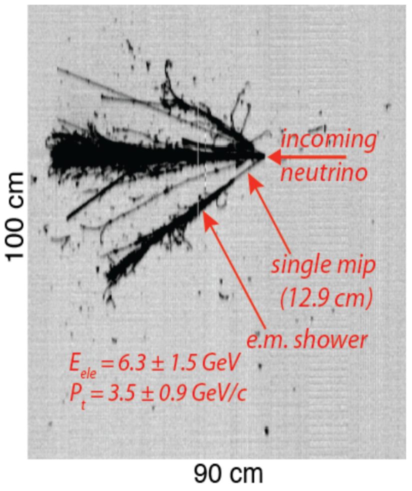
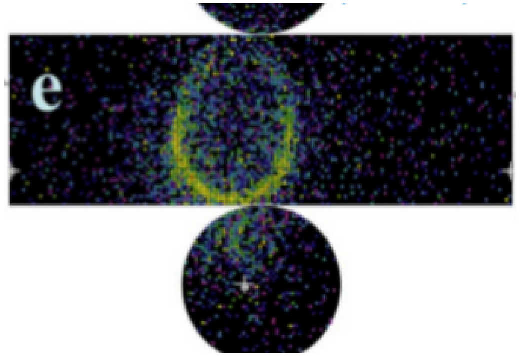
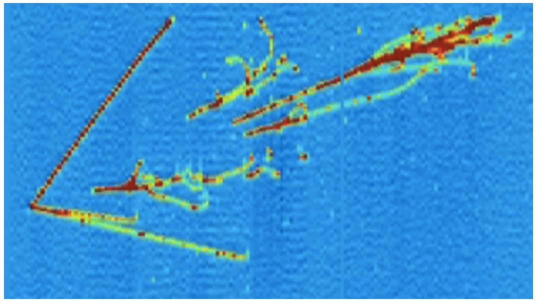
Neutrino oscillations: status and perspectives with accelerator beams

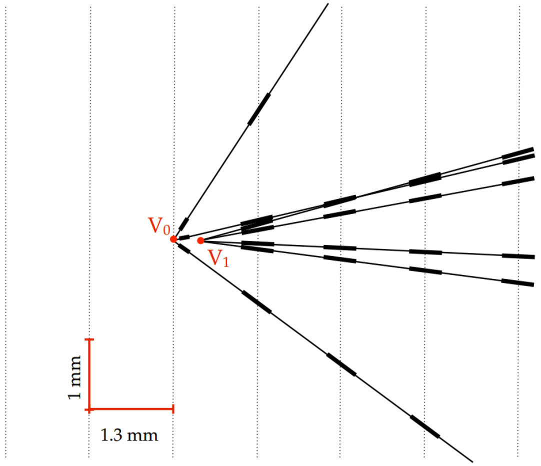
XVIII Roma Tre Topical Seminar on Subnuclear Physics
“Neutrinos”, 9 Dec. 2015

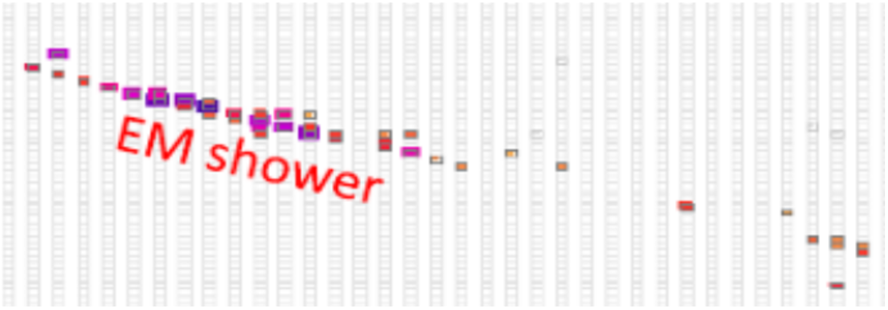


A. Longhin (INFN-LNF)









Outline

- Which Physics and how it is done.
- Fruitful days with present experiments
  - OPERA: $\nu_\mu \rightarrow \nu_\tau$, T2K, NOνA: $\nu_\mu \rightarrow \nu_e / \nu_\mu$
  - Starting to aim at leptonic CP violation, mass hierarchy
- The challenges for the future:
  - "↑ statistics ↓ systematics"
- New ideas and initiatives in EU, JP and US
  - Hyper-K, DUNE, SB program, CERN ν plat

A vast topic … not covered:
exotic searches, sterile neutrinos, cross section, R&D experiments, ...

ν mixing and oscillations

Mass eigenstates $(\nu_1,\nu_2,\nu_3) \leftrightarrow$ weak eigenstates (ν_e,ν_μ,ν_τ)

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i(t)\rangle$$

“atmospheric”

Δm^2_{31}

U: PMNS matrix

“solar”

Δm^2_{21}

s = sin, c = cos

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

SuperK, K2K, MINOS, OPERA, T2K, NOvA

(D)CHOOZ, Daya Bay, RENO T2K, MINOS, NOvA

SuperK, SNO, GNO, Gallex, Borexino, KamLAND

$\theta_{23} = (45.8 \pm 3.2)°$

$\theta_{12} = (33.4 \pm 0.85)°$

$\theta_{13} = (8.88 \pm 0.39)°$

$\Delta m^2_{21} = (7.53 \pm 0.18)\ 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{32}| = (2.44 \pm 0.06)\ 10^{-3}\ \mathrm{eV}^2$

PDG2014

Long baseline experiments

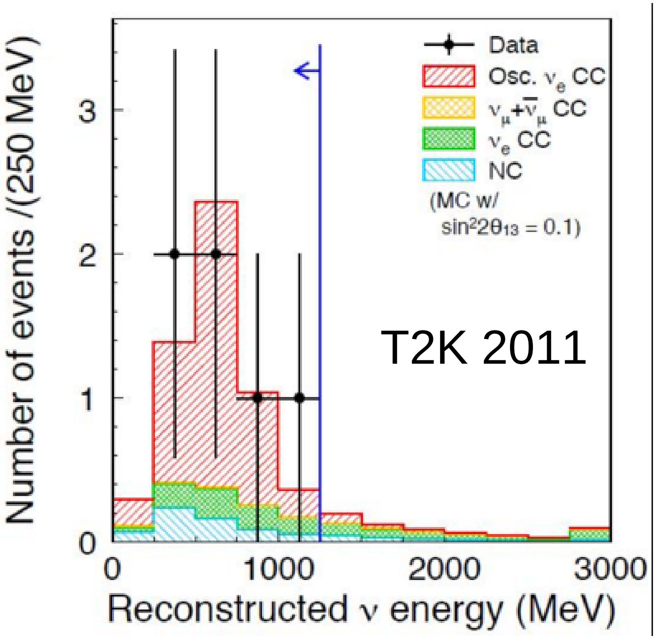
CP violation? mass hierarchy $(m_{1,2} \lessgtr m_3)$? $\theta_{23} = 45^o$? Majorana/Dirac ?

Symmetries? Relation with CKM ? Leptogenesis and BAU ?

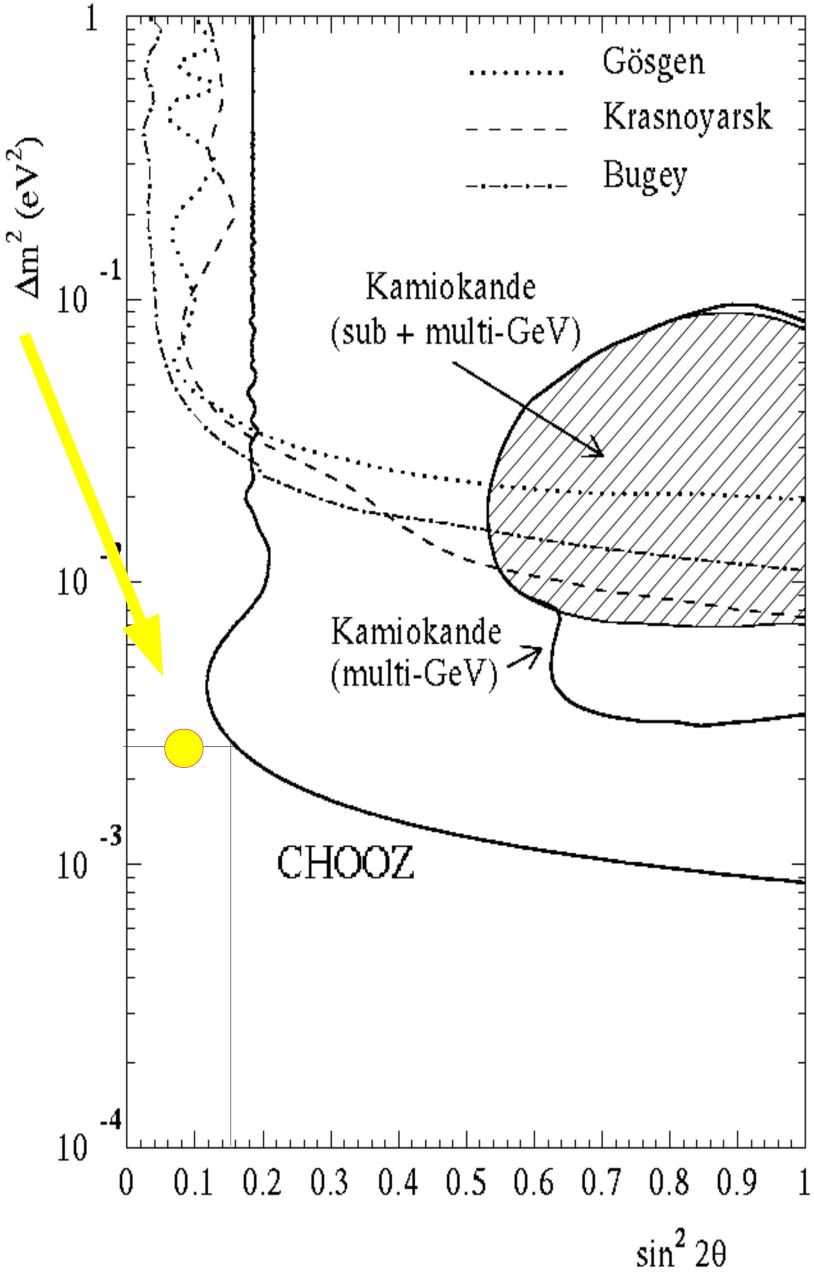
2012: new scenarios from large θ_{13}

$\sin^2 2\theta_{13}$: 14 y “behind the corner”

- >1998: < 0.15 @ 90% C.L. CHOOZ limit
- 2010: hints. Solar+reactor global fits, Fogli et al.
- 2011: 0.11 (0.14), T2K best fit of 2011 (2.5 σ)
- 2012: 0.092 ± 0.017, Daya Bay, (5.2 σ)
- 2013: T2K, 7.5 σ
- 2015: NOvA, 5.5 σ



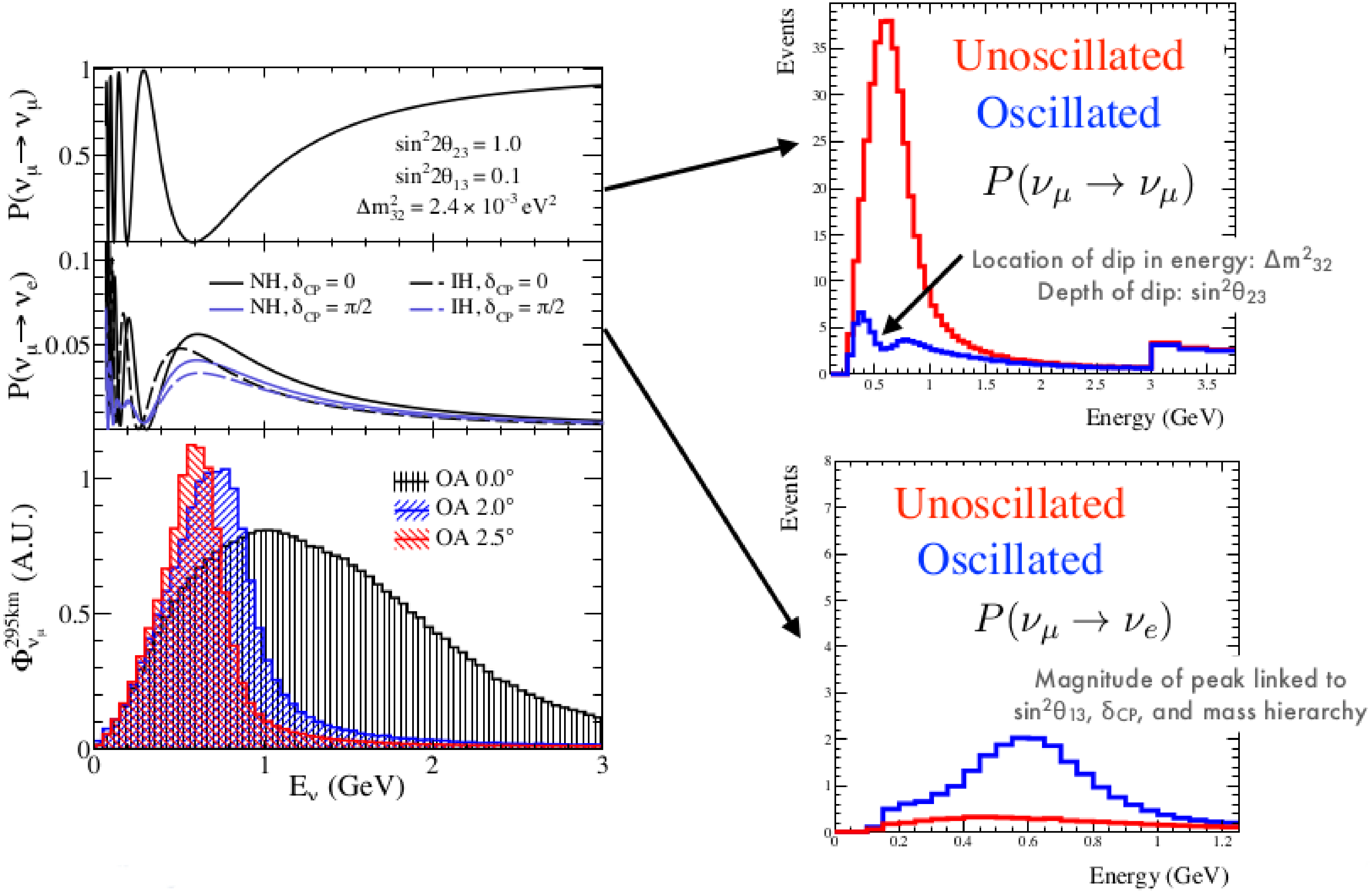
A necessary condition to move forward →



The observables with ν_μ beams

ν_e **appearance** (CC interactions of a diff. flavour) → θ_{13} & δ_{CP}

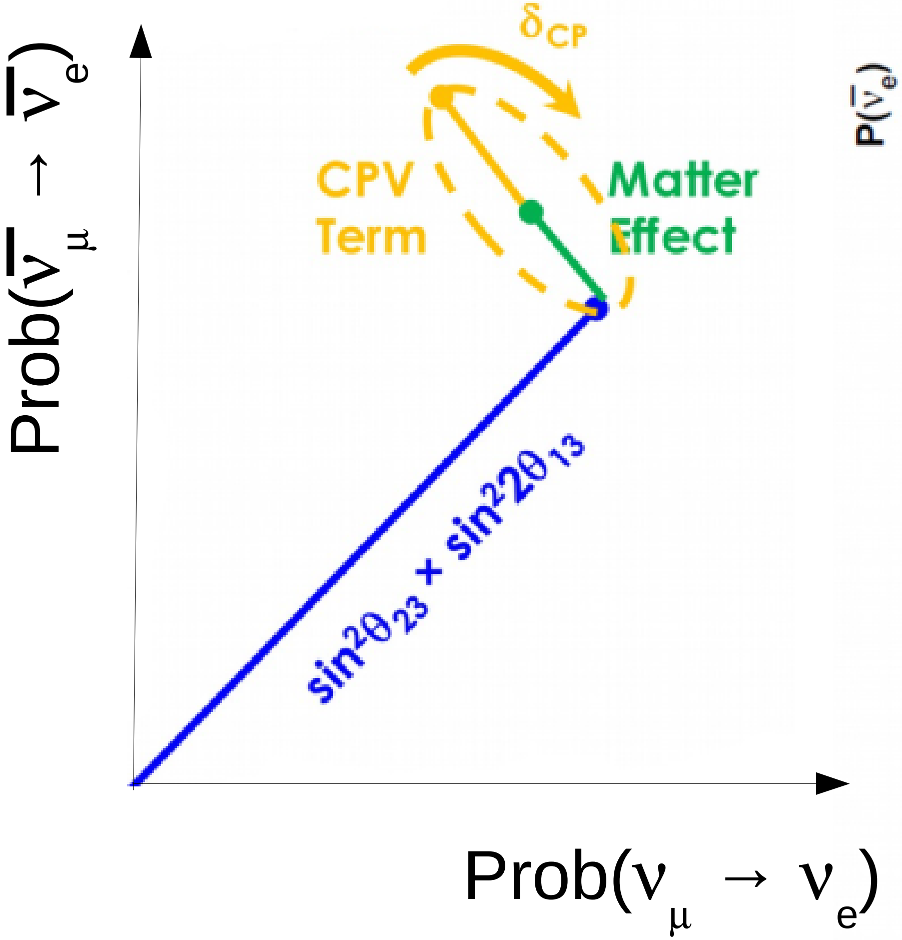
ν_μ **disappearance** (deficit of CC of the initial flavour) → θ_{23} & Δm^2_{23}

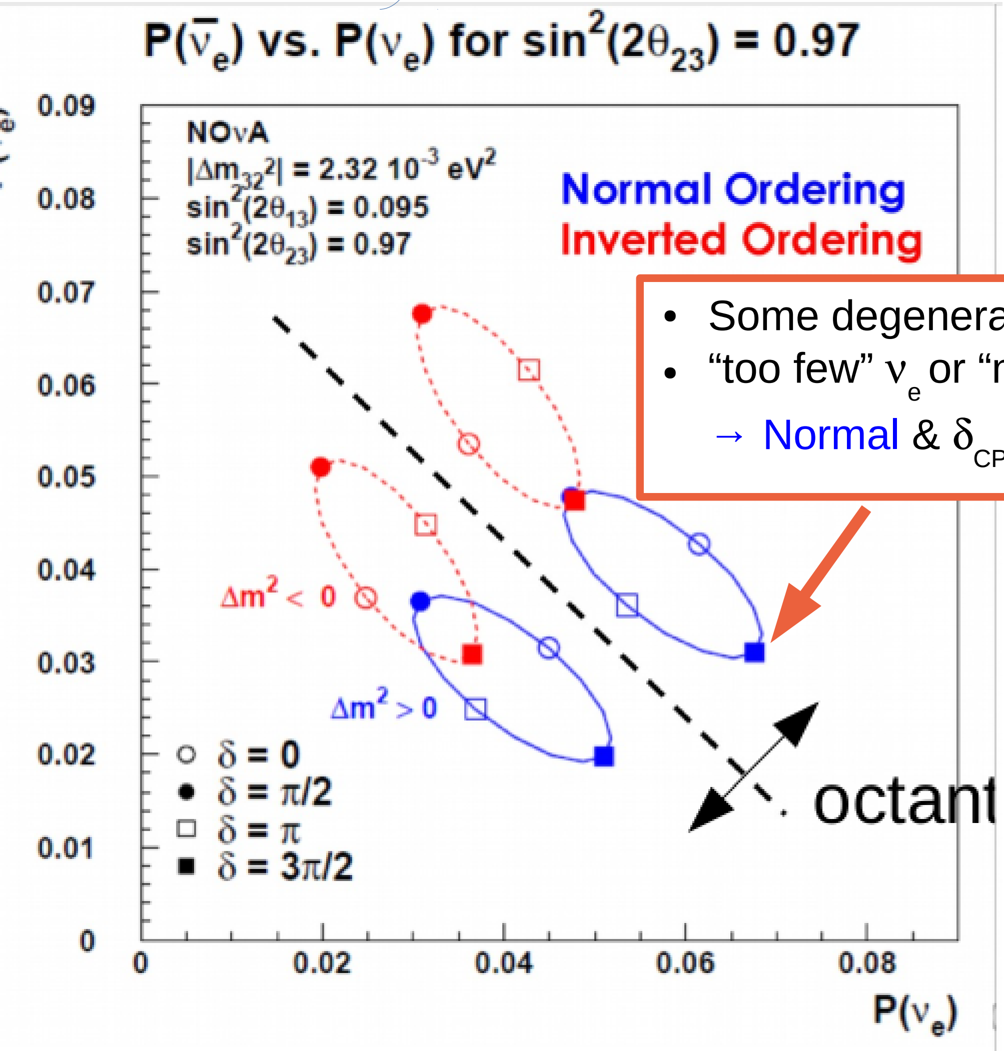


The future: learning a lot from (precisely!) measuring $\nu_\mu \to \nu_e$

$$\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4 c_{13}^2 \underline{s_{13}^2} s_{23}^2 \sin^2\Delta_{31} \qquad \text{dominant term} \\
& + 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& - 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underline{\sin\delta_{CP}} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \qquad \text{CP violation} \\
& + 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \sin^2\Delta_{21} \qquad \text{matter} \\
& - 8 c_{13}^2 s_{13}^2 s_{23}^2 \underline{\frac{aL}{4E_\nu}} (1 - 2 s_{13}^2) \cos\Delta_{32} \sin\Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \underline{\frac{a}{\Delta m_{31}^2}} (1 - 2 s_{13}^2) \sin^2\Delta_{31}
\end{aligned}$$

- **θ_{13}**
- **CP violation,**
- **mass hierarchy**
  - matter effects at large L
- **the octant of θ_{23}**




$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.97$

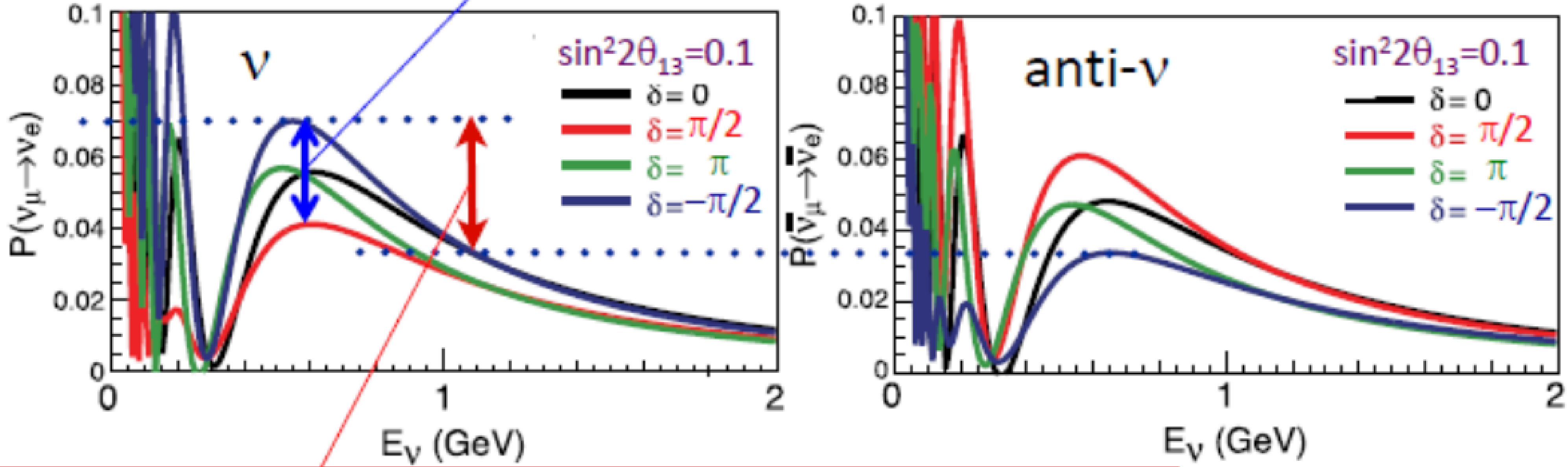
- Some degeneracy
- "too few" ν_e or "many" ν_e

  → Normal & $\delta_{CP} = 3/2\pi$

Learning a lot from (precisely!) measuring $\nu_\mu \rightarrow \nu_e$

- δ_{CP} → a modulation in the spectrum of the appeared ν_e
- The direction of the variation is opposite for ν and anti-ν beams → use both
- Mainly a change in normalization
  - accessing the 2nd maximum (at higher L and E) → more spectral info.
- Sub-leading: crucial role of systematics and statistics

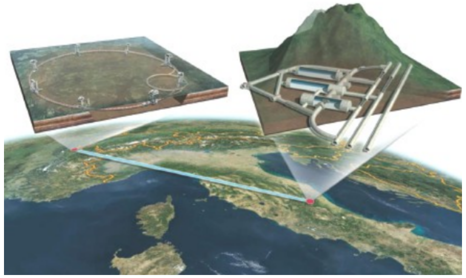
method 1: use θ_{13} from reactor experiments and compare with data



method 2: compare measured $P(\nu_\mu \rightarrow \nu_e)$ with $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

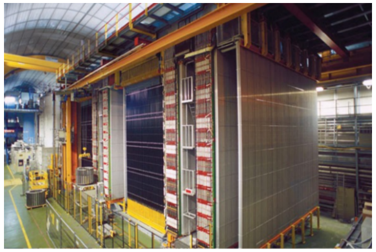
ν-beams (recent past and present)

CERN-SPS (400 GeV) 700 kW
<E> = 17 GeV (2006-2012)

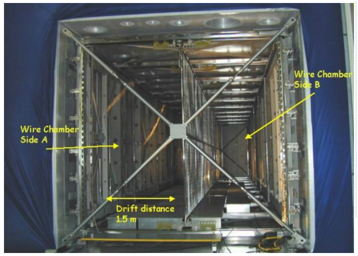


732 km
on-axis

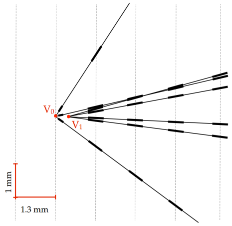
OPERA 1.2 kt



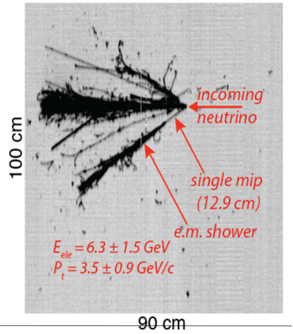
ICARUS 0.6 kt



Emulsions

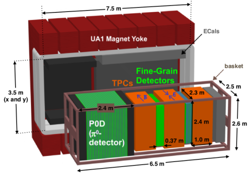


LAr TPC



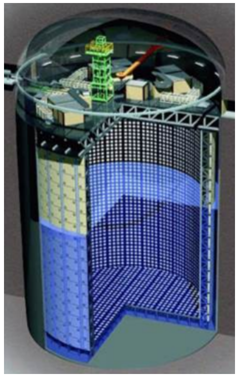
J-PARC Main Ring (30 GeV) 370 kW
<E> = 0.6 GeV (2009)

ND280

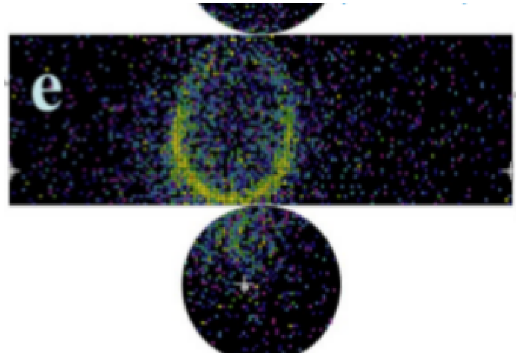


295 km
2.5° off-axis

Super-K 22.5 kt

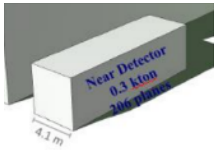


Water Cherenkov

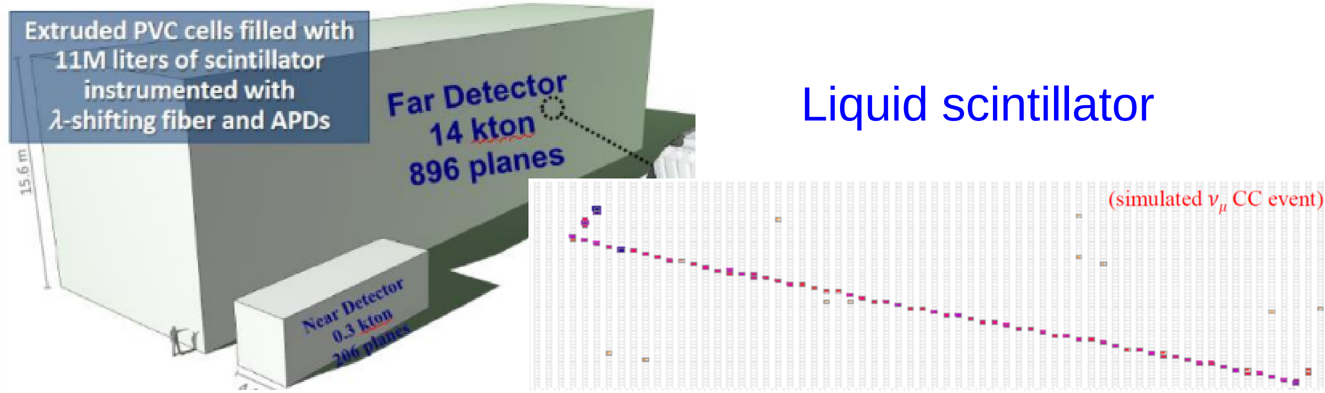


FNAL Main Injector (120 GeV) 520 kW
<E> = 2 GeV (2013)

810 km
0.84° off-axis



NOνA 14 kt



Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

Liquid scintillator

(simulated ν_μ CC event)

The long way to appearance

- **Disappearance** a “leading” effect: deficit of atmospheric ν_μ →
  - 1998 discovery of ν-oscillations by Super-K, MACRO, K2K ...
- **Appearance** on the other hand considered difficult:

- At the **solar scale**. Reactors and solar ν.

$\boldsymbol{\nu_e \rightarrow \nu_\mu}$ "IMPOSSIBLE": μ is below threshold

- At the **atmospheric scale**. Atmospheric-ν, artificial beams.

$\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$ “DIFFICULT” !

mass suppression, small cτ

$\boldsymbol{\nu_\mu \rightarrow \nu_e}$ "RARE"(...)

θ_{13} suppression ?

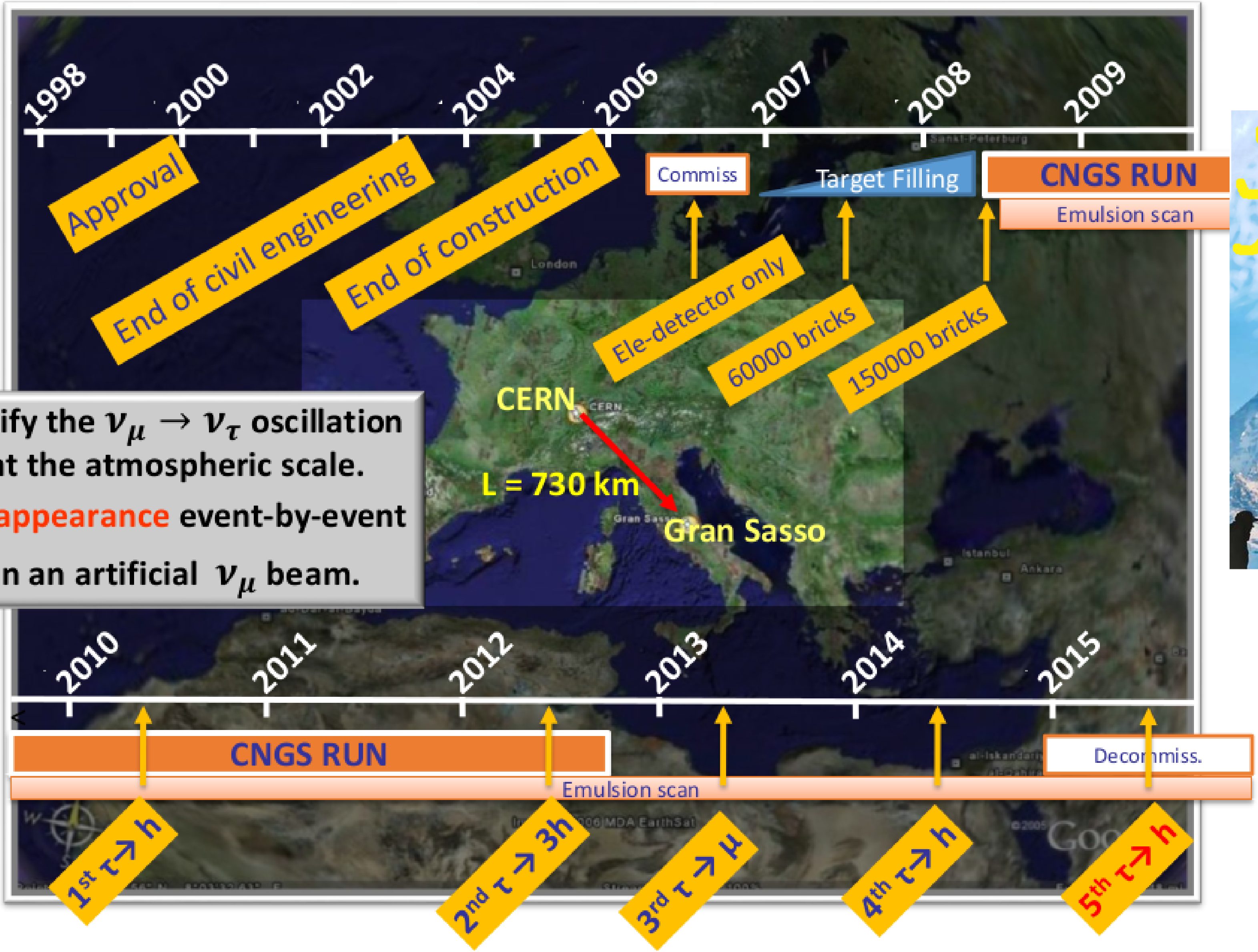
Today's perspective

Confirmed difficult, but event-by-event detection achieved by **OPERA** & **SK** (with a much lower S/B)

- Reactors: **no... θ_{13} is BIG !**
- Appearance seen by **T2K** and **NOνA** (with few POT)

The OPERA road map

An experimental and technological challenge. 732 km baseline. Beam O(10) more energetic (17 GeV) than any other LBL (m$_\tau$). A "fine-grained" detector O(100) more massive (1.25 kt) than the precursors SBL (i.e. CHORUS).


1998
2000
2002
2004
2006
2007
2008
2009
Approval
End of civil engineering
End of construction
Commiss
Target Filling
CNGS RUN
Emulsion scan
Ele-detector only
60000 bricks
150000 bricks
CERN
L = 730 km
Gran Sasso
2010
2011
2012
2013
2014
2015
CNGS RUN
Emulsion scan
Decommiss.
1st $\tau \to h$
2nd $\tau \to 3h$
3rd $\tau \to \mu$
4th $\tau \to h$
5th $\tau \to h$

Verify the $\nu_\mu \to \nu_\tau$ oscillation at the atmospheric scale.

ν_τ appearance event-by-event in an artificial ν_μ beam.

