T2K and J-PARC neutrino experiments

Masashi Yokoyama

Department of Physics, The University of Tokyo

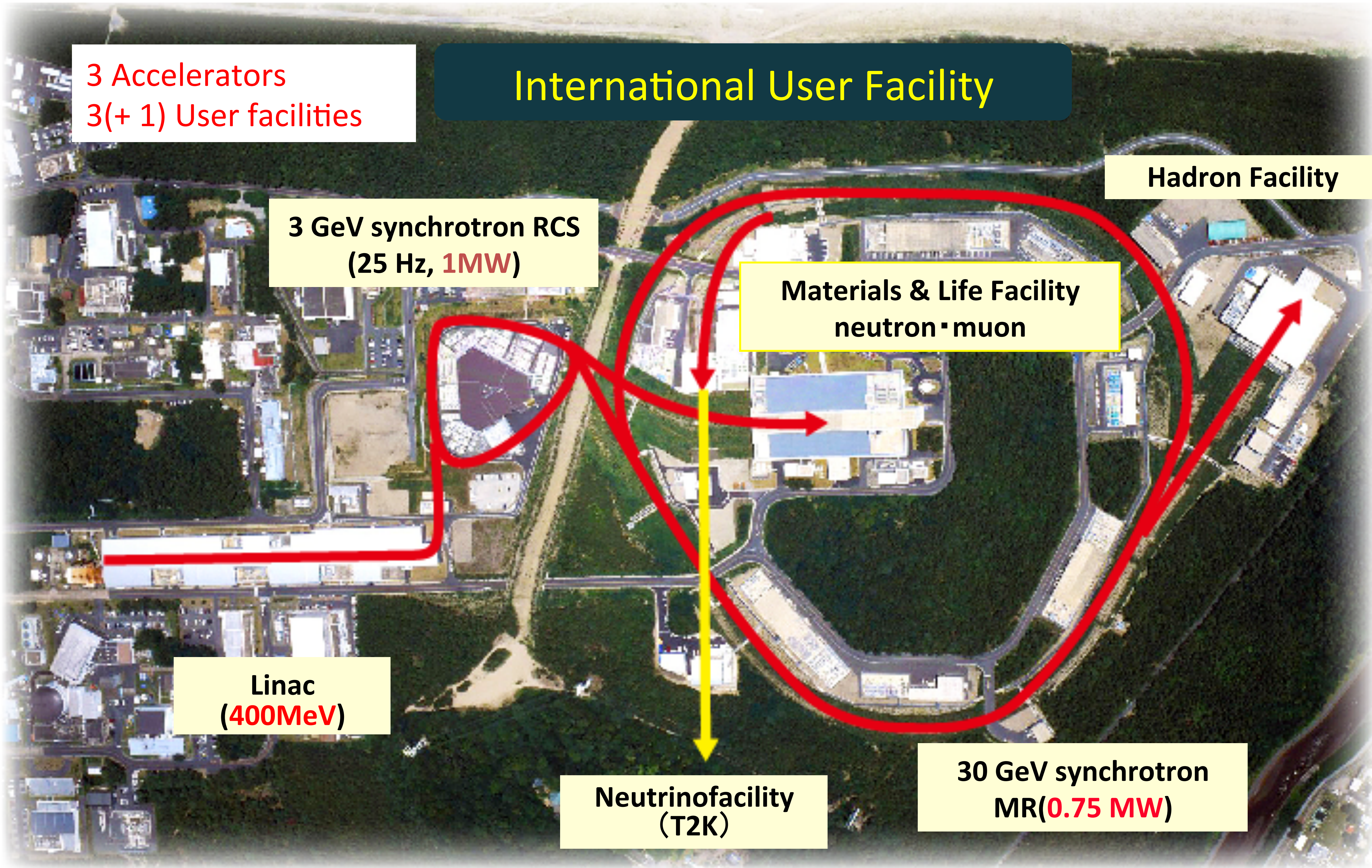
東京大学 THE UNIVERSITY OF TOKYO

SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO

XVI International Workshop on Neutrino Telescopes
2-6 March 2015, Venice

J-PARC

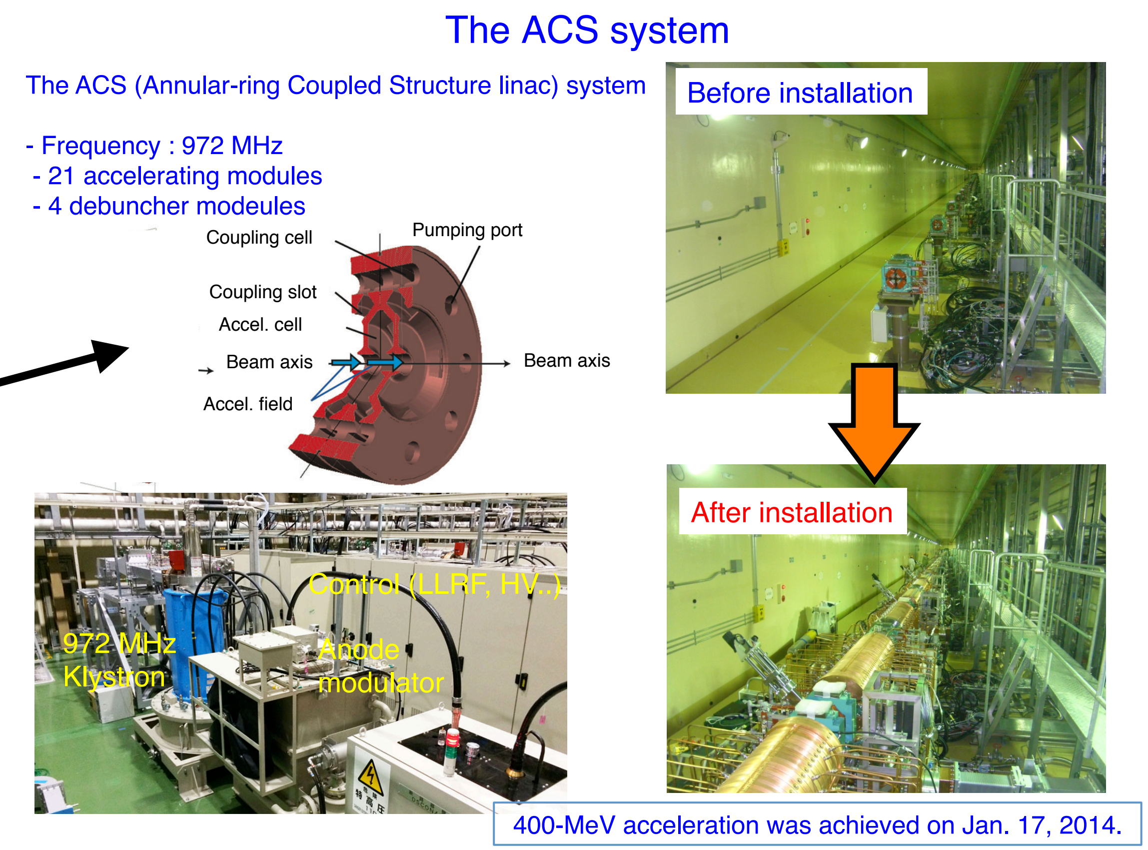
Japan Proton Accelerator Research Complex

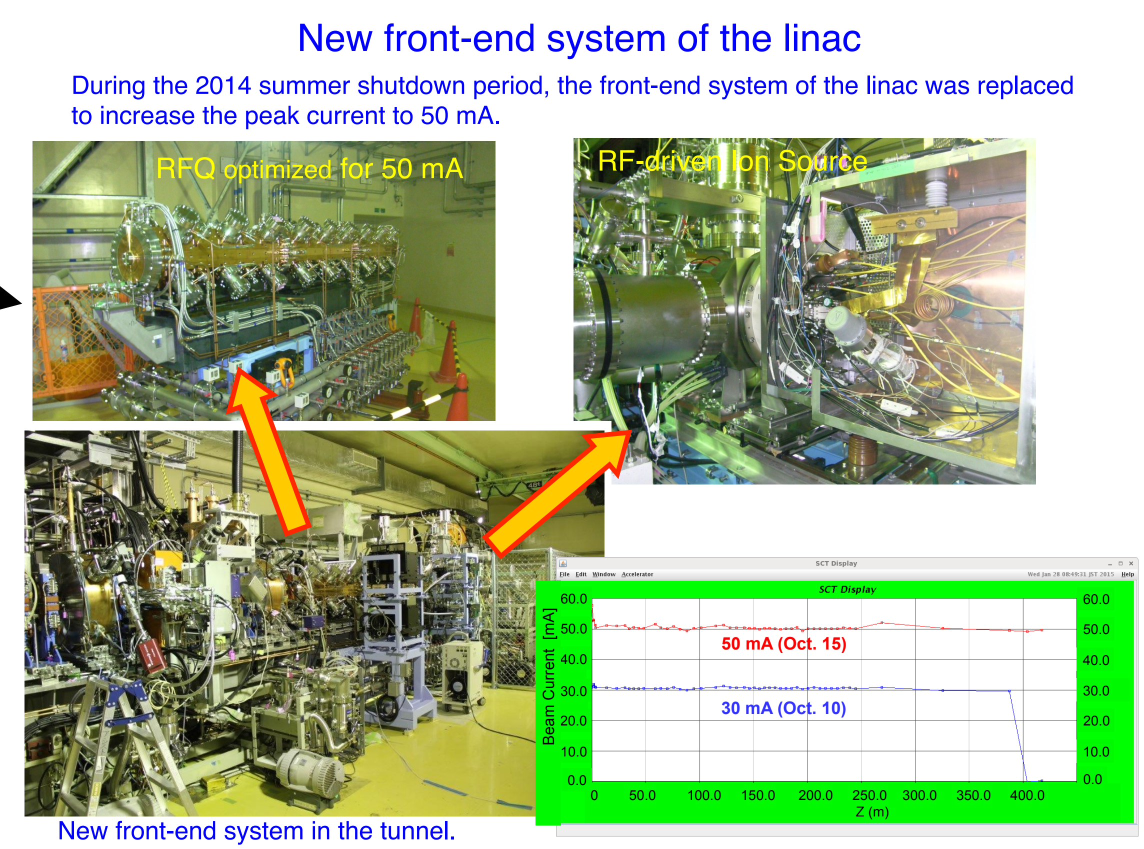


LINAC and ion source upgrade

- Linac energy increased with ACS installation in 2013: 181MeV → 400MeV
- Front-end system replaced with a new one to increase the peak current in 2014: 30mA→50mA

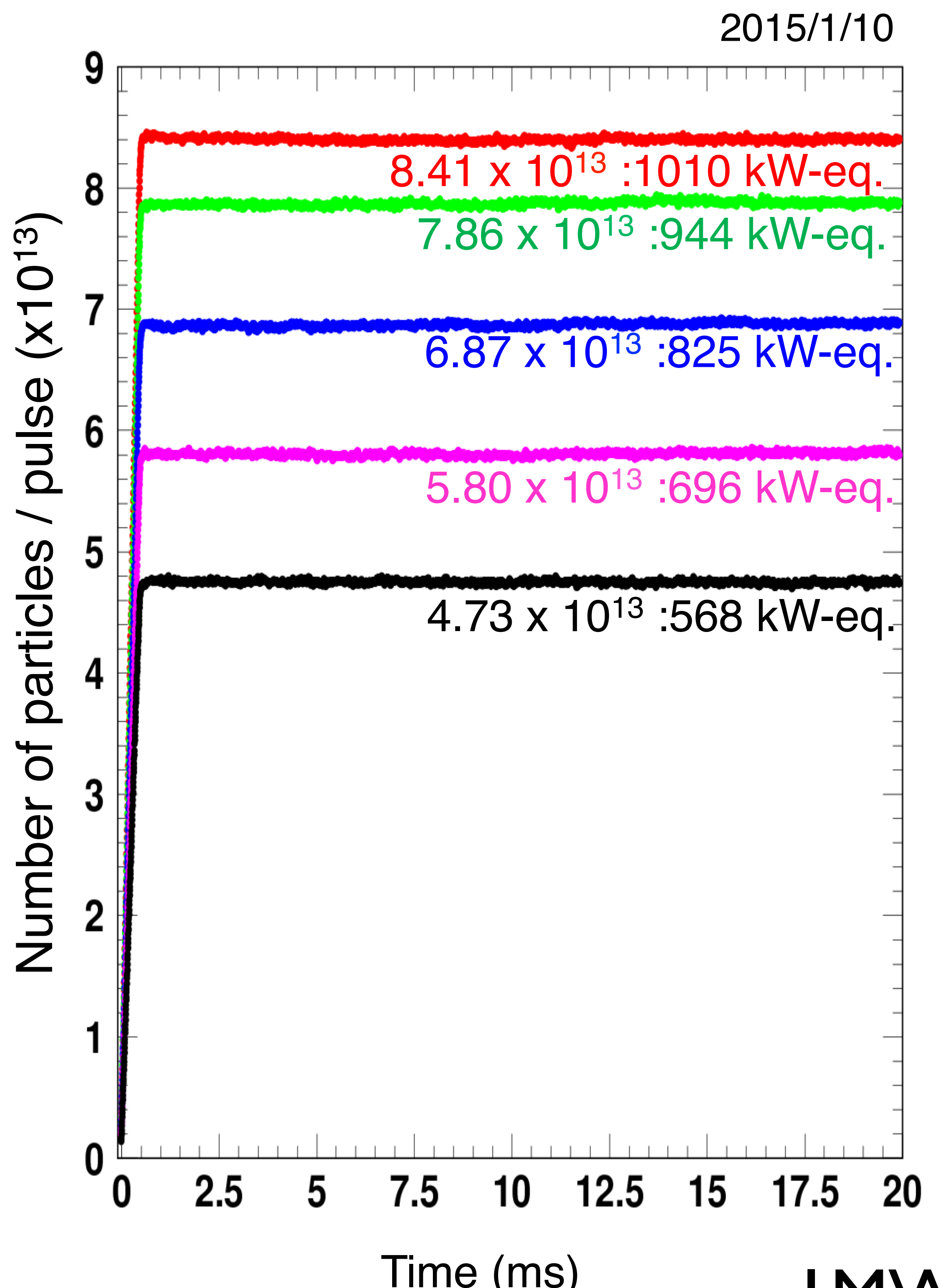
Achieved higher beam intensity



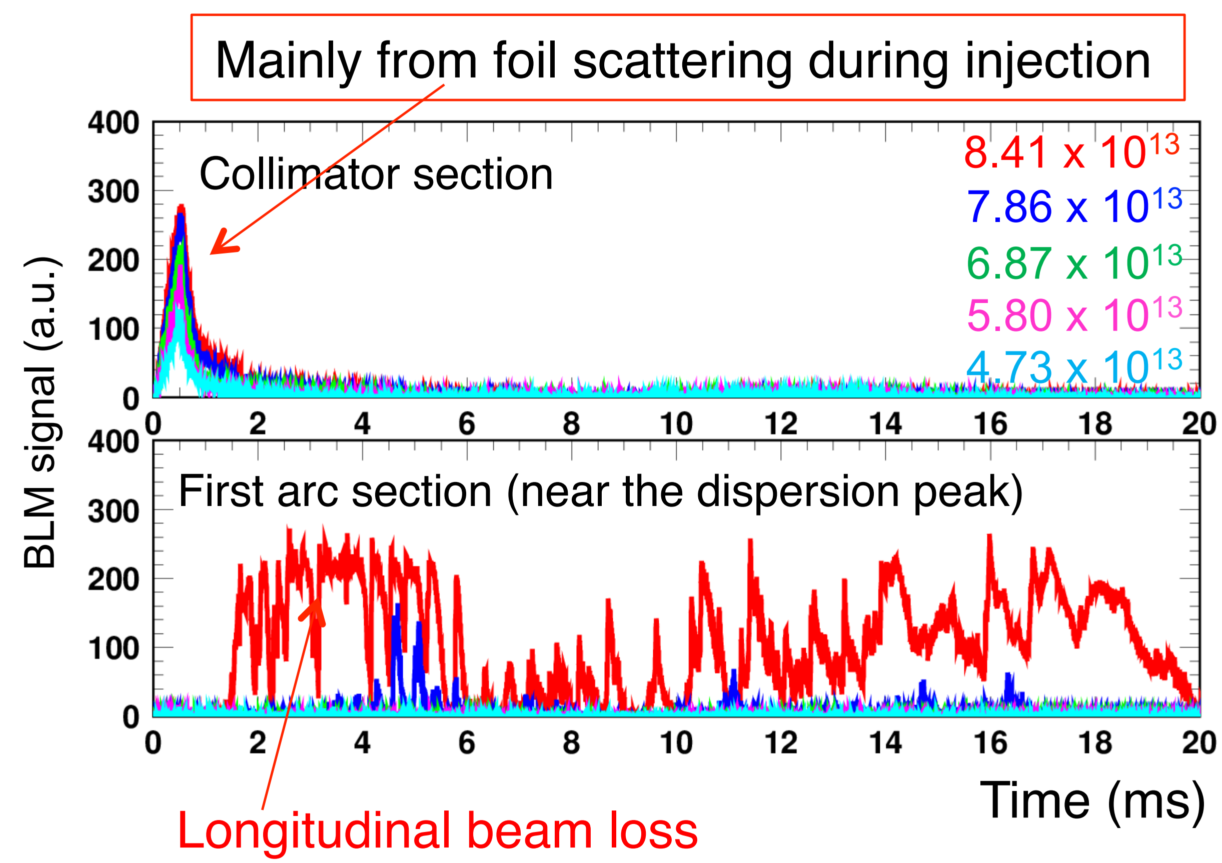


RCS (3GeV) power increase

Demonstration of 1 MW-eq. beam



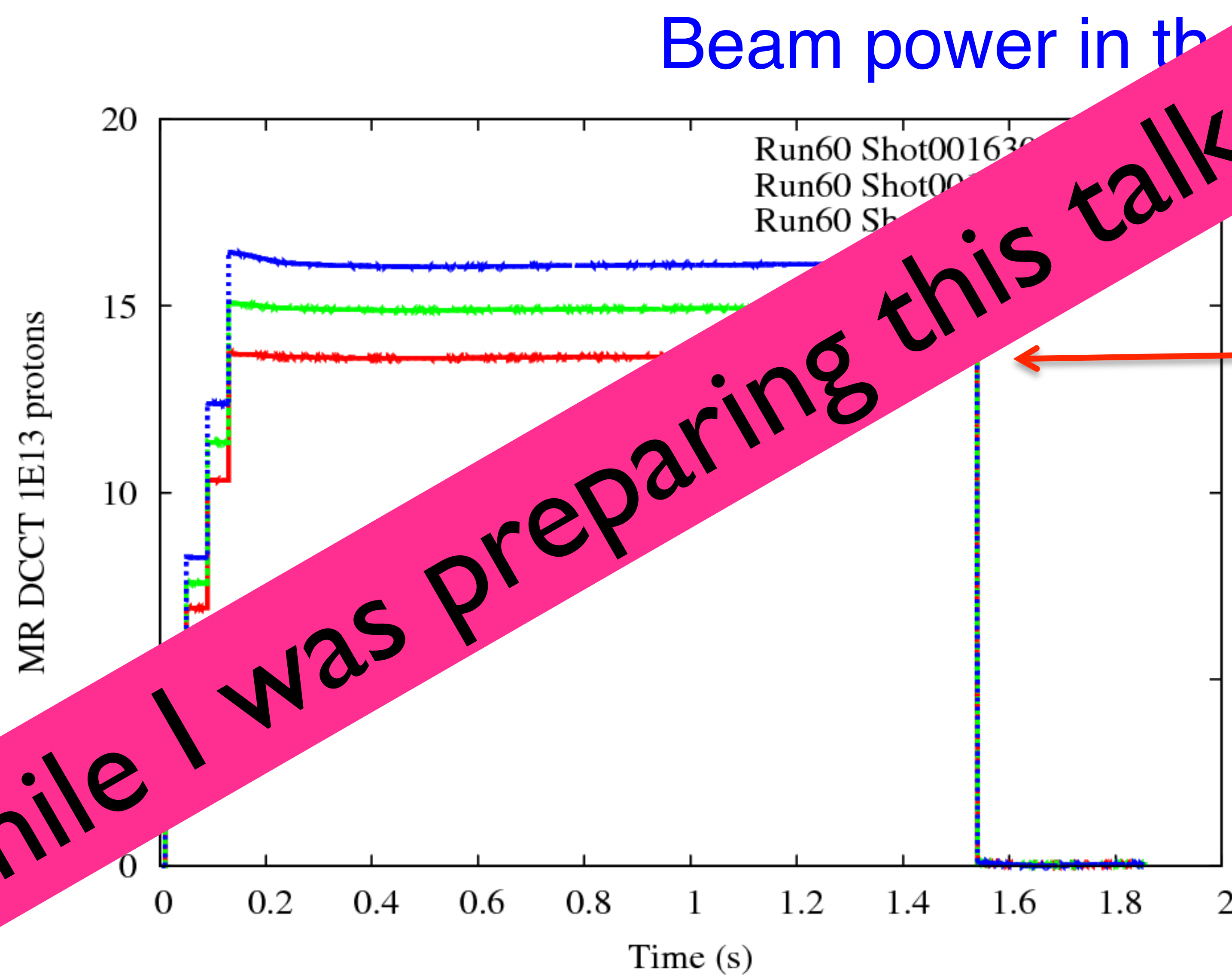
BLM signals @ collimator & arc sections



For 1-MW user operation,
reinforcement of the anode power supplies of the rf power amplifiers is necessary.

1MW operation of RCS foreseen in FY2015

Main Ring (30GeV) high power trial



While I was preparing this talk...

265kW operation achieved

Present user operation

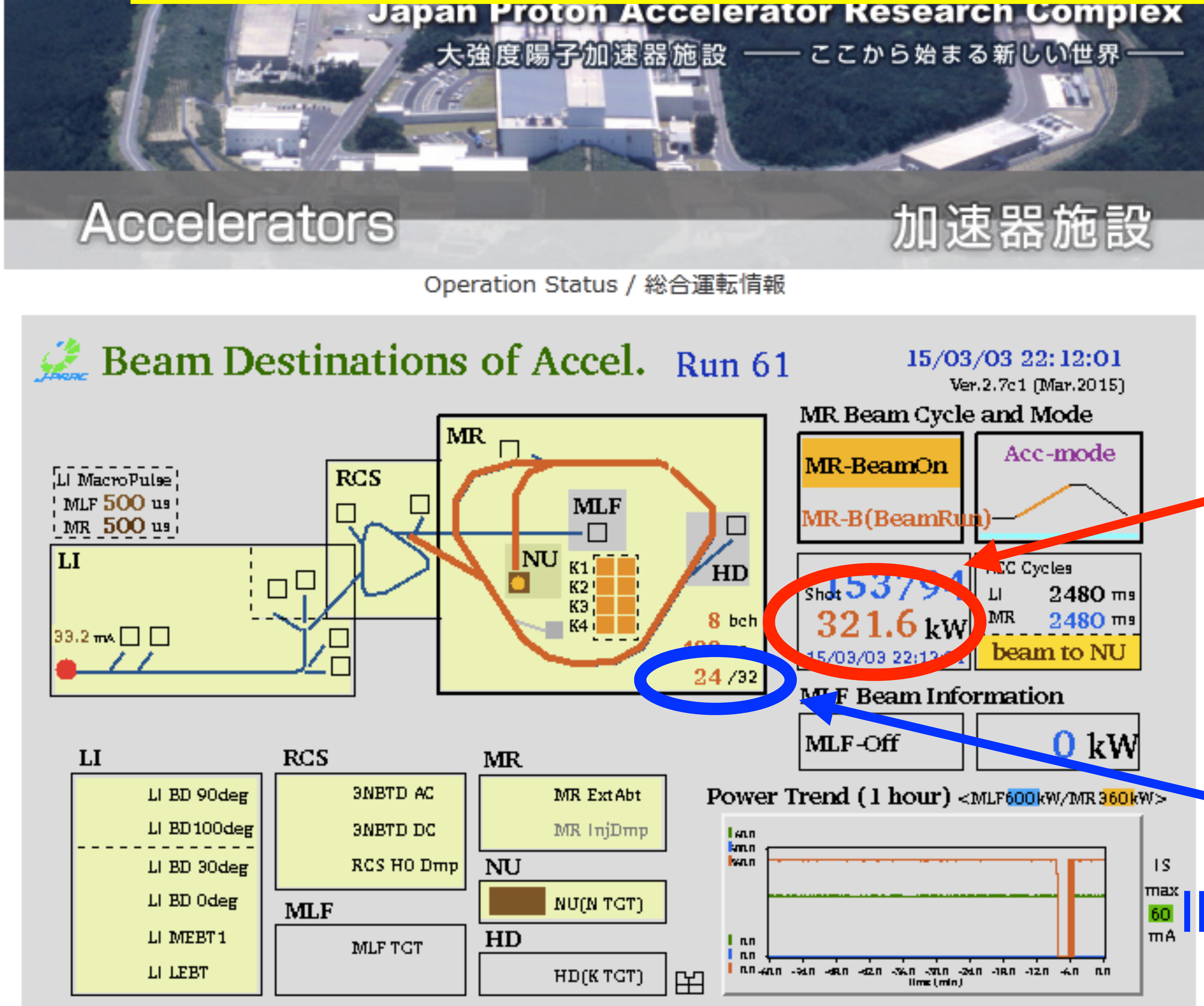
MR power	Inj. loss	Accel. loss
265 kW	~ 100 W	~ 300 W
290 kW	~ 150 W	~ 500 W
310 kW	~ 200 W	~ 900 W

More study time is needed to optimize chromaticity correction, betatron tune, rf patterns during acceleration.
-> The 300 kW user operation will be started soon.

For higher beam power > 300 kW, manipulation of bunching factor using second harmonic rf system is necessary. Operation with a second harmonic rf system will start in JFY2015.

>300kW operation expected in 2015

260kW → 320kW operation!



321kW

24/32 beam

~430kW possible
IF beam loss is reduced

Installation of compensation injection kicker scheduled in Apr. 2015

Aim for ~350kW before summer 2015

MR power mid-term plan

Mid-term plan of MR

FX: Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, rf cavities, ...
SX: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose.

