Accelerator neutrino beams and precision measurements of the PMNS matrix

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Plan of the lectures

These lectures are aimed at understanding experimental neutrino physics after the discovery of θ_{13} – the so-called "precision era" of neutrino oscillations, whose goal is the full determination of the lepton Yukawa sector of the Standard Model: all masses and mixings except the lightest mass eigenstates and Majorana phases (if any)

- Why did the discovery of θ_{13} completely reshape neutrino oscillation physics?
- The tools of the precision era:
  - "Superbeams": the workhorse of modern neutrino physics
  - High-precision massive detectors
  - High-precision neutrino beams
- Building the neutrino mixing matrix (PMNS) with neutrino beams
- Non-conventional neutrino beams and the quest for "ultimate precision"

The issue solved by a large θ_{13}

See lectures by F. Vissani

We don't have universal ν sources!

$$P_{\nu_\alpha\to\nu_\beta}(t) = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2$$
$$= \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{4E}\right),$$

No guarantee that the oscillation frequencies are matched with terrestrial distances

Three family interference effects («beatings») might be unobservable

The matrix elements might be very small (in fact, they are in the CKM matrix)

where $\Delta m^2_{ij} = m^2_i - m^2_j$ and we can rewrite:

$$\frac{\Delta m^2_{ij}L}{4E} \approx 1.267\frac{\Delta m^2_{ij}[eV^2]\times L[km]}{E[GeV]}.$$

There is no reason why the lepton Yukawa sector of the Standard Model should be observable using terrestrial neutrino sources (neutrino beams, atmospheric neutrinos, reactor neutrinos)

Whoops, sometime physicists are **really** lucky ☺

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} \simeq\; & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
- \; & \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ \; & \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ \; & \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \\
\equiv \; & O_1 + O_2(\delta) + O_3(\delta) + O_4 \; .
\end{aligned}
$$

Year 2005 → «**oscillation phase**» It is O(1) for E= O(1 GeV) and L= O(100 km)
Cool, we can build experiment on Earth ☺

Year 2003 → α must be <1 for perturbation to work. **The larger α the better.**
We know now that is 0.028

Year 2012 → **The larger θ_{13} the better**! It is O(1) in neutrinos! (it is tiny in quarks..)

This formula is the "master formula" of accelerator neutrino physics. It is equivalent to the previous one but it incorporates matter effects for small matter density (the Earth) and far from the MSW resonance.

- It is a first order Taylor expansion in $\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$
- It accounts for "moderate" matter effect corrections to the oscillation phases via $\hat{A} \equiv 2\sqrt{2} G_F n_e E/\Delta m^2_{31}$
- It visualizes the size of three family interference effects (and, hence, CP violation sources) via

$$\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^2 2\theta_{13}$$

Back to real life....

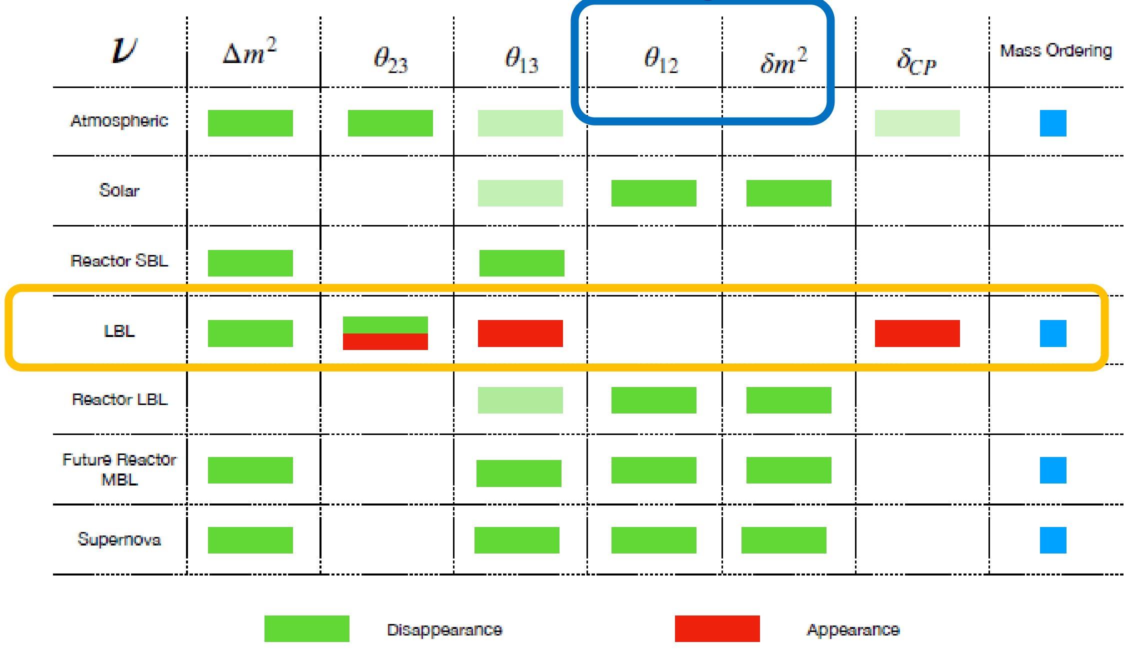
Universal and monochromatic neutrino sources do not exist (yet ☺). Accelerator neutrino beams are their closest approximation but put severe constraints. The most important one is that they cost a fortune...

Accelerator neutrino beams are **mainly ν_μ and anti- ν_μ sources**

Accelerator neutrino beams can operate **in ν_e appearance and disappearance of ν_μ (anti–ν_μ)**

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} \simeq\ & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& - \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

see Yifang Wan's lectures



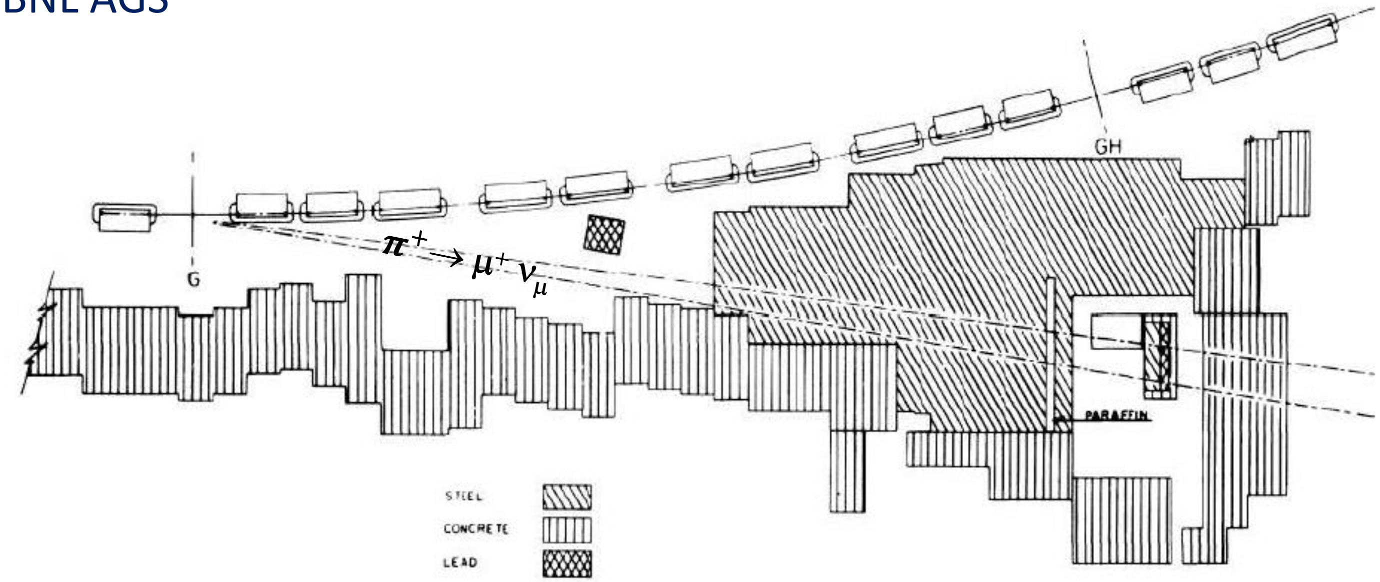
They produce neutrinos in the 0.1-100 GeV and **we mainly focus on O(1 GeV)**

The baseline L has a limited range 10 m – 2000 km and **we mainly focus on 100-1000 km «Long Baseline Experiments» (LBL)**

A bit of history

Original idea by Pontecorvo and Schwartz in 1960. First – remarkable – application in 1962 by Lederman, Schwartz, Steinberger, which brought to the discovery of ν_μ ("neutretto" ☺)

BNL AGS



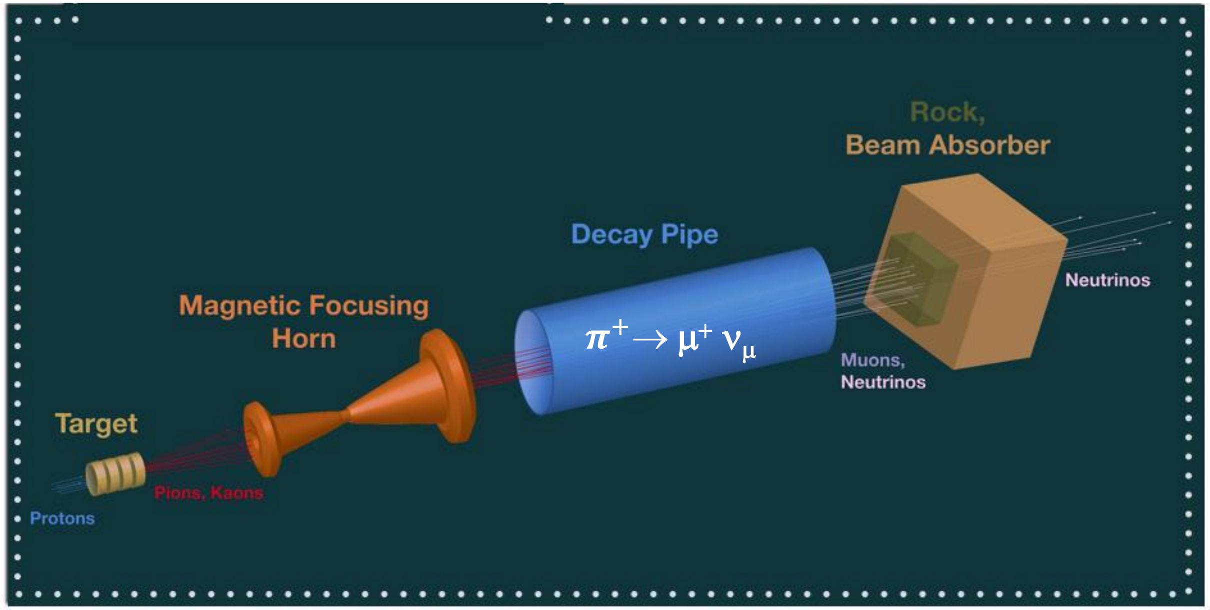
Nobel Prize in Physics 1988

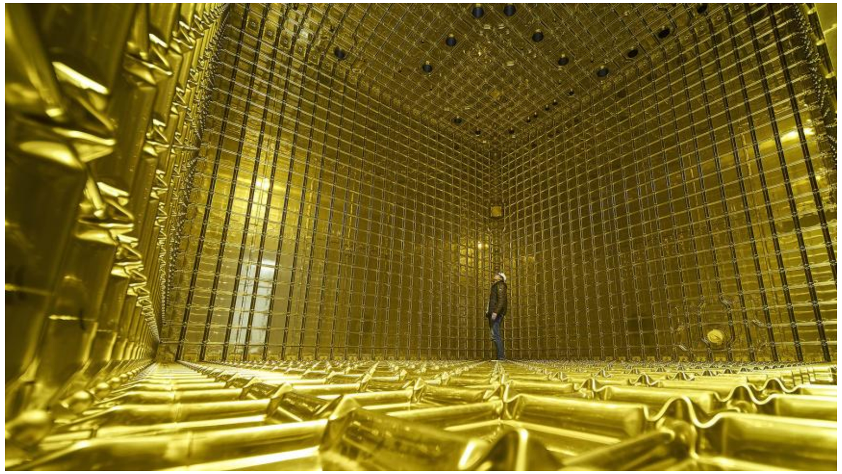
"Bare target experiment": a deflector brings the protons of the accelerator to strike a Be target. All mesons produced at a given angle contribute to the neutrino flux hitting the neutrino detector

The "van der Meer" paradigm

Neutrino beam $\pi^+ \to \mu^+ \nu_\mu$

Antineutrino beam $\pi^- \to \mu^- \overline{\nu}_\mu$





	"Employ the most intense proton accelerator at your disposal"	"Focus as many pions/kaons as possible"	"Eliminate any material along the beamline in the decay tunnel"	"Build the largest possible neutrino detector"
Pros:		Large yield of pions per proton-on-target (pot)	Large number of neutrinos from pion decay	Large statistics of neutrino interaction events (CC and NC)
Drawbacks:		Lack of control on neutrino energy	Coarse beam diagnostics	Limited precision in the final state reconstruction

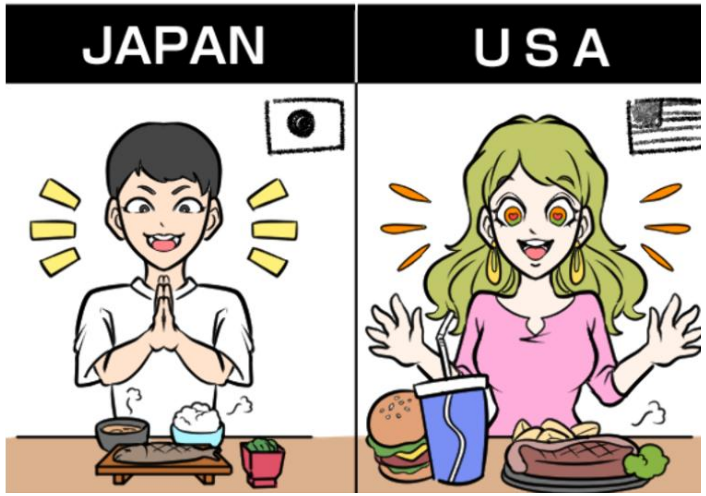
The ideal neutrino beam to measure the PMNS matrix

All modern beams are tuned to maximize the oscillation probability driven by Δm^2_{23} ("atmospheric scale"), which implies "long baselines" since the minimum neutrino energy is >100 MeV and the larger the energy the larger the cross section (see J. Formaggio's lectures)

Employ relatively short baselines (200 km) to minimize matter effect

Pro:
- Outstanding sensitivity to three family interference effects and CP violation
- No matter-related parameters to be disentangled from PMNS
- Simple oscillation probabilities in the proximity of the first oscillation peak

Con:
- no sensitivity to the neutrino mass ordering, which affects the sign of hat-A
- Small neutrino cross section – i.e. huge detector mass



Employ very long baselines (>1000 km) to get large matter effect and high precision neutrino detector to reconstruct the full oscillation pattern

Pro:
- Outstanding sensitivity to mass hierarchy
- Measure "in one shot" all parameters of the PMNS
- Outstanding precision in CP phase

Con:
- Smaller detector mass due to the cost and complexity of the neutrino detector

Anatomy of the van der Meer paradigm: the "proton driver"

We need a proton accelerator ("proton driver") to produce pions and kaons. The main figure of merit (unlike colliders) is **Power** because, at leading order,

- The number of secondary mesons **linearly** grows with the number of proton hitting the target
- The secondary meson yield **linearly** increases with the proton energy (GeV or Joule)

Hence, the meson yield (mesons per second) is proportional to the beam power (n. protons x energy/s)

A note of caution: (nearly) all proton drivers are proto-synchrotrons, hence the protons are accelerated in bunches. The instantaneous power on the target is huge but the meson yield depends on the average power of the machine:

The total number of produced neutrinos is proportional to the **Average power x running time (kW-year)**

The total number of observed neutrinos is proportional to
Average power x running time x detector mass (kW-y-kton)

Examples:

1962 bare target experiment: 1.6×10^{6} pulses ("spills") at an average of 1.9×10^{11} protons-per-pulse at 33 GeV

>2012 CERN-to-Gran Sasso: 9×10^{5} spills-y at an average of 4.5×10^{13} protons-per-pulse at 400 GeV

Anatomy of the van der Meer paradigm: the "proton driver"

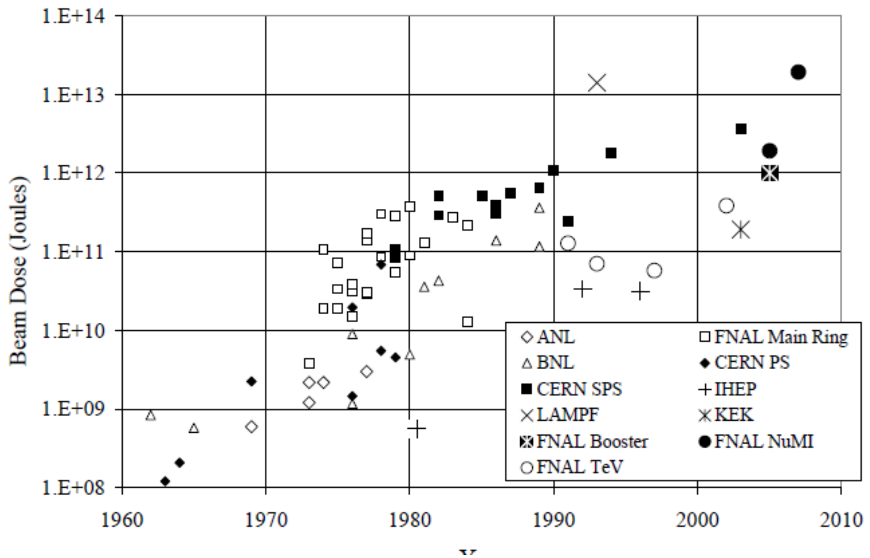
The landscape before the discovery of θ_{13}

Lab	Year	p_0 (GeV/c)	Protons/ Pulse (10^{12})	Secondary Focusing	Dec. Pipe Length (m)	$\langle E_\nu \rangle$ (GeV)	Experiments
ANL	1969	12.4	1.2	1 horn WBB	30	0.5	Spark Chamber
ANL	1970	12.4	1.2	2-horn WBB	30	0.5	12′ BC
BNL	1962	15	0.3	bare target	21	5	Spark Ch. Observation of 2 ν's
BNL	1976	28	8	2-horn WBB	50	1.3	7′ BC, E605, E613, E734, E776
BNL	1980	28	7	2-horn NBB	50	3	7′ BC, E776
CERN	1963	20.6	0.7	1 horn WBB	60	1.5	HLBC, spark ch.
CERN	1969	20.6	0.63	3 horn WBB	60	1.5	HLBC, spark ch.
CERN	1972	26	5	2 horn WBB	60	1.5	GGM, Aachen-Pad.
CERN	1983	19	5	bare target	45	1	CDHS, CHARM
CERN	1977	350	10	dichromatic NBB	290	$50,150^{(a)}$	CDHS, CHARM, BEBC
CERN	1977	350	10	2 horn WBB	290	20	GGM,CDHS, CHARM, BEBC
CERN	1995	450	11	2 horn WBB	290	20	NOMAD, CHORUS
CERN	2006	450	50	2 horn WBB	998	20	OPERA, ICARUS
FNAL	1975	300, 400	10	bare target	350	40	HPWF
FNAL	1975	300, 400	10	Quad. Trip., SSBT	350	$50,180^{(a)}$	CITF, HPWF
FNAL	1974	300	10	dichromatic NBB	400	$50, 180^{(a)}$	CITF, HPWF, 15′ BC
FNAL	1979	400	10	2-horn WBB	400	25	15′ BC
FNAL	1976	350	13	1-horn WBB	400	100	HPWF, 15′ BC
FNAL	1991	800	10	Quad Trip.	400	90, 260	15′ BC, CCFRR
FNAL	1998	800	12	SSQT WBB	400	70, 180	NuTeV exp't
FNAL	2002	8	4.5	1-horn WBB	50	1	MiniBooNE
FNAL	2005	120	32	2-horn WBB	675	$4\text{-}15^{(b)}$	MINOS, MINERνA
FNAL	2009	120	70	2-horn NBB	675	2	NOνA off-axis
IHEP	1977	70	10	4 horn WBB	140	4	SKAT, JINR
JPARC	2009	40	300	3 horn NBB	140	0.8	Super K off-axis
KEK	1998	12	5	2 horn WBB	200	0.8	K2K long baseline osc.

(a) pion and kaon peaks in the momentum-selected channel (b) tunable WBB energy spectrum.

Anatomy of the van der Meer paradigm: the “proton driver”

The discovery of θ_{13} set the scale for the ”right” proton driver. 2012-like drivers were not enough powerful, but not too far...



Why?

