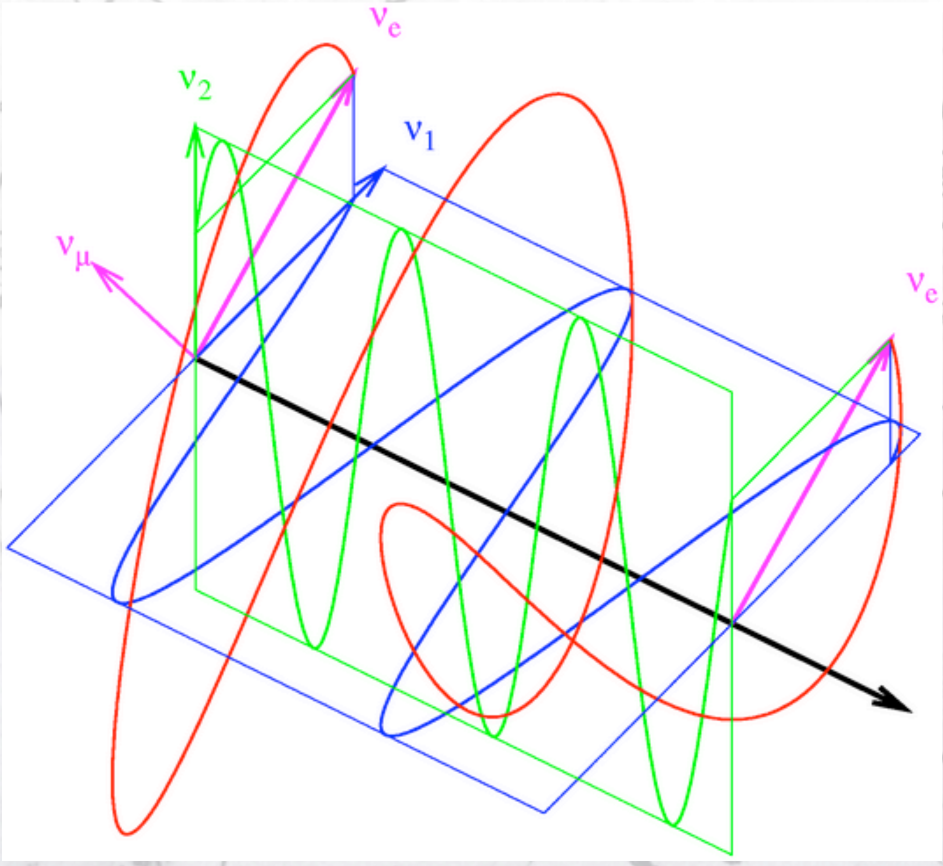
Long base line experiments

Federico Sánchez
IFAE (Barcelona)

- Fast review on oscillations
- The concept: T2K and Nova
- Most recent results: T2K
- Neat future: T2K + Nova
- The future: HK and LBNF(Dune)

Neutrino oscillations

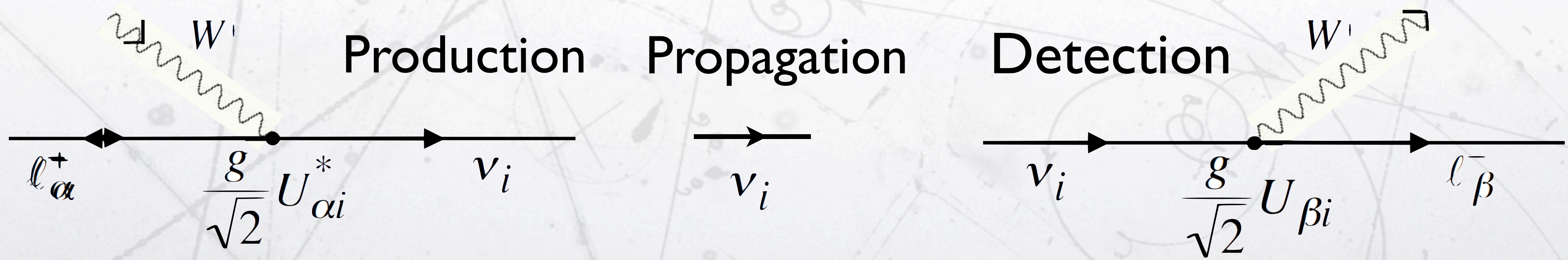


ν oscillations

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

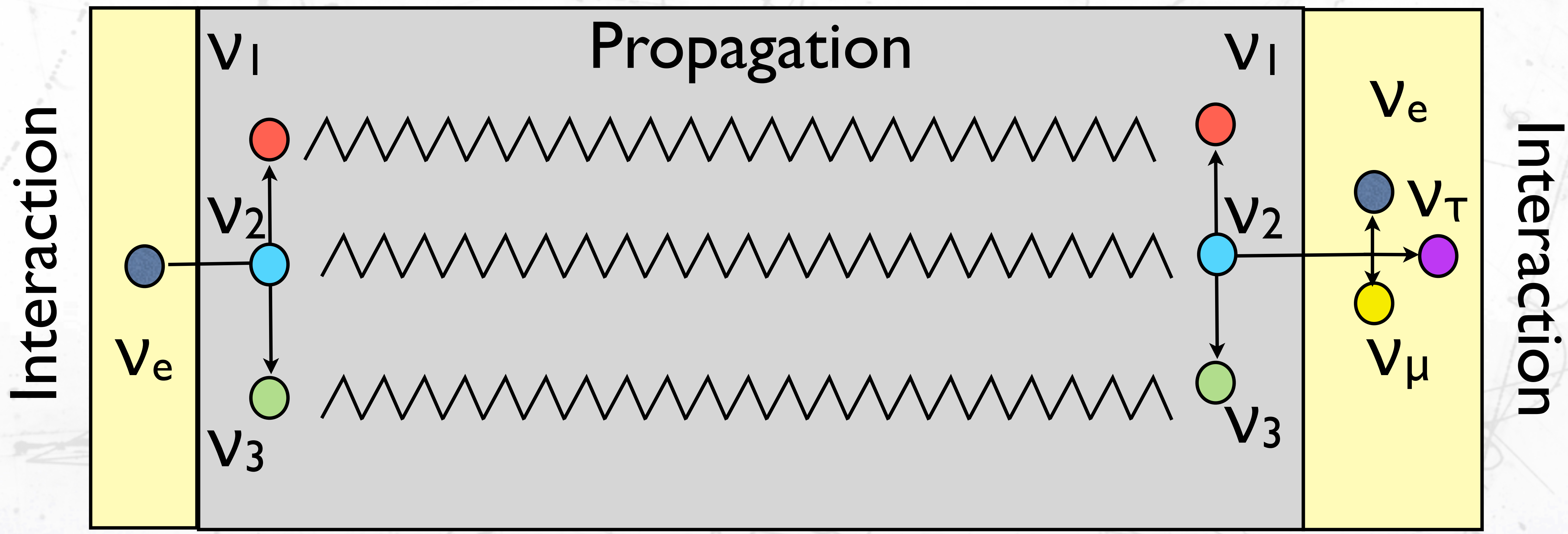
atmospheric   solar

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

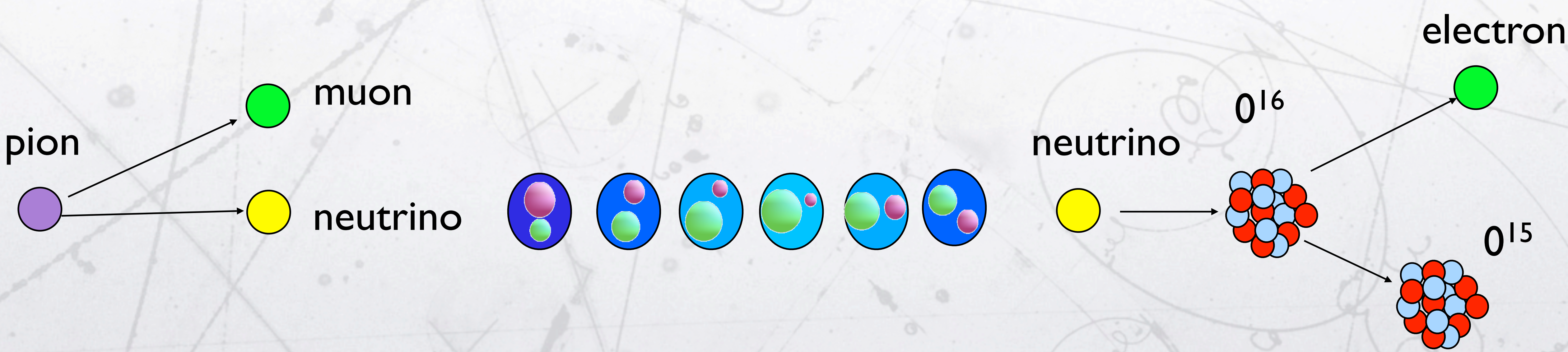
$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

LBL concept



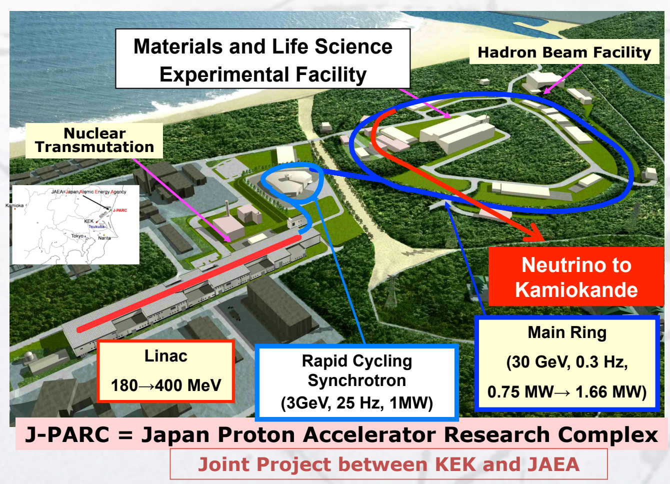
Interaction
ν_e
Propagation
ν_1
ν_2
ν_3
ν_1
ν_2
ν_3
ν_e
ν_τ
ν_μ
Interaction

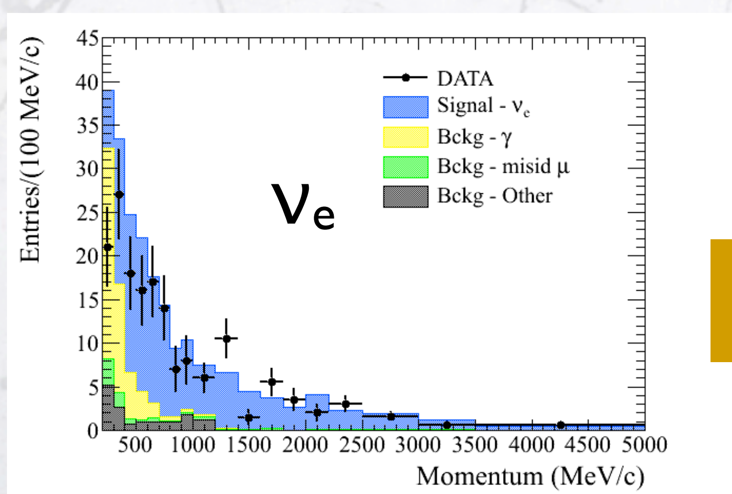


pion
muon
neutrino
neutrino
0^{16}
electron
0^{15}

LBL concept

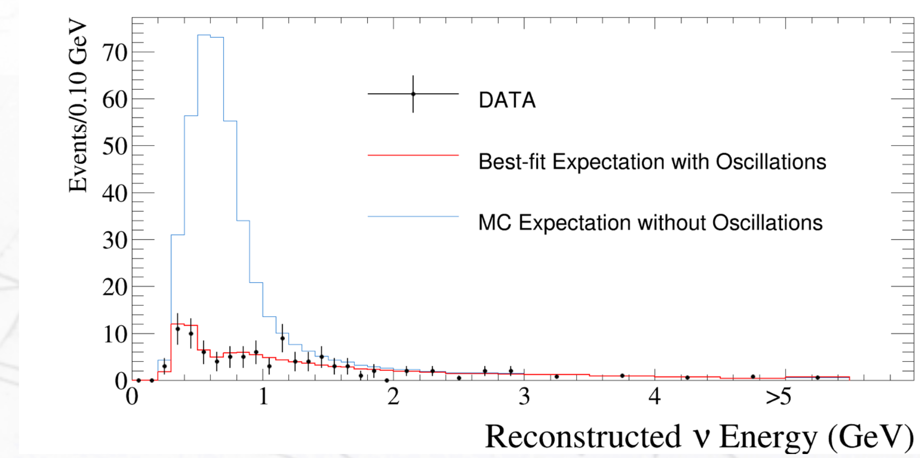
ν_μ





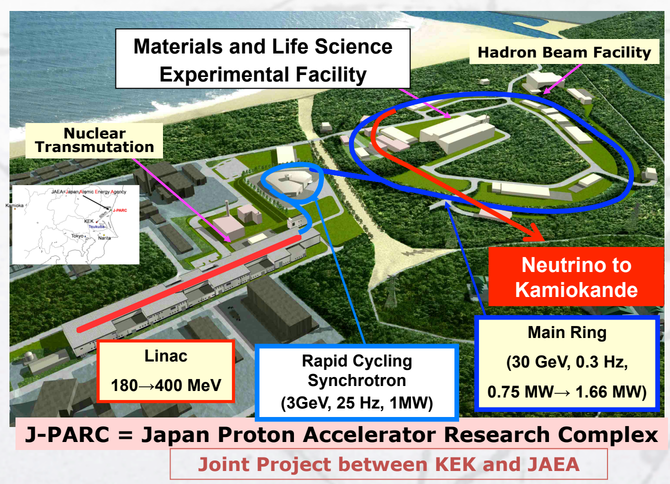
ν_e

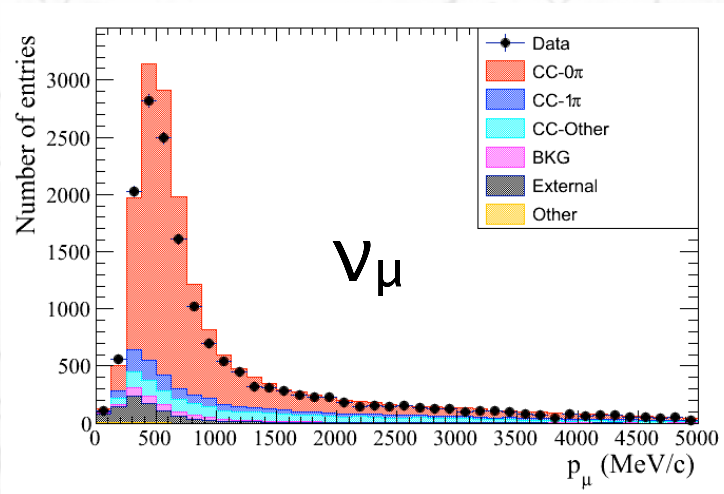
ν_e → ν_e

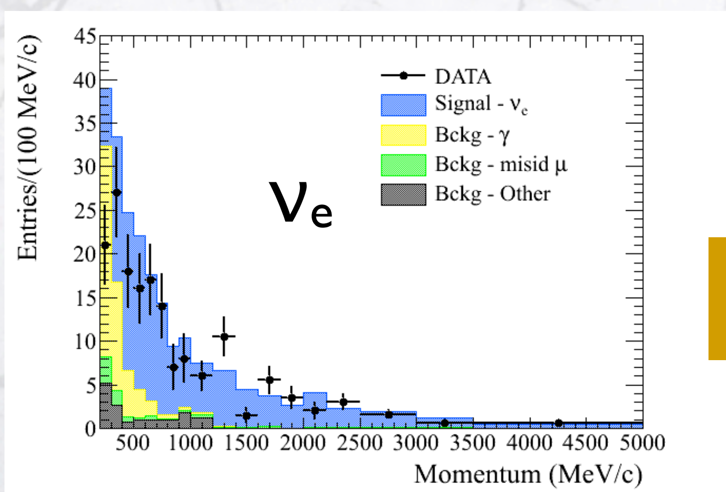


LBL concept

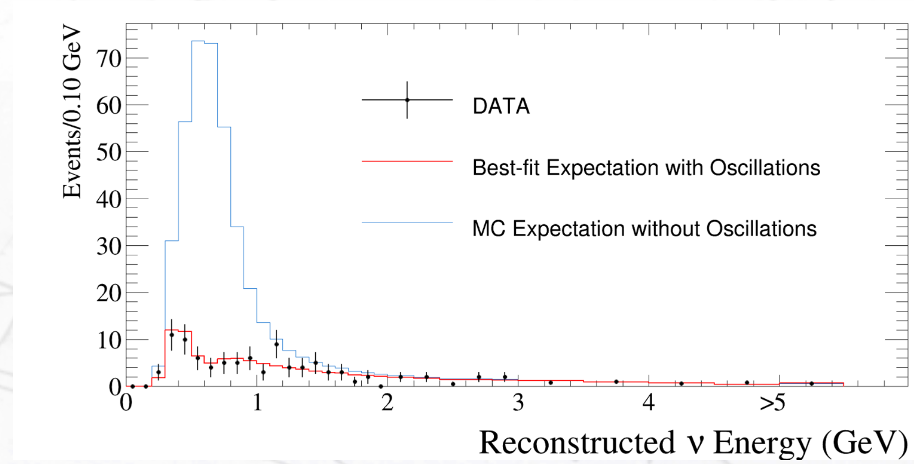
Near detector monitor



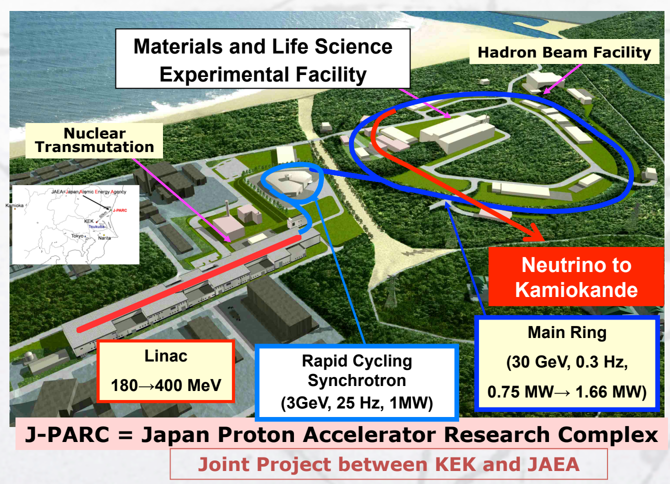


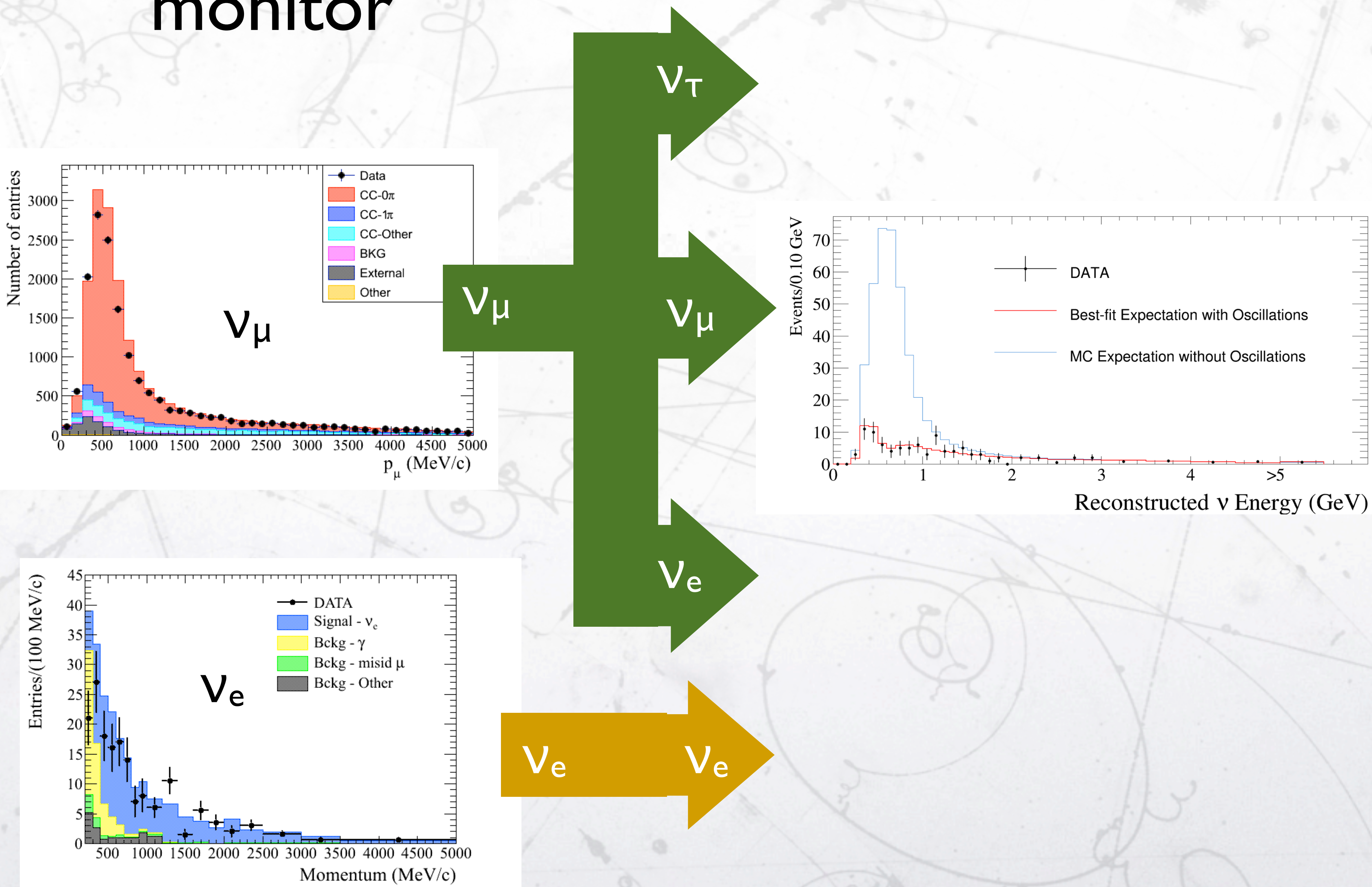


ν_e ν_e



Near detector monitor

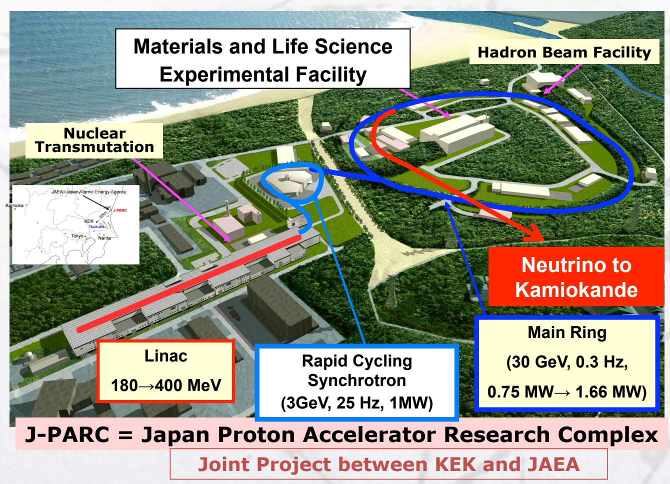


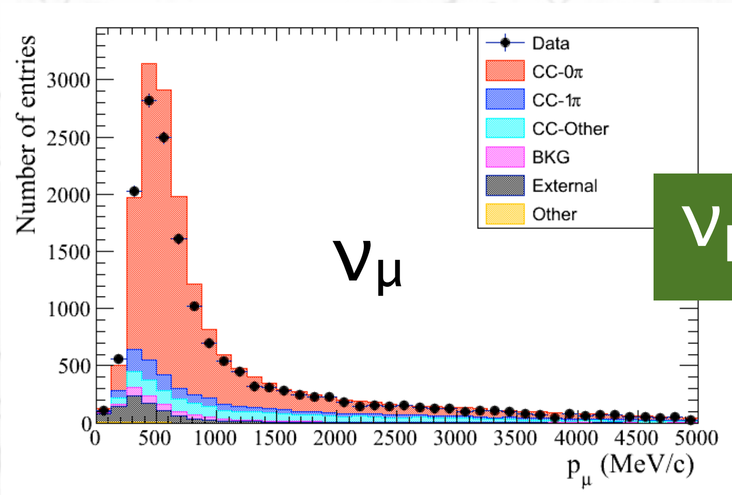


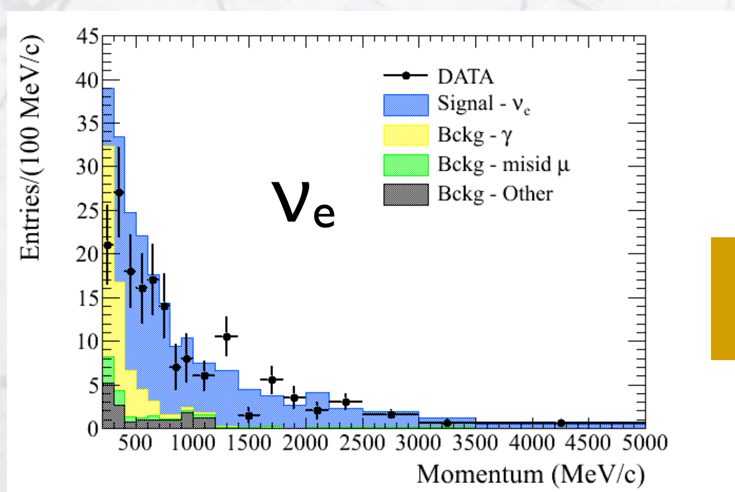
LBL concept

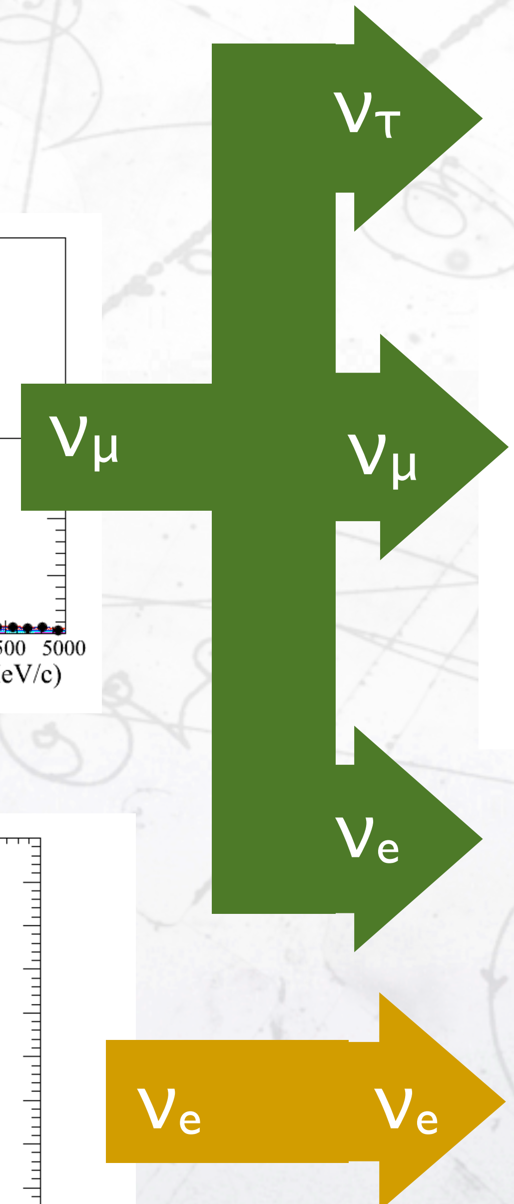
Near detector monitor

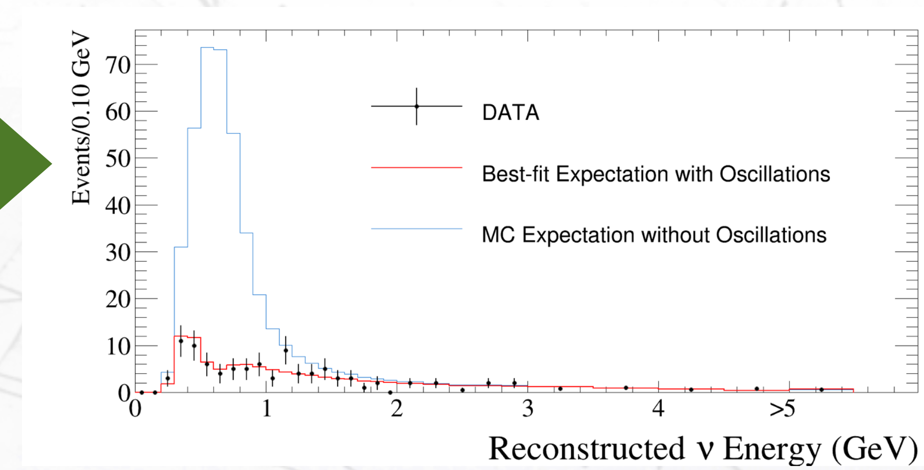
Far detector







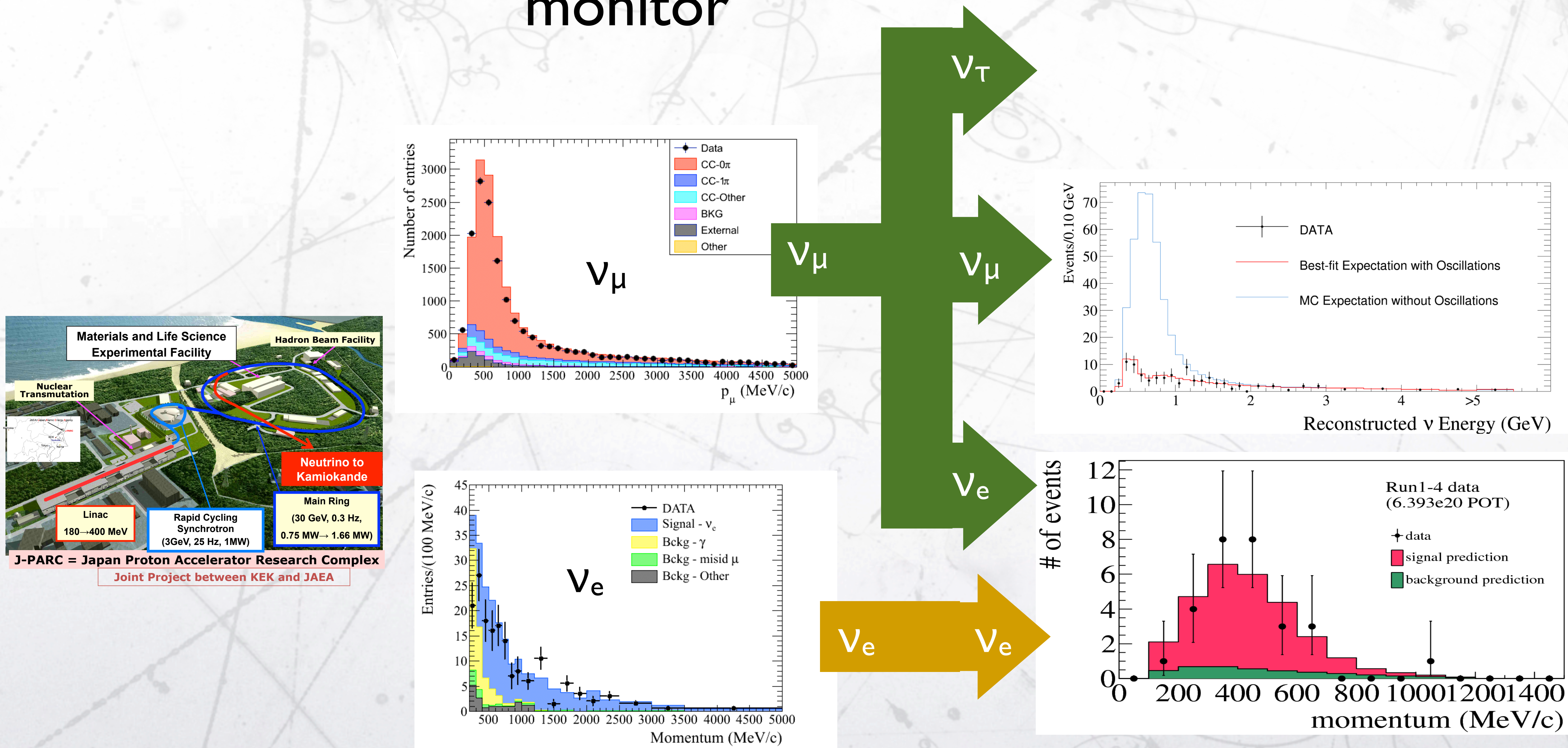




LBL concept

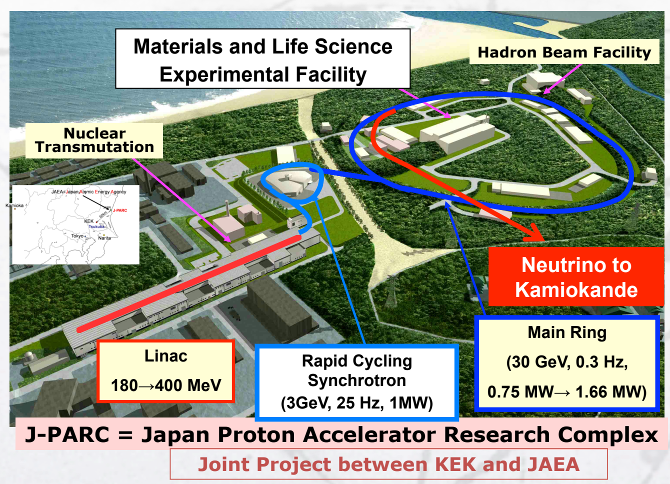
Near detector monitor

Far detector

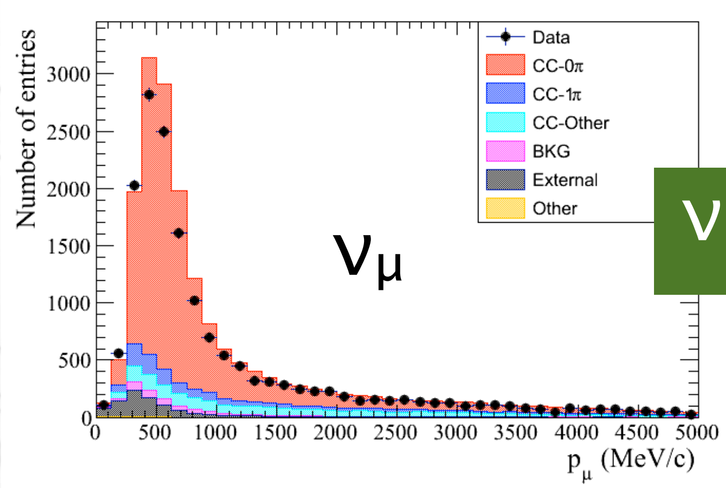


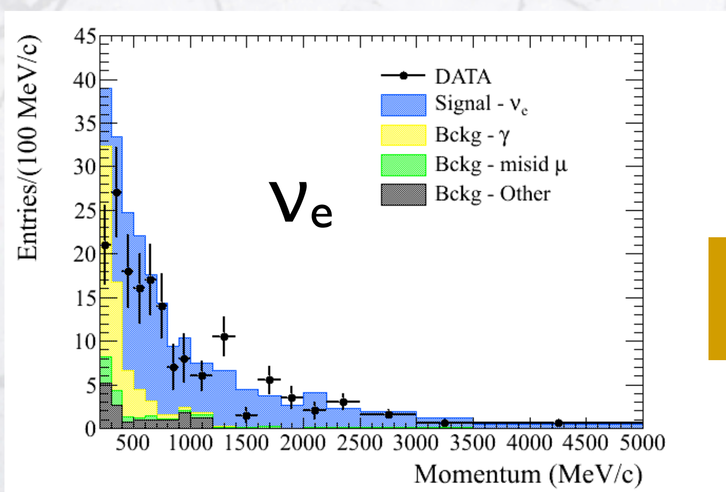
LBL concept

Proton beam



Near detector monitor



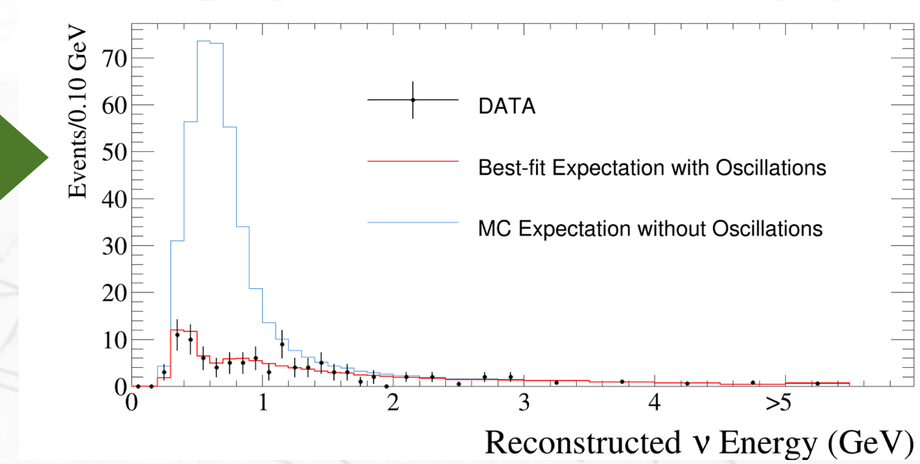


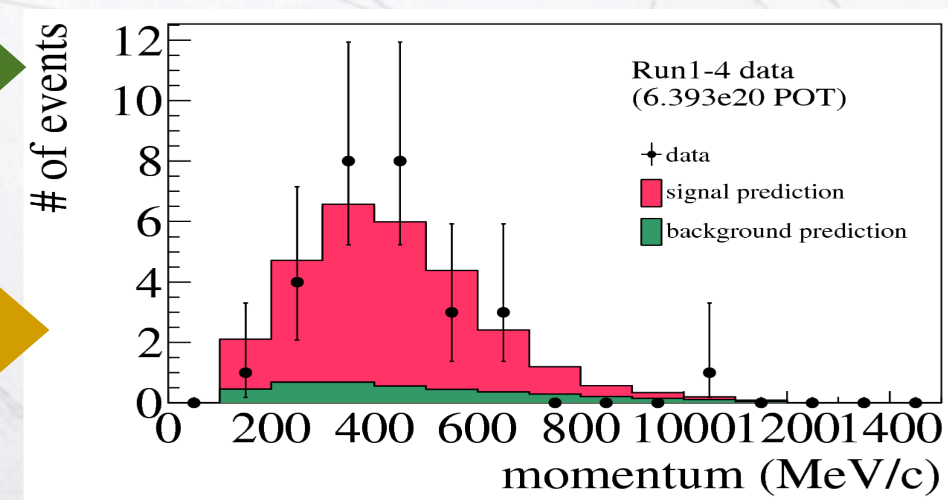
ν_μ → ν_τ, ν_μ, ν_e

ν_e → ν_e

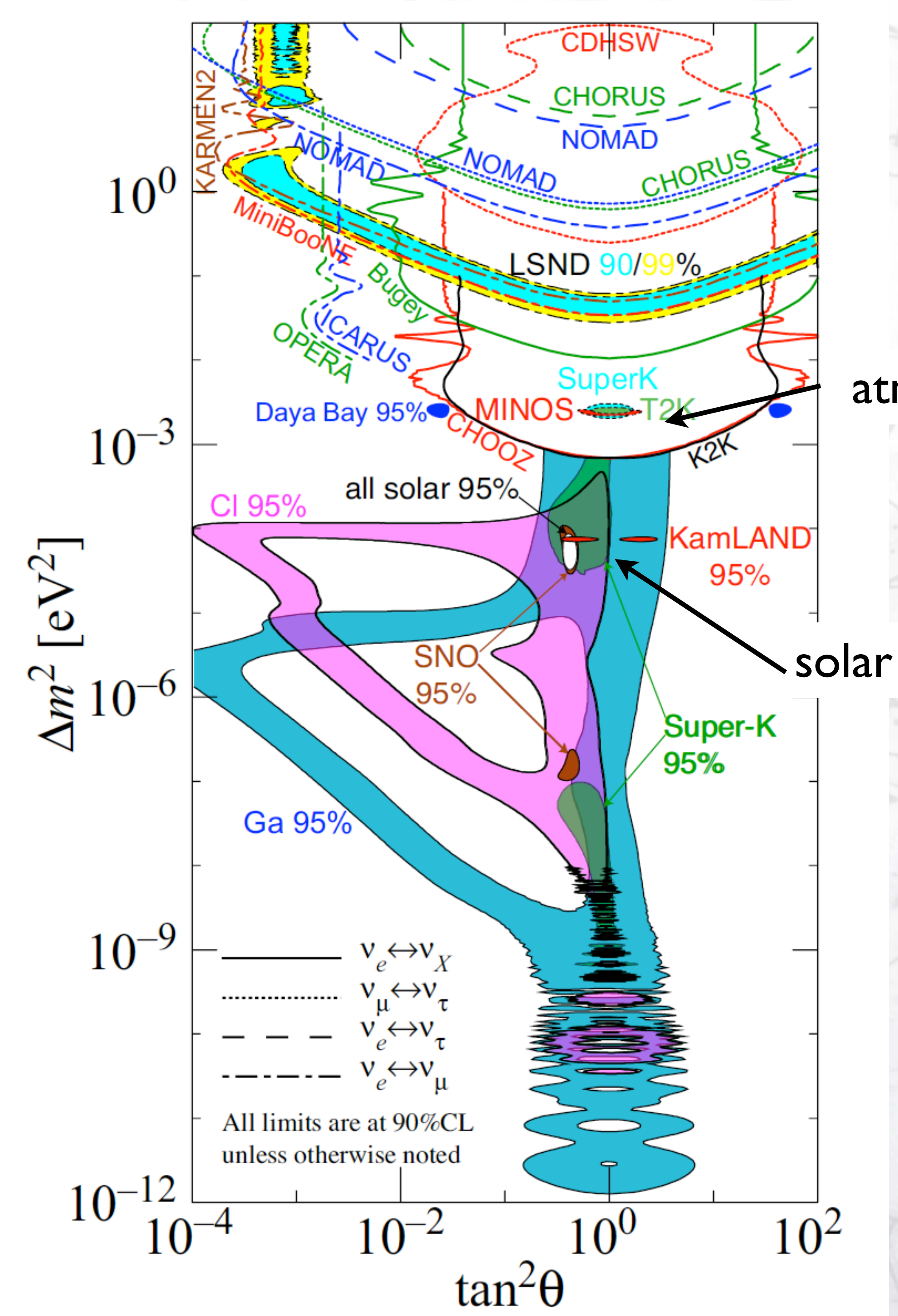
Far detector

Invisible: ν´s are not energetic





ν oscillations



Particle Data Group neutrino review

Status as of 2014

$$\Delta m^2_{12} = 7.54^{+0.26}_{-0.22}(10^{-5}eV^2)$$
$$|\Delta m^2_{23}| = 2.43 \pm 0.06(10^{-3}eV^2)$$
$$\sin^2\theta_{12} = 0.308 \pm 0.017$$
$$\sin^2\theta_{23} = 0.437^{+0.033}_{-0.023}(\Delta m^2 > 0)$$
$$\sin^2\theta_{23} = 0.455^{+0.039}_{-0.021}(\Delta m^2 < 0)$$
$$\sin^2\theta_{13} = 0.0234^{+0.0020}_{-0.0019}(\Delta m^2 > 0)$$
$$\sin^2\theta_{13} = 0.0240^{+0.0019}_{-0.0022}(\Delta m^2 < 0)$$
$$\delta = 1.39^{+0.29}_{-0.33}\pi$$

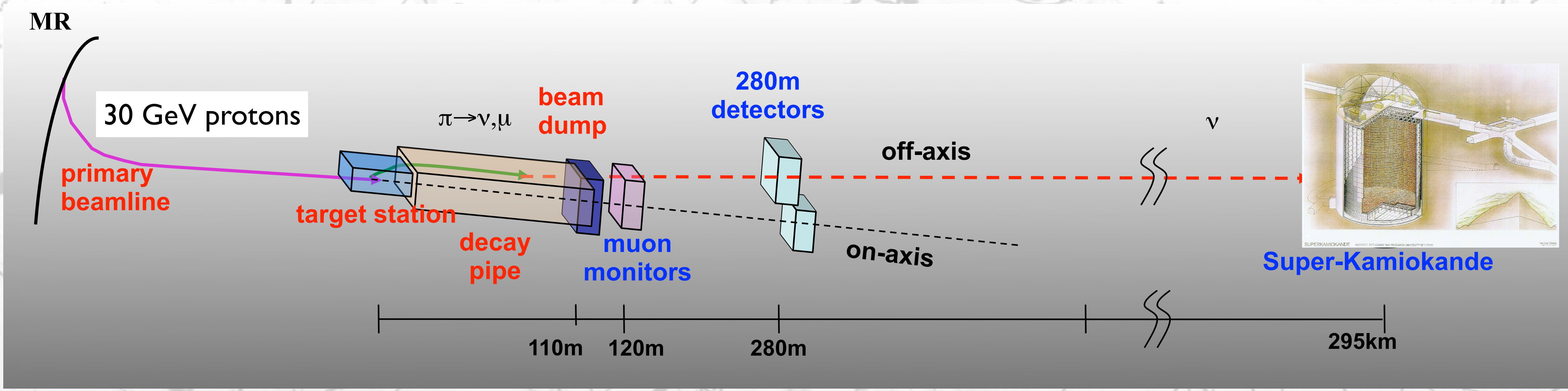
Standard ν oscillations

Next steps

- δ_{CP} accessible through:
  - comparison of appearance with reactor disappearance.
  - comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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

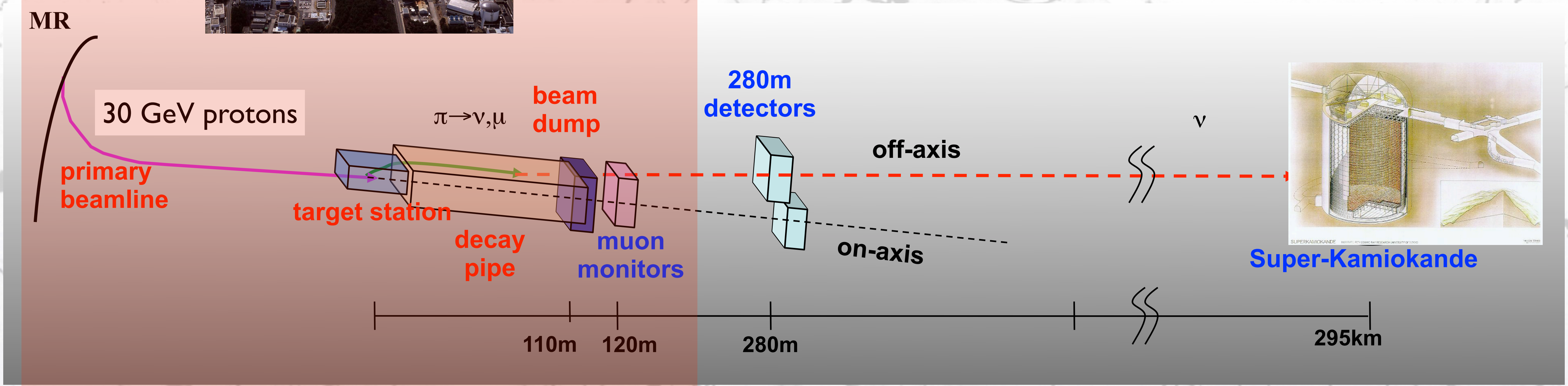
- The θ_{23} octant:
  - The θ_{23} is close to 45° but, how close?, is $\theta_{23}<45°$ or $\theta_{23}<45°$?
- What is the absolute neutrino mass ? (Katrin?, Cosmology?,…)
- The mass hierarchy: is $m_3 > m_1$?



Beam | ND280 | Super-Kamiokande

IFAE
EXCELENCIA SEVERO OCHOA

Beam

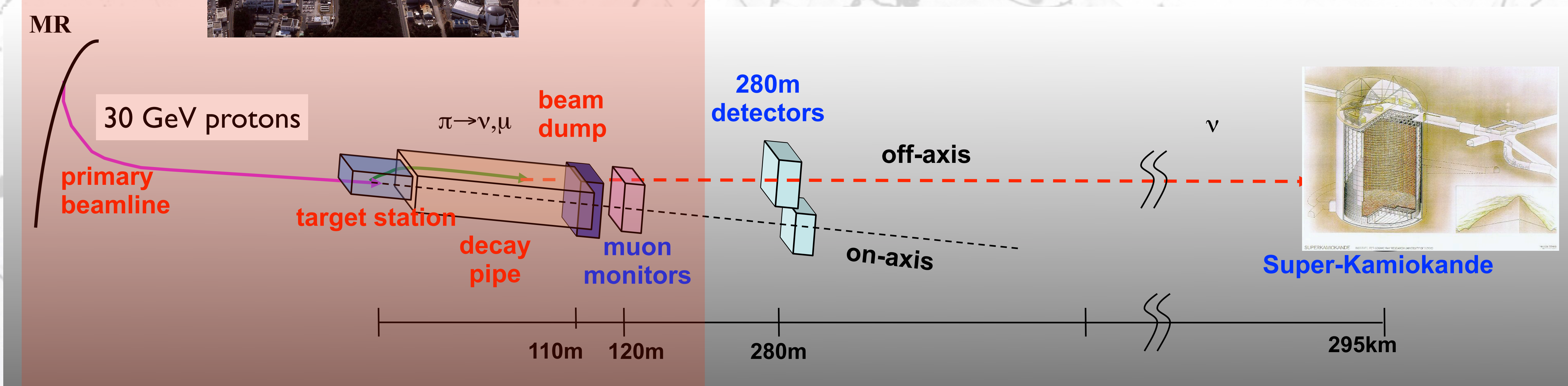


Beam

ND280

Super-Kamiokande

Beam



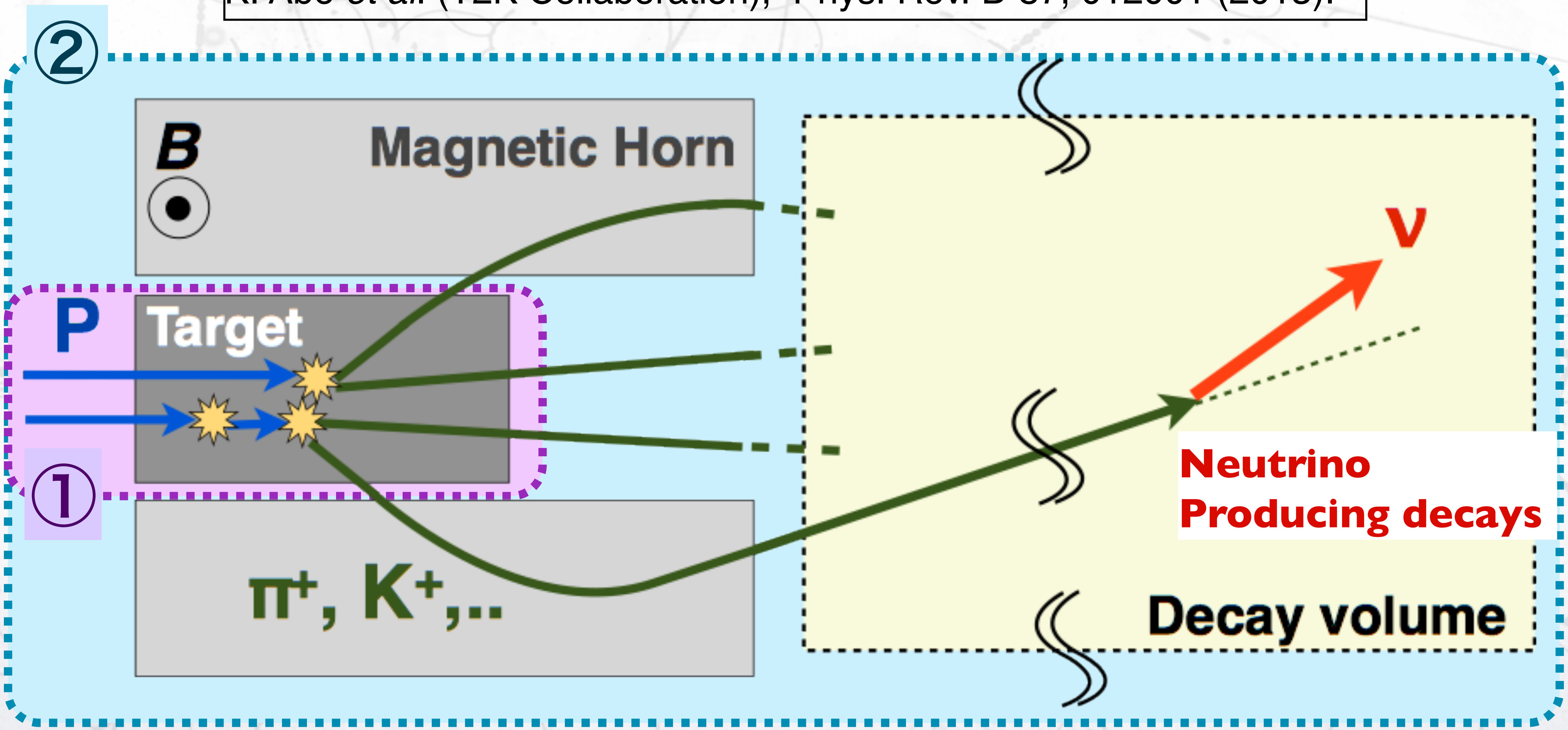
Beam

ND280

Super-Kamiokande

Conventional beam

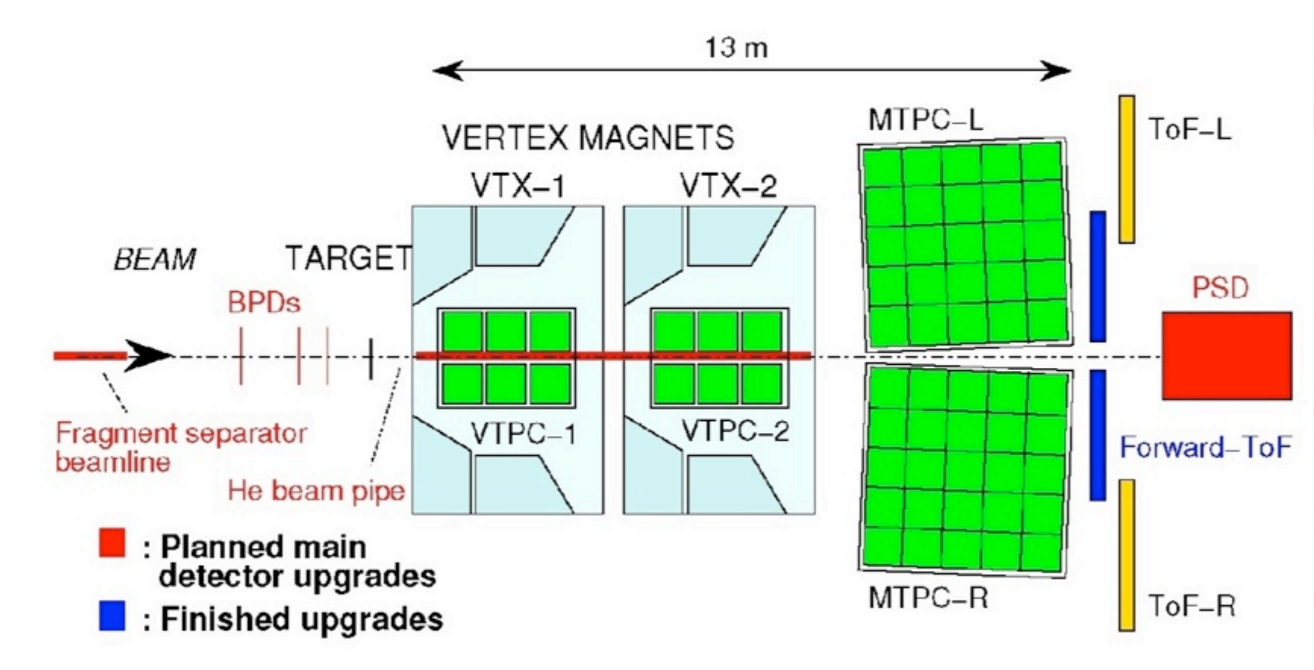
K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).

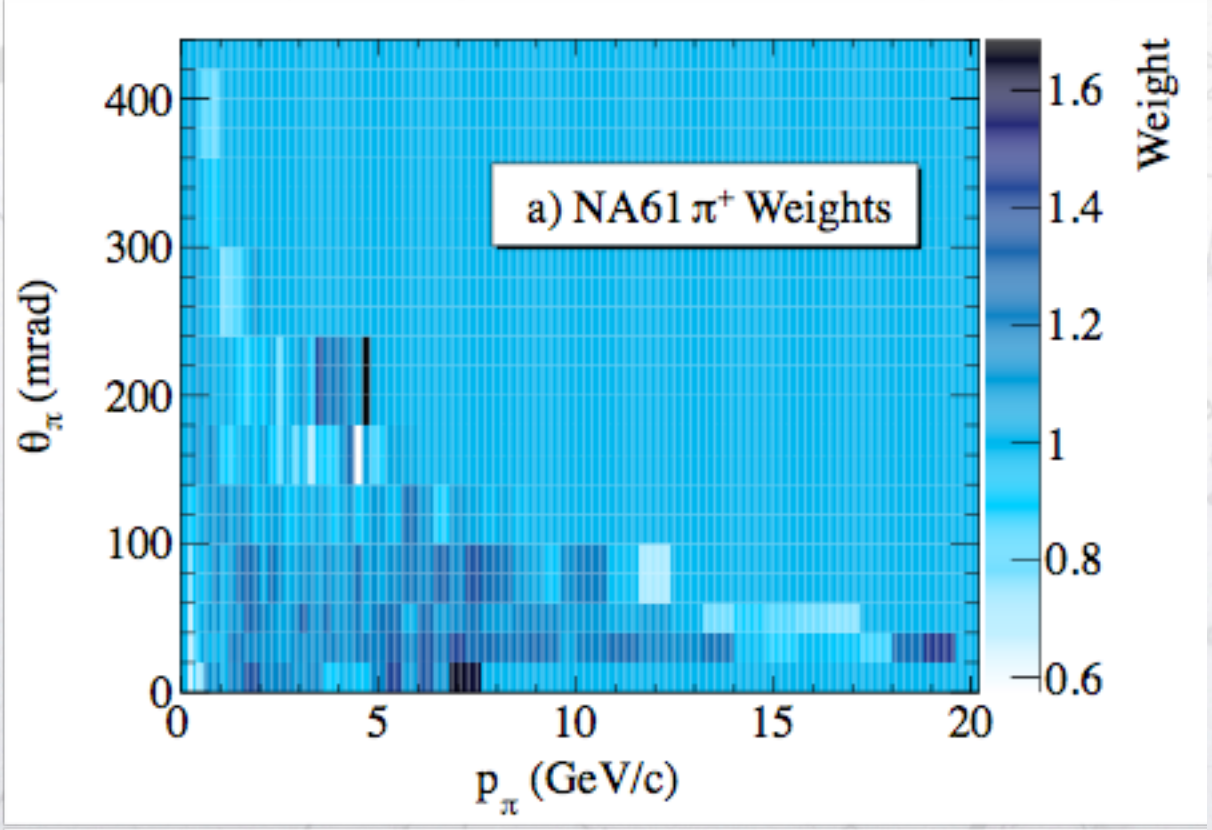


NA61: Shine

CERN SHINE NA61

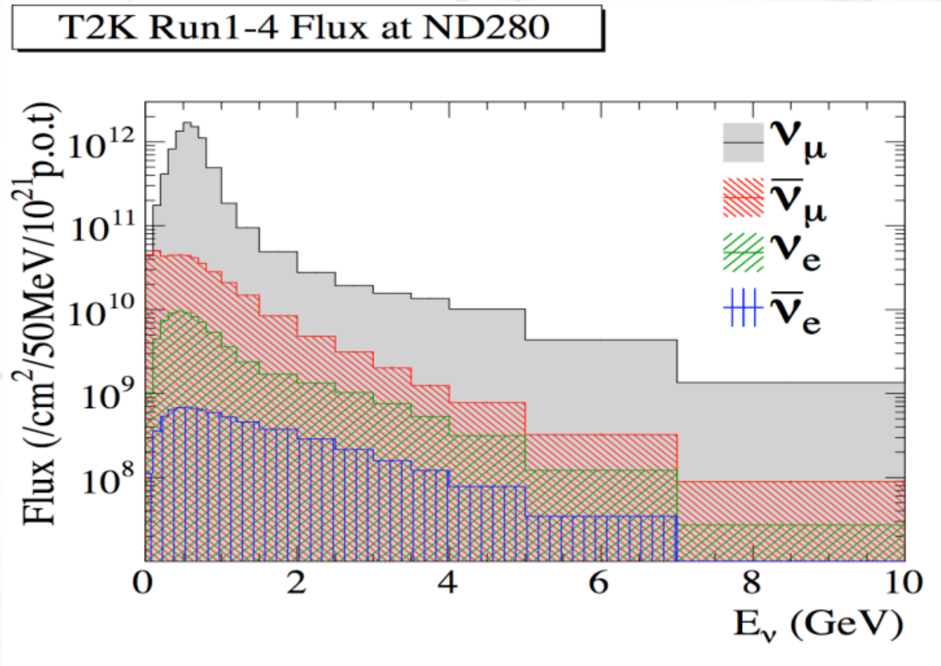
NA61/Shine measures for T2K the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.



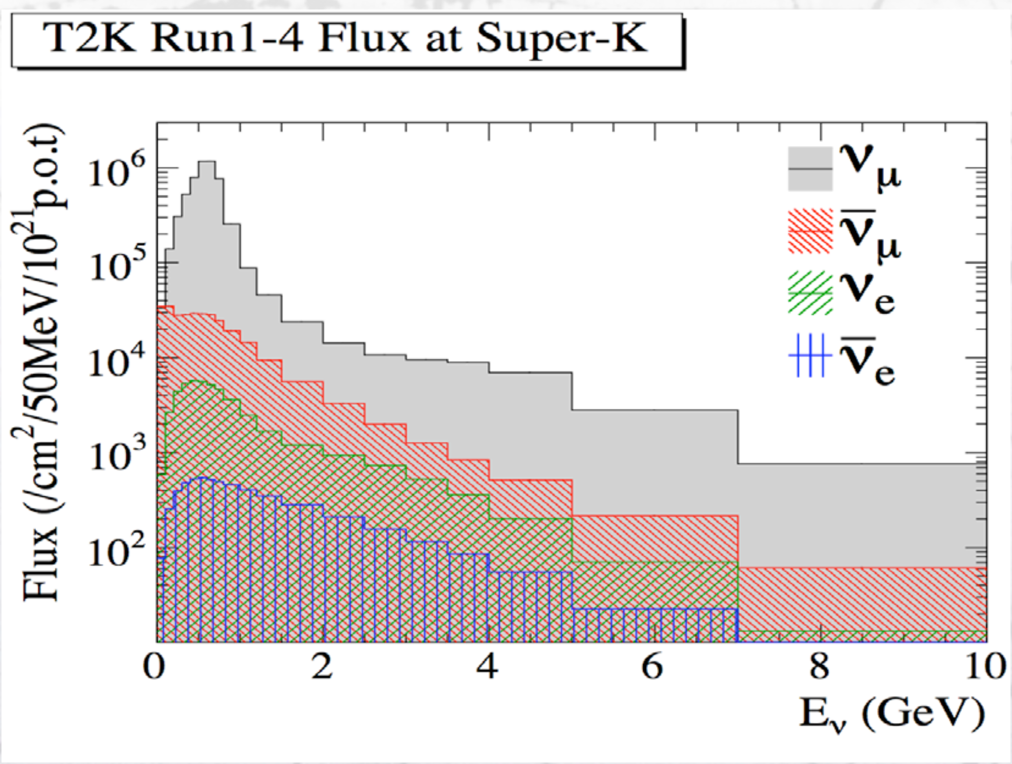


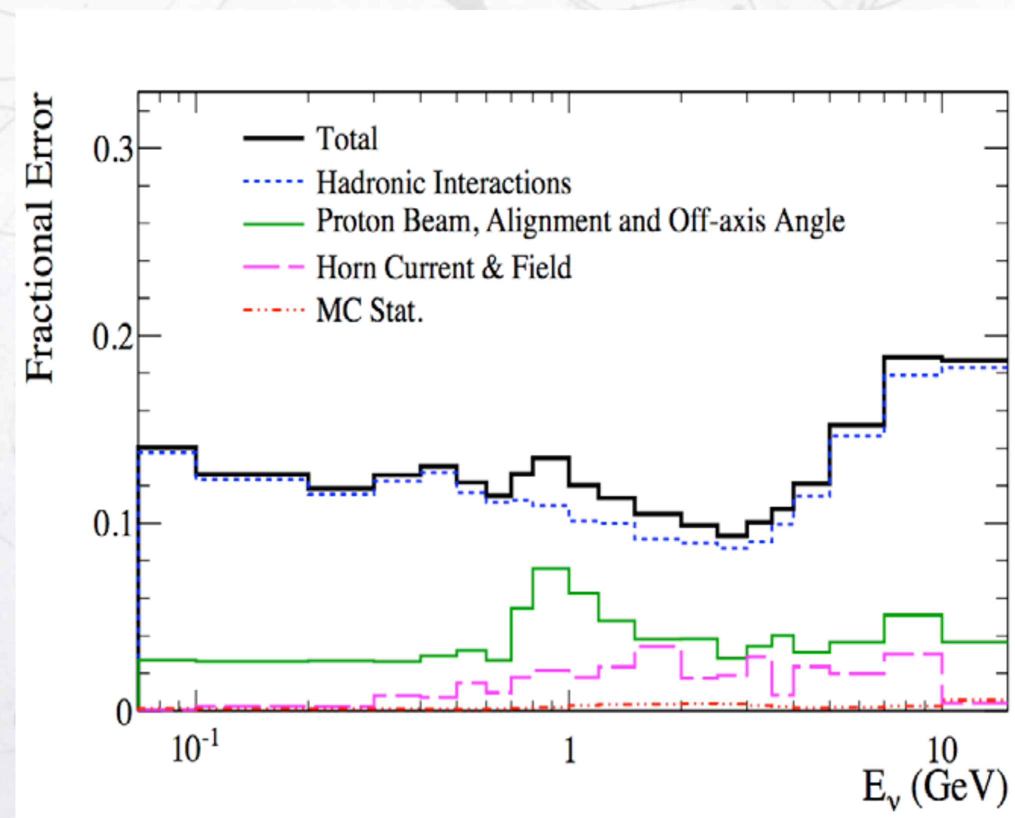
NA61/Shine measures a thin target for absolute production and thick target that is a copy of T2K target and provides also the reinteractions.