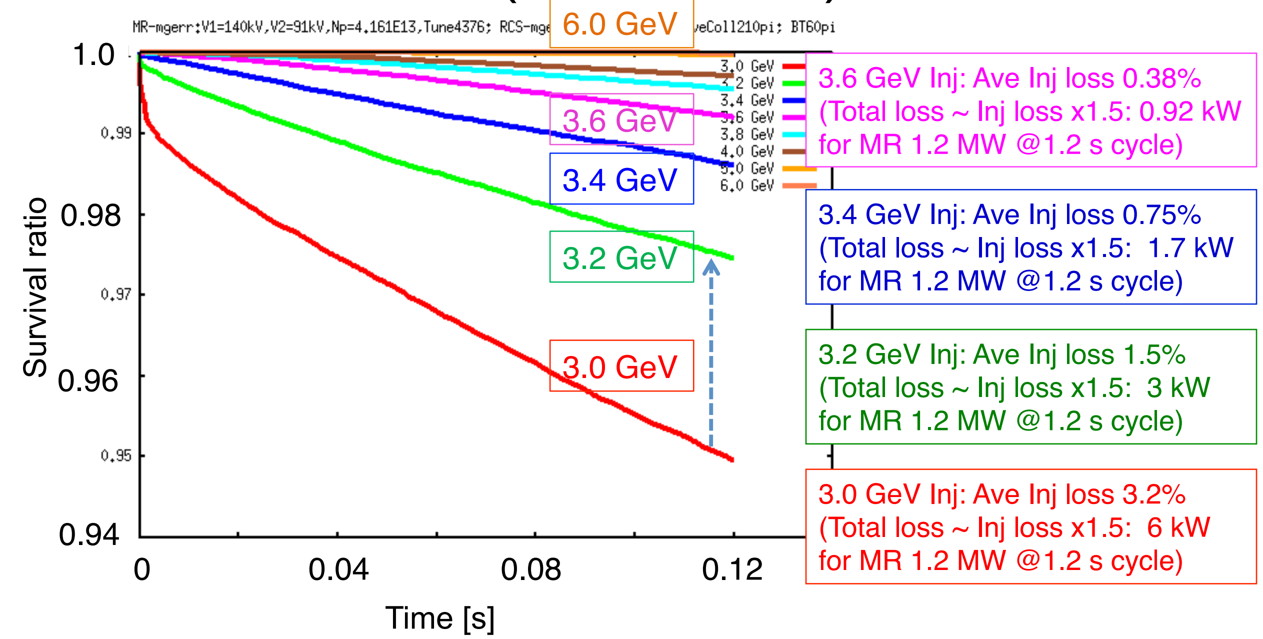
JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial) SX power [kW] (study/trial)	150 3 (10)	200 10 (20)	200 - 240 25 (30)	200 –300 (400) 20-50			750 100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D	2.48 s		Manufacture installation/test		1.3 s
Present RF system New high gradient rf system	Install. #7,8	Install. #9 R&D		Manufacture installation/test			
Ring collimators	Additional shields	Add.collimators and shields (2kW)	Add.collimators (3.5kW) C,D,E,F	Back to JFY2012 (2kW)	Add. coll. C,D	Add. coll. E,F	
Injection system FX system	Inj. kicker	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test					
SX collimator / Local shields	SX collimator				Local shields		
Ti ducts and SX devices with Ti chamber		SX septum endplate	Beam ducts	Beam ducts	ESS		

Long-term plan

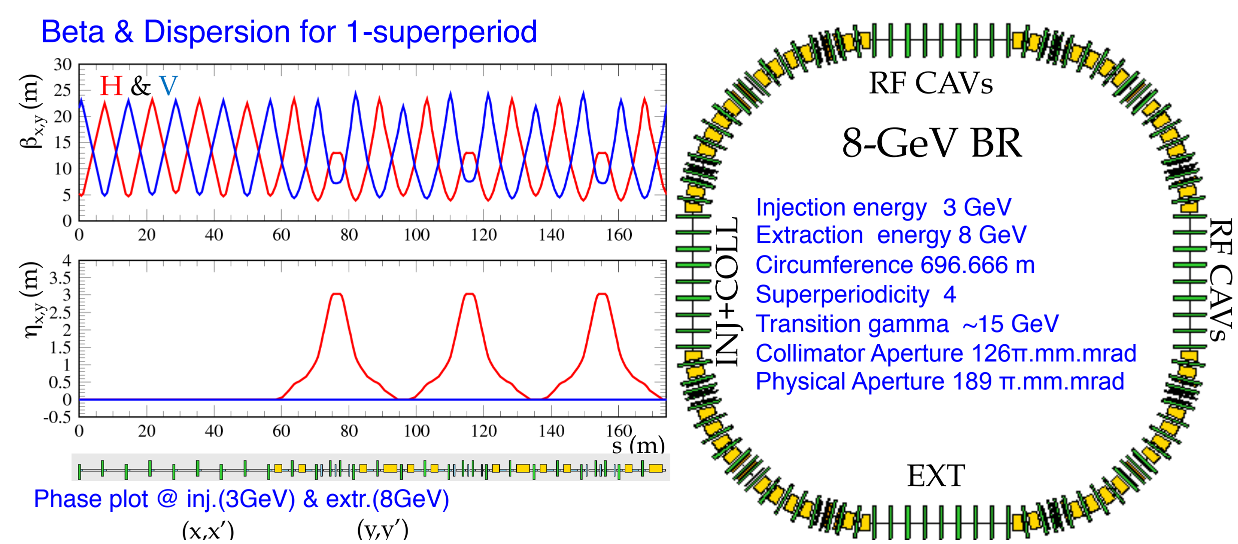
Several ideas under discussion, towards multi-MW facility

- RCS energy increase to reduce space charge effect
  - ~1.5MW
- New Booster Ring (8GeV) between RCS &MR
  - >2MW
- New SC proton linac for neutrino beam (Conceptual study)
  - ~9MW linac with >9GeV energy
  - Using KEKB tunnel?

MR injection energy and beam loss (simulation)



8GeV booster ring



Neutrino experiments at J-PARC

- E11: Tokai-to-Kamioka (T2K) Long Baseline Experiment
- T32, T49: Liq. Ar TPC R&D (test beam)
- E56: A Search for Sterile Neutrino at J-PARC Materials and Life Science Experimental Facility
- P58: A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande (→Shiozawa-san)
- T59: A test experiment to measure neutrino cross sections using a 3D grid-like neutrino detector with a water target at the near detector hall of J-PARC neutrino beam-line
- T60: An emulsion-based test experiment at J-PARC
- LoI: A nuPRISM Detector in the J-PARC Neutrino Beamline

T2K

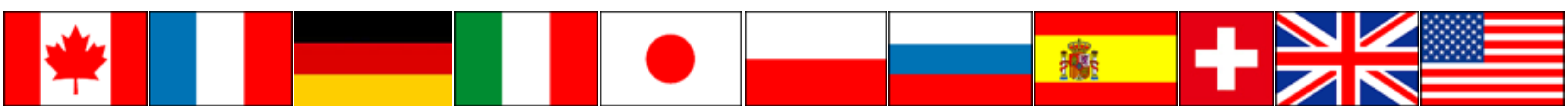
T2K

Tokai-to(2)-Kamioka

Intense proton beam from J-PARC
High quality off-axis beam
High performance near detectors
Gigantic, high performance far detector, Super-K

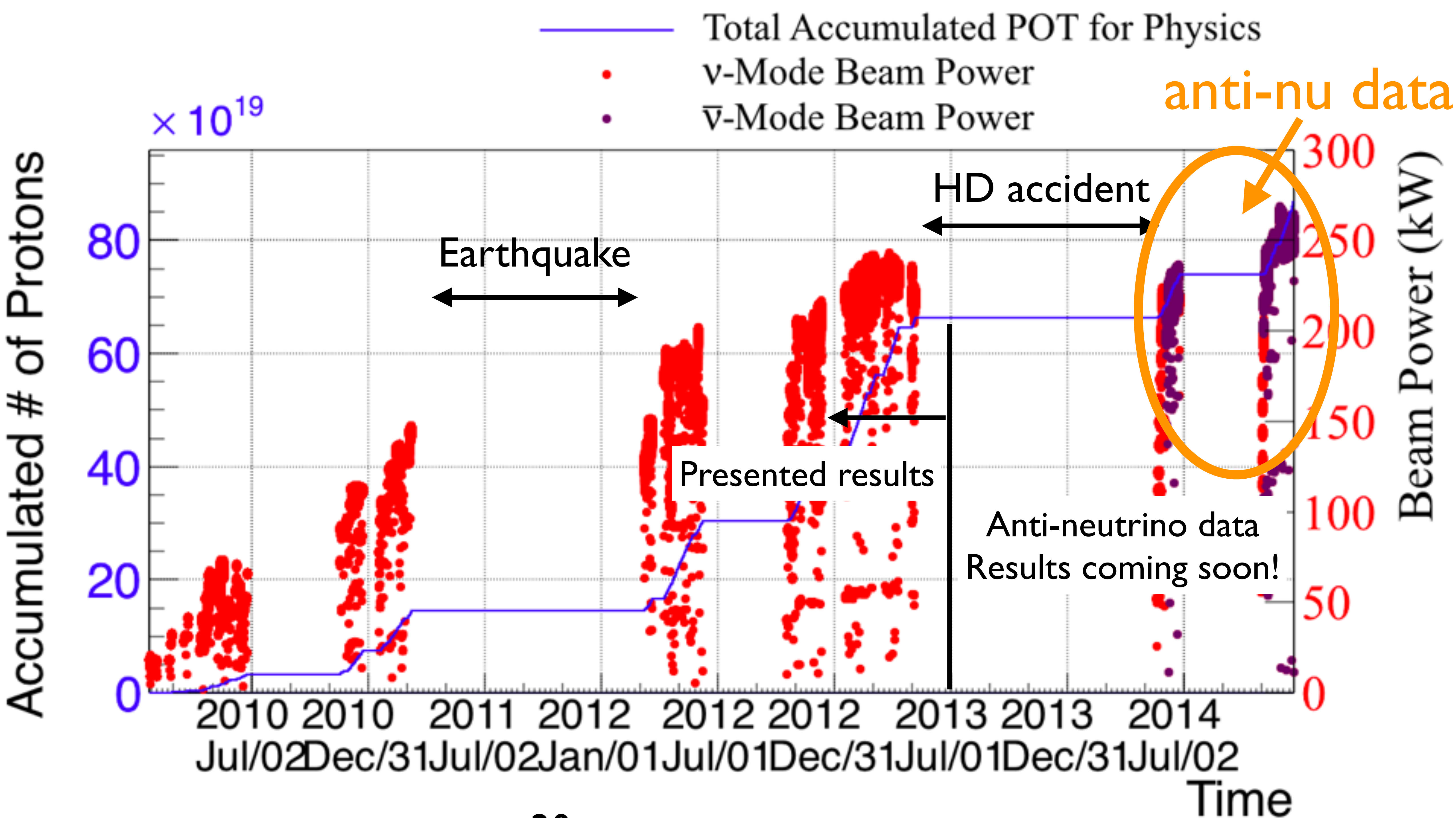
T2K Collaboration

Collaboration photo
Apr. 2014



Spokesperson: T.Nakaya (Kyoto) (from Feb. 2015)
International Co-spokesperson: C.K.Jung (Stony Brook)

Accumulated POT (2010 Jan.–2014 Dec.)



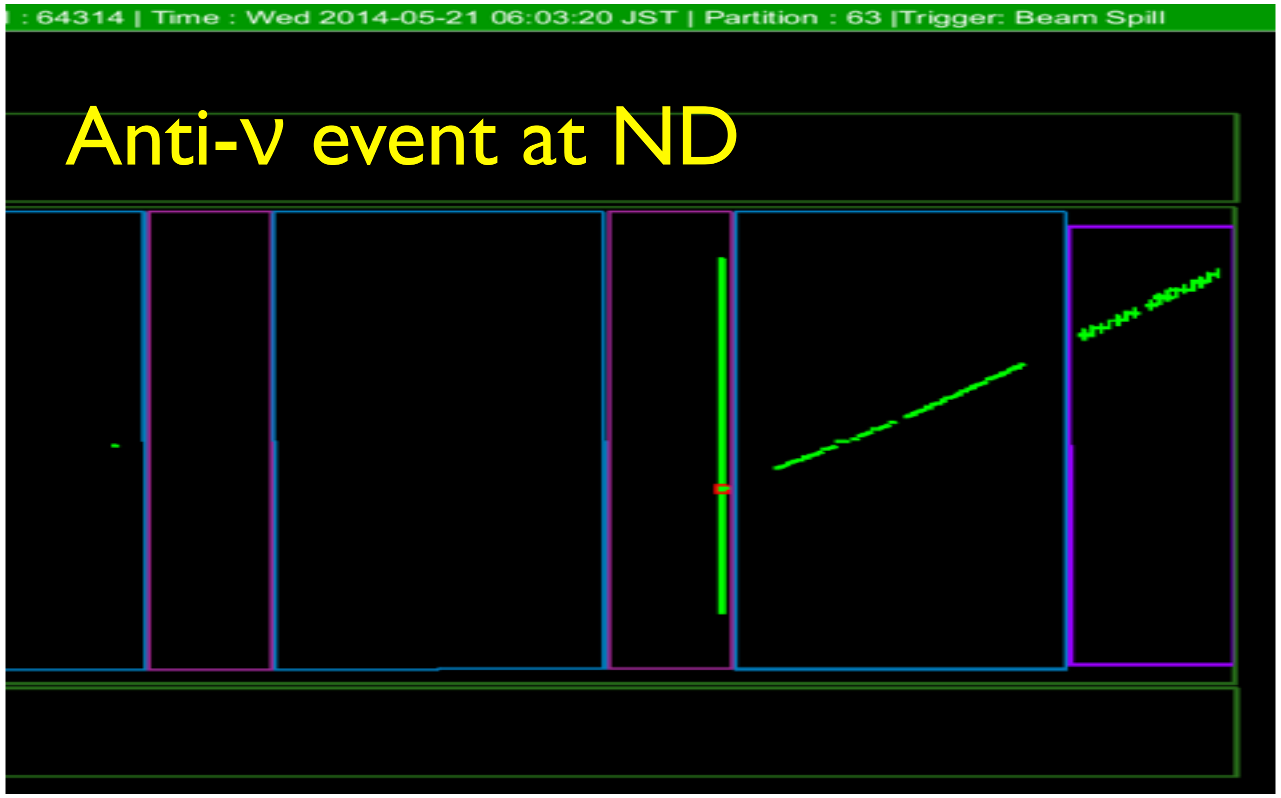
ν mode : 6.9×10^{20} POT

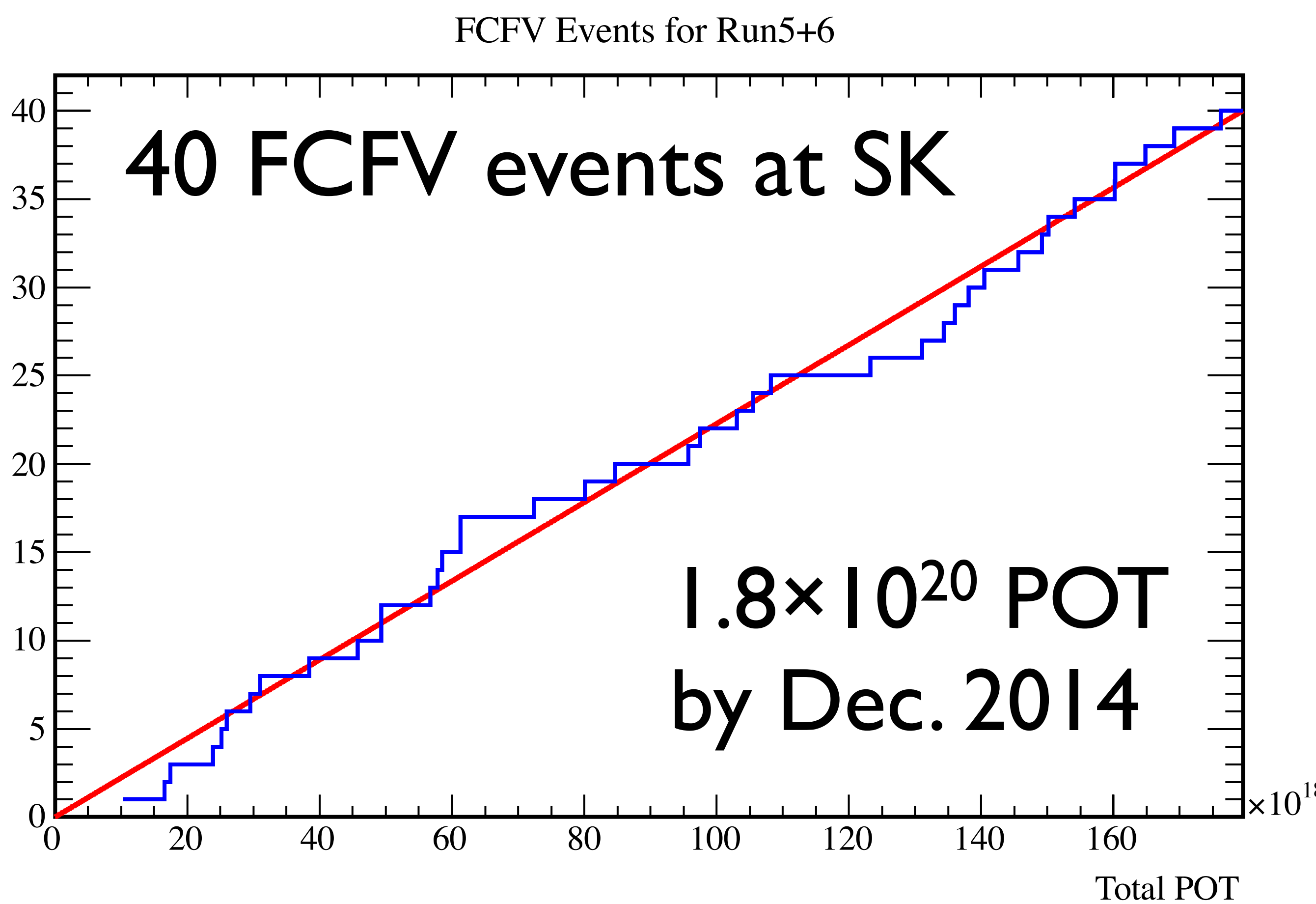
ν̄ mode : 1.8×10^{20} POT

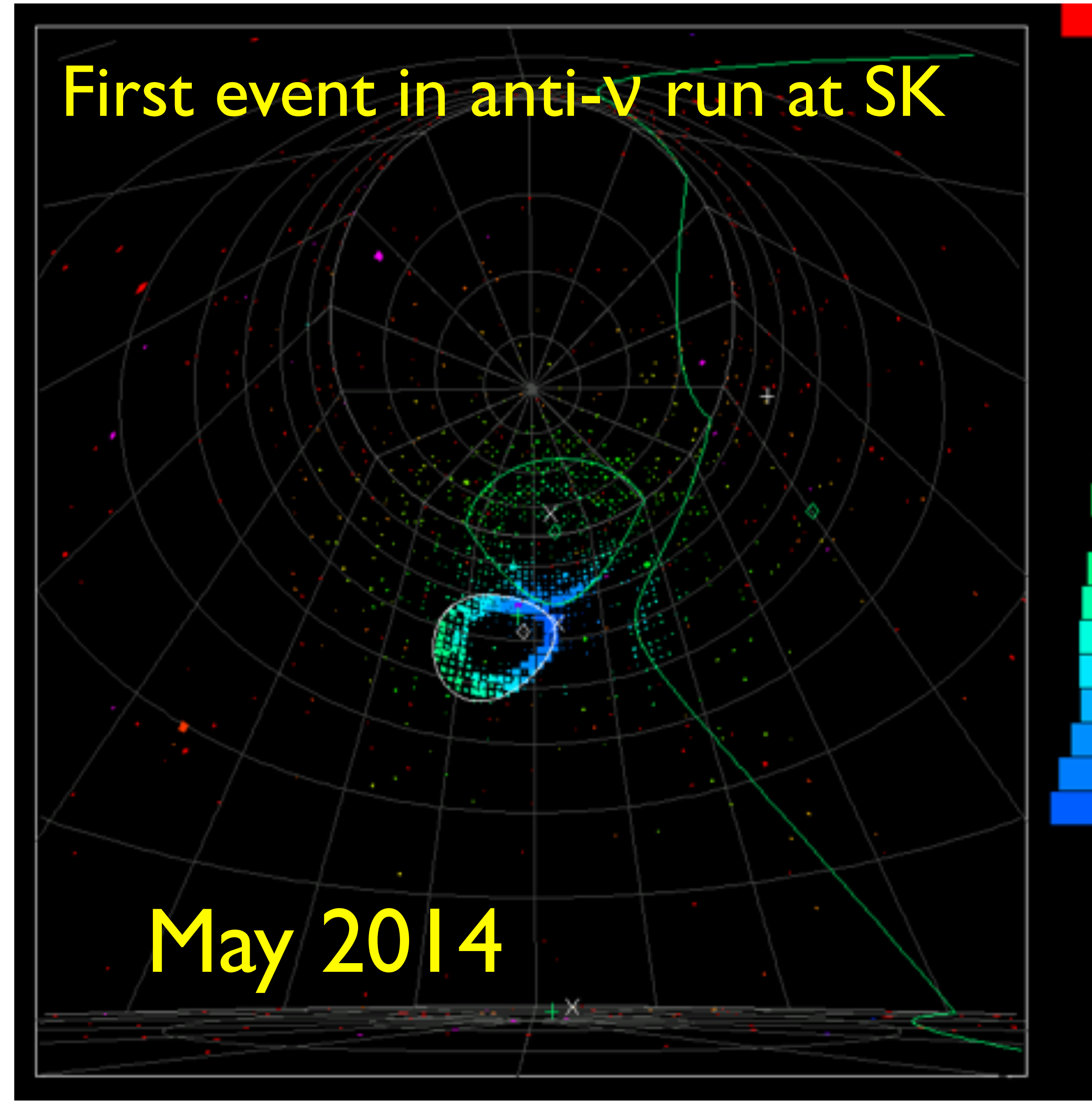
Total : 8.7×10^{20} POT

1.7×10^{14} protons per pulse: World record!

Anti-neutrino data taking

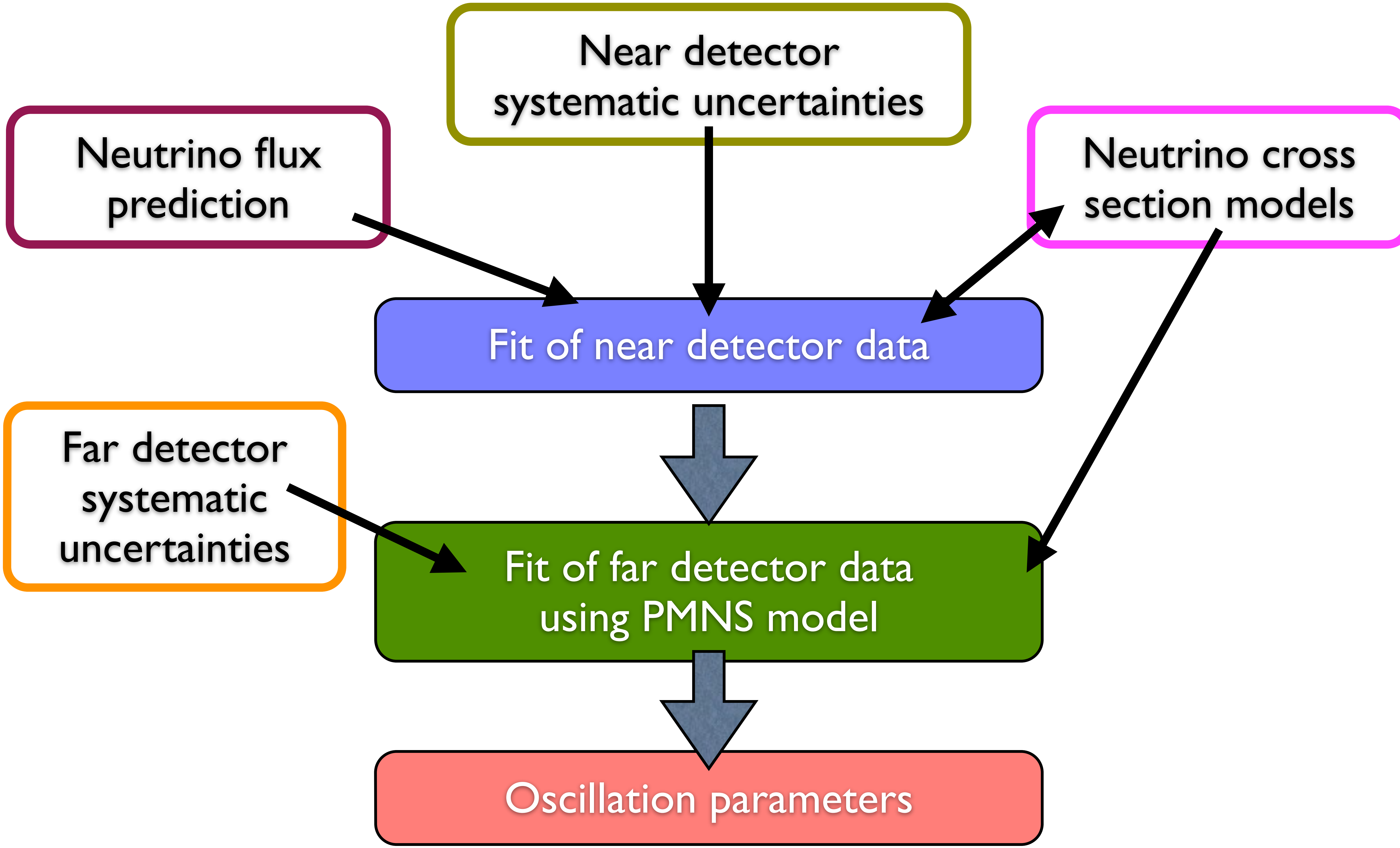




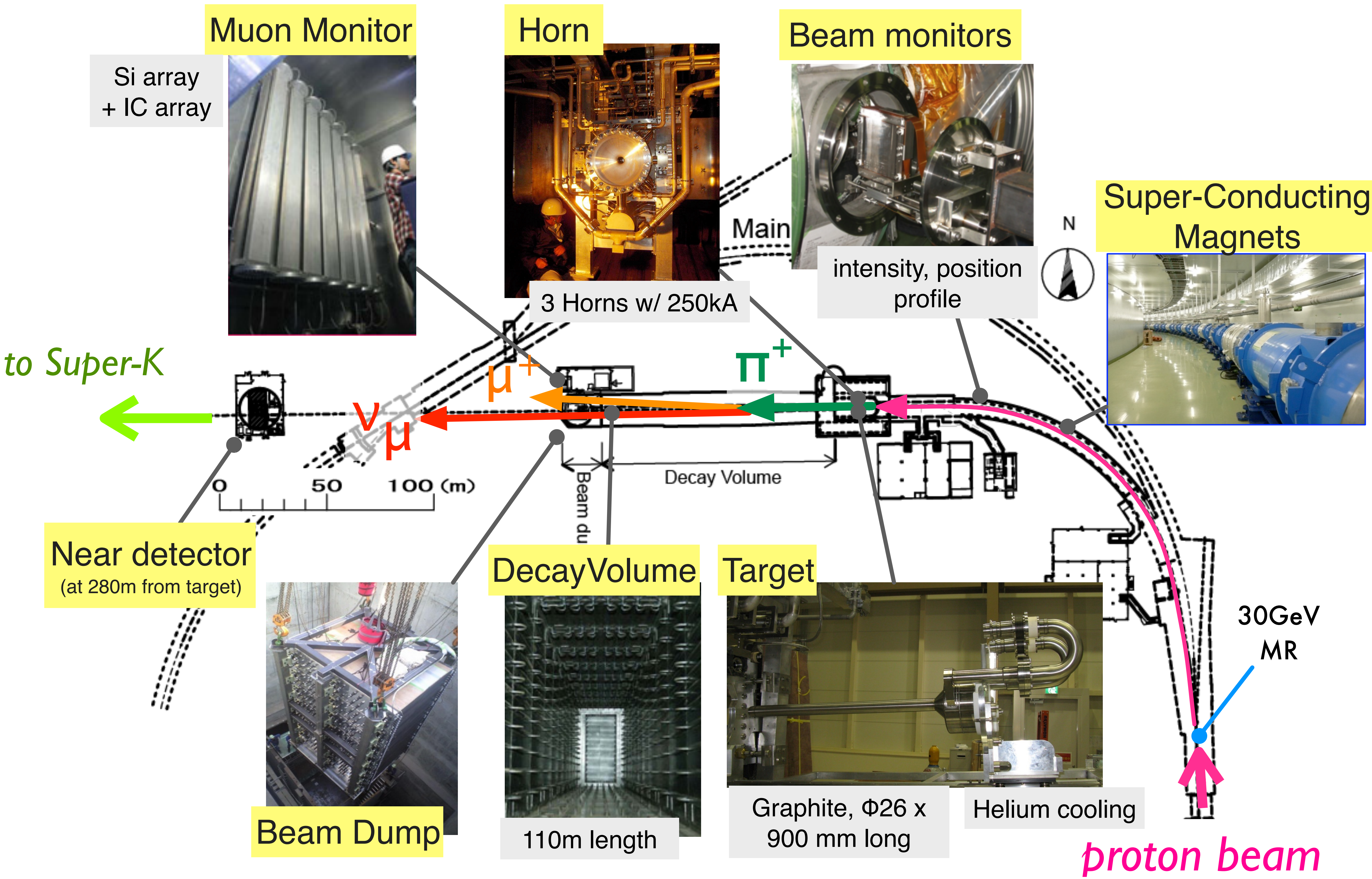


Now accumulating more data
Analysis ongoing, stay tuned!

