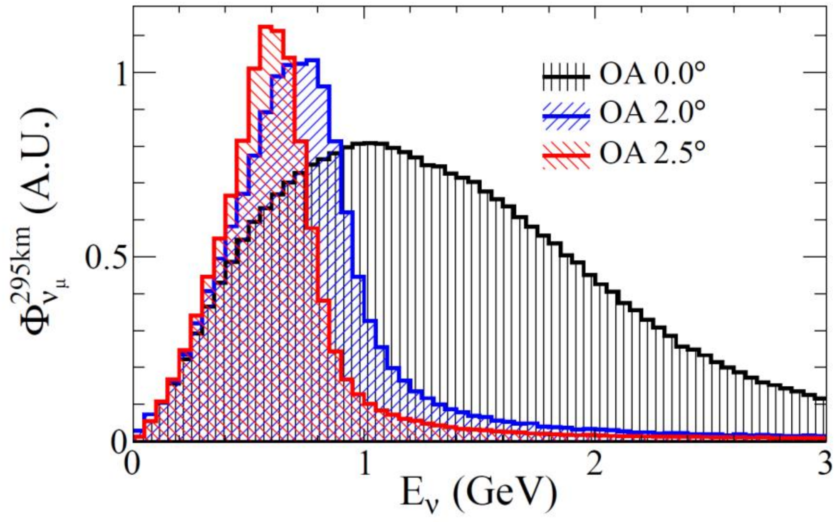




2 Approaches: Shorter Long Baseline

L ≈ few hundred km

- Baseline so short that matter effects have almost no impact
- Focus on 1st maximum => E_ν<1 GeV
- Aim on maximal flux at E_ν^{max} => off-axis configuration
- To improve sensitivity use mass hierarchy from other measurements or add another detector at larger L



(Hyper-KK)

T2K Analysis Strategy

Probability without matter effects (for results they are considered) :

$$\mathrm{P}\left(\nu_\mu \rightarrow \nu_e\right) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$
$$\mp \frac{1.27\Delta m_{21}^2 L}{E} 8 J_{CP} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right). \quad (2)$$

Magnitude of CP violating effect is described by Jarlskok invariant (analog exists in quark sector):

$$J_{CP,l} = \frac{1}{8} \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin(\delta_{CP})$$

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm_{21}^2 , θ_{13}
Reactor LBL (KamLAND)	Δm_{21}^2	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m_{31,32}^2\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m_{31,32}^2\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m_{31,32}^2\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

T2K Analysis Strategy

Probability without matter effects (for results they are considered) :

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right) \mp \frac{1.27\Delta m^2_{21} L}{E} 8 J_{CP} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right). \quad (2)$$

Fit parameters

All appearanch and disappearance channels are used to contrain parameters:

- $\nu_\mu \to \nu_\mu$
- $\bar{\nu}_\mu \to \bar{\nu}_e$
- $\nu_\mu \to \nu_\mu$
- $\bar{\nu}_\mu \to \bar{\nu}_\mu$

Also constraints from ND280 + Beam simulations + NA61/Shine

Magnitude of CP violating effect is described by Jarlskok invariant (analog exists in quark sector):

$$J_{CP,l} = \frac{1}{8} \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin\delta_{CP}$$

Fixed by external measurements 2018 PDG

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Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
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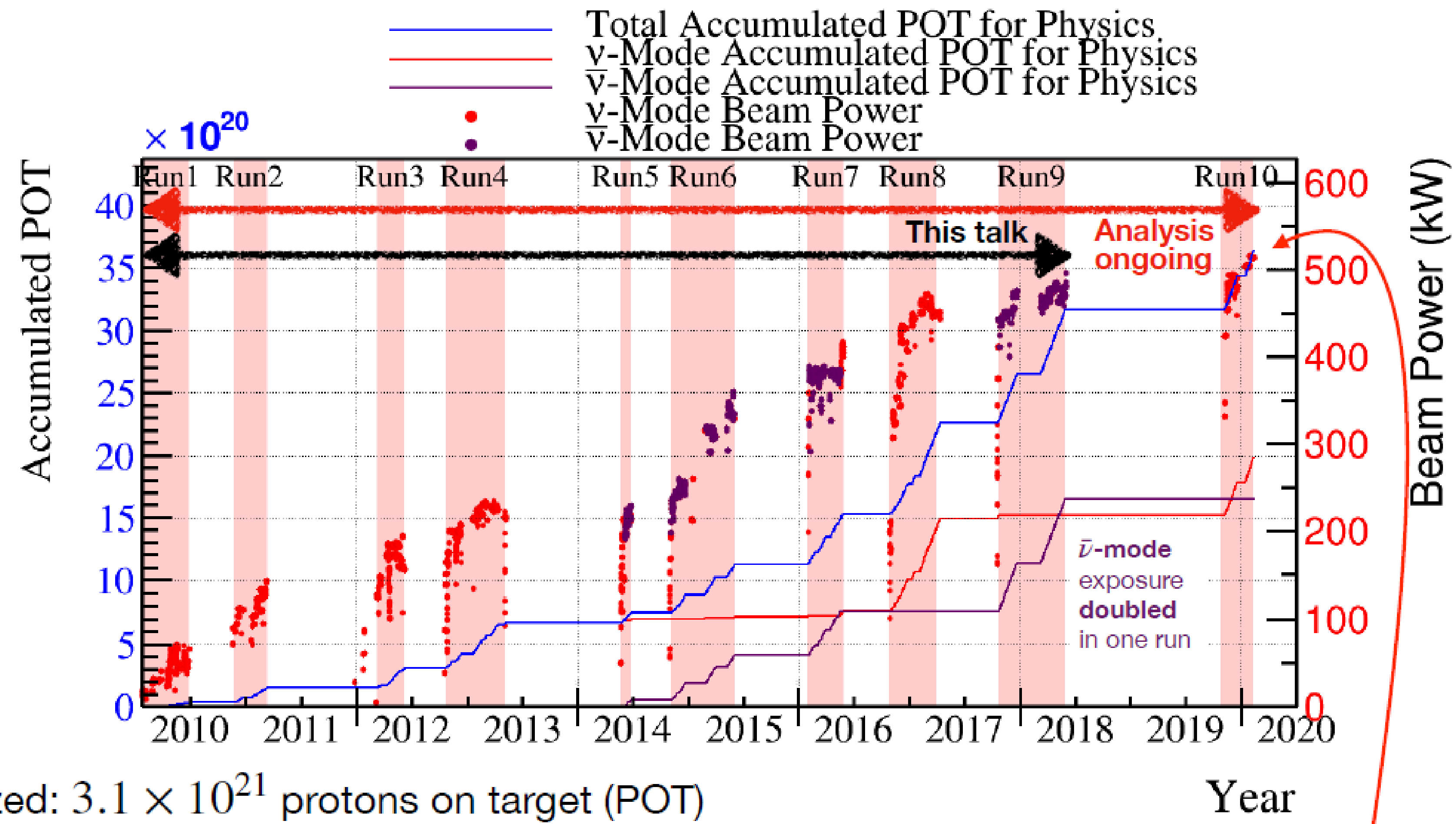
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

Data Set



Analyzed: 3.1×10^{21} protons on target (POT)

