

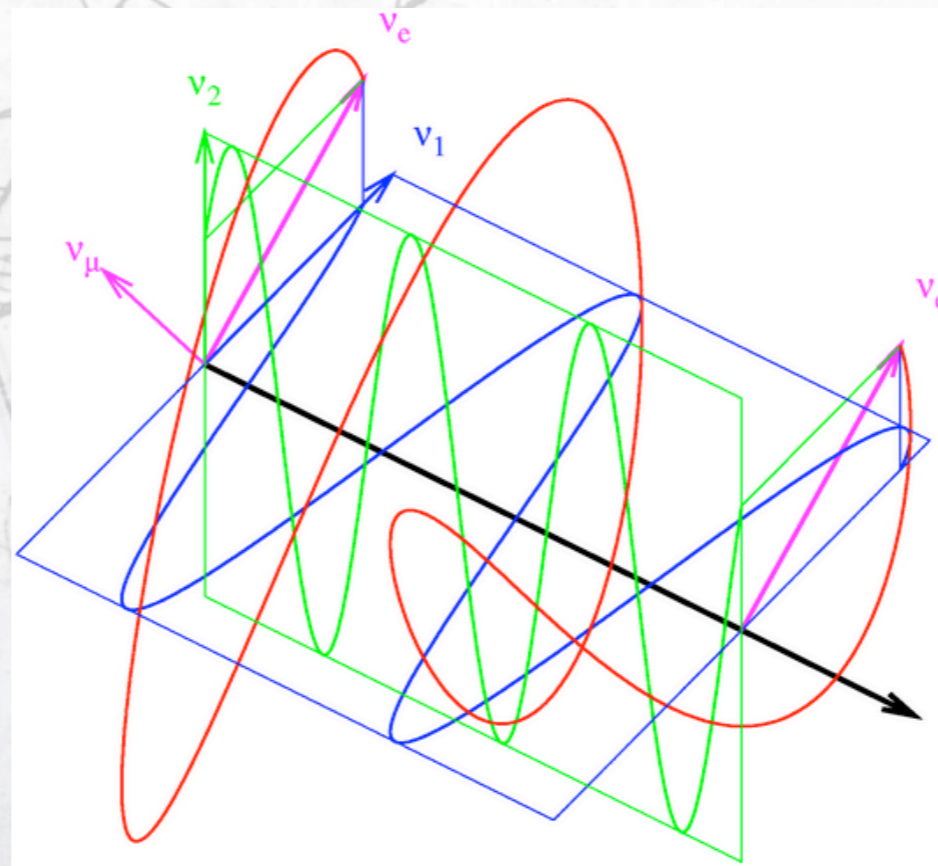
New T2K results



The logo for the T2K experiment, featuring the letters 'T2K' in a bold, red, sans-serif font. A thick green wavy line is drawn over the letters, starting from the bottom of the 'T', curving under the '2', and rising to peak over the 'K' before descending. A shorter, blue wavy line is positioned below the green one, starting under the 'T' and ending under the '2'.

Federico Sánchez, IFAE (Barcelona)
on the behalf of the T2K collaboration.