Neutrino oscillation analysis



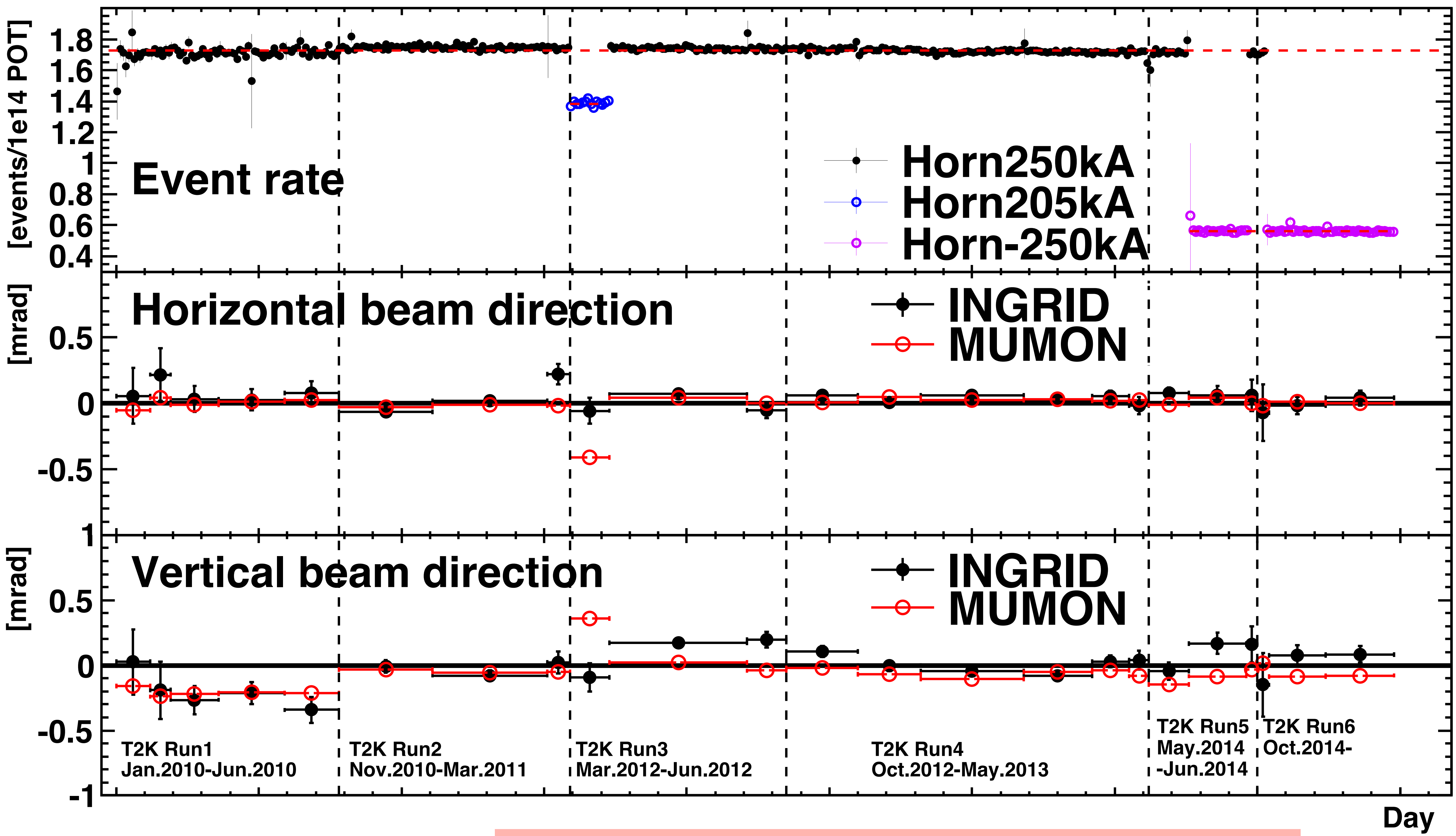
J-PARC neutrino beamline



T2K beamline status

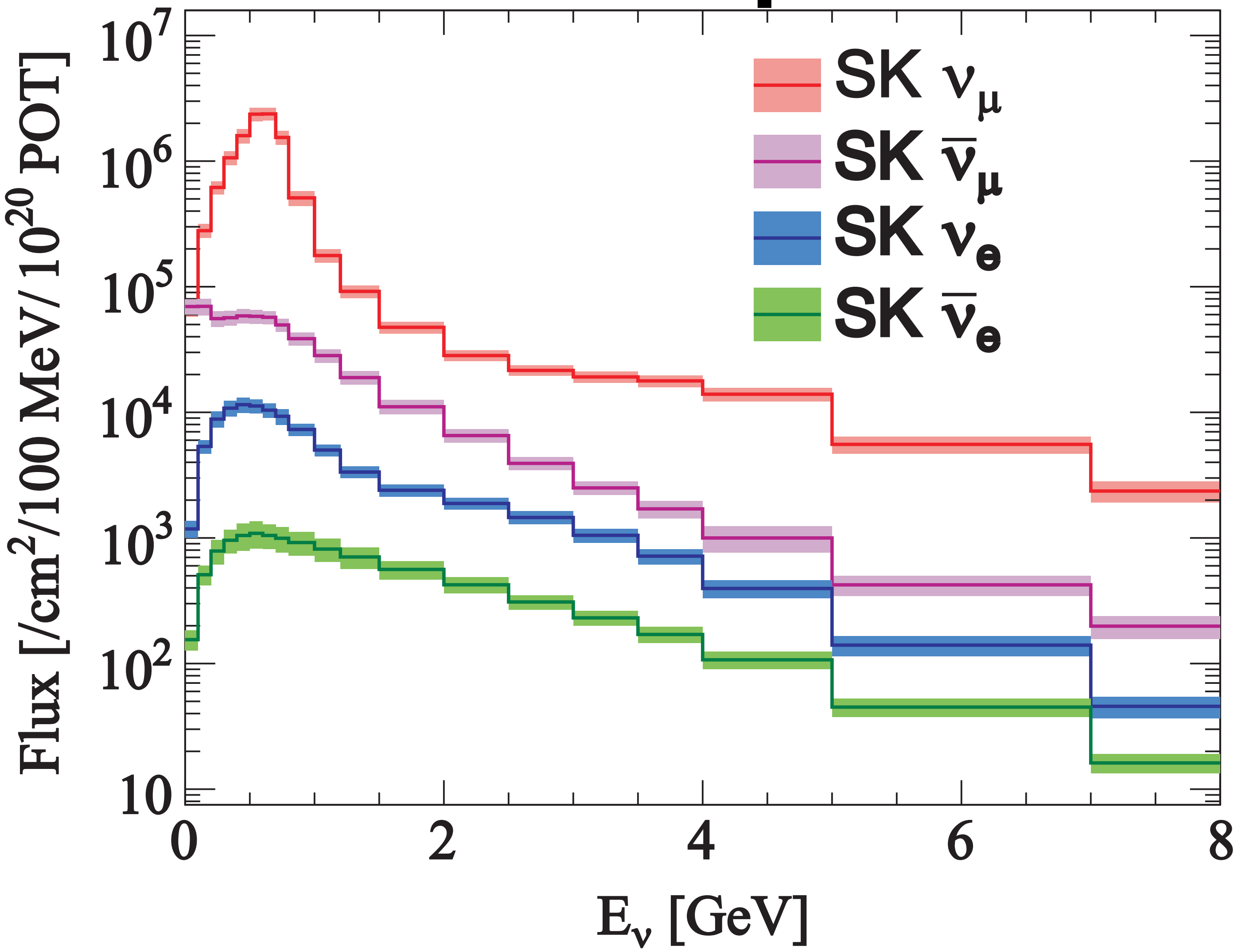
- All horns were replaced with improved ones in 2013-2014
  - Remote handling procedure was established.
- Now 500kW acceptable, improvement for 750kW ongoing
  - Increase radioactive water/air disposal capability
- Inaccessible part (decay vol., beam dump) designed and built for multi-MW

Beam stability (Jan.2010-Dec.2014)



Excellent stability for whole run

Neutrino flux prediction



- GEANT3 based beamline MC simulation
  + In situ proton beam measurements during run
  + Tuned with hadron production measurements e.g. NA61 @CERN
- ~12% uncertainty at peak energy (before ND280 constraints)
  - Still improving : latest NA61 results will be included soon, to go <10%
- Anti-neutrino (reverse horn current) flux with similar uncertainty

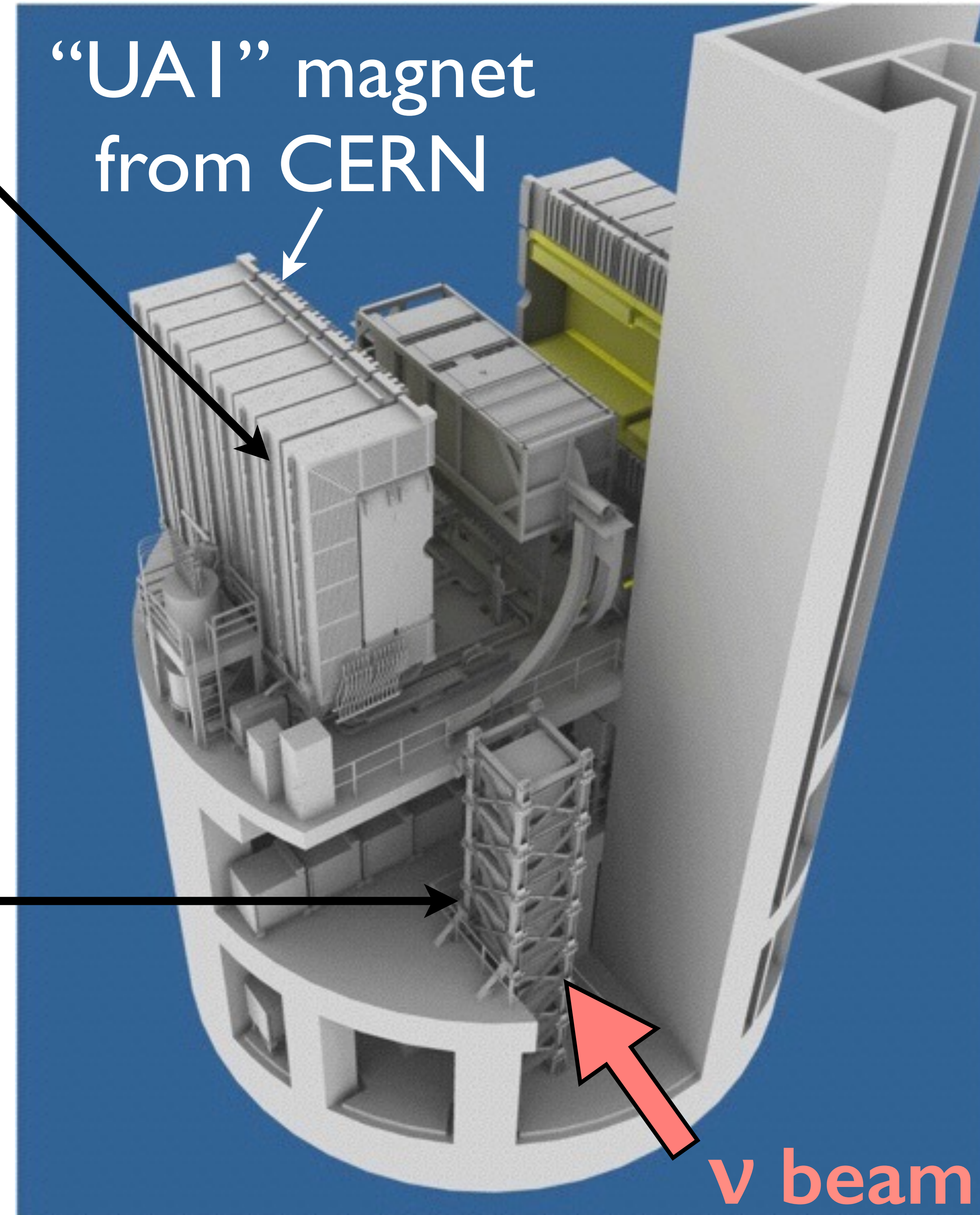
Near detectors

Off-axis detector (ND280)
measure ν beam properties

- Detector suite
  @ 2.5degree off-axis
  - Dipole magnet (0.2T)
  - π^0 detector (P0D)
  - FGD+TPC: target+tracker
  - EM calorimeters
  - Side Muon Range detector

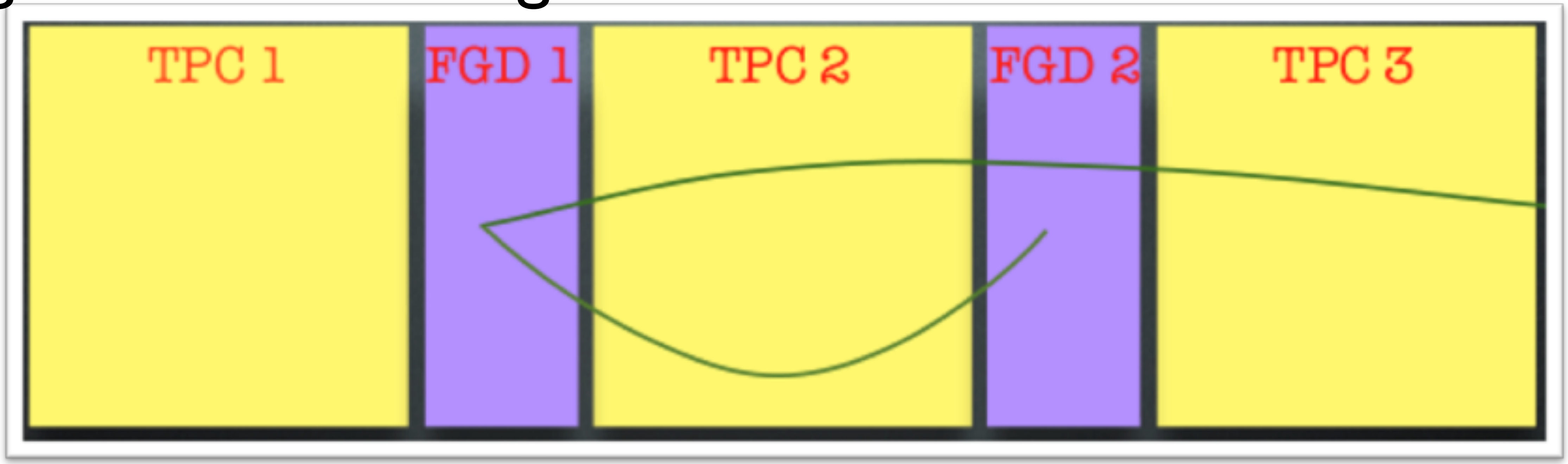
On-axis detector (INGRID)
Monitor direction/stability of ν beam

- Iron-scintillator sandwich modules covering 10m×10m around the beam center

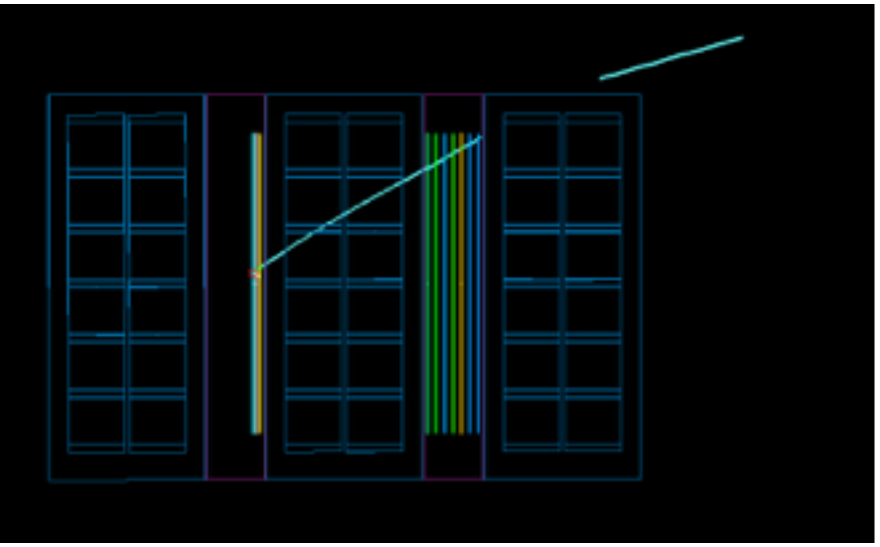


ND280 ν_μ selection

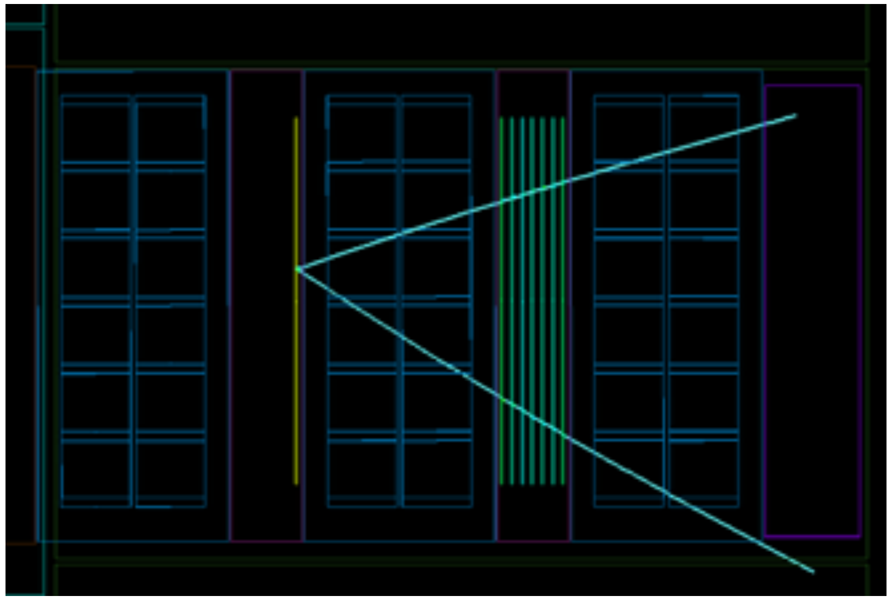
High momentum negative track in TPC = muon candidate



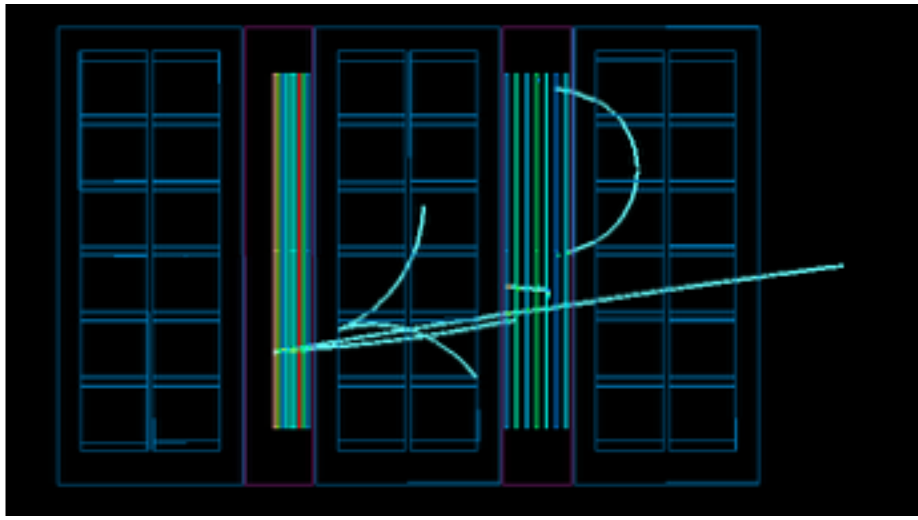
Classify events into 3 samples to enhance sensitivity to interaction models



CC0π

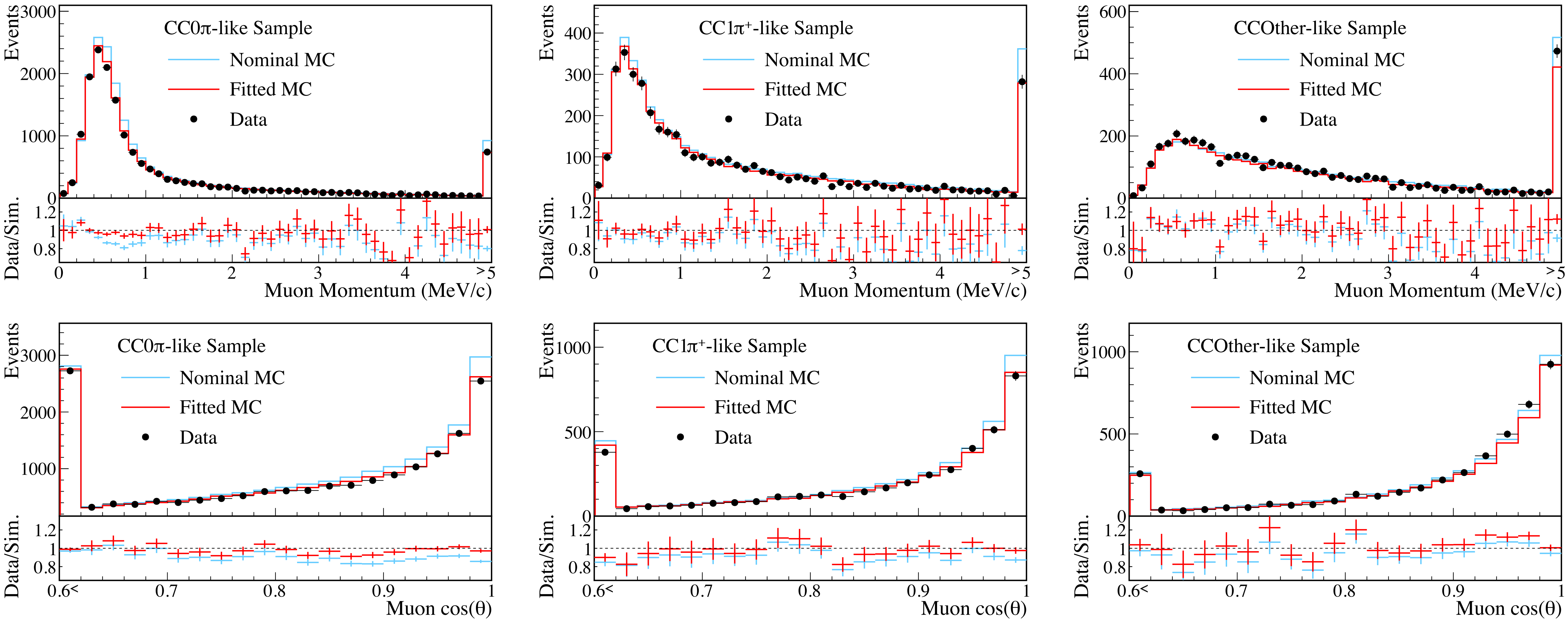


CC1π



CC others

ND280 data distributions



Constrain rate (flux × cross section) and cross section parameters with ND data

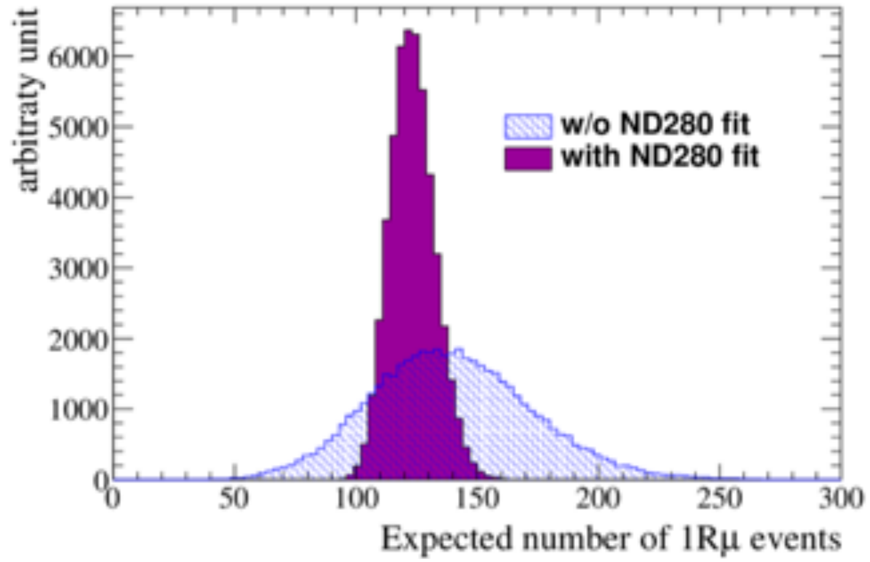
Correlation between energy/samples taken into account

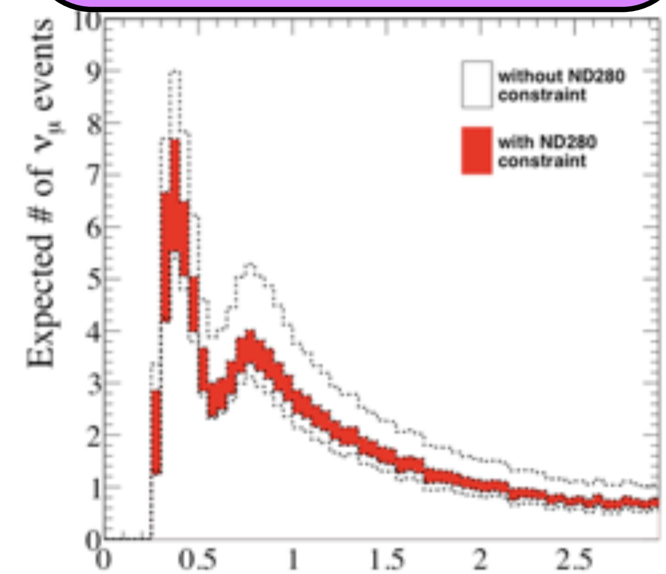
ν_e at SK can be constrained by ν_μ at ND(same parent particle)