- Δm^2_{23} says that we need to locate our detector at L=100-1000 km to see the first oscillation peak for O(1 GeV) ν_μ
- The neutrino flux decreases like $1/L^2$ (see later)
- The CERN-to-Gran Sasso beam had sensitivity to see oscillation terms proportional to $\sin^2 2\theta_{23}$ = O(1)
- We need to see terms proportional to $\sin^2 2\theta_{23}$ = O(0.1) **and better**

$$P(\nu_\mu \to \nu_\tau) \simeq \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta_{32}$$

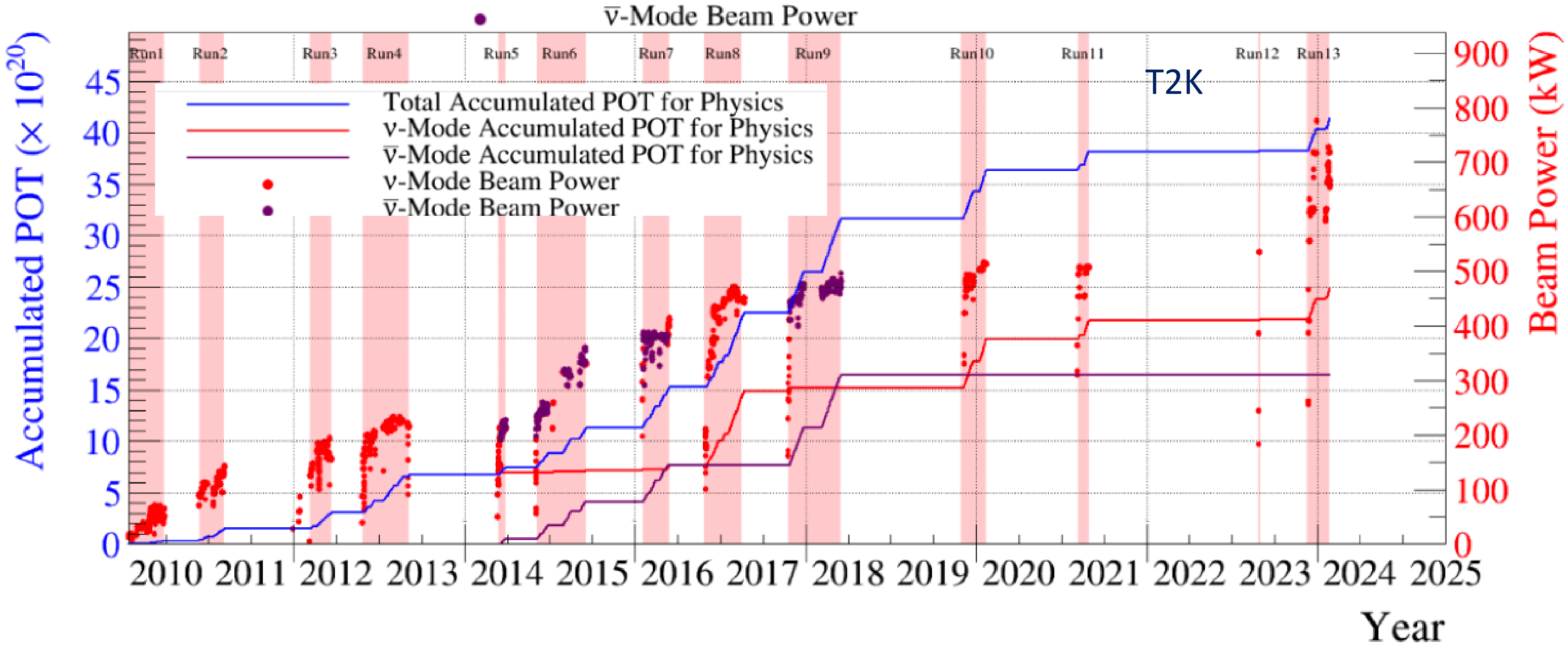
Conclusions:

- **You need at least one order of magnitude more power than CNGS to see $\nu_\mu \rightarrow \nu_e$ oscillations**
- **You need nearly two orders of magnitude to see CP violation effects**
- **Seeing the O_4 term of the master formula (“solar scale”) is hopeless**

$$\begin{aligned}
P_{\nu_\mu\to\nu_e} \simeq\; & \sin^2 2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& - \alpha\sin 2\theta_{13}\,\xi\sin\delta\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha\sin 2\theta_{13}\,\xi\cos\delta\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \\
\equiv\; & O_1 + O_2(\delta) + O_3(\delta) + O_4\,.
\end{aligned}$$

The Superbeam era

The discovery of θ_{13} opened up the “Superbeam era”, which address the O_1 term of the master formula (T2K, NoVA) and is going to address the O_2 and O_3 terms starting from 2028 (HyperKamiokande and DUNE)

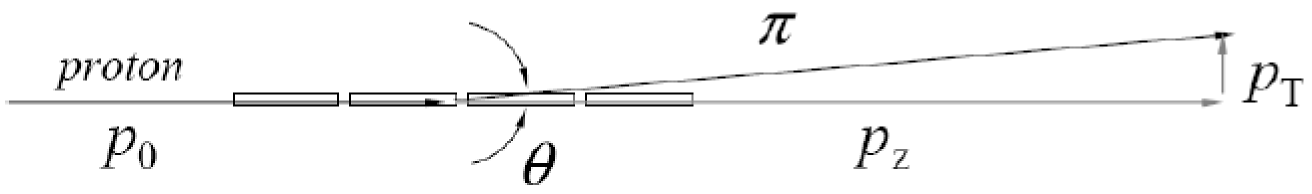


Proton energy	time between spills	spill length	protons-spill	Power
30 GeV (JPARC)	2.48 s	10 μs	>2.65 x 10^{14}	>512 kW

The target

The ideal target:

- has a small interaction length to have all protons interacting in the target and produce mesons → Beryllium rods for "low" power beams
- has a geometry that minimizes meson reinteraction
- can stand the proton instantaneous power (GW!) without mechanical deformation and overheating. → Graphite with special cooling for Superbeams

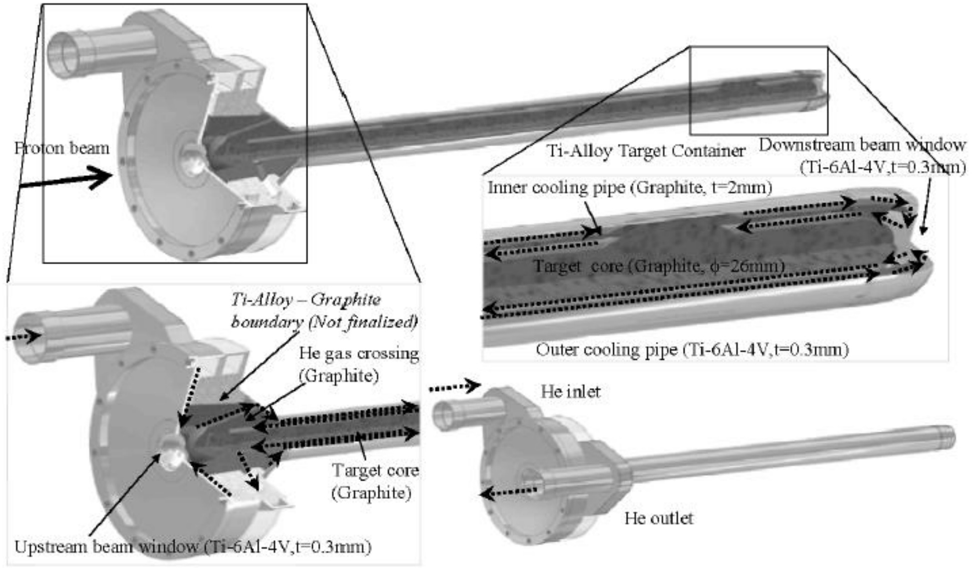


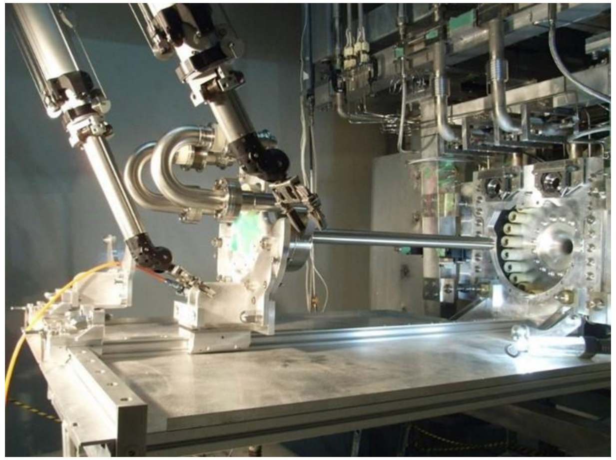
p_0 (GeV/c)	$\langle n_\pi \rangle$	$\langle p_T \rangle$ (MeV/c)	K/π
10	0.68	389	0.061
20	1.29	379	0.078
40	2.19	372	0.087
80	3.50	370	0.091
120	4.60	369	0.093
450	10.8	368	0.098

Note that the average number of pions goes like $p^{0.7}$ so linear scaling is just an approximation

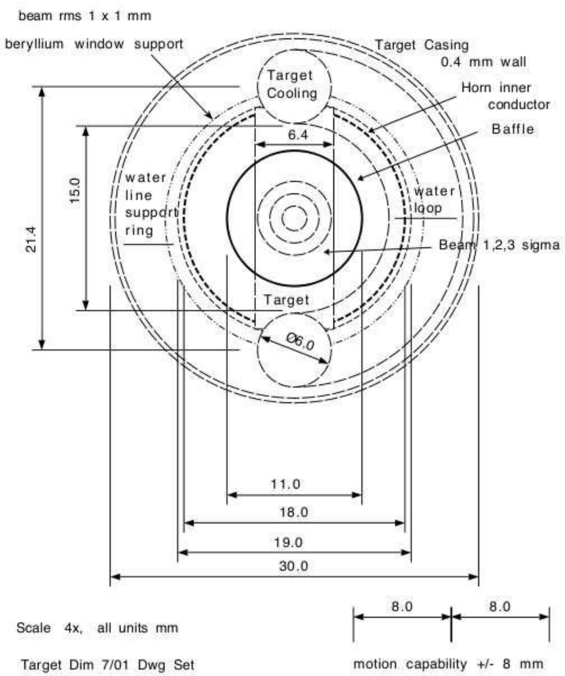
The target

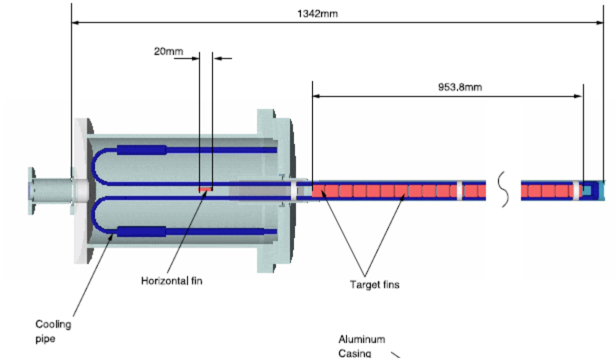
The target design is quite similar in all Superbeams but there are differences in cooling



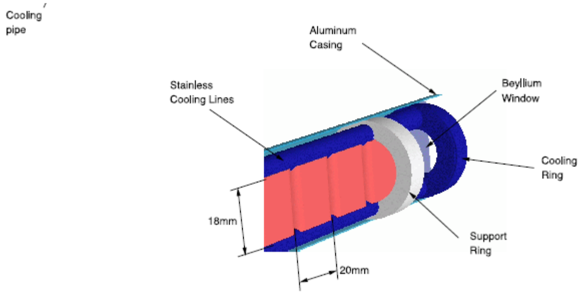


JPARC/T2K





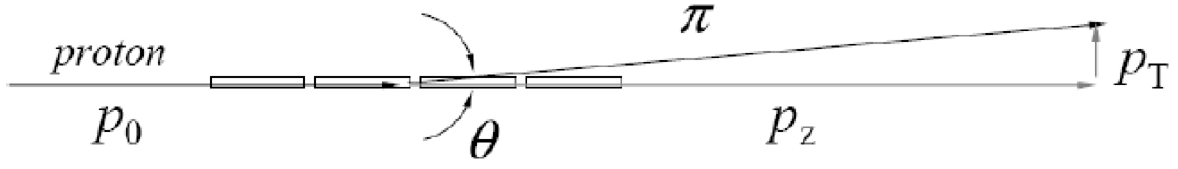
NuMI/NOvA



More aggressive designs have been proposed and tested for power >2 MW (neutrino factories, ESSnuSB) but we stick to “conventional targets” in these lectures

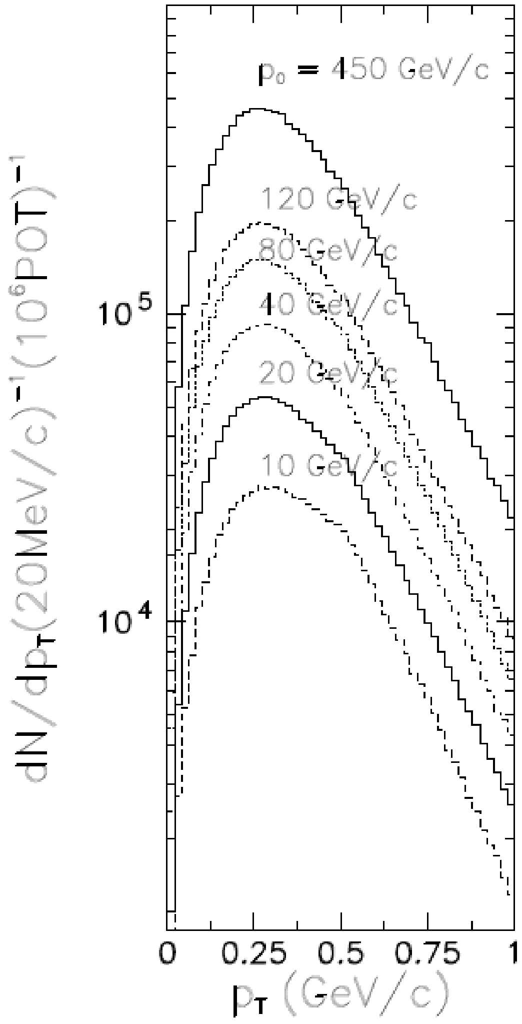
Power is nothing without... focusing ☺

The outgoing particles from target have a huge emittance and standard focusing systems used in accelerators simply do not work. Van der Meer provided the key technology that established the current paradigm: the **magnetic horn** (or **focusing horn**, or **van der Meer horn**)



The Fermi momentum inside the nucleus is about 200 MeV/N. Its transverse component is Lorentz invariant. Hence,

- The production spectrum in transverse momentum is independent on the "Feynman-x", i.e. $p_z/p_{z\,max}$.
- Its peak is around 250 MeV independently of p_0
- The pion momentum scales with p_0
- The pion yield (n. of pion per proton) scales nearly as p_0



That's great news:

- Cross sections factorize!
- our focusing system must remove p_T, which does not rapidly increase with pion momentum!

$$\frac{d^2N}{dx_F dp_T} \approx f(x_F)g(p_T)$$

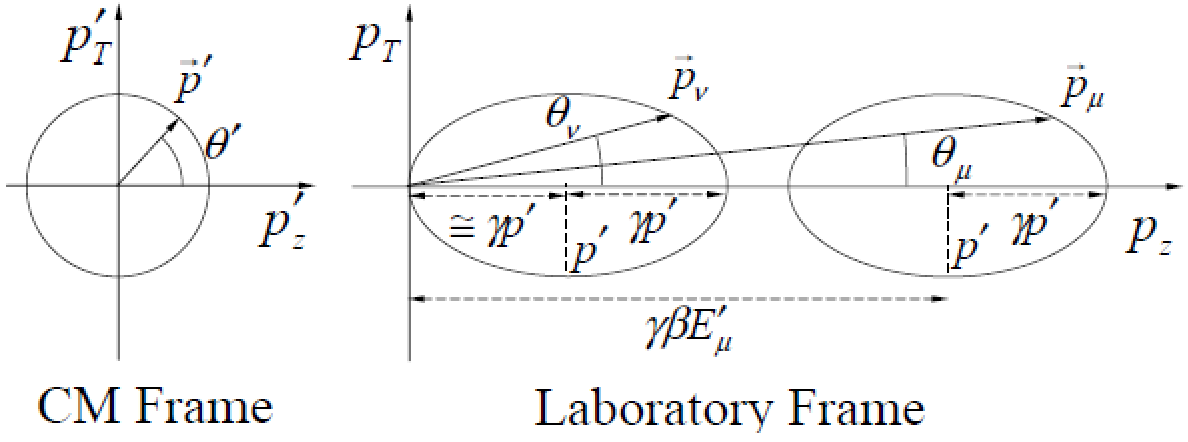
nearly constant

Why focusing?

Pion exhibits an isotropic two-body decay in the rest frame.

$$\gamma \tan\theta = \frac{\sin\theta'}{\cos\theta' + (\beta/\beta')}$$

$$\theta_\nu^{\max} \sim 1/\gamma$$



The pion flux in the detector (A detector front face, z, detector distance) is:

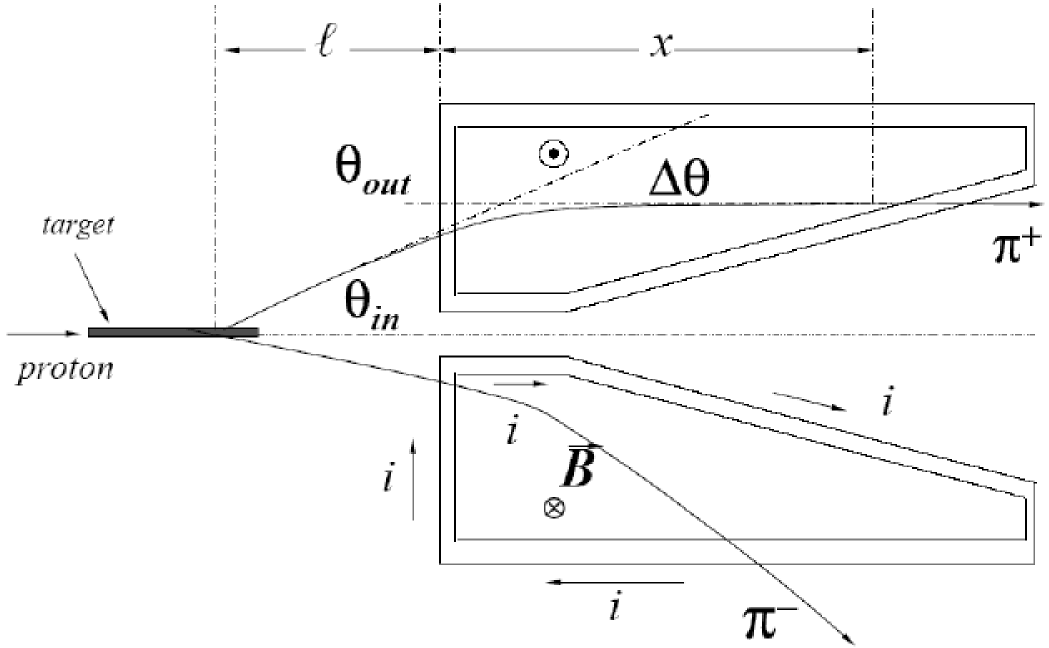
$$\phi_\nu = \frac{A}{4\pi z^2}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

If we don't focus, we will waste a lot of neutrinos (*): $\theta_\pi \approx p_T/p_\pi \approx \langle p_T\rangle/p = 280\mathrm{MeV}/p_\pi = 2/\gamma$

(*) This angle of the pions off the target is larger than the typical angle of neutrinos from pion decay, ~ 1/γ, so is important to correct. Perfect focusing of pions should, in this simple model, improve the flux of neutrinos by ~ 25.

The simpler magnetic horn

In its original design (1961), a conical magnetic horn is a metal conductor where current flows inside the walls. It focuses positive (negative) pions depending on the current direction.



"p_T kick"

$$\Delta\theta = \frac{Bx}{p} = \frac{\mu_0 I}{2\pi r}\frac{x}{p}$$

A focused pion is one in which $\theta_{out} = 0$, or in other words the p_T kick cancels the incident angle of the pion into the horn. A conical horn is set to focus "the most likely" pion angle $\theta_{in} = \langle p_T \rangle / p_0$

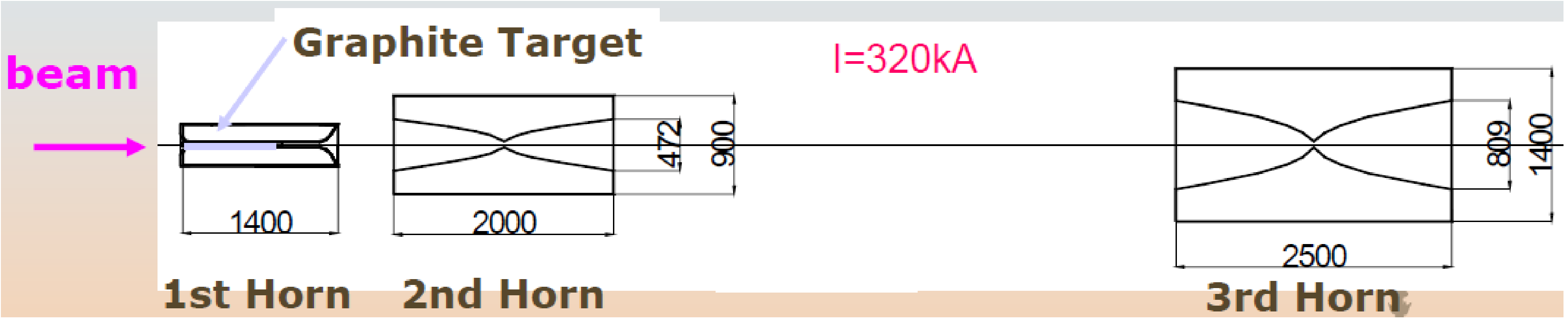
Modern horns are based on the same concept, but the geometry is slightly more complicated ("parabolic horns" – Budker 1961) and we employ multiple horns.

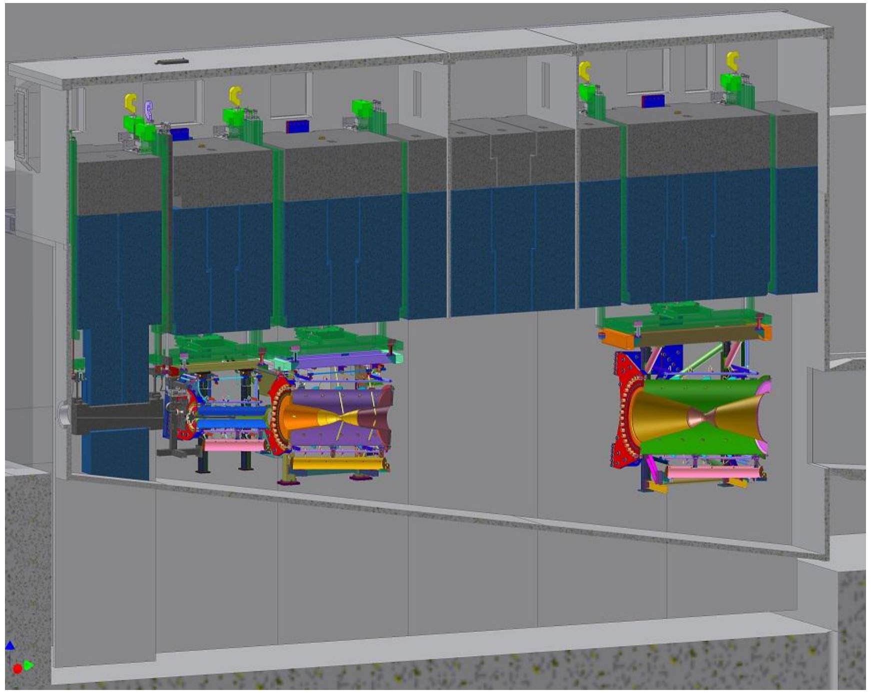
Parabolic horn: focus all angles – not only the most likely θ_{in} – at the expenses of a stronger dependence on p_π ("chromatic dependence")

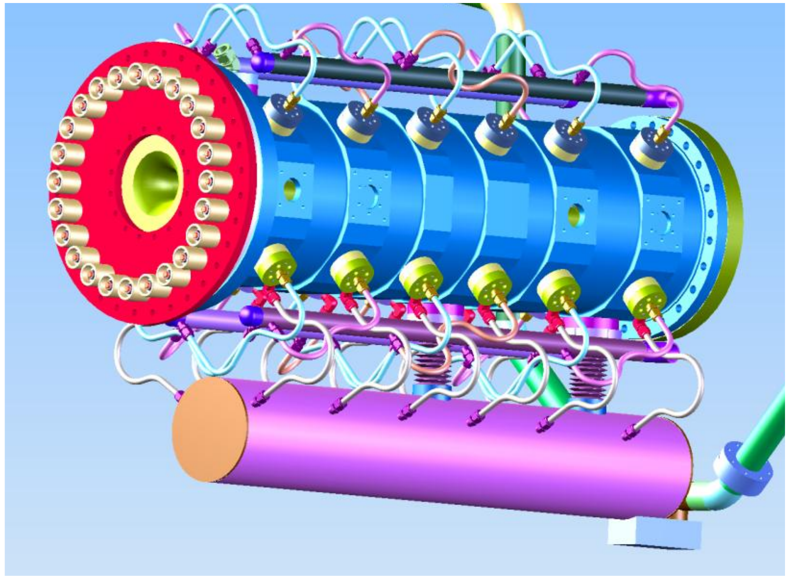
Multiple parabolic horns: mitigate the chromatic dependence

Magnetic horns

Modern horns are pulsed for a short time (peak 100 μs, current flowing for 2-3 ms) to mitigate Joule heating since the currents are huge (about 300 kA). In T2K, water cooling is used for the inner conductors and vertical frames, forced helium flow to cool the strip-lines.