Neutrino oscillations



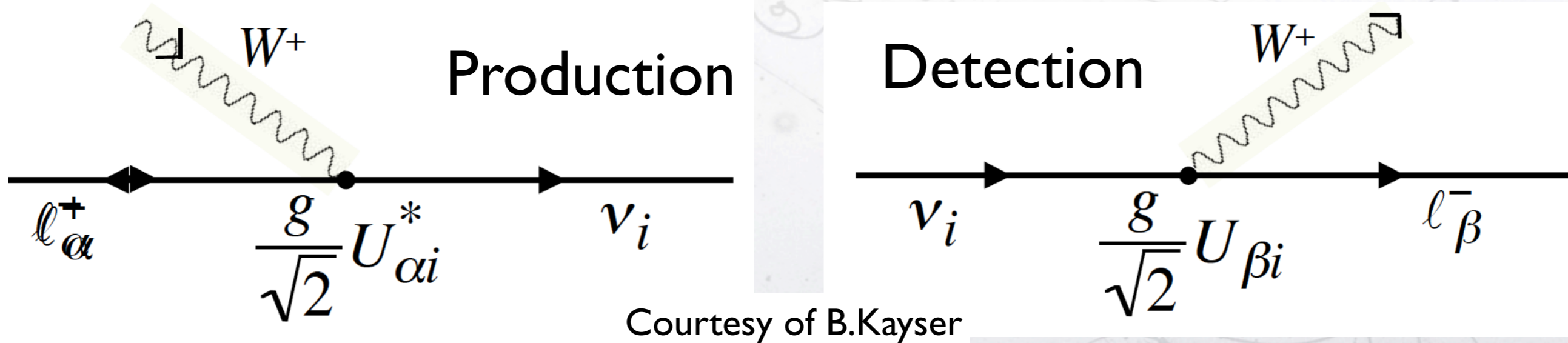
ν oscillations



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}).

$$U_{PNMS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$



ν oscillations



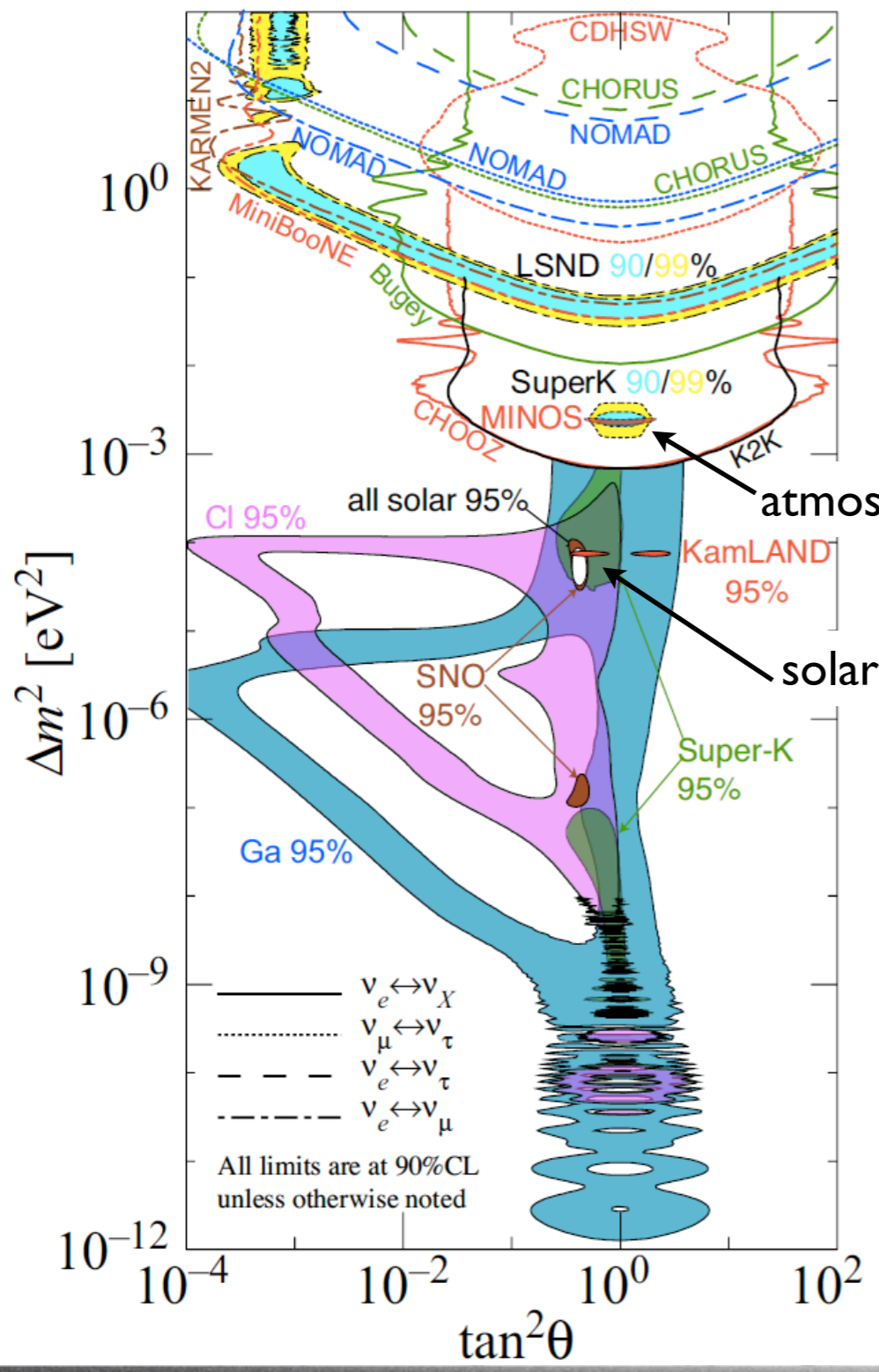
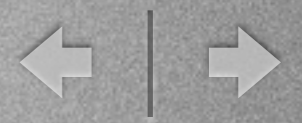
$$U_{PNMS} = \begin{matrix} \text{atmospheric} & & \text{solar} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} & \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13}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