Uncertainties of predictions at the far detector

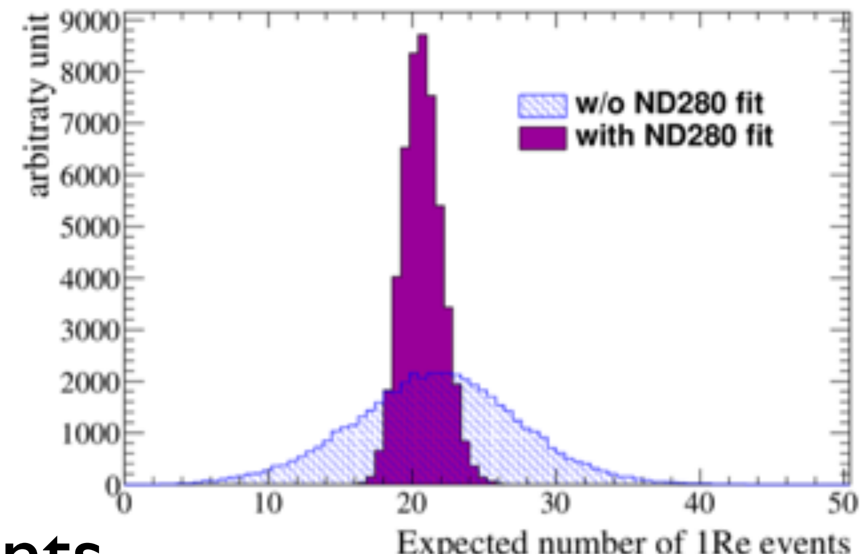
No. of events | Spectrum shape

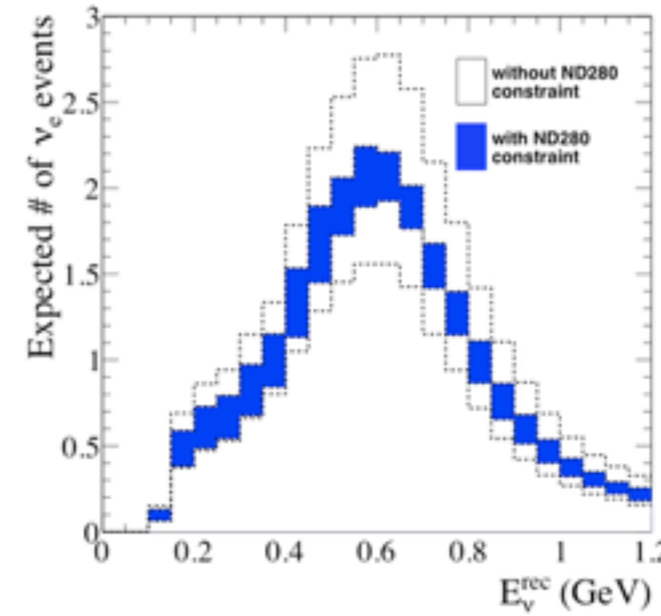
1 ring μ





1 ring e

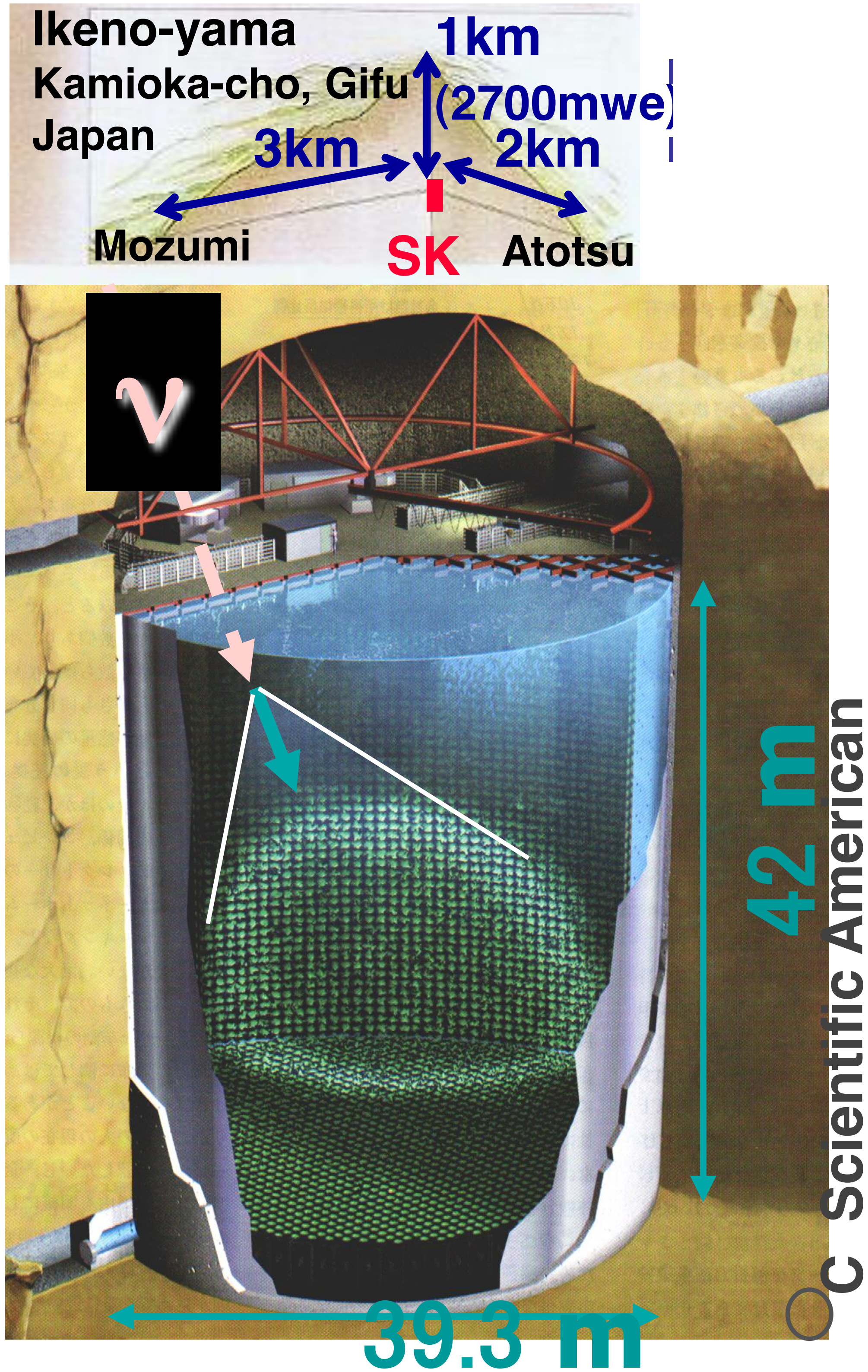




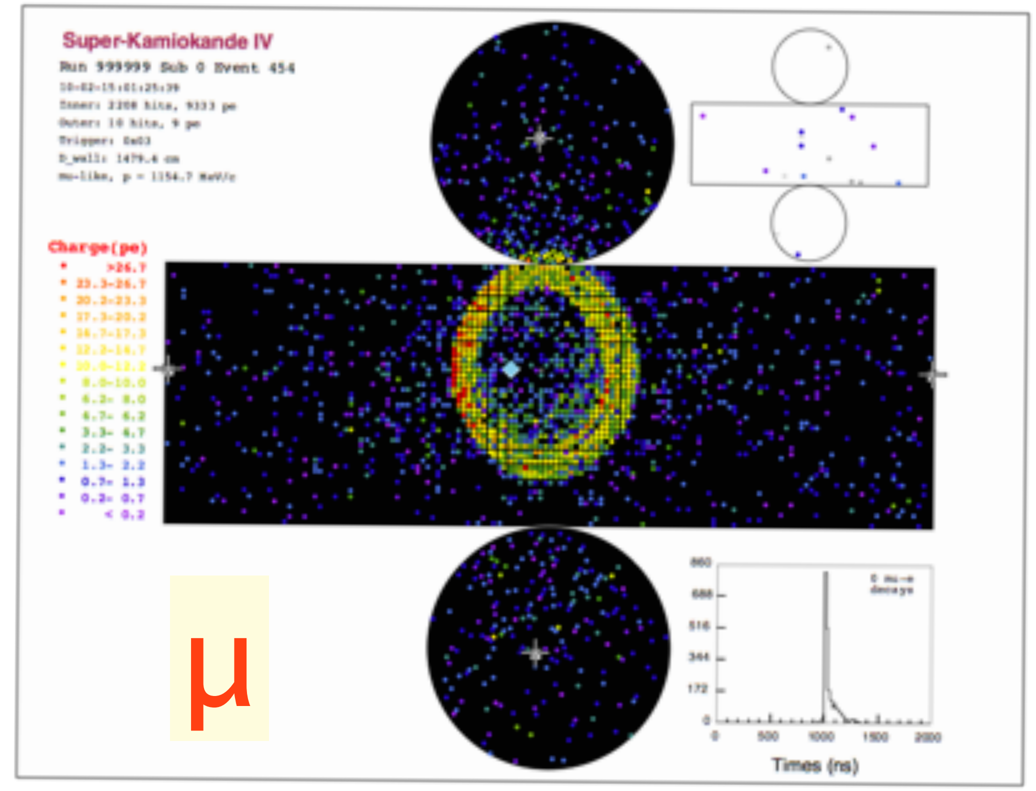
Error on number of events

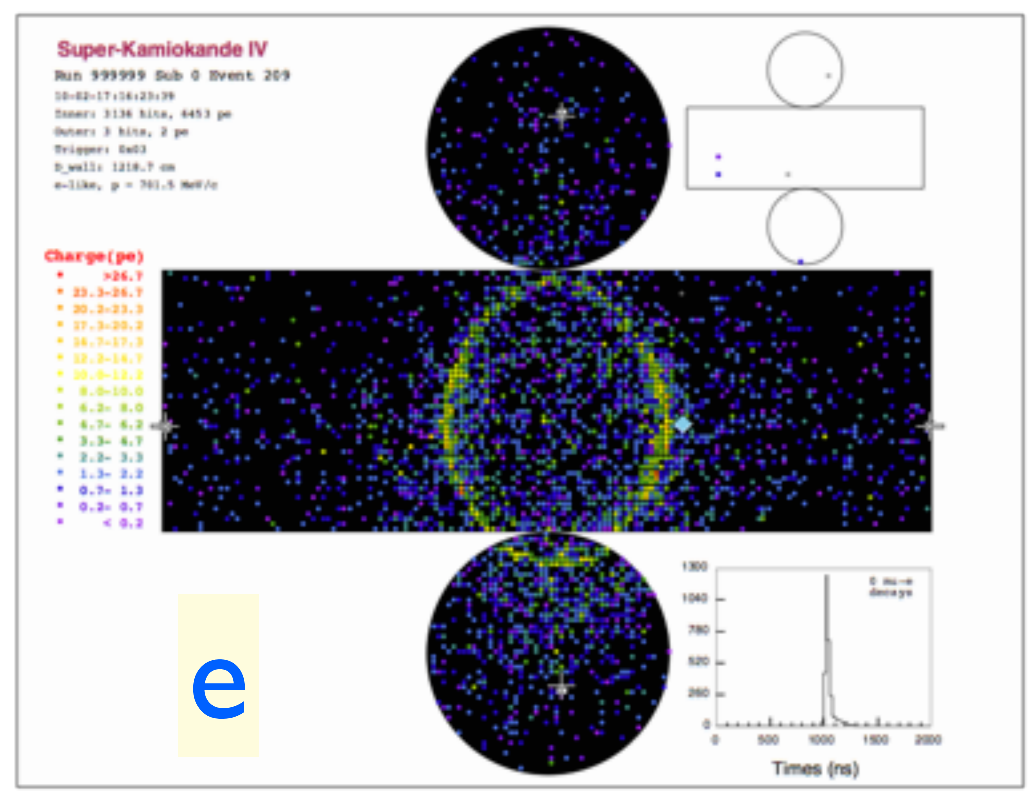
	Flux/cross section w/ ND measurement	Cross section uncertainty due to target diff.	Final state/ secondary interaction	SK detector	Total
νμ	2.7%	5.0%	3.0%	4.0%	7.7%
νe	3.1%	4.7%	2.4%	2.7%	6.8%