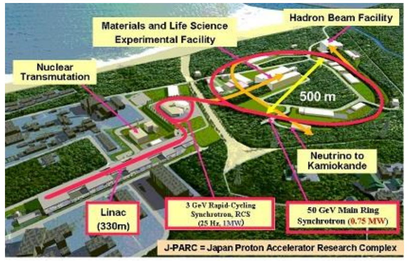
ν-mode : $\bar{\nu}$-mode $\sim$ 50 : 50

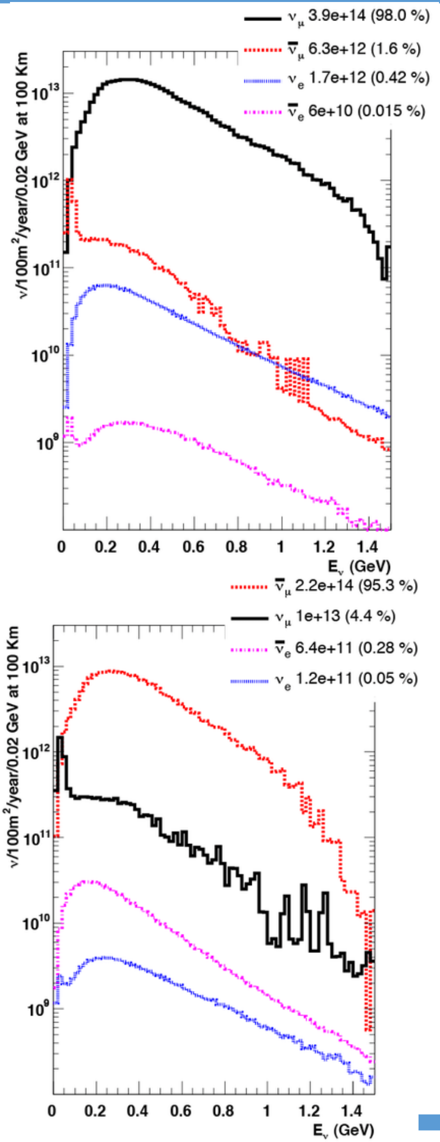
515 kW operation achieved recently!

33% increase of ν-mode data in upcoming analysis.