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

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



ν oscillations



Particle Data Group neutrino review

Status as of 2012

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

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

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

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

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

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



ν oscillations



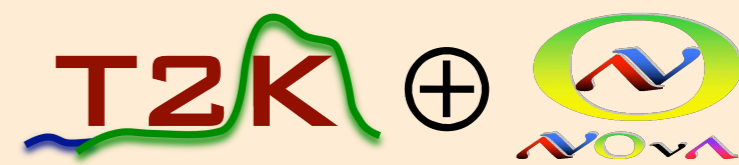
What is missing



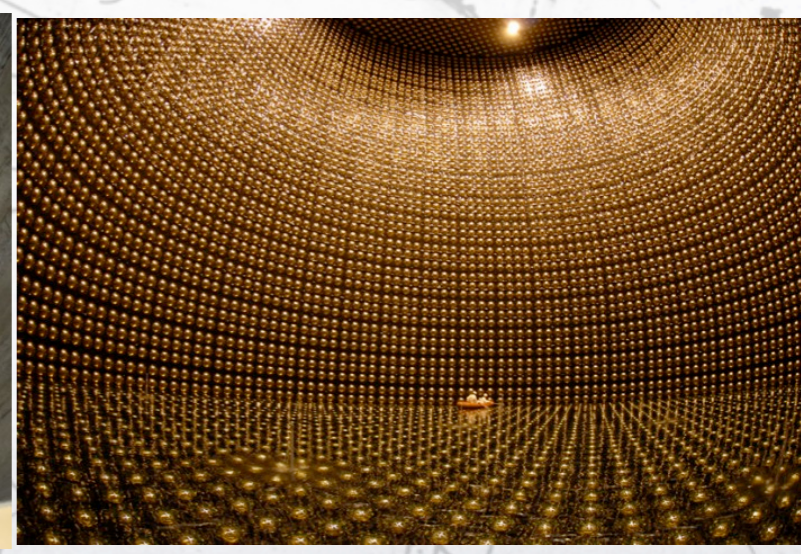
- δ_{CP} accessible through:
 - comparison of appearance with reactor disappearance.
 - comparison of $\nu_{\mu} \rightarrow \nu_e$ and $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$
- The θ_{23} octant:
 - The θ_{23} is close to 45°