The CNGS beam for $\nu_\mu \to \nu_\tau$

$< E_\nu >$	**17 GeV**
$L / < E_\nu >$	**43 km/GeV**

The oscillation peak for L= 732 km at ~ 1.5 GeV (similar to NuMI) but here the goal is to produce τ leptons
→ unbalance at higher energies

$N(\tau) \sim Pr(\nu_\mu \to \nu_\tau) \times \sigma_{\nu(\tau)CC}(E) \times \text{flux}$

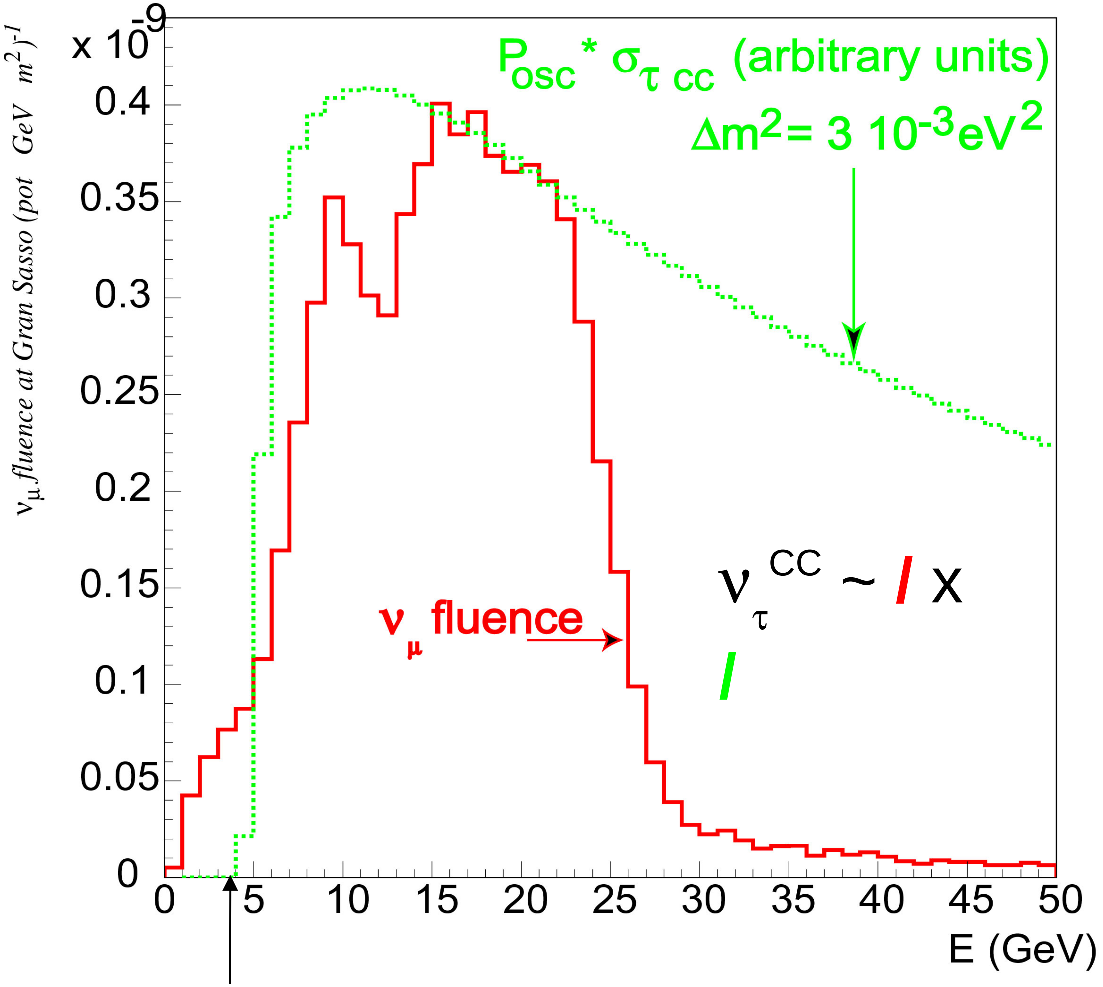
Fluxes:

$(\nu_e + \overline{\nu}_e) / \nu_\mu$	**0.9 %**
$\overline{\nu}_\mu \ / \ \nu_\mu$	**2.1 %**
ν_τ prompt (from D_s)	**negligible**

Interaction rates (1.8×10^{20} pot):

~ 20k ν_μ CC+NC
66.4 ν_τ CC (not efficiency corrected)

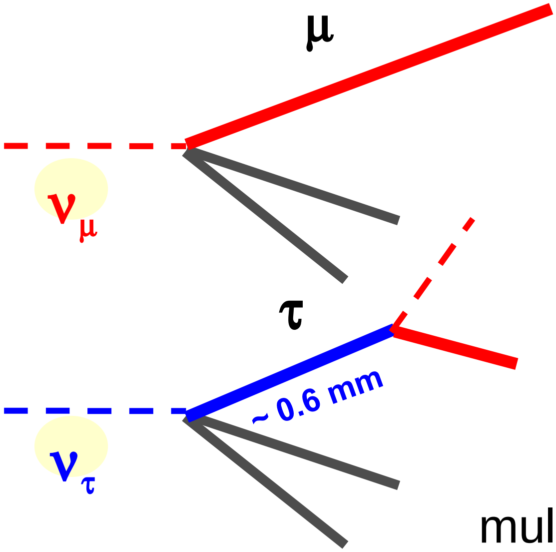
DESIGN: $4.5 \cdot 10^{19}$ pot/year, 200 days/y per 5 y



Threshold for τ at ~ 3.5 GeV.

Slow rise.

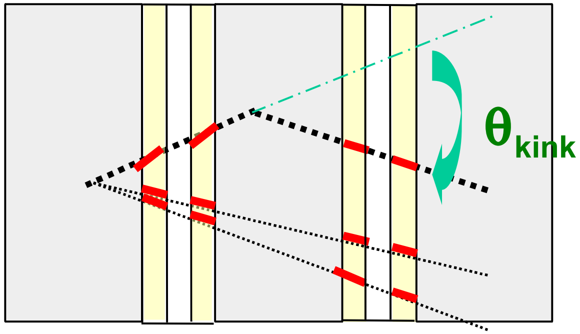
The ν_τ detection challenge



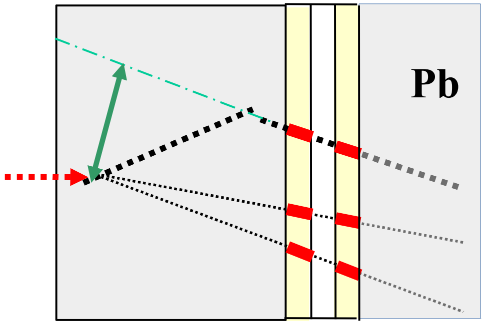
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

kink	$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$	17 %
	$\tau^- \rightarrow e^- \nu_\tau \nu_e$	18 %
	$\tau^- \rightarrow h^- \nu_\tau\, n(\pi^0)$	50 %
multi-prong	$\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_\tau\, n(\pi^0)$	14 %

“long” decays: kink



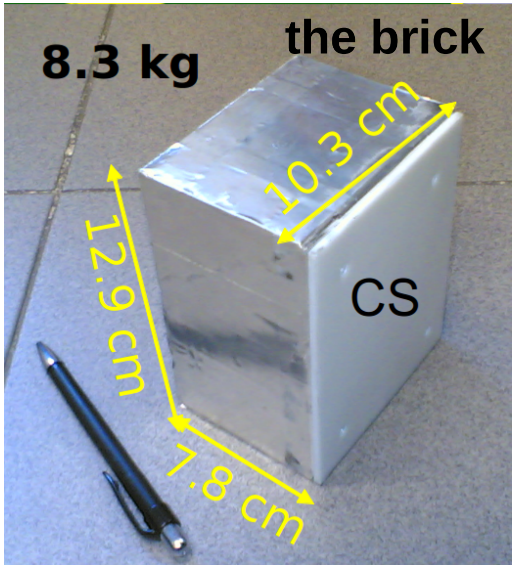
“short” decays: I.P.

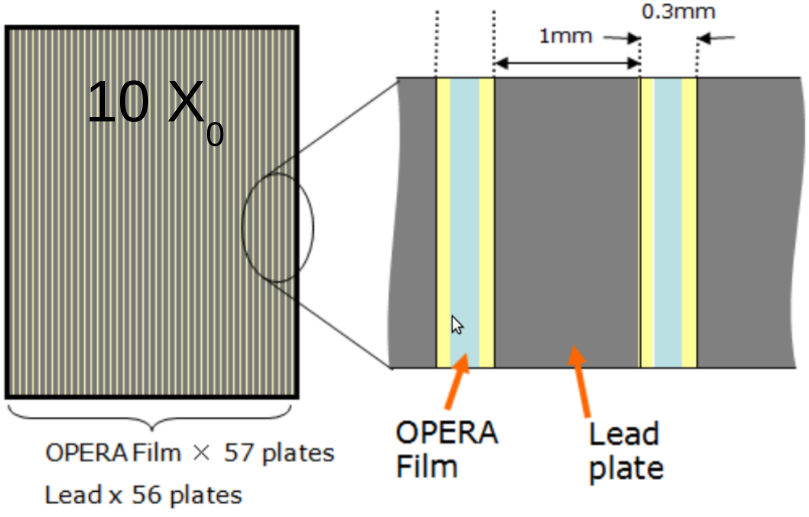


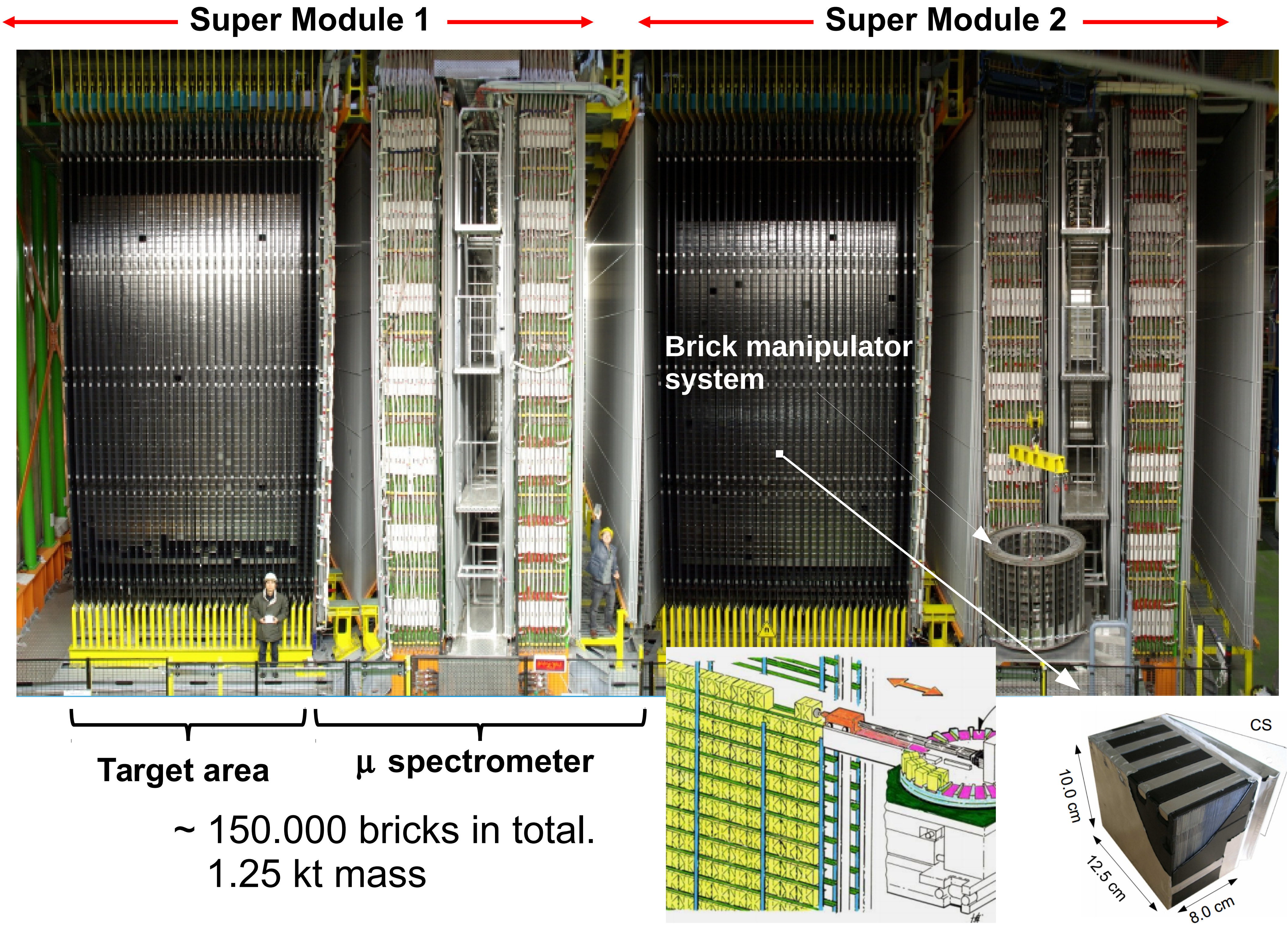
Modular detector of “Emulsion Cloud Chambers” (or bricks)

Reconciles the needs for:

- **Large mass**
  - $N_\tau \propto (\Delta m^2)^2 M_{target}$
- **Extreme granularity**
  - $\sim \mu m$





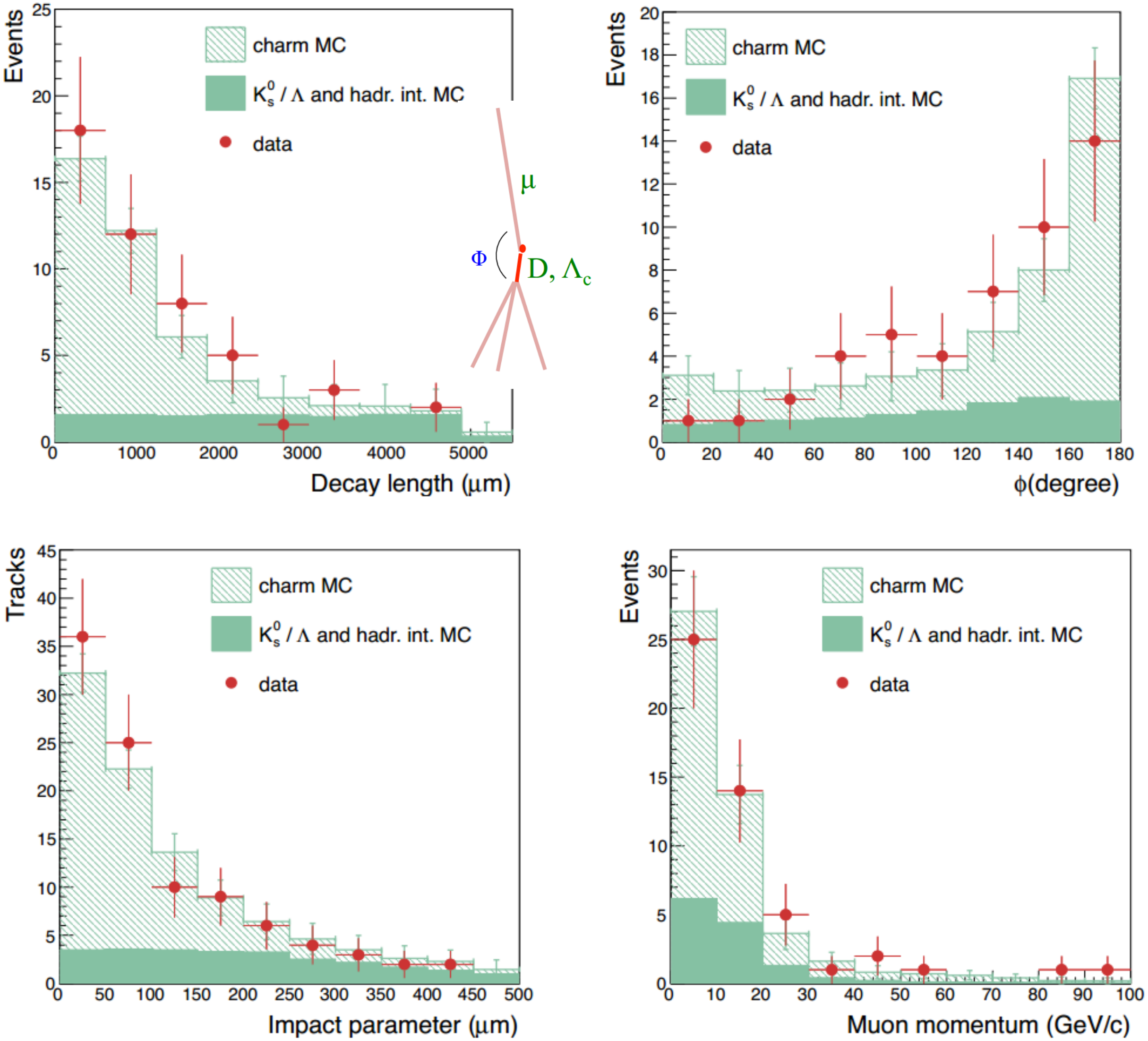


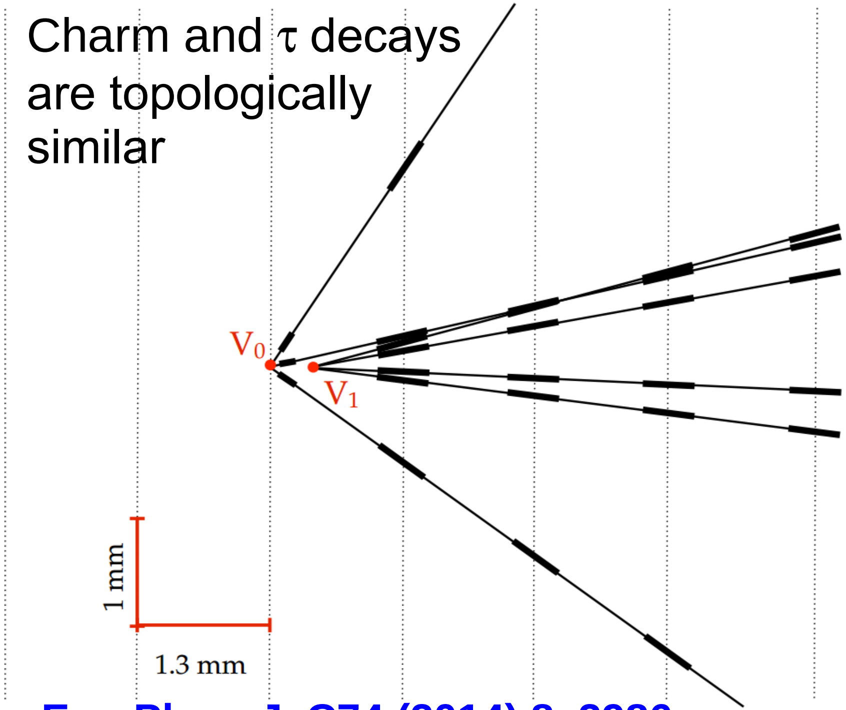
~ 150.000 bricks in total.
1.25 kt mass

Validation with the CNGS charm events sample

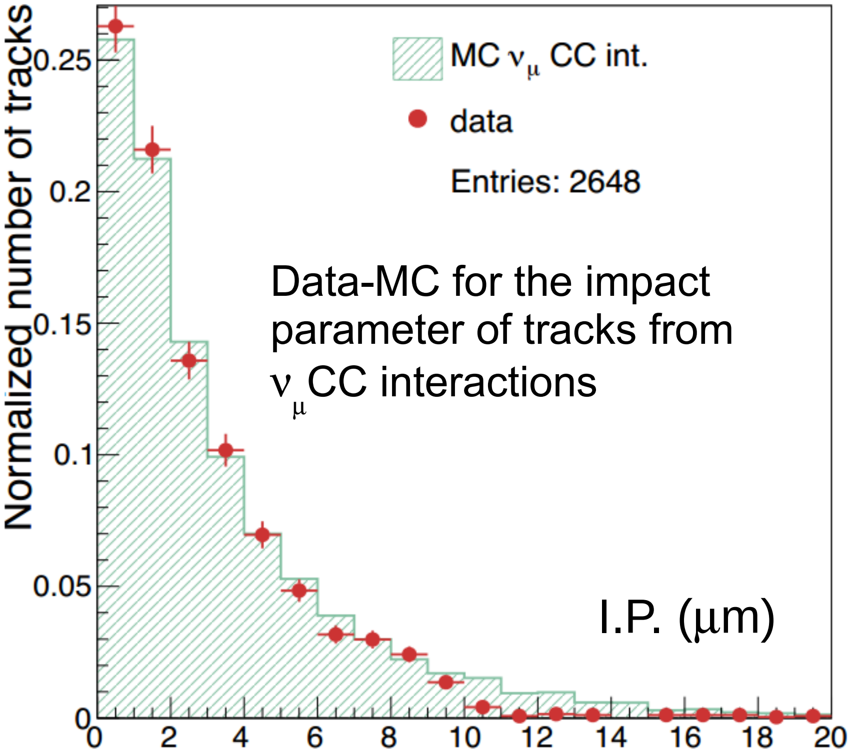
Test for: reconstruction efficiency, description of kinematical variables, charm background.

54 ± 4 expected ↔ 50 observed



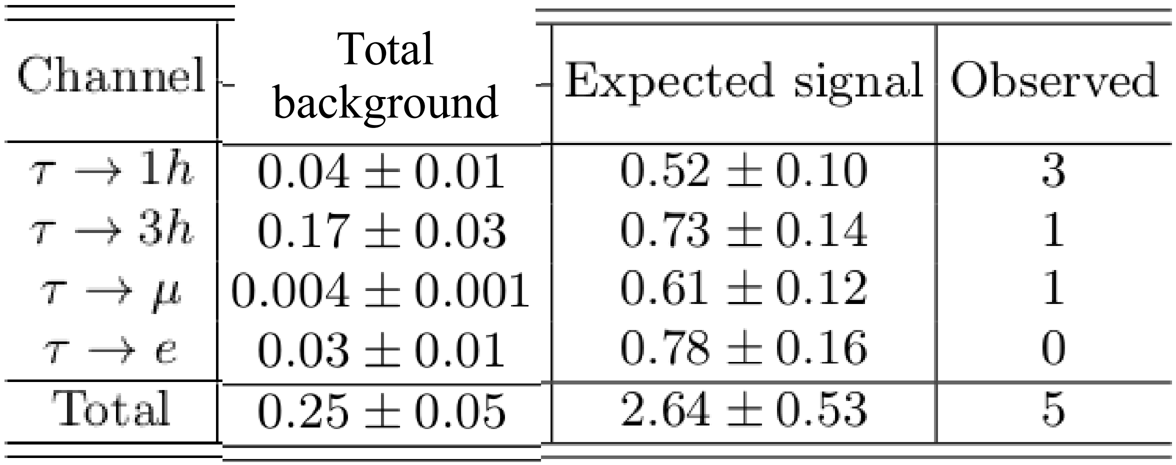

Charm and τ decays are topologically similar

Eur. Phys. J. C74 (2014) 8, 2986


Data-MC for the impact parameter of tracks from ν_μ CC interactions

OPERA ν_τ appearance

PRL 115 (2015) 12, 121802

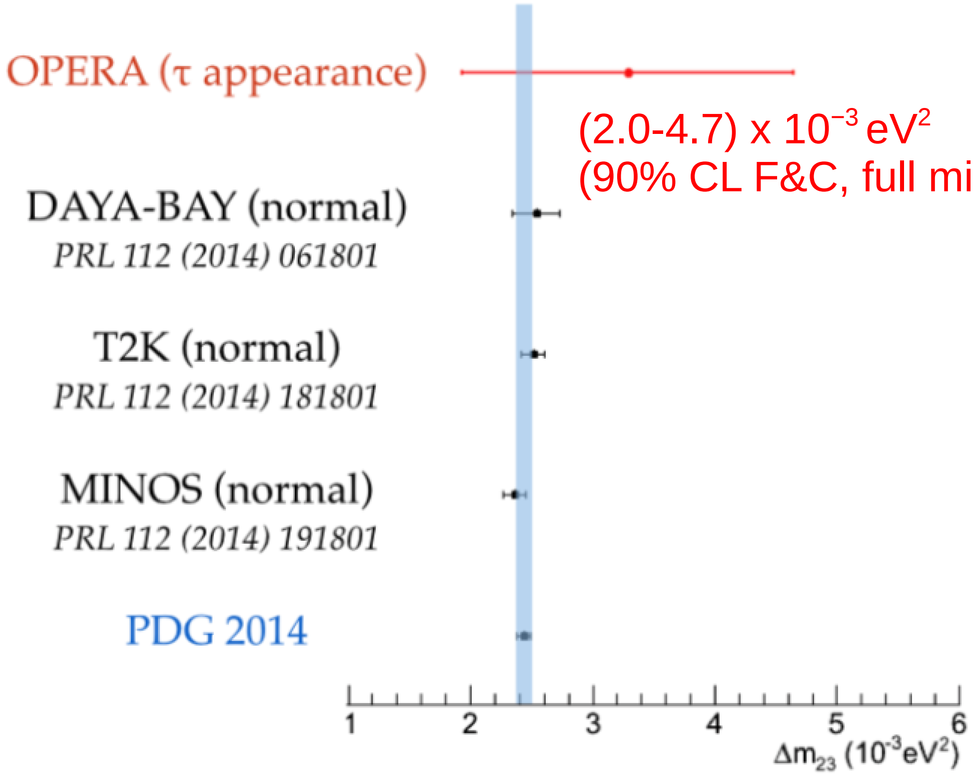


Channel	Total background	Expected signal	Observed
$\tau \to 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

5 candidates fulfilling the kinematic selection defined in the experiment proposal

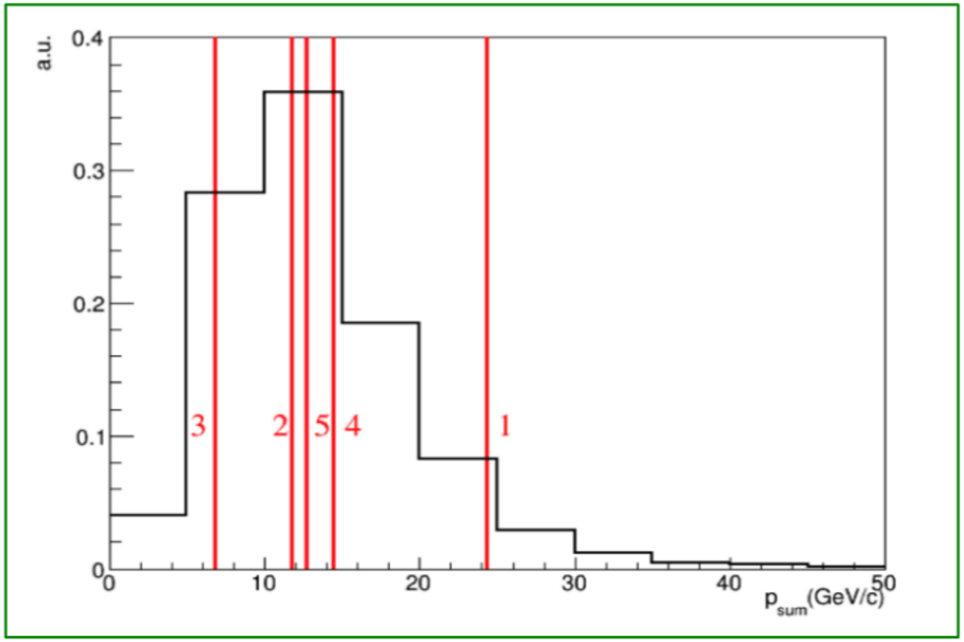
→

5.1 σ exclusion of the background-only hypothesis



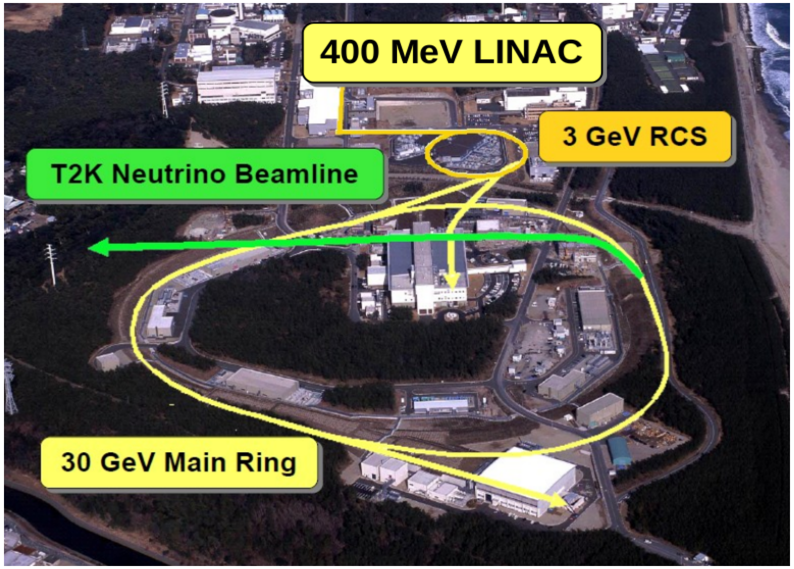
(2.0-4.7) x 10^{-3} eV^2
(90% CL F&C, full mixing)

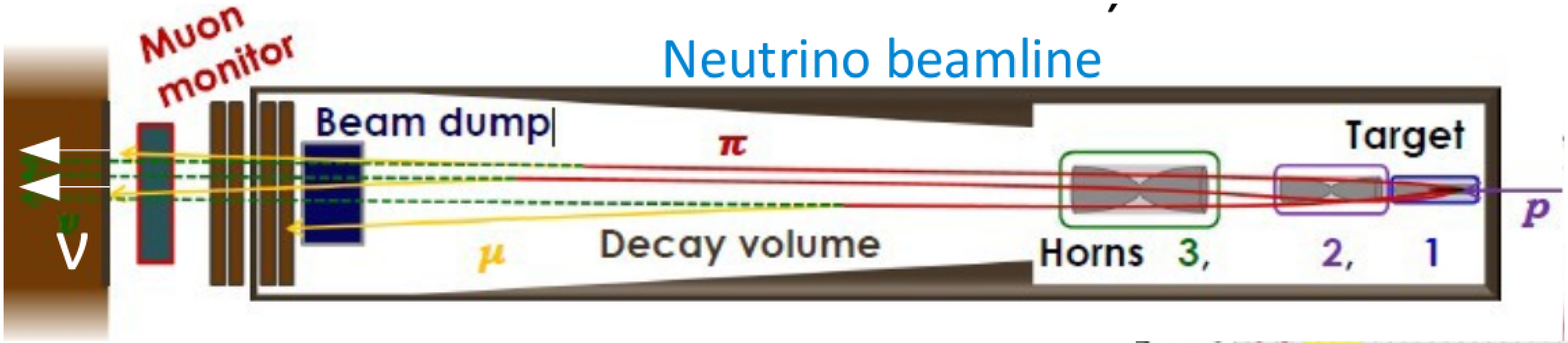
Sum of the momenta of charged particles and γ's measured in emulsion



T2K

500 members
59 istitutes
11 countries

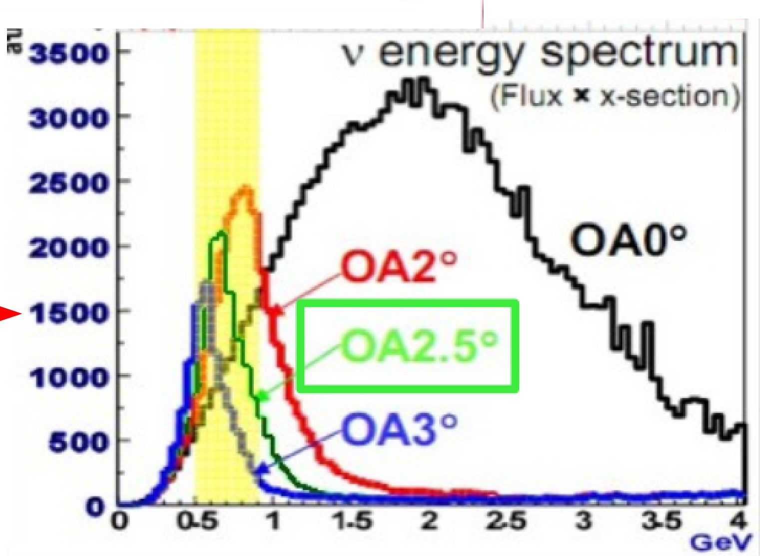


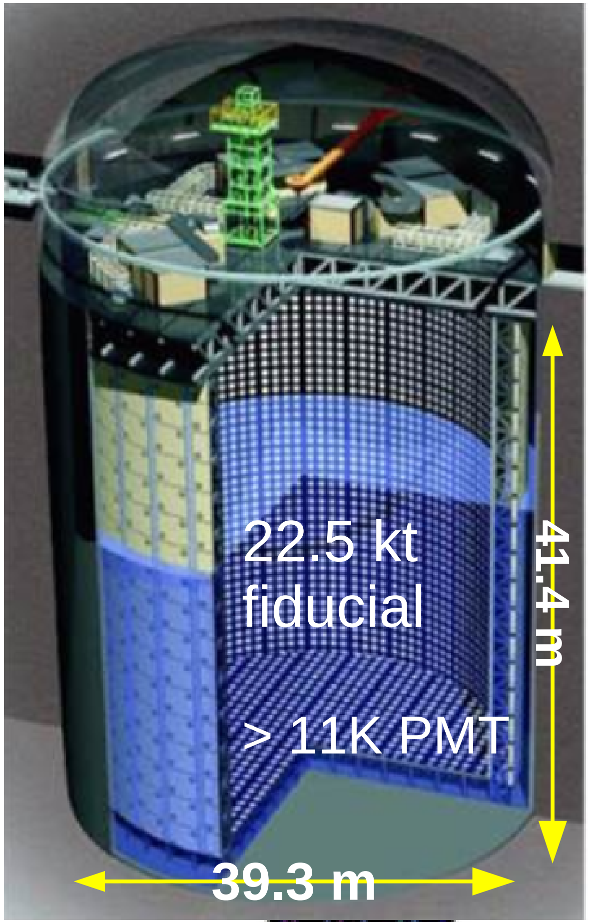


← 30 GeV

First *"off-axis" beam*

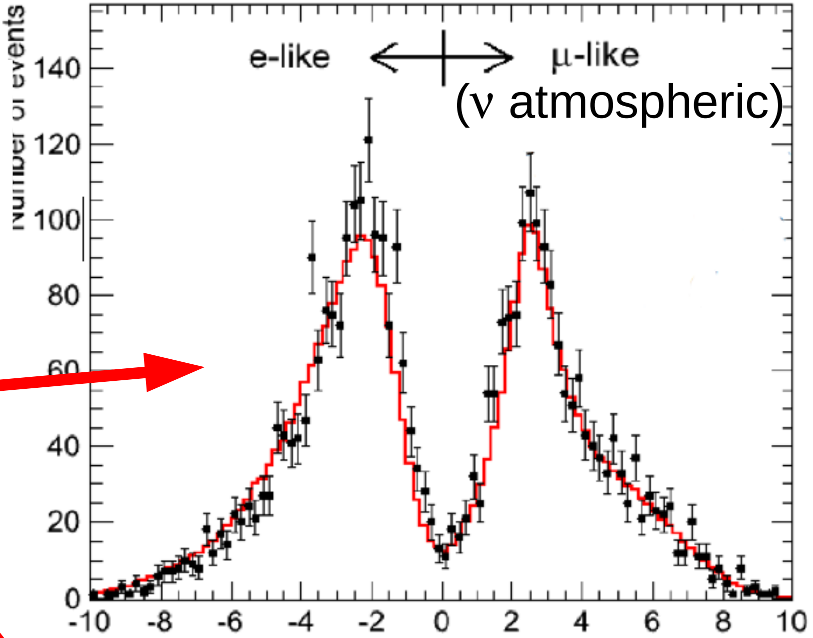
- 2.5^{o} → peak at ~ 0.6 GeV
- Enriched in Quasi-elastic interactions (good measurement of E_{ν})
- Reduced instrinsic ν_{e} background
- Reduced NC π^{0} ~backg. from D.I.S.
- Double detector: **280 m and 295 km**

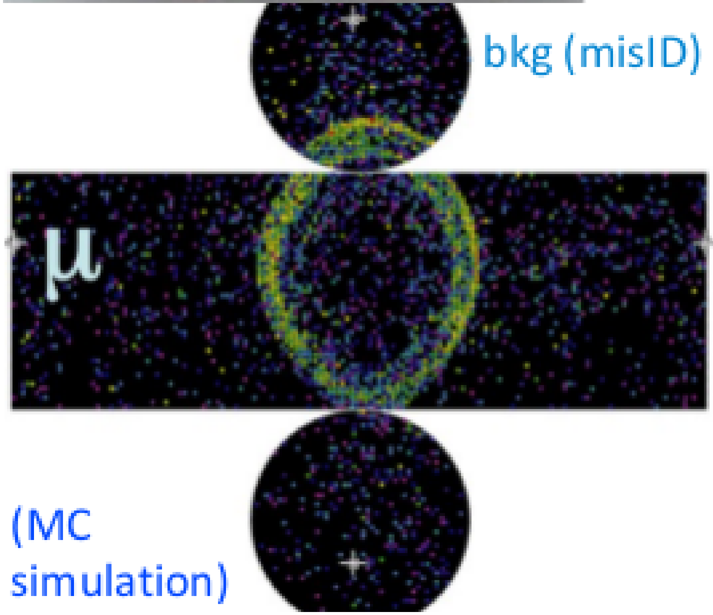




The far detector (295 km): Super-Kamiokande

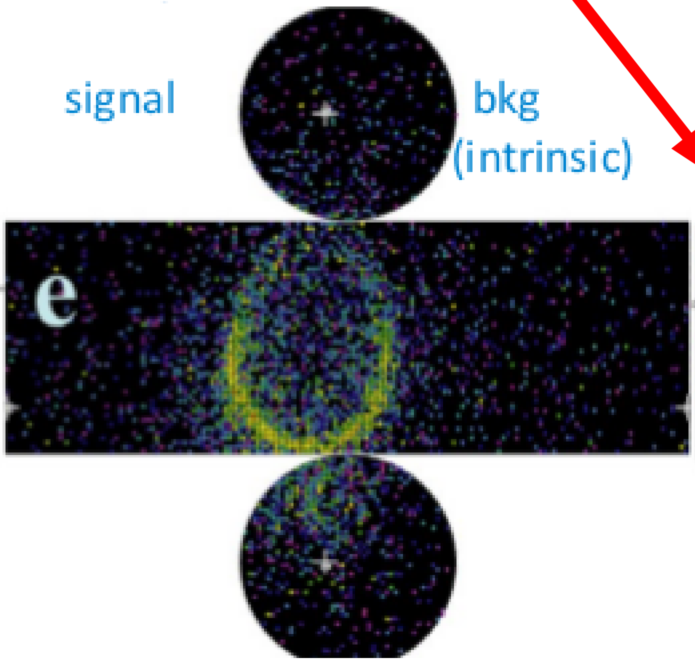
- Water Cherenkov
  - ΔE/E ~10% for quasi-elastic (QE) interactions
- Excellent μ/e separation
- π^0 detection
  - 2 “e-like” rings





