Recent neutrino long base line results and path to future

Federico Sánchez

Introductory words

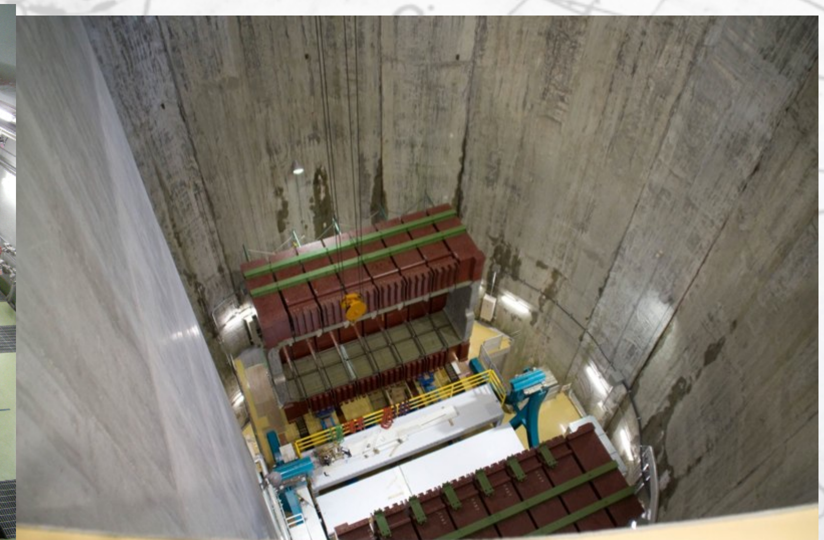
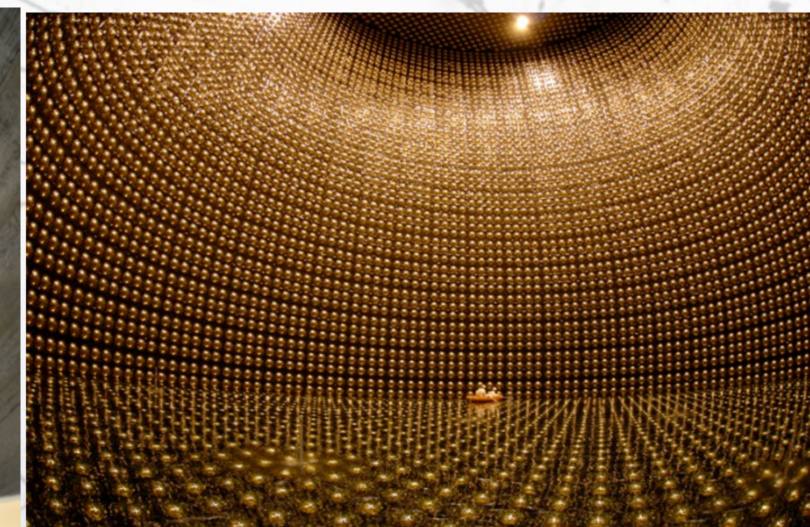
Now	• Recent T2K result that I will use to describe the Long Base Line experimental techniques and needs.
Next	• What to expect from Nova ? Or better, what to expect from T2K, Nova and reactor neutrinos.

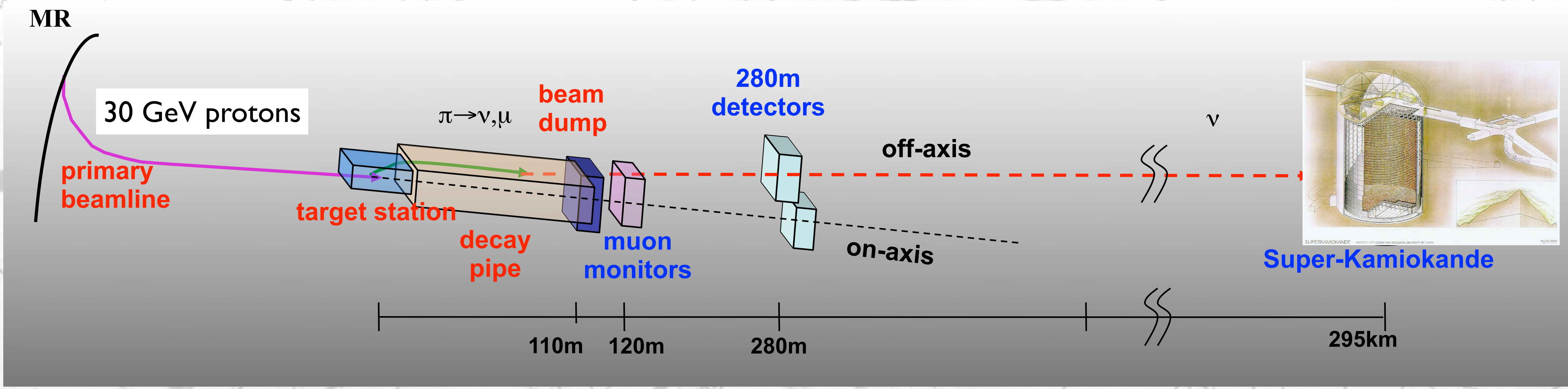
Next to Next	• What is the community planning for the next stage ?
	  • pro's and con's
	  • Is this enough?
	T2HK, LBNE and/or LBNO

Present

T2K

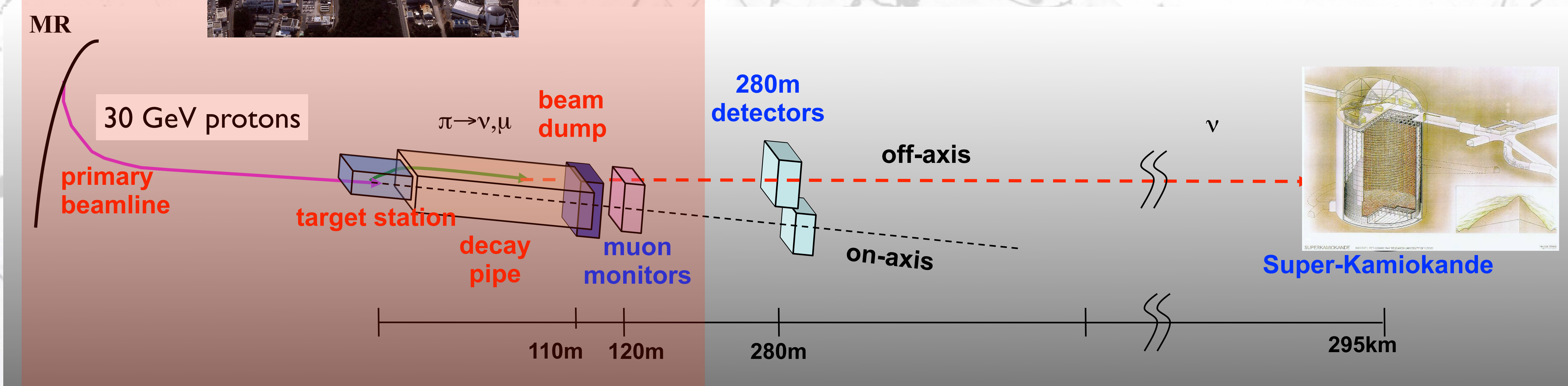




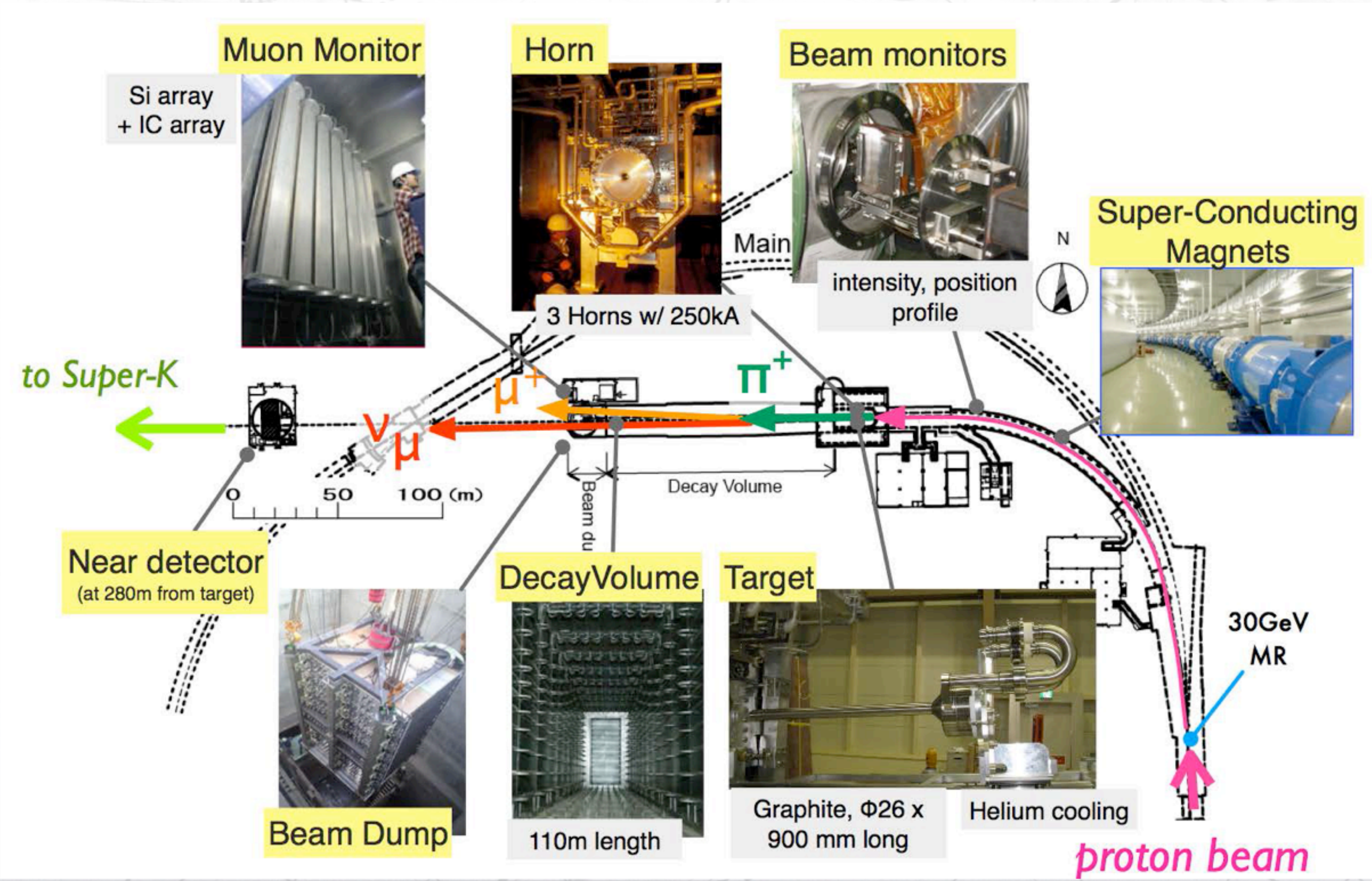
Beam ND280 Super-Kamiokande

Beam



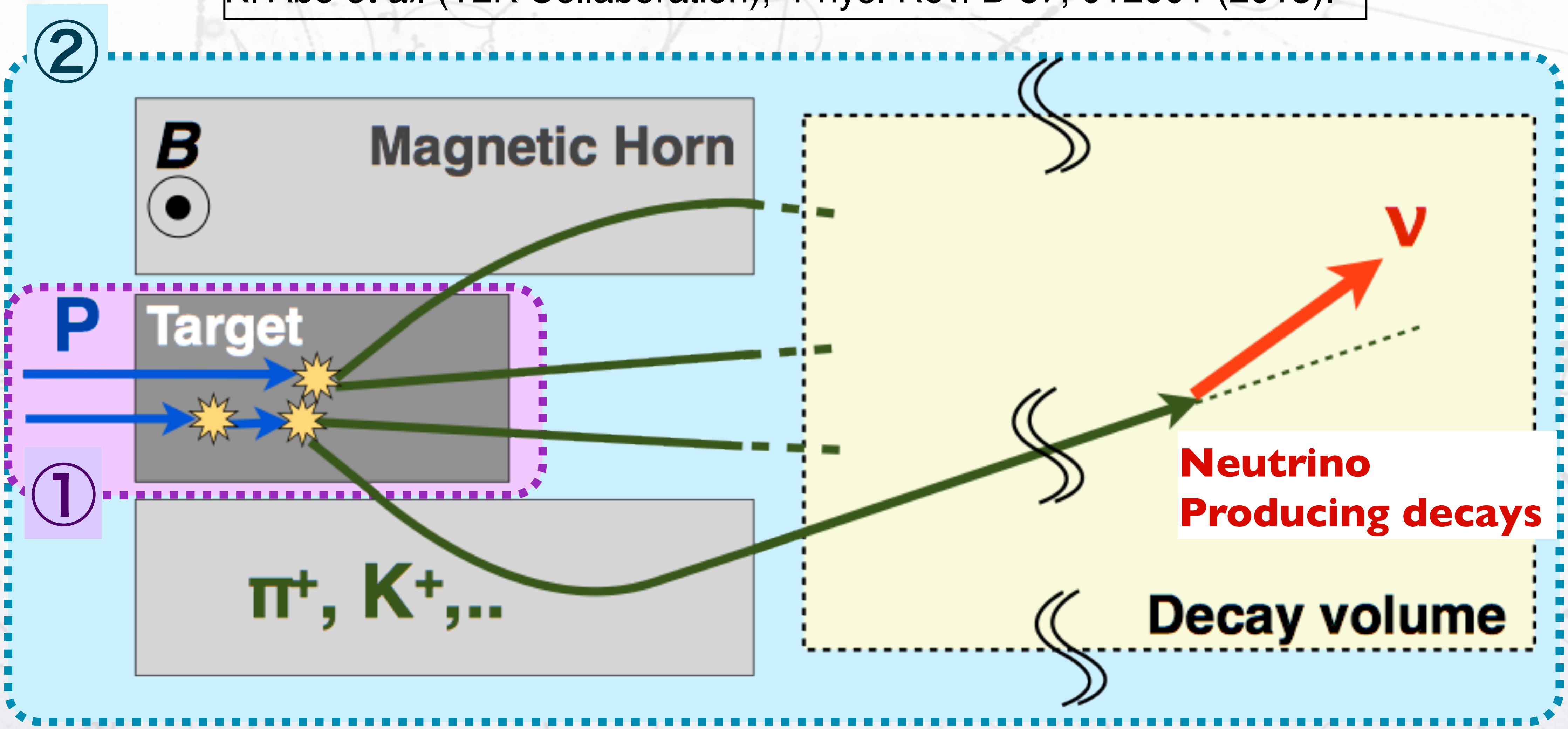
Beam ND280 Super-Kamiokande

ν beam


Muon Monitor
Si array
+ IC array
Horn
Beam monitors
Main
intensity, position
profile
3 Horns w/ 250kA
Super-Conducting
Magnets
N
to Super-K
μ+
π+
ν
μ
0
50
100 (m)
Decay Volume
Beam du
Near detector
(at 280m from target)
DecayVolume
Target
30GeV
MR
Beam Dump
110m length
Graphite, Φ26 x
900 mm long
Helium cooling
proton beam

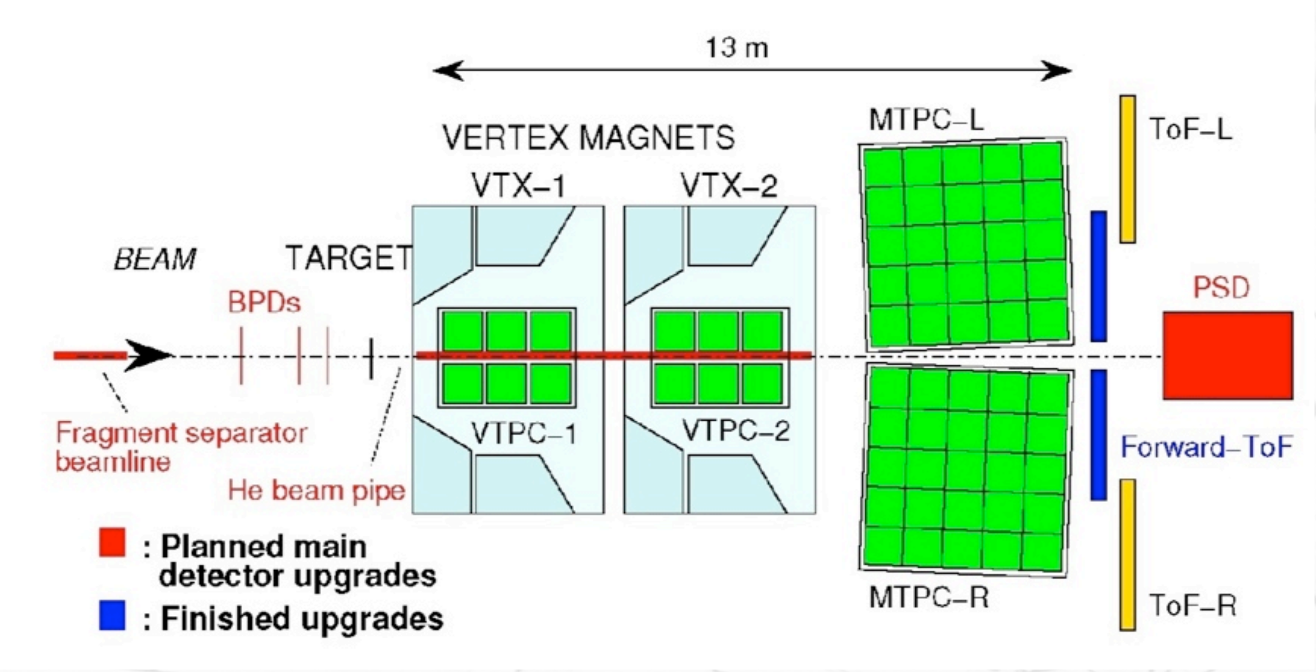
Flux prediction

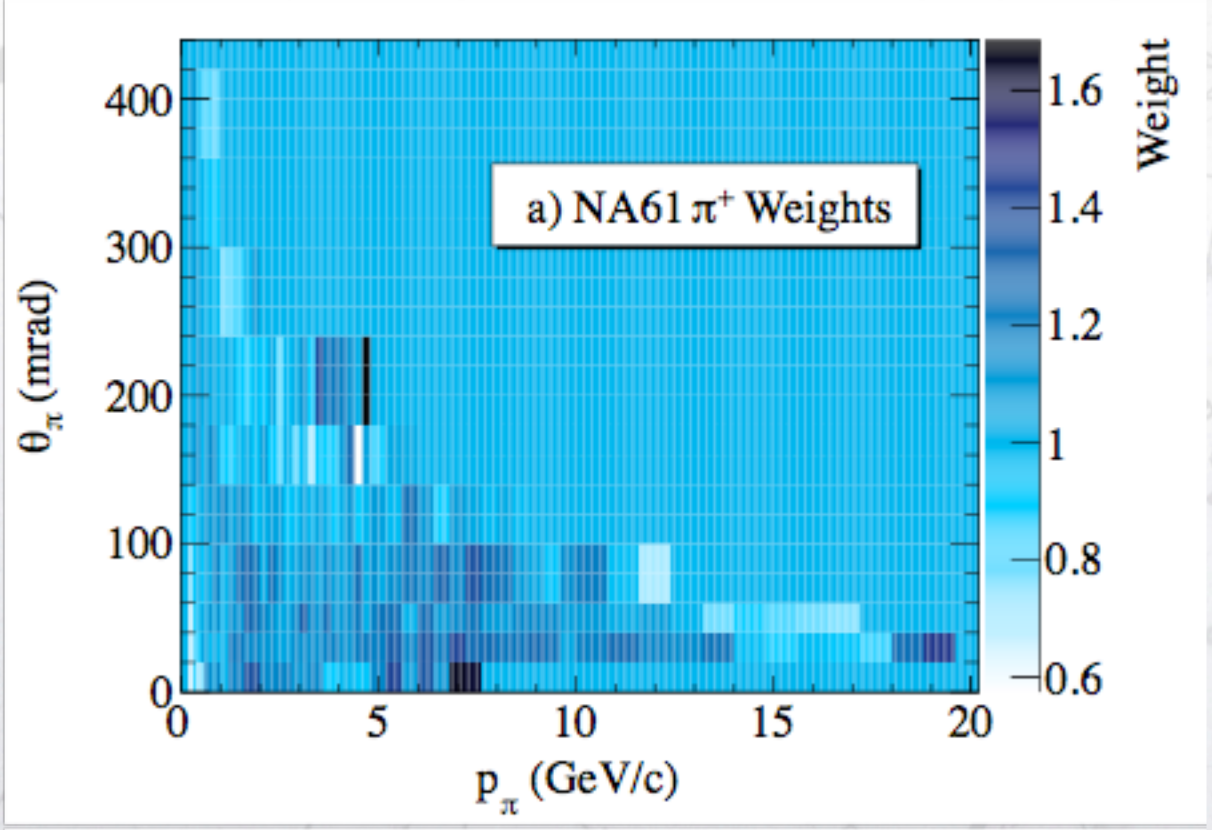
K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



NA61: Shine

NA61/Shine measures for T2K the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

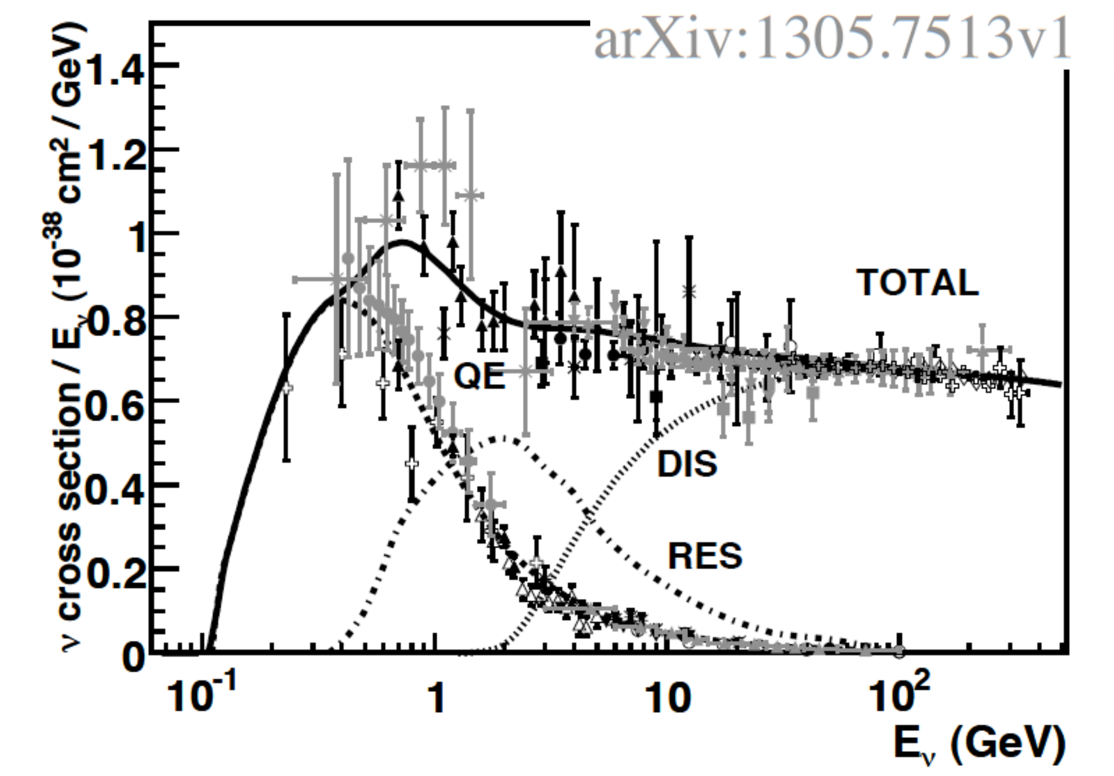


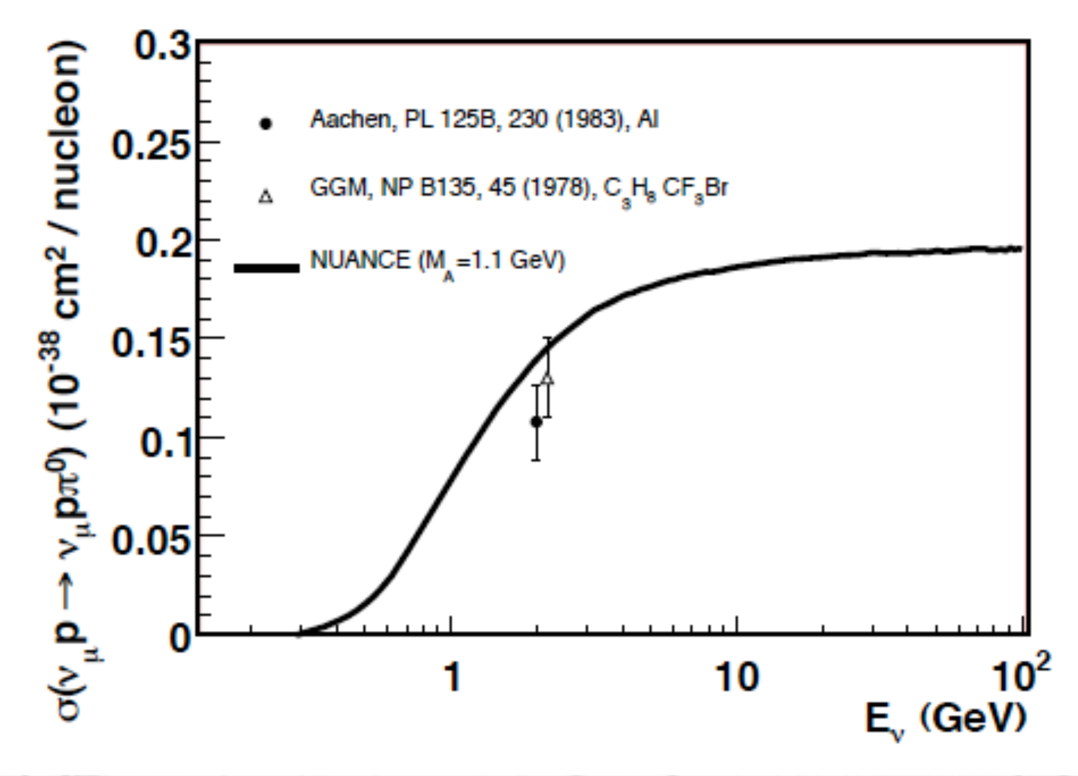


NA61/Shine measures a thin target for absolute production and thick target that is a copy of T2K target and provides also the reinteractions.

$\sigma_{\nu N}$

When E_ν>100MeV the ν-Nucleus cross-section dominates.



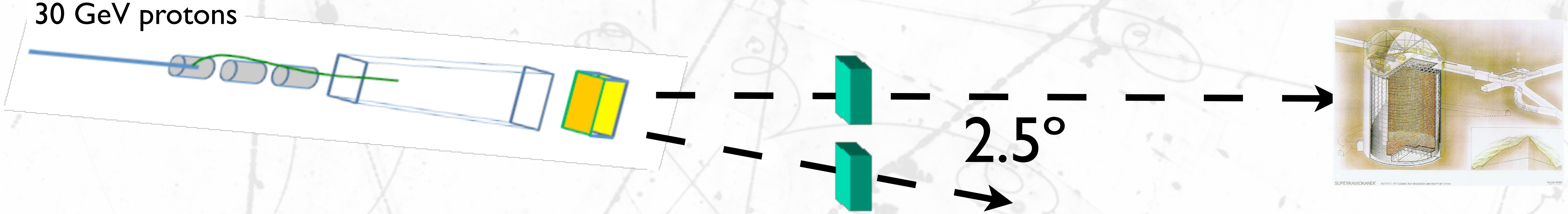


Charge current	
CC-QuasiElastic	$\nu_\mu n \to \mu^- p$
CC-Resonance	$\nu_\mu N \to \mu^- \pi^{+,0} N$
CC-Deep Inelastic	$\nu_\mu N \to \mu^- X$

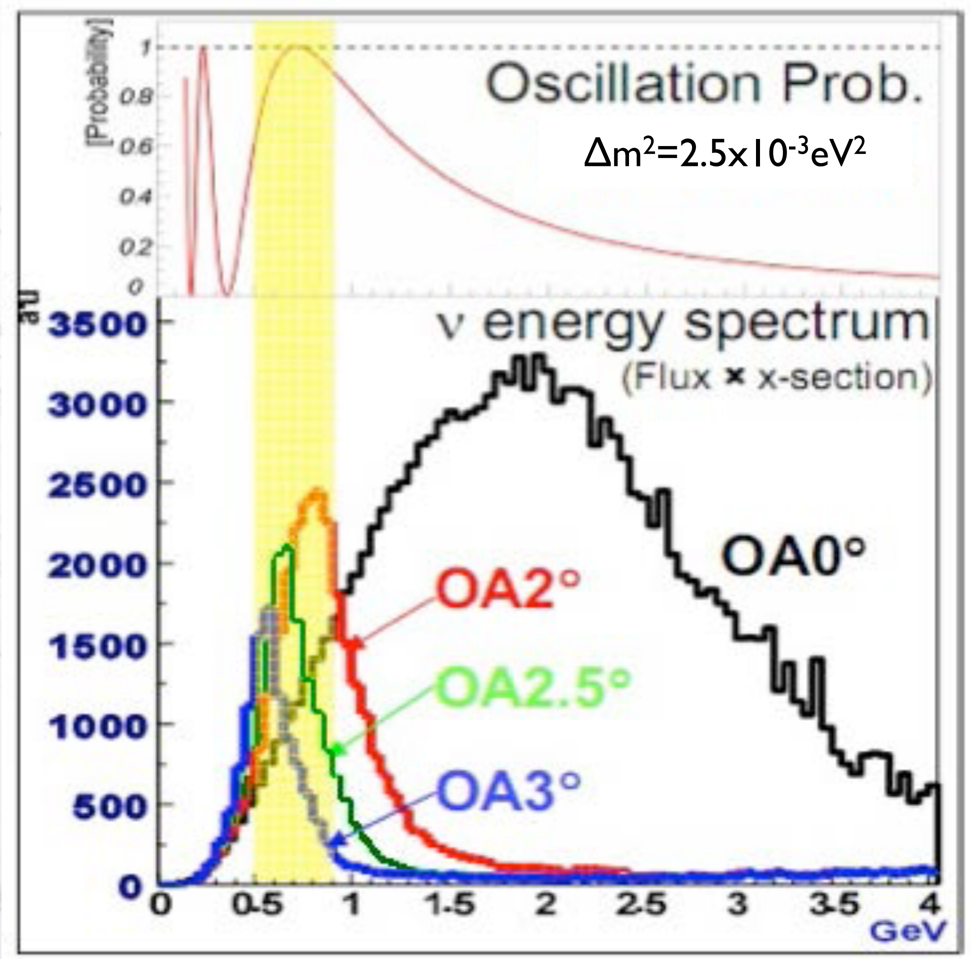
Neutral current	
NC-Elastic	$\nu_\mu(n,p) \to \nu_\mu(n,p)$
NC-Resonance	$\nu_\mu N \to \mu^- \pi^{+,0} N$
NC-Deep Inelastic	$\nu_\mu N \to \nu_\mu X$

Off-axis concept

T2K runs 2.5° off-axis

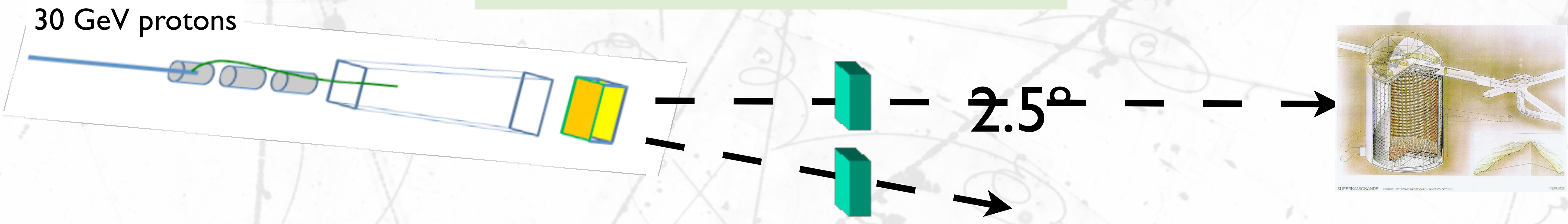


- off-axis optimises the flux at the maximum of the oscillation.

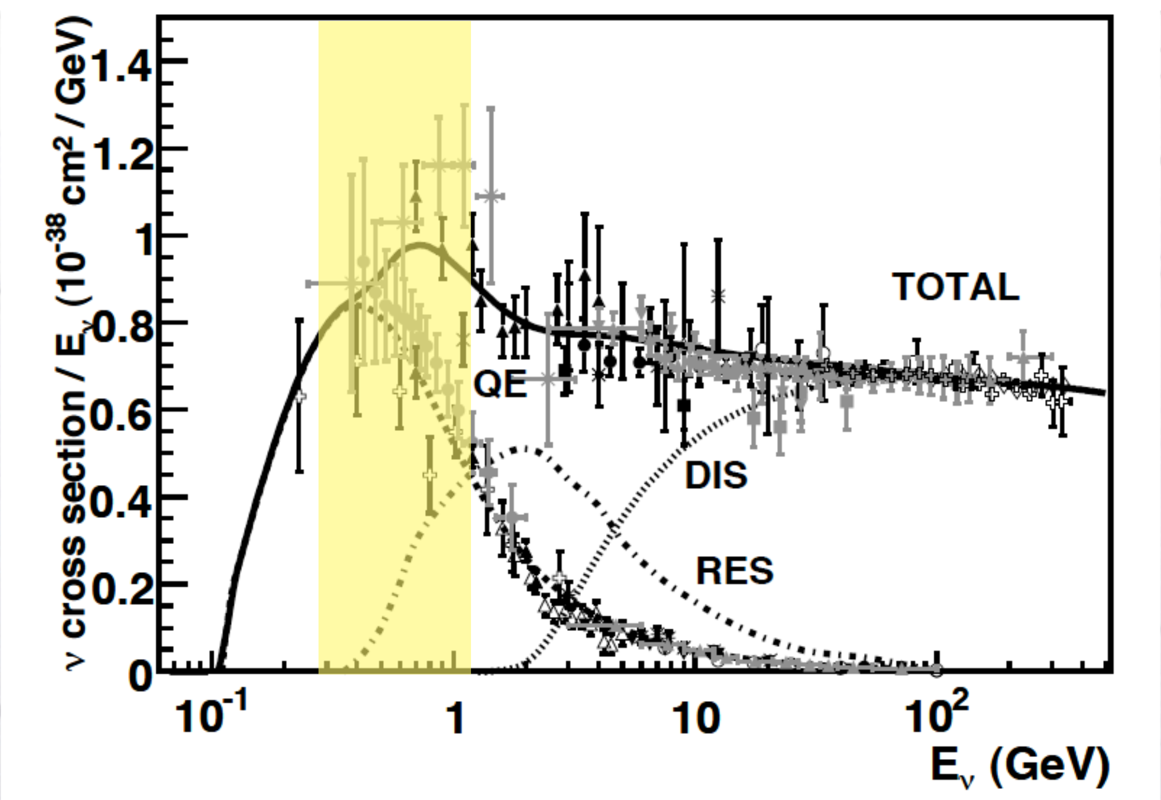


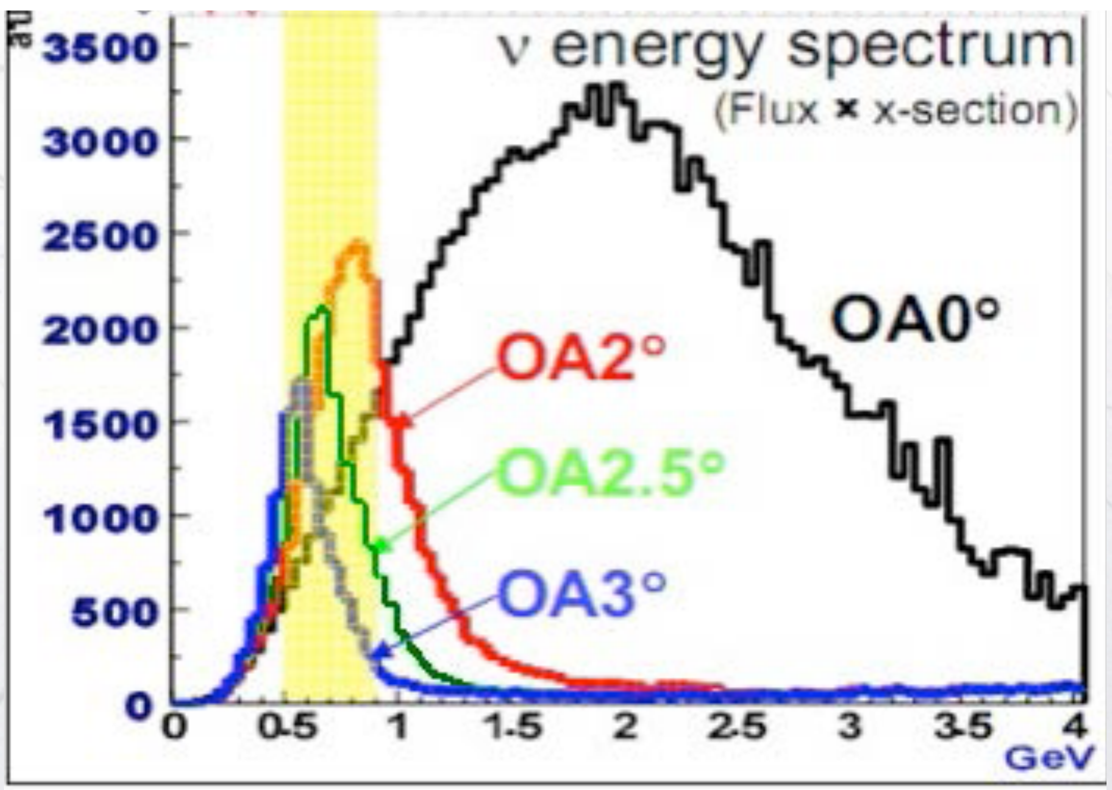
Off-axis concept

T2K runs 2.5° off-axis

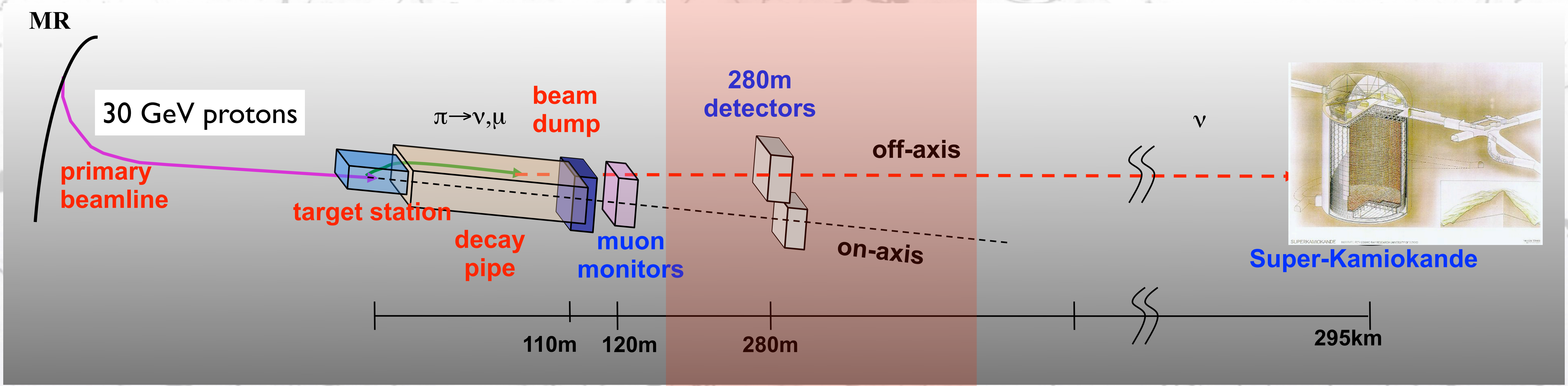


- off-axis reduces the high energy contamination (NCπ^0 and non-CCQE backgrounds.)