Other beam components

Decay tunnel: the length is tuned to have most of the pions decayed before reaching the end of the tunnel

A useful rule-of-thumbs: if E ≫ m: $L \approx \frac{E}{m_\pi} \cdot c\tau$

$$L \approx 56\,\mathrm{m} \cdot \left(\frac{E}{\mathrm{GeV}}\right)$$

pion

$$L \approx 7.5\,\mathrm{m} \cdot \left(\frac{E}{\mathrm{GeV}}\right)$$

kaon

Decay tunnels are usually evacuated and there is no material inside to perform diagnostics

Beam stopper (aka **hadron dump)**: at the end of the tunnel, all undecayed particles and all particles produced by decays except for the neutrino are stopped by a plug of iron and concrete.

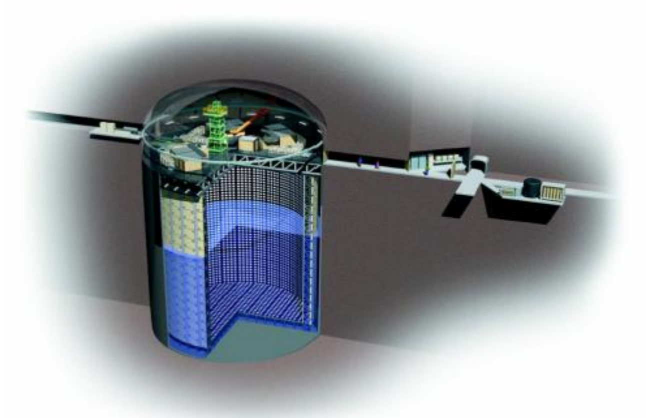
Beam diagnostics: due to the tremendous rate of charged particles, beam diagnostics is coarse but radiation-hard. Detectors for beam diagnostics include:

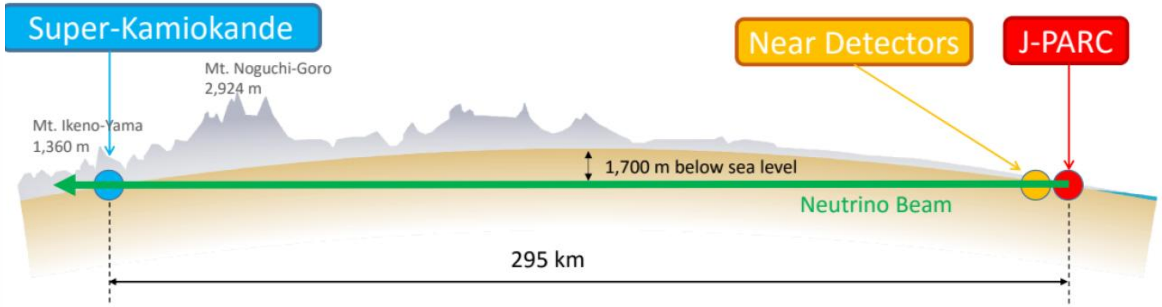
- Primary proton beam monitors
- Muon monitors after the beam stopper (ionization chambers)

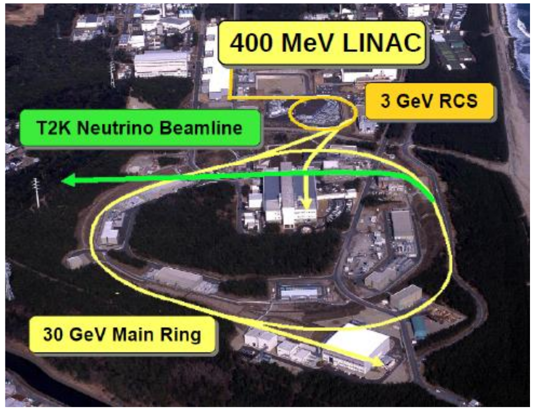
More advanced facilities, as those discussed on Monday, consider the use of advanced diagnostics to measure the neutrino flux by **monitoring** the rate of charged leptons or performing neutrino **tagging**.

A state-of-the-art example: T2K

T2K: a long-baseline experiment from JPARC (Sendai) to SuperKamiokande. L=295 km, E=0.6 GeV







Basic idea:

- produce ν_μ in a laboratory that has a powerful **proton driver** (J-PARC in the case of T2K).
- measure how many ν_μ and ν_e are at the source using a **Near Detector** and compare this with what we observe in the **Far Detector** located at a distance L from the source.

Observables:

- **$\nu_\mu \rightarrow \nu_e$** and **anti-$\nu_\mu \rightarrow$ anti-ν_e** (CP conjugated) oscillations
- **ν_μ survival probability** at the Far Detector

Advantages and disadvantages of T2K:

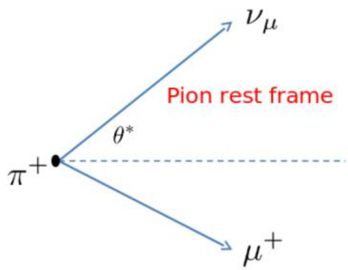
•**T2K** is the ideal facility for discovering CP violation, although the beam (0.75 MW) and the detector mass (40 kton) are too small for a 5-sigma discovery → (*This is one of the motivations for building HyperKamiokande*)

•The source-detector distance (**baseline L**) is too short to measure the mass hierarchy using neutrino interactions through matter (matter effects)

The off-axis technique

The T2K “Far Detector” (SuperKamiokande) is located 2.8º off the beam axis. Why?

$$E_\nu^* = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \approx \boxed{29.8\,\mathrm{MeV}}$$



Conserve 4-mometum in the pion rest frame and the lab frame

Boost to the lab frame: $m_\mu^2 = m_\pi^2 - 2E_\nu^* m_\pi$

$$\begin{aligned} p_{\mu_\nu} &= (E_\nu, E_\nu \sin\theta, 0, E_\nu \cos\theta) \\ &= (\gamma E_\nu^*(1+\beta\cos\theta^*), E_\nu^*\sin\theta^*, 0, E_\nu^*(\beta+\cos\theta^*)) \end{aligned}$$

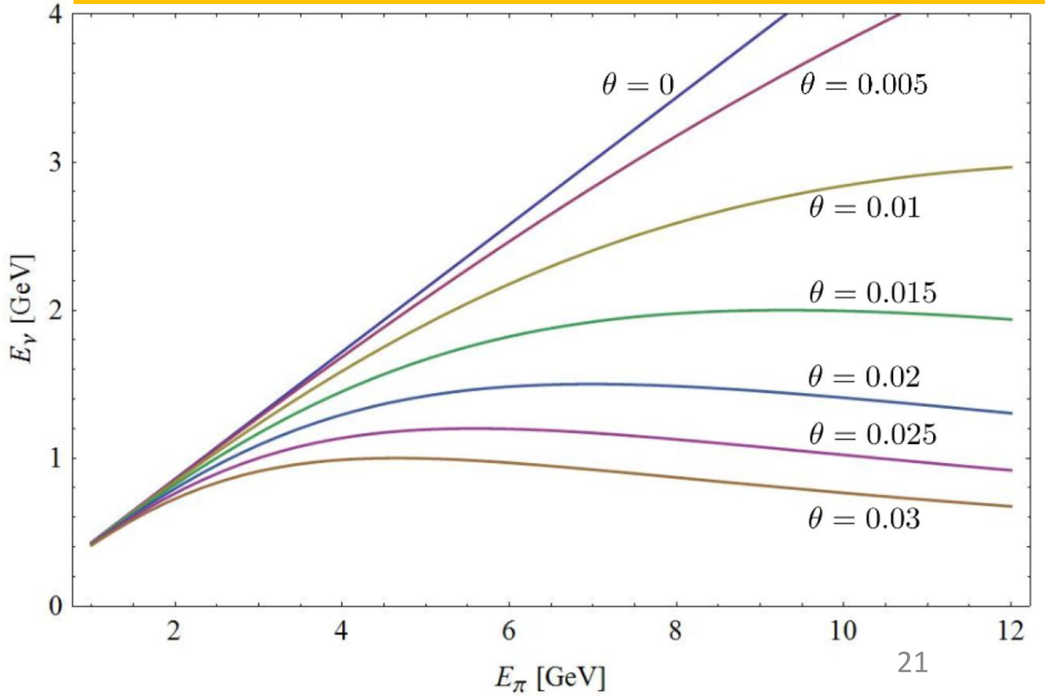
Using the components $\frac{p_{\nu_1}}{p_{\nu_3}}$ can get the relationship

$$\tan\theta = \frac{E_\nu^* \sin\theta^*}{\gamma E_\nu^*(\beta + \cos\theta^*)} \approx \frac{E_\nu^*\sin\theta^*}{E_\nu}$$

We assume an ultra-relativistic neutrino where $\beta \approx 1$
Now we can get neutrino energies as a function of pion energies and angle θ with which the beam is off-axis

$$\gamma = \frac{E_\pi}{m_\pi} \approx \frac{E_\nu}{E_\nu^*(1+\cos\theta^*)} \qquad \cos\theta^* \approx \sqrt{1 - \frac{E_\nu^2}{E_\nu^{*2}}\tan^2\theta}$$

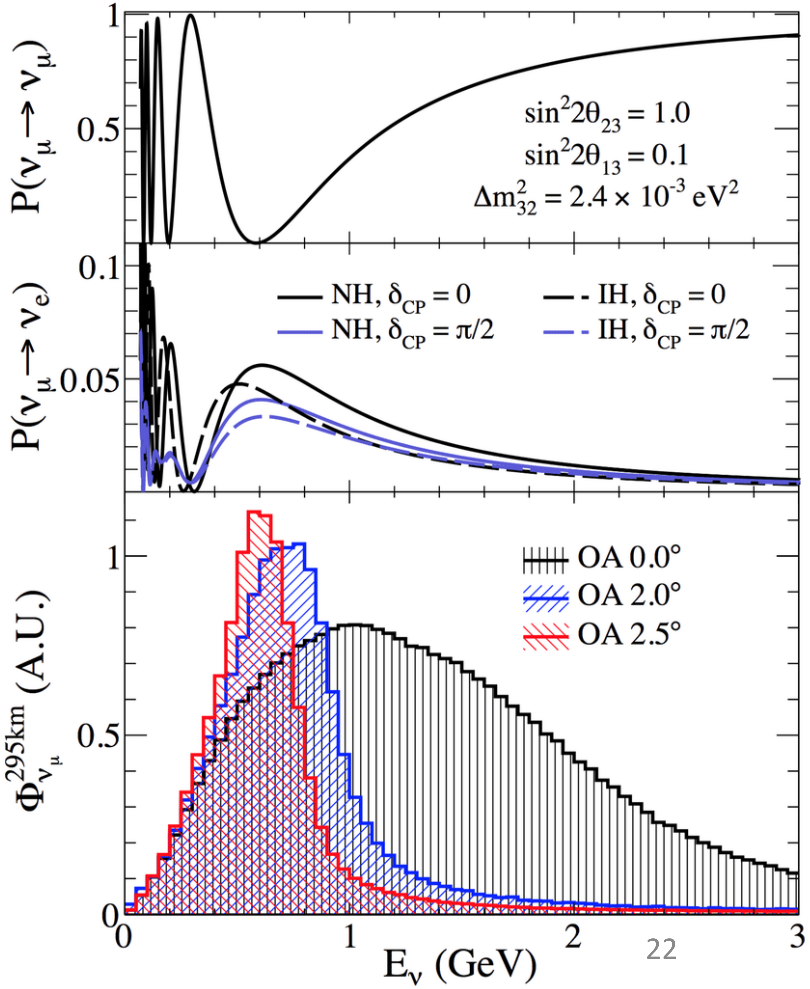
At moderately large angles, the neutrino energy is independent of the pion energy



The off-axis technique in T2K

In two-body decays ($\pi \rightarrow \mu\ \nu$), the neutrino energy **E_ν** depends on the decay angle. At fixed off-axis angle, **Ev** becomes nearly independent of pion energy. By placing the detector a few degrees **off the central beam axis**, one obtains a **narrow-band neutrino energy spectrum** peaked at a specific value (0.6 GeV at 2.8° for T2K)

Feature	On-Axis Beam	Off-Axis Beam
Energy spectrum width	Broad, multi-GeV spectrum	Narrow, sharply peaked around desired energy
Peak energy selection	Dependent on pion energy	Tunable via off-axis angle (~600 MeV for T2K)
Background reduction	Includes high-energy ν backgrounds	Suppresses high-energy tail, reducing NC backgrounds
Oscillation sensitivity	Spread over wide energies	Enhanced at first oscillation maximum



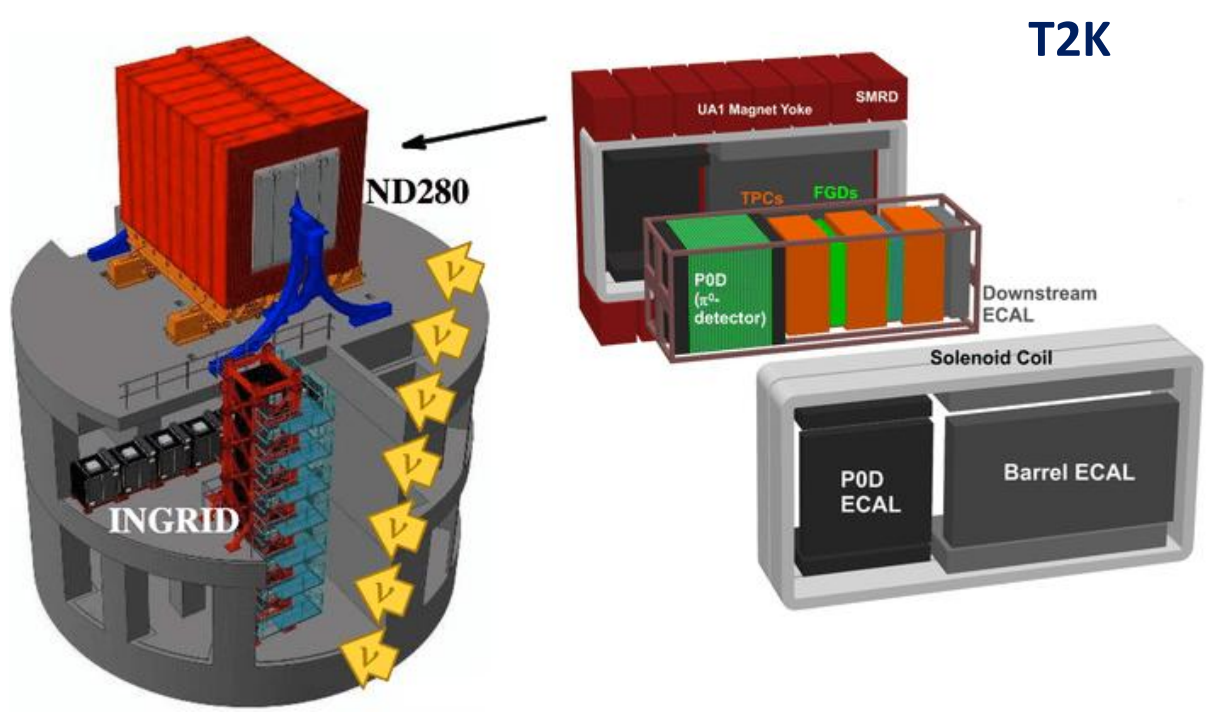
Drawbacks:

- Smaller flux at the detector
- Loss of information on the oscillation pattern

The near-far detector method

This method is universal for any long-baseline experiment. Since the van der Meer paradigm comes with minimum diagnostics, there are large uncertainties - O(10%) - on the neutrino flux at source and flavor contamination (ν_e from muon and kaon decay in the decay tunnel or before). To spot oscillations, we compare the neutrino event rate close to the source (Near Detector) to the one at distance L (Far Detector). Two approaches:

T2K



The Near detector has better resolution than the far and offers a full kinematic reconstruction of the events BUT it is different (different efficiency) from the Far Detector

NOvA

The Near detector is identical to the Far Detector BUT it is smaller and, in general, has a different geometrical acceptance

Near-far detector systematic cancellation

The event comparison between the Near and Far detectors cancels systematics **at leading order**

Number of near detector events = Flux · Cross section · Detector effects

Number of far detector events = Flux · Oscillation probability · Cross section · Detector effects

Want to know this

$$N_k(p_k,\theta_k) \propto \sum_i^{E^{true}\ \text{bins}} \sum_j^{\text{flavors}} \Phi_j^{far}(E_i^{true})\, P_{\nu_j \to \nu_k}(E_i^{true})\, \sigma_k^A(E_i^{true}, p_k, \theta_k \ldots)\, \epsilon(p_k, \theta_k \ldots) M_{det}$$

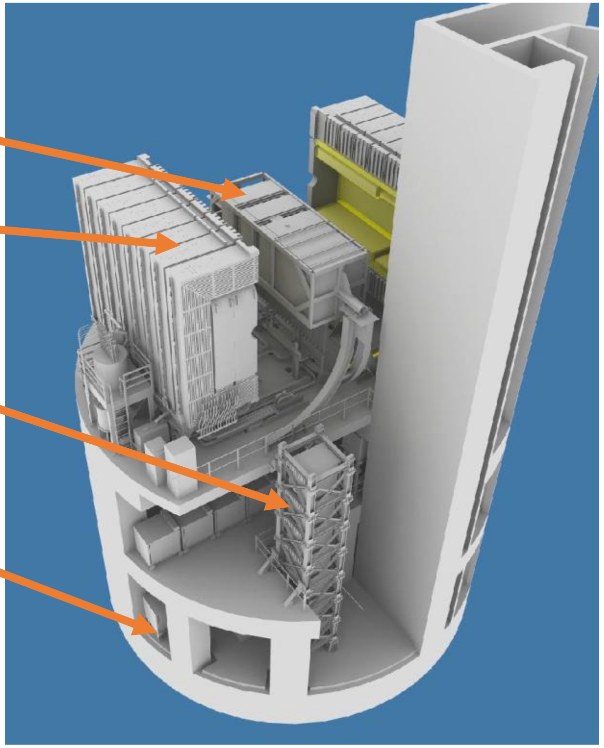
$$N_j(p_j,\theta_j) \propto \sum_i^{E^{true}\ \text{bins}} \Phi_j^{near}(E_i^{true})\, \sigma_j^A(E_i^{true}, p_j, \theta_j \ldots)\, \epsilon(p_j, \theta_j \ldots) M_{det}$$

- Flux: we are interested in the ν_μ flux, which is the same at the different locations except for geometrical acceptance. Still, different geometrical acceptances sample a different energy spectrum at next-to-leading order (NLO). We need to apply corrections and, possibly, reconstruct the spectrum as a function of energy
- Cross section: we observe the flux × $\sigma(\nu_\mu)$ product at the Near location and the flux × $\sigma(\nu_e)$ location. Hence, we mostly rely on lepton universality to assume $\sigma(\nu_e) = \sigma(\nu_\mu)$, which holds except for NLO phase space effects
- Detector effects: we can measure the detector efficiency for ν_e CC events at the near detector using the ν_e beam contamination from kaon and muon decays **if the detectors are the same,** but the energy spectrum of this contamination is very different from the oscillated ν_e spectrum (the latter peaks at the first oscillation maximum). Again, NLO corrections are needed and a high granularity Near Detector helps.