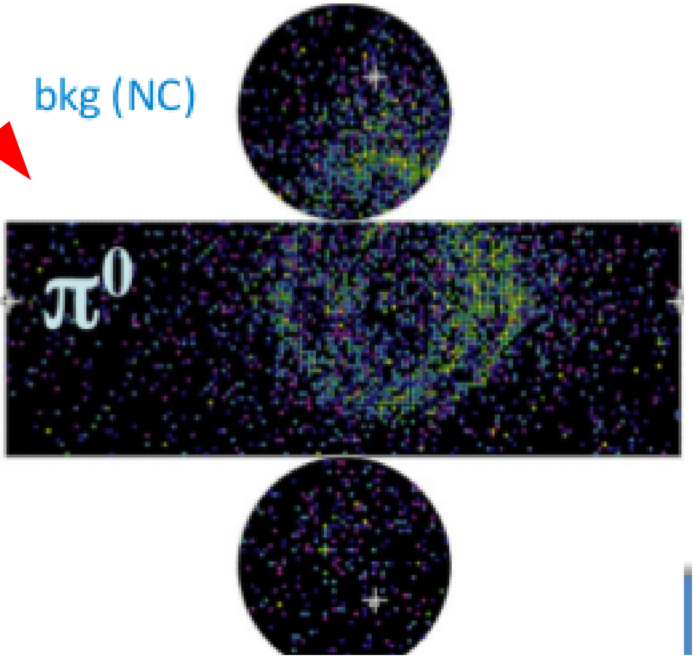
bkg (misID)

signal



bkg (intrinsic)

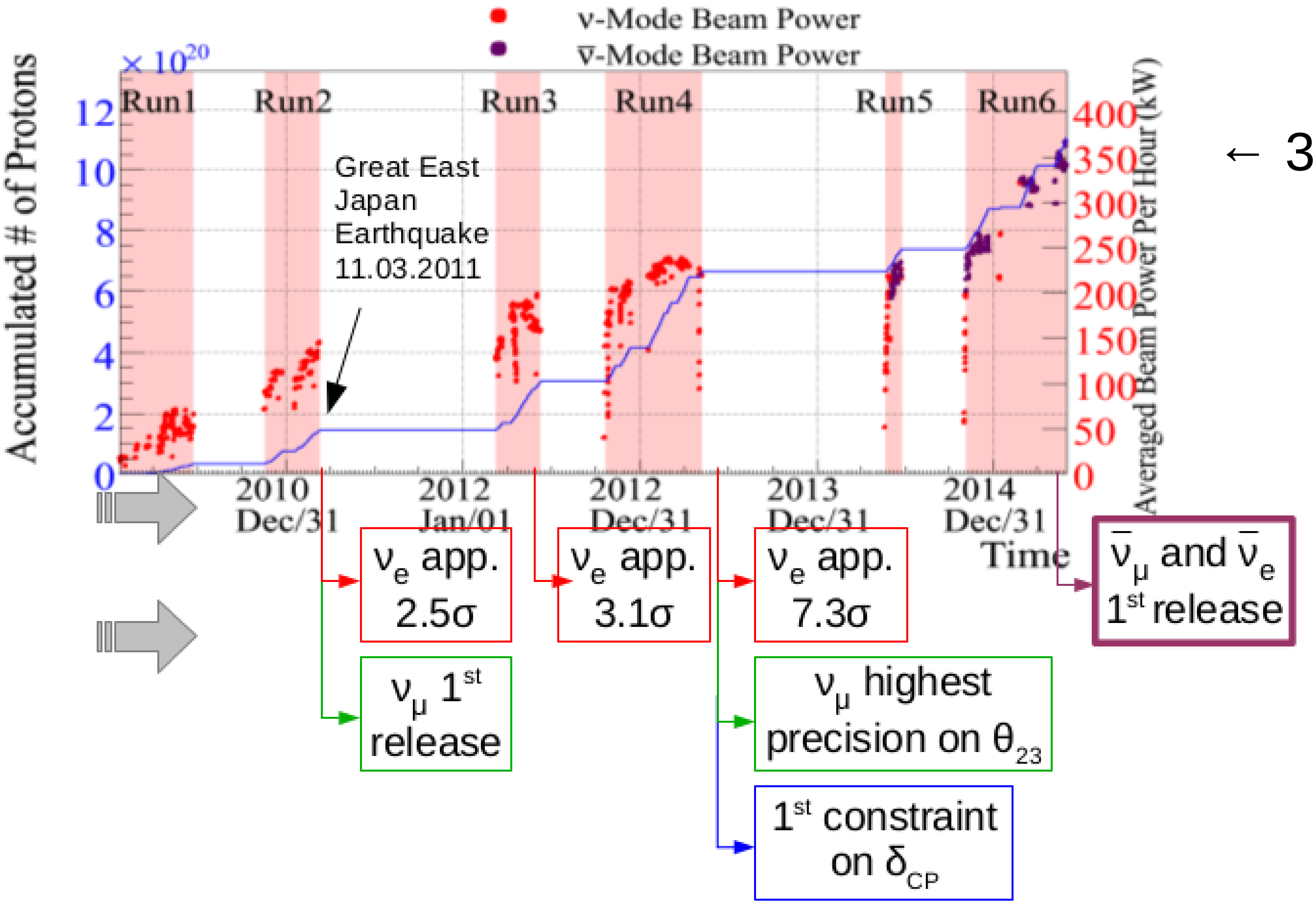
bkg (NC)



(MC simulation)

T2K runs

- 2010-2013: ν beam mode: 7×10^{20} POT
- 2014-... : $\bar{\nu}$ beam mode: 4×10^{20} POT



Great East Japan Earthquake 11.03.2011

← 370 kW

ν_e app. 2.5σ

ν_μ 1st release

ν_e app. 3.1σ

ν_e app. 7.3σ

ν_μ highest precision on θ_{23}

1st constraint on δ_{CP}

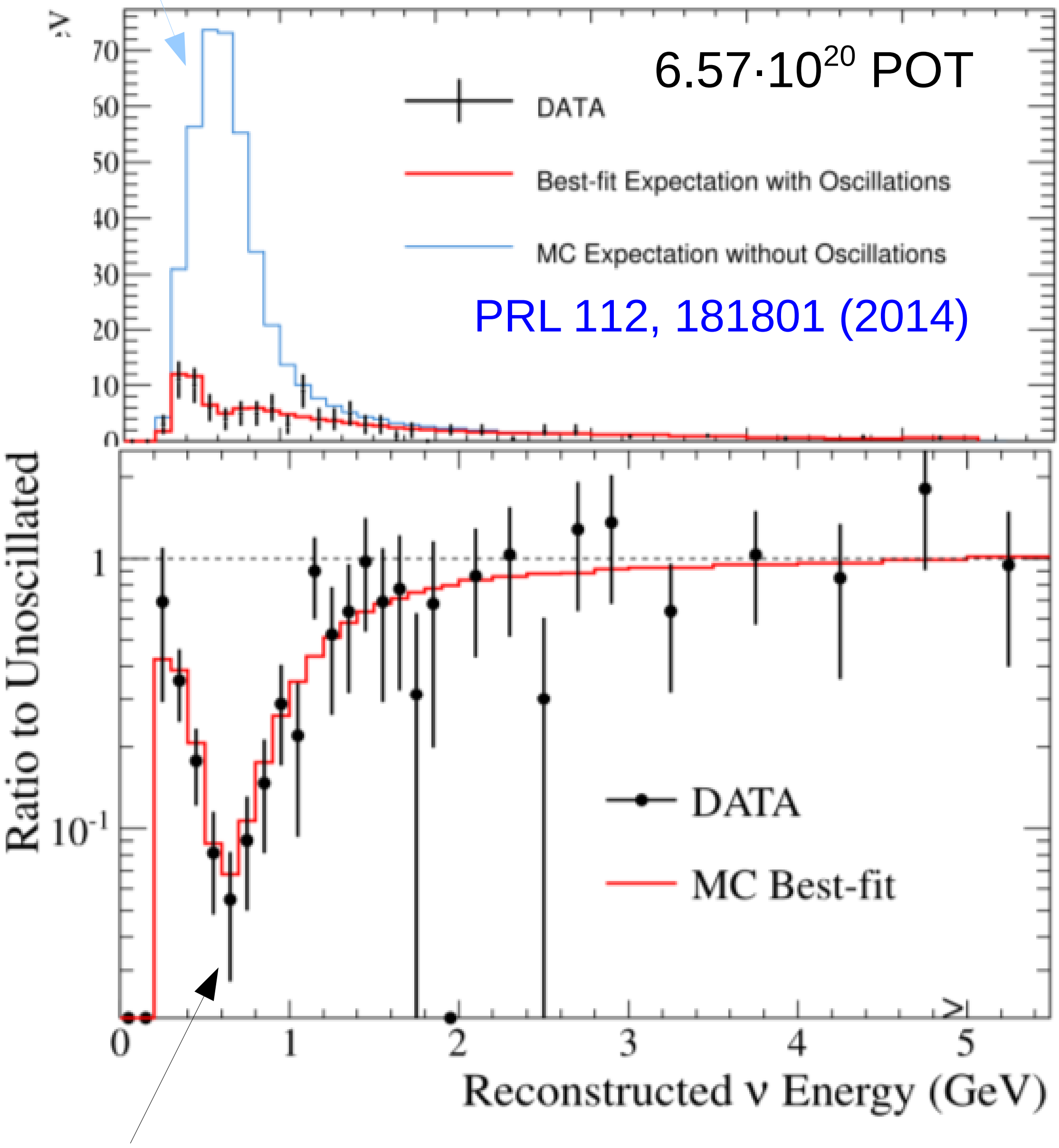
$\bar{\nu}_\mu$ and $\bar{\nu}_e$ 1st release

ν_μ disappearance

Approximate value of Δm_{23}^2 known at design phase.

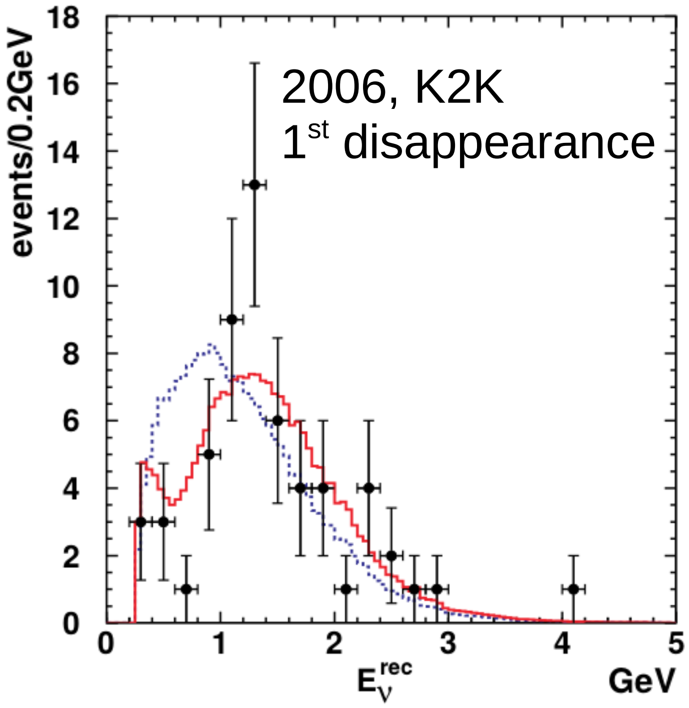
Maximal suppression exactly at peak – not the case f.e. in MINOS.

446 ± 23 exp. (no osc.) **120 obs.**



$6.57 \cdot 10^{20}$ POT

PRL 112, 181801 (2014)



2006, K2K

1st disappearance

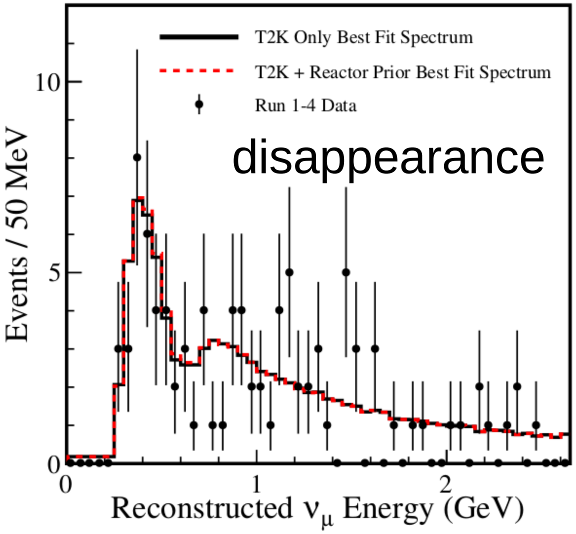
$\sigma(E)/E \sim 10\%$. CCQE formula. 81% ν_μ CCQE purity.

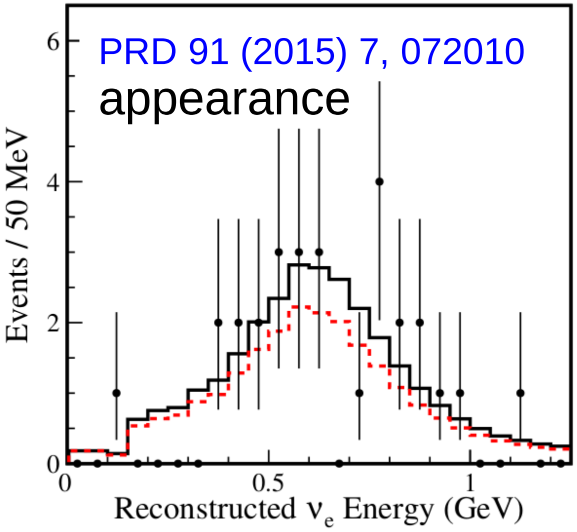
T2K joint $\nu_\mu + \nu_e$

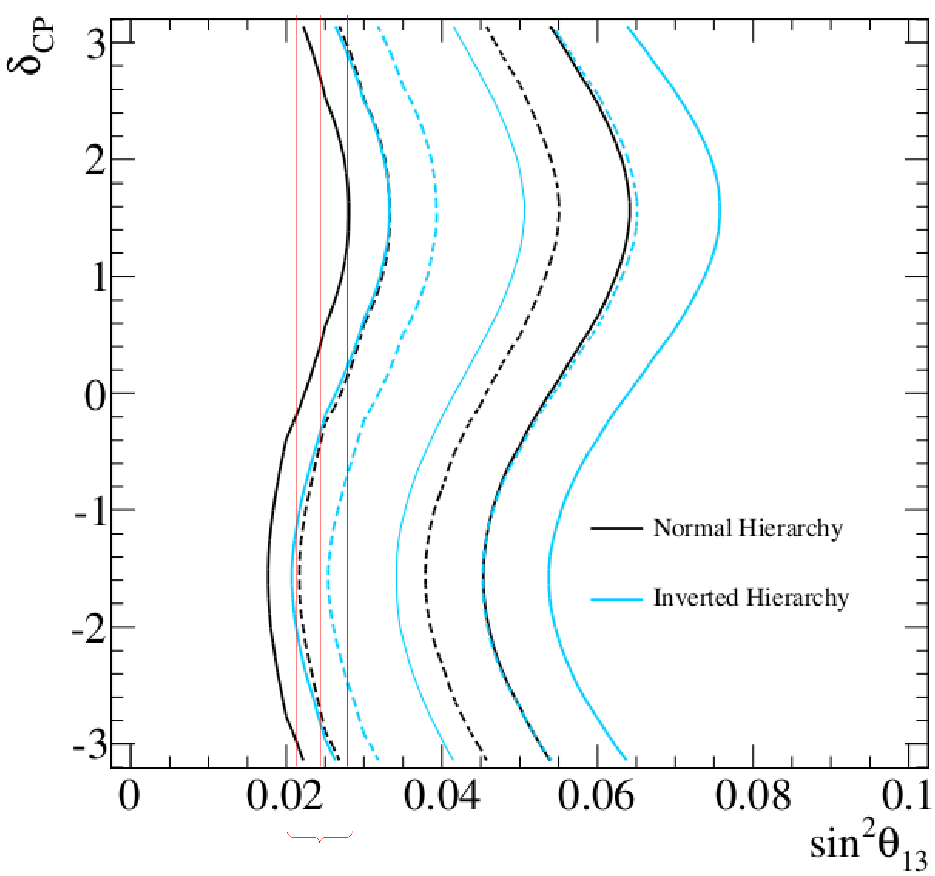
Fit simultaneously θ_{13} θ_{23} Δm^2_{23} δ:

- appearance ($\nu_\mu \rightarrow \nu_e$) &
- disappearance ($\nu_\mu \rightarrow \nu_\mu$) data

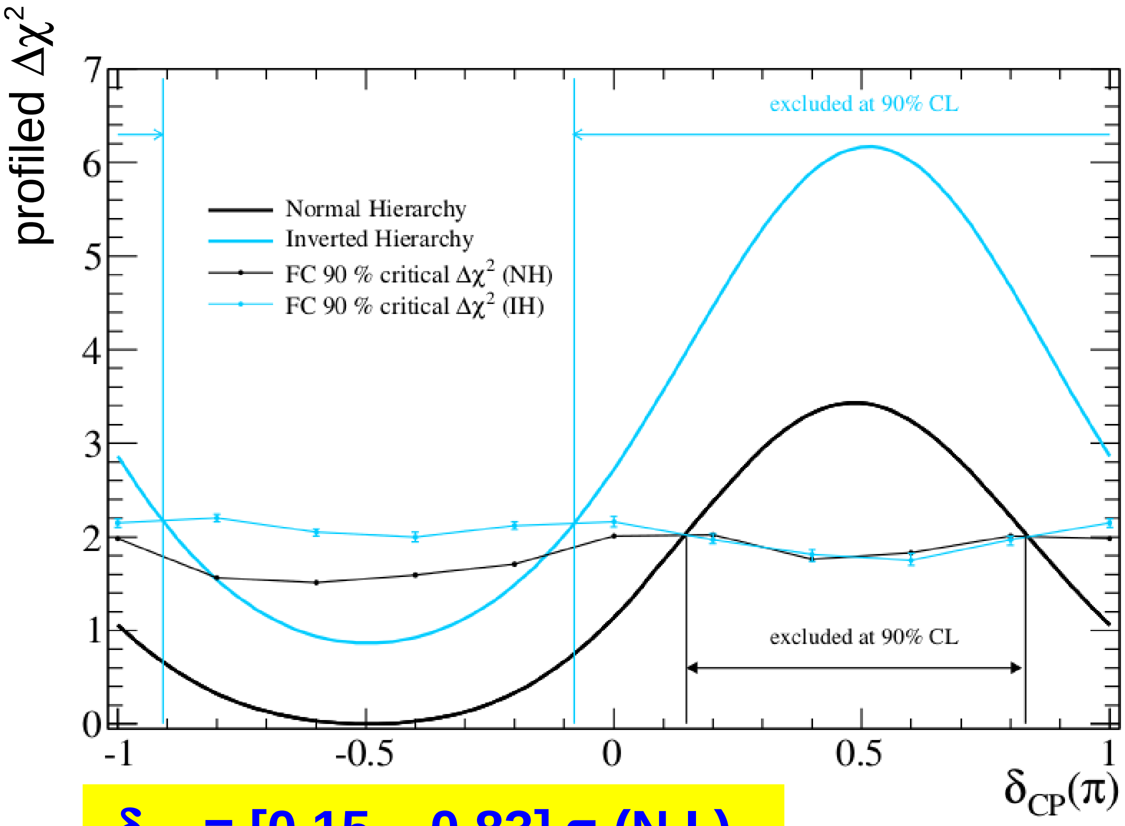
T2K + reactors constraint




PRD 91 (2015) 7, 072010



0.0243 ± 0.0026



δ_{CP} = [0.15, 0.83] π (N.I.)

δ_{CP} = [−0.08, 1.09] π (I.H.)

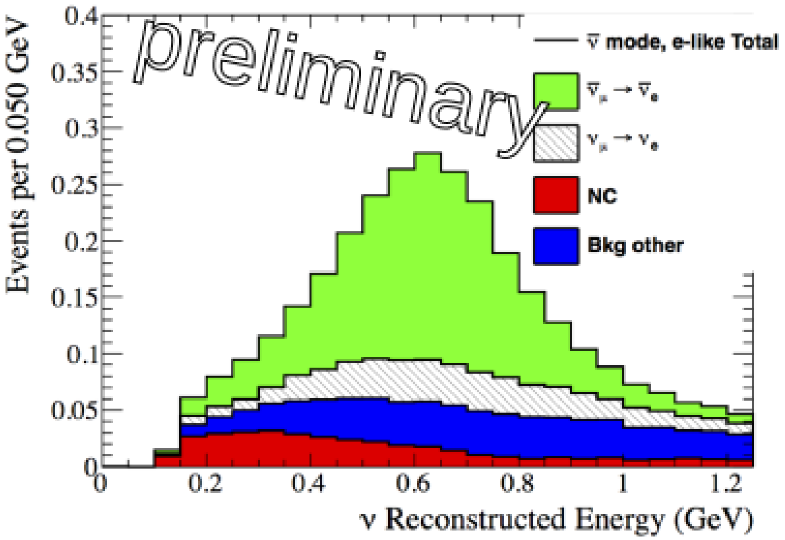
excluded @ 90% CL

T2K: anti-ν_e appearance

- expected number of events

	–π/2	0	π/2	–π/2	0	π/2
signal $\bar{\nu}_\mu \to \bar{\nu}_e$	1.96	2.64	3.29	2.48	3.25	3.94
signal $\nu_\mu \to \nu_e$	0.59	0.50	0.39	0.53	0.42	0.34
background NC	0.35	0.35	0.35	0.35	0.35	0.35
background other	0.83	0.83	0.83	0.82	0.82	0.82
total	3.73	4.32	4.86	4.18	4.34	4.85

normal hierarchy inverted hierarchy



3 events observed in the current sample (4×10^{20} POT)

Short term (1 year) goal: 9.5×10^{20} POT

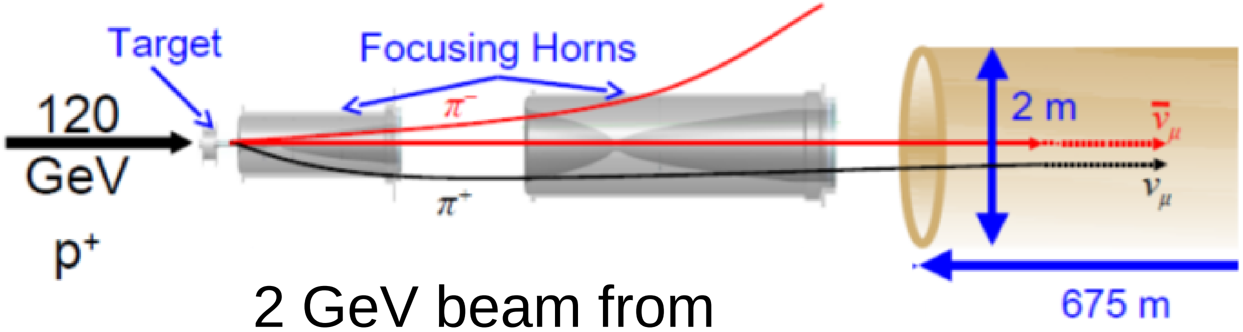
- 2σ rejection for no anti-ν_e appearance
- 60% chance of 99 CL observation

Next step: joint ν+anti-ν fit

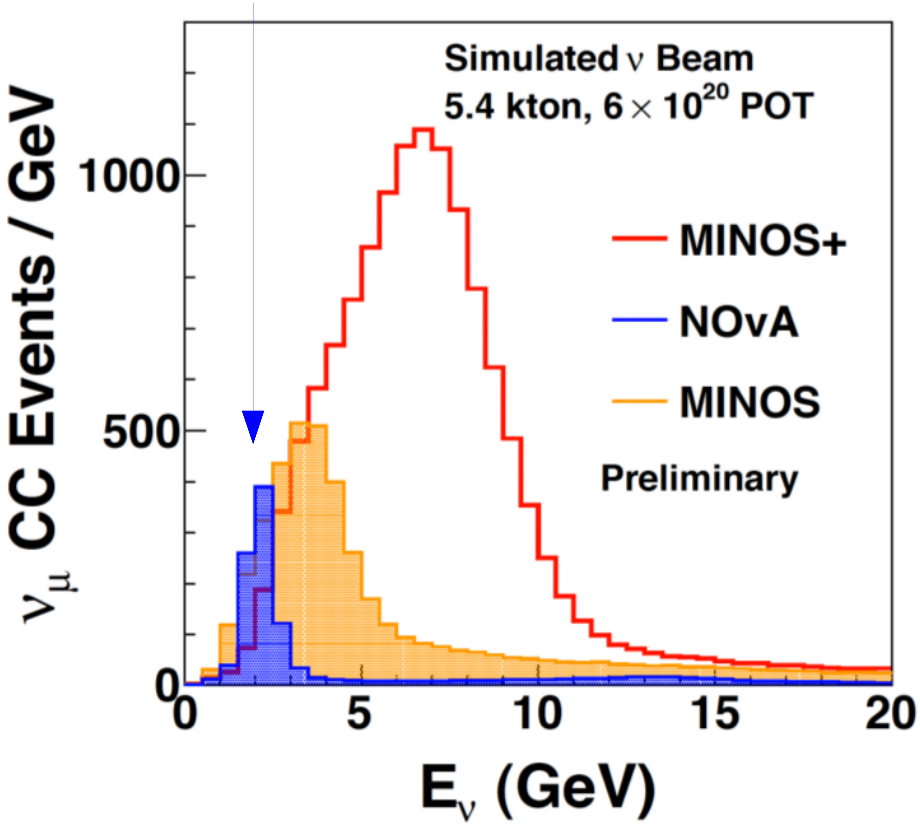
First results on anti-numu disappearance shown later on.

The NOνA experiment

NuMI horns (used also for MINOS) reconfigured: higher on-axis mean energy

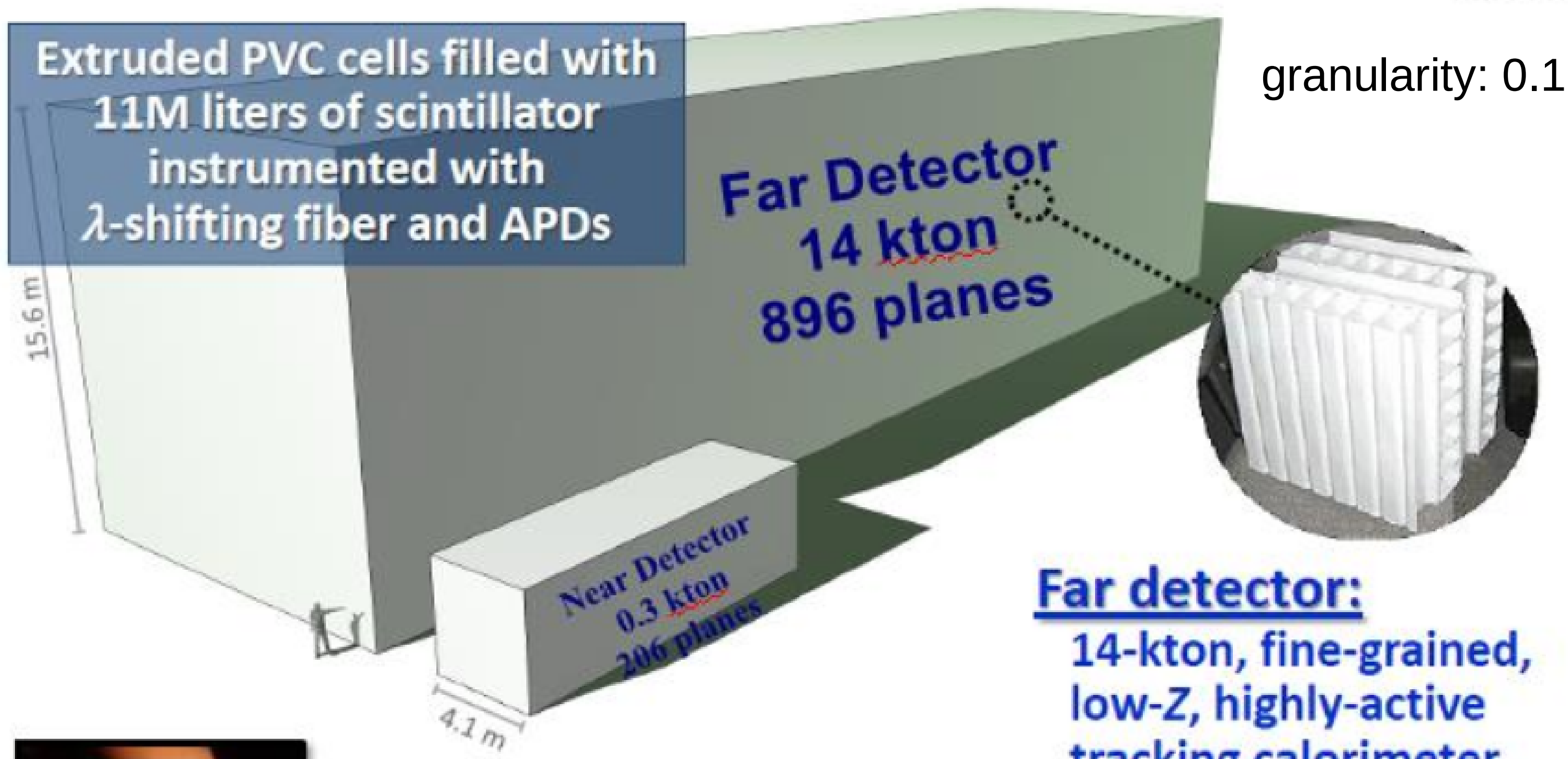


2 GeV beam from
14 mrad off-axis angle

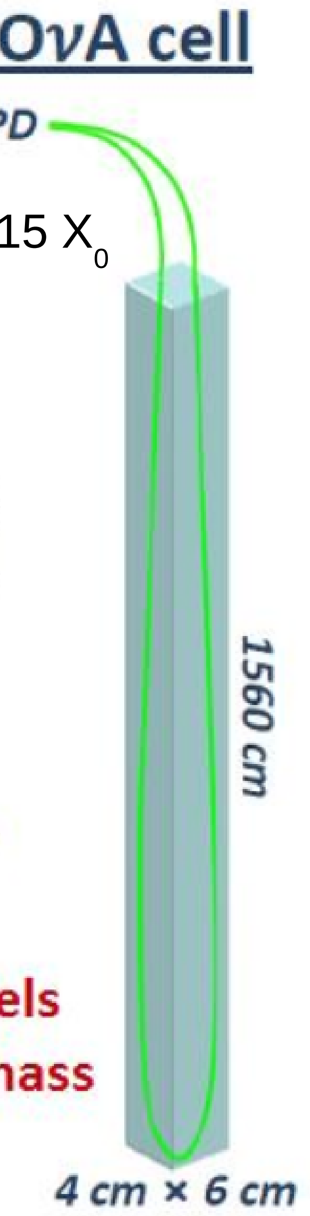


L = 810 km
Near Detector (Fermilab, IL), 0.3 kt
Far Detector (Ash River, MN), 14 kt

The NOνA detectors



granularity: 0.15 X_0

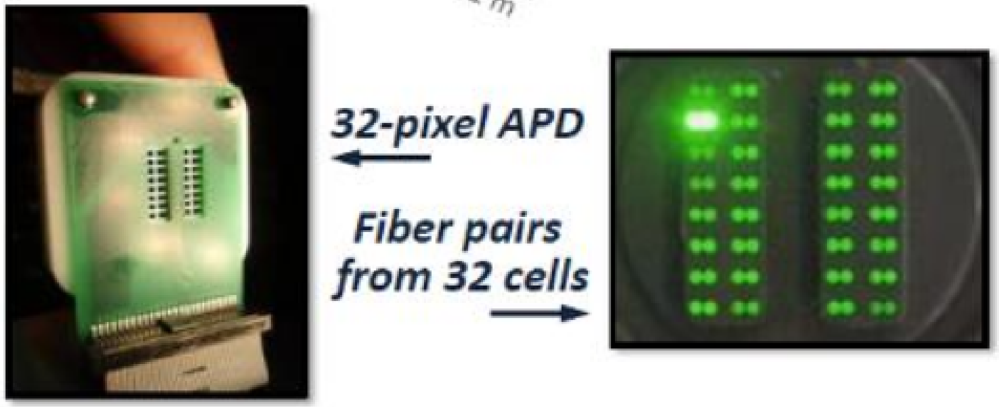


Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

340, 000 channels

77% active by mass



Near detector:

0.3-kton version of the same

18, 000 channels

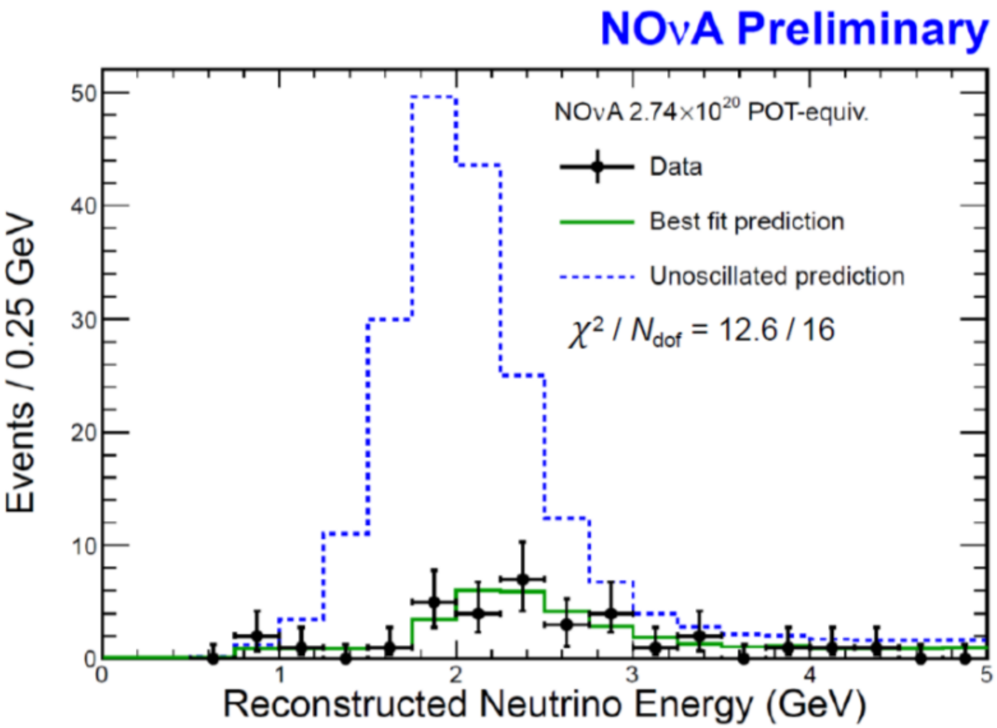
NOνA: $\nu_\mu \rightarrow \nu_\mu$

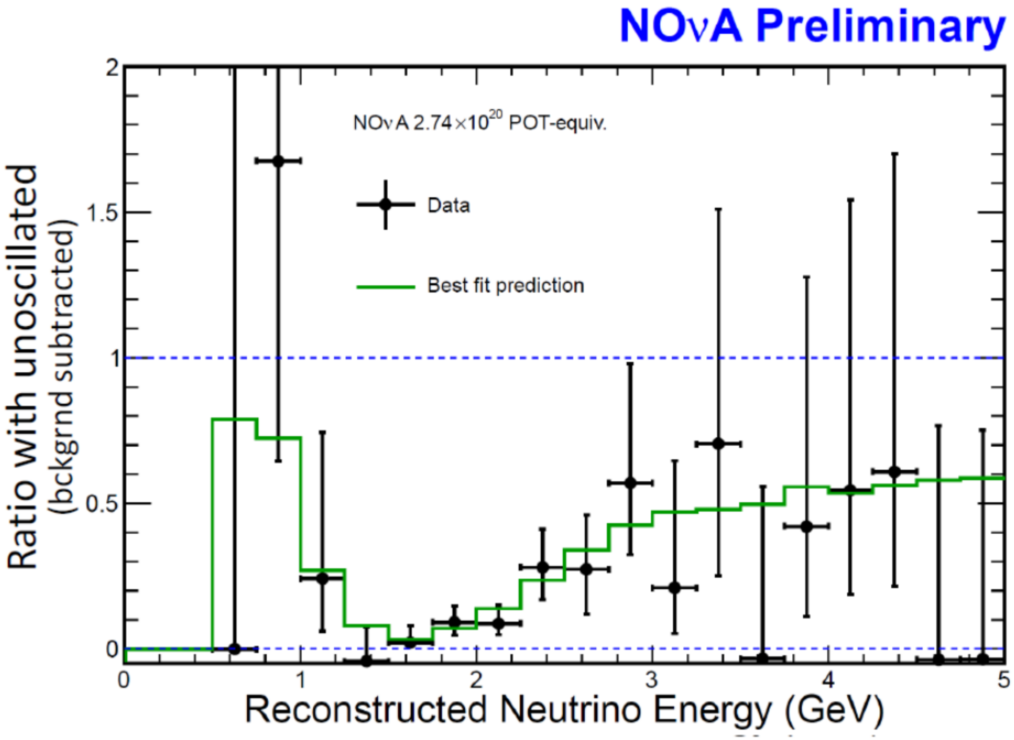
2.74×10^{20} POT (8% of planned)