ND280

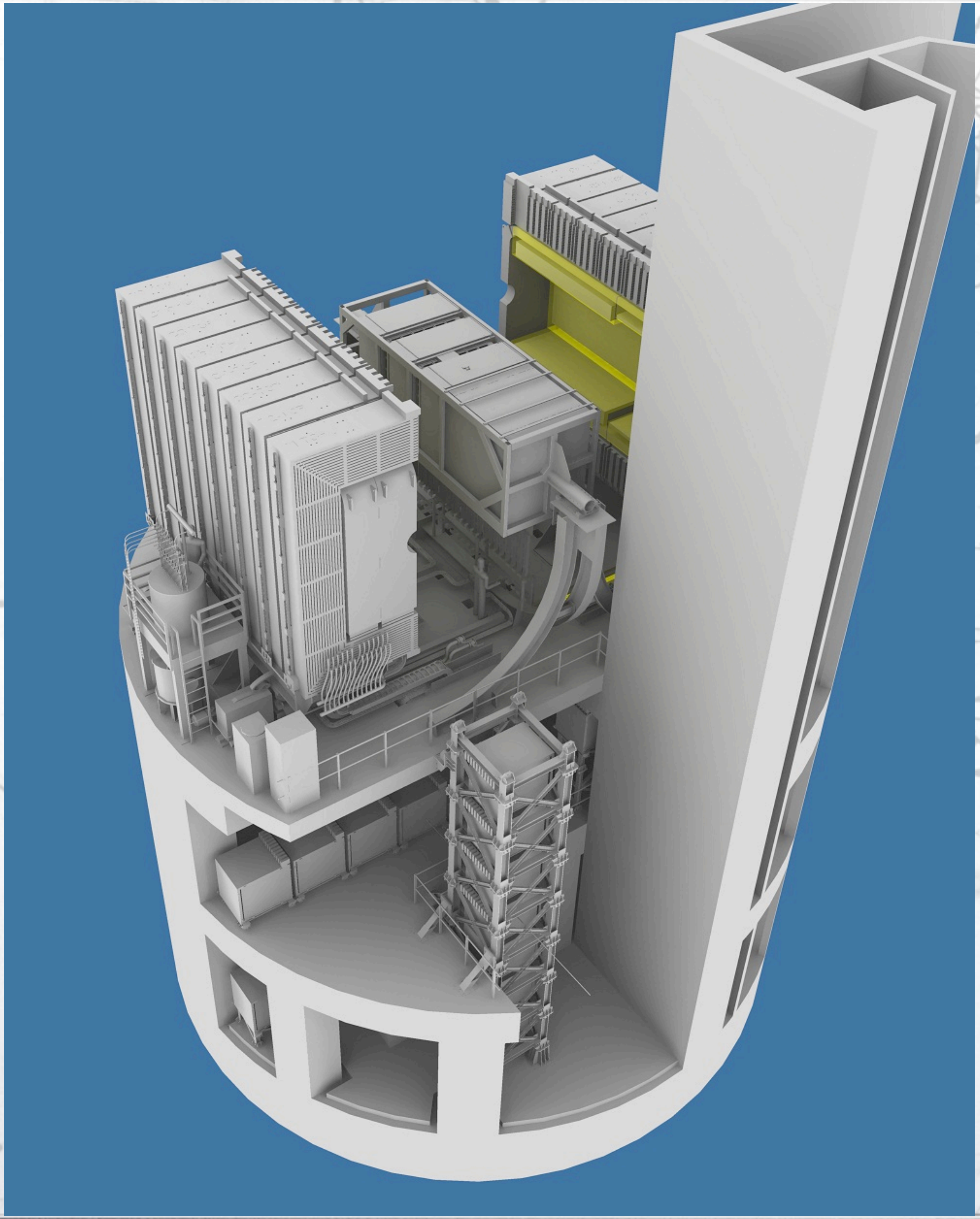


Beam

ND280

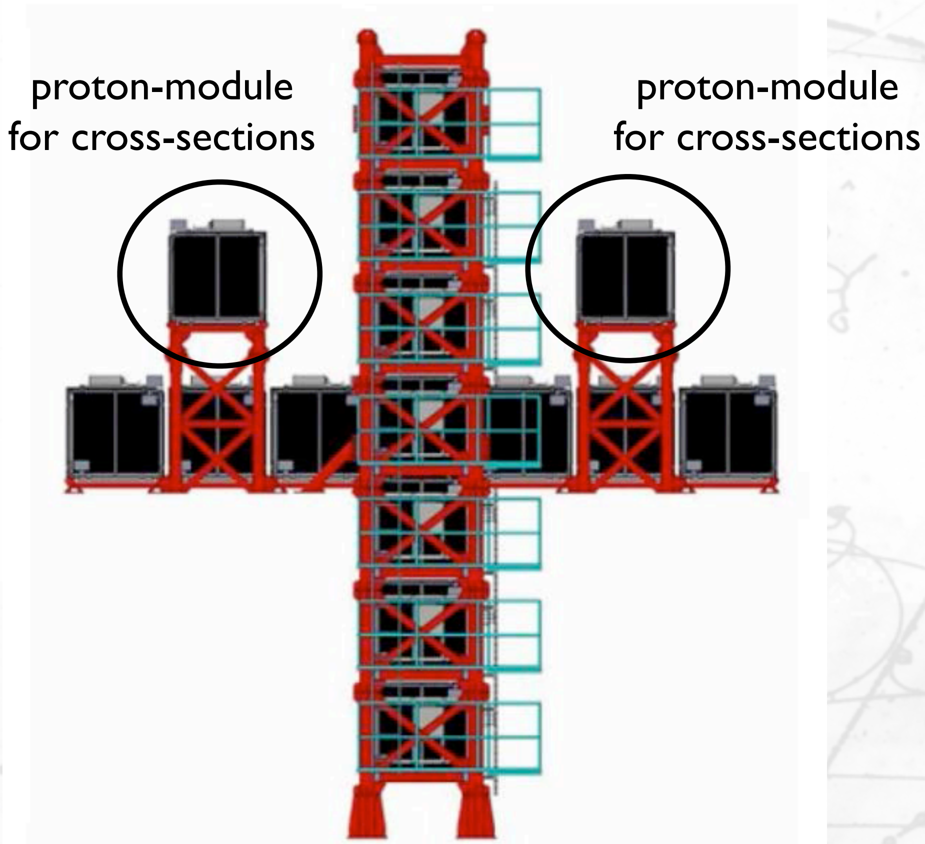
Super-Kamiokande

ND280

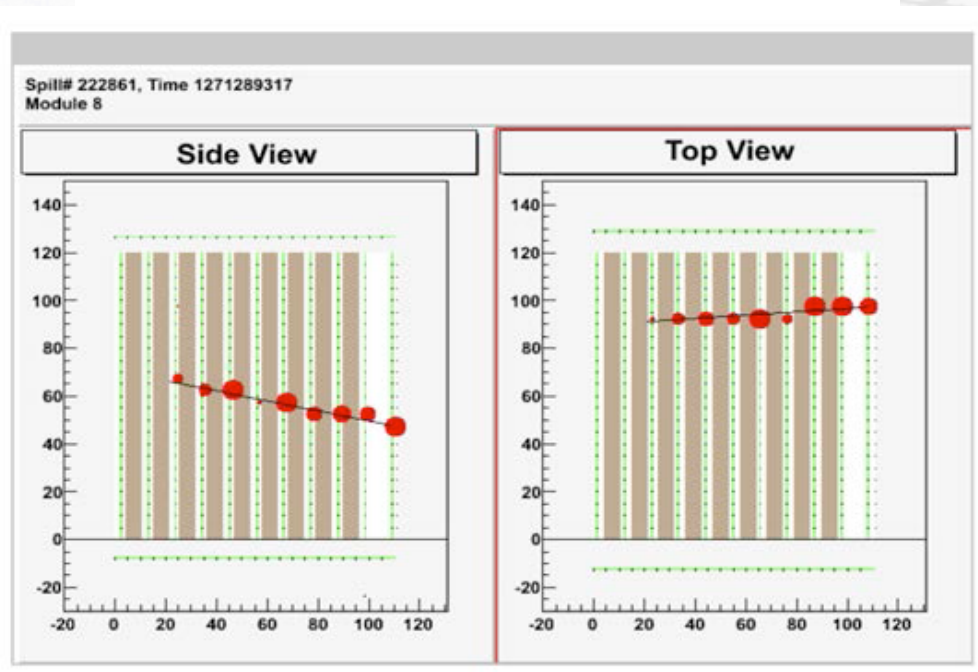


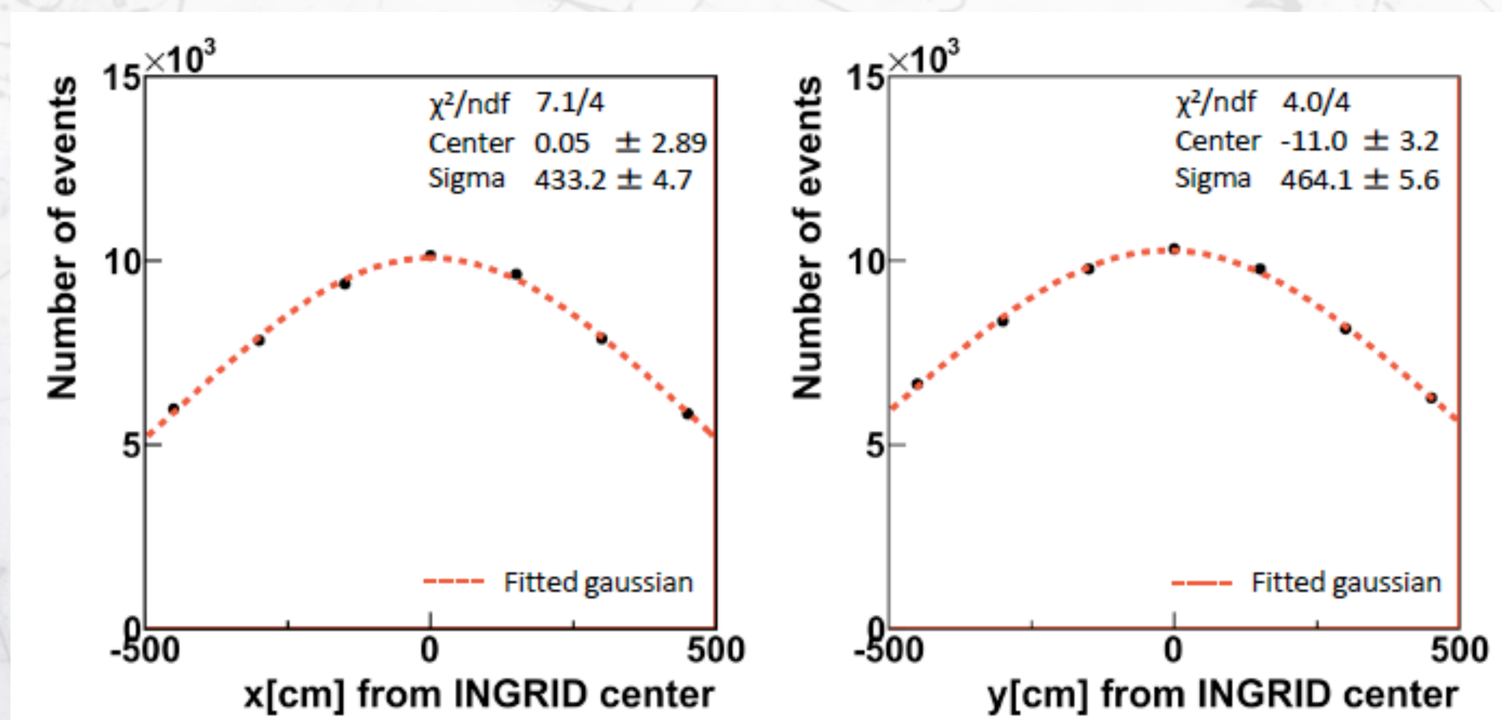
- ND280 is the near detector facility with two main detectors located 280m from the proton interaction point:
  - On-axis INGRID.
  - Off-axis ND280m.
- Three main purposes:
  - ν beam stability.
  - ν cross-sections.
  - ν beam flux constraint.

On-axis (INGRID)



- INGRID counts ν CC events in a cross of 13 identical detectors:
  - total rate monitors beam intensity stability with respect to proton on target counting.
  - The relative event counts between modules monitor the beam direction stability.



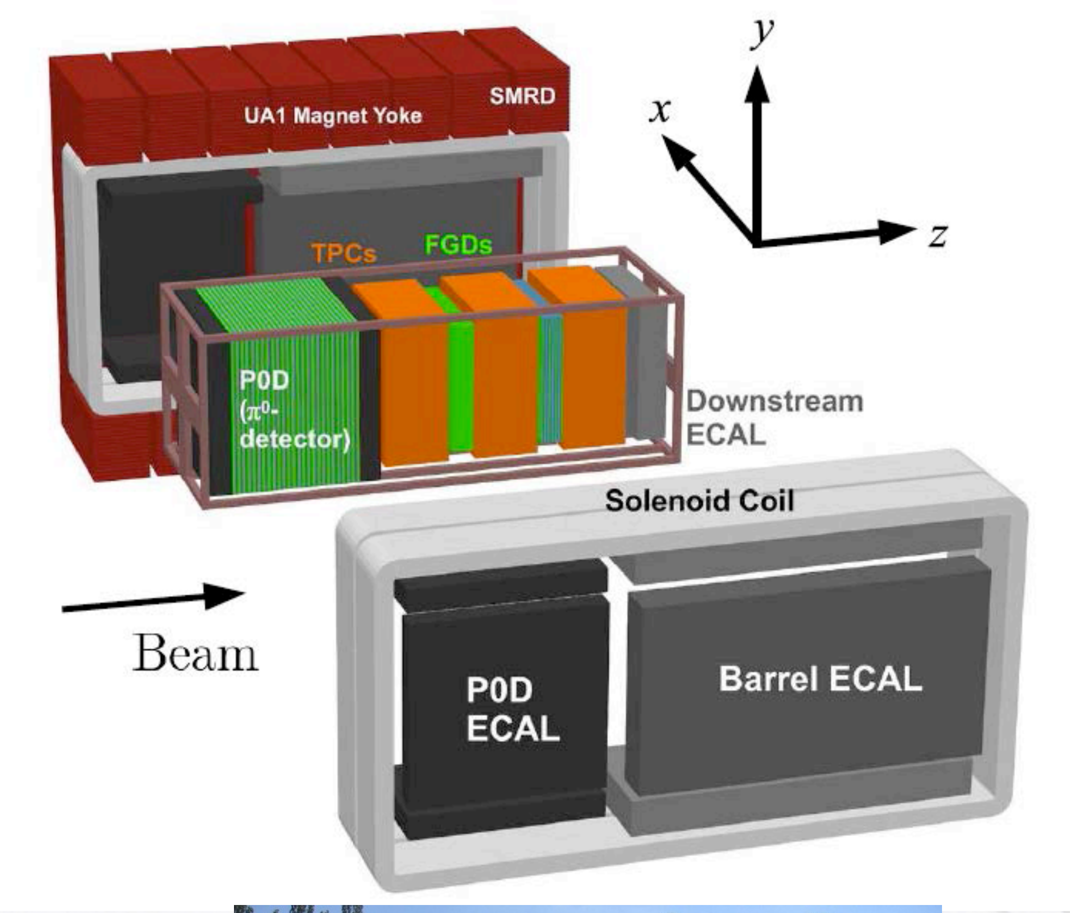


Off-axis: ND280

- Off-axis ND280 is a detector complex with tracking calorimeters, time projection chambers and Electromagnetic calorimeters in the UA1/Nomad 0.2T magnet.
  - ν interaction target polystyrene (CH) and water.
  - Particle ID by dE/dx and calorimetry.
  - Charge sign by curvature.

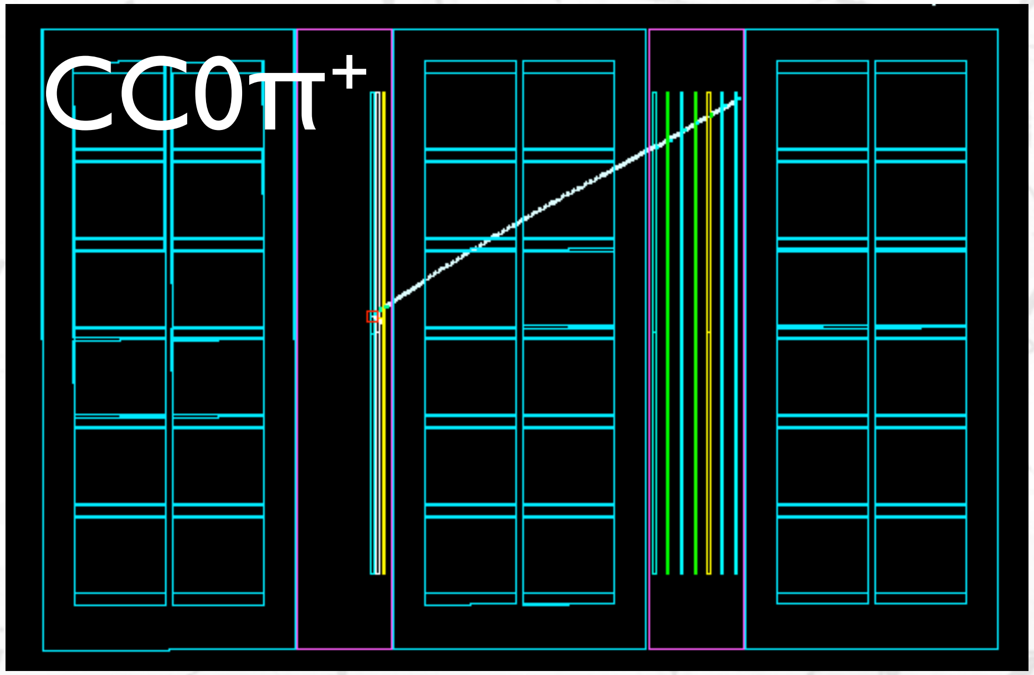
- Specific π^0 detector (P0D) made of water, CH and brass optimised for NC π^0 measurement.

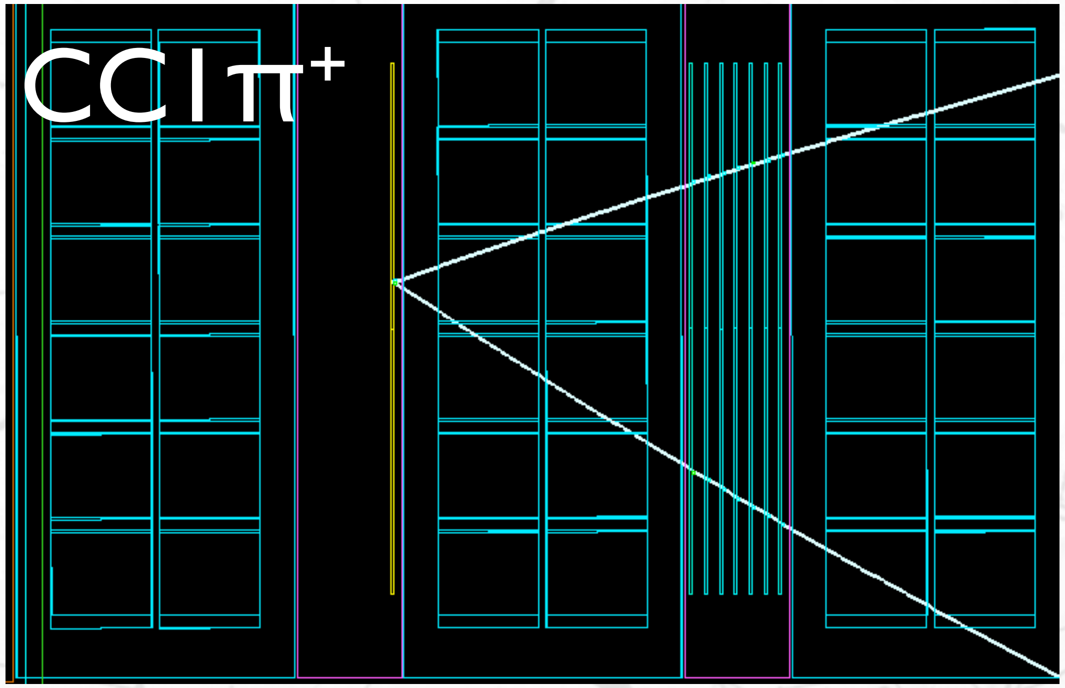
Magnet was granted by CERN

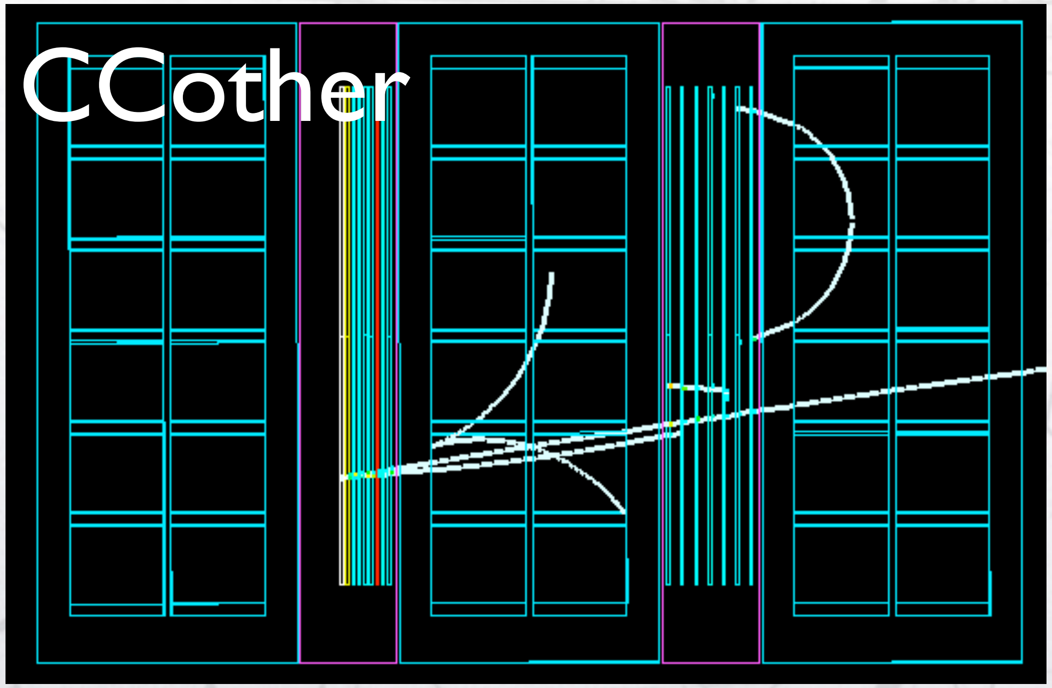



Magnet @ CERN Prévessin

Off-axis: ν_μ analysis

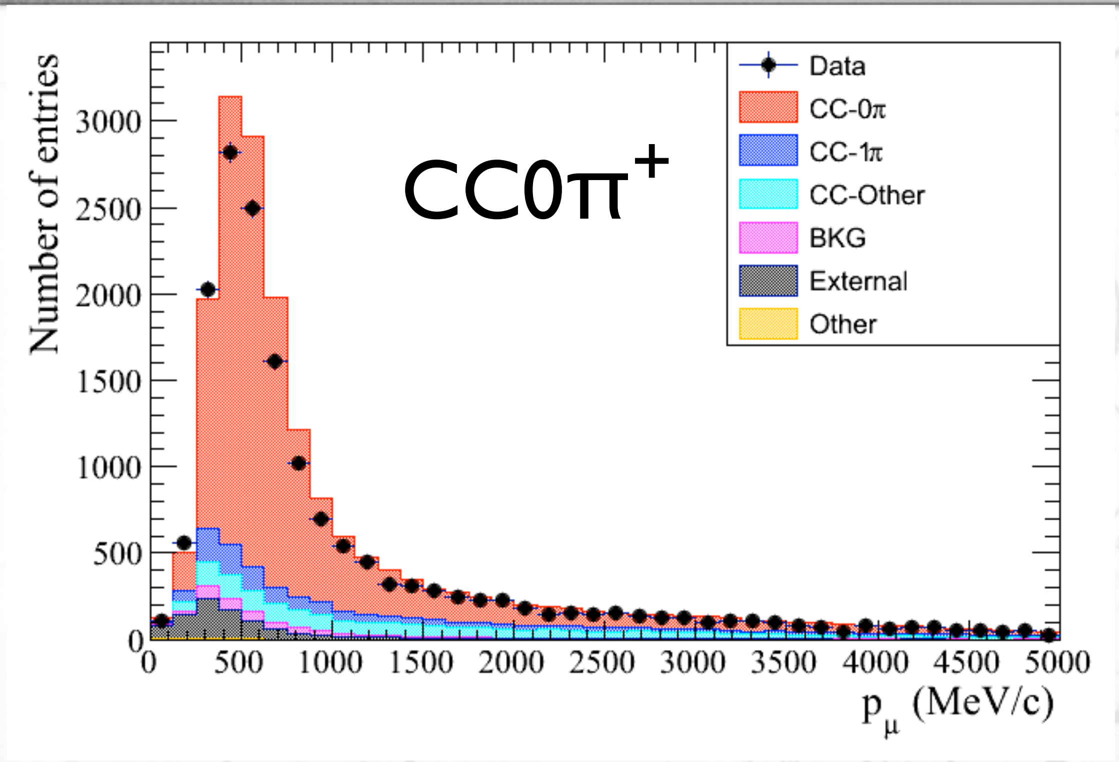


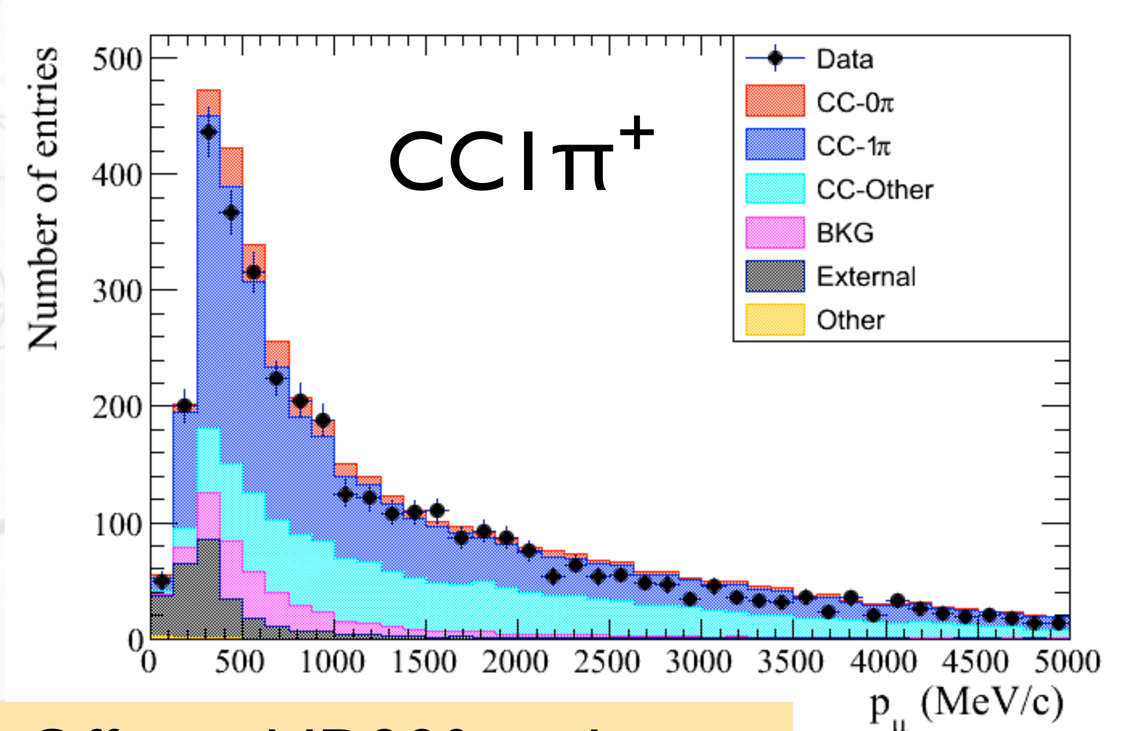


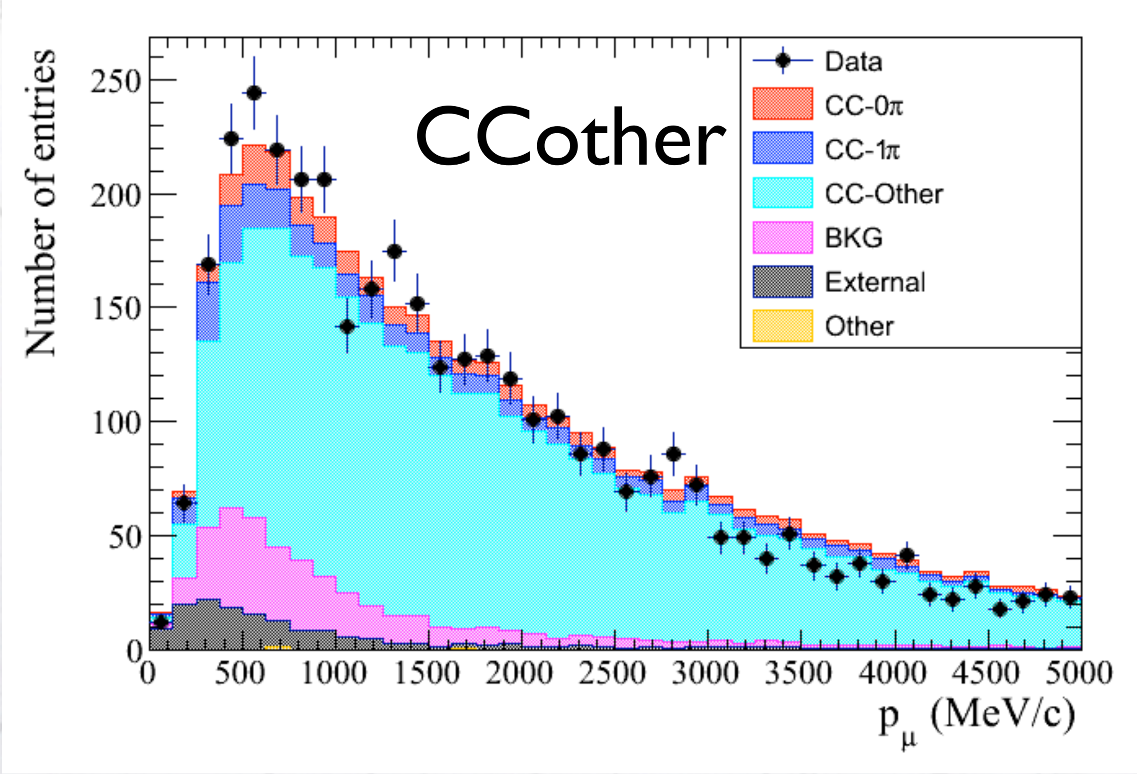


Off-axis ND280 analysis
real events

Off-axis: ν_μ analysis



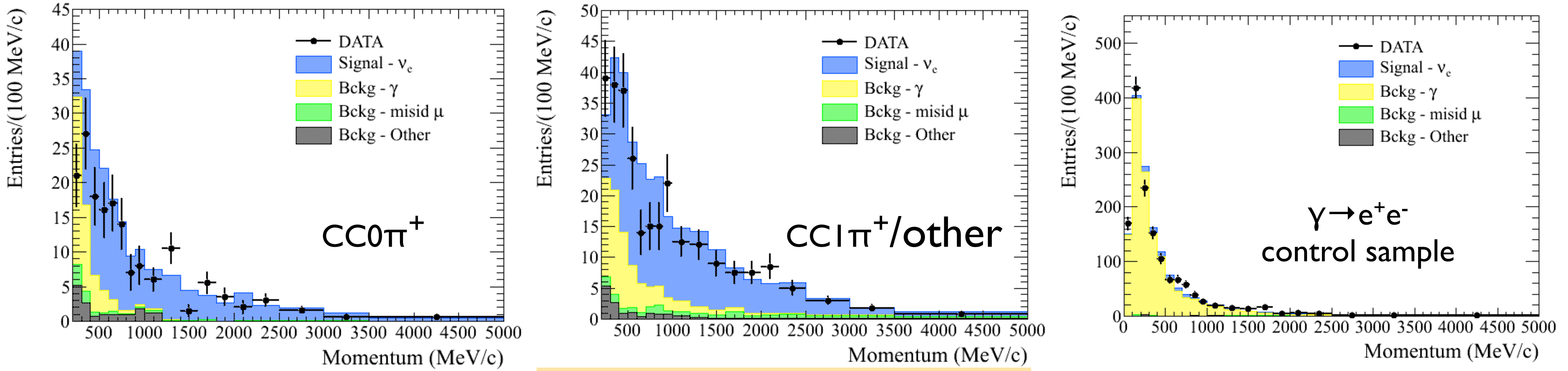




Off-axis ND280 analysis

	Purities			**Efficiency**
	CC0π	CC1π	CCOther	
CC0π	73.5%	6.5%	6.1%	50.1%
CC1π	8.5%	50.5%	8.3%	29.5%
CCOther	10.9%	29.8%	72.9%	35.2%
Background	2.2%	6.8%	8.7%	
Out of FV	4.9%	6.4%	4.0%	

Off-axis: ν_e analysis



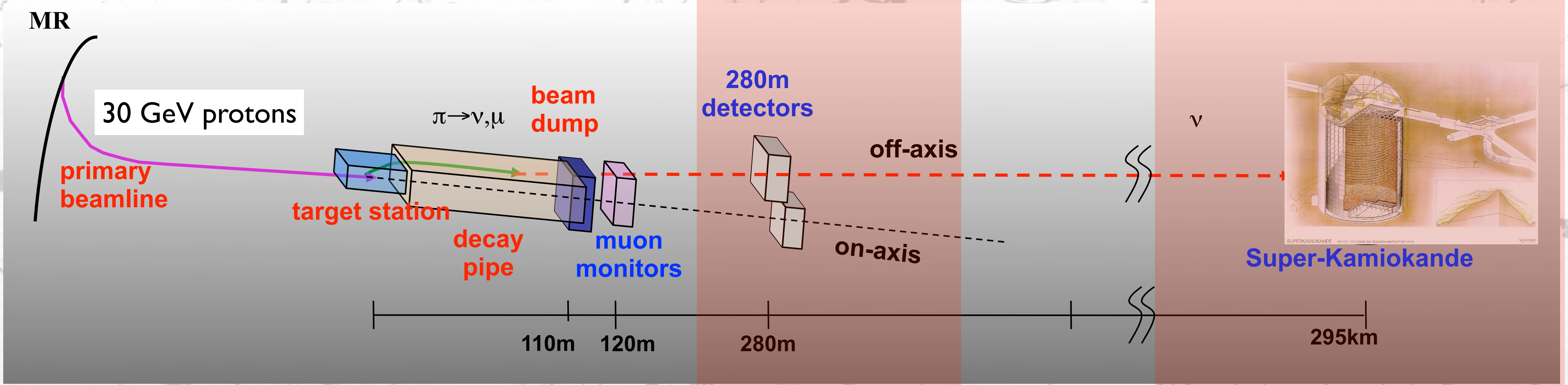
Off-axis ND280 analysis

- Select highest momentum negative track starting in FGD to be compatible with electron according to TPC and ECAL PID.
- Subdivide the sample according to the presence of pions in the event.
- Use the ν_e flux prediction after the ν_μ flux and cross-section fit.
- Use $\gamma \to e^+e^-$ to constrain main background from $\pi^0 \to \gamma\gamma$

$$\frac{N_e^{meas}}{N_e^{pred}} = 1.06 \pm 0.06(stat) \pm 0.08(syst)$$

$$\frac{N_\gamma^{meas}}{N_\gamma^{pred}} = 0.77 \pm 0.02(stat)$$

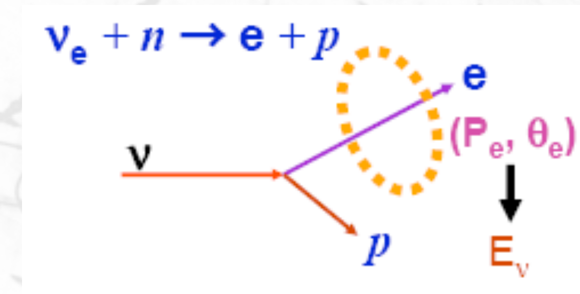
Cross sections



Beam ND280 Super-Kamiokande

Cross-sections

- The T2K signal is the CCQE events. The 2 body kinematics allow to estimate the neutrino energy. $\nu_\mu n \rightarrow \mu^- p$

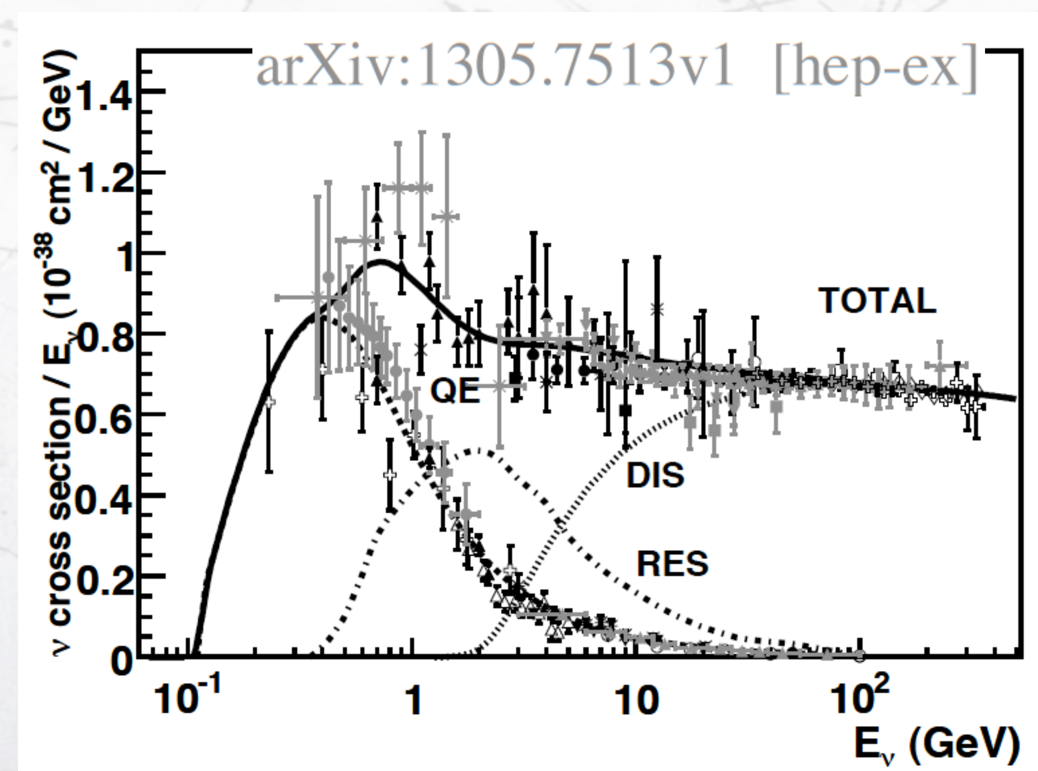


- Other channels can be seen as backgrounds to the CCQE signal.
  - We need to identify the channel by using the hadronic component of the interactions.

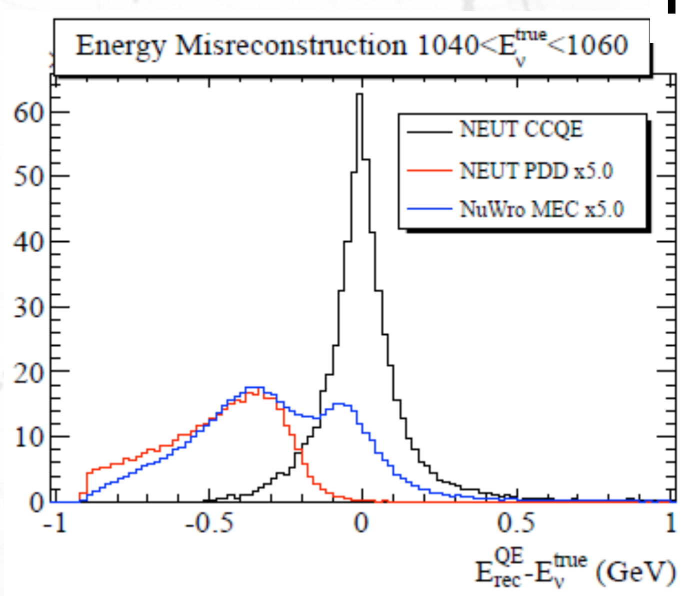
$$E_{reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

E_b is the binding energy

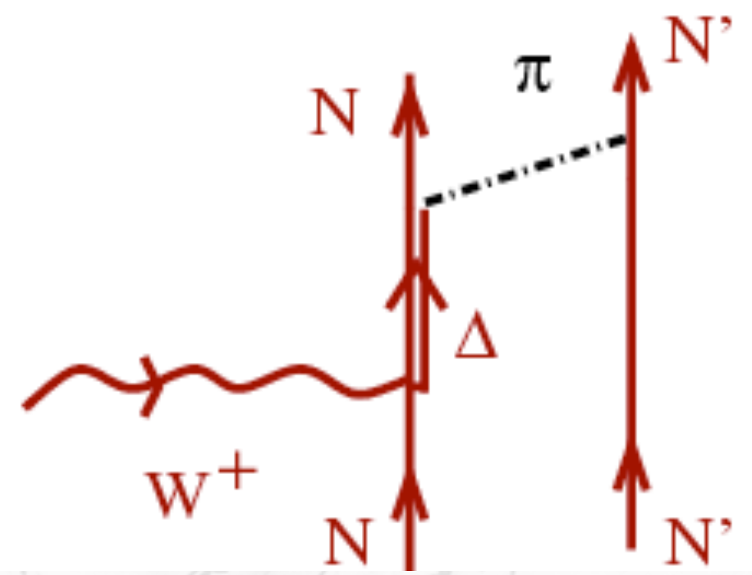
- At T2K energies there are many channel thresholds (CC1π^+, CC1π^0, CC Deep Inelatic Scattering, ...)
- Cross-section models are not precise.
- Final state interactions inside the nucleus alter the hadronic component.

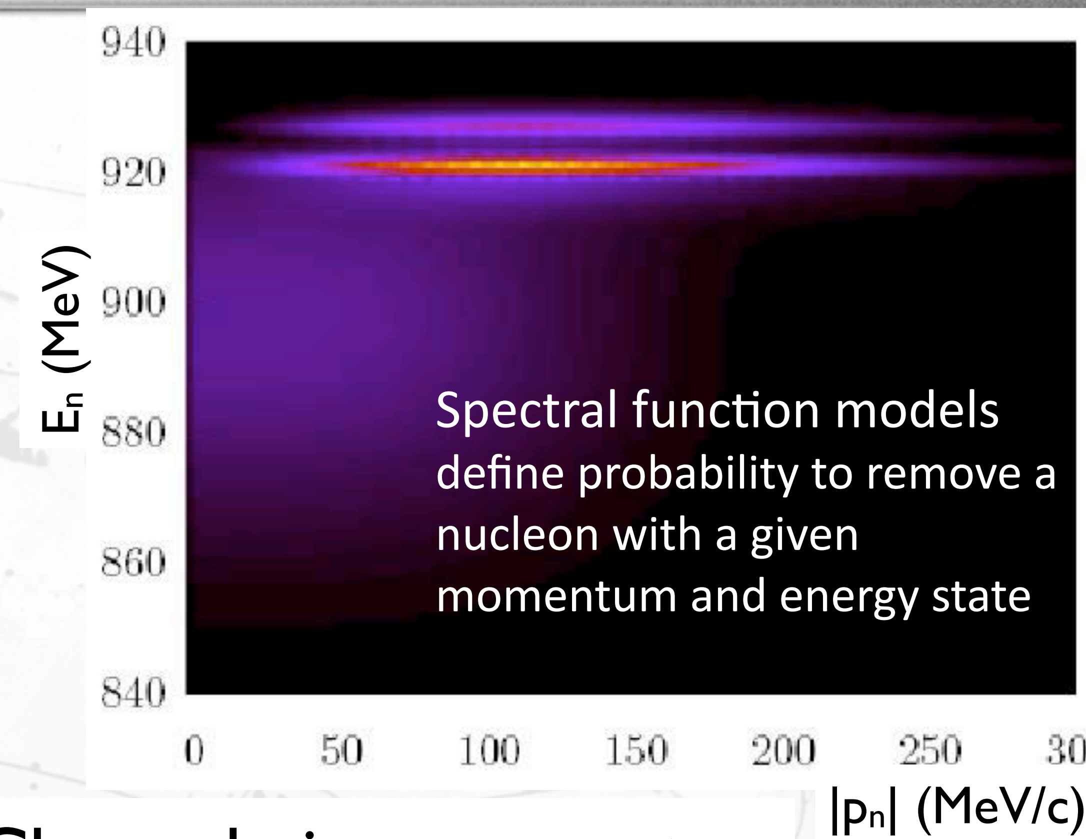


Cross-sections: unknowns

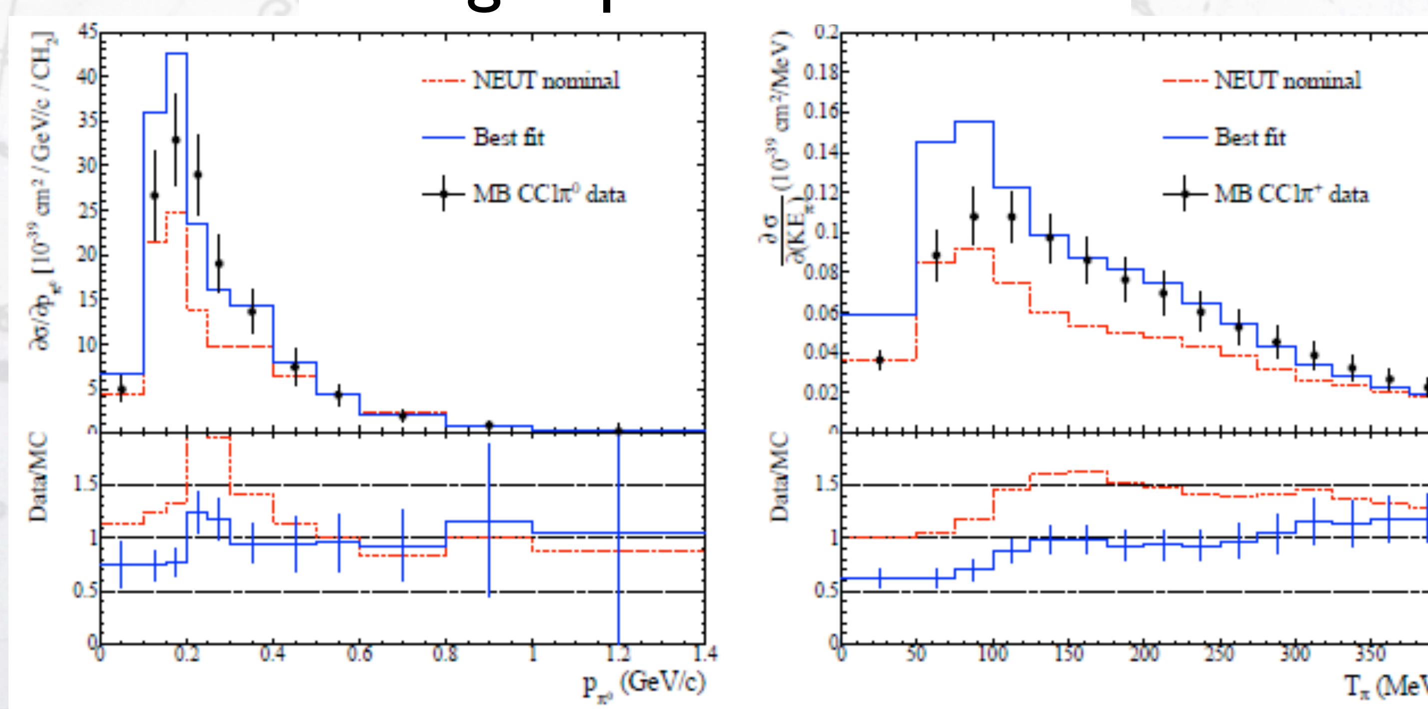


Multi-nucleon interactions





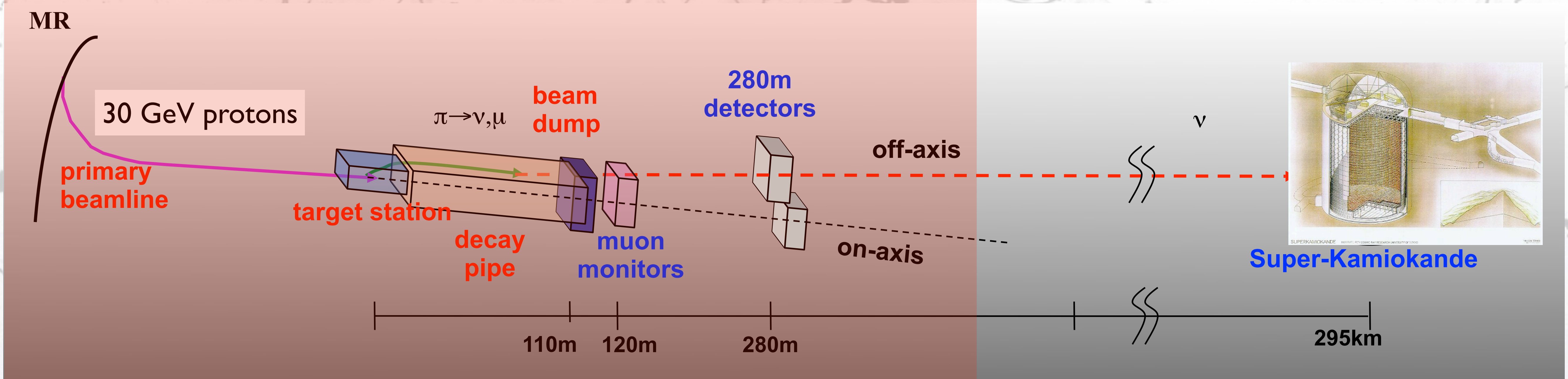
Charged pion momentum



T2K approach

- add effective parameters (MA, cross section normalisation, …) with uncertainties that span the base model and data.
- effective parameters are constrained by ND280 fits.