Reconstructed Energy Spectra

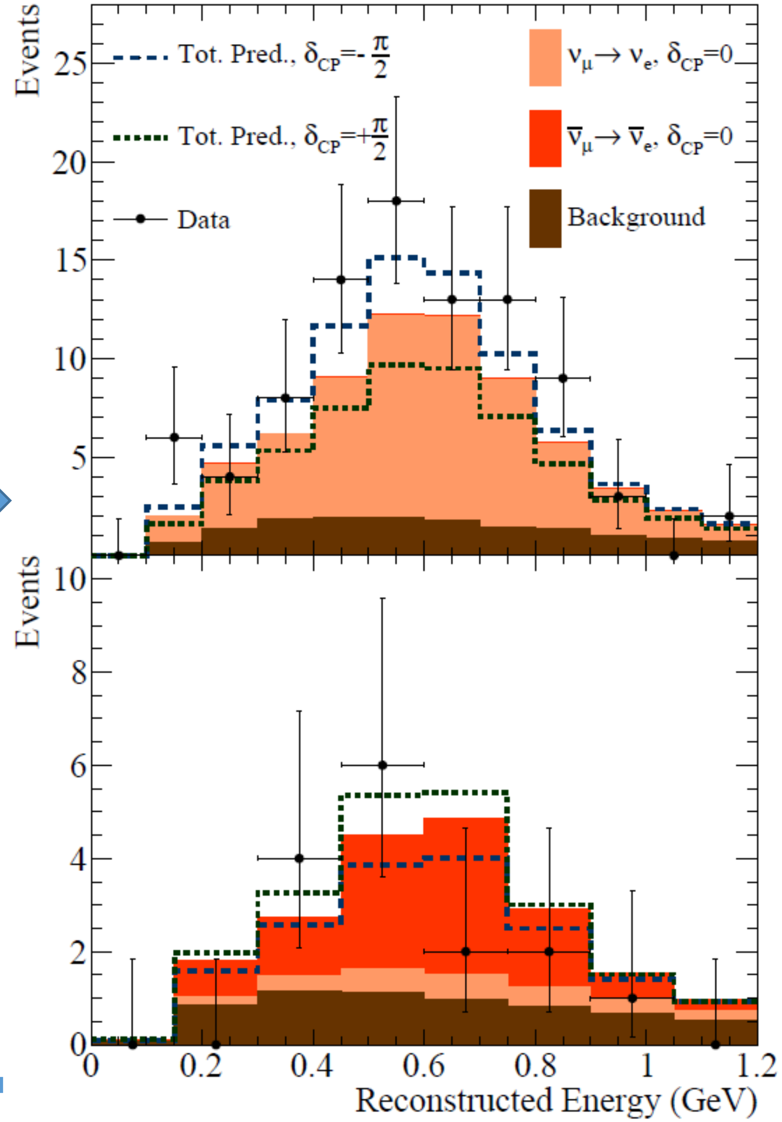
Expected spectrum at J-PARC



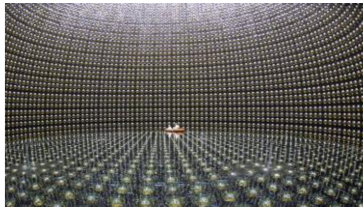


Oscillations + cross sections

295 km



Measured at SK

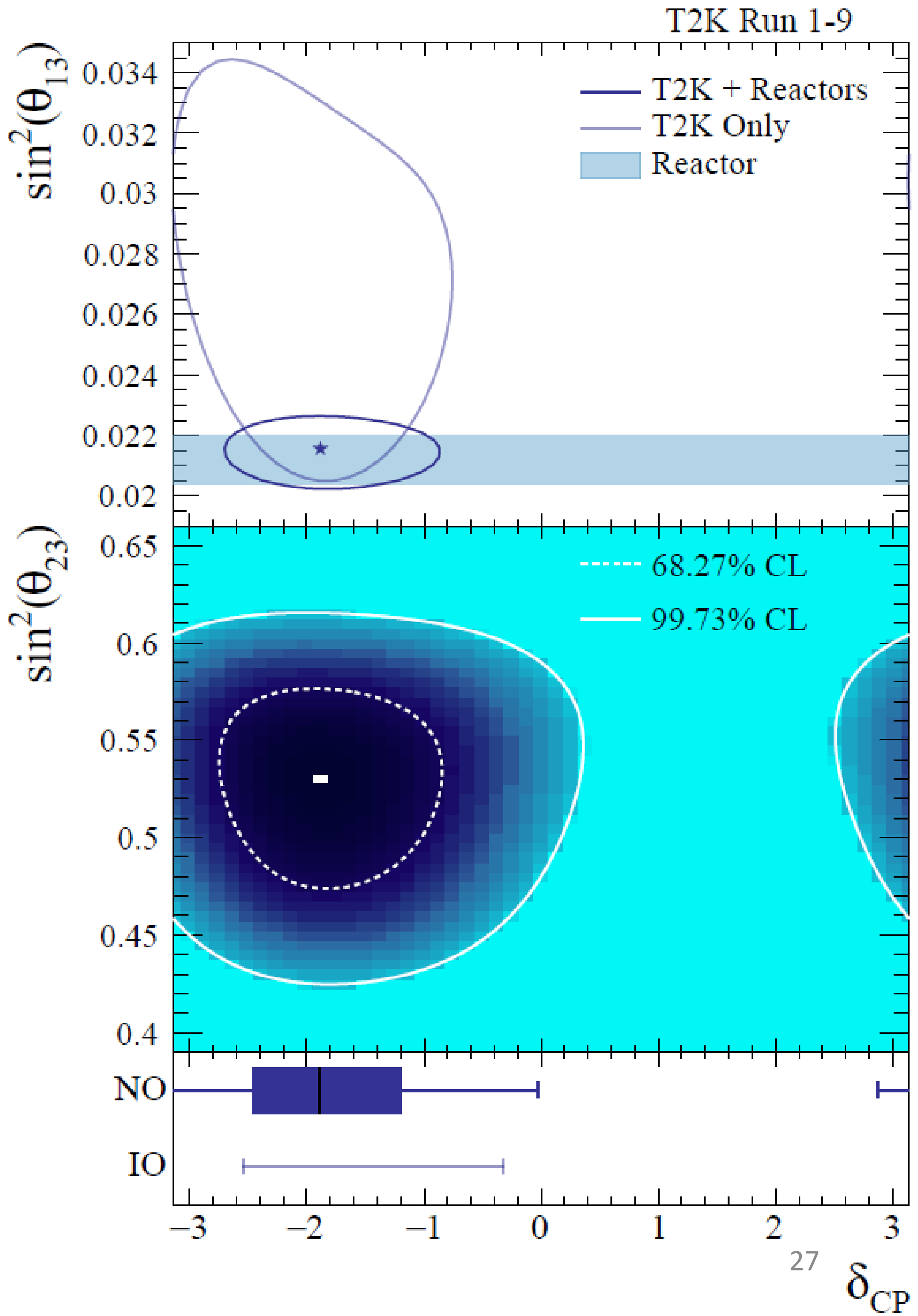


Results

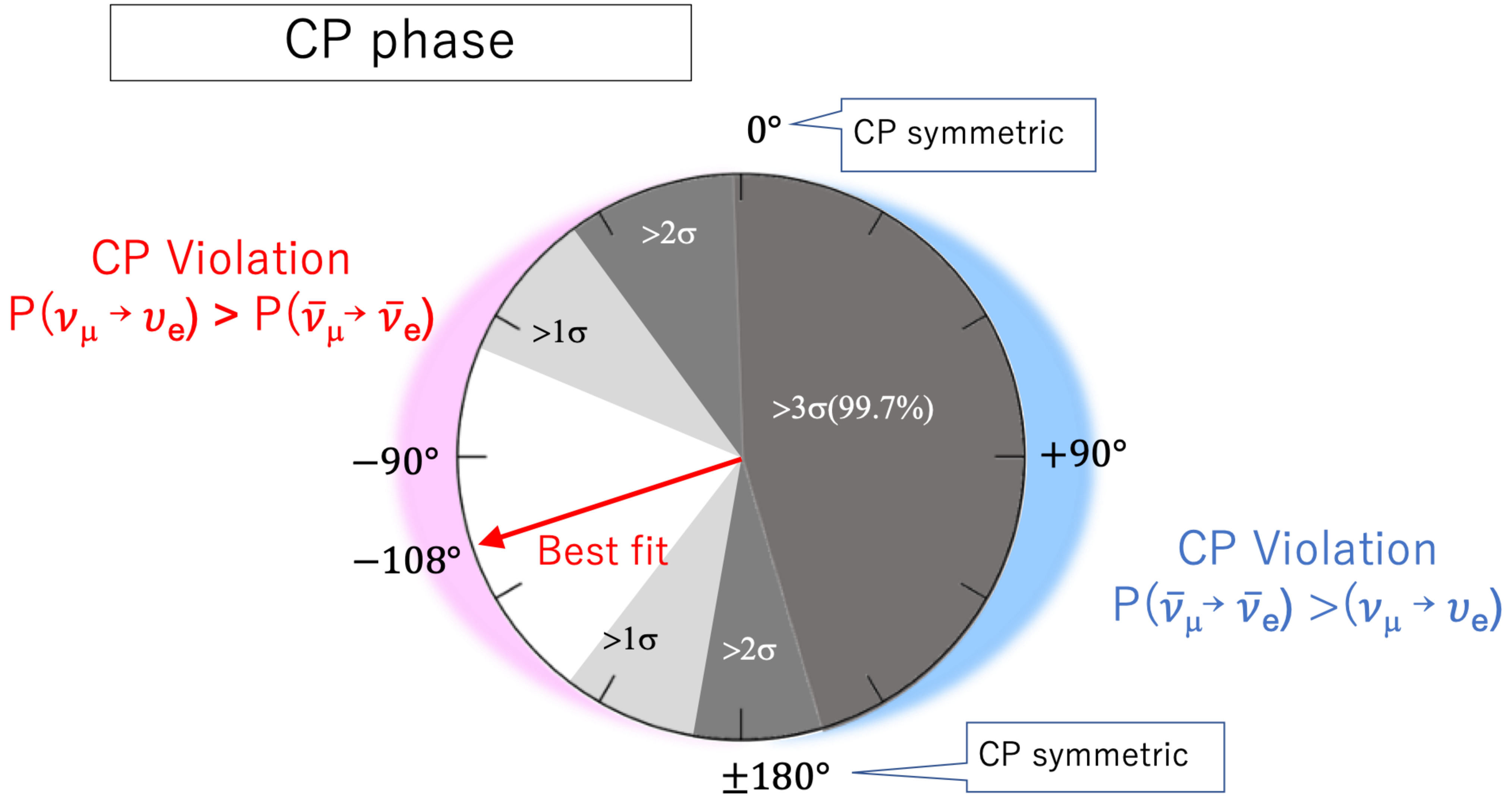
- $\sin^2\Theta_{23}$ = 0.53 −0.04 +0.03 (for both mass hierarchies)
- Δm^2_{32} = (2.45±0.07) × 10^{-3} eV^2/c^4 (normal hierarchy)
- Δm^2_{13} = (2.45±0.07) × 10^{-3} eV^2/c^4 (inverted hierarchy)
- δ_{CP}=−1.89 −0.58 +0.70 (normal hierarchy)
- δ_{CP}=−1.38 −0.54 +0.48 (inverted hierarchy)

- CP conserving phase is excluded at 2+σ confidence level
- Strong preference towards negative CP violating phase

- **Best fit results close to maximal CP violating phase**
- => would imply $J_{CP,l}$ larger than $J_{CP,q}$ by 3 magnitudes



Results



CP phase
0°
CP symmetric
CP Violation
$P(\nu_\mu \to \nu_e) > P(\bar{\nu}_\mu \to \bar{\nu}_e)$
>2σ
>1σ
>3σ(99.7%)
−90°
+90°
−108°
Best fit
CP Violation
$P(\bar{\nu}_\mu \to \bar{\nu}_e) > (\nu_\mu \to \nu_e)$
>1σ
>2σ
±180°
CP symmetric

Does this confirms Leptogenesisis?

