Physique des neutrinos avec les expériences à longue ligne de base
Deuxième partie

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Outline

- Results of LB:
  - Early LB experiments: K2K and MINOS
  - Nu tau Appearance experiments: OPERA
  - Precision numu disappearance experiments and nue appearance experiments: T2K, NovA
  - The next generation: HK and DUNE
- Other interesting physics with a large underground detector (SK, HK, DUNE)

Atmospheric driven oscillations

$$Prob(\nu_\mu \rightarrow \nu_\tau) \simeq \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{\Delta m_{31}^2 L}{4E}$$

$$Prob(\nu_\mu \rightarrow \nu_\mu) \simeq 1-(\sin^2\theta_{13}\sin^2 2\theta_{13}+\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\frac{\Delta m_{31}^2 L}{4E}$$

$$P(\nu_\mu \rightarrow \nu_e) \approx 4C^2{}_{13}S^2{}_{13}S^2{}_{23}\sin^2\frac{\Delta m_{31}^2 L}{4E}$$

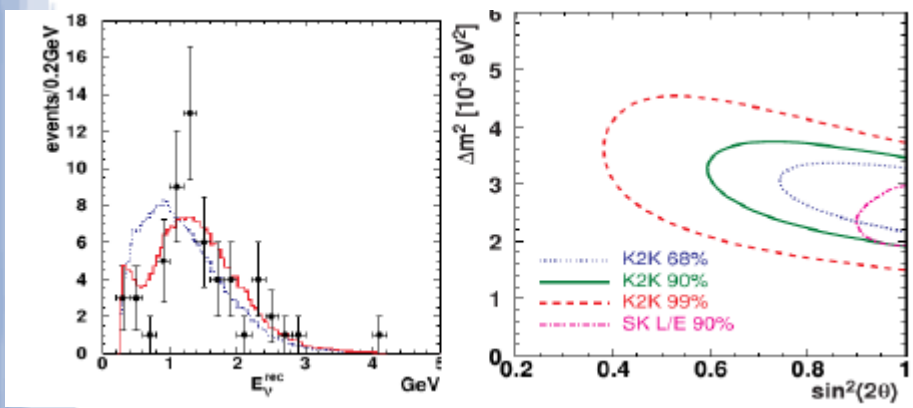
$$\mp 8C^2{}_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin^2\frac{\Delta m_{31}^2 L}{4E}\sin^2\frac{\Delta m_{32}^2 L}{4E}\sin^2\frac{\Delta m_{21}^2 L}{4E}$$

Long baseline experiments

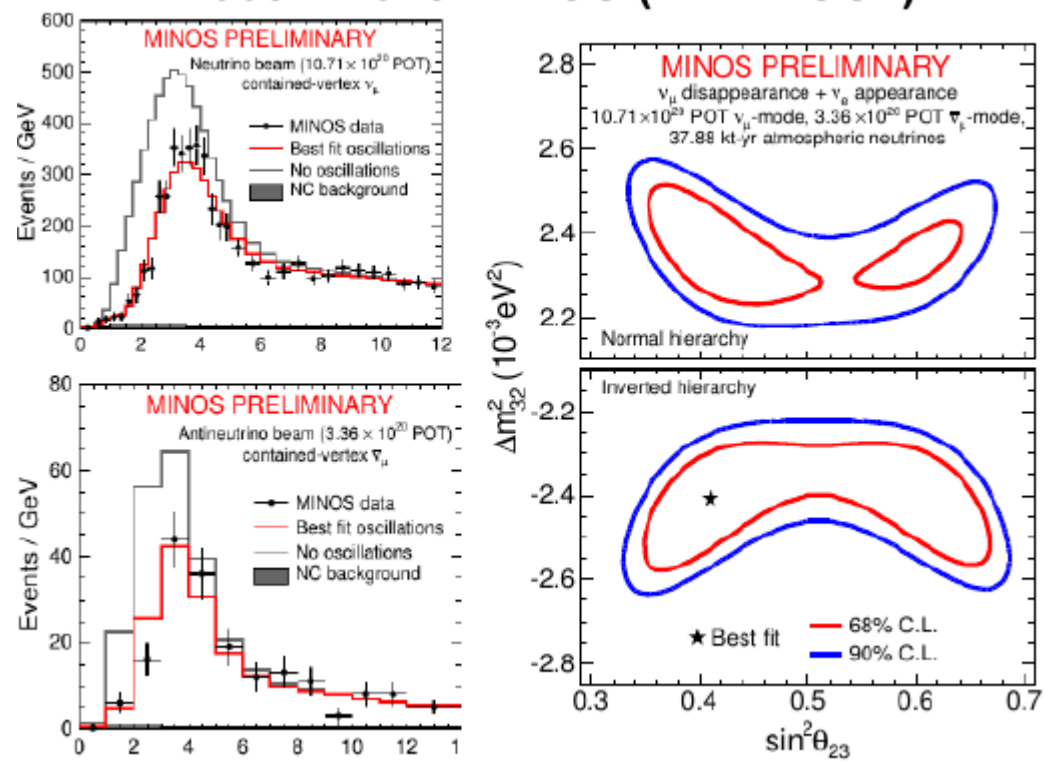
Mode	Parameter	Goal	Experiments
$\nu_\mu \rightarrow \nu_\tau$	θ_{23} Δm^2_{32}	Confirm nutau vs nusterile	OPERA
$\nu_\mu \rightarrow \nu_\mu$	θ_{23} Δm^2_{32}	Precision measurements	K2K, MINOS T2K NOVA
$\nu_\mu \rightarrow \nu_e$	PMNS phase δ, Mass Ordering	CP violation	T2K NOVA HK DUNE

K2K - MINOS

KEK 1999-2006



2003 – 2015 MINOS (→ MINOS+)

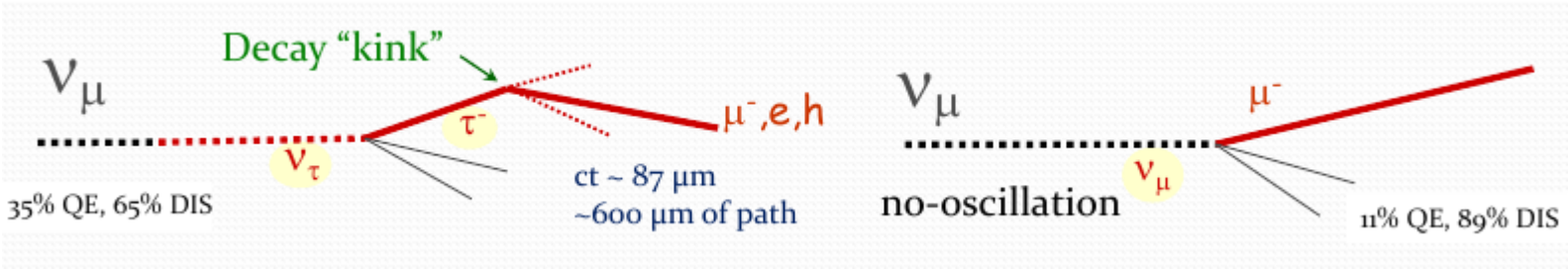


K2K (from KEK to SuperKamiokande) and MINOS (from Fermilab to Soudan) were early longbaseline neutrino experiments. They confirmed neutrino oscillations, measured the θ_{23} angle and Δm^2_{32}.

Detection of tau neutrinos

$\nu_\mu n \rightarrow \mu^- p$

$\nu_\tau n \rightarrow \tau^- p \quad \tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ (h) **Signature: detached vertex, kink, transverse momentum**