Flux prediction



Beam ND280 Super-Kamiokande

Flux constraint

Neutrino Flux Model:

- Data-driven: NA61/SHINE, beam monitor measurements
- Uncertainties: modeled by variation of normalisation parameters (*b*) in bins of neutrino energy and flavour

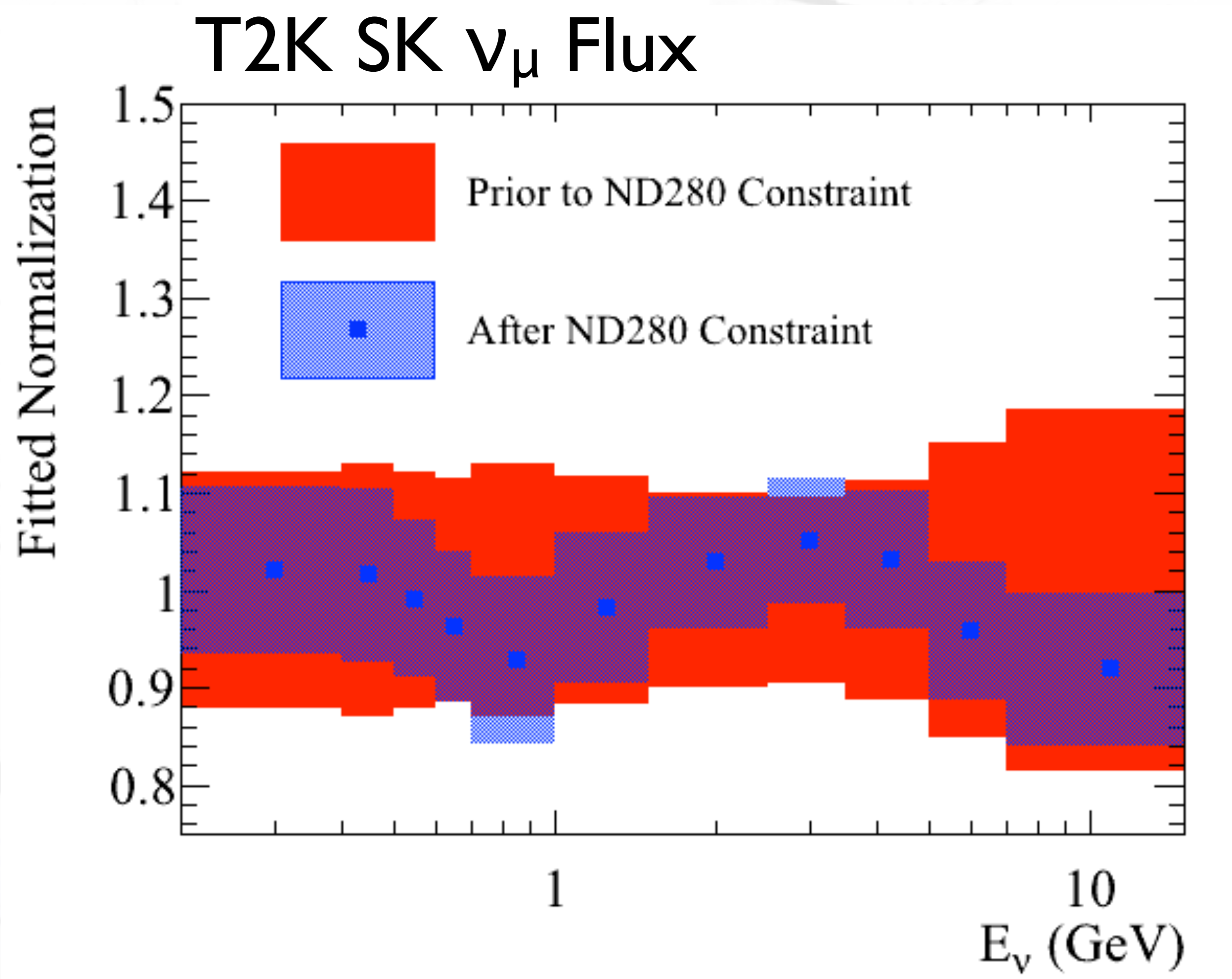
Neutrino Cross Section Model (NEUT):

- Data-driven: External neutrino, electron, pion scattering data
- Uncertainties: modeled by variations of model parameters (M_A, p_F, E_b) and ad-hoc parameters

Constraint from ND280 Data

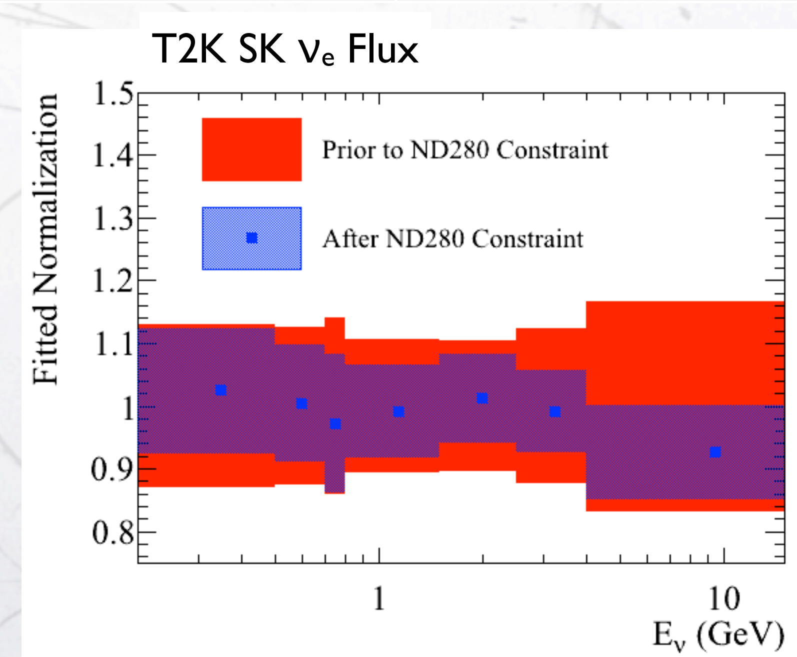
- Data Samples enhanced in CC interactions with 0, 1 or others (mainly multiple pions)
- Fit to data constrains flux, *b,* and cross section, $x=(M_A, p_F, E_b, ad\text{-}hoc, ...)$, parameters
- Constrained SK flux parameters and subset of cross section parameters are used to predict SK event rates

Constrained flux



Cross-section parameters

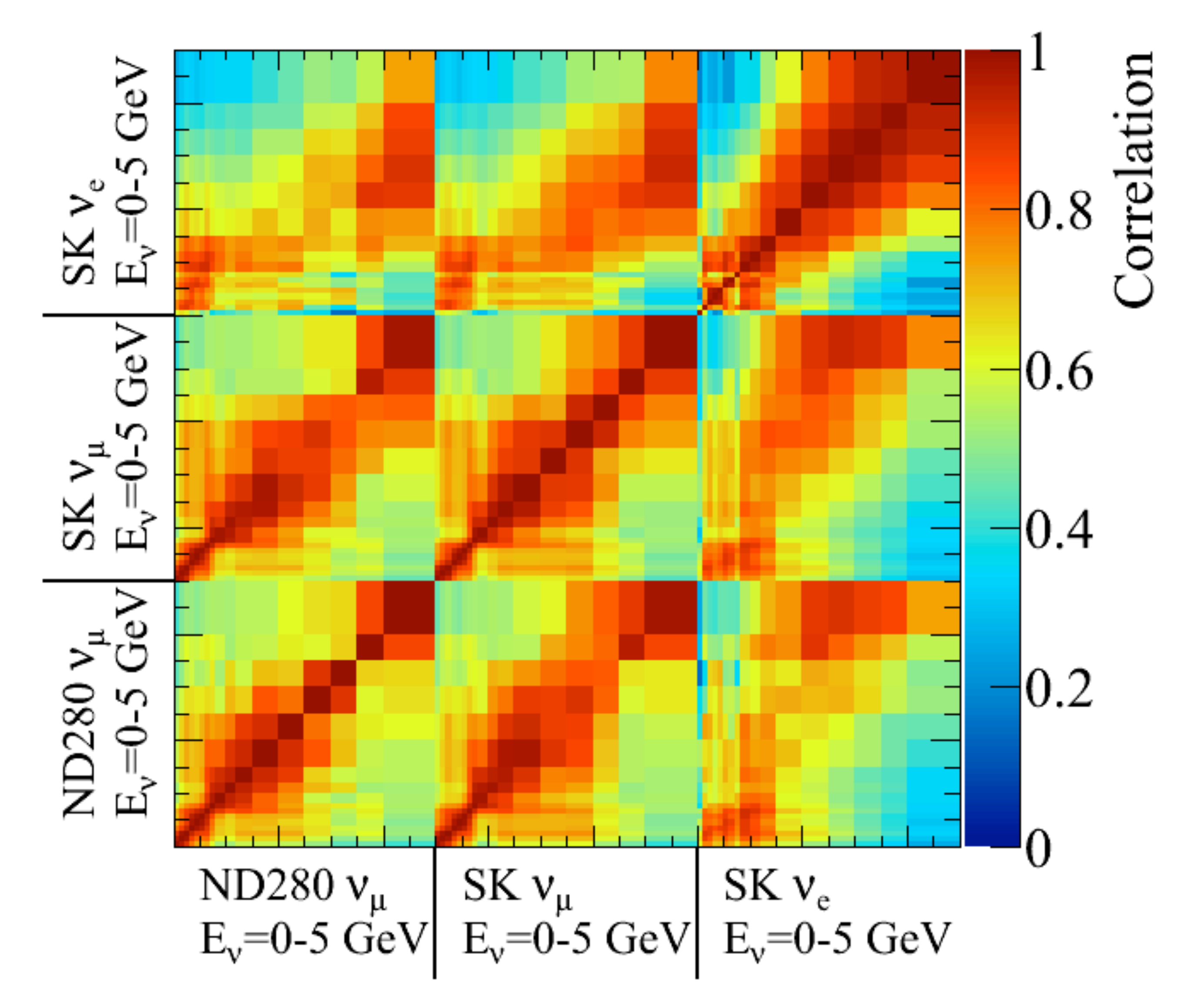
Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.	1.15 ± 0.32	1.22 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25



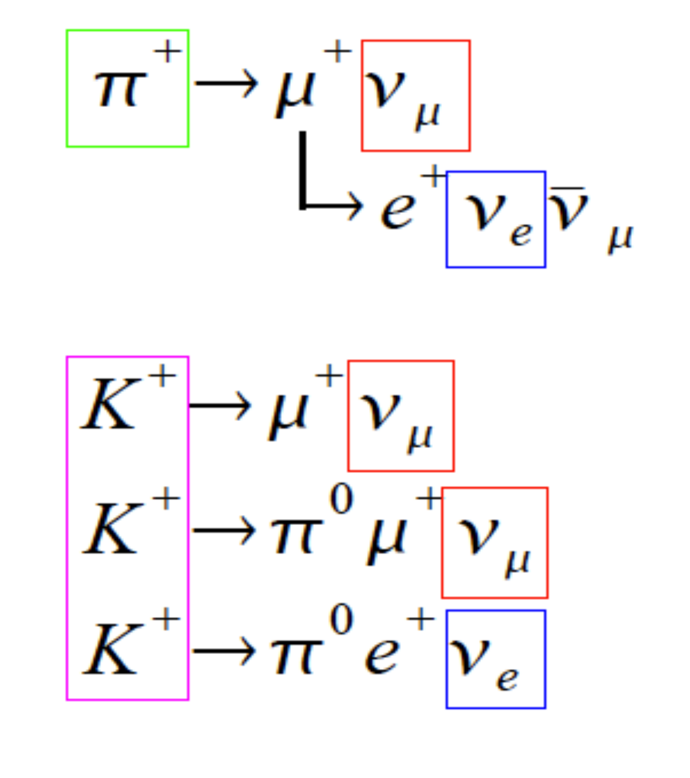
- T2K ν_μ and ν_e flux predictions are constrained by the fit.
- The cross-section parameters are also constrained.
- Plots show central values and error bands for normalisation parameters.

Covariance matrix

T2K SK flux parameters are constrained through their prior correlations with the ND280 ν_μ flux parameters

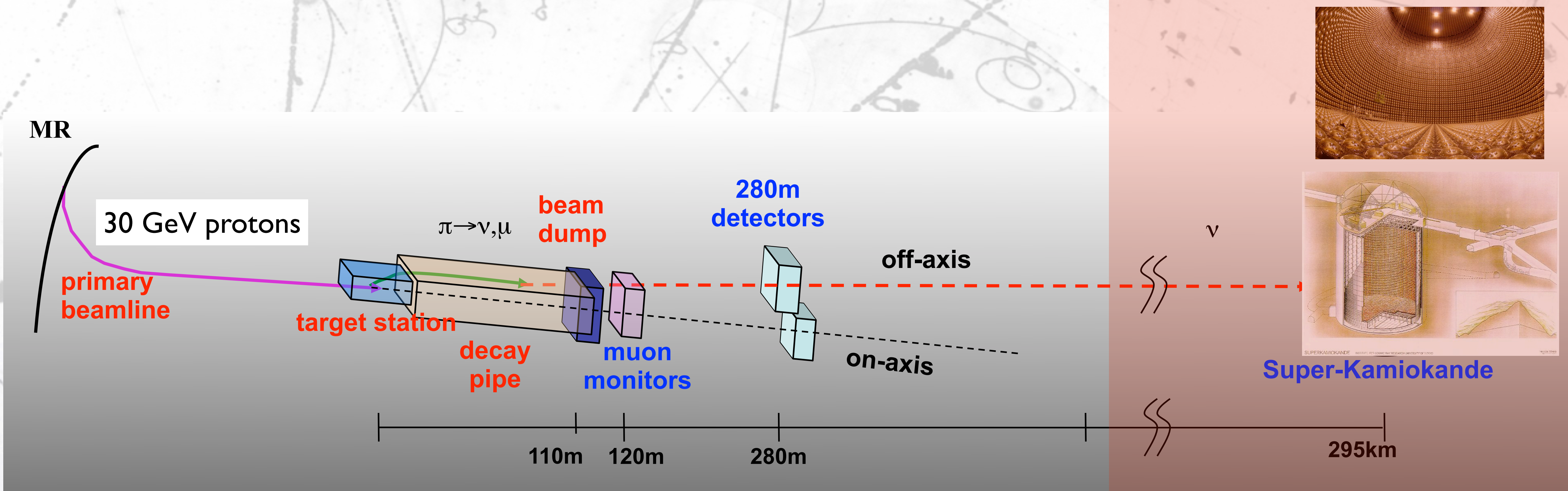


ν_e and ν_μ fluxes are correlated through parent hadrons



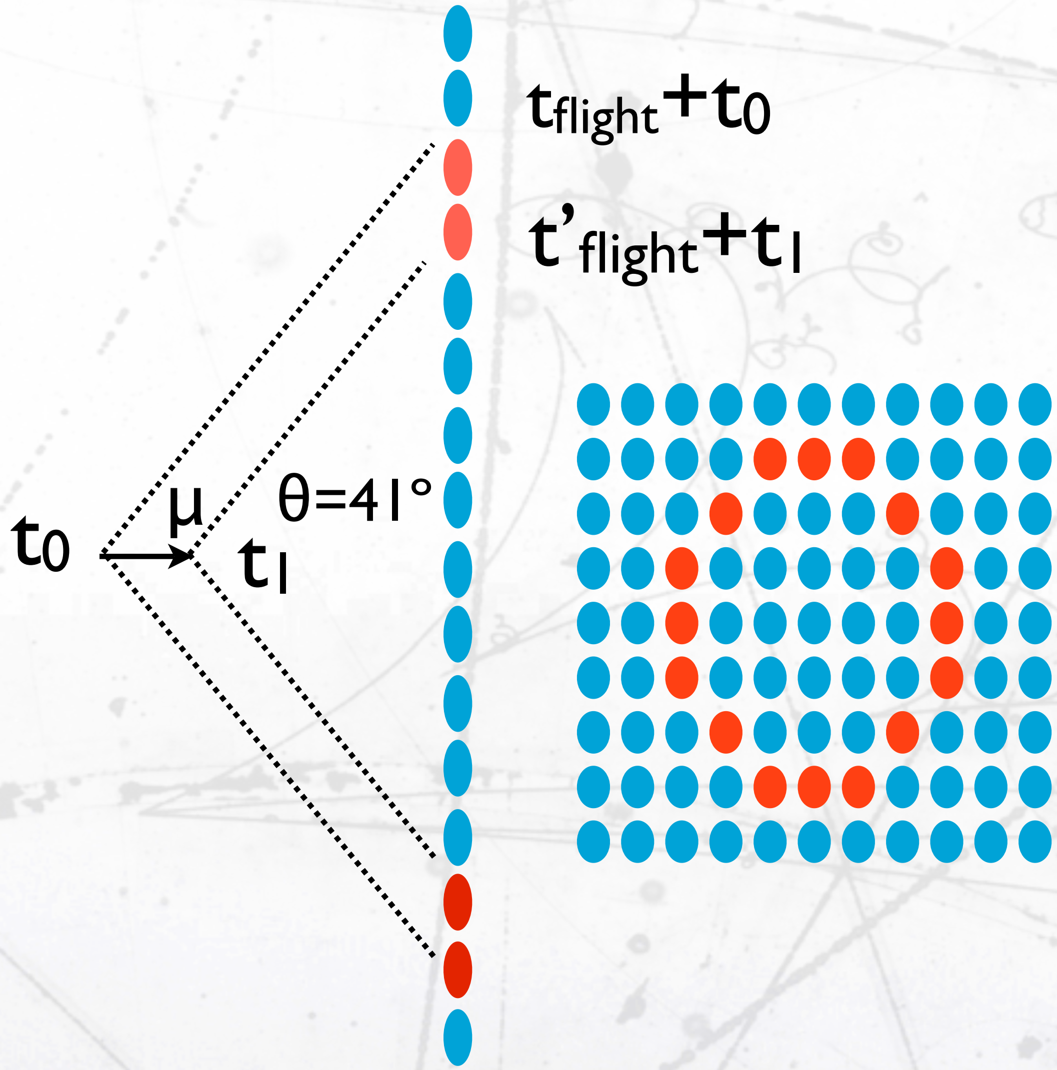
Subset of cross section parameters are correlated at near and far detectors: M_A^{QE}, M_A^{RES}, low energy CCQE normalisation, low energy CC1π normalisation.

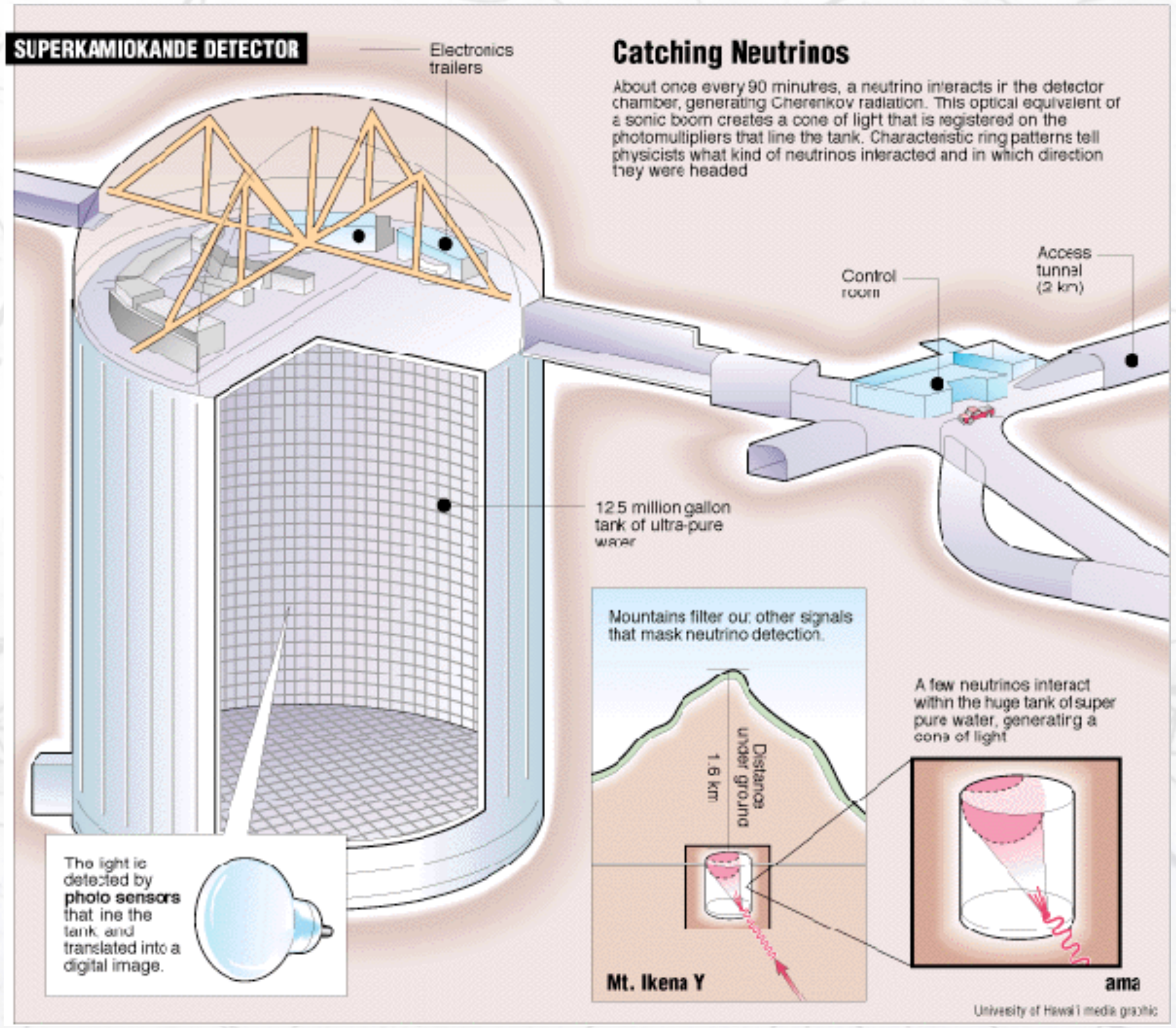
Super-Kamiokande



Beam ND280 Super-Kamiokande

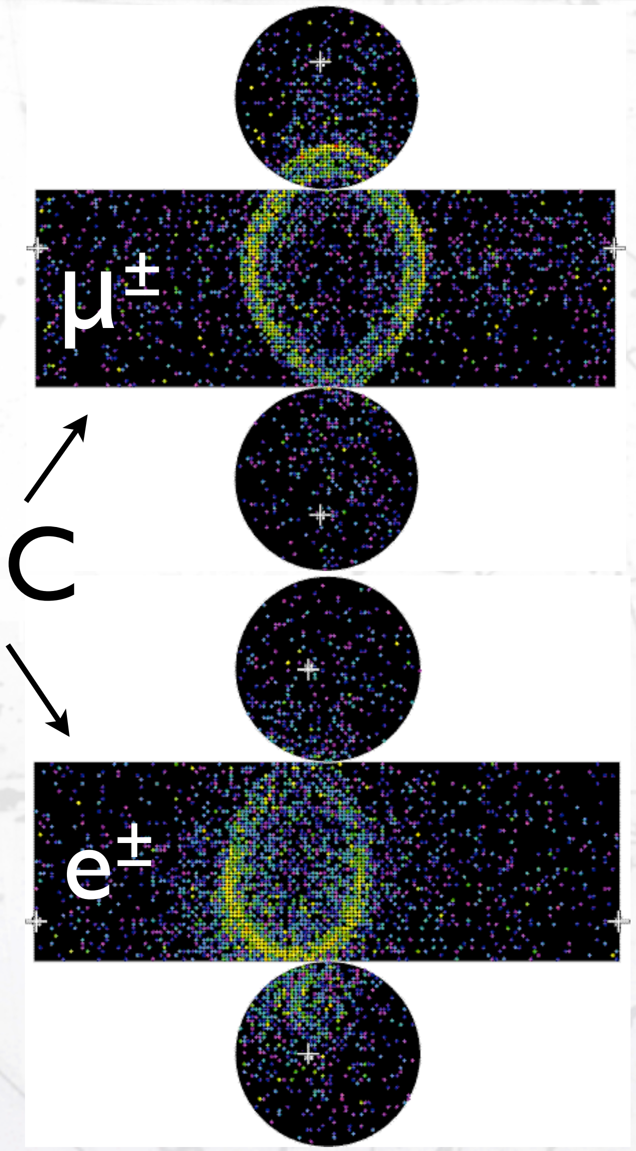
Super-Kamiokande

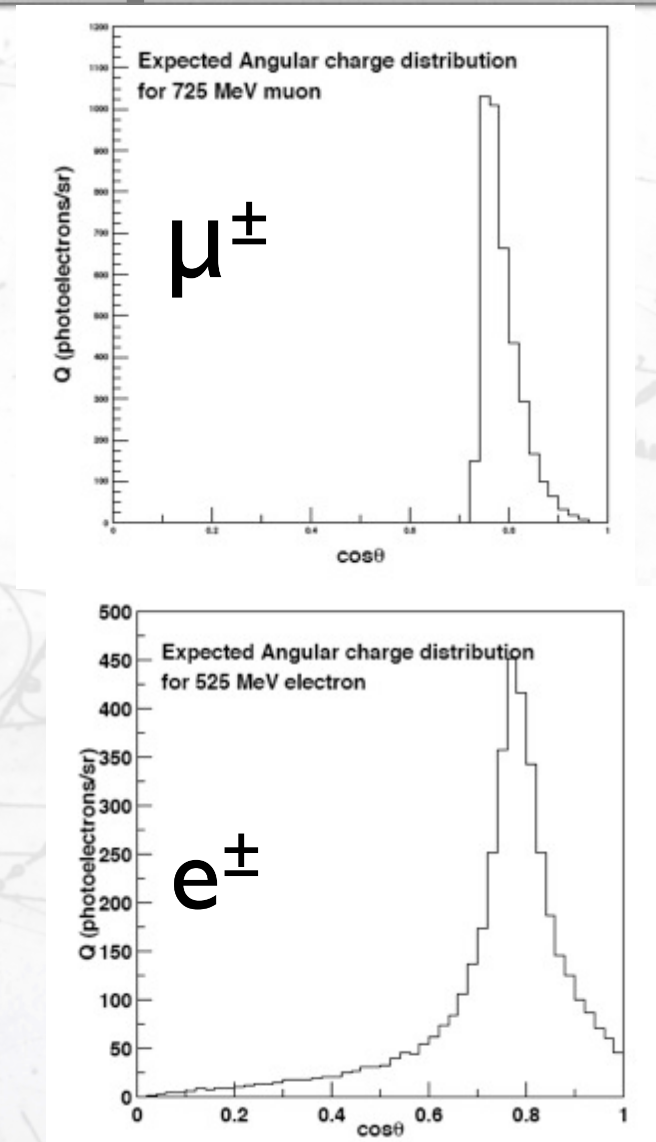


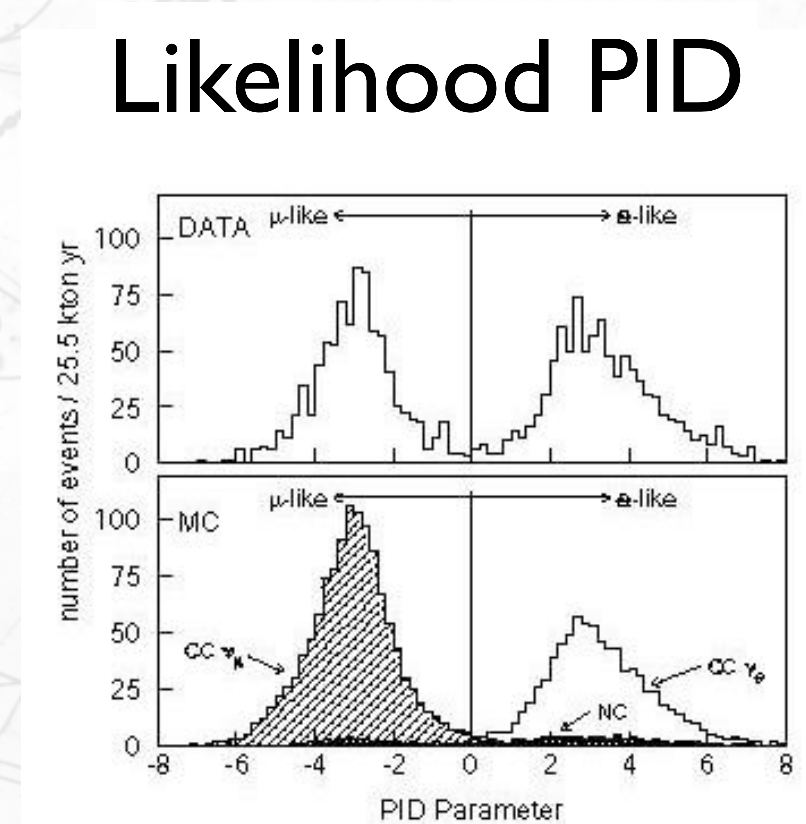


- 50 kTon water Cherenkov detector. (22.5 KTon fiducial).
- ~11 000 20" PMT inner detector.
- ~2000 8" PMT outer detector to veto external background.

SK: particle ID







- The expected angular distribution of Cherenkov photons along the primary particle direction is different in electrons and muons:
- The electron is not sharp due to Multiple Scattering & showering.

Super-Kamiokande & π^0

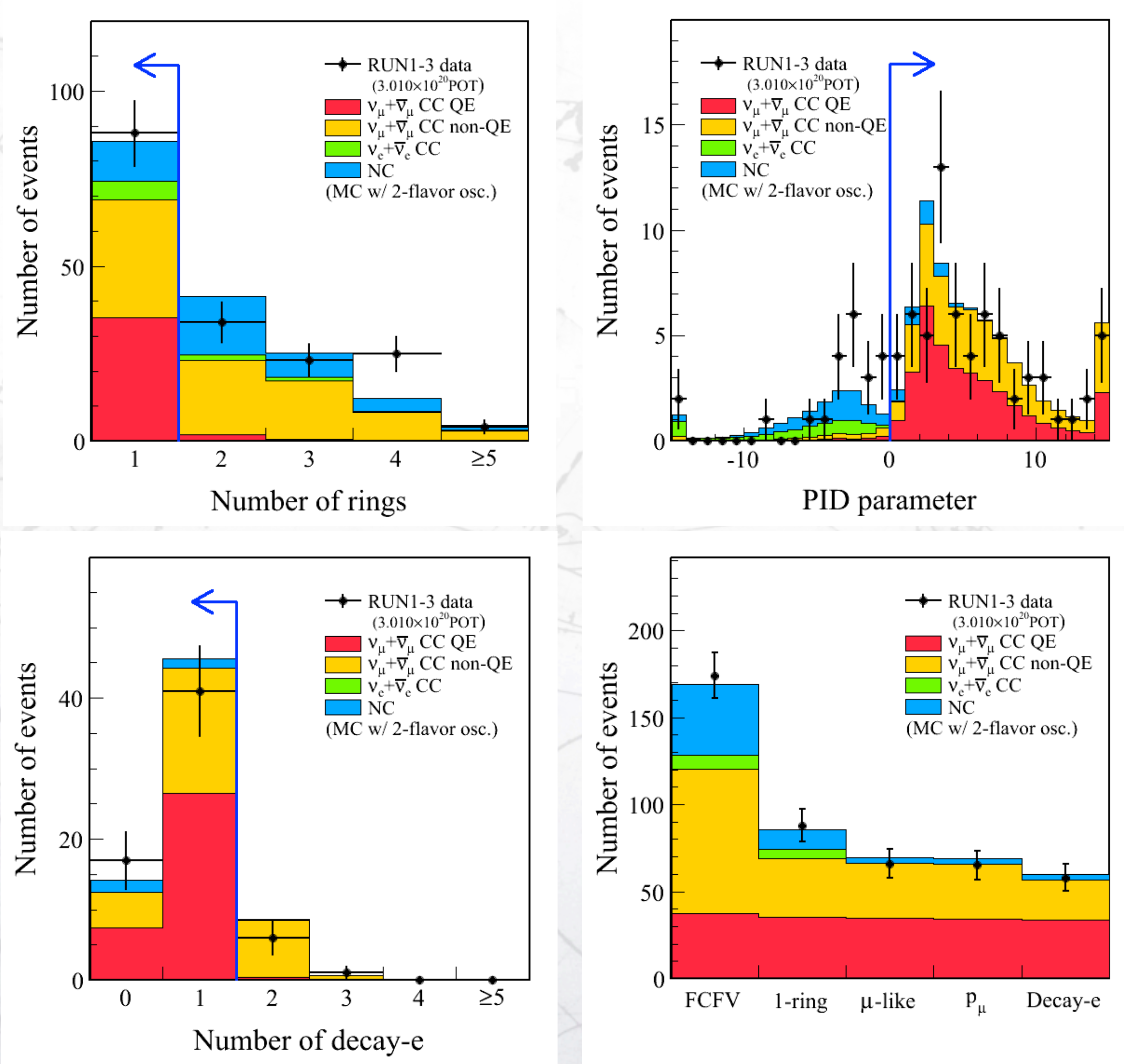
- The misidentification of π^0 and electrons happens when one photon is not identified:
  - The two electron-like rings overlap.
  - One of the two e-like rings is faint and it is lost in the Cherenkov light of the other photon.
- Or with 2 γ, the invariant mass of the photons has poor resolution.

ν_μ selection

ν_μ Selection Cuts

- Number veto hits < 16
- Fiducial Volume=200cm
- Fully contained ring.
- number of rings = 1
- Ring is muon-like
- $E_{visible}$ > 100 MeV
- < 2 Michel electrons
- p_μ > 200 MeV

58 events for 3.01×10^{20} proton on target

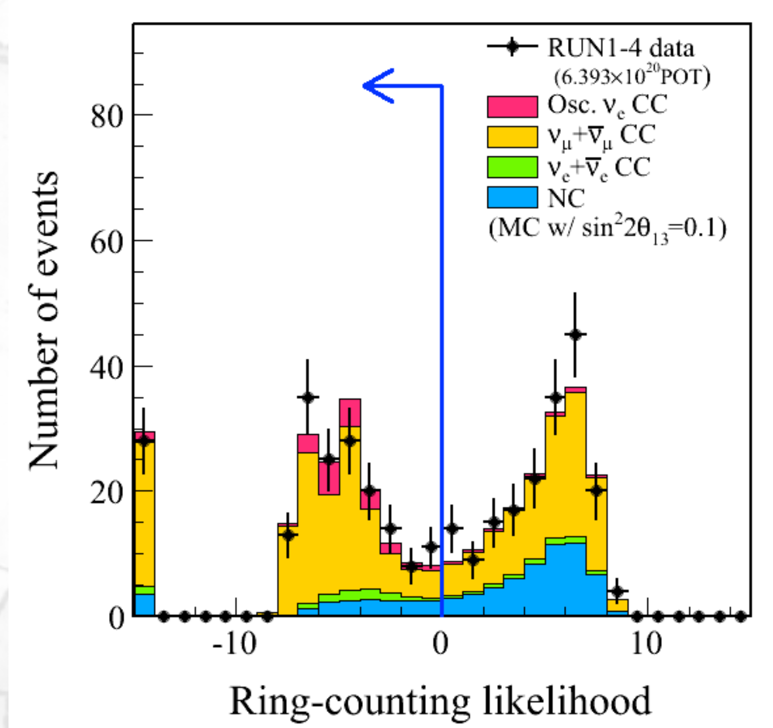


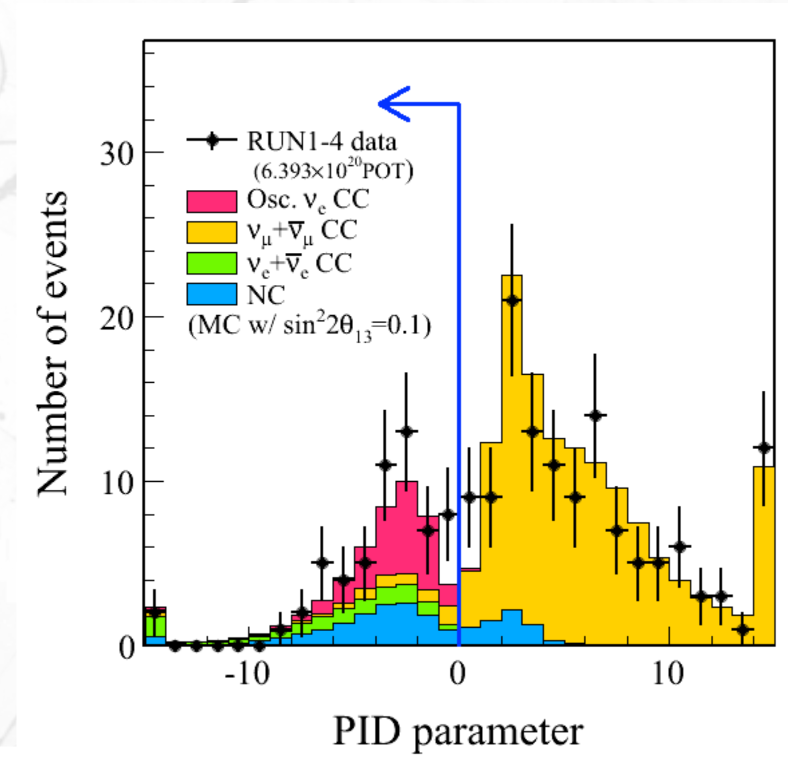
ν_e selection

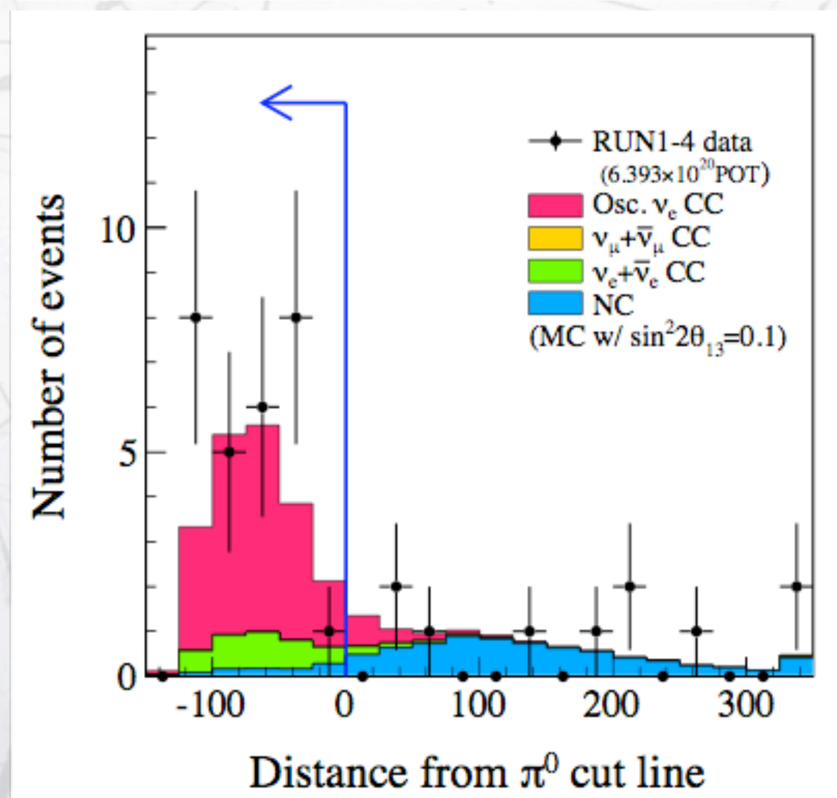
ν_e Selection Cuts

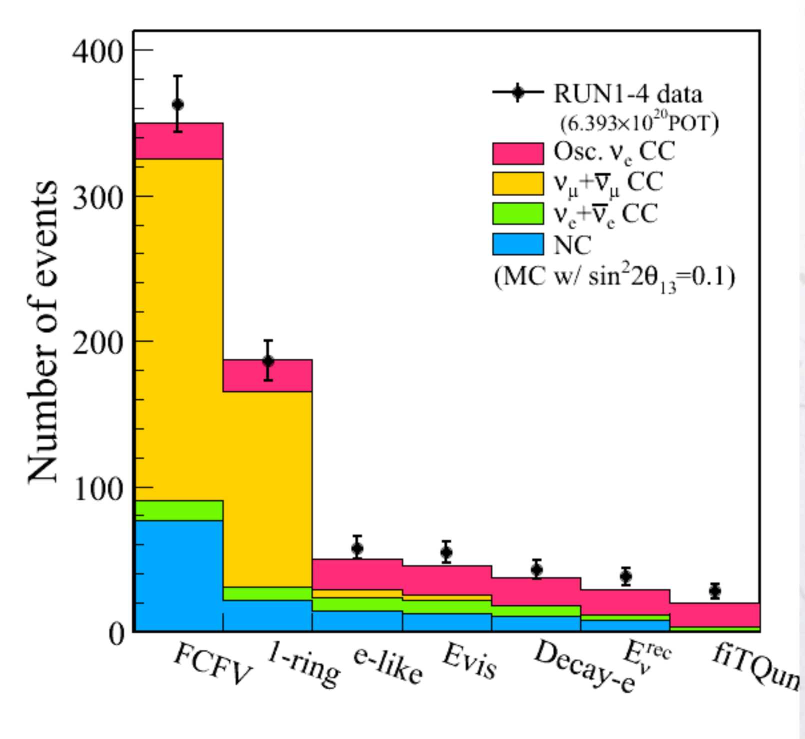
- Number veto hits < 16
- Fiducial Volume=200cm
- number of rings = 1
- Ring is electron-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- new analysis π^0 cut
- 0 < E_ν < 1250 MeV

28 events for 6.4×10^{20} proton on target

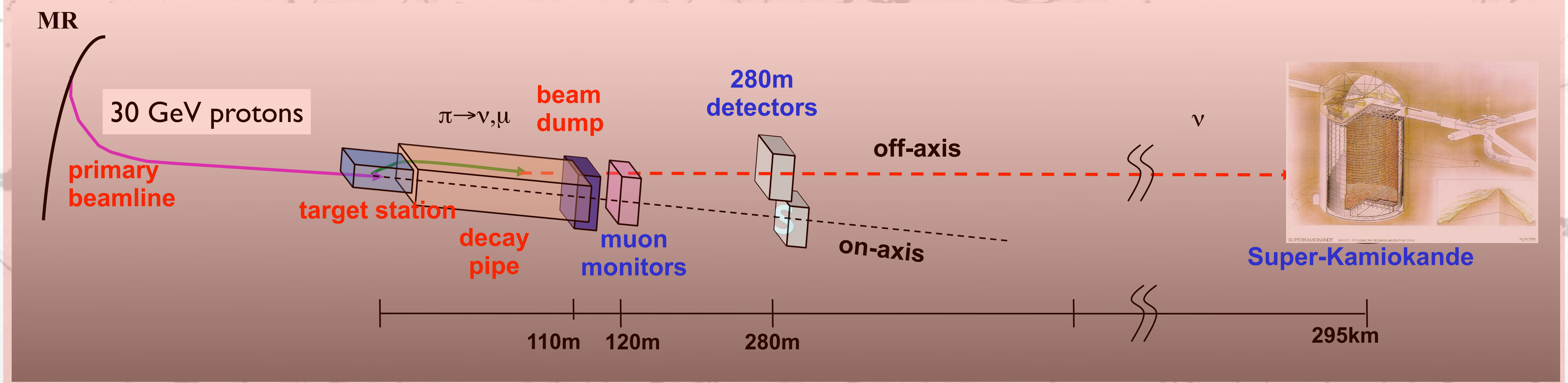








ν oscillation analysis

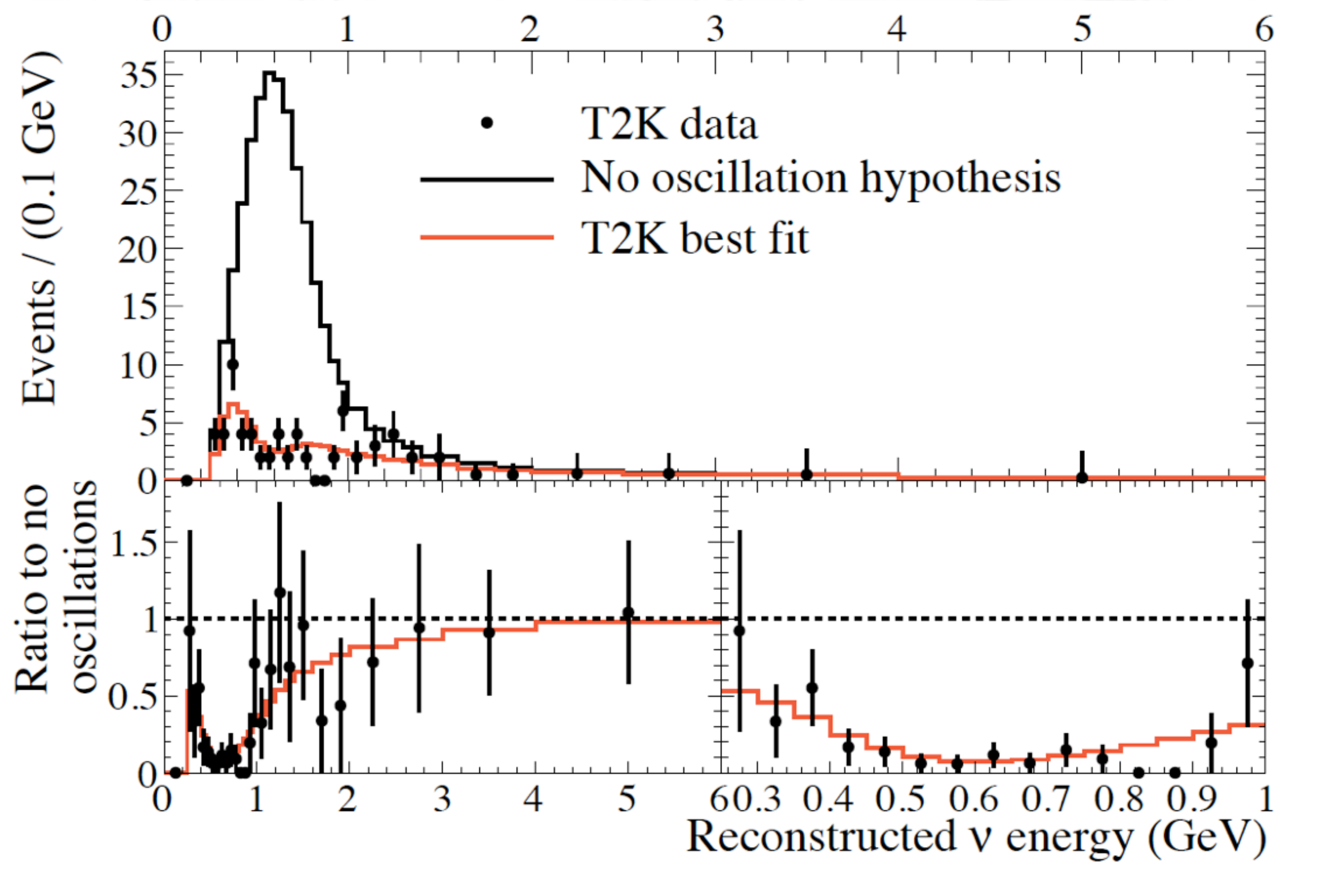


Beam ND280 Super-Kamiokande

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

ν_μ disappearance

- Expected number of events in absence of oscillations: 205 ± 17 (syst). Flux+$\sigma_{\nu N}$
- Observed number of events: 58