- The result is a strong indication for CP violation in the leptonic sector
- But … it does not imply directly leptogenesis
- Leptogenesis models are based on CP violation in decay of heavy neutrinos
- No model available to connect observed CP violation in "standard" neutrinos to CP violation with "heavy" neutrinos
- Heavy neutrinos still not found => SBN programme at Fermilab

More details might be given at CERN seminar:
8th of May at 3 pm
https://indico.cern.ch/event/910572/

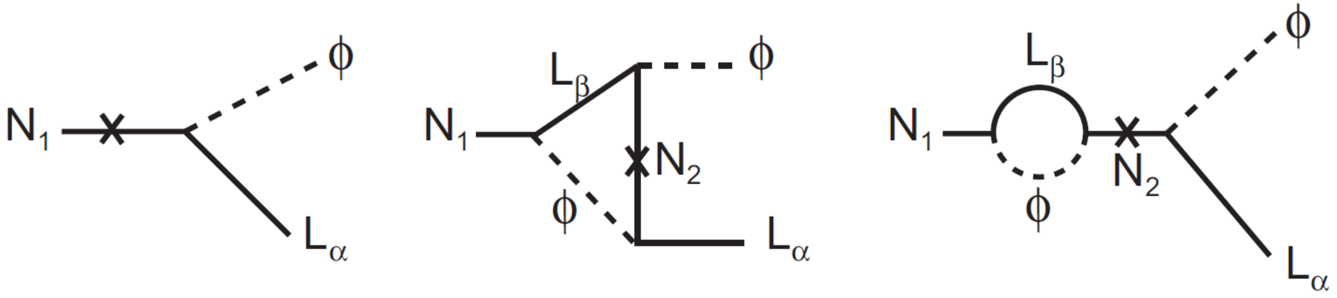


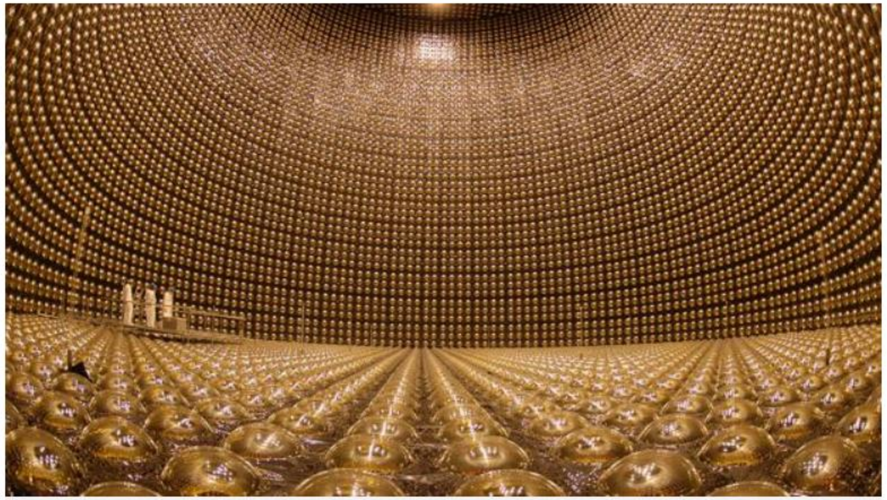
FIG. 4: The diagrams contributing to the CP asymmetry ϵ.

Nature + Abc.es

- Made it on the cover page of Nature
- Great job by Sebastian and Isodoro (IFIC) to translate and distribute press reléase
- Articles ein ElMundo, Abc, …

Un experimento explica por qué la materia sobrevivió después del Big Bang

- Una asimetría en el comportamiento de los neutrinos podría explicar por qué la materia dominó a la antimateria, lo que acabó permitiendo nuestra existencia



Publicidad

...le, en Japón, capaz de albergar 50.000 toneladas de agua

Media Attention

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CERN EP seminar yesterday with more than 450 participants

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by Federico Sanchez — last modified Apr 28, 2020 01:11 PM — History

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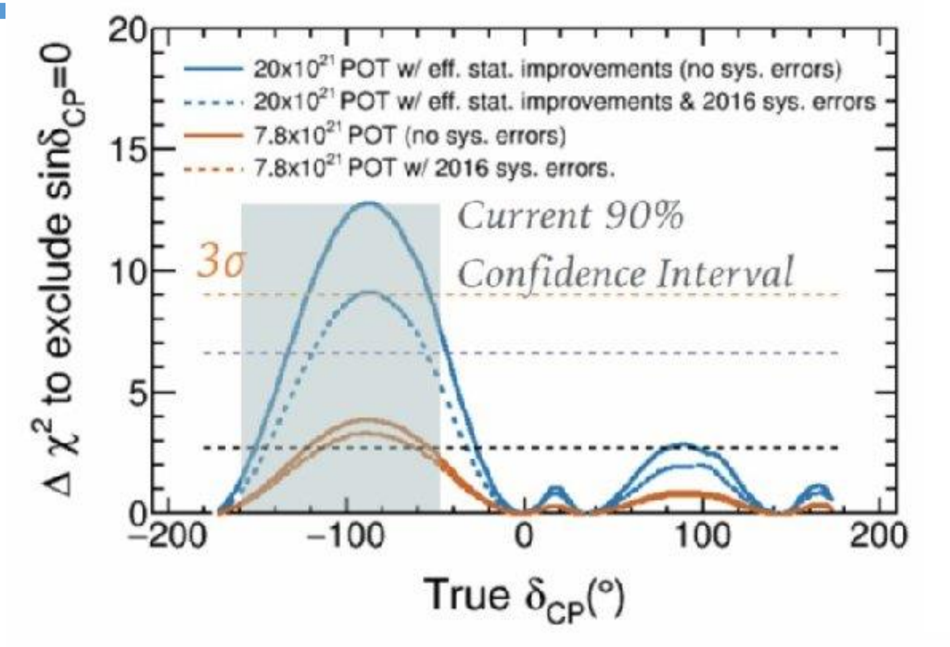
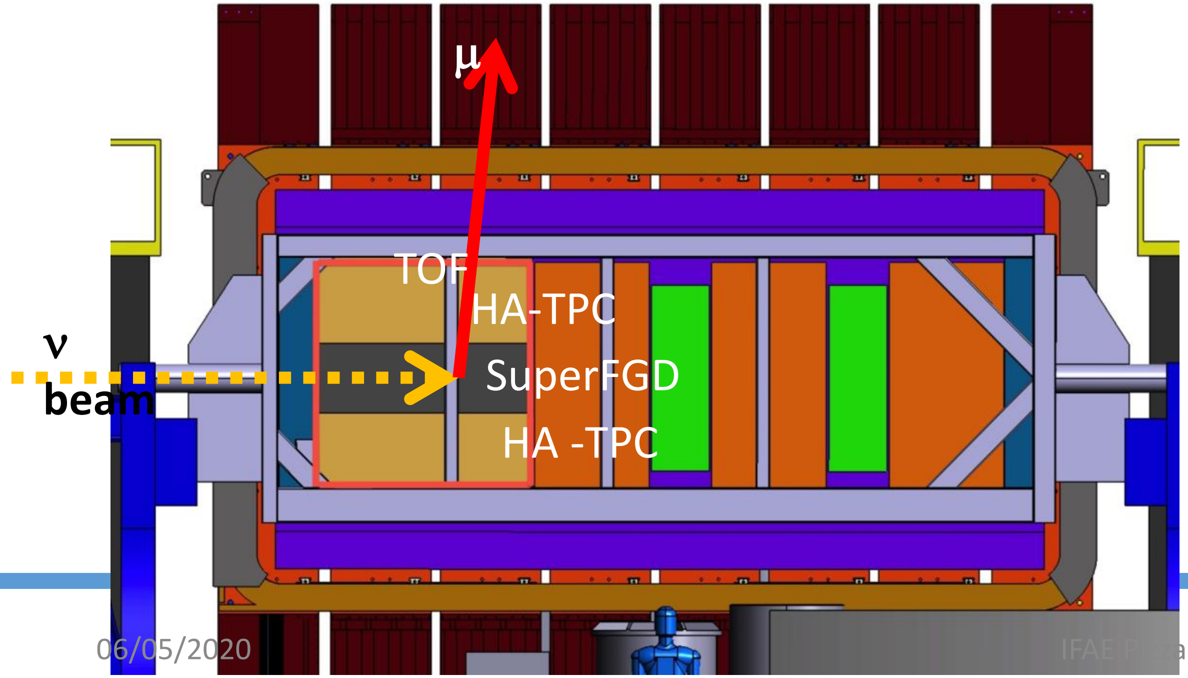
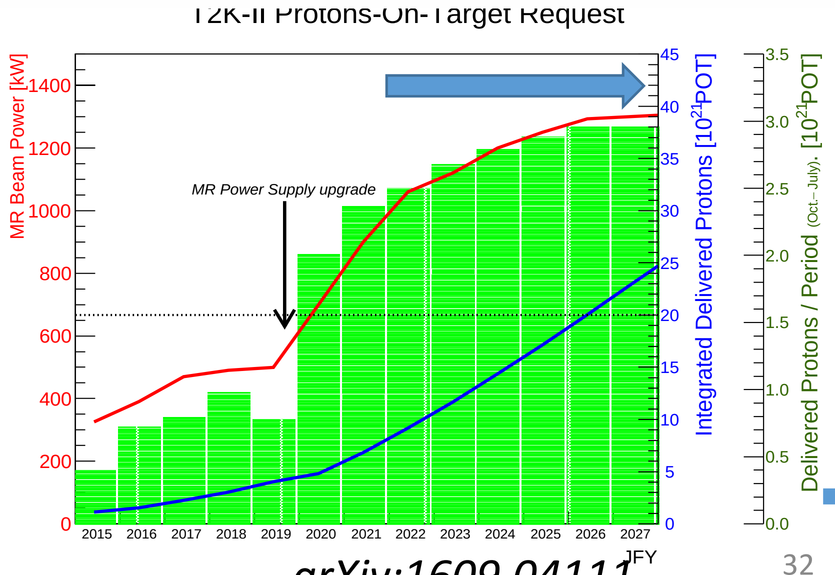
Further Improvements: T2K-II