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.





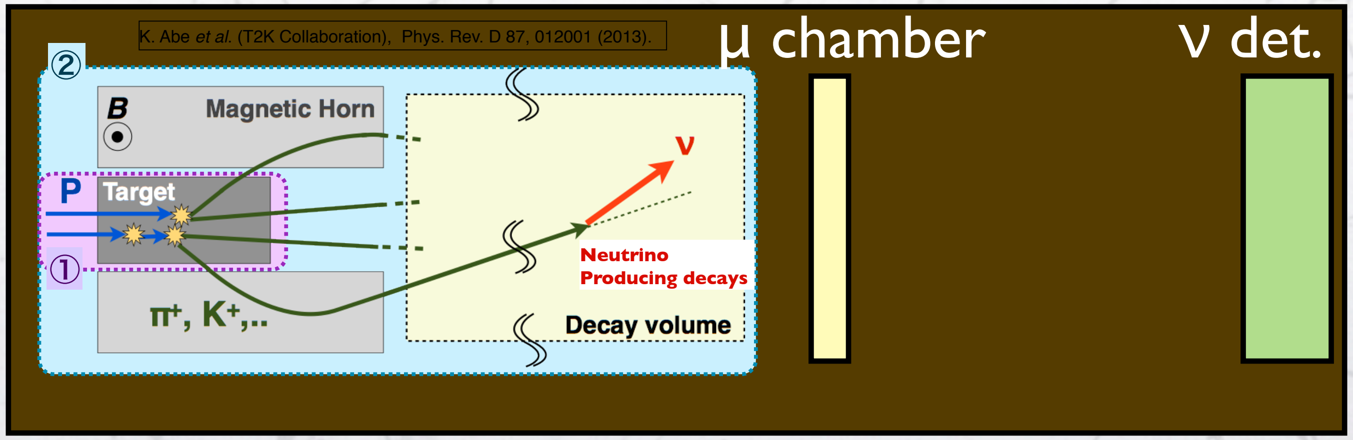
Beam stability

- The beam stability is monitored at two levels:
  - beam direction & intensity
- Using
  - accelerator components.
  - muon flux after the decay volume.

  Spill by Spill

  - neutrino intensity at a near site.

  Day by Day

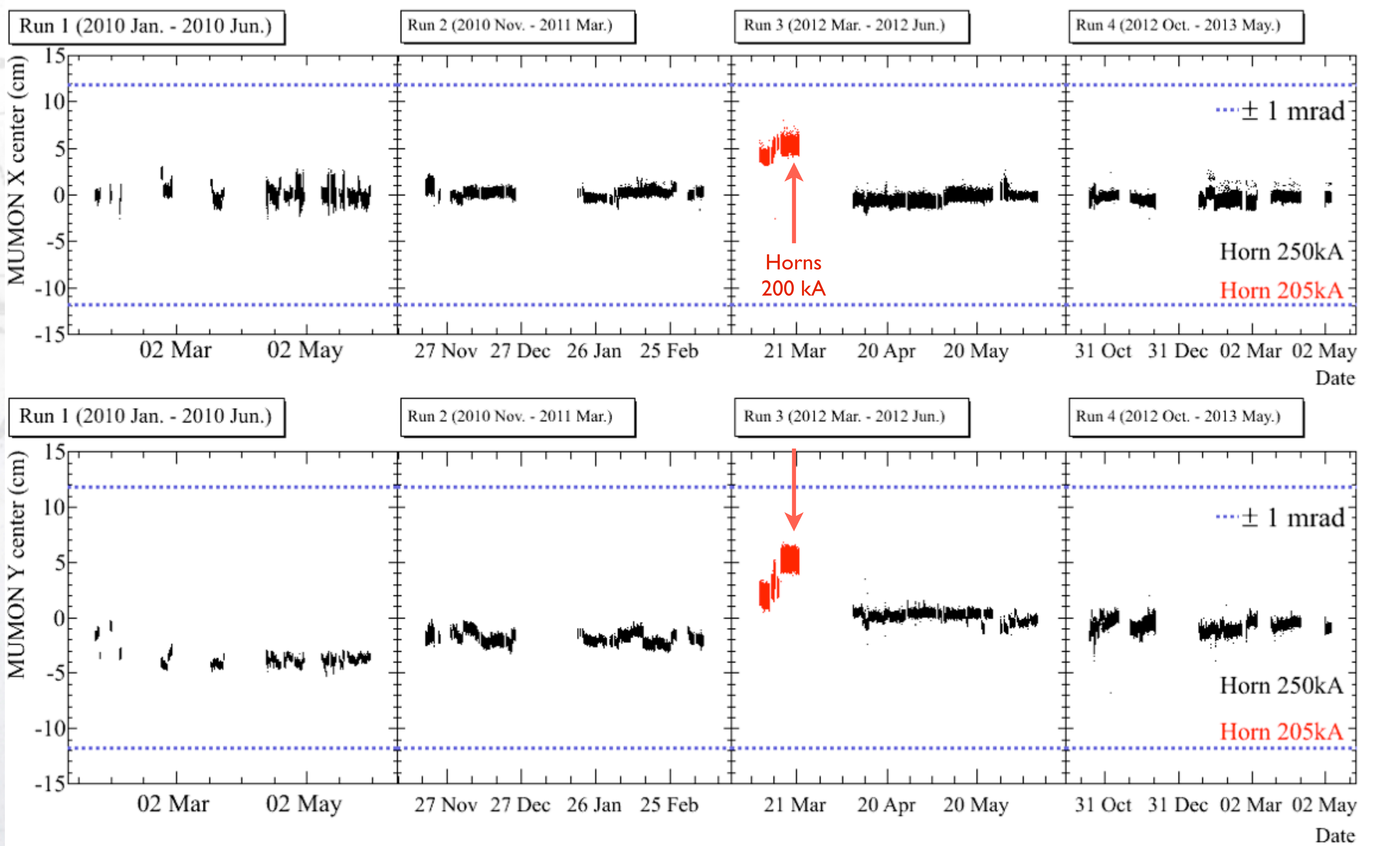


Beam stability

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

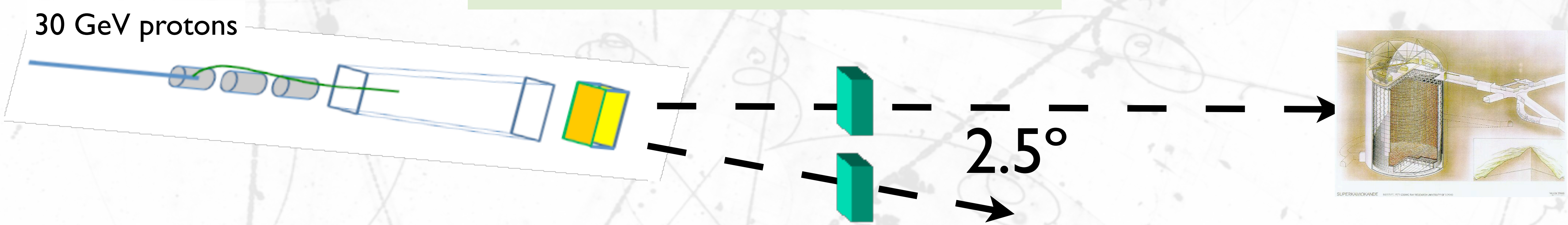
1 mrad change of ν beam direction results in 2-3% change of the neutrino energy scale (~16MeV)

$$\theta \approx \frac{40m}{300km} = 0.13mrad$$

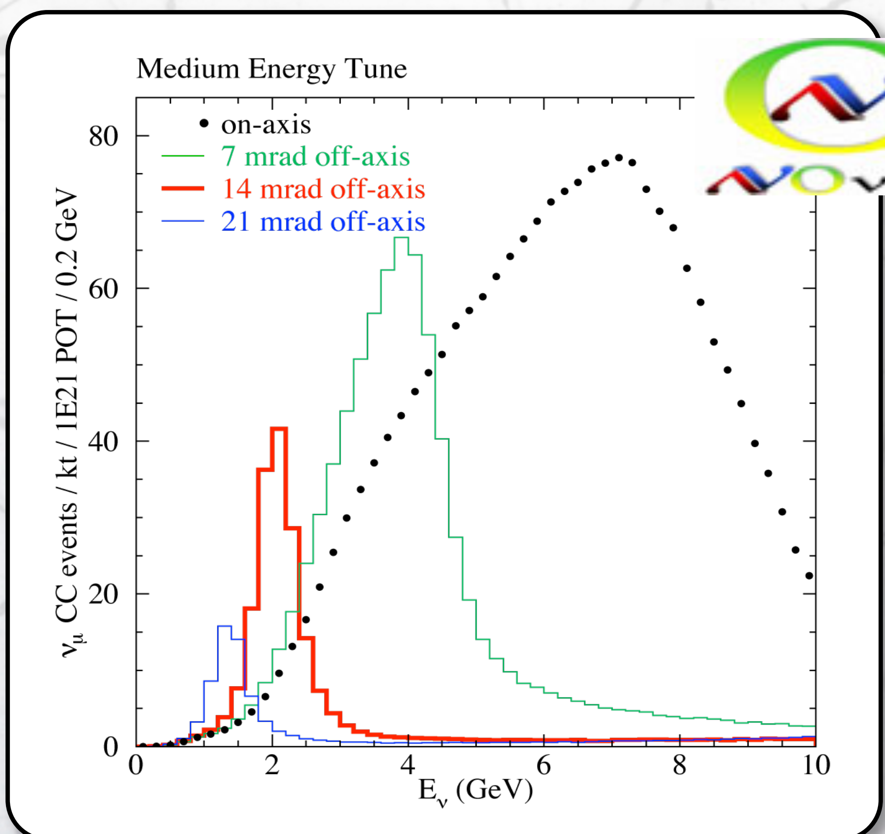


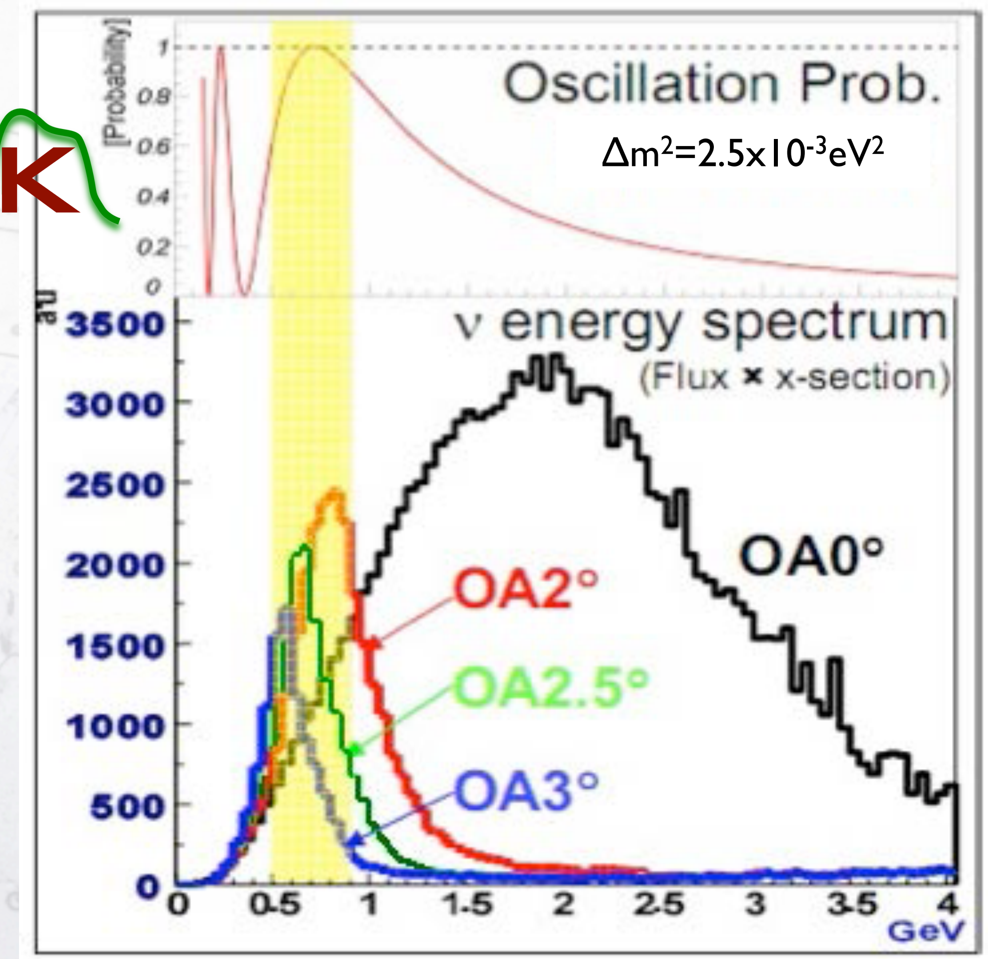
Off-axis concept

T2K runs 2.5° off-axis



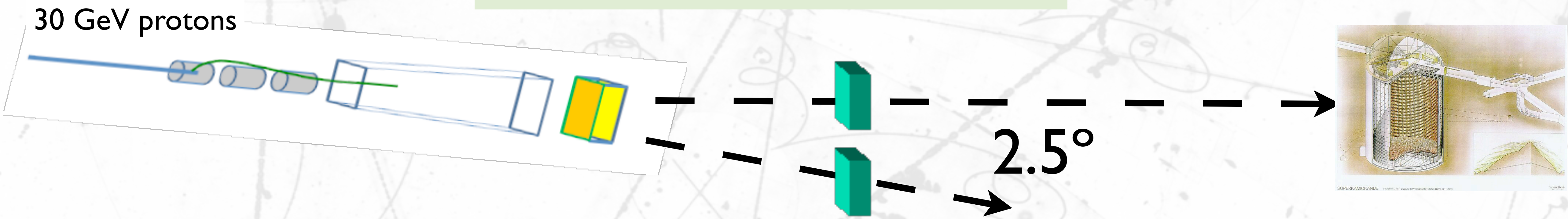
- off-axis optimises the flux at the maximum of the oscillation.



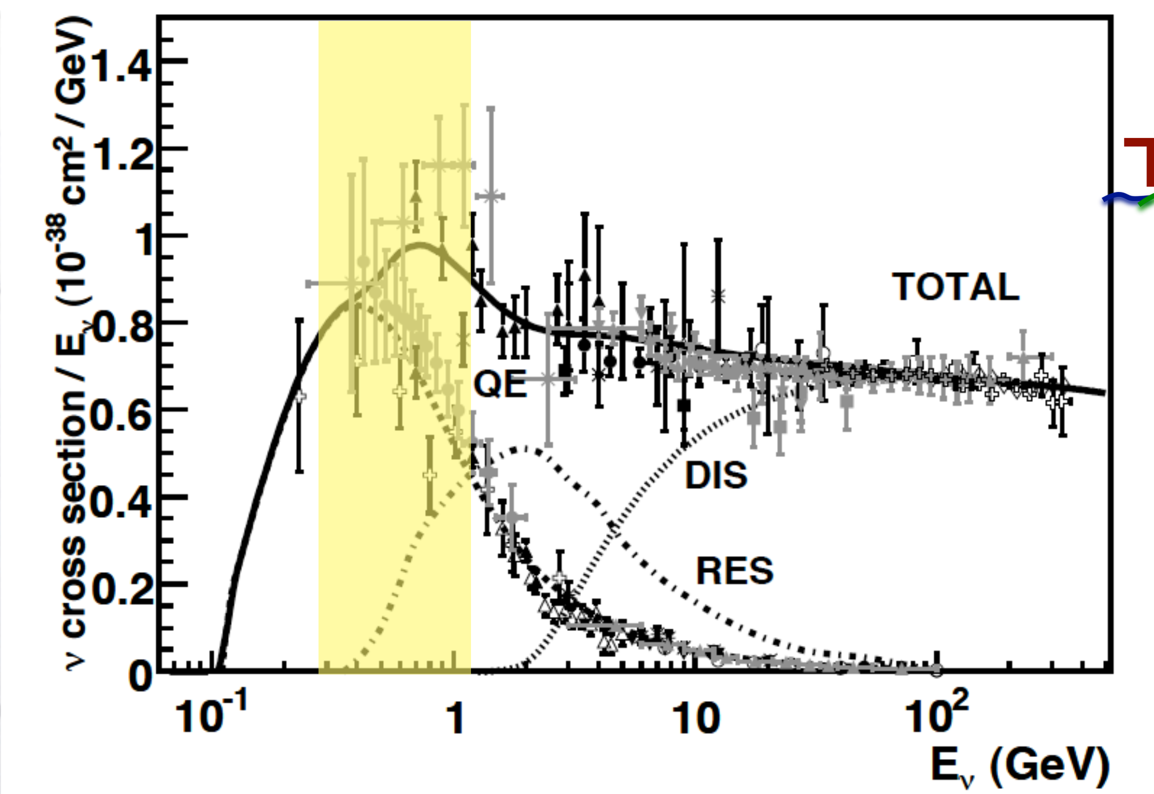


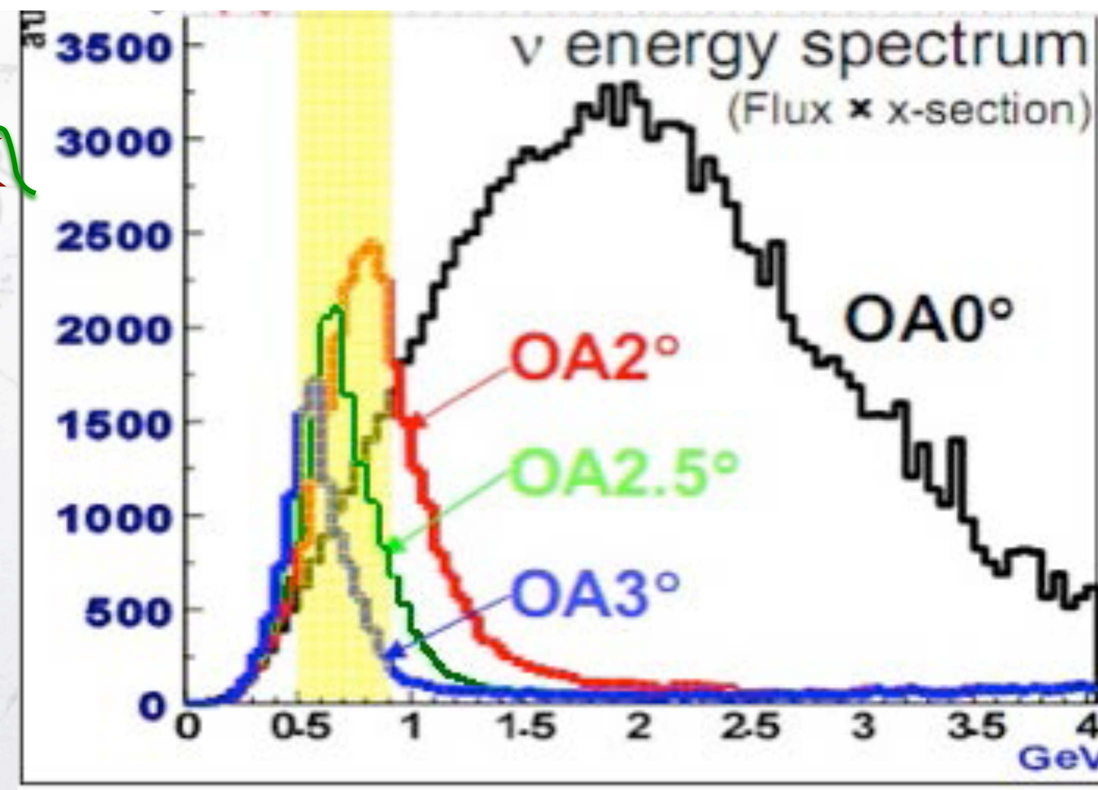
Off-axis concept

T2K runs 2.5° off-axis

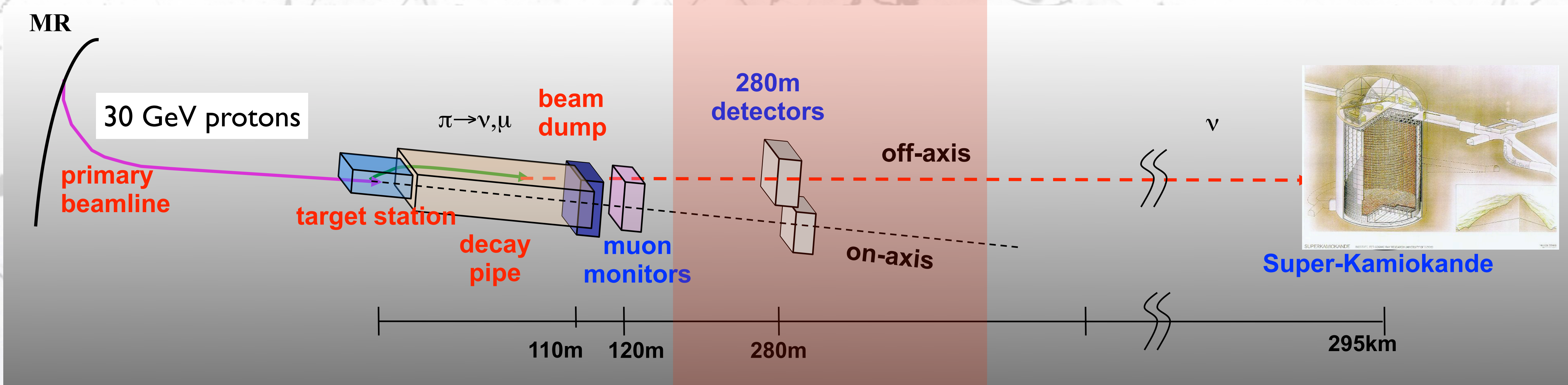


- off-axis reduces the high energy contamination ($NC\pi^0$ and non-CCQE backgrounds.)





Near detector

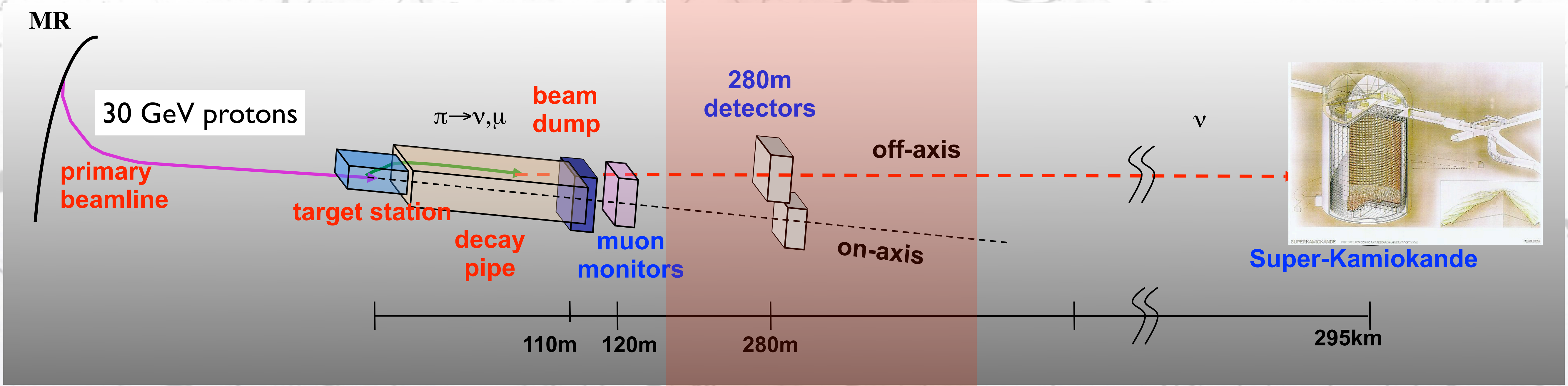


Beam

ND280

Super-Kamiokande

Near detector

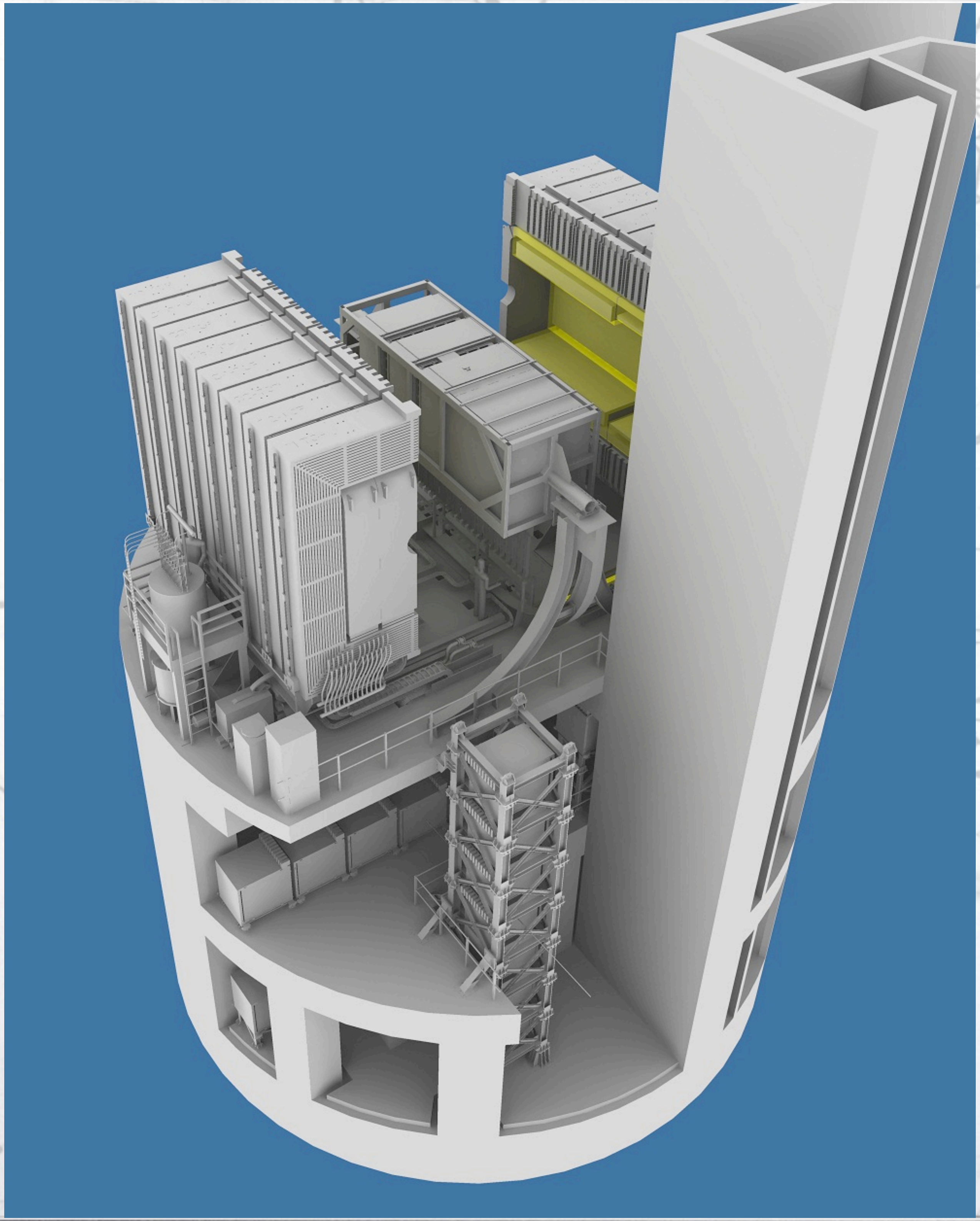


Beam ND280 Super-Kamiokande

Near detectors

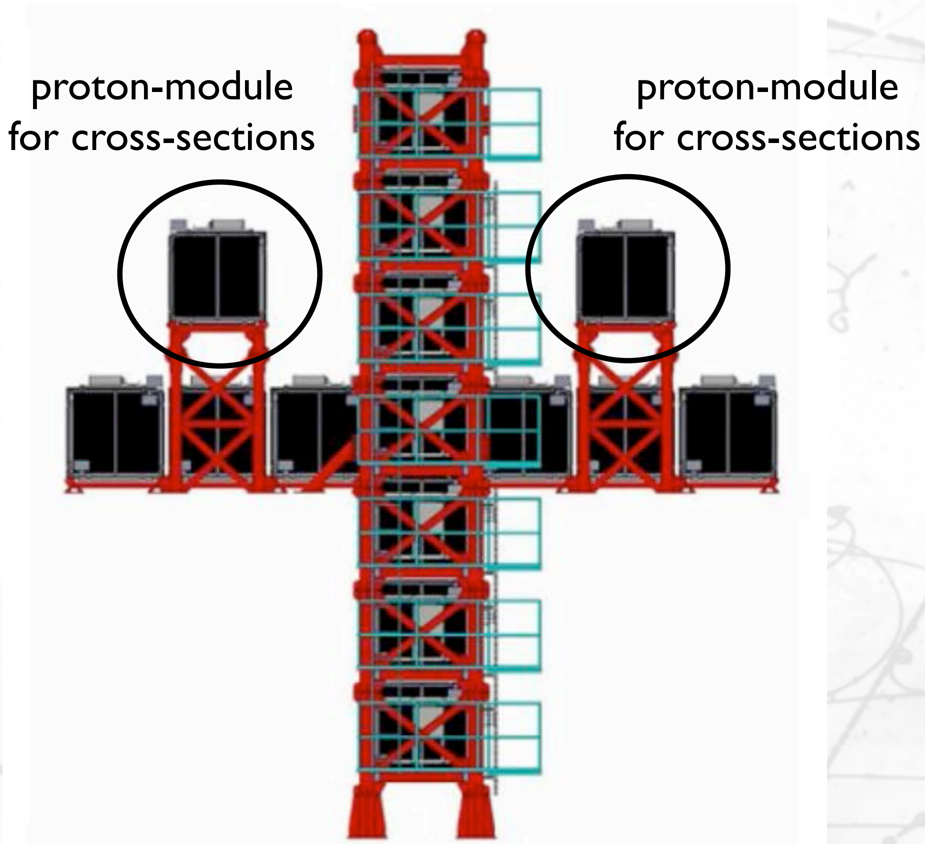
- The long base line near detectors have four functionalities:
  - Tuning of the neutrino flux: neutrino flux constrain.
  - Systematic studies on neutrino cross-sections.
  - Beam stability measurements with neutrinos.
  - Measure backgrounds: intrinsic ν_e and π^0
- And additional physics cases:
  - neutrino cross-sections.
  - search for sterile neutrinos in short base lines.
  - Lorentz violation studies.
  - Search for heavy neutrinos….

ND280 T2K

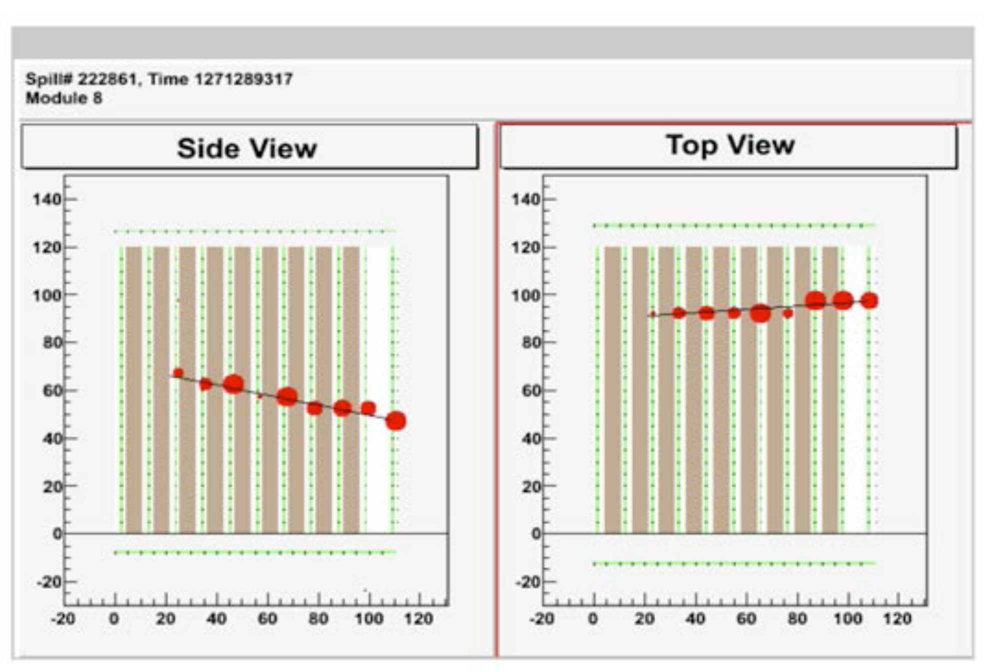


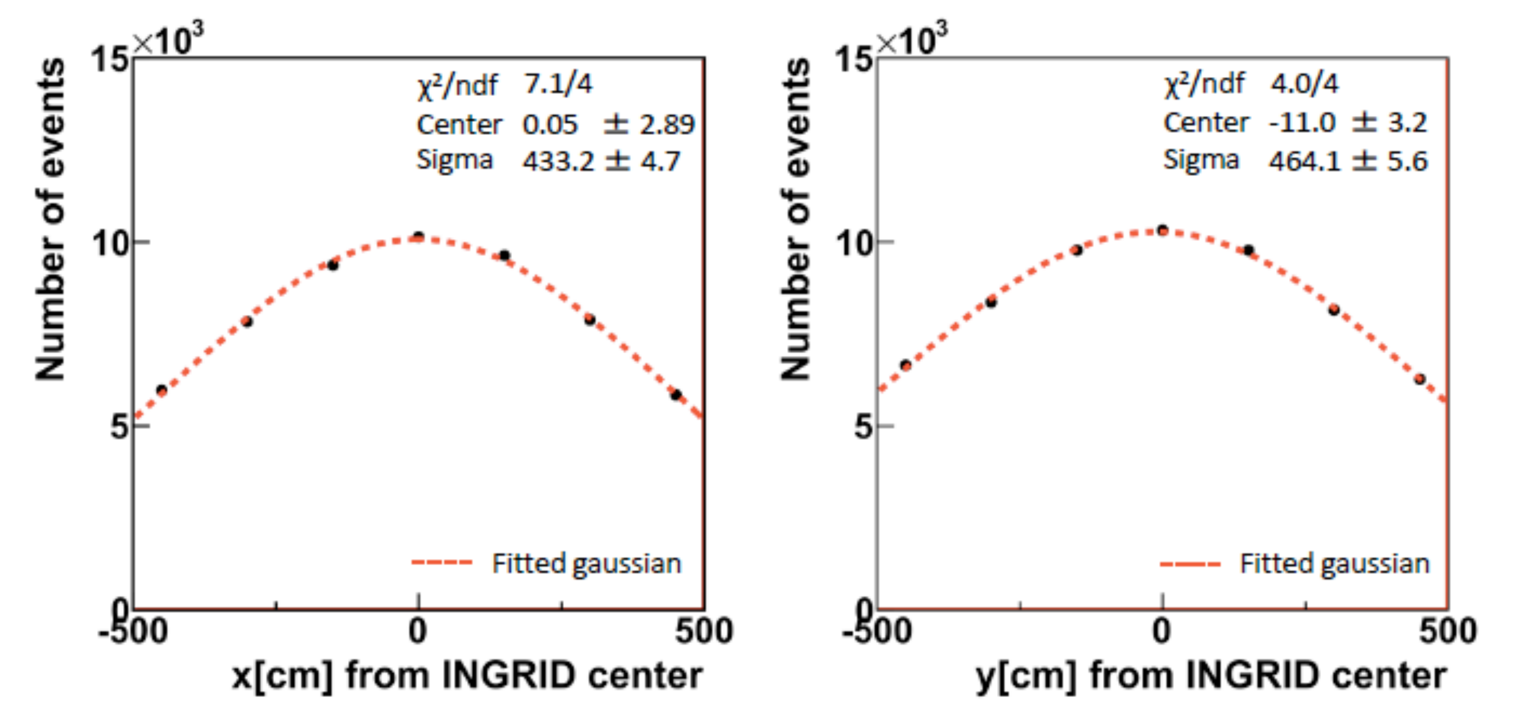
- ND280 is the near detector facility with two main detectors located 280m from the proton interaction point:
  - On-axis INGRID.
  - Off-axis ND280m.
- Three main purposes:
  - ν beam stability.
  - ν cross-sections.
  - ν beam flux constraint.

On-axis (INGRID)

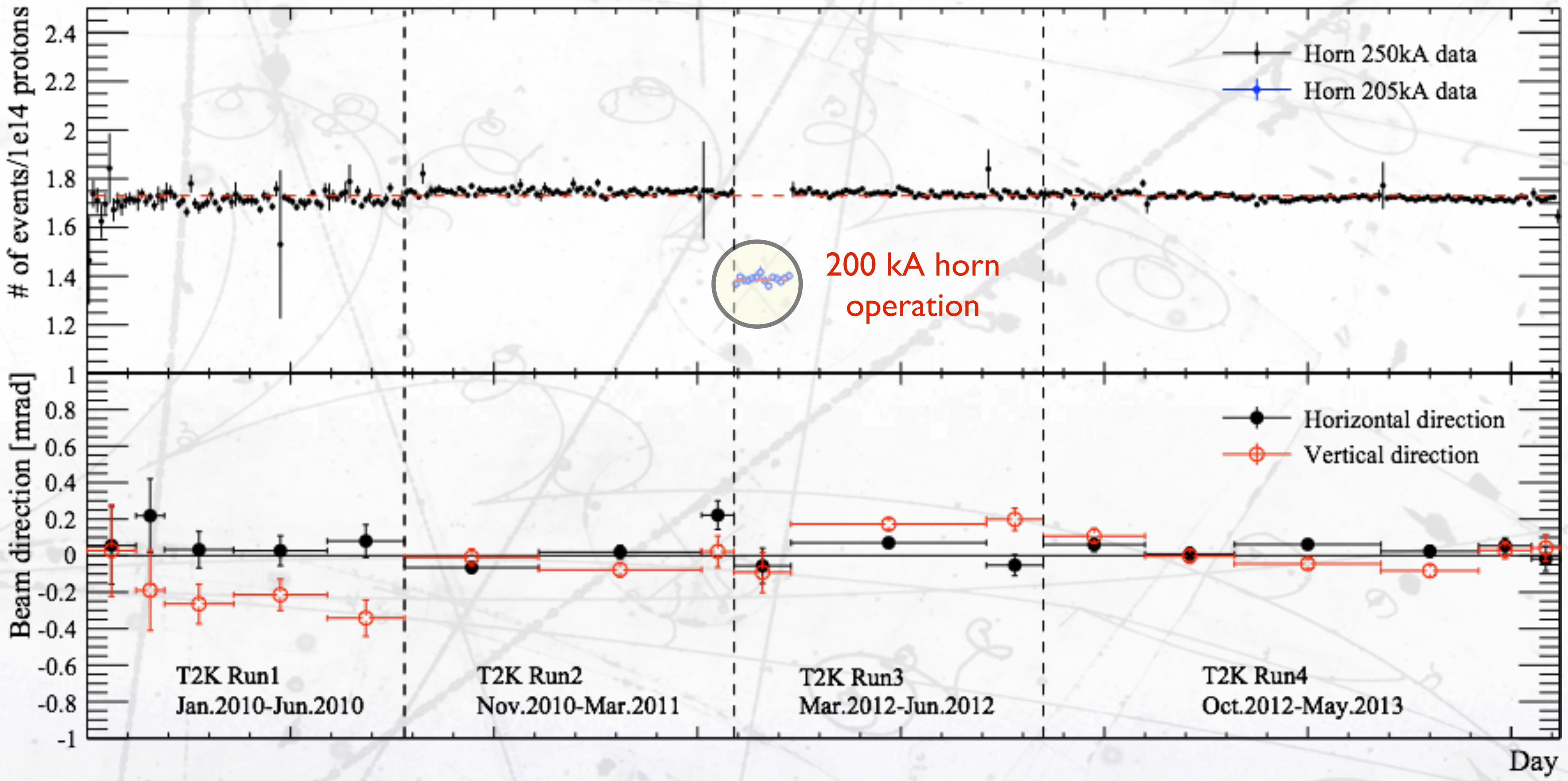


- INGRID counts ν CC events in a cross of 13 identical detectors:
  - total rate monitors beam intensity stability with respect to proton on target counting.
  - The relative event counts between modules monitor the beam direction stability.





On-axis: beam stability



Beam alignment and flux measured with neutrinos

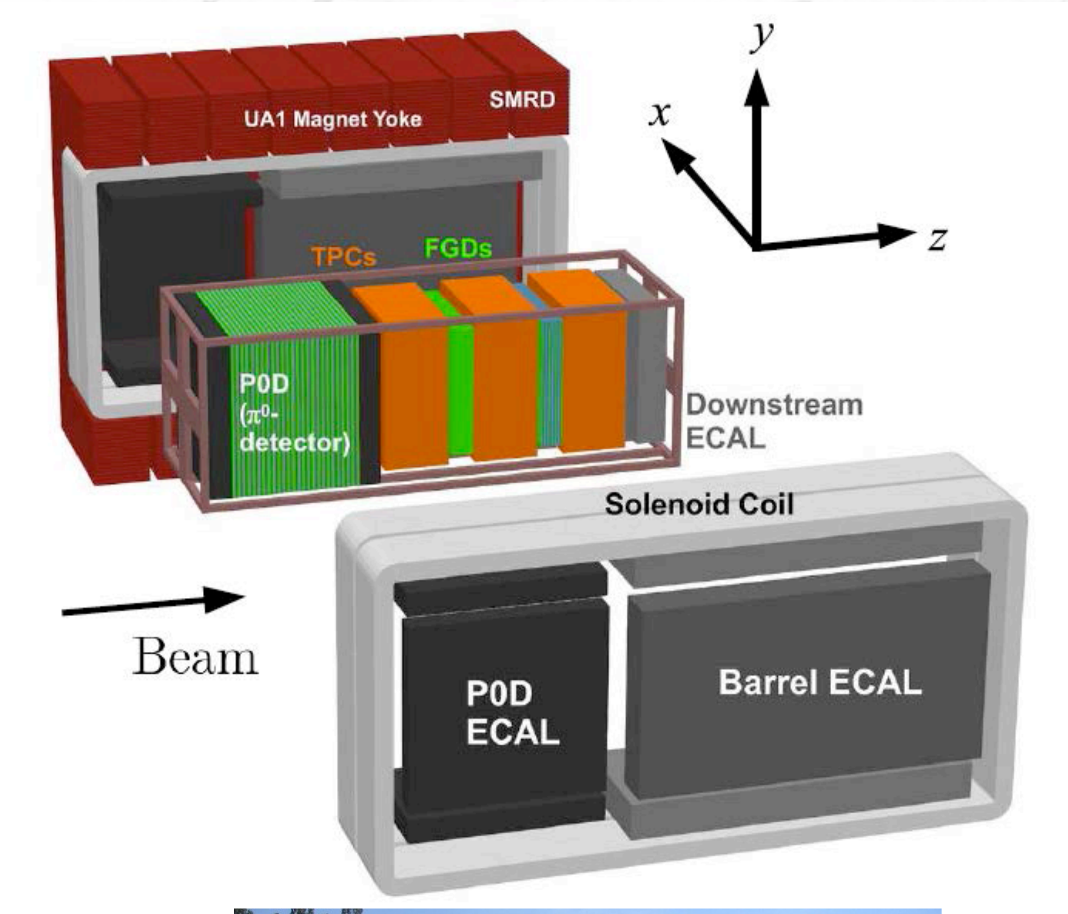
- Neutrino rate stable within 0.7%.
- Beam direction variation << 1 mrad.

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.

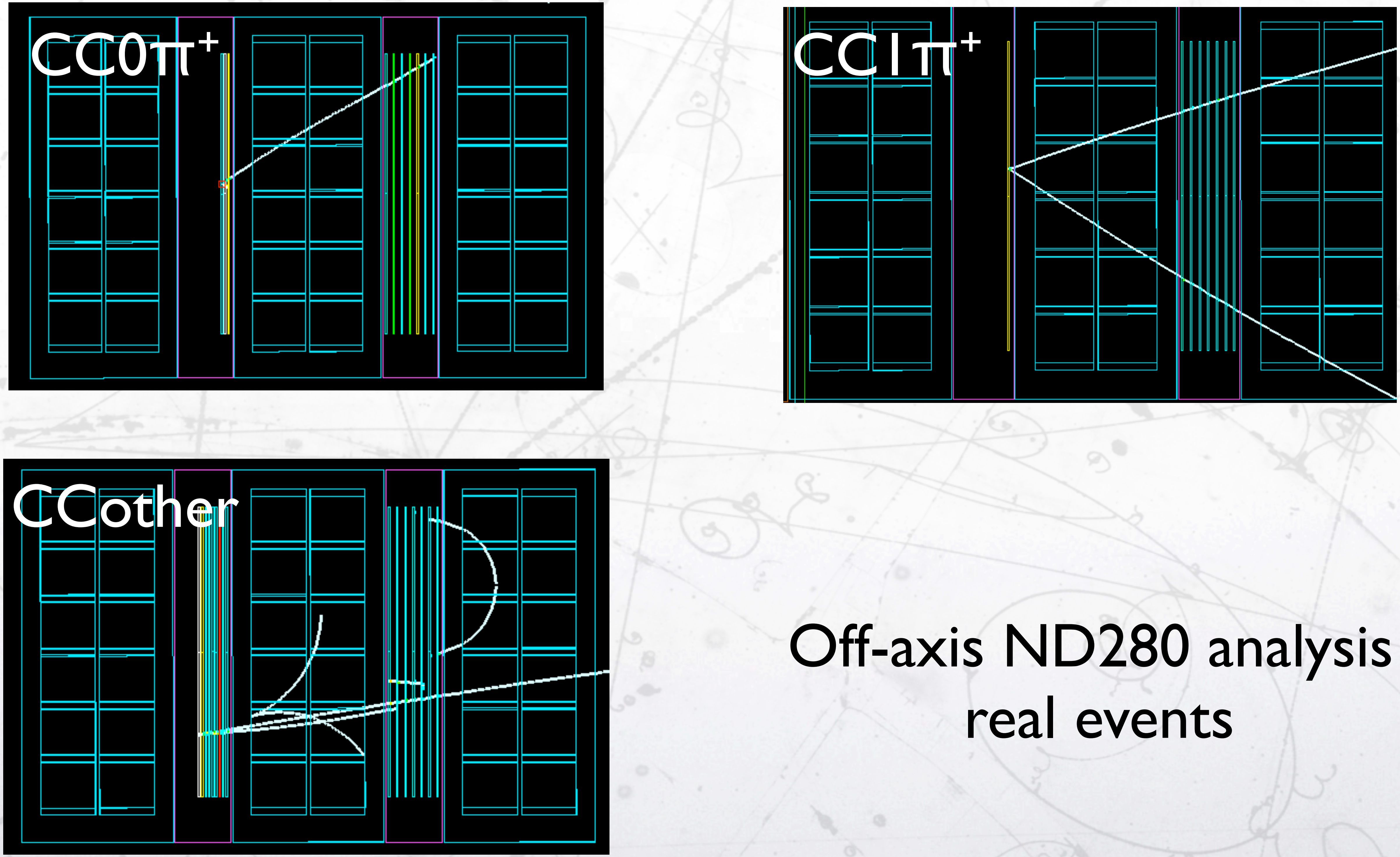
- Specific π^0 detector (P0D) made of water, CH and brass optimised for NC π^0 measurement.

Magnet was granted by CERN



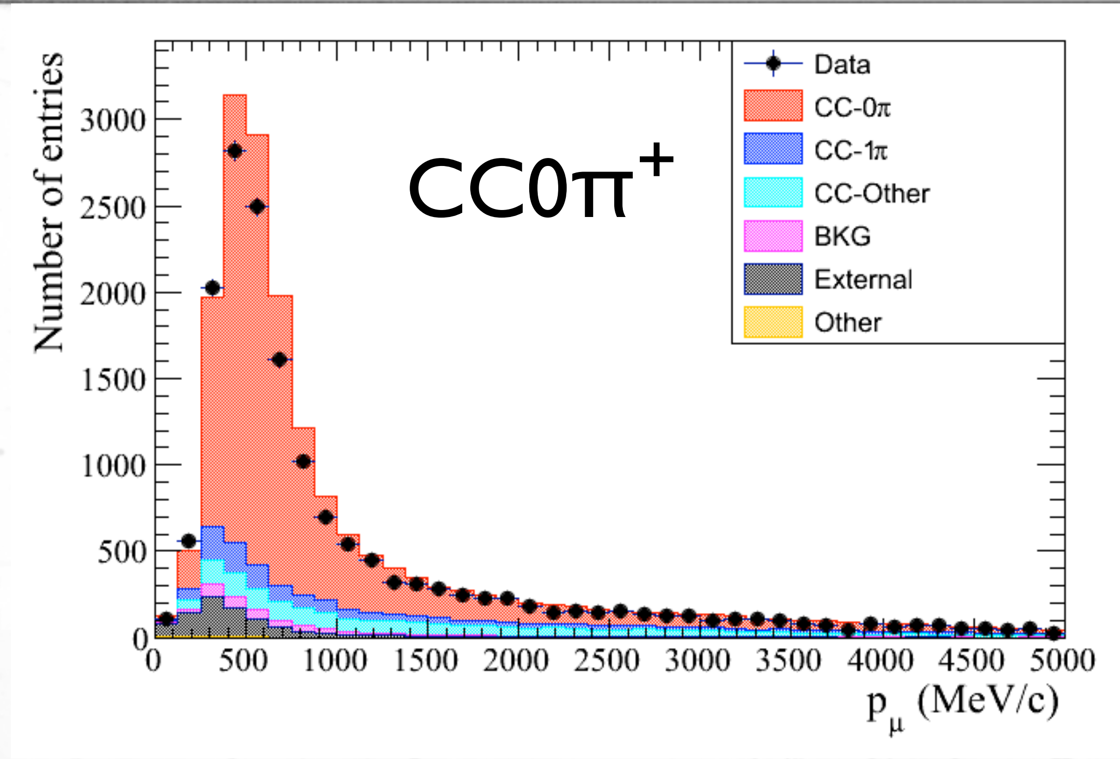
Magnet @ CERN Prévessin

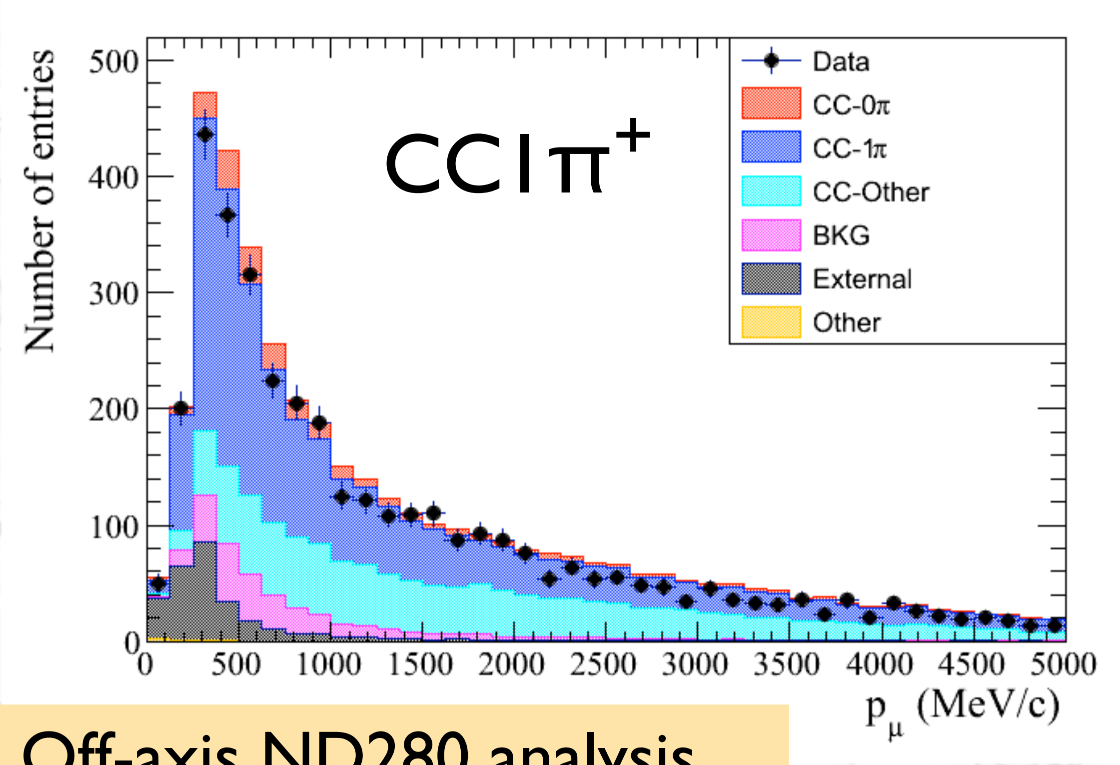
Off-axis: ν_μ analysis

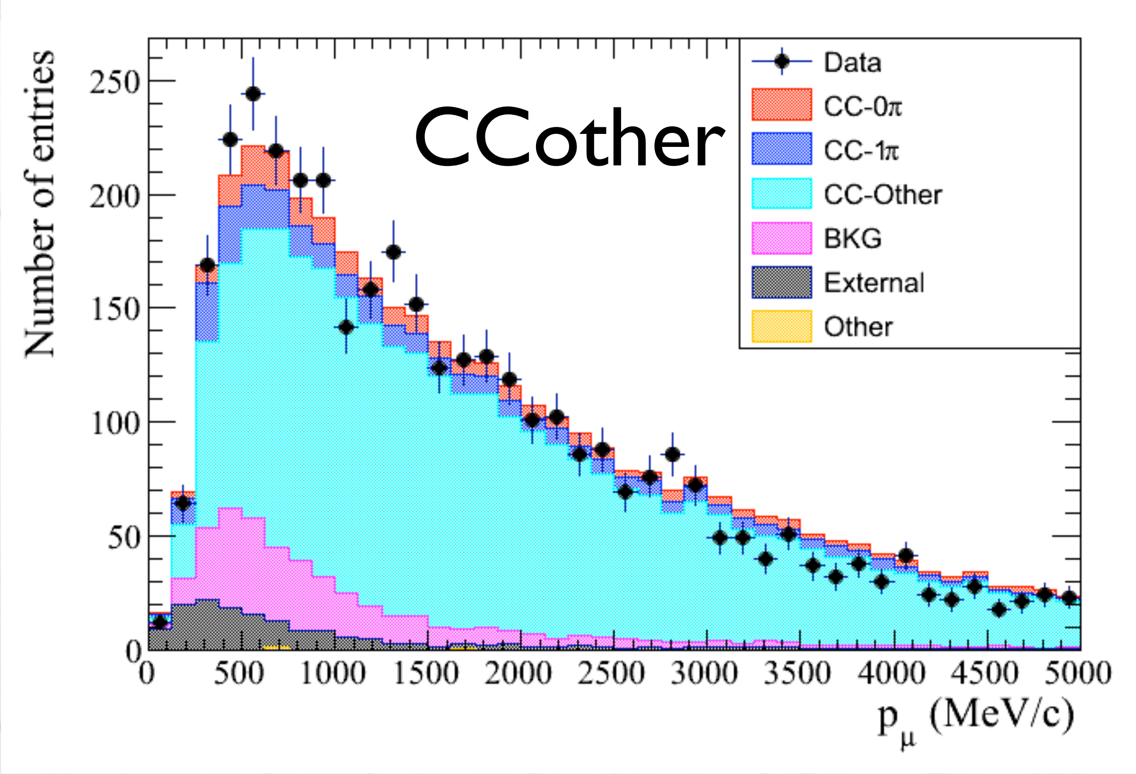


Off-axis ND280 analysis
real events

Off-axis: ν_μ analysis





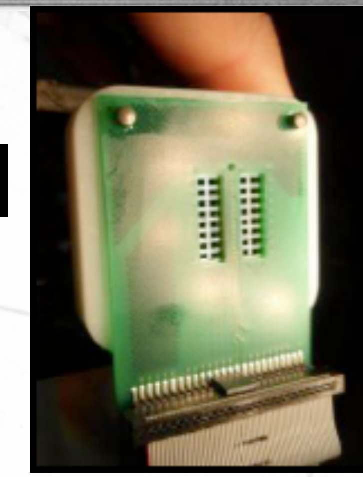


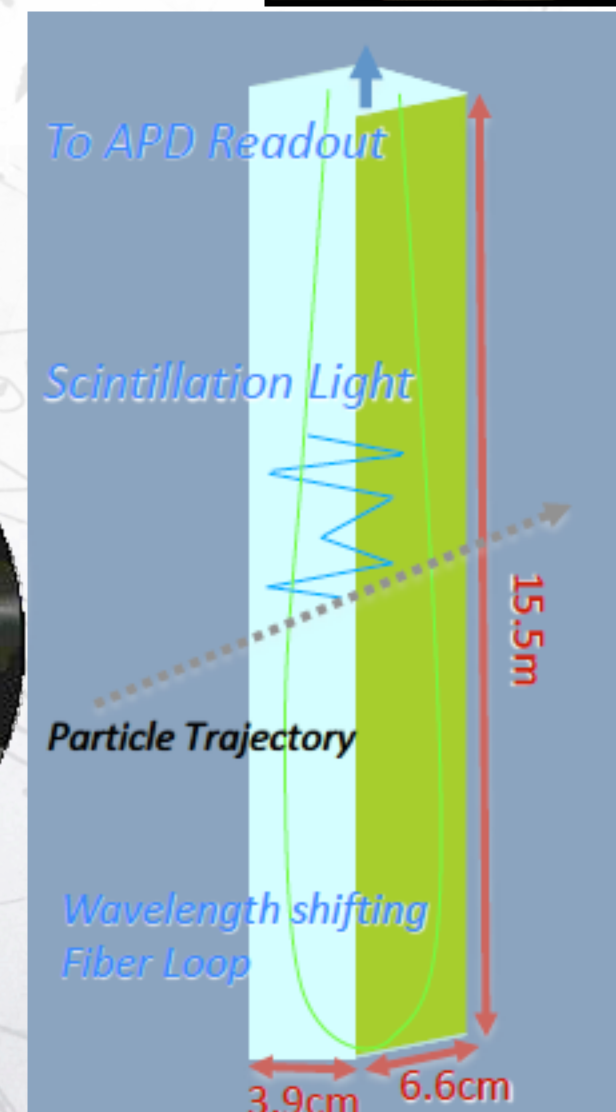
Off-axis ND280 analysis

	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%	

Nova near detector

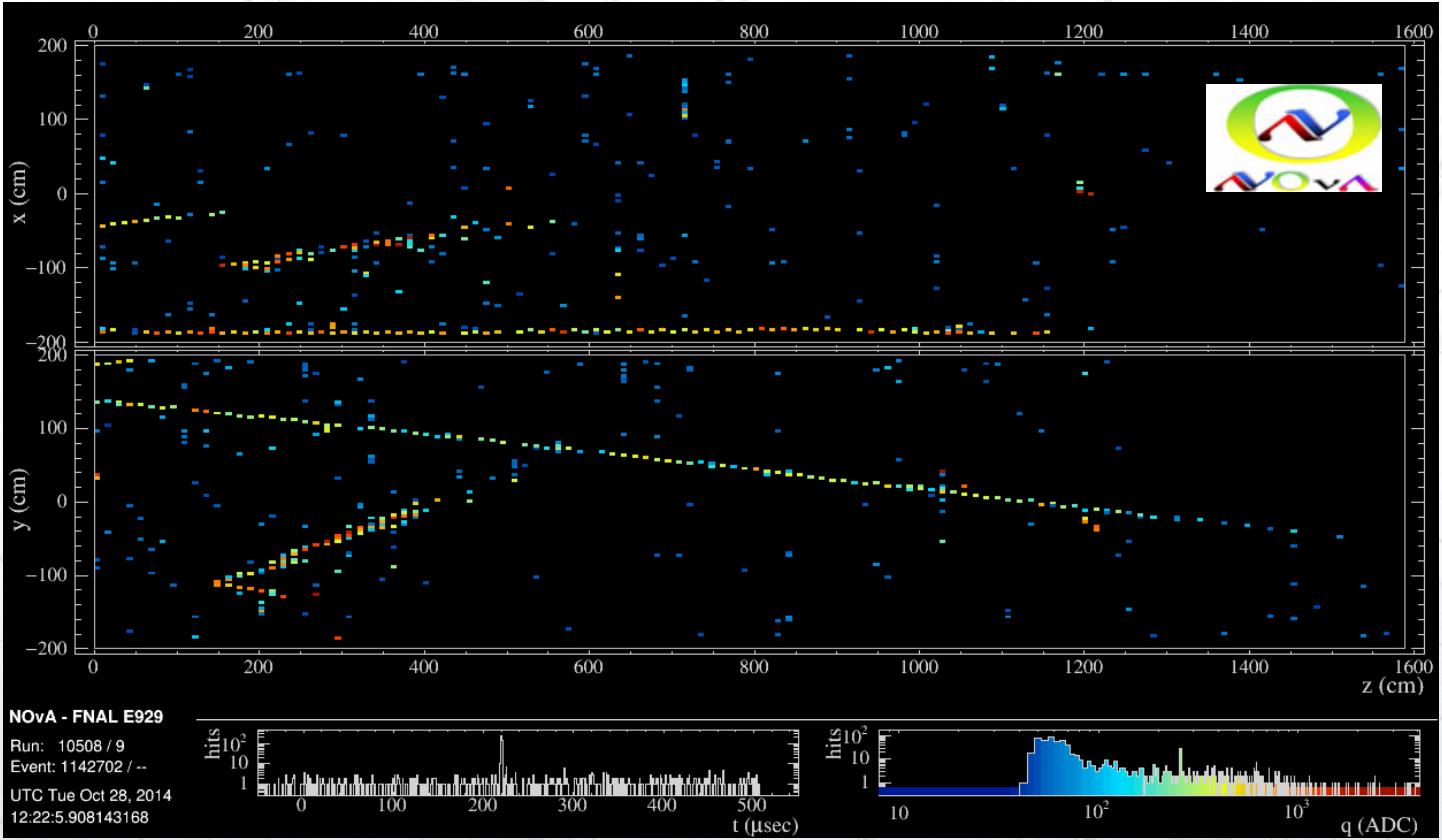
32 pixel APD



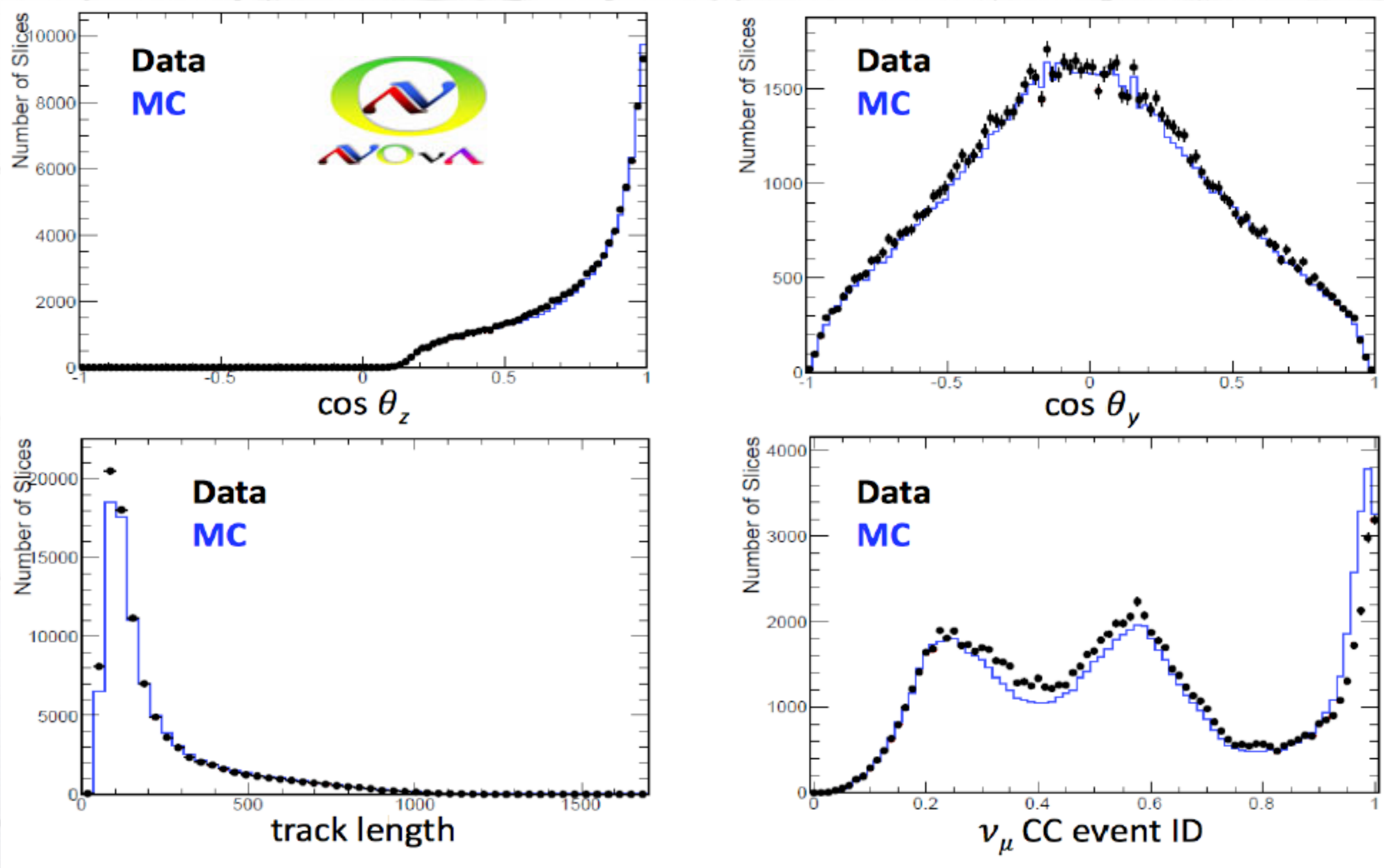


Extruded plastic (PVC) filled with liquid scintillator

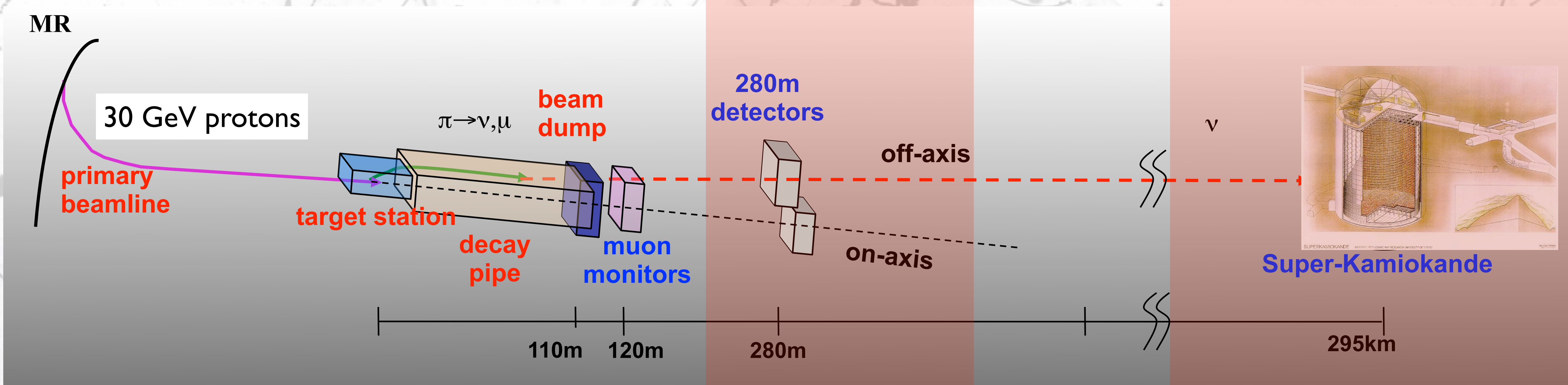
Nova near detector



Nova near detector



Cross sections

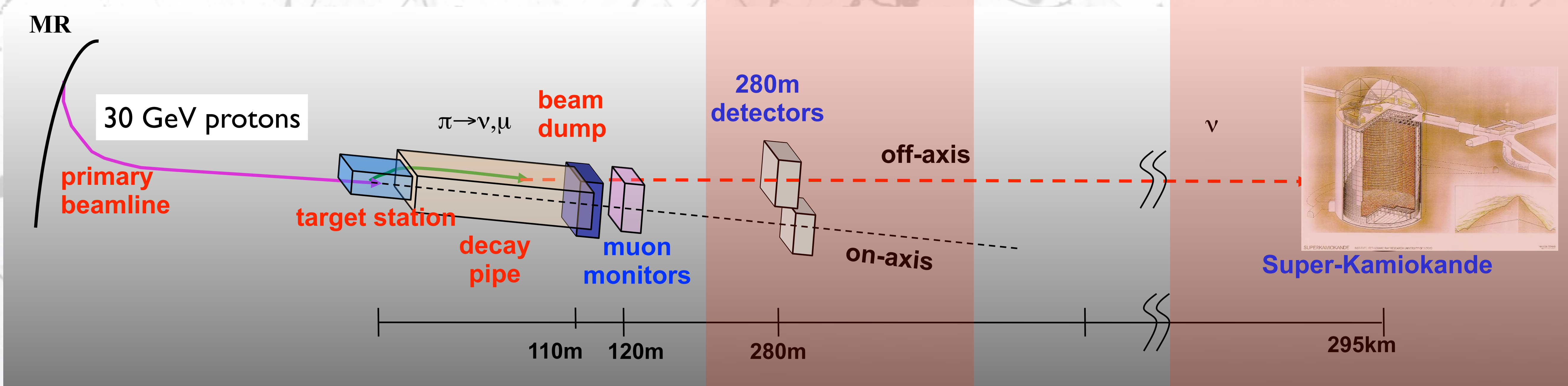


Beam

ND280

Super-Kamiokande

Cross sections



Beam

ND280

Super-Kamiokande

Cross-section problem

- The flux calculation depends on the cross-section:

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

- This is not so critical if we can define the energy of the neutrino, because the correlation is equal at the far detector

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

- and it cancels out in the ratio.