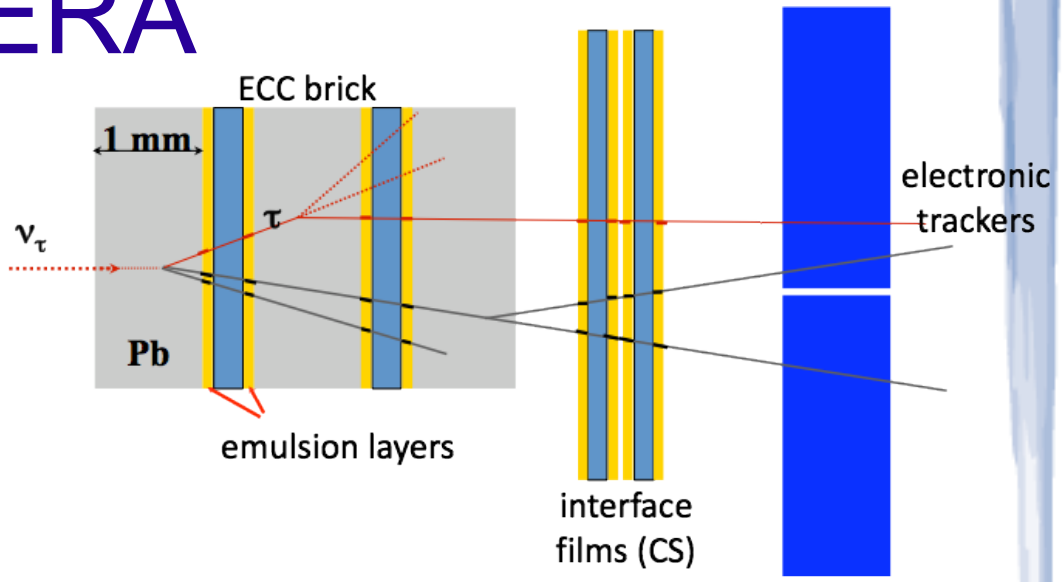


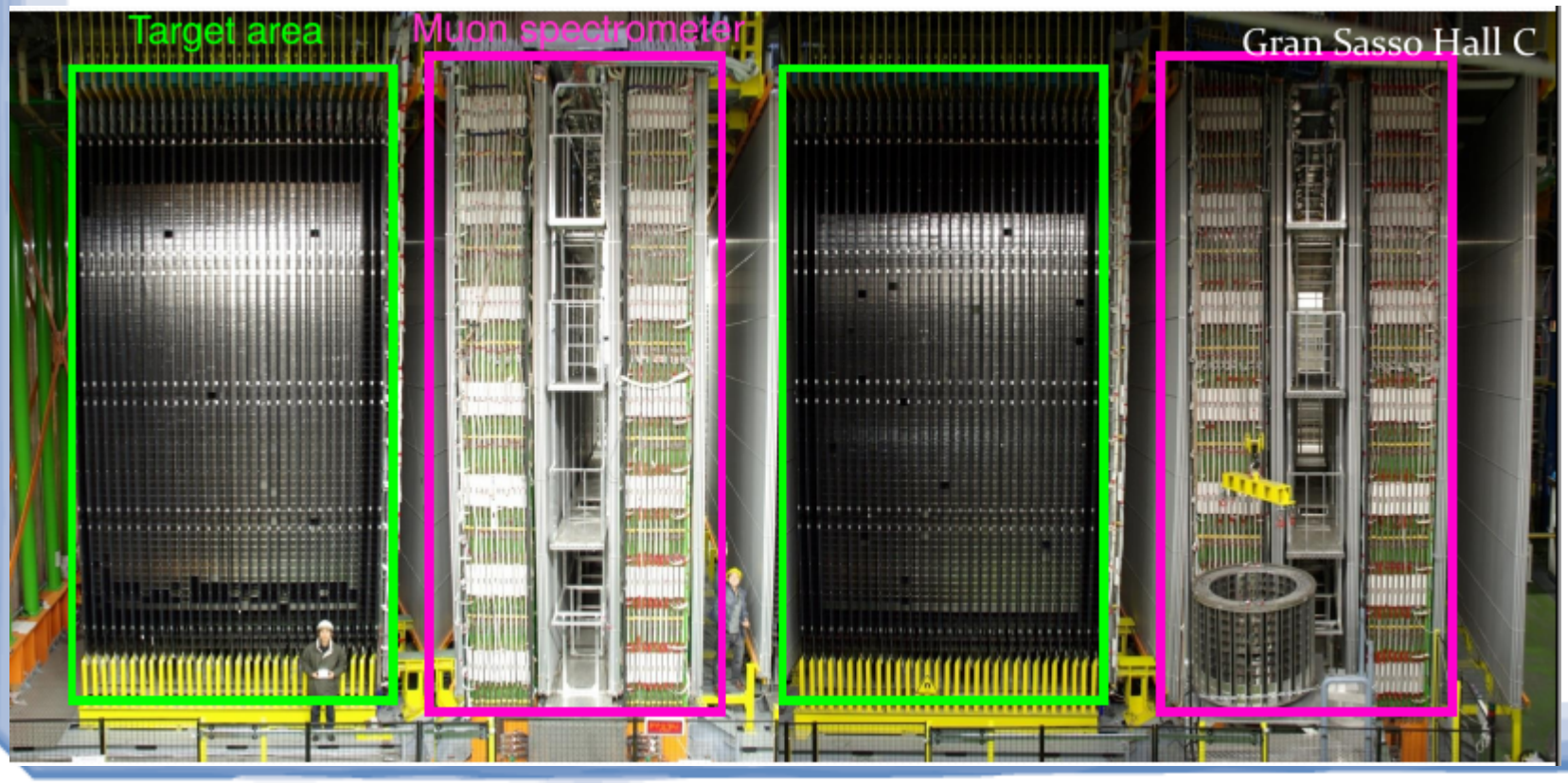
$\nu_\mu \rightarrow \nu_\tau$

2007-2012

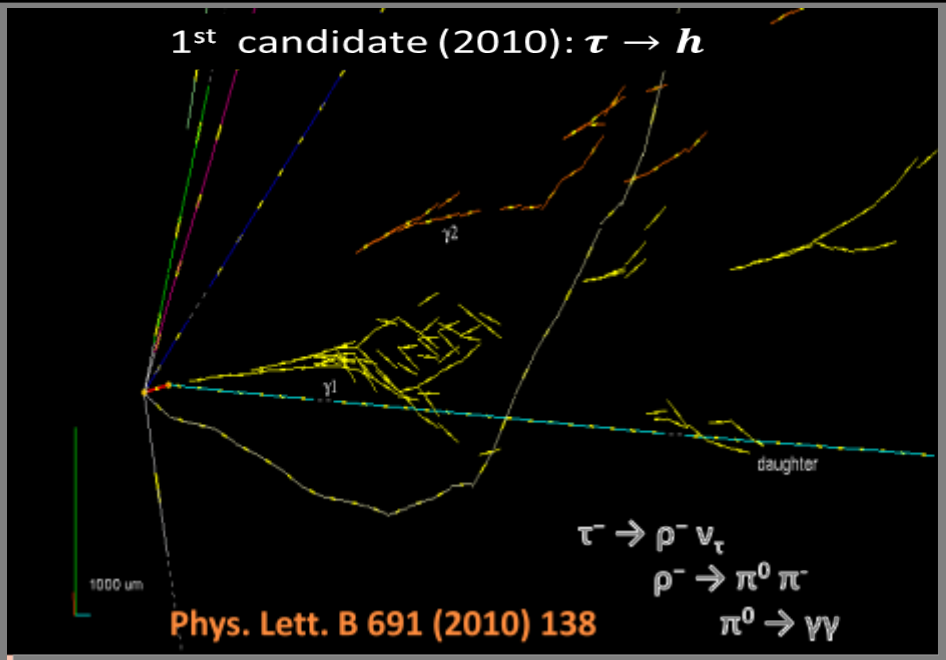
OPERA

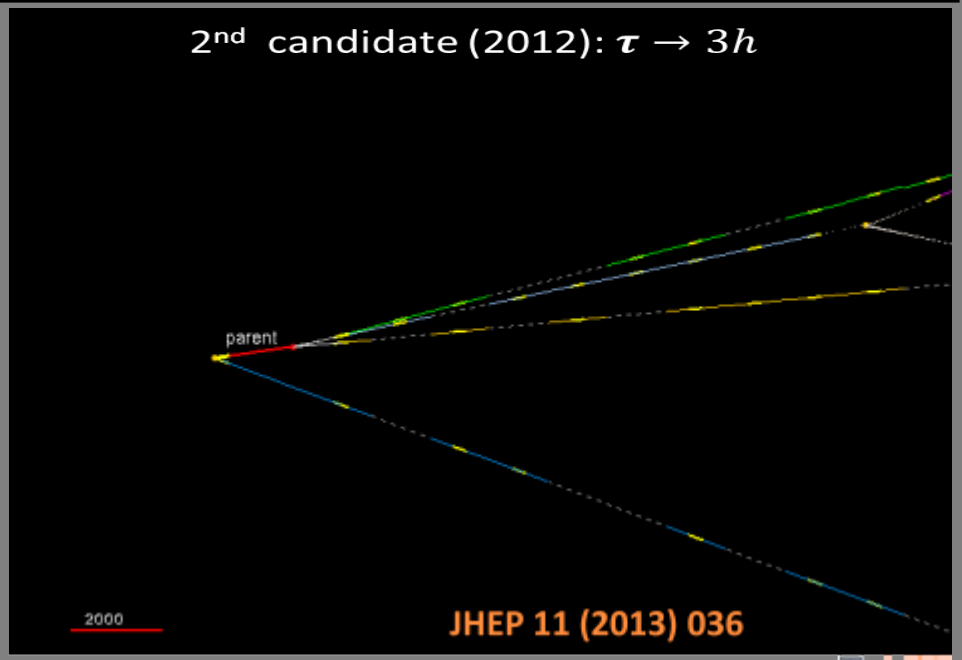
- OPERA: CERN to Gran Sasso

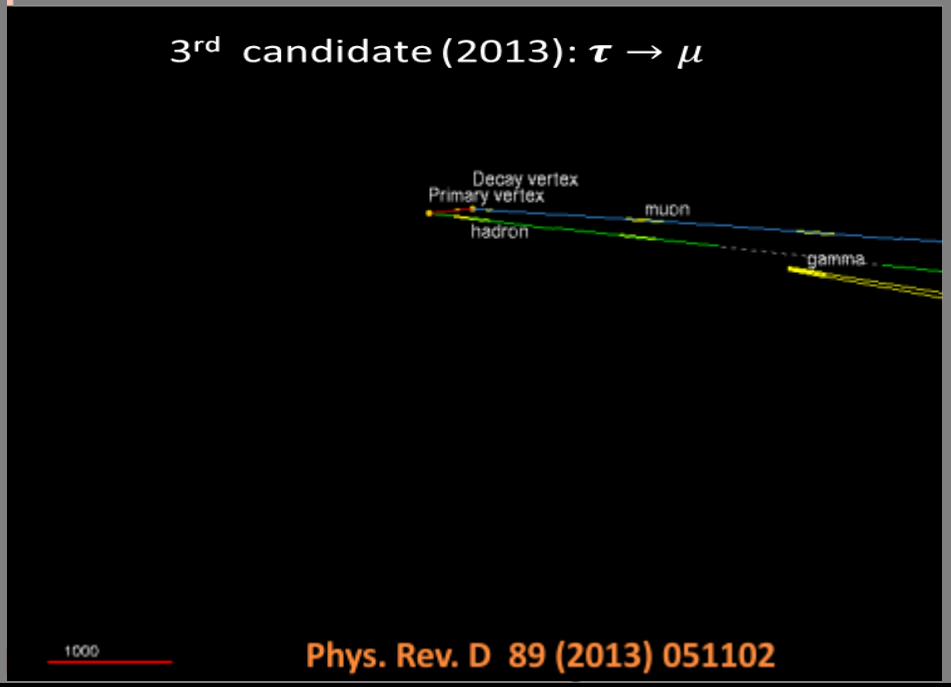


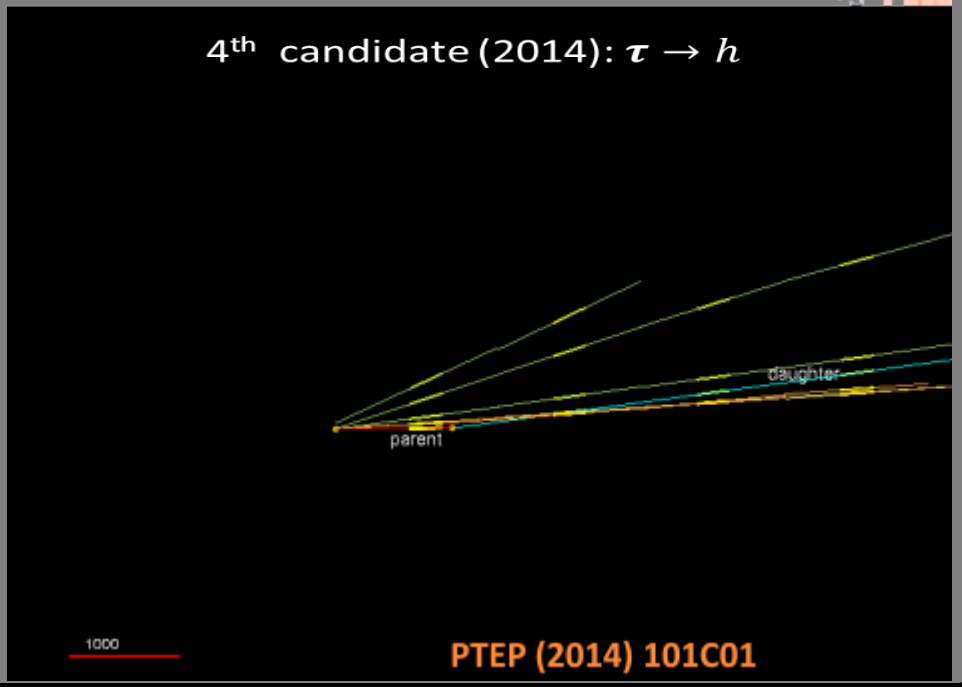


ν_τ events observed in OPERA







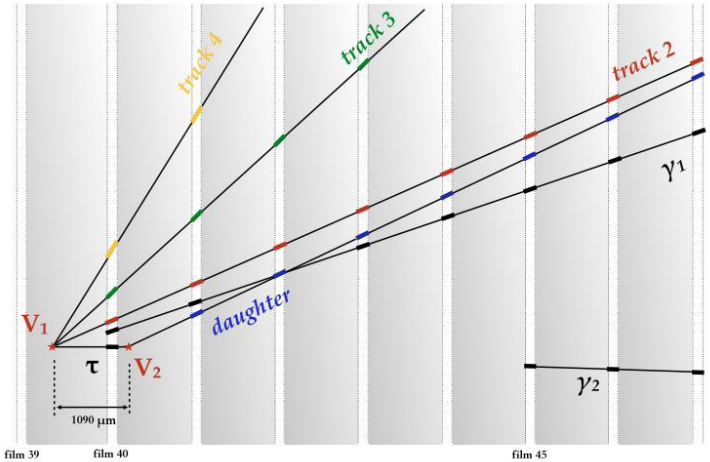


$\nu_\mu \rightarrow \nu_\tau$

Tau neutrino appearance

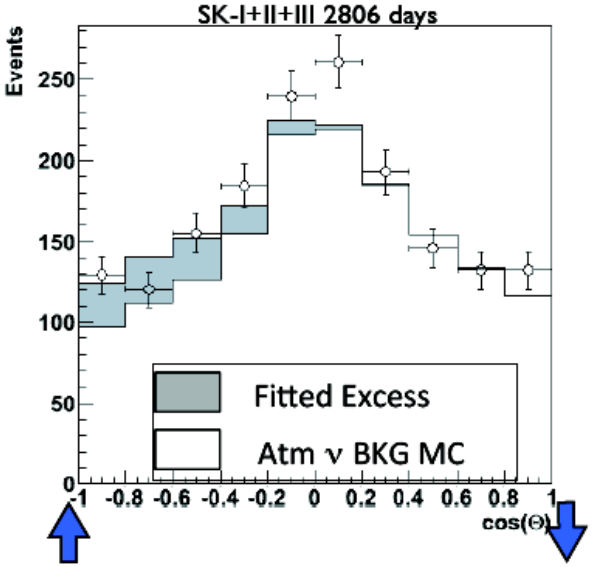
OPERA performed a search for ν_μ to ν_τ appearance with a baseline of 732 km (CERN to Gran Sasso) using the Emulsion Cloud Chamber technique. It has observed five ν_τ candidates (tot bkg = 0.25). The null hypothesis is excluded at the 5.1 σ CL.

Talk by M. Komatsu



Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV²	Total background	Observed
$\tau \rightarrow h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \rightarrow \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \rightarrow e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

Zenith Distribution of τ-like events

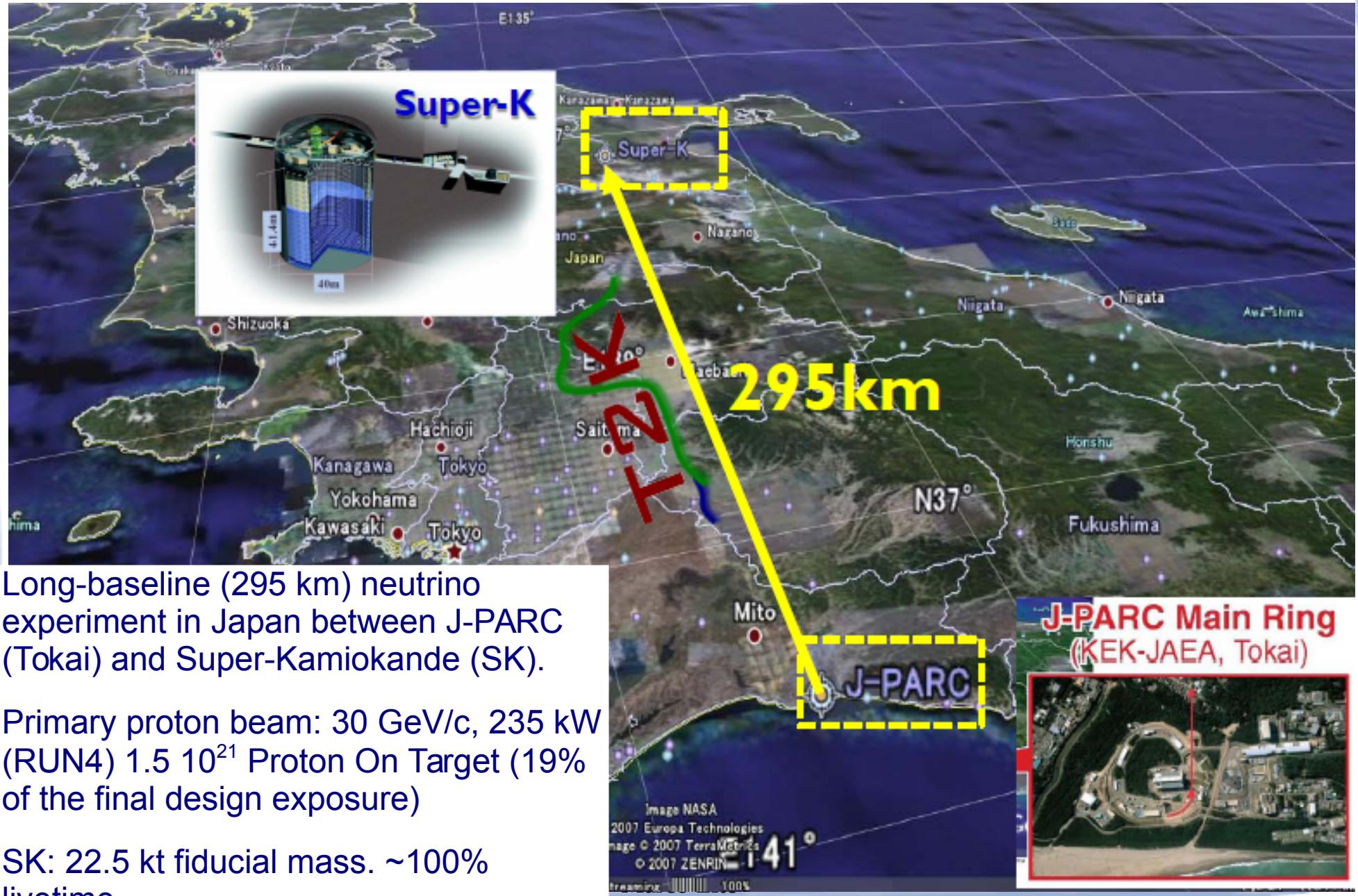


Super-Kamiokande has searched for ν_τ-like events in atmospheric neutrinos and found an excess with 3.8 σ significance.