- Statistics increase:
  - Beam power: 485 kW => 1.3 MW
  - ND280 Upgrade: 2 => 4 tonne
- Reduce systematic error: 6 => 4%
- Best case: CPV at 3+σ



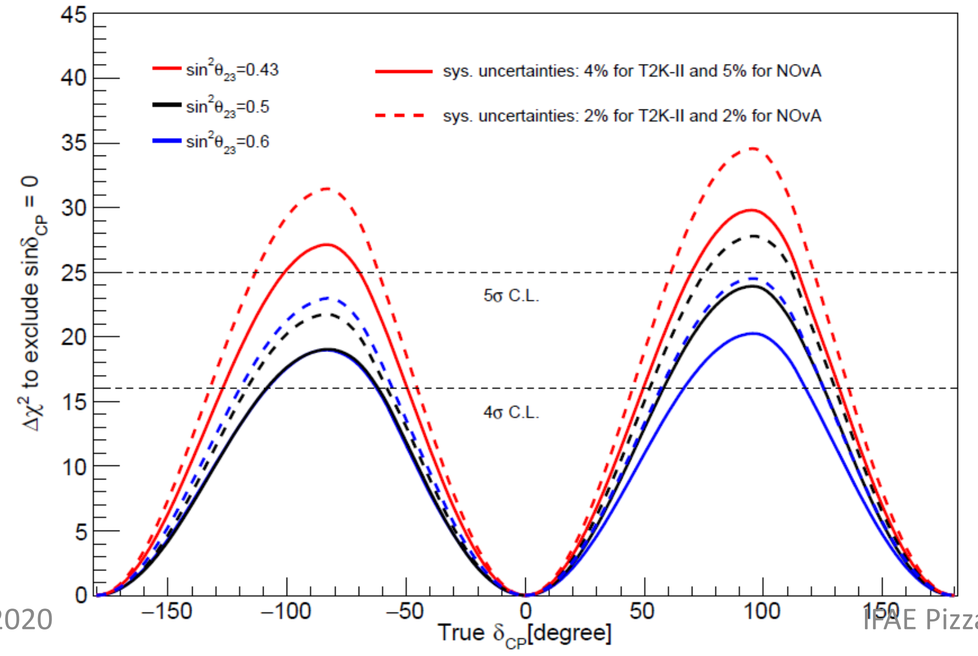




arXiv:1609.04111

Further Improvements: T2K(-II)+Nova

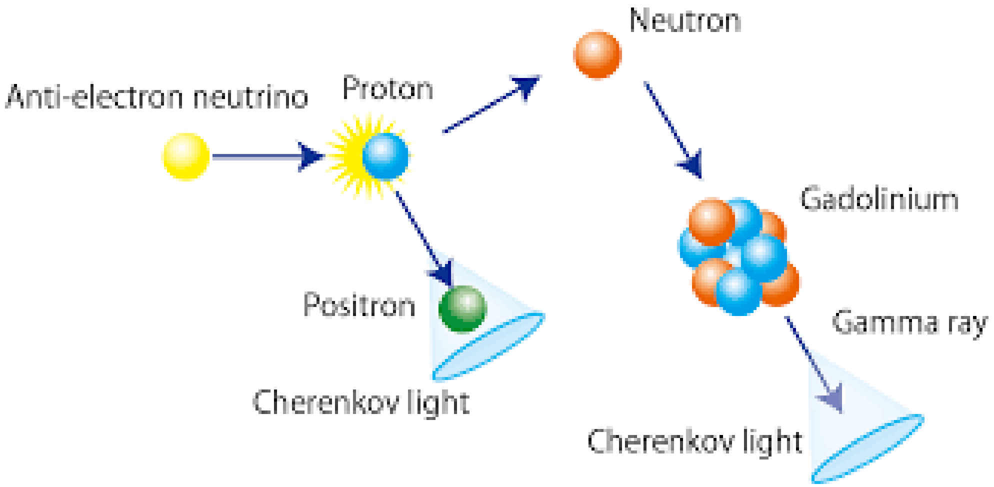
- Nova is another long baseline experiment
- L = 810 km, $E_\nu > 1$ GeV
- Complementary to T2K
- Combined study in ideal case 5σ
- Work on combined study started in 2018