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

Cross-section problem

- But, the neutrino energy is not monochromatic. We need to determine event by event the energy of the neutrino.
- This estimation is not perfect, we have the problem that the cross-section does not cancels out in the ratio.

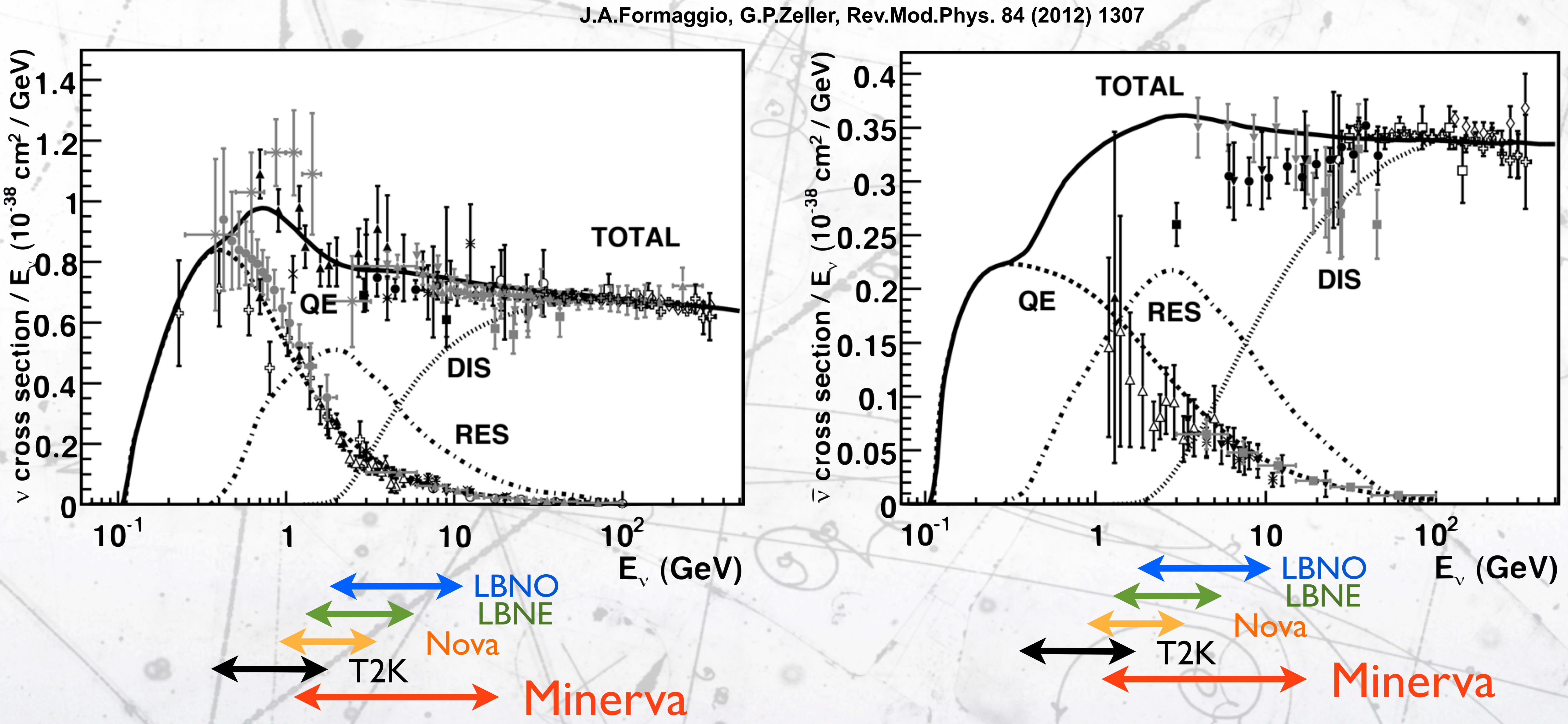
$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- La misma oscilación de neutrinos introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

Oscillation experiments require to know both $\sigma(E_\nu)$ & $P(E_\nu|E'_\nu)$

Both are related to cross-sections

The problem



- Present and future oscillation experiments cover a region full of reaction thresholds and sparse data.

The problem

Neutrino energy reconstruction

T2K

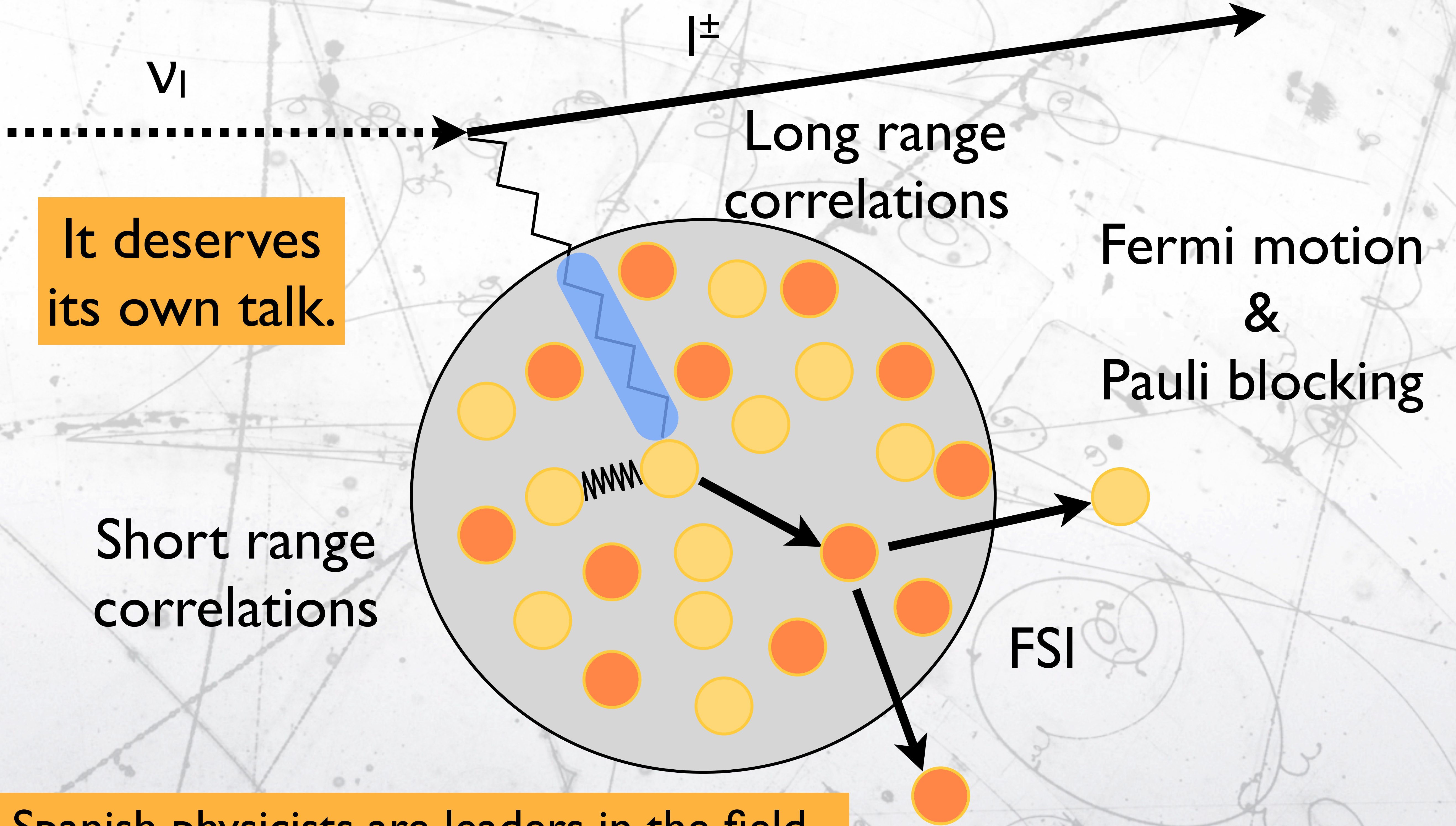
NOvA

Low Energy (≲2 GeV)

- E_ν relies on the lepton kinematics.
- channel identification is critical:
  - Final State Interactions
  - hadron kinematics.
- Fermi momentum, Pauli blocking and bound energy are relevant contributions.

Medium-high Energy (≳ 3 GeV)

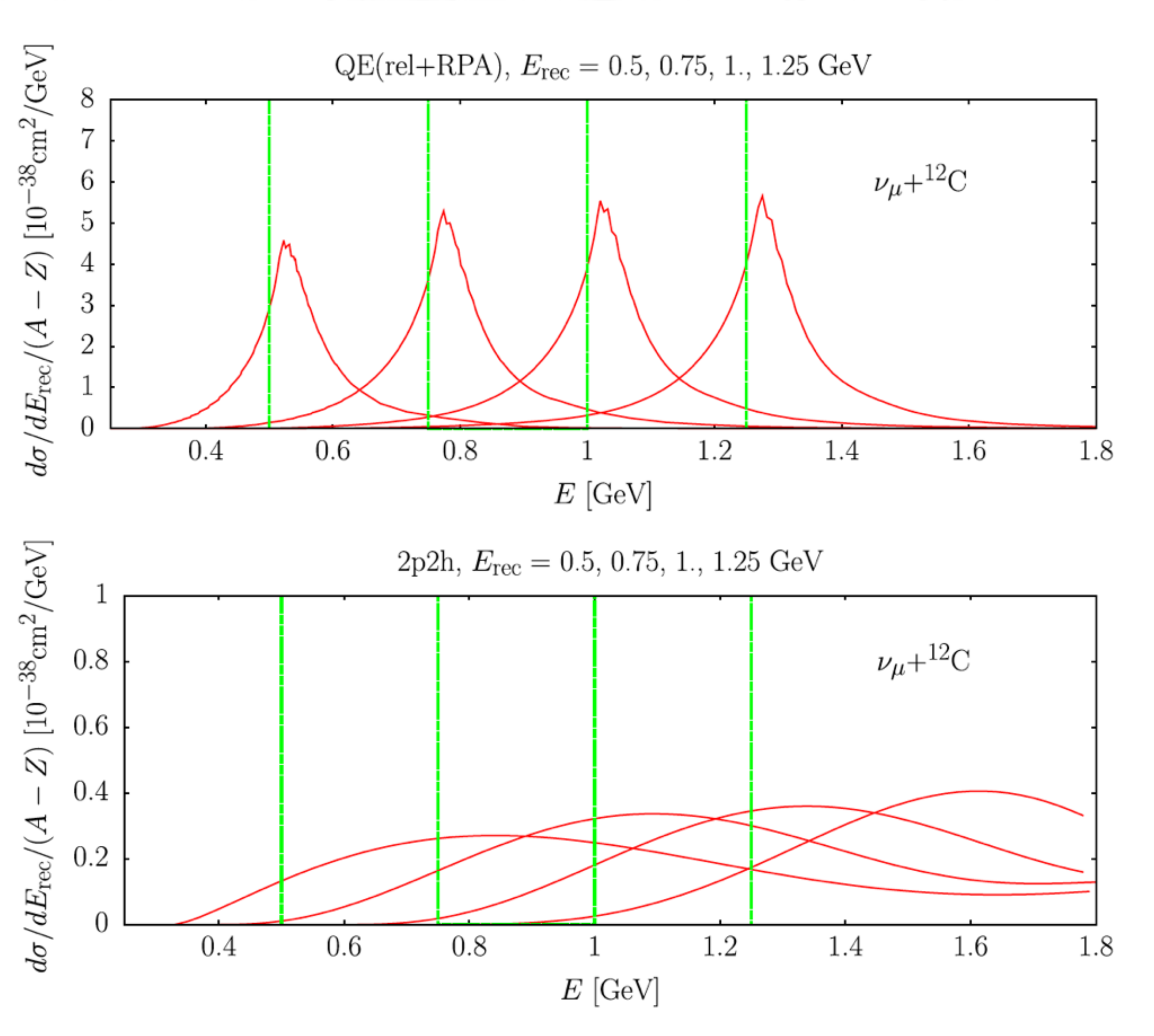
- $E_\nu = E_l + E_{had}$ with $E_{had} << E_l$
- Hadronic energy depends on modelling of DIS and high mass resonances.
- Hadronic energy depends on Final State Interactions.



It deserves its own talk.

Spanish physicists are leaders in the field.

One example: CCQE



PHYSICAL REVIEW D **85,** 113008 (2012)

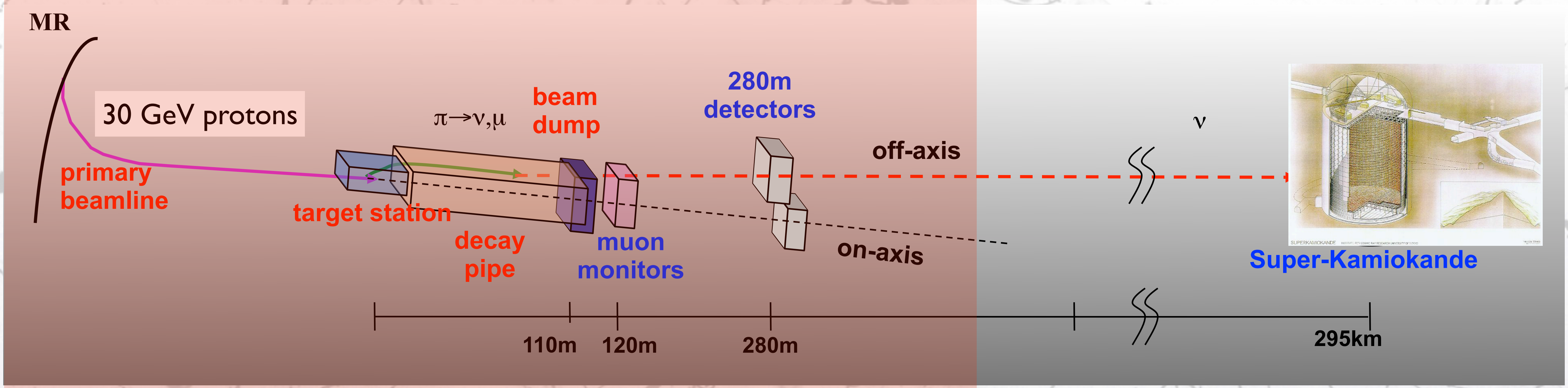
Effect of multi-nucleon (2p2h) interactions in the neutrino energy reconstruction.

- Recon values (E_ν)
- $P(E_\nu|E'_\nu)$

CCQE

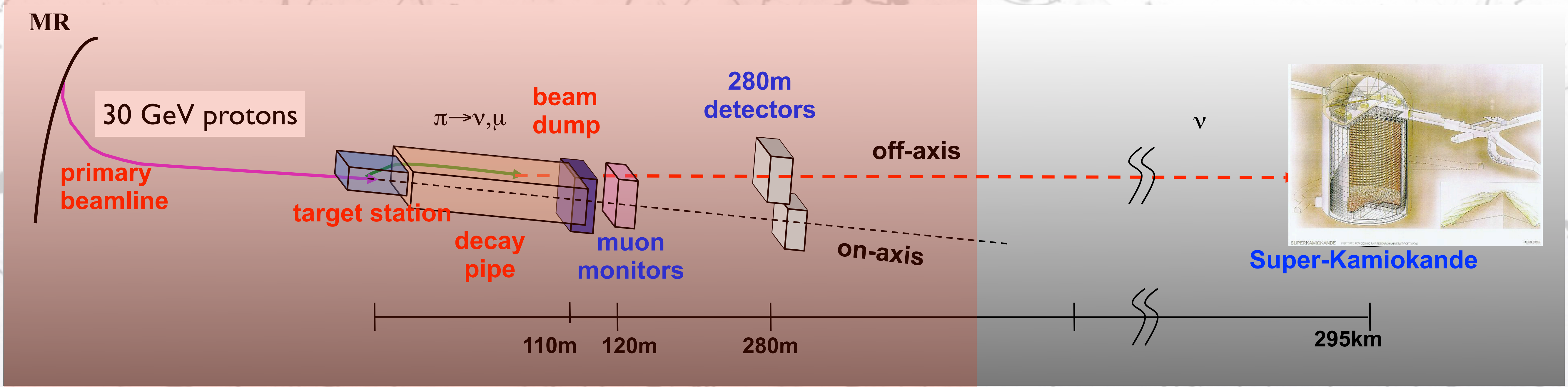
$$\nu_\mu n \rightarrow \mu^- p$$

Flux prediction



Beam ND280 Super-Kamiokande

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

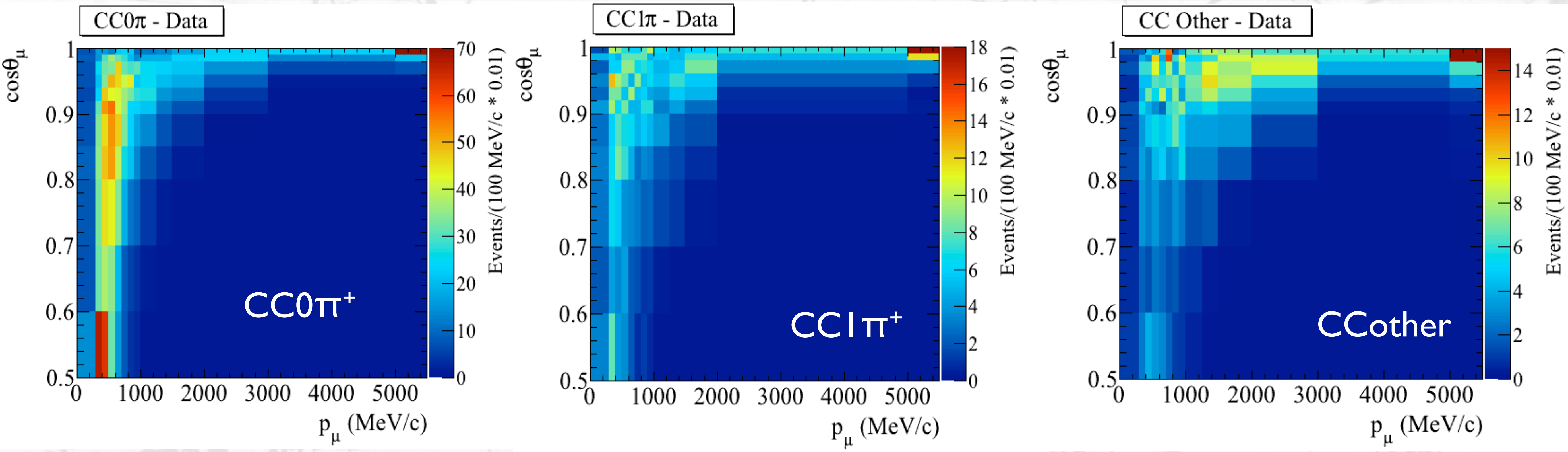
Neutrino Cross Section Model :

- 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 near detector 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 far detector flux parameters and subset of cross section parameters are used to predict far detector event rates

ND280 input data

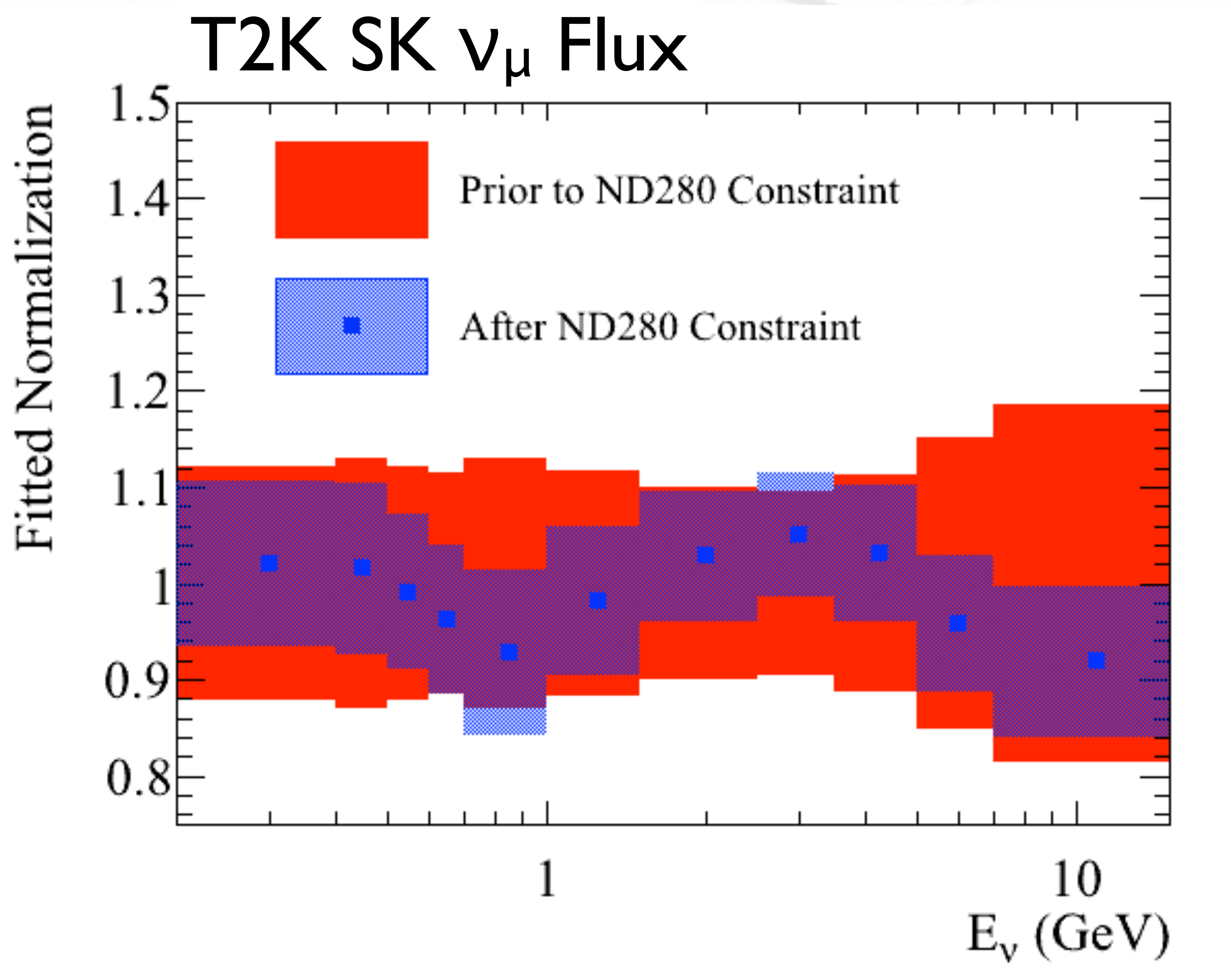


Data from T2K Runs 1-4: 5.9×10^{20} protons on target

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

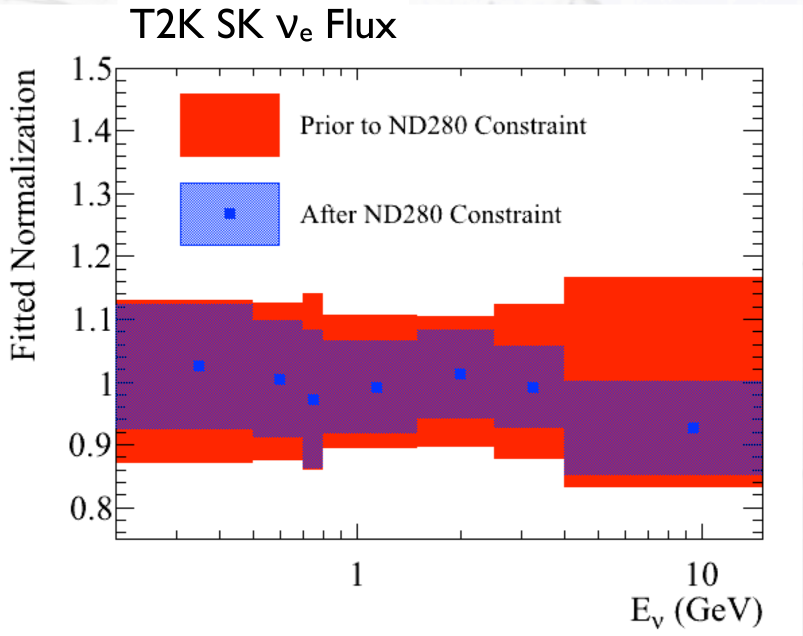
Data are binned in two dimensions: muon momentum (p) and angle (cosθ) preserving information on neutrino energy and interaction q^2

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

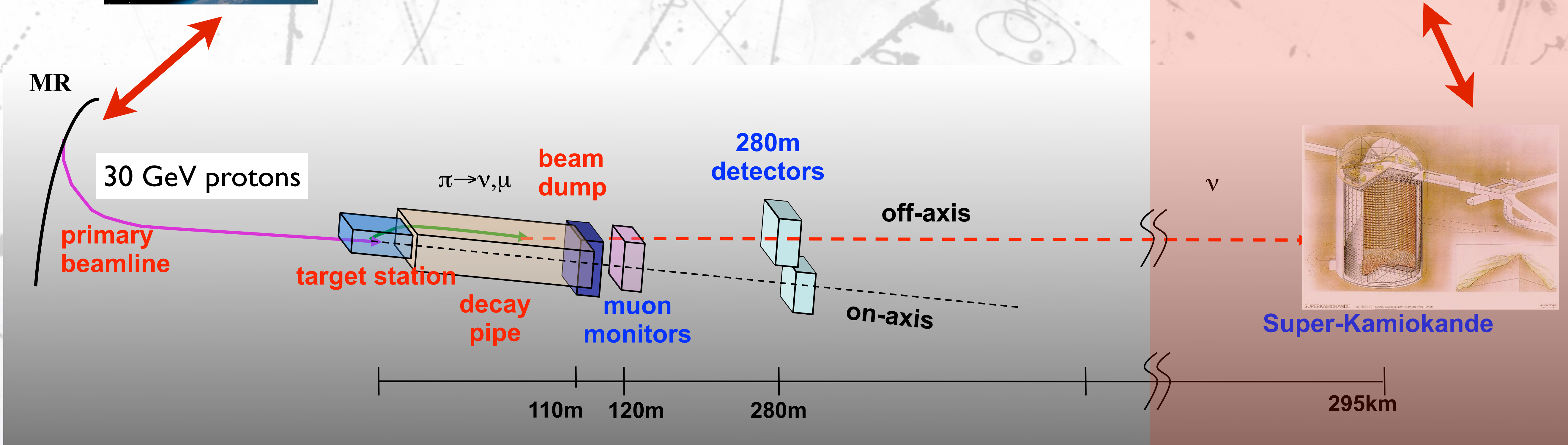


- T2K ν_μ and ν_e flux predictions are constrained by the fit.
- The cross-section parameters are also constrained.
- Plots show central values and error bands for normalisation parameters.

Far detector

GPS

GPS



Beam

ND280

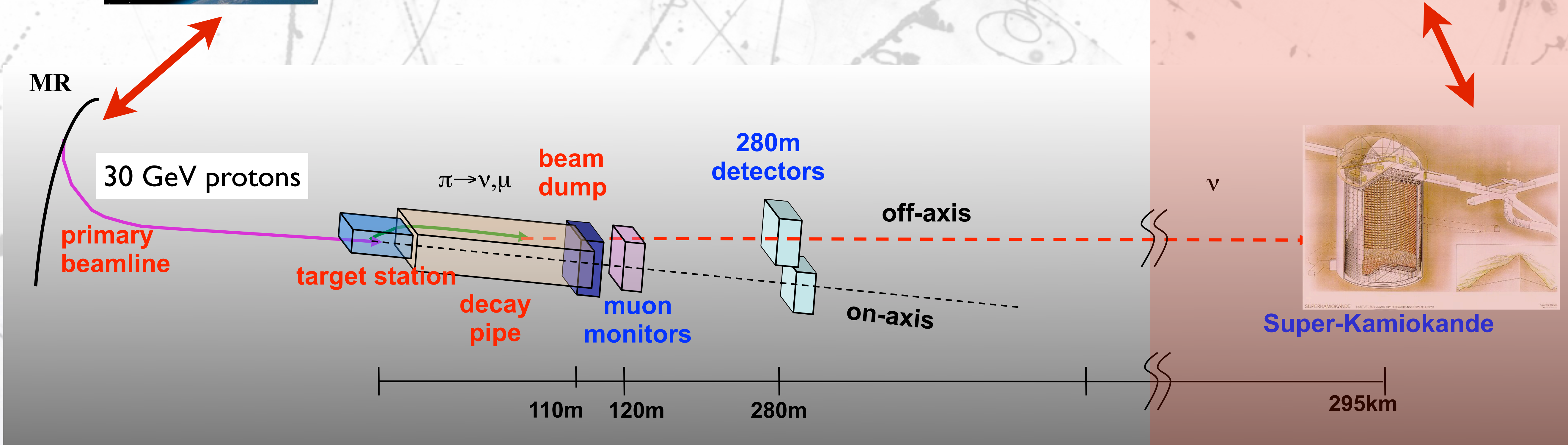
Super-Kamiokande

Concept

GPS

Far detector

GPS

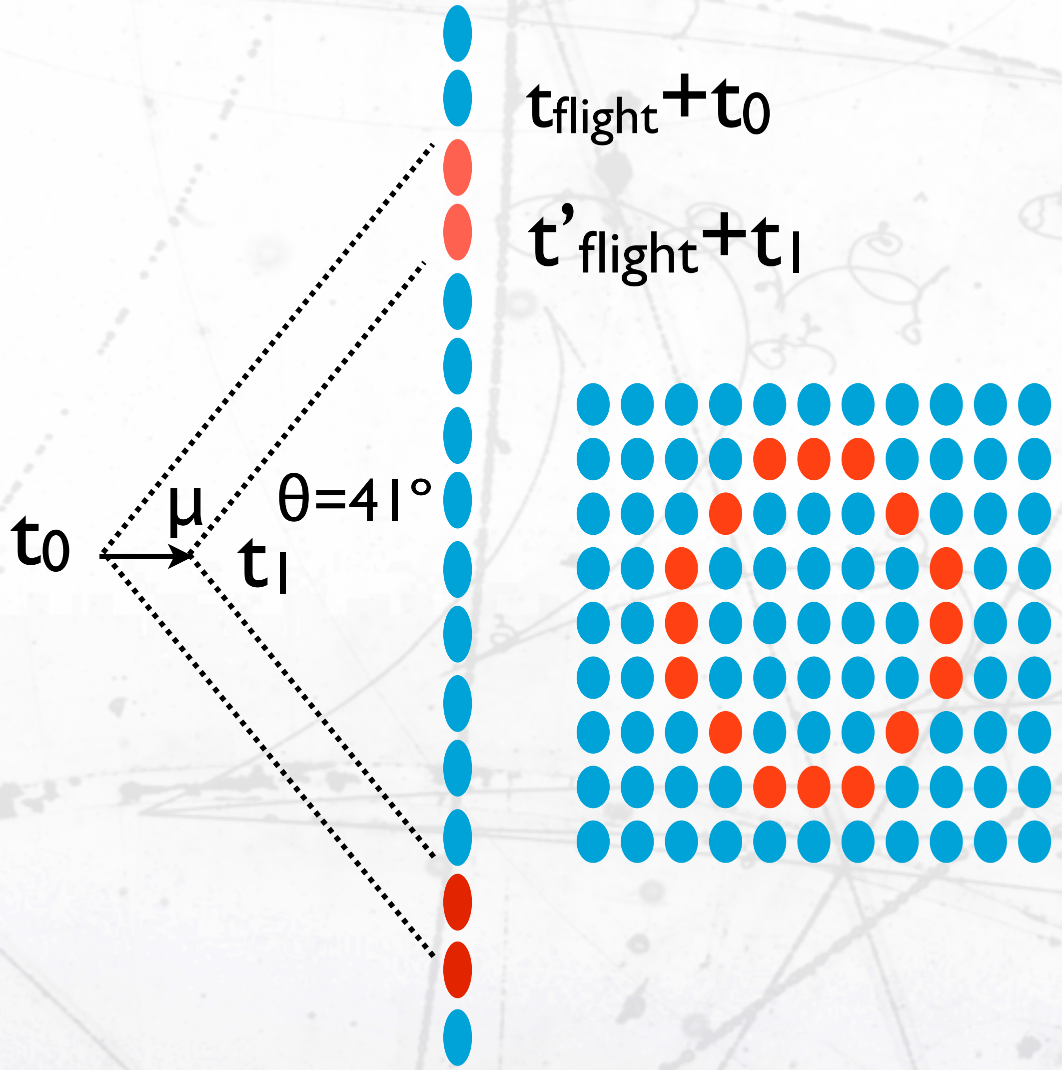


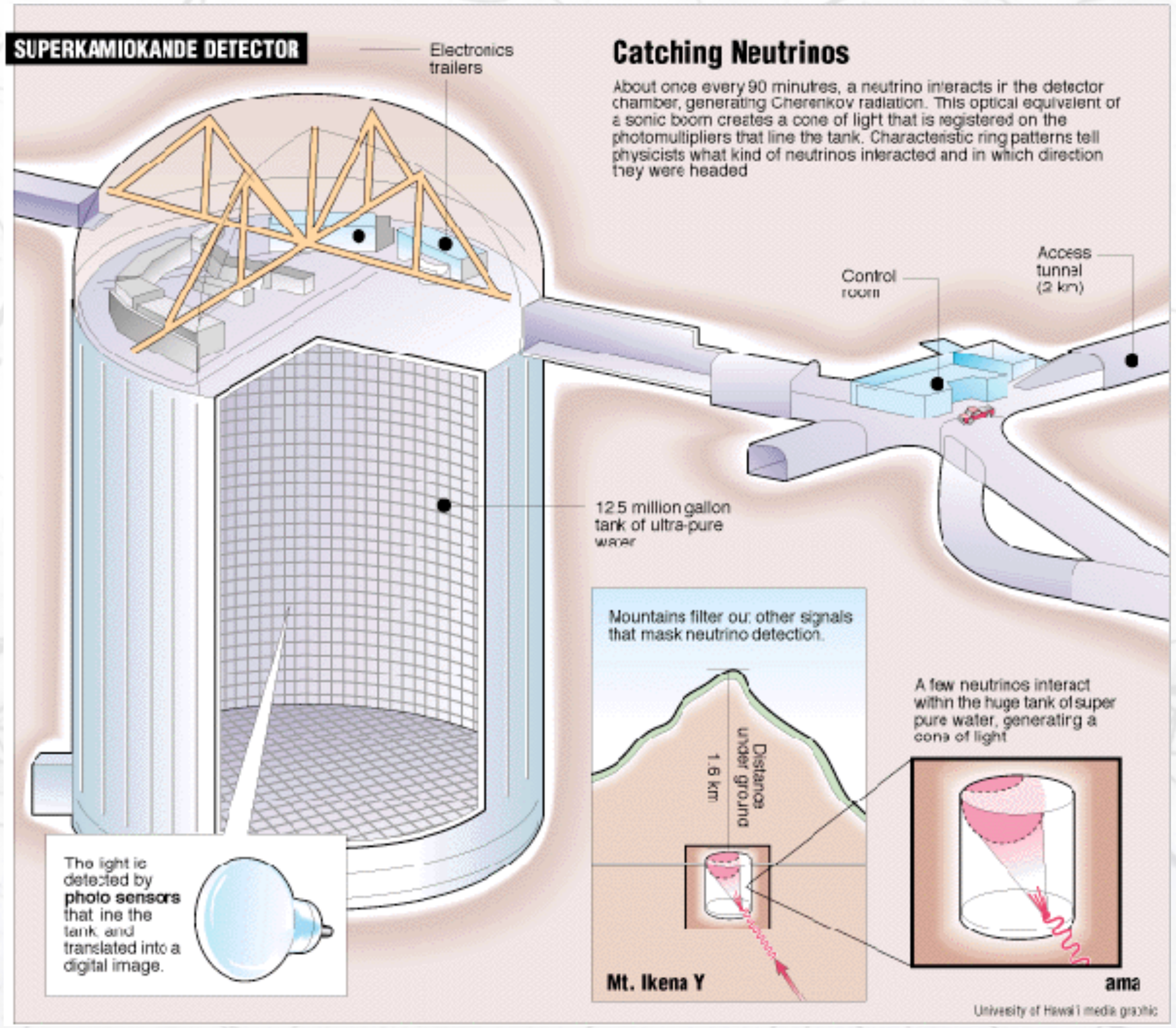
Beam

ND280

Super-Kamiokande

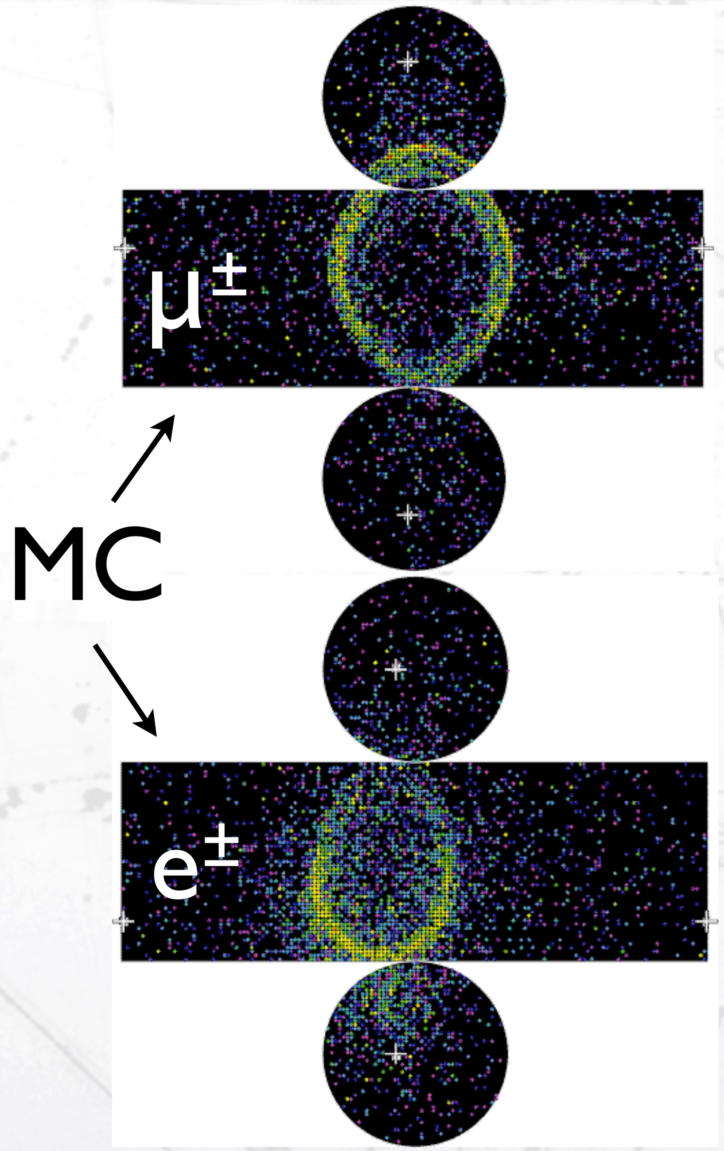
Super-Kamiokande

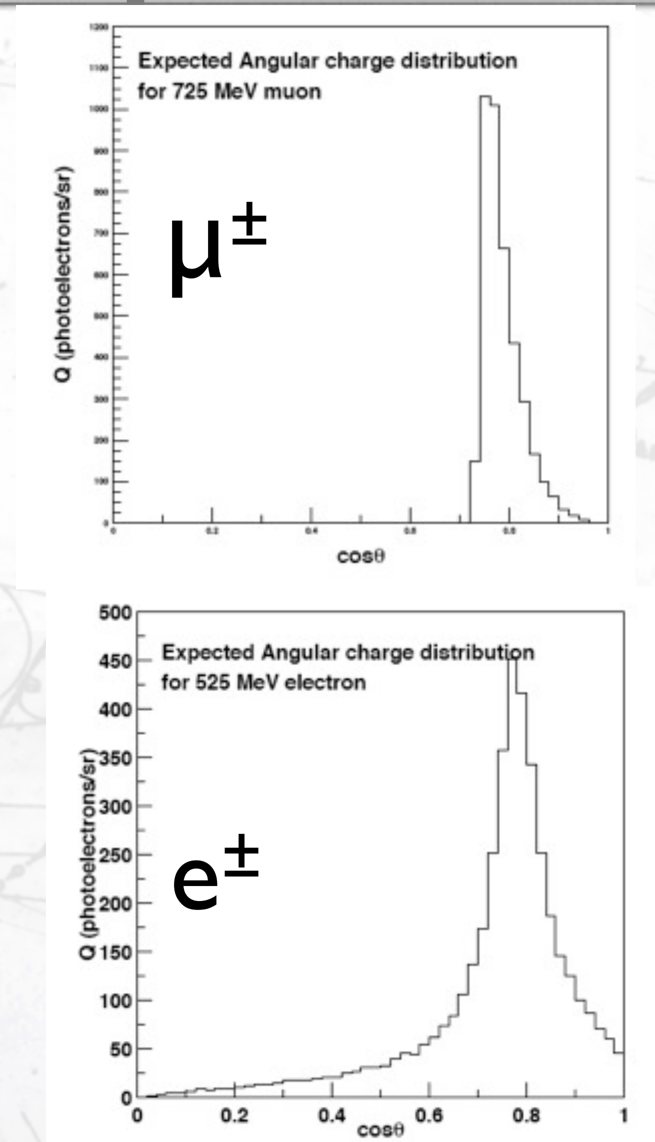




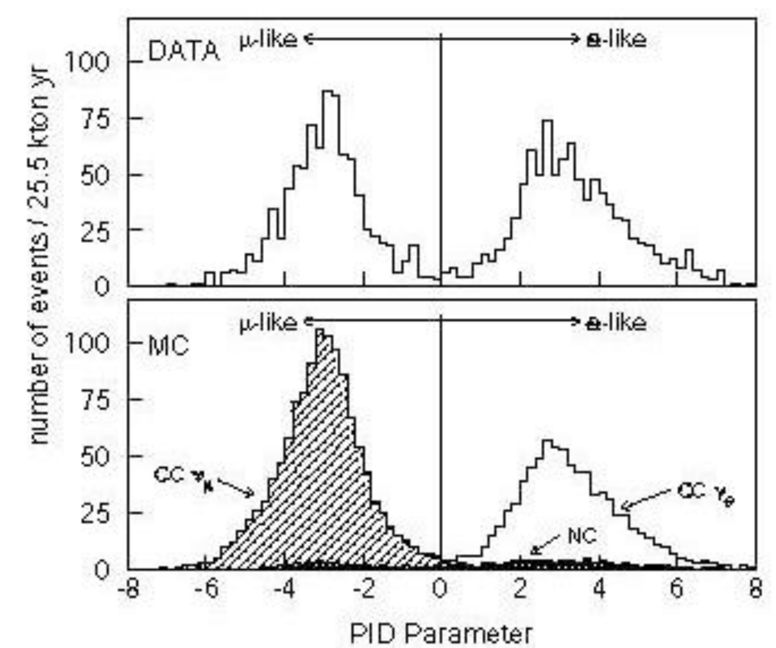
- 50 kTon water Cherenkov detector. (22.5 KTon fiducial).
- ~11 000 20" PMT inner detector.
- ~2000 8" PMT outer detector to veto external background.

SK: particle ID





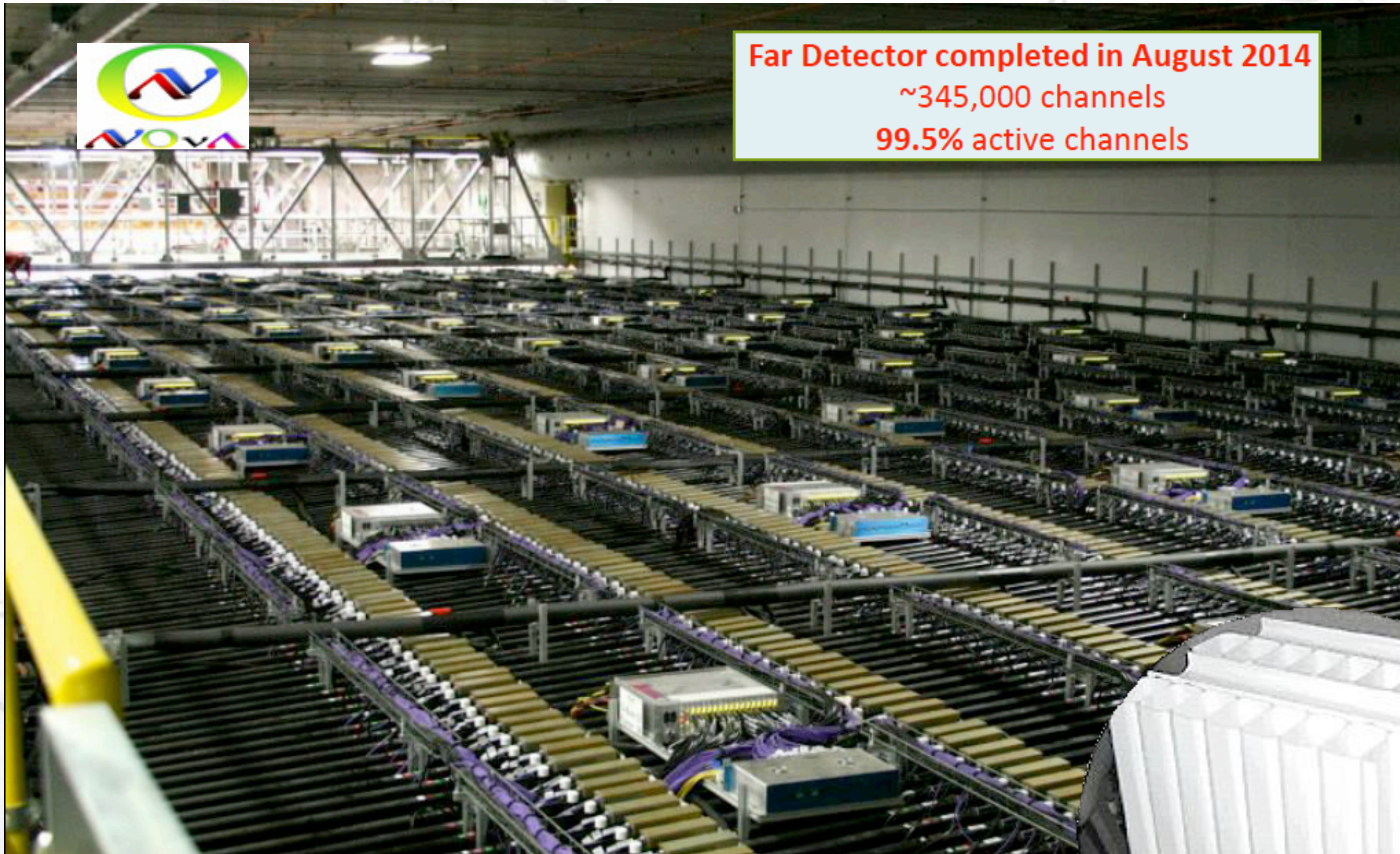
Likelihood PID



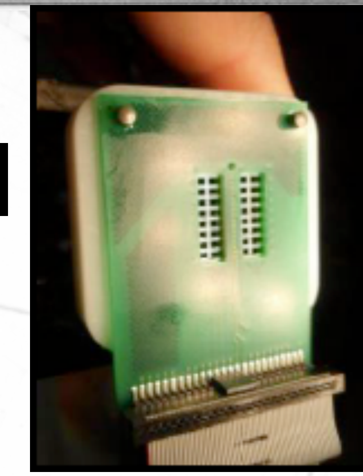
- The expected angular distribution of Cherenkov photons along the primary particle direction is different in electrons and muons:
- The electron is not sharp due to Multiple Scattering & showering.