Far detector: Super-Kamiokande

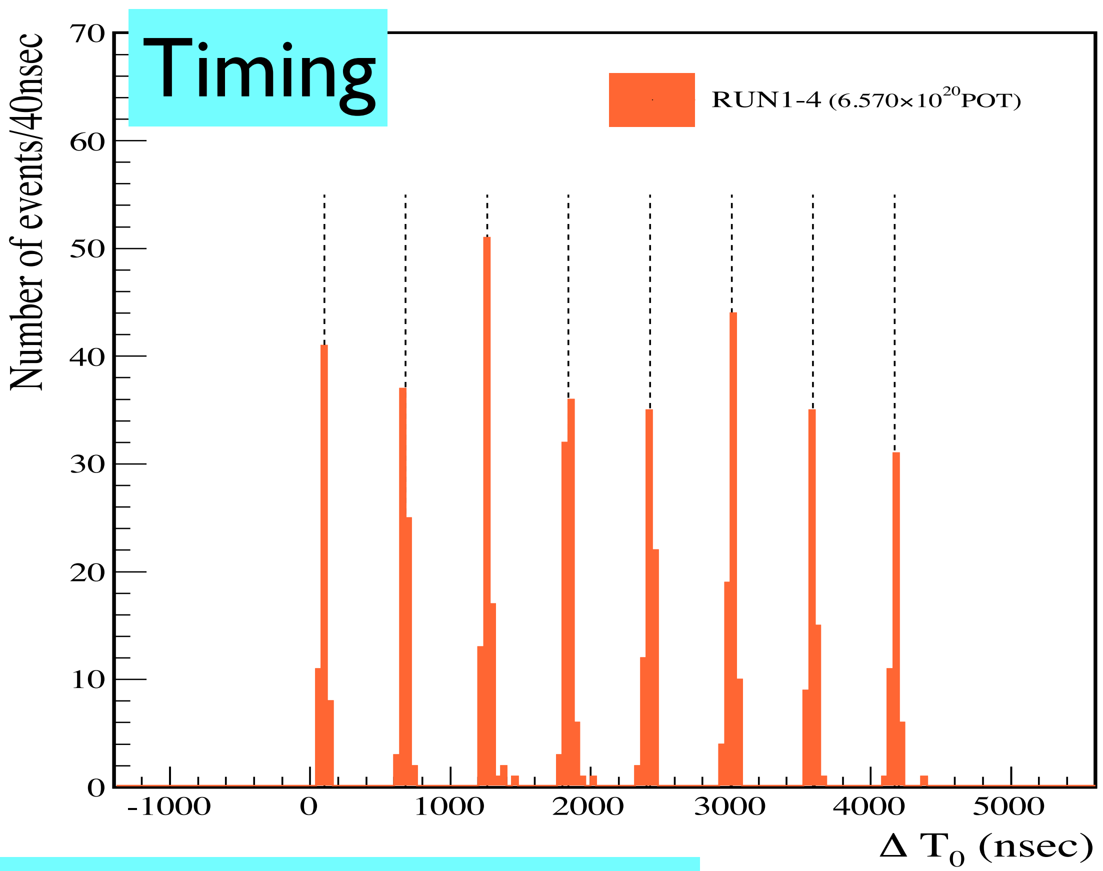


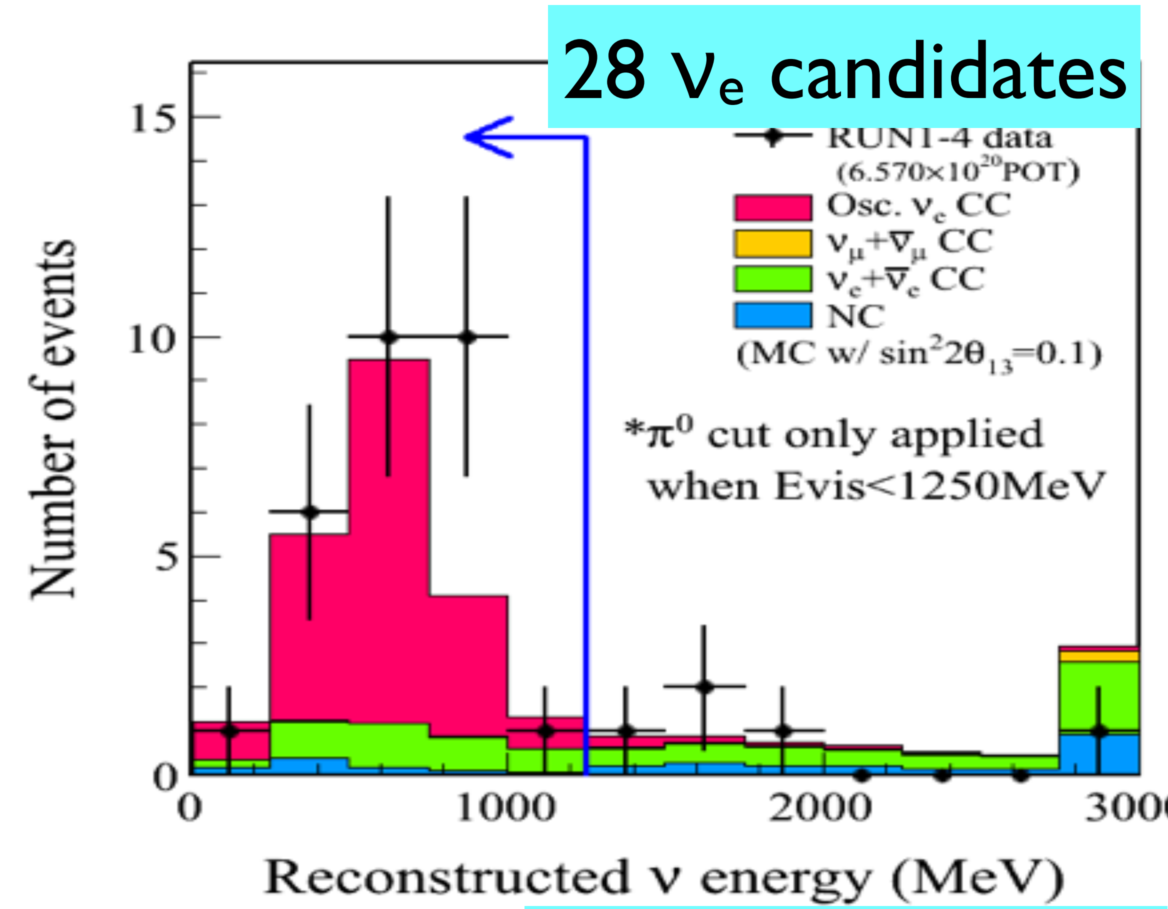
>11,000 50cm PMTs

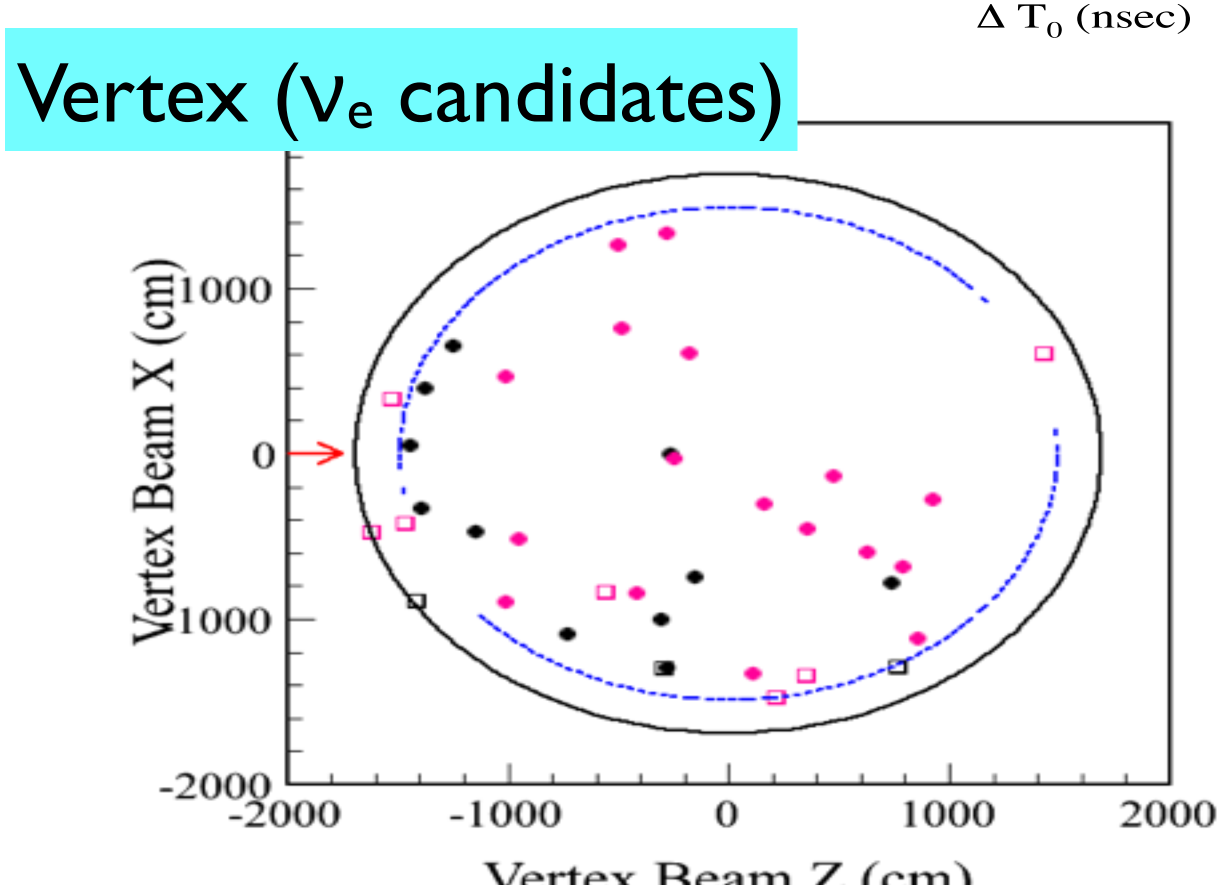


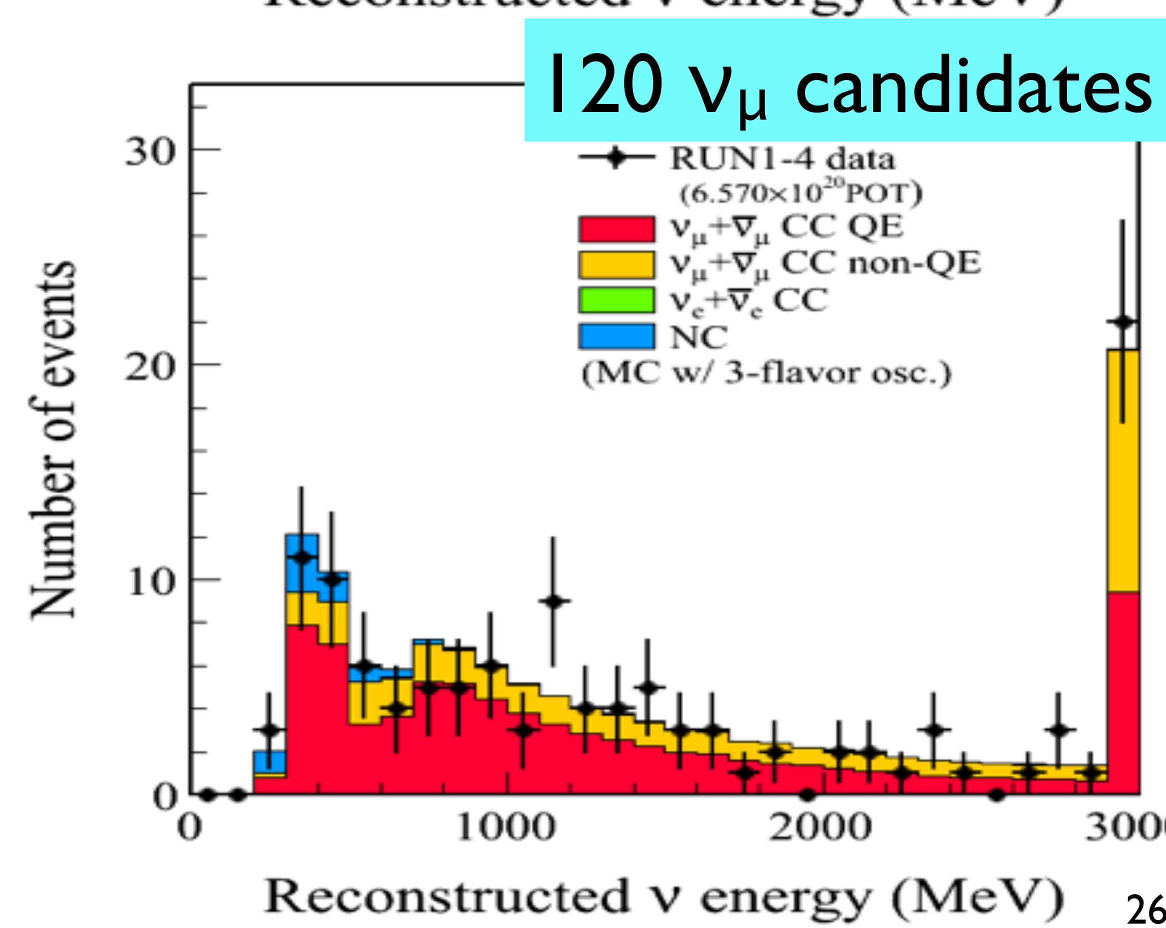


Observed events at SK

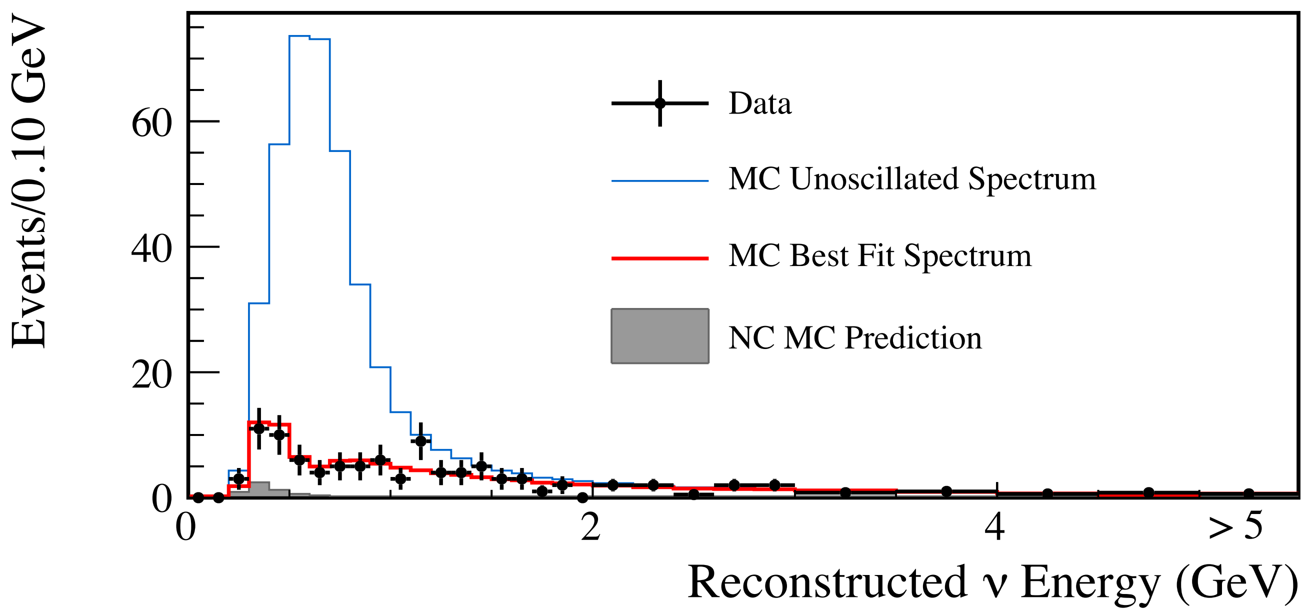


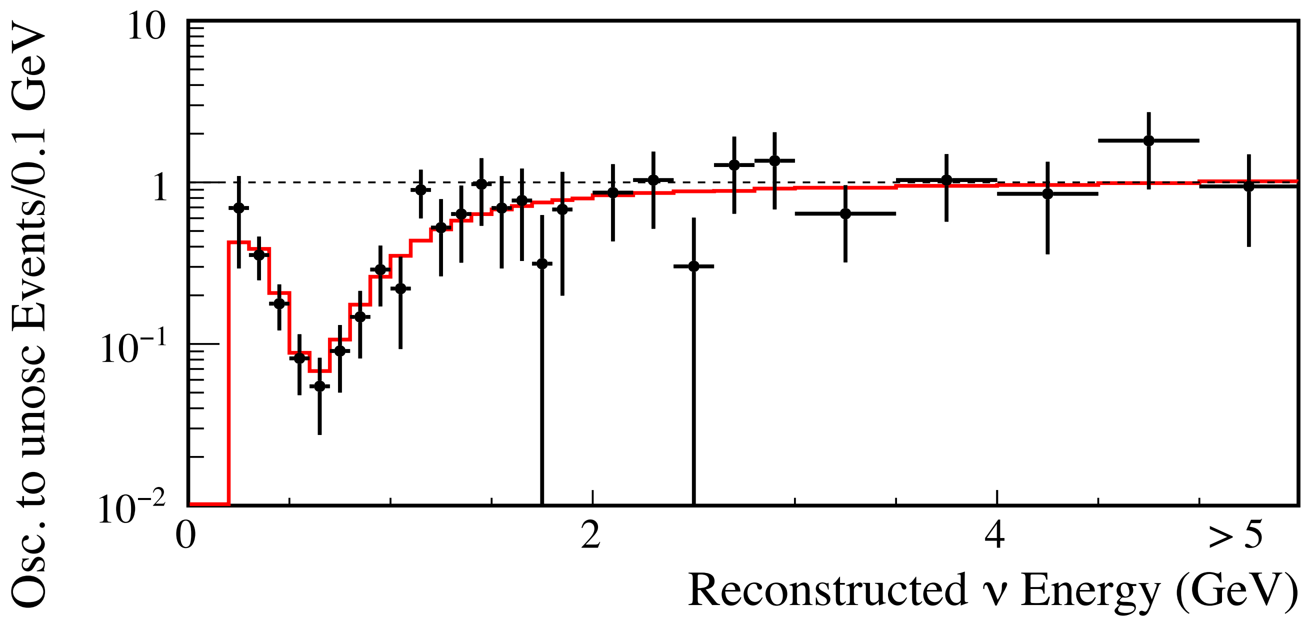


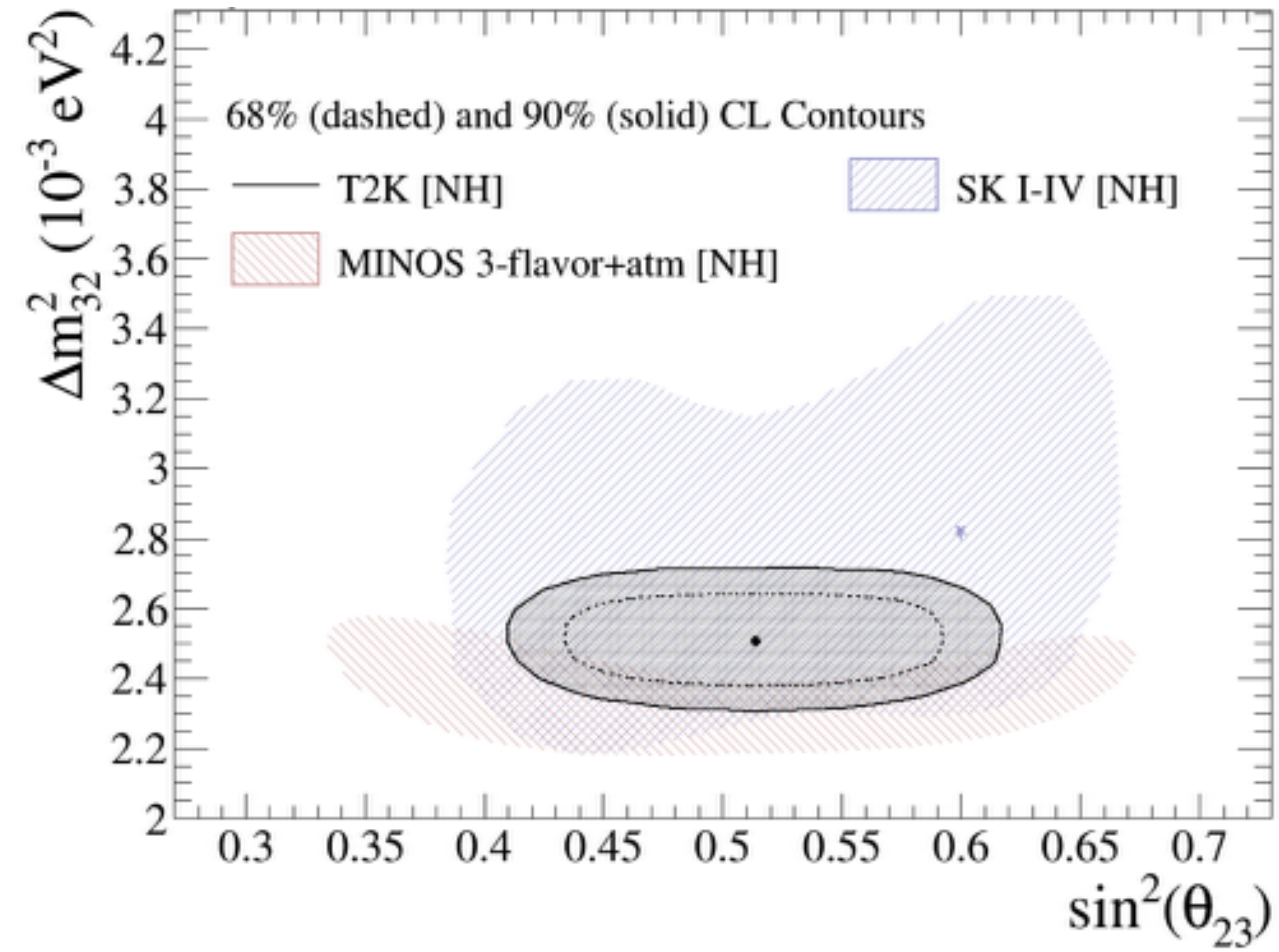




ν_μ disappearance measurement







PRL 112 (2014) 181801
arXiv:1502.01550

	$\sin^2\theta_{23}$	Δm^2 (10^{-3}eV^2)
NH	$0.514^{+0.055}_{-0.056}$	2.51±0.10
IH	0.511±0.055	2.48±0.10

Most precise measurement of $\sin^2\theta_{23}$

arXiv:1502.01550

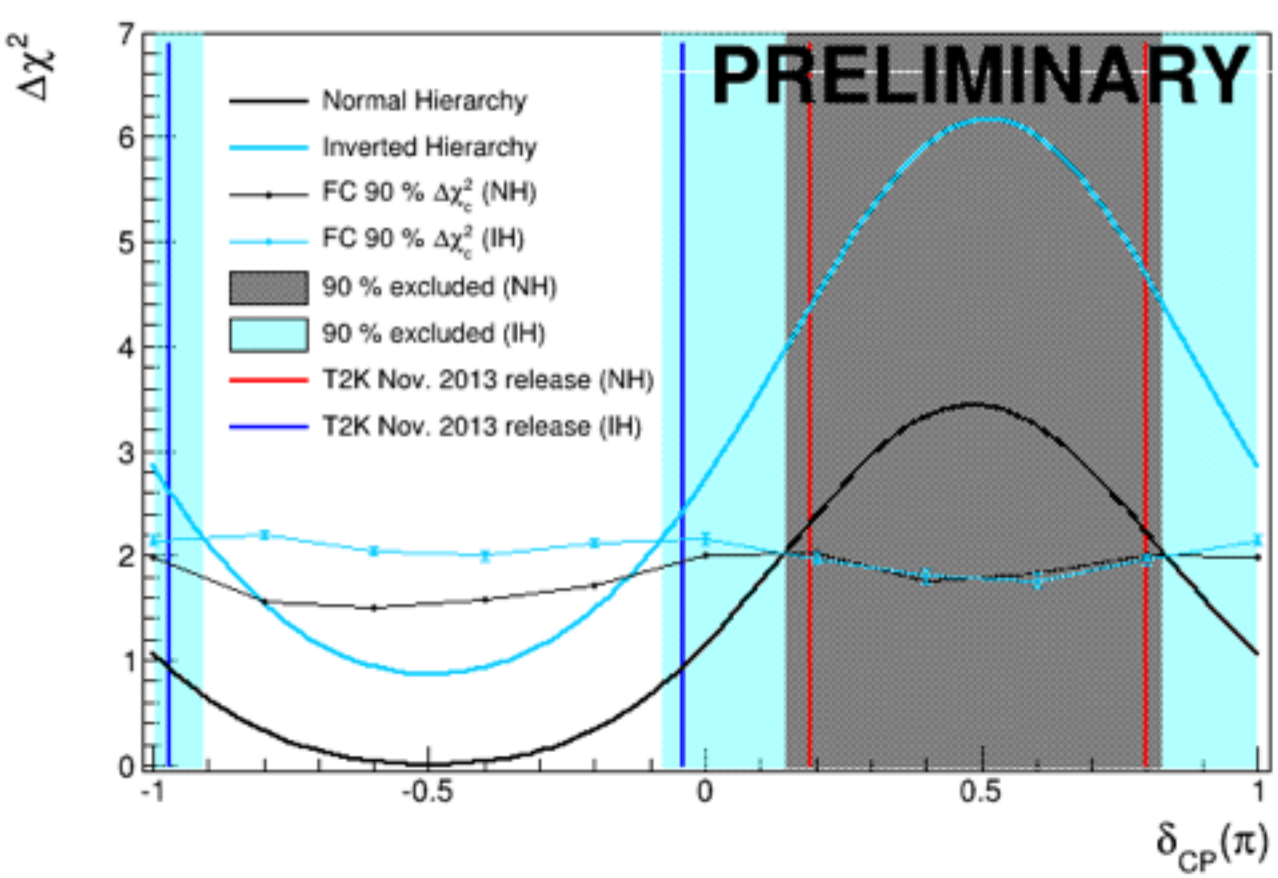
$\nu_\mu + \nu_e$ combined analysis

Frequentist analysis

With reactor constraint

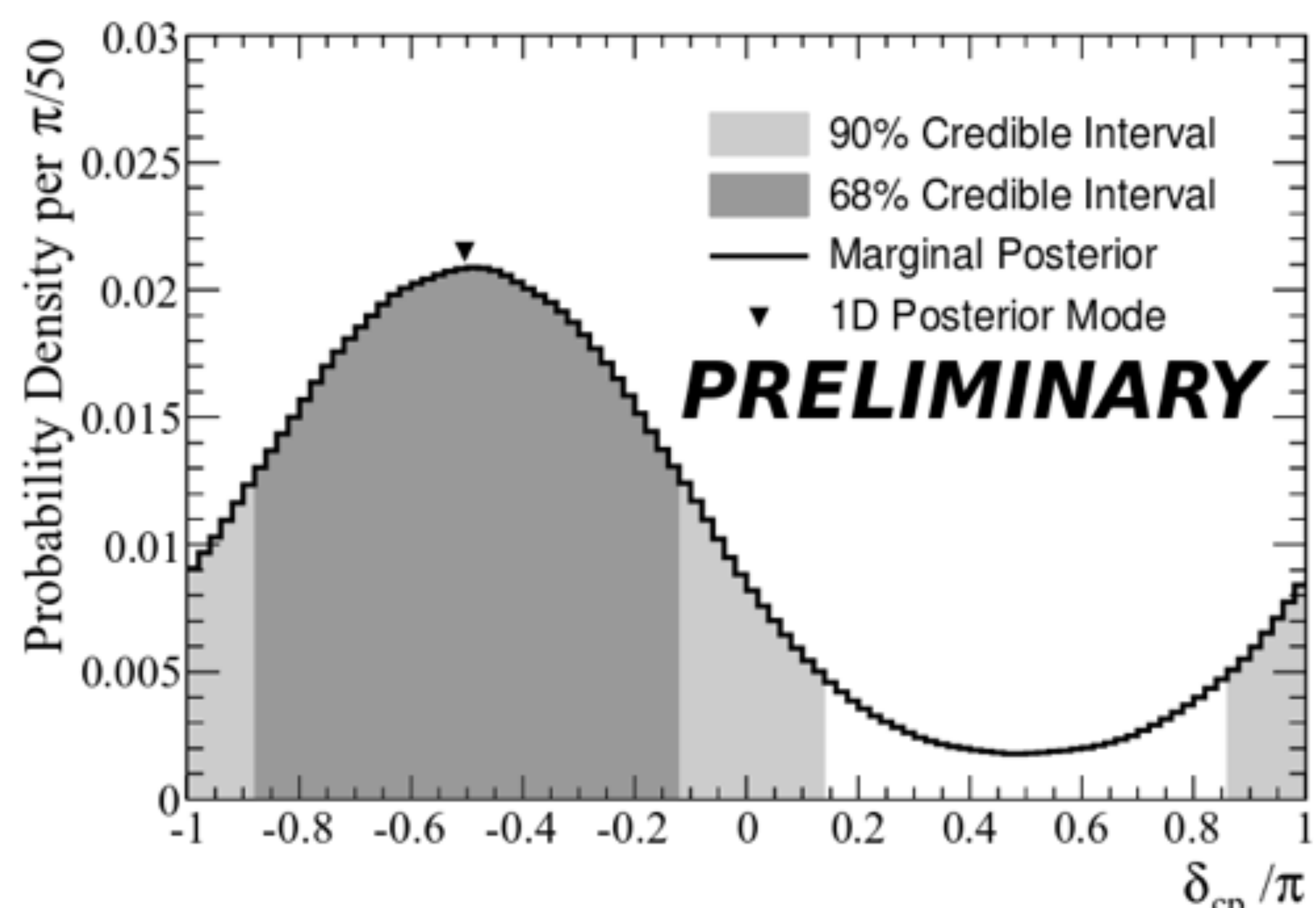
δ_{CP} of [0.15,0.83]π (NH)
[-0.08,1.09]π (IH)

EXCLUDED at 90% CL



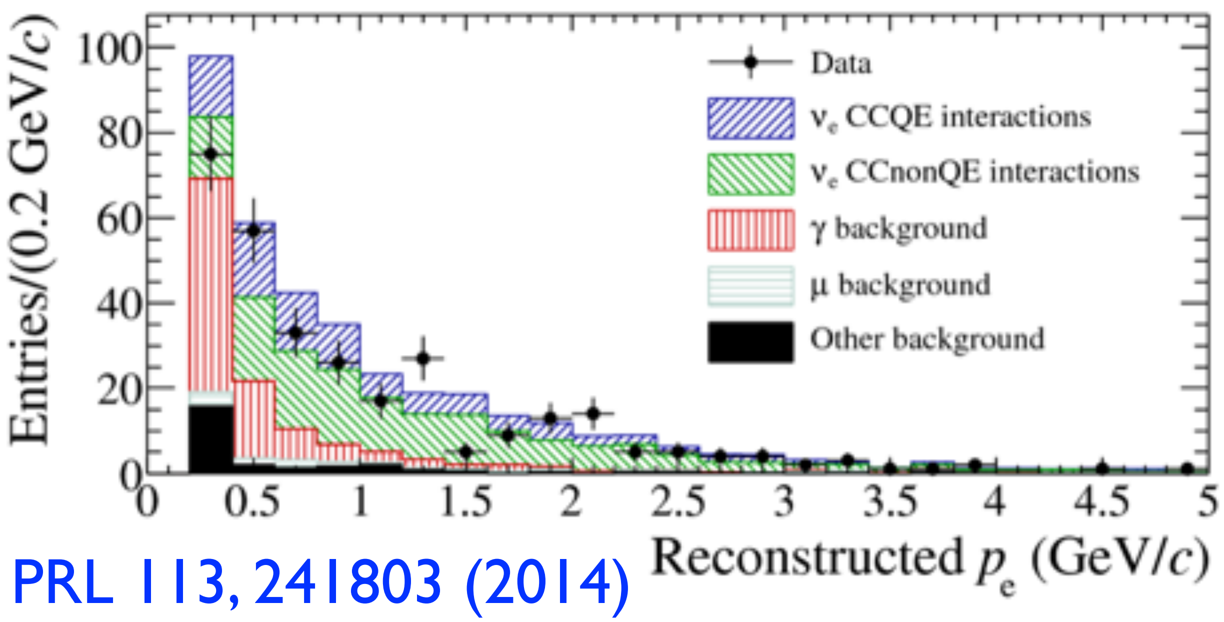
Bayesian probability

	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	0.179	0.078	0.257
$\sin^2\theta_{23} > 0.5$	0.505	0.238	0.743
Sum	0.684	0.316	1.0



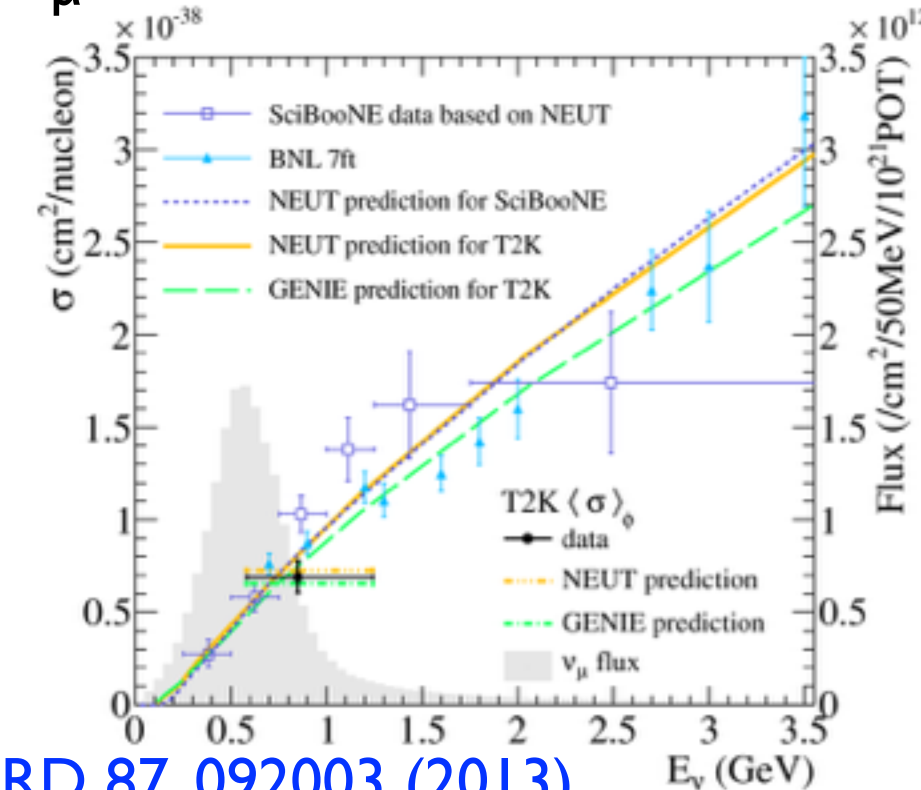
Cross section measurements with NDs

ν_e cross section on CH



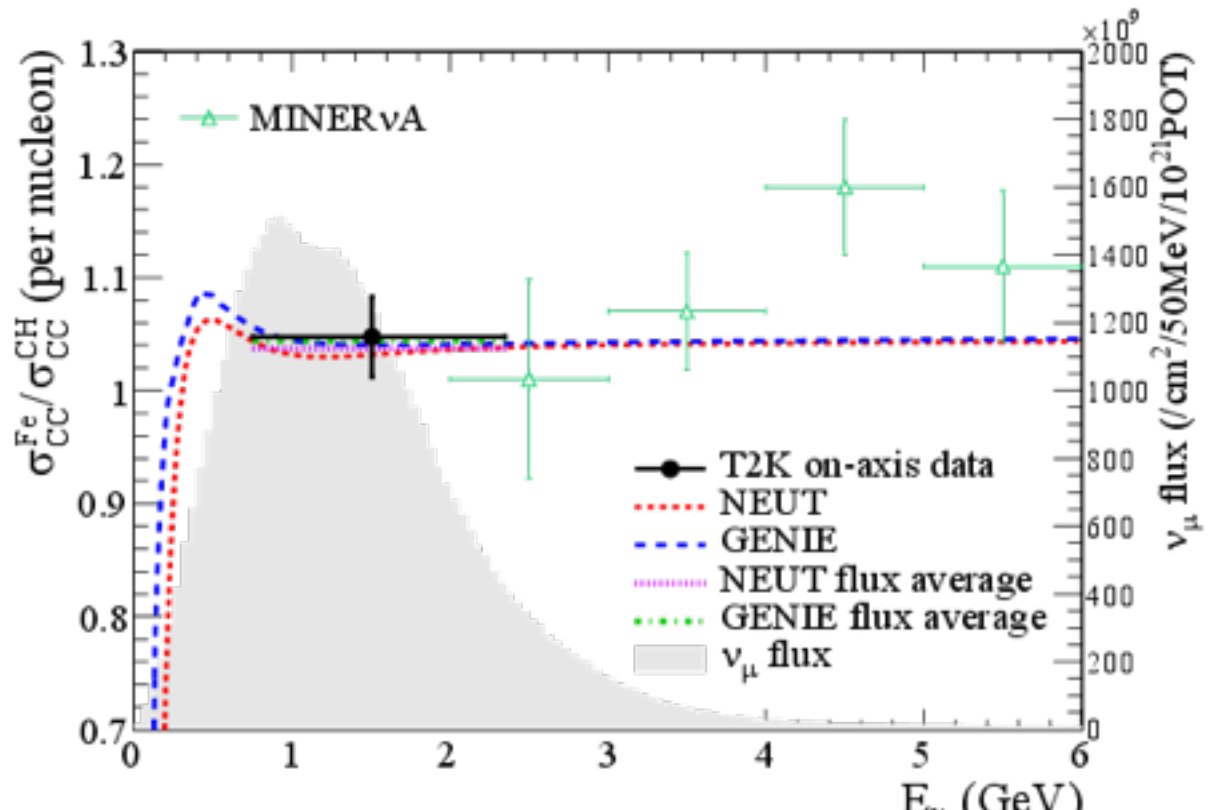
PRL 113, 241803 (2014)

ν_μ inclusive cross section



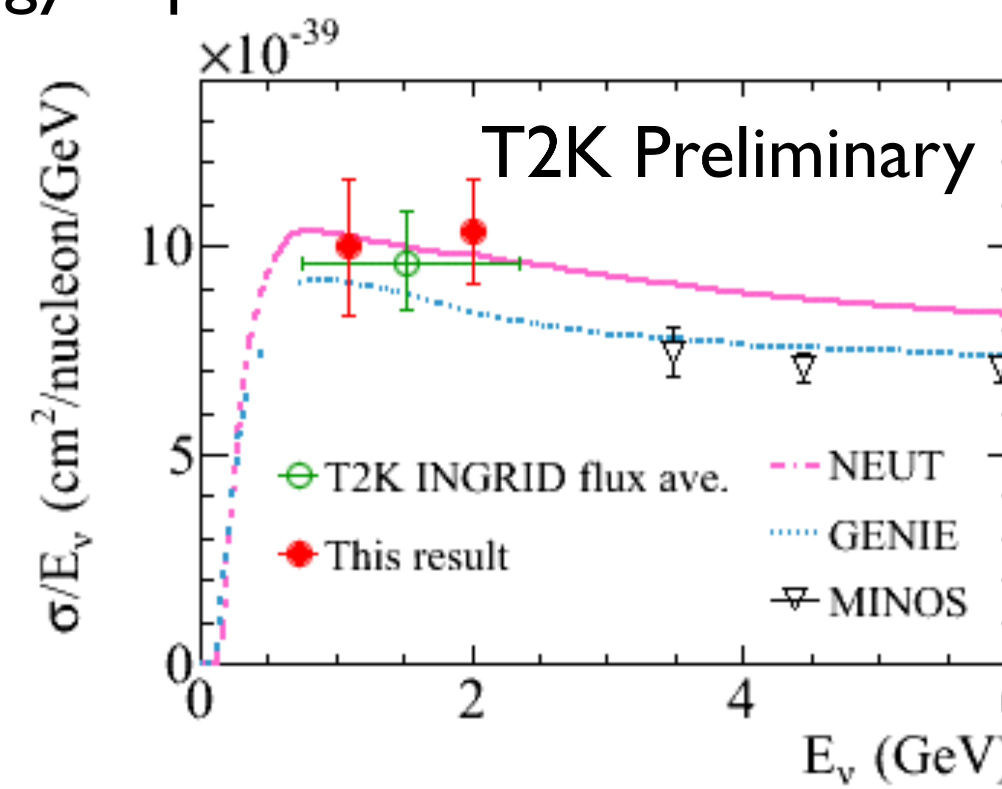
PRD 87, 092003 (2013)

Fe/CH cross section ratio with INGRID



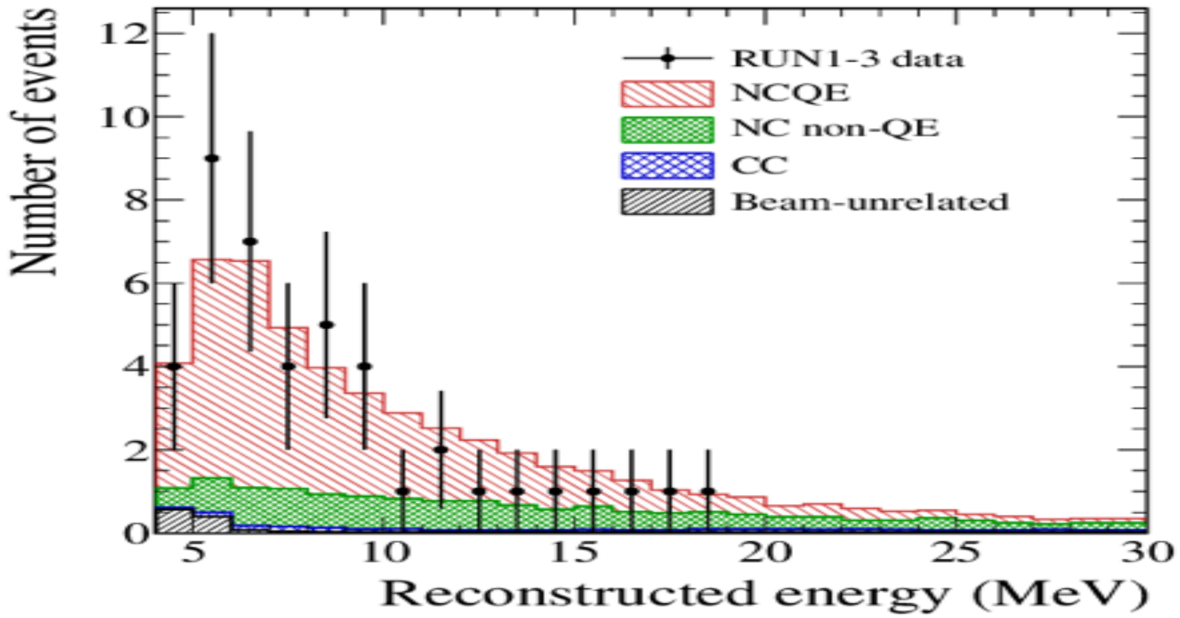
PRD 90, 052010 (2014)