Possible Improvements: SK+Gd / Horn Upgrade

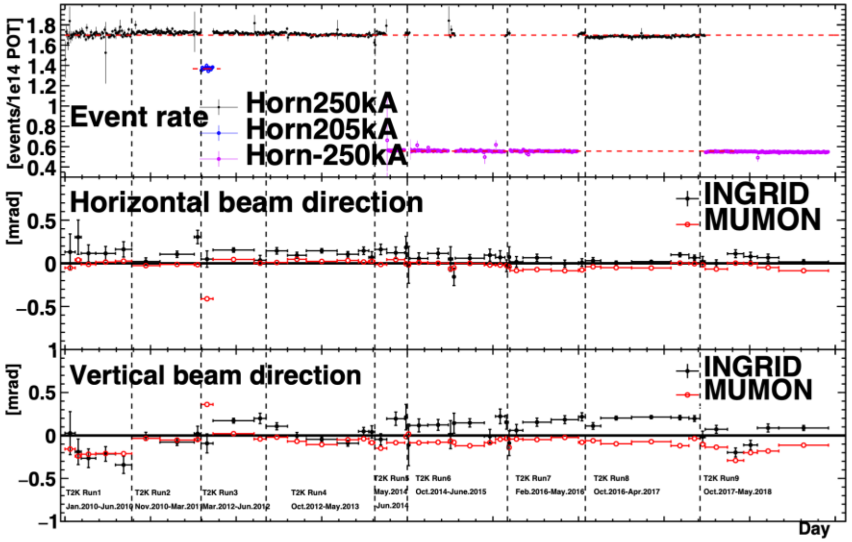
SK + Gadolinium Doping

- Look for delayed signal from n capture (Δt≈30μs, vertex: 50 cm)
- Main purpose: SN neutrinos detection
- Might help to reduce in anti-neutrino mode



Horn current 250 kA -> 320 kA

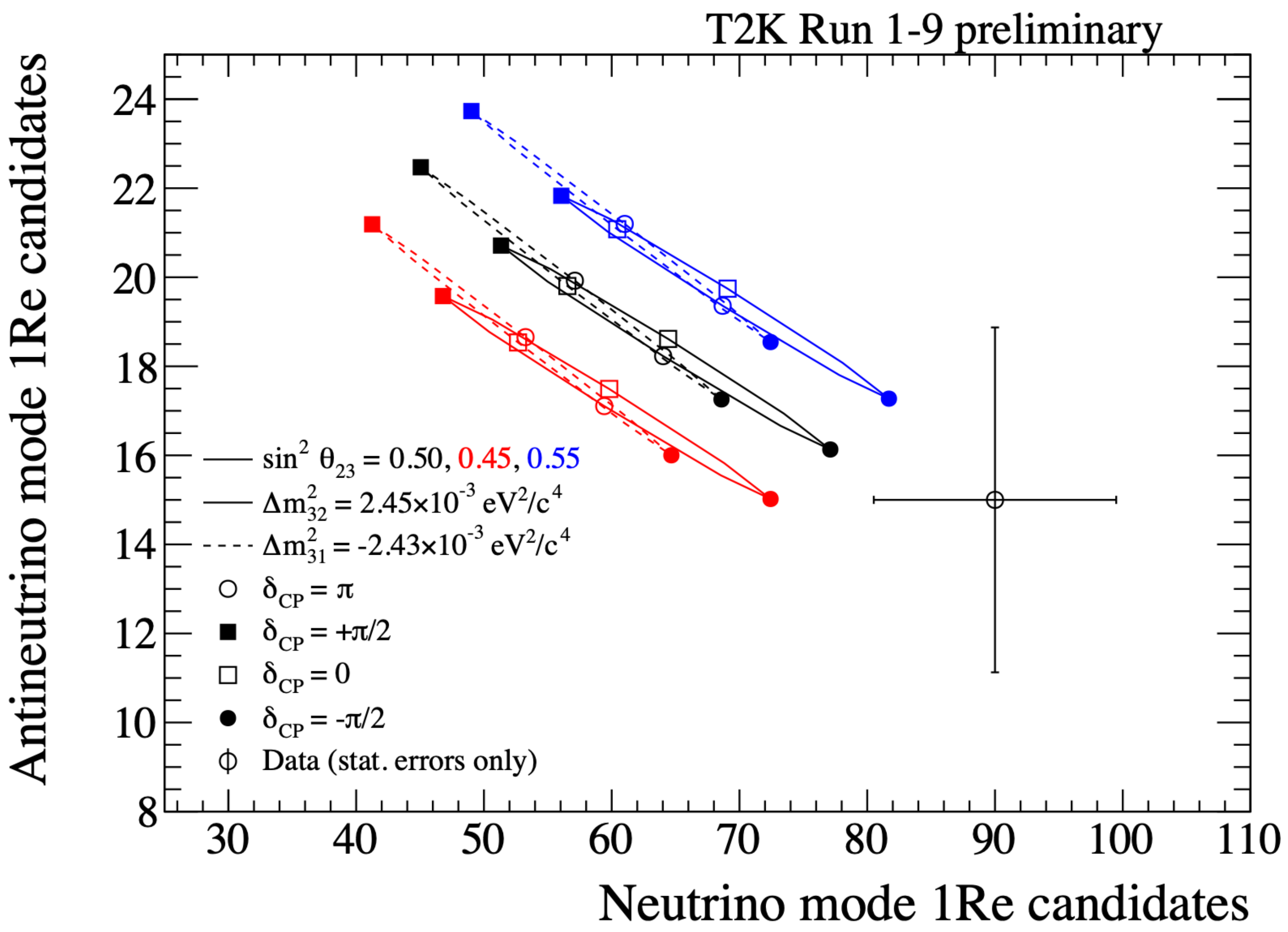
- Increase flux by 20%
- Reduce contamination



Summary

- T2K experiments reported first measurement of δ_{CP}
- Large region of $\delta_{CP}>0$ rejected at 99.7% level
- Best fit result close to maximal CP violation
- $\delta_{CP}=0$ excluded at 3σ, $\delta_{CP}=180$ excluded at >2σ
- Further improvements expected from T2K-II, synergies with Nova, SK + horn upgrade
- Next generation of neutrino oscillation experiments will give precision results
- Measurement of CP violation in oscillations, is not directly related to leptogenesis and is not explaining the full matter asymmetry or serves to explain Dark Matter (via heavy neutrinos)

Backup Slides

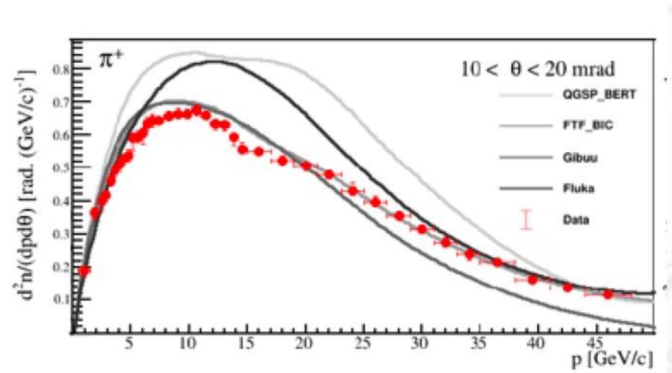

T2K Run 1-9 preliminary
Antineutrino mode 1Re candidates
Neutrino mode 1Re candidates
24
22
20
18
16
14
12
10
8
30
40
50
60
70
80
90
100
110
sin² θ23 = 0.50, 0.45, 0.55
Δm²32 = 2.45×10⁻³ eV²/c⁴
Δm²31 = -2.43×10⁻³ eV²/c⁴
δCP = π
δCP = +π/2
δCP = 0
δCP = -π/2
Data (stat. errors only)