PRL, 2013 vol. 110 (18) p. 181802

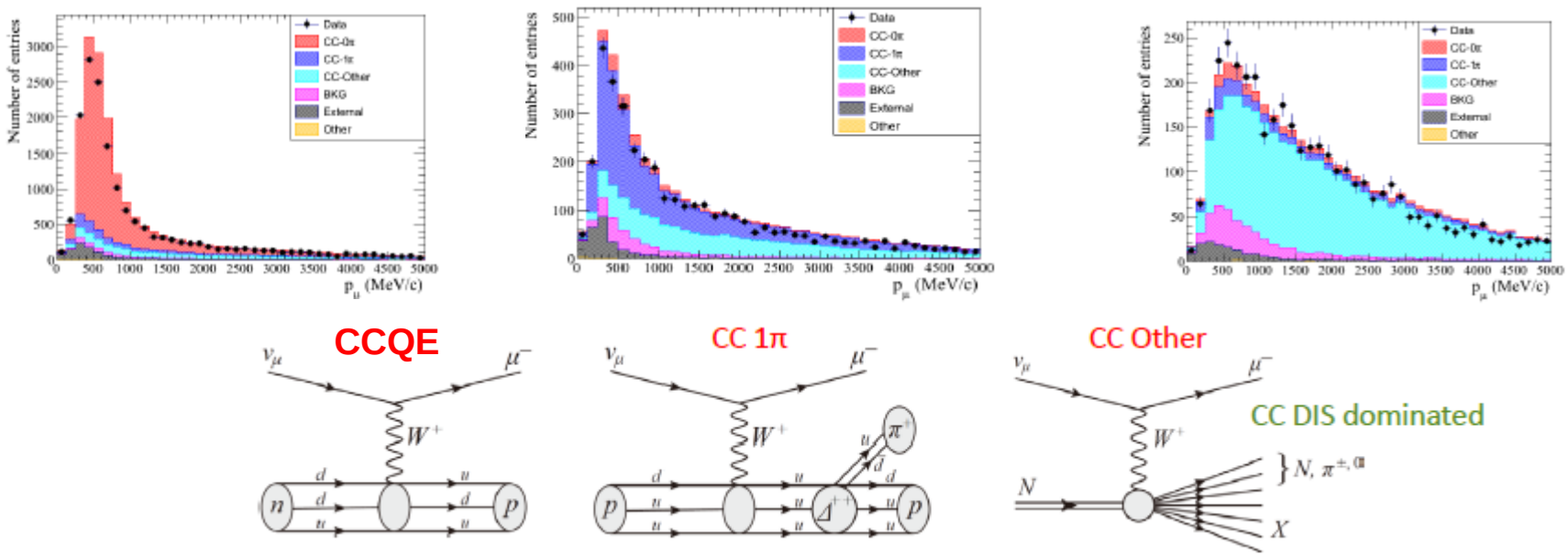
$\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$

The Tokai to Kamioka (T2K) experiment

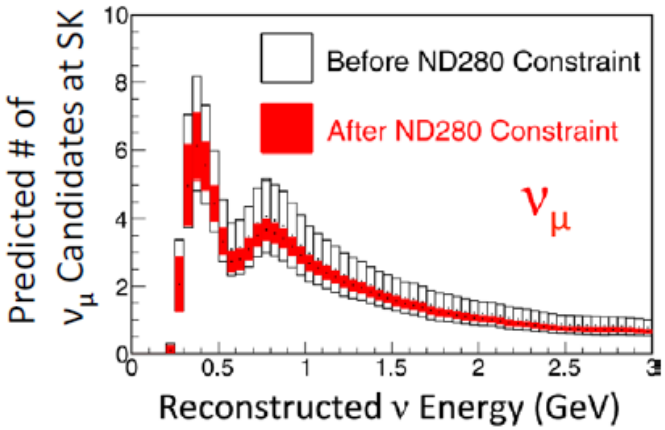


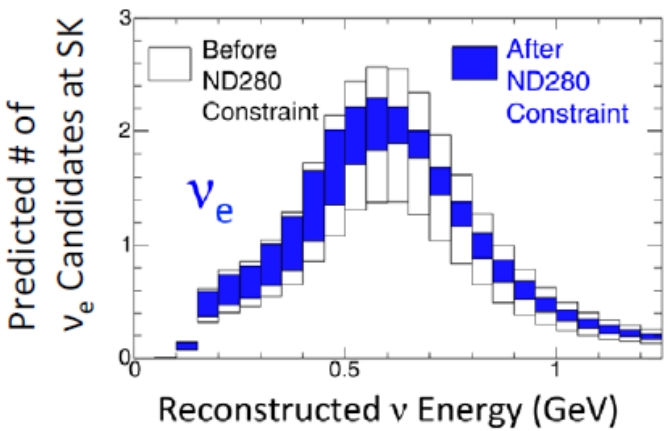
- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 235 kW (RUN4) 1.5 10^{21} Proton On Target (19% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

T2K Near detector constraint

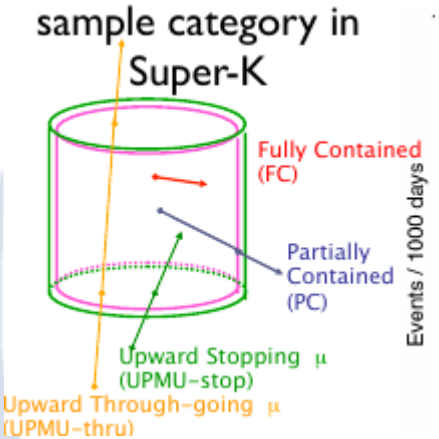


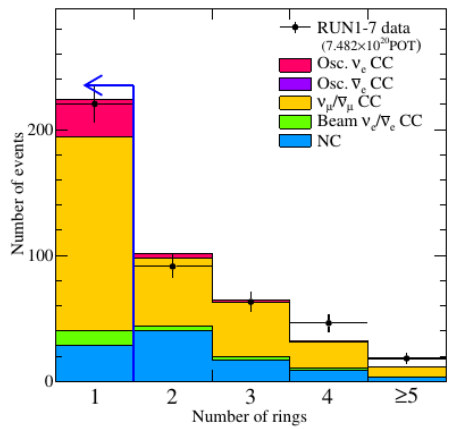
Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~5-6%

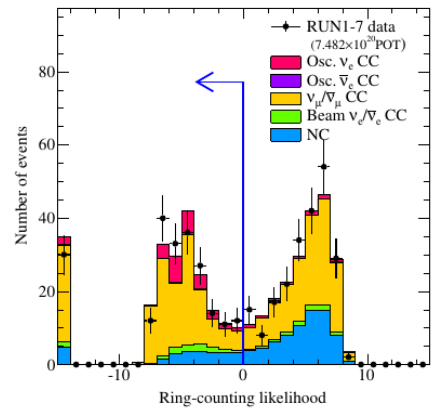


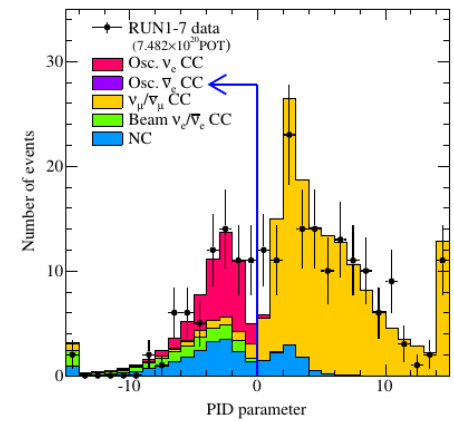


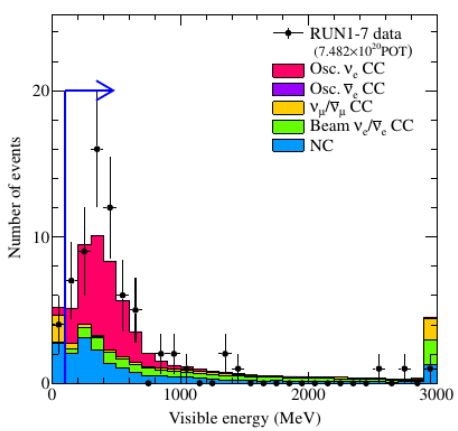
T2K event selection for ν_e

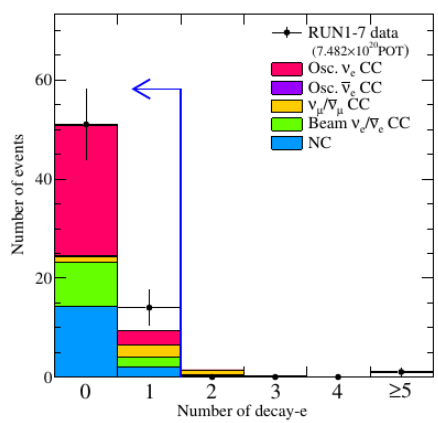


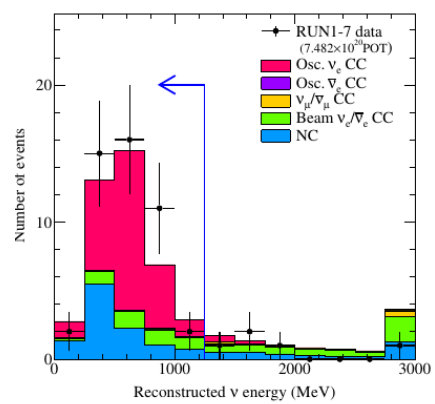


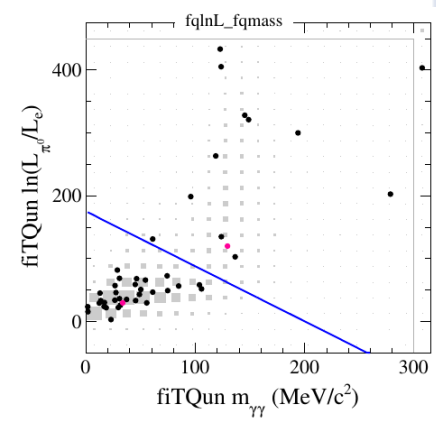












Sequence of cuts: 1) Fully contained Fiducial Volume (FCFV) 2) One Ring 3) Ring likel. 4) e PID 5) E>100 MeV 6) N decay e<2 7) Enu <1300 MeV 8) Pi0 rejection