3.01x10^{20} PoT

Energy reconstruction assuming CCQE

The θ_{23} octant

- In the limit: $\Delta m^2_{12} << \Delta m^2_{23}$ the disappearance probability is given by:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}[1-\cos^2\theta_{13}\sin^2\theta_{23}]\sin^2(1.27\Delta m^2_{32}L/E_\nu)$$

- If $\theta_{13} = 0$

$$P(\nu_\mu \to \nu_\mu) \simeq \quad 1 - 4\sin^2\theta_{23}[1-\sin^2\theta_{23}]\sin^2(1.27\Delta m^2_{32}L/E_\nu)$$
$$1 - 2\sin^2 2\theta_{23}\sin^2(1.27\Delta m^2_{32}L/E_\nu)$$

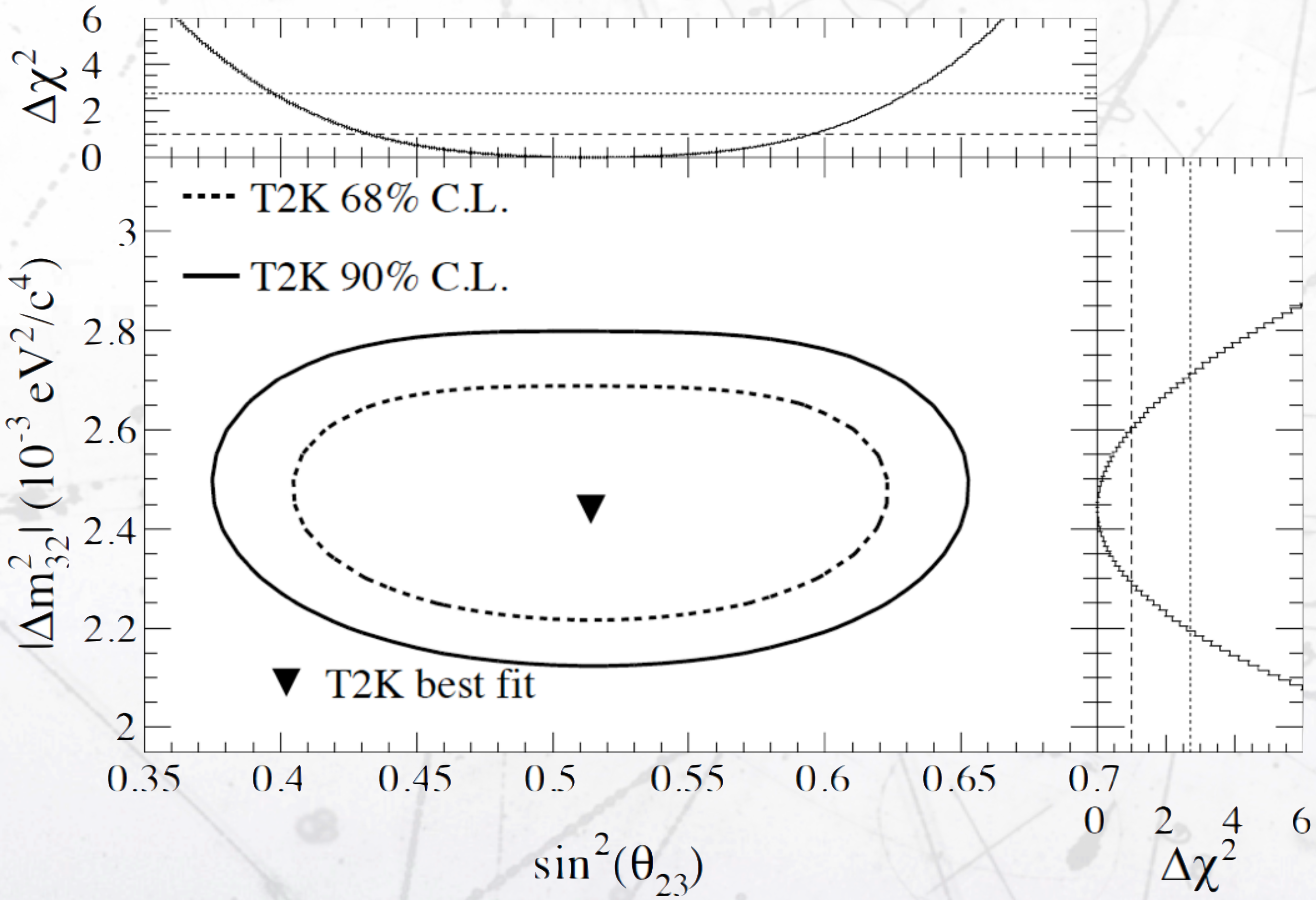
- If θ_{13} != 0 and θ_{23}~45°, the ν_μ disappearance is sensitive to the octant

(i.e. $P_{\nu\mu\to\nu\mu}(\theta_{23}>45°) \neq P_{\nu\mu\to\nu\mu}(\theta_{23}<45°)$)

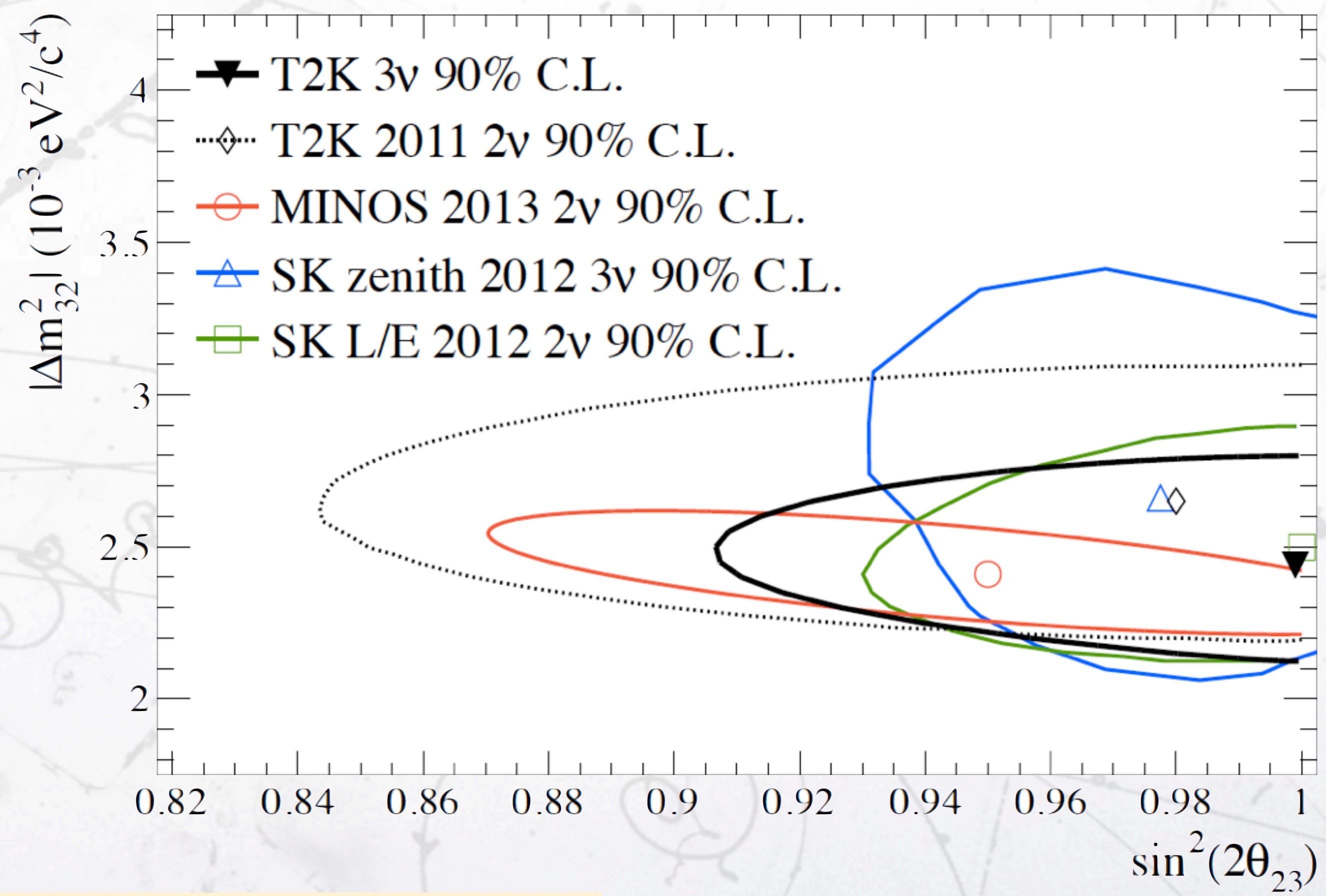
- The right parameter is $\sin^2\theta_{23}$ and not the traditionally used $\sin^2(2\theta_{23})$
- Uncertainty in θ_{13} needs to be propagated.

ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}[1-\cos^2\theta_{13}\sin^2\theta_{23}]\sin^2(1.27\Delta m^2_{32}L/E_\nu)$$



Old representation for comparisons!



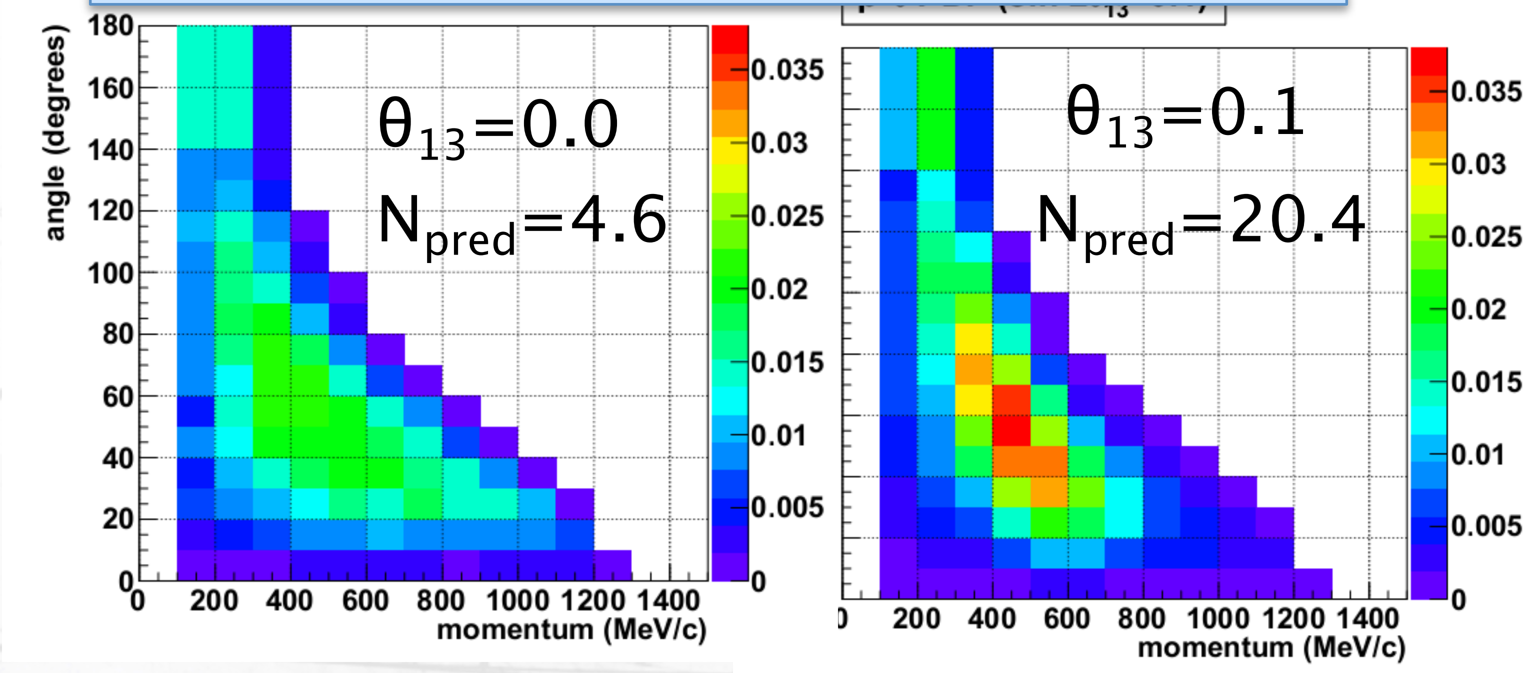
Physical Review Letters in Press. Arxiv:1308.0465

- T2K already dominates the measurement of mixing angle for Long Baseline experiments (x2 more statistics soon!!)

$\nu_\mu \rightarrow \nu_e$

ν_e appearance

Electron momentum vs. angle distribution (MC)

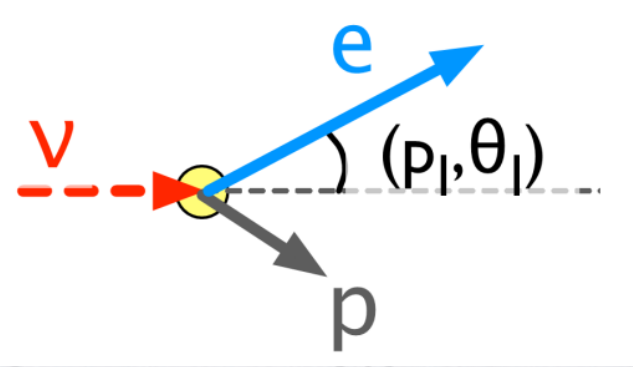


Fixed oscillation parameters

Δm^2_{12}	7.6×10^{-5} eV^2
Δm^2_{32}	2.4×10^{-3} eV^2
$\sin^2 2\theta_{23}$	1.0
$\sin^2 2\theta_{12}$	0.8495
δ_{CP}	0 degree

Analysis method

- We scan over $\sin^2 2\theta_{13}$ space to find the best fit value of $\sin^2 2\theta_{13}$, where the likelihood ($\mathscr{L}$) becomes maximum.
- Likelihood is calculated by comparing the number of observed events (N_{obs}) and the electron momentum & angle (p-θ) distribution with MC.
- We fix the oscillation parameters other than $\sin^2 2\theta_{13}$.



ν_e appearance

$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$$

$\mathcal{L}_{syst}$ → Systematic parameter constraint term

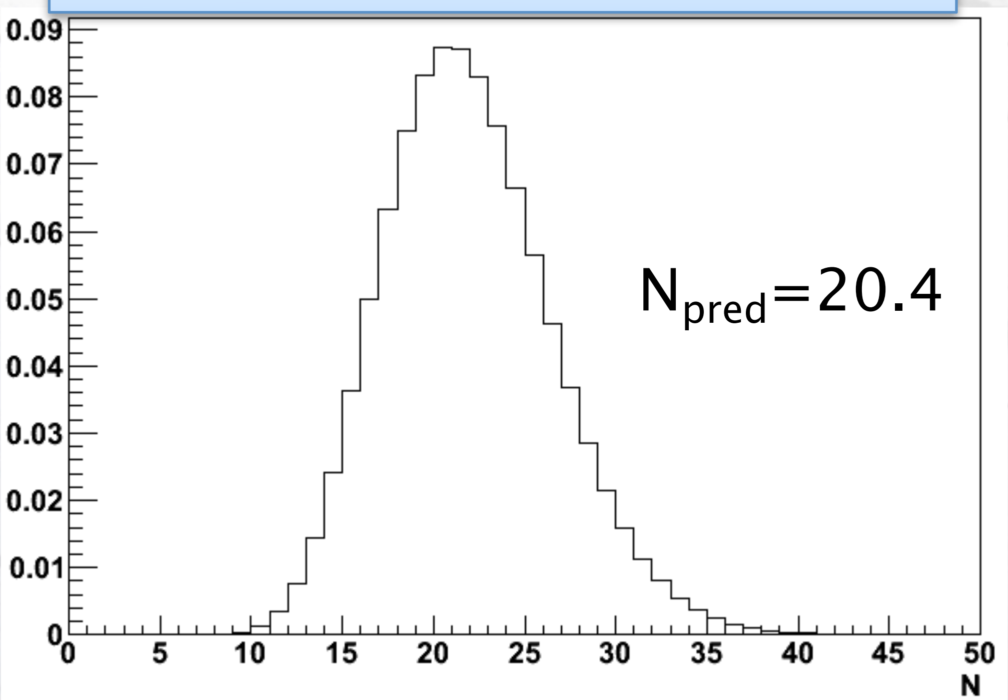
$\mathcal{L}_{norm}$: $Poisson(N_{obs})_{\text{mean}=N_{pred}}$

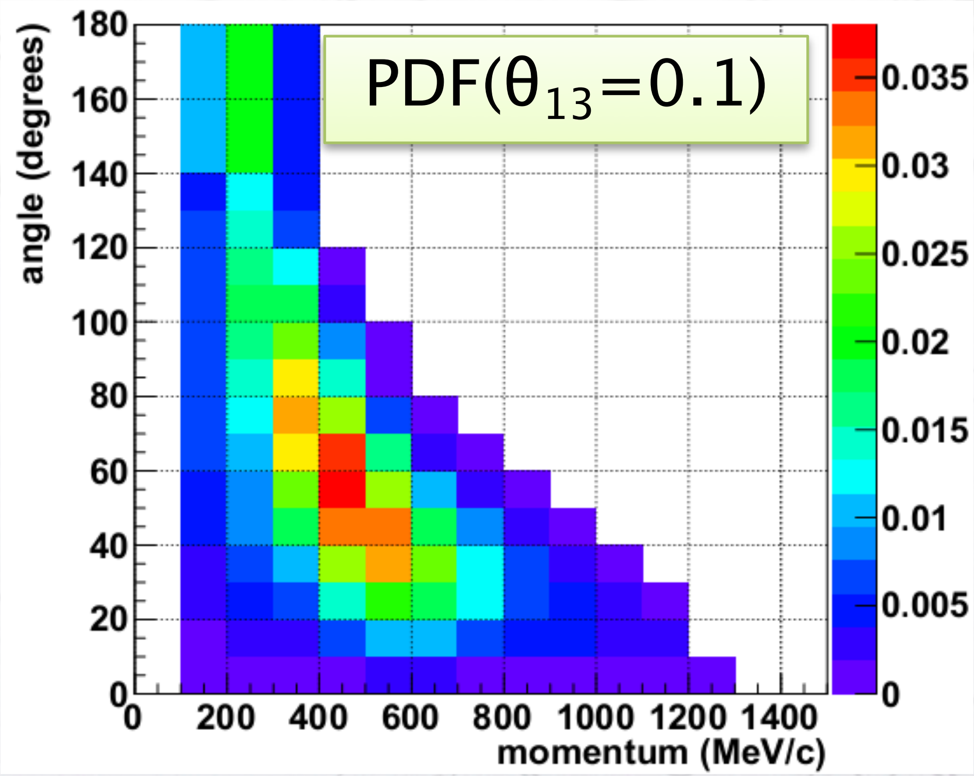
$\mathcal{L}_{shape}$: $\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$

$\mathscr{L}_{norm}$ is the probability to have N_{obs} when the predicted number of events is the Poisson distribution with mean = N_{pred}.

$\mathscr{L}_{shape}$ is the product of the probabilities that each event has (p_i, θ_i). φ: Predicted p-θ distribution (PDF) .

Poisson distribution (θ_{13}=0.1)





ν_e appearance

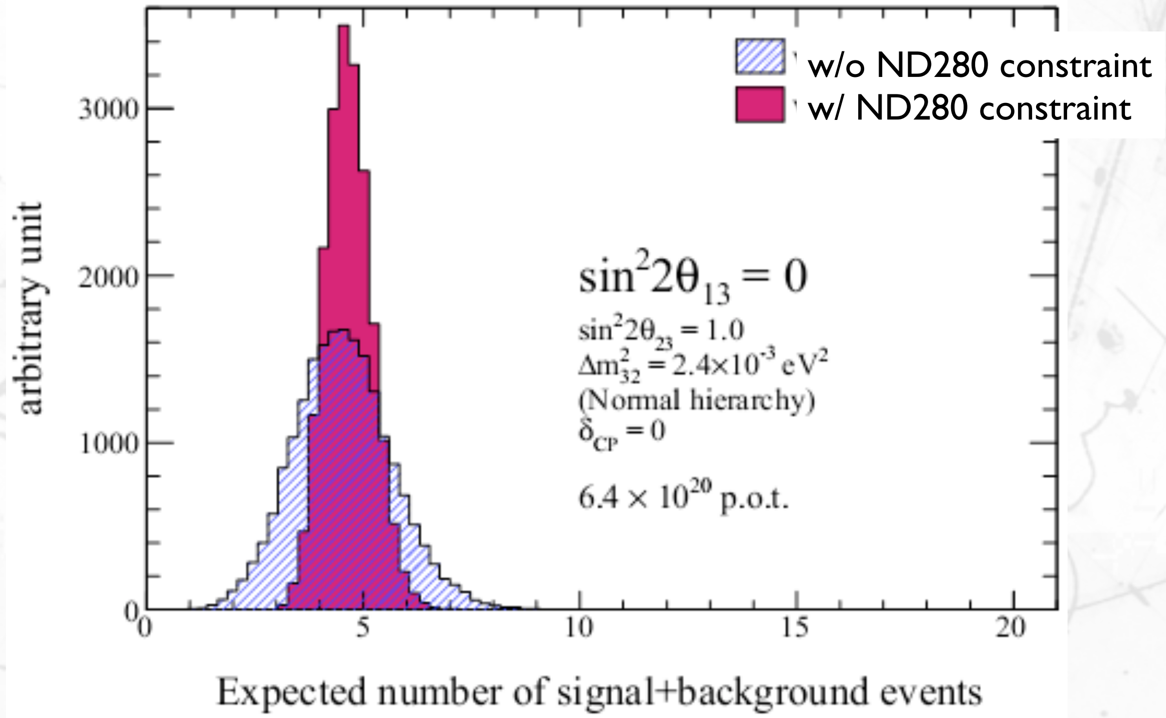
6.4×10^{20} PoT

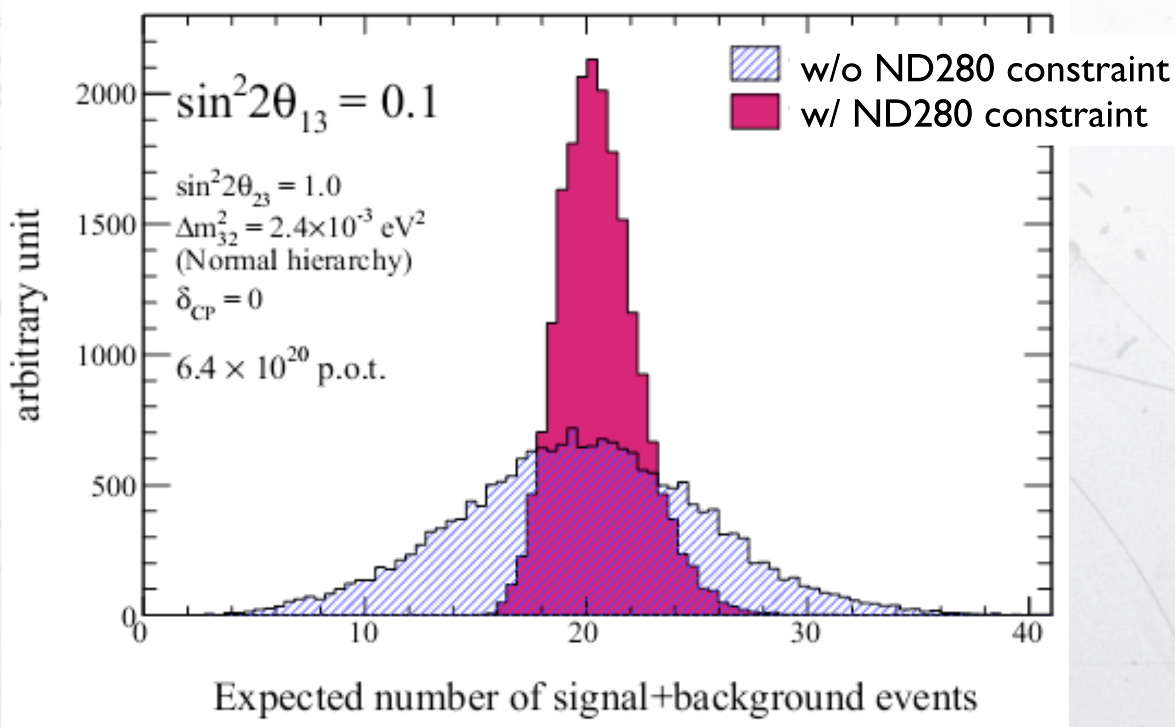
Event prediction

Event cath.	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
ν_e signal	0.38	16.42
ν_e back.	3.17	2.93
ν_μ back.	0.89	0.89
$\nu_{\mu}+\nu_e$ back.	0.20	0.19
Total	4.64	20.44

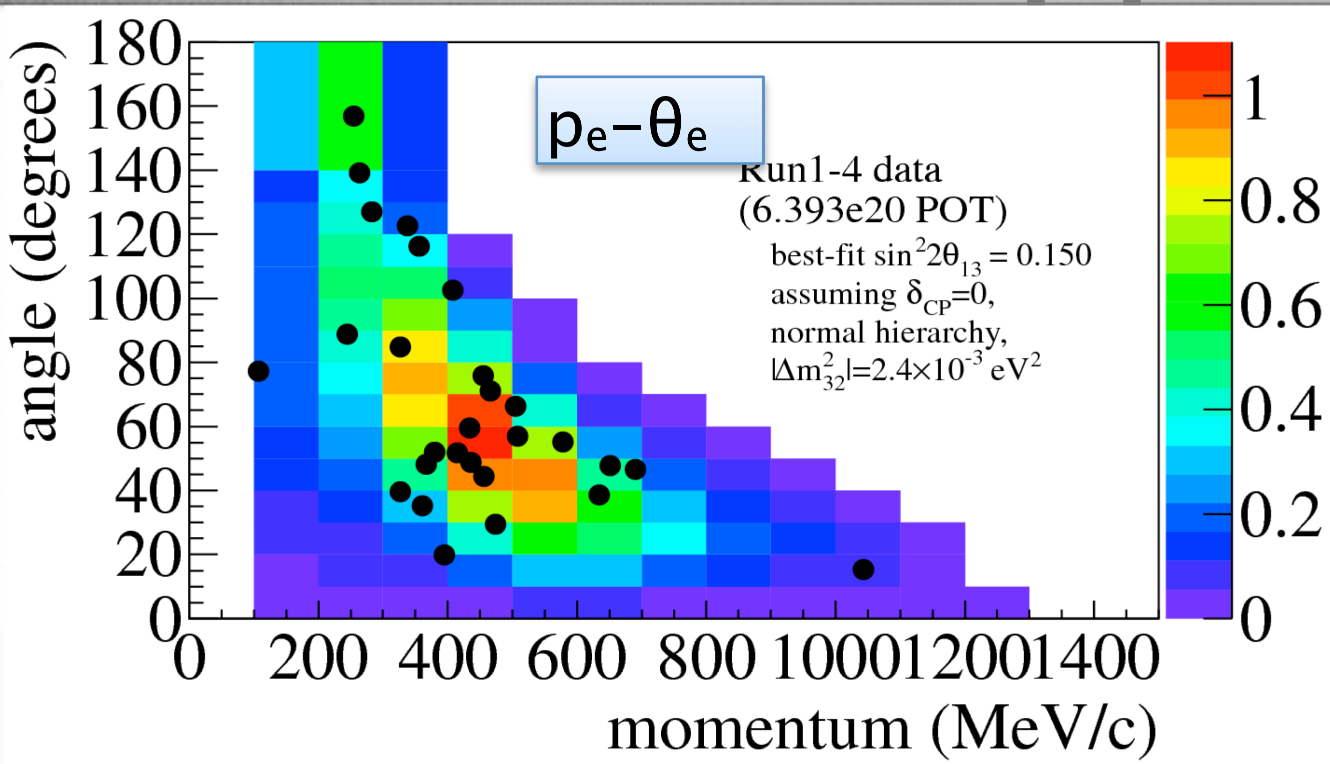
Systematic error

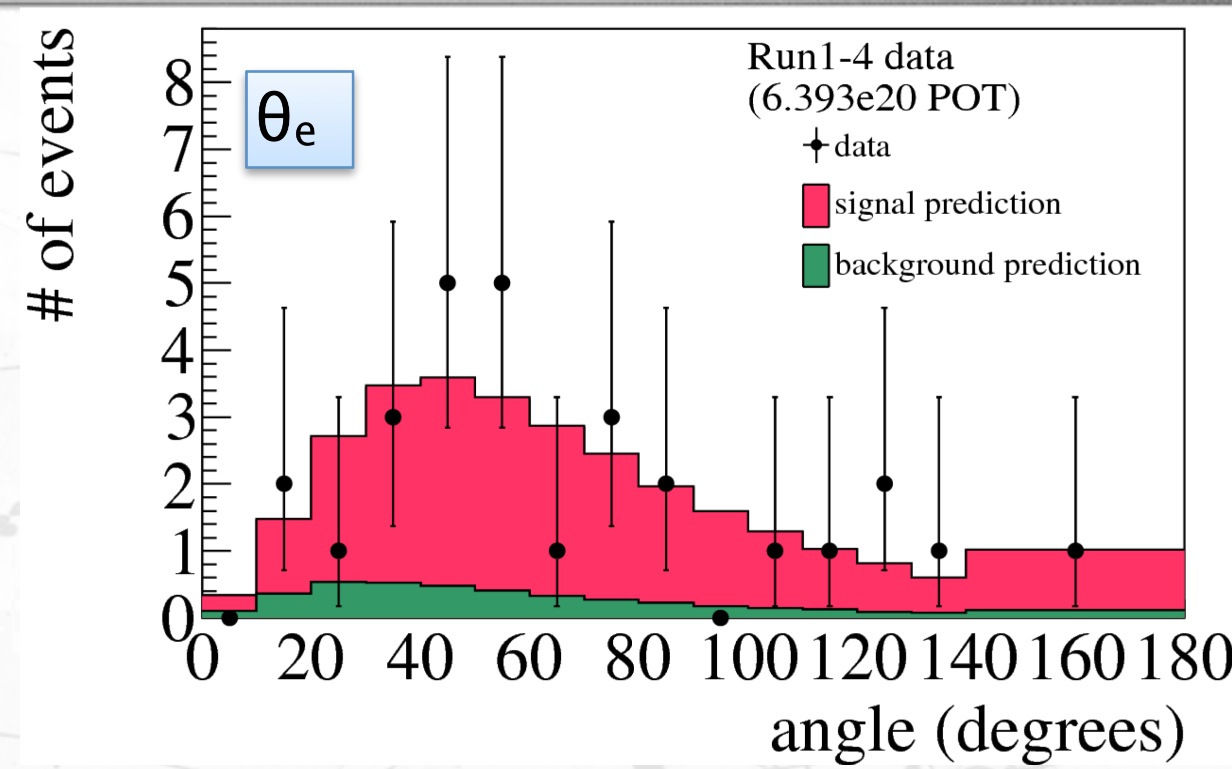
Error source	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
Beam flux and ν int	4.9%	3.0%
Far detector	6.7%	7.5%
+FSI+SI+PN	7.3%	3.5%
Total	**11.1%**	**8.8%**
Total(2012)	13.0%	9.9%

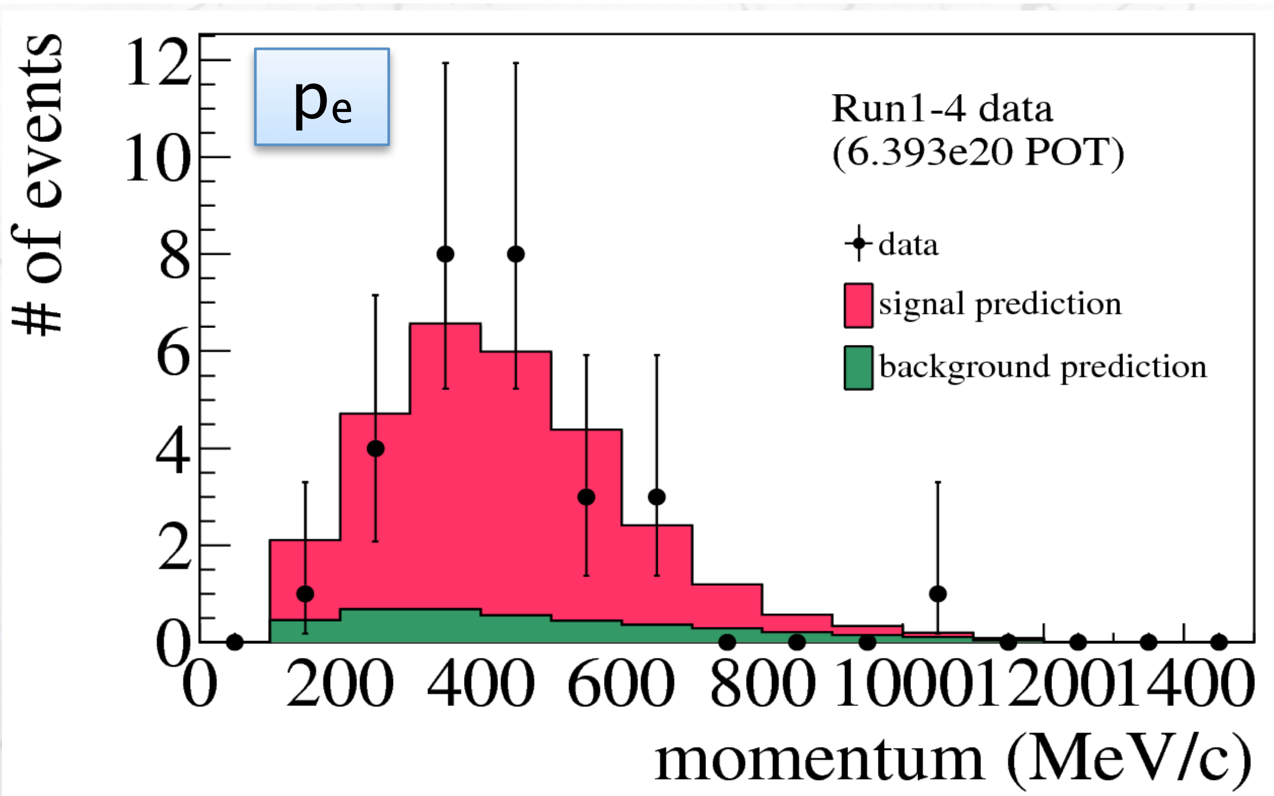




ν_e appearance







Assuming $\delta_{CP}=0$, normal hierarchy, $|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

Best fit w/ 68% C.L. error:

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

90% allowed region:

$$0.097 < \sin^2 2\theta_{13} < 0.218$$

ν_e appearance

Allowed region of $\sin^2 2\theta_{13}$
for each value of δ_{CP}

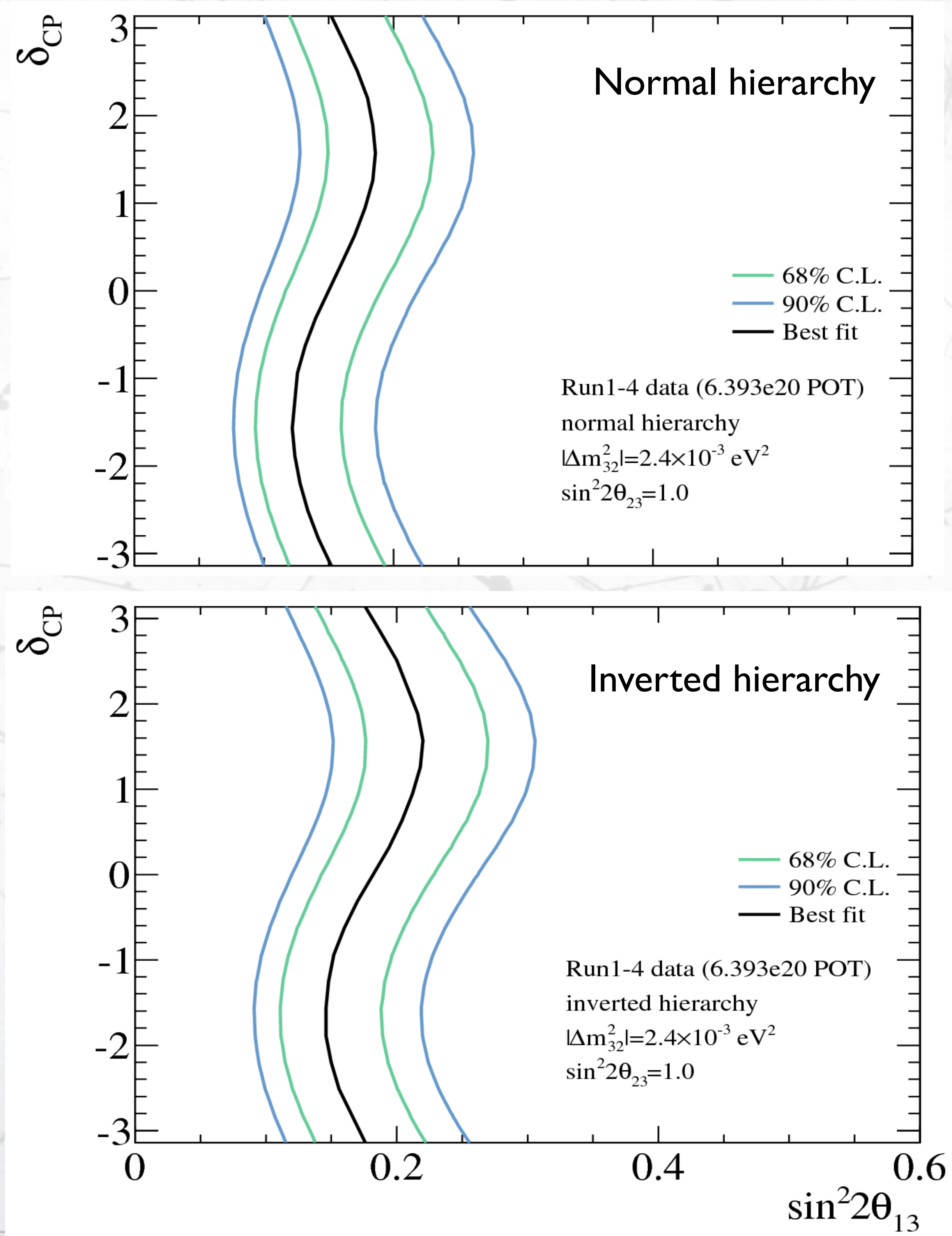
Best fit w/ 68% C.L. error @ δ_{CP}=0

Normal hierarchy: $\sin^2\theta_{13} = 0.150^{+0.039}_{-0.034}$

Inverted hierarchy: $\sin^2\theta_{13} = 0.182^{+0.046}_{-0.040}$

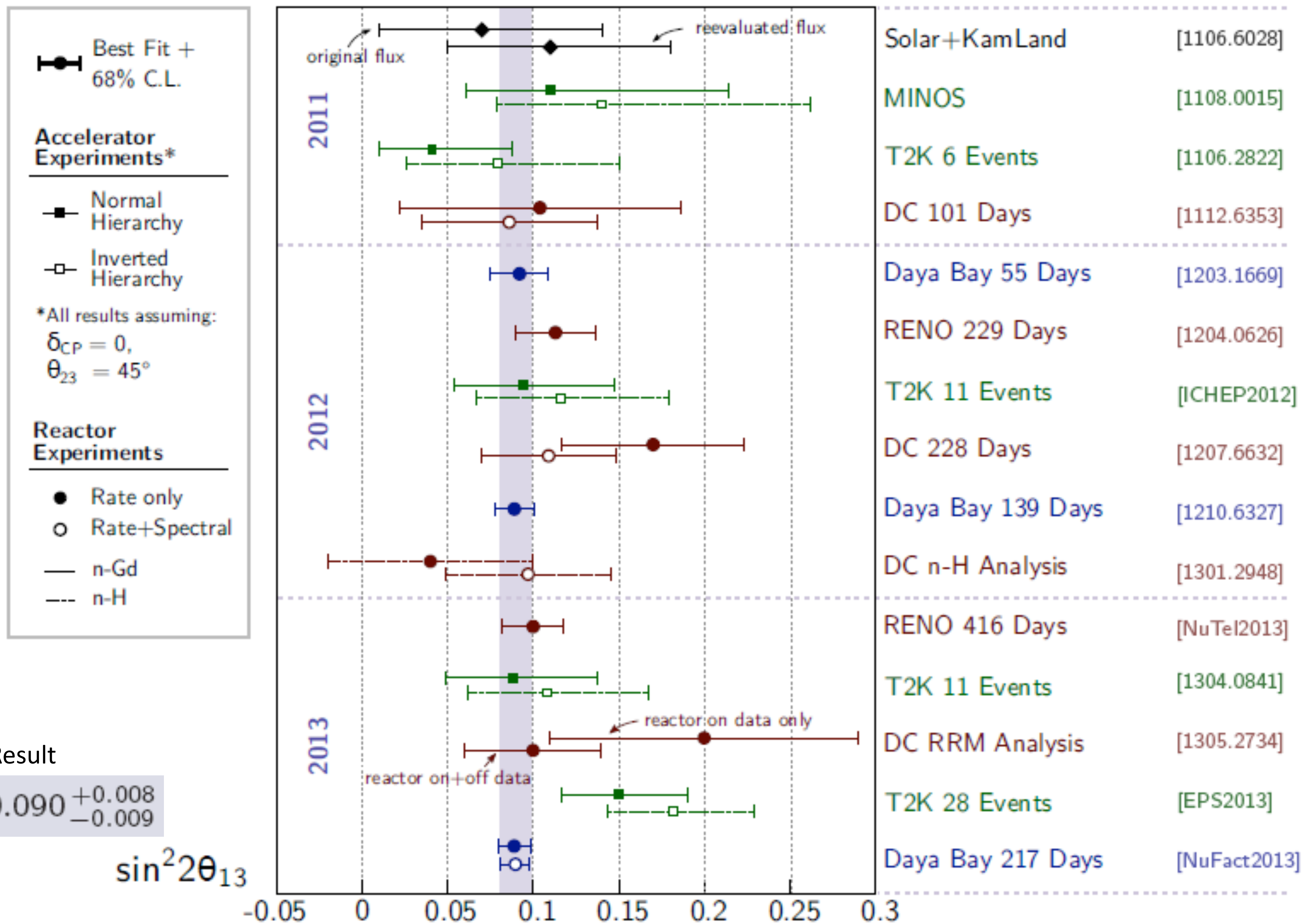
p-value is 9.9 10^{-14} (equivalent to 7.4σ)