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

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



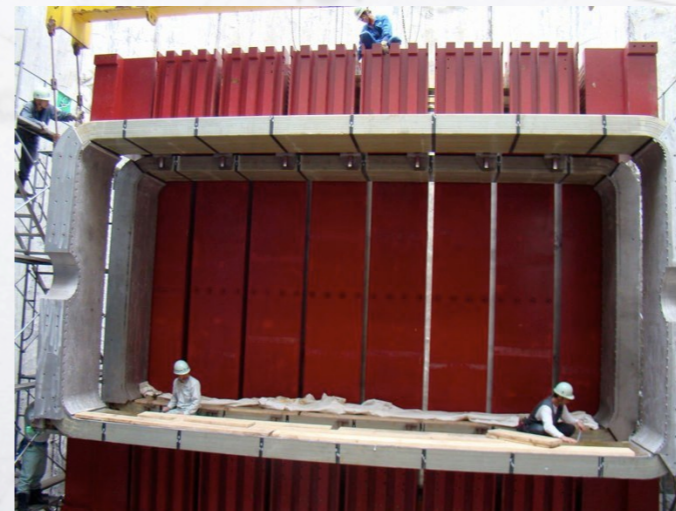
T2K



History



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



~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



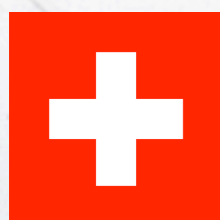
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw Warsaw
U. T. Wroclaw U.



INR



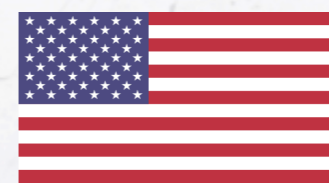
IFAE, Barcelona
IFIC, Valencia



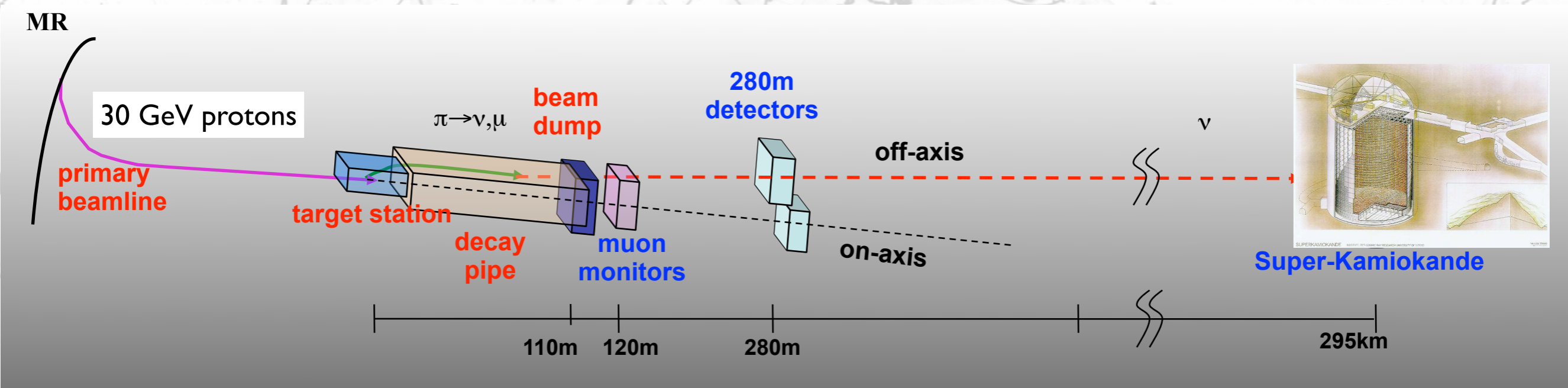
ETH Zurich
U. Bern
U. Geneva



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



Beam

ND280

Super-Kamiokande

Beam



MR

30 GeV protons

primary beamline

target station

$\pi \rightarrow \nu, \mu$

decay pipe

beam dump

muon monitors

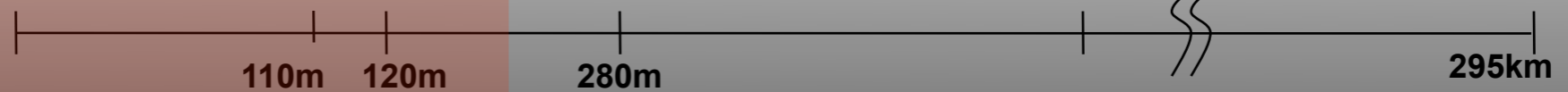
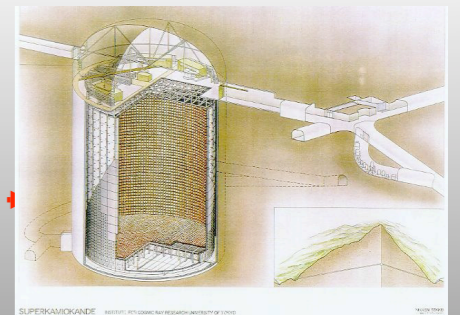
280m detectors