Analysis procedure

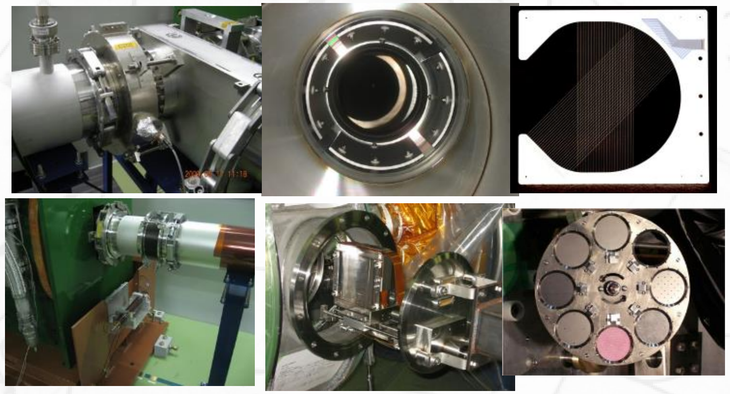
Beam model

Beam model is obtained from a full GEANT simulation of the particle transport reweighed by the NA61 results

Input

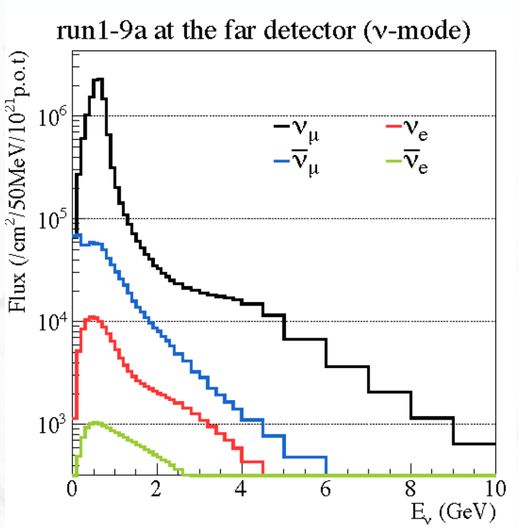


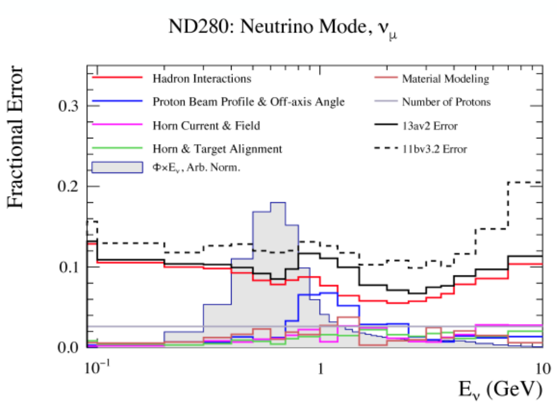
Beam monitors

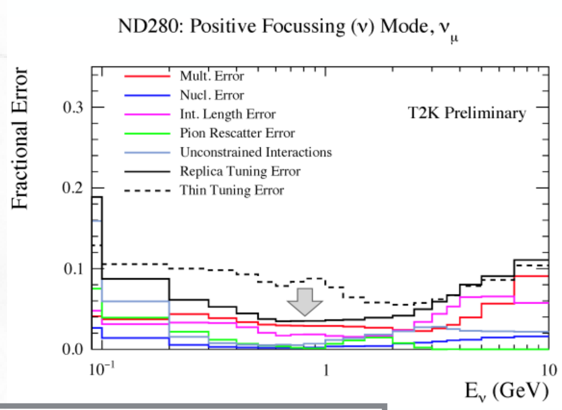


GEANT 3

Output

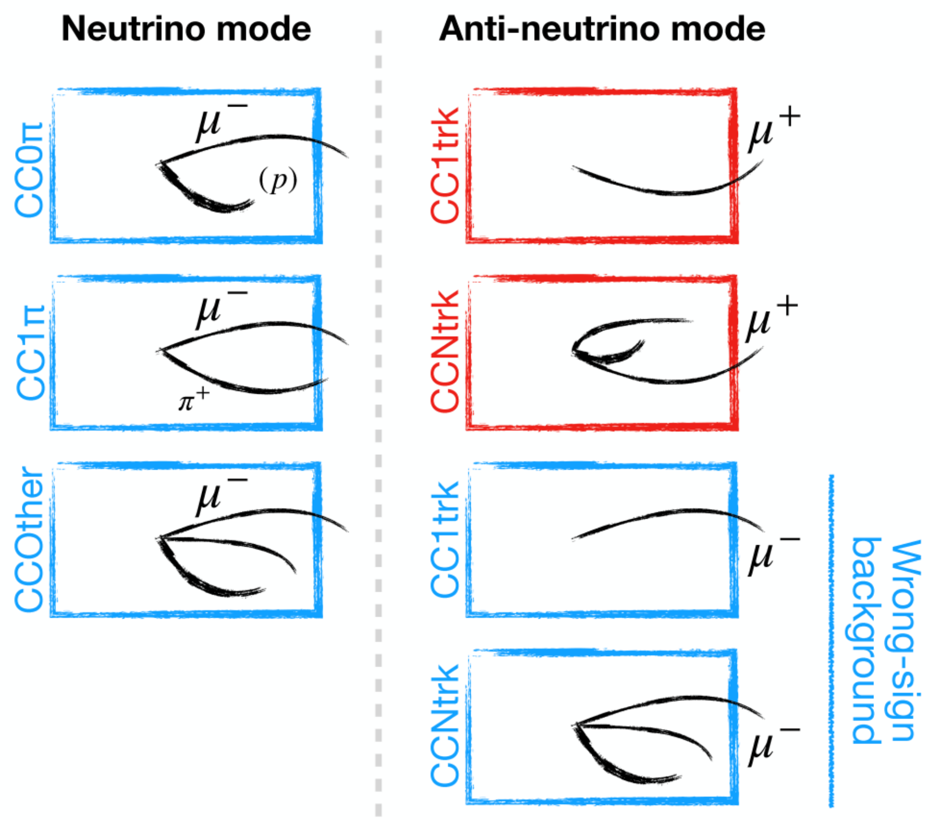






Including error covariance matrix

Near detector data



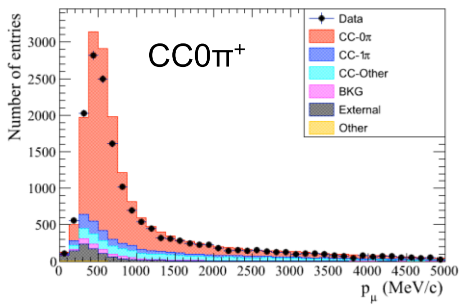
Each sample for two targets FGD1,2 ~ (C,O)