- 201 expected without oscillation
- 33 observed

$\Delta m^2_{32} = 2.37^{+0.16}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$

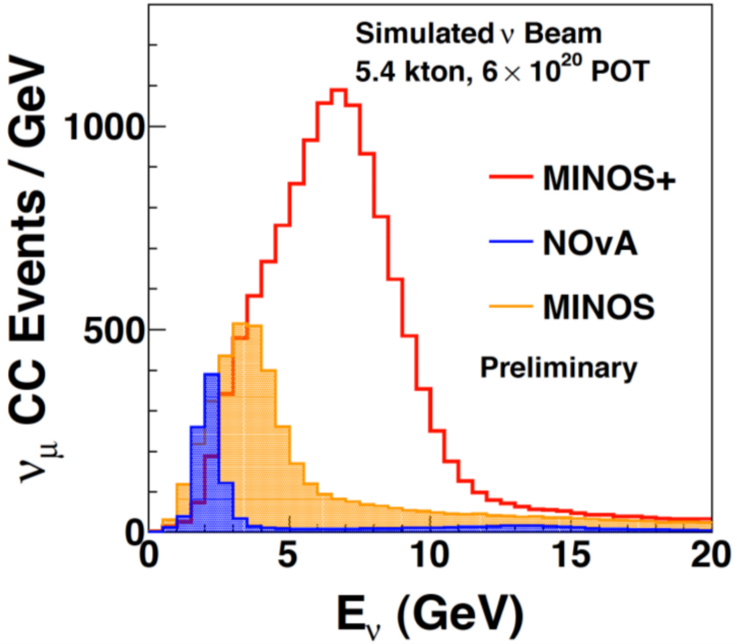
$\sin^2 2\theta_{23} = (0.51 \pm 0.10)$

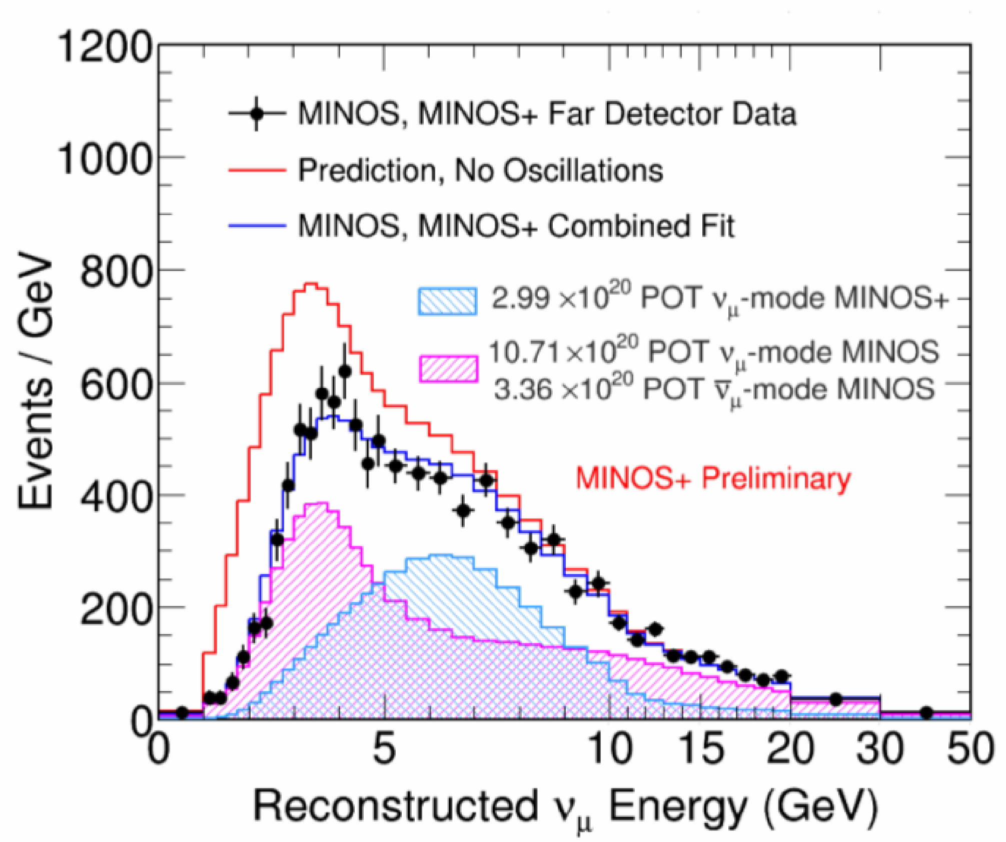


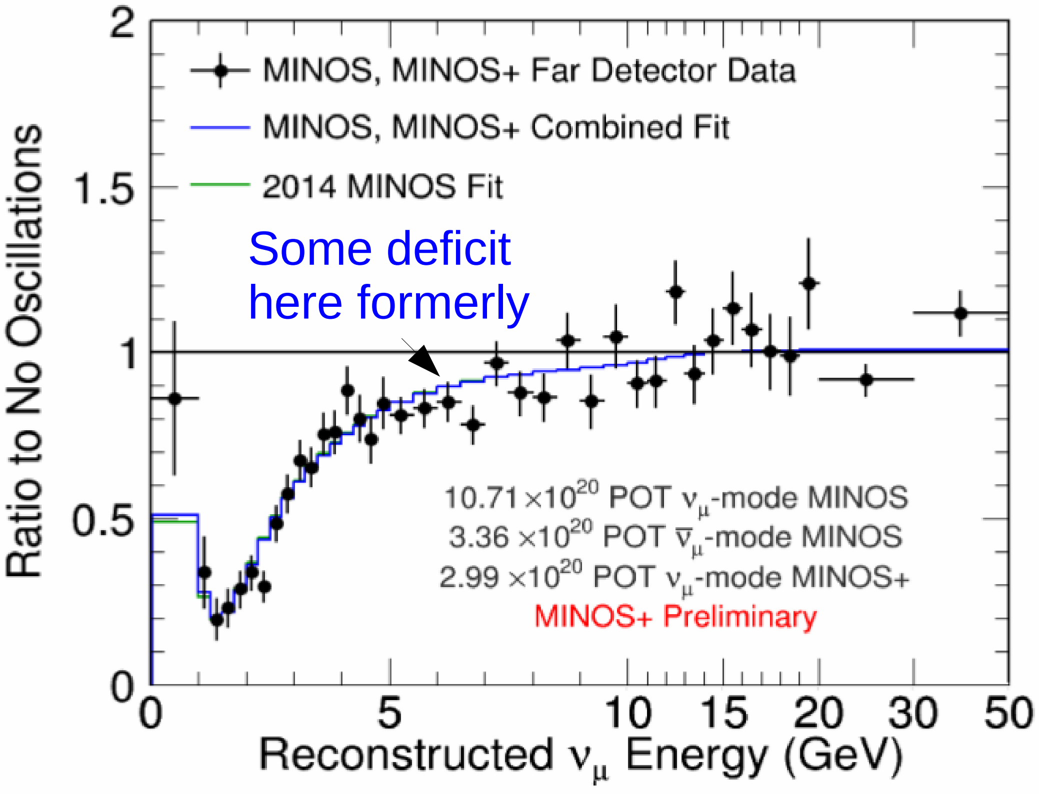


MINOS+

The MINOS detector continues being illuminated by the on-axis beam in “NOνA configuration” (yielding a higher-E beam than before ~ 7 GeV)
→ strengthen the measurement of disappearance (especially **far from of the oscillation maximum**)



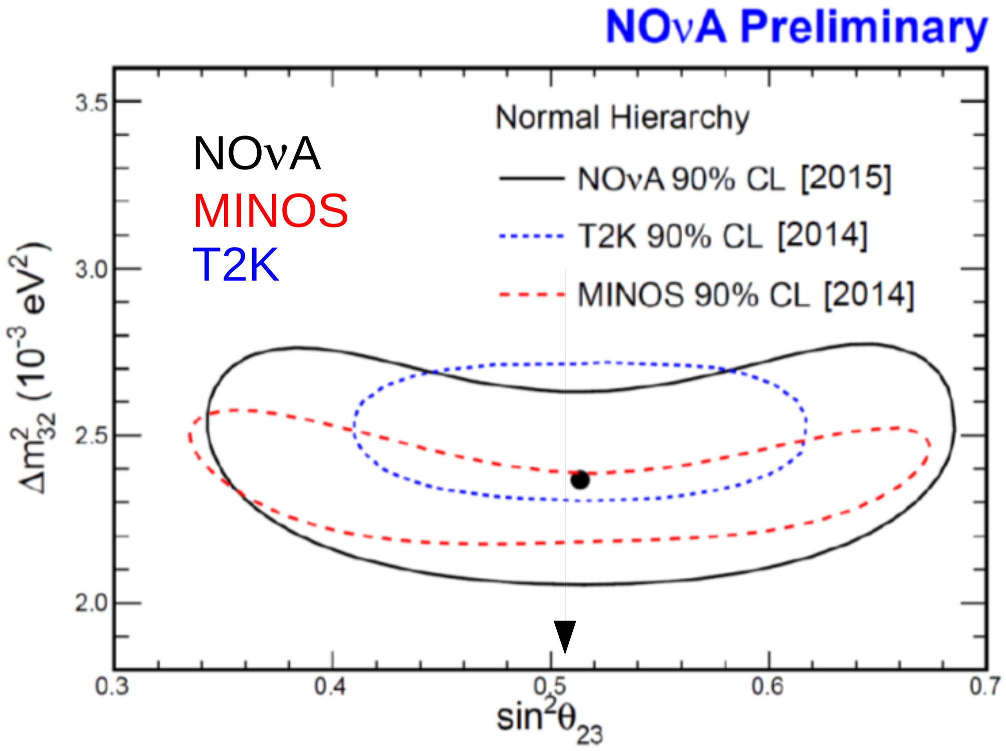


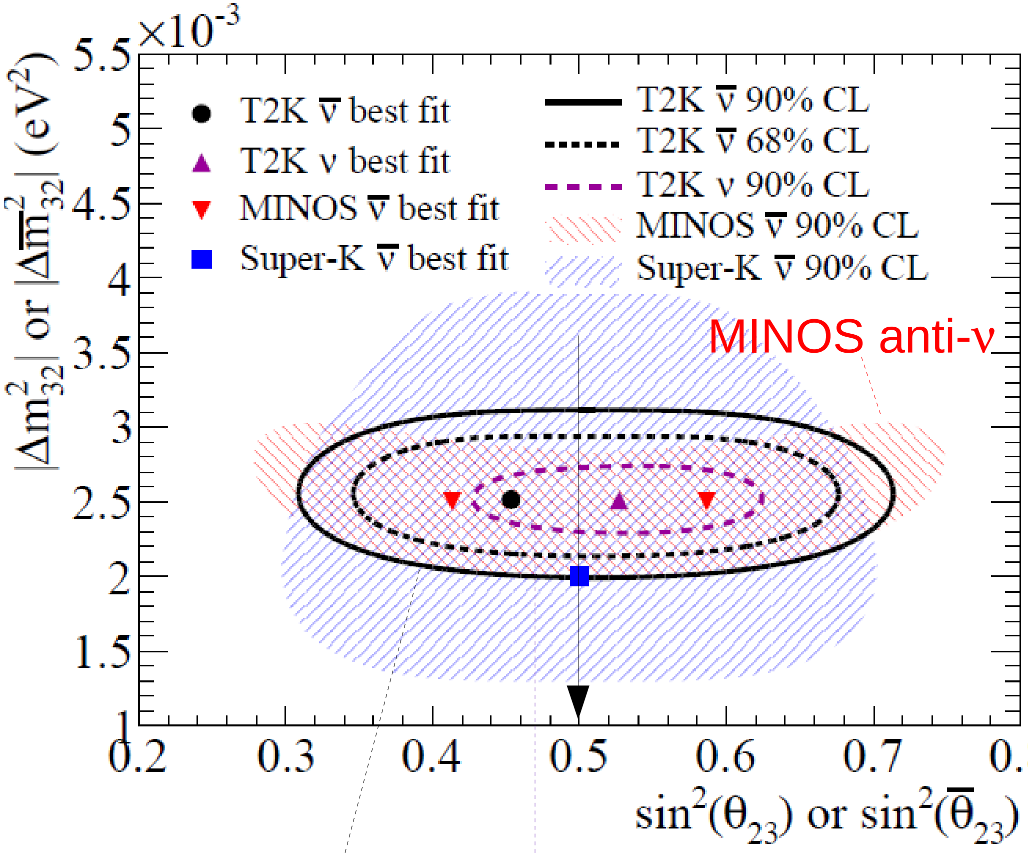

Some deficit here formerly

Summary on disappearance

Neutrinos

Anti-neutrinos





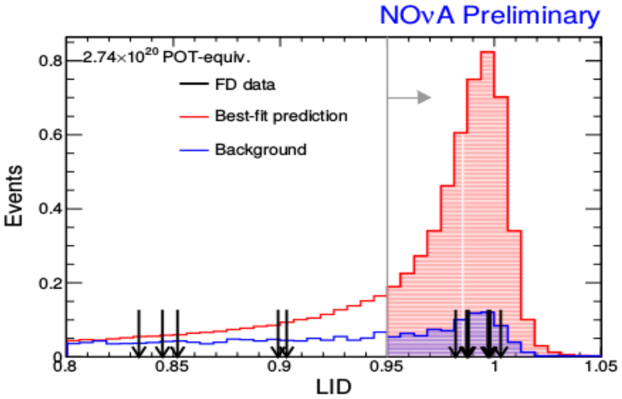
T2K anti-ν T2K ν

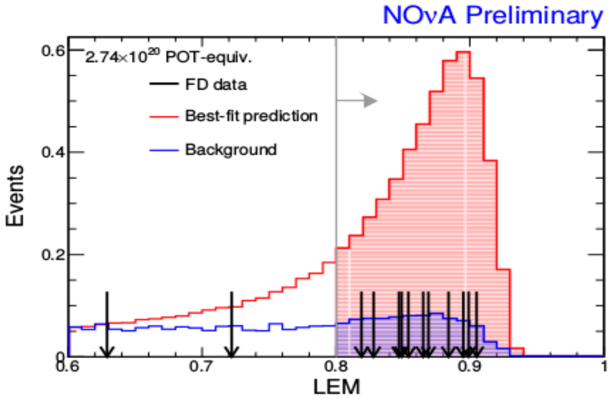
- Both for neutrinos and anti-neutrinos
  - MINOS: still leading for Δm^2 (~ E of the “dip”)
  - T2K: leading for θ_{23} (depth of the “dip”)
- No significant hints for deviation from **maximal mixing or CPT effects**

NEW! T2K result today on the arXiv 1512.02495

NOνA: $\nu_\mu \rightarrow \nu_e$

Two algorithms:
LID (likelihood, ANN)
LEM (Library Event Matching)





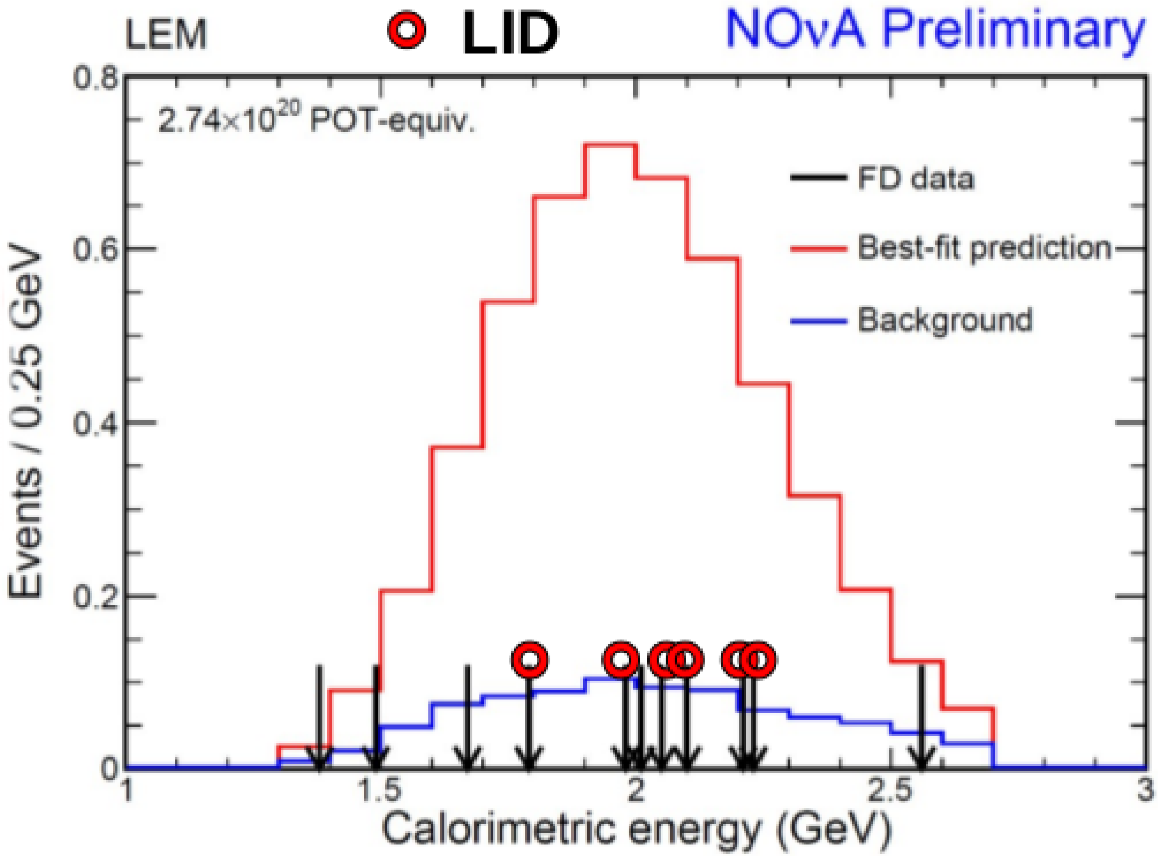
Near candidates used to predict beam backgrounds in the Far
Far Detector excess over predicted backgrounds interpreted as ν_e appearance

(LID) expectations ($\theta_{23} = \pi/4$)**:**

- Background:
  0.94 ± 0.09 events
  [49% ν_e^{CC}, 37% NC]
- Signal: [IH, $\delta = \pi/2$]
  2.24 ± 0.29 events
- **Signal: [NH, $\delta = 3/2\ \pi$]**
  5.62 ± 0.72 events

Observed
LID: 6
LEM: 11

favored



NOνA: δ_{CP} with reactor constraint

For all $\sin^2 2\theta_{23}$ in [0.4,0.6]

LEM analysis

- IH disfavored at > 2.2σ
- NH mildly disfavored (>1σ) for $\delta \in [0, \pi]$

LID analysis

- IH mildly disfavored (>1σ) for $\delta \in [0, 0.8\pi]$

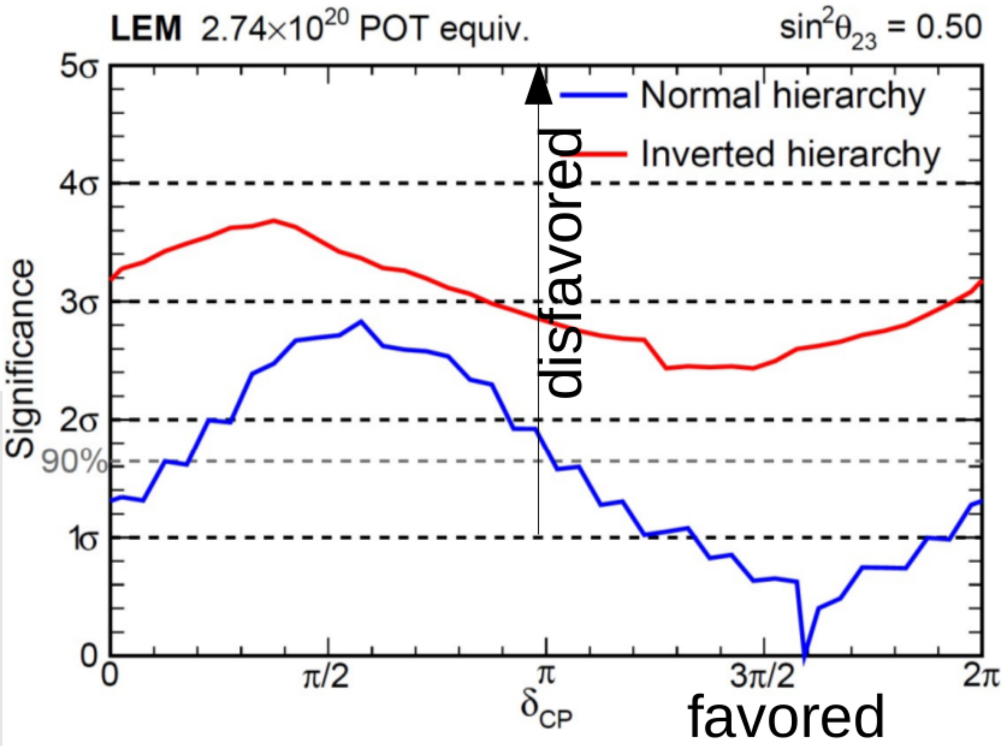
Both LEM and LID prefer
- normal hierarchy
- $\delta \sim 3/2\pi$ (= $-\pi/2$)

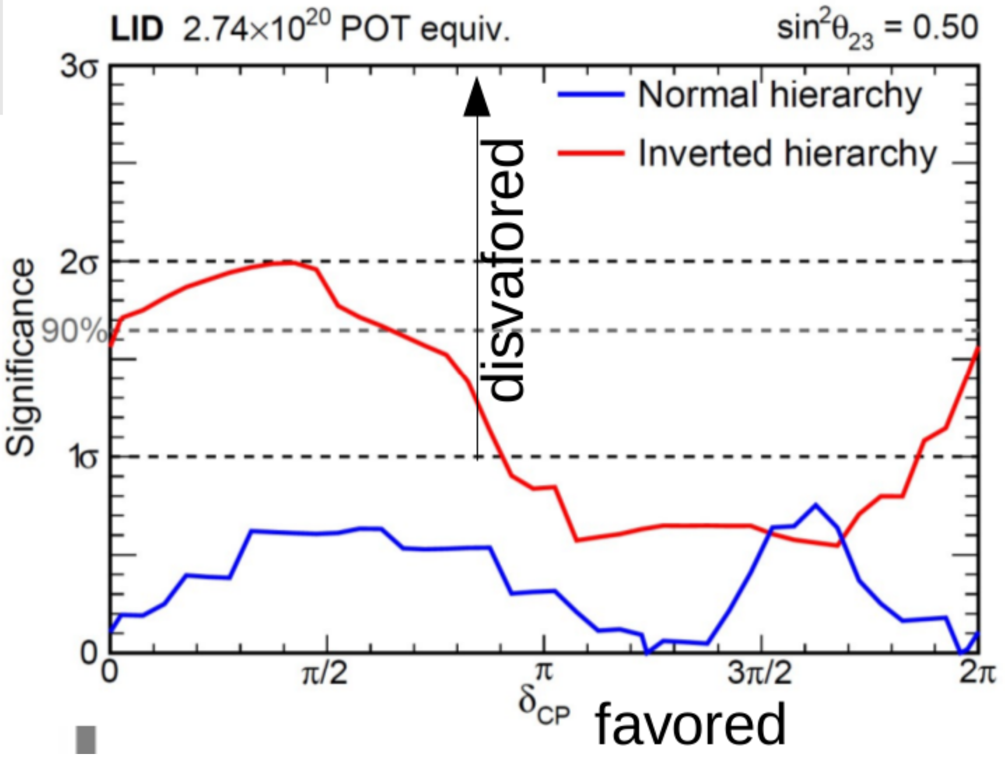
In the same direction of T2K

T2K excludes (90% CL):

$0.15\,\pi < \delta_{CP} < 0.83\,\pi$ (NH)

$-0.08\,\pi < \delta_{CP} < 1.09\,\pi$ (IH)





Looking forward

Near and far detectors

Ideally ... in a near-far double detector oscillation experiment

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

$$N^{far}_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

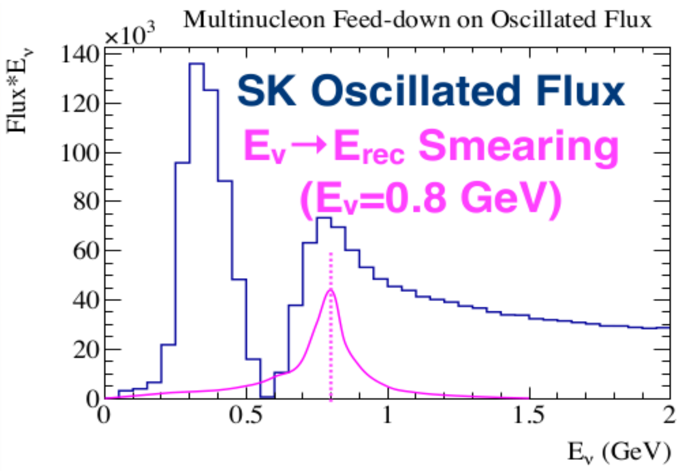
$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

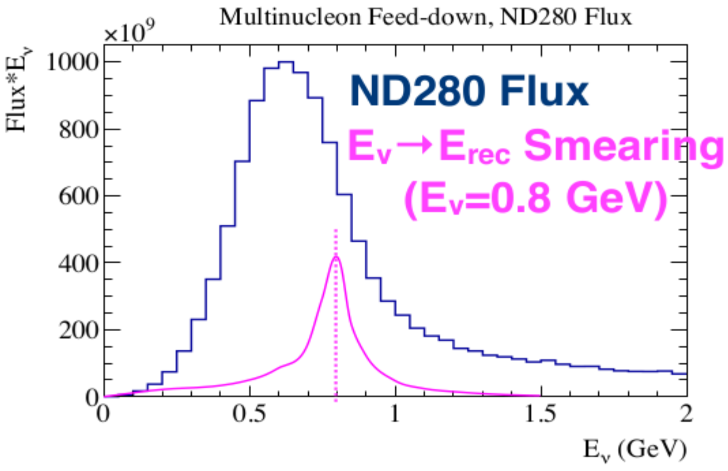
Neutrino cross sections factorize out

But beams are not monochromatic → we need to determine E_ν event by event

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

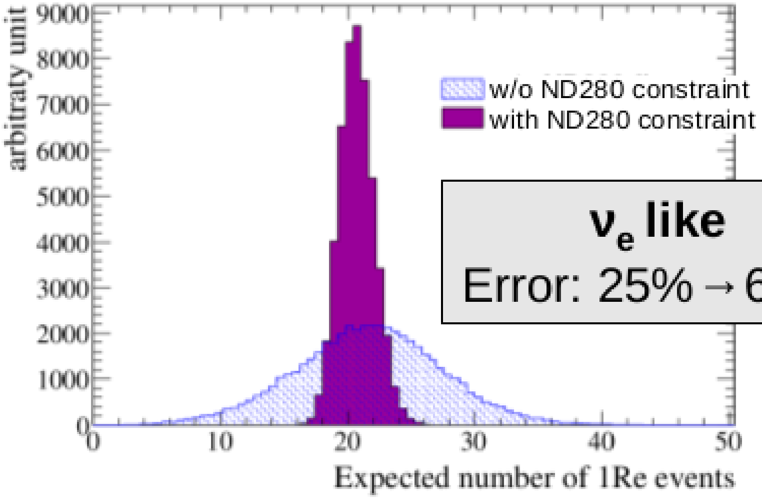
Oscillations introduce differences in the flux spectrum: cross-sections do not cancel out


Multinucleon Feed-down on Oscillated Flux


Multinucleon Feed-down, ND280 Flux

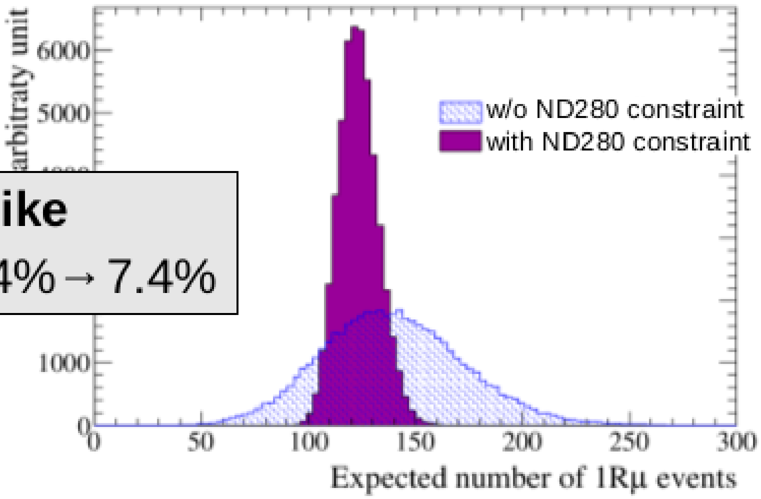
We need: $\phi(E_\nu)$, $\sigma(E_\nu)$, $P(E_\nu|E'_\nu)$

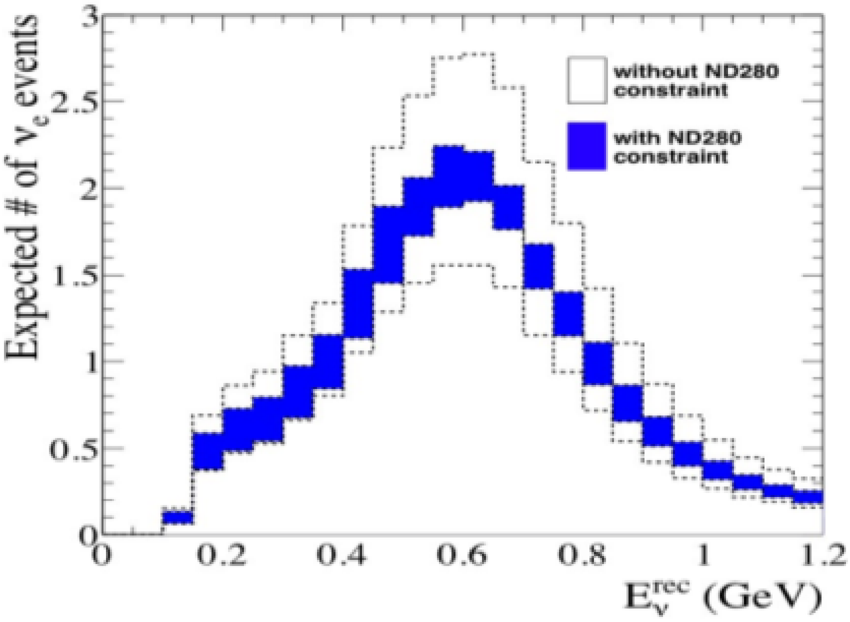
Uncertainty on events at SK after the T2K near detector constraint

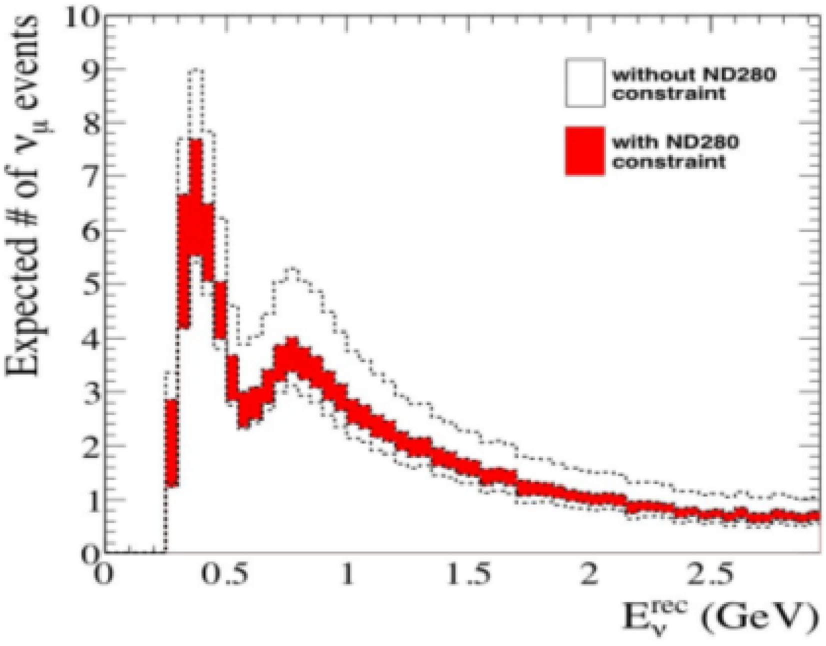


ν_e like
Error: 25% → 6.3%

ν_μ like
Error: 23.4% → 7.4%







T2K systematics today

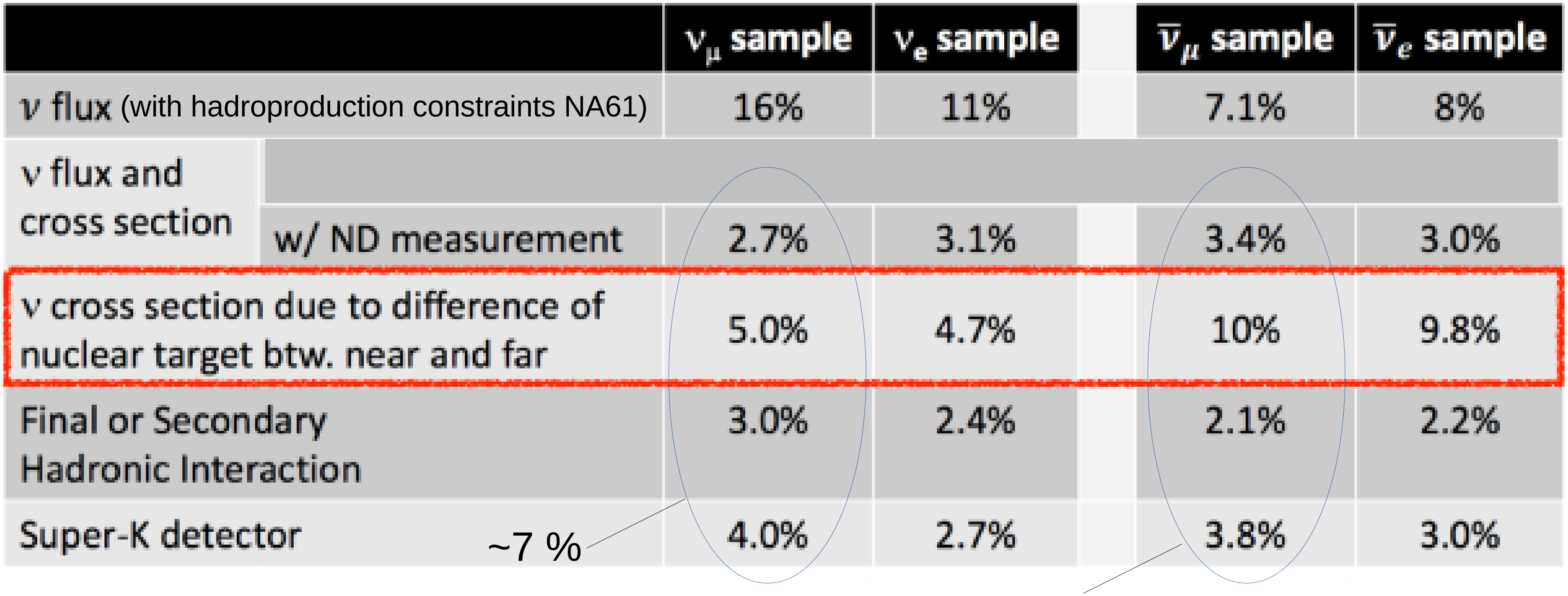
Events prediction at Super-K with the near detector constraints:

- ~ 7 % for ν
- ~10% for anti-ν

Largest contributions:

- difference in nuclear targets between far and near
- effect of the poorly known multi-nucleon processes (MEC) cross section

2014 → 2015



		ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
ν flux (with hadroproduction constraints NA61)		16%	11%	7.1%	8%
ν flux and cross section	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%

~7 %

~10 %

* 2015 uncertainties include additionally MEC

Desiderata for systematics reduction

$\phi(E_\nu) \times \sigma(E_\nu)$ at near and far

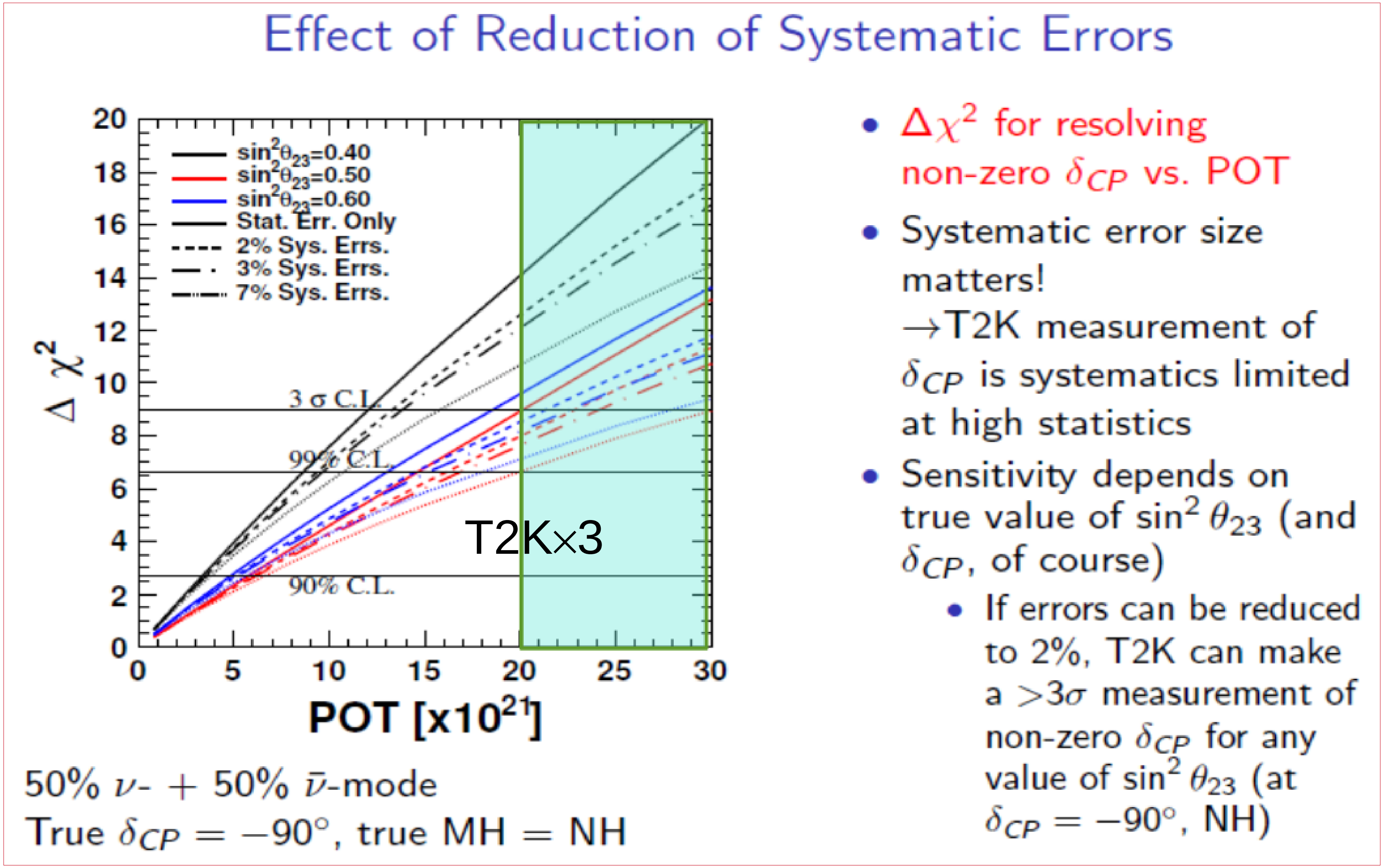
- **Same target** nuclei:
  - ✓ cancellation of nuclear effects, final state interactions (FSI)
- **Same acceptance**:
  - ✓ avoid model dependence in the not common p-θ phase space
- **Same flux (shape):**
  - ✓ a tunable beam (combine different off-axis angles - νPRISM) (to mimic oscill. distorsion)
  - ✓ a “not too near” NEAR (to reduce finite-distance effects)
- **$\sigma(\nu_e)$ measured independently** (ν_e at near is subdominant):
  - tagged ν_e beams, μ facilities (nuSTORM).