off-axis

on-axis

ν

Super-Kamiokande

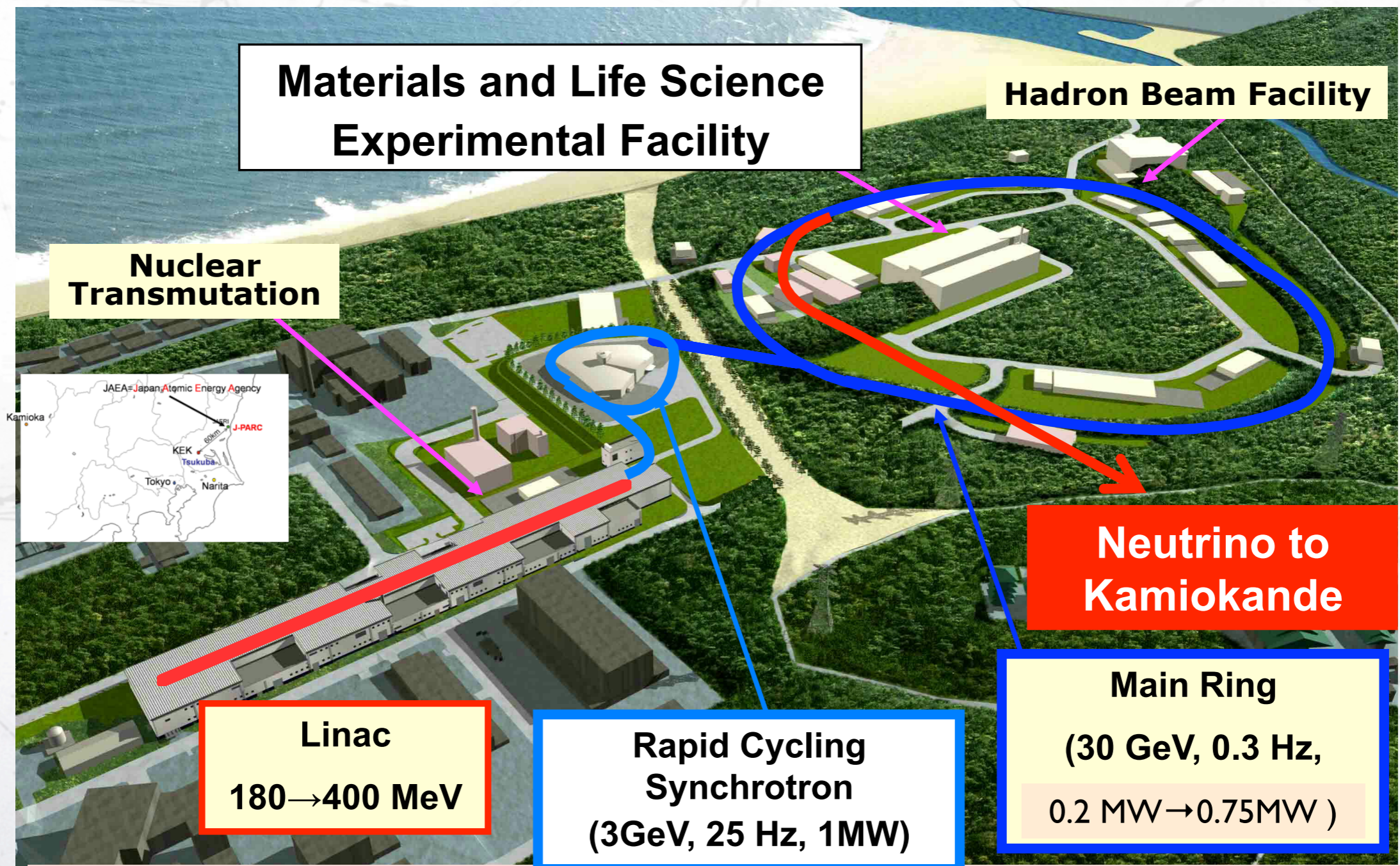


Beam

ND280

Super-Kamiokande

J-PARC