Energy dependent cross section with INGRID



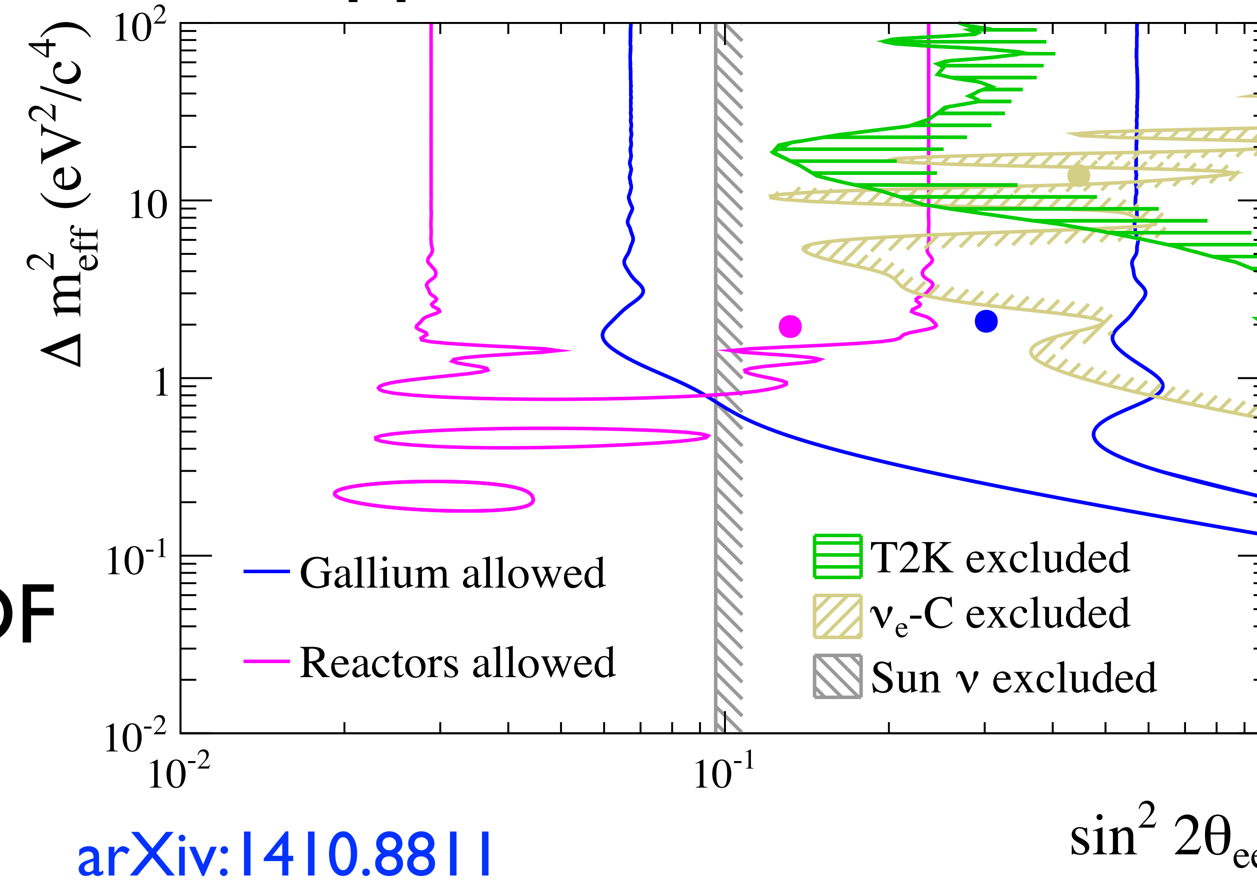
More physics results

NC interaction at far detector



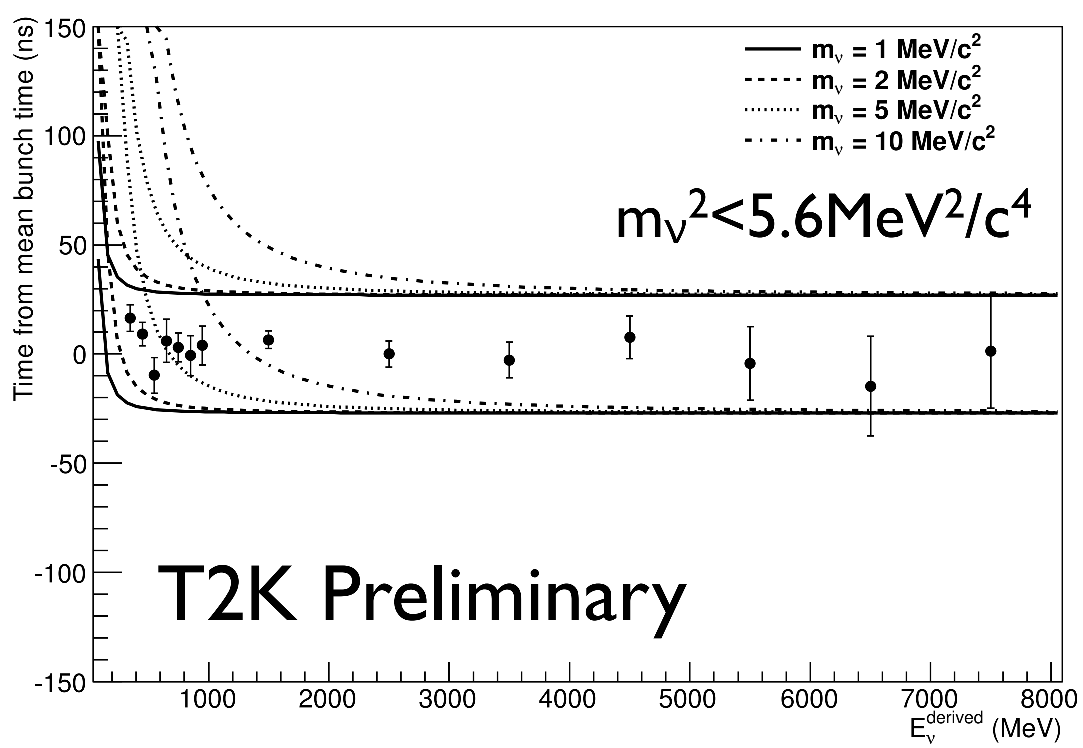
PRD 90, 072012 (2014)

νe disappearance search with ND



arXiv:1410.8811
Accepted for publication in PRD

Neutrino mass limit from relative TOF



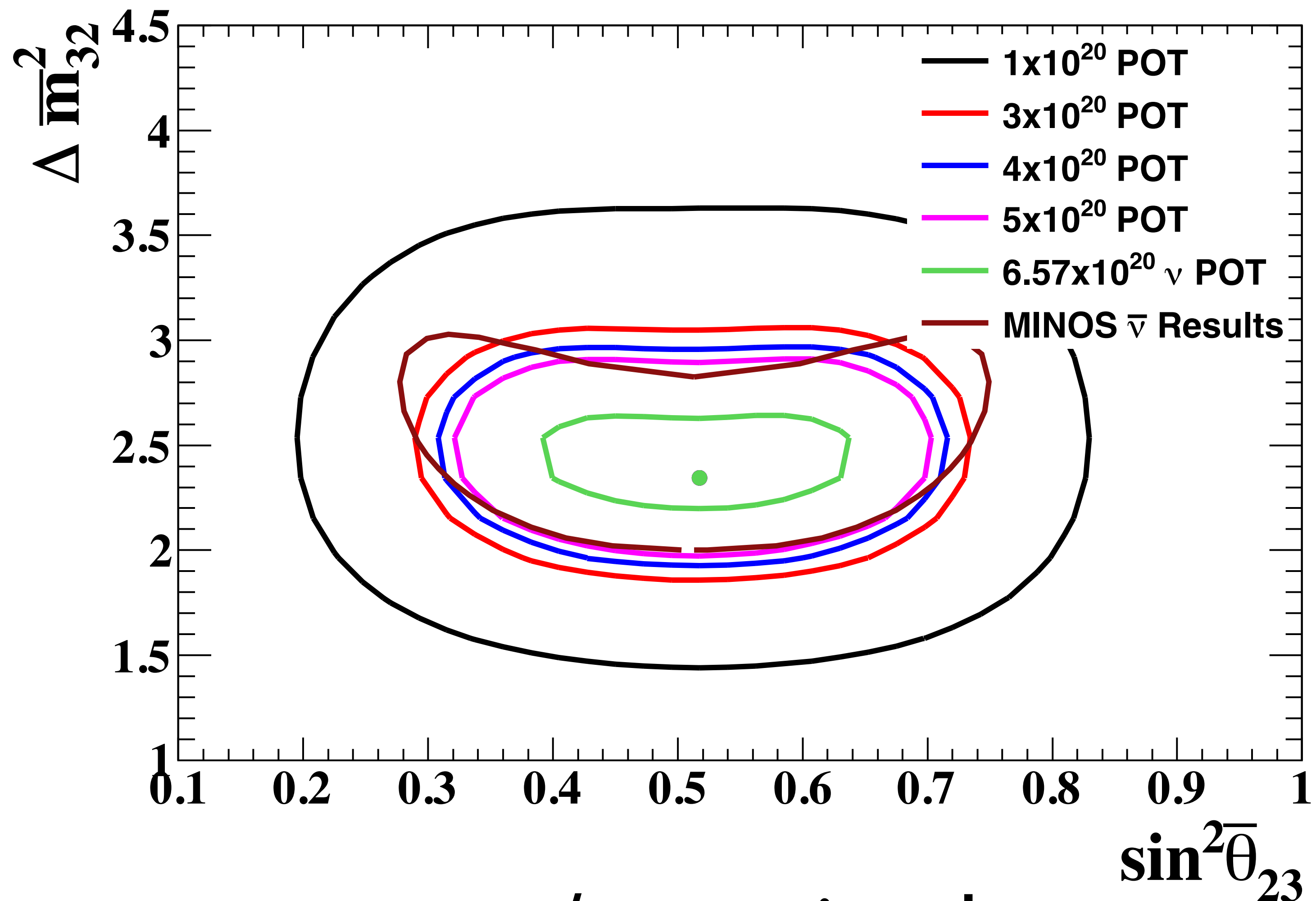
arXiv:1502.06605

See poster by Stefania for
short baseline oscillation studies in T2K

More results are published/coming soon!
(Also, results with anti-nu beam running)

T2K: Near Future Plan

- Before summer 2015:
  - World best anti-neutrino oscillation measurement with ~5×10^{20} POT



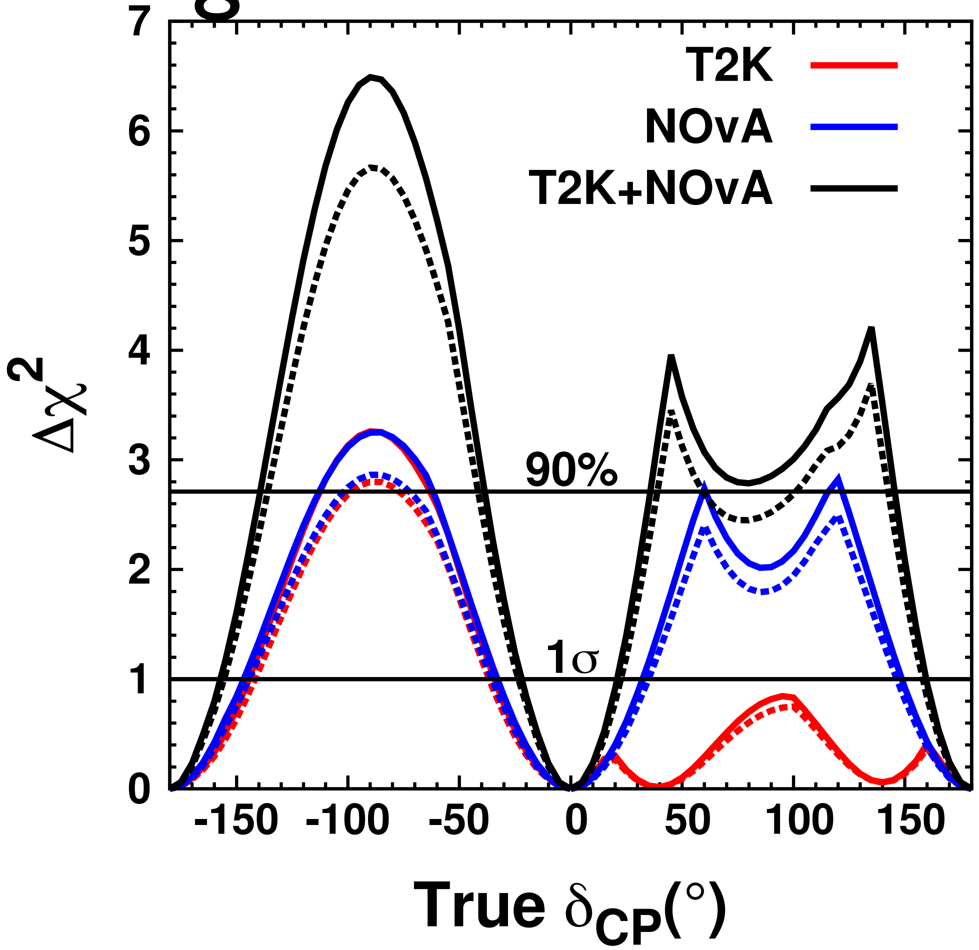
- In 1-2 years:
  - Improve oscillation parameter meas. w/ neutrino beam (Will tension with reactor data remain or not?)
  - Search for the first evidence of electron anti-neutrino appearance with anti-neutrino beam
- Can accumulate ~7×10^{20} POT in 1 year with >400kW beam

Long term plans

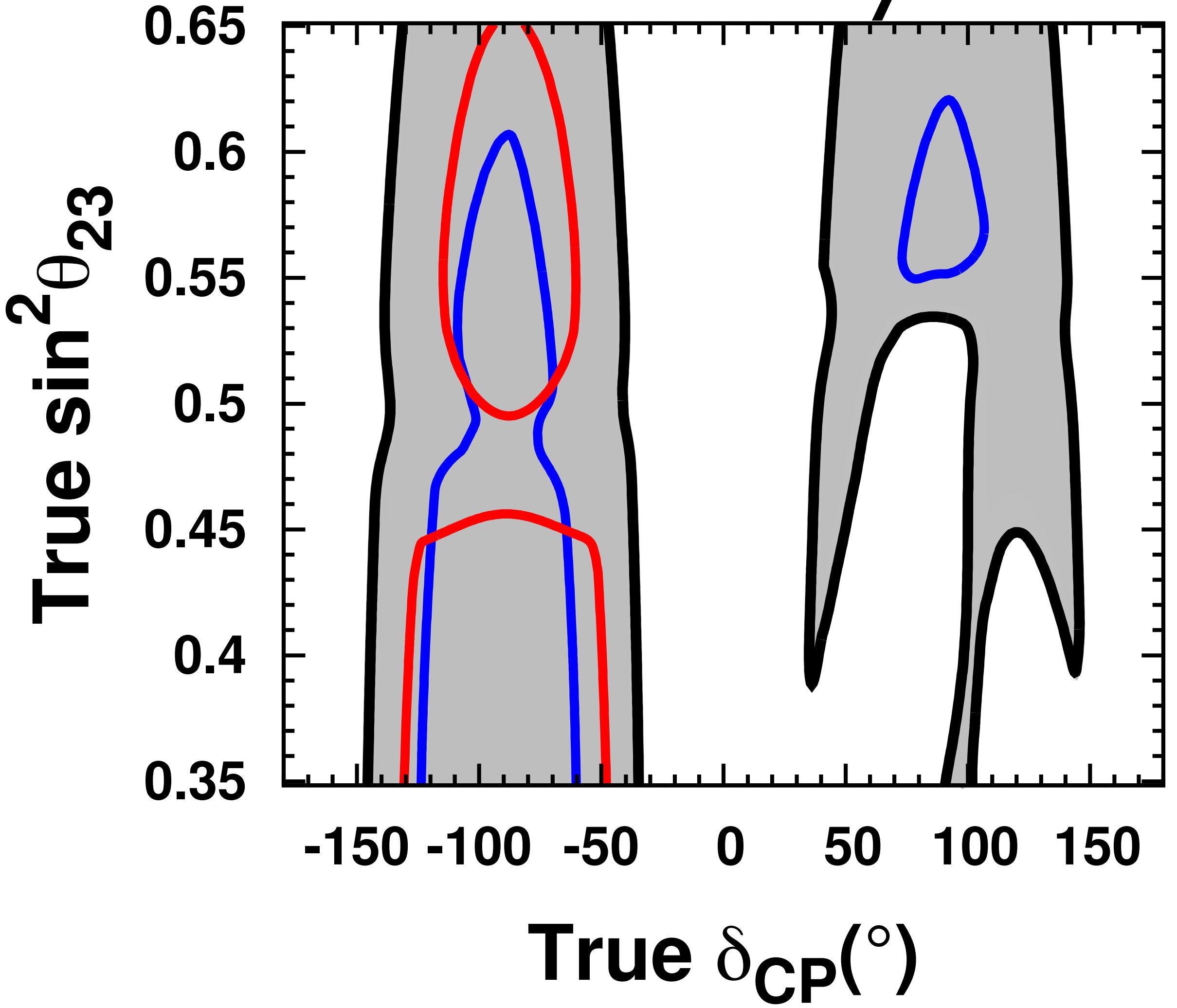
arXiv:1409.7469
to be published in
PTEP

- Search for CP violation with up to 2.5σ level sensitivity
- Precise measurements of oscillation parameters
- Various ν and $\bar{\nu}$ ross section measurements
- Combination with NOvA and SK will enhance the reach

Significance of CPV



90%CL sensitivity to CPV



Other ν experiments at J-PARC

Neutrino experiments at J-PARC

- E11: Tokai-to-Kamioka (T2K) Long Baseline Experiment
- T32, T49: Liq. Ar TPC R&D (test beam)
- E56: A Search for Sterile Neutrino at J-PARC Materials and Life Science Experimental Facility

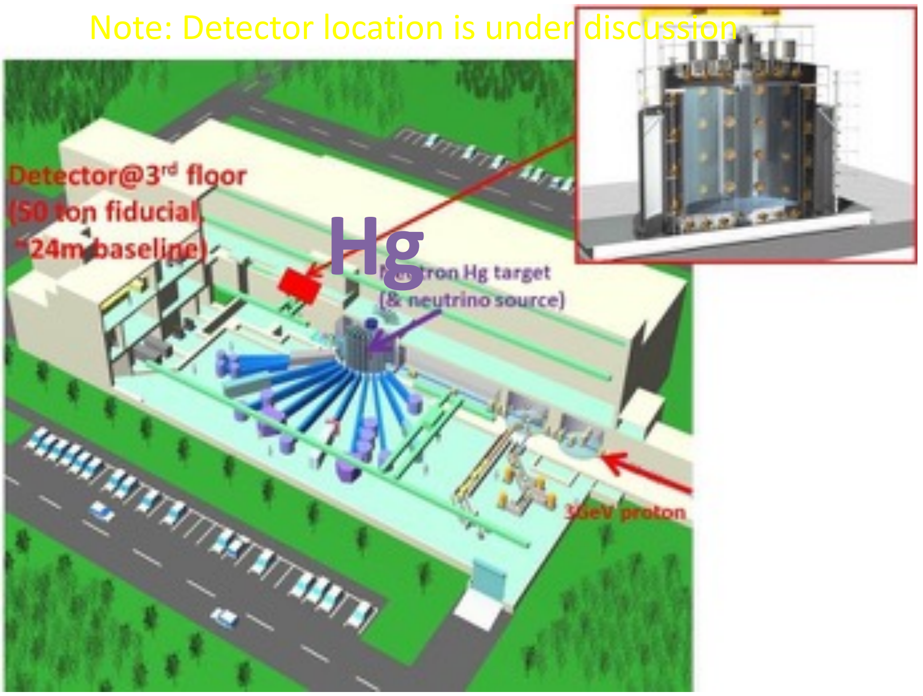
Recent Stage-1 approval

- P58: A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande (→Shiozawa-san)
- T59: A test experiment to measure neutrino cross sections using a 3D grid-like neutrino detector with a water target at the near detector hall of J-PARC neutrino beam-line
- T60: An emulsion-based test experiment at J-PARC
- LoI: A nuPRISM Detector in the J-PARC Neutrino Beamline

New initiatives emerging in J-PARC neutrino experimental facility

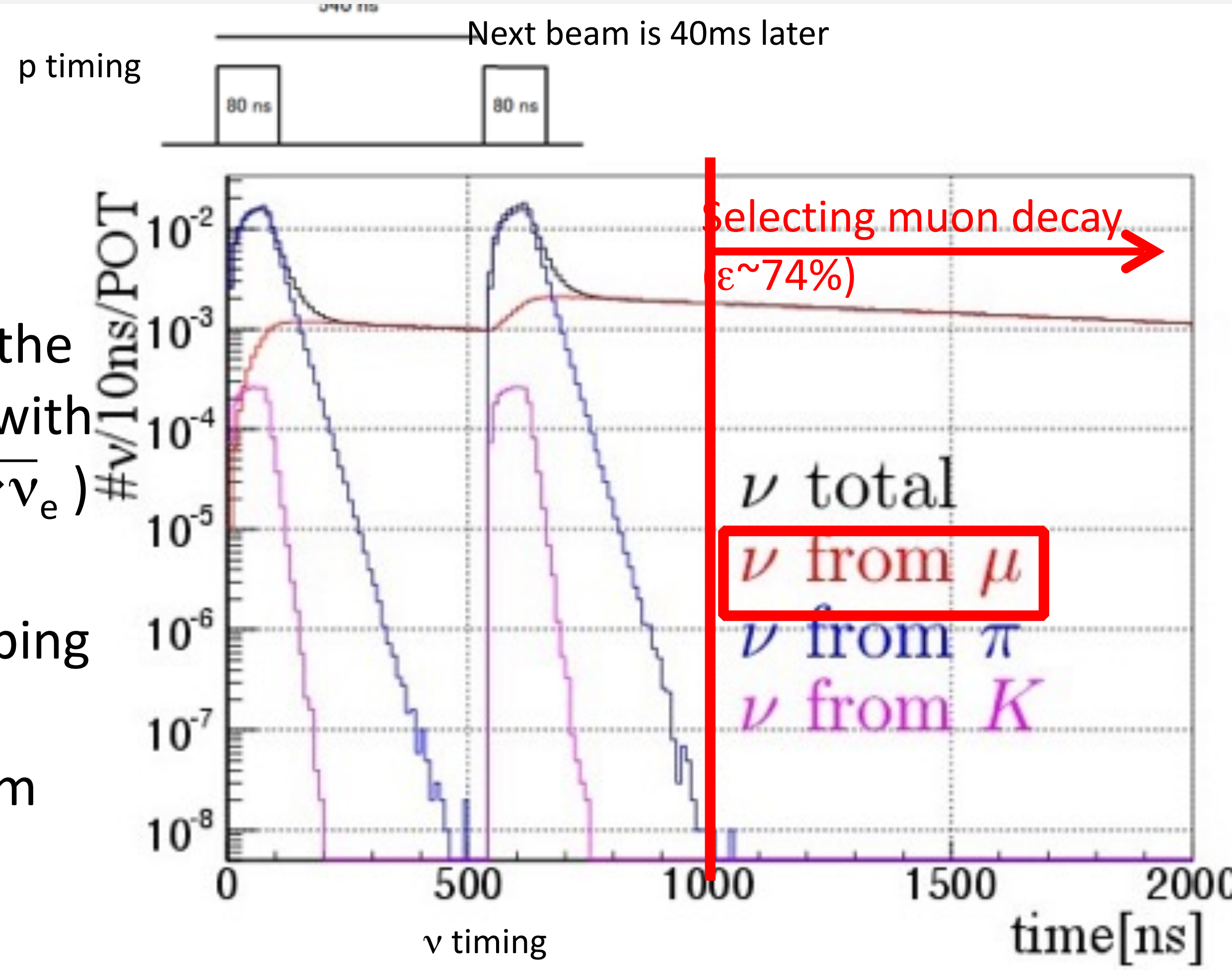
E56: Sterile neutrino search @MLF (proposal in 2013)

M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]

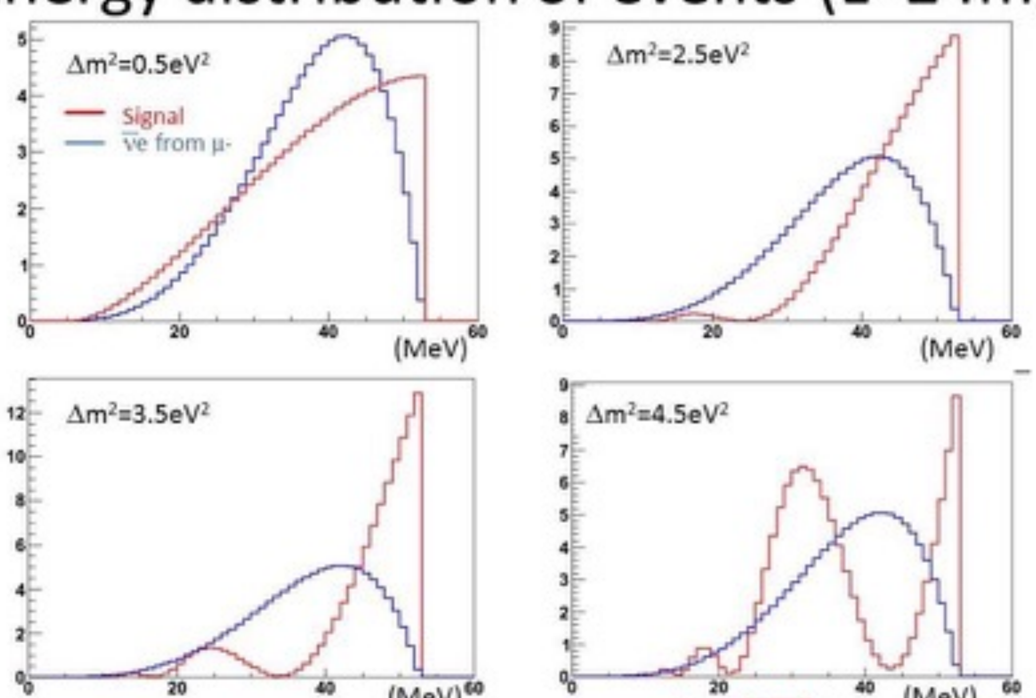


J-PARC E56

- confirms or refutes the neutrino oscillation with sterile neutrino($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- uses ultra-pure neutrinos from stopping μ^+
- separates signals from BKG by measuring energy distortion

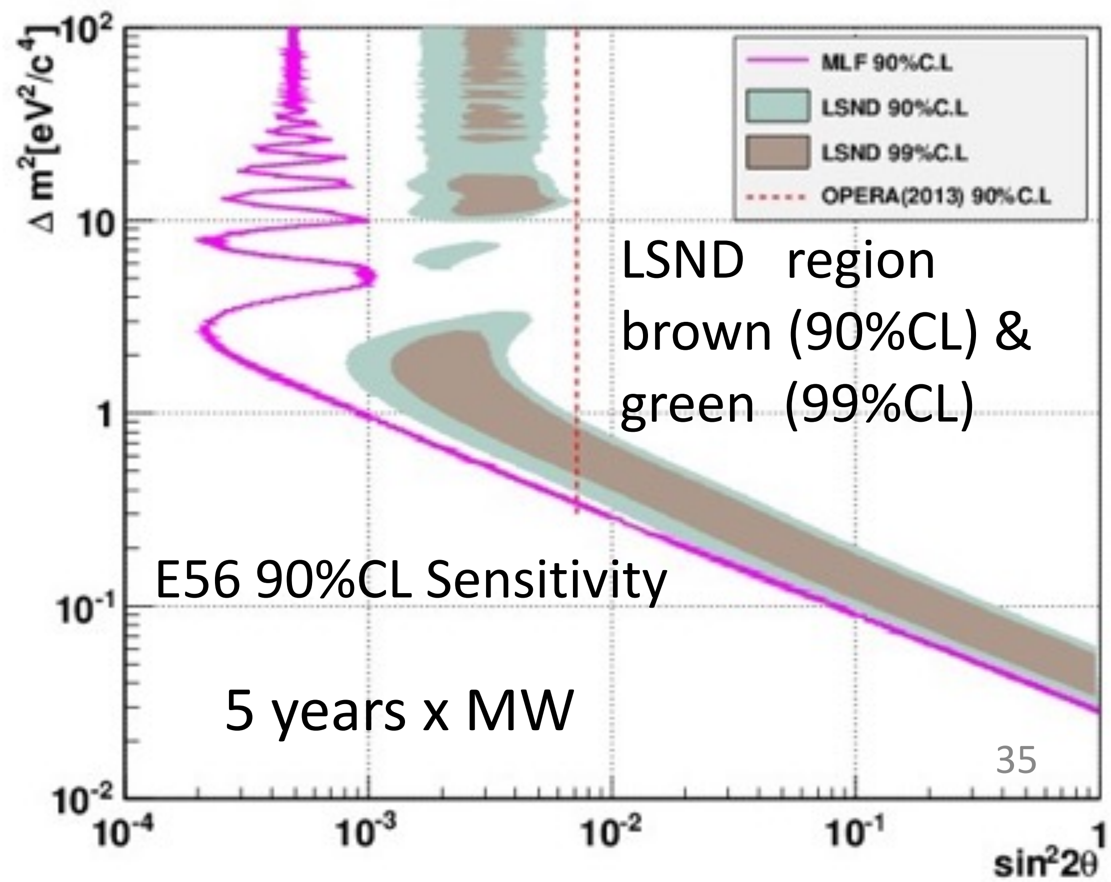


Energy distribution of events (L=24m)