Energy reconstruction $P(E_\nu | E'_\nu)$ at near and far

- multi-nucleon interactions, π absorption in nuclei (FSI) → non genuine CCQE (CCQE-like) → “QE formula” is applied giving bias, broadening of $P(E_\nu|E'_\nu)$
  - ✓ **high granularity**, **low-thresholds** (demanding at far!)
  - ✓ **neutron tagging**

T2K perspectives, upgrades

- JPARC Main Ring upgrade approved: 7.8×10^{21} POT (=T2K design), 0.9 MW by 2020
- "T2K×3" (2020-25) phase (2×10^{22} POT). Before Hyper-Kamiokande (~2025).
- If **sys. < 2-3 %** "T2K×3" could give > 3σ CPV for **any value of θ_{23}**
- Discussions on upgrading the near/intermediate detectors already in 2020



Effect of Reduction of Systematic Errors

50% ν- + 50% $\bar{\nu}$-mode

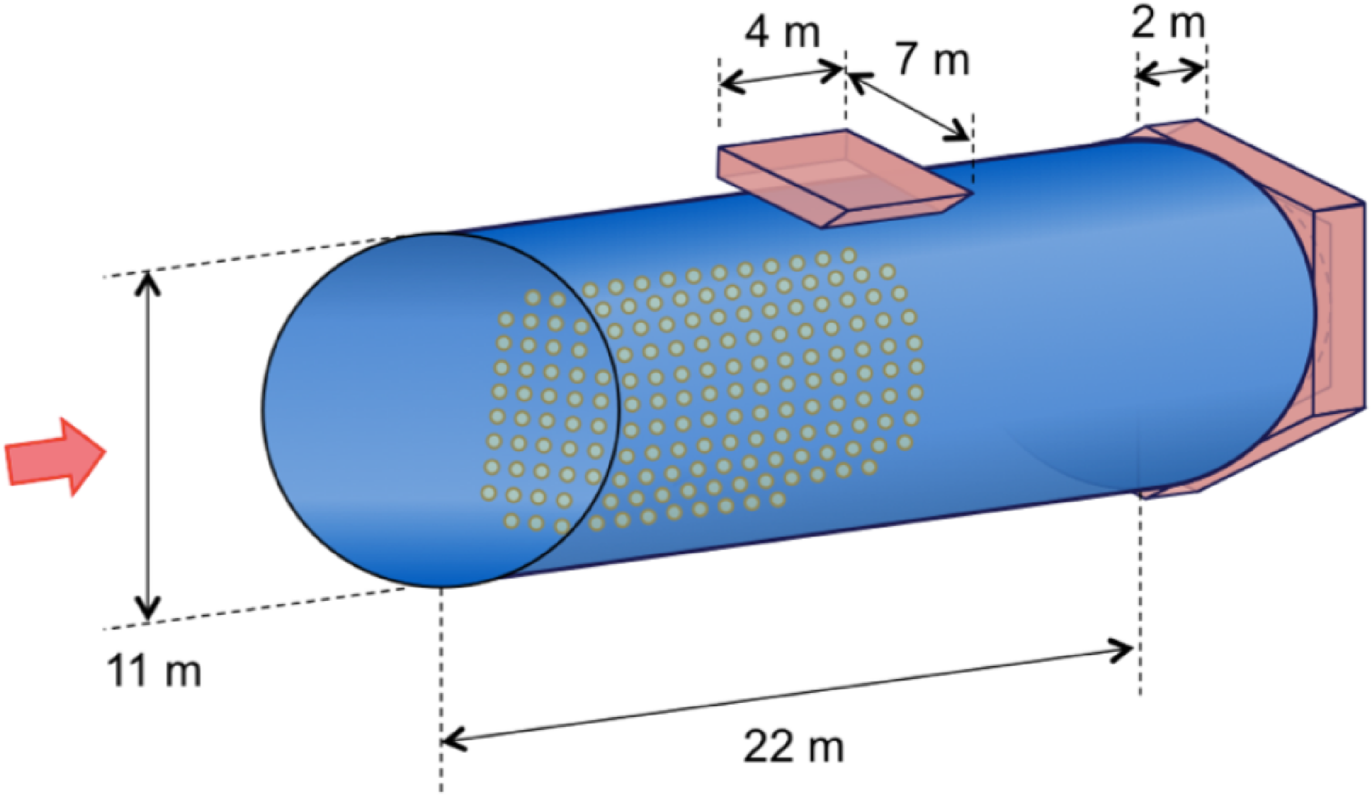
True $\delta_{CP} = -90°$, true MH = NH

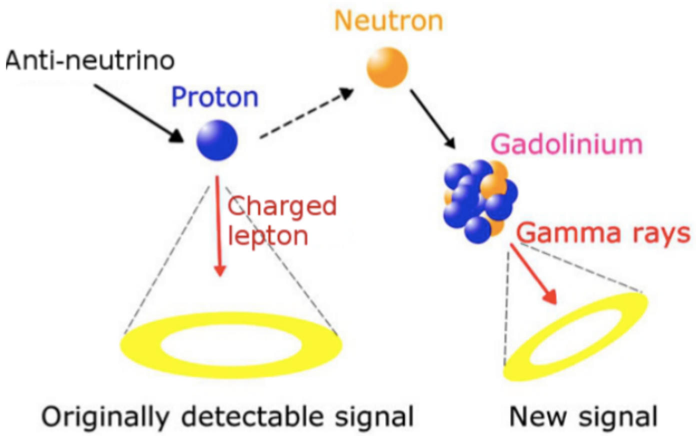
- $\Delta\chi^2$ for resolving non-zero δ_{CP} vs. POT
- Systematic error size matters!
  →T2K measurement of δ_{CP} is systematics limited at high statistics
- Sensitivity depends on true value of $\sin^2\theta_{23}$ (and δ_{CP}, of course)
  - If errors can be reduced to 2%, T2K can make a $>3\sigma$ measurement of non-zero δ_{CP} for any value of $\sin^2\theta_{23}$ (at $\delta_{CP} = -90°$, NH)

TITUS

Tokai Intermediate Tank with
Unoscillated Spectrum

- 2kt Gd doped (0.1%) water Cherenkov
- ~2 km from J-PARC, 2.5° off-axis
- Magnetized downstream Muon Range Detector (MRD)
- Small side MRD





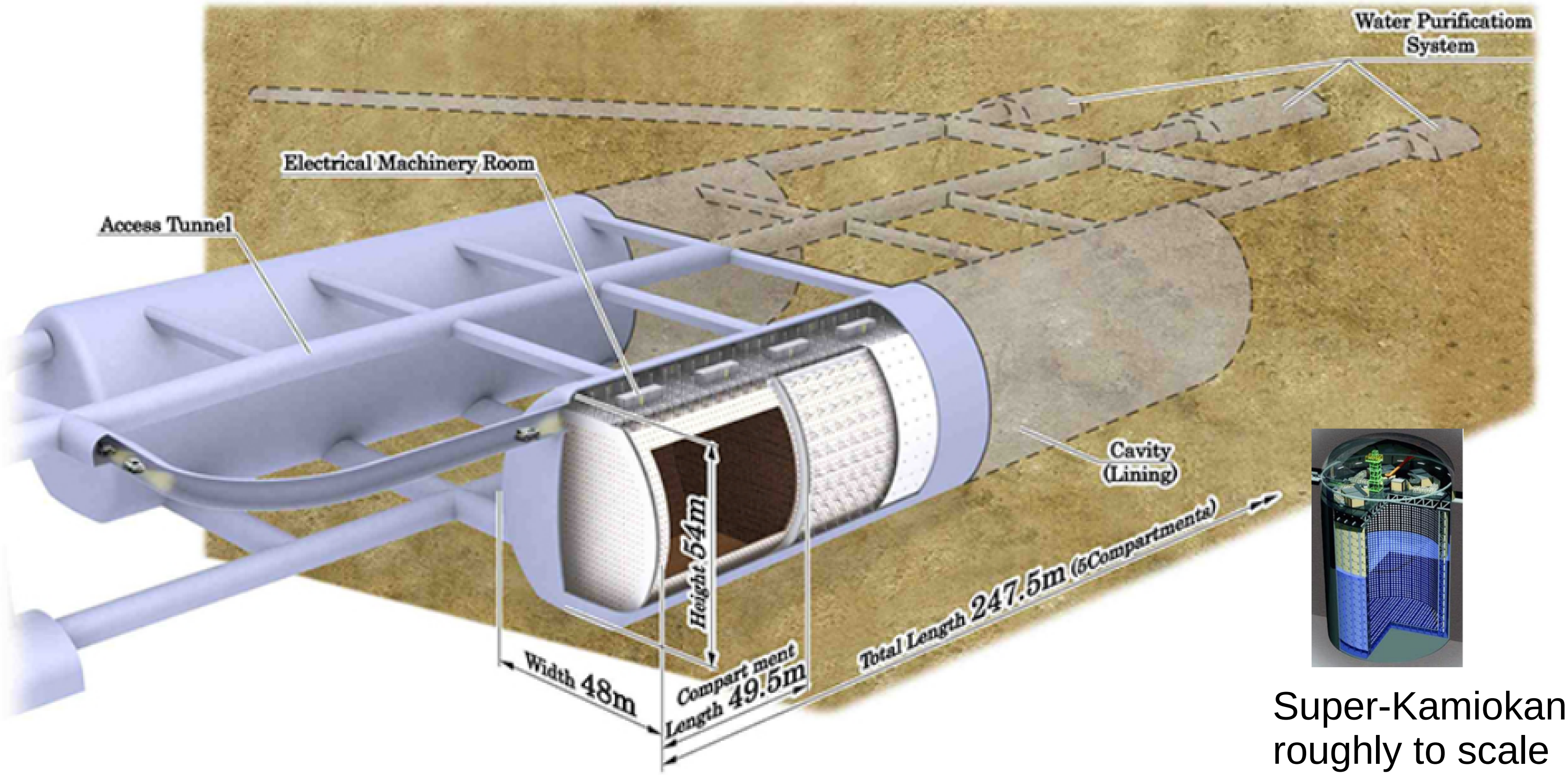
0.1% Gd doping:

- 49000 b vs 0.3 b (H)
- 8 MeV γ (4-5 MeV visible)
- 90% capture efficiency

NB. **> 2018 also SuperKamiokande planned to become Gd-doped** (EGADS demonstrator)

Same target, similar acceptance, same flux, sensitivity to multi-nucleon with n-tagging

Hyper-Kamiokande



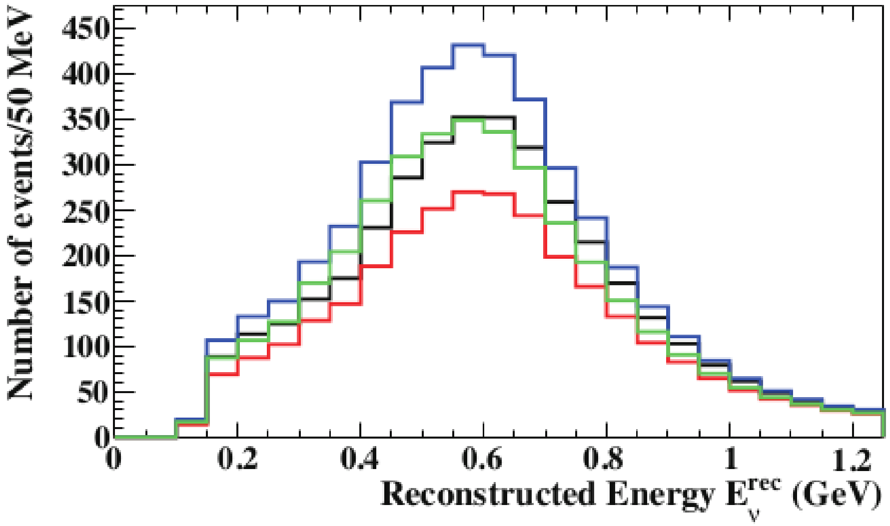
Super-Kamiokande
roughly to scale

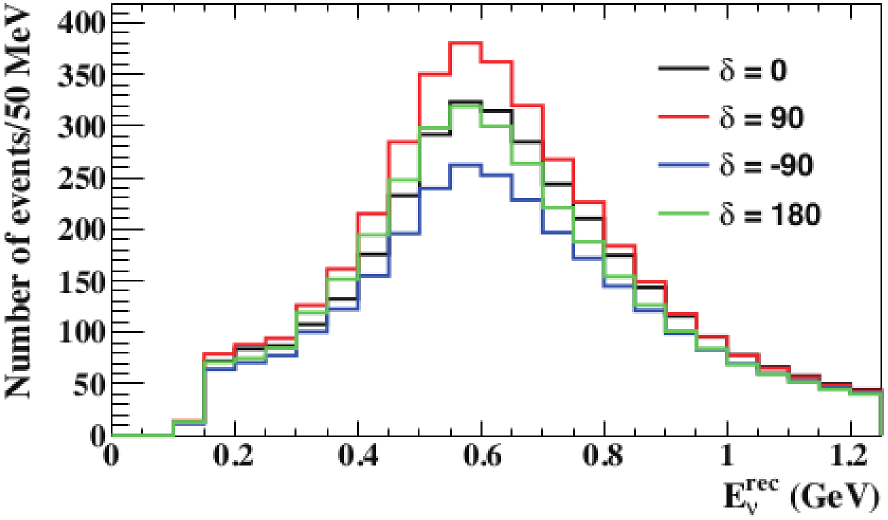
1 Mton mass

Ring-imaging **water Cherenkov detector**
Tochibora mine: 648 m overburden (1.750 mwe)
2.5° at 295 km (= Super-K)

99.000 20” PMTs 20% photo-coverage
25.000 8” PMTs
Light attenuation > 100 m @ 400 nm

Hyper-K: ν_e samples & δ_{CP}

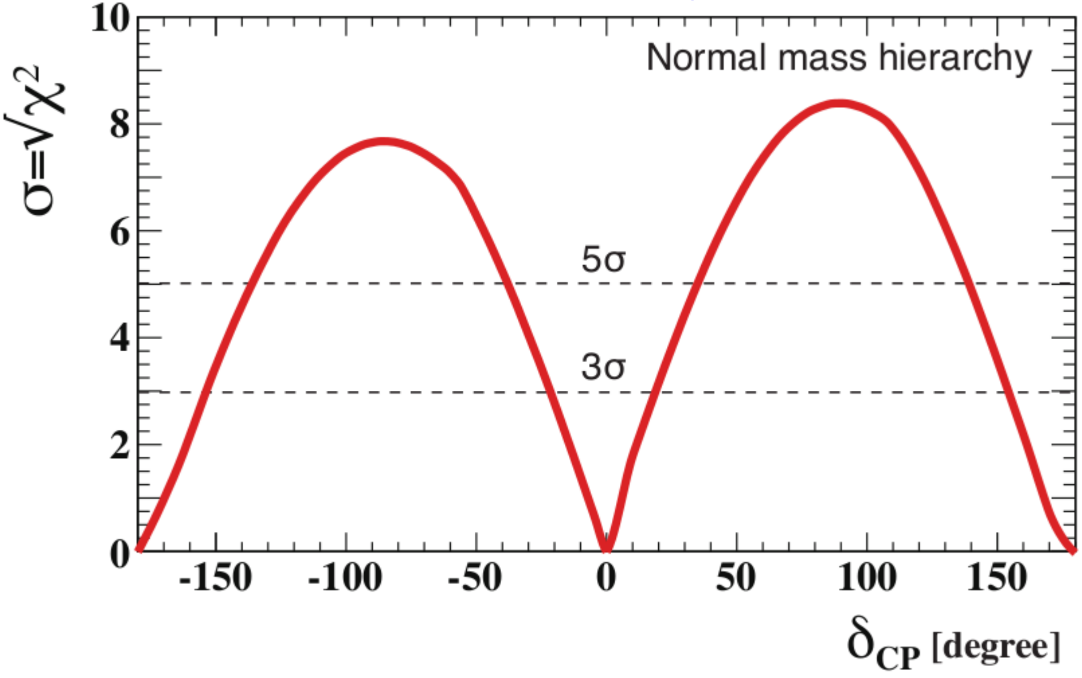

Neutrino mode: Appearance


Antineutrino mode: Appearance

	signal		BG Total	Total
	$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$		
ν mode	3016	28	706	3750
$\bar{\nu}$ mode	396	2110	891	3397

Well known detector technology and analysis. Robust/realistic estimation of systematic uncertainties. Large statistics.

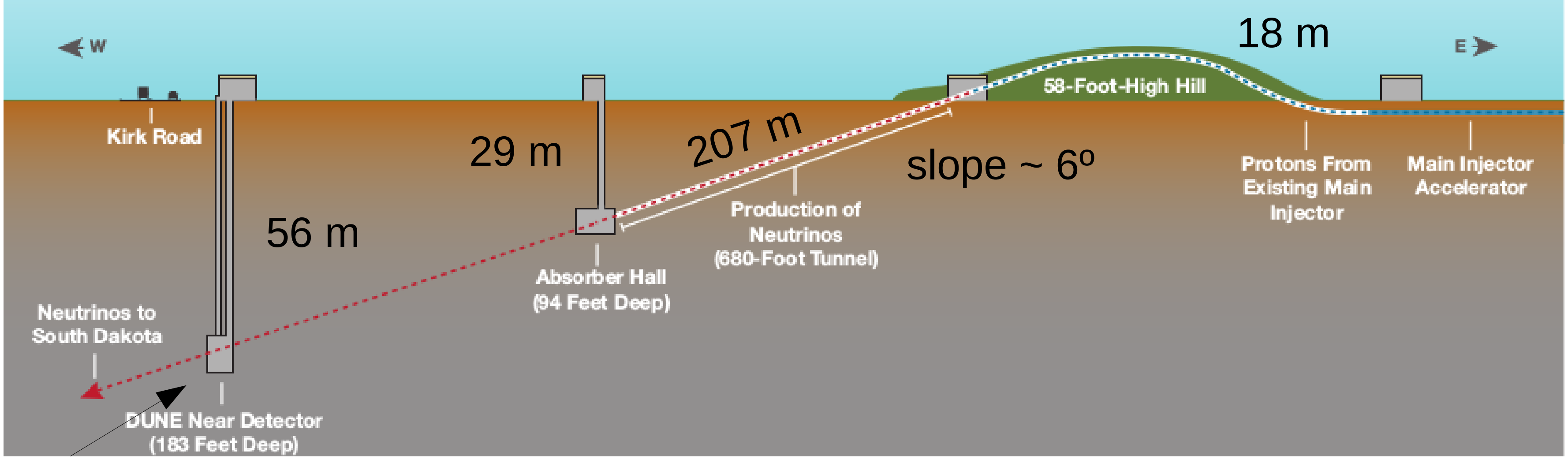
CPV discovery   CPV: δ_{CP} = 0 or π

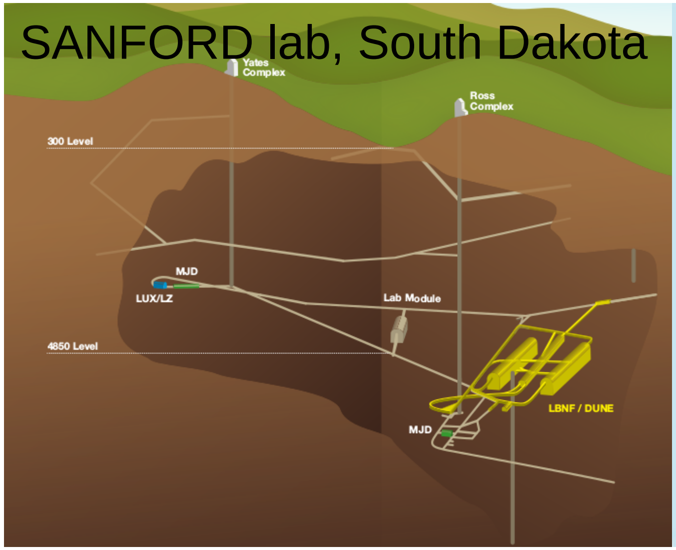


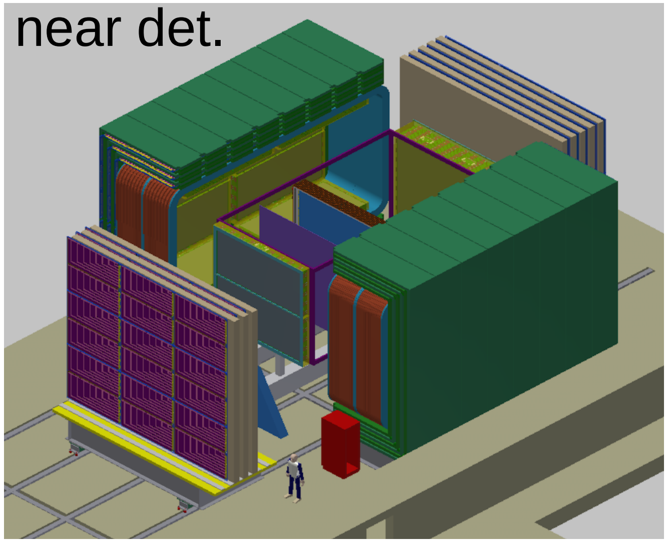
LBNF and DUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

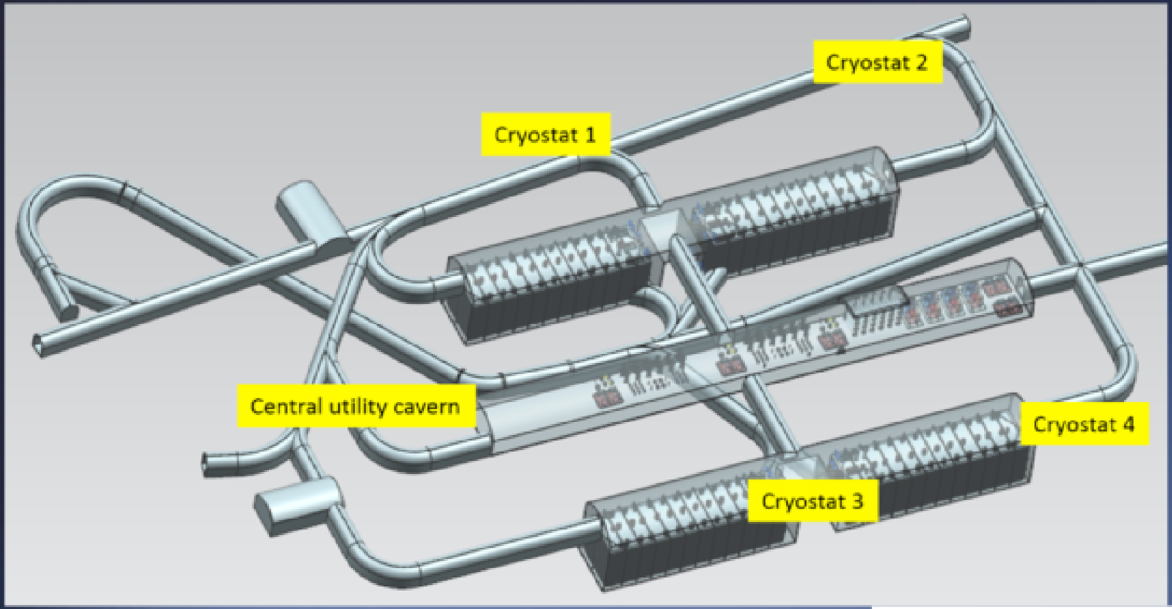
- (staged) 40 kt LAr detector, at the SURF site, 1300 km from FNAL
- high granularity/high precision near detector
- 1.2 MW, tunable ν beam produced by the PIP-II upgrade at FNAL by 2024, evolving to a power of 2.3 MW by ~ 2030.




SANFORD lab, South Dakota


near det.

DUNE far detectors



4 detectors in 4 caverns

1’500 m underground

~ 17’400 tons of LAr / detector

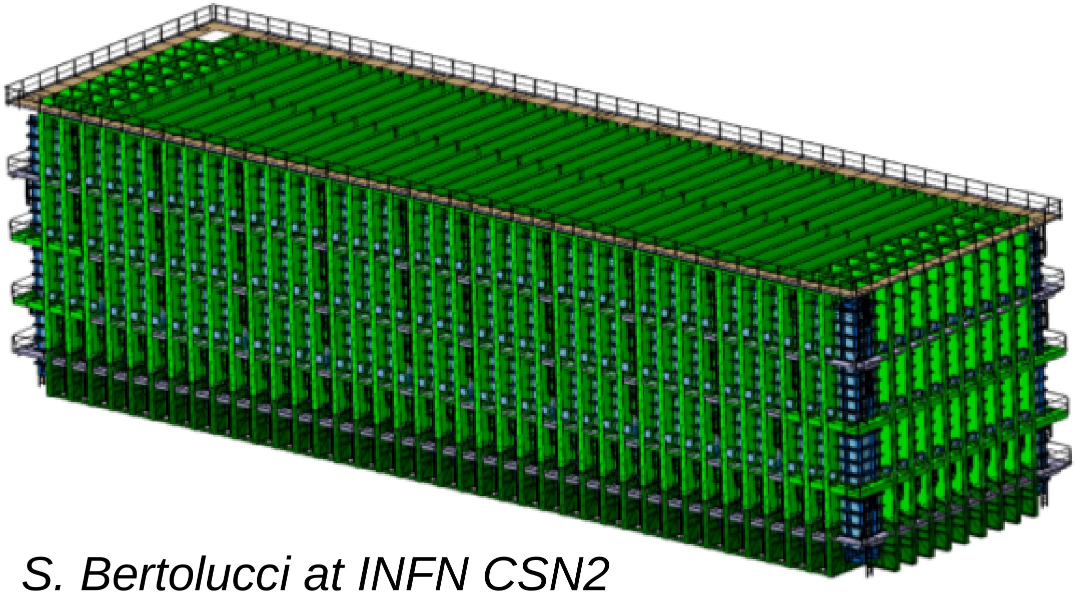
Inner dimension (liquid+gas):
- L = 62.00 m
- W = 15.10 m
- H = 14.00 m