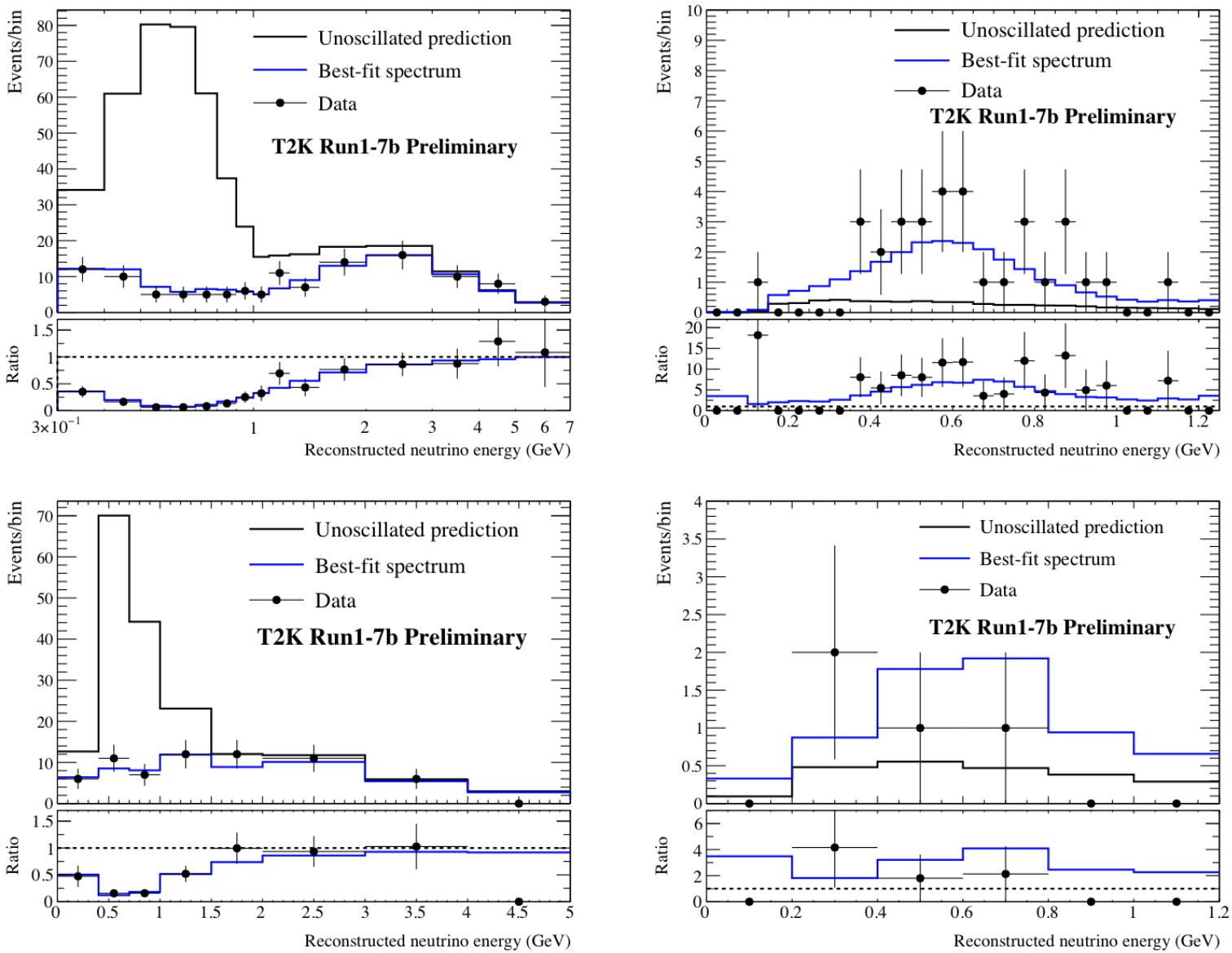
T2K ν_e selection

	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	$\bar{\nu}_\mu \to \bar{\nu}_e$	Bkg. total	$\nu_\mu \to \nu_e$	DATA
In FV	365.2	18.6	327.0	0.4	711.2	35.6	654
FCFV	280.6	18.1	99.0	0.4	398.1	34.9	438
1R	153.8	11.2	28.8	0.3	194.0	30.0	220
e-like	6.5	11.1	19.6	0.3	37.5	29.6	70
Evis>100	4.6	11.0	16.9	0.3	32.8	29.1	66
0 Decay-e	1.0	9.0	14.3	0.3	24.5	26.2	51
Erec	0.3	4.3	10.9	0.2	15.6	25.2	46
π^0 rej.	0.1	3.7	1.4	0.2	5.3	23.3	32
Eff. (%)	0.0	19.8	0.4	46.2	0.7	65.6	

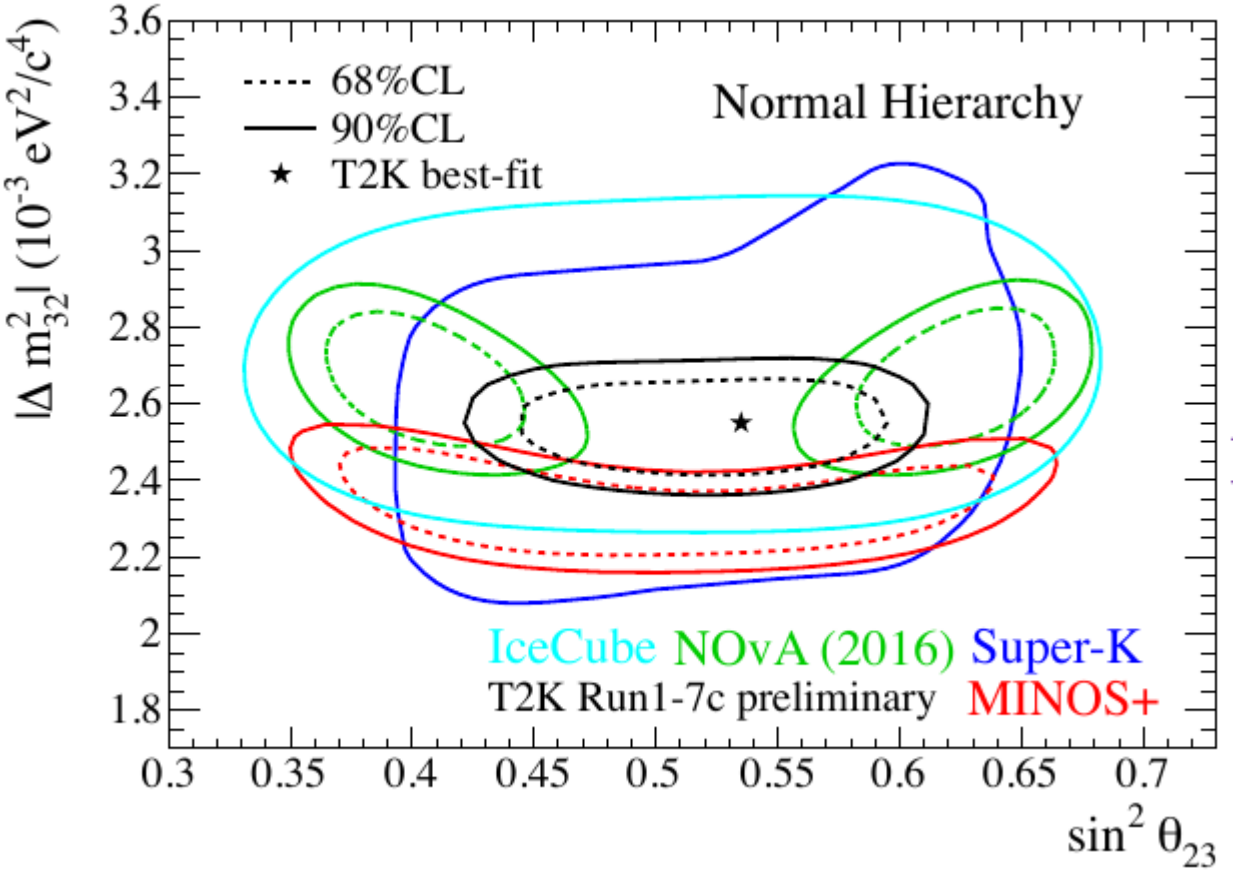
5.3 ev background 23 expected. Main background beam nue, then NC.

19% of full data set: nu/antinu=1

T2K combined ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ analysis



T2K ν_μ disappearance



CP violation effects

$\nu_\mu \rightarrow \nu_e$: beyond the leading term in vacuum

$$P(\nu_\mu \rightarrow \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

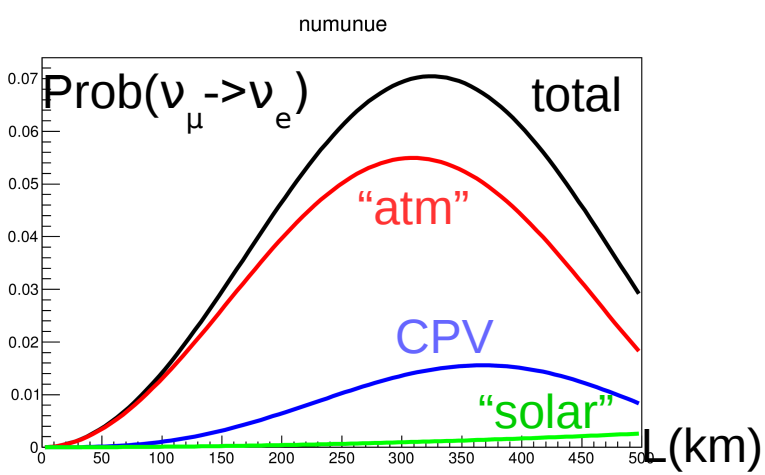
$$\mp 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

$$+4 S^2_{12} C^2_{13} \left(C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta \right) \sin^2 \Phi_{21}$$ "Solar" term

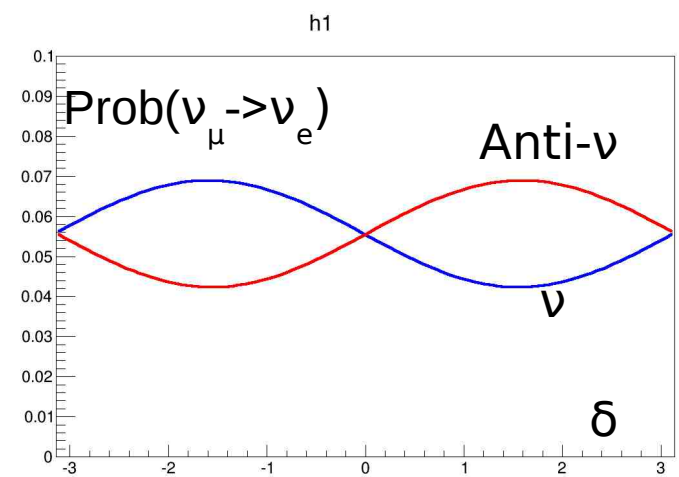
$$C_{ij} = \cos(\theta_{ij})$$

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

Change sign from nu to anti-nu! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced



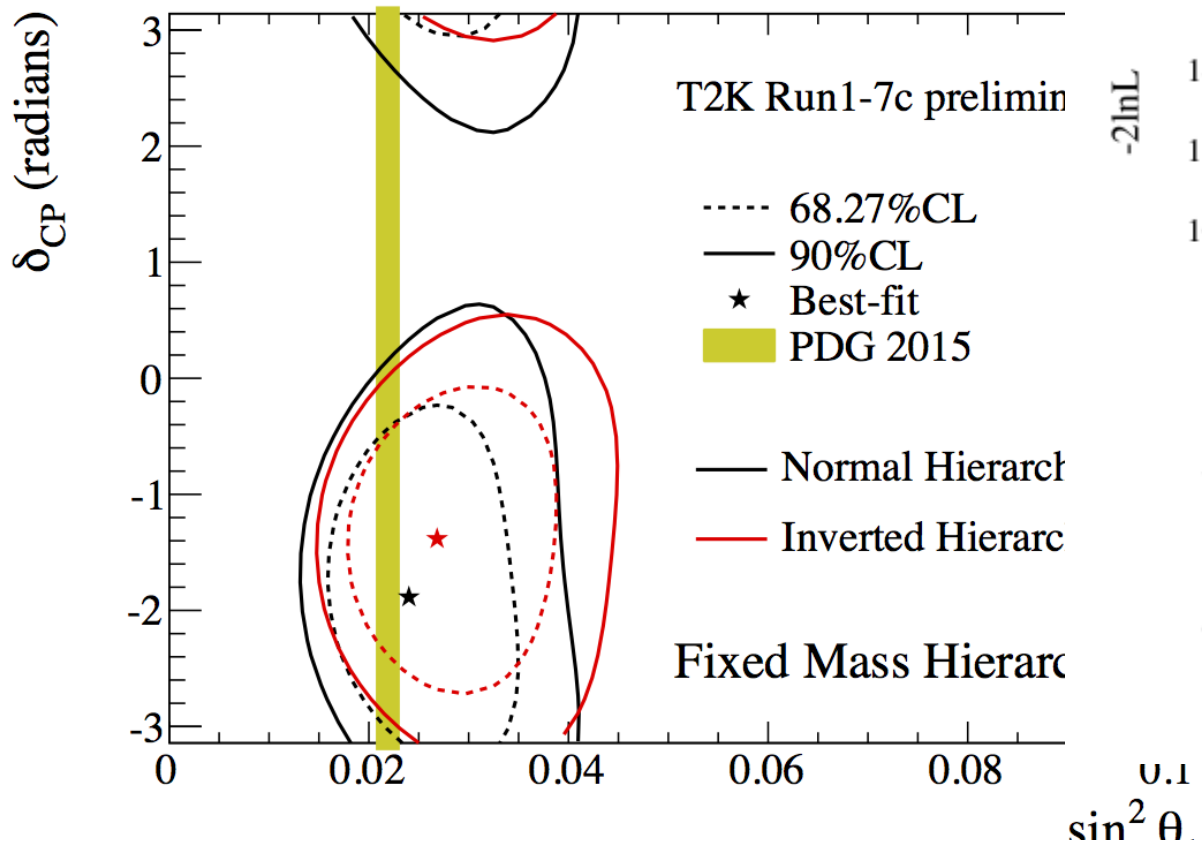
E=0.6 GeV

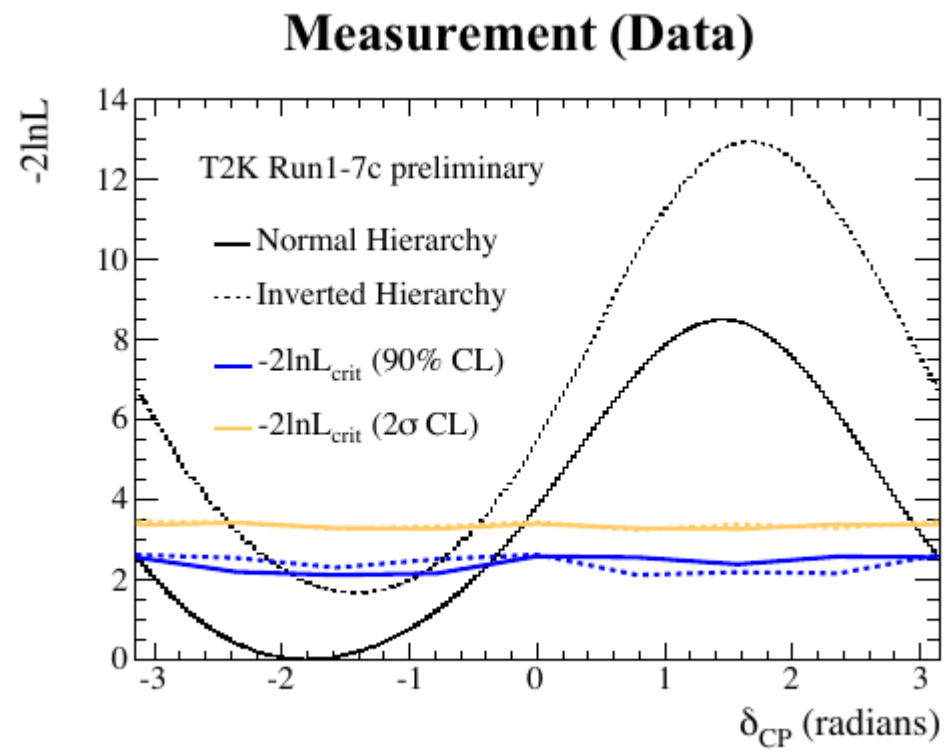


~27% modulation

Caution: indicative plots !!