NOTE: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space



Global θ_{13}

Compilation from Soeren Jetter (HEP), NuFact 2013



New Daya Bay Result

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

ν_e appearance

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

Best fit w/ 68% C.L. error @ $\delta_{CP}=0$

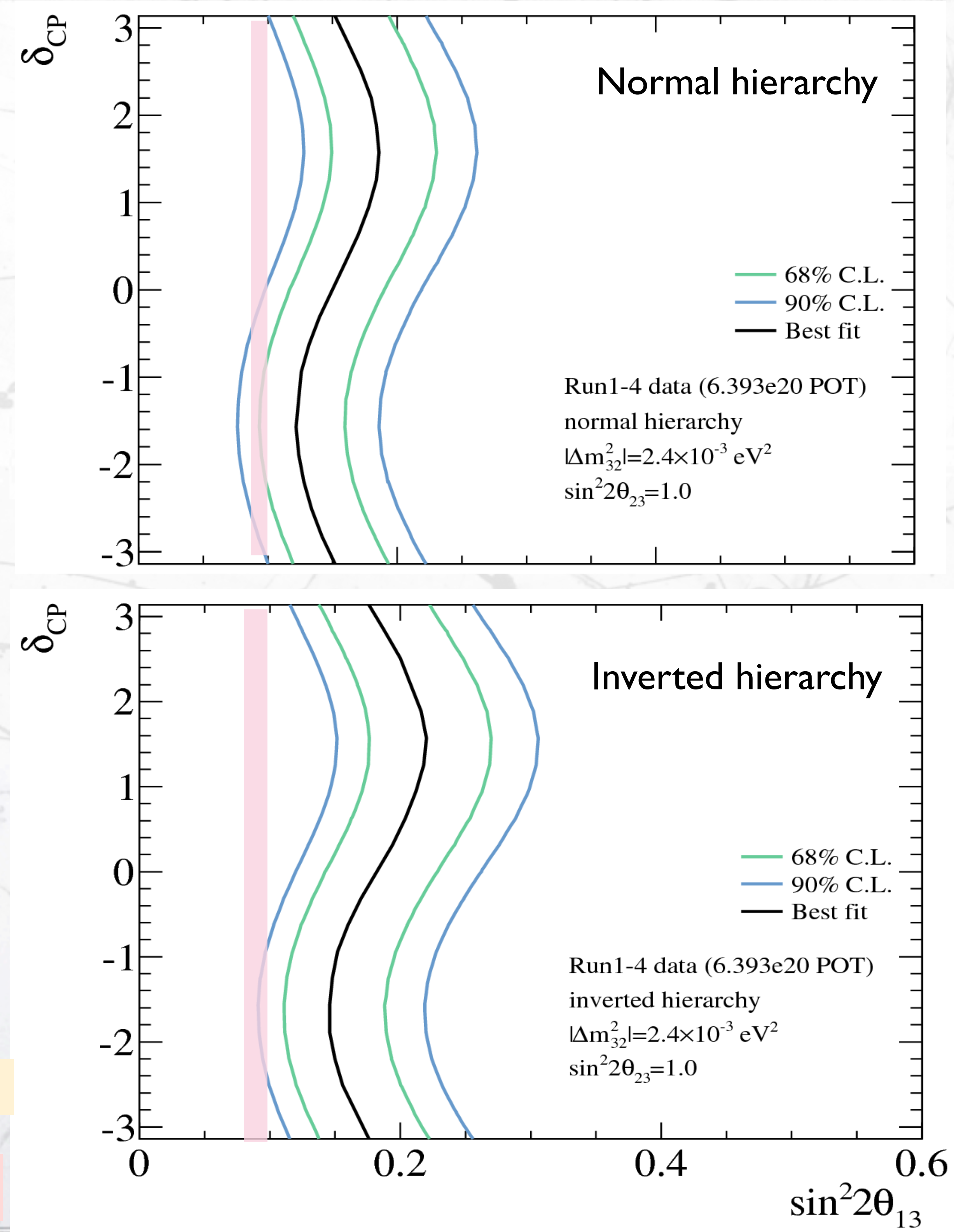
Normal hierarchy: $\sin^2\theta_{13} = 0.150^{+0.039}_{-0.034}$

Inverted hierarchy: $\sin^2\theta_{13} = 0.182^{+0.046}_{-0.040}$

p-value is 9.9 10^{-14} (equivalent to 7.4 σ)

NOTE: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

New Daya-Bay result. (NUFACT13)

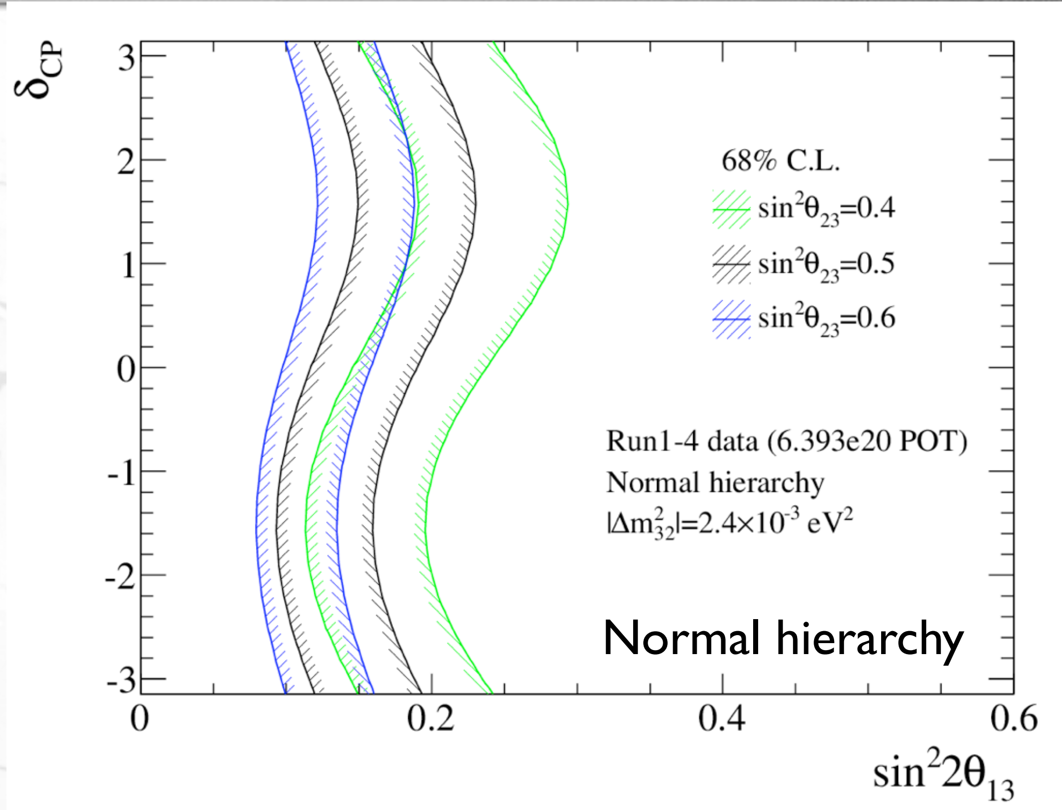


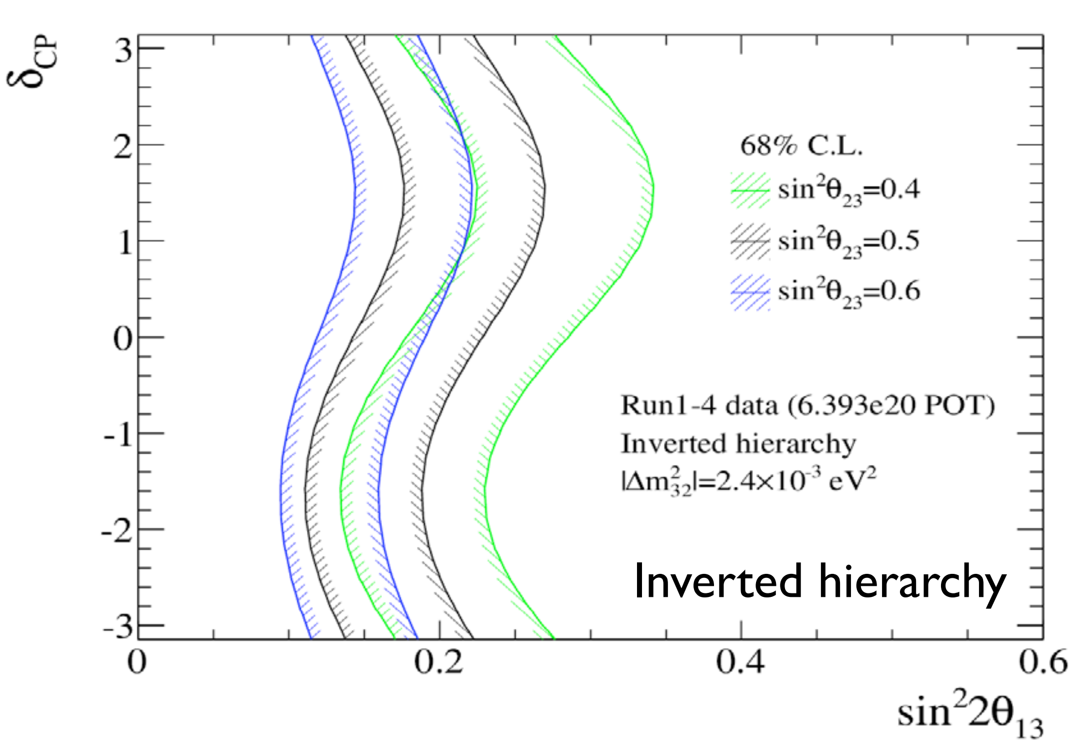
ν_e appearance

The uncertainty in the atmospheric mixing angle.

- δ_{CP} vs. $\sin^2 2\theta_{13}$ contour depends significantly on the value of $\sin^2\theta_{23}$.

- The θ_{23} octant is relevant for the future δ_{CP} vs. $\sin^2 2\theta_{13}$ sensitivity.

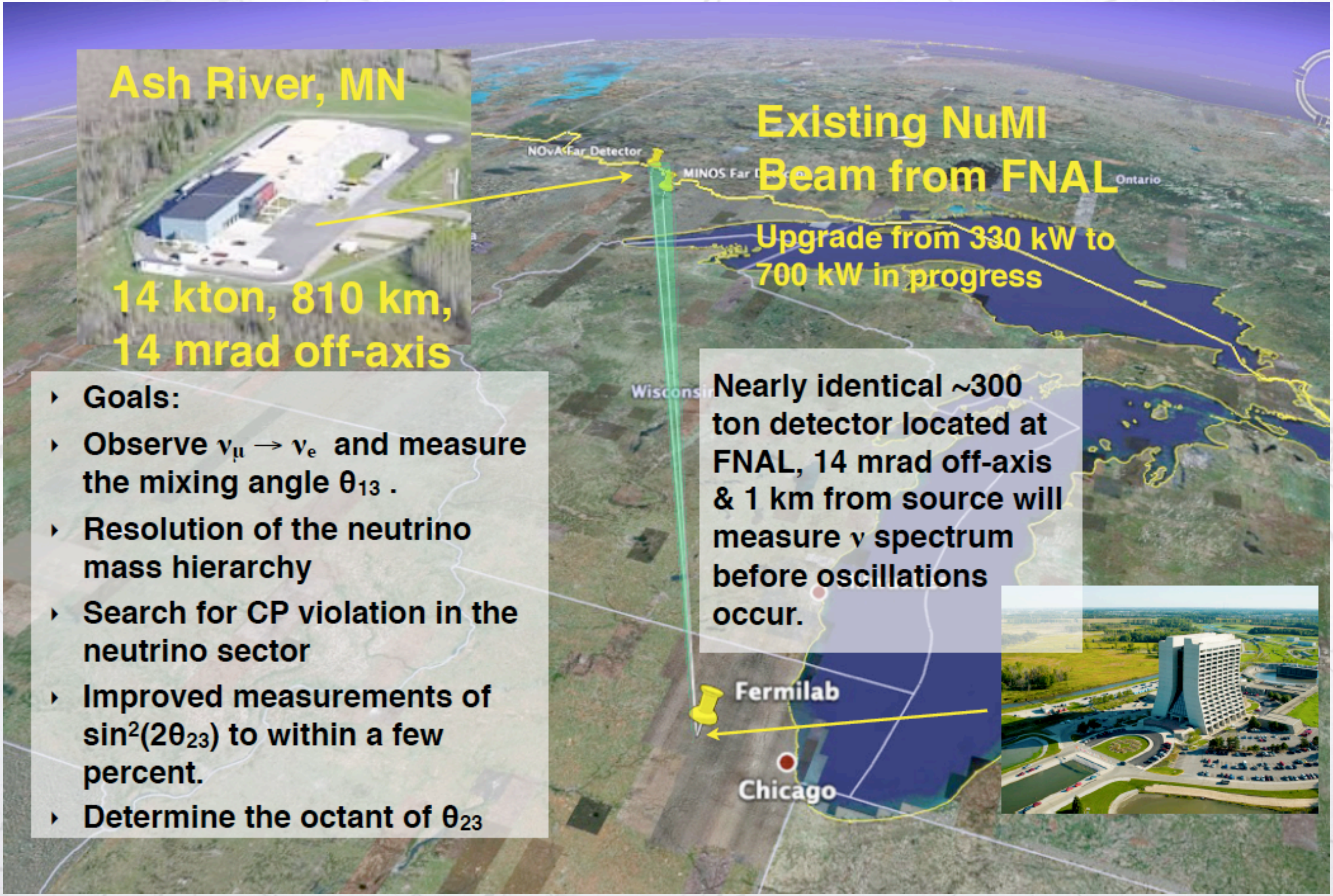




NOTE: These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

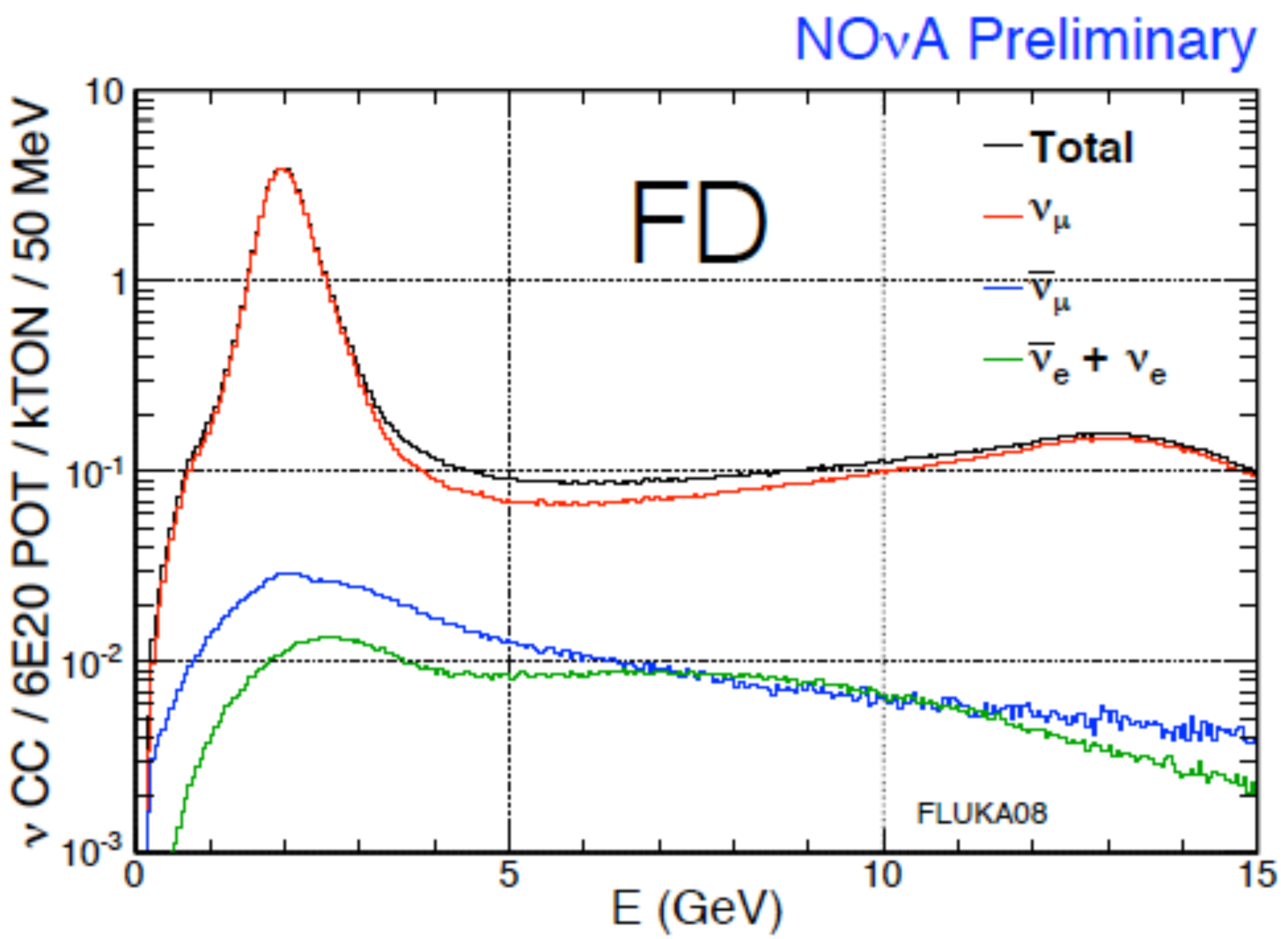
Next

Nova



- Goals:
- Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13} .
- Resolution of the neutrino mass hierarchy
- Search for CP violation in the neutrino sector
- Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.
- Determine the octant of θ_{23}

Flux

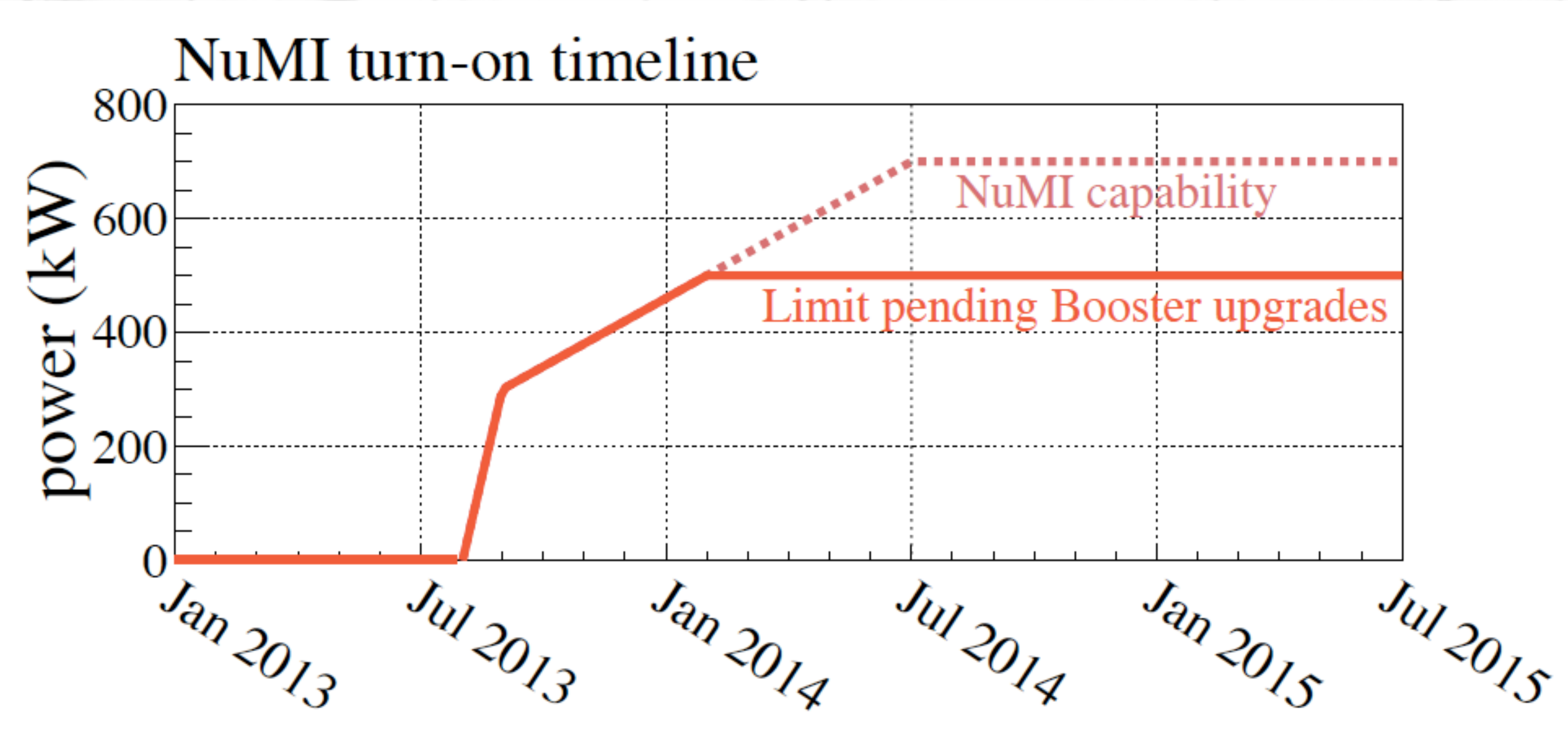


	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

[1,3]GeV: $\bar{\nu}_\mu / \nu_\mu$ = 1.6%

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 0.6%

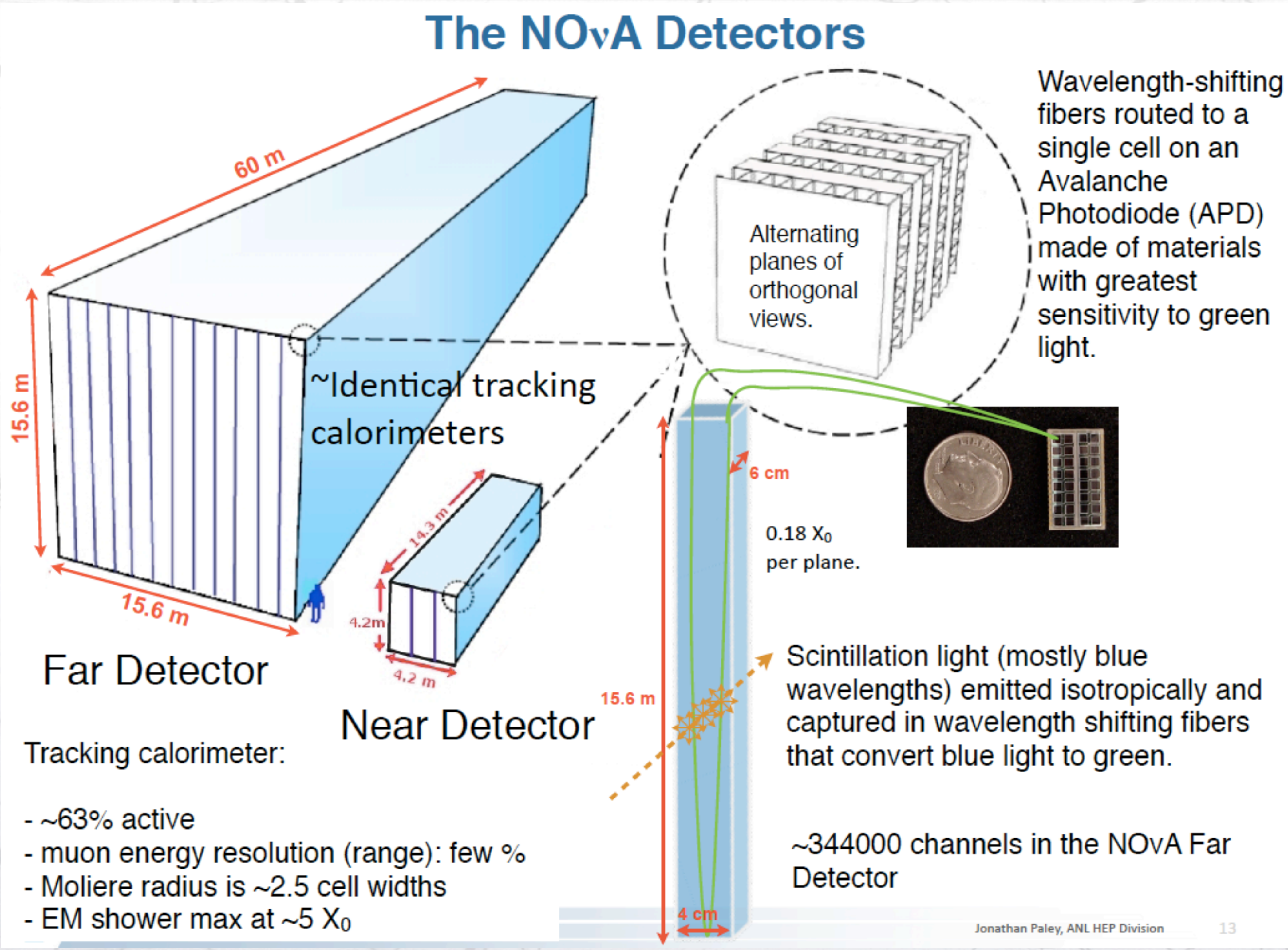
Beam status



- Commissioning of the NuMI beam has begun and will continue through end of the year
  - beam to target hall achieved Aug. 5
  - horn and target scans with beam should happen any day now
- 330 kW (pre-shutdown capability) → 500 kW achieved by use of recycler and reduction of cycle time in MI.
- Limited in short-term to ~500 kW until Booster RF system upgrades are complete.

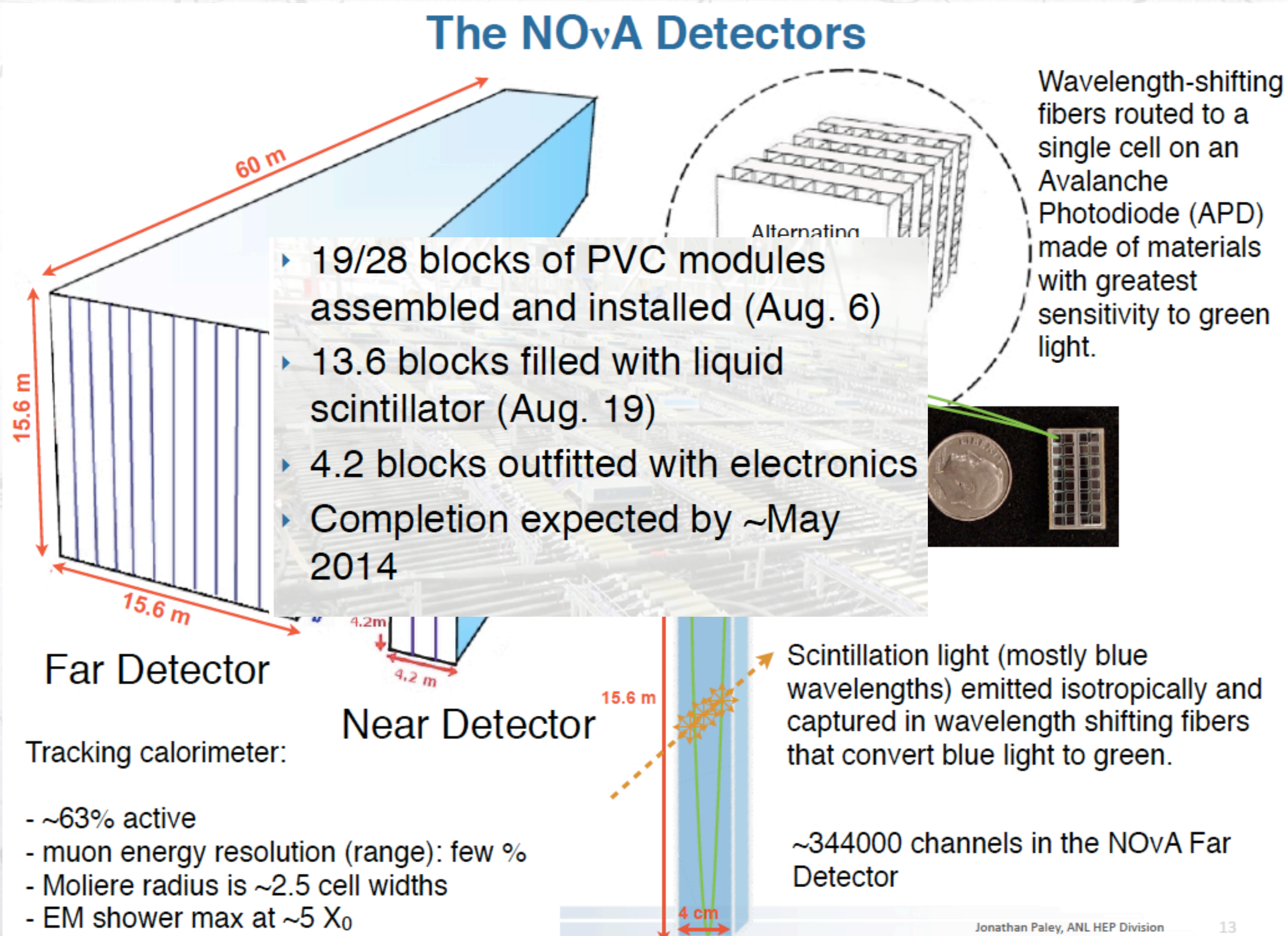
T2K might get up to 400 kW in 2014

Nova detector



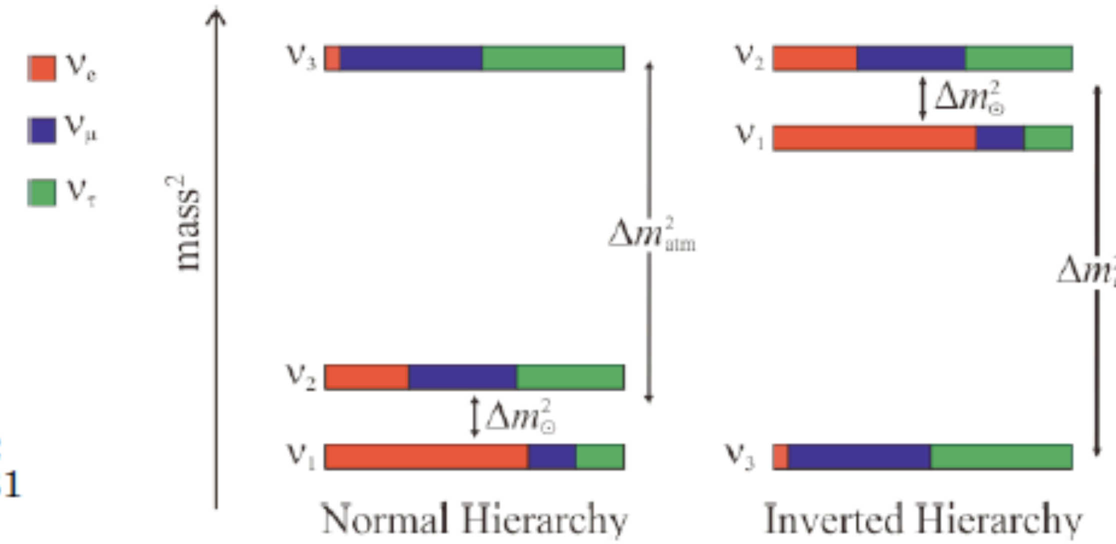
Nova detector

- 19/28 blocks of PVC modules assembled and installed (Aug. 6)
- 13.6 blocks filled with liquid scintillator (Aug. 19)
- 4.2 blocks outfitted with electronics
- Completion expected by ~May 2014



Nova oscillations

- Long-baseline $\nu_\mu \rightarrow \nu_e$ experiments have the potential to simultaneously measure θ_{13}, δ_{CP}, sign(Δm_{31}^2), sign(θ_{23}-45°):



$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$\alpha \sin 2\theta_{13} \cos \delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos \Delta_{32} -$$

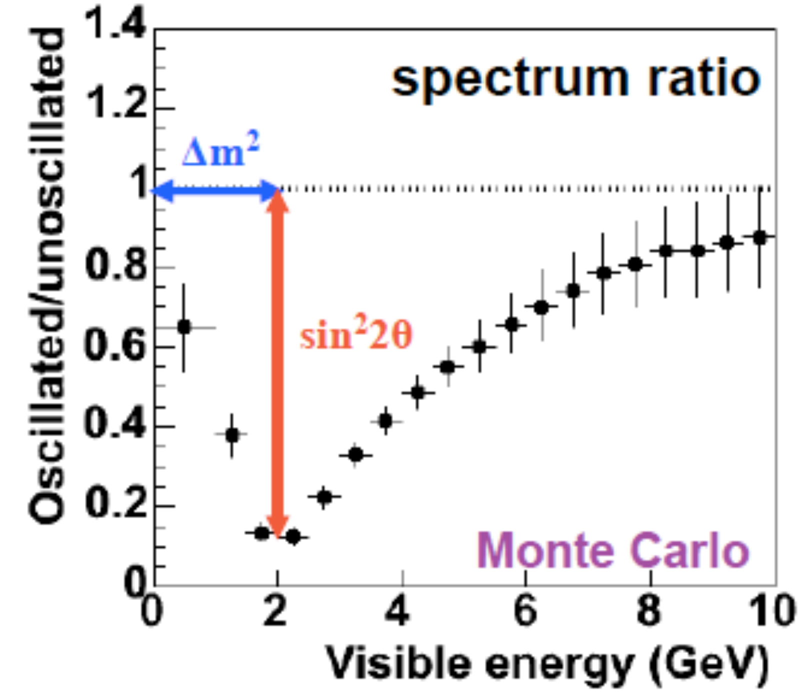
$$\alpha \sin 2\theta_{13} \sin \delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin \Delta_{32}$$

$$\Delta_{ij} \equiv \frac{1.27 \Delta m_{ij}^2 [\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

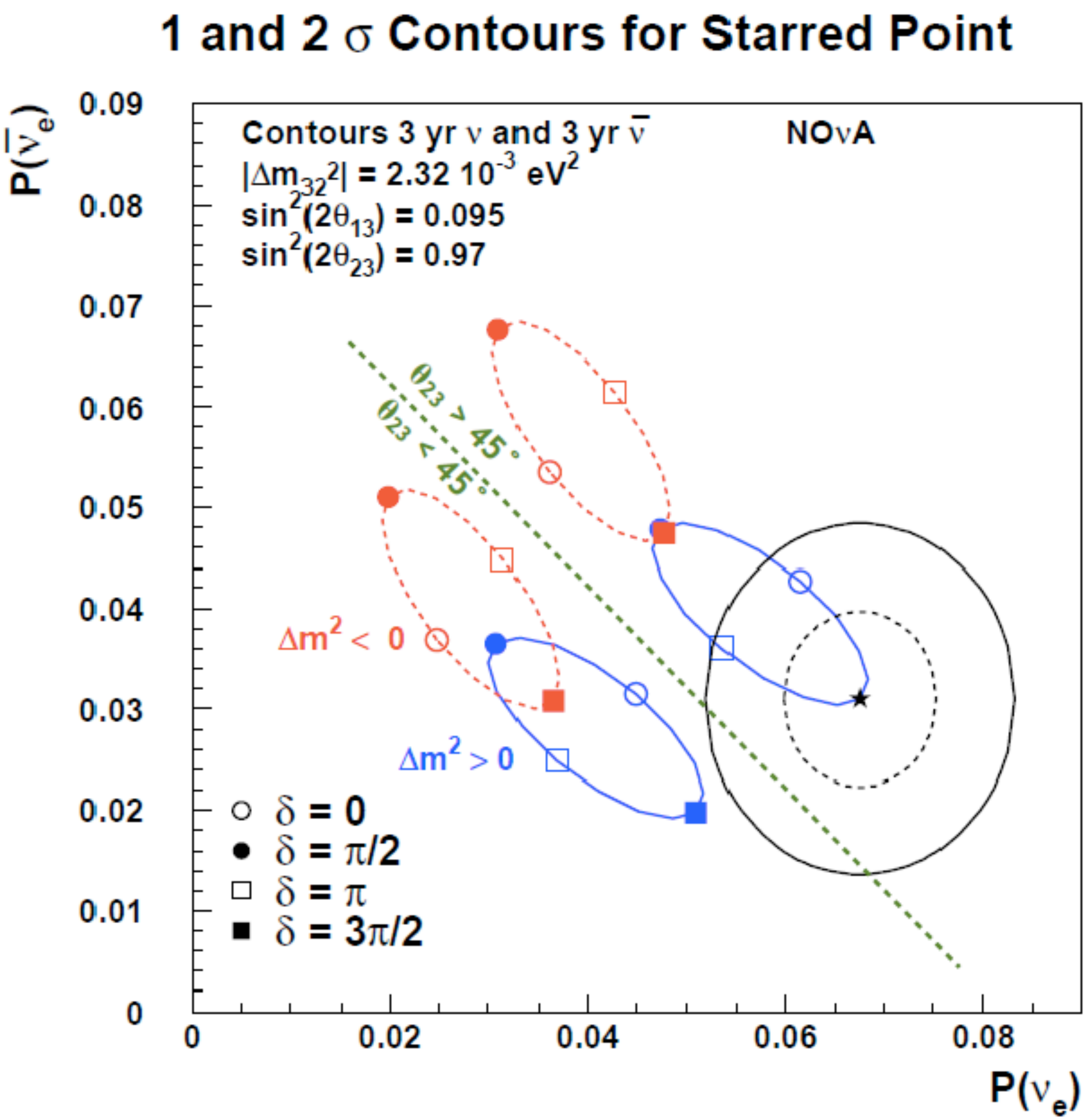
$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$ eg, in NOvA: $aL \simeq 0.23$

- Separate measurement of $\nu_\mu \rightarrow \nu_\mu$ gives access to $\sin^2(2\theta_{23})$ and Δm^2_{32}:

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2 \left(1.27 \Delta m_{32}^2 \frac{L}{E}\right)$$



NoVa oscillations



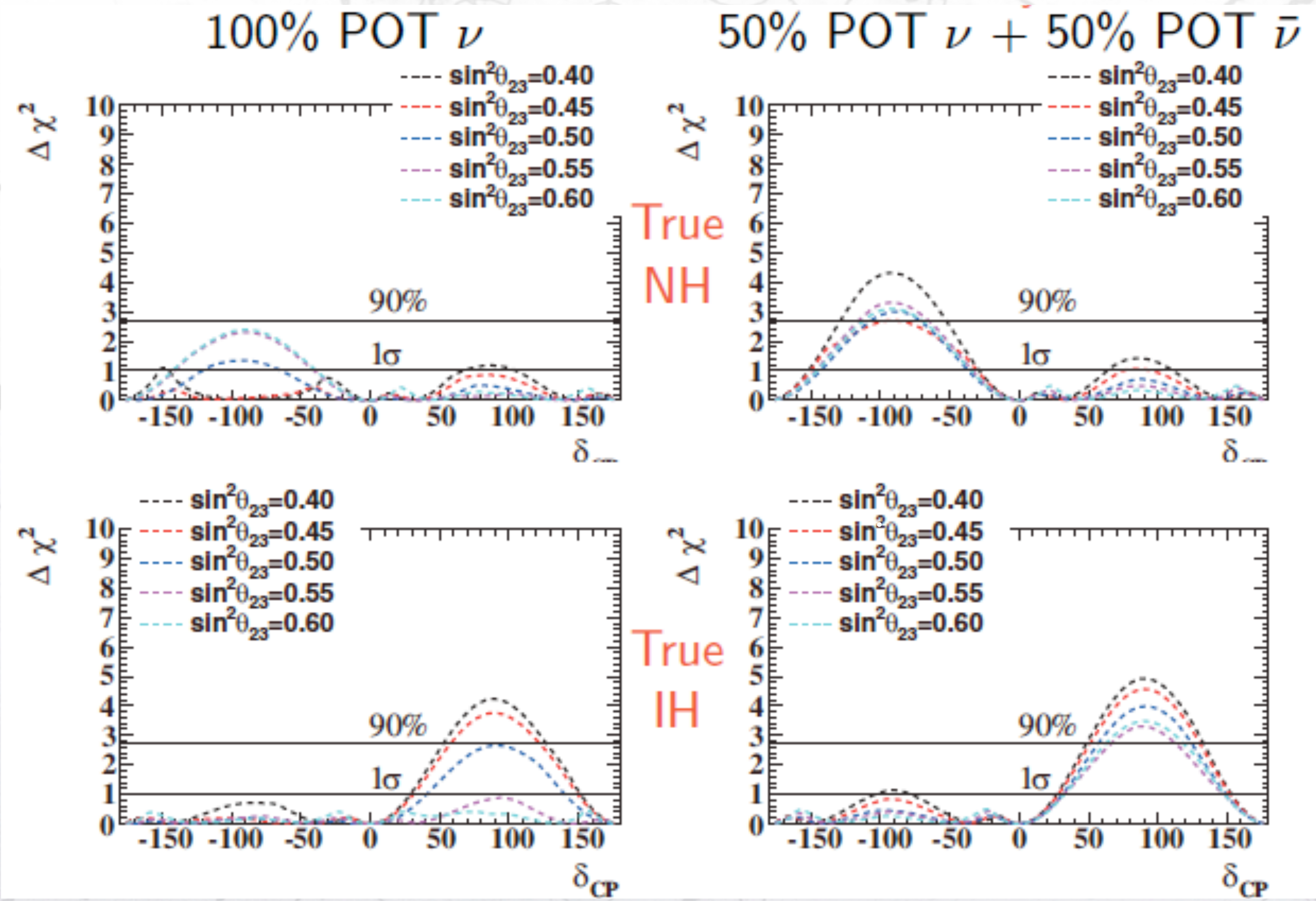
- The strategy in NOνA is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to extract mass hierarchy and first information on δ_{CP}
- Precision measurement of $\sin^2(2\theta_{23})$ from $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- If θ_{23} is non-maximal, then we also have the capability of determining the octant; this tells us whether or not ν_μ couples more strongly to ν_2 or ν_3.

Potential of Nova & T2K

Future δ_{CP} sensitivity

7.8×10^{21} PoT + 2012 systematics

T2K



T2K + reactor

Assumptions

$$\sin^2 2\theta_{13} = 0.1$$

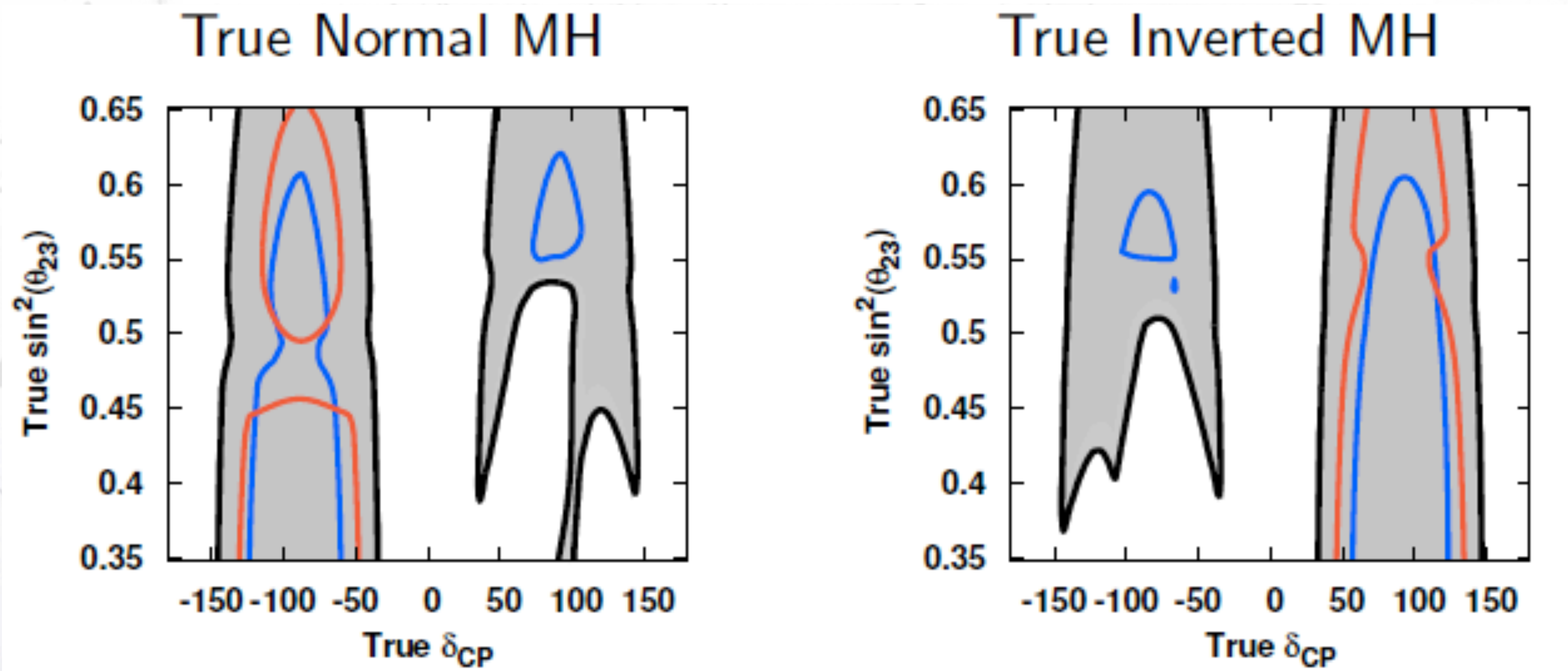
$$\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$$

$$\delta(\sin^2\theta_{13}) = 0.005$$

Future δ_{CP} sensitivity

T2K + Nova + reactor

Region where δ_{CP} can be discovered with 90% C.L.