Excavation starts in 2017

First detector ready in 2022

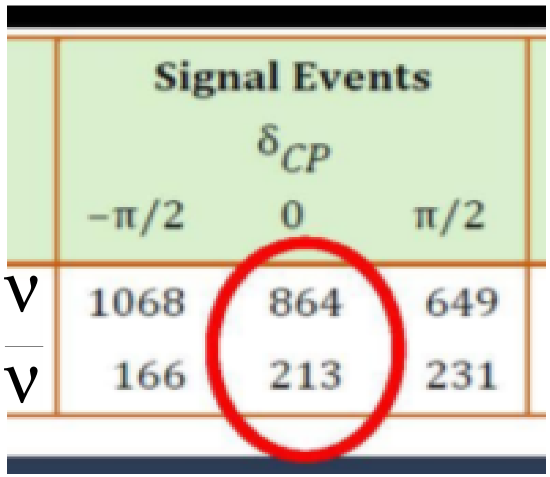
All 4 detectors in 2026

Neutrino beam in 2026

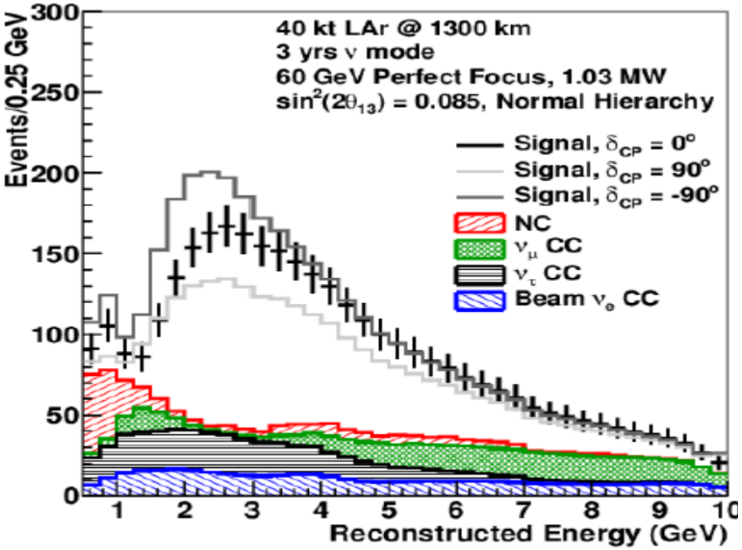


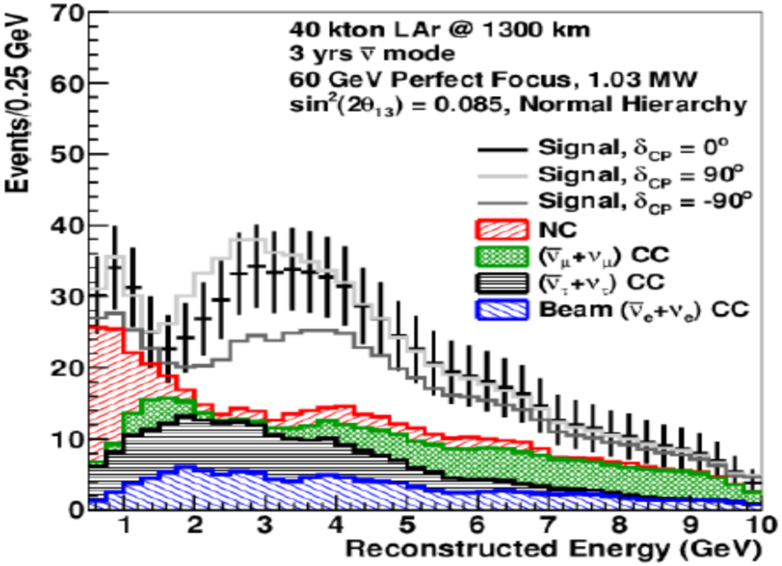
S. Bertolucci at INFN CSN2

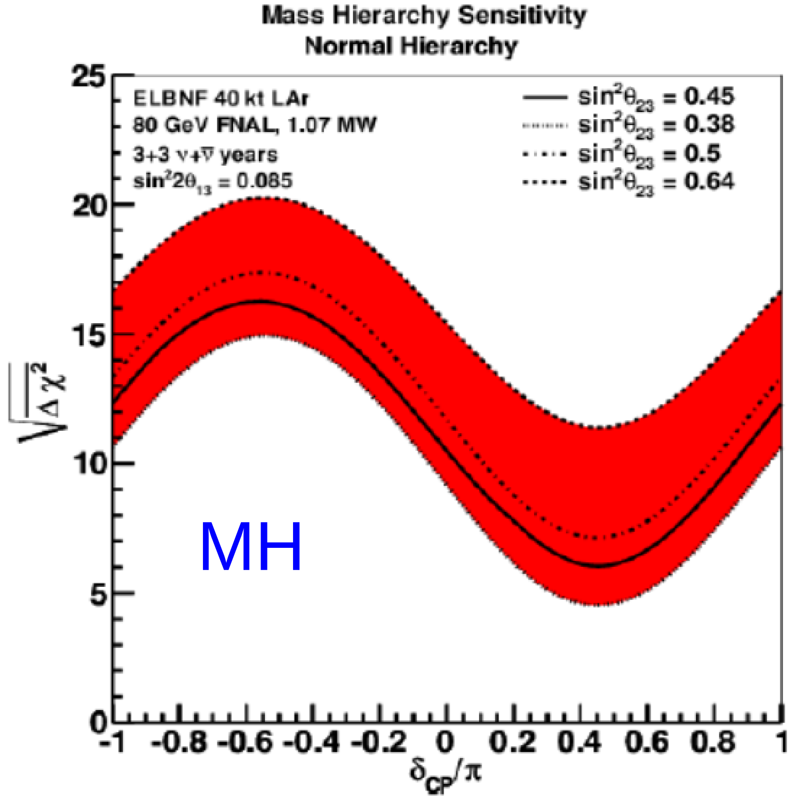
DUNE: ν_e samples, δ_{CP}, MH

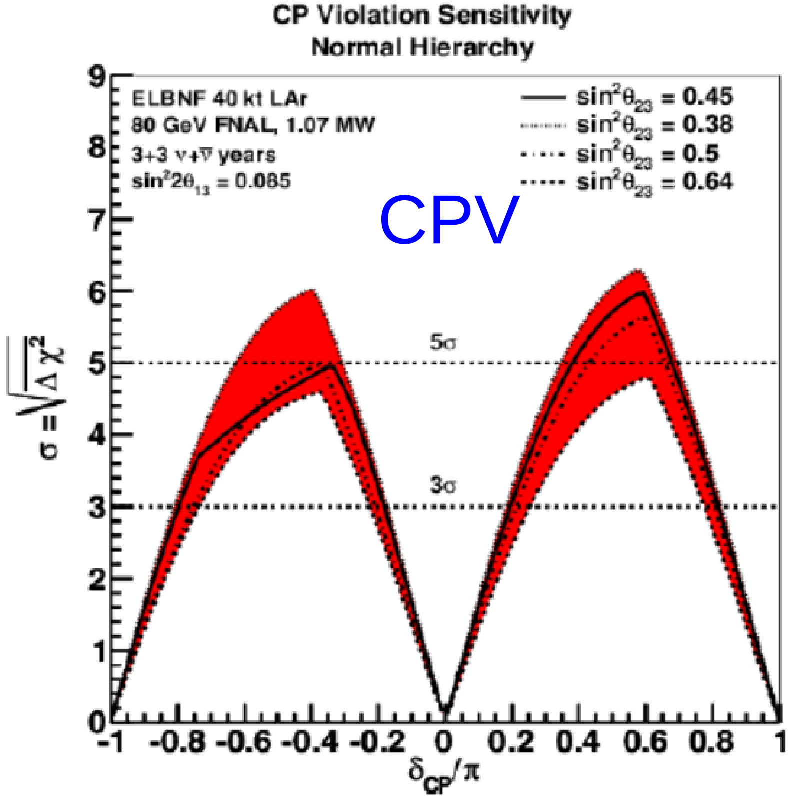


	Signal Events δ_{CP} $-\pi/2$	 0	 $\pi/2$
ν	1068	864	649
$\bar{\nu}$	166	213	231





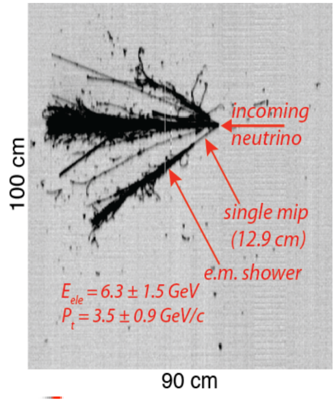


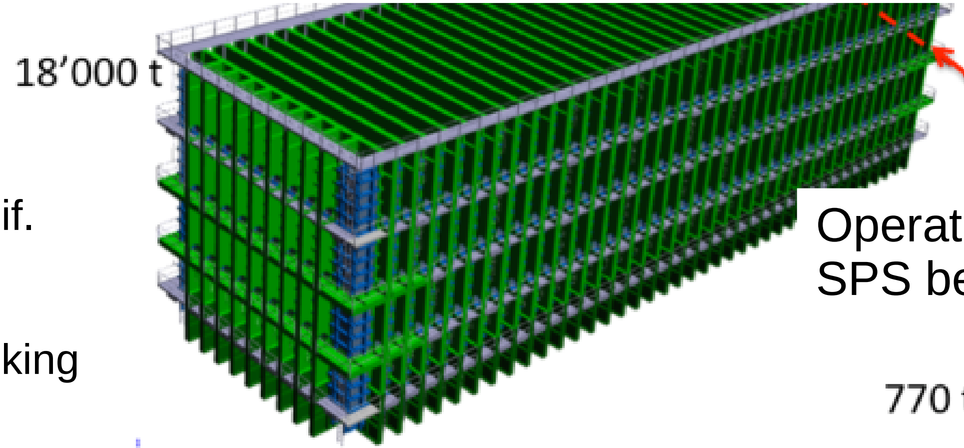


LAr TPC roadmap

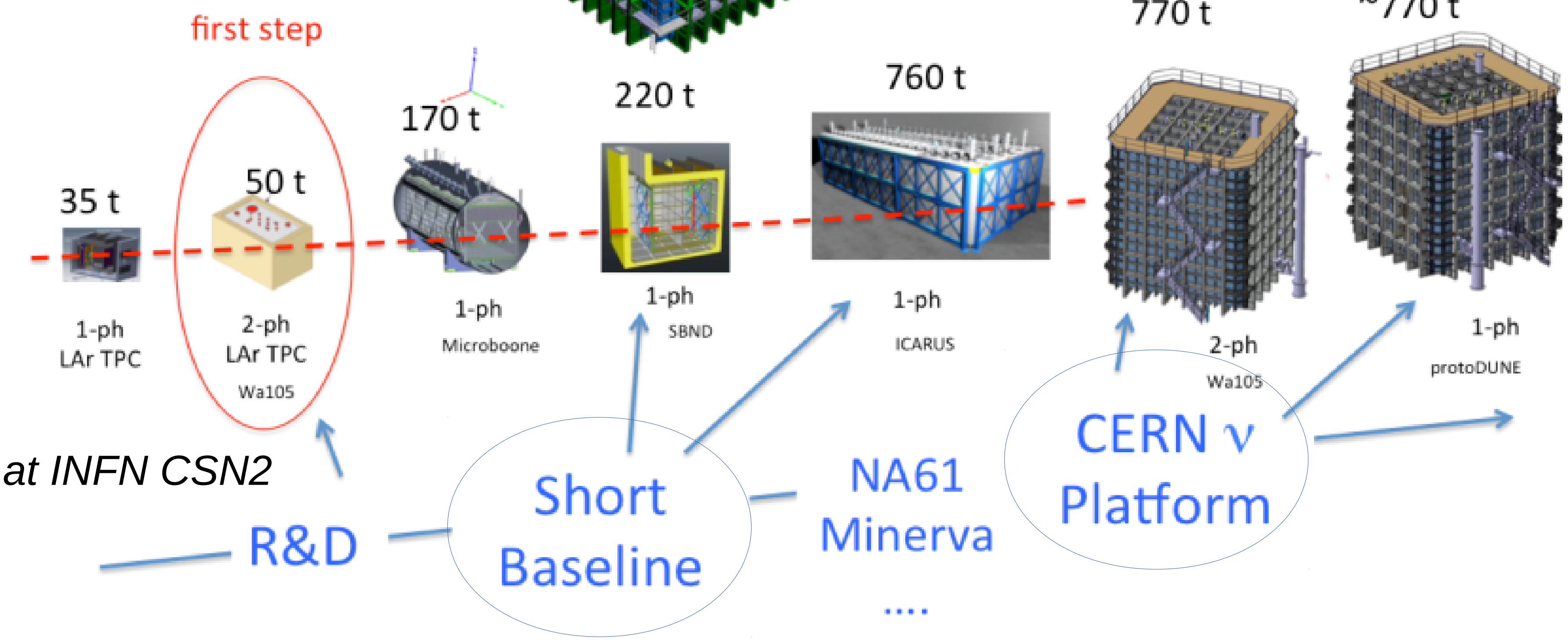
Challenges

- Large cryostats ~ 13000 m^3
- Deep underground activities
- Long drifts > 3.5 m
- High liquid purity at the ppt level
- High T stability ~0.3^o - 0.5^o
- Cold FE electronics or in gas amplif.
- Low threshold signals
- Large data handling capabilities
- Automatic pattern recognition, tracking





Operational 2017
SPS beams in 2018-19



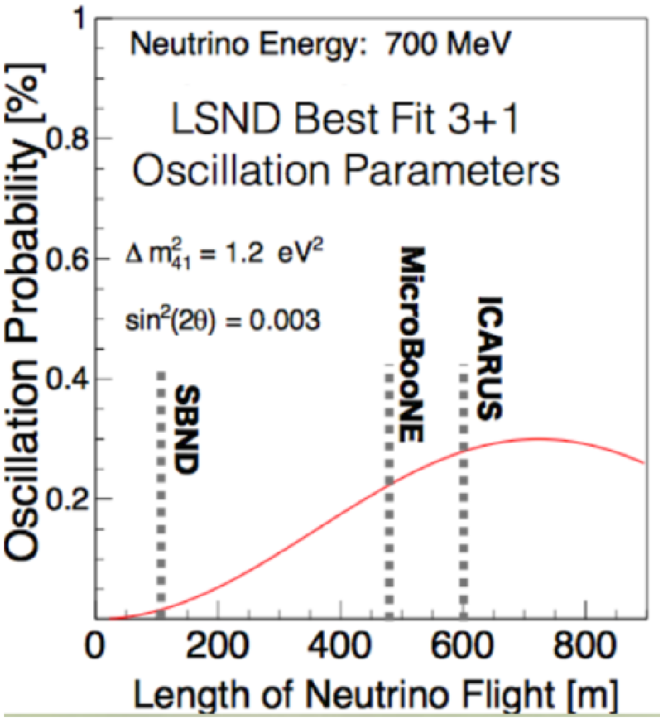
S. Bertolucci at INFN CSN2

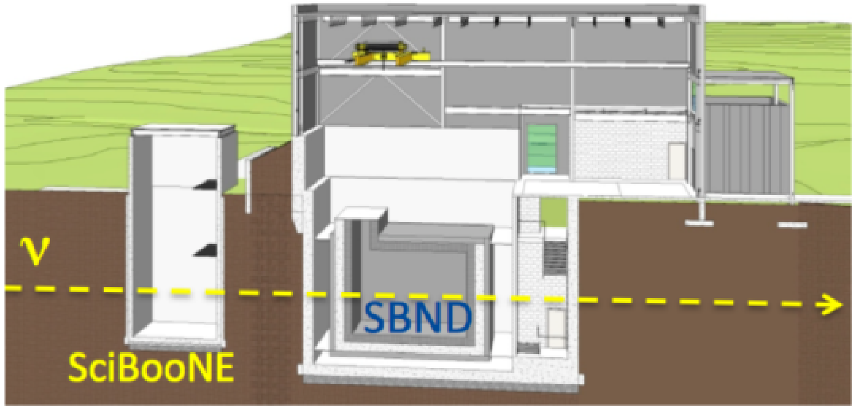
To succeed we need to proceed in steps (for cryostats, cryogenics and detectors)

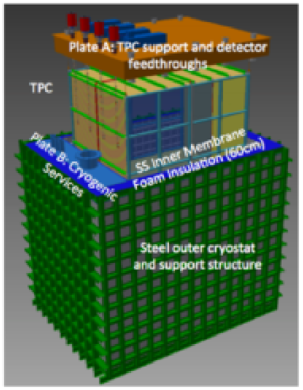
FNAL short baseline program

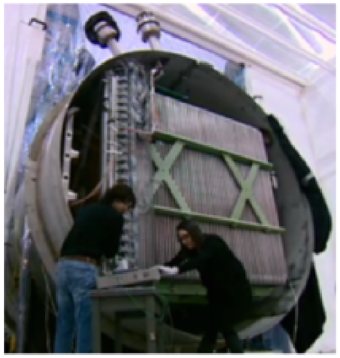
SBND, μBooNE, ICARUS-T600

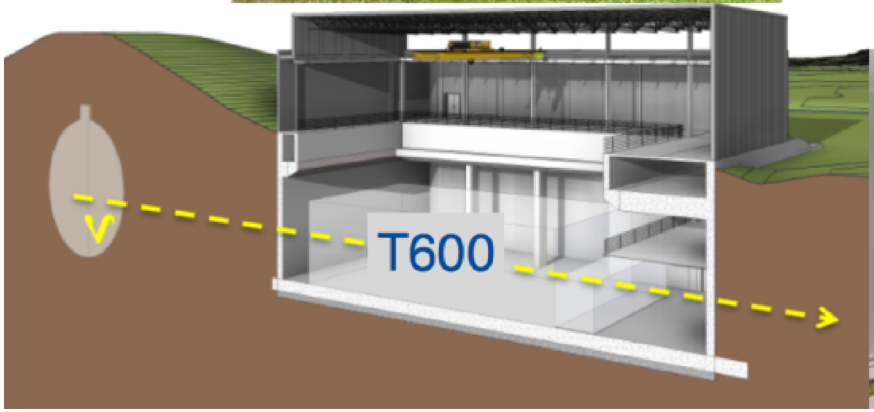
- LAr TPC R&D
- (together with the reactor's program) likely clarify the scenario of sterile neutrino disproving or confirming previous hints with beams:
  - LSND anomaly?
  - MiniBooNE low-E excess ?
  - Differences ν / anti-ν?





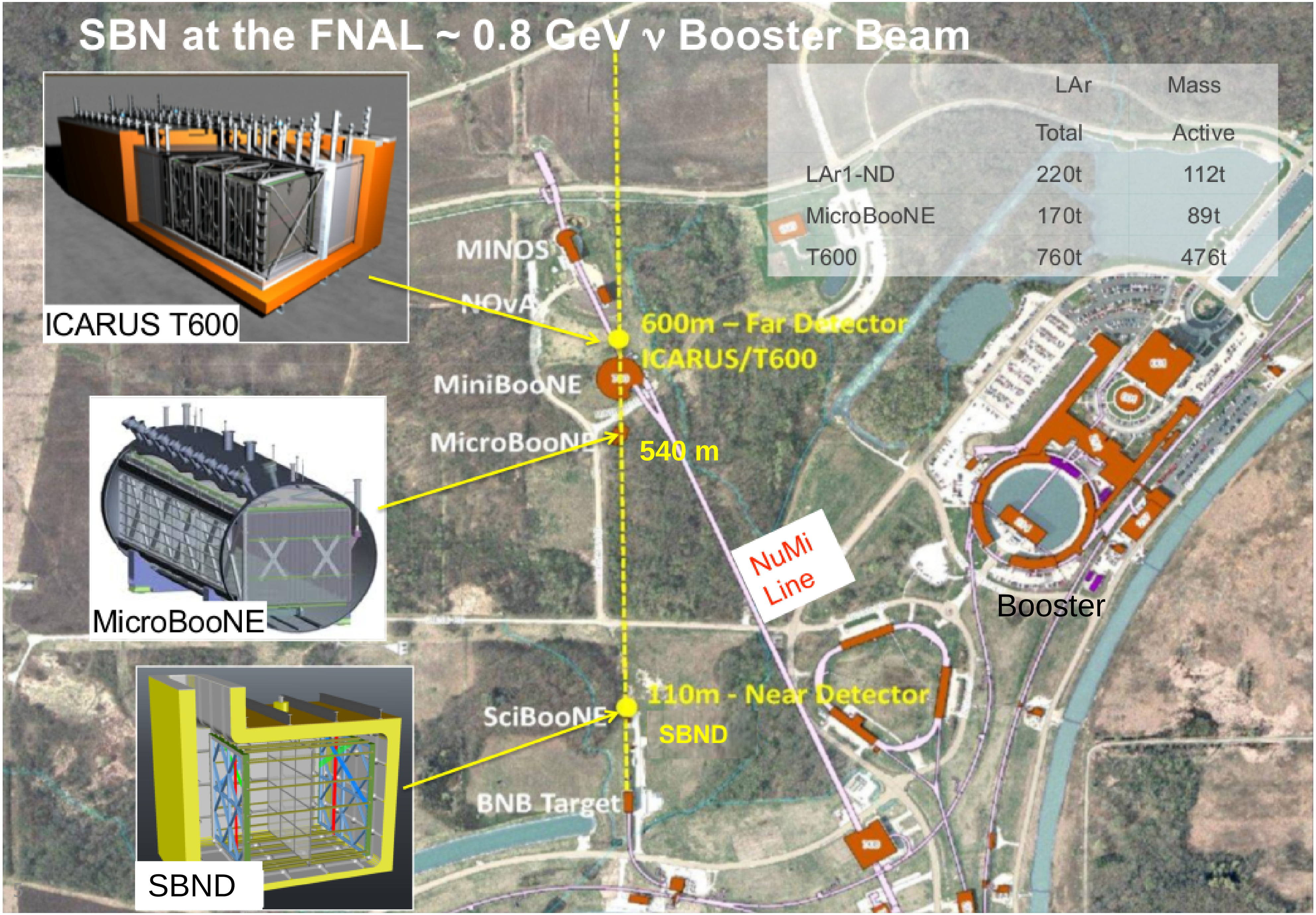







First T300 in Cleanroom at CERN

FNAL short baseline layout



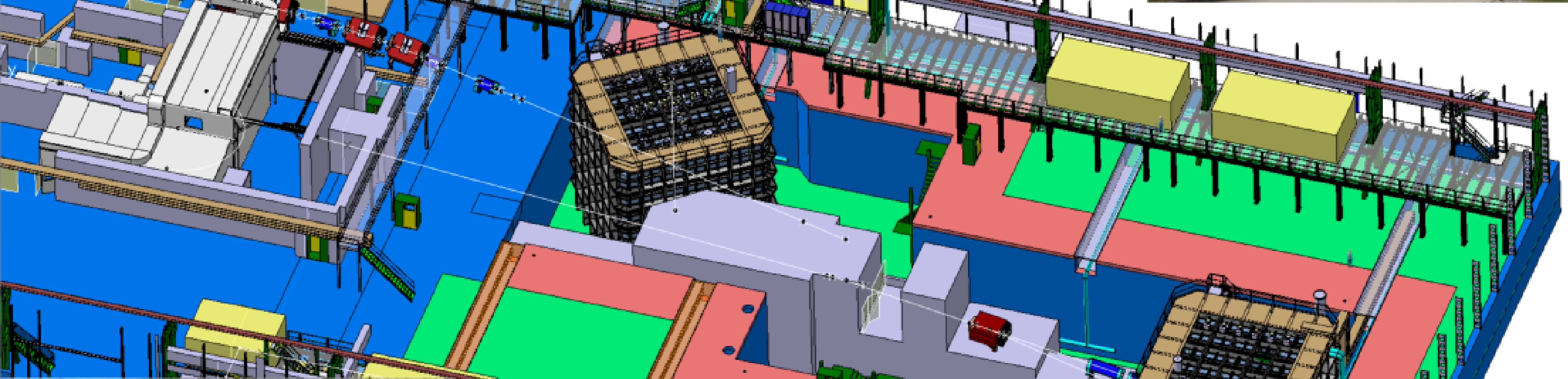
SBN at the FNAL ~ 0.8 GeV ν Booster Beam

	LAr Total	Mass Active
LAr1-ND	220t	112t
MicroBooNE	170t	89t
T600	760t	476t

CERN ν platform: EHN1

- ✓ *PLAFOND : an generic R&D framework*
- ✓ *WA104 : ICARUS as far detector for SBN*
- ✓ *WA105 : demonstrator + engineering prototype for a double ph. TPC*
- ✓ *ProtoDUNE : engineering prototype for a single phase TPC*
- ✓ *Baby MIND : a muon spectrometer for the WAGASCI experiment*
- ✓ *ArgonCube : a modular TPC R&D*

S. Bertolucci at INFN CSN2



- ✓ *HKK detector components R&D*
- ✓ *Darkside 20K*
- ✓ *ARIADNE*

- ✓ *LBNF cryostat and LAr cryogenics*
- ✓ *SBND cryostat and LAr cryogenics*
- ✓ *CERN member of DUNE and SBN*

- ✓ For the moment CERN is not committing to any neutrino beam at CERN, in view of an agreed road map between all partners
- ✓ The CERN Neutrino Platform represents a gateway for the European Neutrino Community towards a global, organized accelerator neutrino program
- ✓ In the short- and medium-term, Europe is helping in getting a Short Baseline operational at FNAL with an agreed physics program … and later a Long Baseline

Conclusions

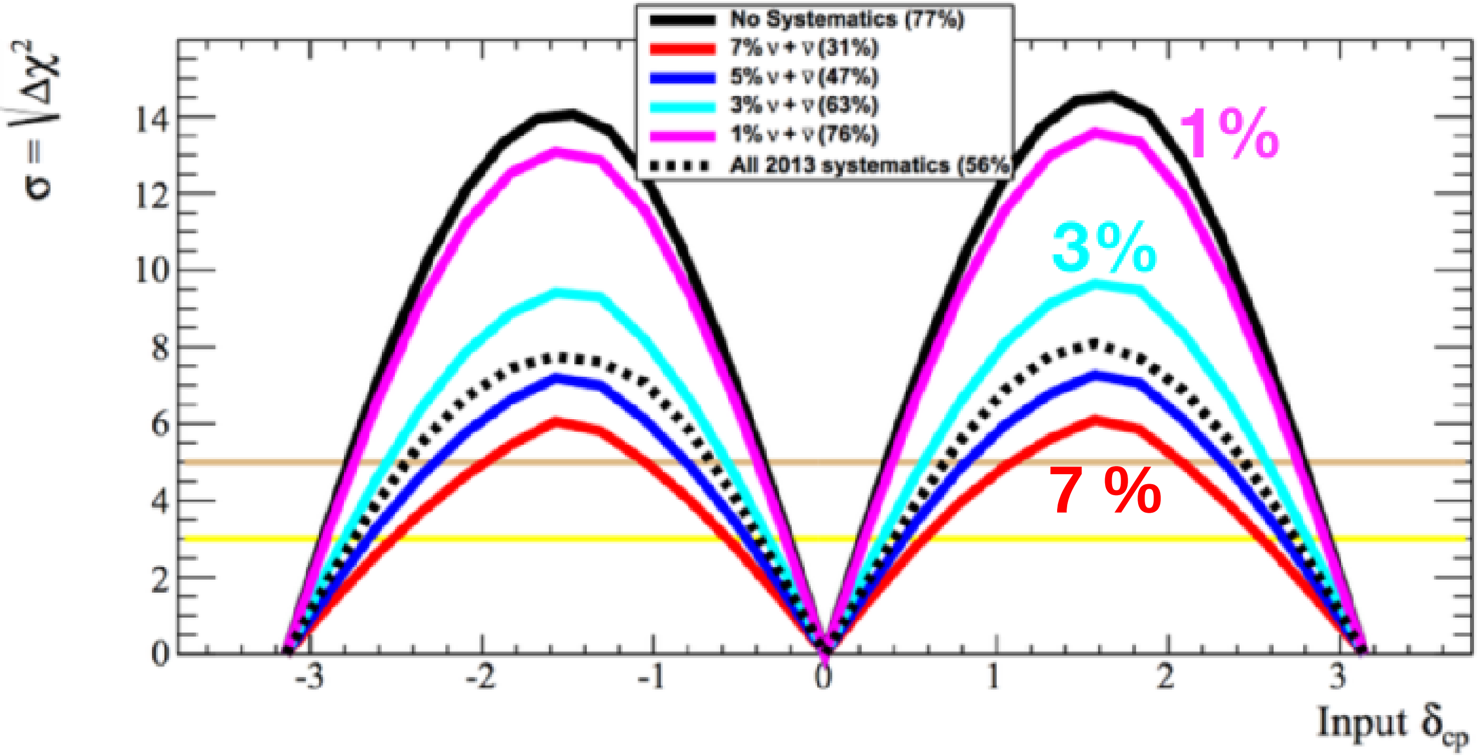
- Neutrino oscillation physics with accelerator beams is living an exciting phase. Beautiful measurements in done/progress & good future prospects for fundamental physics.
- CPV out of reach if θ_{13} or θ_{12} would have been small! Will δ "continue the tradition" and finally establish the (somewhat deserved) good luck of neutrino physicists ?
- Or: Will indications for (N.I., $\delta = -\pi/2$) of T2K/NOνA survive further data?
- Even with the help of Nature … need for smart experimental designs and inputs from several sides (cross-sections, hadro-production measurements...). New ideas to reduce systematics being proposed for present and future infrastructures.
- The international scenario is getting clearer. Opportunity of a new class of large experiments: will strengthen the reach for CPV and mass hierarchy. Precision neutrino measurements. Boost the potential for unexpected discoveries (Super-K docet).

Backup slides

Impact of systematic uncertainties on Hyper-K *Dr. Mark HARTZ*

$\nu_e,\bar{\nu}_e$ Cross Section Sensitivity Impact

- Perform sensitivity study where the ν_e and $\bar{\nu}_e$ cross sections are assigned two uncorrelated normalization systematic parameters
- The uncertainties on the normalization parameters are varied and the impact on the CPV sensitivity is studied.



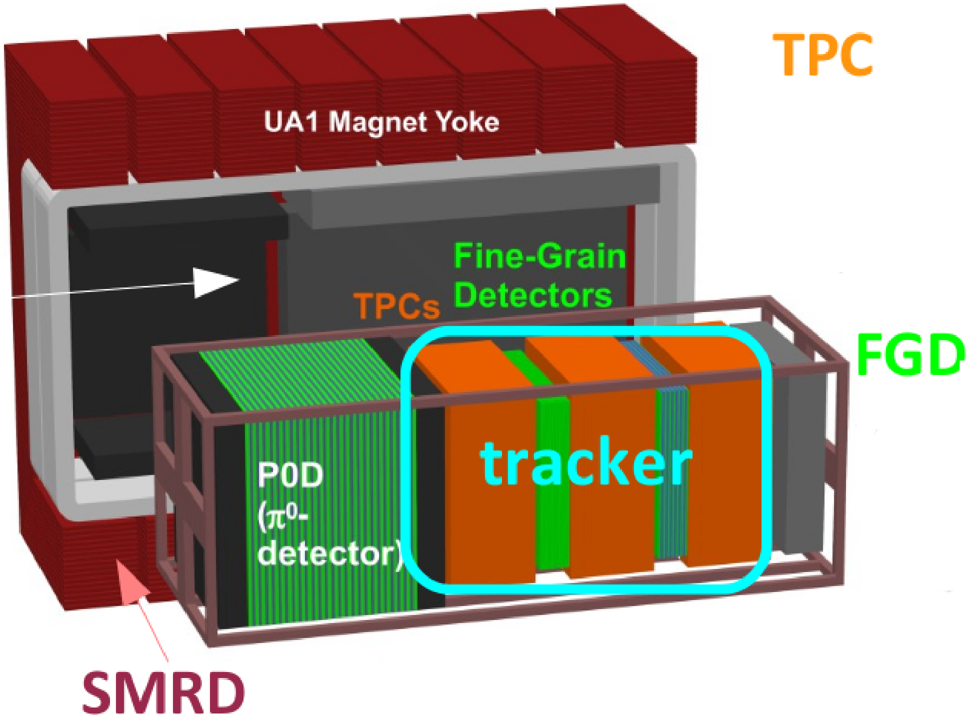
- The systematic uncertainty should be controlled to <1-2% to minimize the impact on the CPV discovery sensitivity

The near detector (280 m)

ND280 (off-axis)

Measures ν_μ & ν_e fluxes and cross-sections

Magnet B = 0.2 T
TPC: p measurement + particle-ID with dE/dx
FGD: Fine grained detectors (2 x 0.8 t): Proton tagging
SMRD: magnitized muon range detector

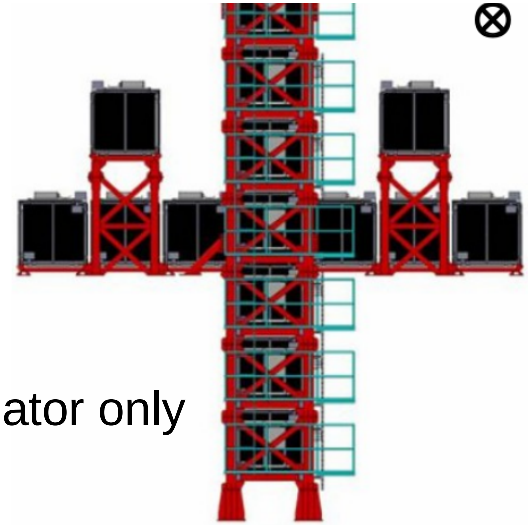


P0D: pi-zero detector (Pb/brass-H_2O-scintillator)
ECAL: electromagnetic calorimeter

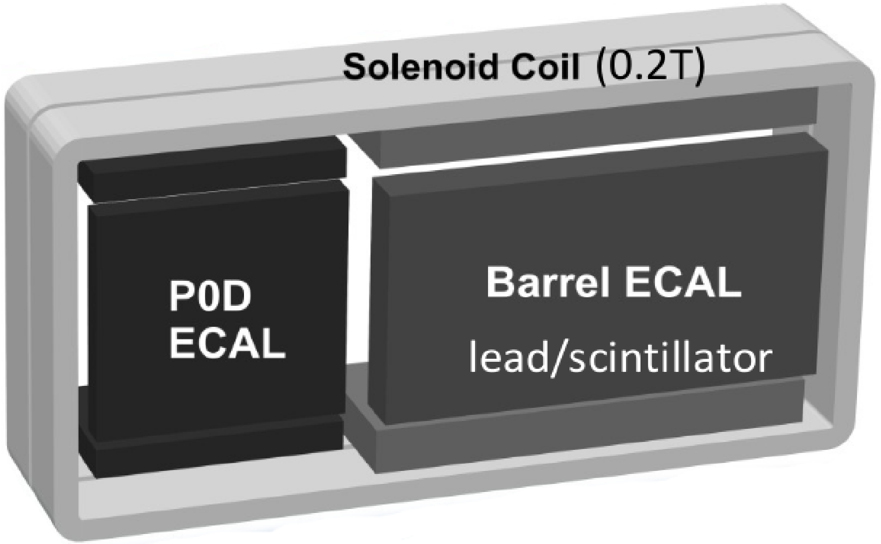
INGRID (on-axis)

ν_μ CC rate → beam profile

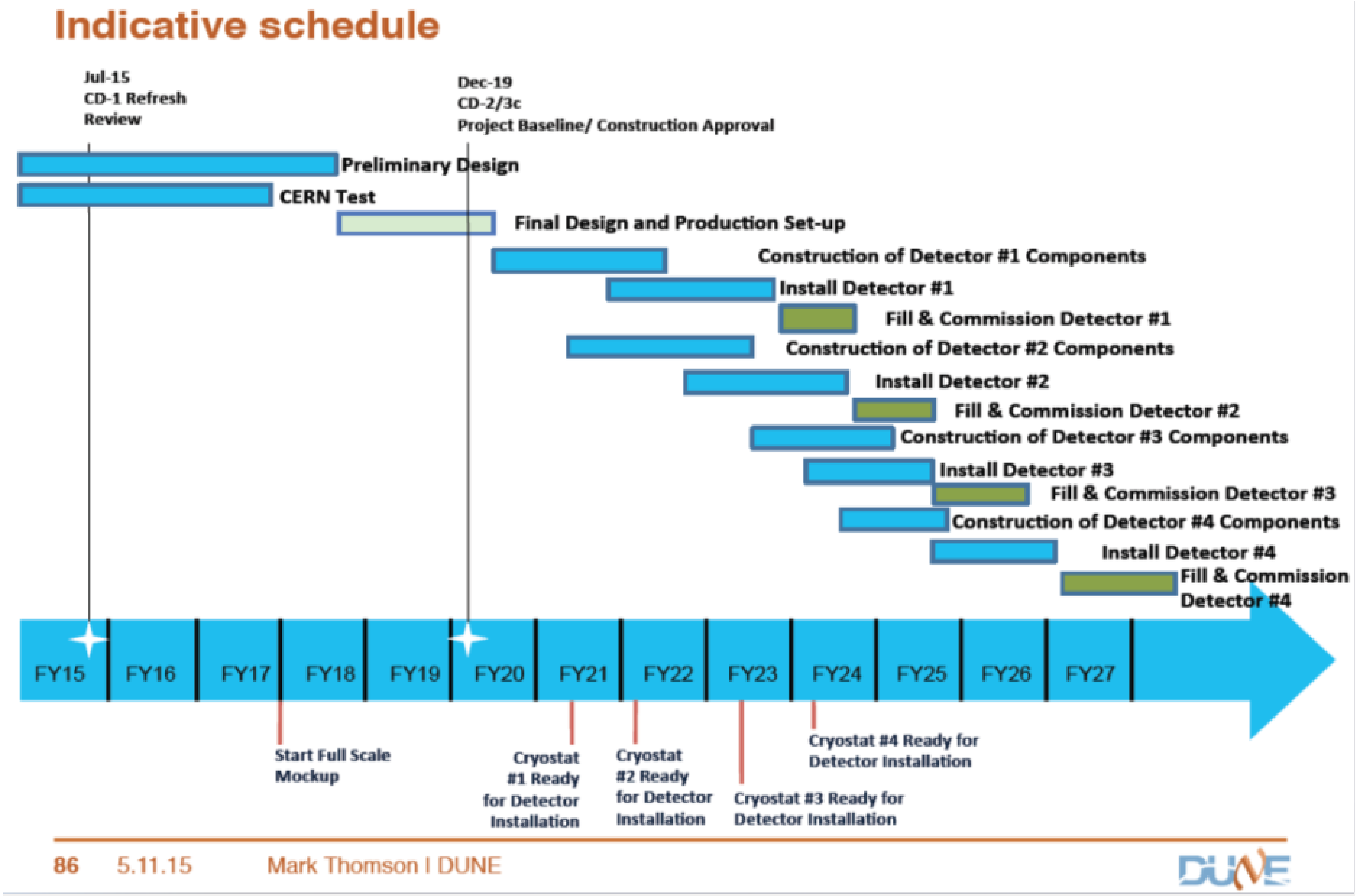
Fe/scintillator tracking calorimeter



16 modules
central one scintillator only



DUNE schedule

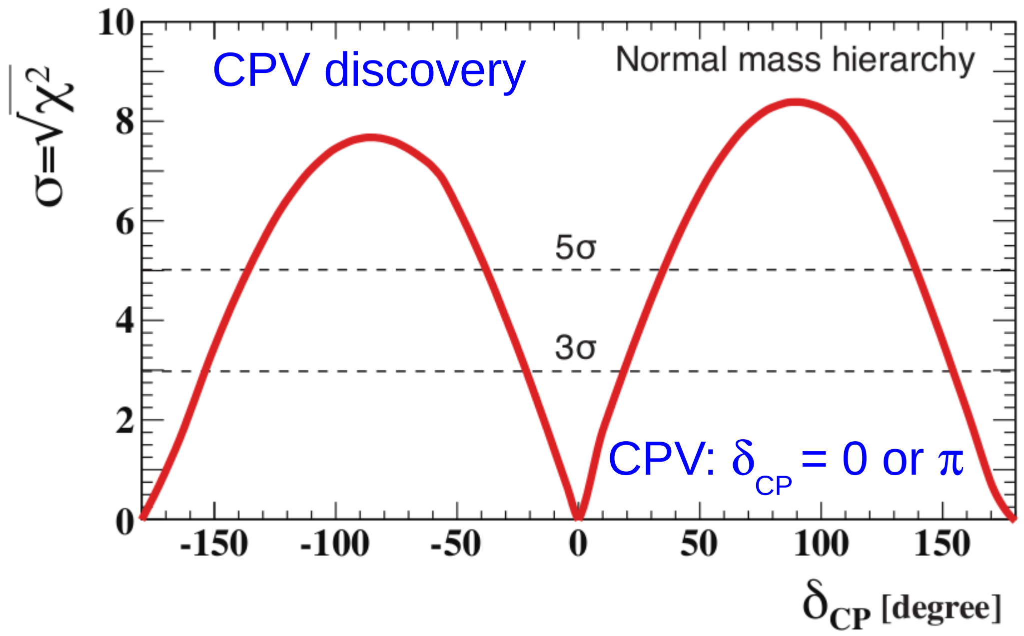


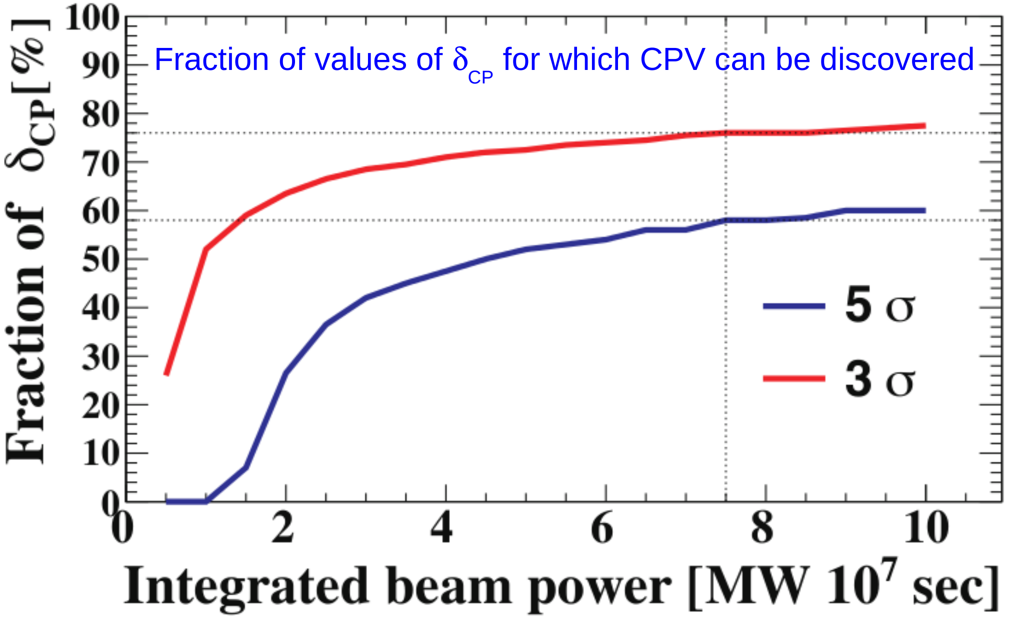
Indicative schedule

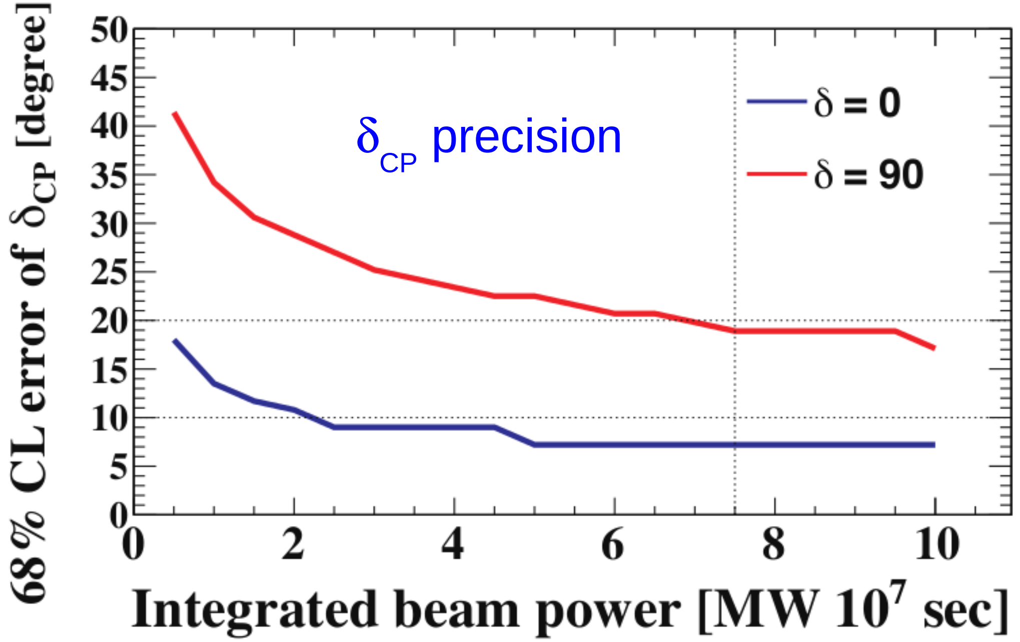
86 5.11.15 Mark Thomson I DUNE

Hyper-K: CPV reach and δ_{CP} precision

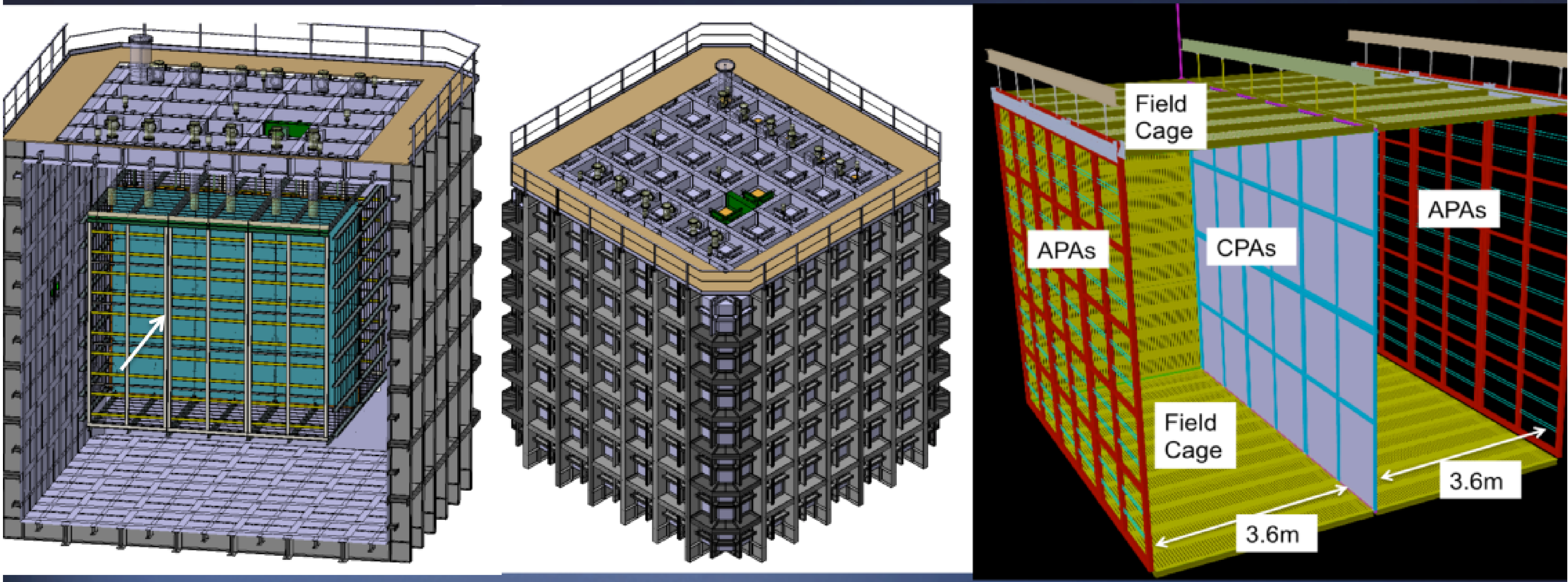
Well known detector technology + analysis. Robust/realistic estimation of systematic uncertainties