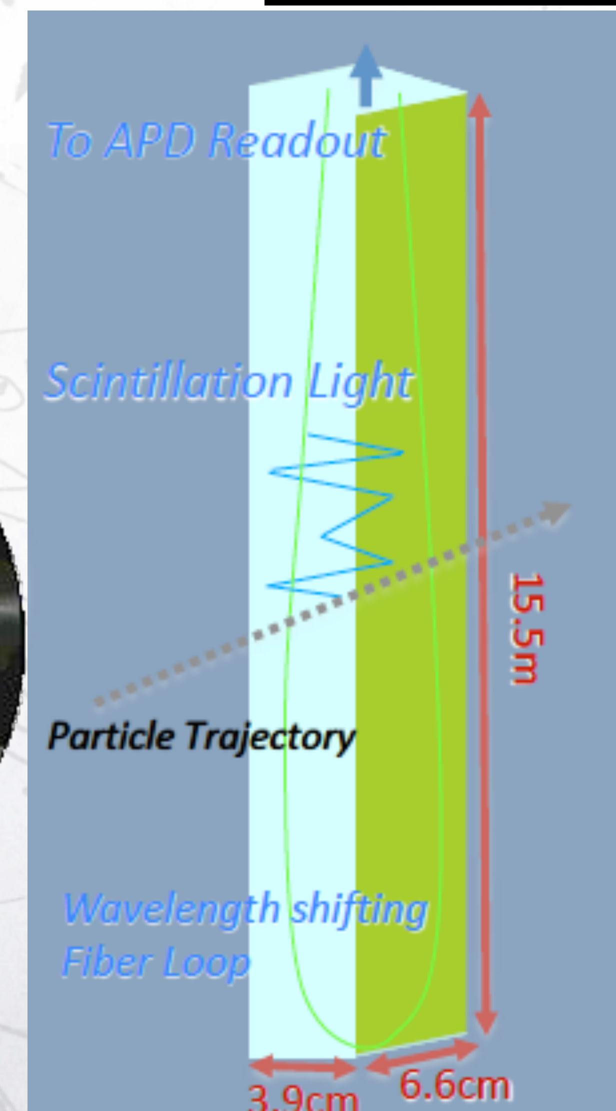
T2K

Nova detector



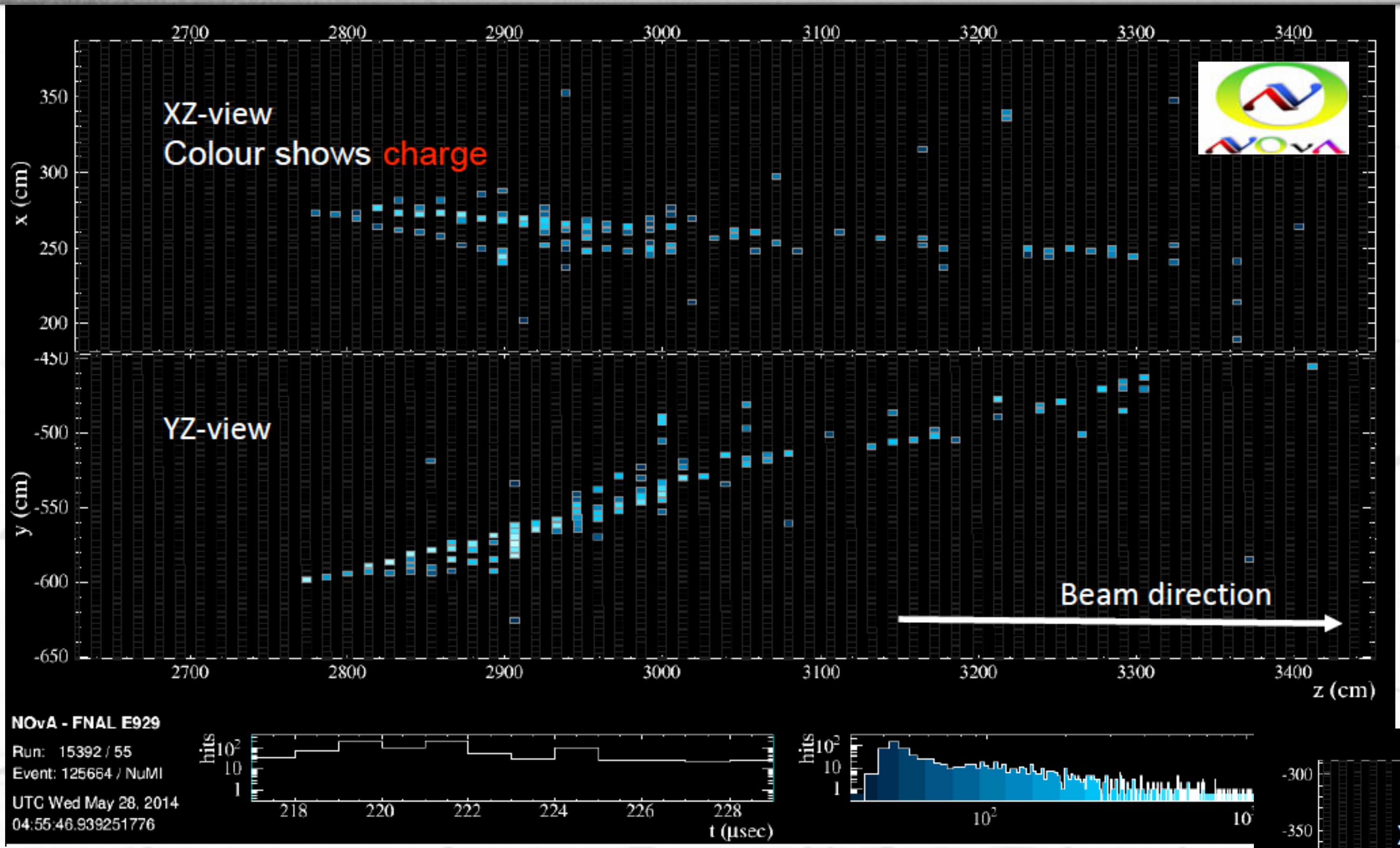
32 pixel APD



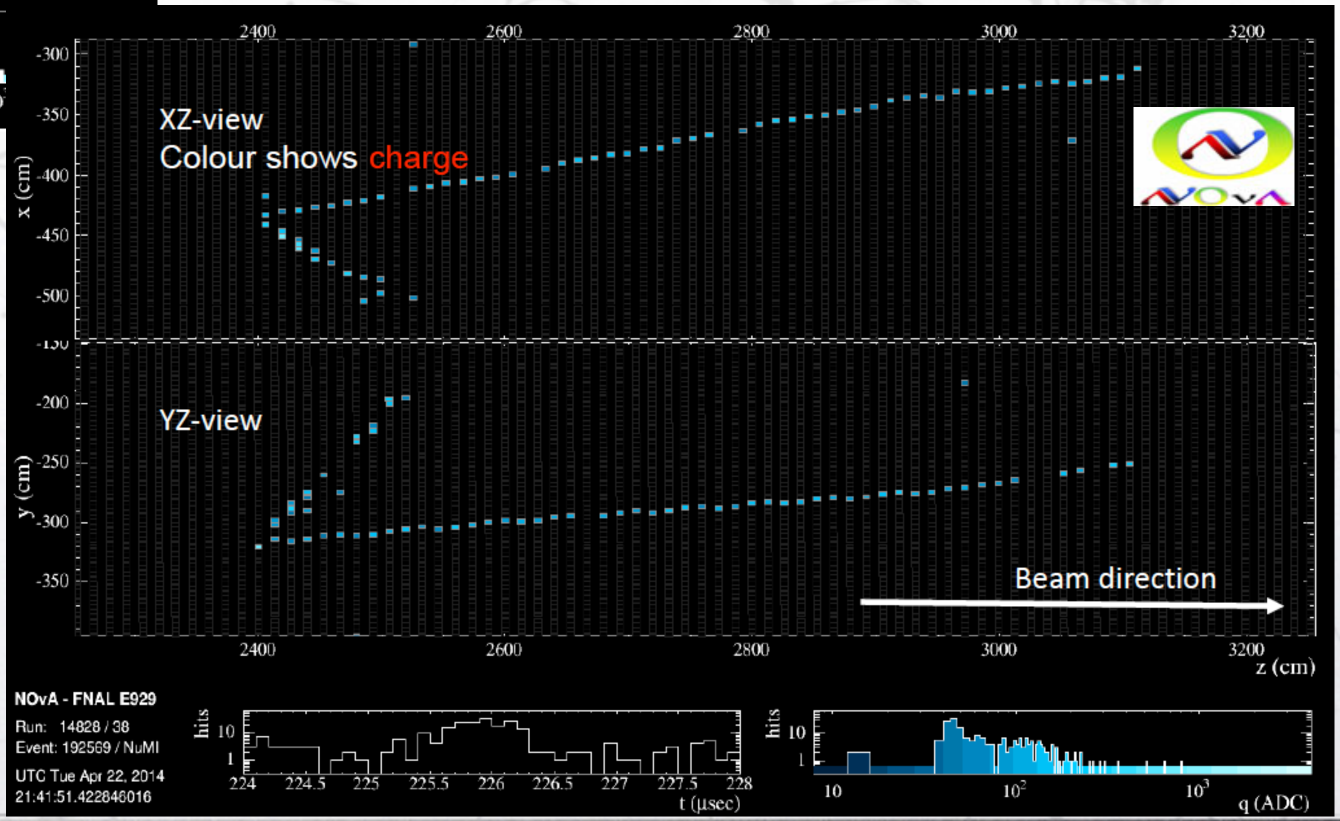


Extruded plastic (PVC) filled with liquid scintillator

Nova events



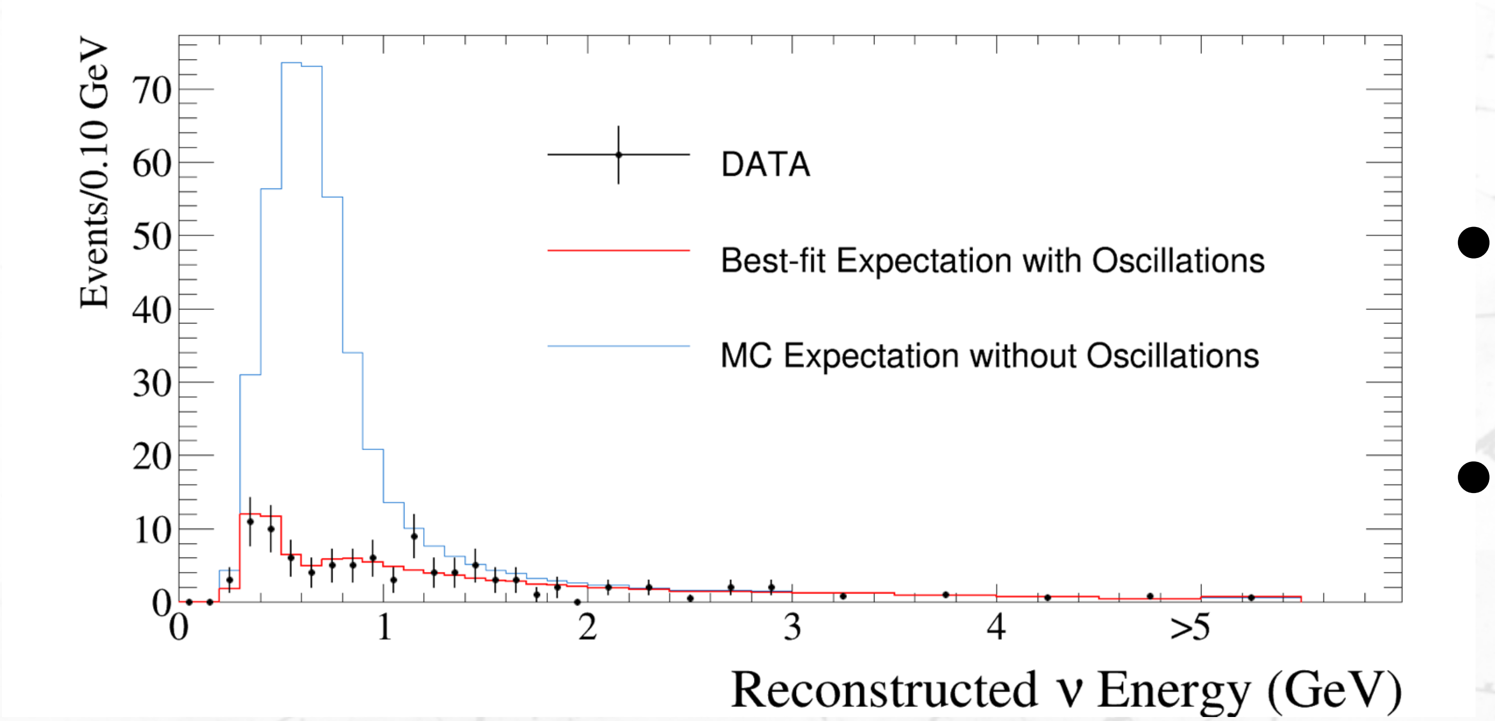
ν_e candidate

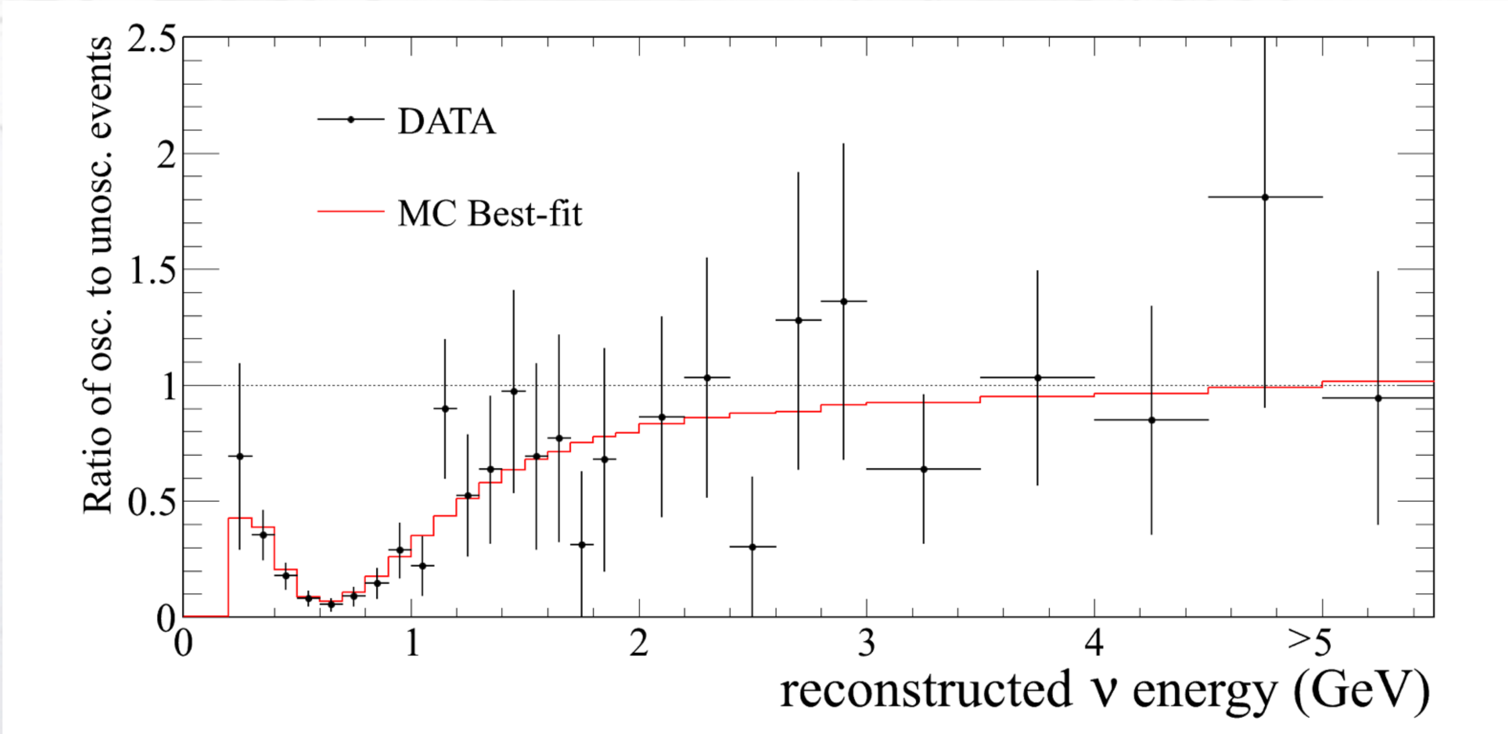


ν_μ candidate

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

ν_μ disappearance





Flux x $\sigma_{\nu N}$

- Expected number of events in absence of oscillations: 446.0 ± 22.5 (syst).
- Observed number of events: 120

6.57×10^{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 $\theta_{13} = 0$

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

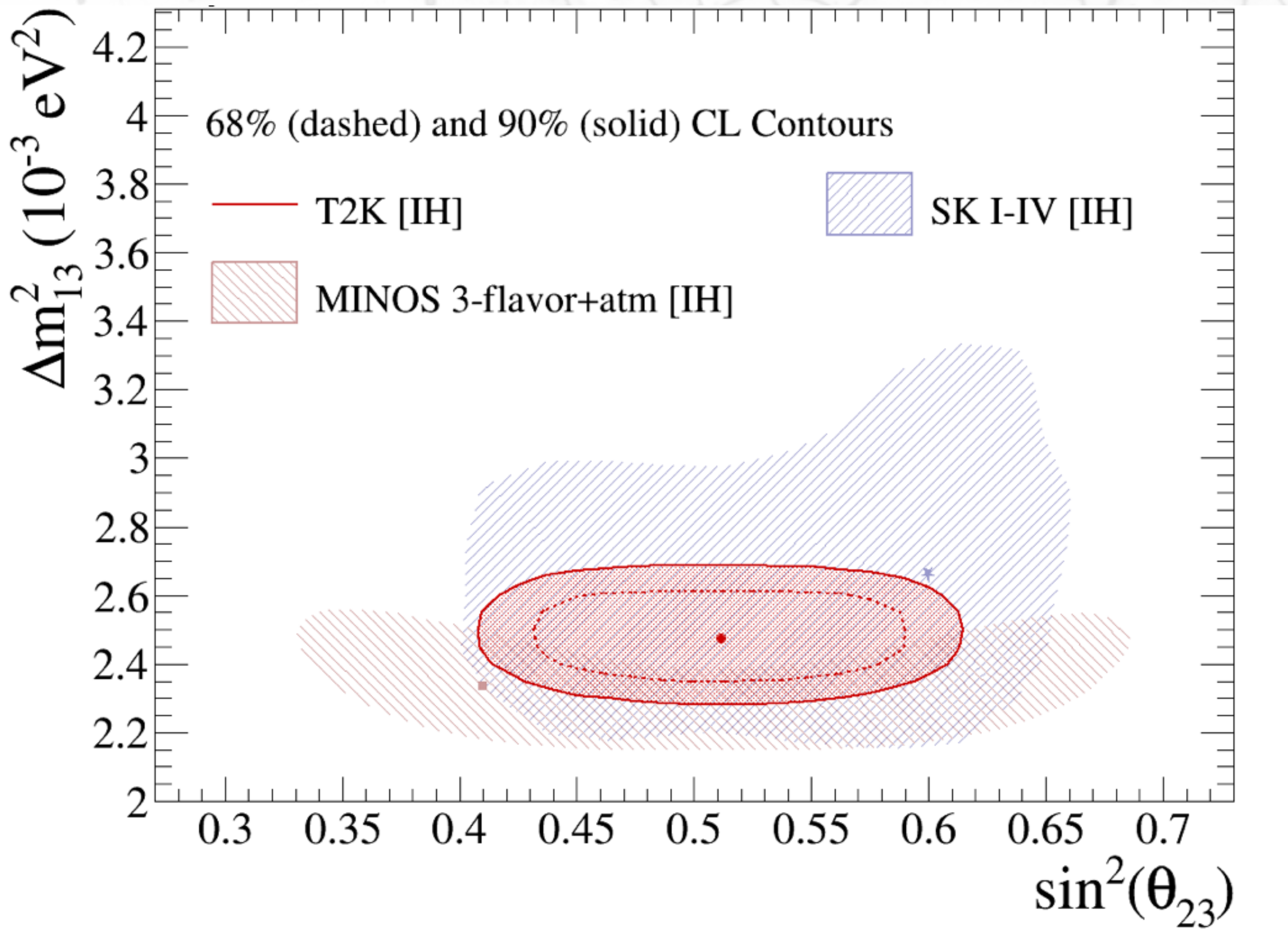
- If θ_{13} != 0 and θ_{23}~45°, the ν_μ disappearance is sensitive to the octant

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

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

ν_μ disappearance

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

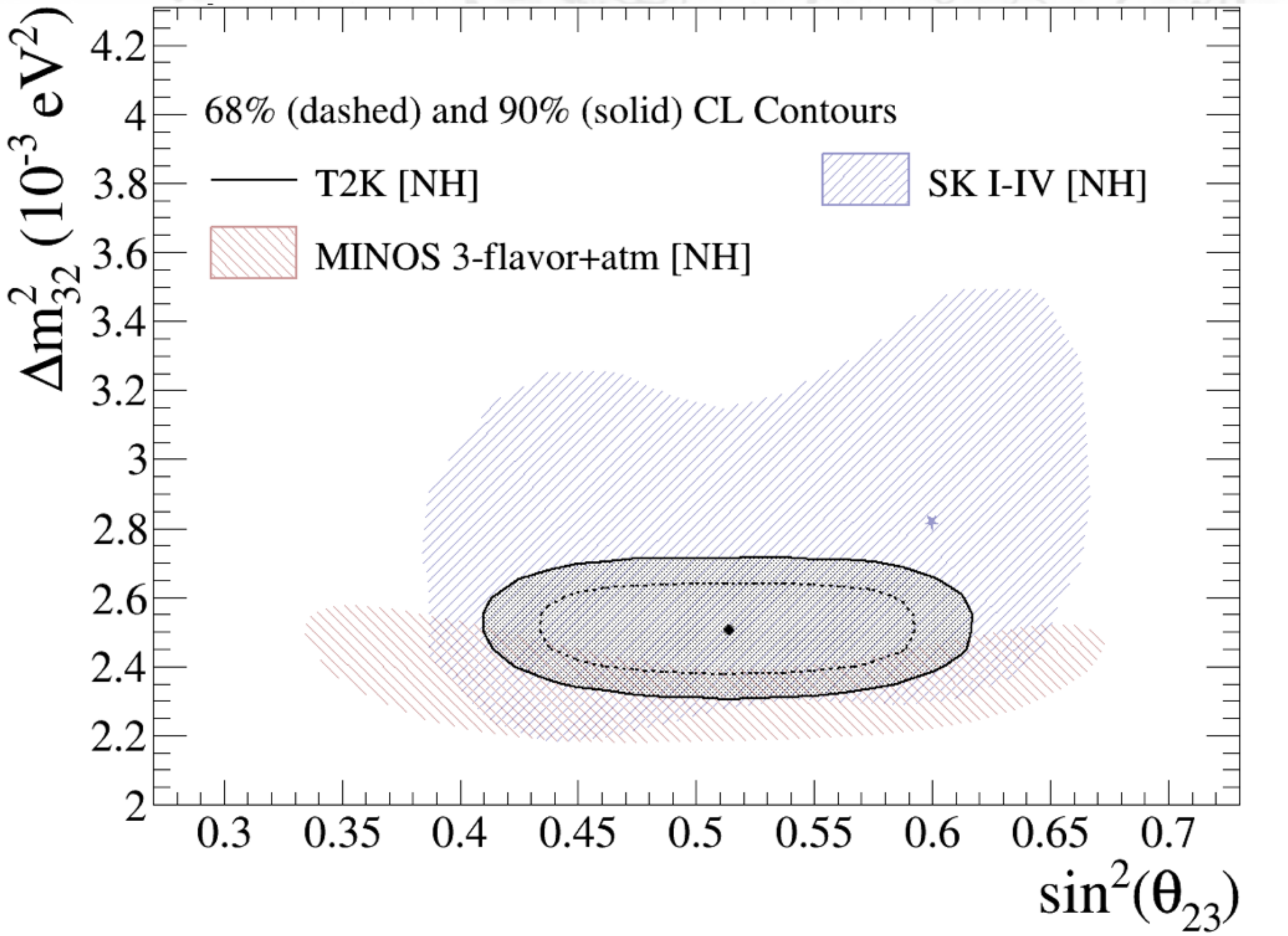


arXiv:1403.1532 (2014)		Best-fit ± FC 68% CL
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{23} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{23} (10^{-3} eV^2)	2.48 ± 0.10

- T2K already dominates the measurement of mixing angle.
- Off-axis configuration reduces sensitivity to Δm^2

ν_μ disappearance

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

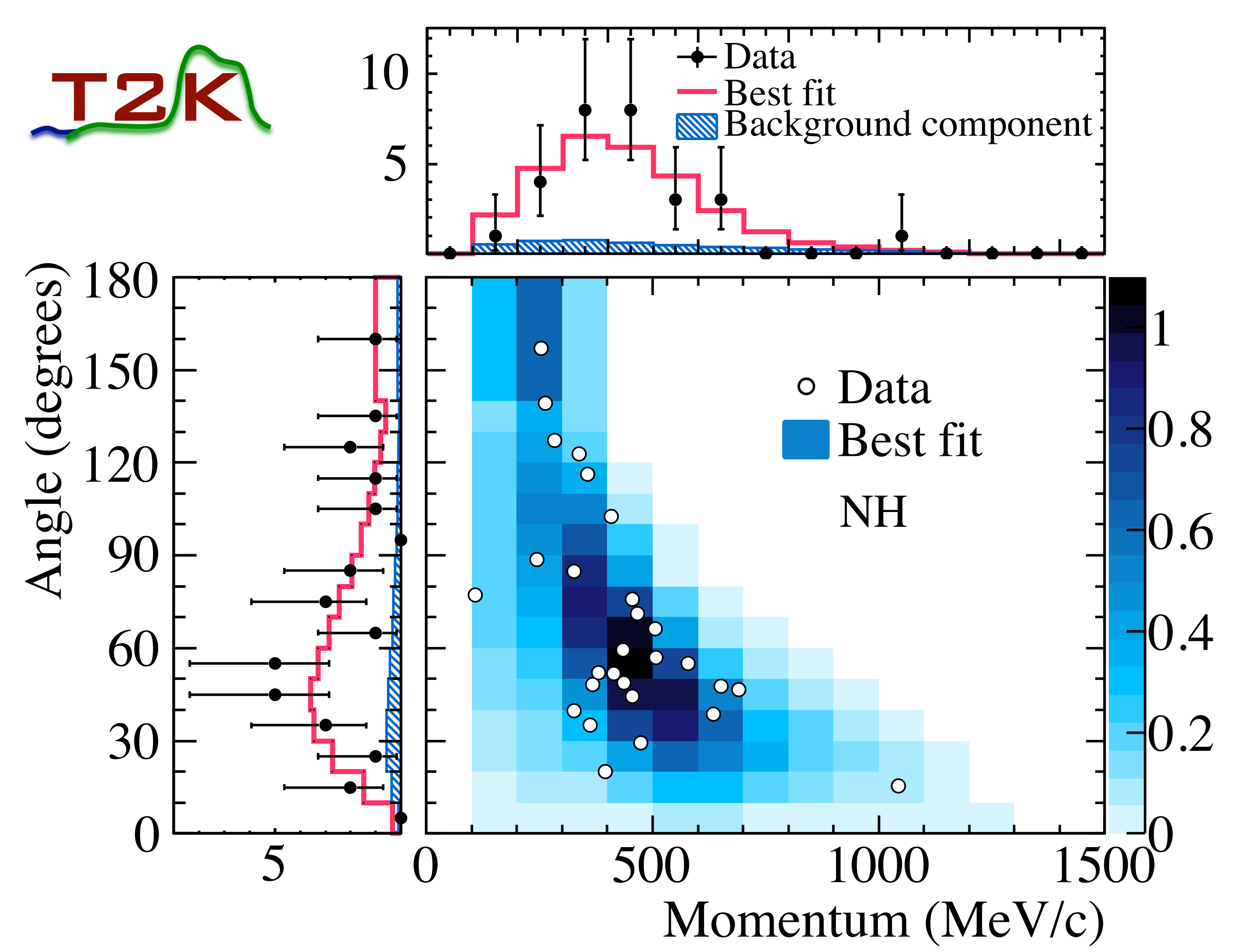


arXiv:1403.1532 (2014)		Best-fit ± FC 68% CL
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{23} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{23} (10^{-3} eV^2)	2.48 ± 0.10

- T2K already dominates the measurement of mixing angle.
- Off-axis configuration reduces sensitivity to Δm^2

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

ν_e appearance



Best fit with 68% C.L. error:

$$\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

PRL 112, 061802 (2014)

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

Reactor results

$\sin^2 2\theta_{13} = 0.095 \pm 0.010$

(PDG 2013)

Tension between T2K and reactor experimental results → assumptions

ν_e appearance

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

T2K

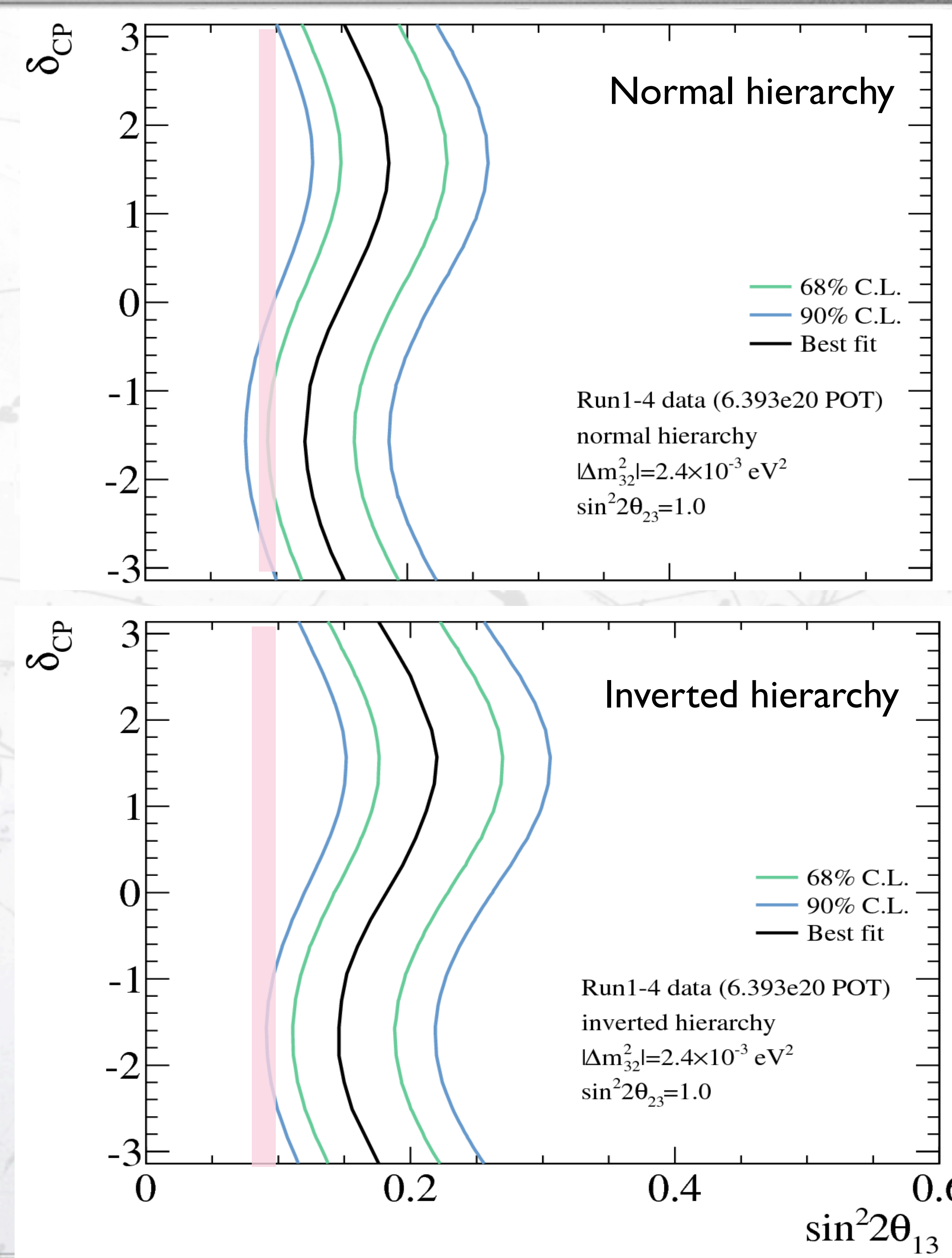
Best fit w/ 68% C.L. error @ δ_{CP}=0

Normal hierarchy: $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$

Inverted hierarchy: $\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$

7.3 σ observation claim

This is the first time an exclusive neutrino flavour appearance is measured.



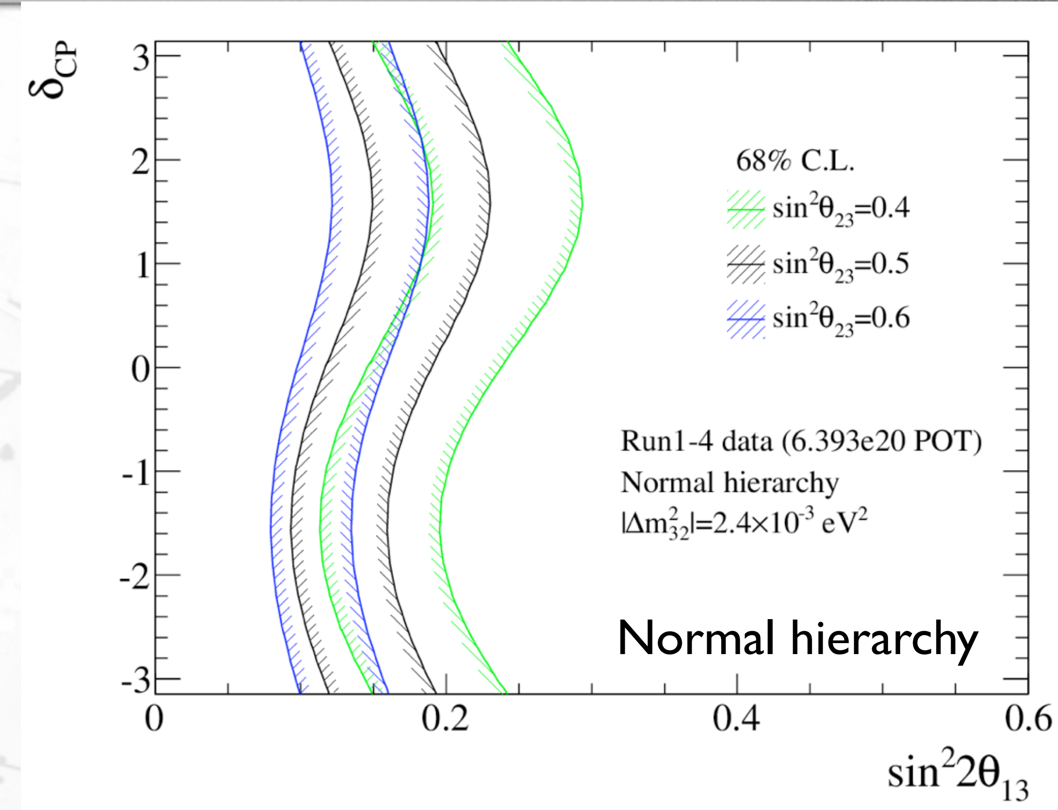
ν_e appearance

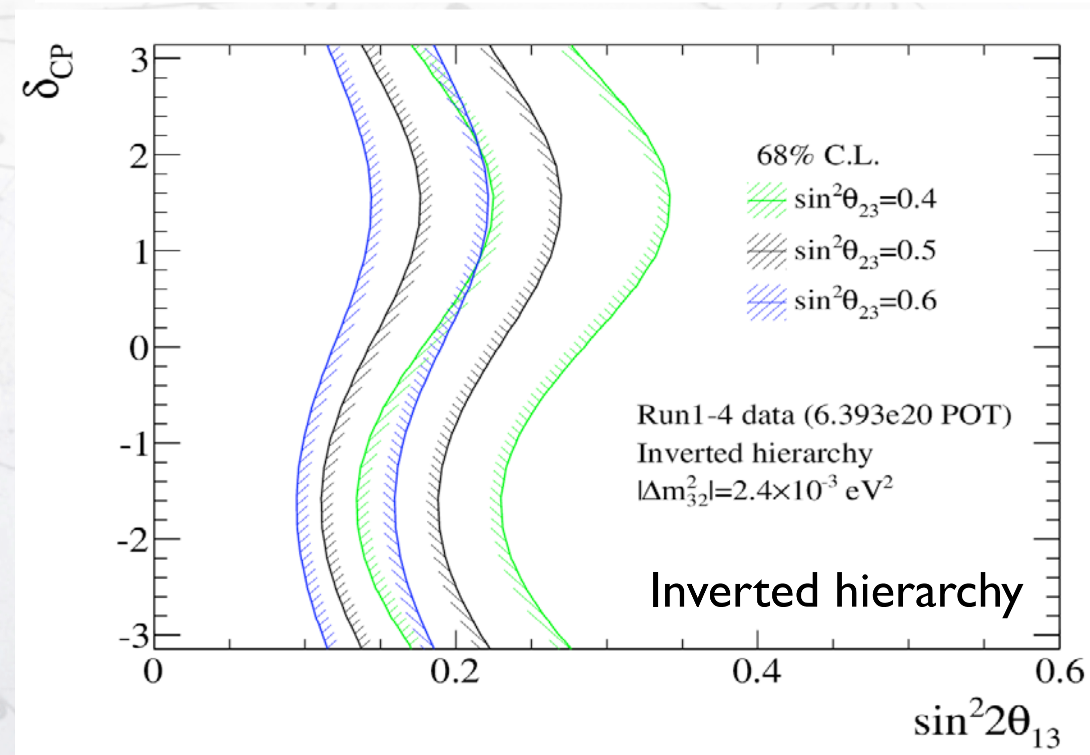
T2K

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.





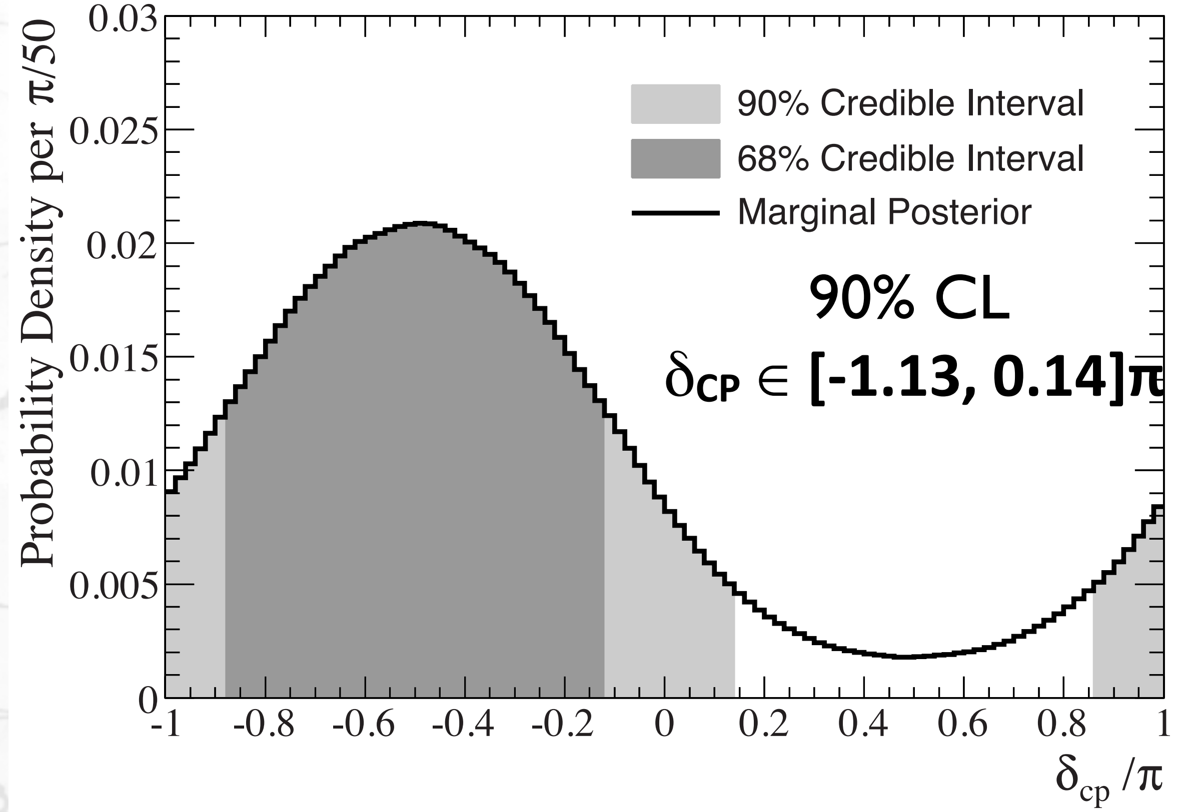
Joint analysis (Bayes)

Markov Chain Monte Carlo (MCMC) with both T2K-SK $\nu_\mu + \nu_e$ and ND280 samples

Can easily marginalize over e.g. mass hierarchy (MH)

And compare the probabilities for each MH and θ_{23} octant combination

Assuming flat priors for $\sin^2\theta_{23}$, $|\Delta m^2_{32}|$; P(NH) = P(IH) 0.5



	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18%	8%	26%
$\sin^2\theta_{23} > 0.5$	50%	24%	74%
Sum	68%	32%	

Where do we stand?

LBL provide solid results on

- ν_μ disappearance.
  - Is it maximal (45°)?
  - In which octant?
- ν_e appearance.
  - Reactor neutrinos will be more precise always.
  - ν_e is the window to matter effects (hierarchy) and CP violation.

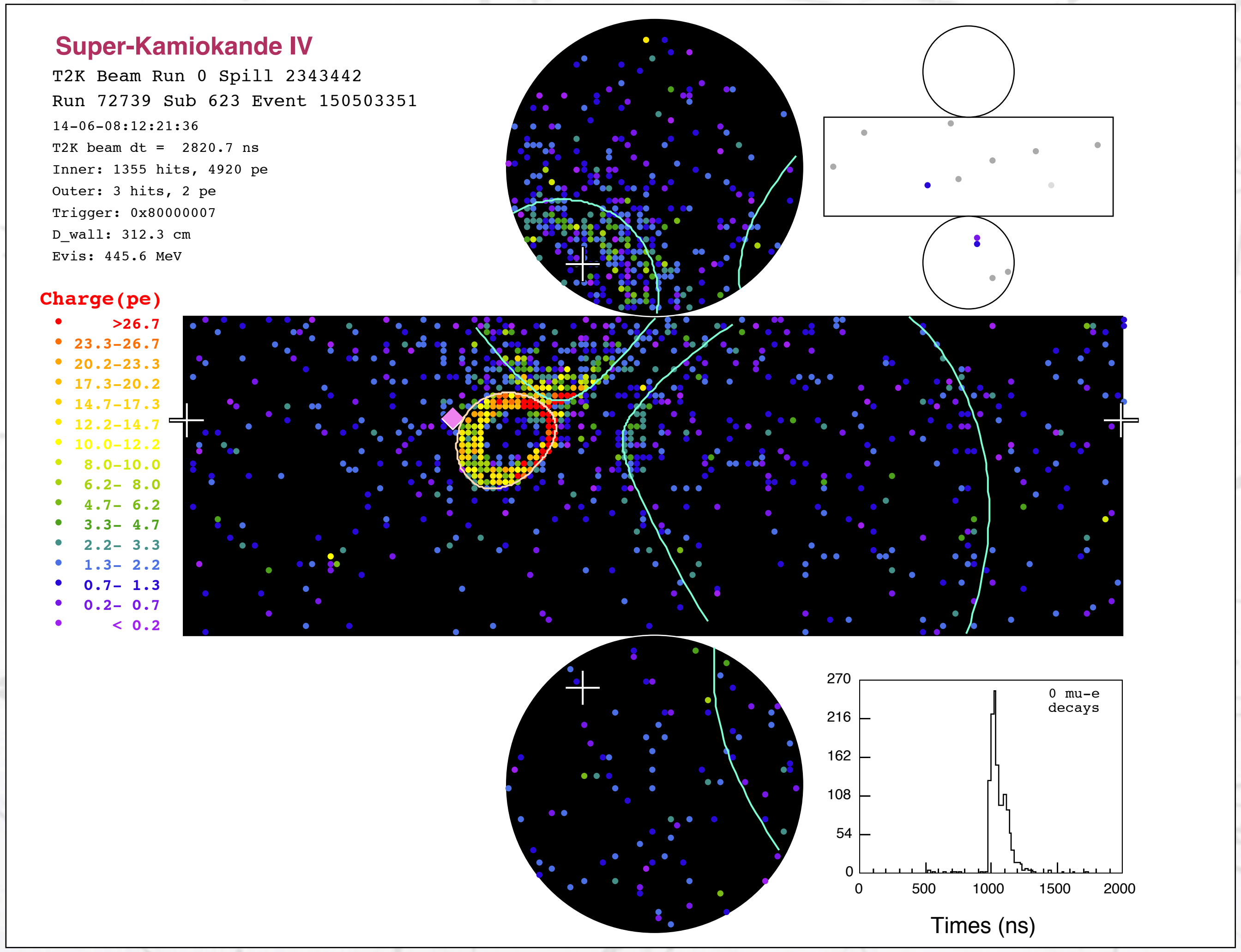
More and more data

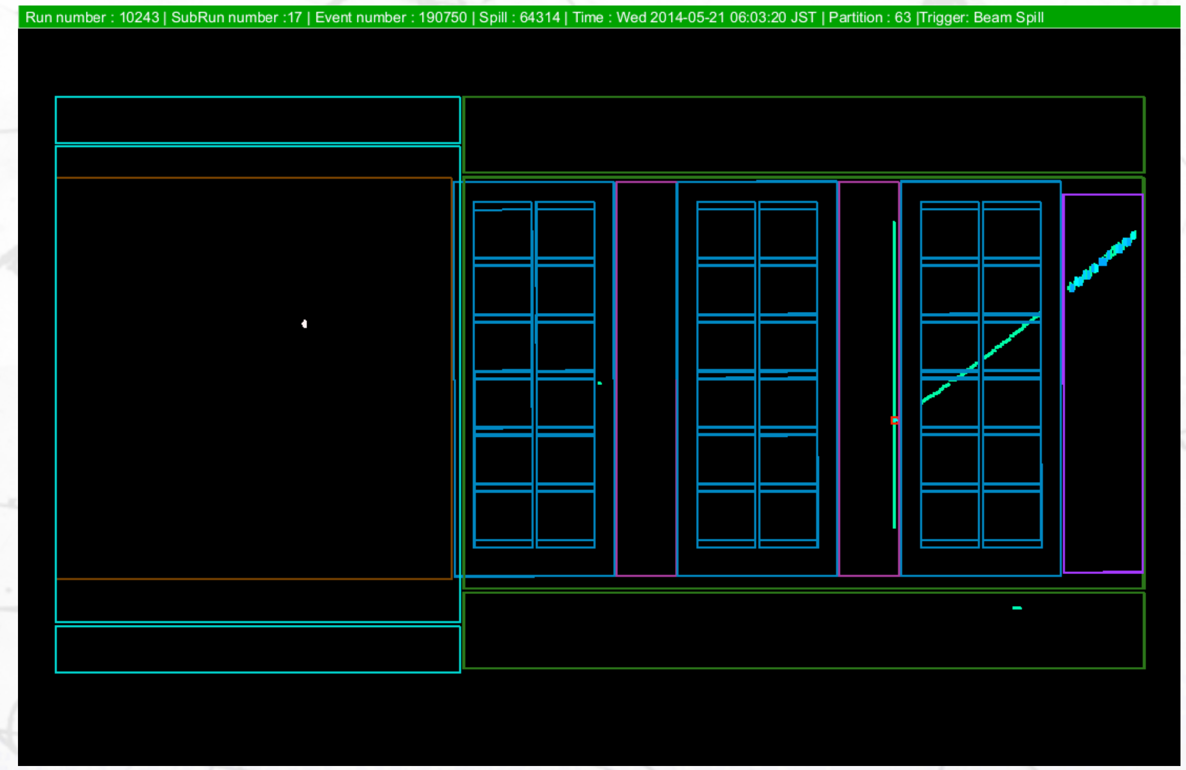
Better control on beam and cross-sections!

anti-neutrino runs

two baselines

T2K antineutrinos



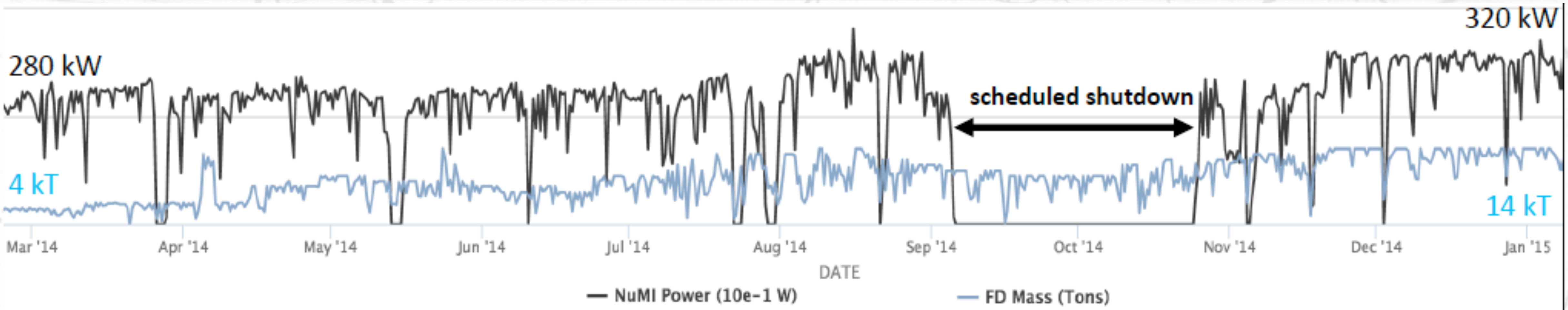


1st antineutrino candidate @ SK

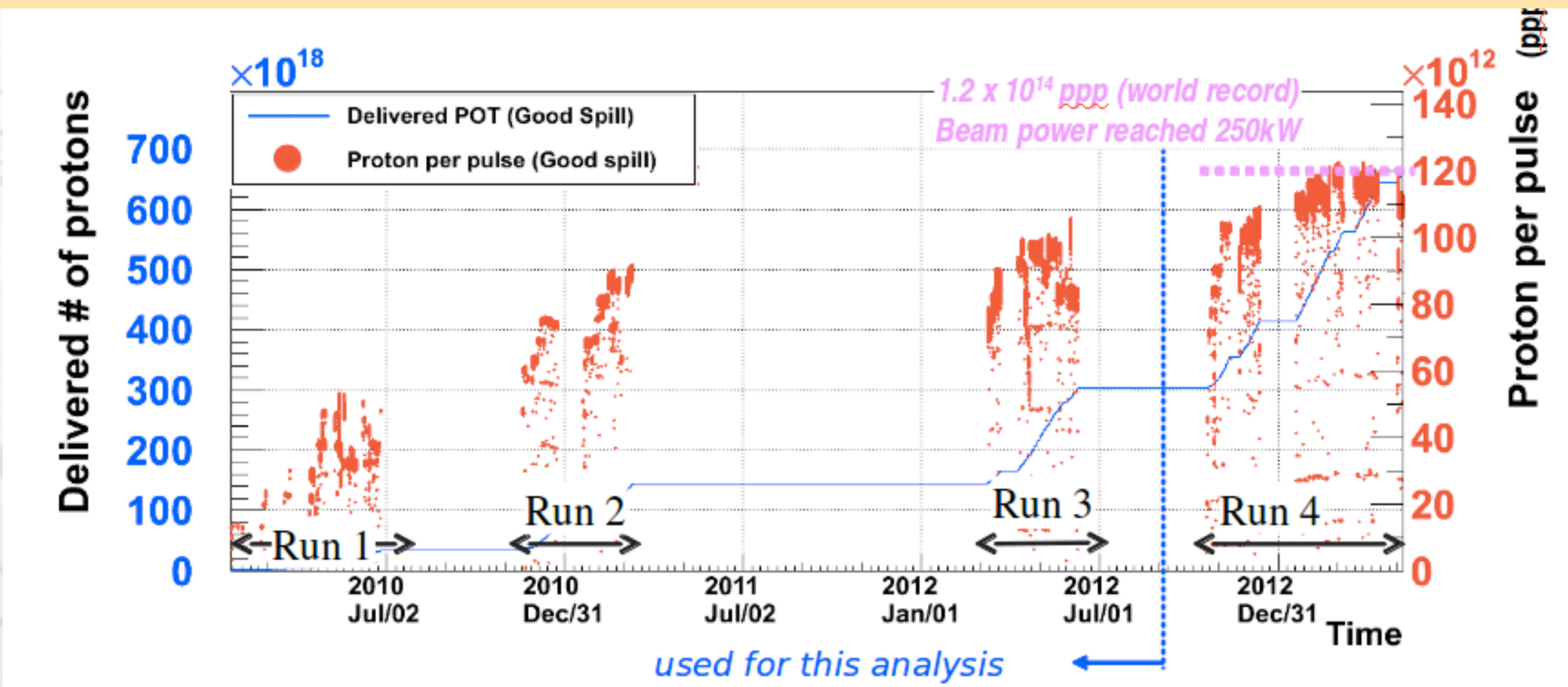
Antineutrino candidate @ ND280

8th July 2014

Nova and T2K



- Nova: 1.7 10^{20} p.o.t. already collected.

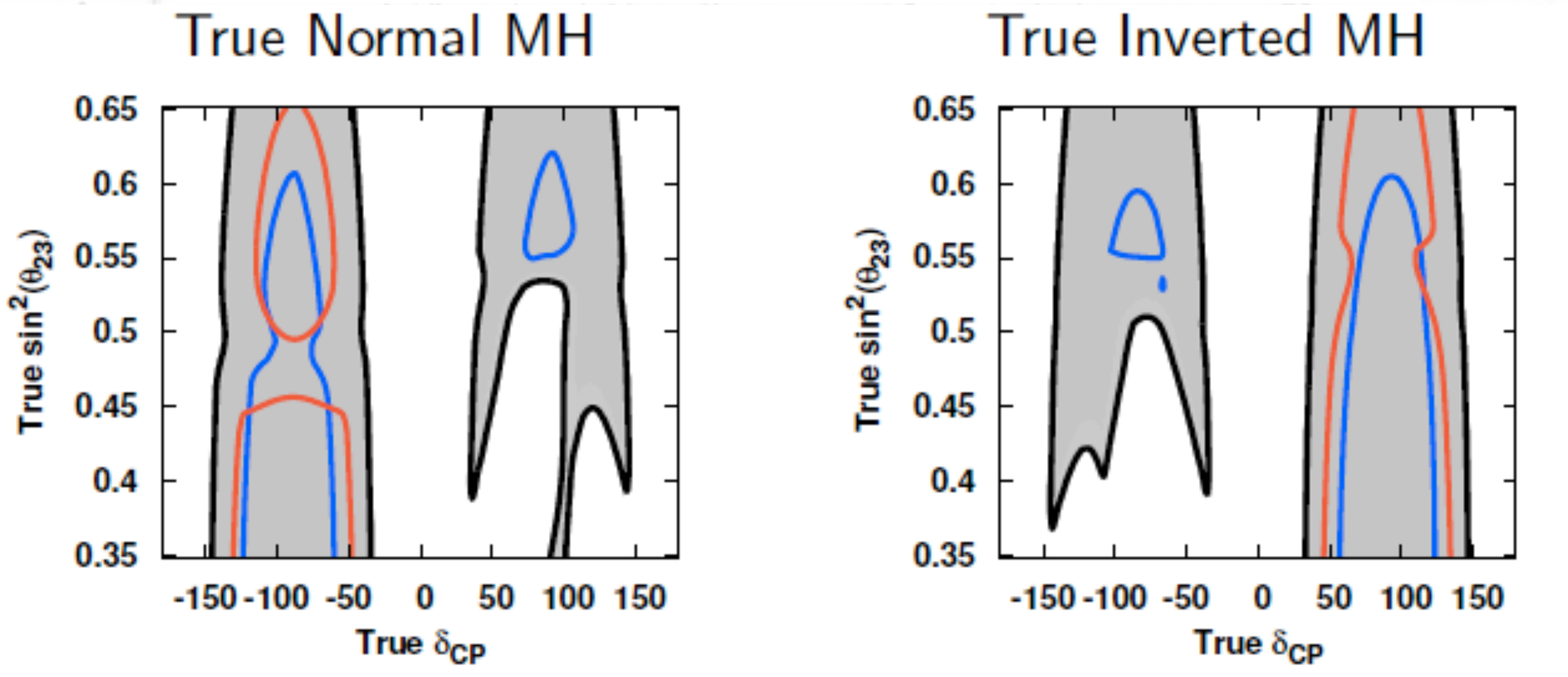


- T2K: 6.6 10^{20} p.o.t. for neutrinos (~3 10^{20} for antineutrinos)

T2K + Nova 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

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

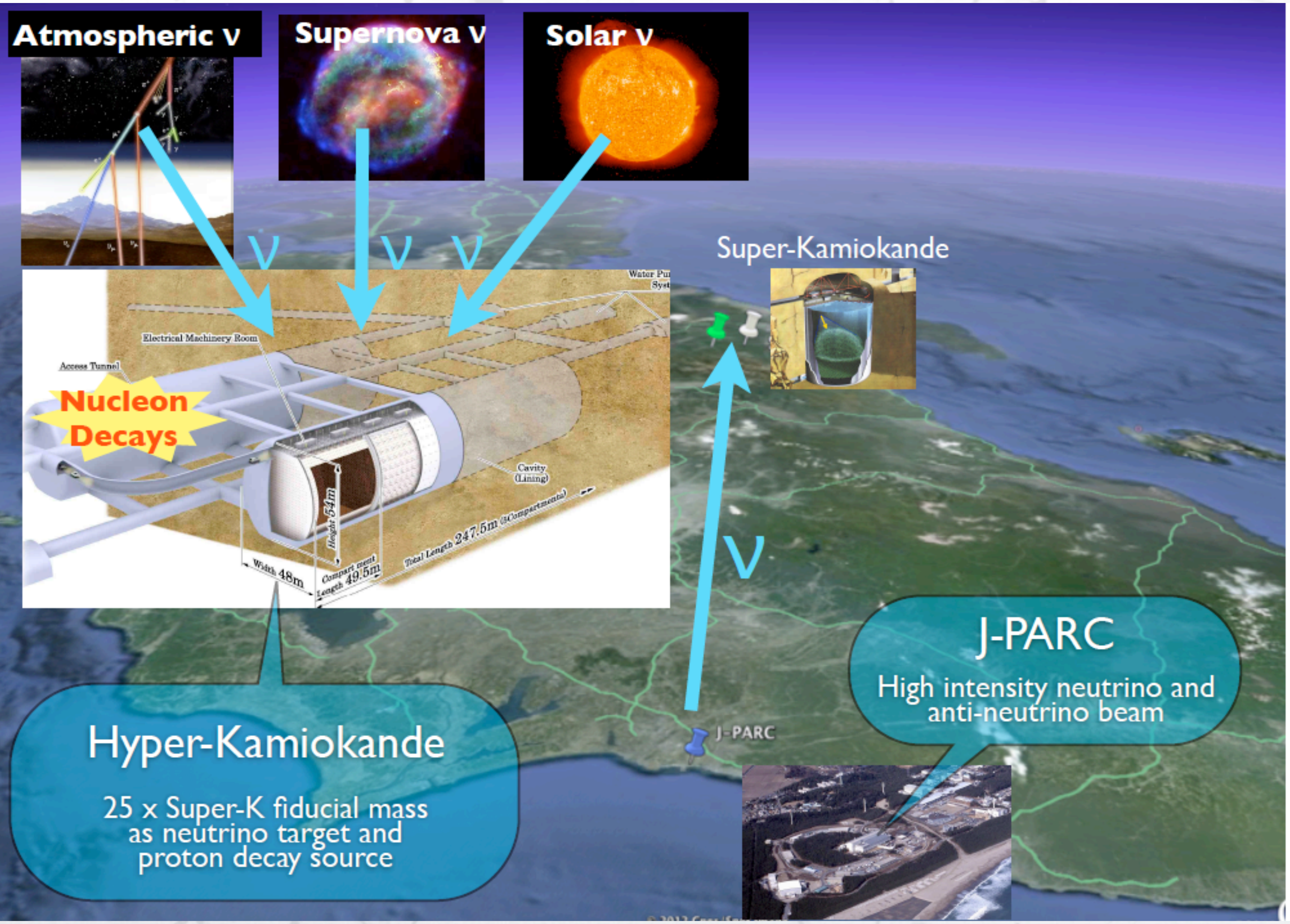
$\oplus$ simple normalisation errors.

The future

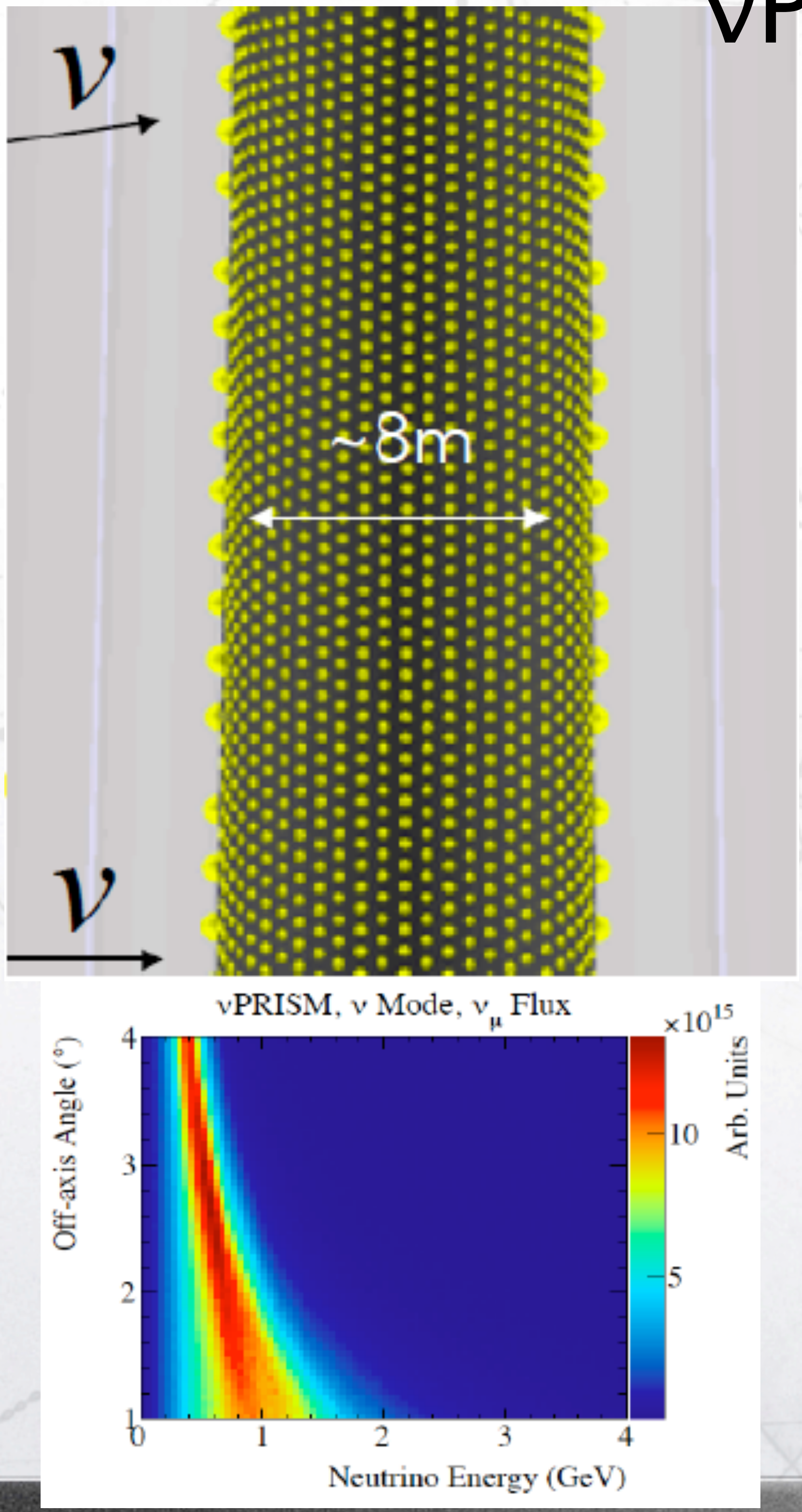
- T2K and Nova might not be sufficient:
  - low statistics.
  - low matter effects.
- The community is thinking in the next step:
  - LBNE — Large matter effect + Large statistics
  - T2HK — Large statistics

Require intense beam and new far detectors

T2HK



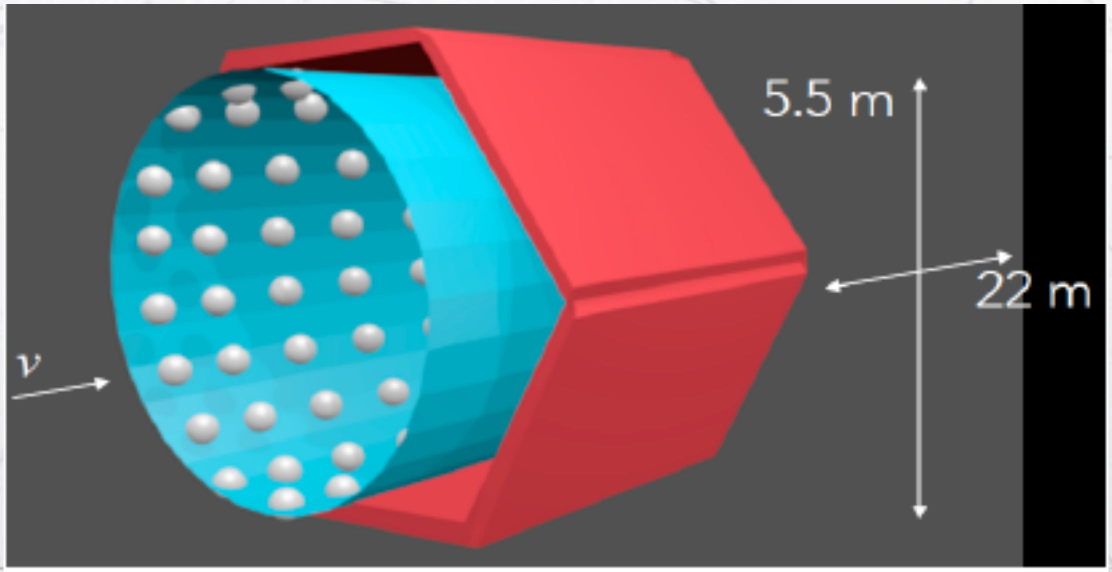
- HK, water Cherenkov detector with 10 times the mass of SK for:
  - proton decay
  - Atmospheric
  - solar
  - SuperNova
  - Off-axis LBL with same flight distance than T2K.
    - No matter effects.
    - Sensitive to δ_{CP}
    - Not sensitive to hierarchy



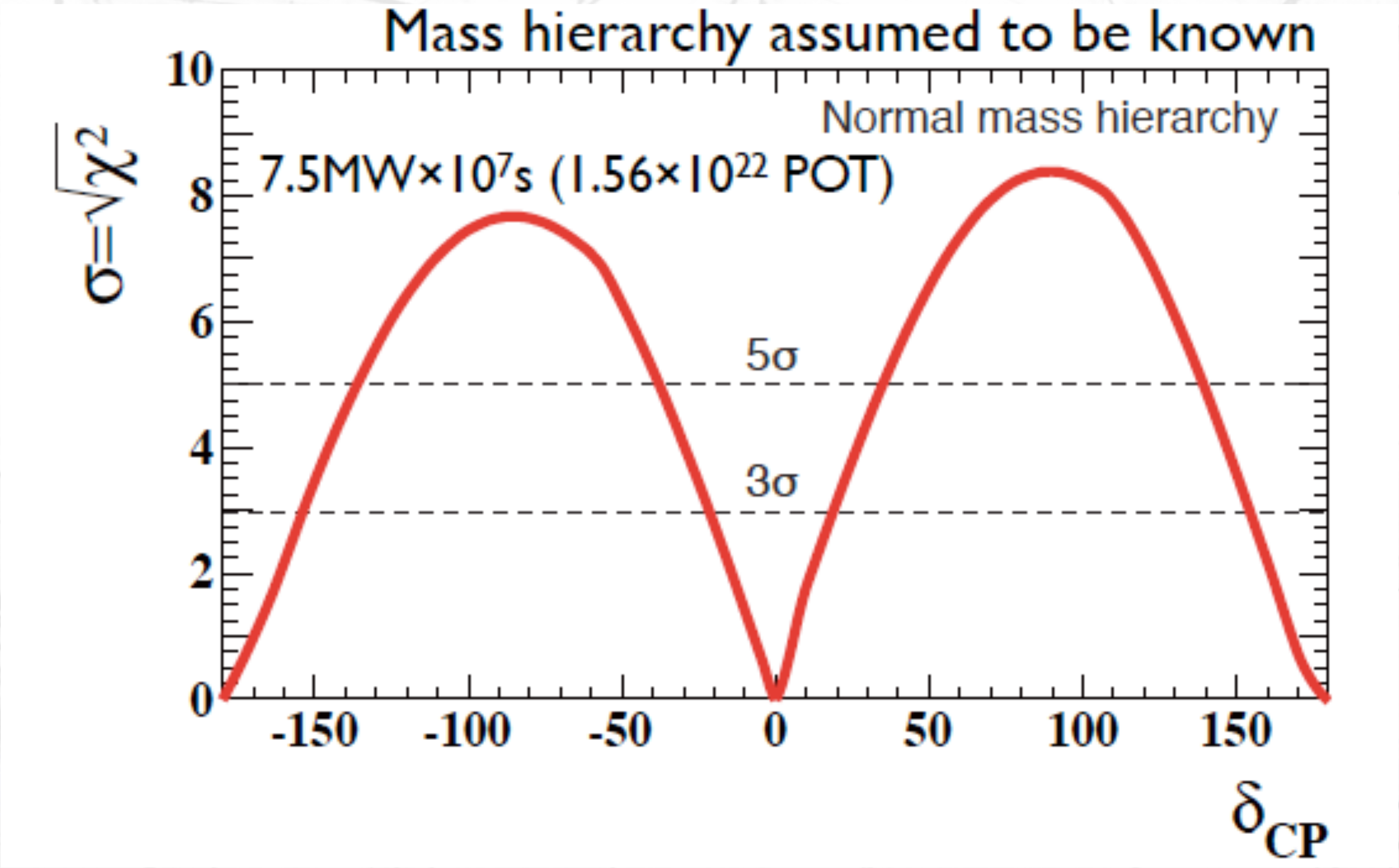
νPrism

- New near detectors (Titus, νPrism) to improve:
  - flux control
  - cross-section control.
- Using upgraded ND280 as a first near detector.