The T2K near detector complex

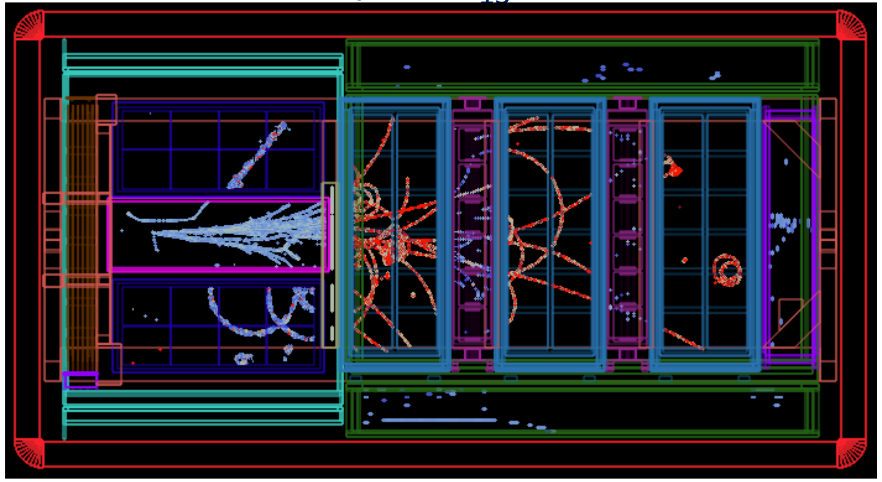
The rationale:

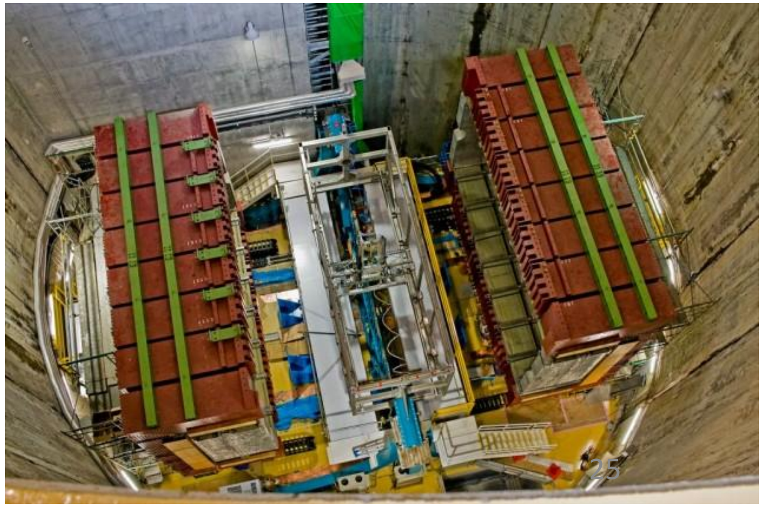
- Use gas TPC, scintillators and calorimeters because – unlike the T2K Far Detector – they can stand the neutrino rate at the near location
- Use a magnetic field surrounding ND280 to measure the ν_μ neutrino interactions as a function of the reconstructed neutrino energy
- Use an on-axis coarse detector (INGRID) to monitor changes of the neutrino flux in time
- Use scintillators interleaved with carbon to measure the interactions of neutrino in water (Far Detector target) + a dedicated detector (WAGASHI)



	$N(\nu_e)/N(\nu_e)$
Error source	FHC/RHC
SK Detector	1.47
SK FSI+SI+PN	1.57
Flux + Xsec constrained	2.67
E_b	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	3.03
NC1γ	1.50
NC Other	0.18
Osc	0.77
All Systematics	5.96
All with osc	6.03

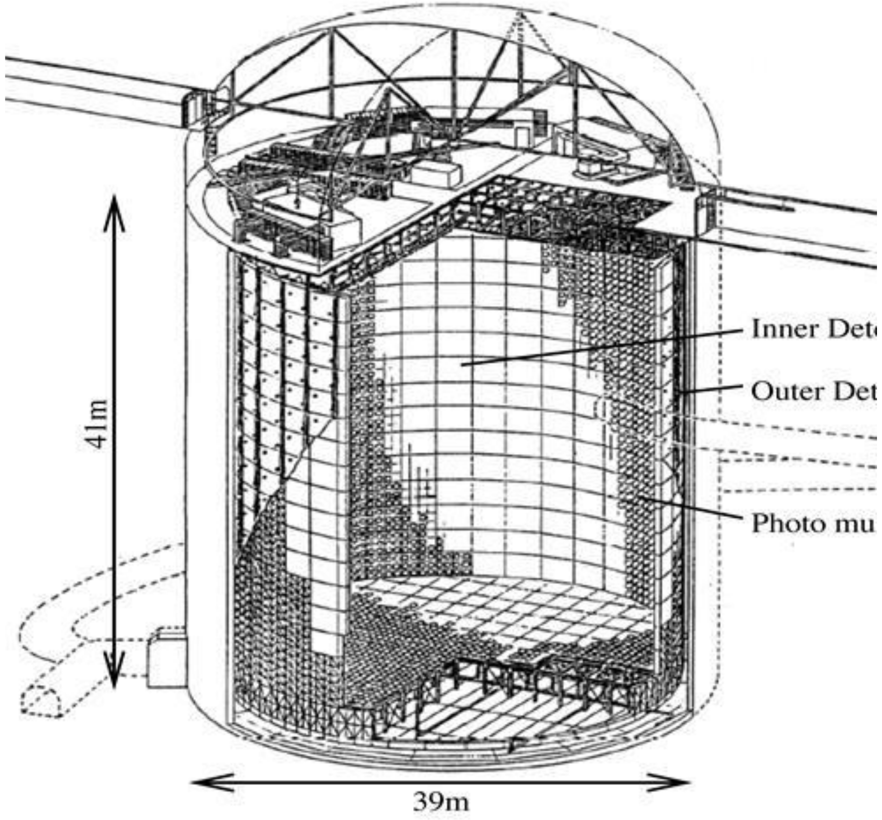
Next-to-leading order (NLO) effects contribute a 5% systematic uncertainty - acceptable before the precision era, but must be reduced in the post-θ_{13} era





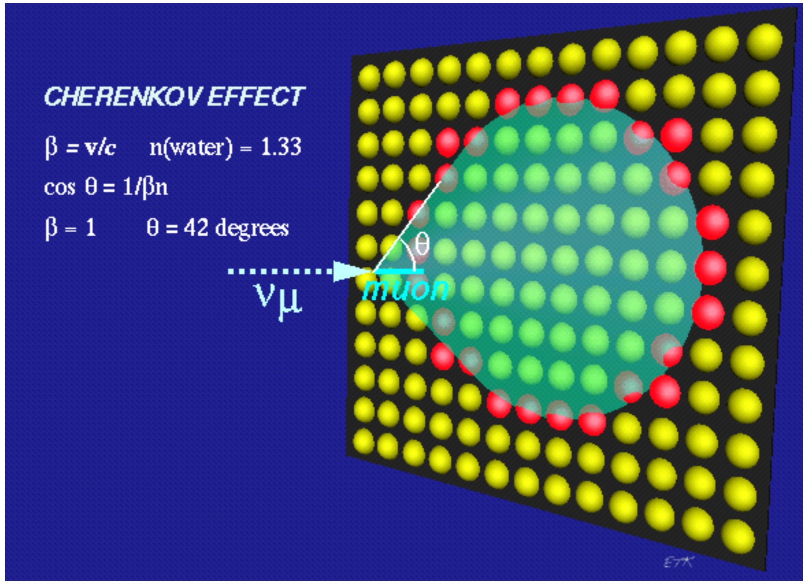
The T2K Far Detector: SuperKamiokande

The T2K Far Detector is the same detector that discovered neutrino oscillations in atmospheric neutrinos in 1998 (see F. Vissani's lectures) - SuperKamiokande



Parameter	Value	Notes
Location	Kamioka Mine, Japan	Underground for shielding from cosmic rays
Detector Type	Water-Cherenkov	Detects Cherenkov radiation emitted by charged particles produced by neutrino interactions
Tank Size	39.6 m diameter, 42.2 m height	Stainless steel tank containing 50 ktons of ultra-pure water
Inner Detector (ID)	32 ktons of water	Viewed by 11,000 50-cm PMTs
Outer Detector (OD)	~2 m water layer	Viewed by nearly 2,000 20-cm PMTs
Fiducial Volume	22.5 to 27.5 ktons	Region within ID away from edges to minimize background and edge effects
PMTs	11,146 50-cm PMTs in ID, 1,885 8-inch in OD	Detect Cherenkov light
Depth	2700 m water equivalent	Shields detector from cosmic rays

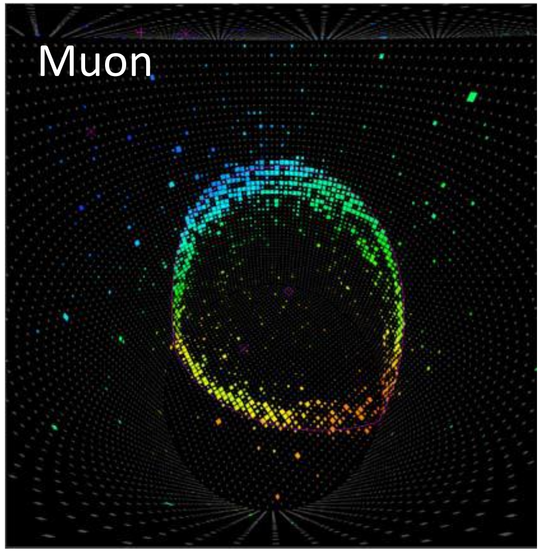
Particle identification in SuperKamiokande (SK)

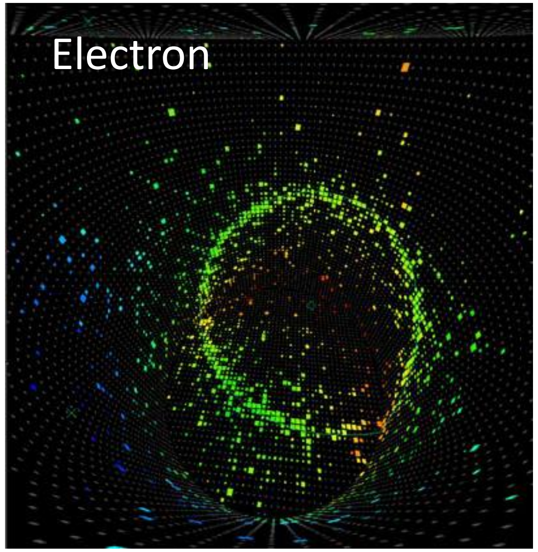


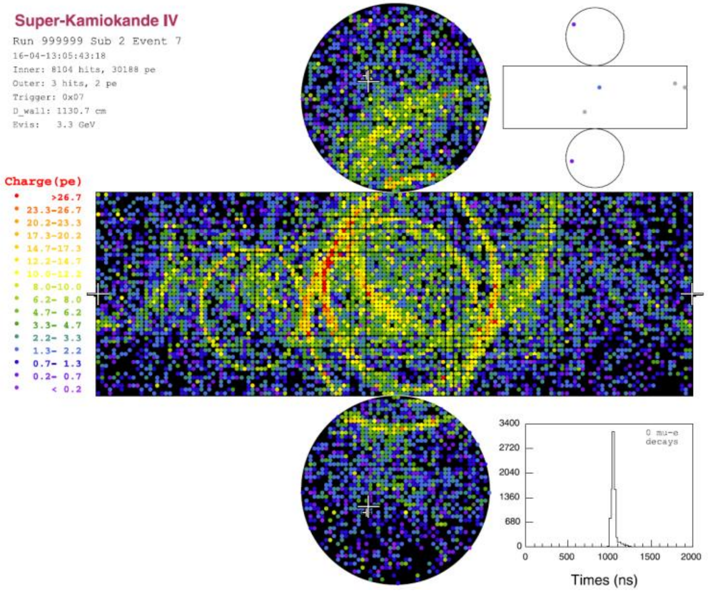
SK is a **coarse and cheap** detector, which therefore can be scaled to **huge masses**

- Cheap target material (water)
- Surface instrumentation
- Vertex from Photomultiplier (PMT) timing
- Direction from ring edge
- Energy from pulse height, range and opening angle

It can observe only particles above the Cherenkov threshold in water (β>0.75).







Historically, demonstrating the reliability of such a coarse particle ID by independent samples and test-beam data was key to the success of SK

This technology is now very well established

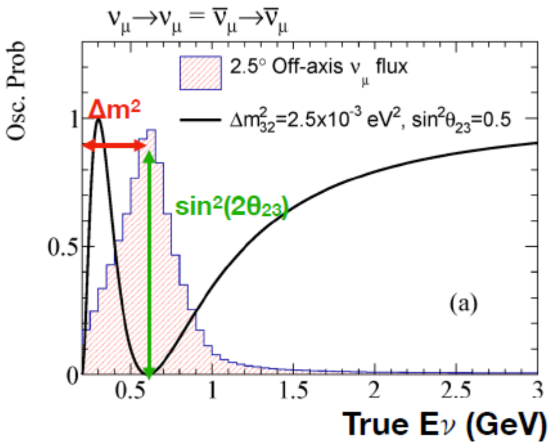
The physics of T2K

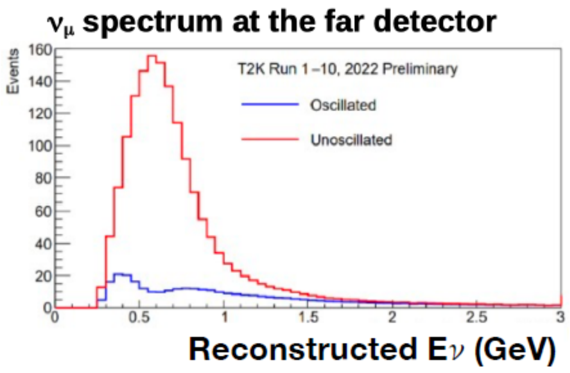
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}$$

$$(\mp)\alpha\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}]$$

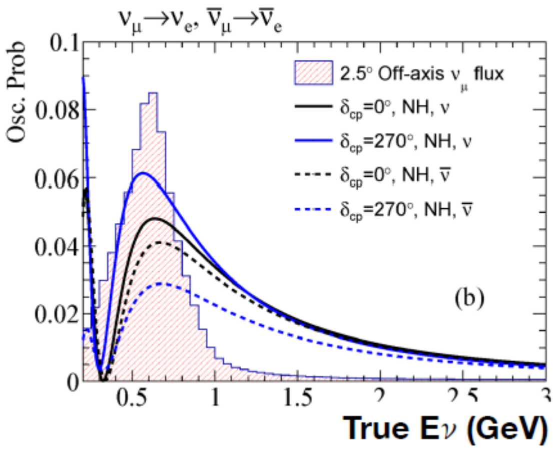
$$+\alpha\frac{J_0 \cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

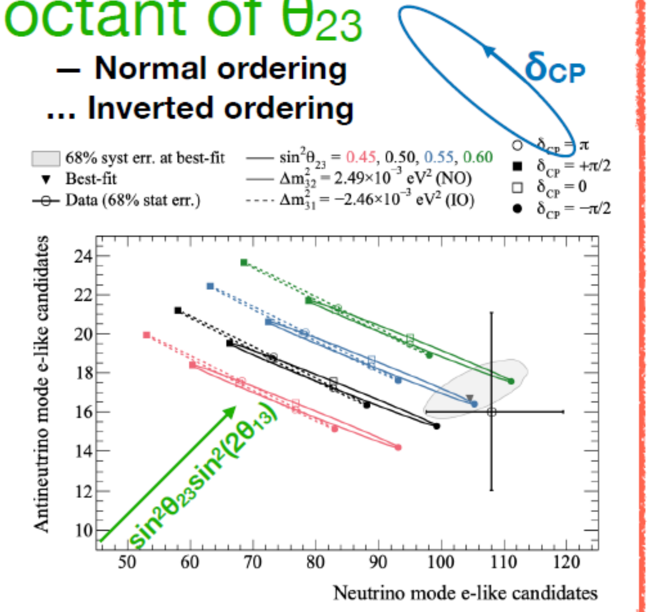
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$$

$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

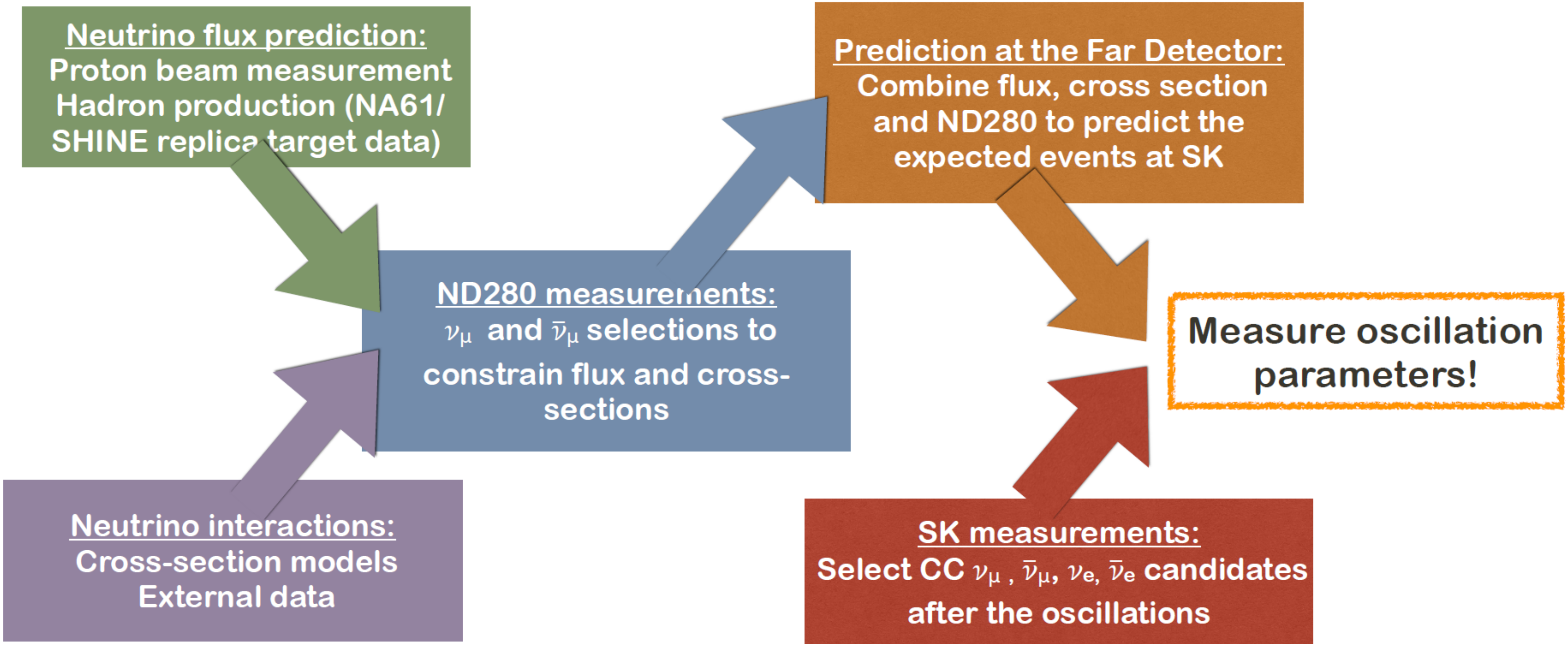
$$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$$

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}





The analysis chain



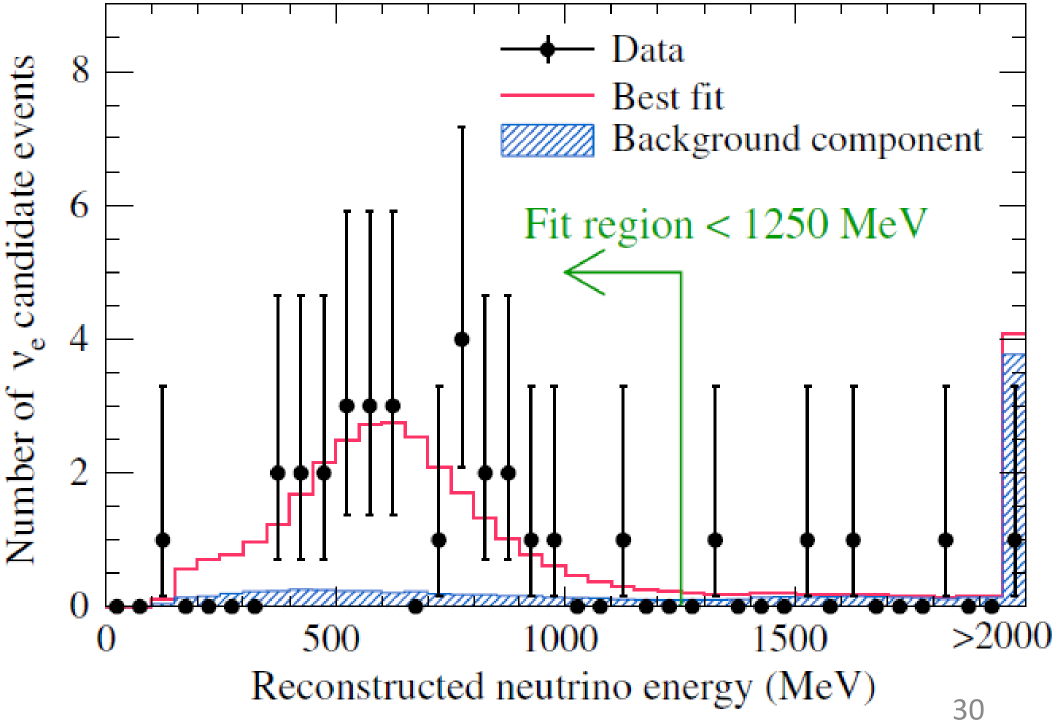
The events observed by SuperKamiokande in 2010-2014

T2K was the first accelerator experiment gathering evidence for a non-zero (indeed, large) size of θ_{13}. Hint in 2011, 7sigma evidence for $\nu_\mu \rightarrow \nu_e$ appearance in 2014. Together with OPERA at Gran Sasso, they also provided the **first ever direct measurement of appearance of new flavors due to oscillations**!

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31} L}{4E}$$

Signal: ν_e charged current events. They correspond to 1-ring electron-like events in SK

Background:
low energy electrons from muon decay in ν_μ CC events (removed by a 100 MeV energy cut)
ν_e CC events from beam contamination. Mostly at higher energy than 1st oscillation peak (energy cut <1250 MeV)
Neutral current (NC) events with a production of a π^0 – **the most dangerous background in a coarse detector**- removed with a multivariate fit that also includes the reconstructed invariant mass of the π^0 candidate



Phys.Rev.Lett. 112 (2014) 061802

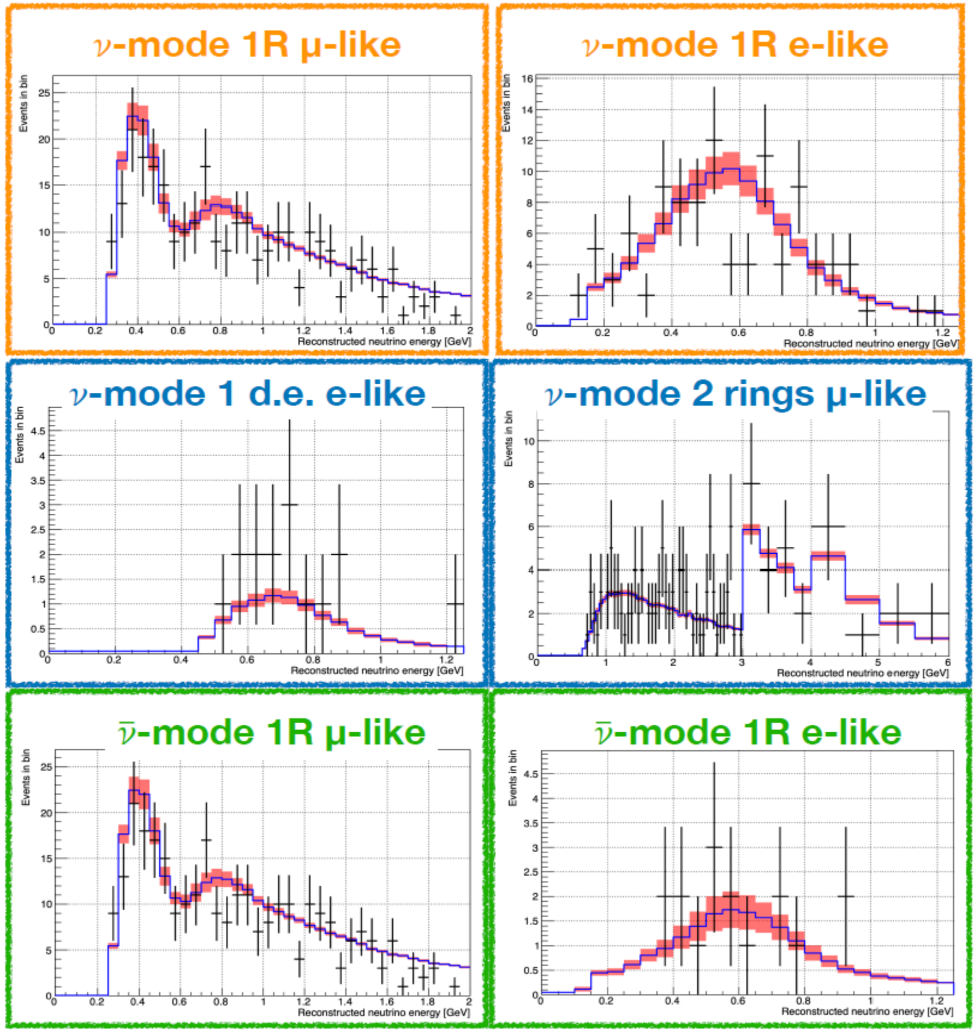
Precision physics with T2K

Modern T2K analyses use multiple samples to perform simultaneous fits of all appearance and disappearence probabilities for neutrino-enriched and antineutrino enriched runs. Note: SK cannot measure the lepton sign, hence the “antineutrino run” is contaminated by remnant neutrinos at the source (30% !)