$50\%\nu + 50\%\bar{\nu}$

T2K alone

Nova alone

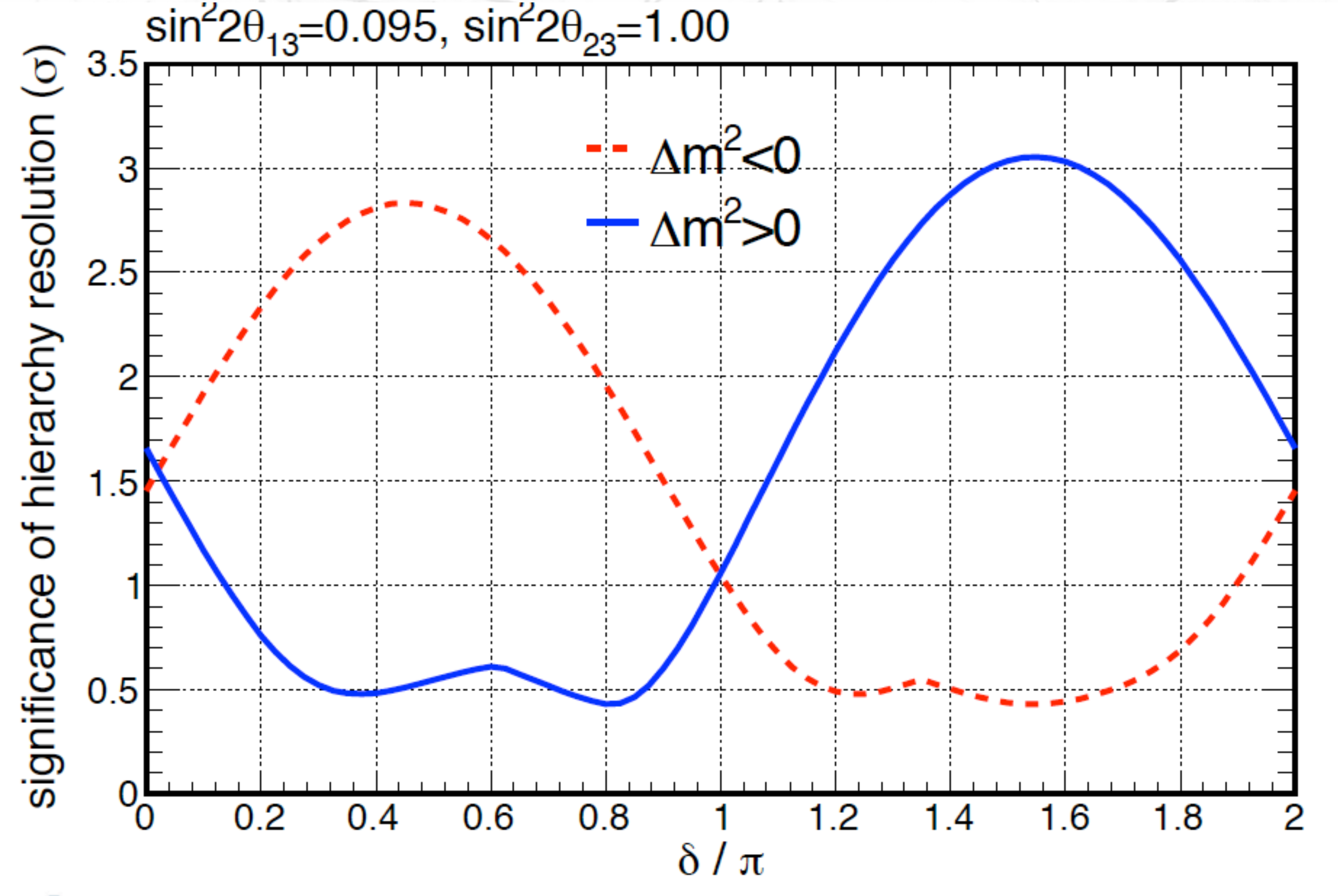
T2K+ Nova

Assumptions

$$\sin^2 2\theta_{13} = 0.1$$
$$\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$$
$$\delta(\sin^2\theta_{13}) = 0.005$$

$\oplus$ simple normalisation errors.

Future hierarchy sensitivity



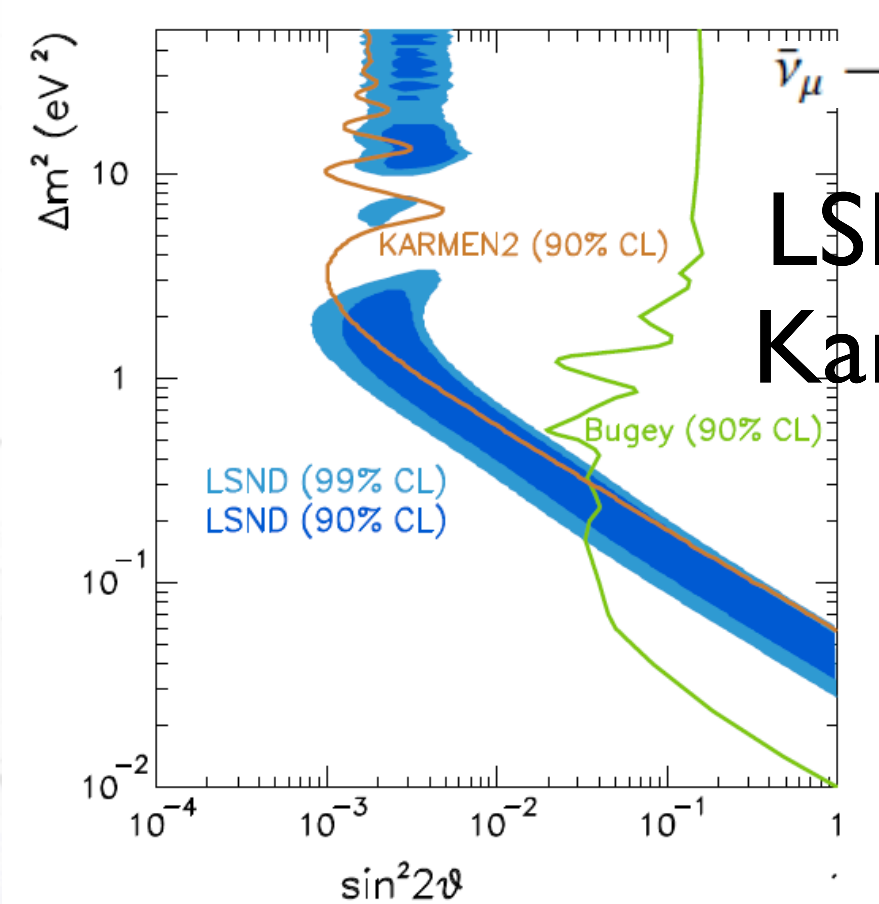
A word on steriles

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

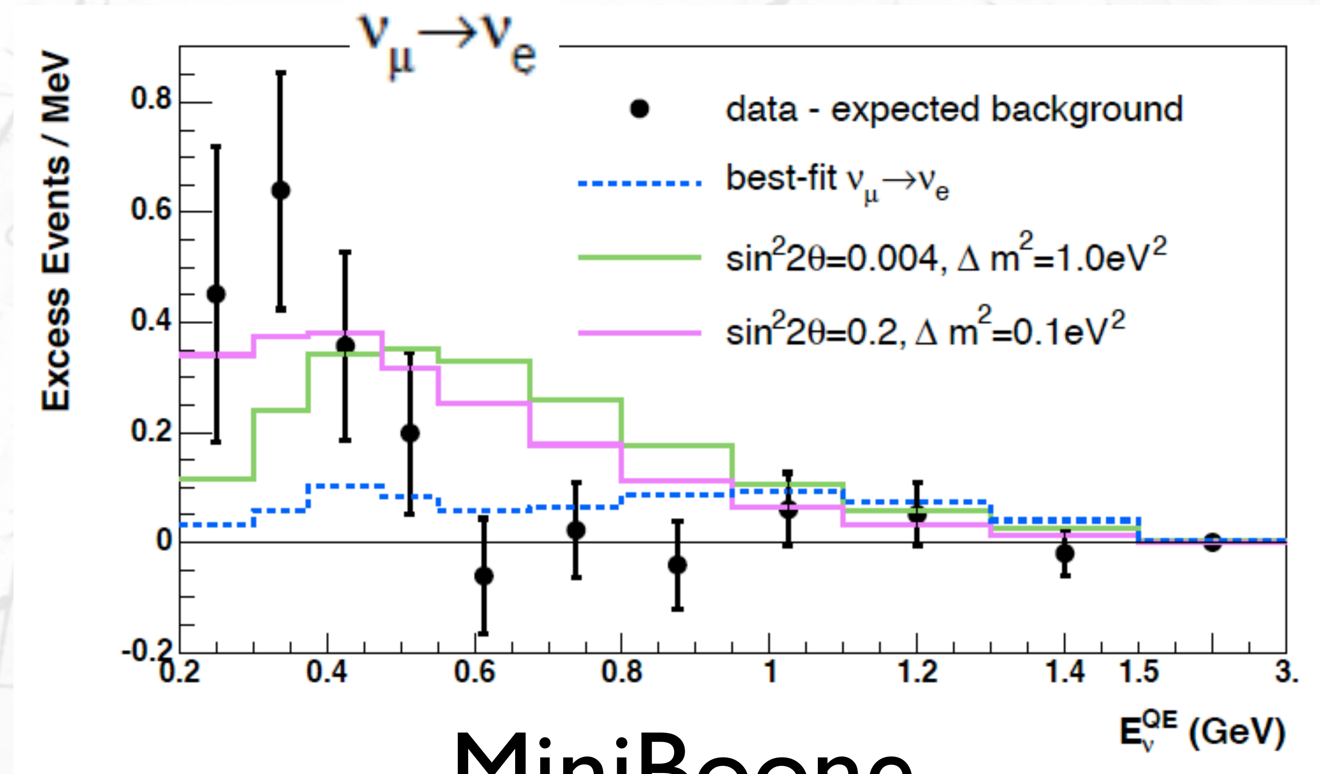
All you (might) want to know about steriles:

arXiv:1204.5379v1 [hep-ph]

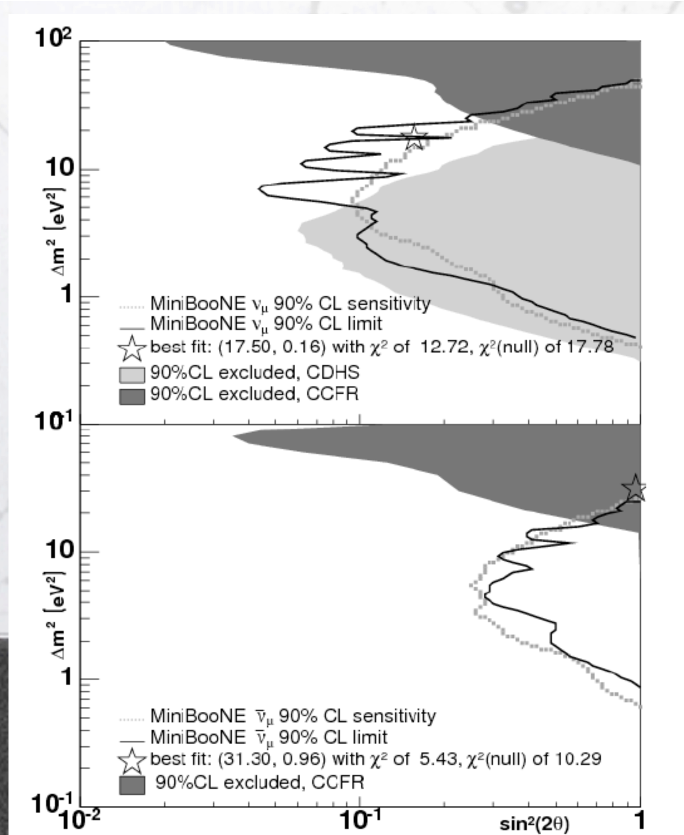
Steriles

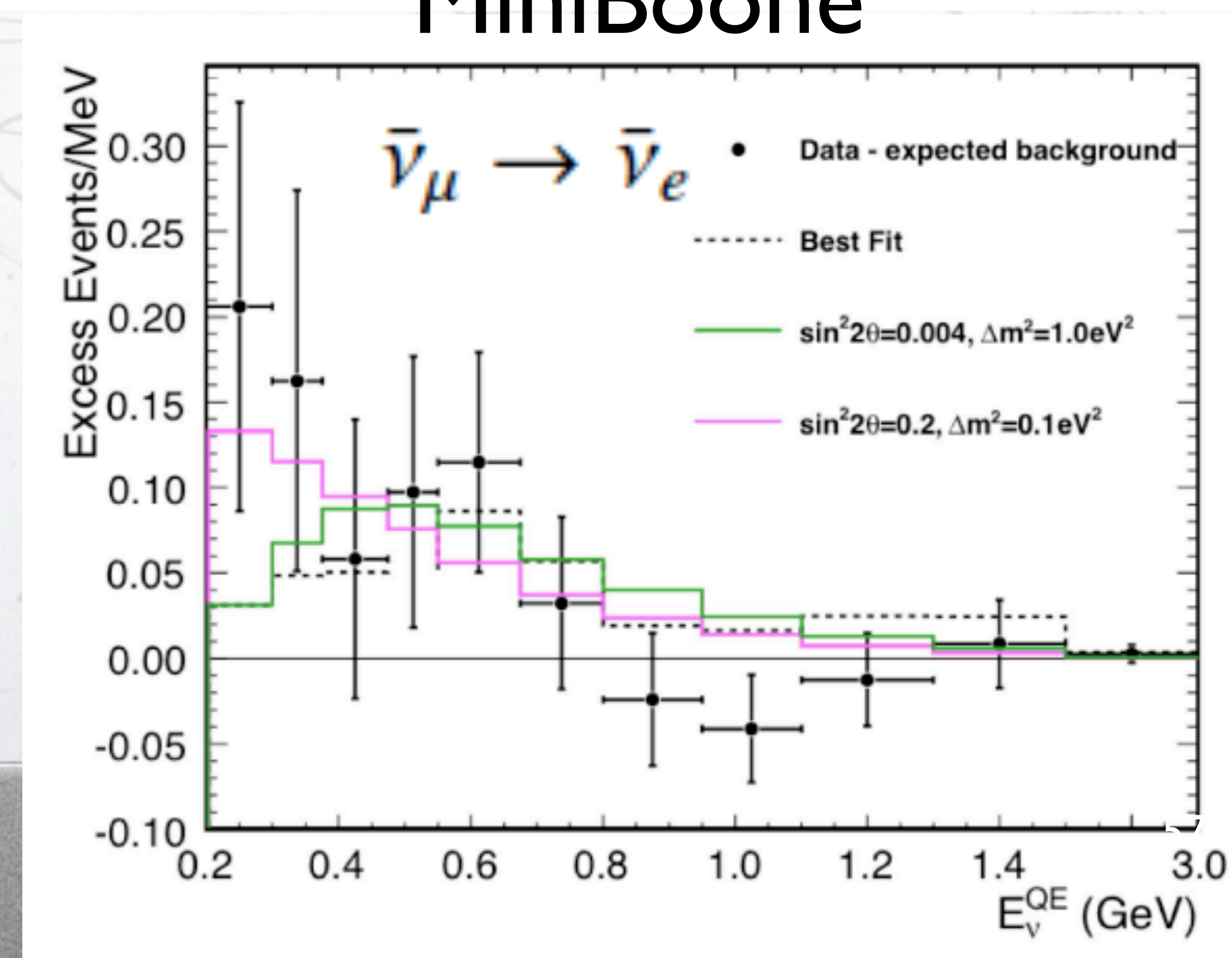


LSND
Karmen



MiniBoone





Next to Next Long Base Line experiments

T2K-H

LBNE

LBNO
LAGUNA

What's next

- It is not obvious T2K+Noνa will resolve the mass hierarchy + CP violation.
  - Mass hierarchy might be addressed with LBL + ν atmospheric experiments (INO, Pingu,SK,etc…)
  - CP violation seems to be reachable "only" by long base line experiments (initial conditions are relevant).

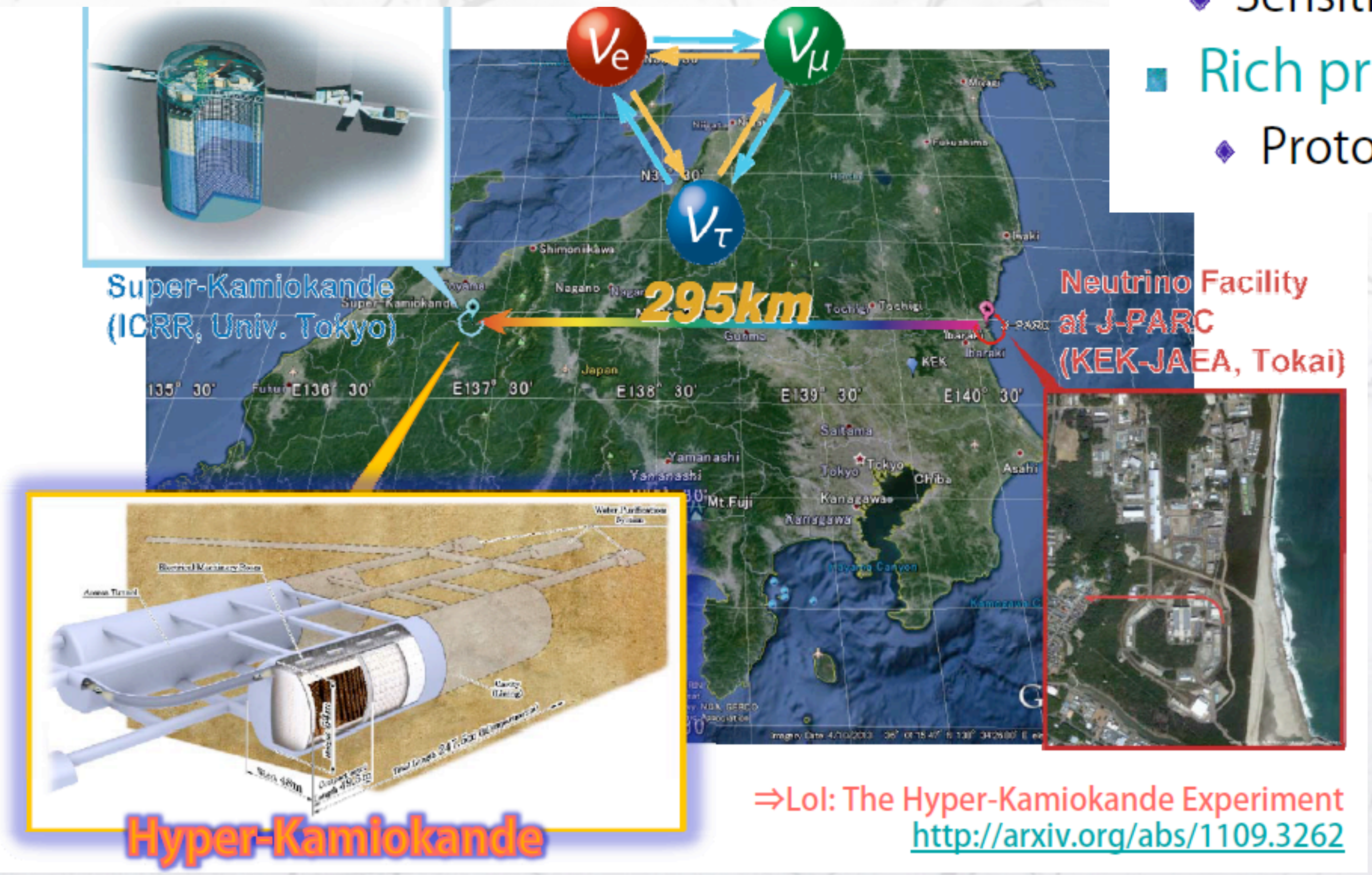
Large uncertainties in their capabilities

- Two approaches:
  - Short base line, no matter effects, large statistics for CP but no hierarchy. **T2HK**
  - Long base line, matter effects + 2 oscillation peaks for CP and matter effects. **LBNE-LBNO**

T2HK

- Natural extension of the technique being proven by the success of T2K
  - Off-axis narrow band beam, E_ν~0.6GeV, 750kW~1MW
  - Hyper-Kamiokande: HUGE water Cherenkov detector
- Mainly focus on measurement of CP asymmetry
  - 295km baseline (=less matter effect)
- Complementary to >1,000km baseline experiments (LBNE/LAGUNA-LBNO)
  - Sensitivity (CP/MH), technology (WaterC./Liq.Ar)
- Rich programs with both near and far detectors
  - Proton decay / atm. ν / solar・SN ν / ν interaction…

Moderate acc power of 1MW. Rely on huger mass



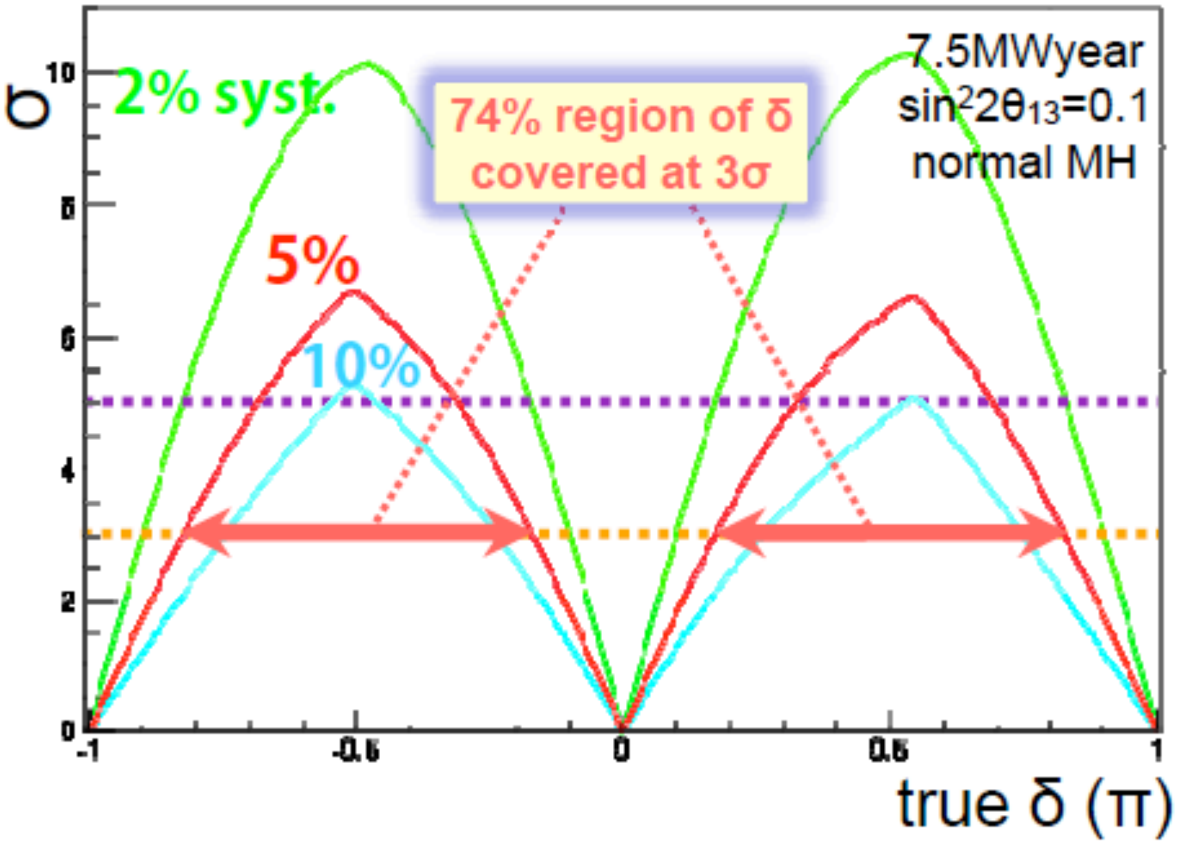
⇒LoI: The Hyper-Kamiokande Experiment
http://arxiv.org/abs/1109.3262

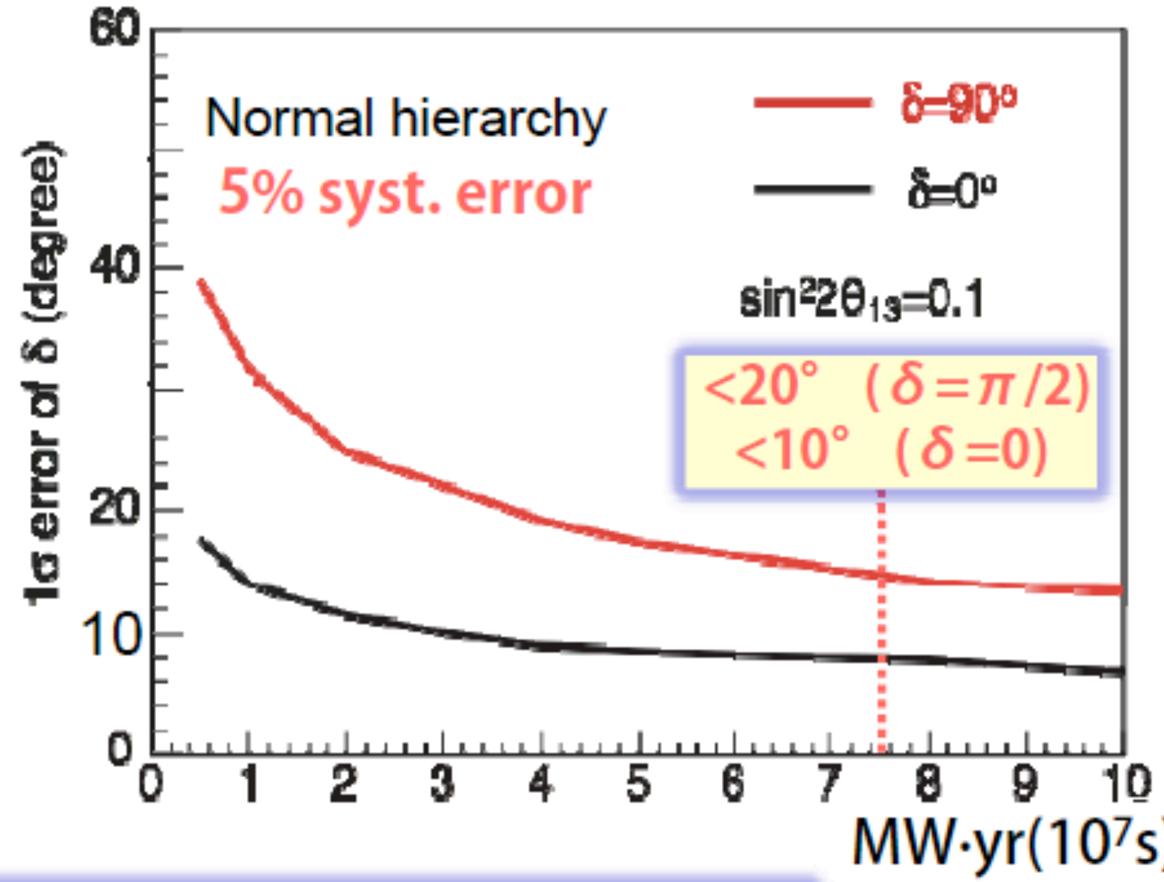
This is basically a gigantic T2K

my view

+ statistics
+ known technology
- no matter effects, no hierachy

T2HK





High sensitivity to CPV w/ <~5% sys. Error

- To go to CPV discovery, intensity upgrade of J-PARC is the key together with the efforts to reduce systematic errors
- Required run-time in LOI: 7.5MW x years
  - 750kW (J-PARC MR design power): 10 years = 3yr x ν + 7yr x ν bar

5% syst is what T2K expects!!!

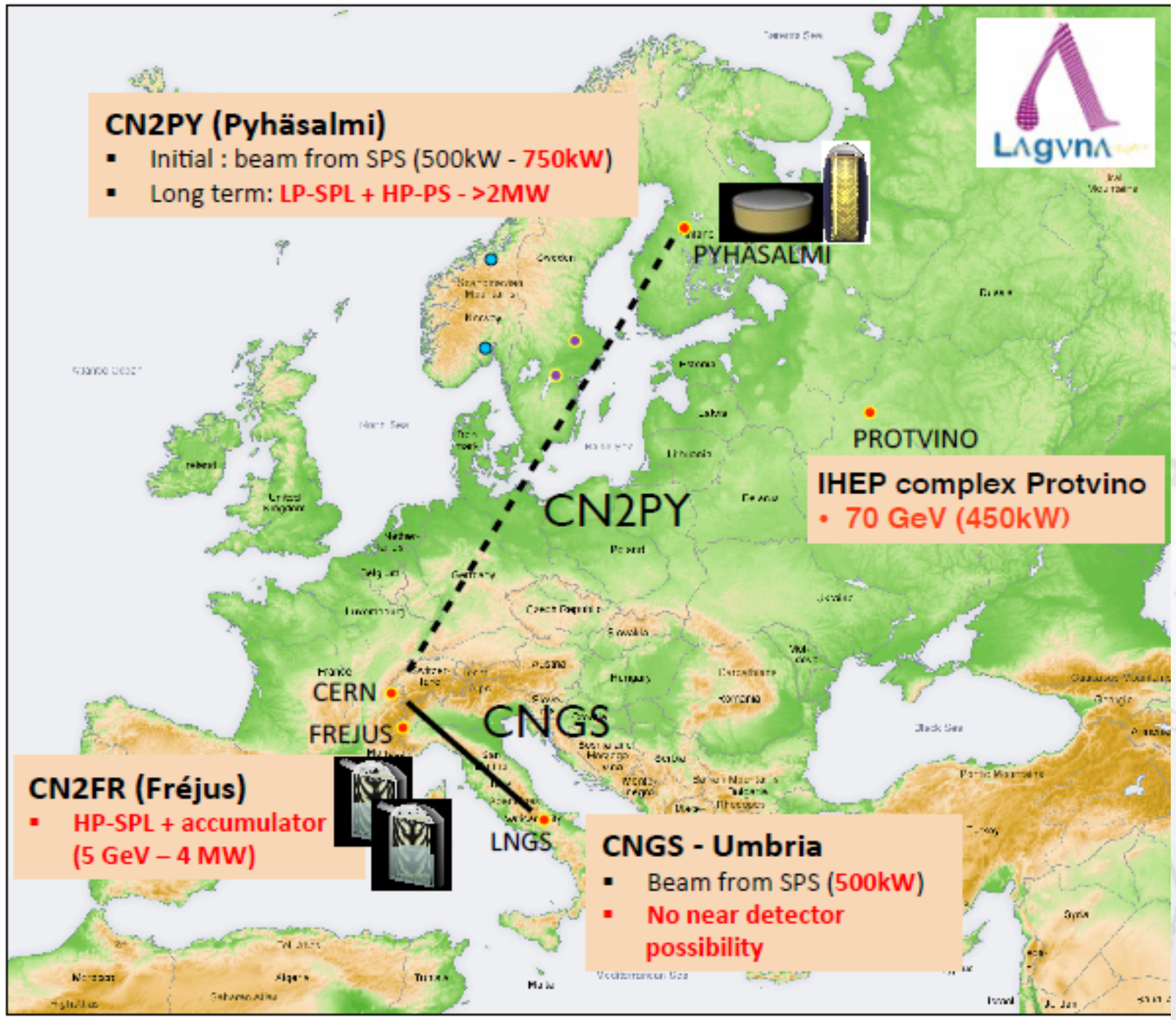
LBNO

LAGUNA-LBNO: sites overview

Three far sites considered in details

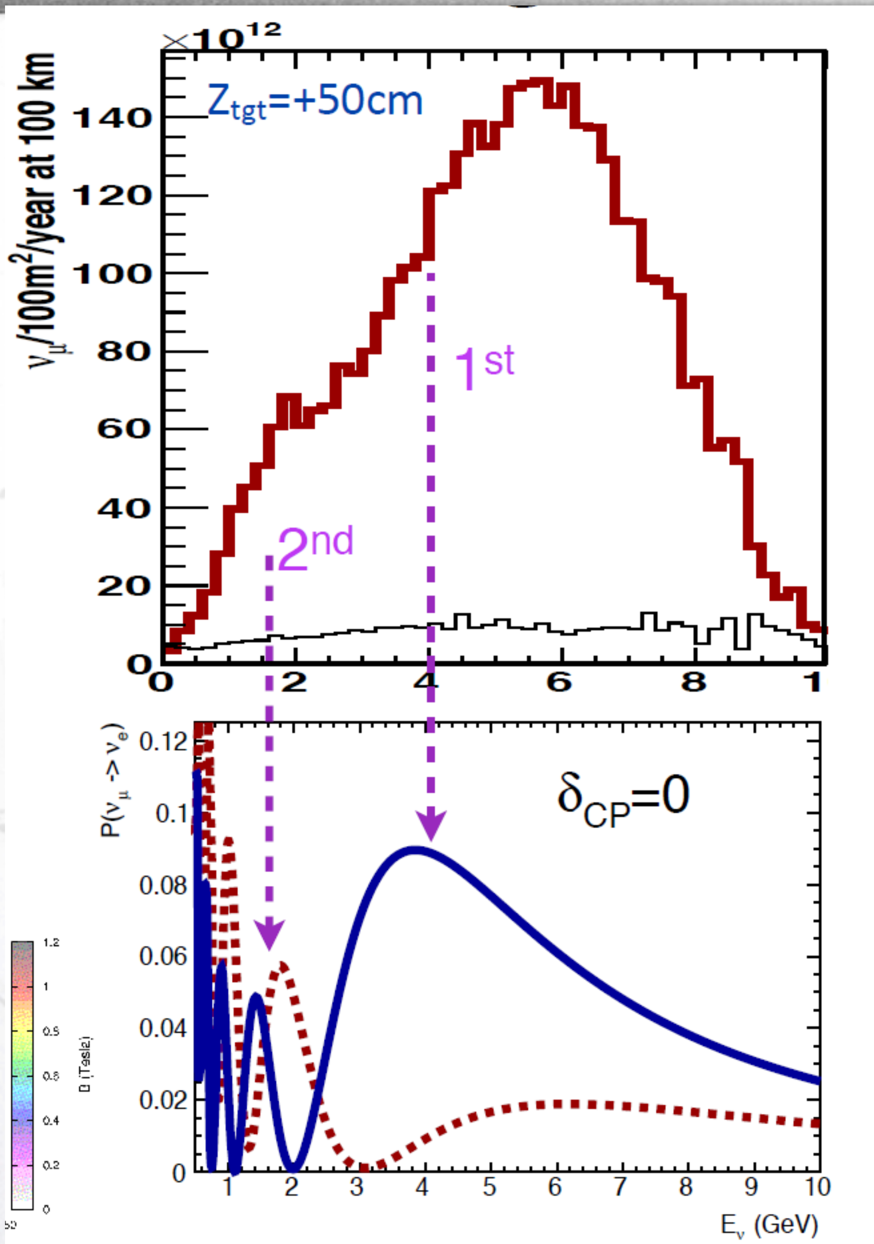
arXiv:1003.1921 [hep-ph]

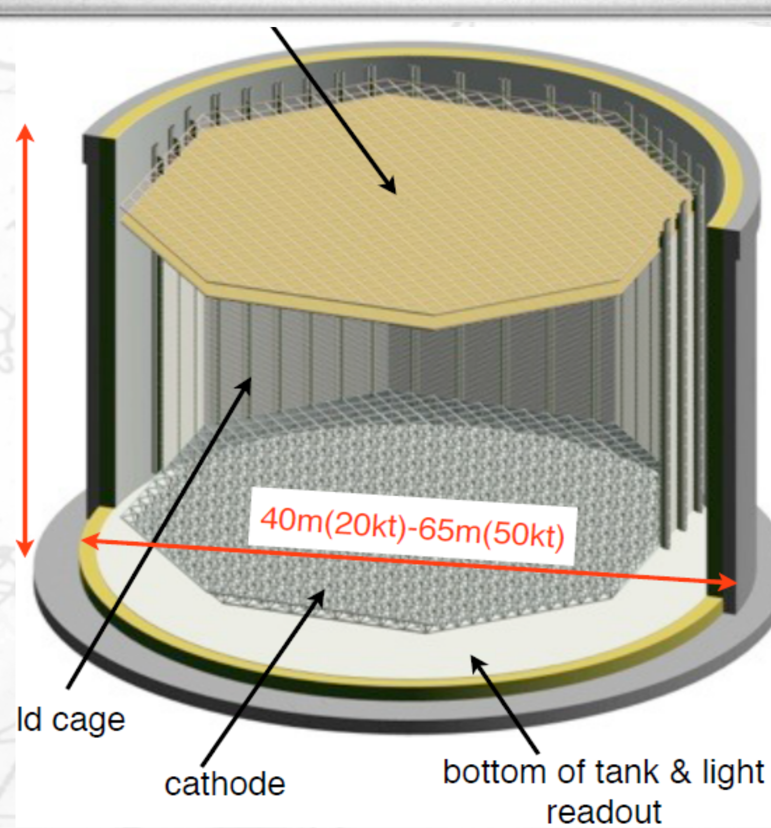
- **Option 1: Pyhäsalmi mine** (privately owned), 4000 m.w.e overburden, excellent infrastructure for deep underground access
- **Option 2: Fréjus**, nearby road tunnel, 4800 m.w.e. overburden, horizontal access
- **Option 3: Umbria** (LNGS extension), green site with horizontal access, 2000 m.w.e., CNGS off-axis beam
- **Protons and beams:**
  - Design of new CERN conventional neutrino beam to Finland (CN2PY) Baseline = 2300 km
  - Upgrades of CERN SPS to 700kW
  - New CERN HP-PS (2MW@50 GeV)
  - Recently: assessment of a new conventional beam coupled to accelerator upgrade at Protvino, Russia (OMEGA project) – Baseline = 1160 km

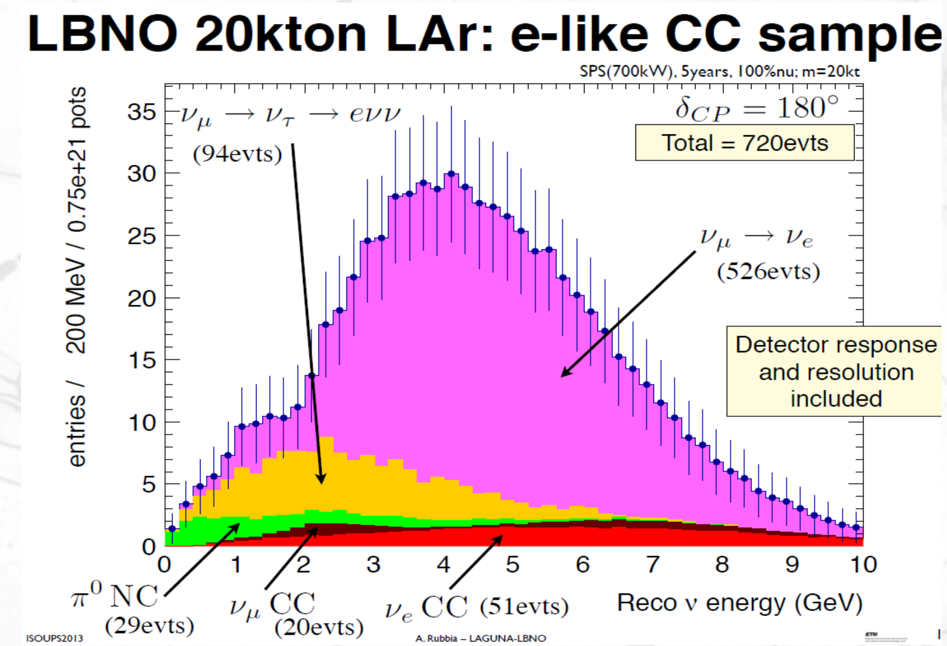


- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

LBNO







1st phase with 20 kt LiqAr
2nd phase with 50 kt or 100 kT LiqAr
Power from 700kW to 2MW
2300 km base line

LBNO

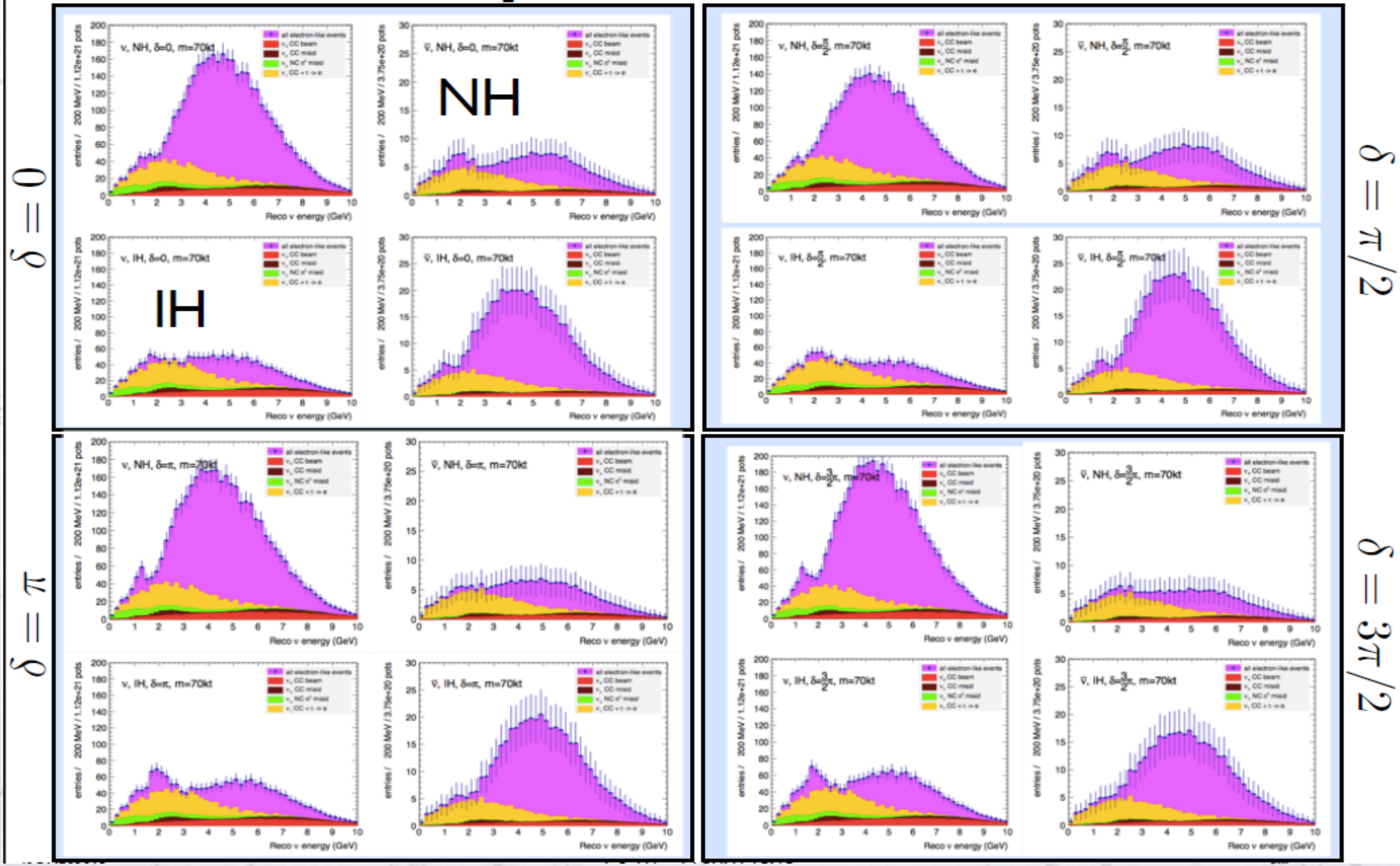
my view

- low mass → low statistics
- risky technology (maybe a +)
- possible tau contamination
+ matter effects, hierarchy
+ 2 oscillation peaks.
+ high energy → $\sigma_{\nu N}$ well known