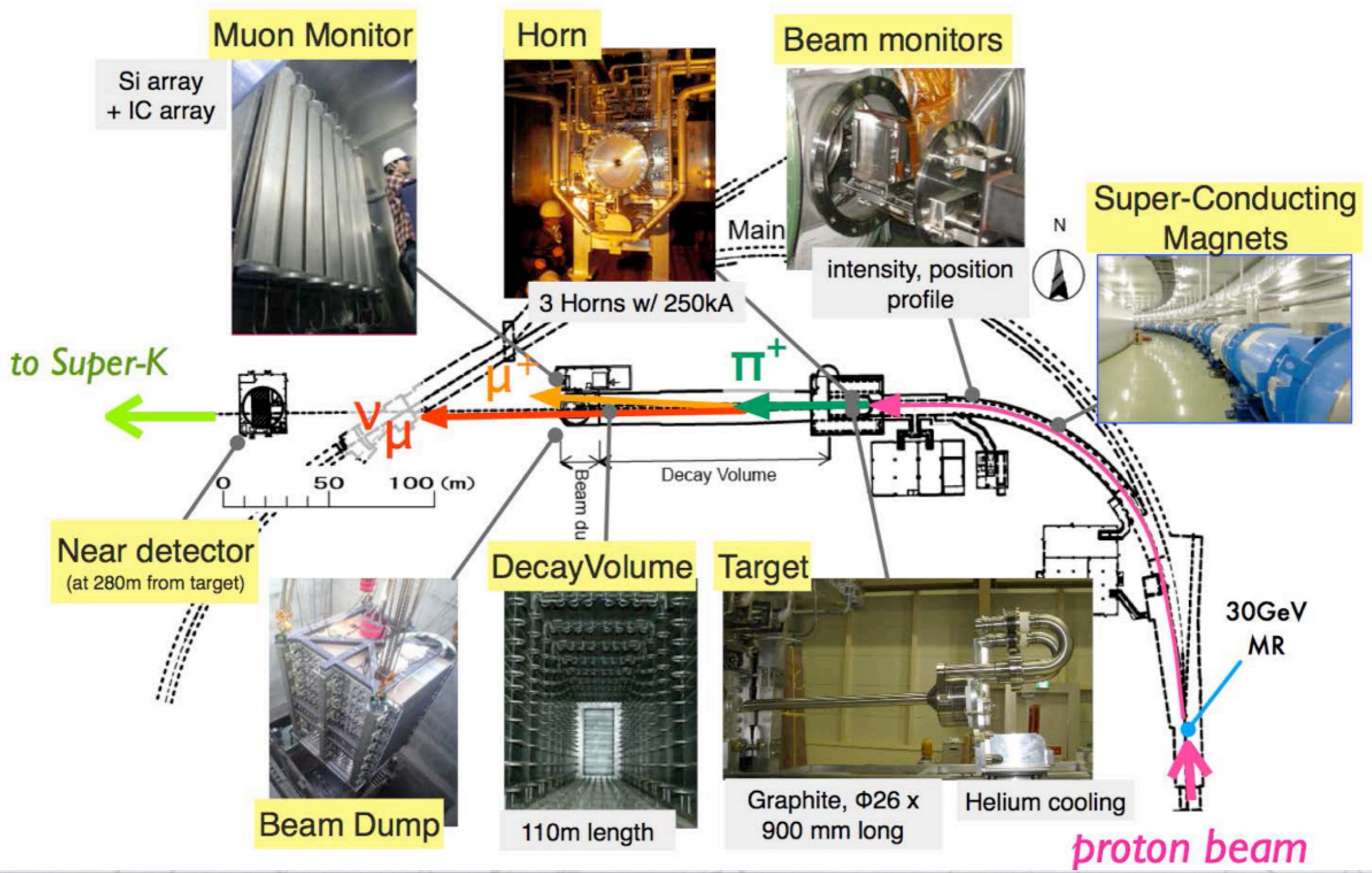


J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA



ν beam

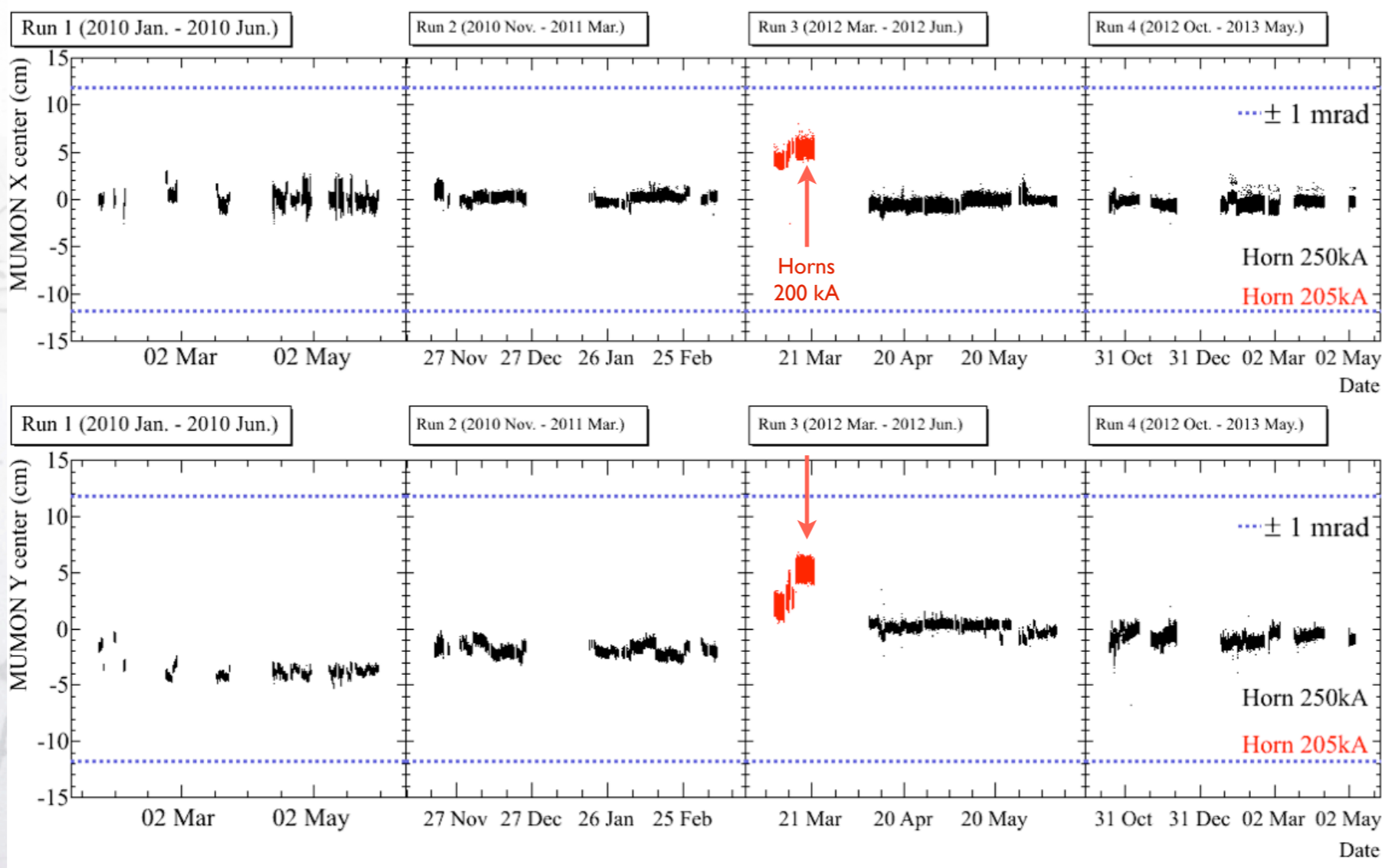