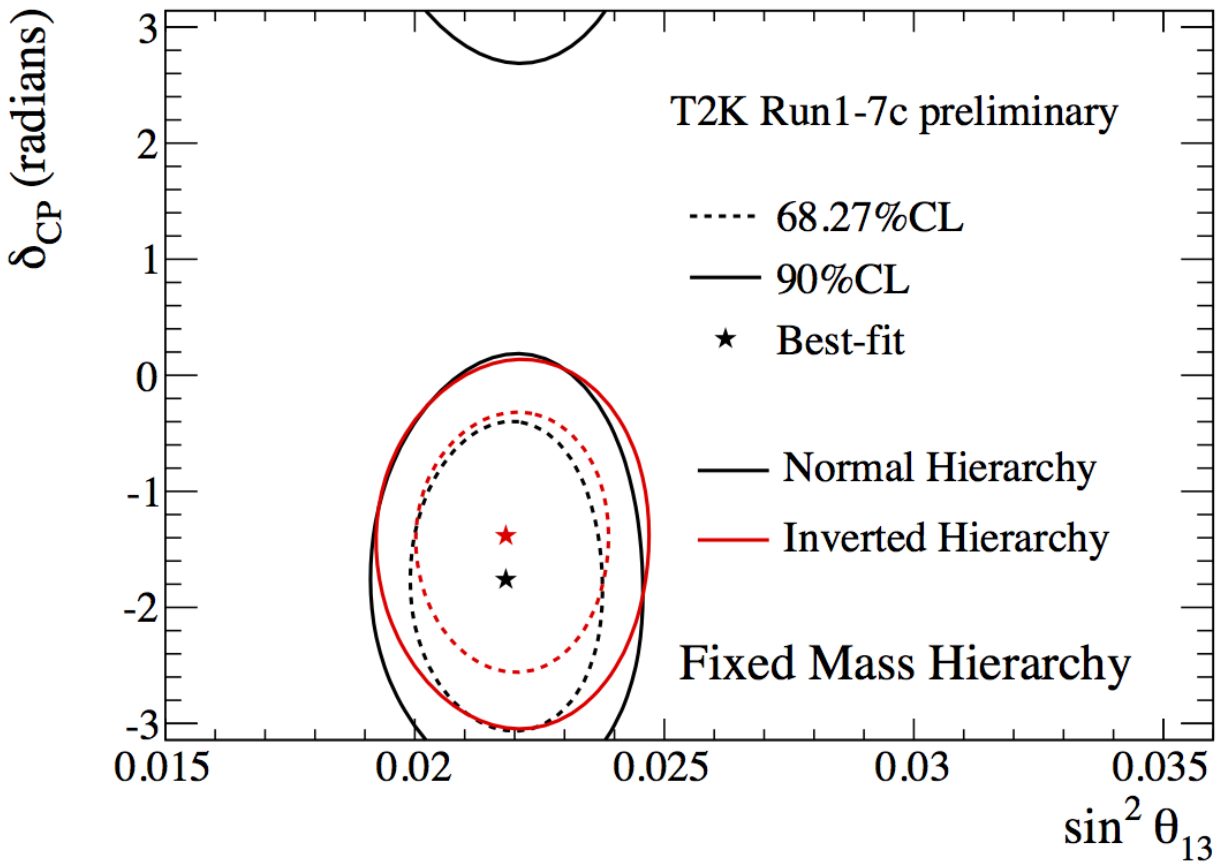
T2K first search for CP violation



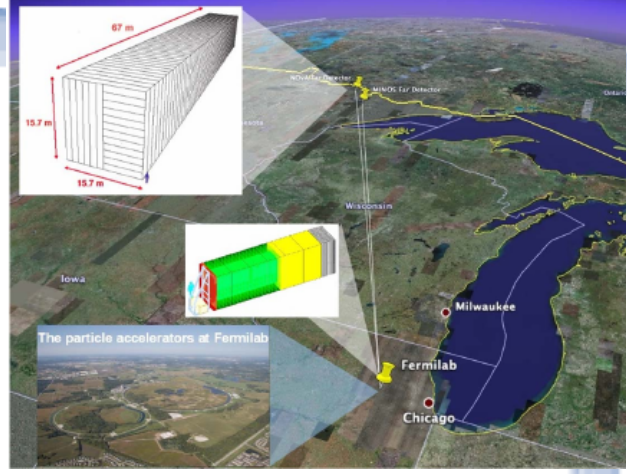


	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

T2K+reactor

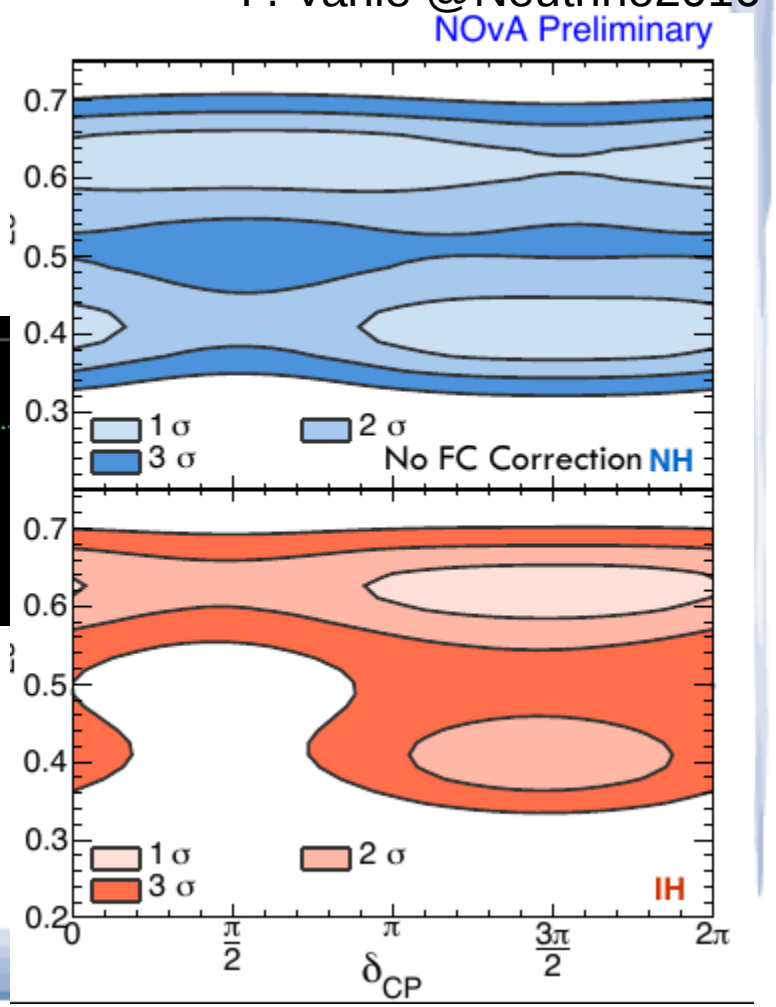

T2K Run1-7c preliminary
68.27%CL
90%CL
Best-fit
Normal Hierarchy
Inverted Hierarchy
Fixed Mass Hierarchy
δ_{CP} (radians)
$\sin^2\theta_{13}$
3
2
1
0
-1
-2
-3
0.015
0.02
0.025
0.03
0.035

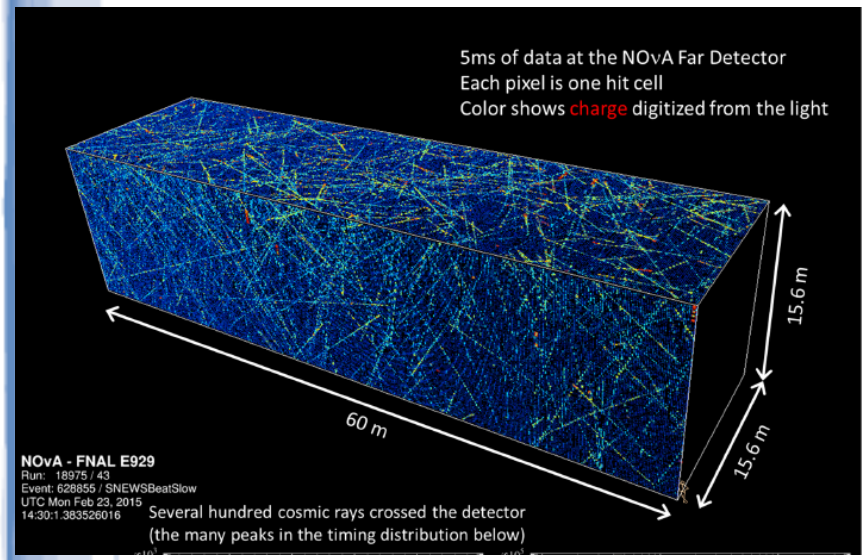
NOvA

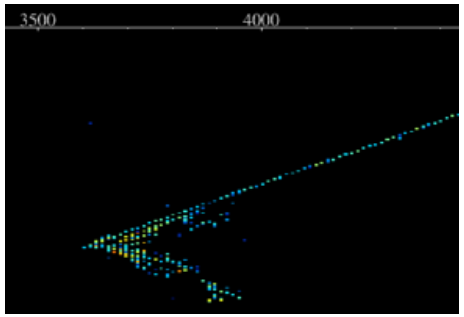


- L=810 km from FNAL to Ash River (Minnesota)
- Off-axis NUMI beam (2 GeV) with 500->700 kW
- 14kt surface liquid scintillator segmented detector
- Weak preference for NH
- Region around delta=π/2 IH excluded

P. Vahle @Neutrino2016



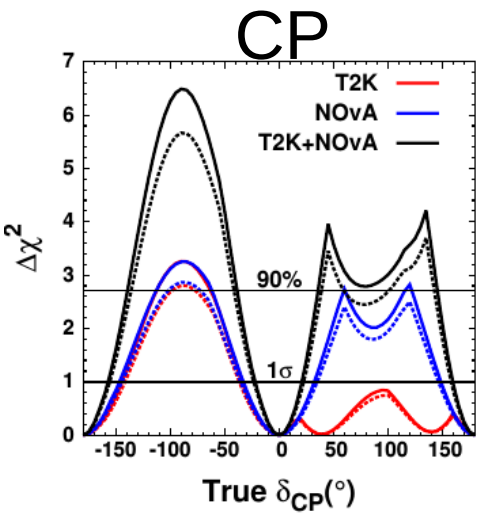




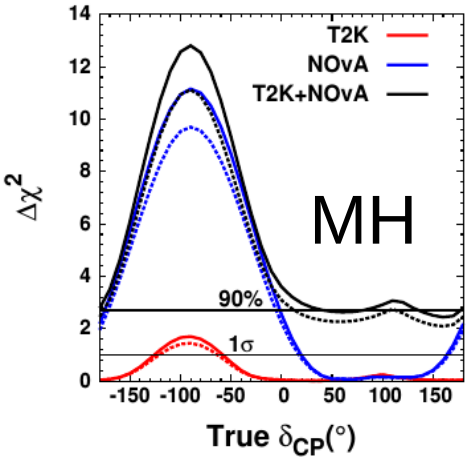
1409.7469

Final reach of T2K and NOvA

- Presently weak indications favoring NH
- Similar sensitivity to CP for T2K and NovA, better sensitivity to MH for NOvA (larger baseline)
- Best sensitivity for δ=-π/2 and NH
- T2K proposes an extension (T2K-II) up to 2026 to increase by ~3 the effective data set
- Might reach 3σ on CP violation around 2021 for a sizable fraction of the parameter space



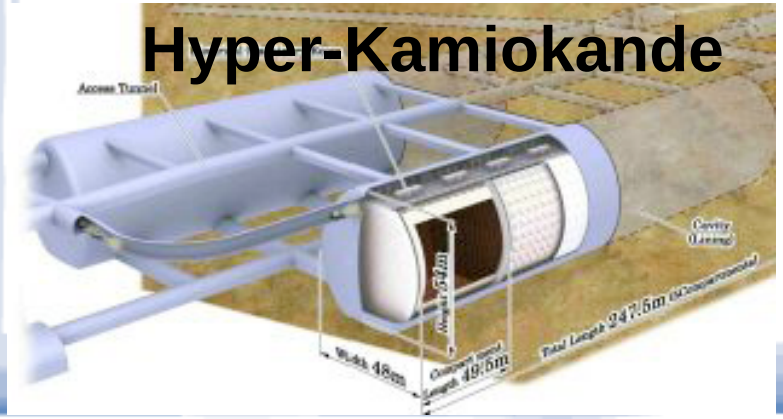
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