Simplest topology: candidate quasi-elastic ν_μ and ν_e CC events

Sample rich of $\nu_e CC\pi$ and ν_μ $CC\pi$

Candidate quasi-elastic anti-ν_μ and anti- ν_e CC events (plus contaminations from ν_μ and ν_e remnants)



Muon-like

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$|\Delta m^2_{23}|$ θ_{23}

Electron-like – see the master formula in slide 4

δ θ_{13}

Δm^2_{12} θ_{12} Sign Δm^2_{23}

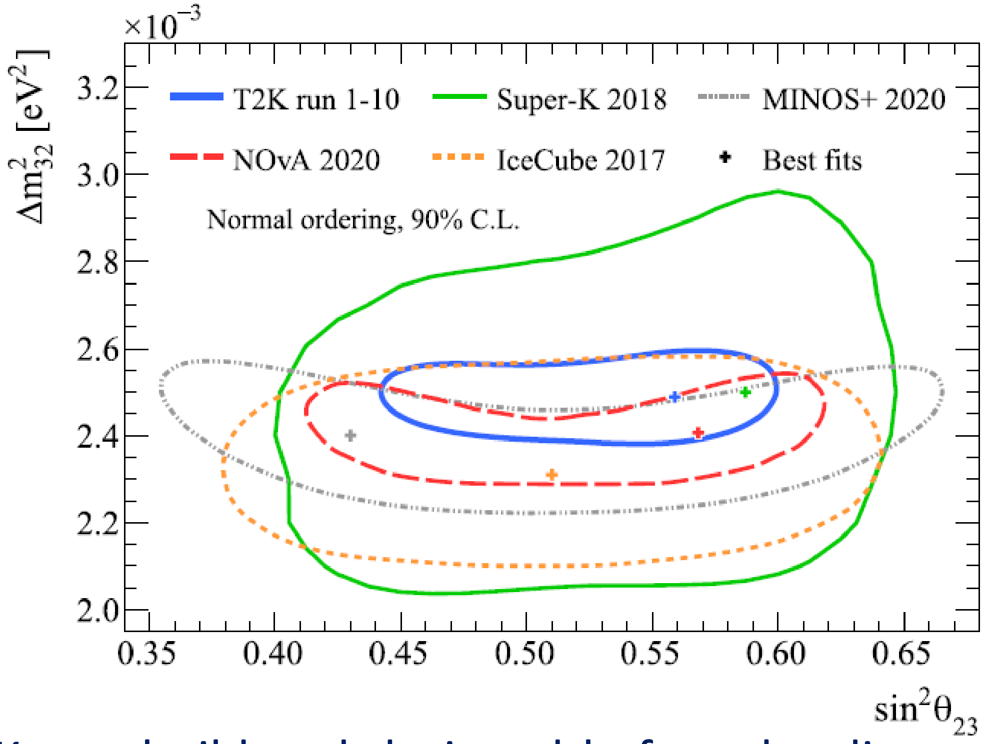
Outstanding sensitivity

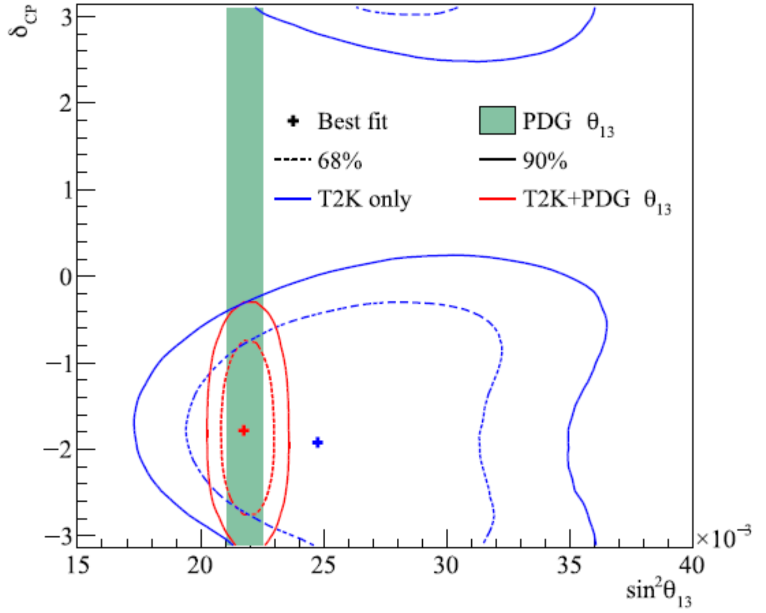
Moderate sensitivity

No sensitivity

Precision physics with T2K

Eur. Phys. J. C (2023) 83:782

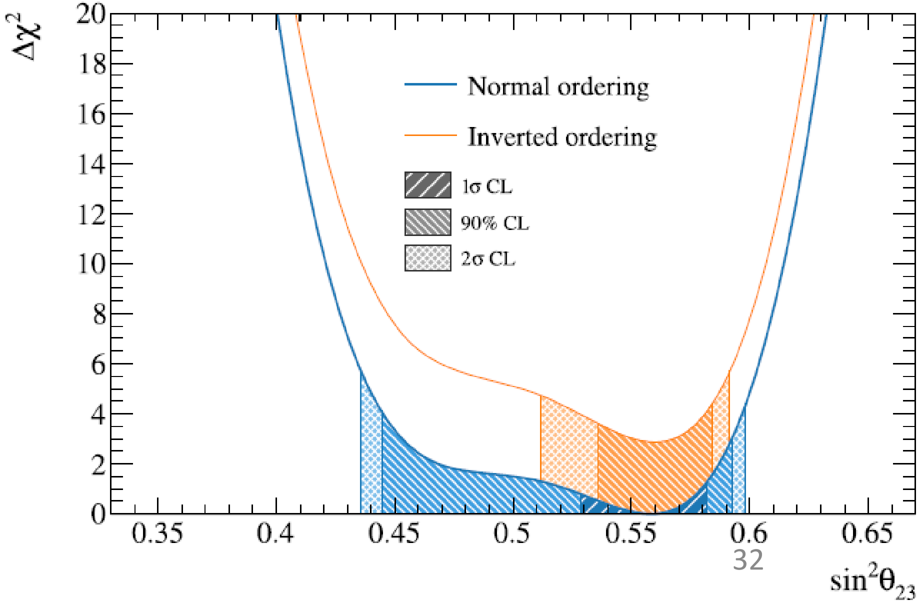




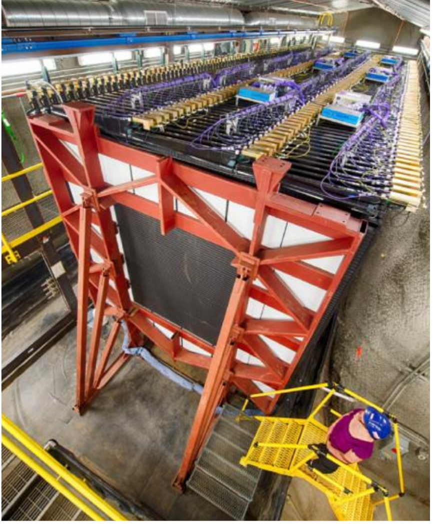
T2K was build and designed before the discovery of θ_{13}. Hence, it moderate sensitivity to CP but:

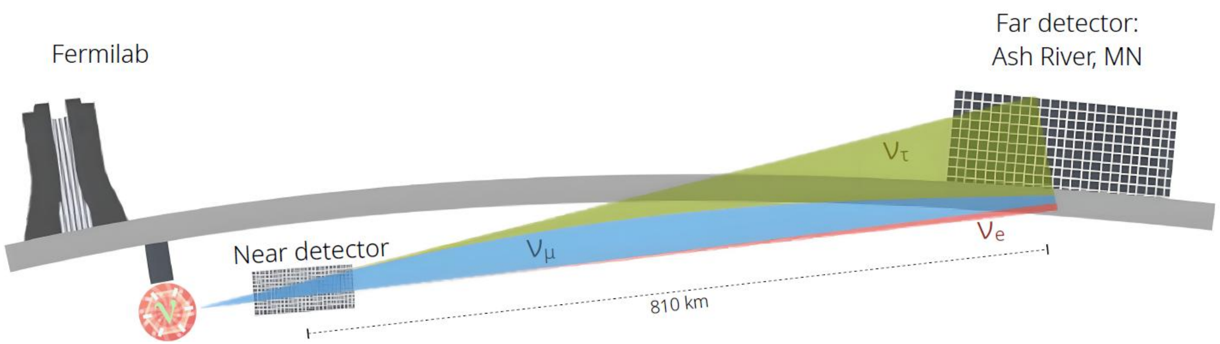
- It shows a 2σ hint for CP violation *Nature* **580**, 339–344 (2020)
- It has a slight preference for "Normal ordering" (sign Δm^2_{23} > which is corroborated by atmospheric data (p-value for invert ordering is 0.08).
- Slight preference for θ_{23} >45°

It support our earlier statement: current experiments benefit fror large θ_{13} but the full potential is still to be reaped



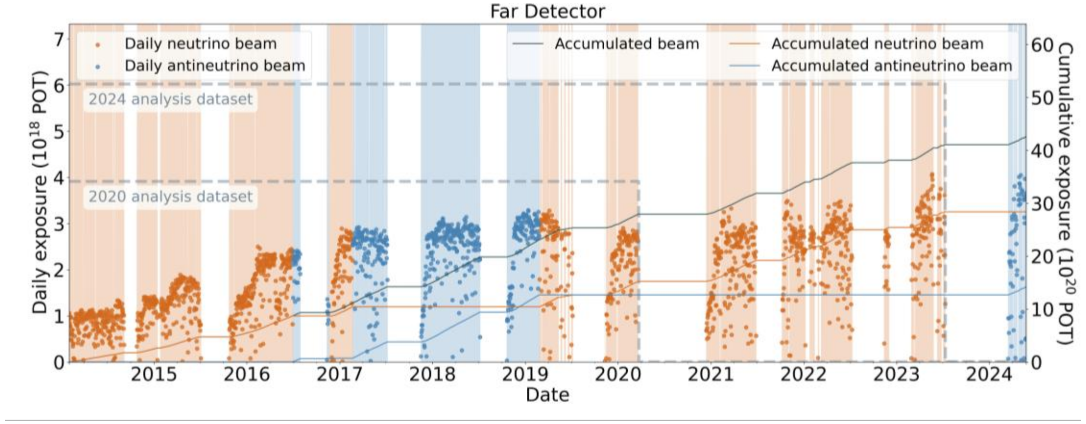
NOvA

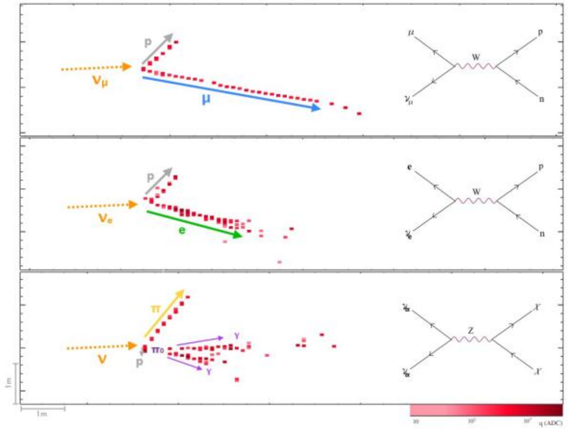




NOvA is complementary to T2K in many respects:

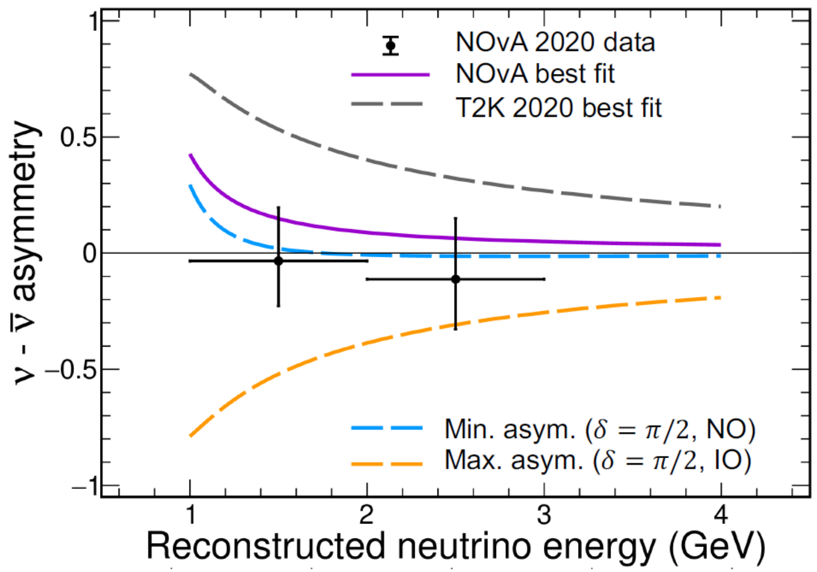
- It employs a baseline where matter effects are sizable, and oscillation probabilities depend on sign Δm_{23} – at the expenses of a slight reduction in δ sensitivity
- The neutrino detector is smaller, but the granularity is much better than T2K. It can access multi-particle final states and reduce the main $NC\pi^0$ background
- It has a Near detector that is identical to the Far detector, which reduces the uncertainties on detector efficiency – at the expenses of moderate kinematic reconstruction of near-site neutrino interactions
- It employs a 900 kW beams!





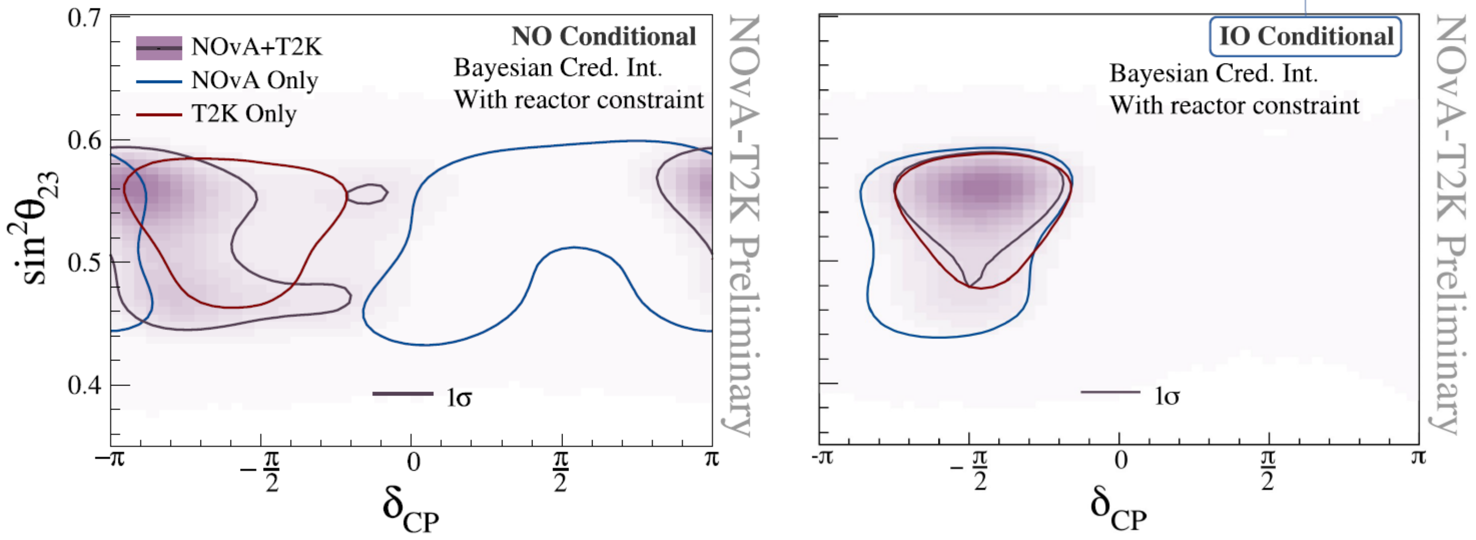
The T2K versus NOvA saga ☺

When θ_{13} was discovered, we were hoping for a superior sensitivity of the combined T2K-NOvA dataset because we can use these data to lift degeneracies between CP violation effects (δ) and matter effects (sign Δm^2_{23}). In fact, we hoped mass hierarchy would have been fixed at 3σ in 2025 and CP violation was expected to be established at 3σ if maximal (δ=90°). Unfortunately, this is not the case – at least now.



NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

"assuming IO is true"
(does not include relative probability of IO vs. NO)



We don't know the reason for this mild tension – may still be a statistical fluctuation (unlikely), systematic bias (my favorite option), or new physics (no comment ☺). This is also due to the moderate sensitivity of this generation of experiments to the most challenging parts of PMNS and foster the construction of a new (post- θ_{13}) generation of long baseline experiments. Still, current long baseline experiments have given major contributions to the precision measurement of the PMNS.

PMNS: state of the art

NuFIT 6.0 (2024)

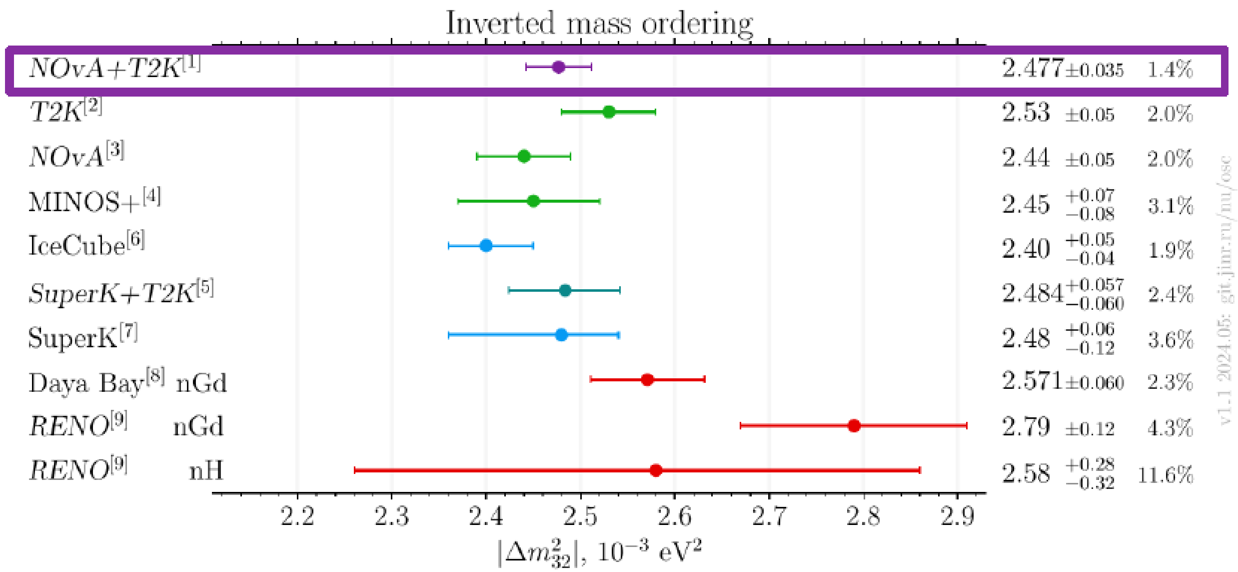
$$|U|_{3\sigma}^{\text{IC19 w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.248 \to 0.505 & 0.473 \to 0.682 & 0.649 \to 0.764 \\ 0.270 \to 0.521 & 0.483 \to 0.690 & 0.628 \to 0.746 \end{pmatrix}$$

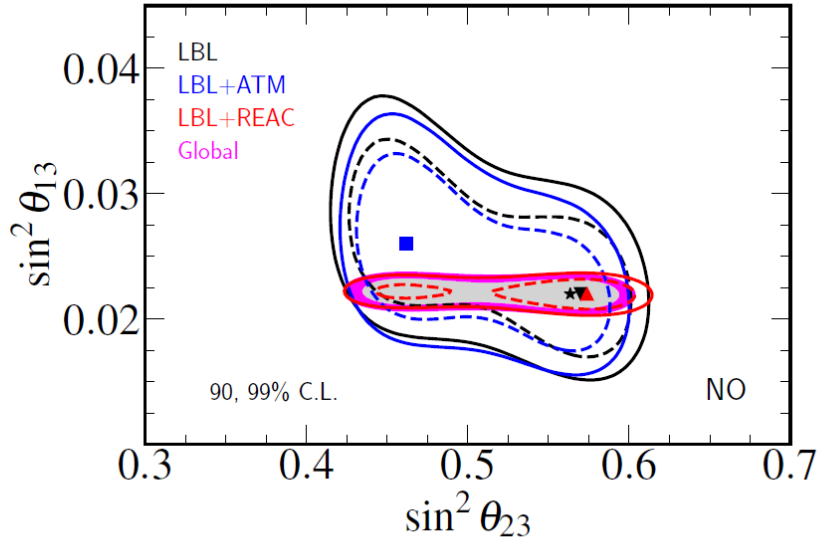
$$|U|_{3\sigma}^{\text{IC24 with SK-atm}} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.252 \to 0.501 & 0.496 \to 0.680 & 0.652 \to 0.756 \\ 0.276 \to 0.518 & 0.485 \to 0.673 & 0.637 \to 0.743 \end{pmatrix}$$

NuFIT 6.0 (2024)

IC19 without SK atmospheric data

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$





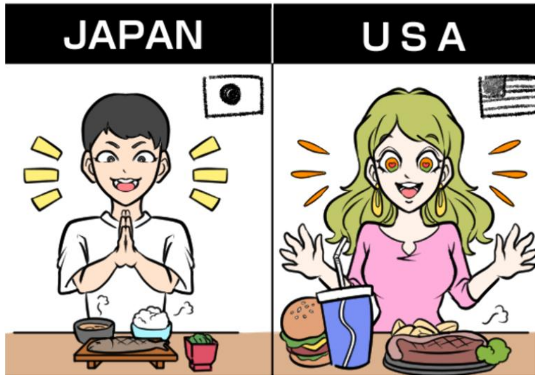
The next-generation long-baseline experiments (>2028)

What do we need to fully reap the opportunities of a large θ_{13}? We do not need a change of paradigm: we need a major but incremental improvement of the van der Meer paradigm (*)

Facility	Beam power	Detector mass	Precision	Resolution
LBNF/DUNE	↑ 1.2 to 2.1 MW	↔ 20 to 40 kton	↑ PRISM + LAr TPC	↑LAr TPC
JPARK/HyperKamiokande	↔ 0.75 to 1.2 MW	↑ 190 kton	↑PRISM + IWCD	↔ Water Cherenkov

Hyper-Kamiokande

- Huge detector mass compared with T2K
- More powerful beam (up to 1.2 MW)
- Same baseline and off-axis beam as T2K
- Better Near Detector complex

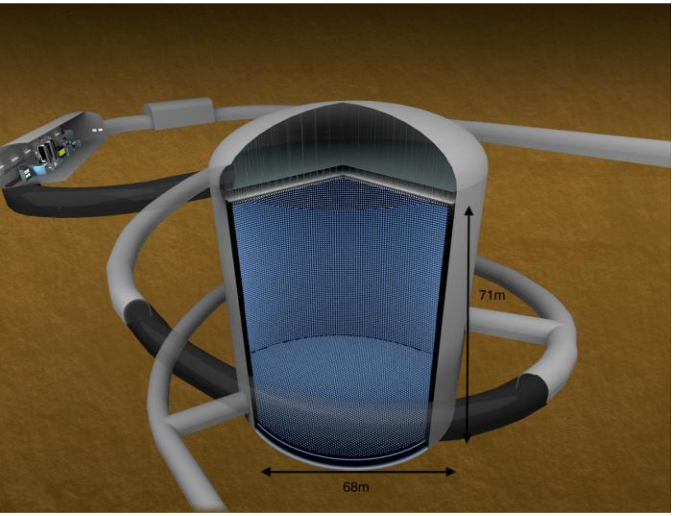


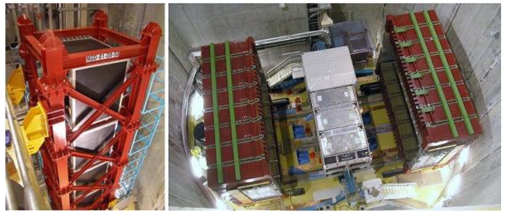
DUNE

- 20-40 kton detector mass with high resolution
- Much more powerful beam (up to 2.1 MW)
- Even larger baseline than NOvA
- Better Near Detector complex

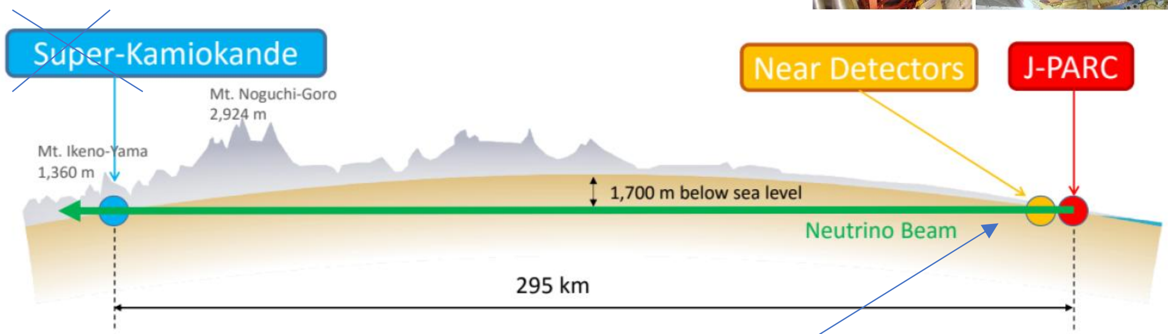
(*) I don't mean to suggest that a change of paradigm is unwelcome — on the contrary, post-superbeam facilities like those I'll be discussing on Monday would be highly desirable. What I do mean is that we can already measure the full PMNS matrix at the 1–10% level using existing technologies, which could be up and running within three years!