LBNO

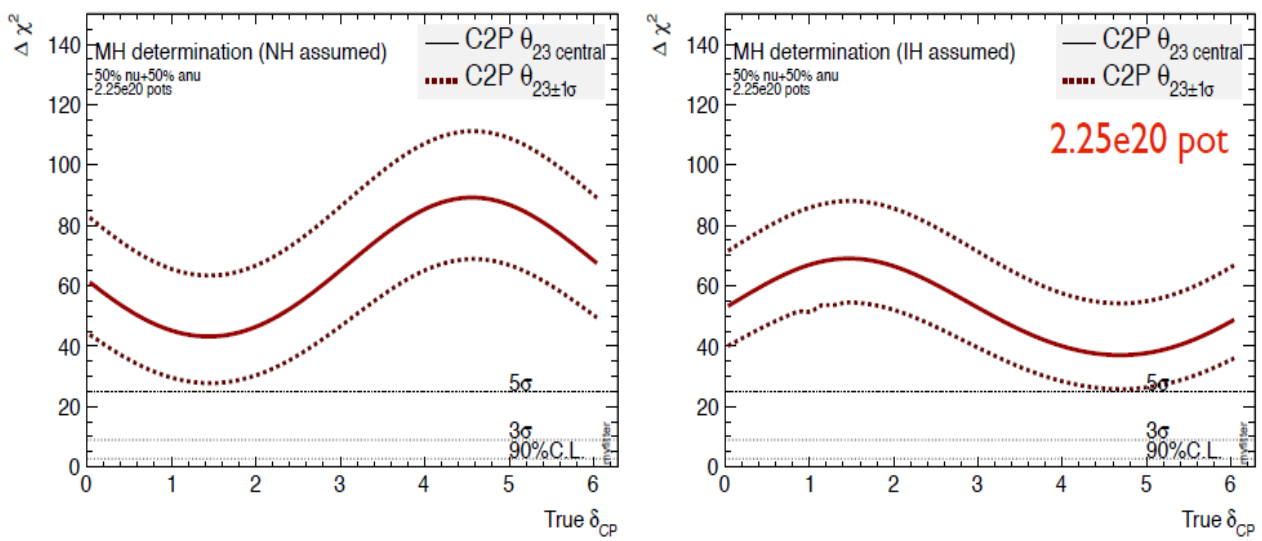
δ_{CP} & MH dependence

SPS(700kW), 10y, 75%nu-25%antinu; m=70kt



LBNO

Hierarchy

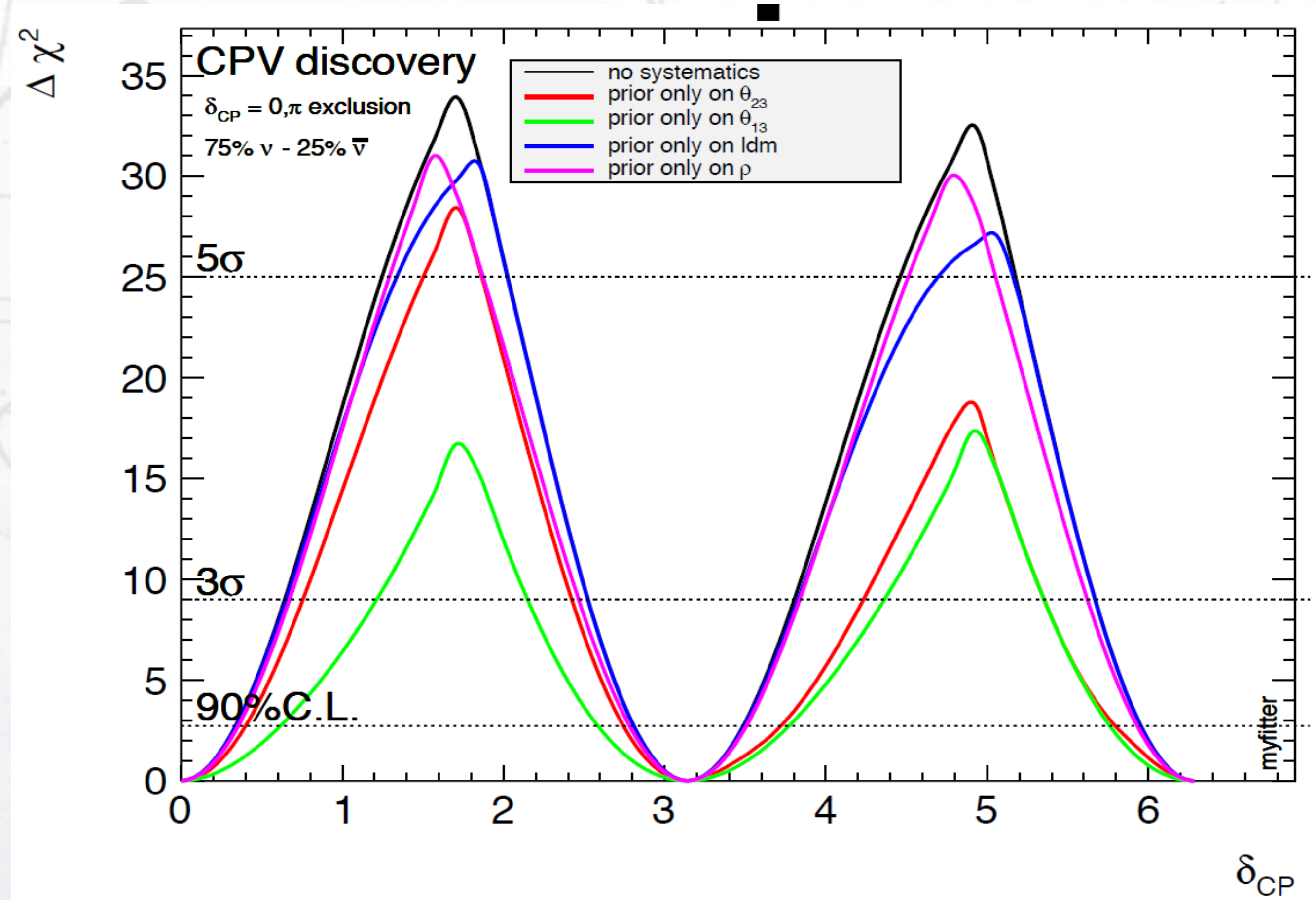


Provide a >5σ direct determination of MH independent of the values of θ_{23} & δ_{CP} in ≈2 years of running

Other methods proposed (atmospheric neutrinos, reactors) do not provide such a level of sensitivity and could be prone to irreducible systematic errors

2300 km is unique for hierarchy

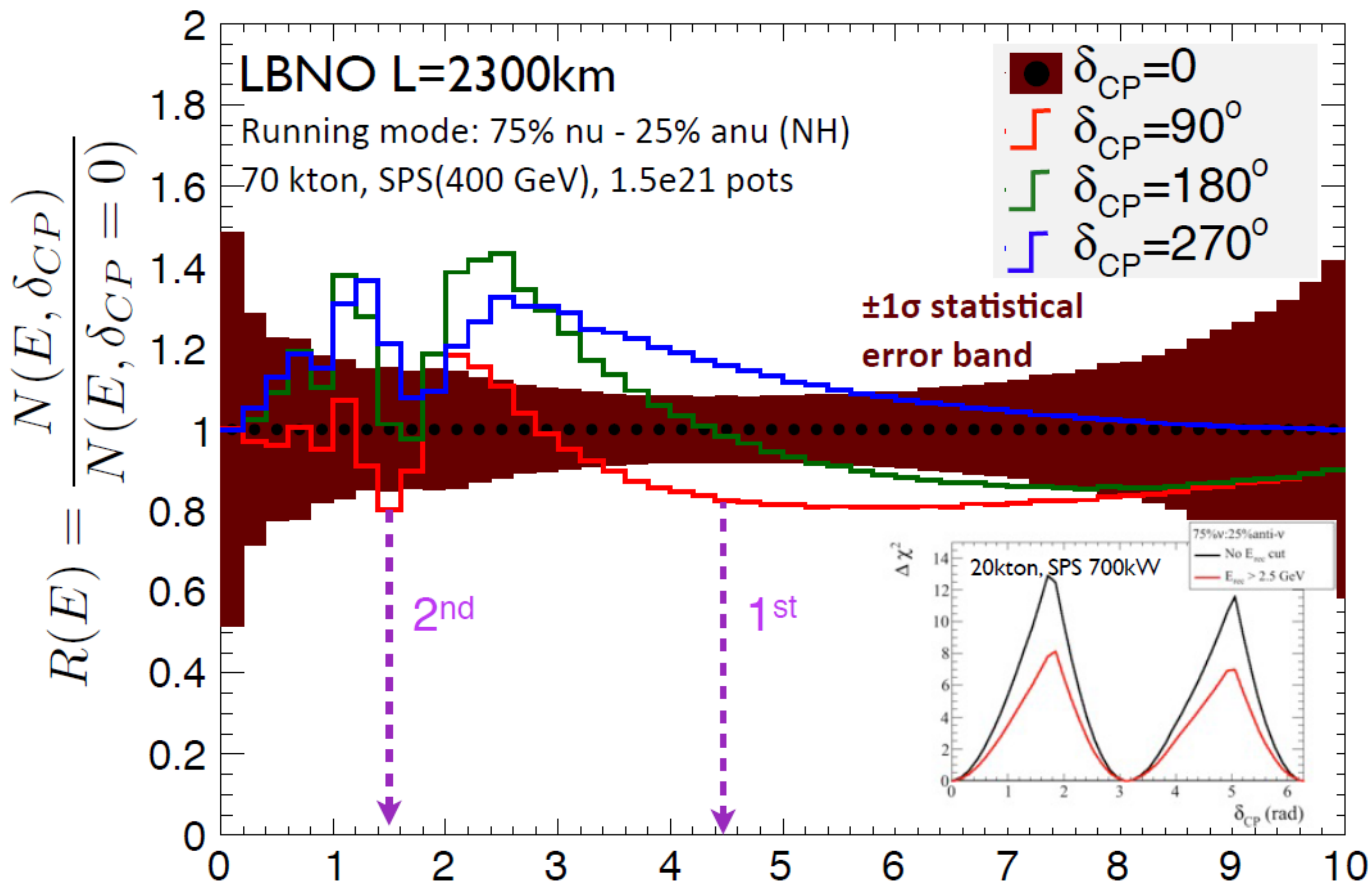
δ_{CP}



Not as good as T2KHK

LBNO

Sensitivity to CPV: importance of 2^{nd} max



The 1^{st} maximum, although statistically significant, is rather featureless !

Very reach phenomenology, reduced systematics?

LBNE

1300 km base line

1st phase with 10 kt LiqAr

2nd phase with 34 kt LiqAr ?

Accelerator power from 750 kW to 2.3 MW

LBNE — my view

- very low mass → very low statistics
- risky technology (maybe a +)
- Matter effects might be not too large.
+ matter effects, hierarchy
+ 2 oscillation peaks.
+ lower energy → $\sigma_{\nu N}$ poorly known

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LBNE

my view

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+ matter effects, hierarchy
+ 2 oscillation peaks.
+ lower energy → $\sigma_{\nu N}$ poorly known

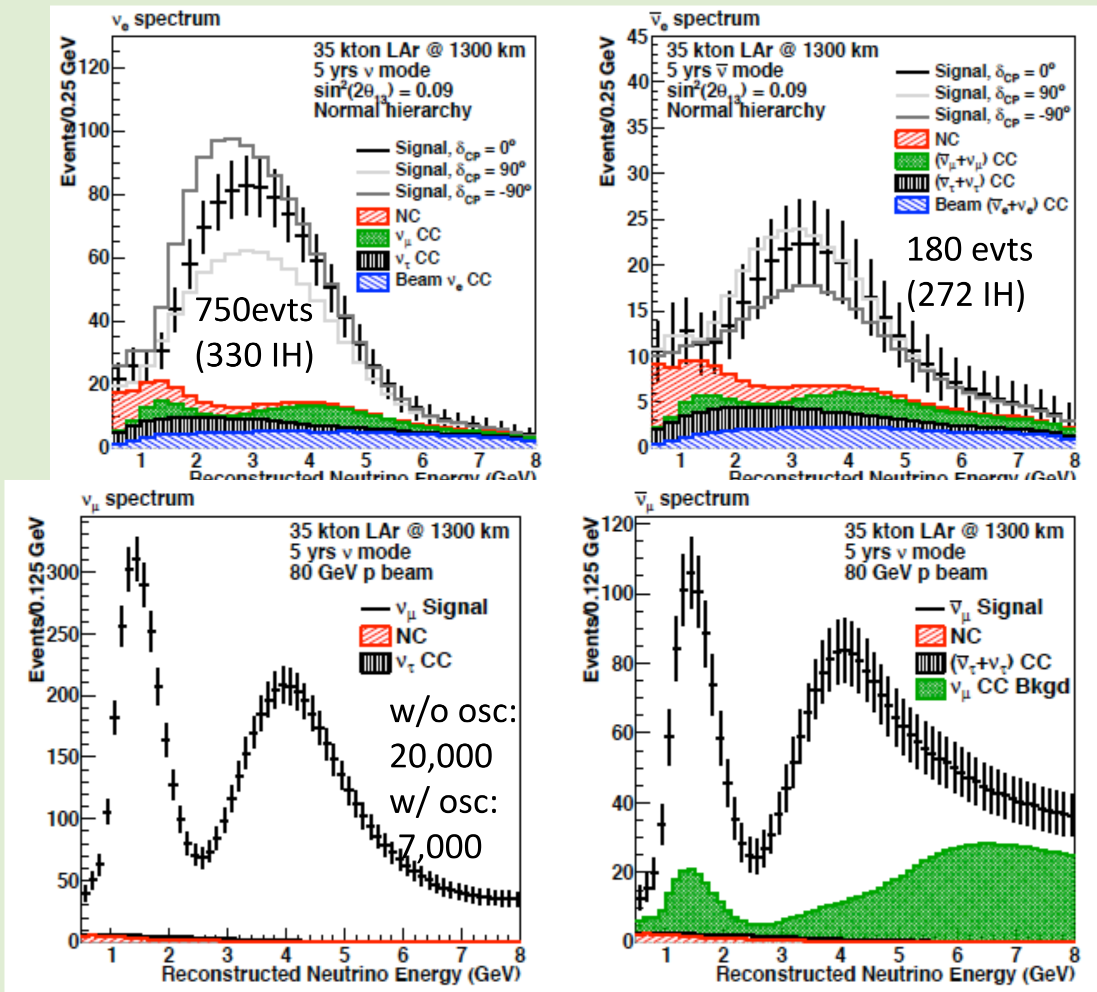
LBNE

ν (5 yrs) | $\overline{\nu}$ (5 yrs)

Appearance

Disappearance

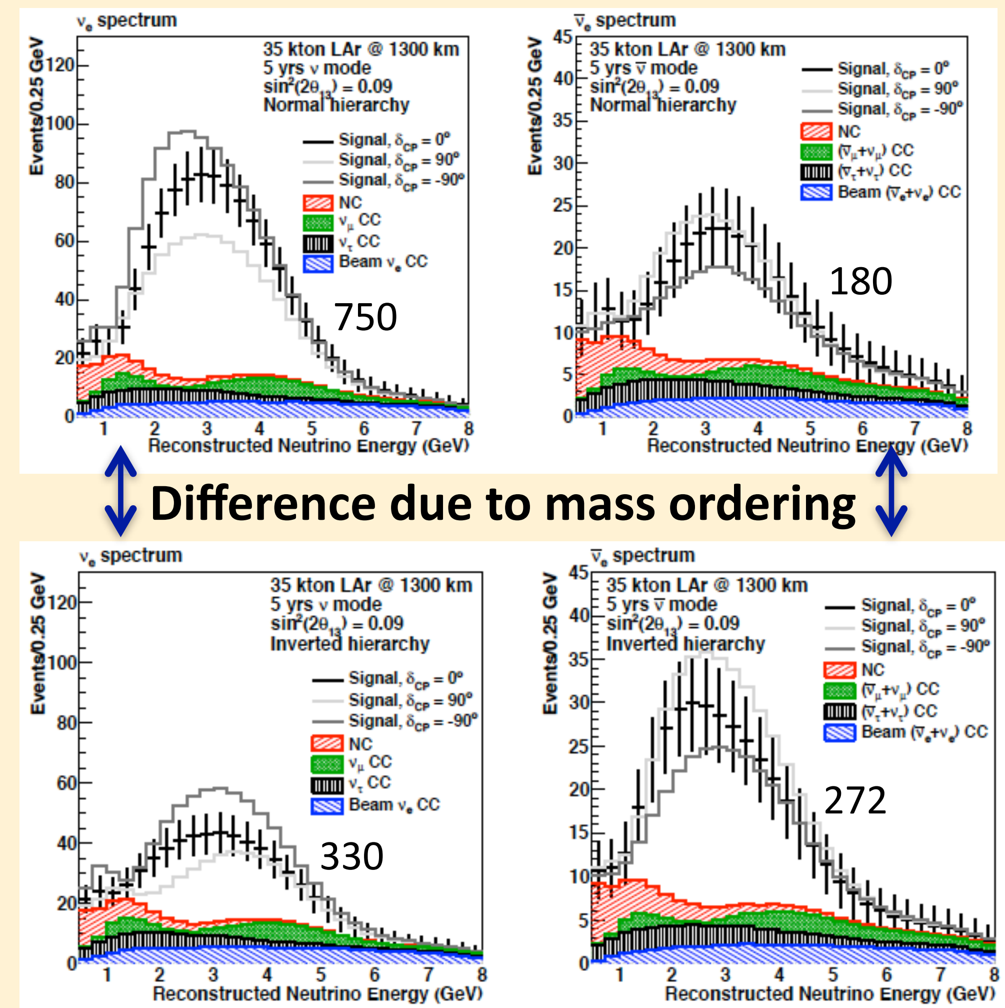
w/o osc: 6,700
w/ osc: 2,200



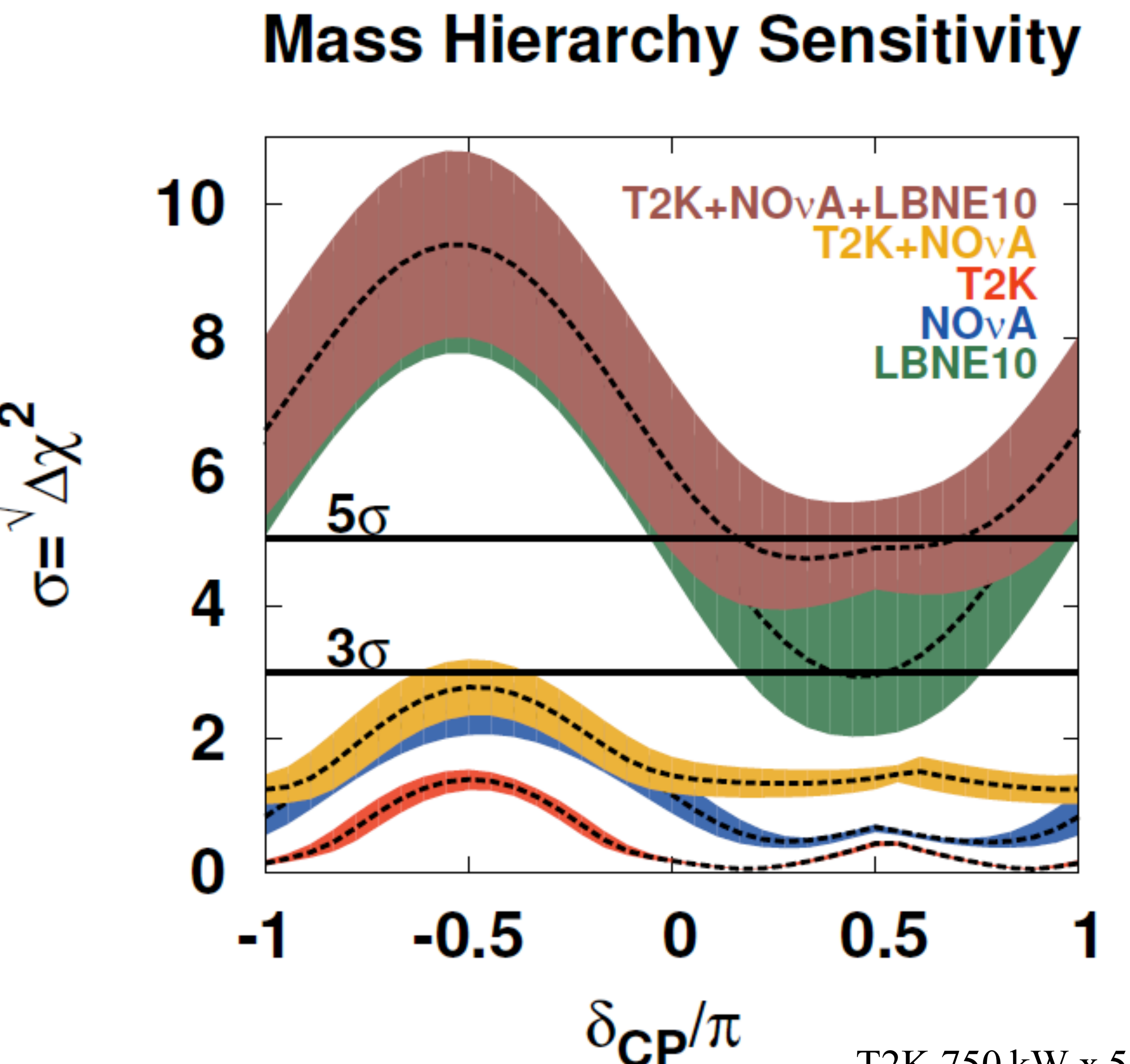
34 kt fid.

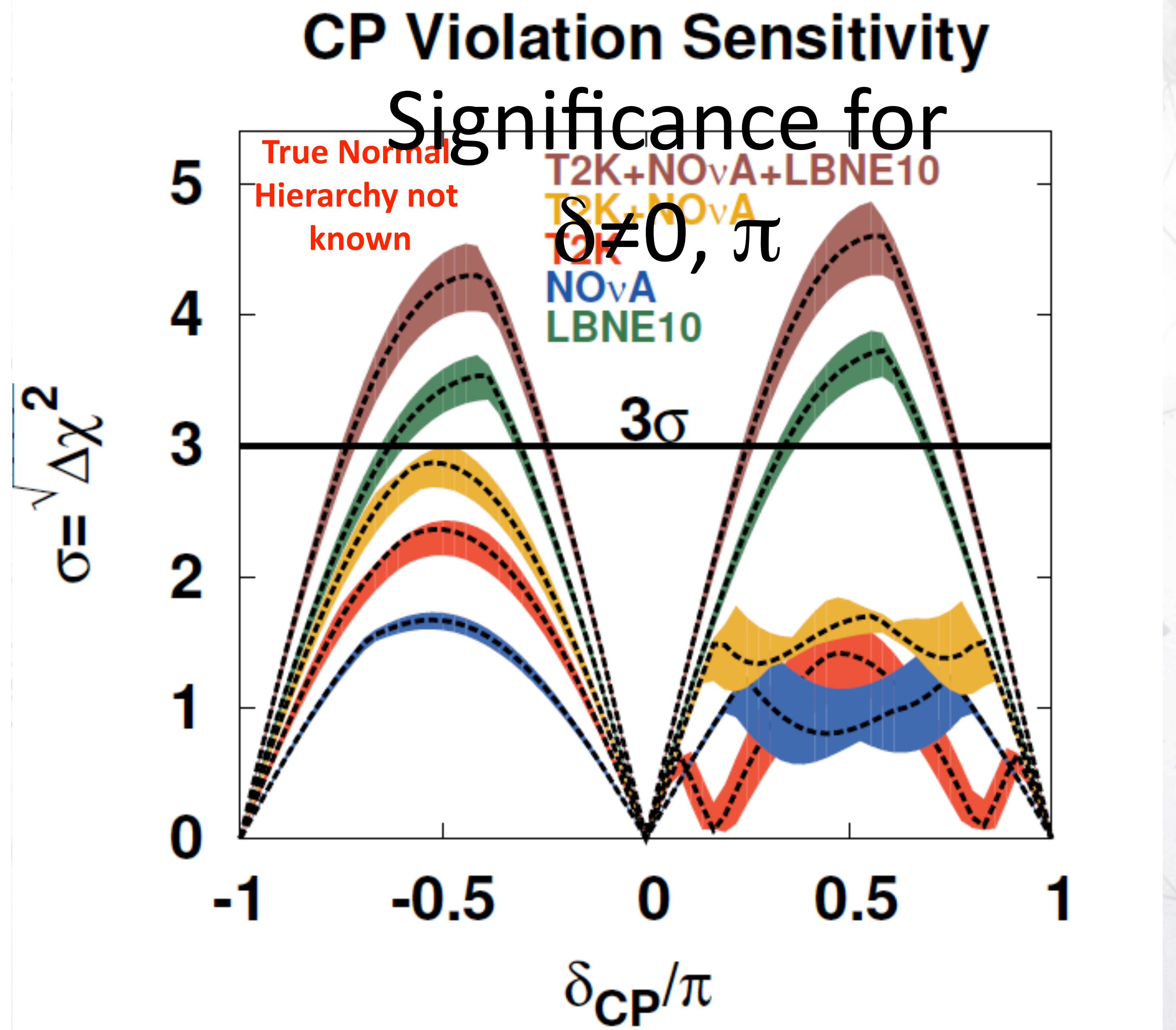
Normal

Inverted



LBNE10 does much better than full program for existing experiments





LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$)

T2K 750 kW x 5 yr (7.8×10^{21} pot)ν

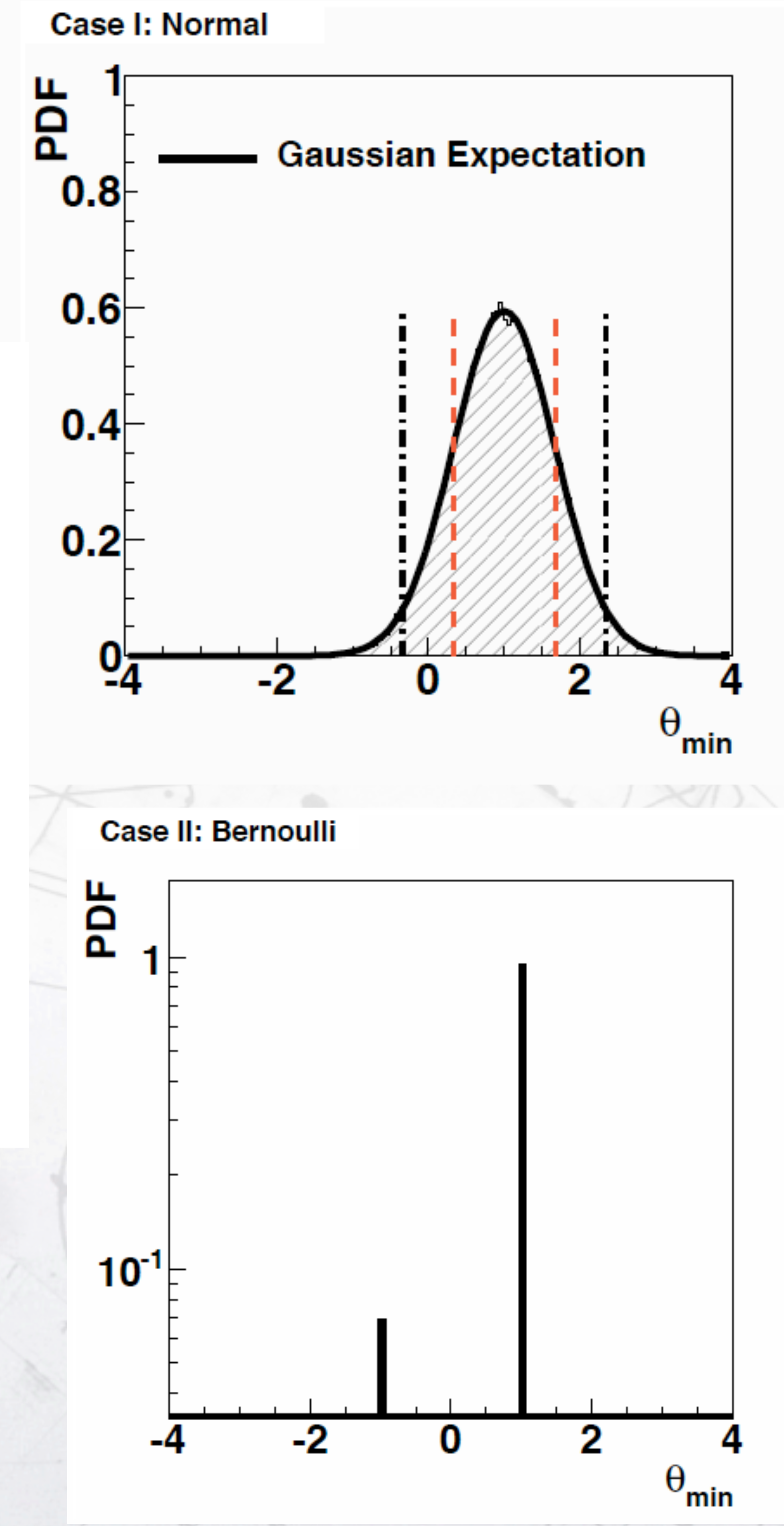
NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$) (3.8×10^{21} pot)

*Improved over CDR 2012 120 GeV MI proton beam

Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

Mass hierarchy

- Old of the previous sensitivity plots for mass hierarchy were done assuming a gaussian distribution of probability.
- Since the value of $|\Delta m^2|$ is very well known. The distribution is more a Bernouille probability with only one try.
- This fact was ignored, all the collaborations are reconsidering their sensitivities.



Some observations

- T2HK has the highest sensitivity to CP violation but this implies: 74% coverage δ_{CP} @ 3σ.
- LBNE/LBNO can make hierarchy at 5σ after 5 years of running.
- LBNE/LBNO CP violation will depend on the total mass achieved by the far detector.
- We can be lucky and get hints of CP in the next 5 years or be unlucky and get no hint in the next 15 years.

Very confusing panorama, many unknowns from physics, finance and politics.

Conclusions

- T2K has finally stablished the transition $\nu_\mu \rightarrow \nu_e$ with a 7.5σ C.L.
  - this opens the possibility to measure the CP phase in the future:
    - comparing neutrinos and anti-neutrinos.
    - with the very precise constrain from the reactor experiments.
- Current generation of experiments has limited sensitivity to CP phase and mass hierachy:
  - But not null!!!!.
- Next generation increases the sensitivity but to values that are not definitive:
  - T2HK cover 75% of the possible values with 90% CL but does not measure hierarchy.
  - LBNE/LBNO can do hierarchy and possibly CP depending on the final achieved mass of detector.

Mass hierarchy sensitivity needs to be revisited!

All in all, there is an exciting time in fron of us.

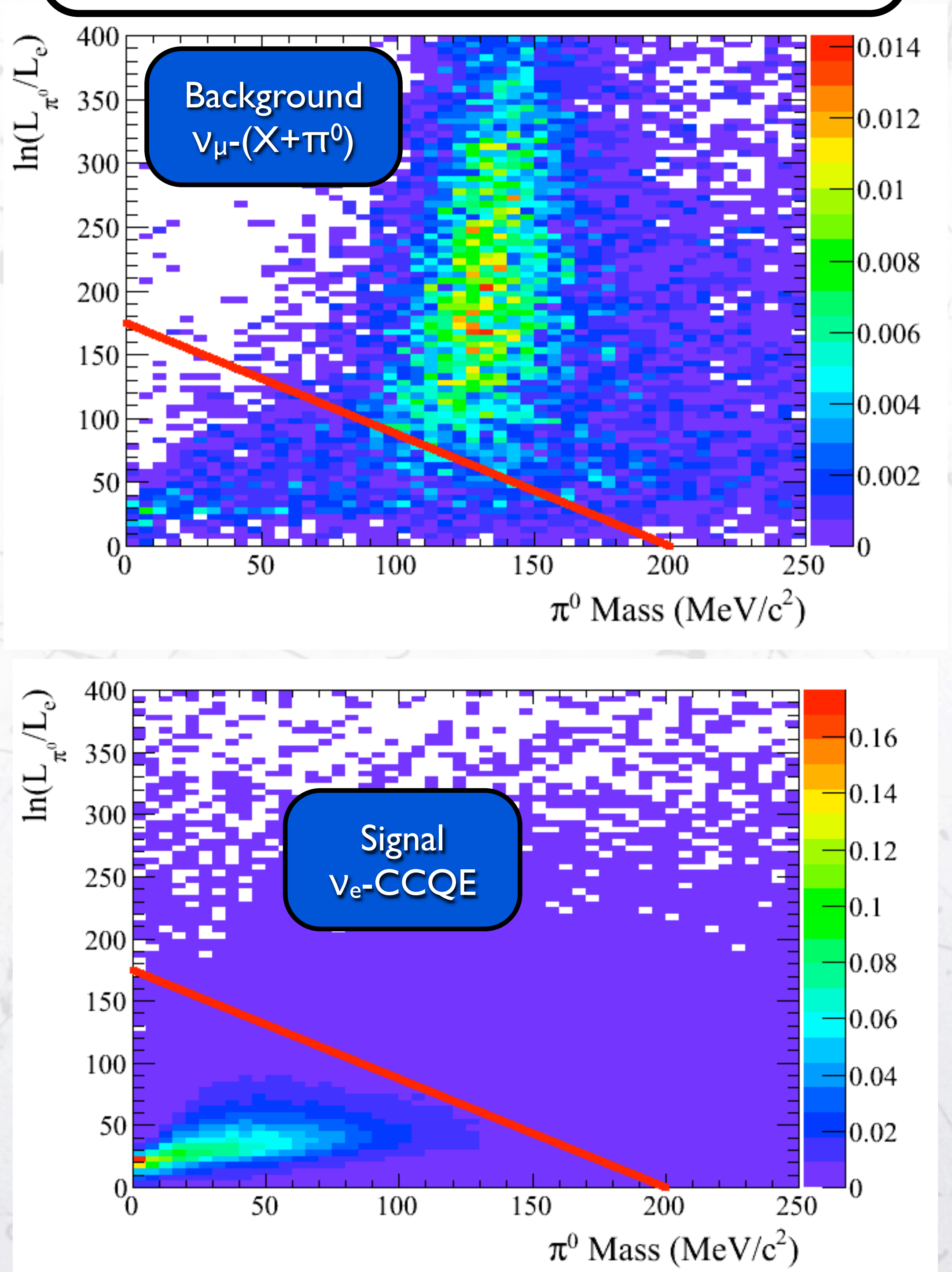
The era of ν precision physics has started.

Support slides

Super-Kamiokande & π^0

- New algorithm can also use the best-fit likelihood ratio to distinguish e^- from π^0
  - Even if 2nd photon is identified, it may be on the tail of the π^0 mass resolution.
  - In this case, the 2-ring likelihood will still be preferred and the event is identified as π^0
- 2D cut removes 70% more π^0 background than previous method for the same signal efficiency.

Likelihood Ratio vs π^0 Mass



SK: new reconstruction

$$L(\mathbf{x}) = \prod_{\text{unhit}} P(i\text{unhit};\mathbf{x}) \prod_{\text{hit}} P(i\text{hit};\mathbf{x}) f_q(q_i;\mathbf{x}) f_t(t_i;\mathbf{x})$$

- A single track in the detector can be specified by a particle type, and 7 kinematic variables (**x**):
  - A vertex position (X,Y, Z,T)
  - A track momentum (p)
  - A track direction (θ, φ)
- For a given **x**, a charge and time probability distribution function (PDF) is produced for every PMT
- All 7 track parameters fit simultaneously
- For particle ID: compare final likelihoods for different particle hypotheses

Time PDF

Charge PDF

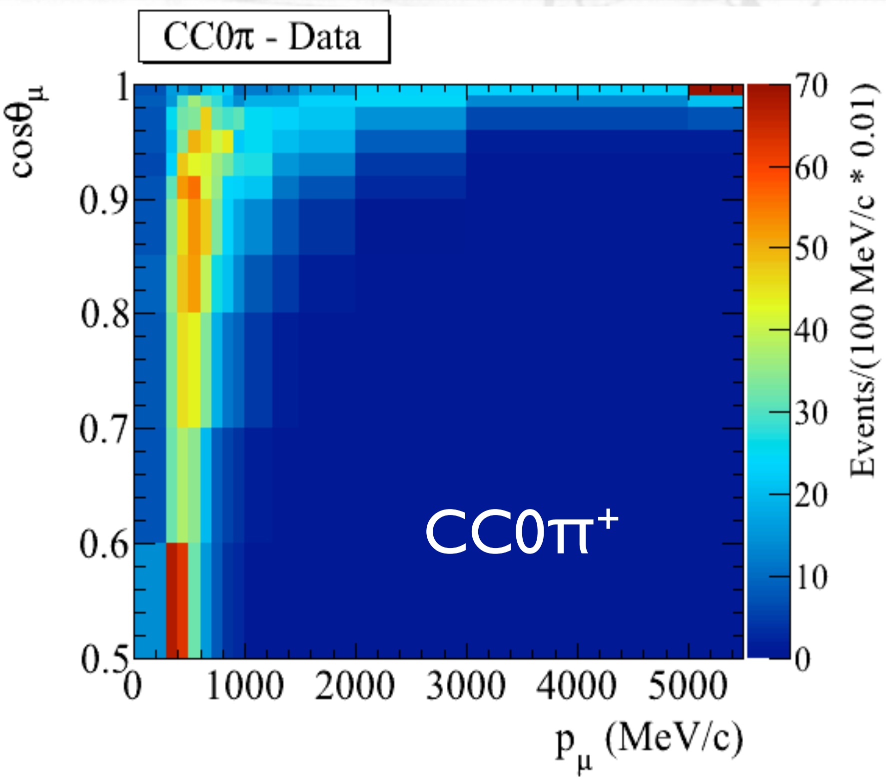
PMT Charge Response:

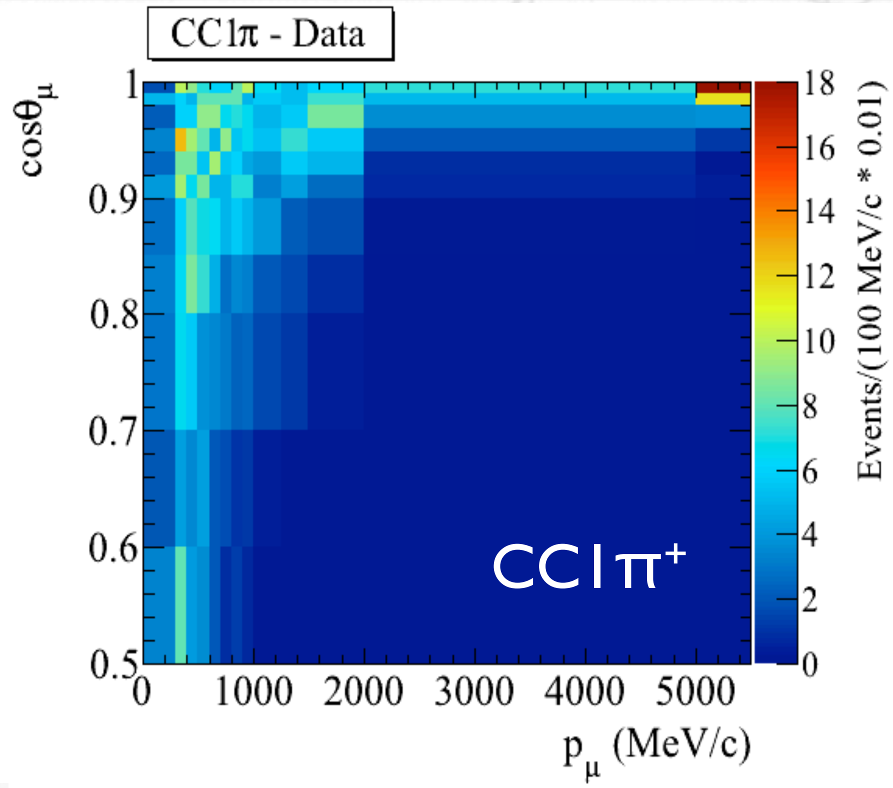
Property of the electronics and PMT properties

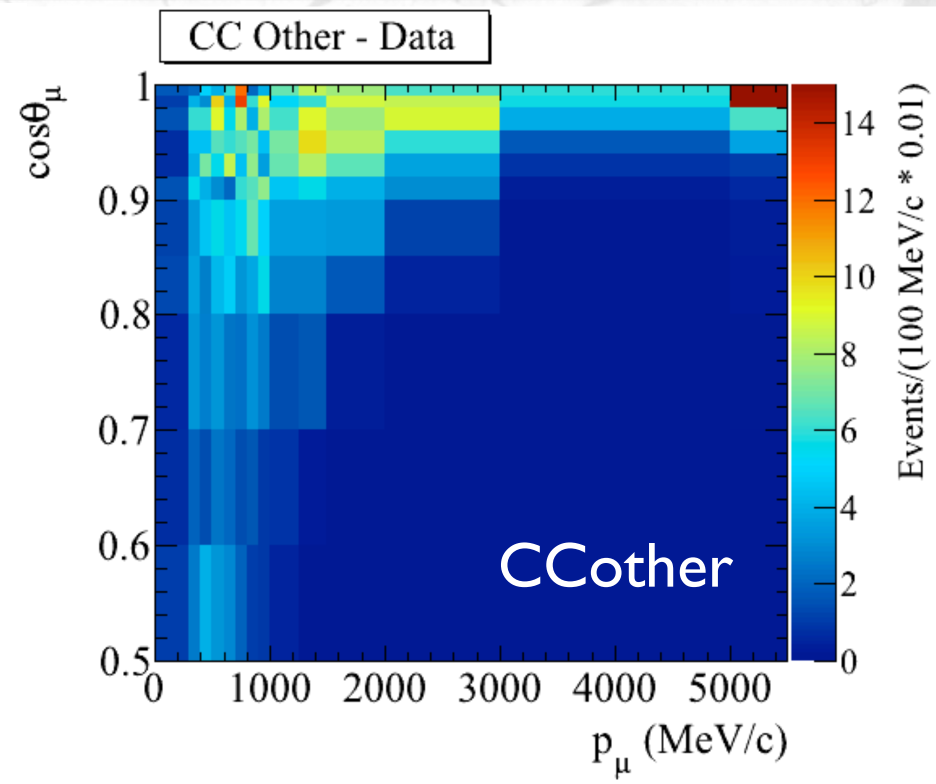
Predicted Charge (μ):

- Number of photons that reach the PMT
- Depends on detector properties (scat, abs, etc.)