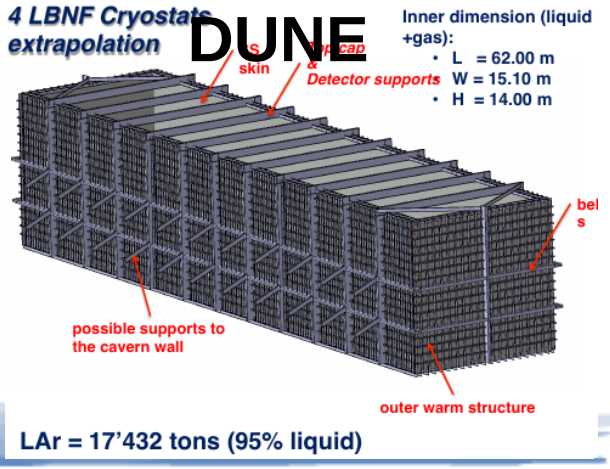


(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

Strategies for CP

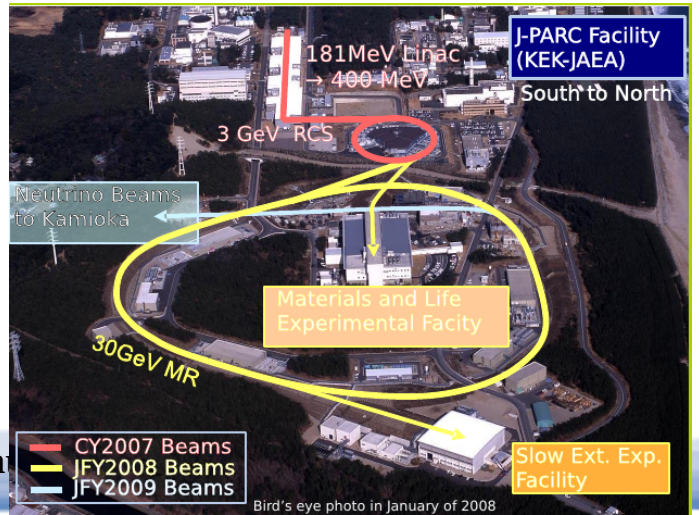
- Short baseline (~100-300 km), lower energy (<1 GeV), narrow beam, large Water Cherenkov (~500 kT). Concentrates on $\nu/\bar{\nu}$ asymmetry around the first oscillation max.
- Longer baseline (>1000 km), higher energy (>1 GeV), wide beam, Liquid Argon TPC. All final states accessible, E/L oscillation pattern and second maximum



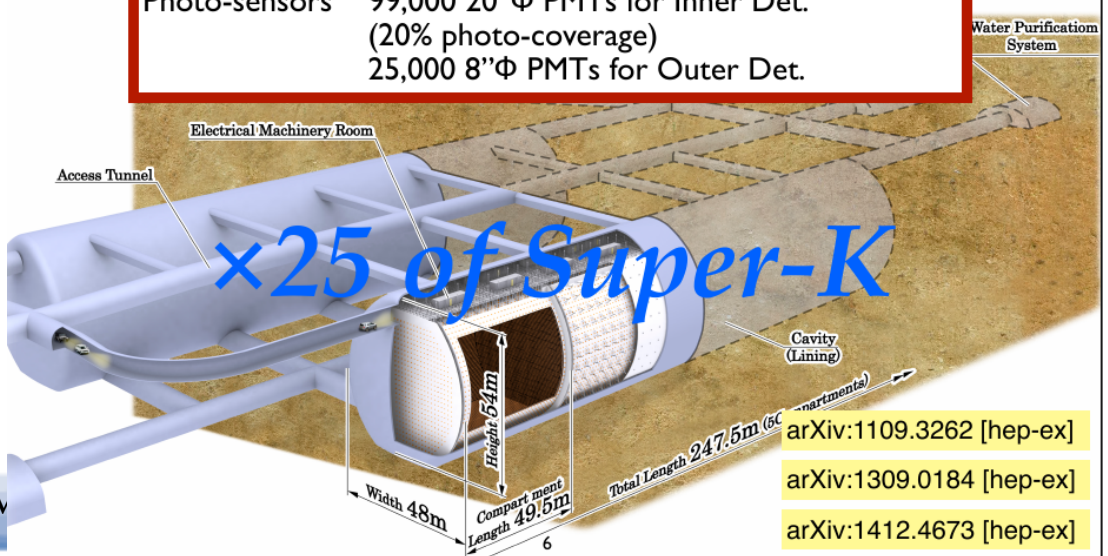


Hyper-Kamiokande

- Tokai to Kamioka 295 km baseline with the same beam as T2K (with possible upgrades)
- 0.56 Mt fiducial mass based on the Water Cherenkov technique
- Selected as top priority in Japanese Master Plan of Large Research Project
- Now preparing the Design Report
- Timescale: data taking in 2025



Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20"Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8"Φ PMTs for Outer Det.



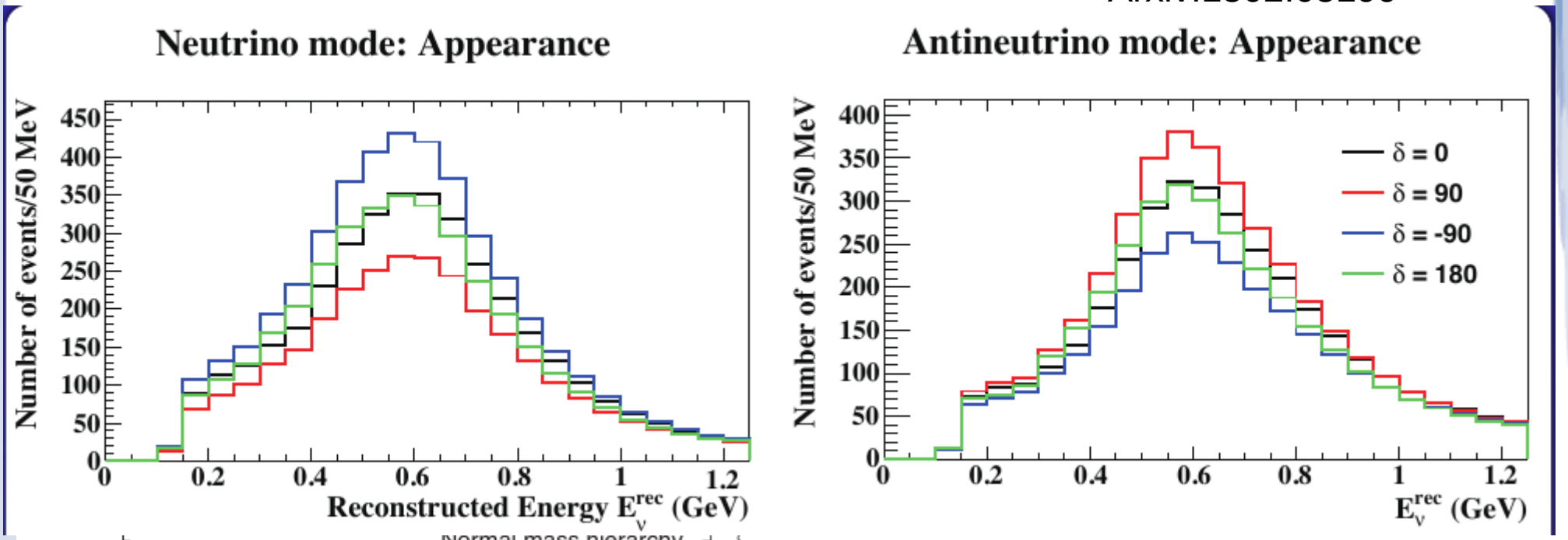
arXiv:1109.3262 [hep-ex]

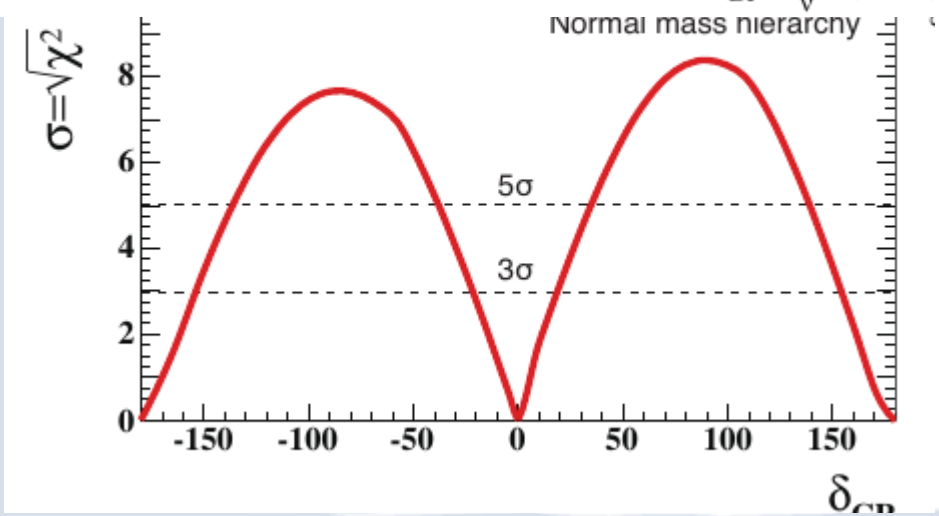
arXiv:1309.0184 [hep-ex]

arXiv:1412.4673 [hep-ex]

Hyper-Kamiokande CP sensitivity

Arxiv:1502.05199

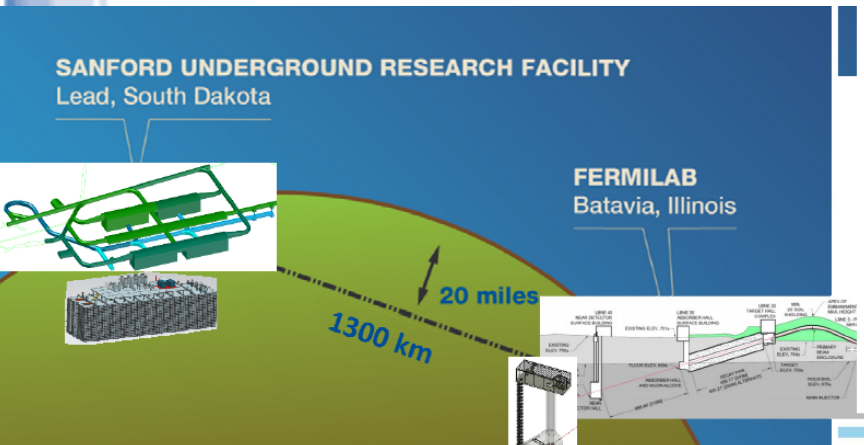




- >3000 ν_e appearance events (nu-mode) with ~700 bck
- Systematics extrapolated from T2K analysis (signal 3% nu mode)
- CPV >3 σ for 76% of δ values

The LBNF/DUNE project

- LBNF DUNE: flagship particle physics project in the US (P5 recommendation)
- 1300 km baseline from FNAL to SURF (South Dakota)
- Based on PIP-II upgrade to FNAL accelerator complex: 1.2 MW at 120 GeV (ultimate beam power 2.4 MW)
- Sophisticated near detector(s) on FNAL site
- SURF: 4 caverns with 4x10 kt fiducial mass far detector

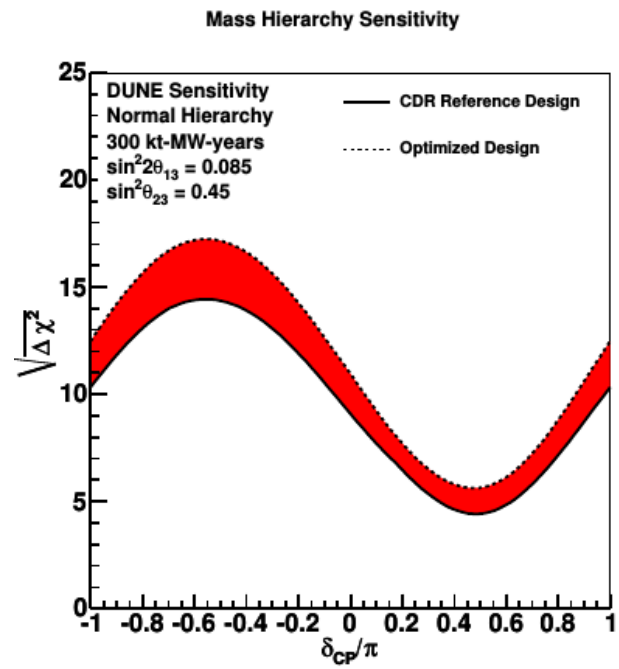


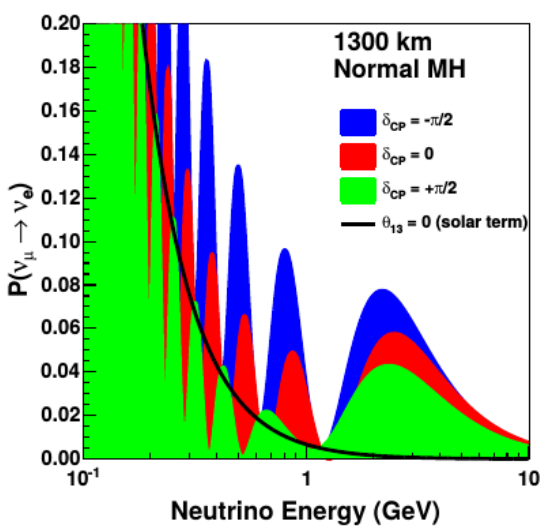
CDR released last July: CD1 passed, CD3-a (excavation) ~OK. CD2 in 2019.
LBNF LOI: deployment of first 10kt module in 2021
Collaboration strengthened (>700) and more international (India, CERN, Laguna-LBNO)