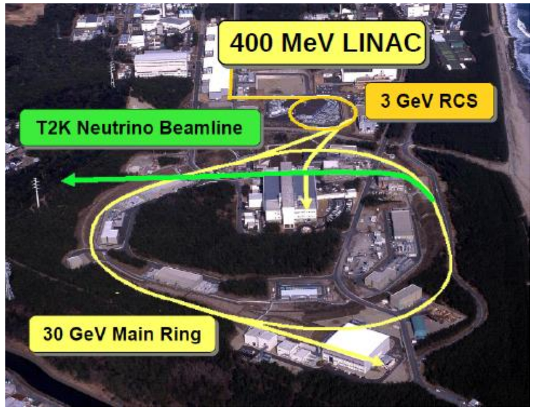
HyperKamiokande



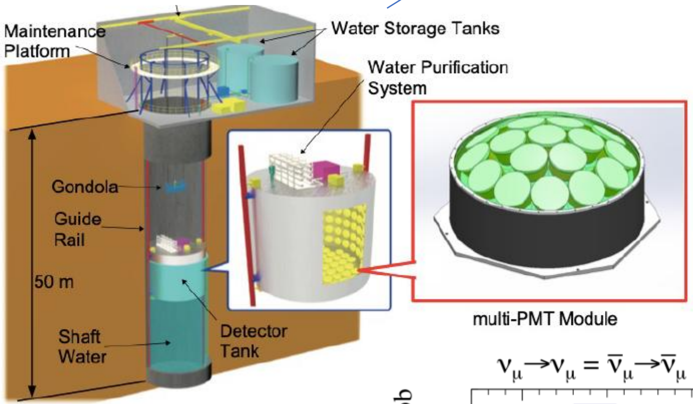


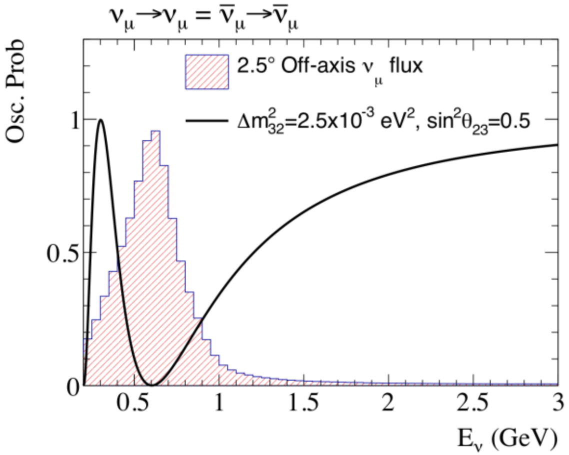
Hyper!!

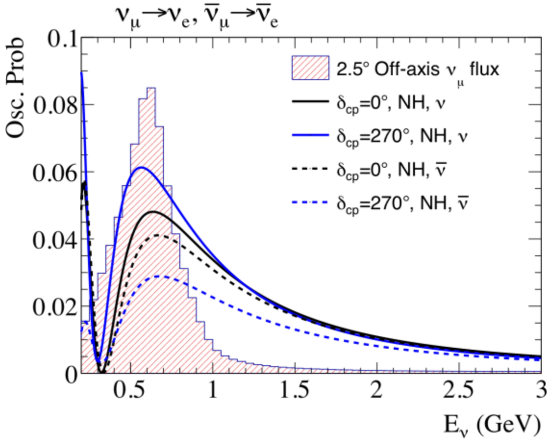




Intermediate detector

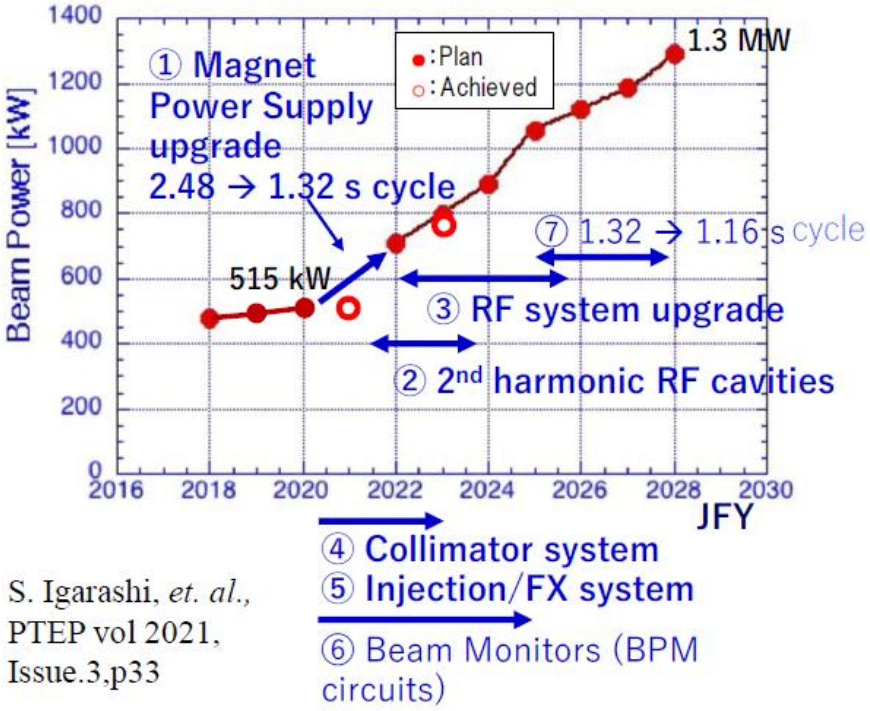






Beam and Far Detector

Substantial improvements to the **proton driver** of the T2K beam



S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

Parameter	Value
Location	~600 m underground, Kamioka Mine, Hida, Gifu, Japan
Detector shape and size	Cylindrical: 68 m diameter × 71 m height
Water volume (ultrapure)	~258,000 tons total
Fiducial mass	~188,000 tons (**8× Super-Kamiokande**)
Inner PMTs	~20,000 × 50 cm Hamamatsu R12860 PMTs (high QE, **2× SK performance**)
Multi-PMT modules	~800 modules (each with 19 × 8 cm PMTs)
Photo-coverage	~40 % (including single and multi-PMT contributions)
PMT time resolution	~1.5 ns (about **half of Super-Kamiokande**)
PMT charge resolution	~30 % (~60 % in Super-Kamiokande)
Outer detector (veto)	~10,000 × 8 cm PMTs + WLS plates + reflective Tyvek
Start of operation	Planned for 2027
Baseline from J-PARC	~295 km

PMT production ongoing, >10,000 delivered. Screening both at Hamamatsu and Kamioka

The PRISM technique

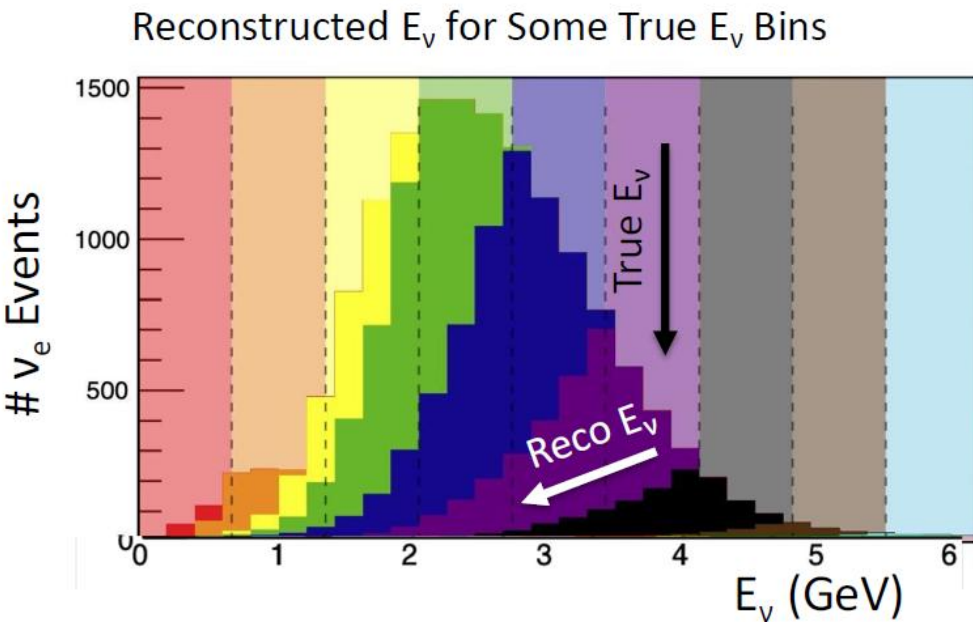
S. Bahdra et al. arXiv:1412.3086

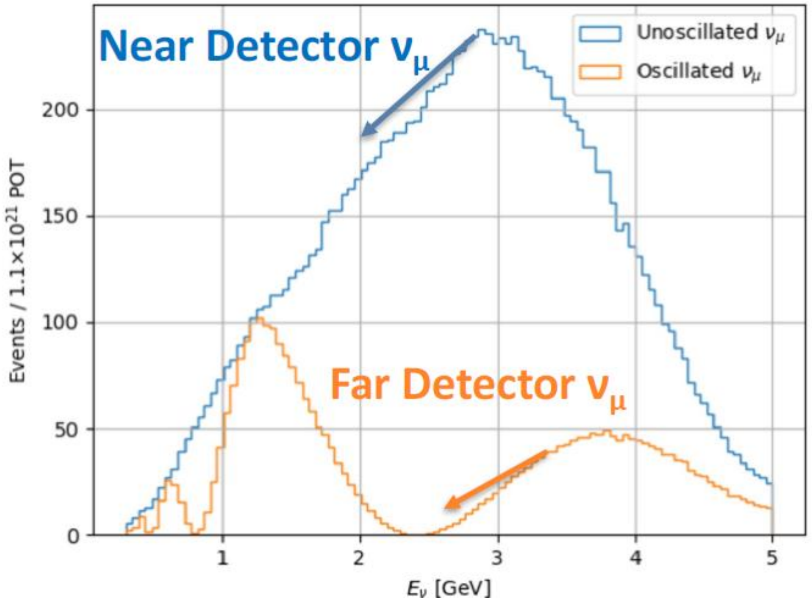
The problem – handling next-to-leading order contributions to the Near-Far cancellation

- The observed energy in the detector is always less than the incident neutrino energy because the some transferred neutrino energy is lost (nuclear binding energy, part of the energy in neutrons, the rest mass of untagged pions, etc)
- The "feed-down" of E_{reco} in each E_{true} bin "fills-in" the oscillation dip(s) at the far detector, but is difficult to constrain in an on-axis near detector because the Near Detector integrates the energy spectrum over a wide region (lack of energy features)
- The shape of the feed down is strongly dependent on neutrino-nucleus interaction modeling, and we do not have reliable neutrino interaction models we can trust at any energy

If we choose the "wrong" interaction model, **we will bias the oscillation parameters**

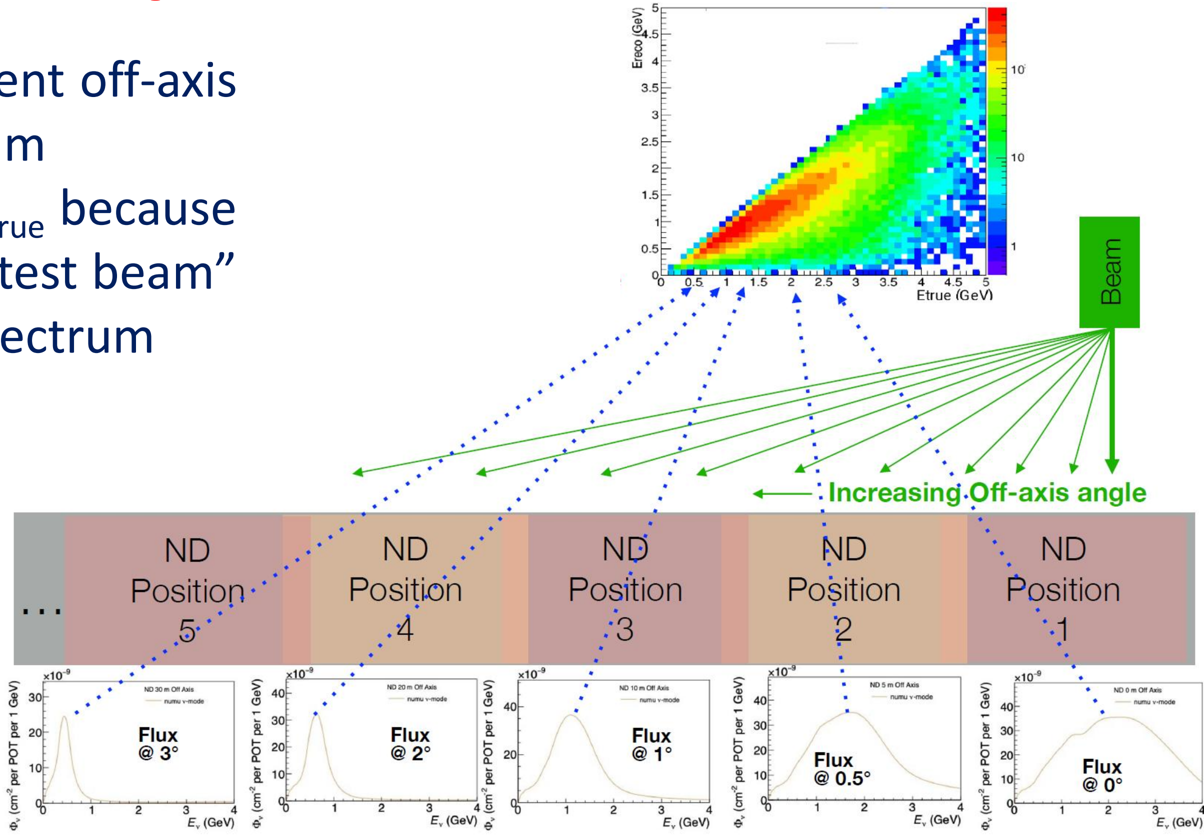
If we don't choose, we will have large systematic uncertainties





The PRISM technique

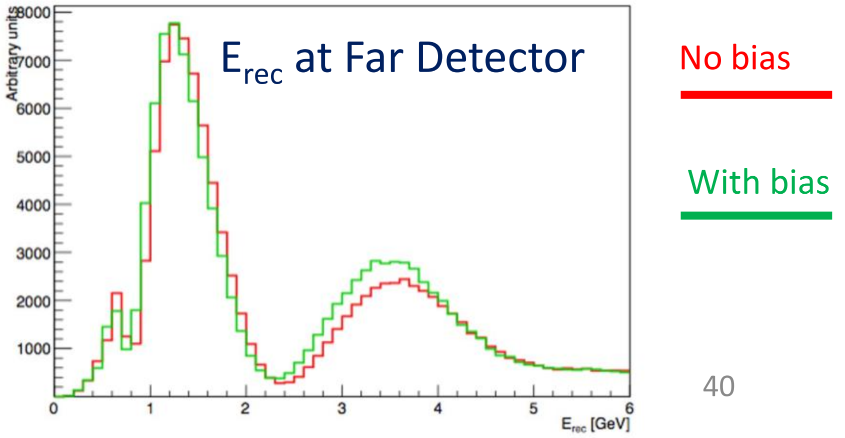
- A movable near detector that samples the beam at different off-axis angles will sample a continuously changing energy spectrum
- This provides a direct calibration of E_{rec} as a function of E_{true} because each off-axis location provides an independent "neutrino test beam" measurement with a different incident neutrino energy spectrum



Example (M. Wilking at Nufact2023)

Consider a case when 20% of the proton kinetic energy is transferred to unseen neutron energy.

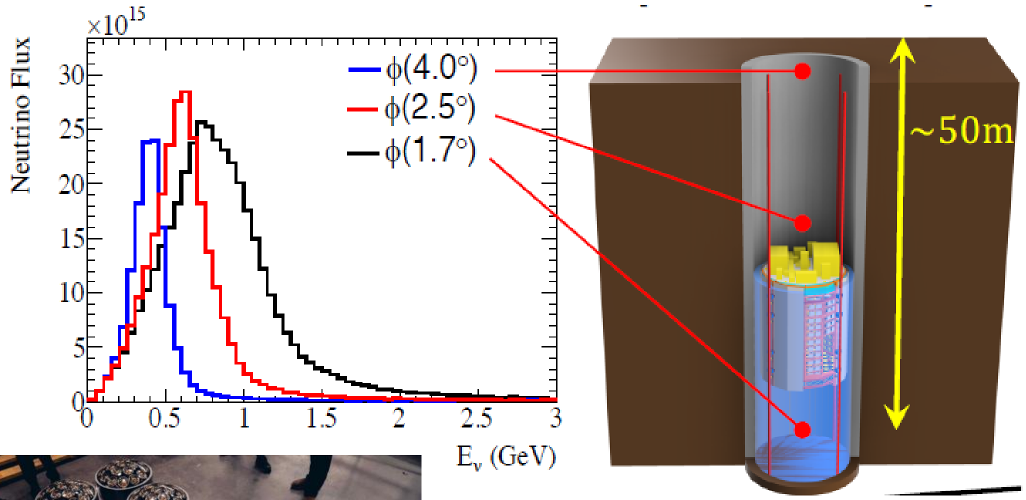
- This specific model failure won't be spotted on-axis because the cross section model will be tuned on Near Detector data and the spectrum agrees "by definition".
- The result is a fake dataset that provides model agreement in an on-axis near detector (by design), but does NOT contain the same $E_{true} \rightarrow E_{rec}$ relationship as assumed by the model



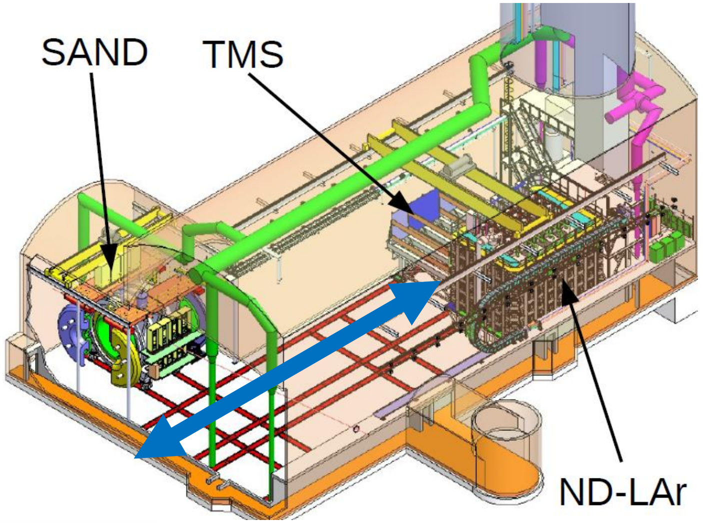
Despite good agreement in the ND, the bias is clearly apparent in the oscillated FD spectrum and, hence, **generates a bias in the fitted oscillation parameters**

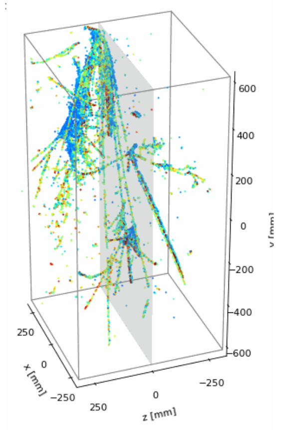
Movable near detectors

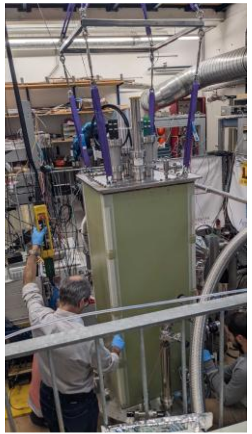
HyperKamiokande needs a **water Cherenkov detector**, which cannot be installed too close to the beam due to event pile-up issues. They are building an “intermediate detector” located 800 m from the target



DUNE need a **liquid argon TPC** (see later). It can be installed close to the beam because this technology can separate pile-up events and pile-up can be further mitigated by building small, modular TPCs