ND280 input data







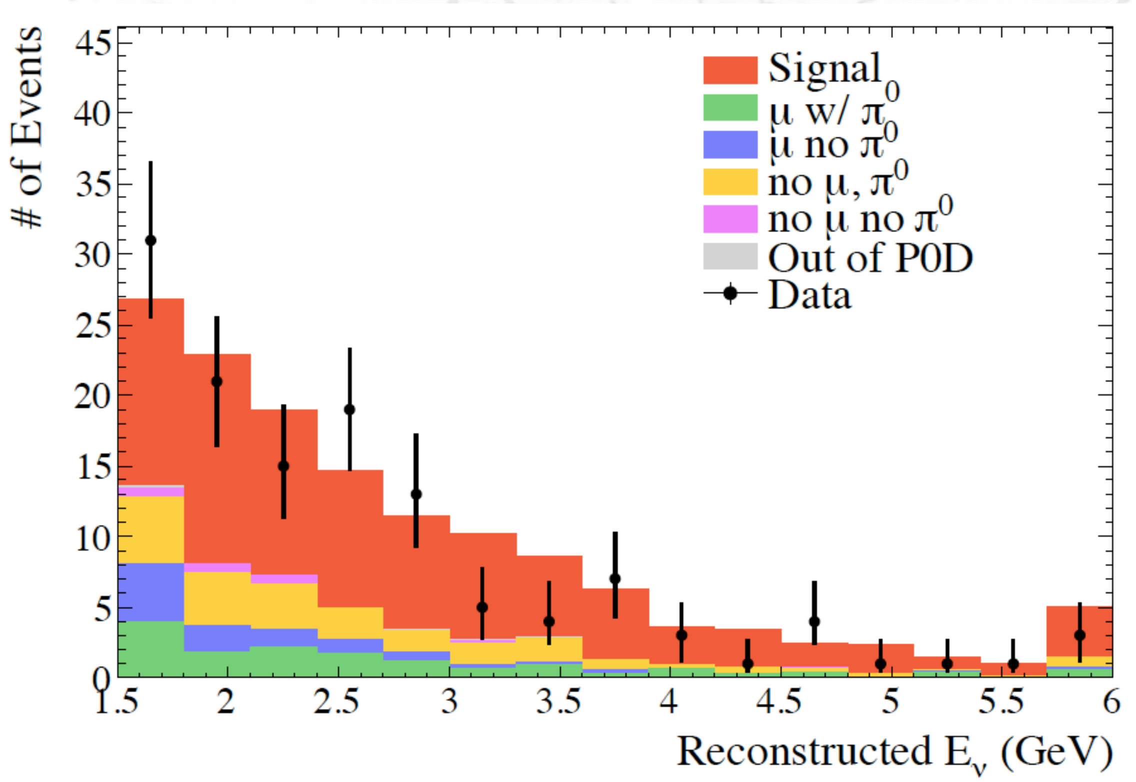
Data from T2K Runs 1-4: 5.9×10^{20} protons on target

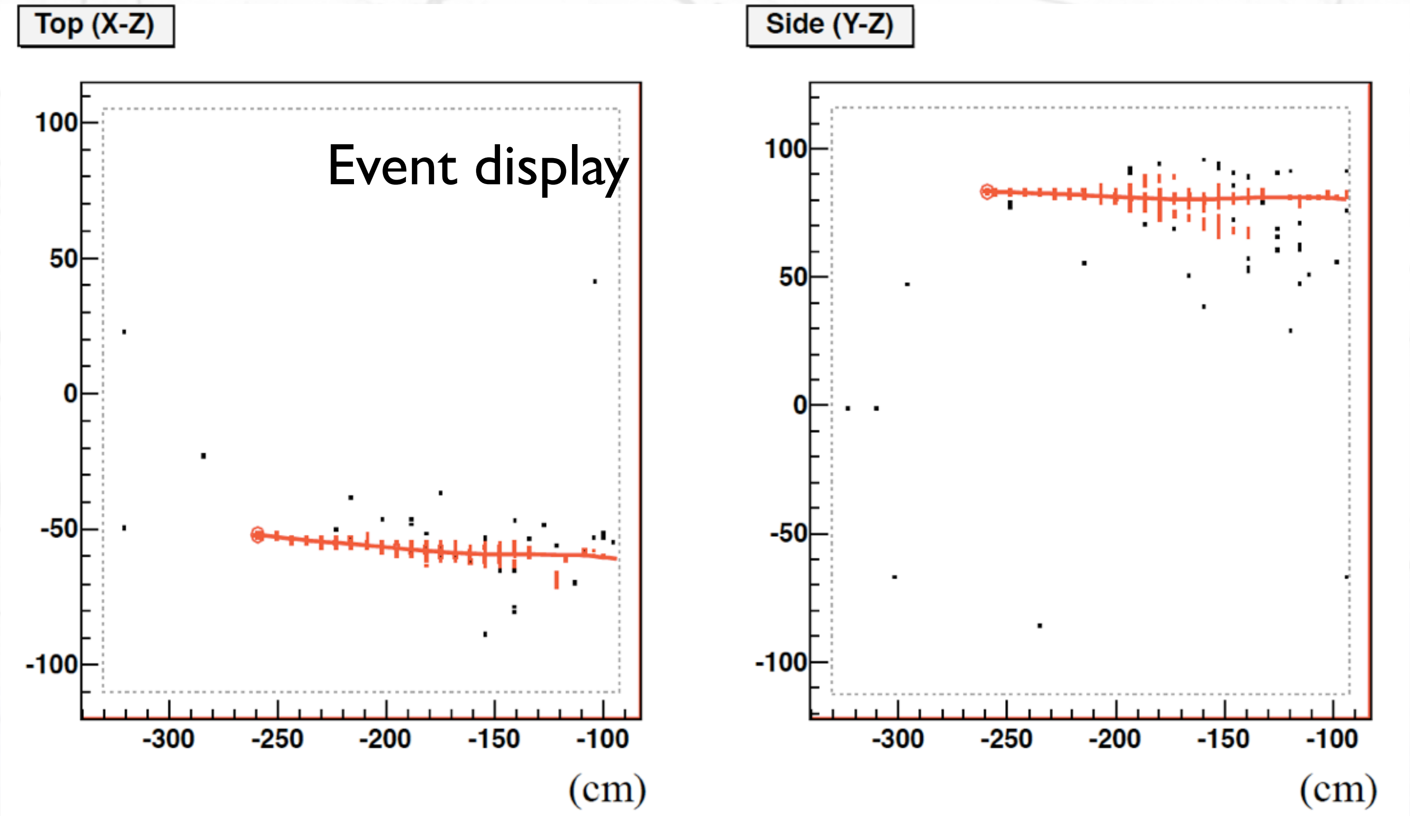
Selection	Number of Events
CC0π	16912
CC1π	3936
CC Other	4062
CC Inclusive	24910

Data are binned in two dimensions: muon momentum (p) and angle (cosθ) preserving information on neutrino energy and interaction q^2

Off-axis: ν_e analysis

- ν_e events at the ND280 P0D detector calculated with 8.6×10^{19} PoT.



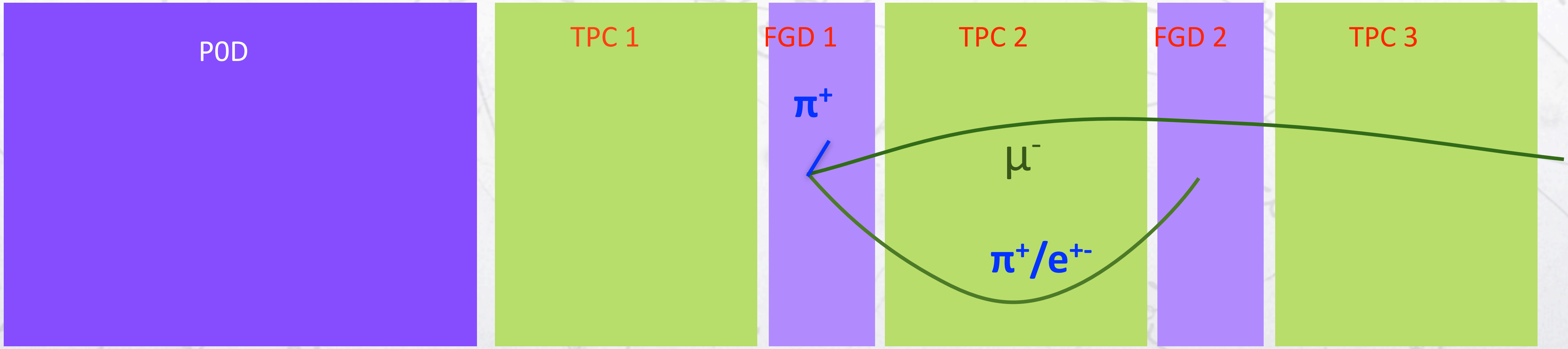


$$\frac{Data - Back_{MC}}{Sign_{MC}} = 0.91 \pm 0.13(stat) \pm 0.18(det) \pm 0.13(flux)$$

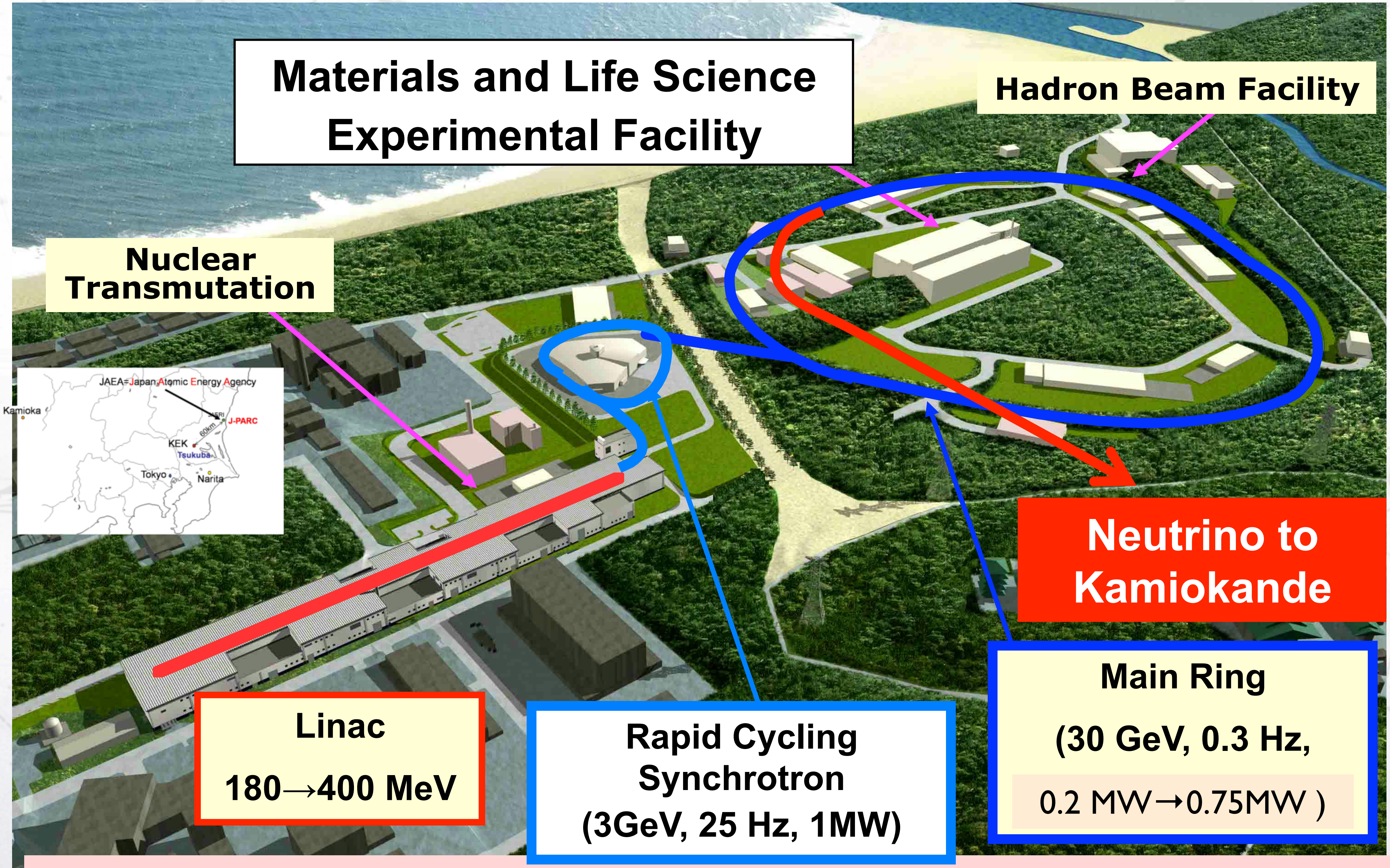
In good agreement with the tracker ν_e measurement

Off-axis: ν_μ analysis

- The ND280 constrains flux and cross-section.
- Sample of CC events is selected. Muon as highest momentum negative track in the event in the target fiducial volume compatible with muon Pid in TPC.
- The sample is divided in 3 categories: $0\pi^+$, $1\pi^+$ and others (mainly Deep Inelastic Scattering) based on the detection of pions in the event.
  - Pions are detected as tracks in TPC, FGD or Michel electron signature near vertex.



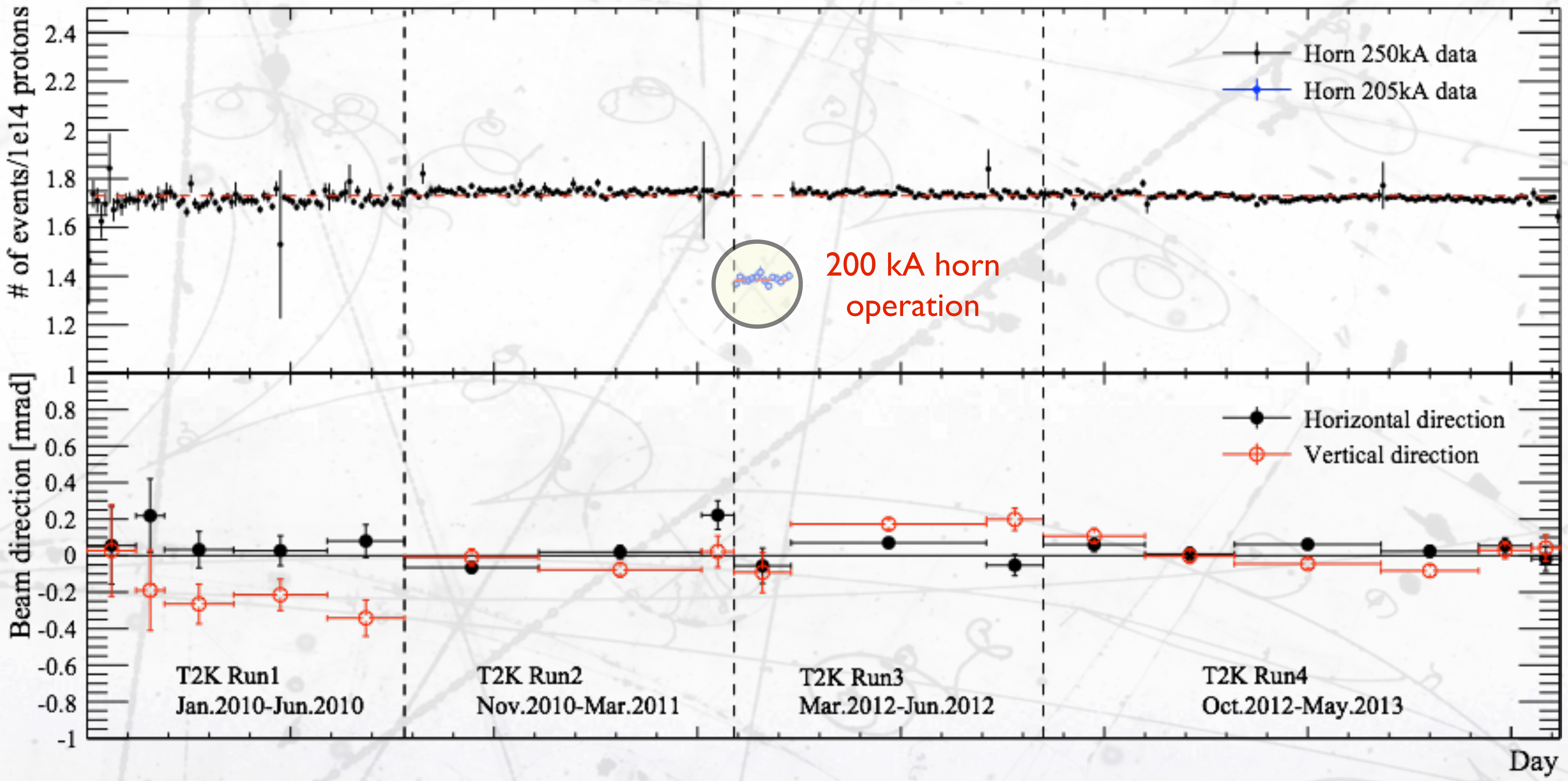
J-PARC



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

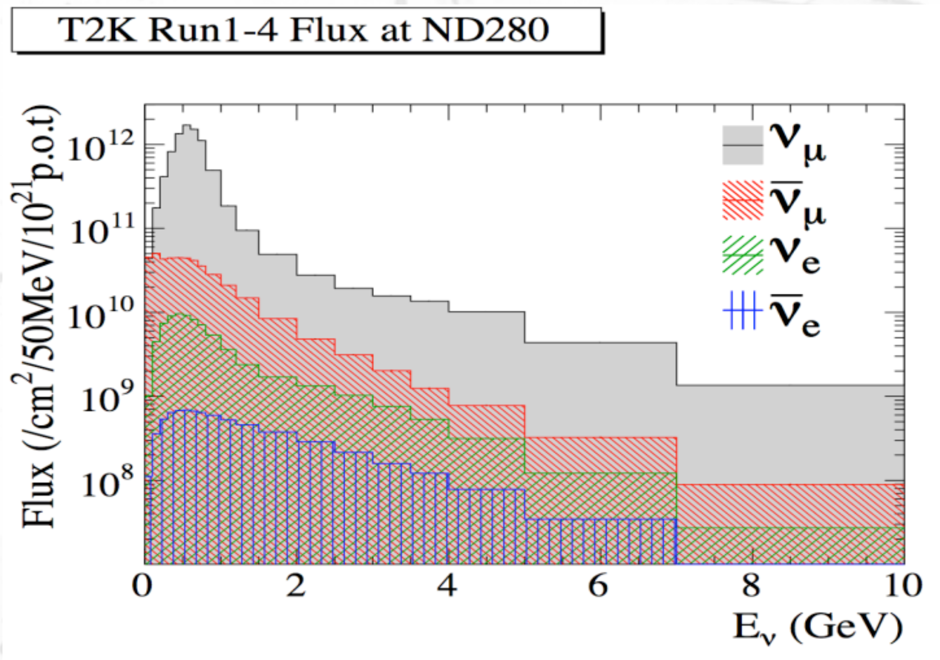
On-axis: beam stability

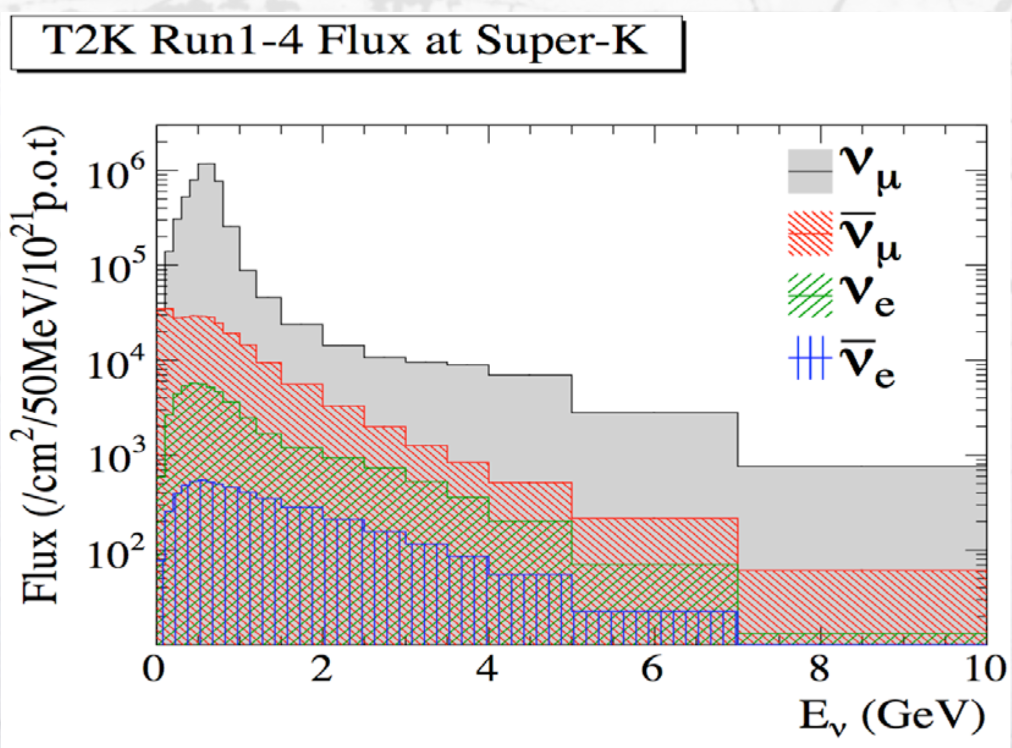


Beam alignment and flux measured with neutrinos

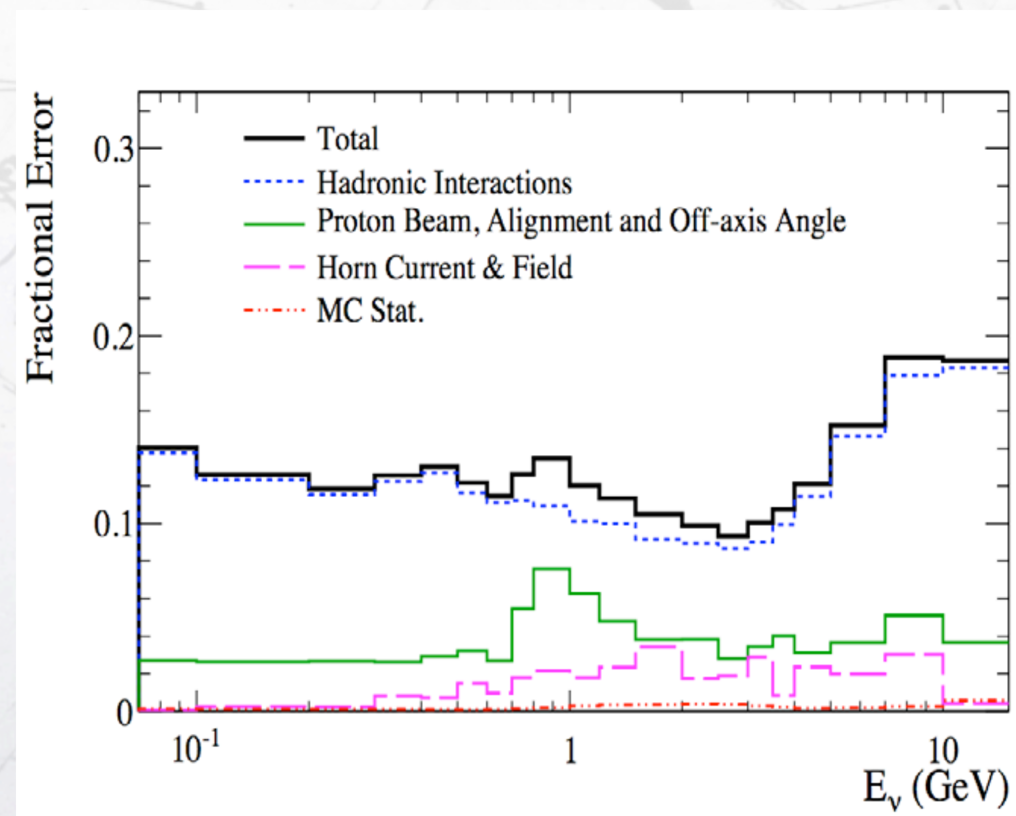
- Neutrino rate stable within 0.7%.
- Beam direction variation << 1 mrad.

Flux prediction





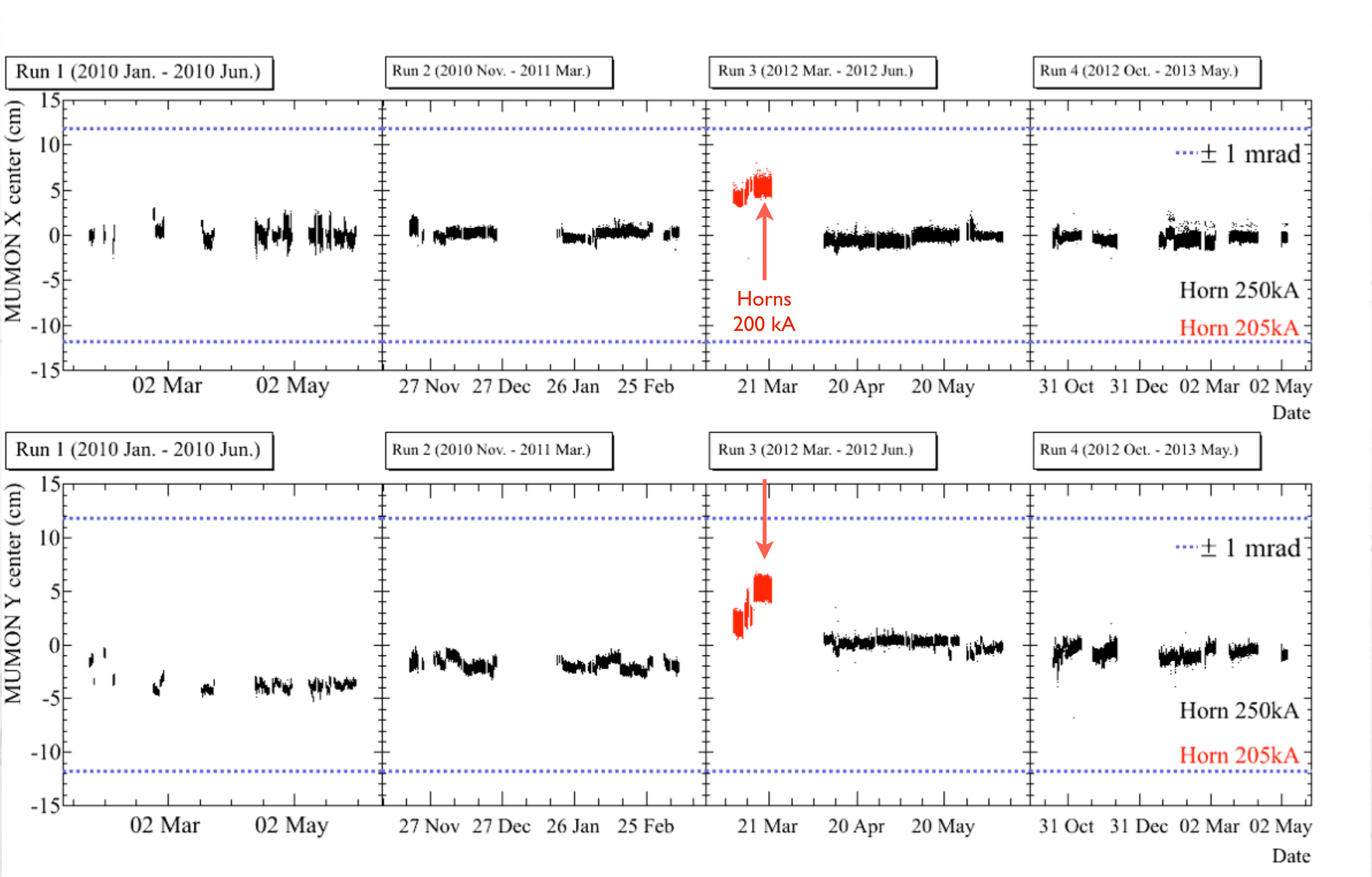
- Simulation is carried out by Fluka2008 3d.
- The pion and kaon production is weighted to the results from NA61-Shine.
- “A priori” flux error: ~15% below @ 1 GeV.
- Strong correlation between near and far detector.



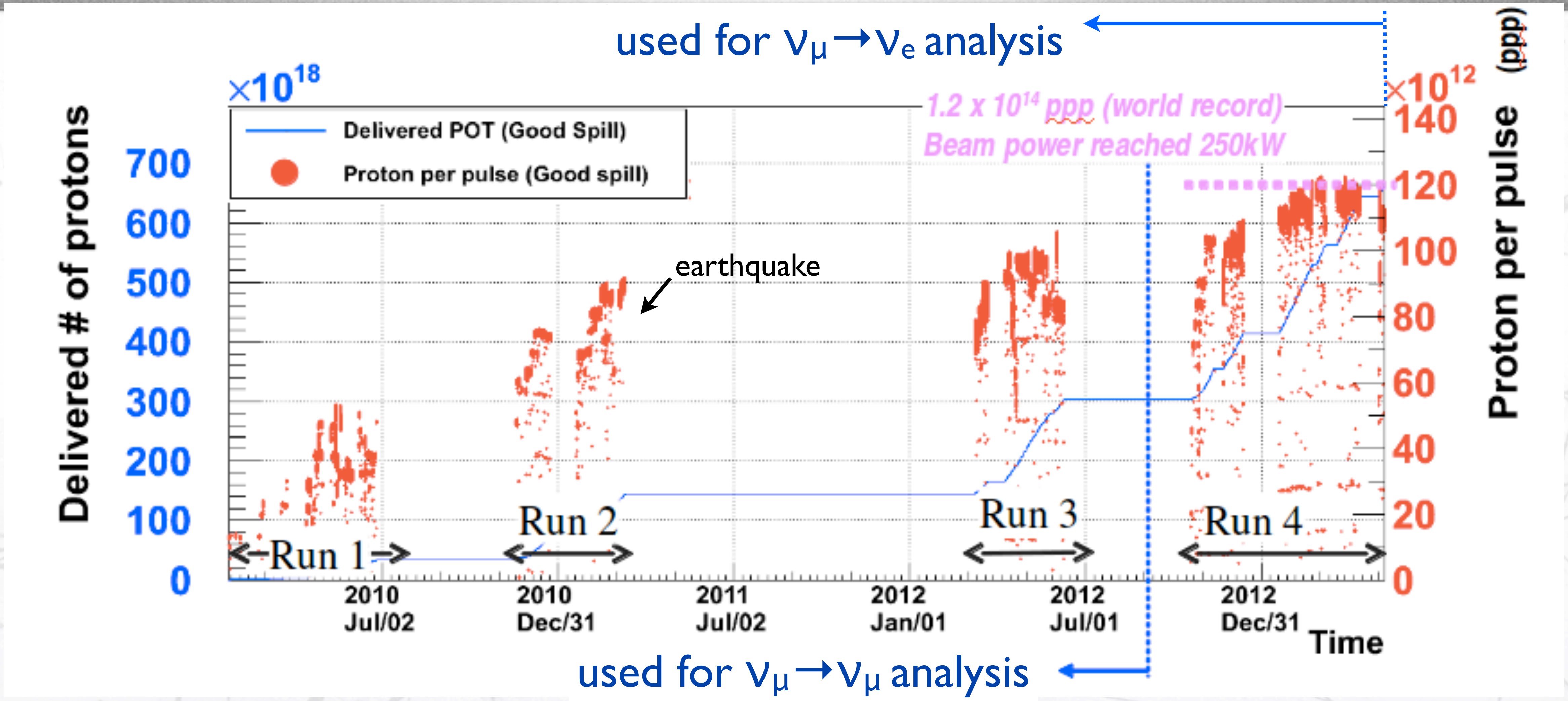
Beam stability

- Muon monitor downstream the beam dump monitors beam direction. Stability requirements < 1mrad

1 mrad change of ν beam direction results in 2-3% change of the neutrino energy scale (~16MeV)



Data sets



- Total delivered beam: 6.63×10^{20} protons on target.
  - 8.3% of the expected T2K PoT (7.8×10^{21} PoT)
- $\nu_\mu \to \nu_e$ analysis uses 96.3% of acquired Run 1-4 PoT.
- $\nu_\mu \to \nu_\mu$ analysis uses Run 1-3 (3.01×10^{20})

x~2 PoT in Run4!

History

- 1999 Ko Nishikawa and Yoji Totsuka formulate $\nu_\mu \rightarrow \nu_e$ experiment at J-PARC.
- 1999-2004 K2K finds the first evidence of neutrino oscillation in a Long Base Line experiment.
- 2000-2004 Letter of Intent; Detailed design; Formation of international collaboration.
- 2004 Five year construction plan for T2K approved by Japanese government.
- February 2008, finished ND280 pit construction.
- May 2008, installation ND280 magnet.
- April 2009 Commissioning of beamline.
- January 2010 First neutrino events for neutrino oscillation studies.
- March 2011 Great East Japan earthquake.
- June 2011 T2K announces 2.5σ "indication" of $\nu_\mu \rightarrow \nu_e$
- March 2012 T2K resumes data taking after earthquake recovery.

T2K collaboration

~500 member, 59 institutions, 11 countries.

TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

RWTH Aachen U.

INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

ICRR Kamioka
ICRR RCCN Kavli
IPMU KEK Kobe
U. Kyoto
U. Miyagi
U. Edu. Osaka City
U. Okayama
U. Tokyo Metropolitan
U. U. Tokyo

IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw Warsaw
U. T. Wroklaw U.

INR

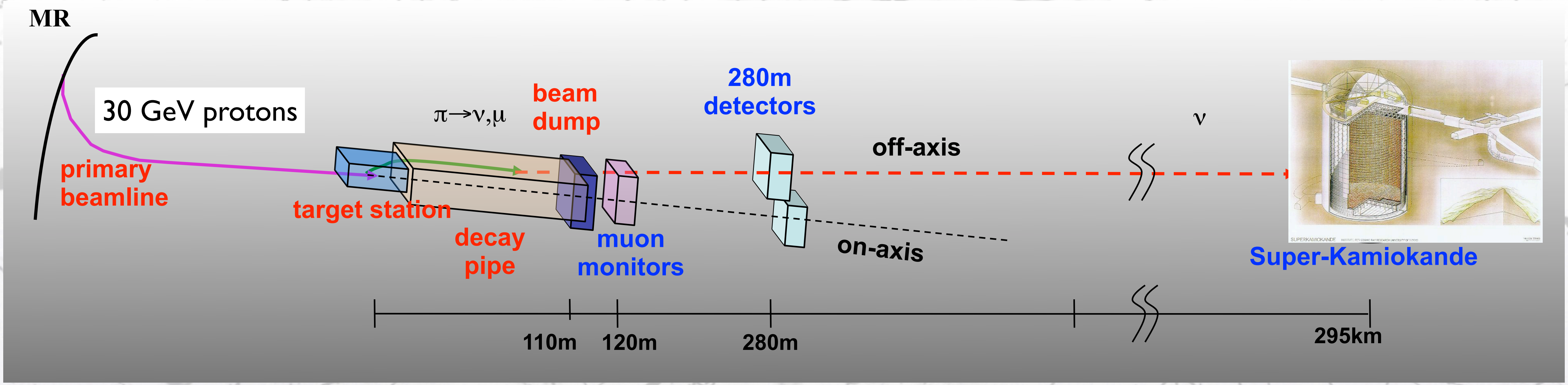
IFAE, Barcelona
IFIC, Valencia

ETH Zurich
U. Bern
U. Geneva

Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

T2K: the future

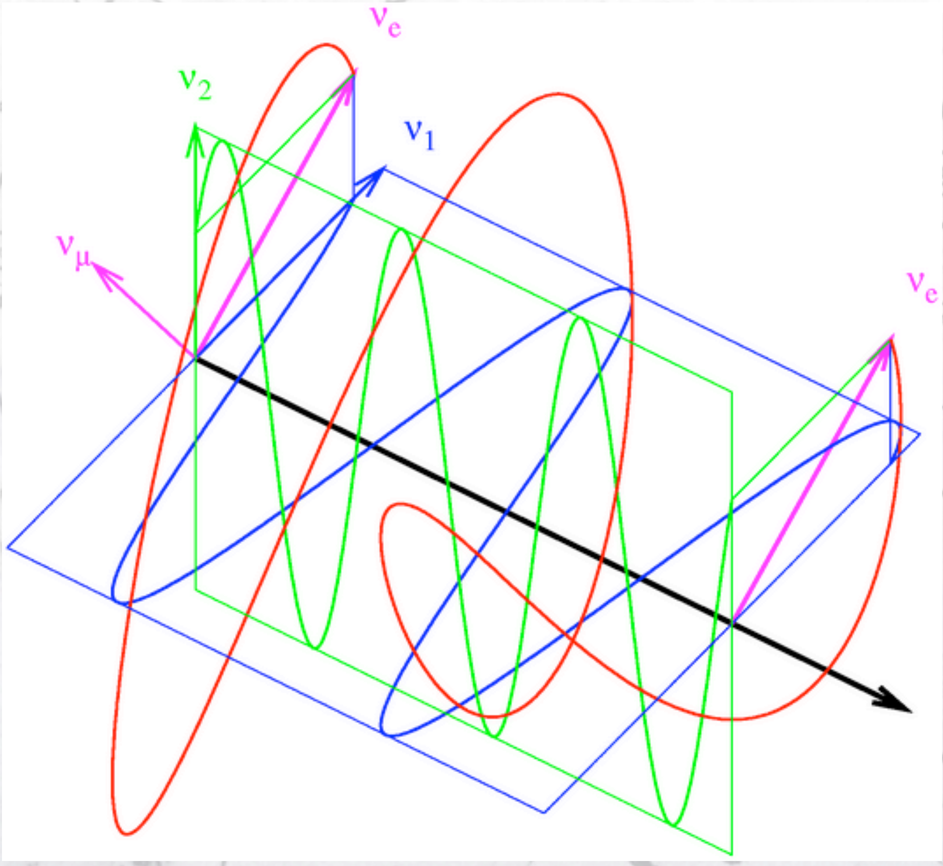


Beam ND280 Super-Kamiokande

Upgrade plan

- Planned J-PARC Main Ring (MR) power improvements 220 kW operation in CY2013. Integrated 6.7×10^{20} PoT to date.
  - Linac upgrade to be completed within a year. Expect range of steady MR operation for neutrino between 200-400 kW
  - Planned MR upgrade (depends on funding). Up to 750 kW
  - Possible staged upgrade scenario:
    1. Double current protons on target.
    2. Next-to-next doubling.
    3. If MR upgrade, reach full planned statistics (78×10^{20} PoT).

Neutrino oscillations

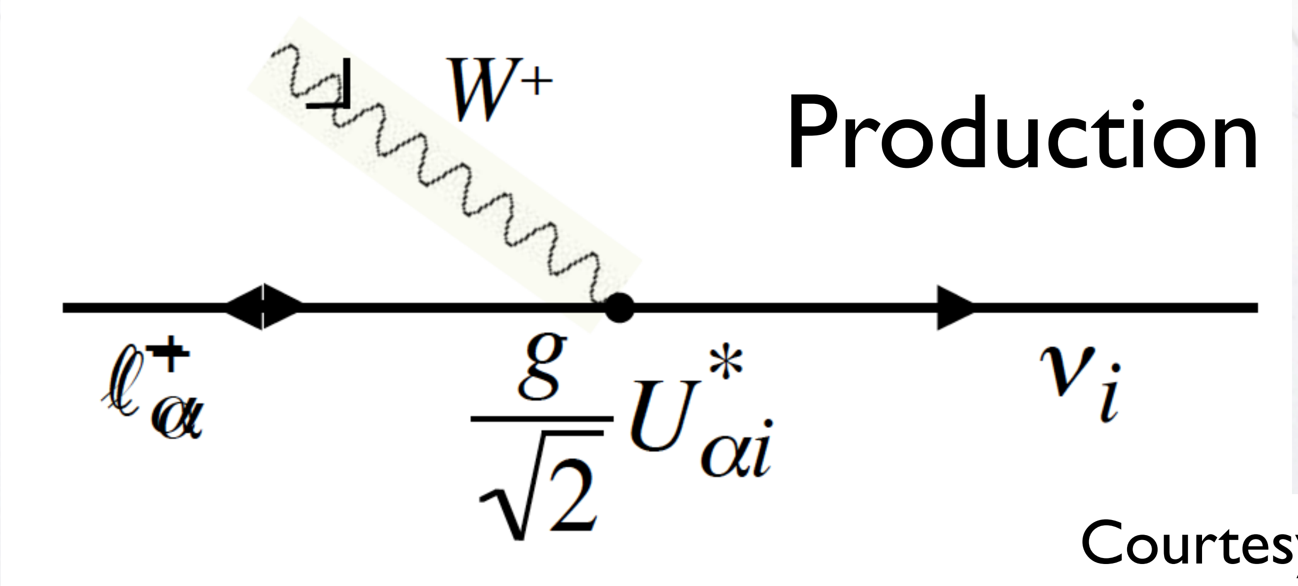


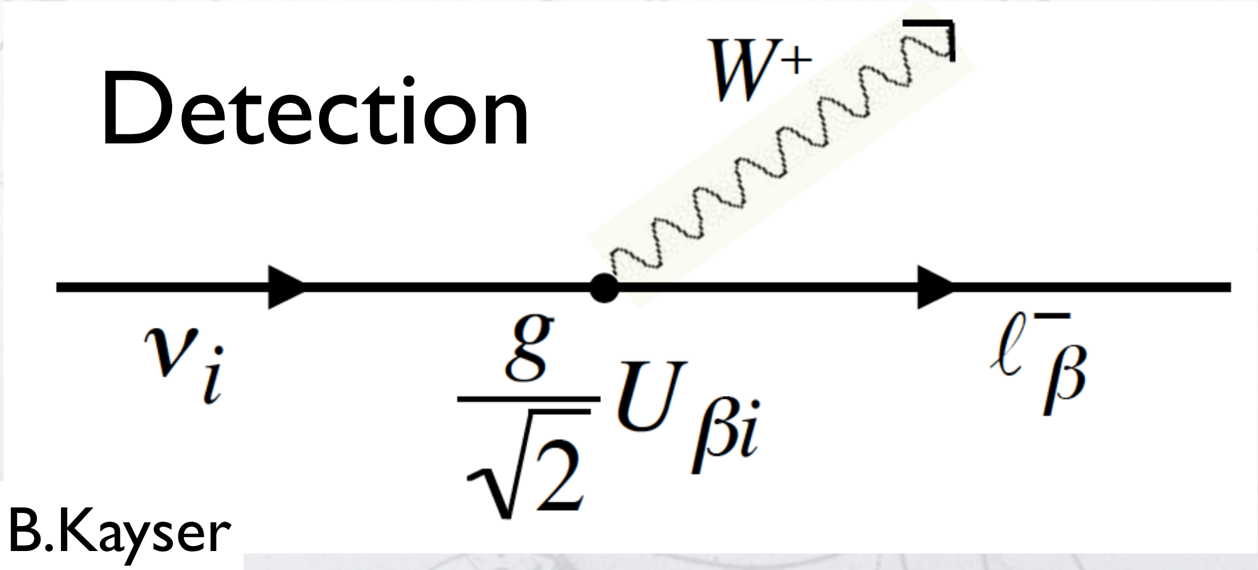
ν oscillations

Similar to quarks, flavour and Lorentz eigenstates of massive neutrinos are not identical.

The two eigenbases are related through the Pontecorvo-Maki-Nakagawa-Sakata matrix (U_{PNMS}).

$$U_{PNMS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$





Courtesy of B.Kayser

ν oscillations

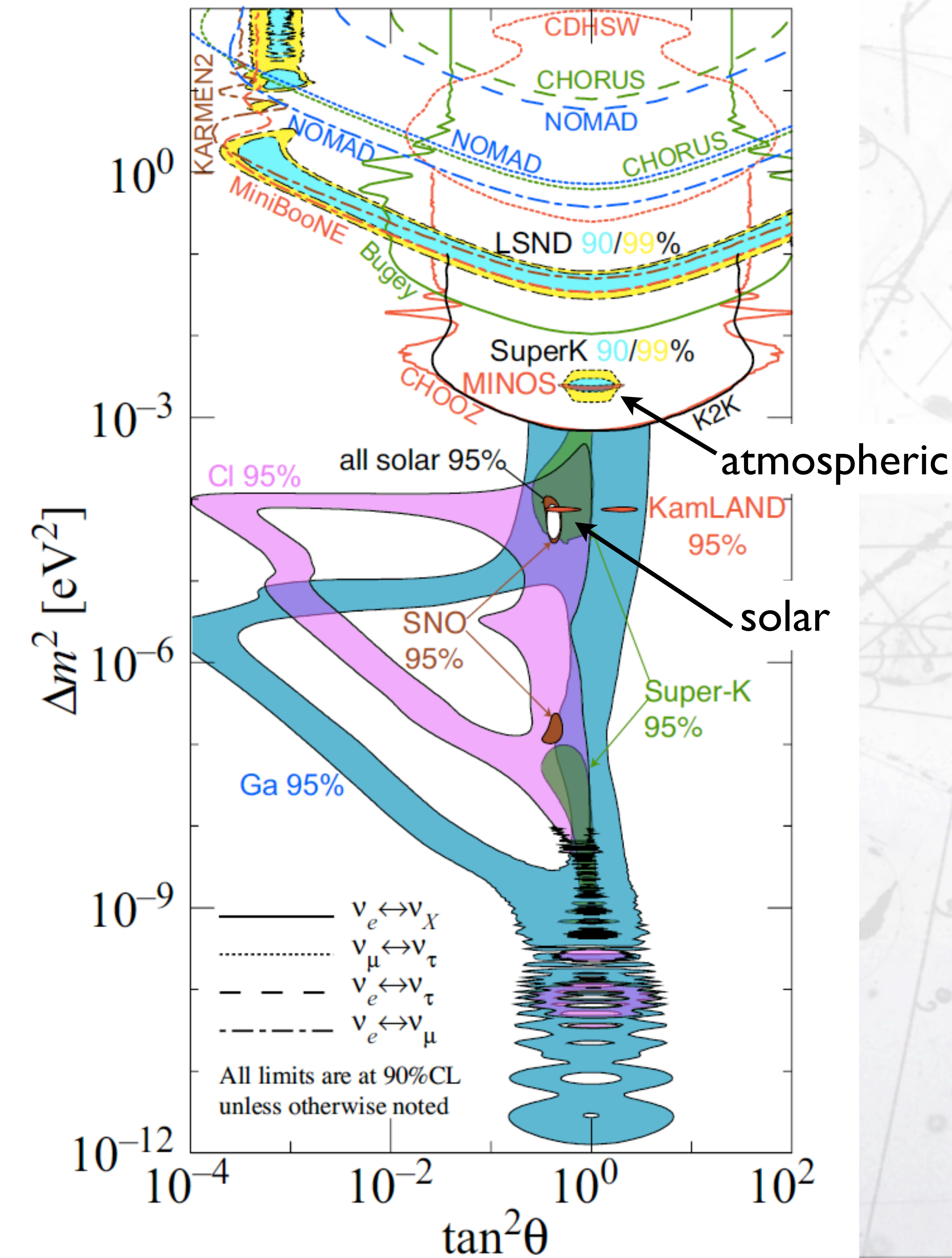
atmospheric | solar

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{21} & \sin\theta_{21} & 0 \\ -\sin\theta_{21} & \cos\theta_{21} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2: traditionally Δm^2_{12} & Δm^2_{23}.

ν oscillations



Particle Data Group neutrino review

Status as of 2012

$$\Delta m^2_{12} = 7.58^{+0.22}_{-0.26} \times 10^{-5} eV^2$$

$$|\Delta m^2_{23}| = 2.35^{+0.12}_{-0.09} \times 10^{-3} eV^2$$

$$\sin^2\theta_{12} = 0.306^{+0.018}_{-0.015}$$

$$\sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}$$

$$\sin^2\theta_{13} = 0.021^{+0.07}_{-0.08}$$

$$\delta_{CP} \in [0^o, 360^o]$$

ν oscillations

What is missing

- δ_{CP} accessible through:
  - comparison of appearance with reactor disappearance.
  - comparison of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- The θ_{23} octant:
  - The θ_{23} is close to 45°

T2K

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

- The absolute neutrino mass.
- The mass hierarchy: is $m_3 > m_1$?

T2K ⊕ NOvA