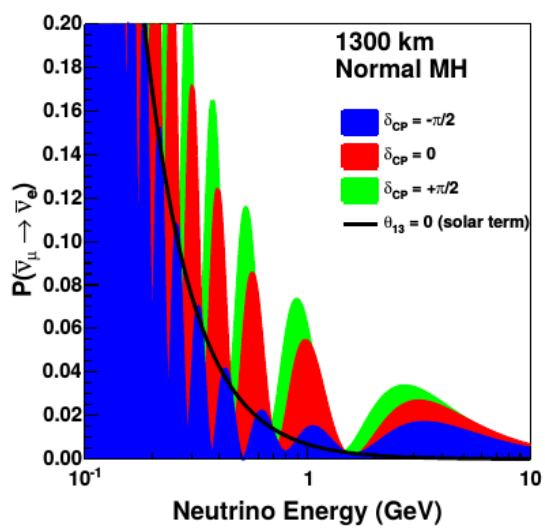
ArXiv:1512.06148

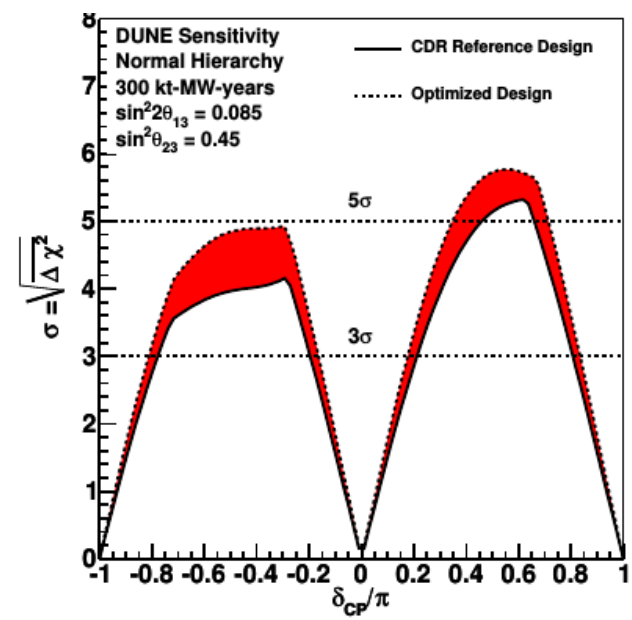
LBNF/DUNE sensitivity

- >3 σ for CP sensitivity over a large fraction of the phase space
- >5 "σ" for Mass Ordering
- 300 kt-MW-years = 3.5 (nu)+3.5 antinu) with 40kt and 1.07 MW beam (80 GeV)









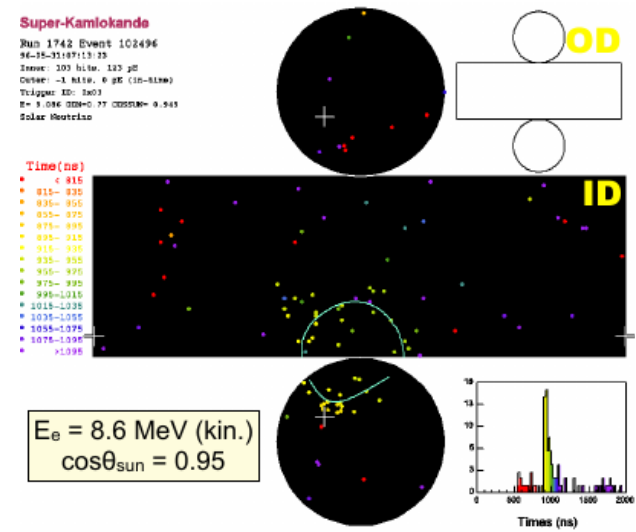
Physics with a very large underground detector

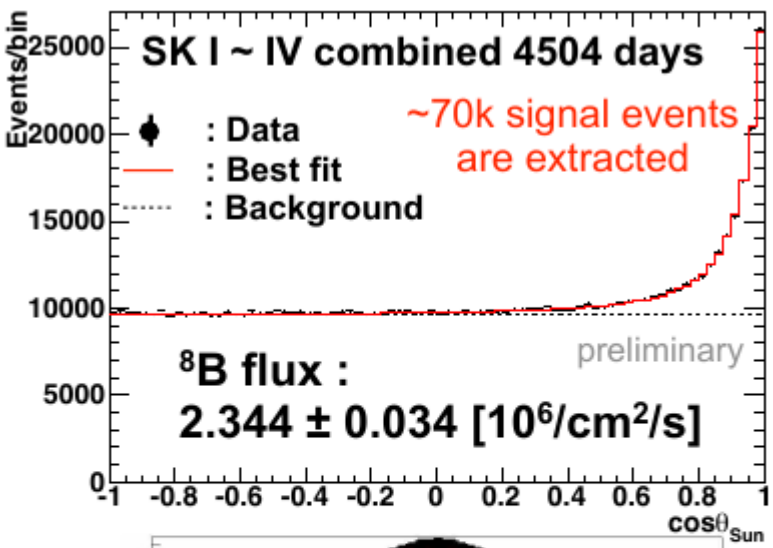
- A large underground detector sensitive to neutrino interactions is an excellent observatory of the neutrino Universe including
  - Solar Neutrinos (at the origin of the discovery of nu oscillations)
  - Atmospheric neutrinos
  - SN neutrinos
  - Proton Decay searches

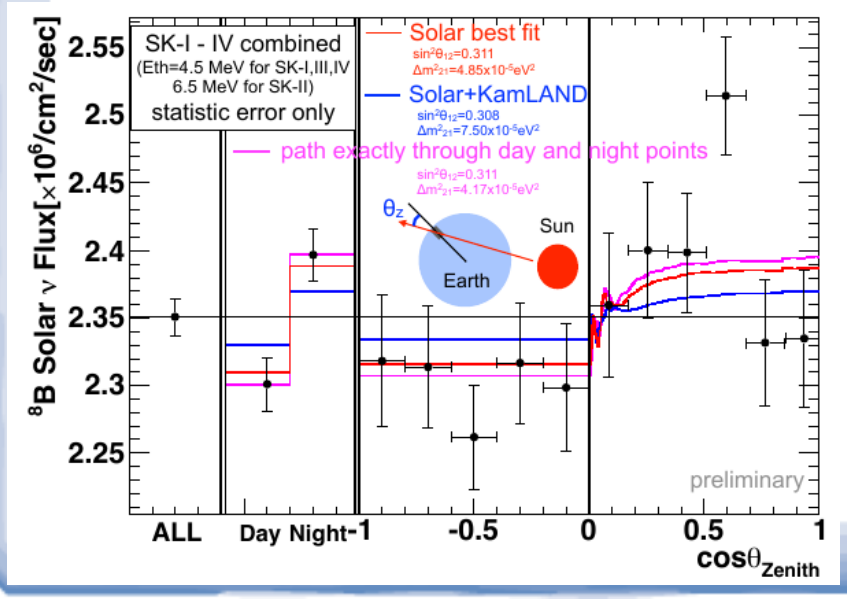
Solar neutrinos

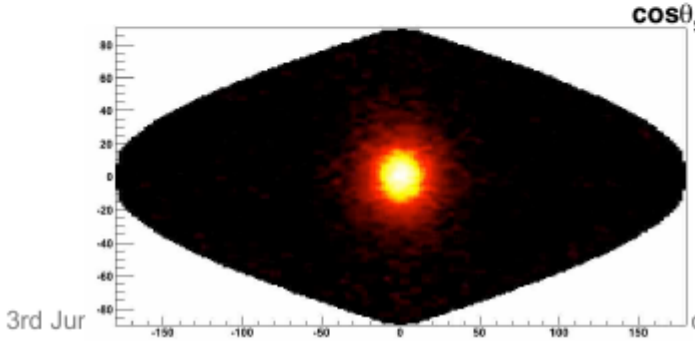
- Super-Kamiokande has observed for the first time solar neutrinos in real time
- These measures contributed to the measurement of solar oscillation parameters
- SK has recently observed day/night effects (similar to the neutral kaon regeneration effect in matter)

Typical event

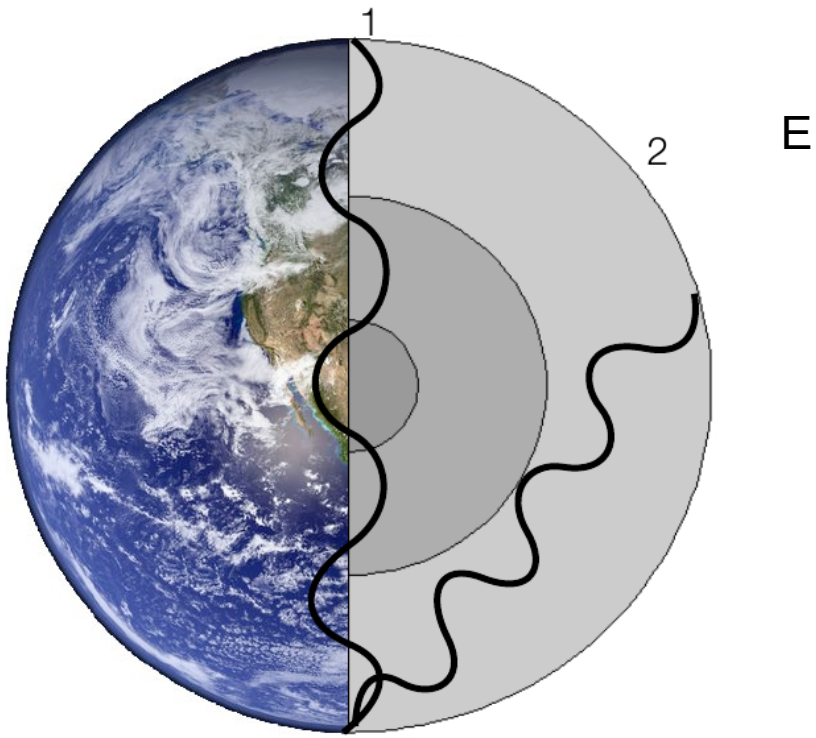




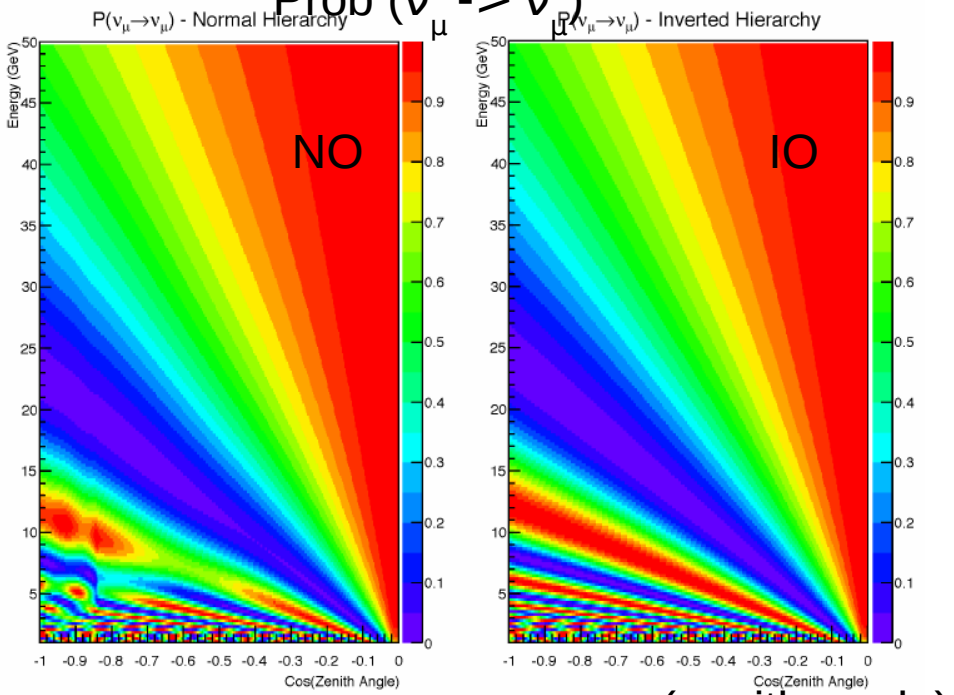




Matter effects for atmospheric neutrinos



Prob (ν_μ -> ν_μ)