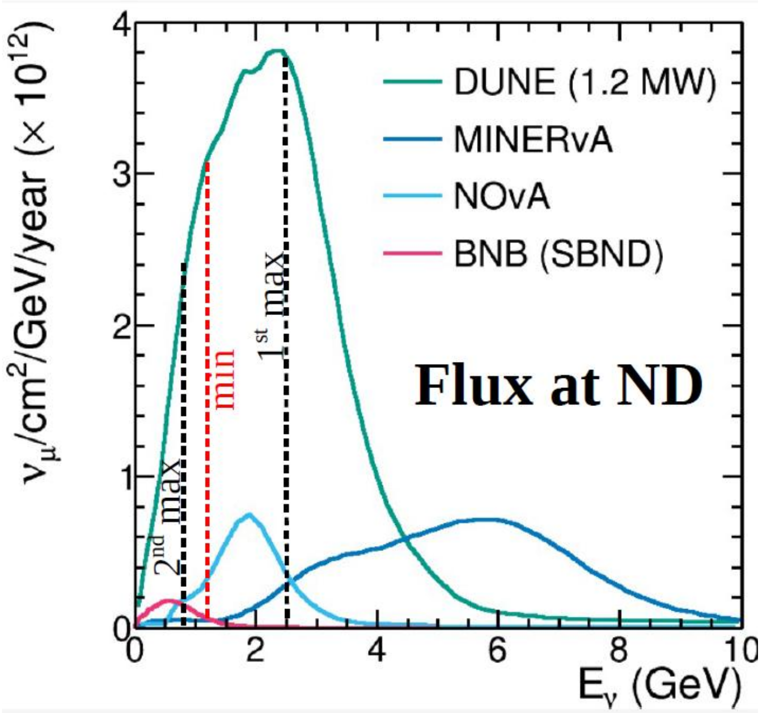


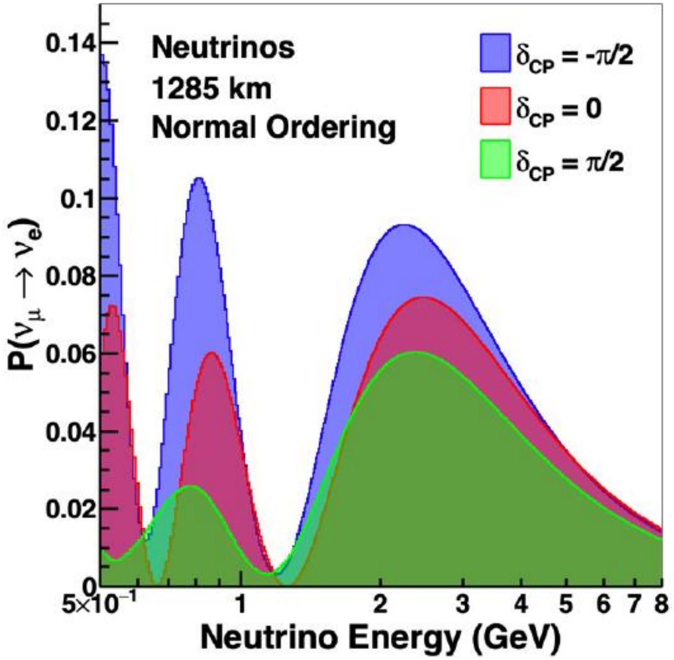


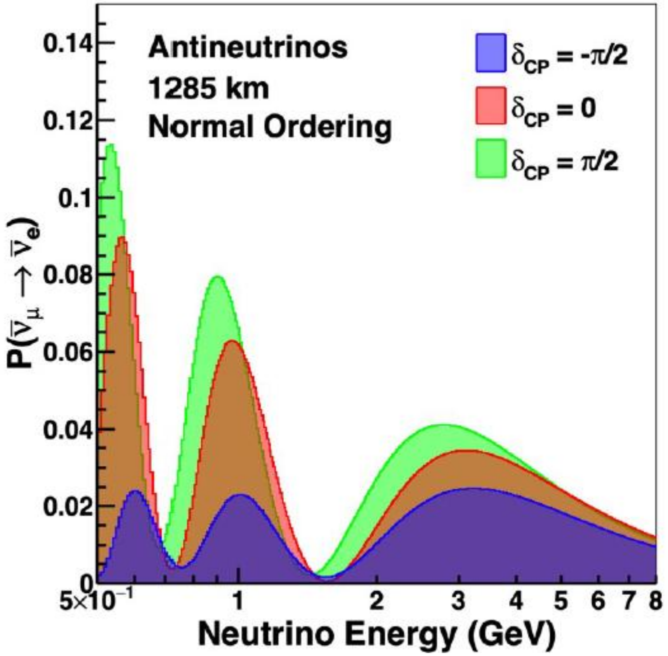


DUNE

Unlike Hyper-Kamiokande, DUNE represents a significant leap forward compared to NOvA, even though it retains some of its features. The main innovation is the use of a **wide-band beam** (with a large energy spread) over a very long baseline of 1300 km, which allows the full oscillation pattern to be observed. This enables the disentangling of matter effects from CP-violation effects, making it possible to simultaneously determine CP violation, the sign of Δm^2_{23}, and the θ_{23} octant—all in a single experiment. It also provides a self-contained test of the three-family oscillation paradigm.



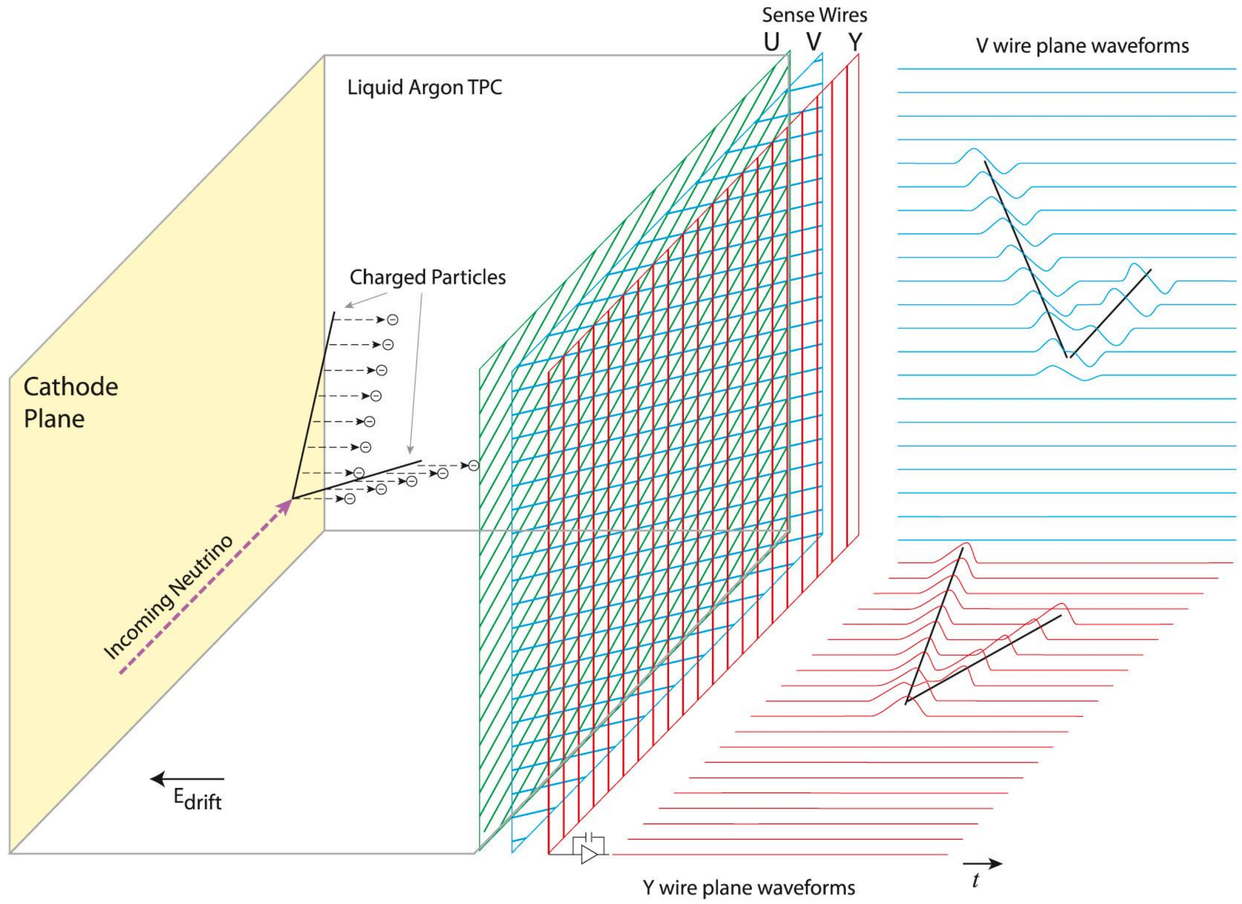




It looks cool but… you need a massive detector with excellent resolution to observe the full oscillation pattern

The DUNE detector technology: liquid Argon TPCs

This technology (C. Rubbia, 1977) is likely the most innovative technology for neutrino oscillations developed in the last 20 years. It offers a space resolution of about 2 mm in volumes that can exceed 10,000 tons and provide superior particle identification because it measures energy (dE/dx in liquid argon), direction (2 mm precision), time (at few ns level) and is not limited to particles above the Cherenkov threshold



Ionization electrons produced in the active volume drift toward the wire planes, generating signals continuously recorded by the electronics. Upon a trigger, each wire plane provides a 2D view of the ionization event. Multiple 2D views can then be combined to reconstruct a 3D image of the event.

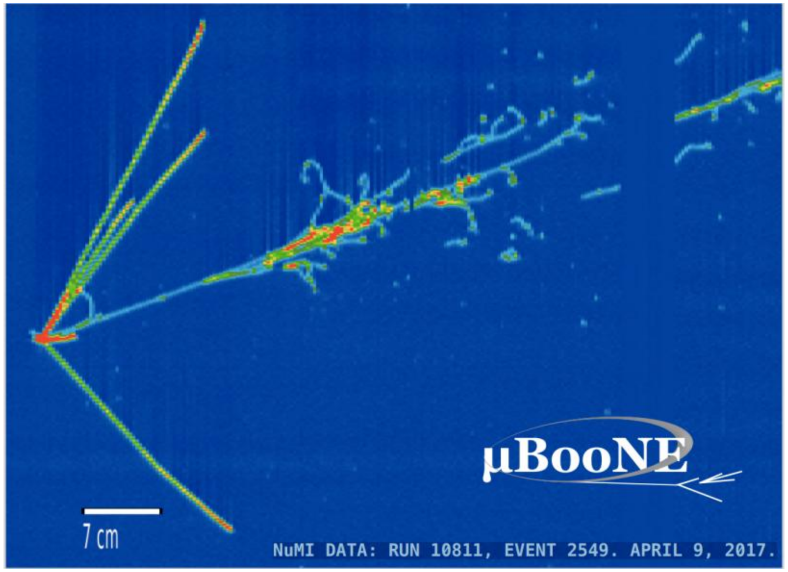
The event's t_0 is provided by a flash of scintillation light, as argon is a high-yield liquid scintillator. However, this light has a wavelength of 128 nm (VUV) and requires special techniques to be detected.

The DUNE predecessors: ICARUS, MicroBoone, SBND, ProtoDUNE

Technical challenges were enormous:	Solved by
• Argon purity: electronegative pollutants must be removed at 0.1 parts-per-billion level to allow electron drift for several meters	ICARUS, ProtoDUNE
• Argon is liquid at 87 K and we need huge and cost-effective cryostats to contain the target	ProtoDUNE, SBND
• The readout electronics must sample the electrical signals in all wires for long time because the electrons drift slowly (1 mm/us)	ICARUS, MicroBoone
• Scintillation light must be down-shifted to more amenable wavelengths for detection	ICARUS, MicroBoone, ProtoDUNE
• All components must be modular to be installed underground	ProtoDUNE, SBND

But physics results are amazing!

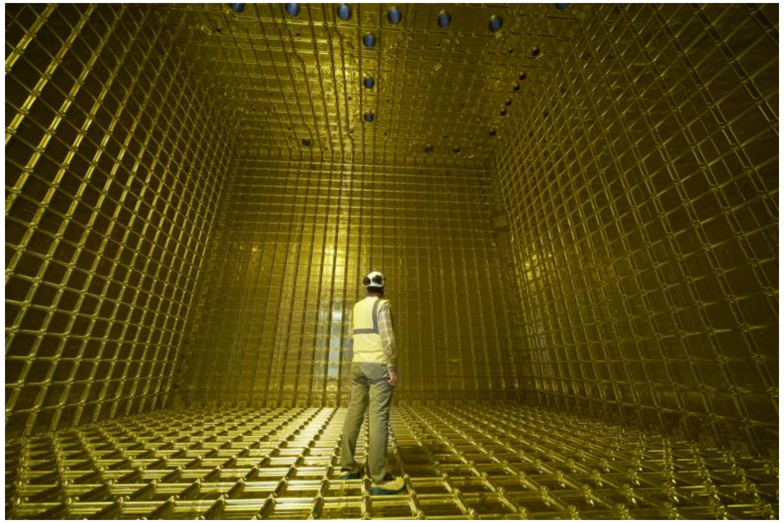
- Identification of photons to completely suppress the NCπ^0 background
- Particle identification (p/K/μ) from the dE/dX pattern
- Energy resolution of 10% and 40% for electrons and hadrons, respectively

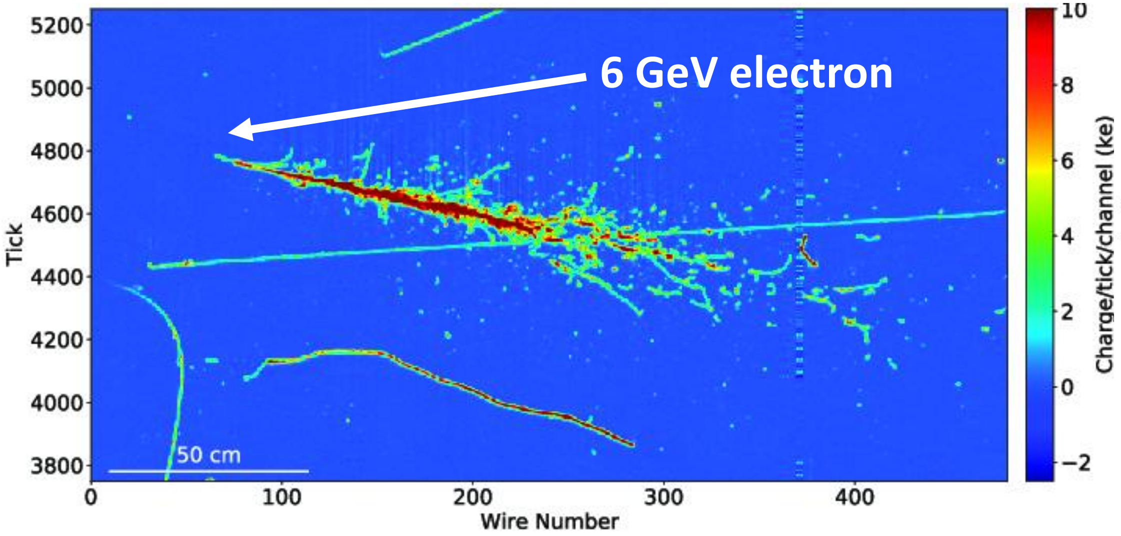


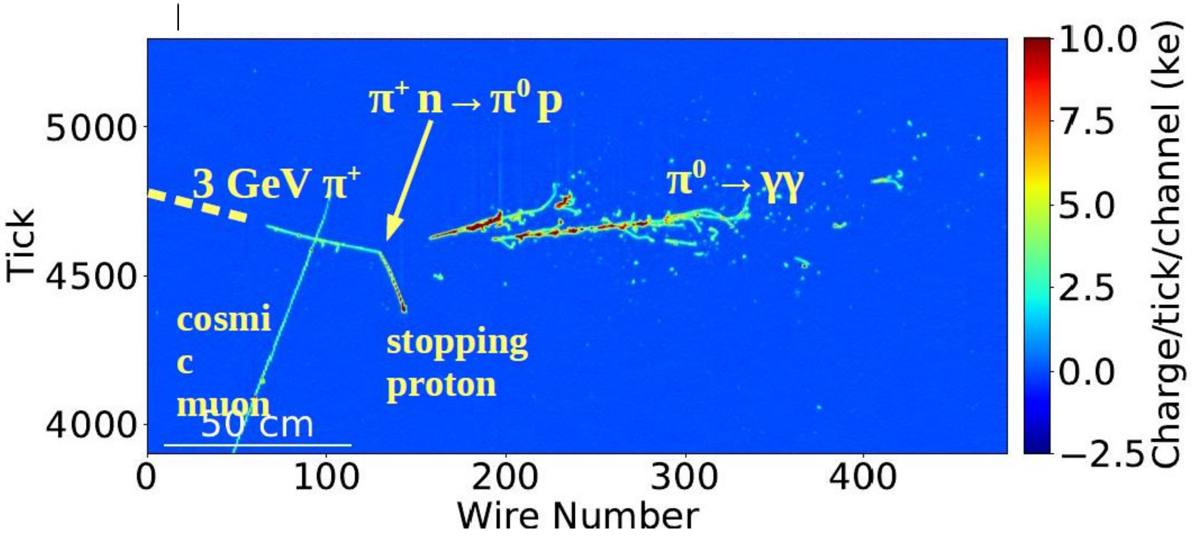
The DUNE demonstrator: the two ProtoDUNEs at CERN

ProtoDUNE-VD ProtoDUNE-HD

Membrane cryostat



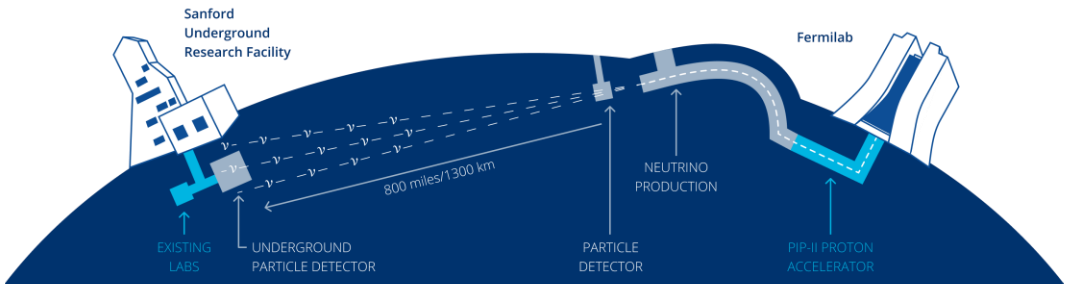


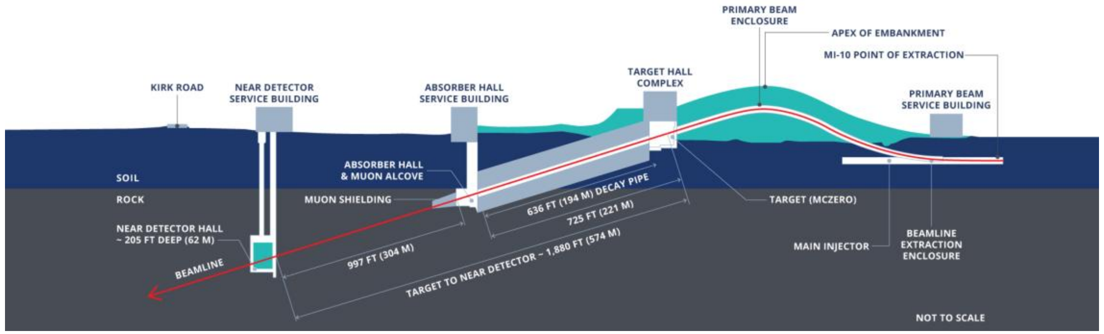


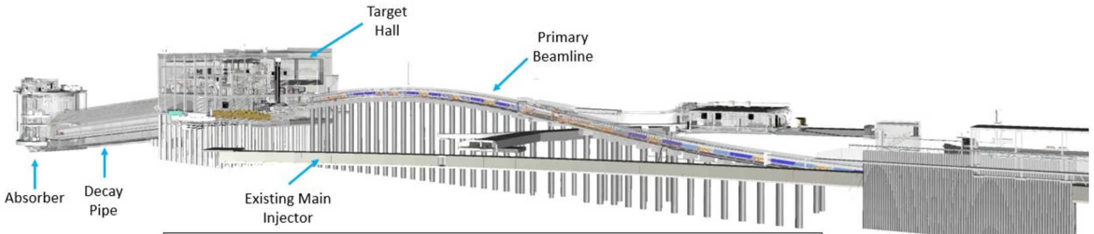
The DUNE beamline

Parameter	Value	Notes
Proton Beam Energy	60 – 120 GeV	Typical operation at 120 GeV
Beam Power (initial)	1.2 MW	Upgradable to 2.1 MW
Repetition Rate	~0.7 Hz	Based on Main Injector cycle
Beam Intensity	~7.5 × 10^{13} protons/pulse	Approx. 1.1 × 10^{21} protons/year
Pulse Duration	~10 µs	
Target	Graphite (water-cooled)	
Focusing System (Horns)	Two magnetic horns	Pulsed at ~300 kA to focus secondaries
Decay Pipe	194 m length, 4 m diameter	Allows meson decay into neutrinos
Decay Pipe Material	Filled with helium	Minimizes secondary interactions
Beam Absorber	Steel, aluminum, concrete	
Baseline Length (FNAL → SURF)	1300 km	
Beam Angle	5.8° below horizontal	Aimed to reach SURF depth
Neutrino Beam Mode	Neutrino or antineutrino selectable	By reversing horn polarity
Beam Type	Wide-band beam	between 1–5 GeV

The DUNE neutrino beam (LBNF) employ the same proton driver as NOvA but a different beamline