Titus

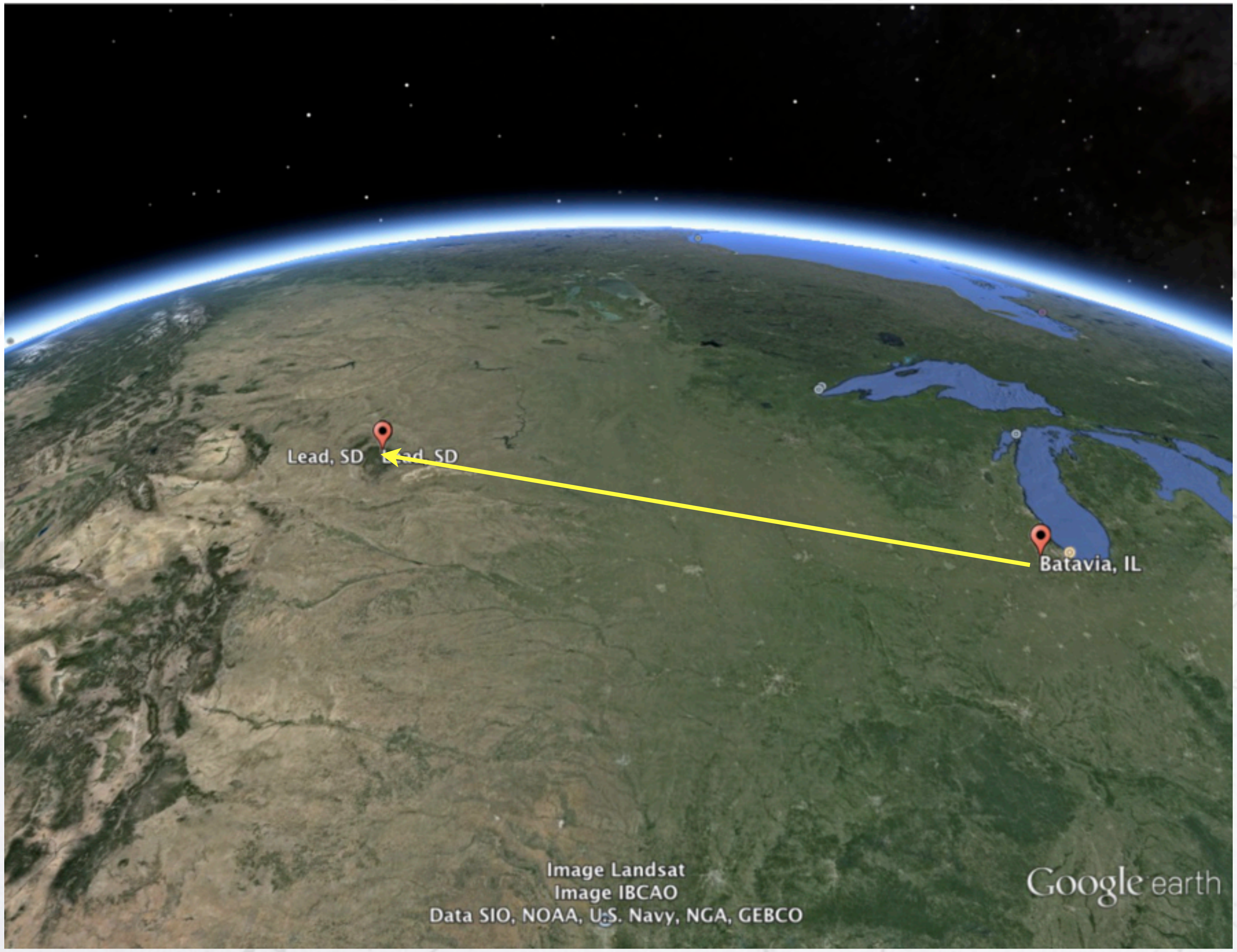


T2HK



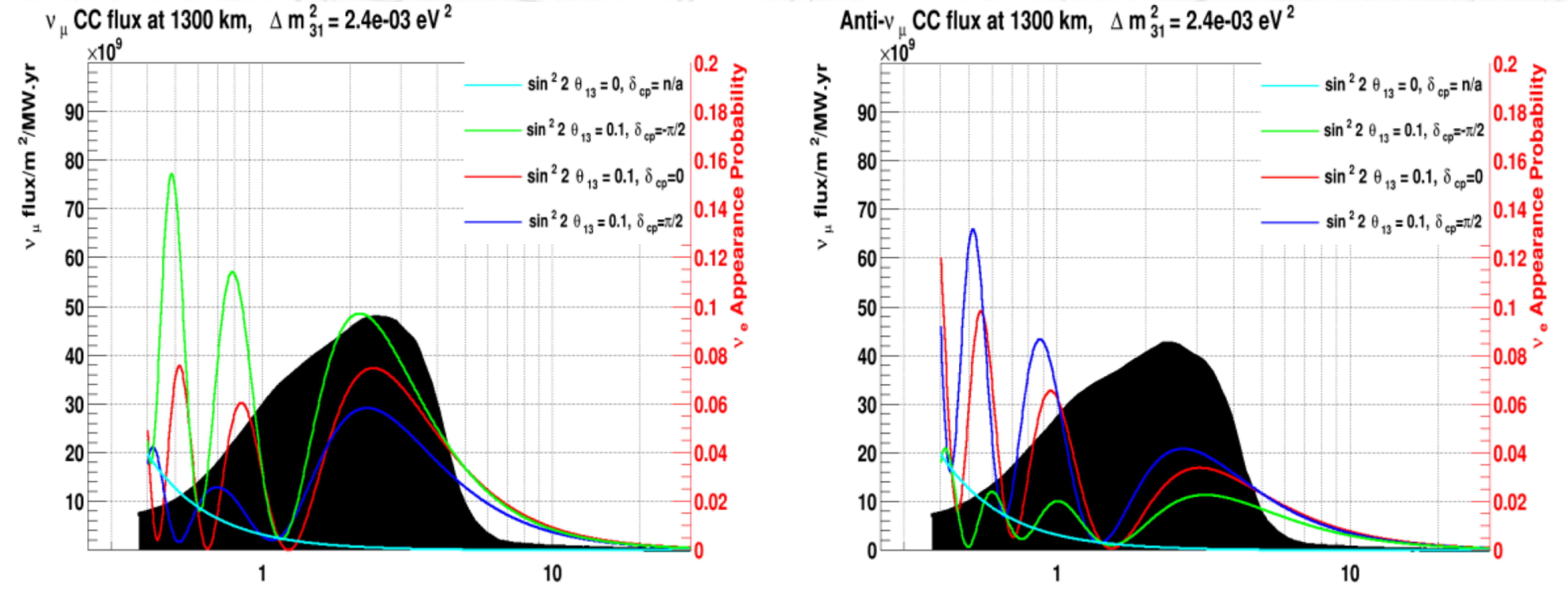
- Exclusion of sin δ = 0
  - > 3σ for 76% of δ
  - > 5σ for 58% of δ
- 8° to 19° precision depending on the value of δ.

LBNE (DUNE)



- 40 kTon liquid argon underground:
  - proton decay
  - Atmospheric
  - solar
  - SuperNova
  - On-axis LBL with 1300 km flight distance
    - Matter effects.
    - Sensitive to δ_{CP}
    - Sensitive to hierarchy

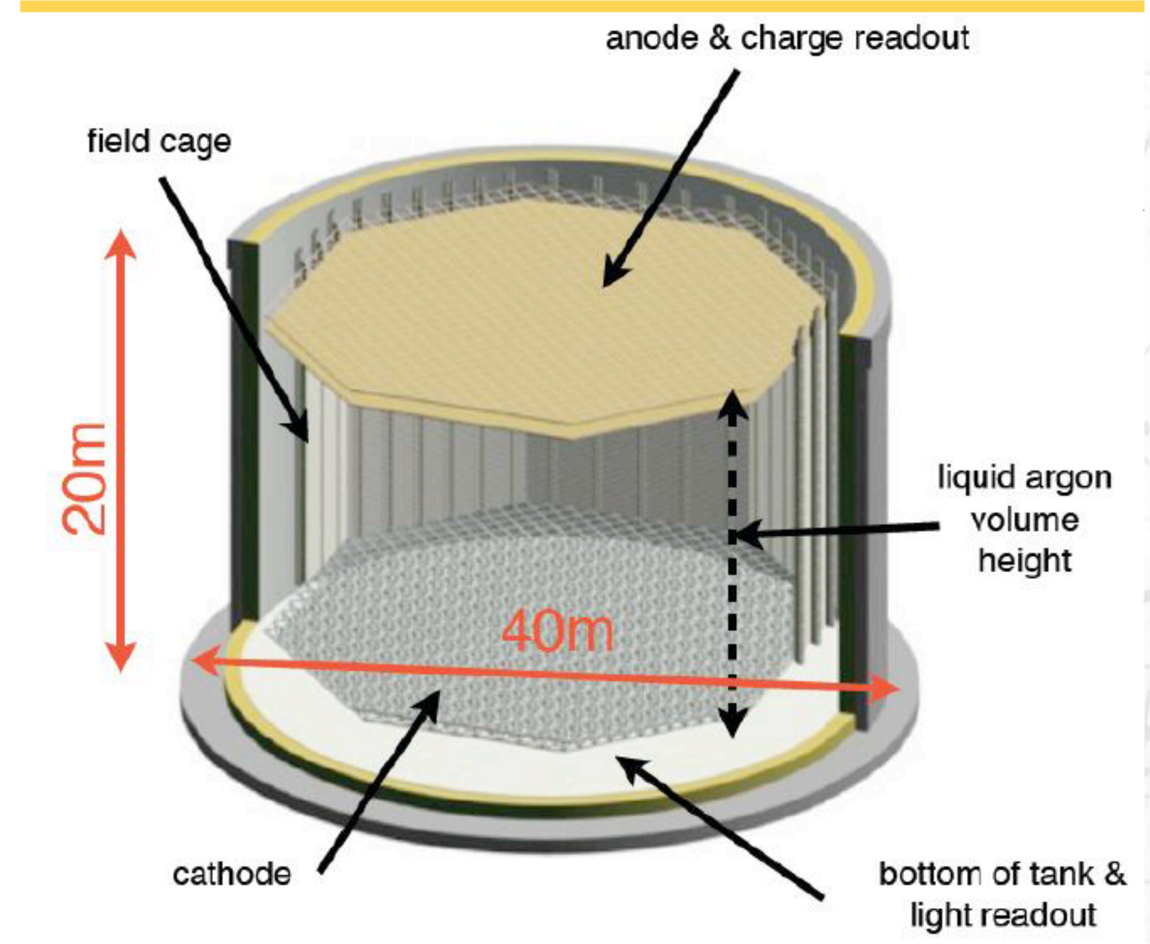
Double peak issue

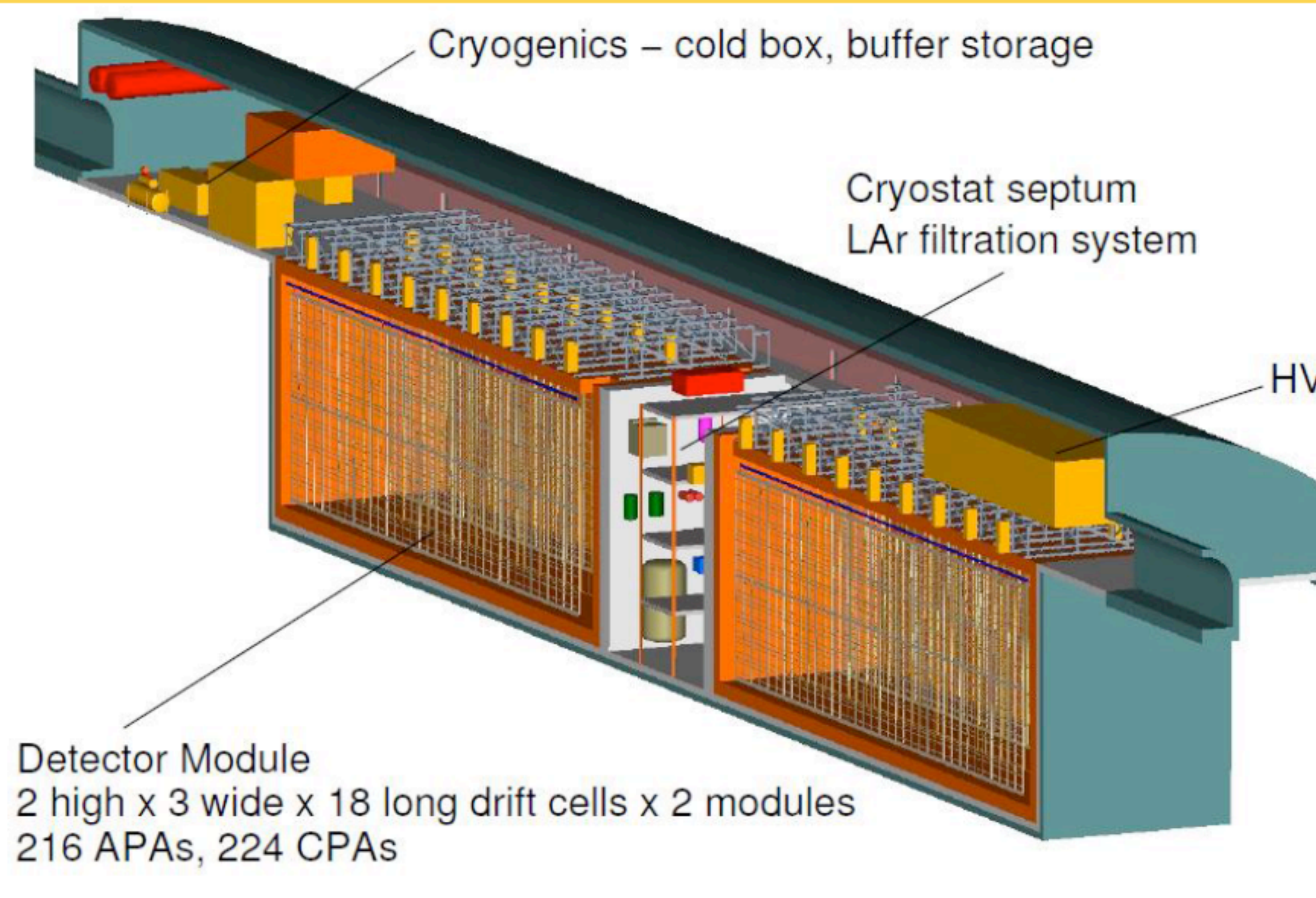


- Off-axis configuration might not be the optimal for CP search.
- A broad beam allows to access to oscillation maxima with different functional dependencies of δ: like 2 experiments in one!.

Excellent energy reconstruction is a must!

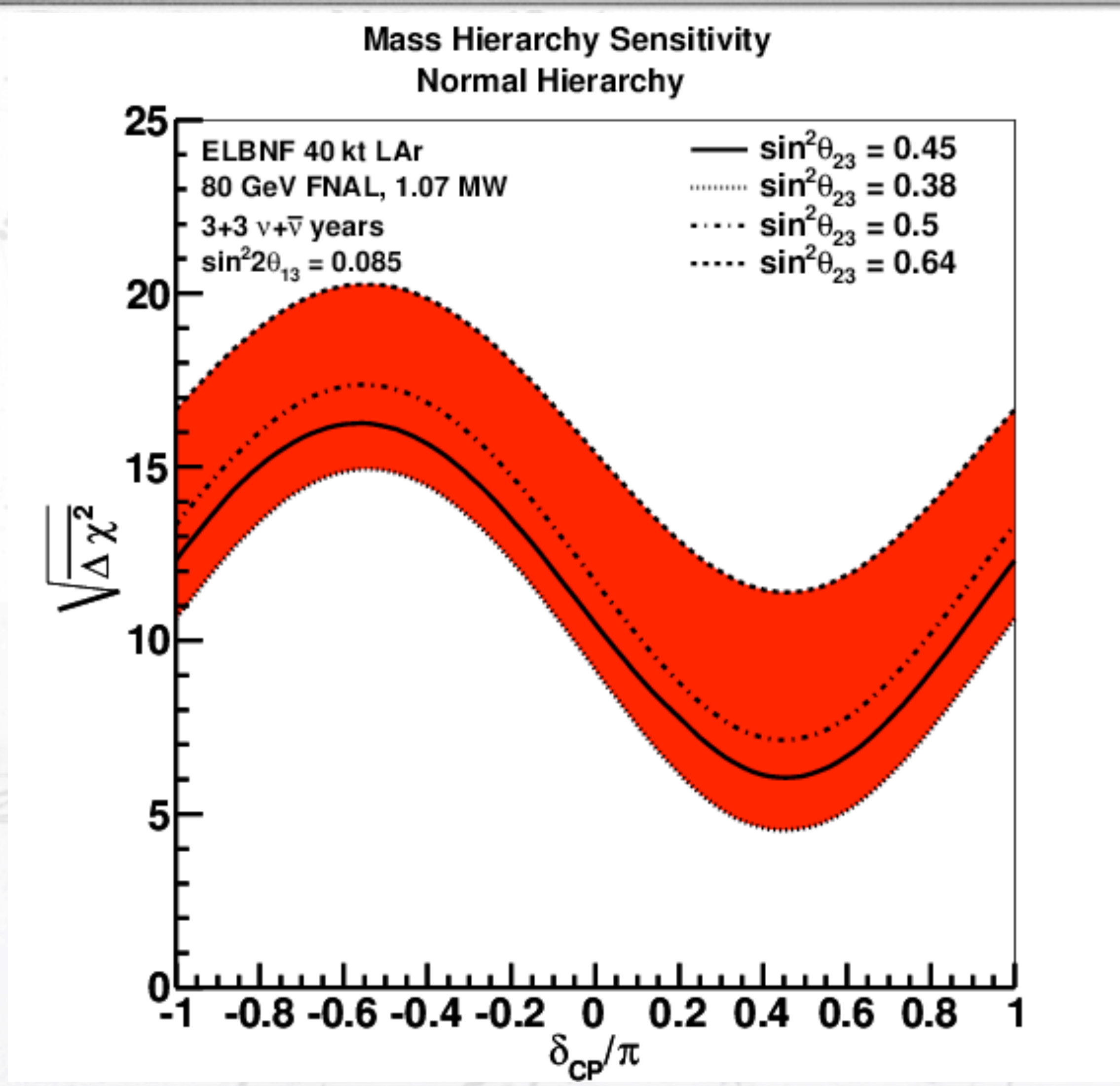
ELBNF

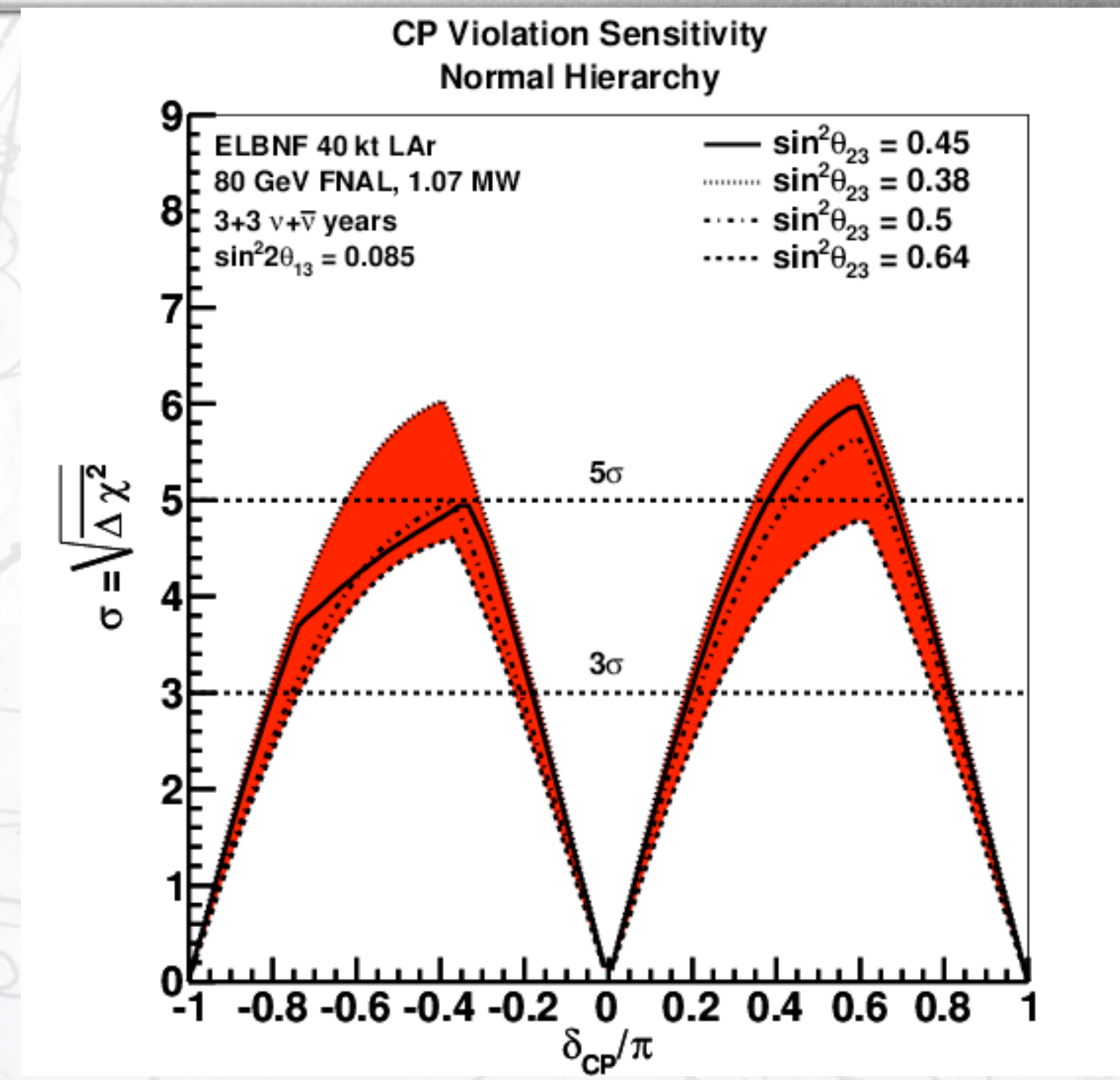




- 40 kTon Liquid Argon far detector with two candidate technologies:
  - single phase with no charge amplification.
  - double phase (liquid/gas) with charge amplification.

LBNE

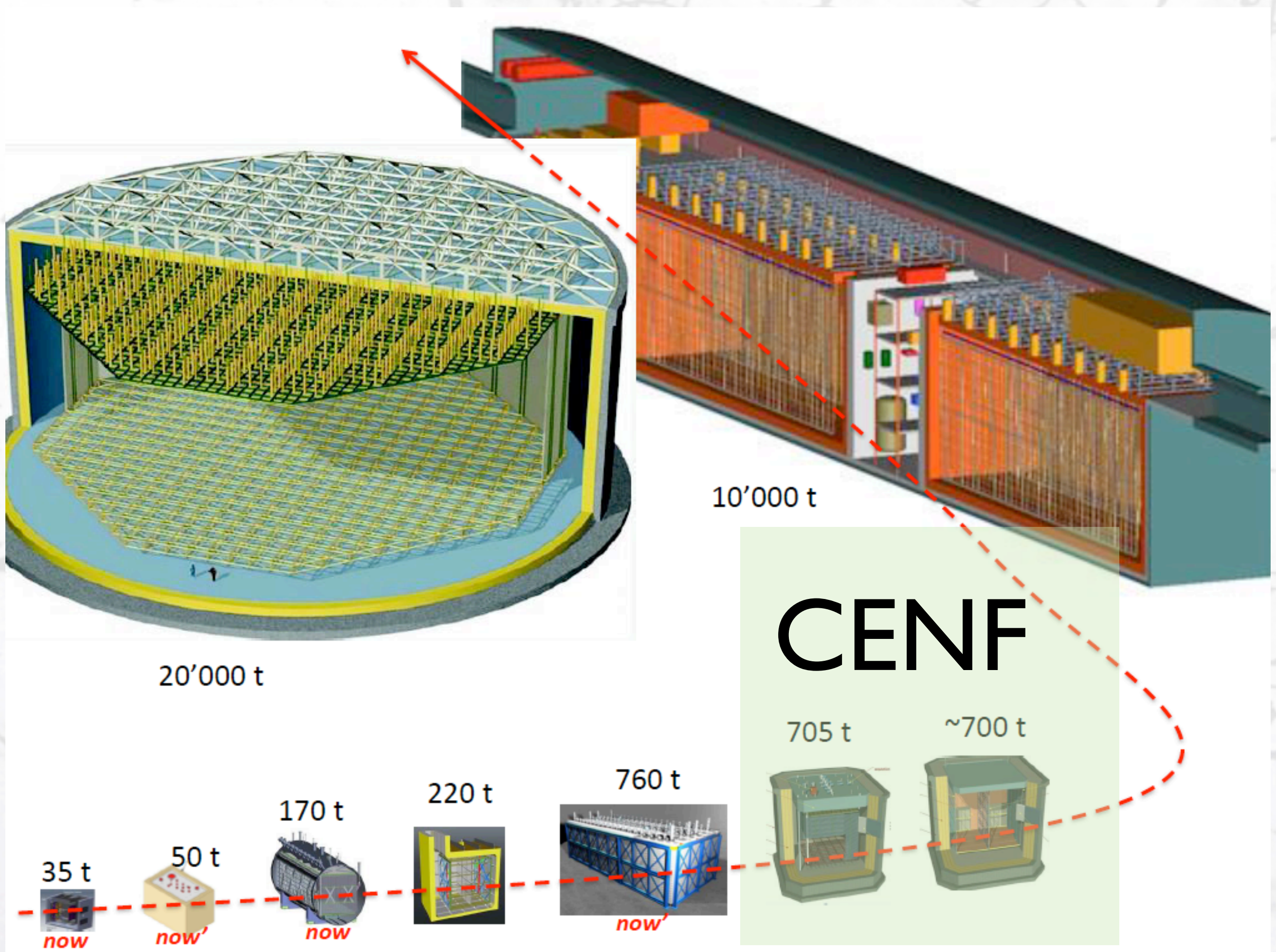


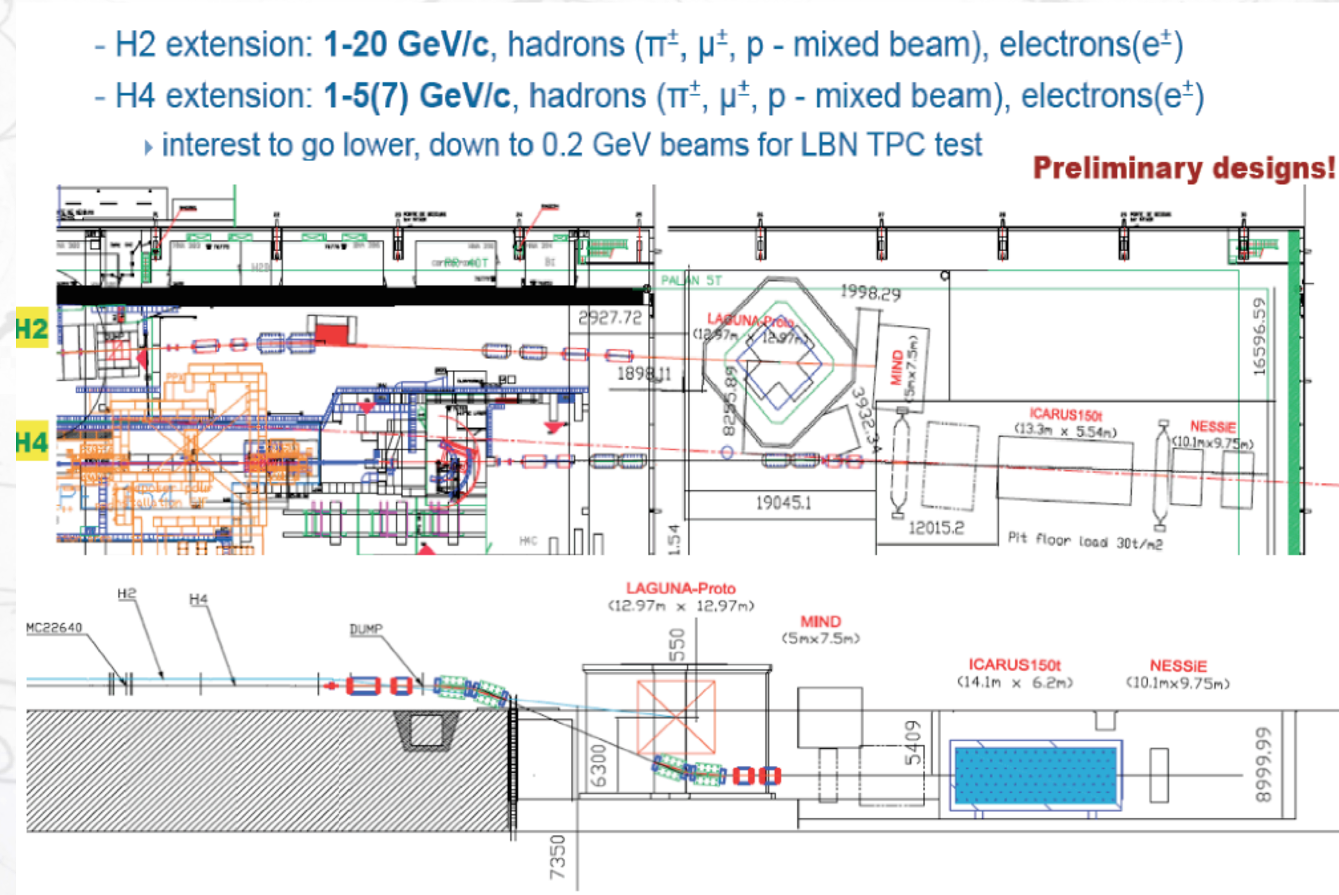


- LBNE has a final sensitivity to δ_{CP} similar to T2K.
- LBNE can determine mass hierarchy in some ranges of δ_{CP}.

CERN Neutrino Facility

Extract of European strategy document: "CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments."





- Refurbish West Area to accomodate large detector prototype and beam for LBNE (double phase -WA105-, single phase), Neutrino Factory (Mind) and HK.

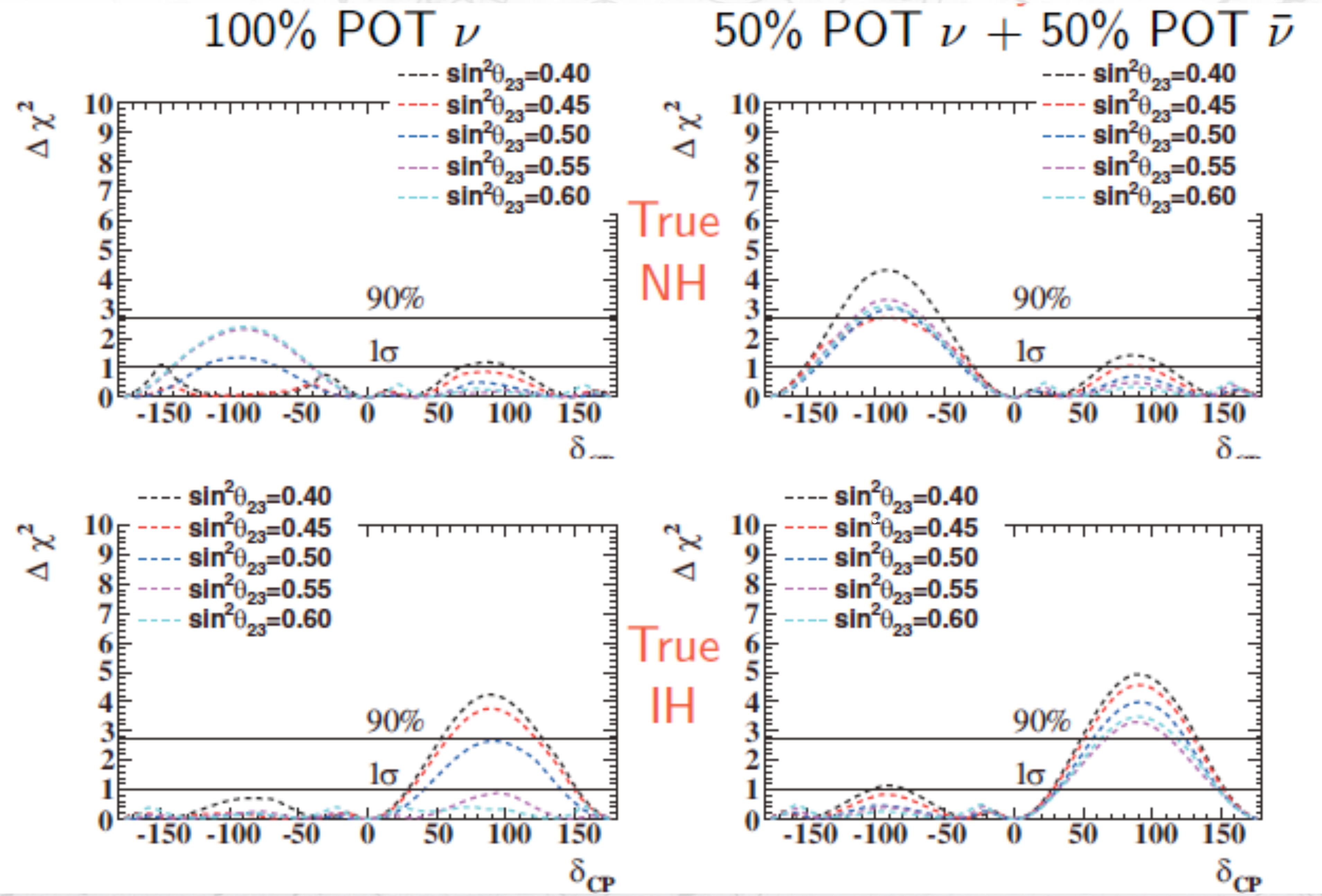
Concluding remarks

- Current LBL experiments are profiting from the large value of θ13 and started to provide early measurements of CP violation. Keep eyes open for surprises:
    - first Nova results in summer, first anti-neutrino data from T2K in summer.
- The current LBL program will cover only a fraction of the potential values of δ_{CP}. A new generation of experiments under design with two complementary approaches: long-medium base line, high-low energies, matter-nomatter effects.
- These experiments will require another level of understanding on neutrino cross-sections and neutrino fluxes.
- CERN has created the CENF to gather the European initiatives to increase the potential contributions and visibility of European neutrino groups.

Support slides

Future δ_{CP} sensitivity

7.8x10^21 PoT + 2012 systematics



T2K + reactor

Assumptions

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

ν_e appearance

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

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

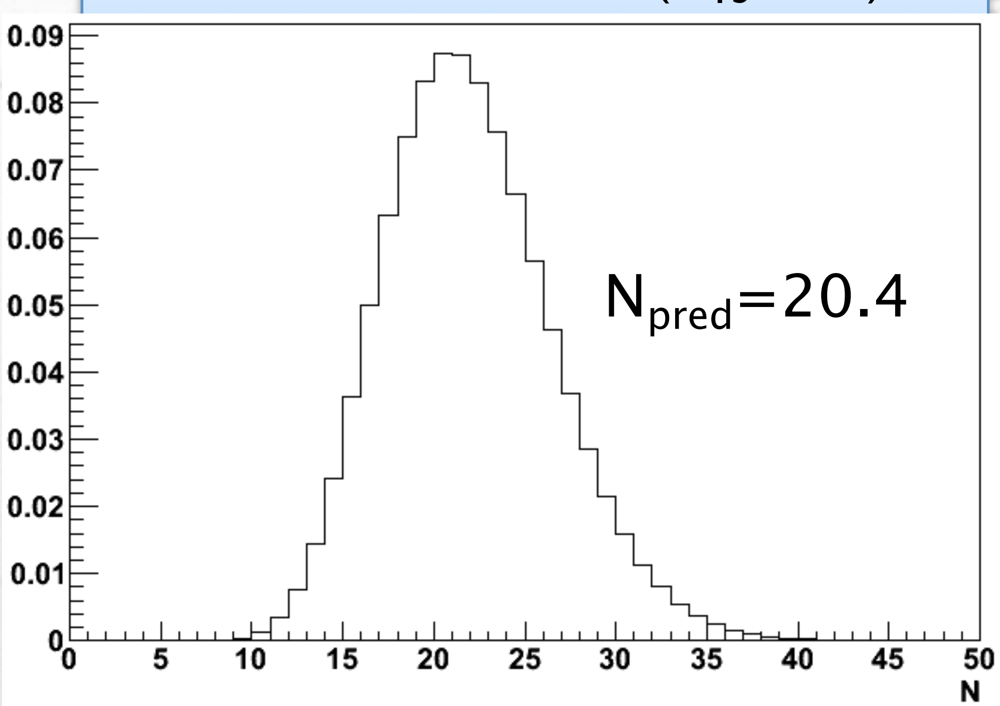
$\mathcal{L}_{norm}$ → $Poisson(N_{obs})_{\text{mean}=N_{pred}}$

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

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

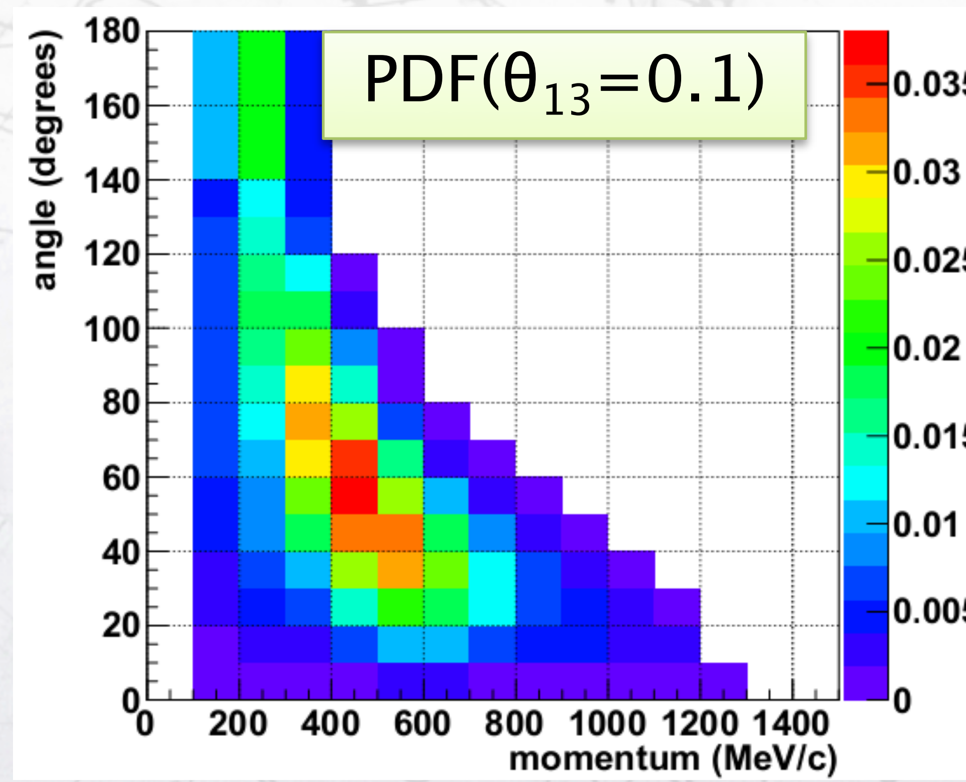
$\mathscr{L}_{shape}$ is the product of the probabilities that each event has (p_i, θ_i). φ: Predicted p-θ distribution (PDF) .

Poisson distribution (θ_{13}=0.1)



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



ν_e appearance

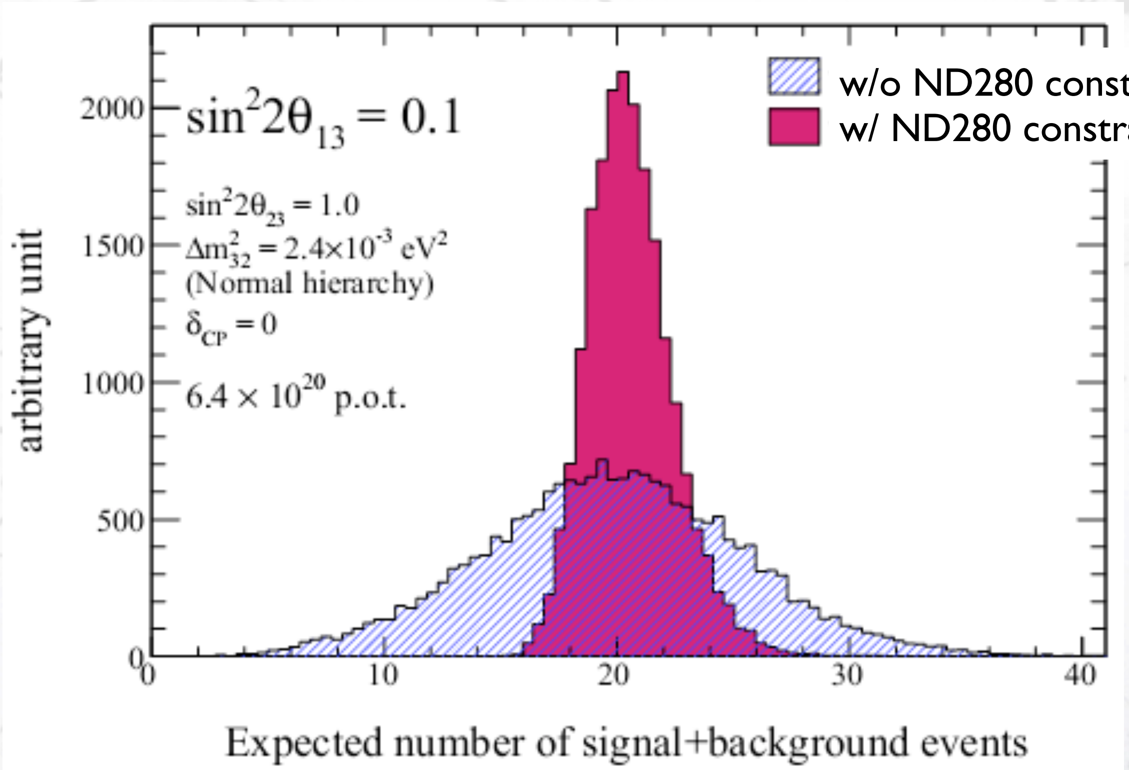
6.4×10^{20} PoT

Event prediction

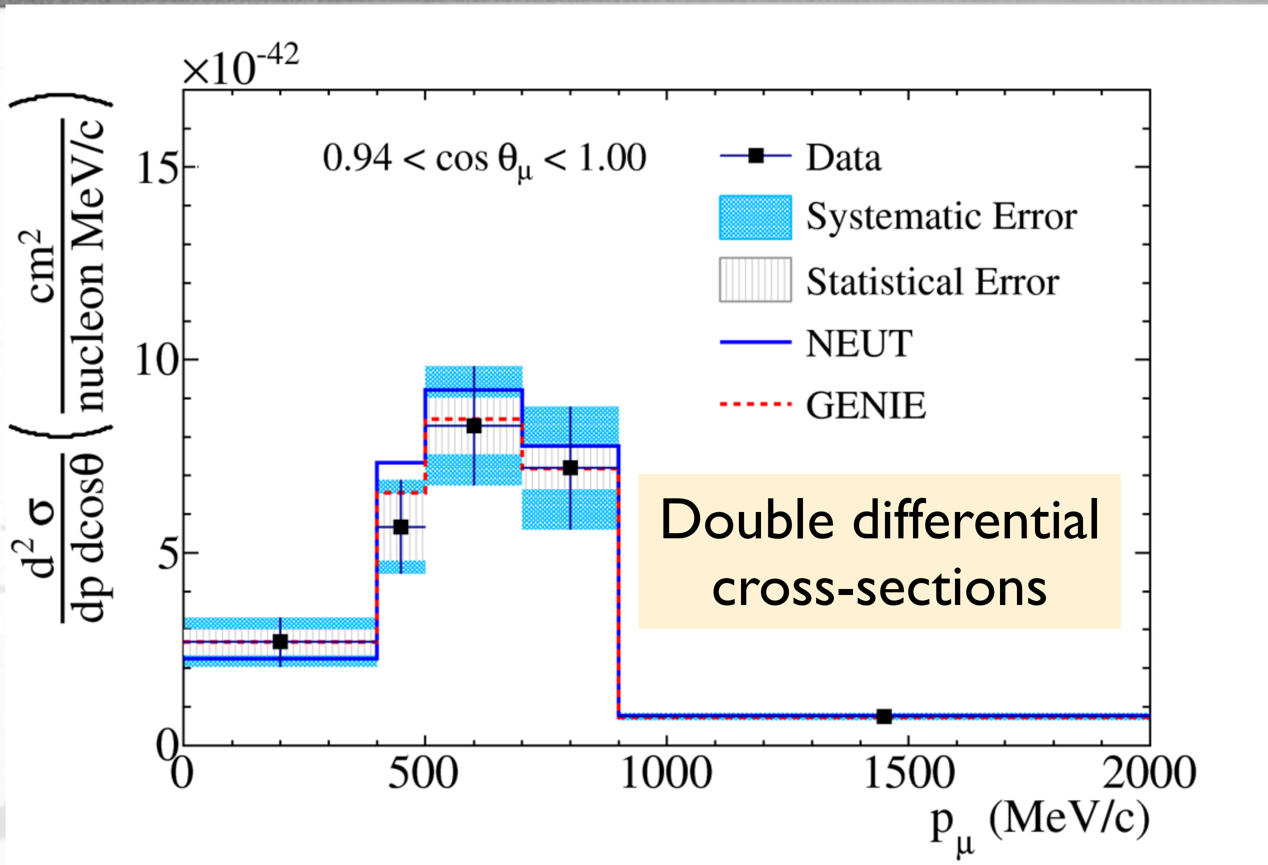
Event cath.	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
ν_e signal	0,38	16,42
ν_e back.	3,17	2,93
ν_μ back.	0,89	0,89
$\nu_\mu + \nu_e$ back.	0,20	0,19
Total	4,64	20,44

Systematic error

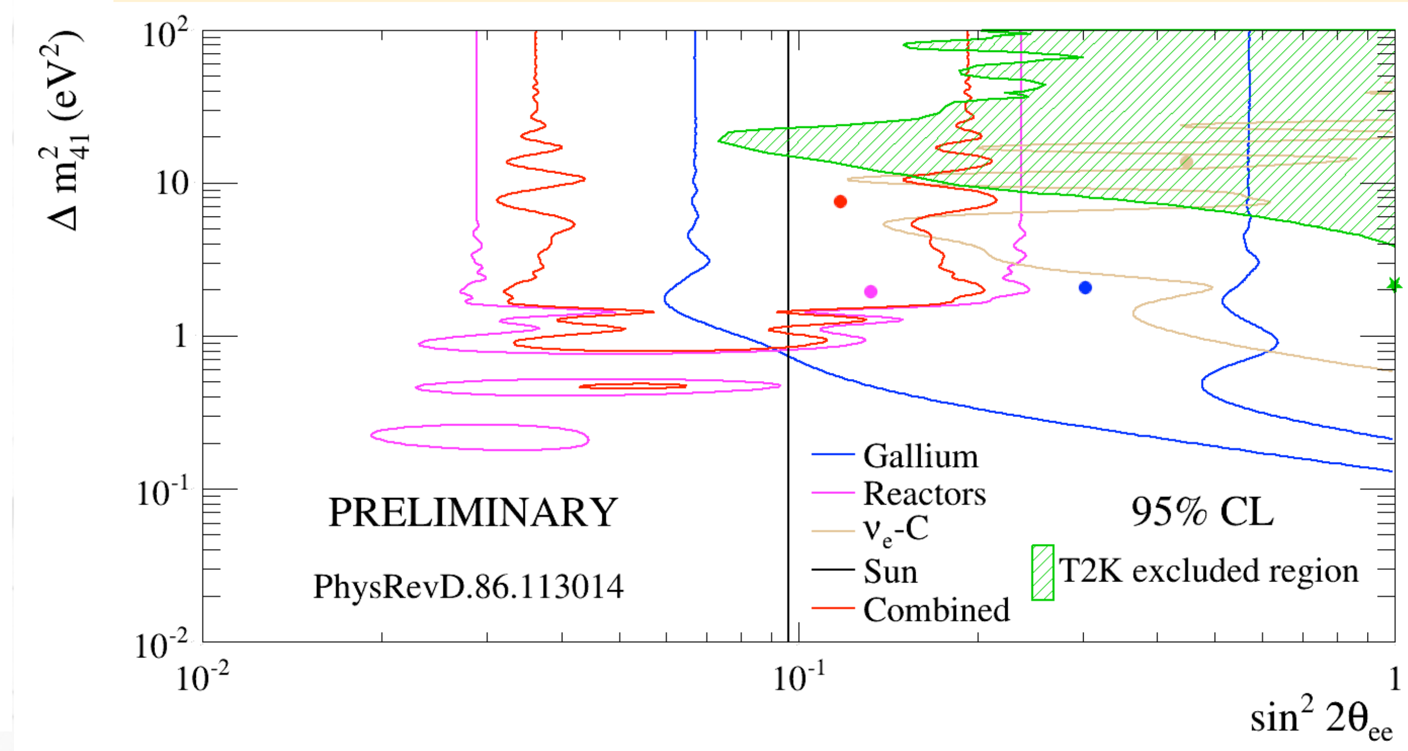
Error source	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
Beam flux and ν int	4,9%	3,0%
Far detector	6,7%	7,5%
+FSI+SI+PN	7,3%	3,5%
Total	**11,1%**	**8,8%**
Total(2012)	13,0%	9,9%

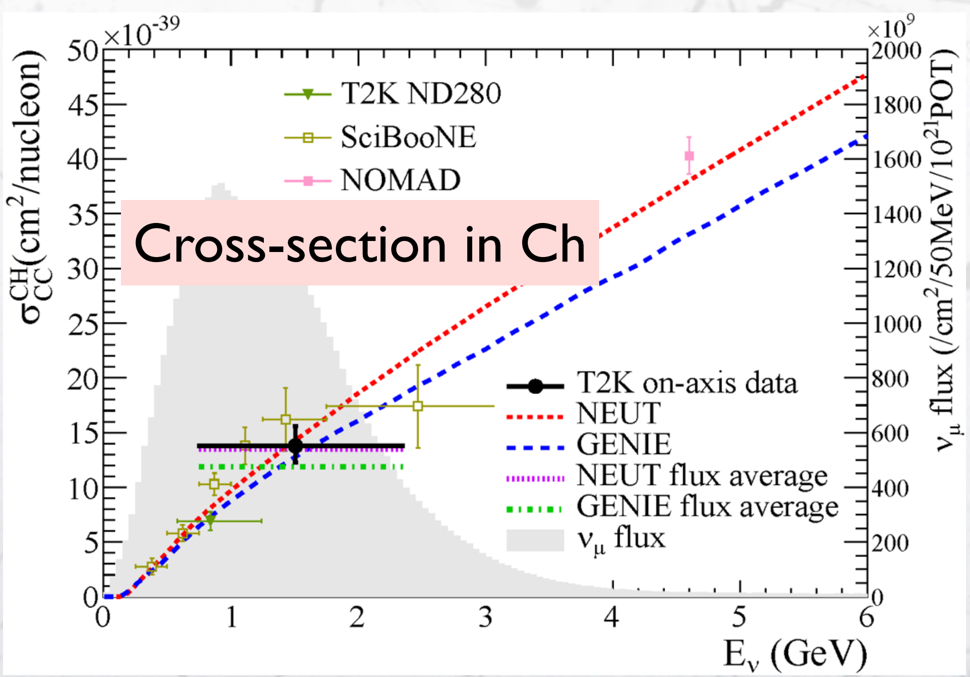


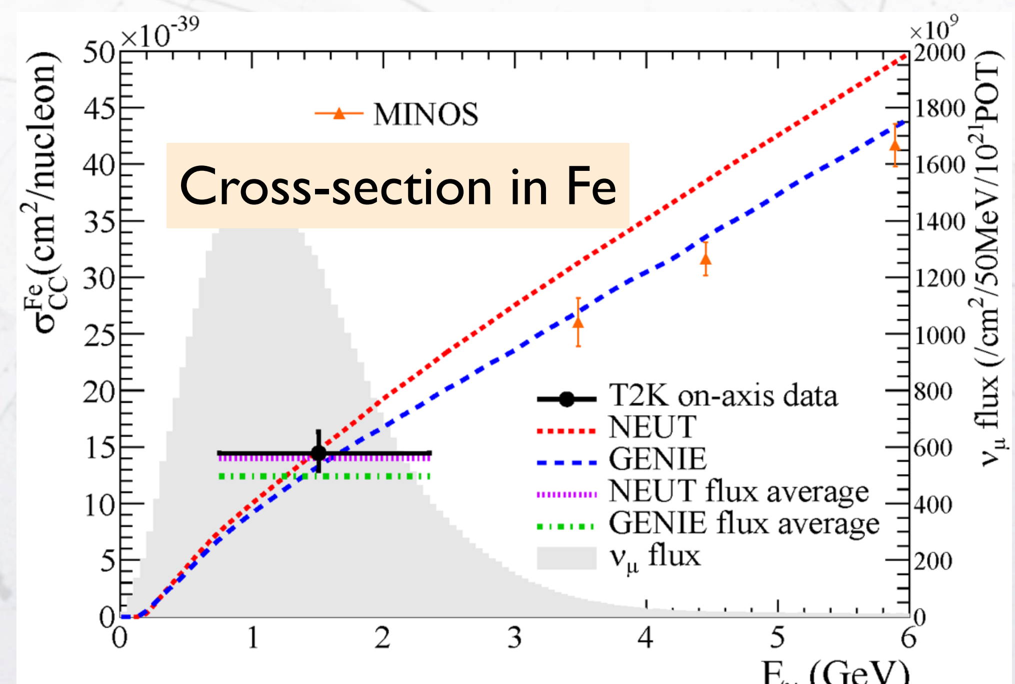
ND280 other analysis



ν_e disappearance for sterile searches

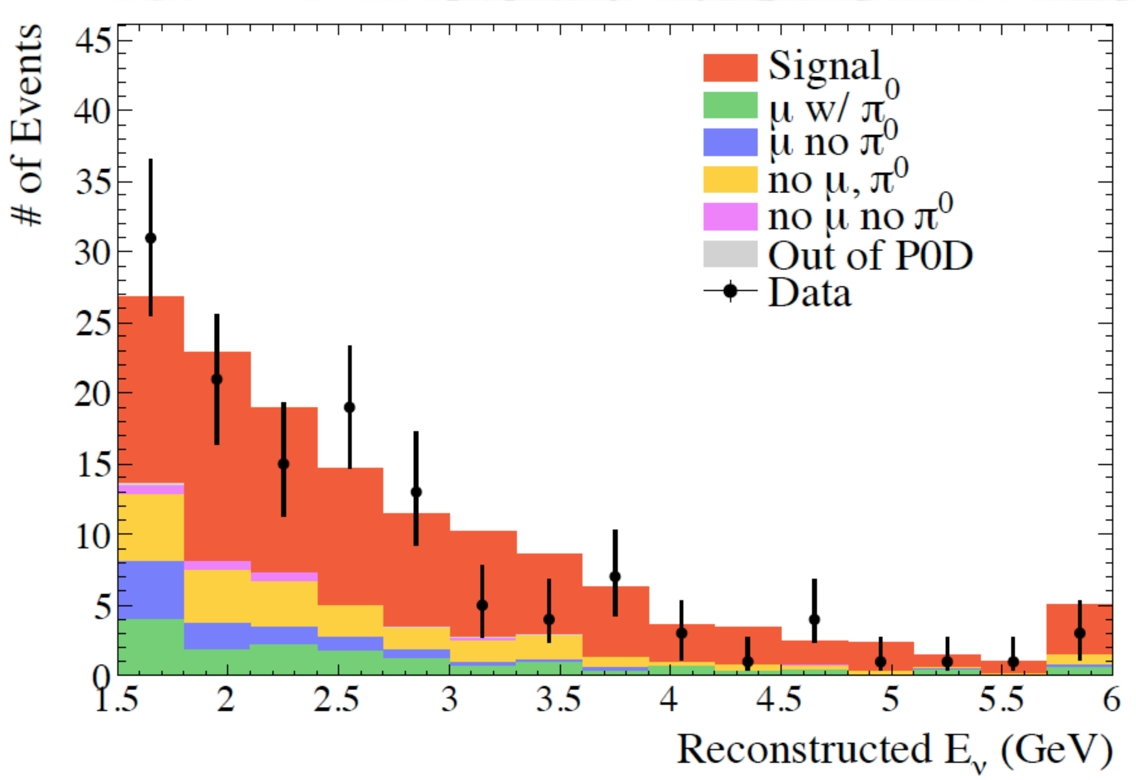


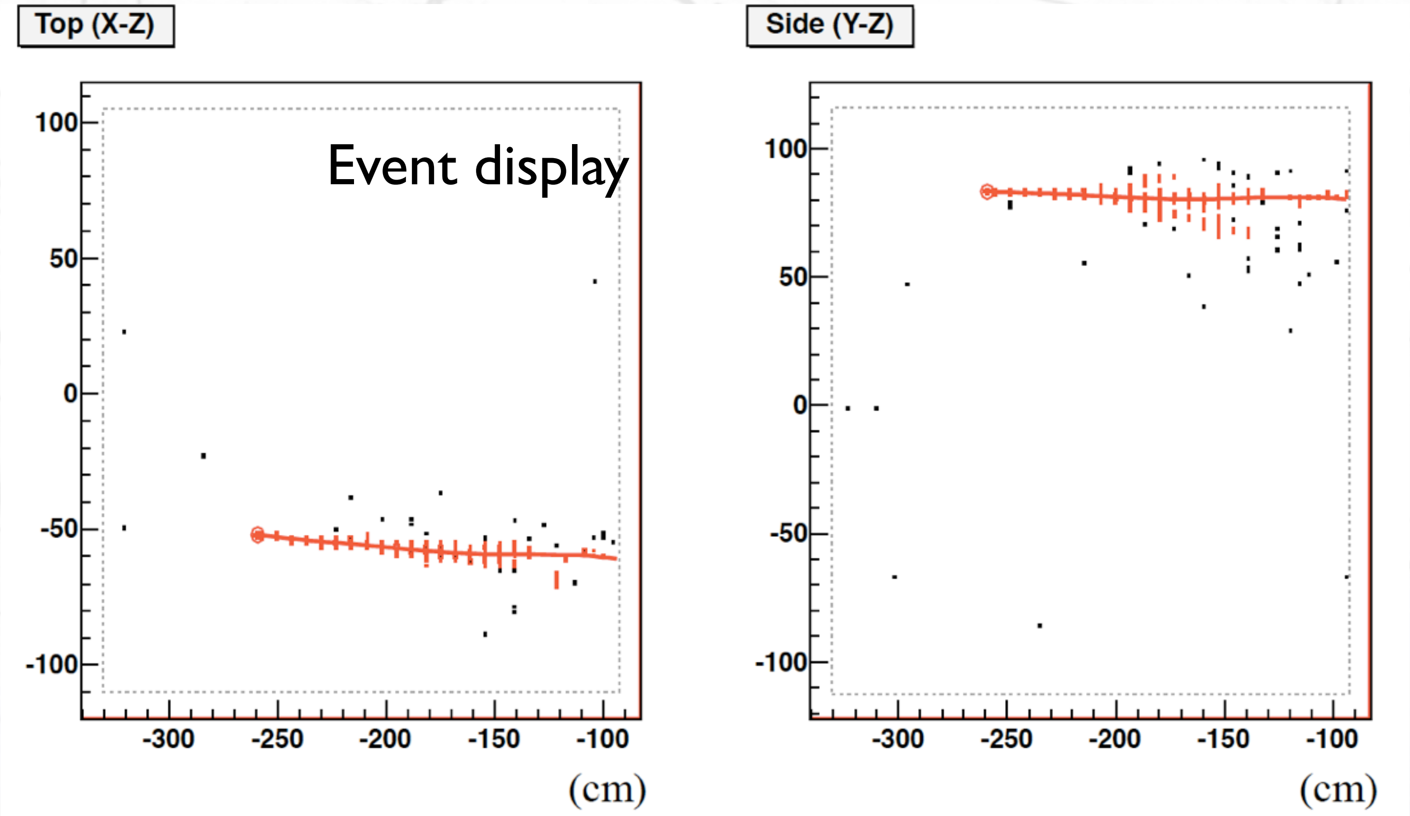




Off-axis: ν_e analysis

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





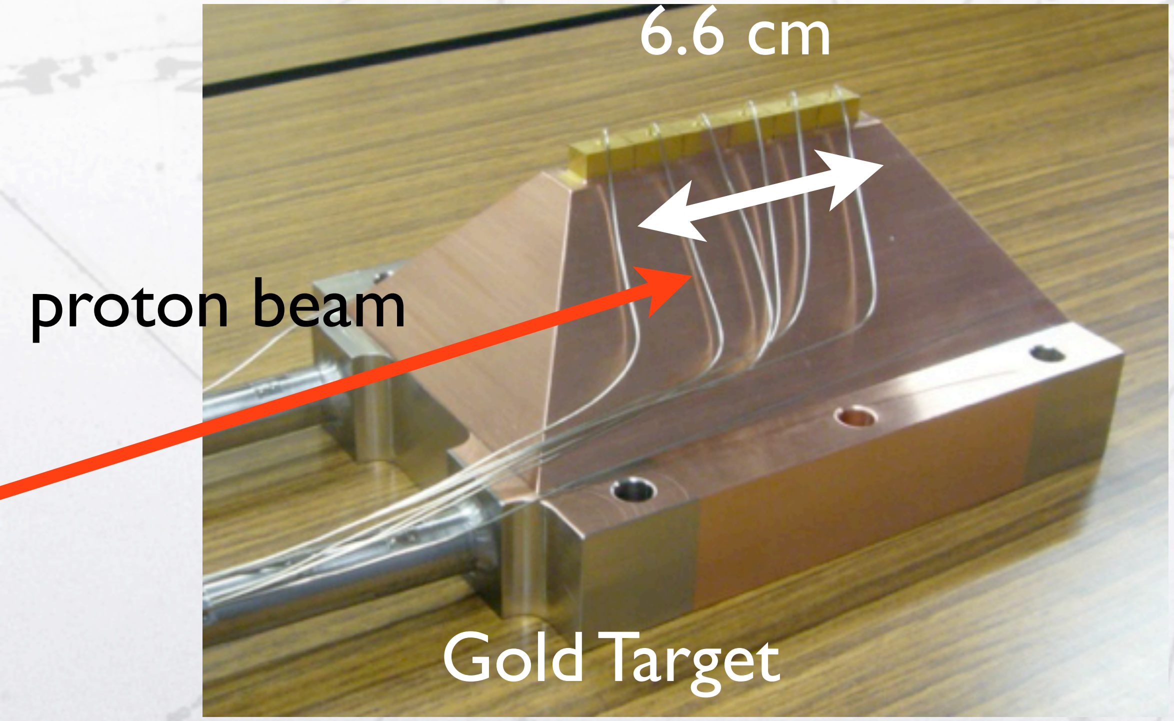
$$\frac{Data - Back_{MC}}{Sign_{MC}} = 0.91 \pm 0.13(stat) \pm 0.18(det) \pm 0.13(flux)$$

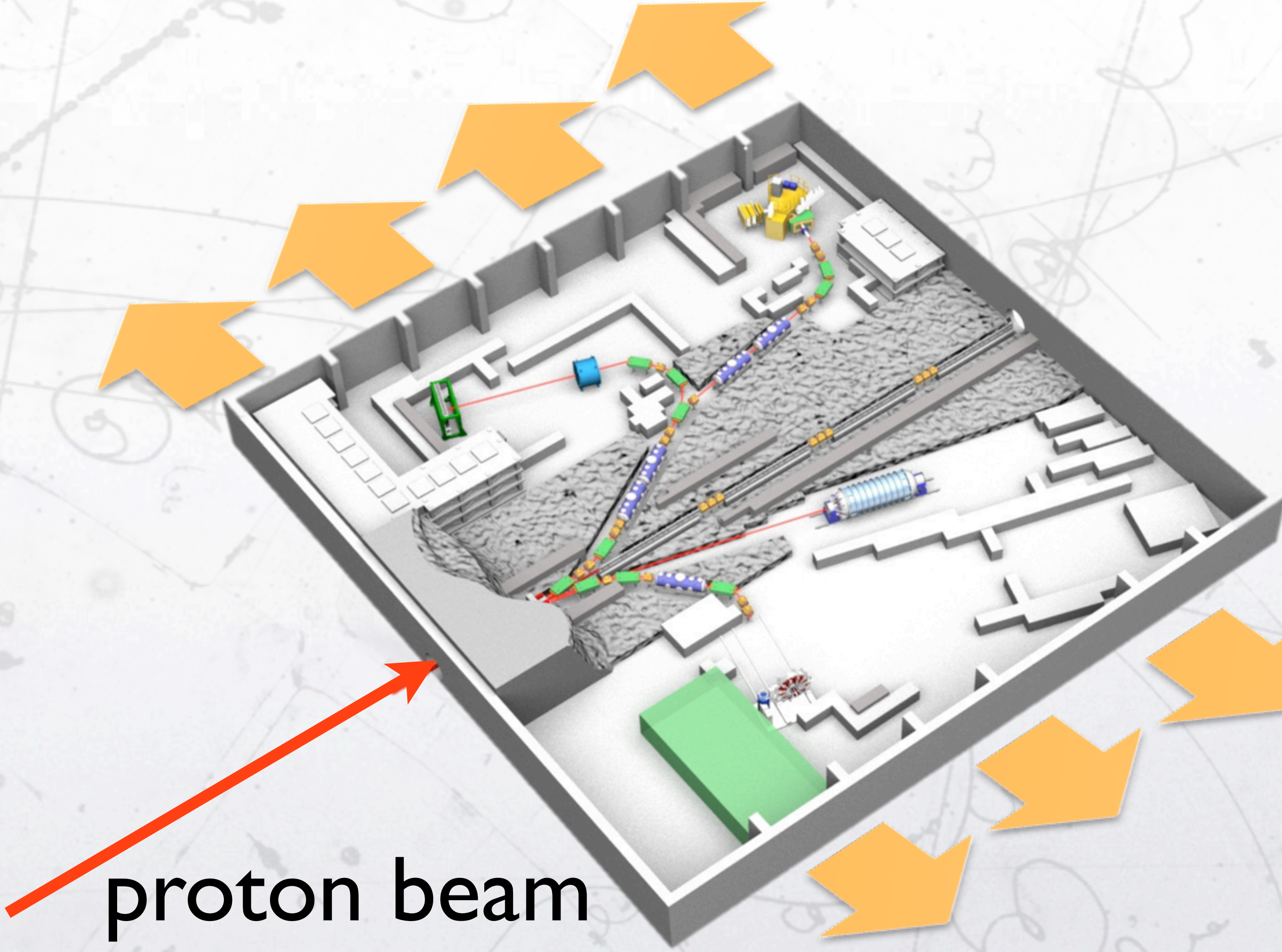
In good agreement with the tracker ν_e measurement

J-PARC accident

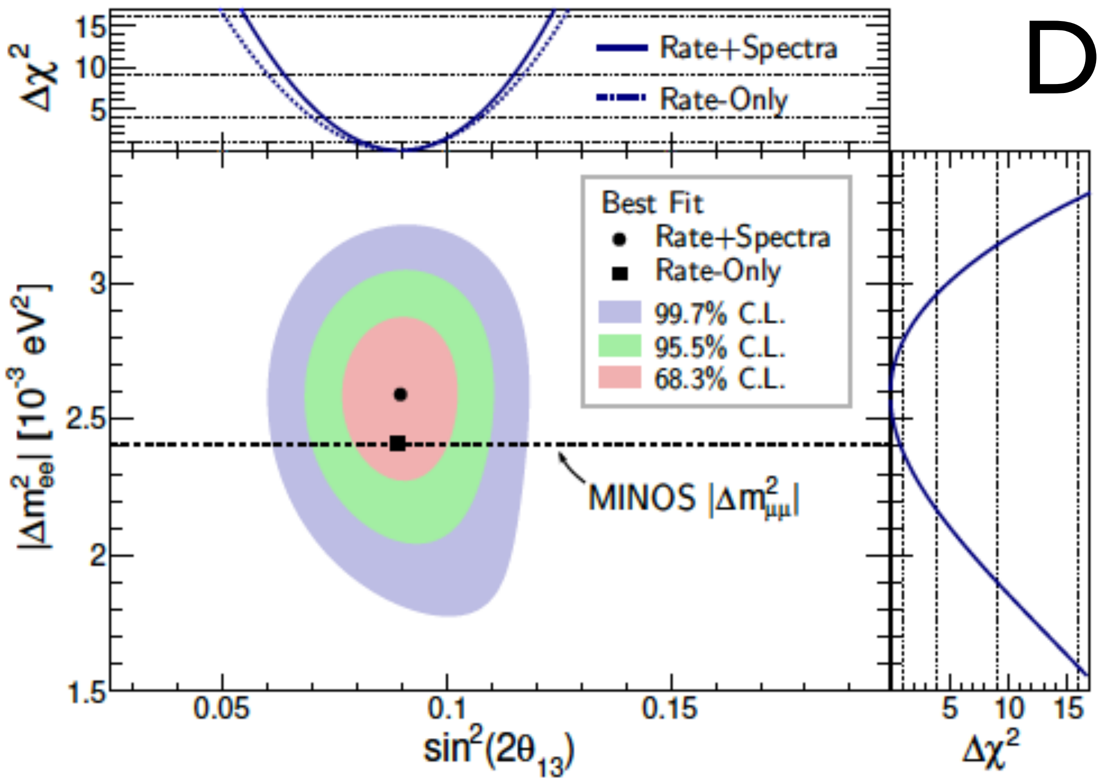
11:55 on May 23

- An abnormal proton beam was injected to the gold target.
- The target heated up to a extraordinarily high temperature.
- Radioactive material was released from the target.
- The radioactive material was leaked into the HD hall: xWorkers were exposed to radiation.
- The radioactive material was released to the outside of the radiation controlled area and to the environment outside of the HD hall.