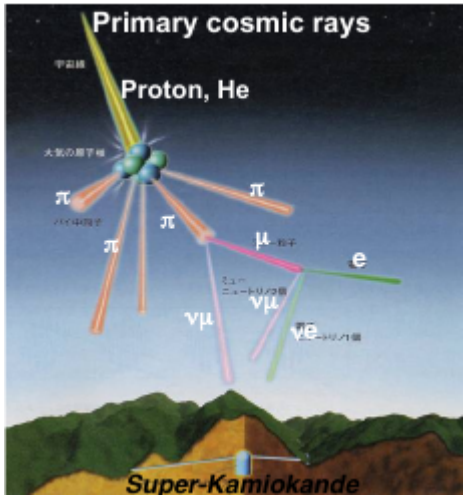


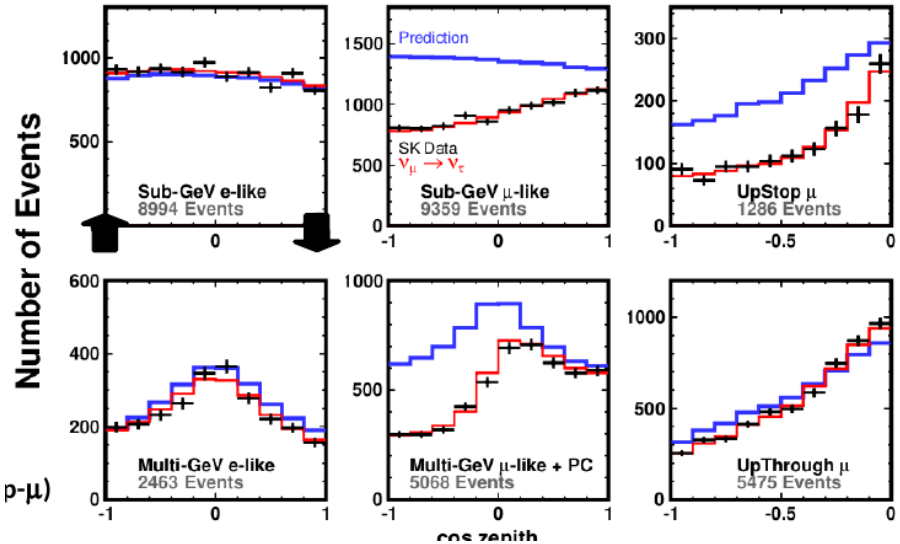
cos(zenith angle)

arXiv:1401.2046

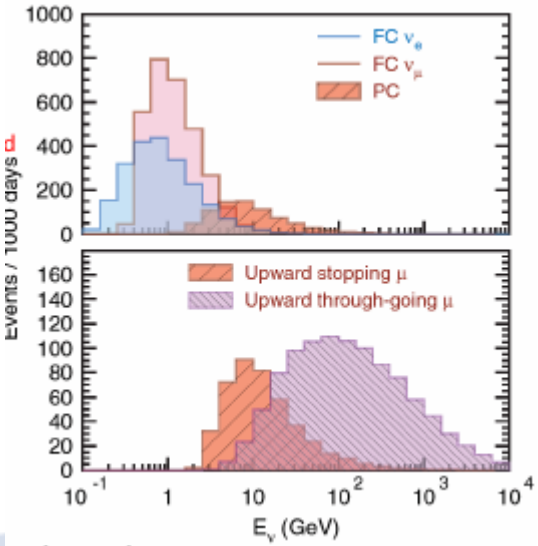
- The matter effect can be studied with atmospheric neutrinos traveling in the mantle or the core (cos theta)<-0.8. Two channels are available: Prob (ν_μ -> ν_e) and Prob (ν_μ -> ν_μ). Max sensitivity below 20 GeV.
- These plots get smeared by angular and energy resolutions.
- Some detectors do not separate neutrinos from antineutrinos and rely on the difference in neutrino and antineutrino cross-sections (additional smearing).

Studies with atmospheric neutrinos



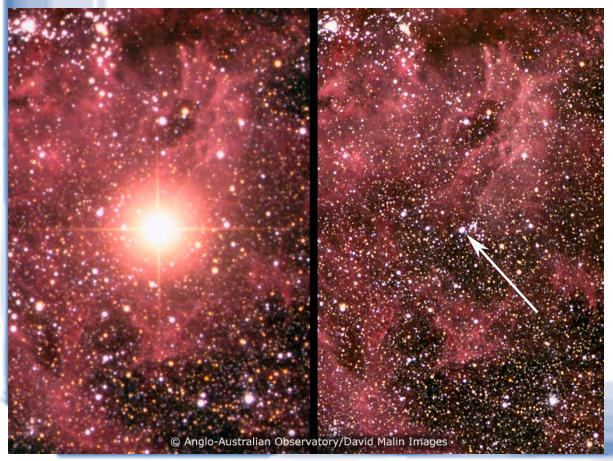


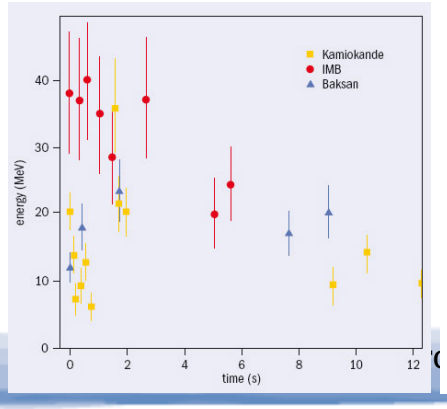
- Atmospheric neutrinos cover a large range in energies and oscillation lenghts
- Recent result: observation of nu_tau
- Current hot analysis: 3 neutrino oscillation fit to all the samples to get some sensitivity to mass ordering and CP violation
- Will improve with Gadolinium allowing to better tag neutrons
- HK: >5 sigma sensitivity to mass ordering

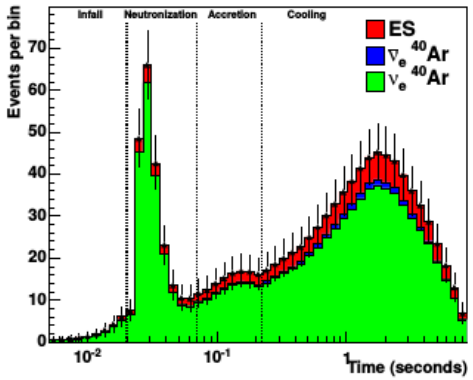


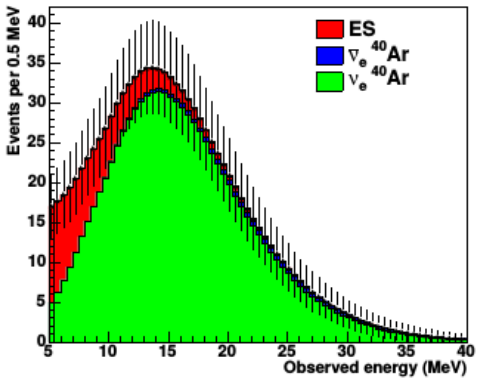
Supernova neutrinos

- Core collapse supernovae are very bright sources of neutrinos (10^{53} erg, 99% of the energy in ν)
- The observation of SN1987A also in neutrino (IMB, Baksan, Kamiokande) was a huge step forward, even though only 25 ν were observed
- In the last 10 years theorists have discovered very interesting collective effects (similar to matter effects, but due to ν ν interactions!)
- The next generation large underground detectors will collect 10^5 events (for a SN in our galaxy) and will therefore provide many detailed informations to help understand these explosions

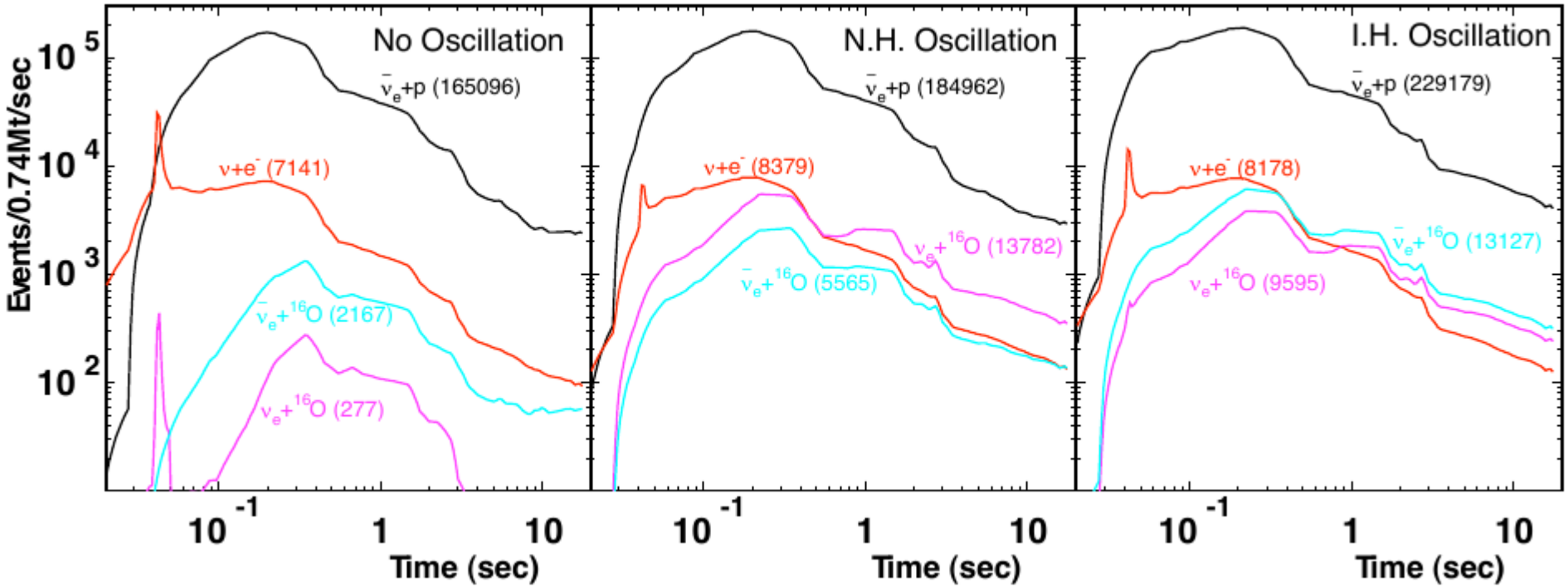








How a SN could be observed by HK

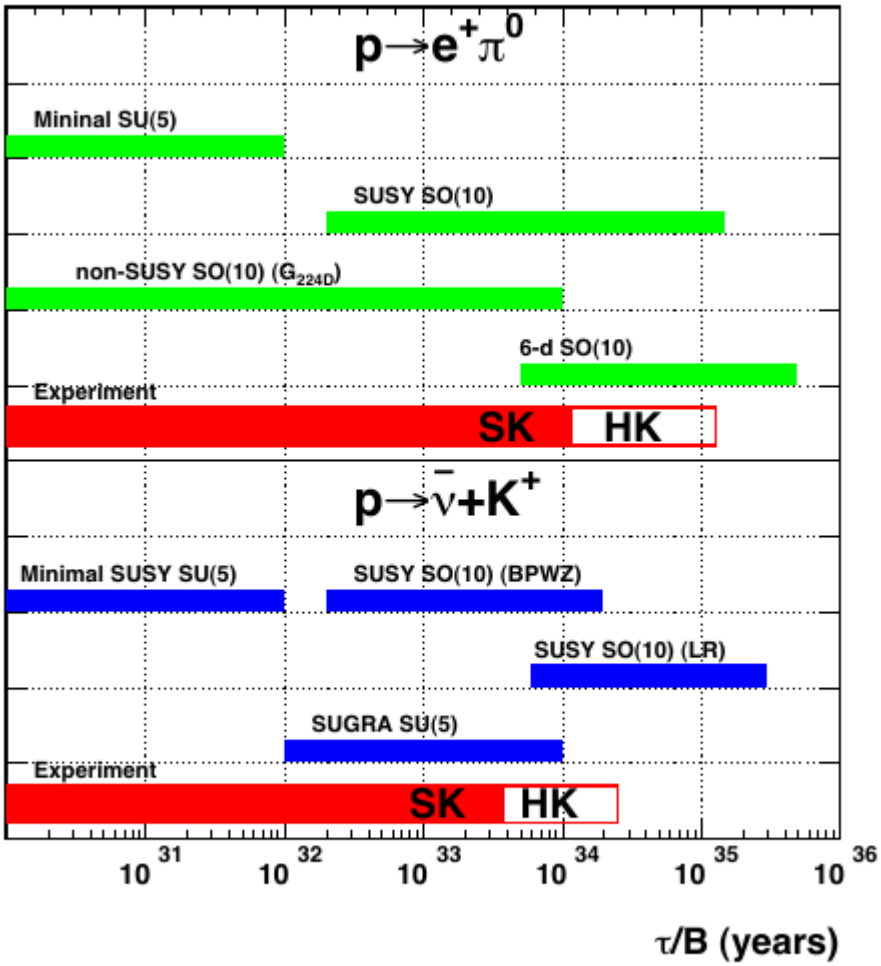


Proton decay searches

- Grand Unified theories predict that the proton is unstable with lifetime~10^{25}-10^{32} years
- The favored decay mode is p-> e+ π° (ideally suited for a large Water Cherenkov detector)
- Large detectors were built in the 80's (among which Fréjus, IMB, Kamiokande) to study this and ruled out SU(5) models
- However other GUT models are still viable and predict other decay modes like $p \rightarrow \nu K^+$
- HK and DUNE will have sensitivities up to ~10^{35} years

Proton decay searches

Mode	Sensitivity (90% CL)	Current limit
$p \to e^+\pi^0$	13×10^{34} years	1.3×10^{34} years
$p \to \mu^+\pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+\eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+\rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+\omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+\omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+\pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+\pi^-$	2.9×10^{34}	0.10×10^{34}
$p \to \overline{\nu}K^+$	2.5×10^{34}	0.40×10^{34}



HK LOI arxiv:1209.3262

Example of the physics program of HK

		LOI	2TankHD
LBL (13.5MWyr)	δ precision ($0°,90°$)	7°-19°	7°-21°
	CPV coverage ($3/5\sigma$)	76%/58%	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.015	±0.017
ATM+LBL (10 years)	MH determination ($\sin^2\theta_{23}=0.40$)	$>6.9\sigma$	$>5.3\sigma$
	Octant ($\sin^2\theta_{23}=0.45$)	7.2σ	5.8σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}	1.2×10^{35}
	$\bar{\nu}K^+$ 90%CL	3.5×10^{34}	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KamLAND)	$3.5\sigma/7.5\sigma$	$6\sigma/12\sigma$
	Upturn	Not possible	5.3σ
Supernova	Burst (10kpc)	160k-240k evts	104k-158k
	Nearby galaxies	3~30 events	2~20 events
	Relic (10 yrs)	220evt/5.1σ	154evt/5.3σ

Conclusions

- 1st physics program for LB successfully completed (K2K MINOS OPERA): oscillation, confirmation of measurements with atm. ν
- 2nd part still ongoing (T2K NOVA): first hints of CP violation ! mass ordering in the next 5-10 years
- Next generation: HyperKamiokande, DUNE starting ~2026
- Rich non-accelerator physics program with large underground detectors