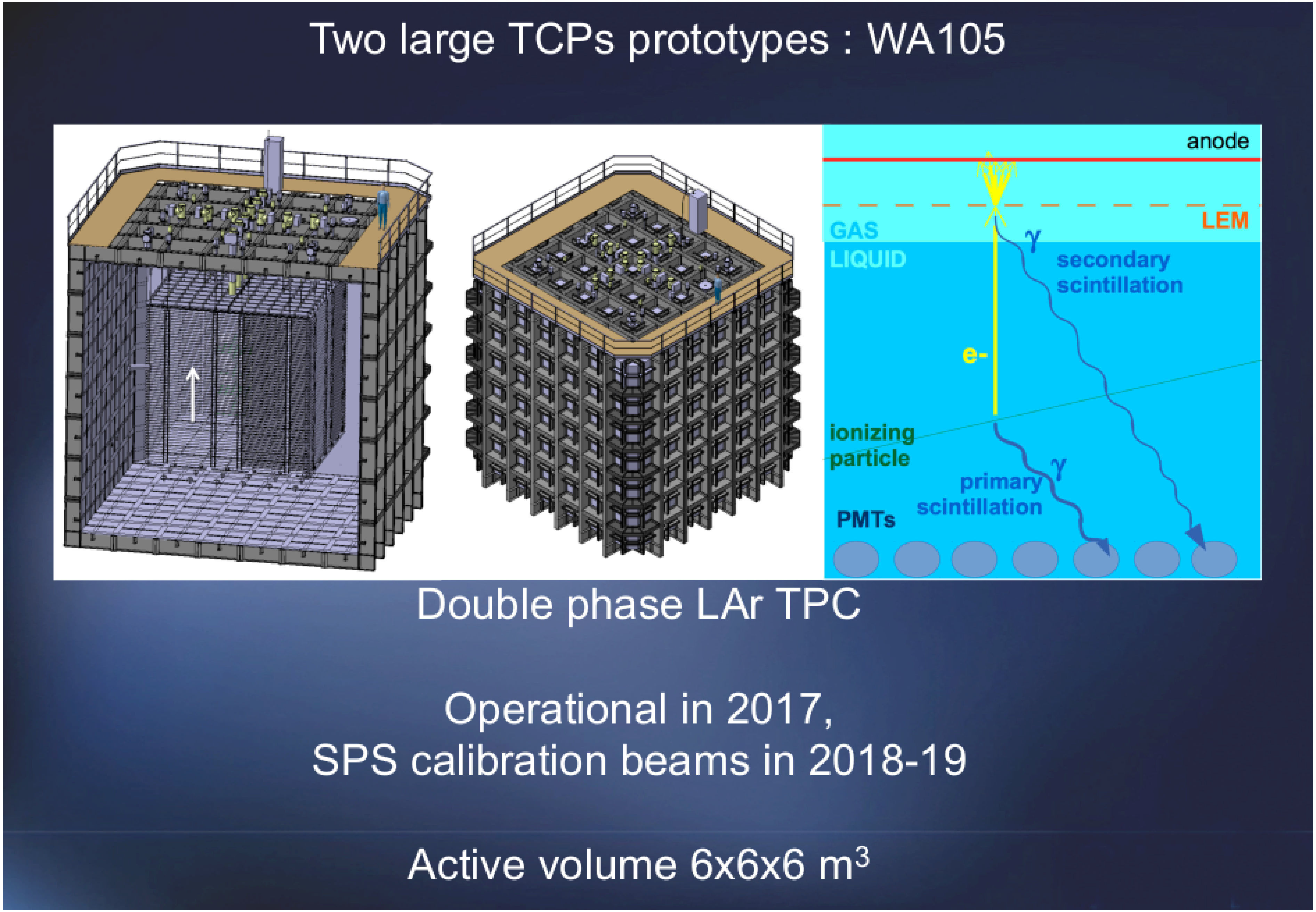


Two large TCPs prototypes : protoDUNE



Single phase LAr TPC

Operational in 2017,
SPS calibration beams in 2018-19



Two large TCPs prototypes : WA105

Double phase LAr TPC

Operational in 2017,
SPS calibration beams in 2018-19

Active volume 6x6x6 m^3

ν_μ disappearance: Δm^2_{23} & $\sin^2 2\theta_{23}$

3ν scheme

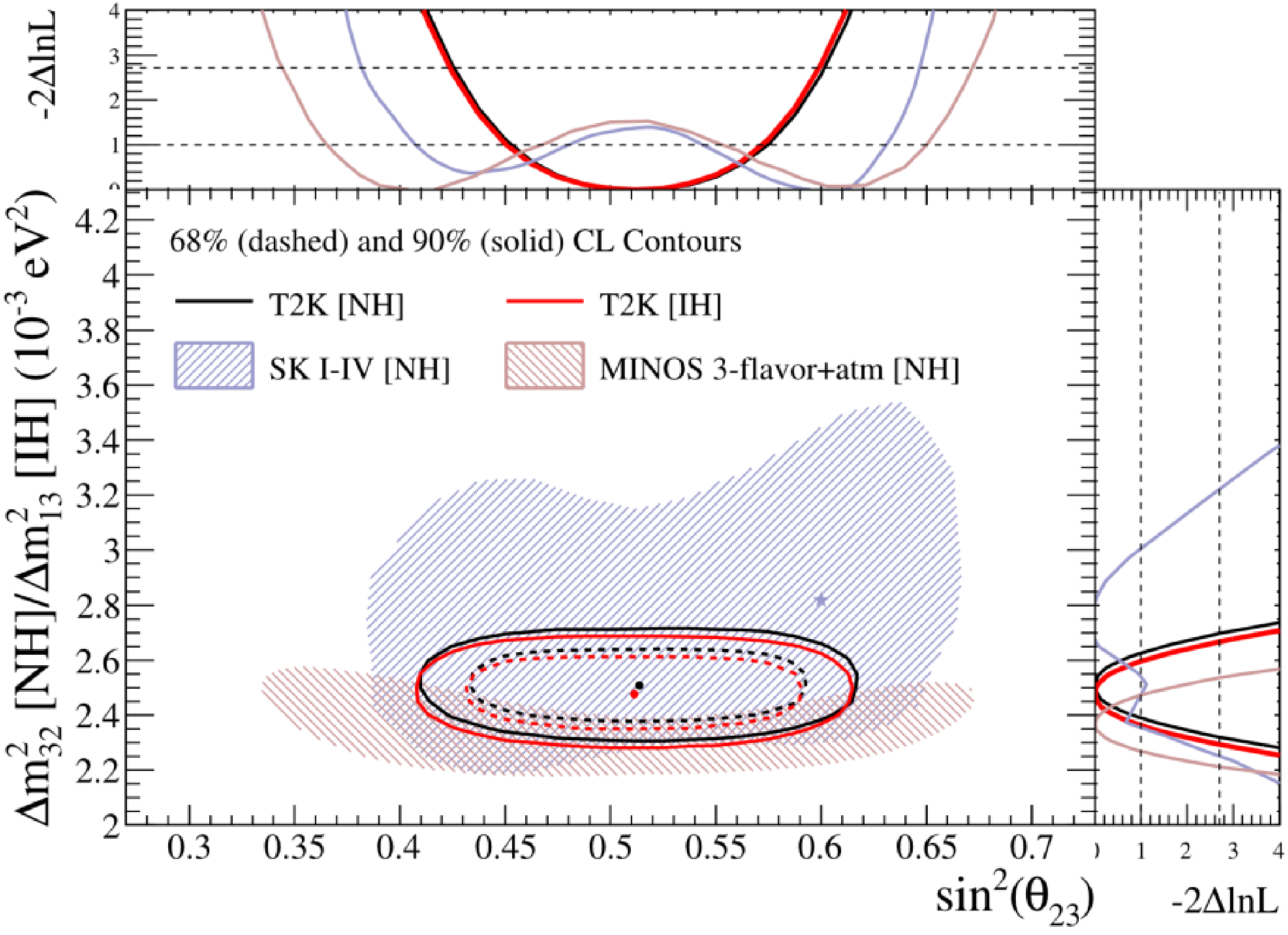
$$P(\nu_\mu \to \nu_\mu) = 1 - (\overbrace{\cos^4\theta_{13}\sin^2 2\theta_{23}}^{\text{leading}} + \overbrace{\sin^2 2\theta_{13}\sin^2\theta_{23}}^{\text{sub-leading}})\sin^2\frac{\Delta m^2_{32} L}{4E}$$

θ_{23} dependence
non π/4 symmetric
(sub-leading term)

Normal hierarchy (NH)
$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$
$|\Delta m^2_{32}| = (2.51 \pm 0.10)\ 10^{-3}\ \text{eV}^2$

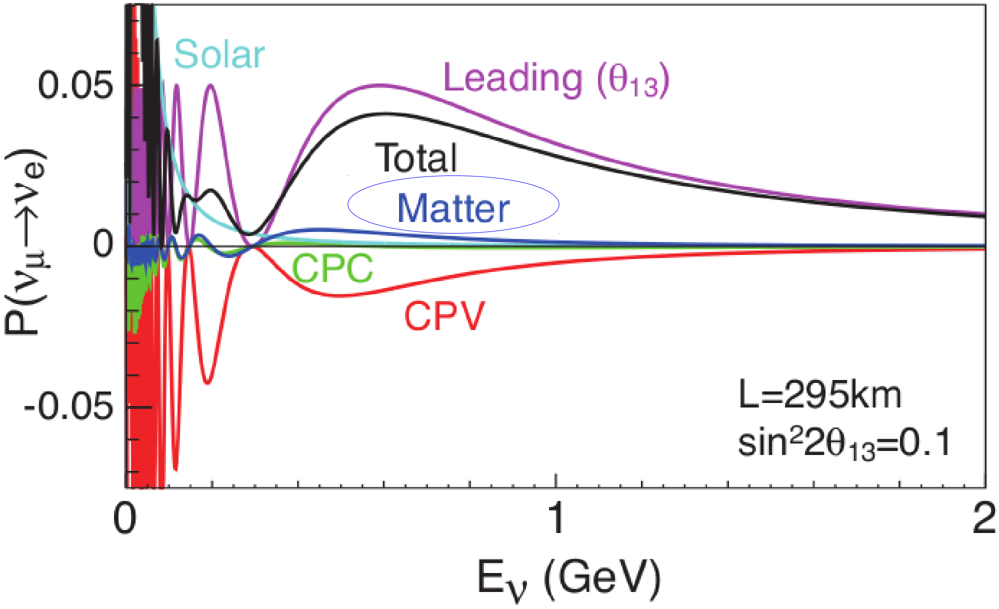
Inverted hierarchy (IH)
$\sin^2\theta_{23} = 0.511 \pm 0.055$
$|\Delta m^2_{32}| = (2.48 \pm 0.10) \cdot 10^{-3}\ \text{eV}^2$

- θ_{23} : world leading (improved SK atm. ν)
- Δm^2 : close to MINOS

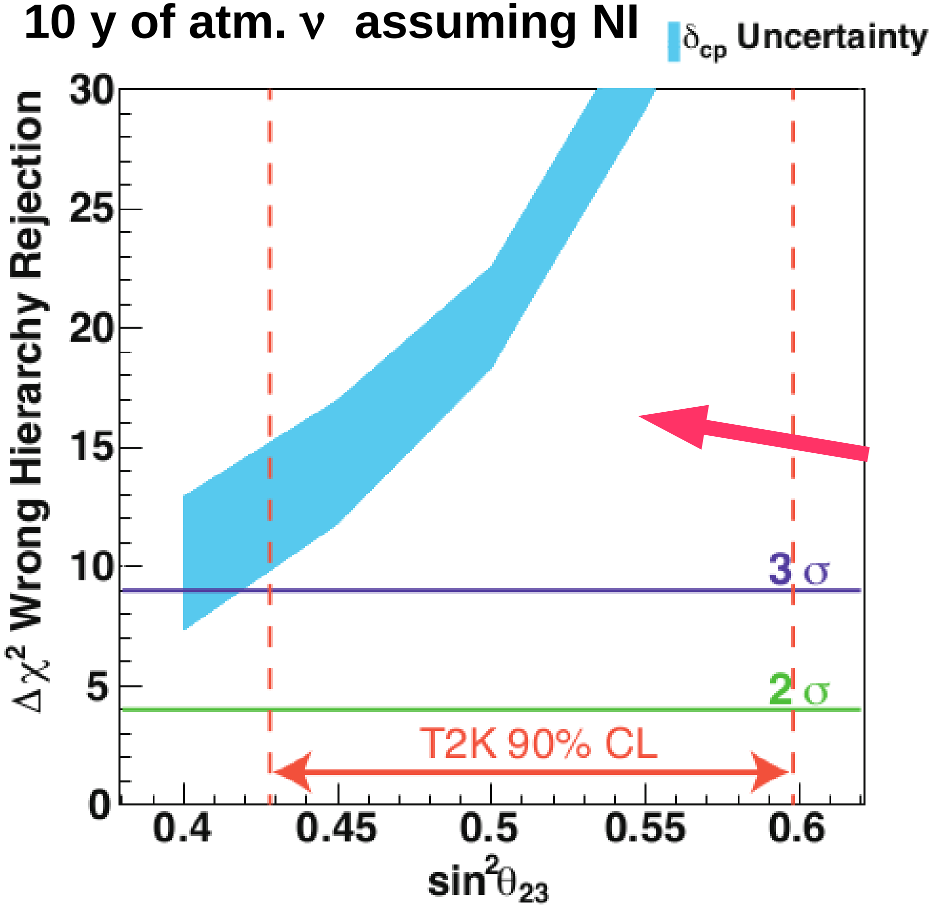


Hyper-K atmospheric data

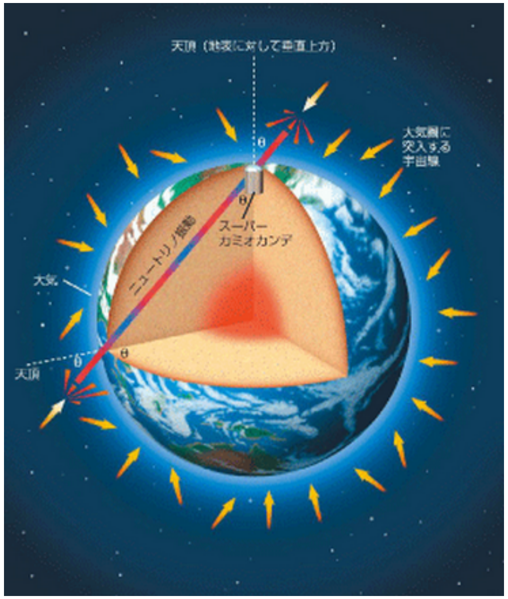
295 km → small matter effects
→ limited contribution from
CPV induced by matter effects
→ clean measurement of
genuine CPV



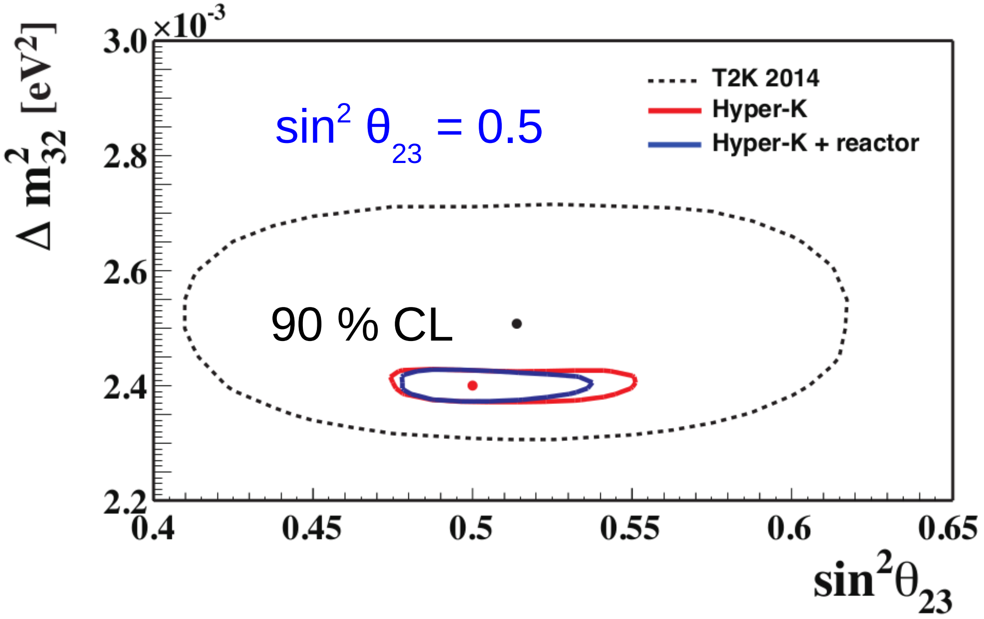
10 y of atm. ν assuming NI

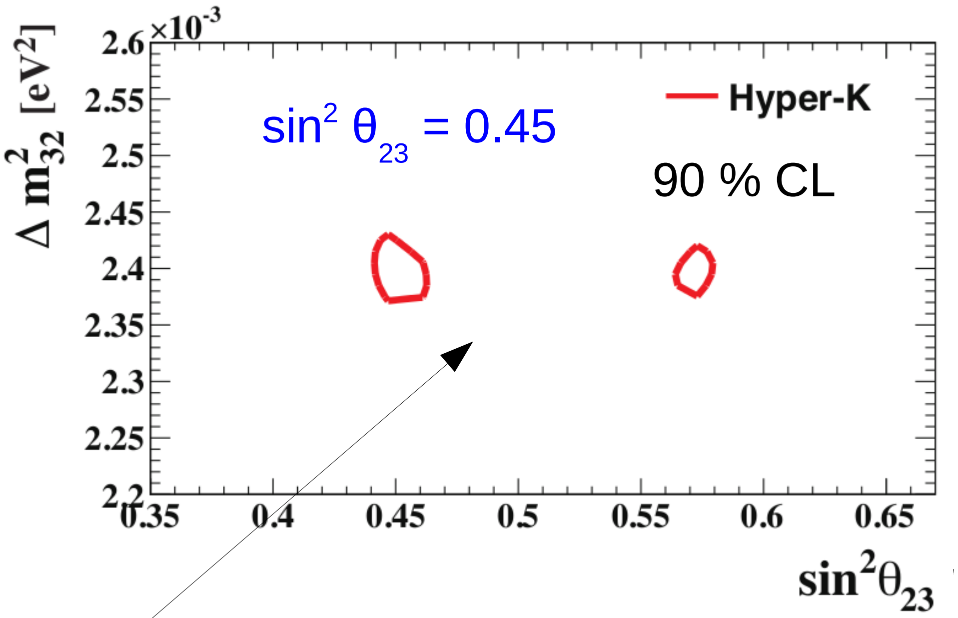


Would mass hierarchy be still unknown by the time of Hyper-K: use large samples of atmospheric neutrinos for which matter effects are definitely large.

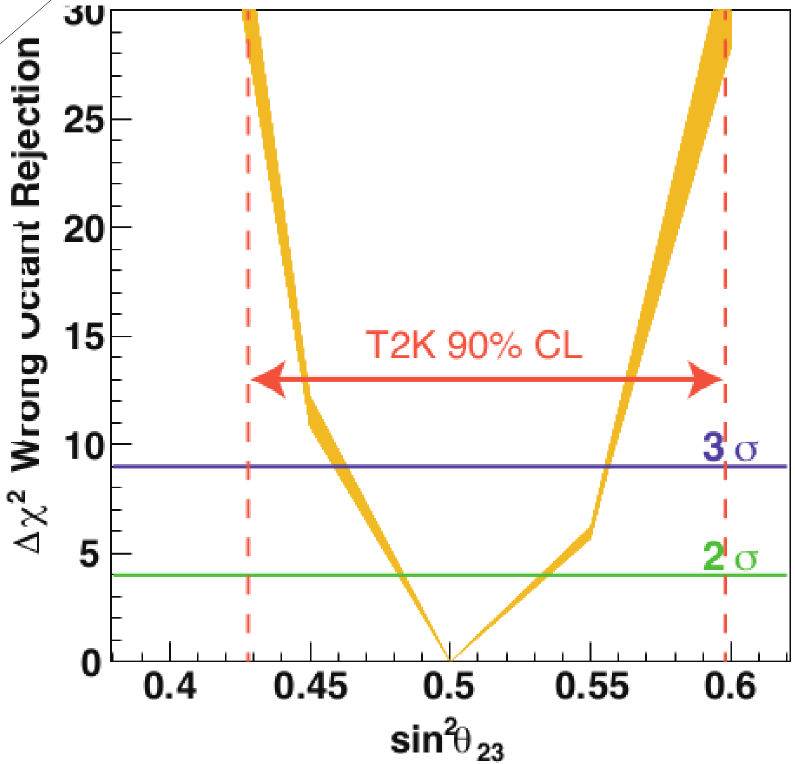


Hyper-K: θ_{23} octant





Octant degeneracy can be solved using reactor data and atmospheric neutrino data



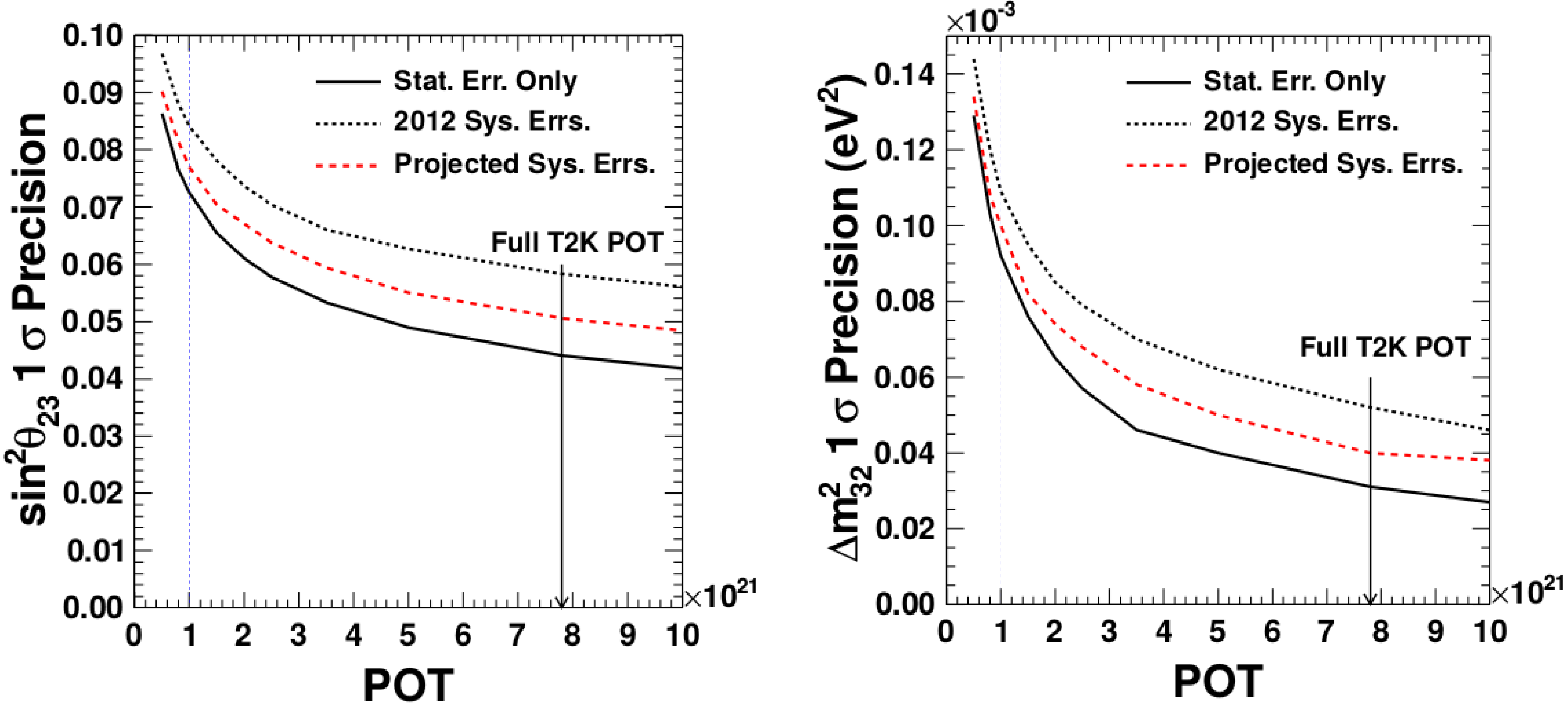
T2K potential: θ_{23} and Δm^2_{32}

7.8e21 POT+2012 syst. err. + 50-50% ν-anti-ν

390 ν_μ CCQE, 130 anti-ν_μ CCQE

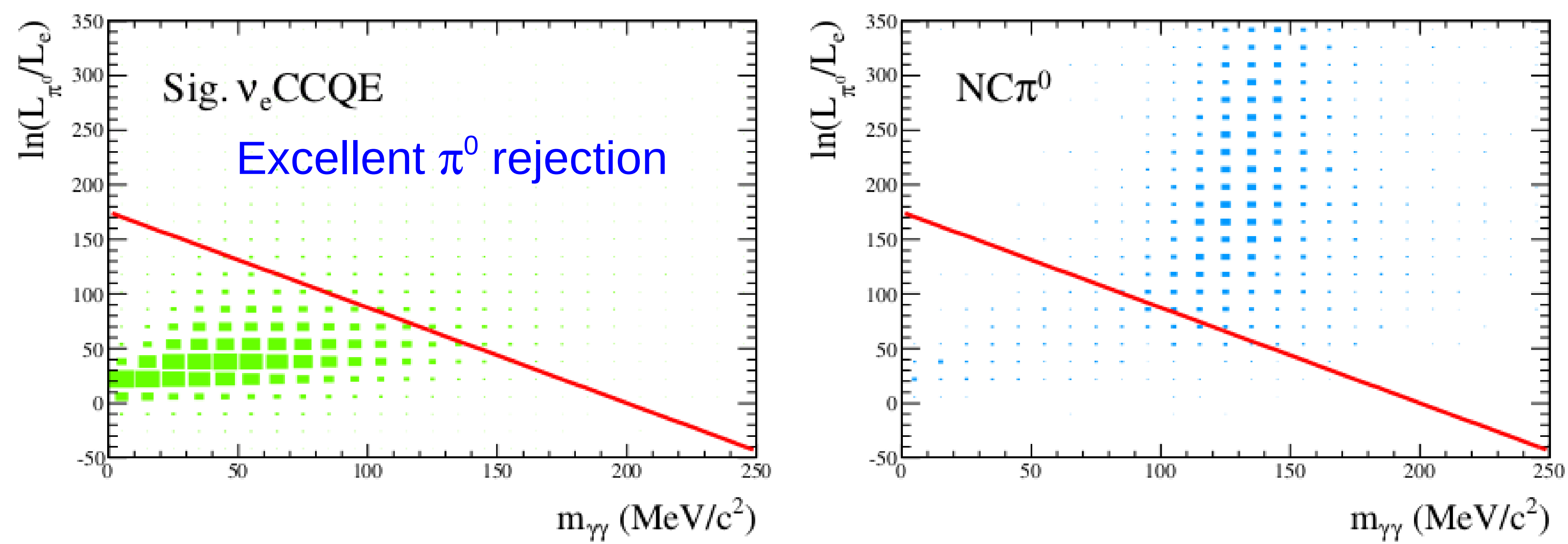
$\sigma(\sin^2\theta_{23})$ = 0.05 (10%)

$\sigma(\Delta m^2_{32})$ = 0.04 x 10^{-3} eV^2 (1.6%)

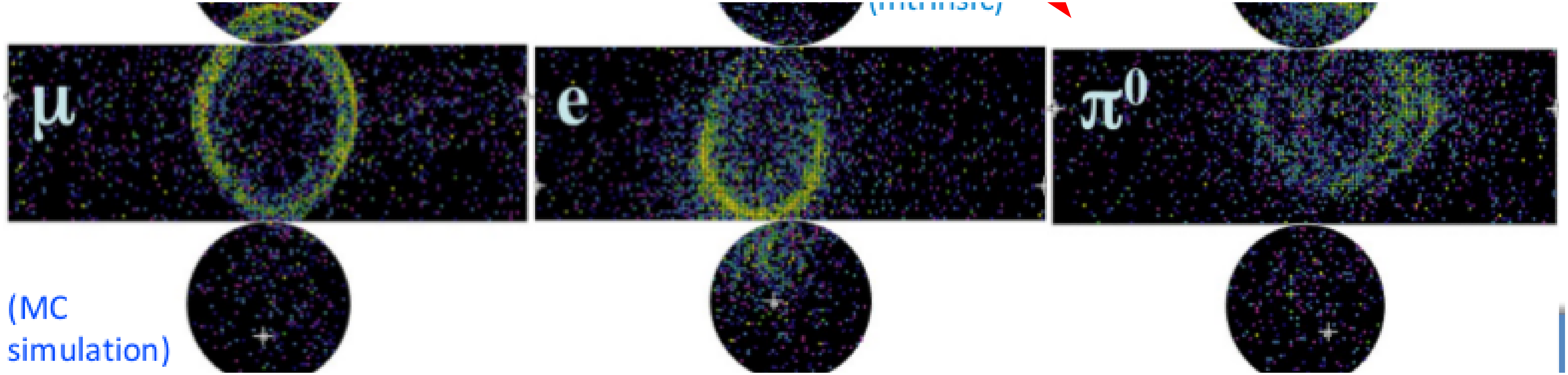


PTEP 2015 (2015) 4, 043C01

The far detector (295 km): Super-Kamiokande



Excellent π^0 rejection



(MC simulation)

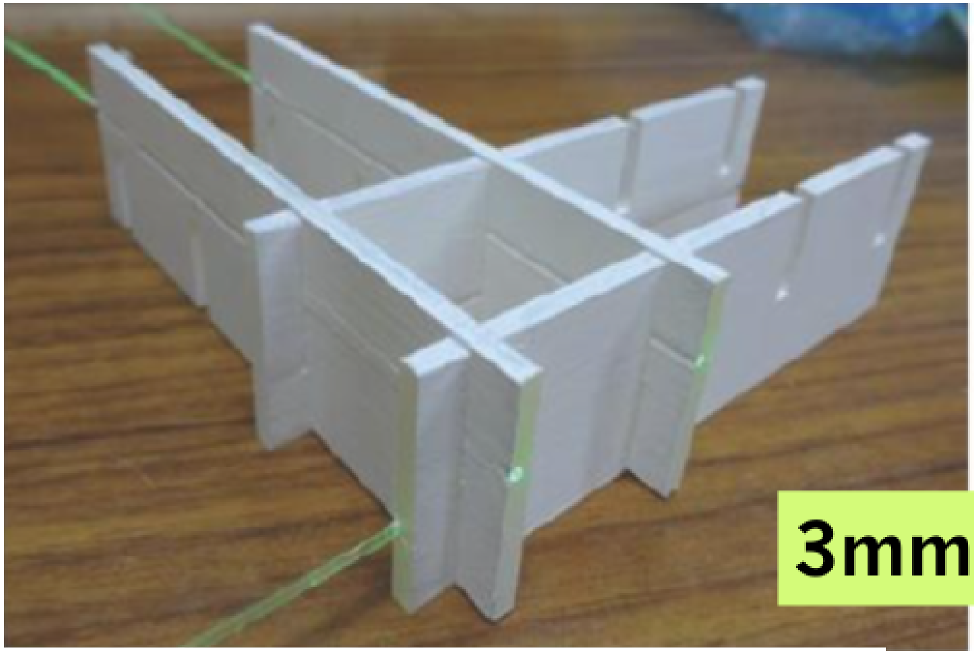
WAGASCI

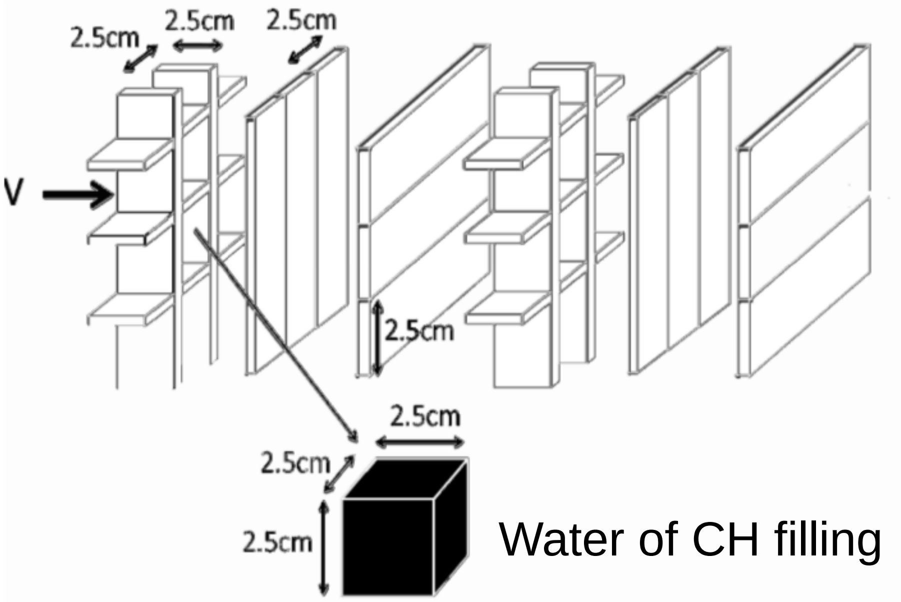
Addresses the issues of: **acceptance, target definition, external backgrounds.**

Goal: 3 % error on cross section ratio (water/CH)

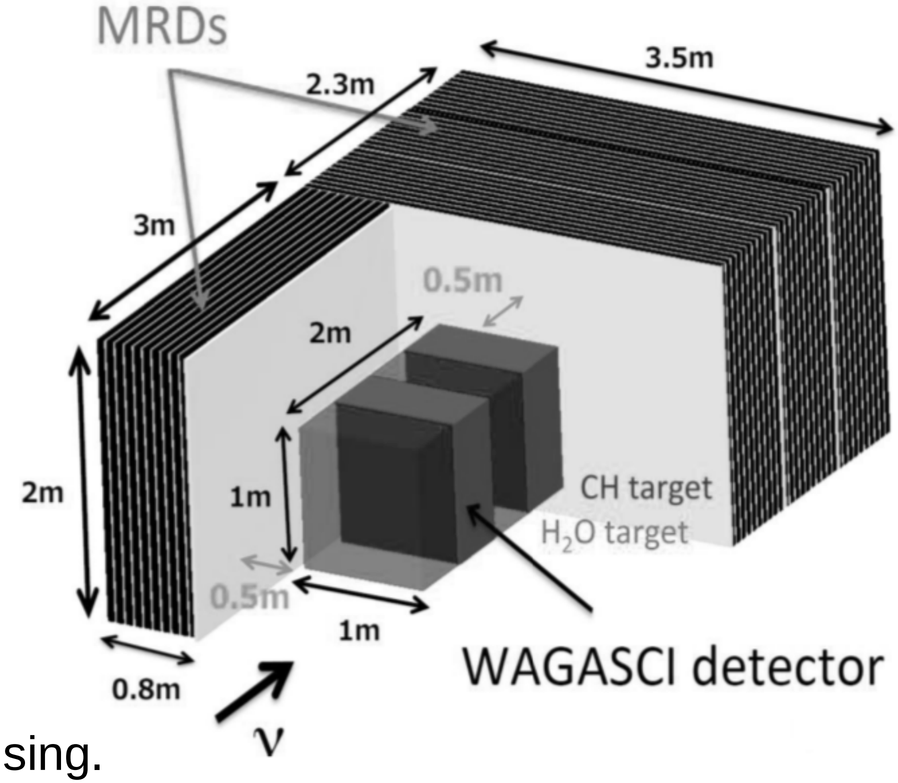
Plastic scintillators + WLS fibers in arrays (water/plastic) filled. Hamamatsu MPPC (SiPM) readout.