θ_{13}: other results



Daya-Bay result NuFact'13

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

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{DoF} = 162.7/153$$

Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

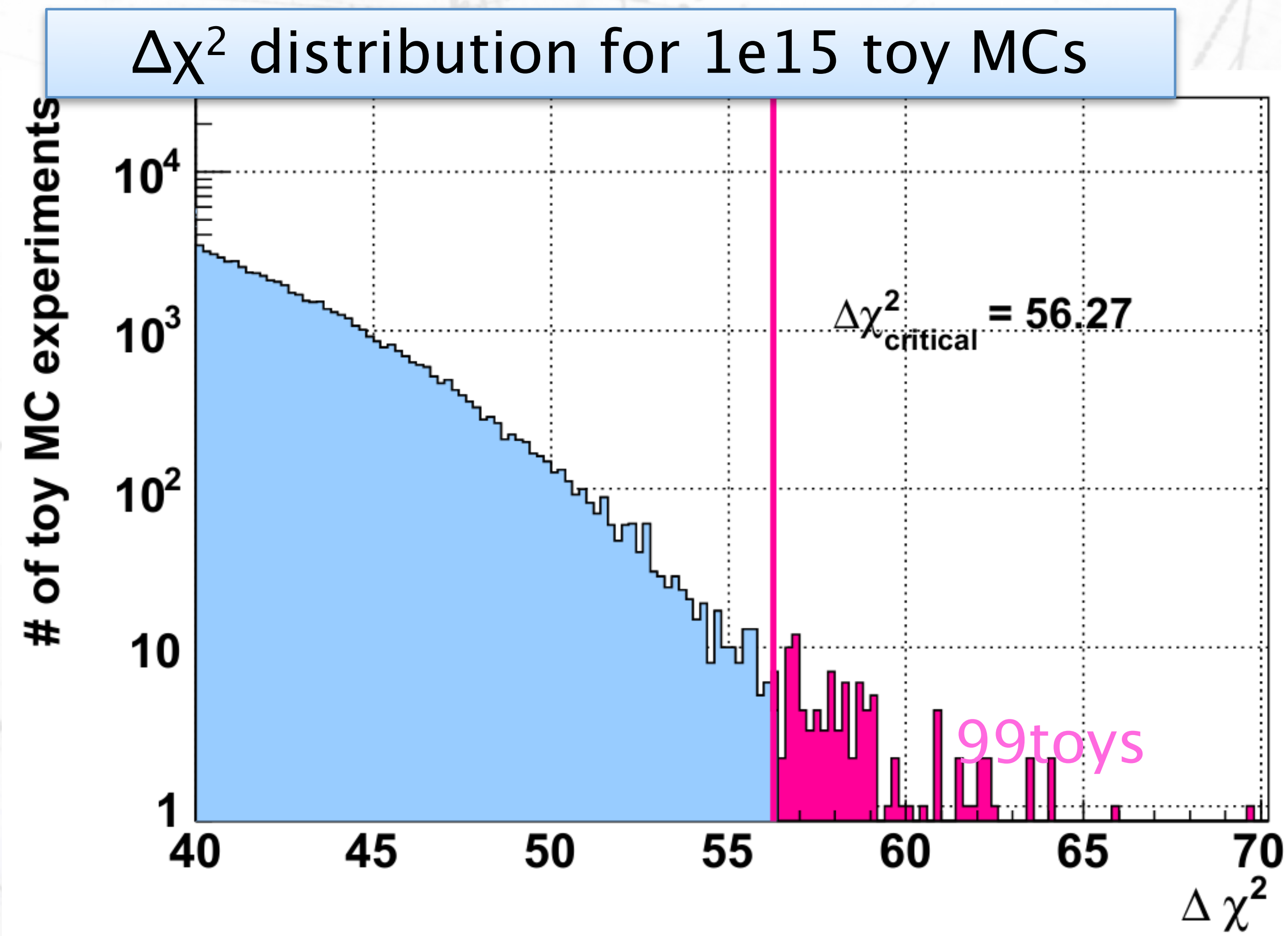
	Normal MH Δm^2_{32} $[10^{-3}\text{eV}^2]$	Inverted MH Δm^2_{32} $[10^{-3}\text{eV}^2]$
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.12}_{-0.09}$

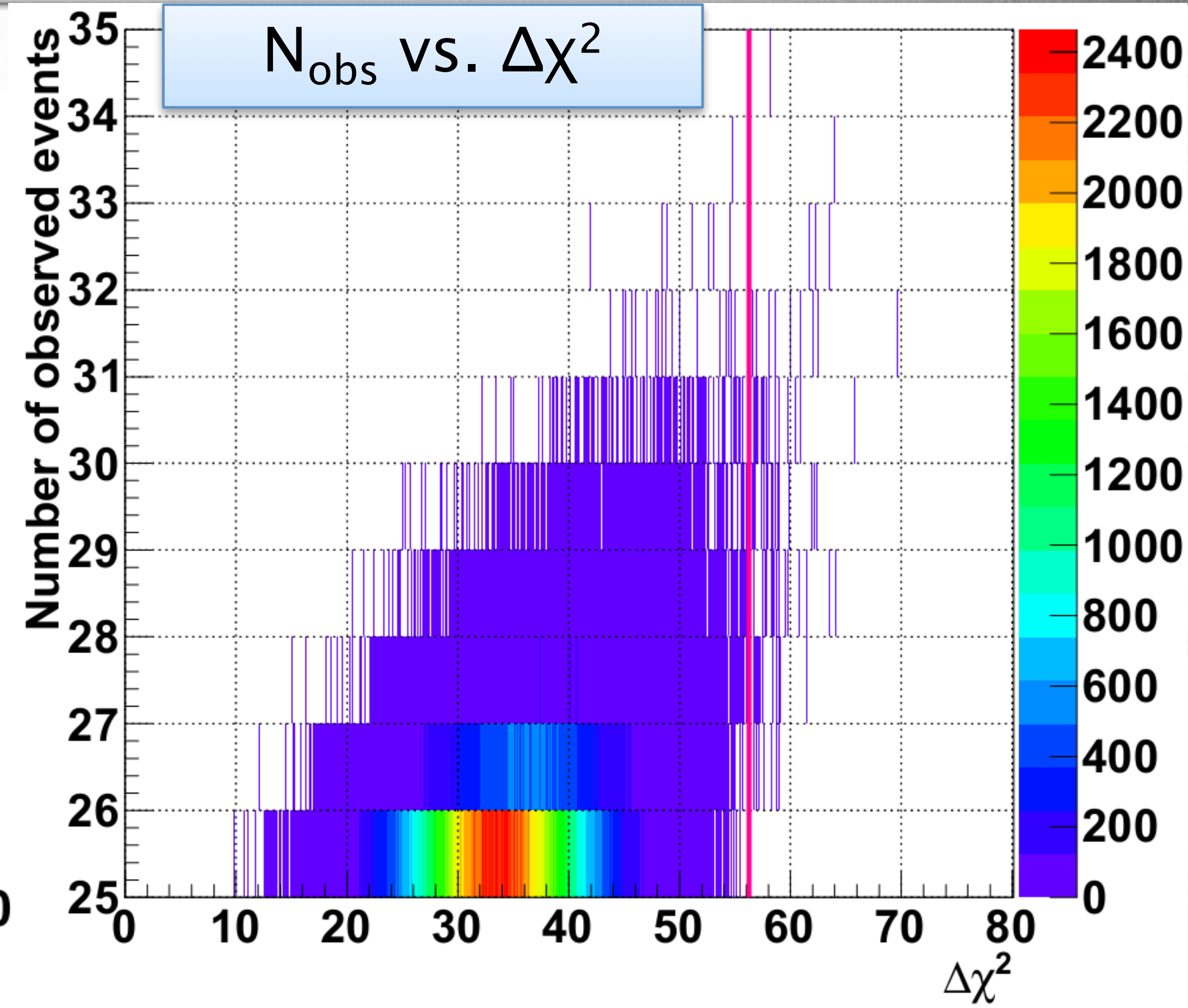
[João, NuFact2013]

Reactor experiments measure θ_{13} with no degeneracies.

ν_e analysis

p-value calculation





p-value is calculated as followings:

1. Generate 1e15 toy experiments with $\sin^2 2\theta_{13}=0.0$.
2. Fit each toy experiment to extract $-2\Delta\ln L$ ($=\Delta\chi^2$).
3. p-value is the fraction of toy experiments above $\Delta\chi^2_{data}$

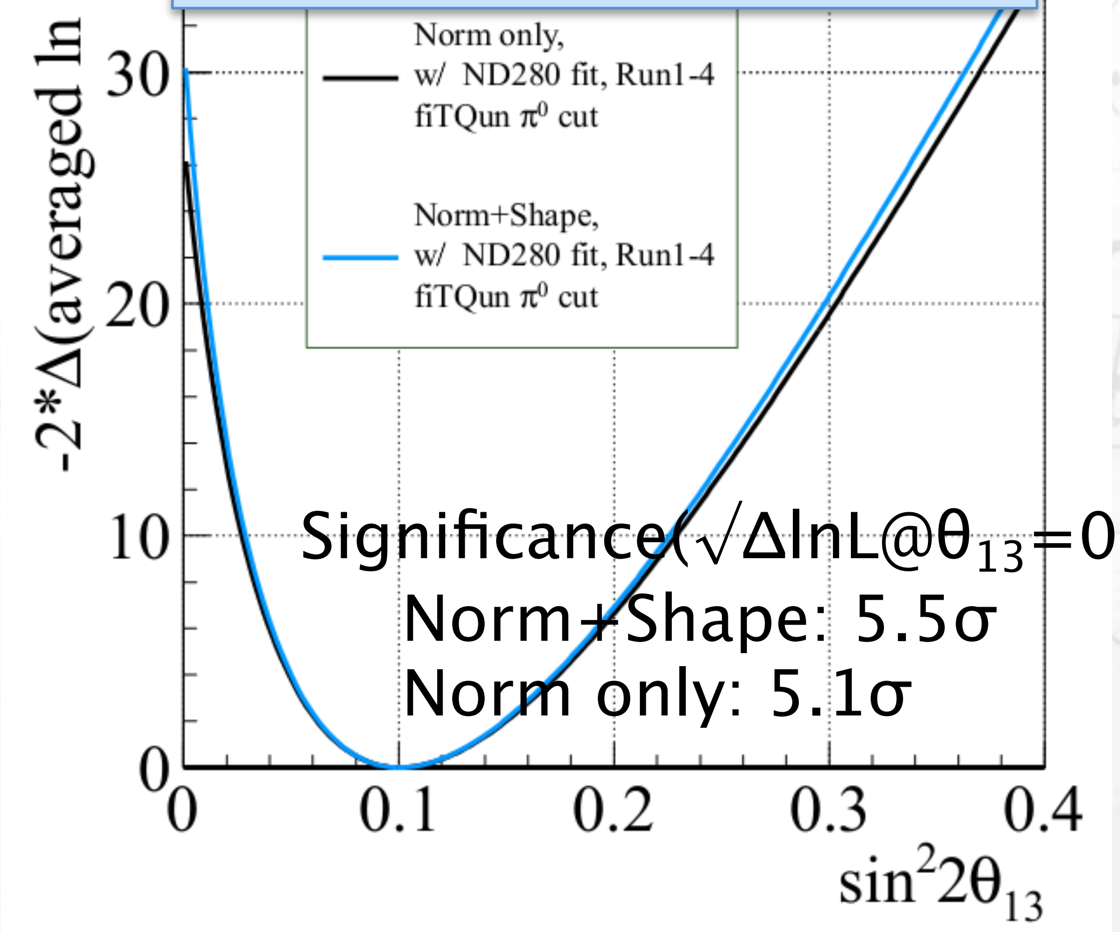
For the actual calculation, we use time saving method.

- We only fit the data if $N_{obs}>24$.
- We do not throw systematic parameters for 1e15 times.

Sensitivity checks

We fit the toy MC experiments (true $\sin^2 2\theta_{13}=0.1$) to check the sensitivity.
The averaged ln L curves ↓ are generated by averaging 4000 toy experiments.

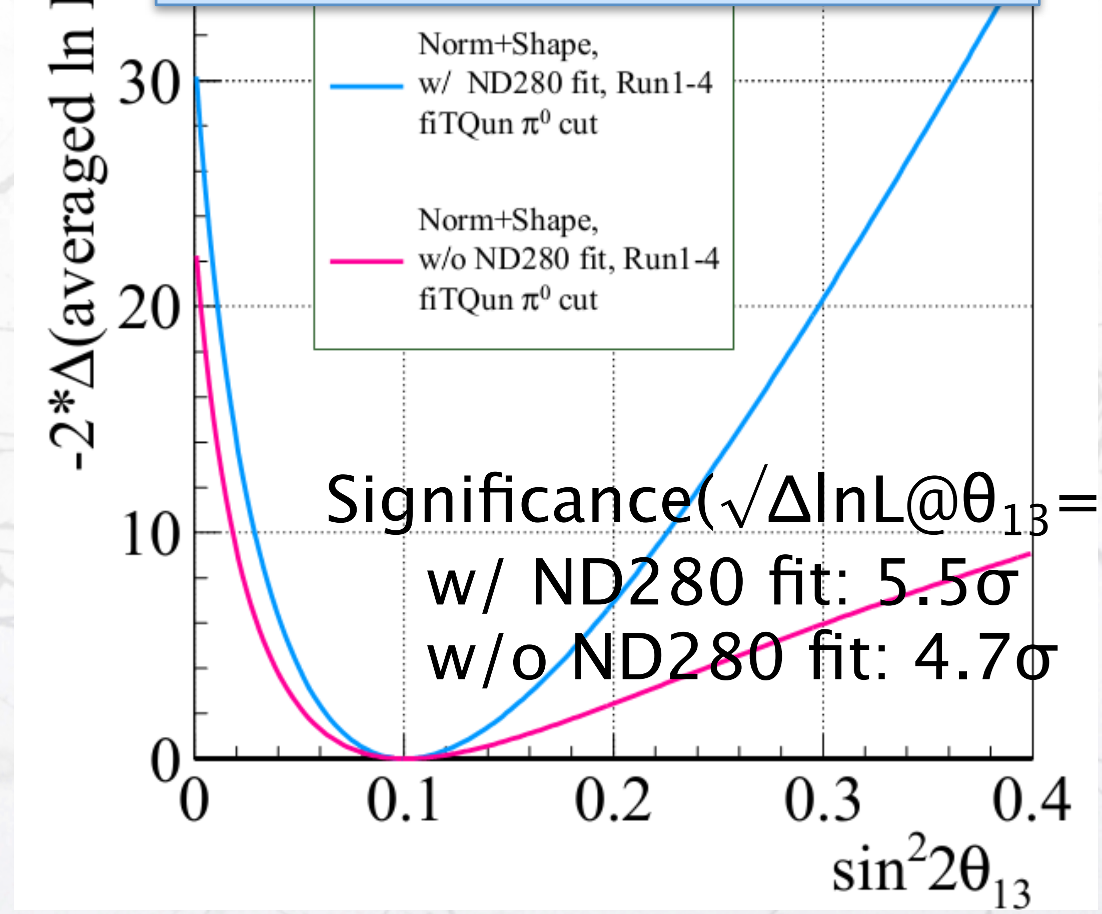
Norm only & Norm + Shape



Significance($\sqrt{\Delta \ln L}$@$\theta_{13}=0$):
Norm+Shape: 5.5σ
Norm only: 5.1σ

Effect of using shape information is not significant but important.

w/ ND280 fit & w/o ND280 fit

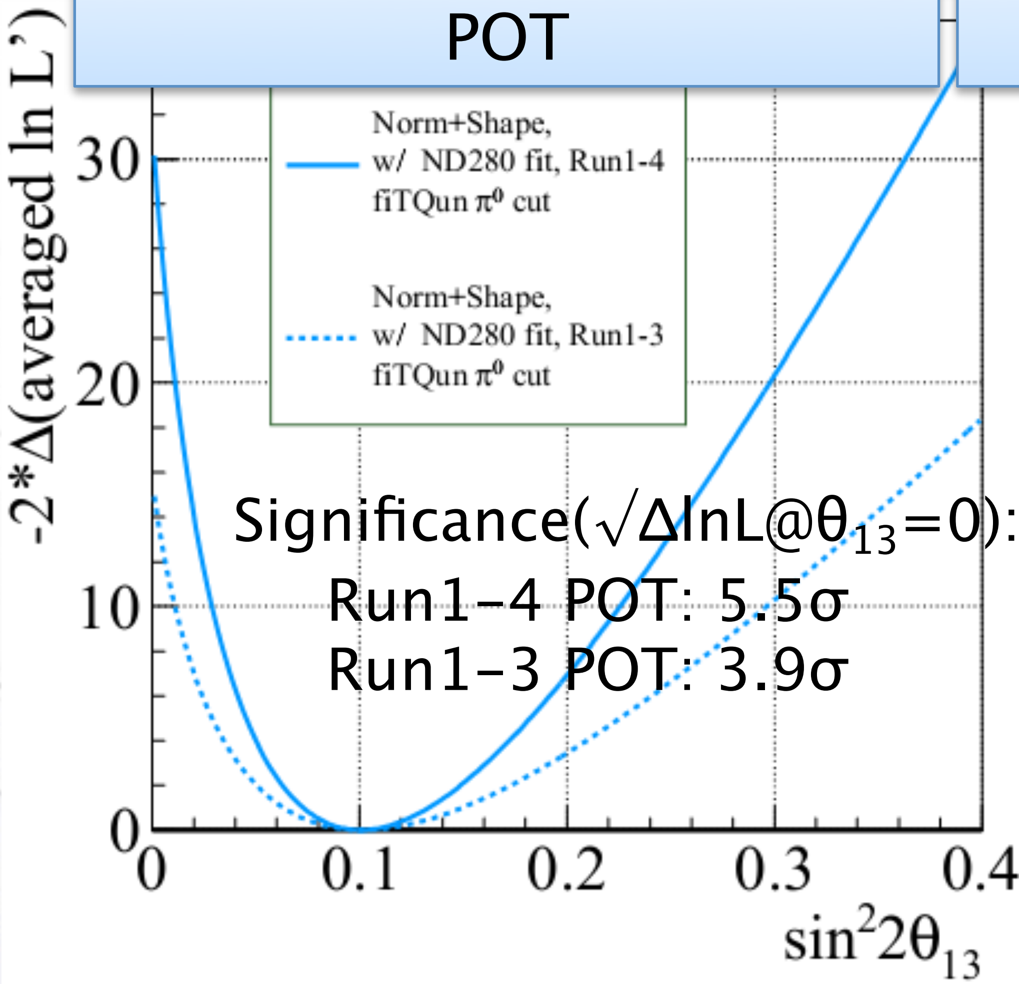


Significance($\sqrt{\Delta \ln L}$@$\theta_{13}=0$):
w/ ND280 fit: 5.5σ
w/o ND280 fit: 4.7σ

ND280 fit makes relatively large improvement.

Sensitivity checks

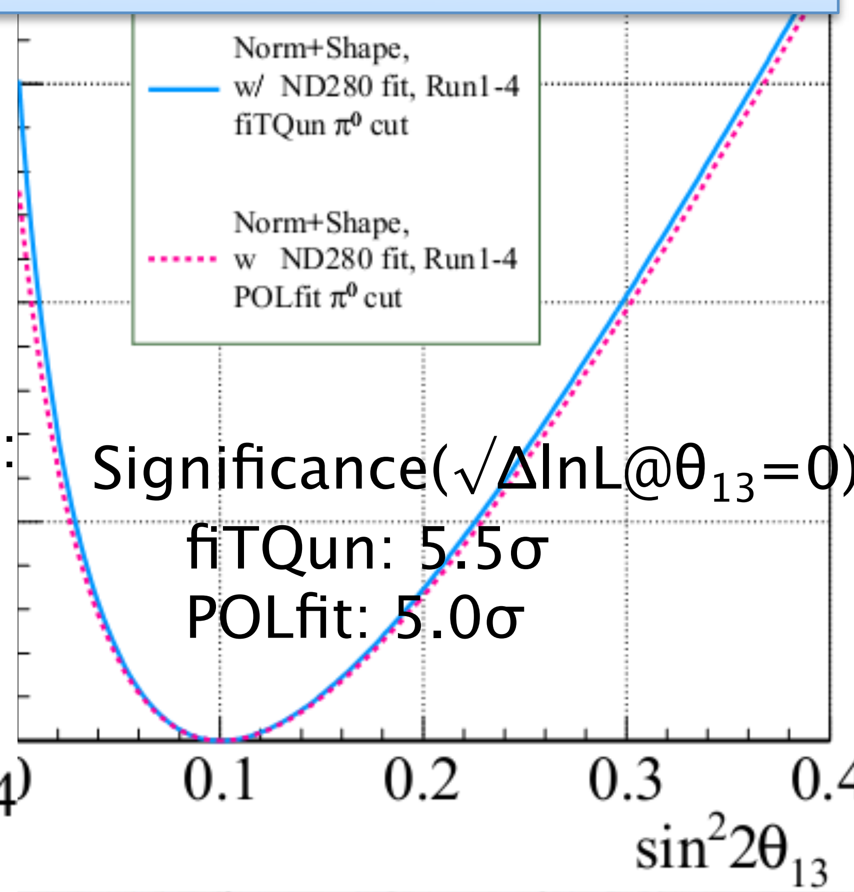
Run1-4 POT & Run1-3 POT



Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
Run1-4 POT: 5.5σ
Run1-3 POT: 3.9σ

Significance becomes much larger by adding Run4.

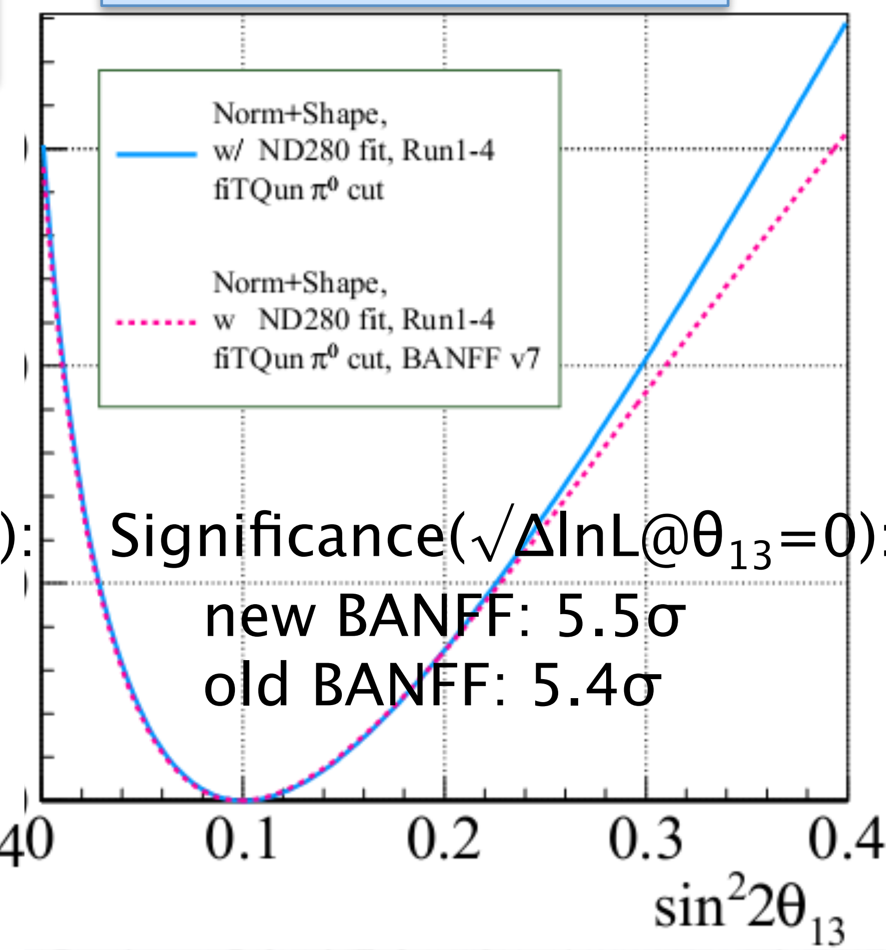
fiTQun π^0 cut & POLfit π^0 cut



Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
fiTQun: 5.5σ
POLfit: 5.0σ

Effect of using fiTQun is not significantly large but important.

old & new BANFF



Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
new BANFF: 5.5σ
old BANFF: 5.4σ

Significance is not much different for toy MC, because the N_{exp} become smaller with new BANFF while the errors are improved.

Fake data fit results

True values

Data set	D	E	F	G
Δm^2_{21} (eV^2)	7.6×10^{-5}	7.6×10^{-5}	7.6×10^{-5}	7.6×10^{-5}
Δm^2_{32} (eV^2)	-2.5×10^{-3}	2.5×10^{-3}	-2.7×10^{-3}	2.4×10^{-3}
$\sin^2\theta_{12}$	0.35	0.32	0.32	0.32
$\sin^2\theta_{23}$	0.42	0.62	0.50	0.50
$\sin^2\theta_{13}$	0.018	0.039	0.010	0.0251
$\sin^2 2\theta_{13}$	0.0707	0.150	0.0396	0.0980
δ_{CP} (radians)	4.712	0.0	3.14159	0.0
N_{obs}	18	35	8	27

Four different sets of fake data sets are prepared by Roger. The true values were blinded.

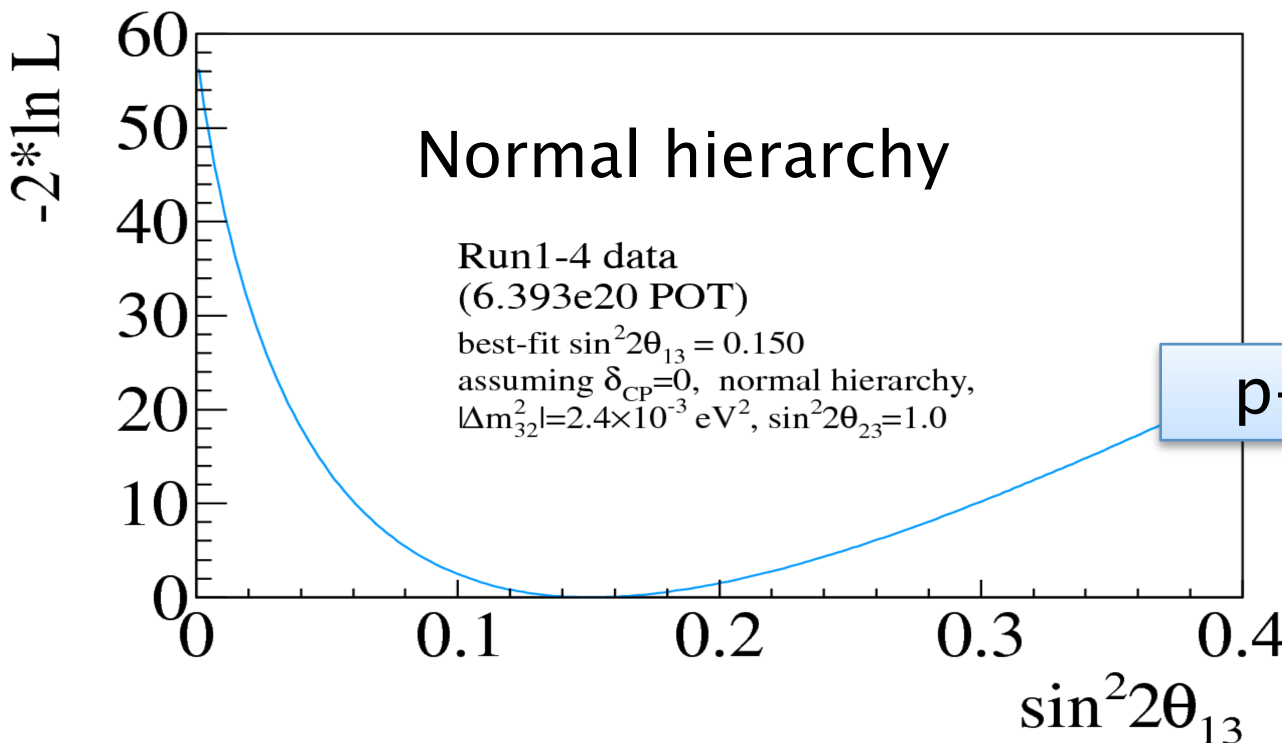
Fitted values

set		Normal hierarchy	Inverted hierarchy
	best-fit	0.090	0.110
set D	68% C.L. allowed	$0.063 < x < 0.121$	$0.077 < x < 0.147$
	90% C.L. allowed	$0.048 < x < 0.145$	$0.060 < x < 0.175$
	best-fit	0.174	0.210
set E	68% C.L. allowed	$0.139 < x < 0.216$	$0.168 < x < 0.259$
	90% C.L. allowed	$0.118 < x < 0.247$	$0.144 < x < 0.294$
	best-fit	0.026	0.032
set F	68% C.L. allowed	$0.010 < x < 0.046$	$0.012 < x < 0.057$
	90% C.L. allowed	$0.002 < x < 0.062$	$0.002 < x < 0.077$
	best-fit	0.140	0.170
set G	68% C.L. allowed	$0.107 < x < 0.178$	$0.132 < x < 0.216$
	90% C.L. allowed	$0.089 < x < 0.206$	$0.110 < x < 0.249$

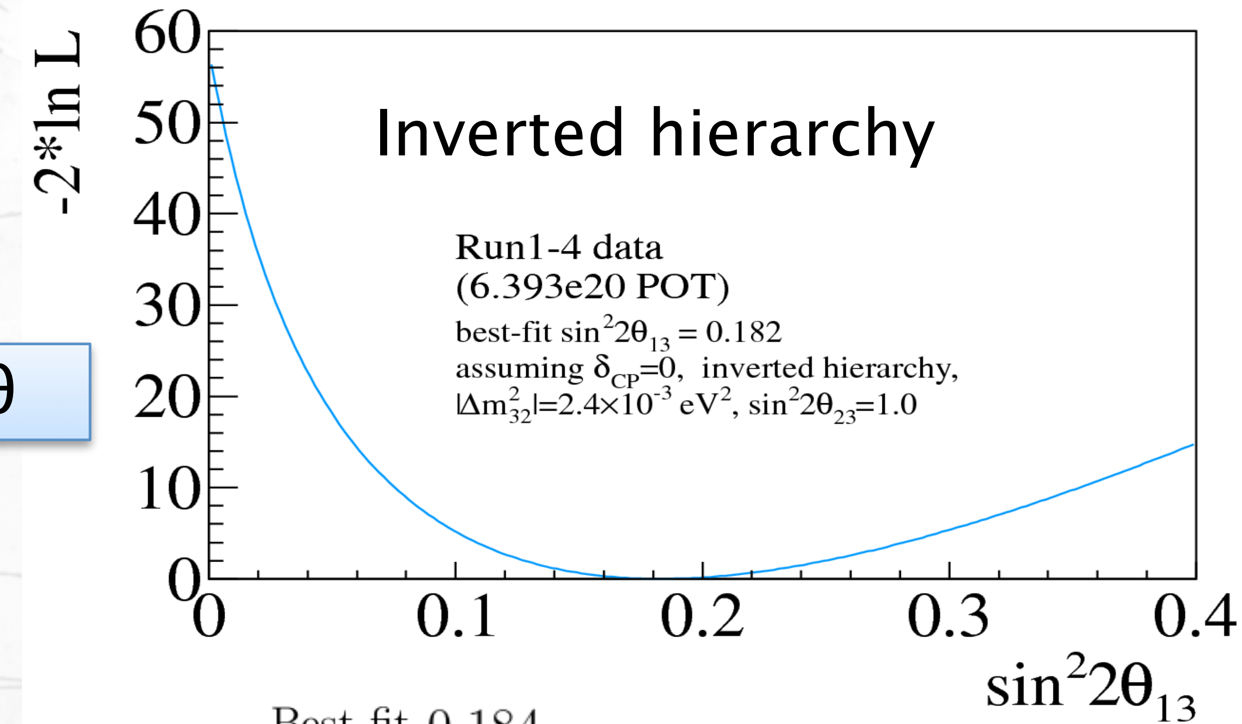
The fitted values were consistent with the true values. p-θ and E_{rec} were also consistent with each other.

(Osc. params other than $\sin^2 2\theta_{13}$ are fixed in the fit. i.e. $\sin^2 2\theta_{23}=1.0$, $\Delta m^2_{32}=2.4\times10^{-3}$, $\delta=0$)

Likelihood curves for Run1-4 data

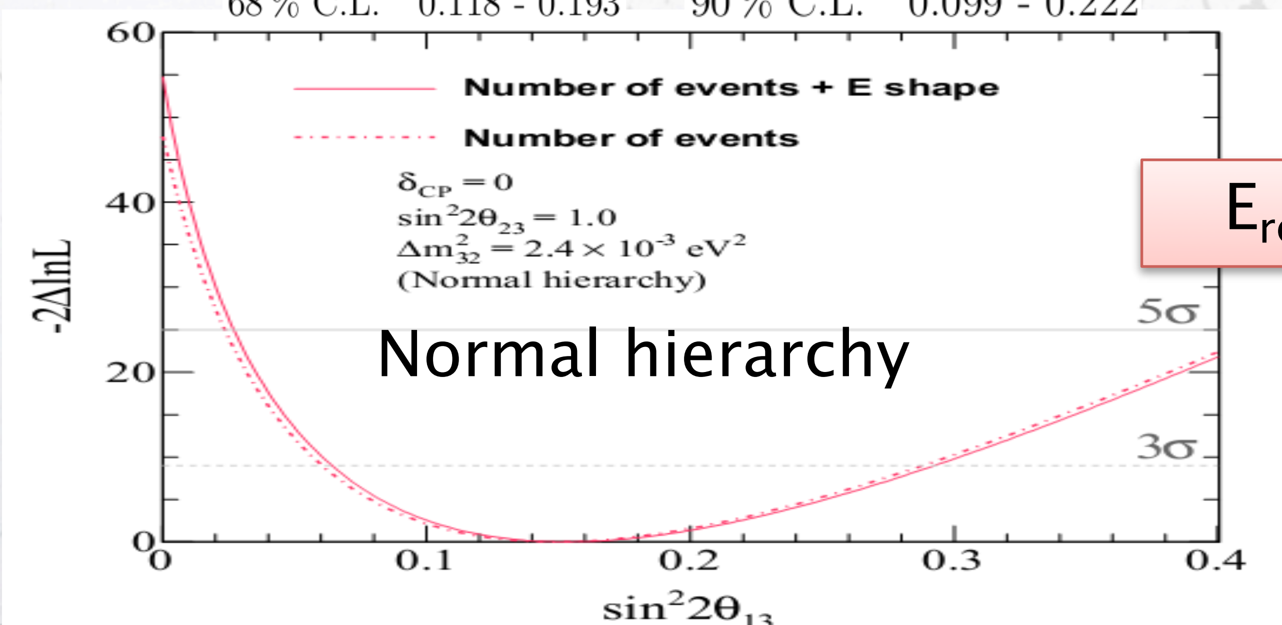


p−θ

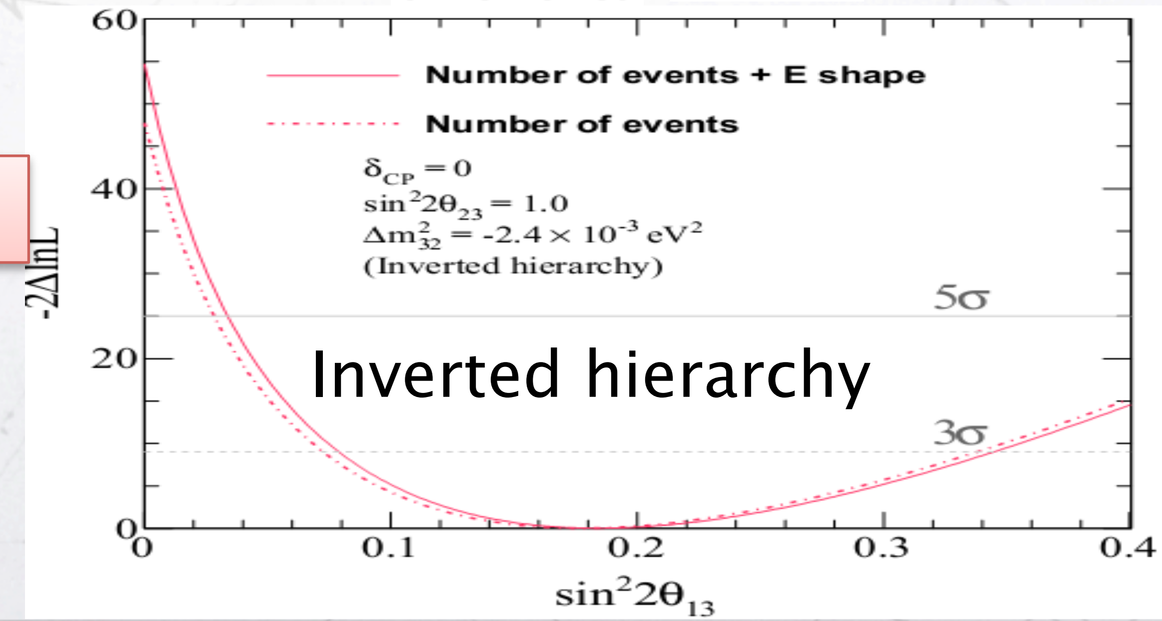


Best fit 0.152
68 % C.L. 0.118 - 0.193 90 % C.L. 0.099 - 0.222

Best fit 0.184
68 % C.L. 0.143 - 0.230 90 % C.L. 0.120 - 0.264

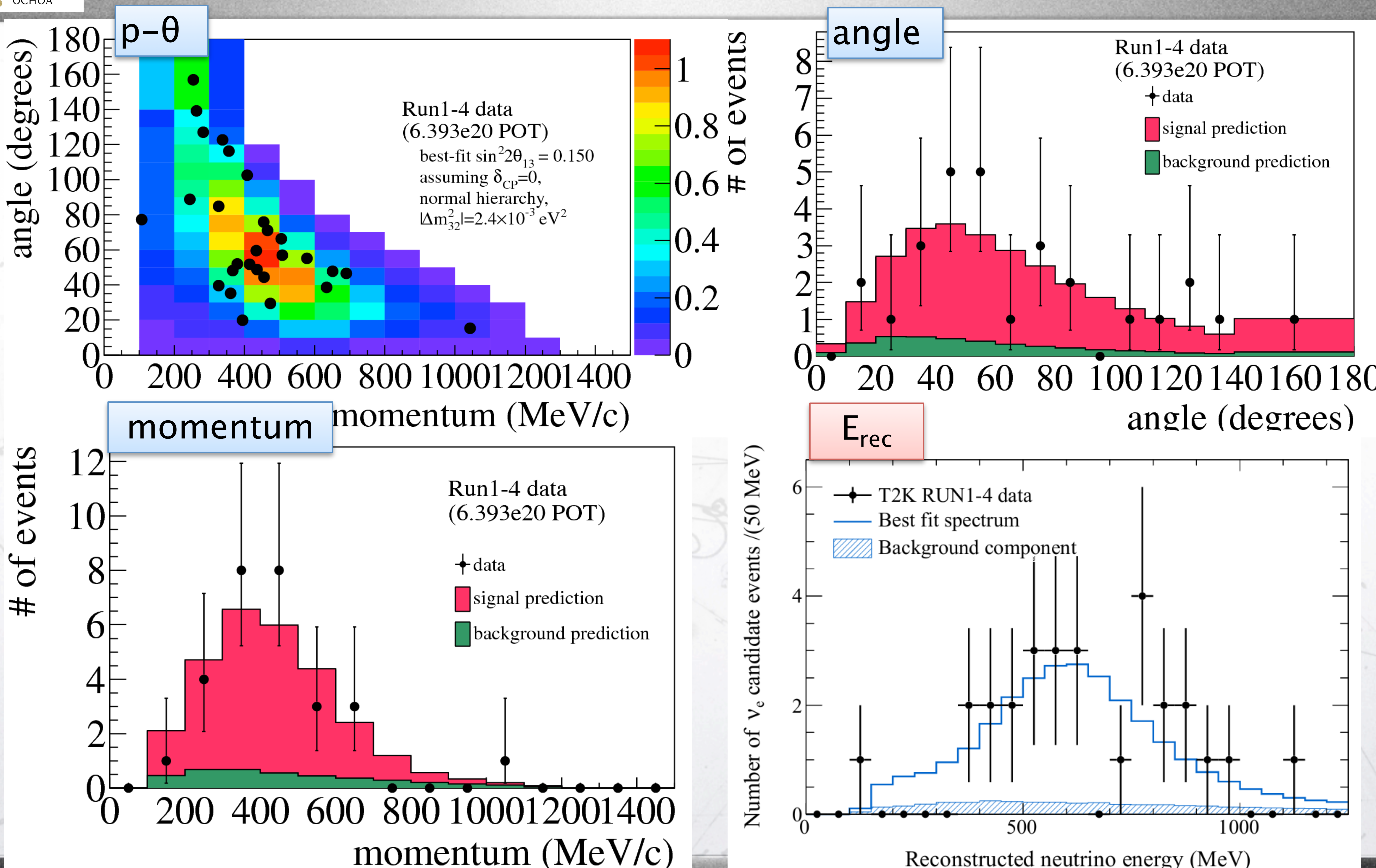


E_{rec}

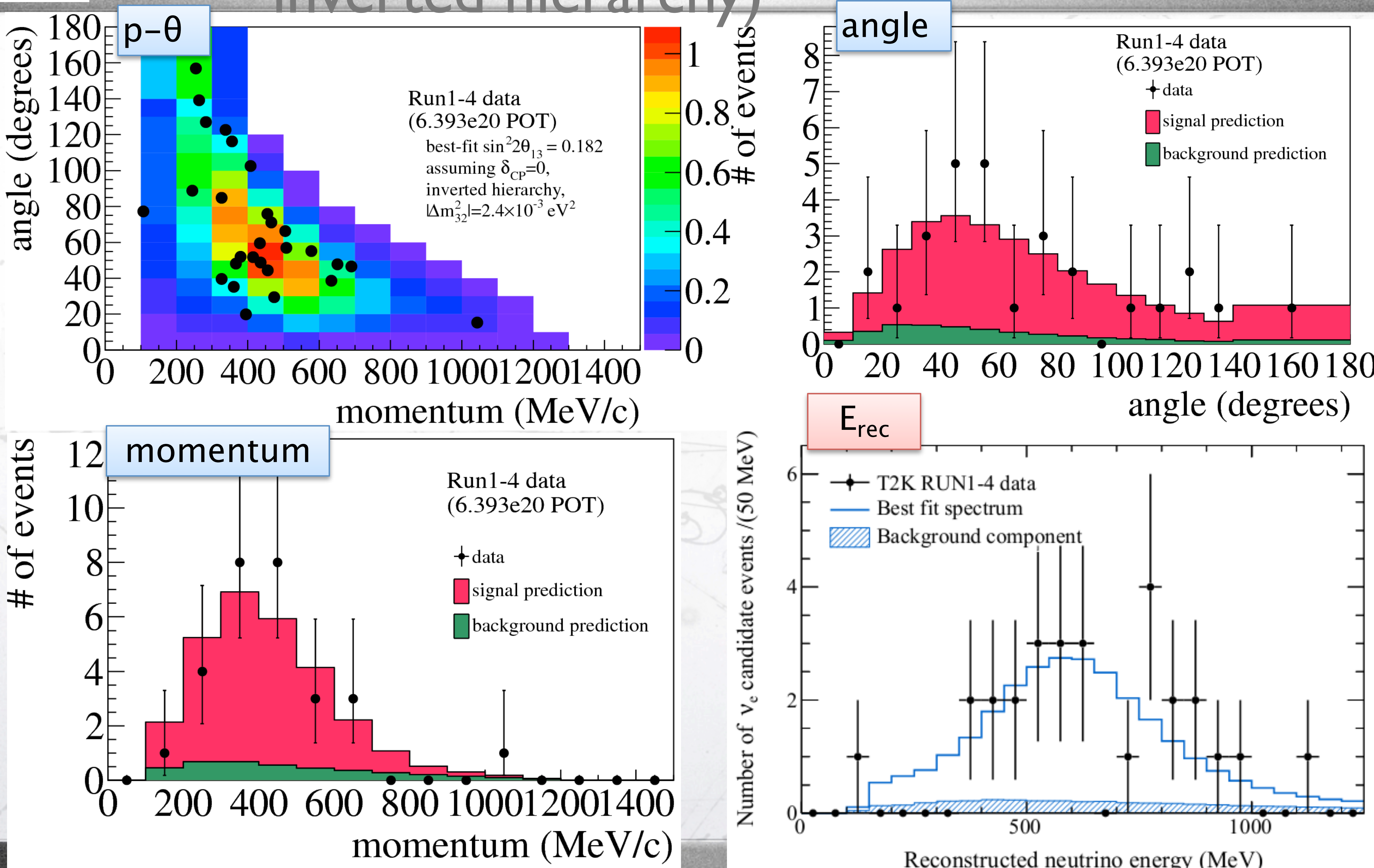


(summary table will be shown later.)

Best fit distributions (Run1-4, normal



Best fit distributions (Run1-4, inverted hierarchy)



Fit summary table

	Run1-4 (p-θ)	Run1-4 (E_{rec})	Run4 only	Run1-3 (2013 analysis)	Run1-3 (2012 analysis)
POT	6,39E+20	6,39E+20	3,38E+20	3,01E+20	3,01E+20
Observed number of events	28	28	17	11	11
Normal hierarchy Best fit 90% C.L. 68% C.L.	0.150 0.097 - 0.218 0.116 - 0.189	0.152 0.099 - 0.222 0.118 - 0.193	0.180 0.105 - 0.280 0.131 - 0.237	0.112 0.050 - 0.204 0.072 - 0.164	0.088 0.030 - 0.175 0.049 - 0.137
Inverted hierarchy Best fit 90% C.L. 68% C.L.	0.182 0.119 - 0.261 0.142 - 0.228	0.184 0.120 - 0.264 0.143 - 0.230	0.216 0.129 - 0.332 0.160 - 0.283	0.136 0.062 - 0.244 0.088 - 0.198	0.108 0.038 - 0.212 0.062 - 0.167

Systematic errors for N_{exp}

(unit: %)

Black: 2013
Blue: 2012

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	10.6 10.8	7.3 7.5	11.6 11.9	7.5 8.1
M_A^{QE}	15.6 9.5	2.4 4.0	21.5 16.3	3.2 6.7
M_A^{RES}	7.2 4.5	2.1 3.9	3.3 2.0	0.9 1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1 4.9	4.8 3.8	9.3 7.9	6.3 6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9 5.1	2.4 3.5	4.2 5.2	2.0 3.5
NC1π^0 norm.	2.7 7.9	1.9 7.3	0.6 2.3	0.4 2.2
CC other shape	0.3 0.2	0.3 0.2	0.1 0.1	0.1 0.1
Spectral Function	4.7 3.3	4.8 3.3	6.0 5.7	6.0 5.7
p_F	0.1 0.3	0.1 0.3	0.1 0.0	0.1 0.0
CC coh. norm.	0.3 0.2	0.3 0.2	0.3 0.2	0.2 0.2
NC coh. norm.	1.1 2.1	1.1 2.0	0.3 0.6	0.2 0.6
NC other norm.	2.3 2.6	2.2 2.6	0.5 0.8	0.5 0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4 1.8	2.4 1.8	2.9 2.6	2.9 2.6
W shape	1.0 1.9	1.0 1.9	0.2 0.8	0.2 0.8
pion-less Δ decay	3.3 0.5	3.1 0.5	3.7 3.2	3.5 3.2
SK detector eff.	5.7 6.8	5.6 6.8	2.4 3.0	2.4 3.0
FSI	3.0 2.9	3.0 2.9	2.3 2.3	2.3 2.3
PN	3.6	3.5	0.8	0.8
SK momentum scale	1.5 0.0	1.5 0.0	0.6 0.0	0.6 0.0
Total	24.5 21.0	11.1 13.0	28.1 24.2	8.8 9.9

Systematic errors for N_{exp}

(unit: %)

Black: 2013
Blue: 2012

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	10.6 10.8	7.3 7.5	11.6 11.9	7.5 8.1
M_A^{QE}	15.6 9.5	2.4 4.0	21.5 16.3	3.2 6.7
M_A^{RES}	7.2 4.5	2.1 3.9	3.3 2.0	0.9 1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1 4.9	4.8 3.8	9.3 7.9	6.3 6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9 5.1	2.4 3.5	4.2 5.2	2.0 3.5
NC1π^0				
CC oth				
Spectra				
p_F				
CC coh				
NC coh				
NC oth				
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$				
W shap				
pion-less Δ decay	3.3 0.5	3.1 0.5	3.7 3.2	3.5 3.2
SK detector eff.	5.7 6.8	5.6 6.8	2.4 3.0	2.4 3.0
FSI	3.0 2.9	3.0 2.9	2.3 2.3	2.3 2.3
PN	3.6	3.5	0.8	0.8
SK momentum scale	1.5 0.0	1.5 0.0	0.6 0.0	0.6 0.0
Total	24.5 21.0	11.1 13.0	28.1 24.2	8.8 9.9

- Photo Nuclear effect is added in SK MC.
- SK momentum scale was only implemented as PDF error, but now it is also implemented for N_{exp} error. (It was already implemented for E_{rec}.)
- Enu 1pi shape error is removed from BANFF.
- SK error is improved thanks to additional atm. nu. data set and MC improvements.

Systematic errors for N_{exp}

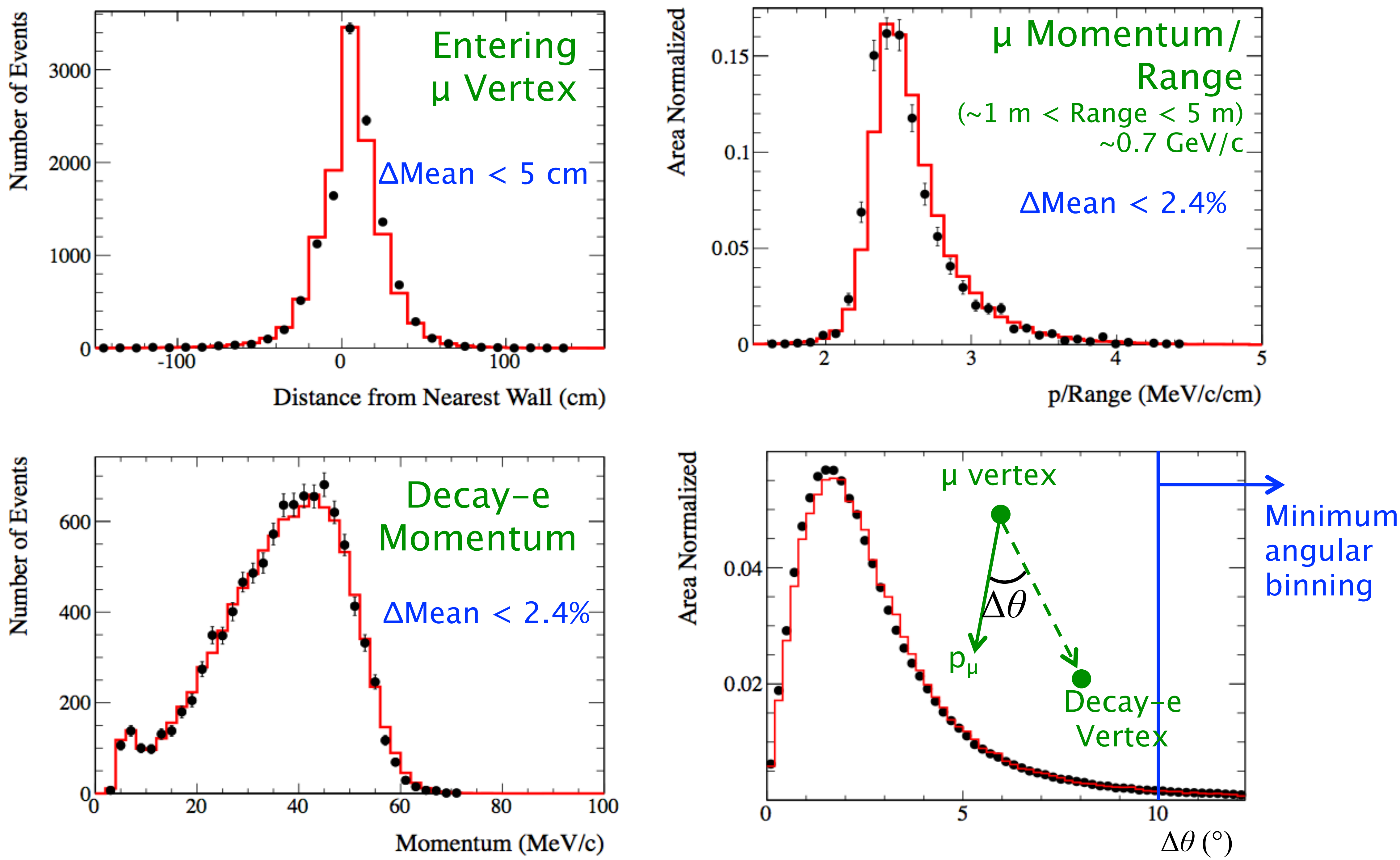
(unit: %)

Black: 2013
Blue: 2012

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit (2013)	(2012)	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit (2013)	(2012)	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit (2013)	(2012)	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit (2013)	(2012)
Beam only	10.6	10.8	7.3	7.5	11.6	11.9	7.5	8.1
M_A^{QE}	15.6	9.5	2.4	4.0	21.5	16.3	3.2	6.7
M_A^{RES}	7.2	4.5	2.1	3.9	3.3	2.0	0.9	1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1	4.9	4.8	3.8	9.3	7.9	6.3	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1π^0 norm.	2.7	7.9	1.9	7.3	0.6	2.3	0.4	2.2
CC other shape	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Spectral Function	4.7	3.3	4.8	3.3	6.0	5.7	6.0	5.7
p_F	0.1	0.3	0.1	0.3	0.1	0.0	0.1	0.0
CC coh. norm.								
NC coh. norm.								
NC other norm.								
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$								
W shape								
pion-less Δ decay								
SK detector eff.	5.7	6.8	5.6	6.8	2.4	3.0	2.4	3.0
FSI	3.0	2.9	3.0	2.9	2.3	2.3	2.3	2.3
PN	3.6		3.5		0.8		0.8	
SK momentum scale	1.5	0.0	1.5	0.0	0.6	0.0	0.6	0.0
Total	24.5	21.0	11.1	13.0	28.1	24.2	8.8	9.9

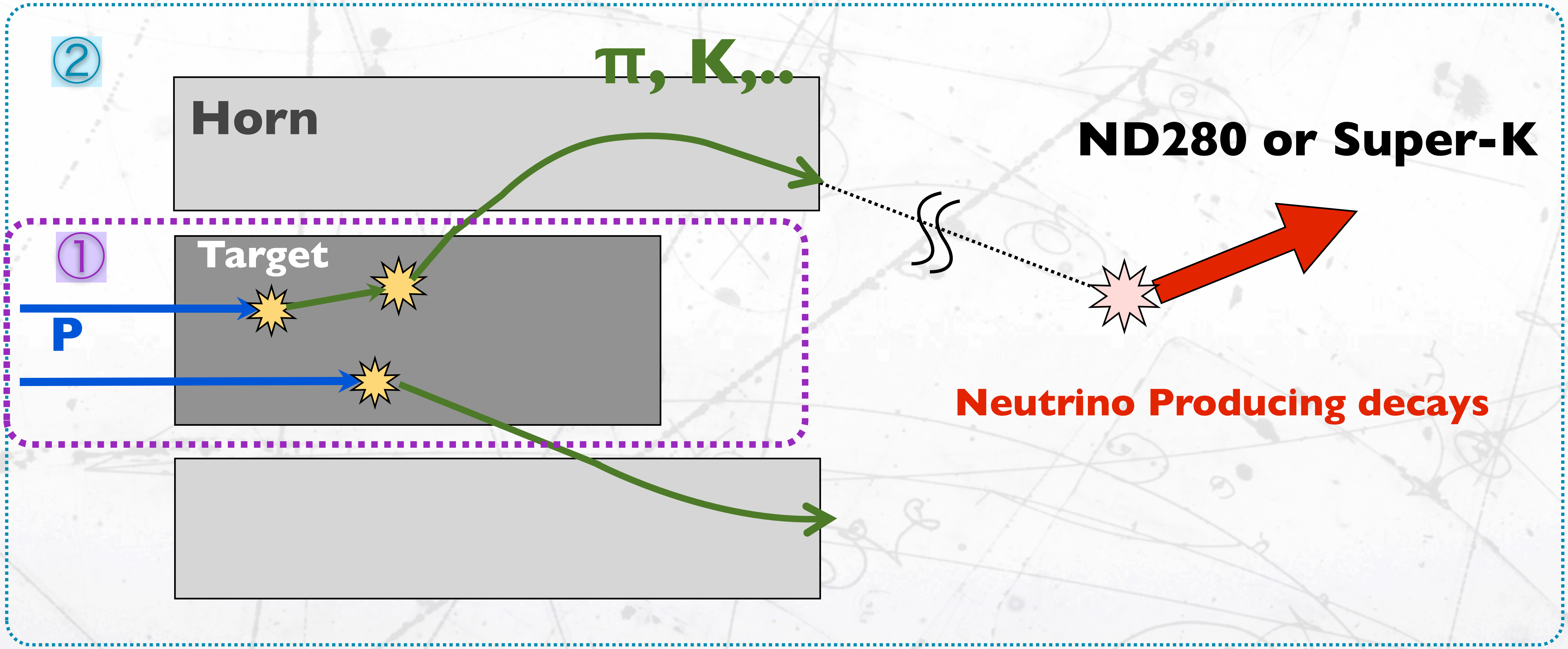
By using fiTQun, the fraction of ν_e signal events (i.e. CCQE events) increased. Therefore, the dominant error (M_A^{QE}) increased and the total error increased.
(This is a fractional error. The absolute error is decreased.)