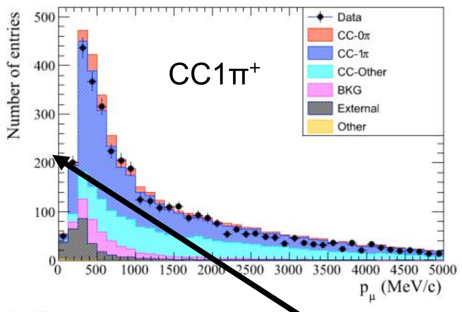
CCOther are CC events with multiple π's, π^0 or π^- candidates

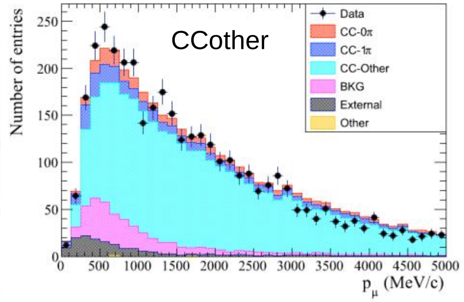
- Analysis of muon kinematics: (p_μ cos θ_μ)
  - E_ν obatined from interaction model in generators.
- Three samples of neutrinos (two for antineutrinos): enriched in
  - CCQE → CC0π
  - CCRes → CC1π
  - CC-DIS → CCOther
- the different samples also have different E_ν dependencies.
- Wrong Sign background:
  - neutrinos in anti-neutrino mode.
- Neutrino interaction in Oxygen from FGD2 data.

Conceptually

Near detector data

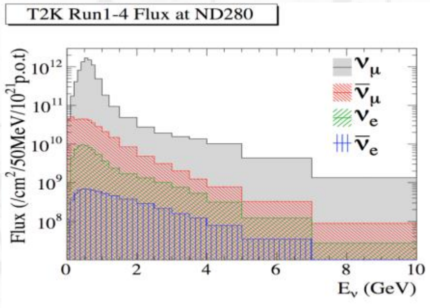






⊕

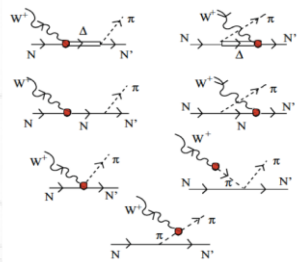
Hadron production flux prediction Shive + beam monitors



feed back

⊕

Cross-section model



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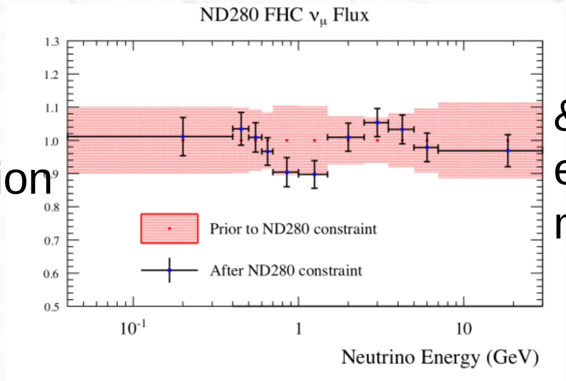
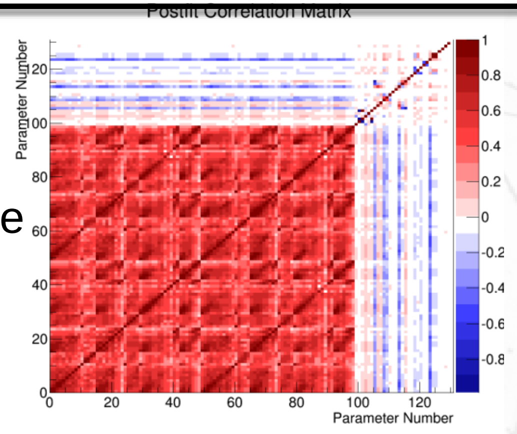
Corrected flux and cross-section model



& error covariance matrix



Oscillation fits

$\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ combined analysis within the 3ν oscillation paradigm (PMNS).

Other oscillation parameters from 2018 PDG values.

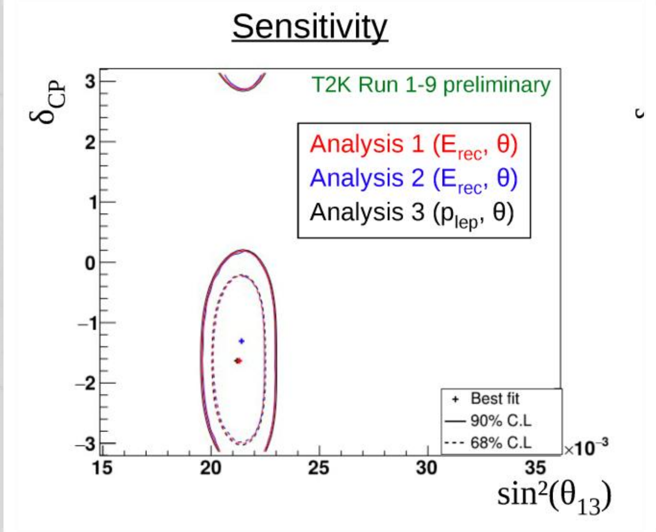
$$-2\ln\lambda(\overline{\delta_{CP}};\boldsymbol{a}) = 2\sum_{i=1}^{N}\left[n_i^{obs}\ln\left(\frac{n_i^{obs}}{n_i^{exp}}\right)+n_i^{exp}-n_i^{obs}\right] +(\boldsymbol{a}-\boldsymbol{a}_0)^T\mathbf{C}^{-1}(\boldsymbol{a}-\boldsymbol{a}_0)$$

Binned likelihood comparing data to MC predictions.

Bins of reconstructed energy from lepton kinematics assuming CCQE two body interactions.

$$E_{rec} = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu|\cos\theta_\mu}$$

ν_e sample also bins in θ_e



Bayesian Markov Chain MonteCarlo and 2 frequentist approach.

Frequentists confidence intervals (grid search) agree with the Bayesian factors and credible intervals.

Oscillation Probabilities for 3ν

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2([1-x]\Delta)}{[1-x]^2}$$

Leading term

$$-\alpha \sin\delta_{CP} \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\Delta \frac{\sin[x\Delta]\sin([1-x]\Delta)}{x[1-x]}$$

CP violating term

$$+\alpha \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\Delta \frac{\sin[x\Delta]\sin([1-x]\Delta)}{x[1-x]}$$

CP conserving term

$+$

For $P(\overline{\vartheta_\mu^R} \to \overline{\vartheta_e^R})$:

- "-" => "+"
- replace δ and x with -δ and -x

$$x = \frac{2\sqrt{2}G_F n_e E_\vartheta}{\Delta m_{31}^2}, \alpha = \left|\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right| \cong \frac{1}{30}, \Delta = \frac{\Delta m_{31}^2 L}{4E_\vartheta}$$

But how to disentagle matter from CP violation effects?

Approx oscillation formulae

Appearance

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Conserving

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CP Violating

$$+4s_{12}^2 c_{13}^2 (c_{12}c_{23} + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta)\sin^2\Delta_{21}$$ Solar term

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2}G_F n_e E$

Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23})\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$