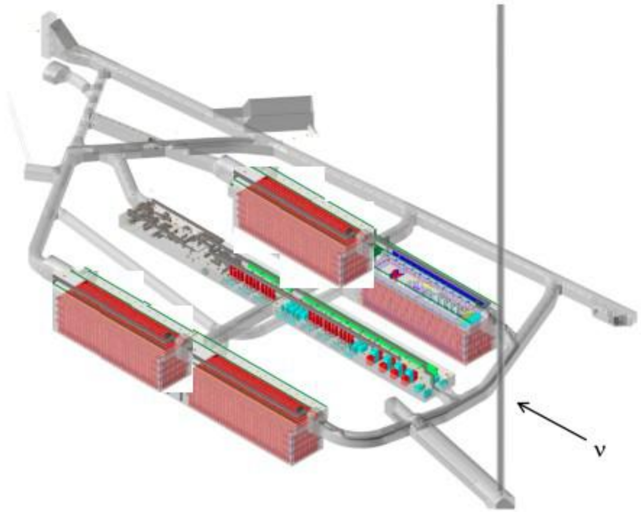




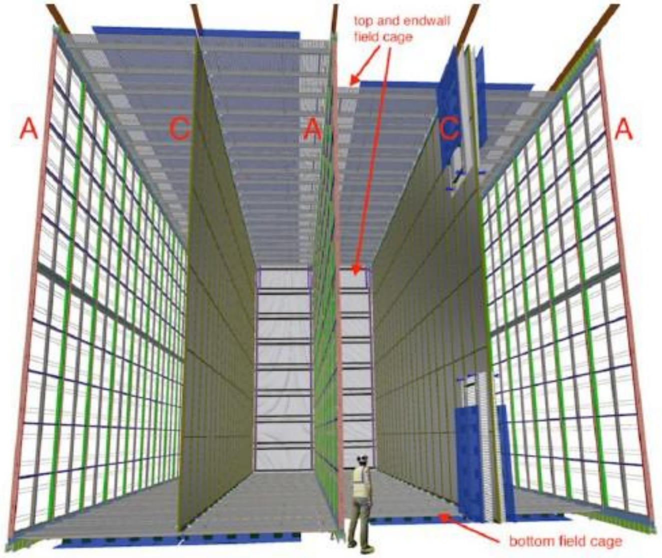


Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

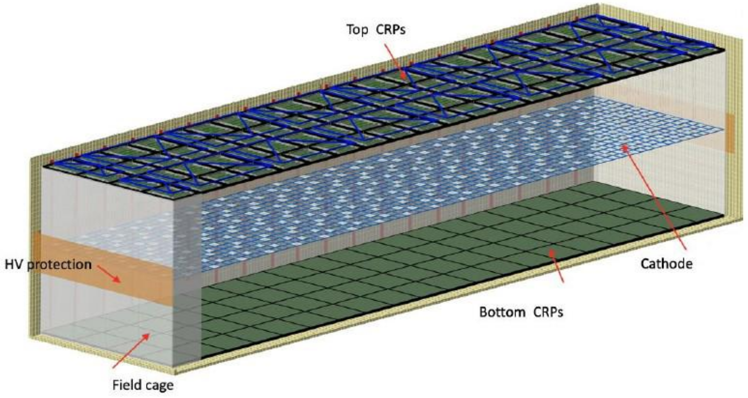
SURF in Lead, South Dakota



Horizontal drift (HD, left) using wire readout planes, four drift regions



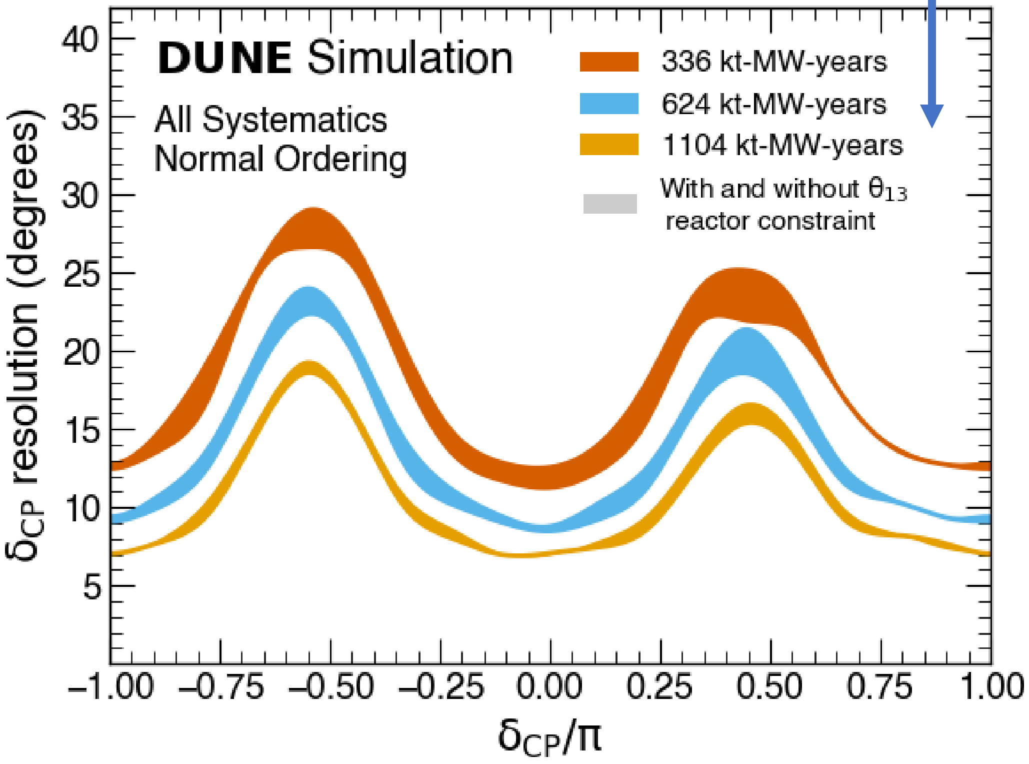
Vertical drift (VD, right) using two 6.25m drift regions and central cathode



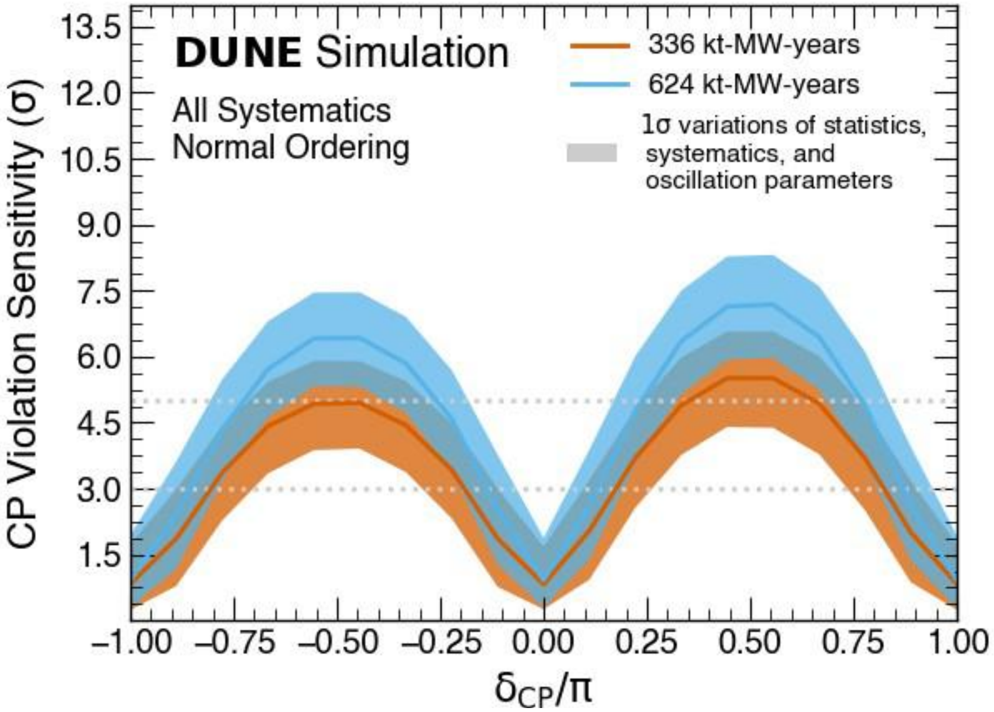
The physics of DUNE and HyperK: CP violation

Two ways to express CP sensitivity, which answer two – somehow different - questions:

- Is there a new source of CP violation in the Standard Model?
- How well can we measure the Dirac CP phase?



This class of plots provide the impact of the experiment in the determination of δ. Note that the worst sensitivity corresponds to the largest CP violation



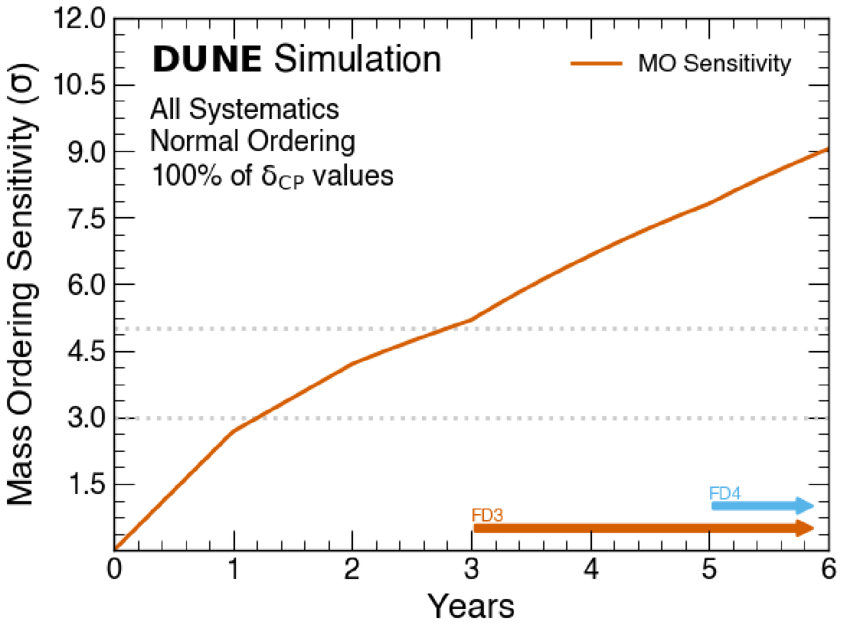
This class of plots says the fraction of possible δ value by which we get a $n\sigma$ evidence for CP violation, i.e. observe a difference between $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-ν_e

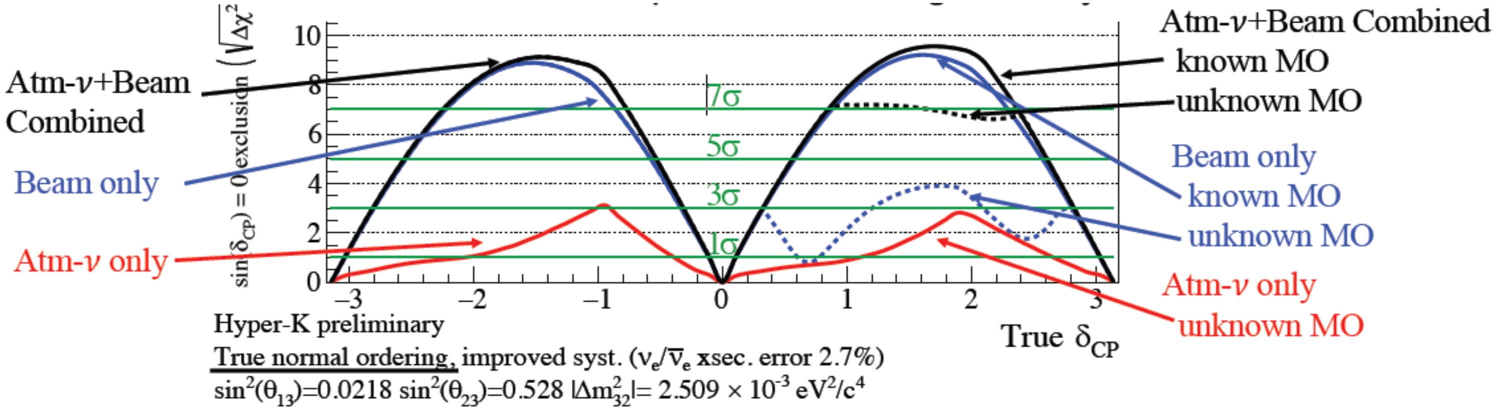
The physics of DUNE and HyperK: CP violation vs mass ordering

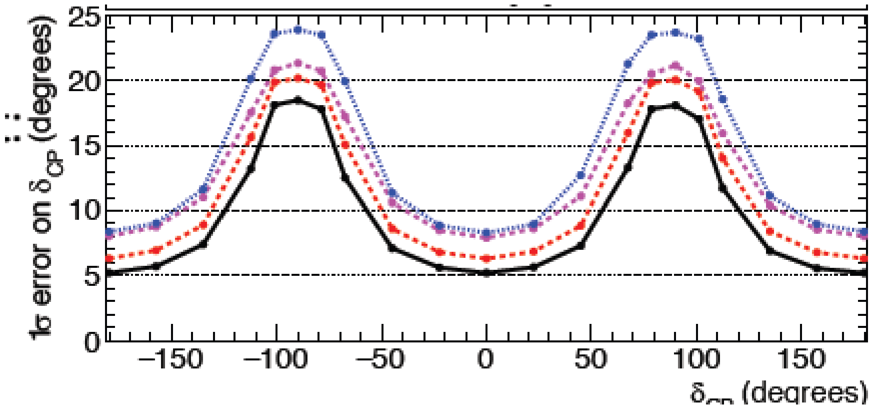
CP violation and mass ordering are entangled in the master formula and we need to disentangle their effects. In particular, **in half of the parameter phase, a CP violating solution in a given mass ordering corresponds to a CP conserving solution in the opposite mass ordering** ("mass ordering ambiguity").

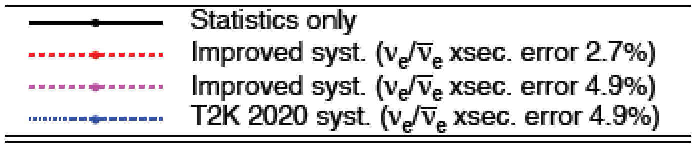
Not an issue for DUNE, which has an unprecedented sensitivity to mass ordering

It can be solved quite easily in HyperK either using external measurements of mass ordering (JUNO, neutrino telescopes) or measuring mass ordering in HyperK from atmospheric neutrinos









The physics of DUNE and HyperK: θ_{23} octant

The issue: In $\nu_\mu \rightarrow \nu_\mu$ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$. Now, if $\sin^2 2\theta_{23}$ differs from 1, then we get two solutions for θ_{23}: one < 45°, termed as lower octant (LO) and the other > 45°, termed as higher octant (HO). In other words, if the quantity ($0.5 - \sin^2 \theta_{23}$) is positive (negative) then θ_{23} belongs to LO (HO)

Should we care? (it looks like a technical detail ☺). Yes, we should.

- The lack of knowledge of the octant introduce another ambiguity (octant degeneracy) in the determination of the CP phase δ
- Maximal mixing and its deviations are usually hints for a symmetry and, therefore, the octant (deviation from maximality) is an important input to understand the origin of flavor in the Standard Model

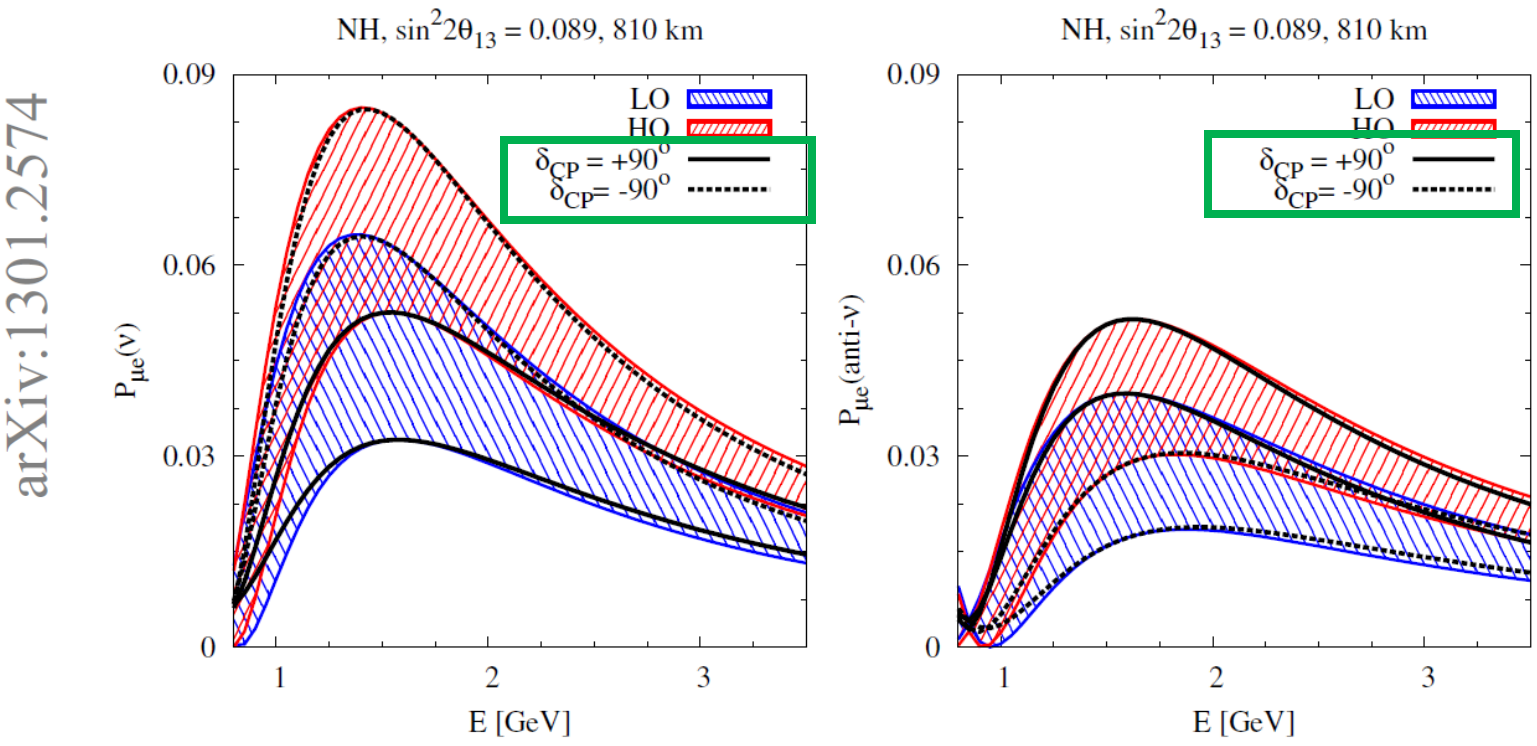
$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right) \qquad P_{\nu_\mu \to \nu_e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

The octant is a small effect and subleading terms are important – they require a knowledge of mass ordering and δ. It creates another degeneracy between θ_{23}, mass ordering and δ (the “eight-fold degeneracy”).

Determining the octant is very difficult today but much easier in the DUNE and HyperKamiokande era

θ_{23} octant

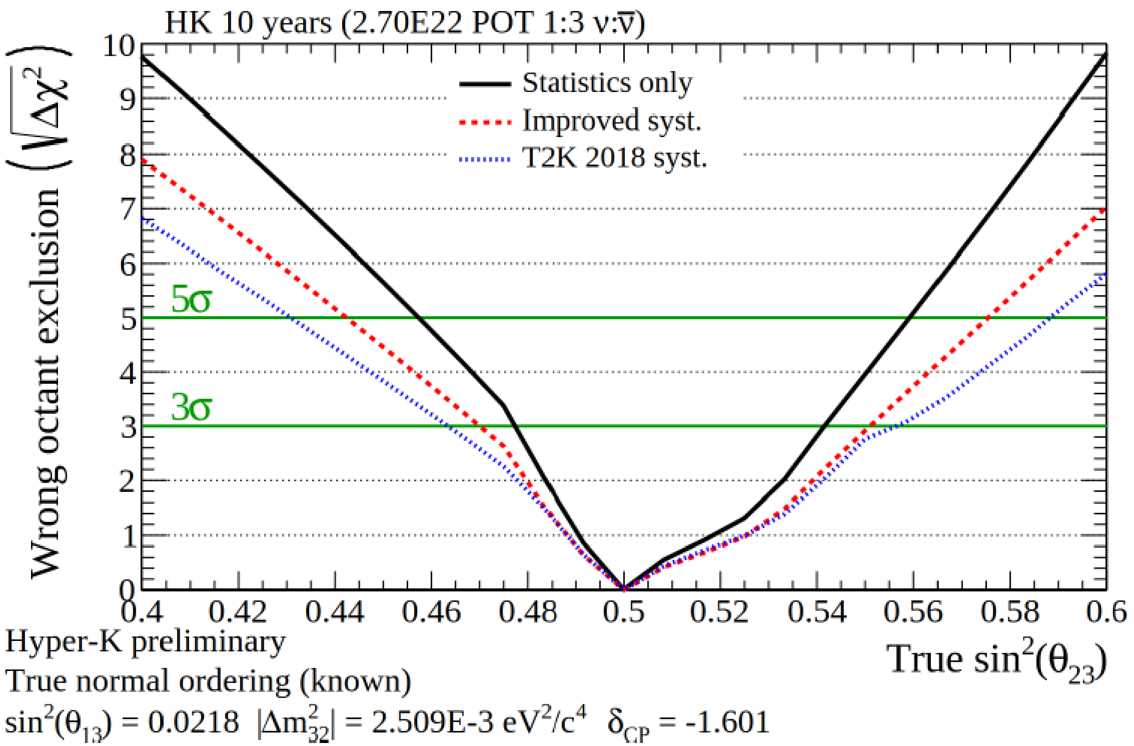
- The mass ordering will be known and it is a yes/no parameter - precision does not matter as soon as we get a strong evidence (DUNE and/or JUNO+neutrino telescopes)
- Unlike the "mass ordering-δ" degeneracy, where the effect contribute both to ν and anti-ν oscillation probabilities, comparison between neutrino and antineutrino data helps!



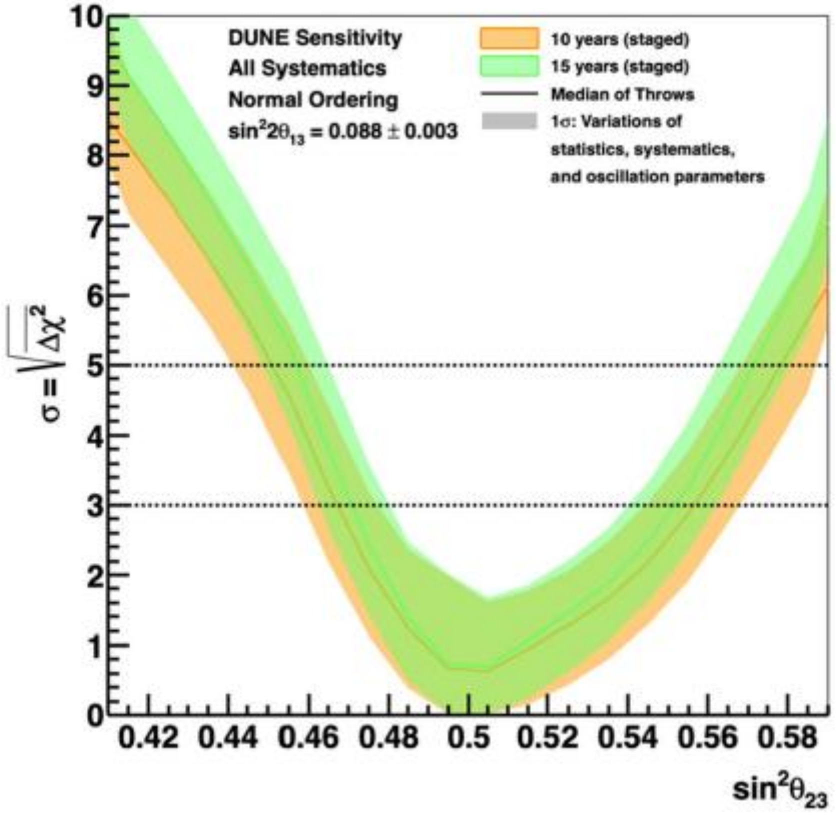
Once, the mass ordering is known, both DUNE and HyperK can make a good job because they can compare neutrinos with antineutrinos to lift the degeneracy

The physics of DUNE and HyperK: θ_{23} octant

HyperK: 3σ rejection of wrong-octant of θ_{23} for $\sin^2 2\theta_{23} < 0.47$ or $\sin^2 2\theta_{23} > 0.55$



DUNE



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