Validation with stopping muons



Beam

Simulating neutrino flux

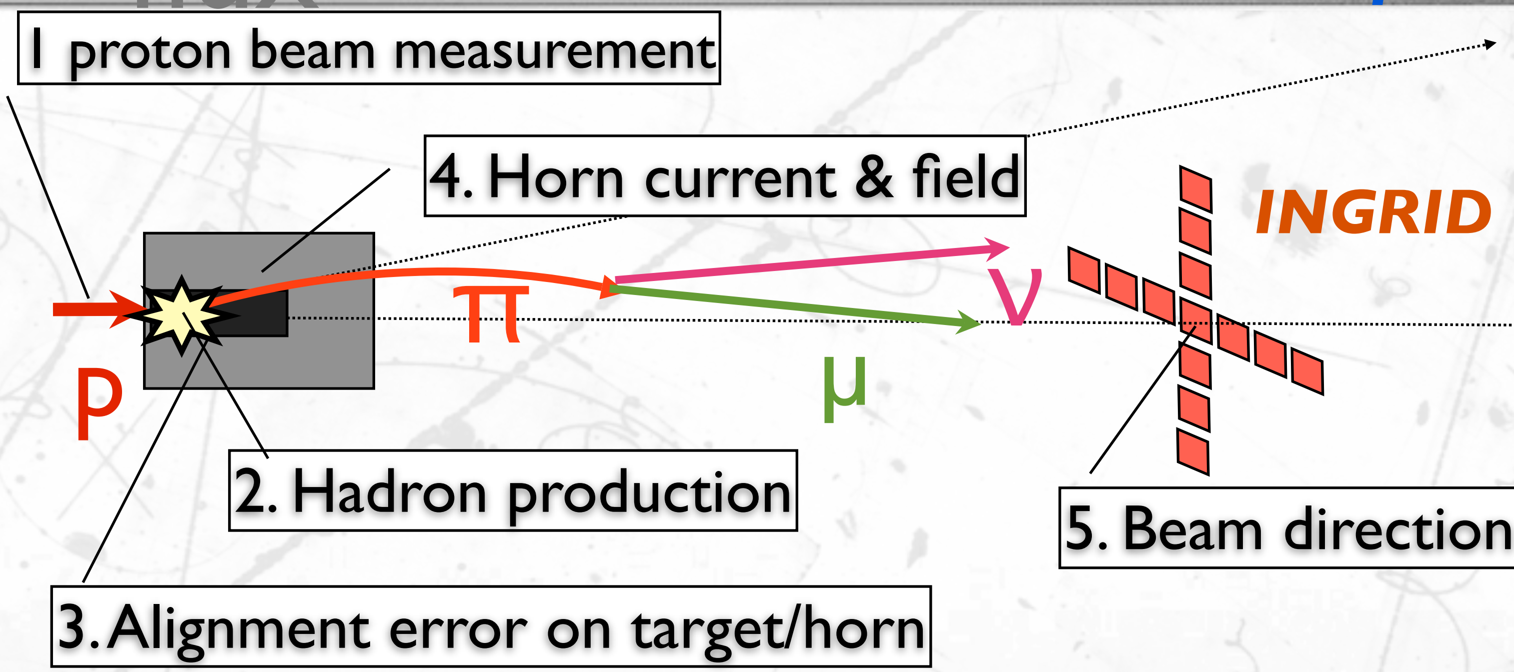


1. p interaction inside the carbon target with FLUKA2008.3d
2. Tracking through horn fields and decay volume using GEANT3 with GCALOR

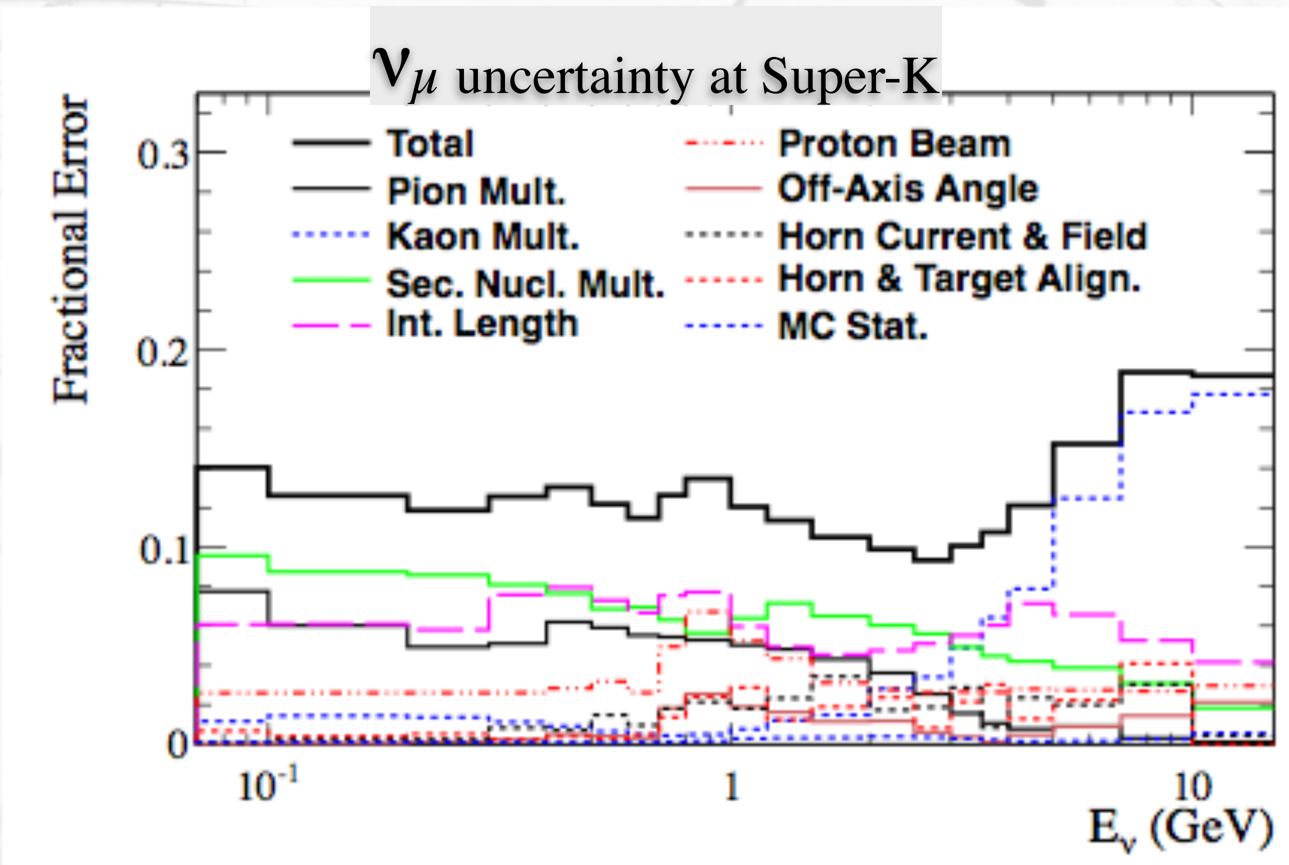
   Calculate neutrino producing decays

   Estimate the flux at the near/far detector

Systematic error sources for neutrino flux

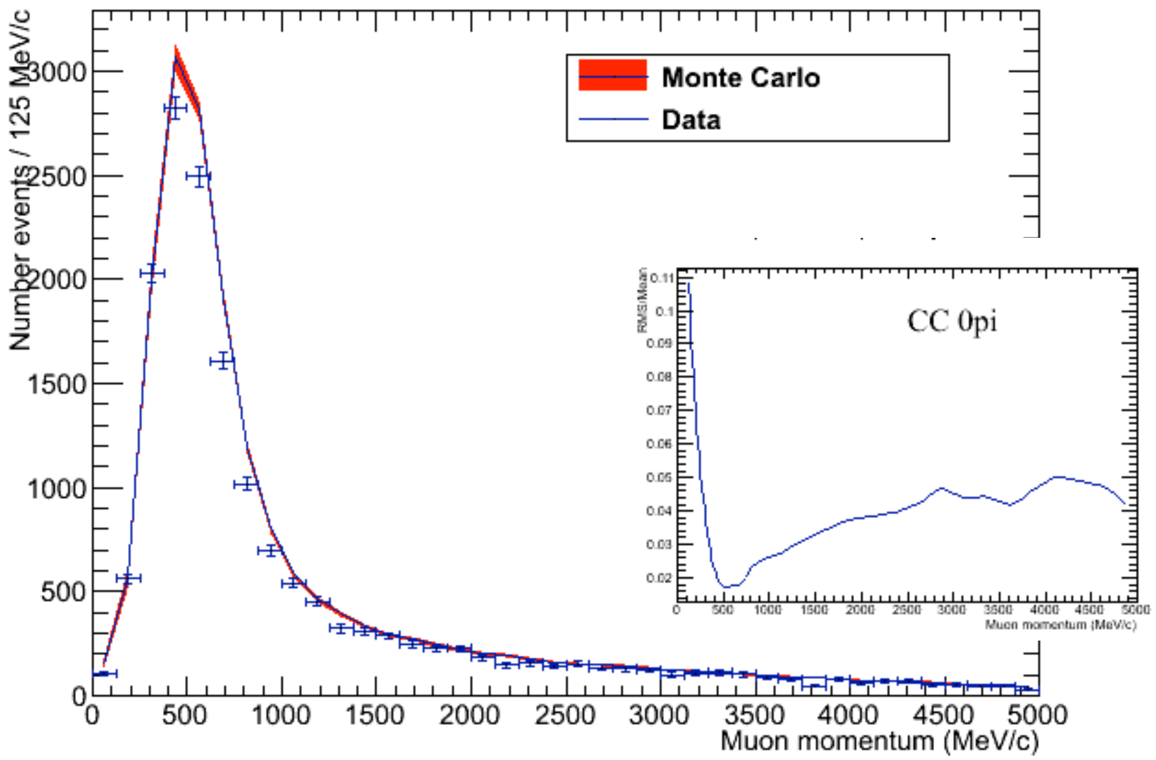


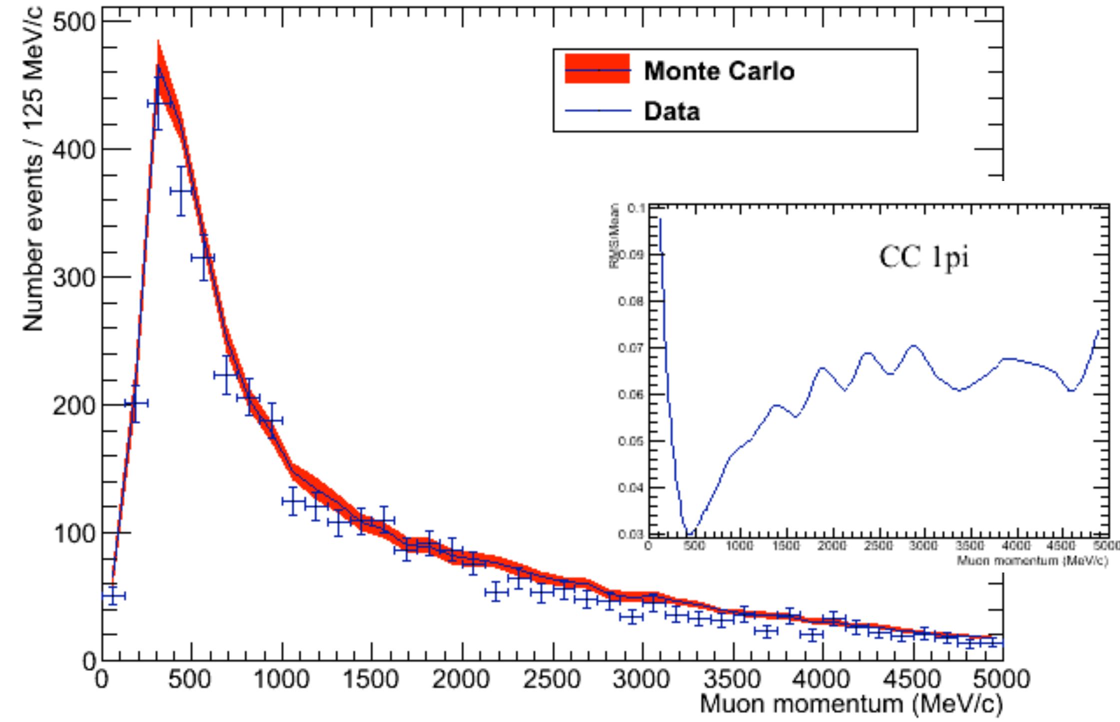
1. Measurement error on monitoring proton beam
2. Hadron production
3. Alignment error on the target and the horn
4. Horn current & field
5. Neutrino beam direction (Off-axis angle)

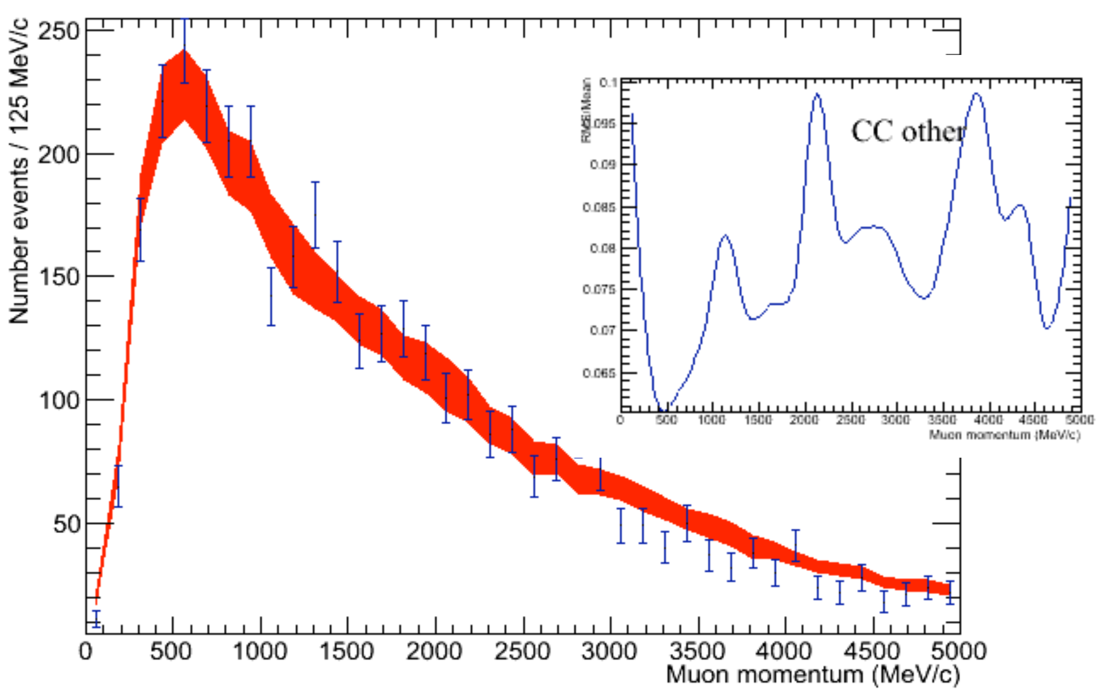


ND280

Detector systematics

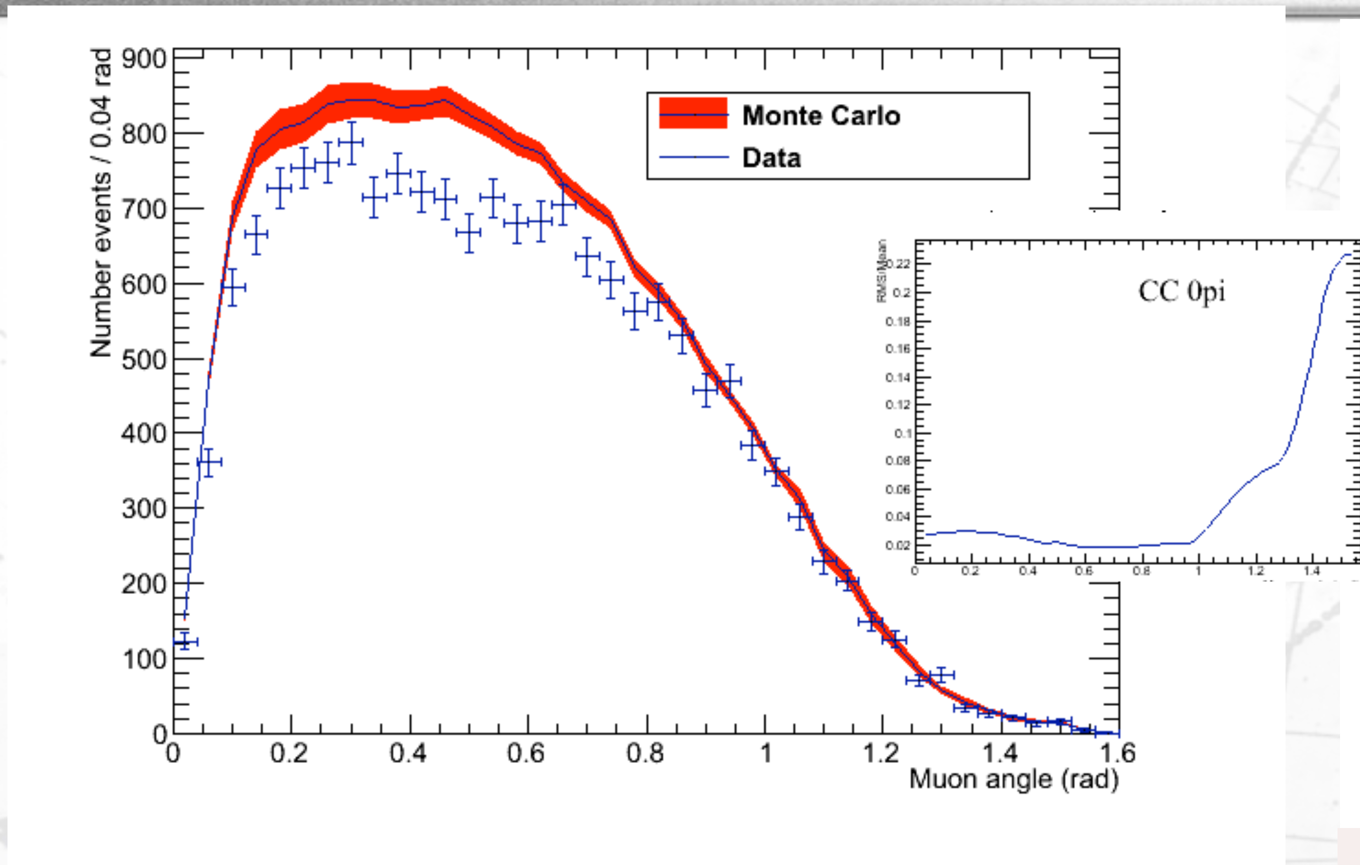


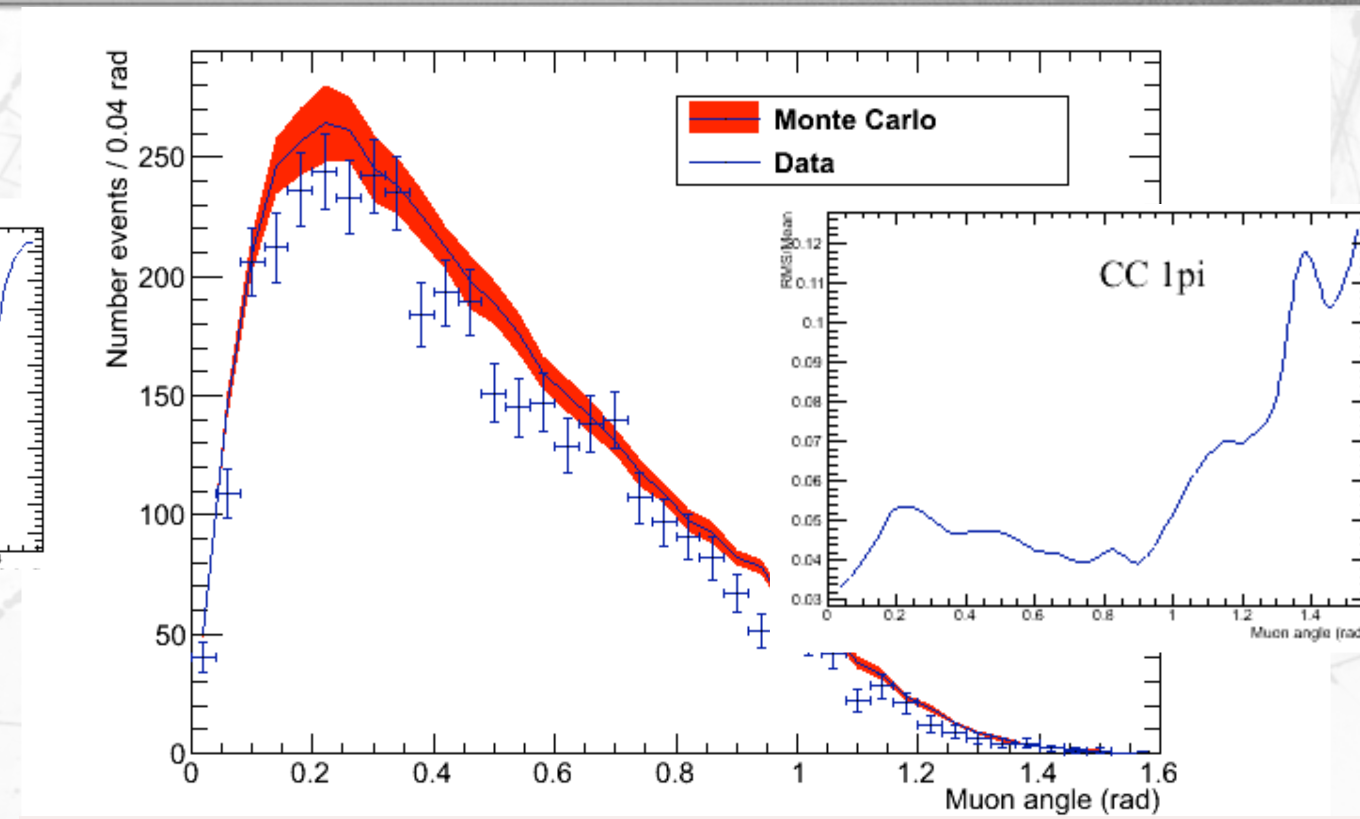


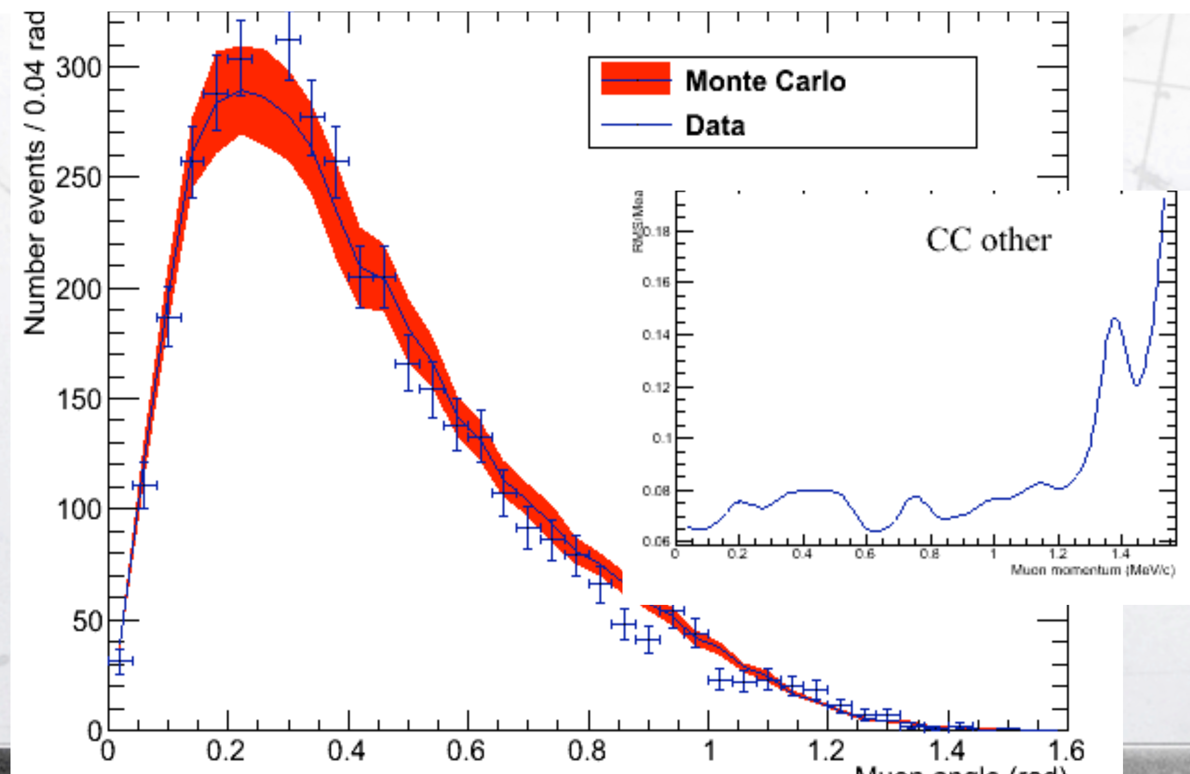


B Field distortion (0.3%)	TPC Tracking efficiency (0.6%)
TPC-FGD matching efficiency (1%)	***TPC Charge confusion (2.2%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (10%)***
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (3.5%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	***Pion secondary interaction (8%)***

Detector systematics

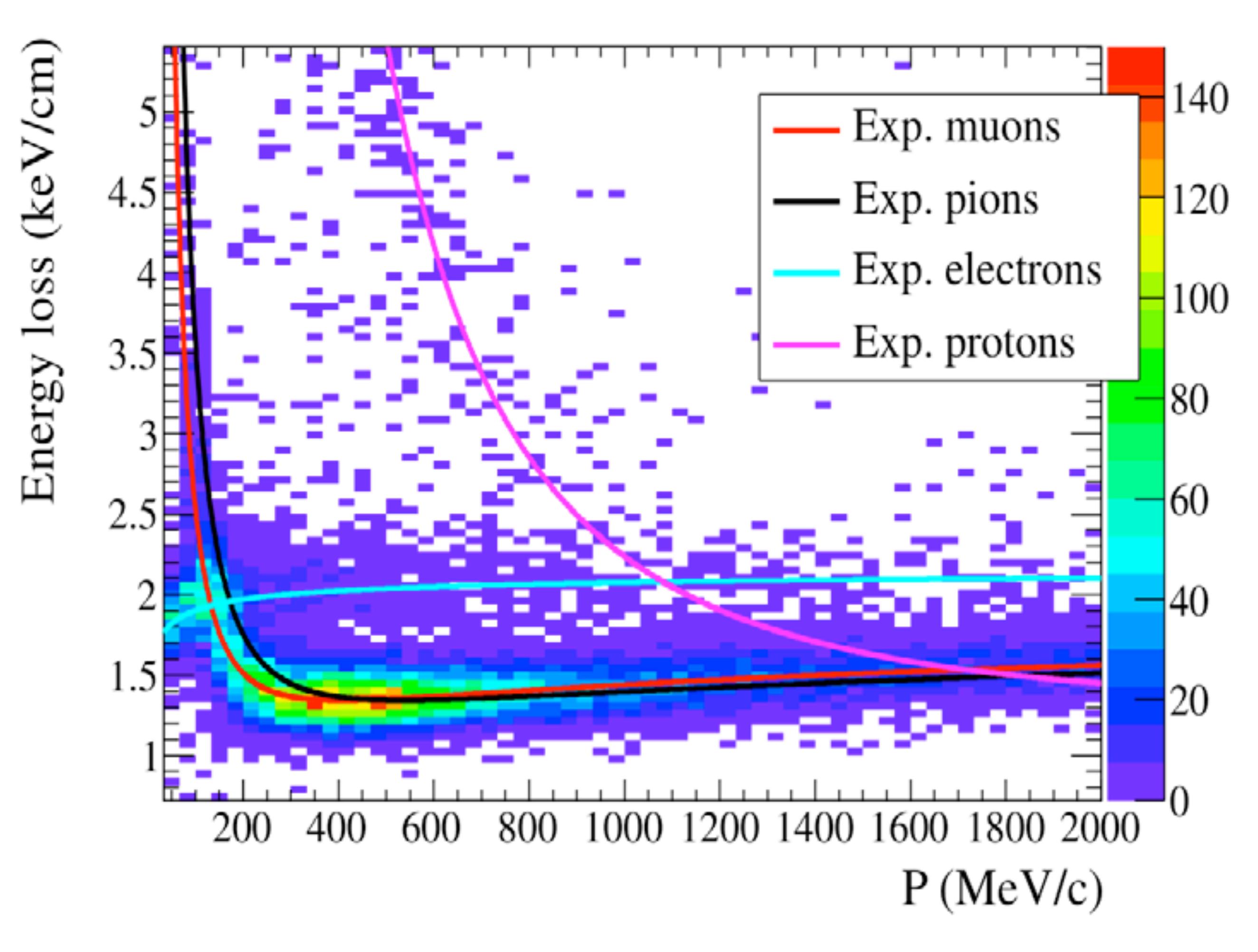




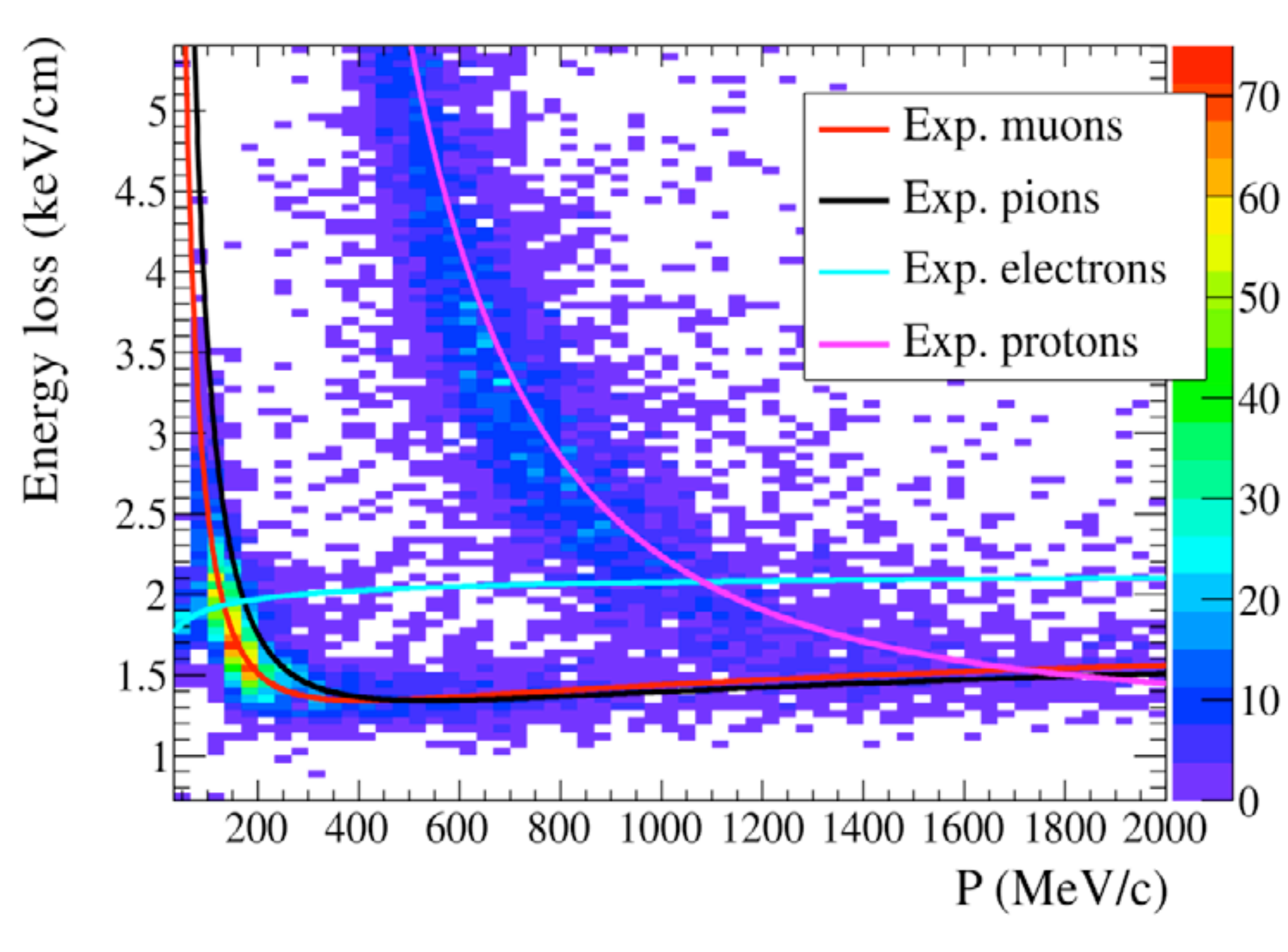


B Field distortion (0.3%)	TPC Tracking efficiency (0.2%)
TPC-FGD matching efficiency (1.8%)	***TPC Charge confusion (5.0%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (22%)***
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (9.0%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	***Pion secondary interaction (8%)***

Negative Tracks in TPC



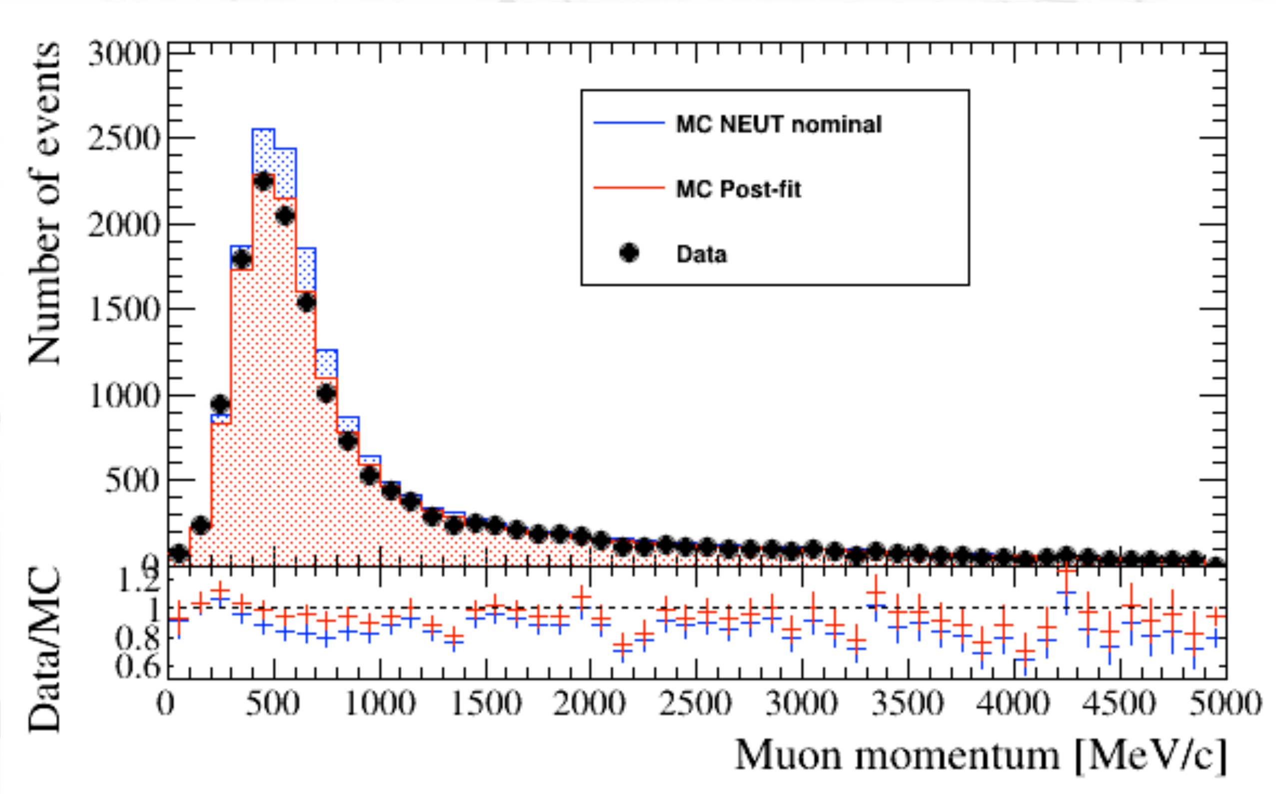
Positive Tracks in TPC

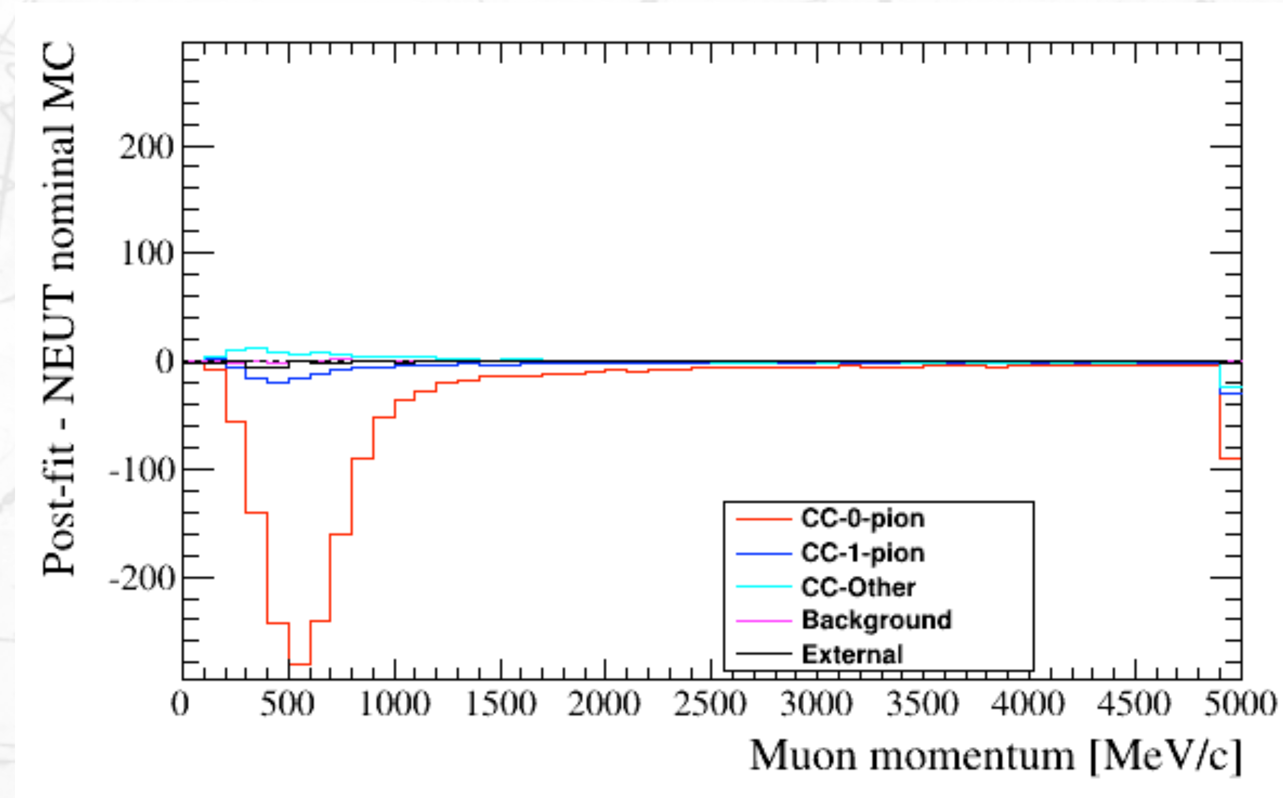


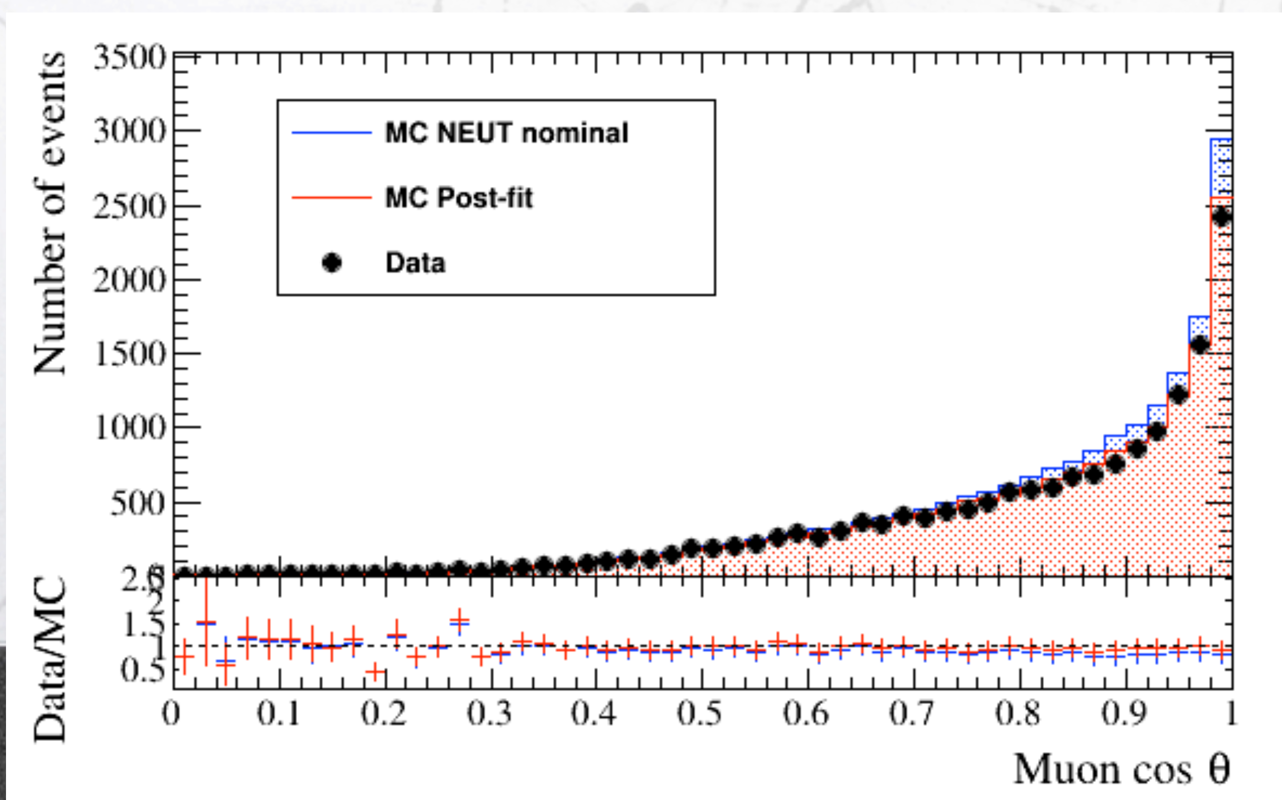
Post-fit ν_μ ND280

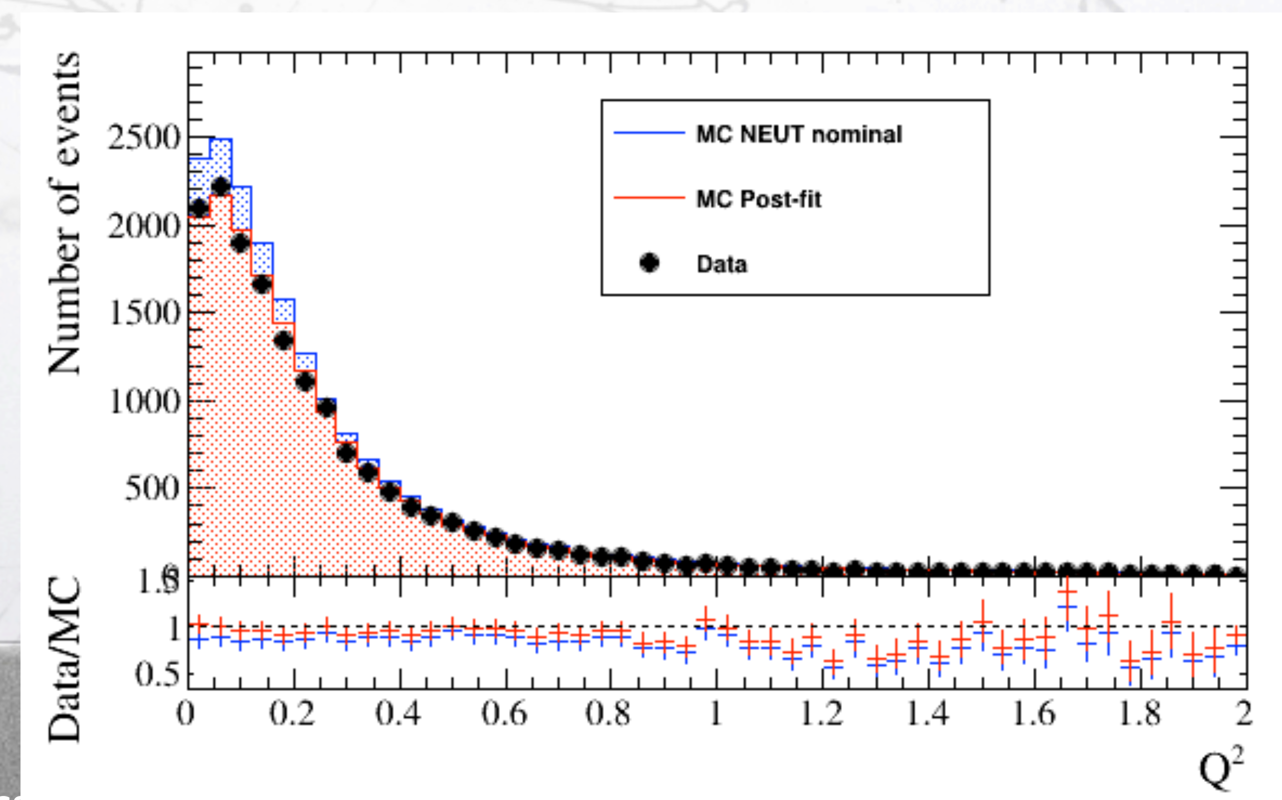
- Use beam and cross section parameters obtained from the constrained fit to the ND280 ν_μ (p_μ, $\cos\theta_\mu$) spectra to re-weight the MC.
- Improved agreement between the MC distributions, after post-fit re-weight, and the data.

CC-0-pion post-fit

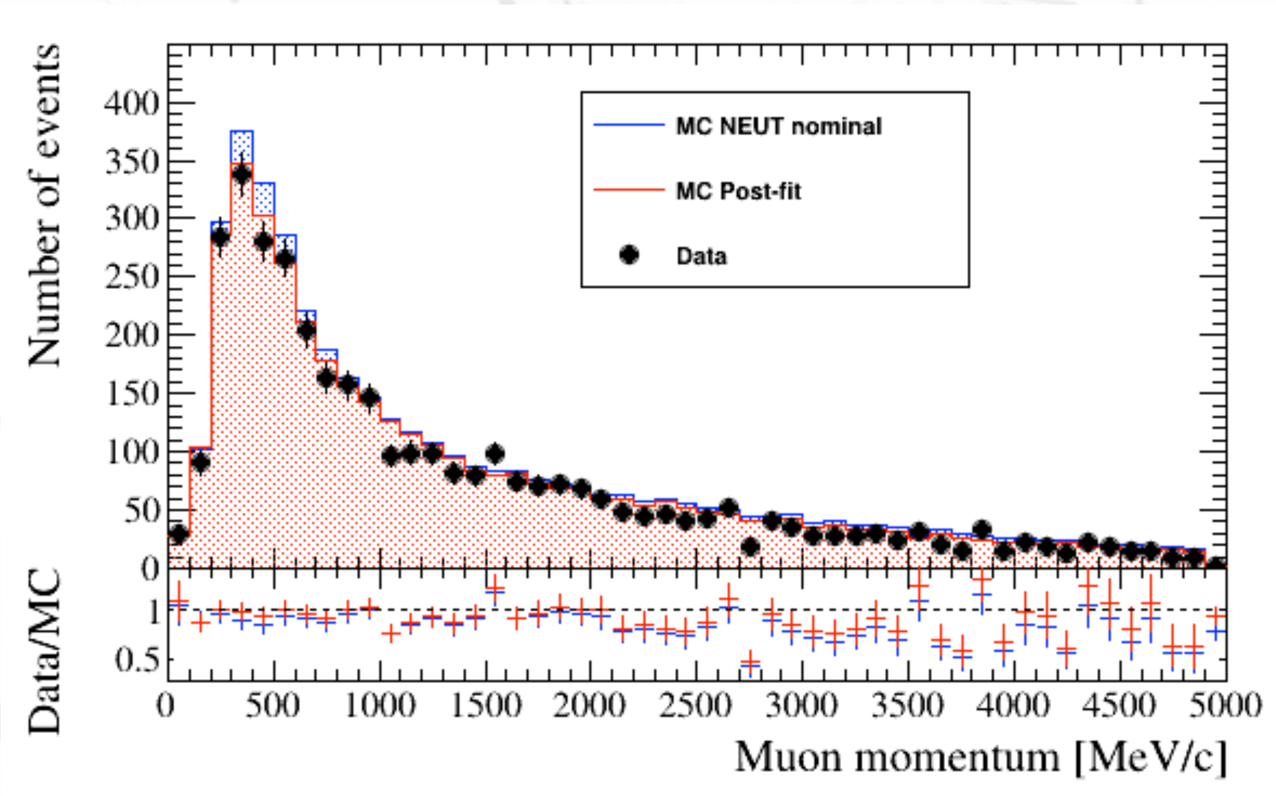


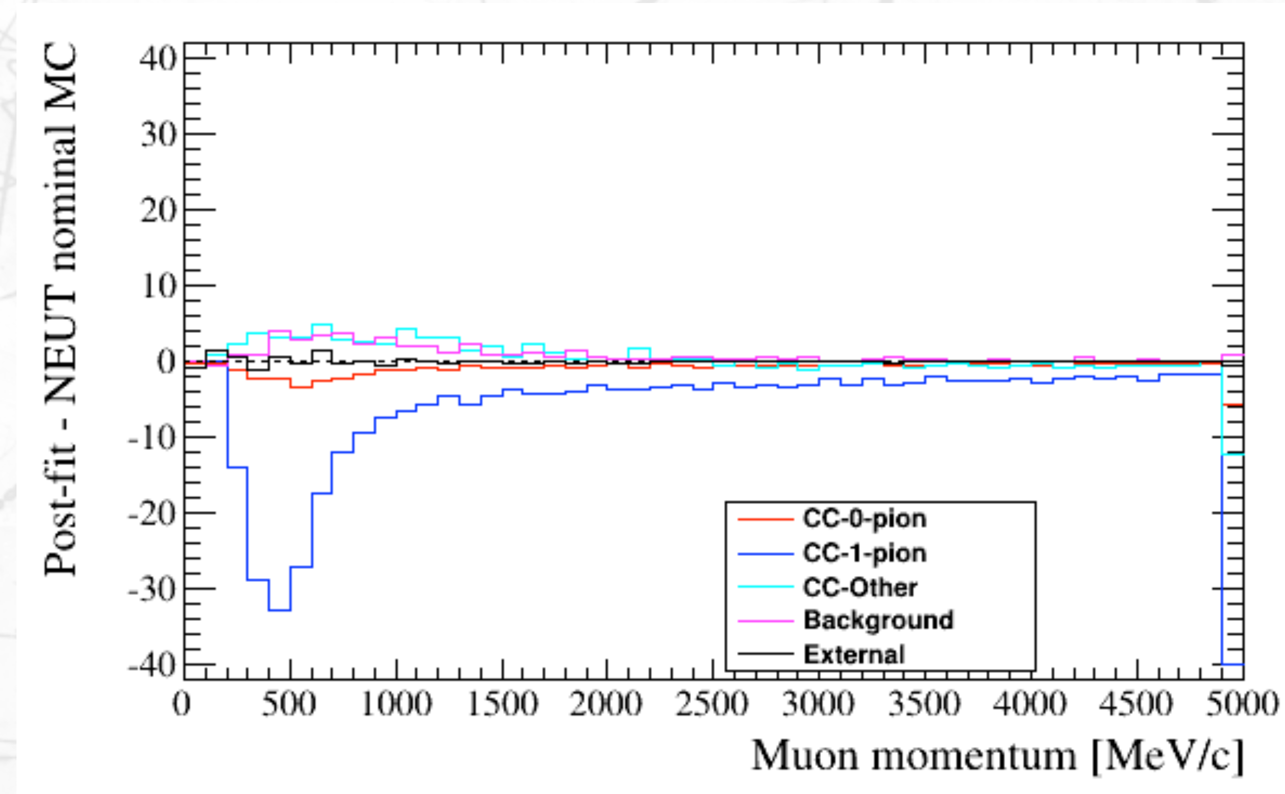


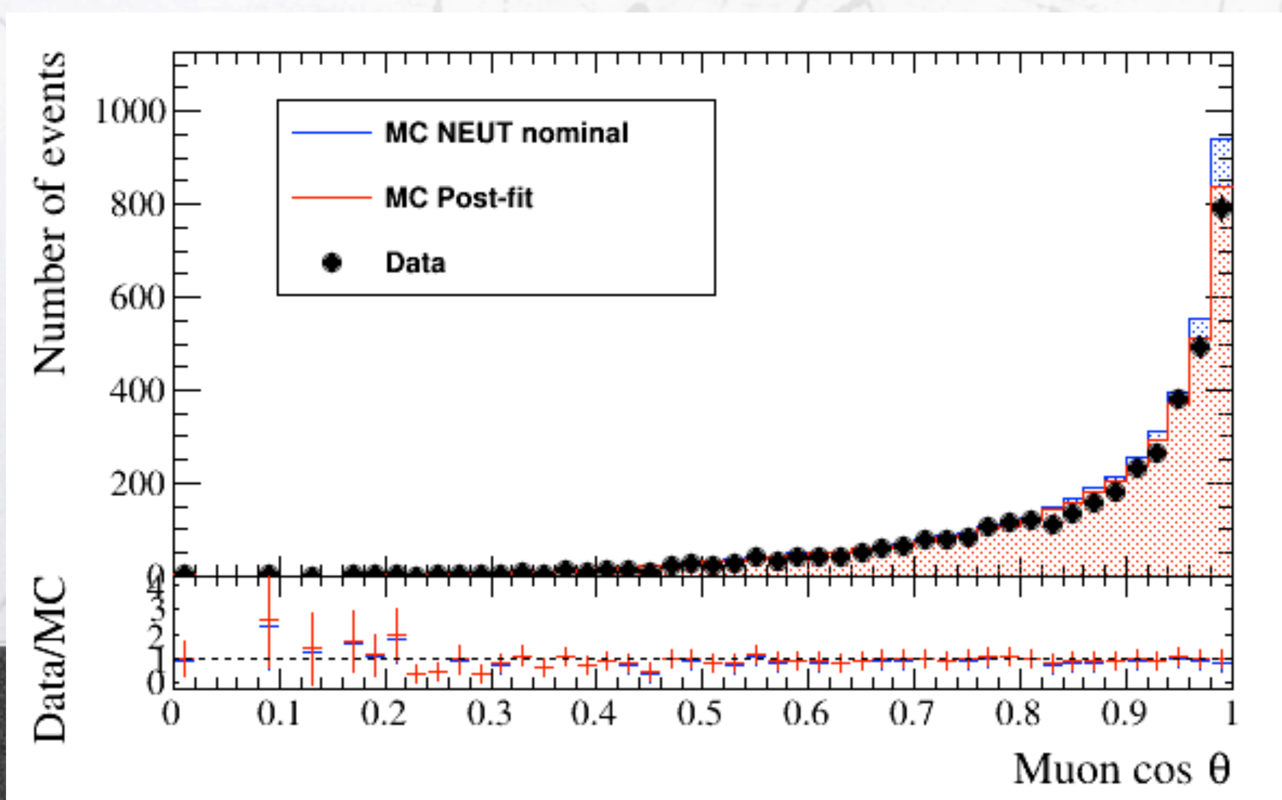


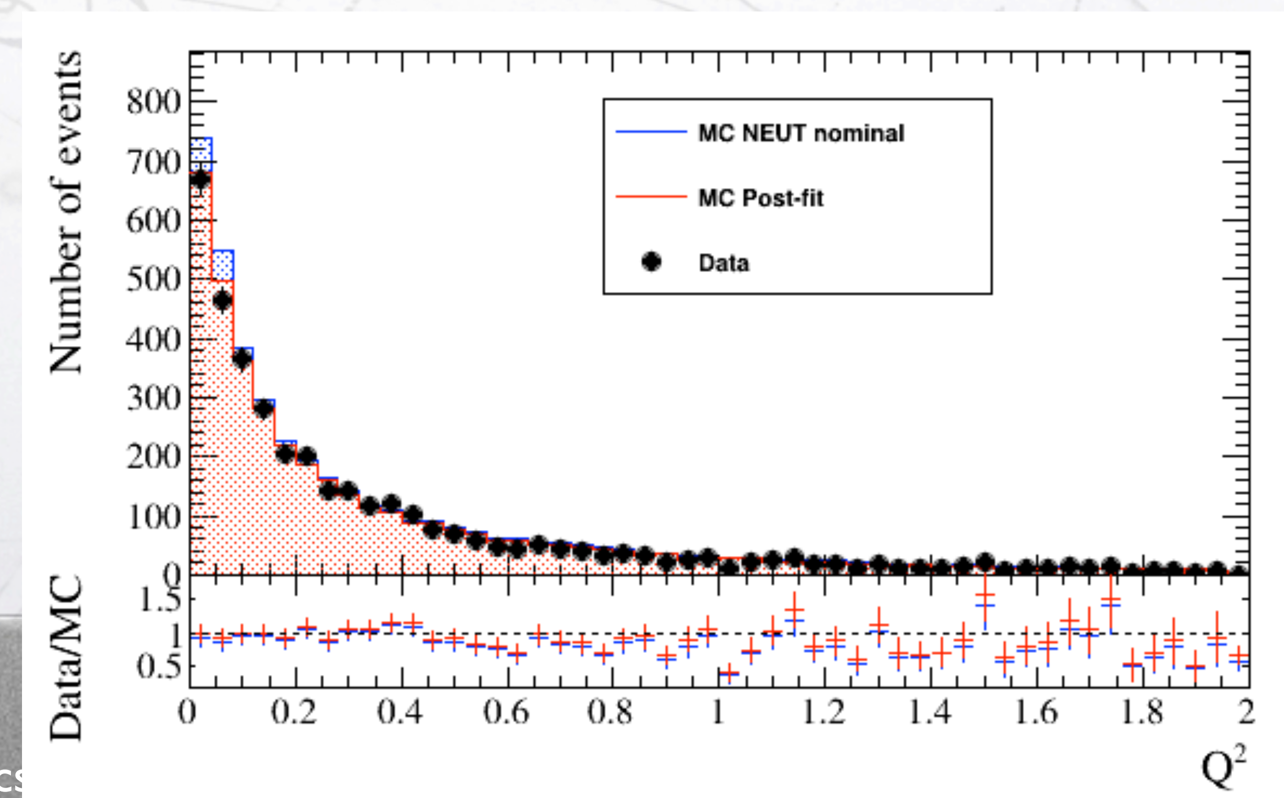


CC-1-pion post-fit

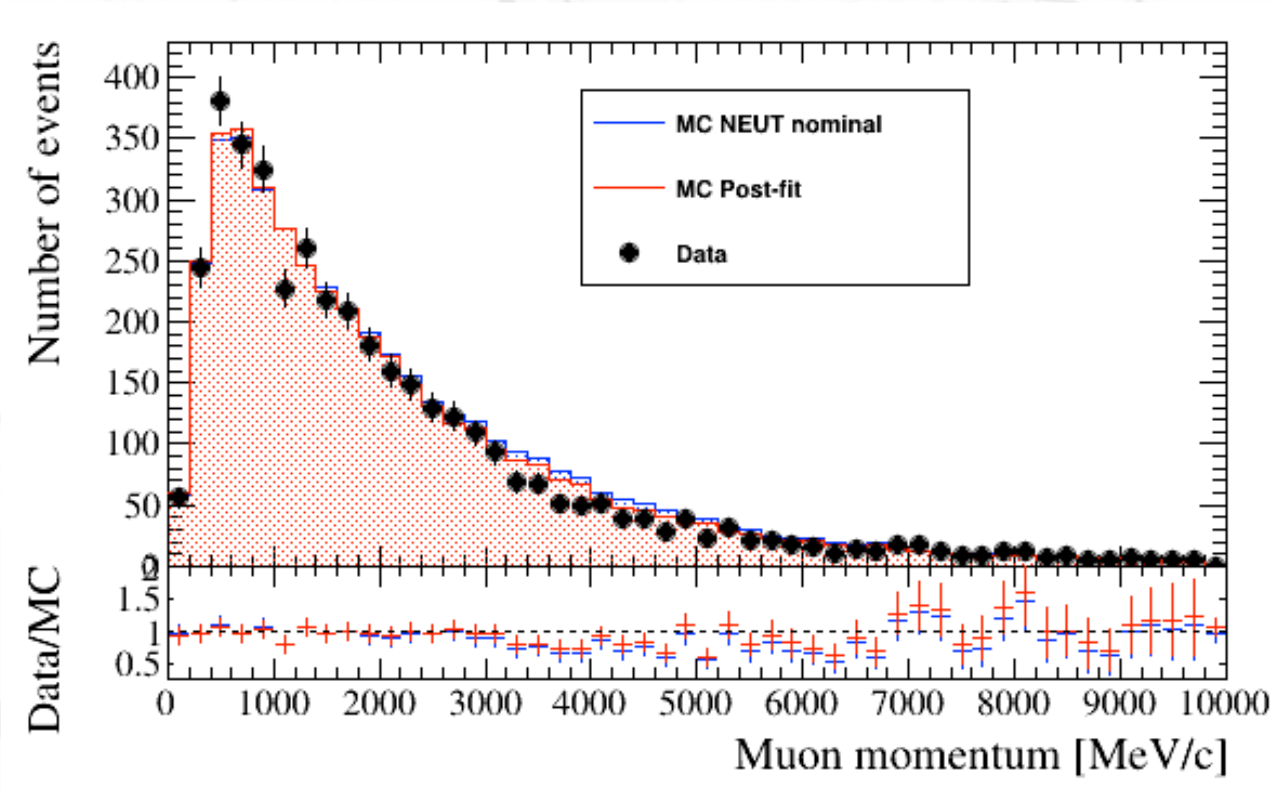


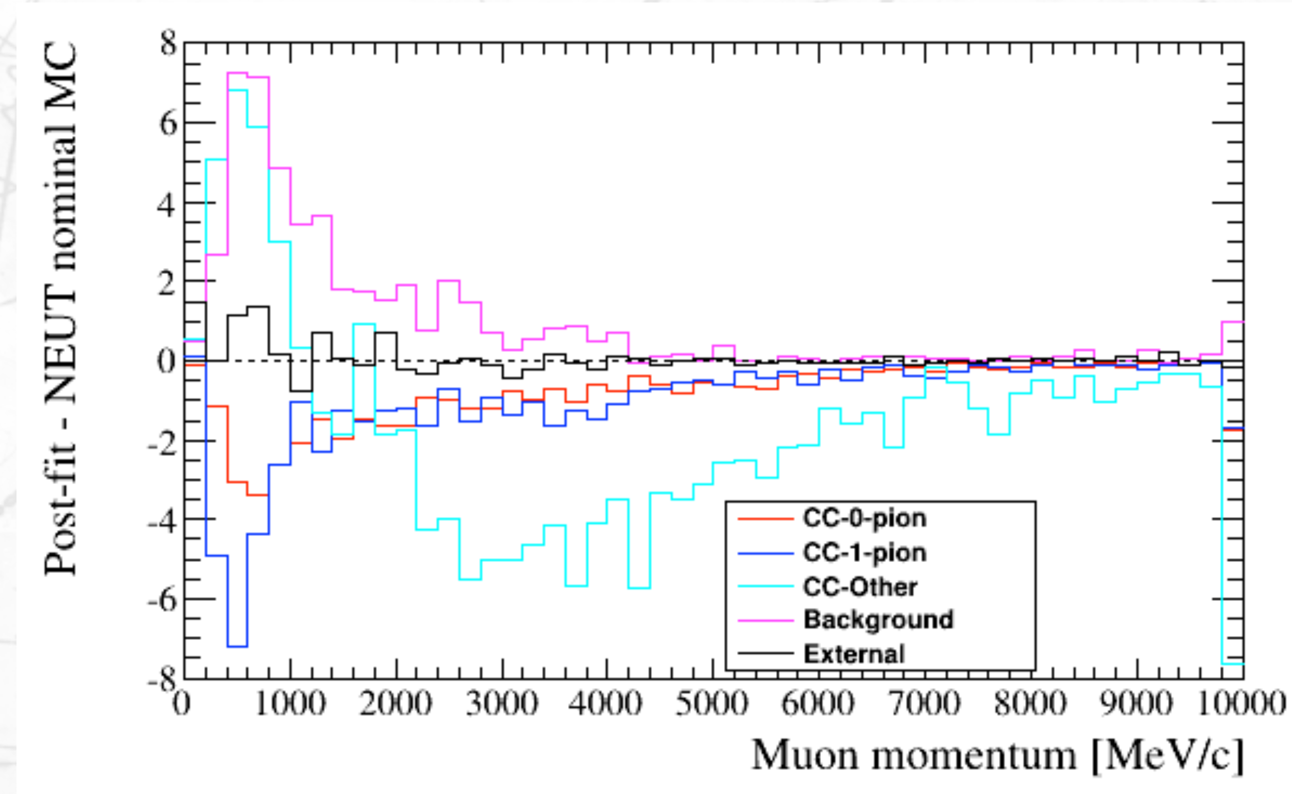


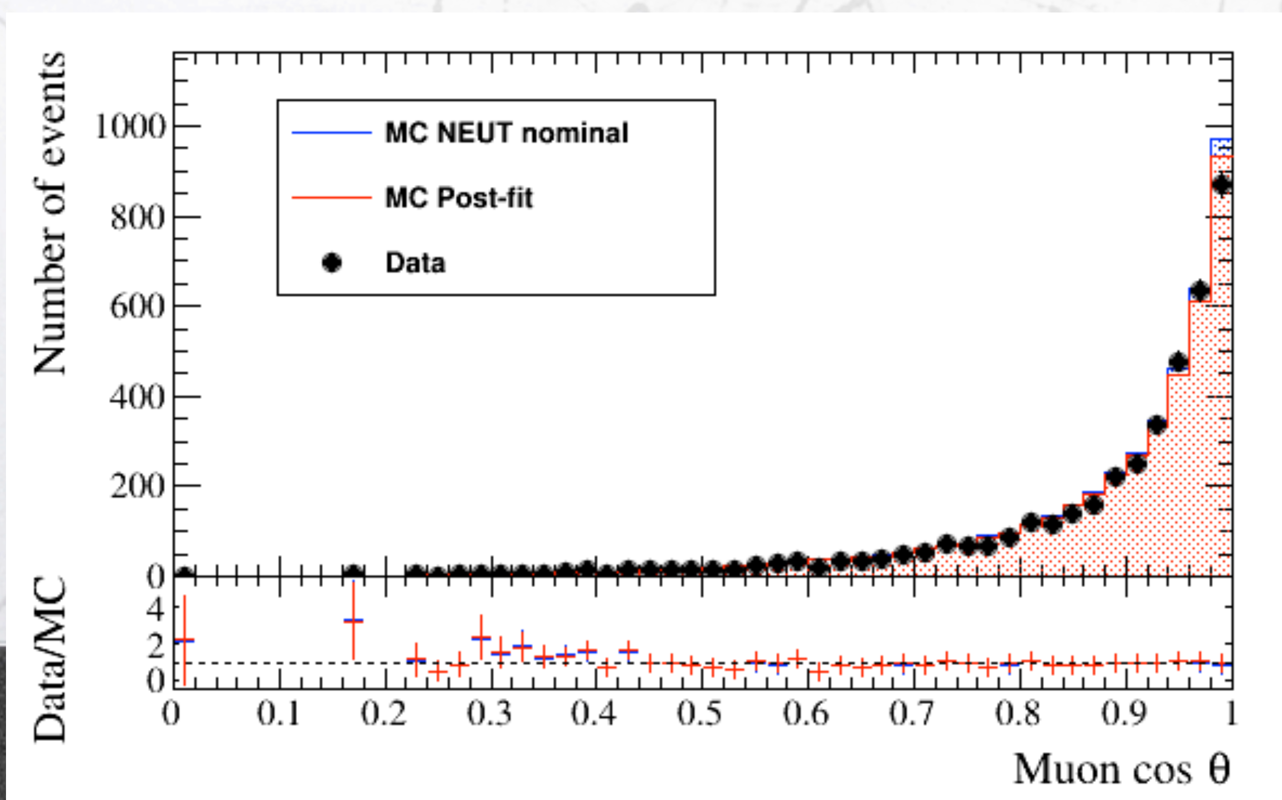


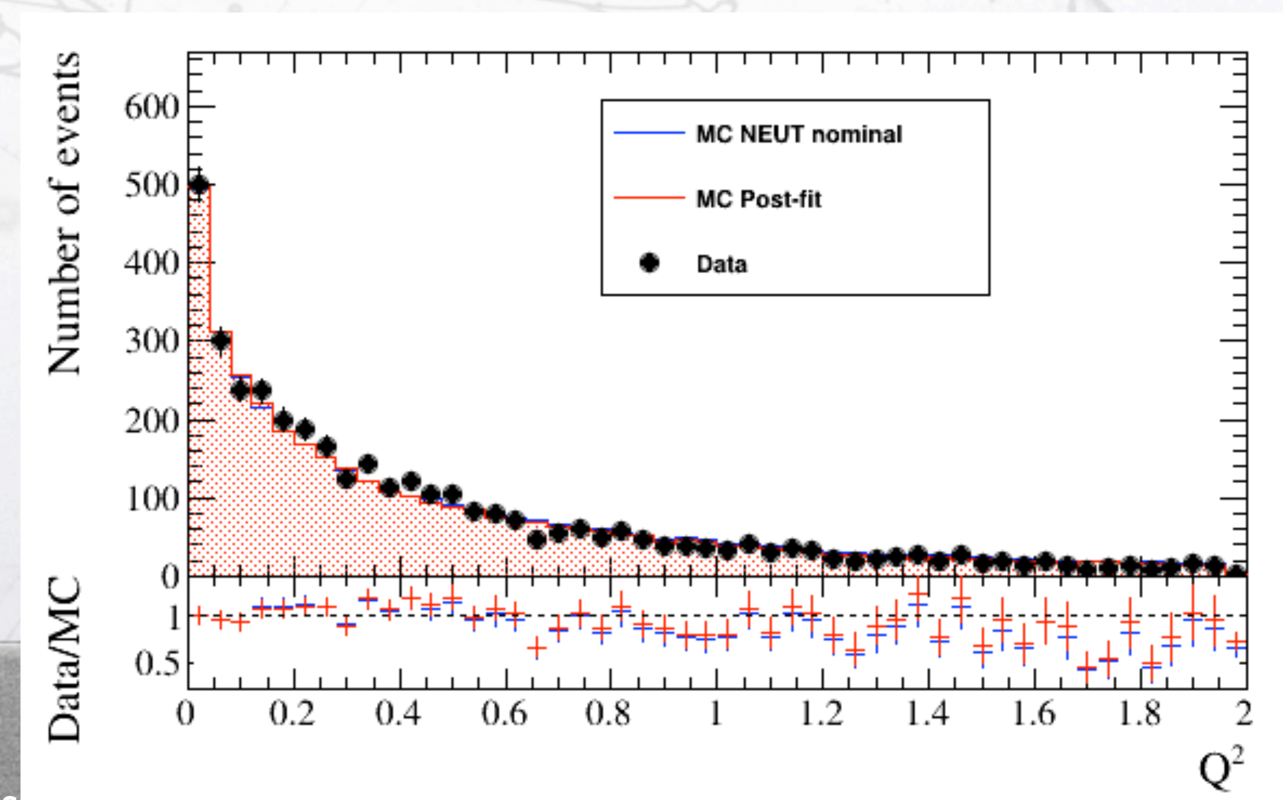


CC-Other post-fit









Flux fit

ND280 Fit $\Delta\chi^2$

$$\Delta\chi^2 = 2\sum_{i}^{p,\cos\theta\ bins} N_i^{pred}(\vec{b},\vec{x},\vec{d}) - N_i^{data} + N_i^{data}\ln[N_i^{data}/N_i^{pred}(\vec{b},\vec{x},\vec{d})]$$

$$+\sum_{i}^{E_\nu\ bins}\sum_{j}^{E_\nu\ bins}(1-b_i)(V_b^{-1})_{i,j}(1-b_j) + \sum_{i}^{xsec\ pars}\sum_{j}^{xsec\ pars}(x_i^{nom}-x_i)(V_x^{-1})_{i,j}(x_j^{nom}-x_j)$$

$$+\sum_{i}^{p,\cos\theta\ bins}\sum_{j}^{p,\cos\theta\ bins}(d_i^{nom}-d_i)(V_d^{-1})_{i,j}(d_j^{nom}-d_j)$$

b = flux nuisance parameters
x = cross section nuisance parameters
d = detector/reconstruction model nuisance parameters
V_b, V_x, V_d = covariance matrices (pre-fit uncertainties)

$$N_i^{pred}(\vec{b},\vec{x},\vec{d}) = d_i\sum_{j=1}^{MC\ Events} b_j x_j^{norm} w_j^x(\vec{x})$$