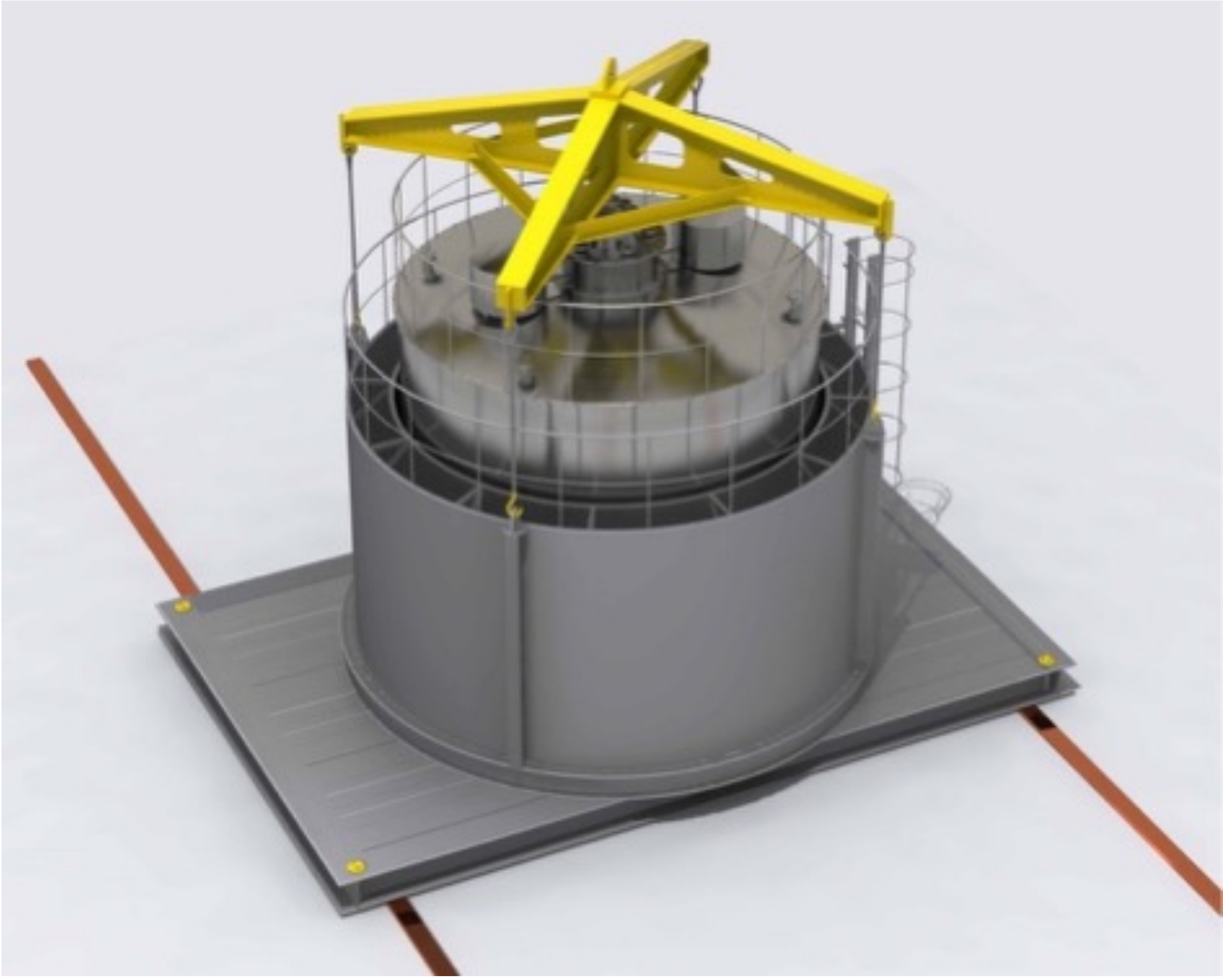
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \boxed{\Delta m^2} \cdot L}{E_\nu}\right)$$

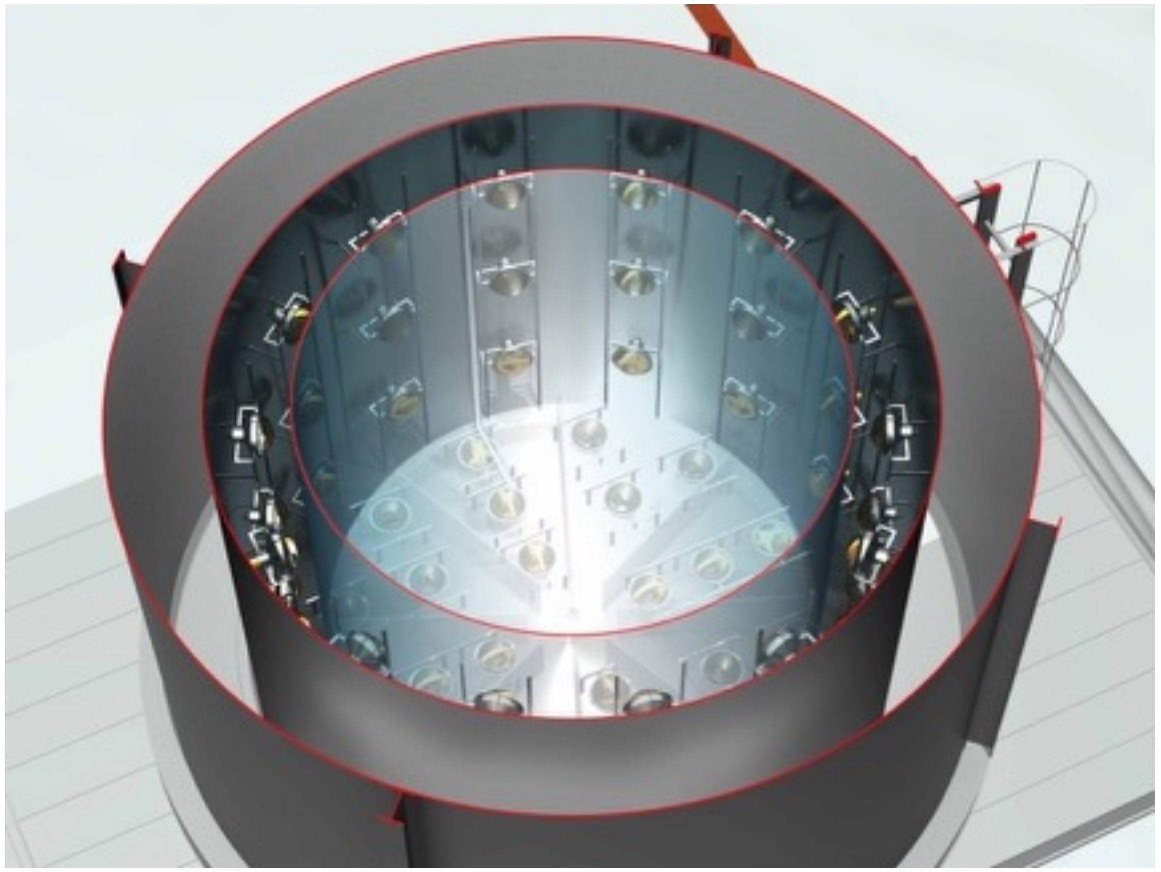
- Energy is smeared by 15%/sqrt(E) (detector E resolution)



E56: Detector

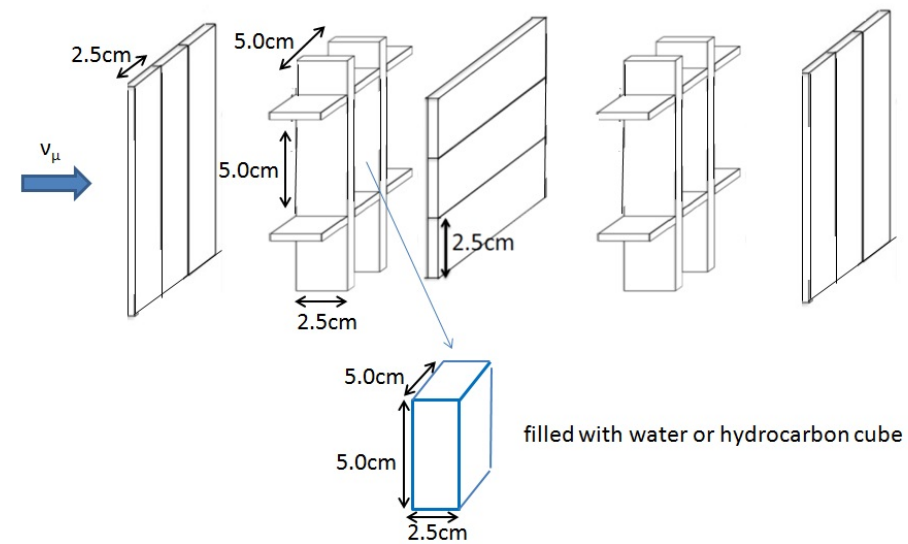
- 50 tons Gd-loaded liquid scintillator.
- Well established technique.
- Strength of tank / endurance for earthquakes were calculated.
- Some of Double Chooz / Daya-Bay collaborators joined E56.
- Will be located at MLF 3rd floor : the maintenance area → need to avoid interference



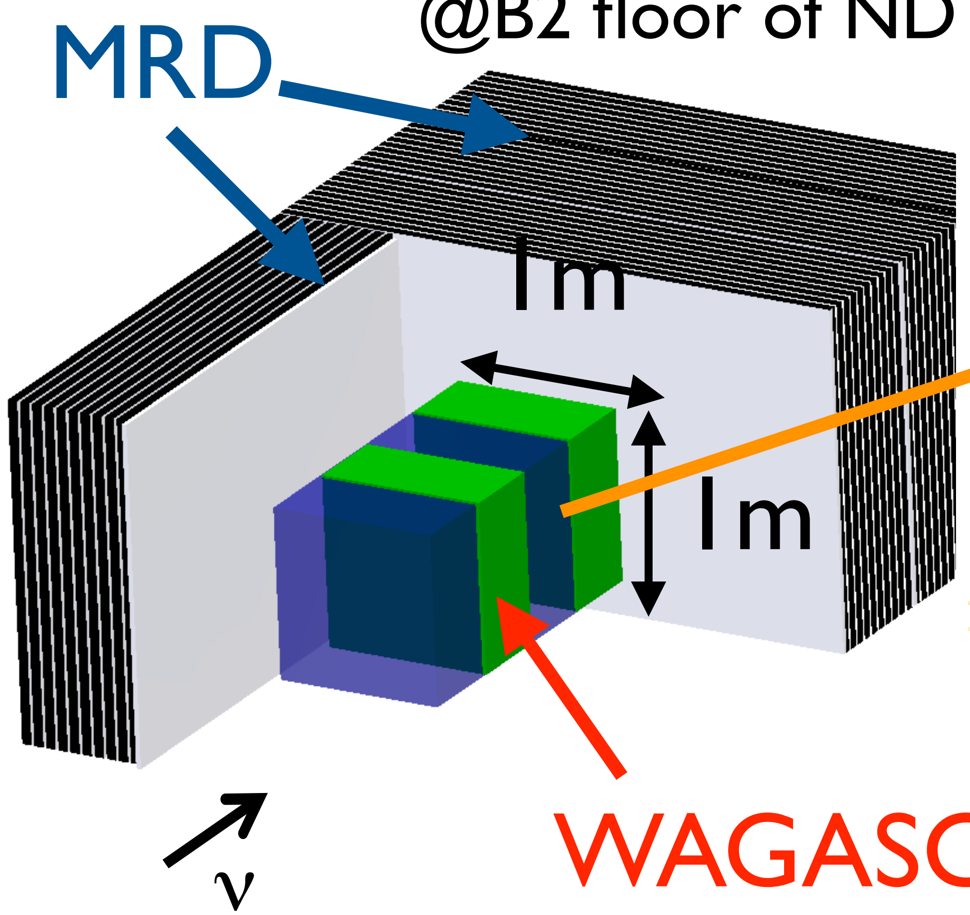


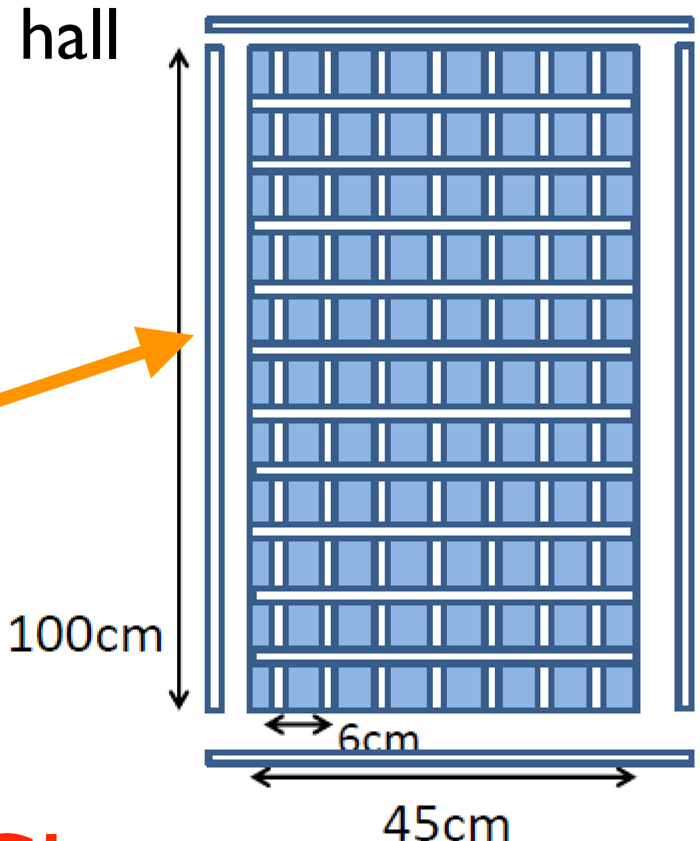
T59: 3D grid detector, WAGASCI

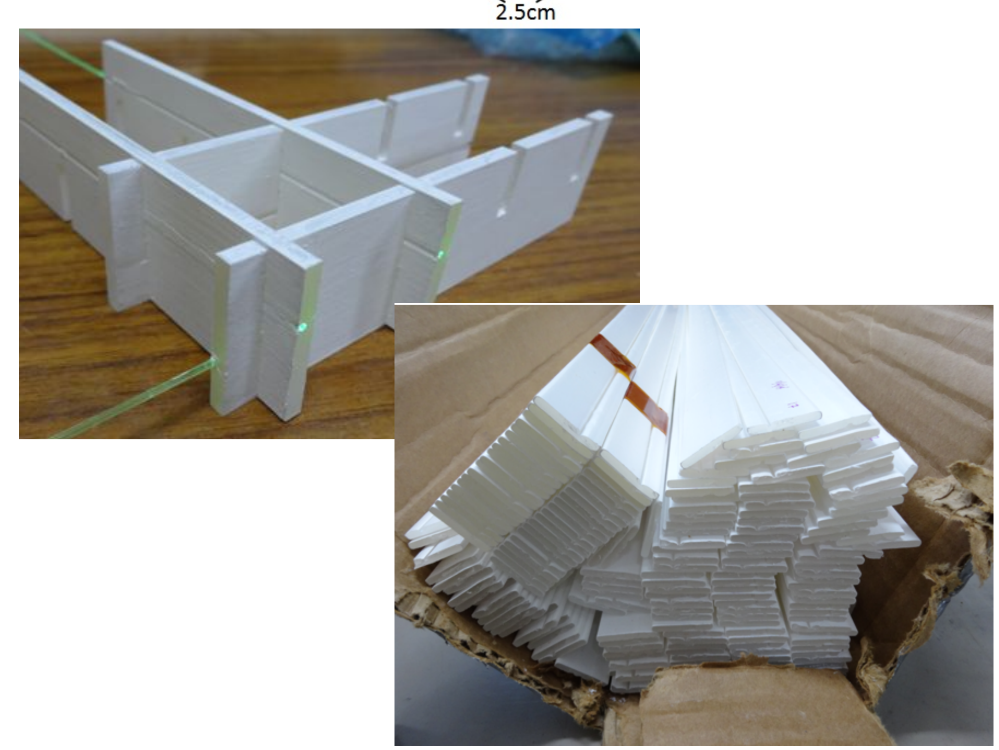
- Confirm basic performance of 3D grid detector
  - Large angular acceptance with less material
- Cross section measurements
  - Water target (fraction of water ~80%)
  - Close to 4π acceptance



@B2 floor of ND hall







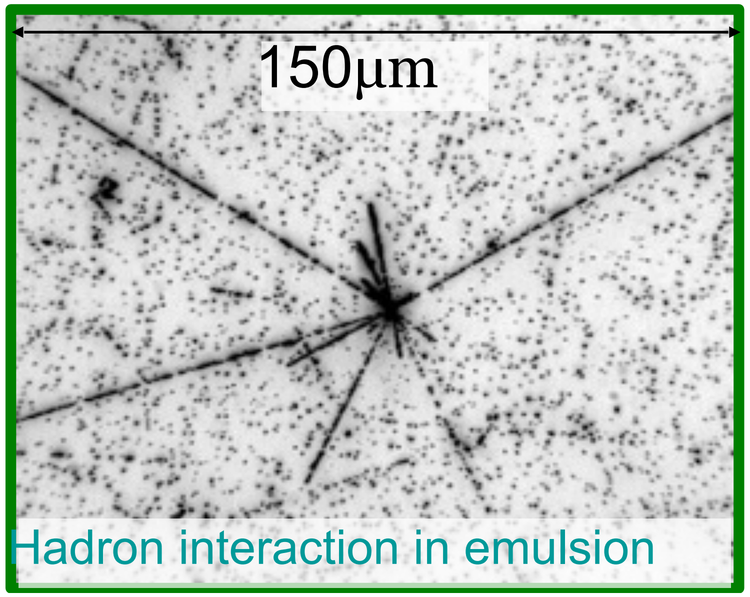
3mm-thick scintillator produced at Fermilab

T60: Emulsion

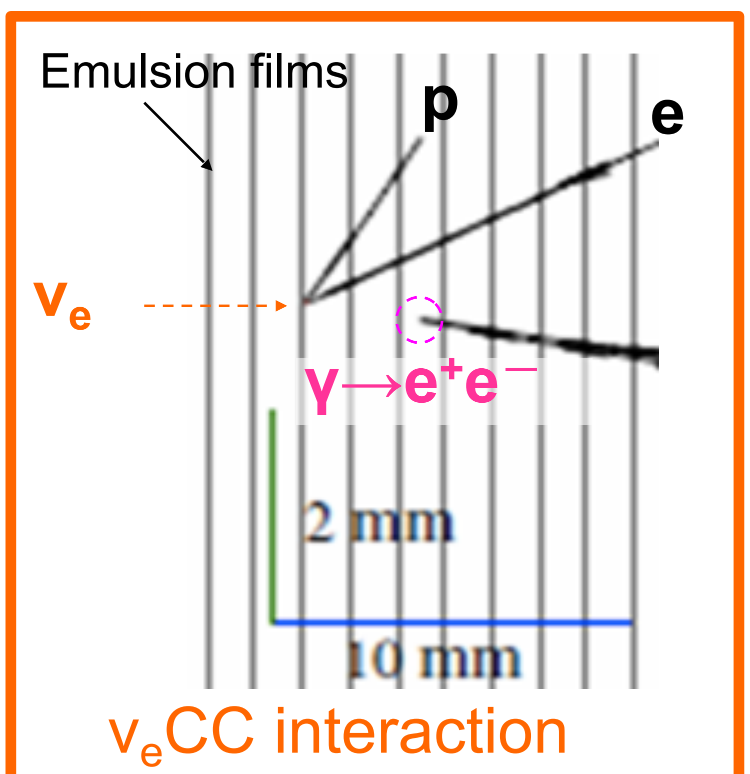
- Feasibility test of Emulsion in the J-PARC environment

Future Physics goals
- Neutrino Cross Sections
- Sterile neutrinos

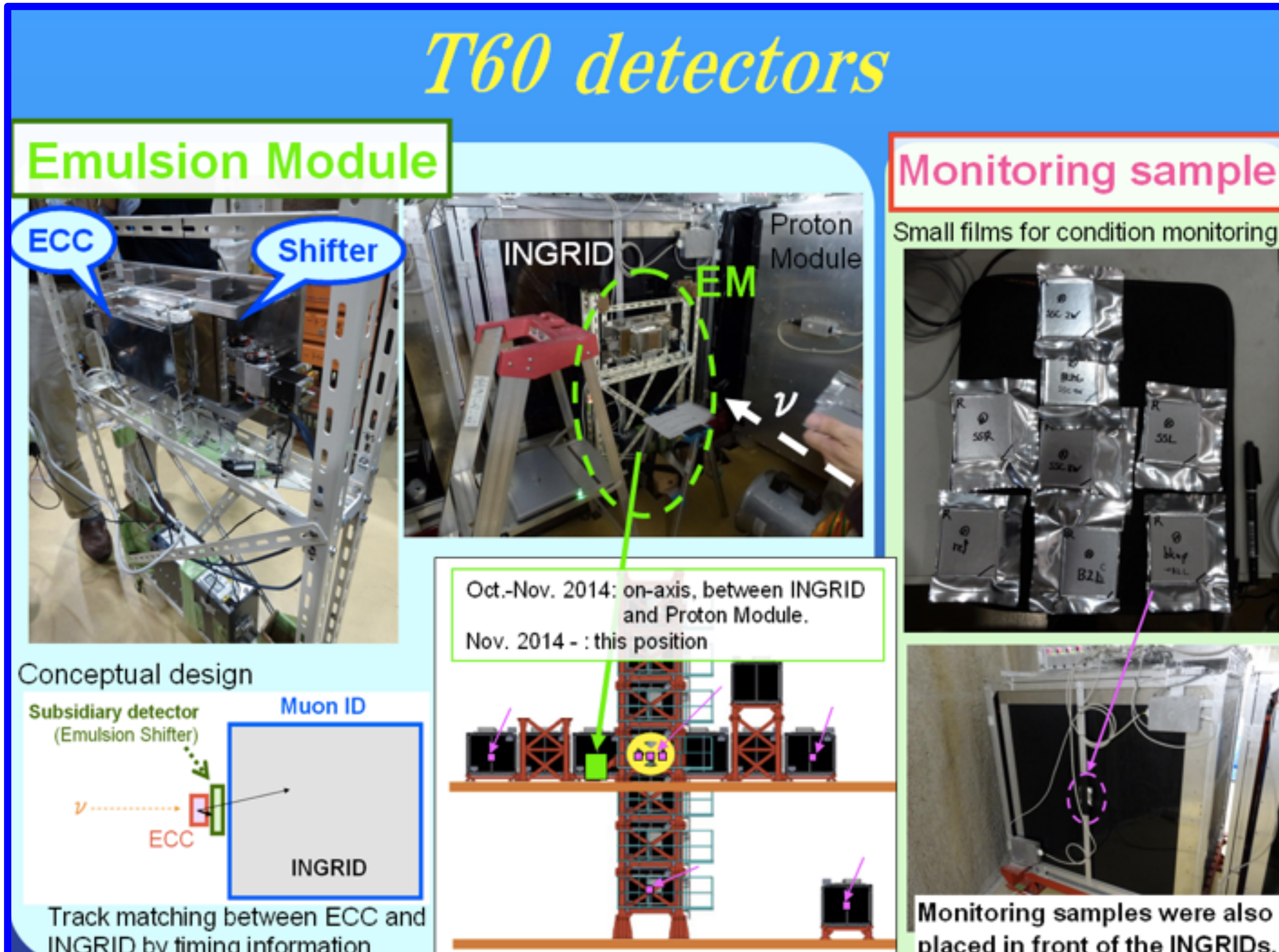
Ultimate position resolution



Hadron interaction in emulsion

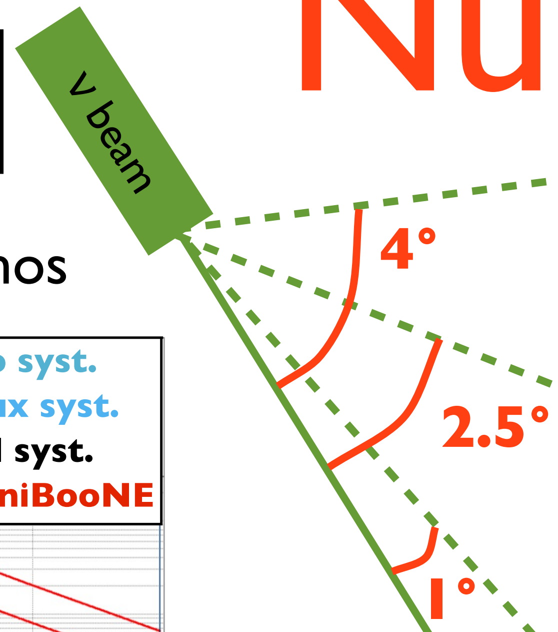


ν_eCC interaction

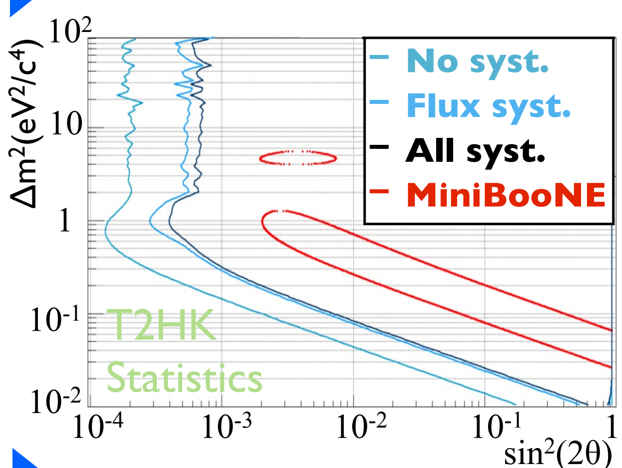


NuPRISM

Spans many off-axis angles to measure many E_ν spectra

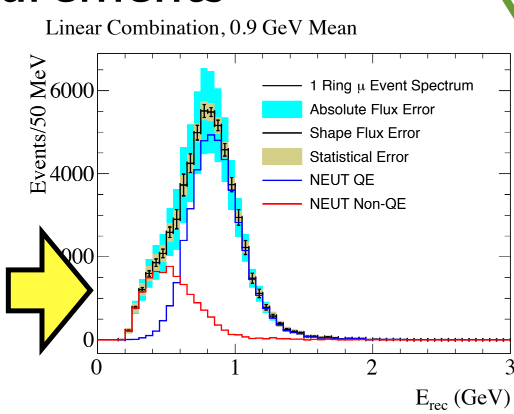


Sterile Neutrinos

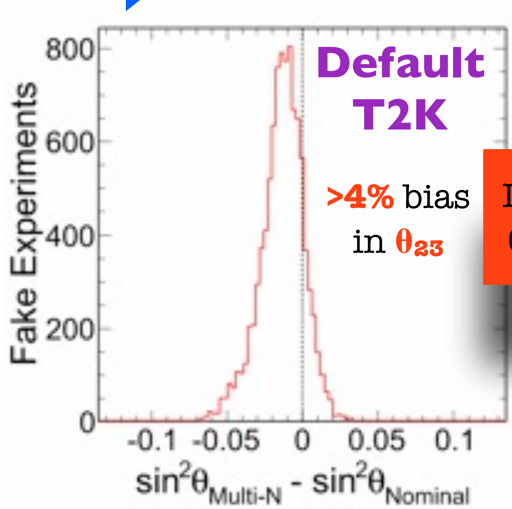


Unique σ_ν Measurements

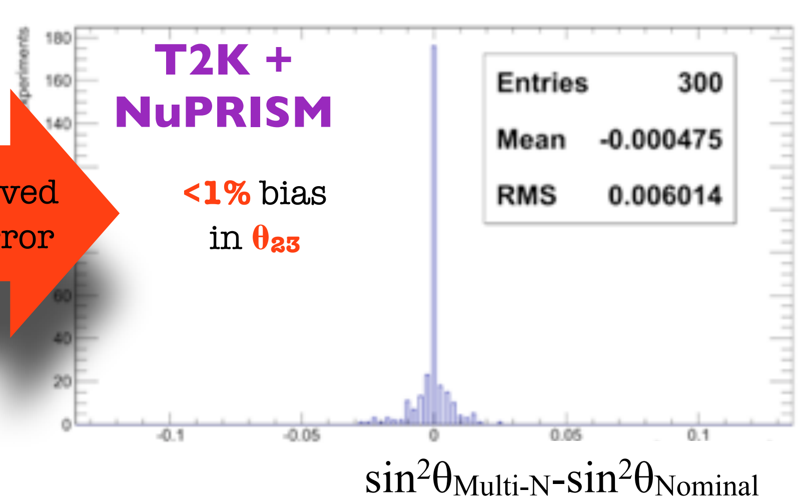
- First ever measurements of $\sigma_{\text{Neutral Current}}(E_\nu)$
- Clear separation of single and multi-nucleon events