Being constructed close to ND280, INGRID

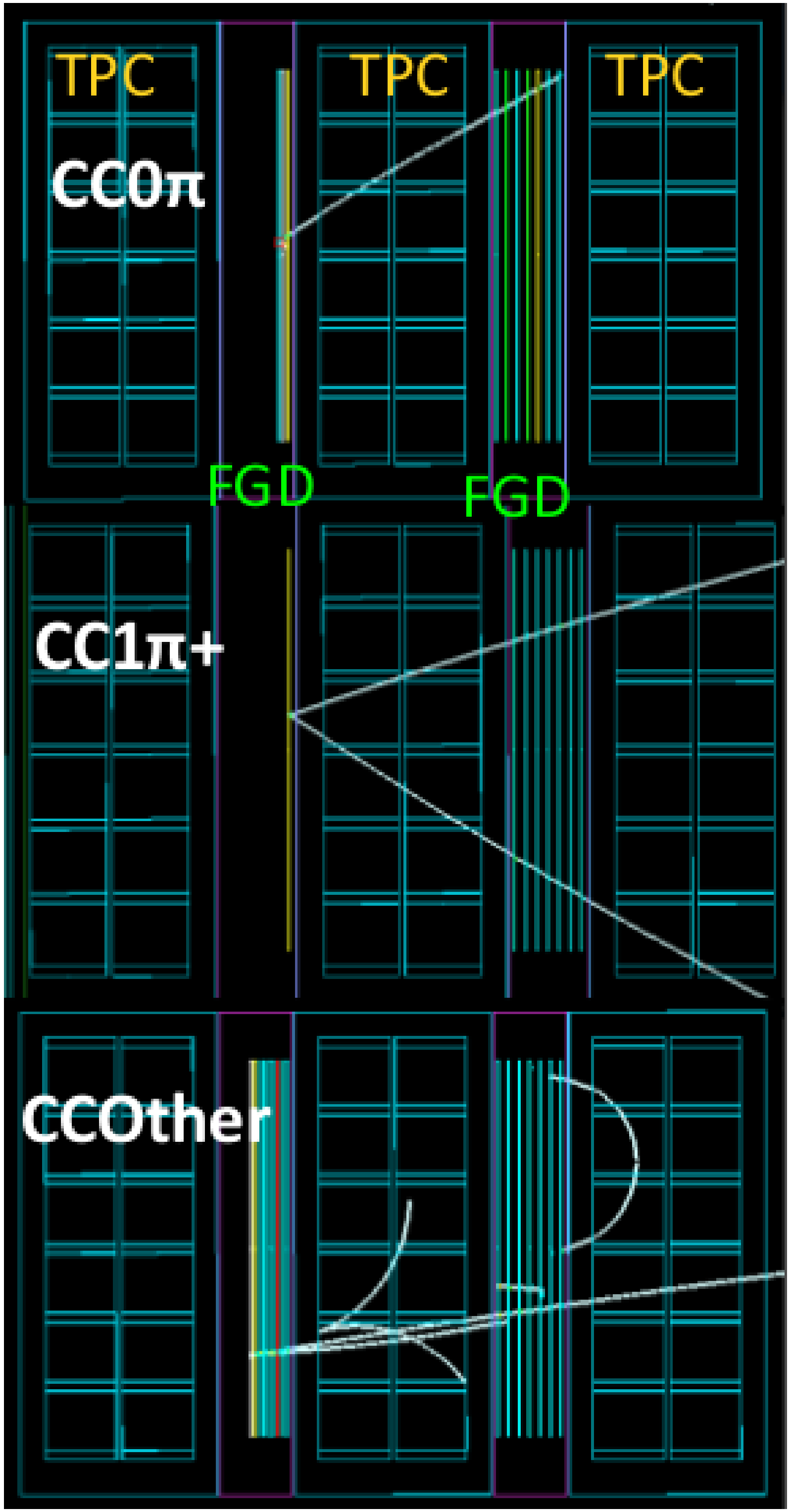




Water of CH filling

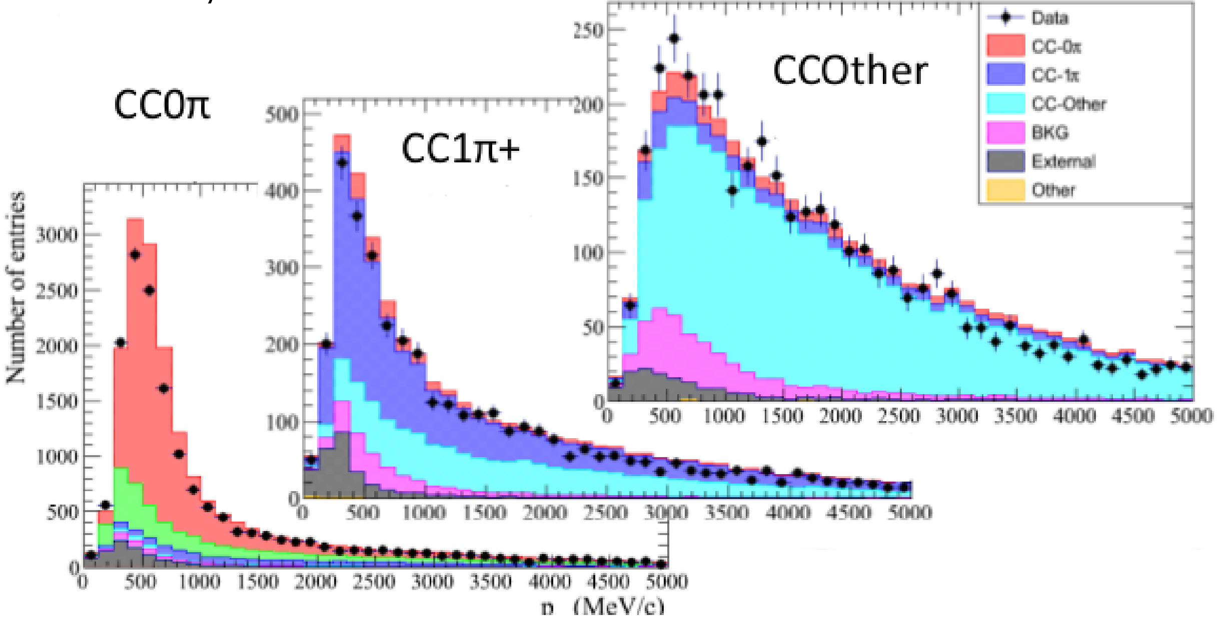


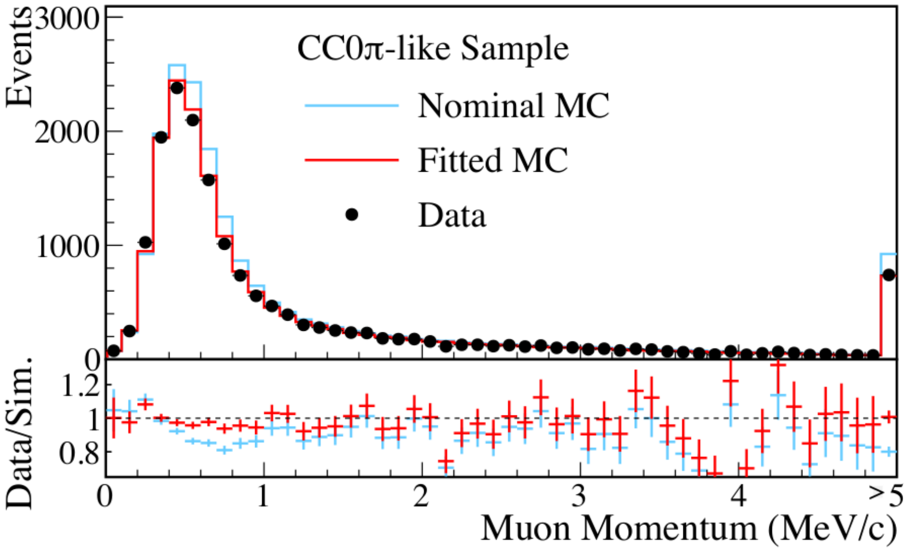
Grooves to mechanically connect orthogonal scintillator bars. Shallow enough to allow fiber housing.



Off-axis near detector analysis

Fit of ν_μ spectrum to constrain flux X cross-section (ν_μ also constrain ν_e via correlation in the production mechanism). 3 subsamples with final state π “CC 0π”, “CC 1π” and “CC other”

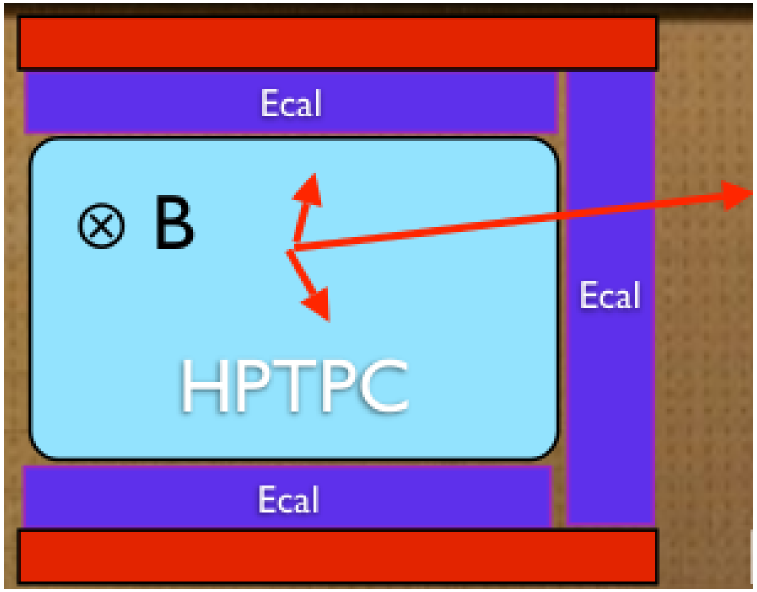




High pressure TPC

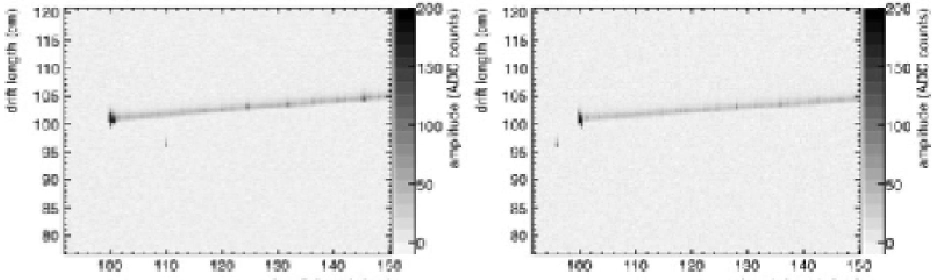
- No passive material (interactions in the gas)
- Low thresholds (5-10 bar pressure)
  disentangle multi-nucleon processes from CCQE
- Realistic gases:
  He, Ne, Ar, CF_4
- H and D would “by-pass” nuclear physics … not realistic

- In principle more appealing for the US program (Argon). Difficult to use CO_2, H_2O (for water)

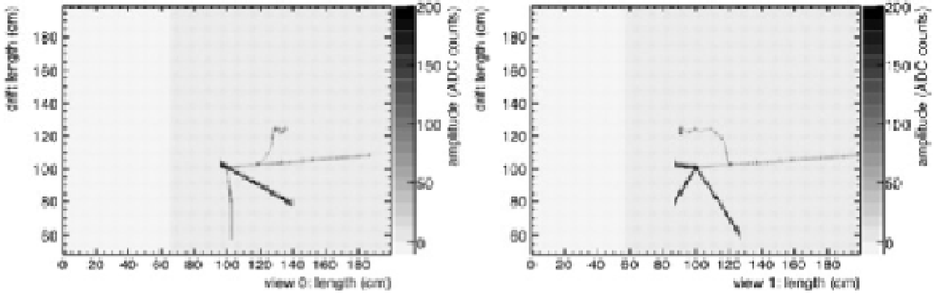


Taken from
F. Sanchez

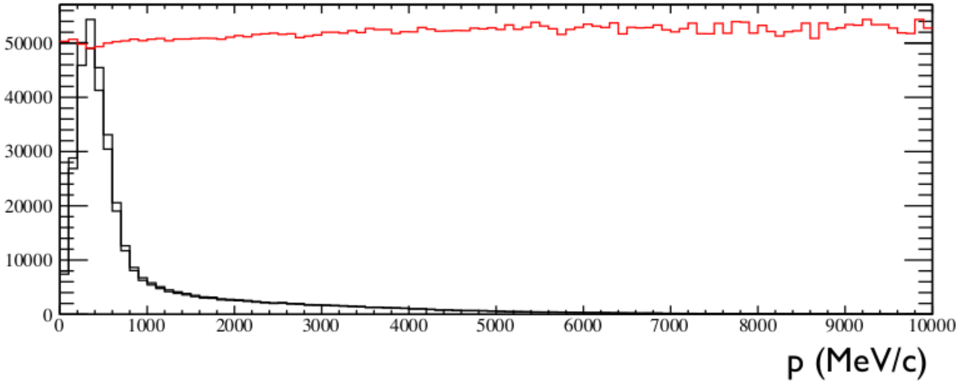
liquid Ar

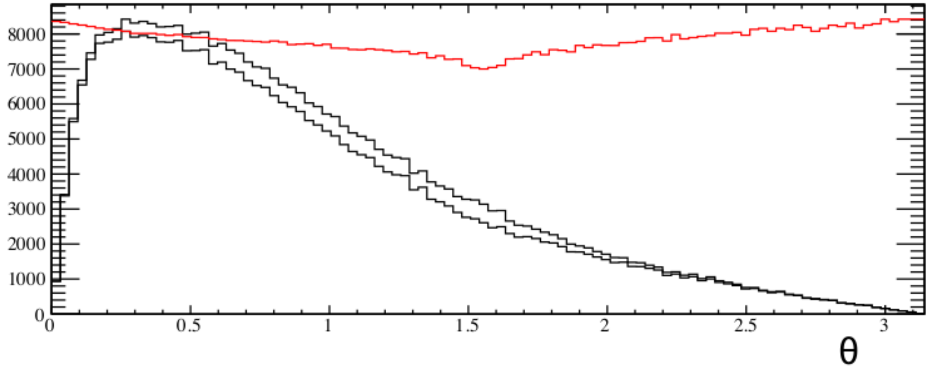


Ar gas 20 bar

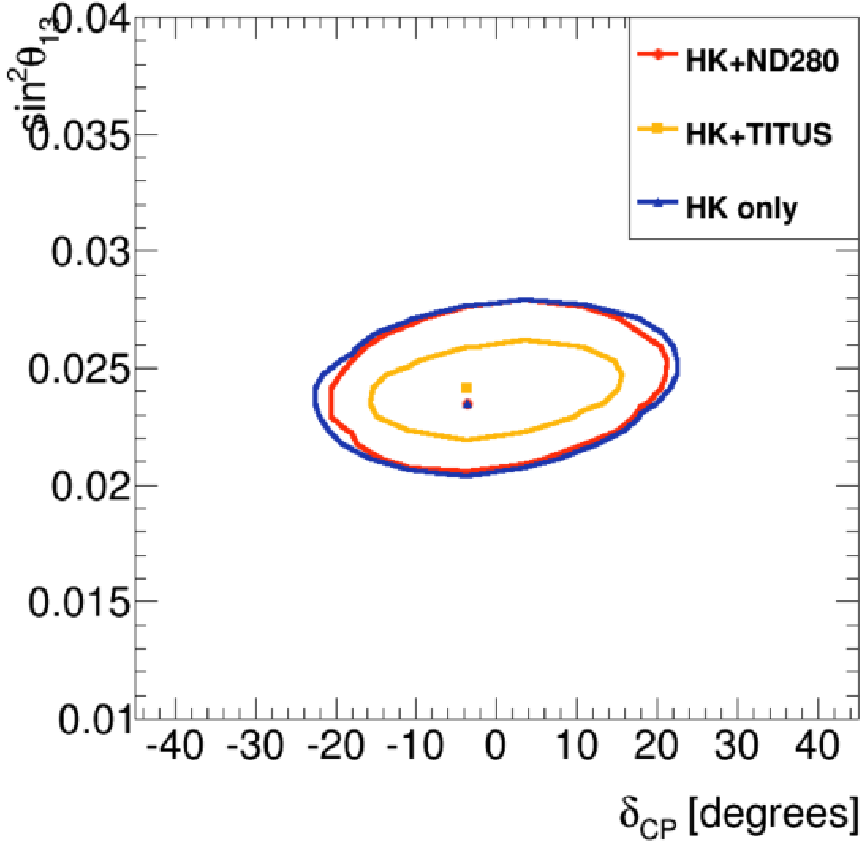


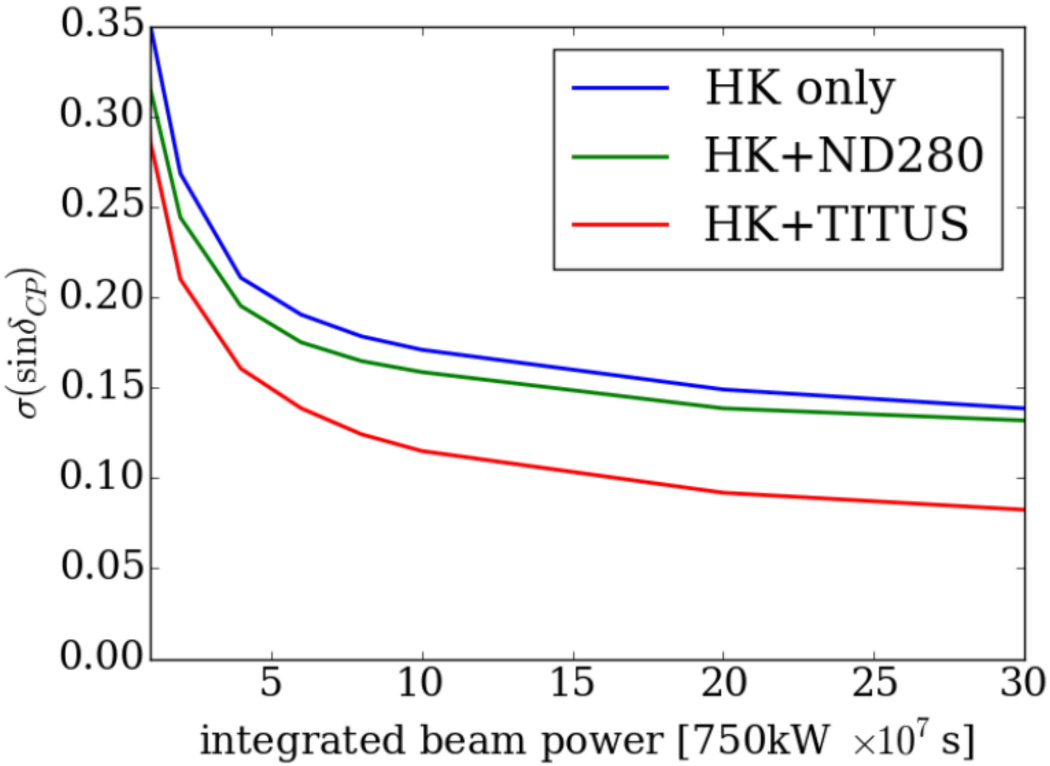
A. Curioni





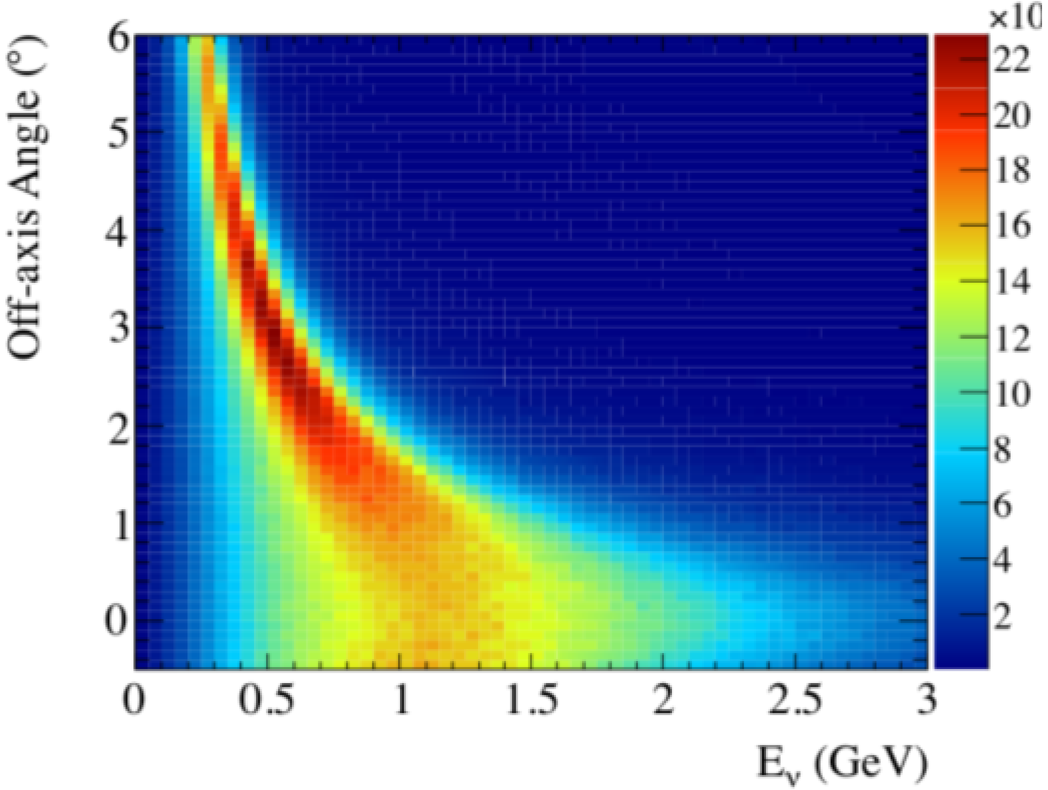
TITUS + HyperK: impact on δ_{CP}





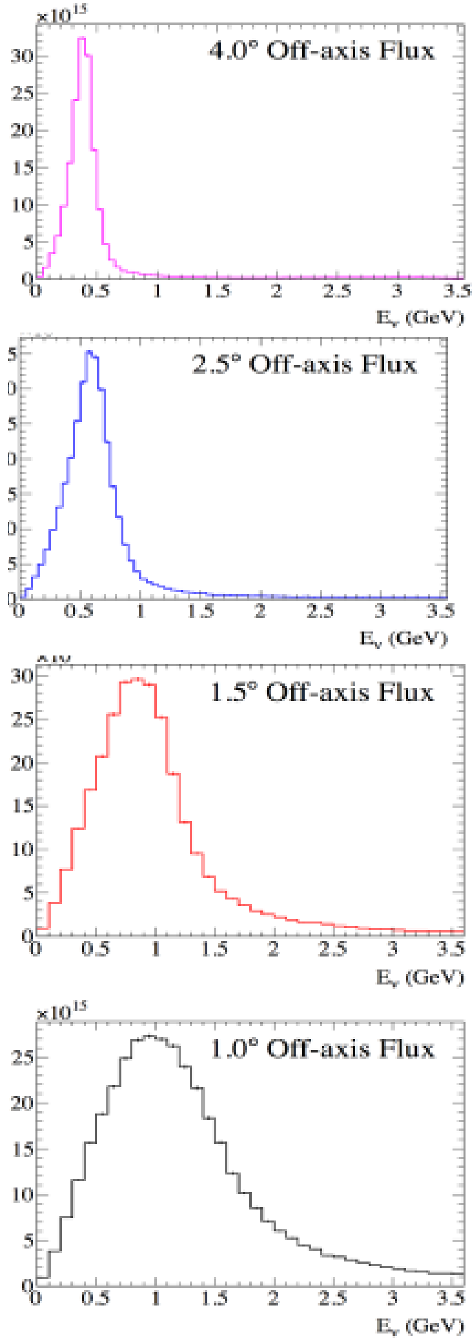
νPRISM

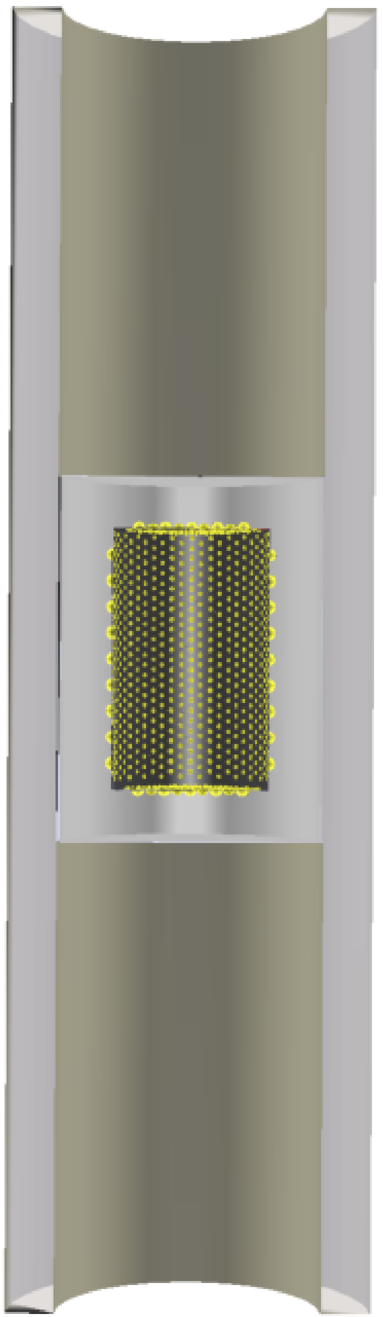
Extract the energy dependence by measuring the rates and final state kinematics over a range of off-axis angles



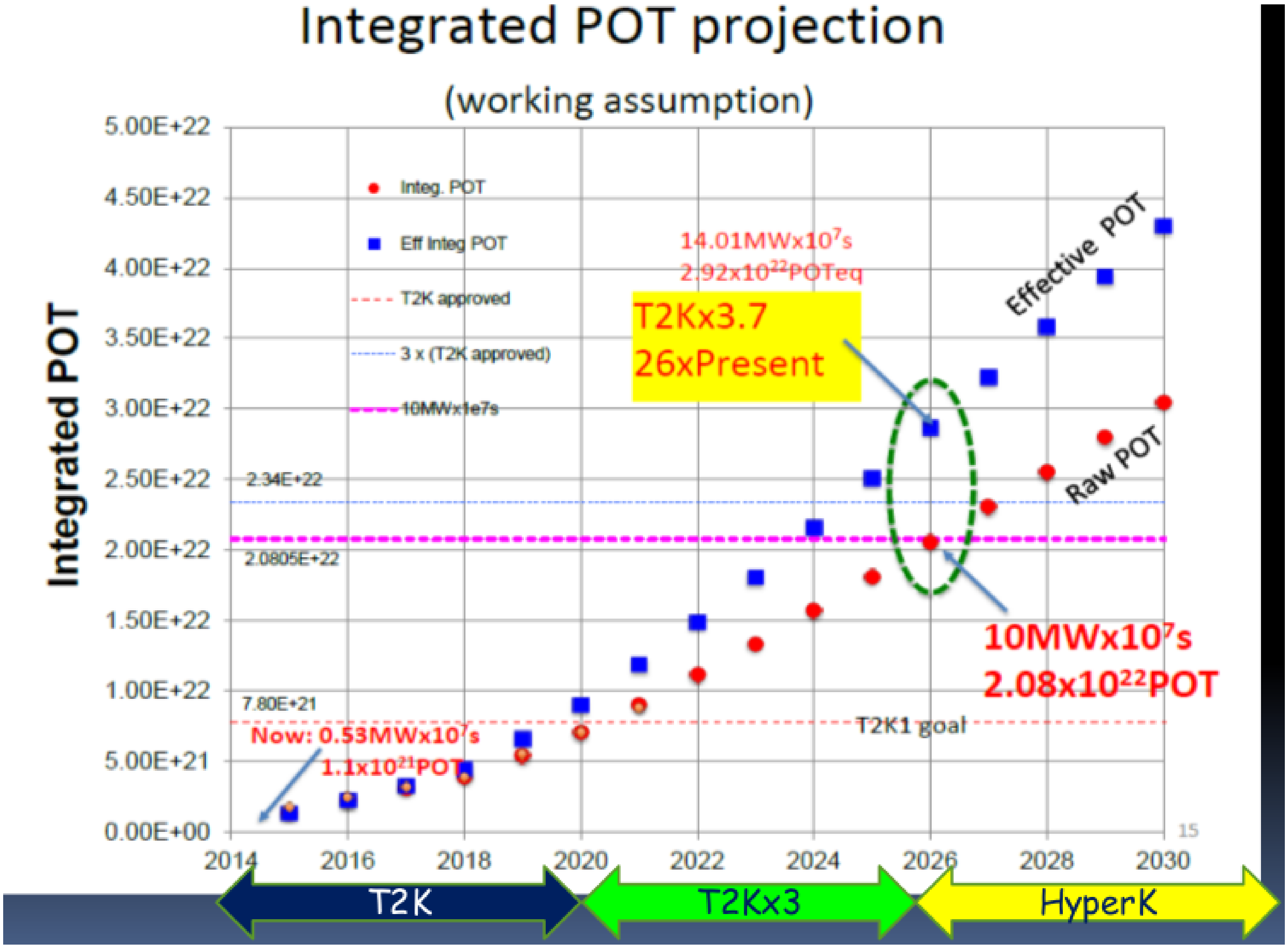
Detector moved up and down a shaft
~ 1 km baseline: span: 1-4 degrees

WC detector: 6 m diameter x 10 m height
40 % photo-coverage: 3120 8” PMT or 7385 5” PMT

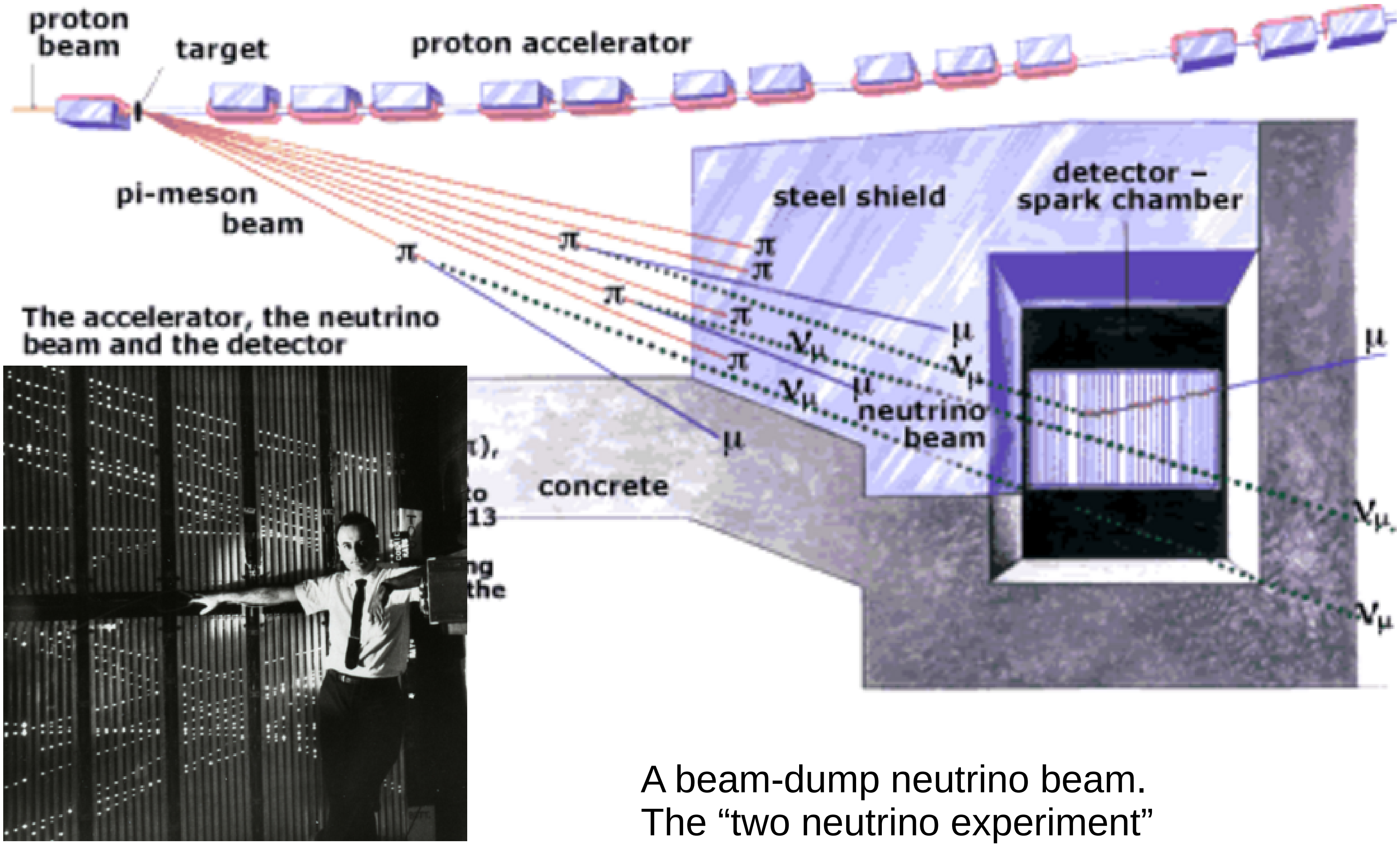




- An intermediate phase: “T2K x 3”
    - 3x T2K statistics (20 × 10^{21} POT)



The tool: accelerator-based ν-beams (prehistory)

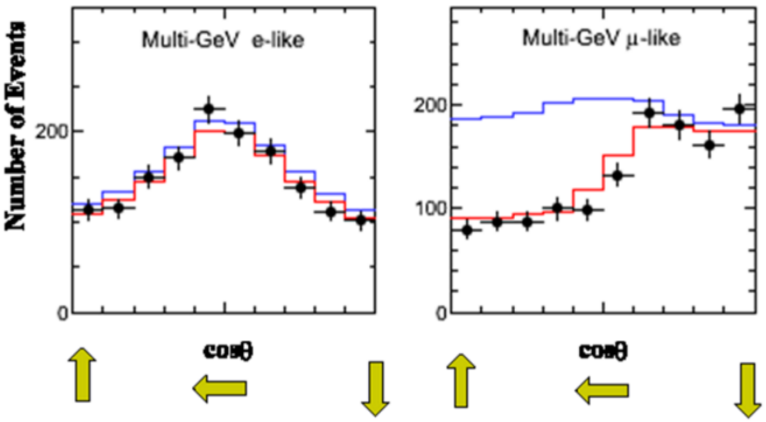


A beam-dump neutrino beam.
The “two neutrino experiment”

The tool: accelerator-based ν-beams (history)

K2K confirms atmospheric oscillation by Super-K
with an artificial neutrino beam at long baseline

Super-K atmospheric ν




Horn focusing,
Van Der Meer.