Pre-calculated weight function for cross section parameters with non-linear response

Results from Fit to ND280 Data

Selection	Number of Events (Data)	Number of Events (MC before ND280 constraint)	Number of Events (MC after ND280 constraint)
CC0π	16912	20016	16803
CC1π	3936	5059	3970
CC Other	4062	4602	4006
CC Inclusive	24910	29678	24779

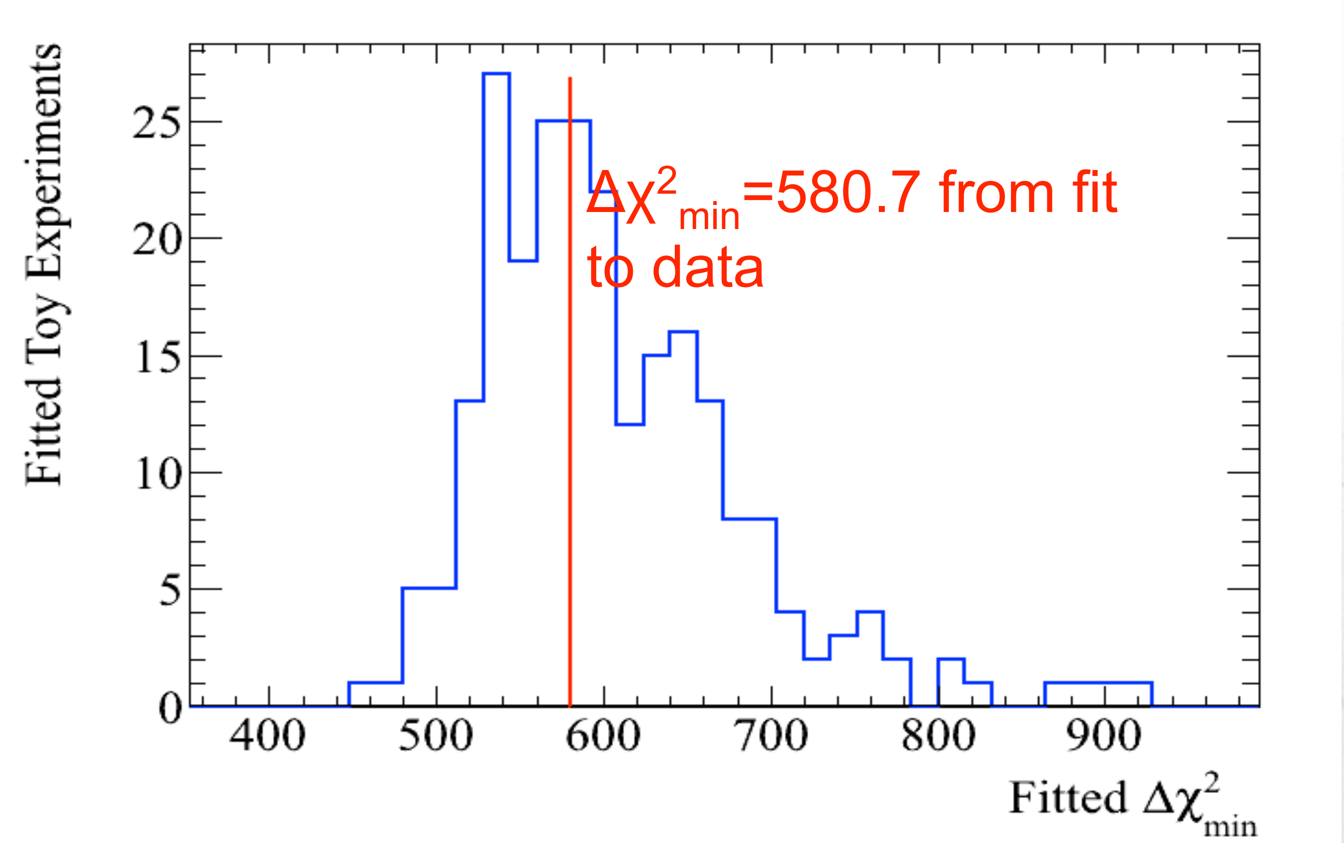
Test the data and constrained MC agreement with toy experiments:

Generated variations of models within prior uncertainties

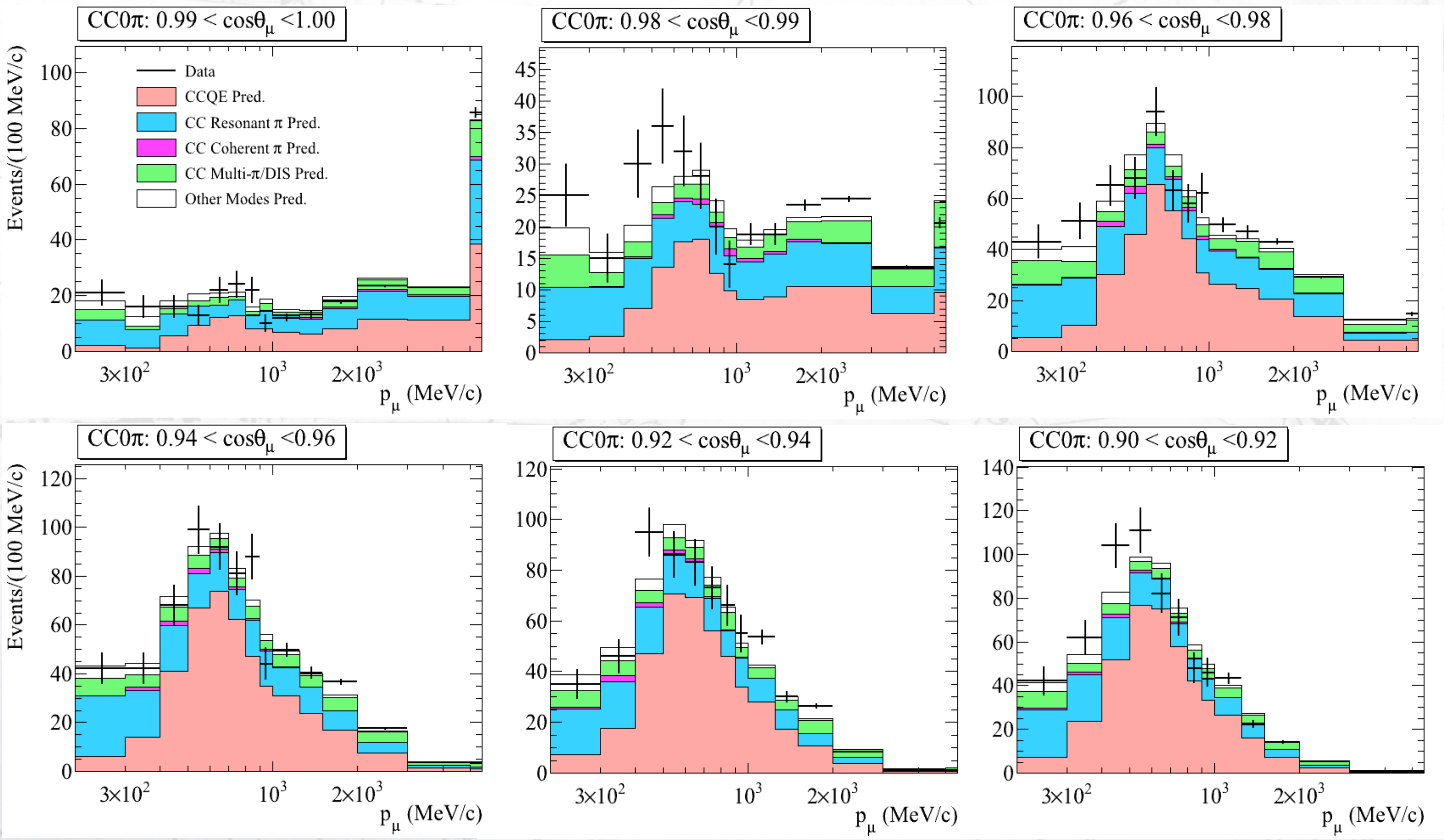
Fit toy data in same manner as data

Record $\Delta\chi^2$ at minimum for each toy fit

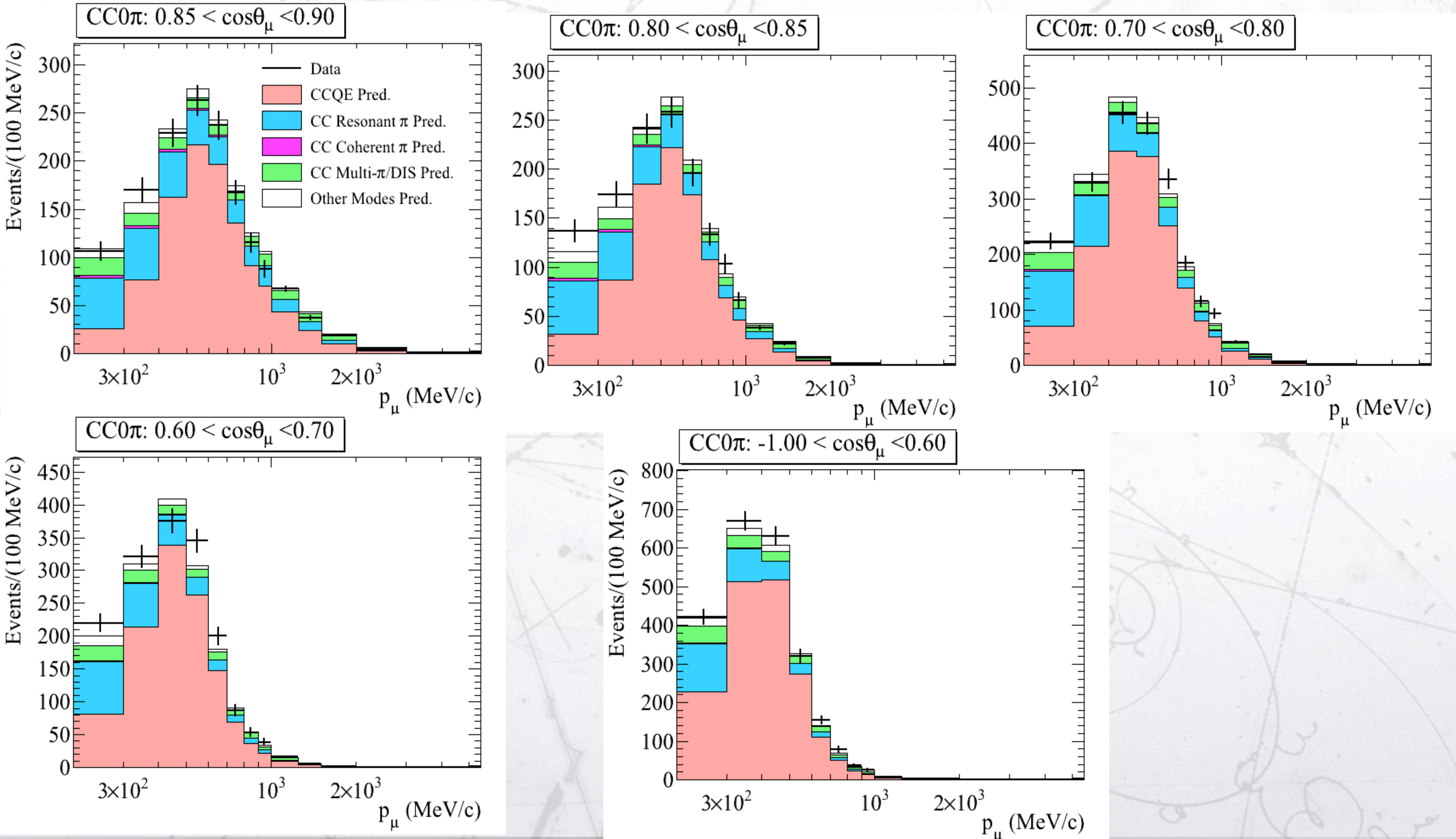
$\Delta\chi^2_{min}$=580.7 for data has p-value of 0.57



Data and Constrained Model (CC0π)

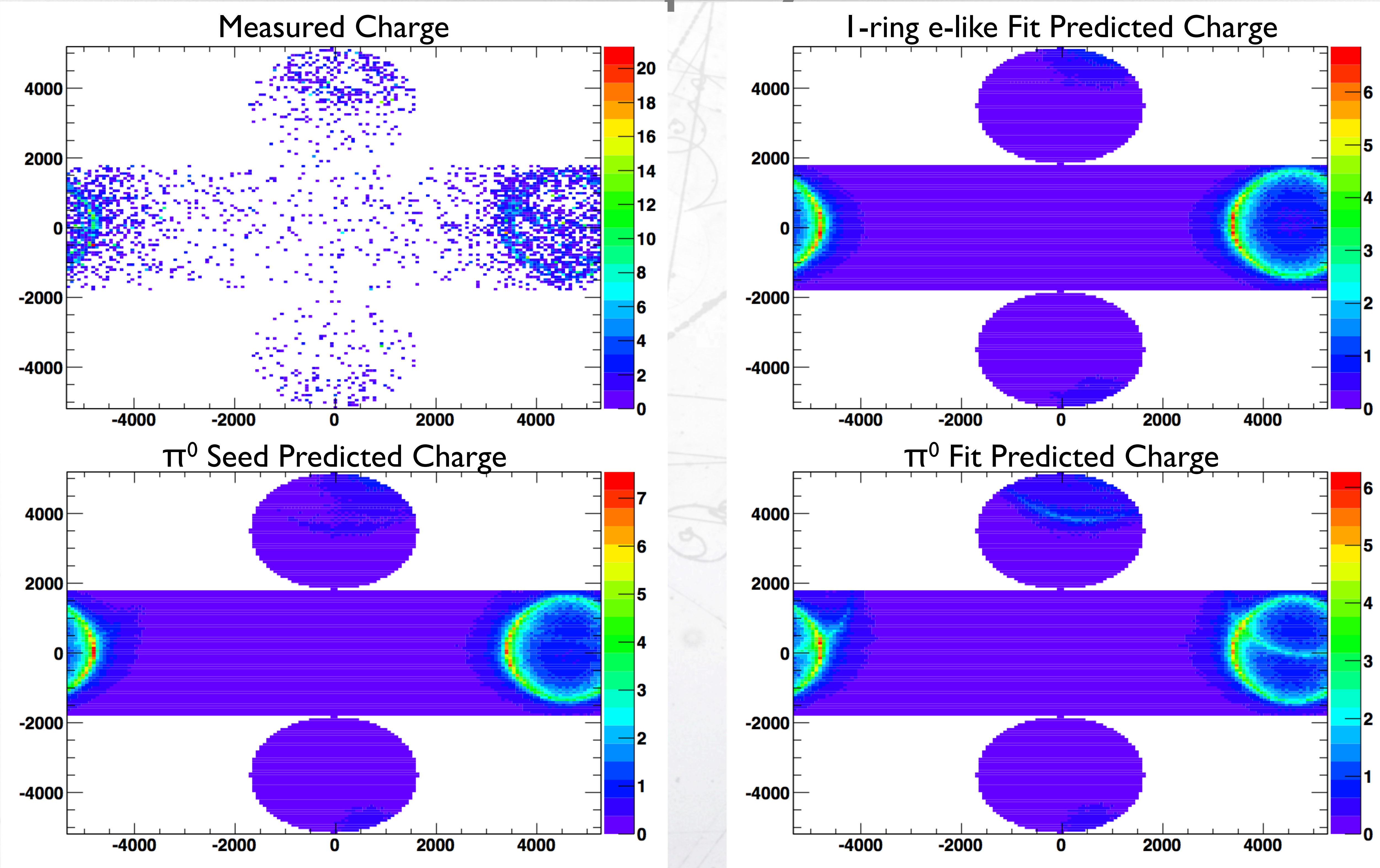


Data and Constrained Model (CC0π)



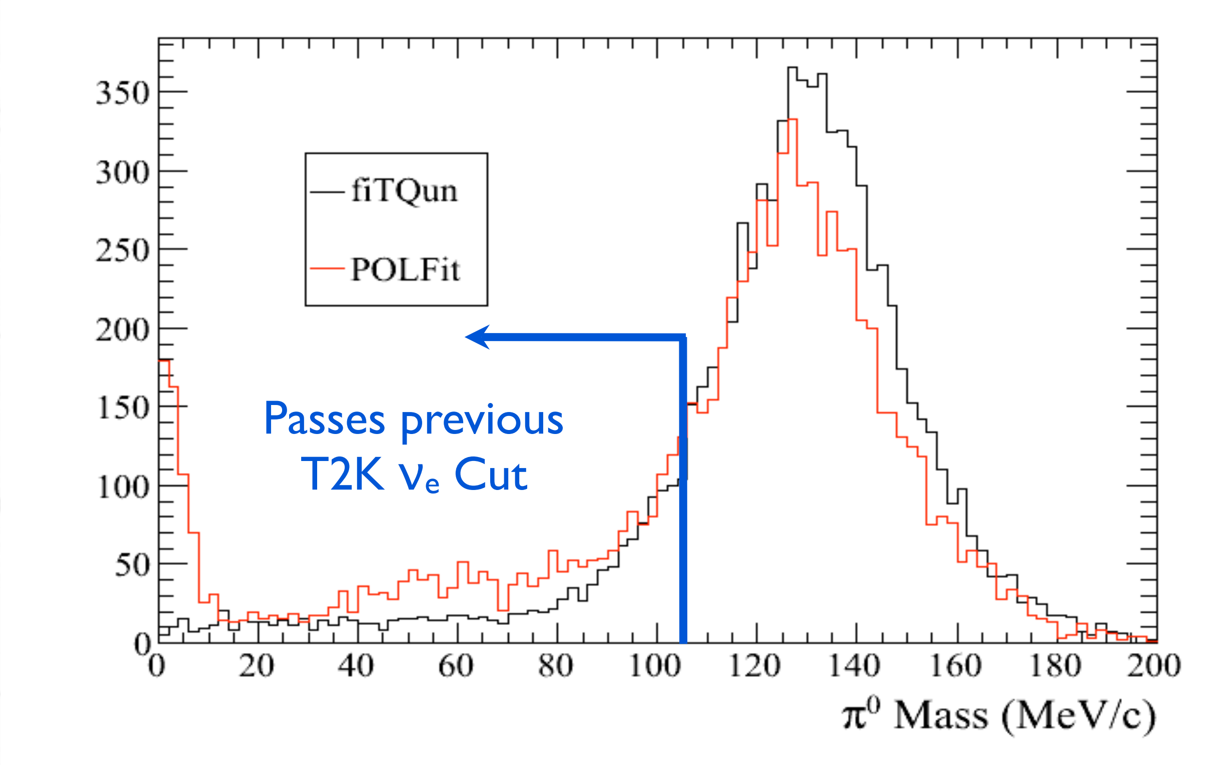
New SK π^0 analysis

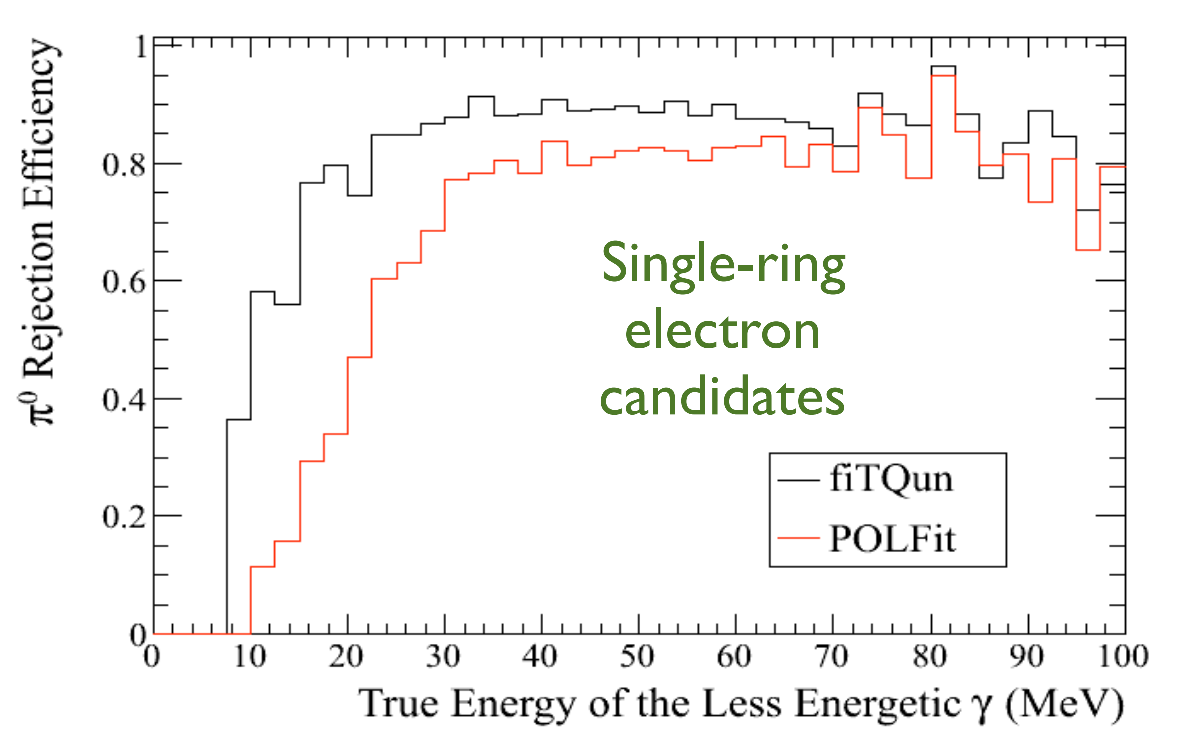
Event Display: π^0 Fit



π^0 Fit Performance

- Previous T2K ν_e appearance cut: m_{π^0} < 105 MeV/c^2
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in standard fitting algorithm (POLFit)
- Lower plot: π^0 rejection efficiency vs lower photon energy
  - fiTQun is more sensitive to lower energy photons





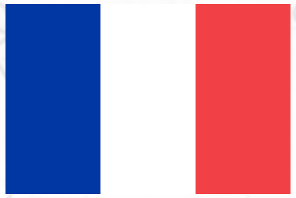
History

- 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.
- Febr 2008 ND280 pit construction is completed.
- May 2008 installation ND280 magnet.
- April 2009 commissioning of beamline.
- Janu 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.

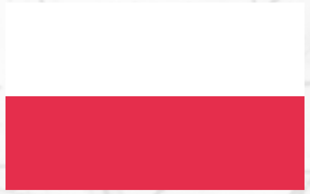


CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

RWTH Aachen U.

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

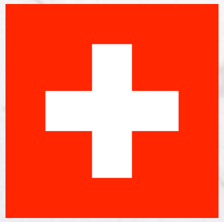
ICRR Kamioka
ICRR RCCN Kavli
IPMU KEK Kobe
U. Kyoto
U. Miyagi
U. Edu. Osaka City
U. Okayama
U. Tokyo Metropolitan
U. U. Tokyo



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

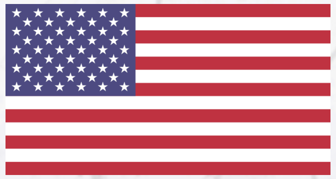
INR

IFAE, Barcelona
IFIC, Valencia



ETH Zurich
U. Bern
U. Geneva

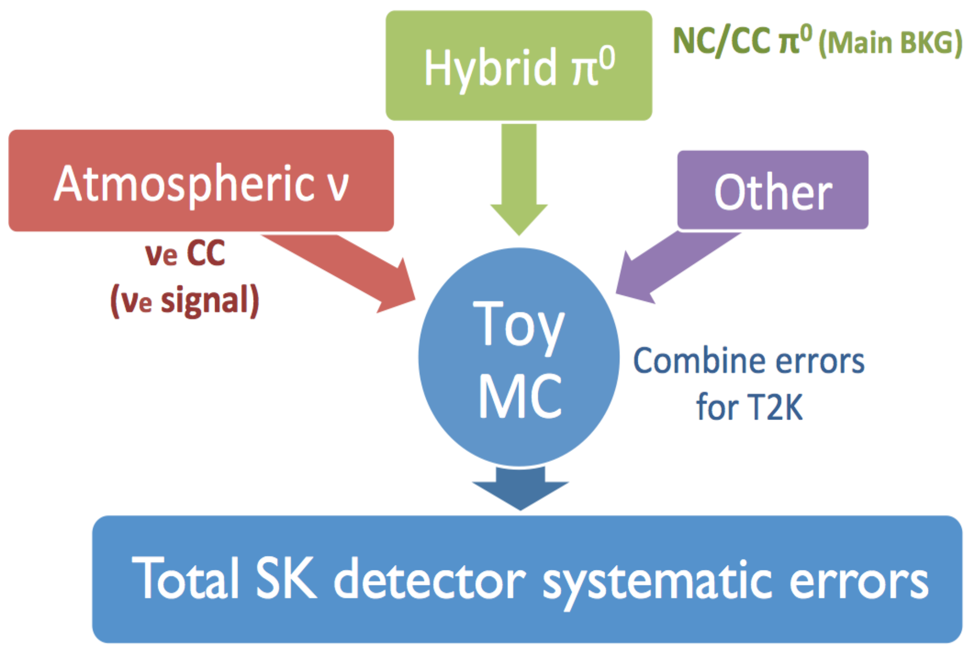
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick



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

SK systematics and control sample

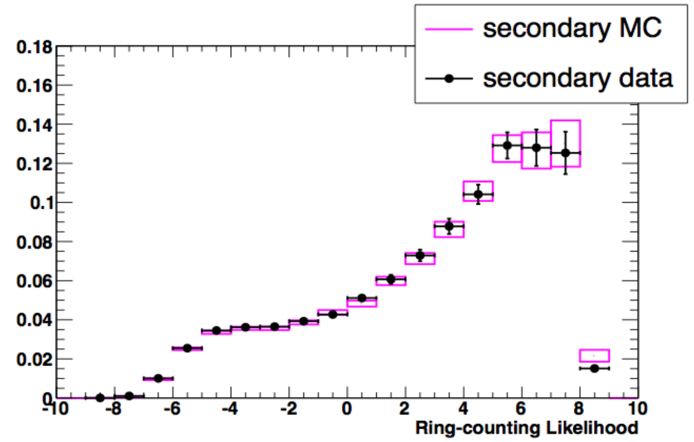
SK detector error estimation



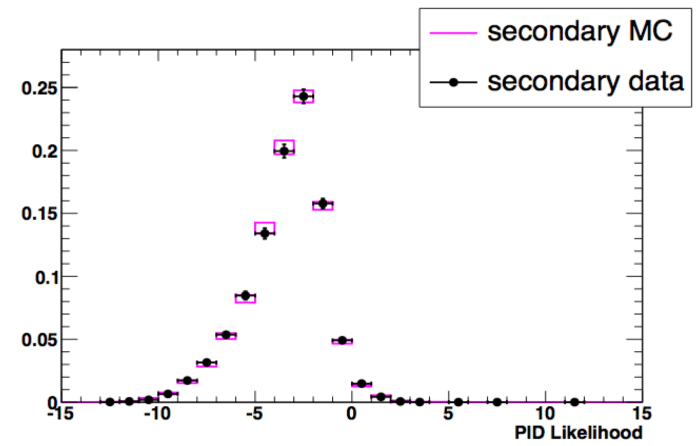
- To evaluated SK detector systematic uncertainties, employ several control samples:
  - Atmospheric νe samples (errors on νe's), "Hybrid-$\pi 0$" samples (errors on $\pi 0$'s), Cosmic-ray muon samples, ...
- The errors evaluated with the control samples are combined with Toy MC method

Basic distributions

Ring Counting

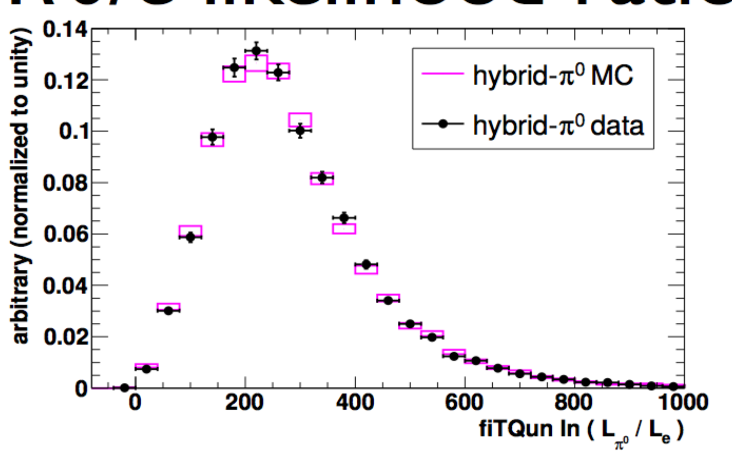


PID

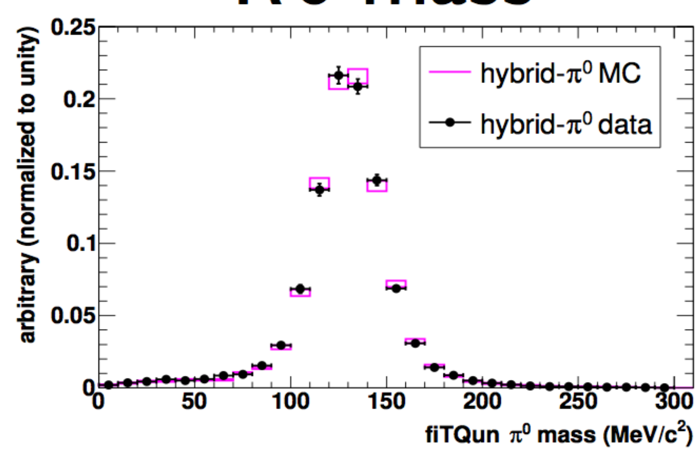


π0 rejection

π0/e likelihood ratio

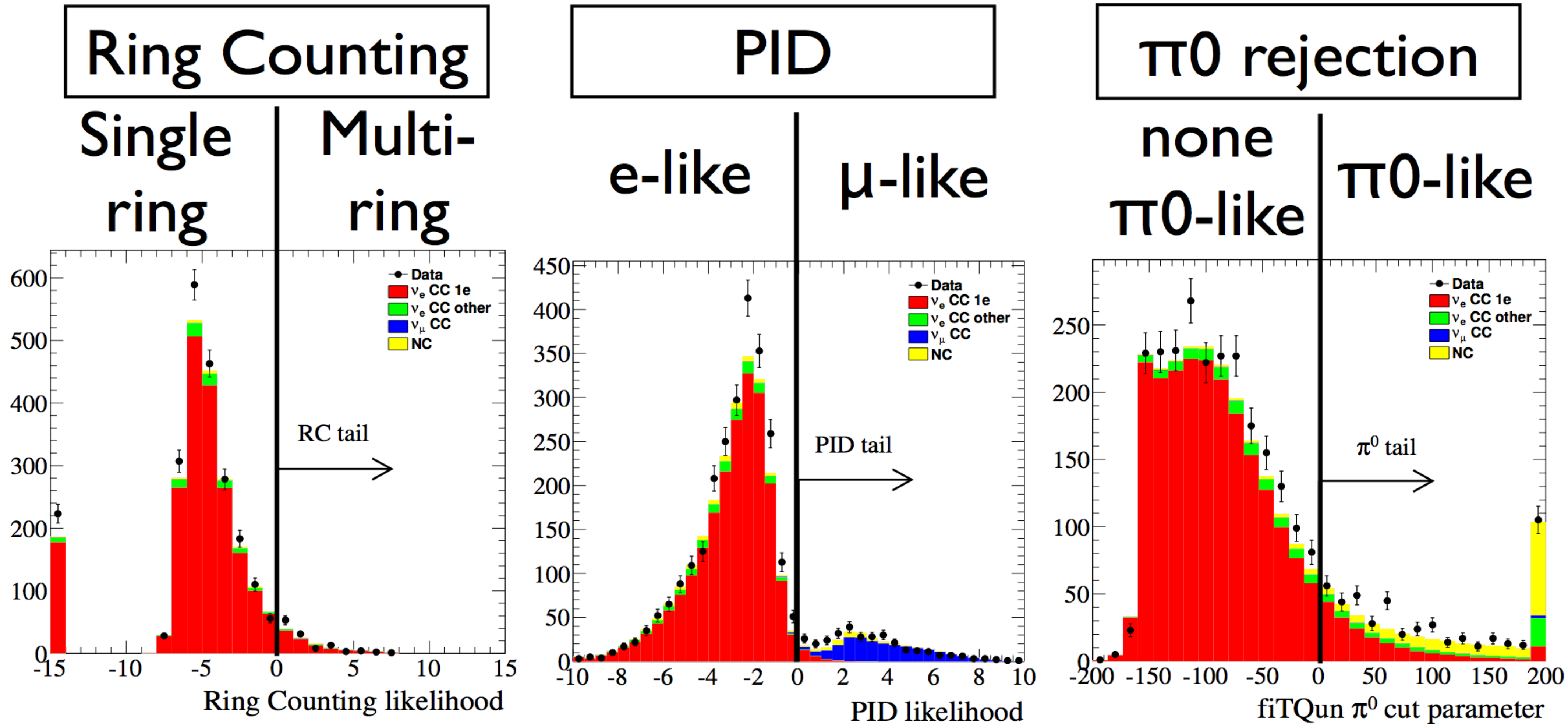


π0 mass



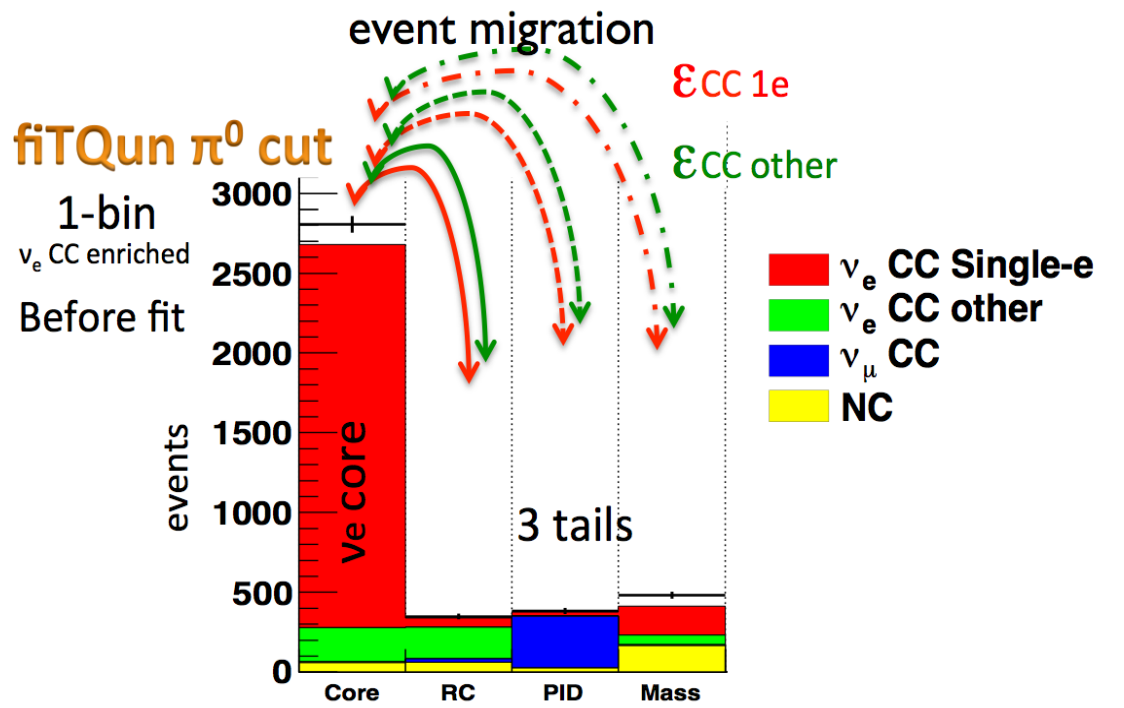
Control Samples

- νe candidate sample ("core" sample) + rejected samples (three "tail" samples)
  - Selections: ring counting, PID, and π0 rejection
  - (cf. νe candidates: 1-ring & e-like & none π0-like)



Atmospheric ν fit

- Evaluate errors on 'νe selection efficiencies' by fit the MC predictions to data by introducing the efficiency parameters ε, that describes event migration between 'core' and 'tail' samples

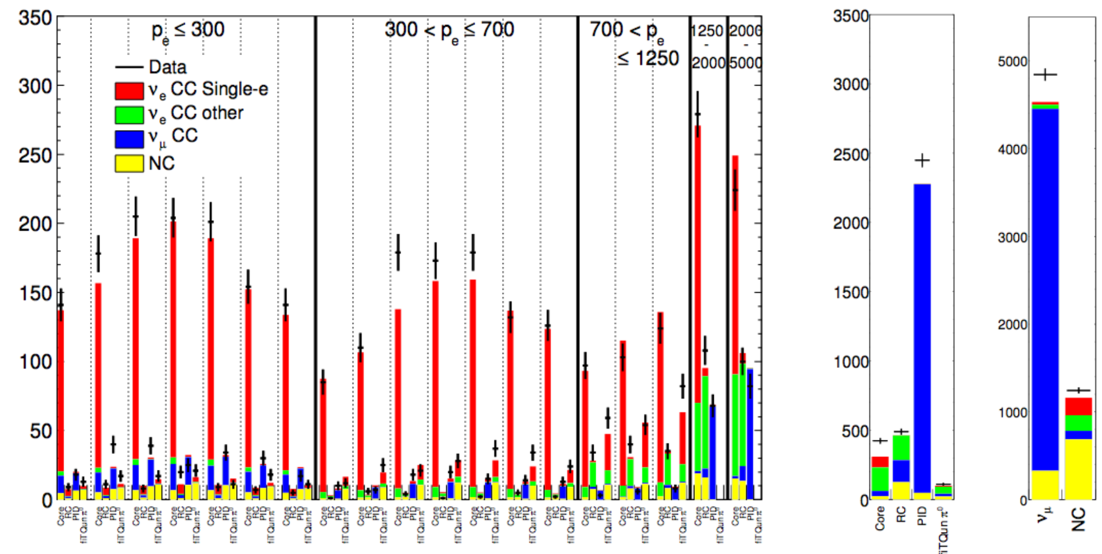


- Evaluate the errors in bins of momentum (p) and scattered angle (θ)
  - p bins: 100, 300, 700, 1250, 2000, 5000 MeV/c
  - θ bins: 0, 40, 60, 80, 100, 120, 140, 180 deg.

atm-ν fit results

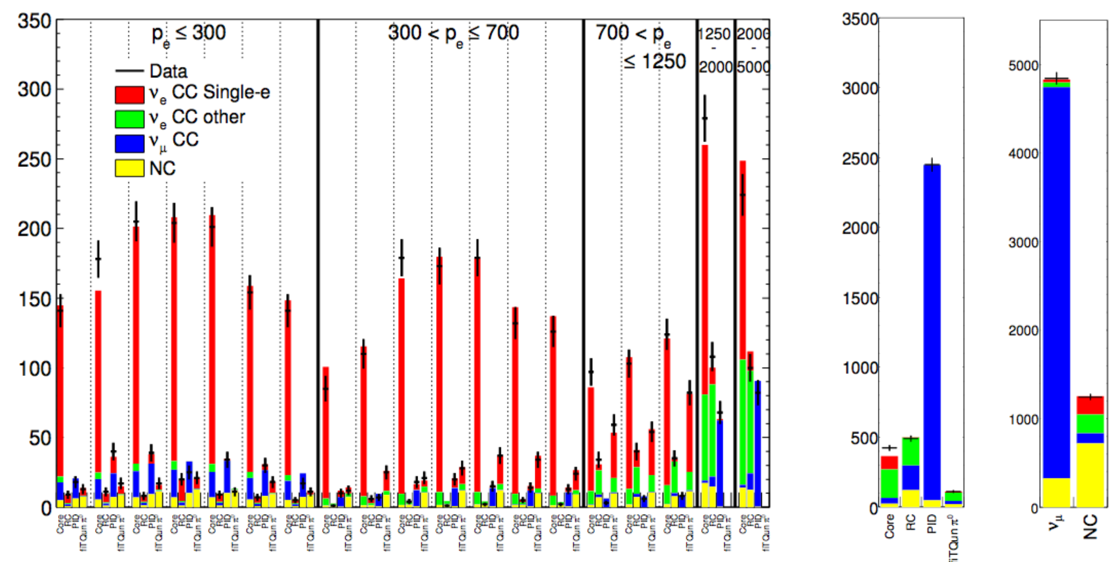
Number of events in p-θ bins and control samples.

Before fit



(a) Before atm-ν fit (Original MC) ($\chi^2 = 336.8$)

Best fit

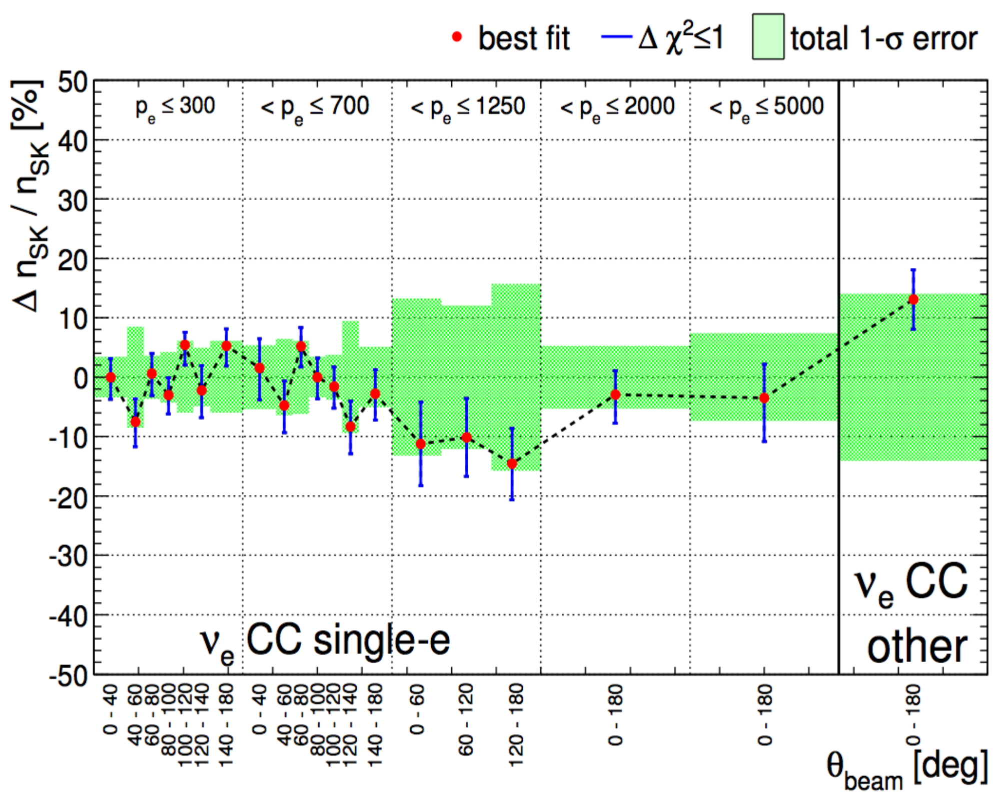


(b) Best fit (Minimized all parameters) ($\chi^2 = 165.4$) / ($d.o.f. = 186\text{bins} - 58 = 128$)

8

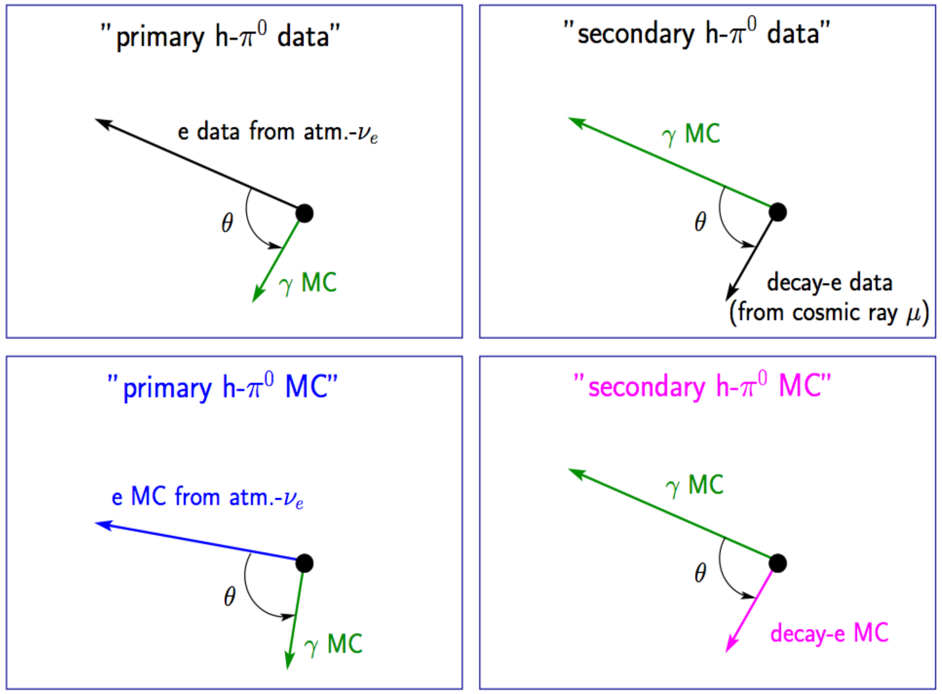
SK error w/ atm-ν fit

- Errors on number of νe candidates (n_{SK}) in 19 p-θ bins for 'νe CC single-electron' events and 1 bin for 'νe CC other' events
  - Correlated error (red point): difference from the 'best fit'
  - Uncorrelated error (blue bar): fit error (stat. error)



"Hybrid-π0" samples

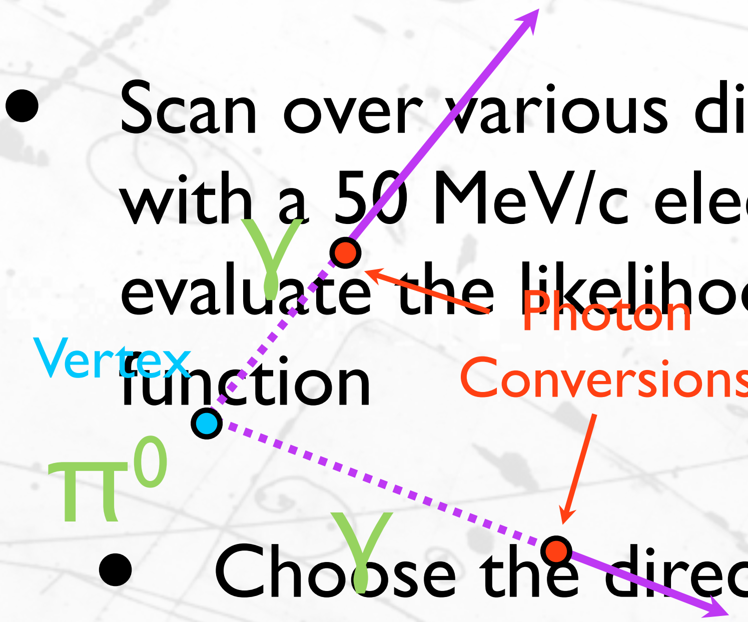
- "Hybrid-π0" samples
  - Electron track from atm-ν data is combined with γ from MC following π0 decay kinematics



- Control samples:
  - Primary: electron from atm-ν is used for the higher energy "γ", and the lower energy γ from MC
  - Secondary: electron of atm-νe (and decay-e from cosmic-ray μ) is the lower energy "γ", and higher energy γ from MC

fiTQun π^0 Fitter

- Assumes two electron hypothesis rings produced at a common vertex
- **12 parameters** (single track fit had 7)
    - Vertex (X,Y, Z,T)
    - Directions (θ_1, φ_1, θ_2, φ_2)
    - Momenta (p_1, p_2)
    - Conversion lengths (c_1, c_2)
- **Seeding the fit**
- Use result of single-track electron fit
- Scan over various directions with a 50 MeV/c electron and evaluate the likelihood function
    - Choose the direction that yields the best likelihood

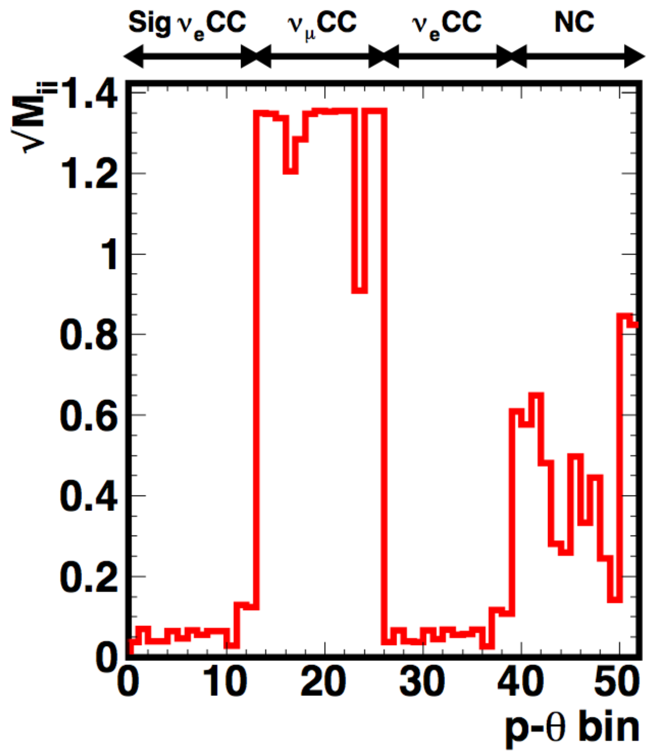


- First, fit while floating only p_1 and p_2
- **Do full 12 parameter fit**

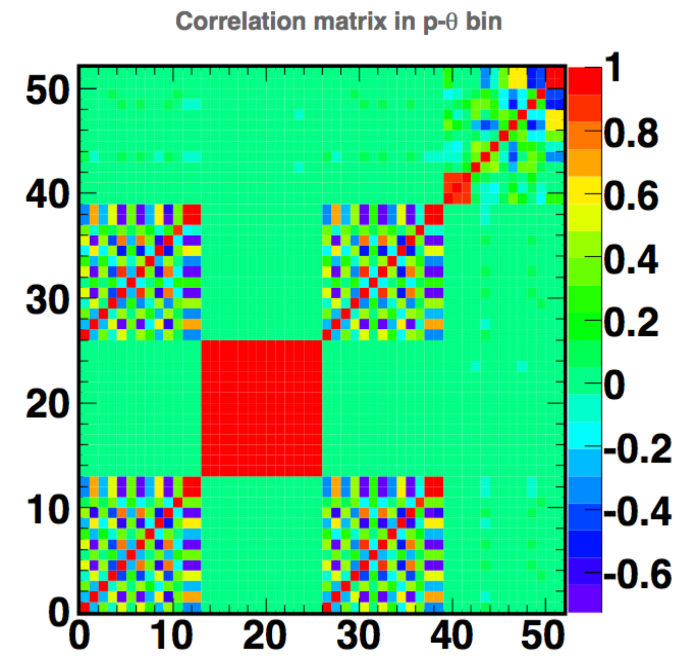
Error matrices in p-θ

- Error matrices for inputs to oscillation analyses in p-θ bins

Square-root of diagonal elements of covariance matrix



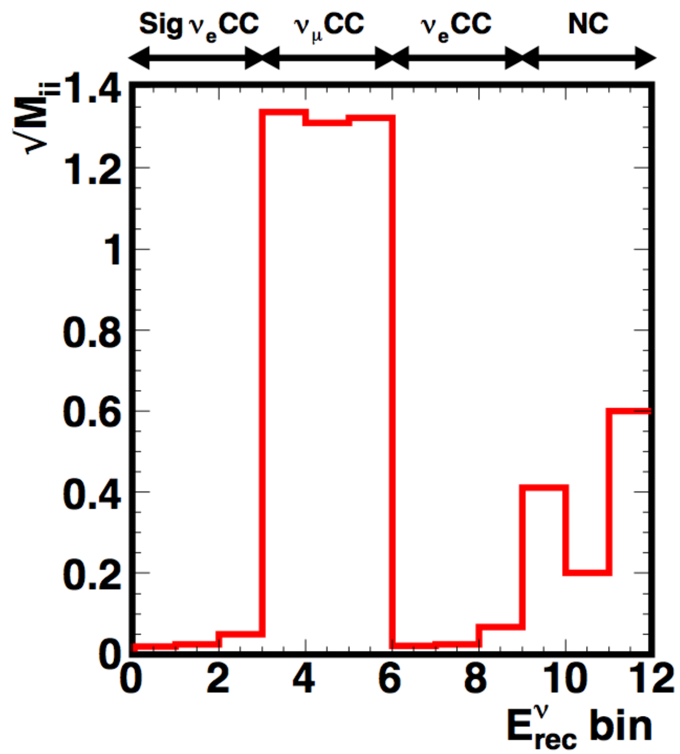
Correlation matrix



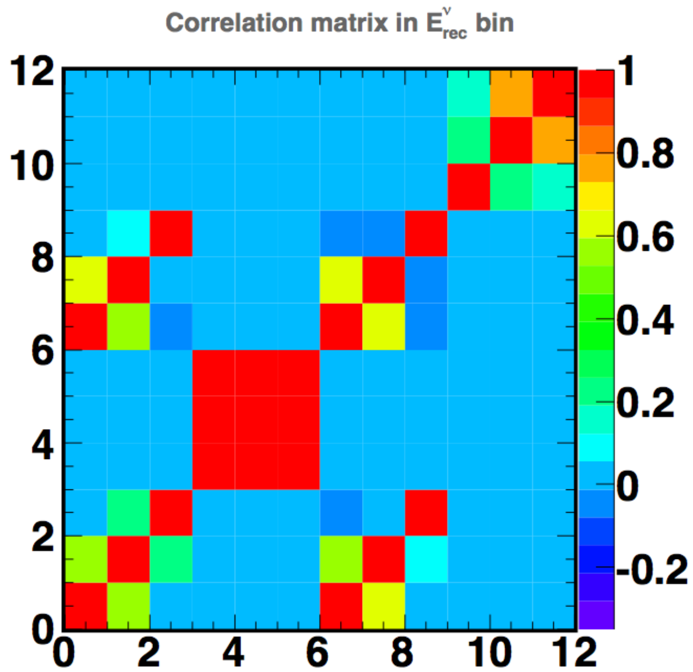
Error matrices in rec Eν

- Error matrices for inputs to oscillation analyses in Eν bins

Square-root of diagonal elements of covariance matrix



Correlation matrix



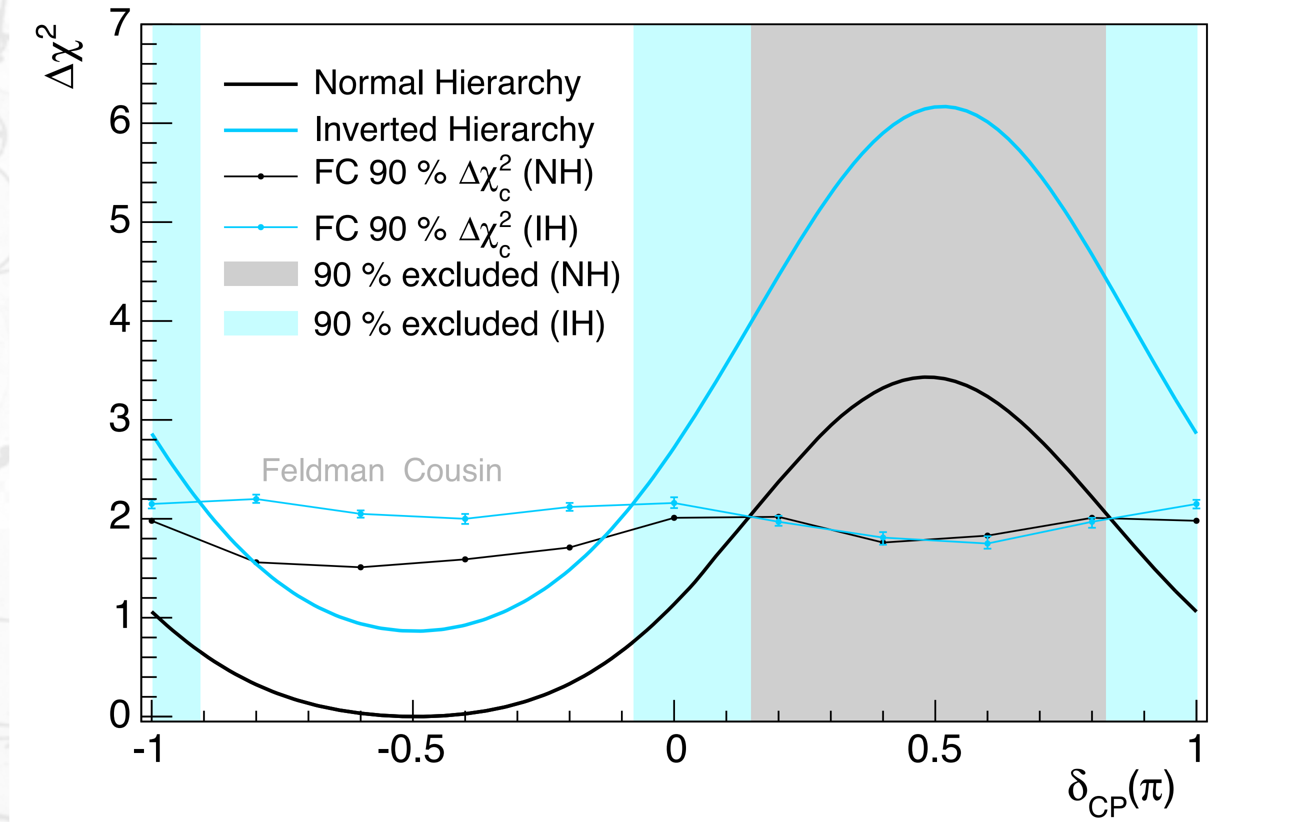
Joint analysis

No assumptions!

Likelihood ratio fit
to both $\nu_\mu + \nu_e$
event samples

Accounting for correlations in the parameter space
$(\theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{32})$

T2K



Including constraint from reactor experiments *Daya Bay, RENO, Double Chooz*

$\sin^2 2\theta_{13} = 0.095 \pm 0.010$
(PDG 2013)

	90% CL
NH	$\delta_{CP} \in [-1.18, 0.15]\ \pi$
IH	$\delta_{CP} \in [-0.9, -0.08\ ]\ \pi$

Cross-sections: FSI

Nucleus Final State Interactions (FSI)

- Interactions of final state hadrons in nucleus can cause migration from signal to background type events.
- Constrain with external pion-nucleus scattering data in a cascade model.
- Uncertainties assigned to span the pion-nucleus scattering data.