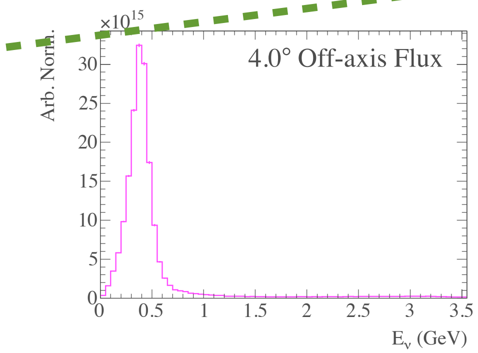


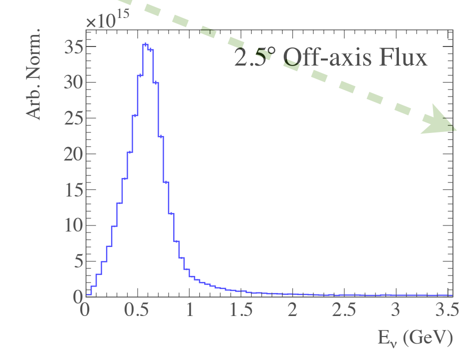
Enhanced Sensitivity for T2K and T2HK

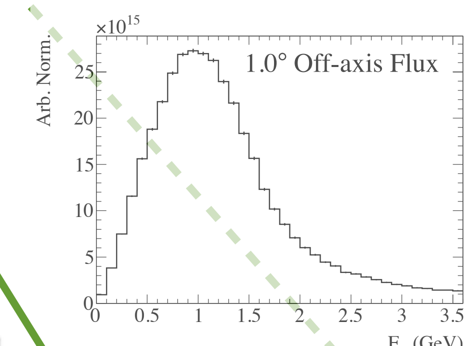


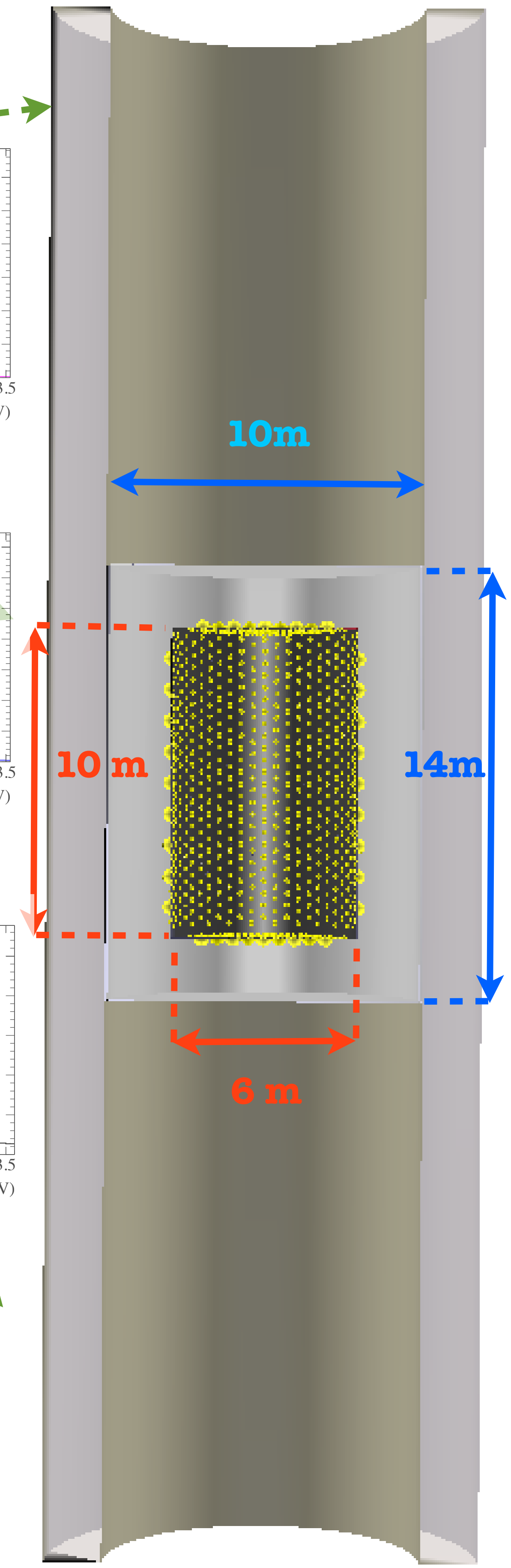
Improved θ_{23} Error











LoI to J-PARC PAC, arXiv:1412.3086

Summary

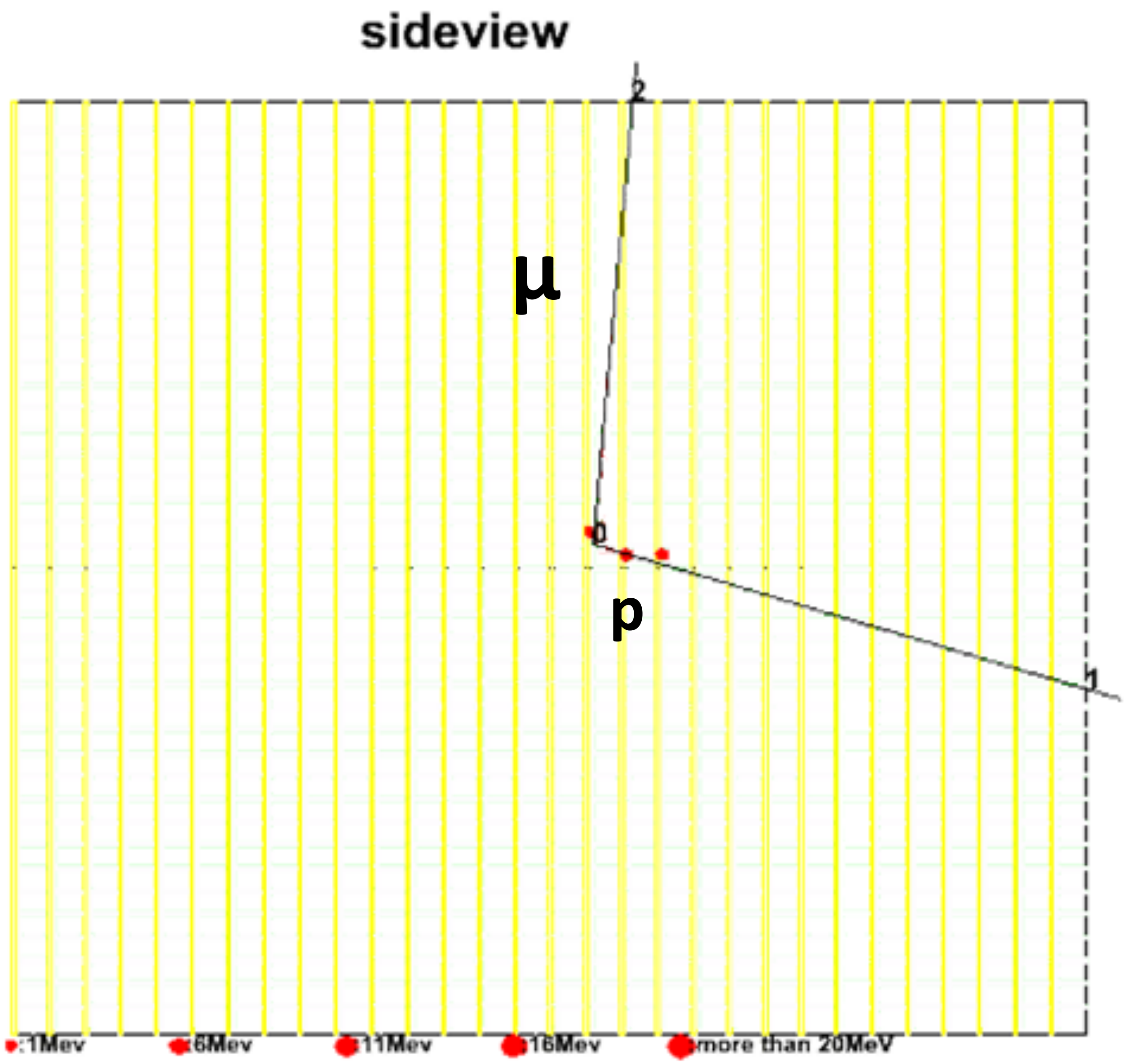
- Observation of ν_e appearance by T2K has opened a door to the CP asymmetry study in the lepton sector!
  - T2K+reactor already placing limits on δ_{CP}.
- T2K will continue to lead the neutrino oscillation study.
  - First anti-neutrino oscillation result expected soon.
  - Collecting data with 320kW, higher intensity expected.
- Planning J-PARC beam power increase to the design value of 750kW, and beyond (>MW).
- New neutrino experiments are emerging in J-PARC with international collaborations.
- Next generation experiment: Hyper-K (→Shiozawa-san's talk)

Backup

T59: 3D grid-detector: WAGASCI

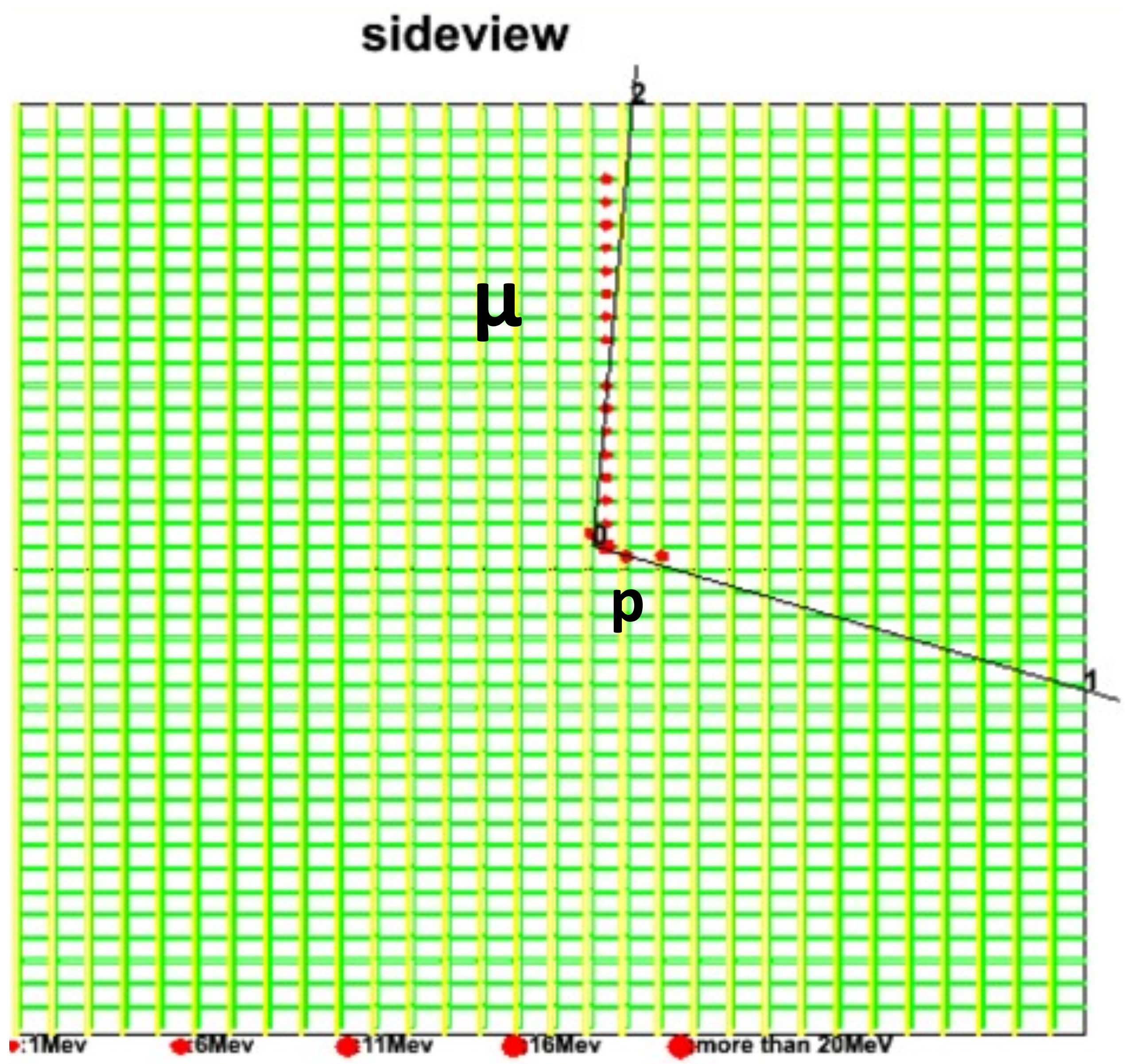
Event display (same CCQE event)

w/o grid layer



hard to track
large scattering μ

with grid layer



easy to track
large scattering μ

Constraining flux × cross section

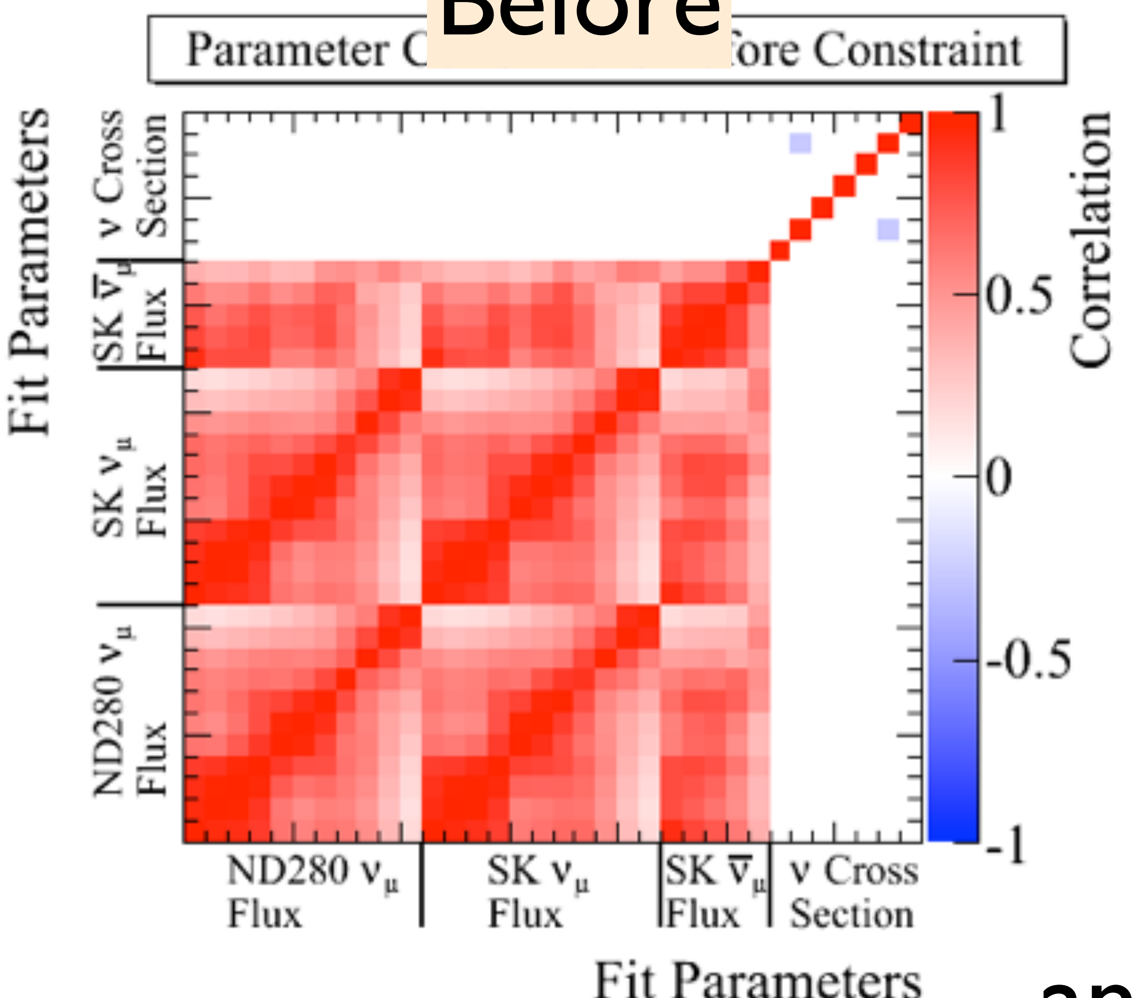
Flux prediction
(NA61, beamline meas.)

ND280 measurements
(p_μ, θ_μ)

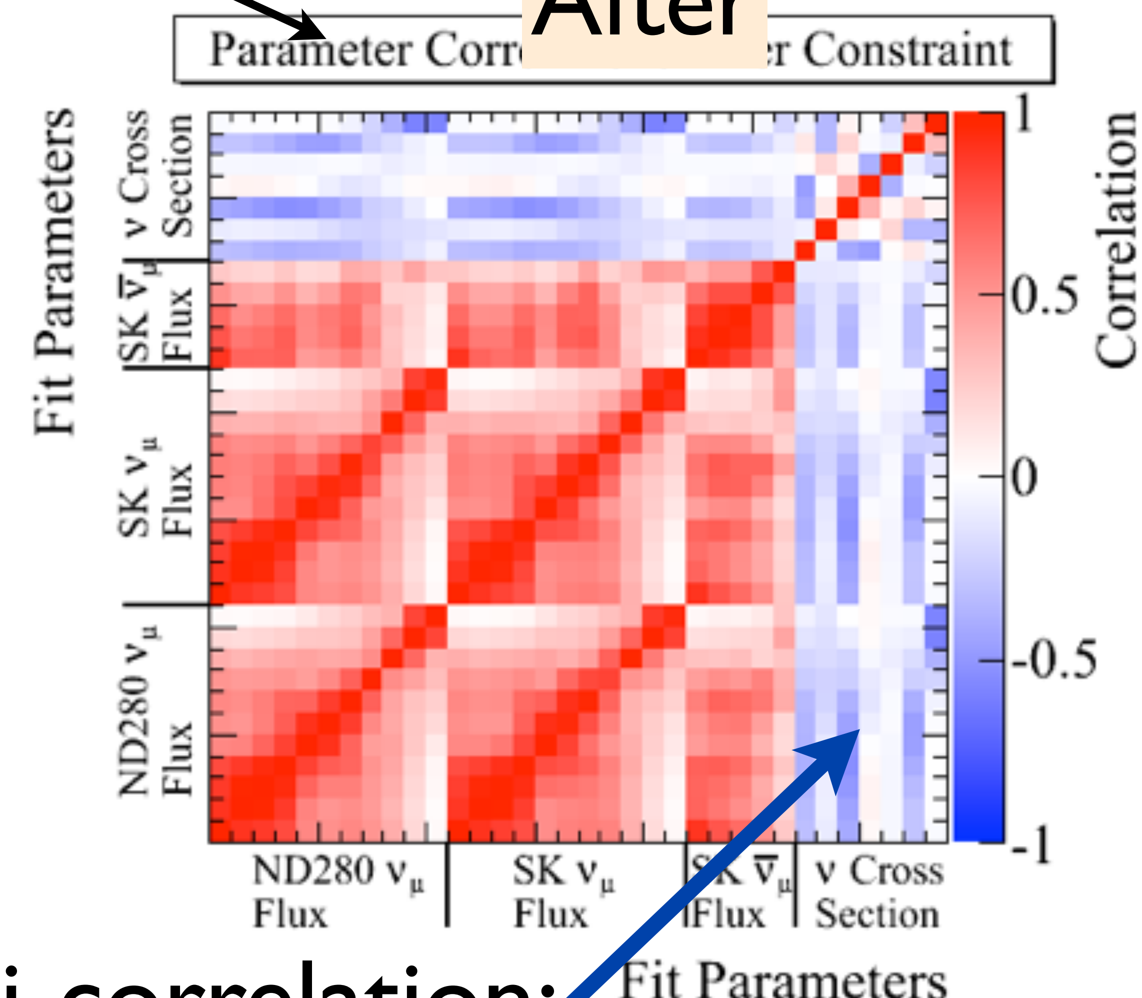
Cross-sec. uncertainties
(external meas., models)

Fit with correlations taken into account

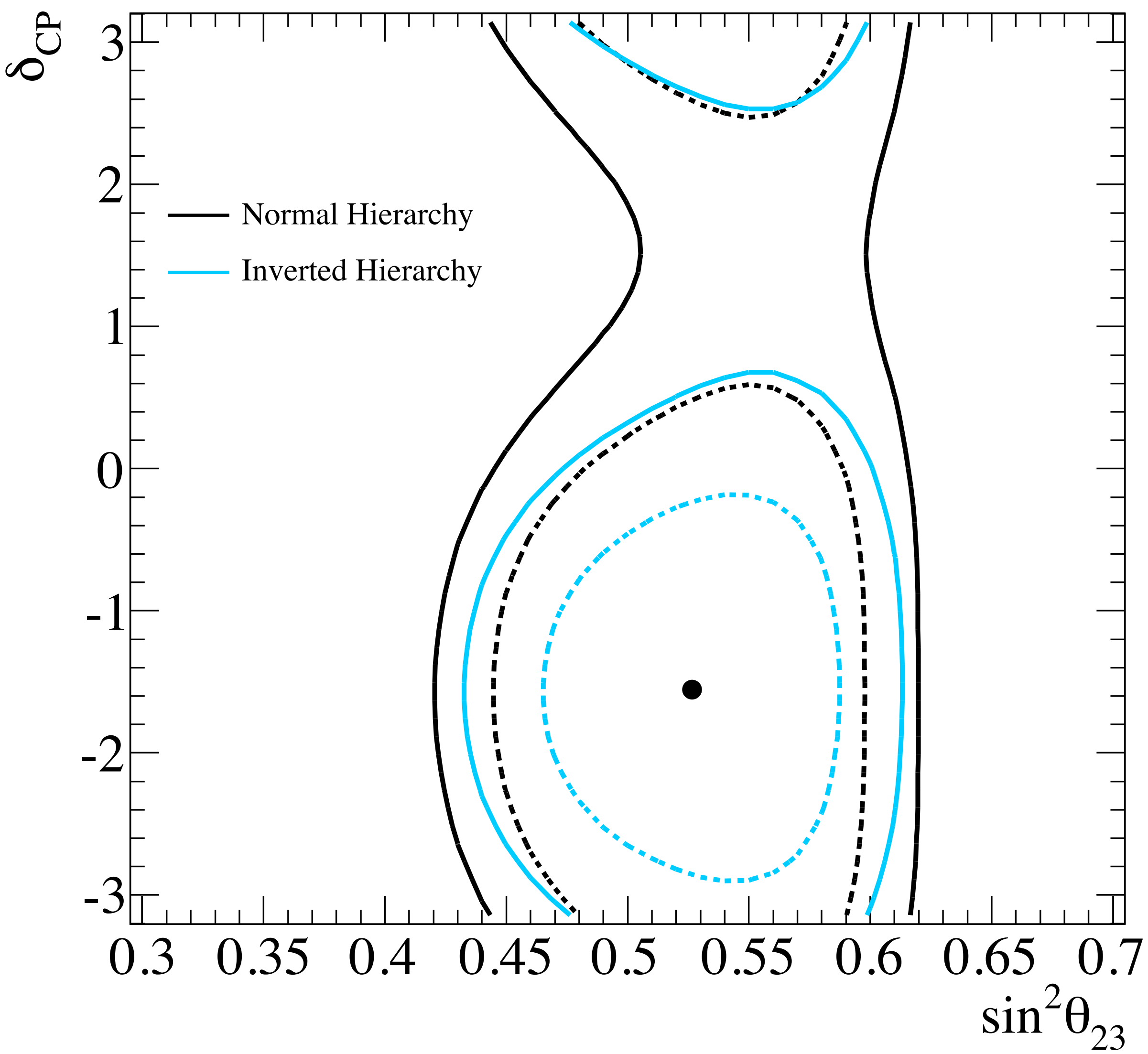
Before



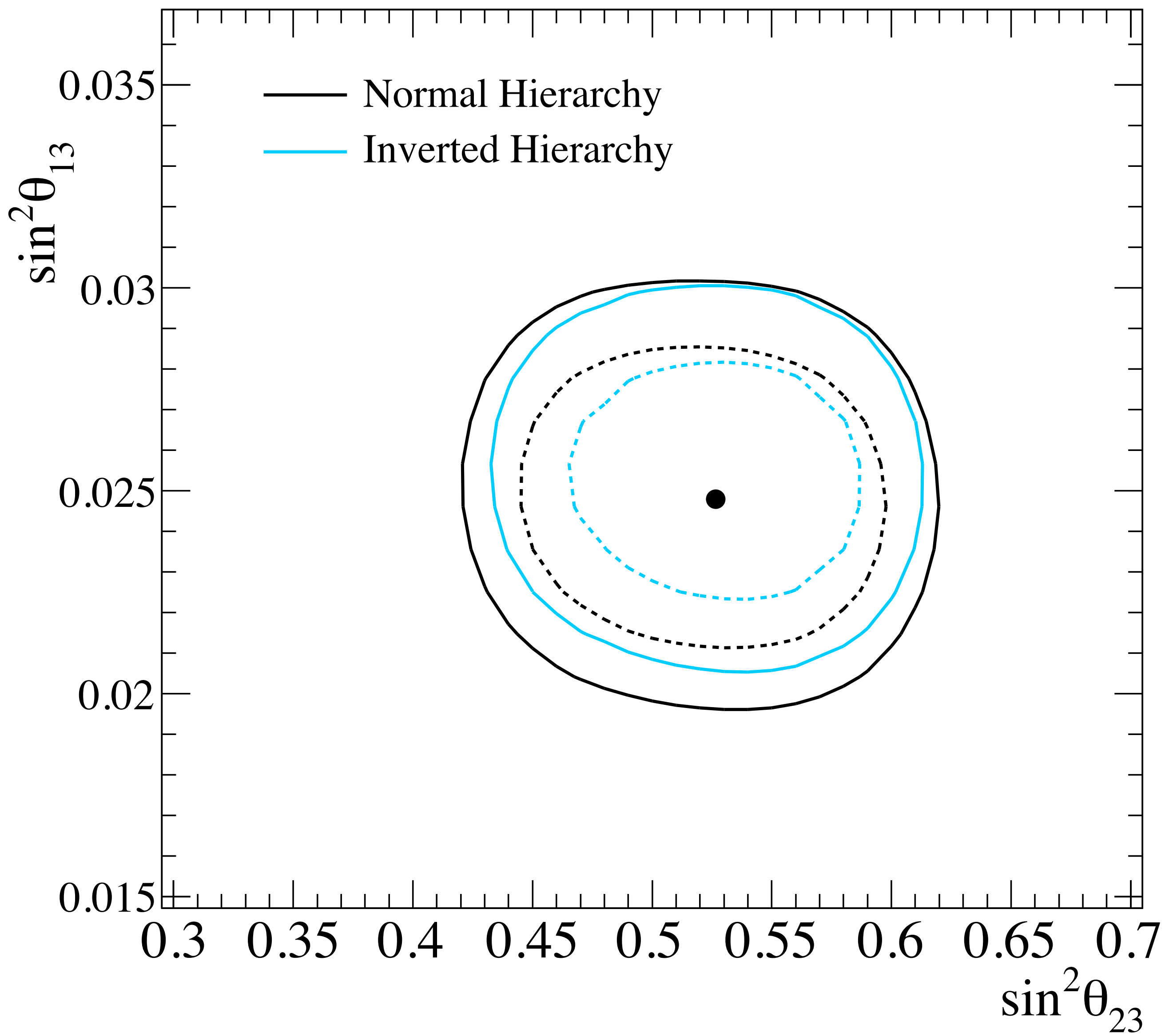
After



anti-correlation:
reduced rate (flux × cross section) uncertainty



δ_{CP}
3
2
1
0
-1
-2
-3
Normal Hierarchy
Inverted Hierarchy
0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7
$\sin^2\theta_{23}$



$\sin^2\theta_{13}$
0.035
0.03
0.025
0.02
0.015
Normal Hierarchy
Inverted Hierarchy
0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7
$\sin^2\theta_{23}$