Beam stability

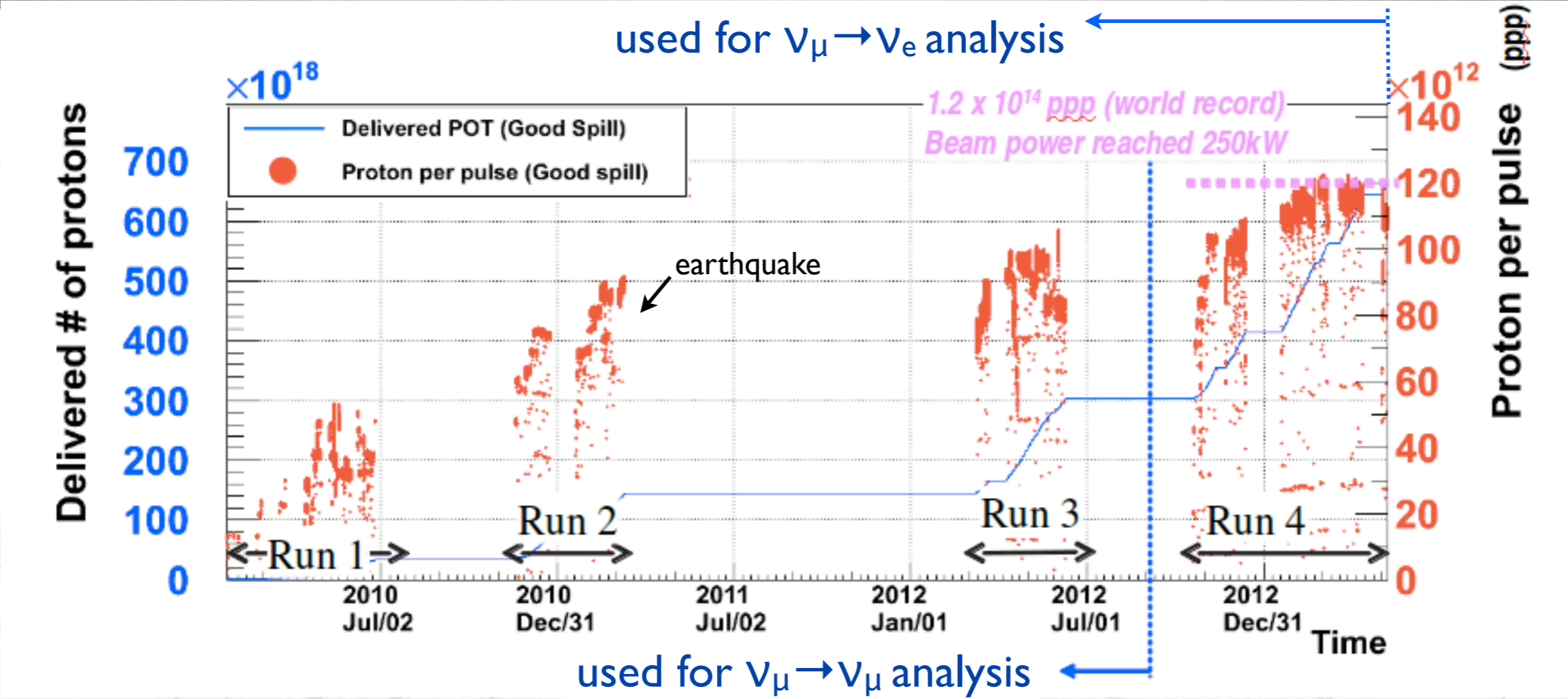


- Muon monitor downstream the beam dump monitors beam direction. Stability requirements < 1 mrad

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



Data sets



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

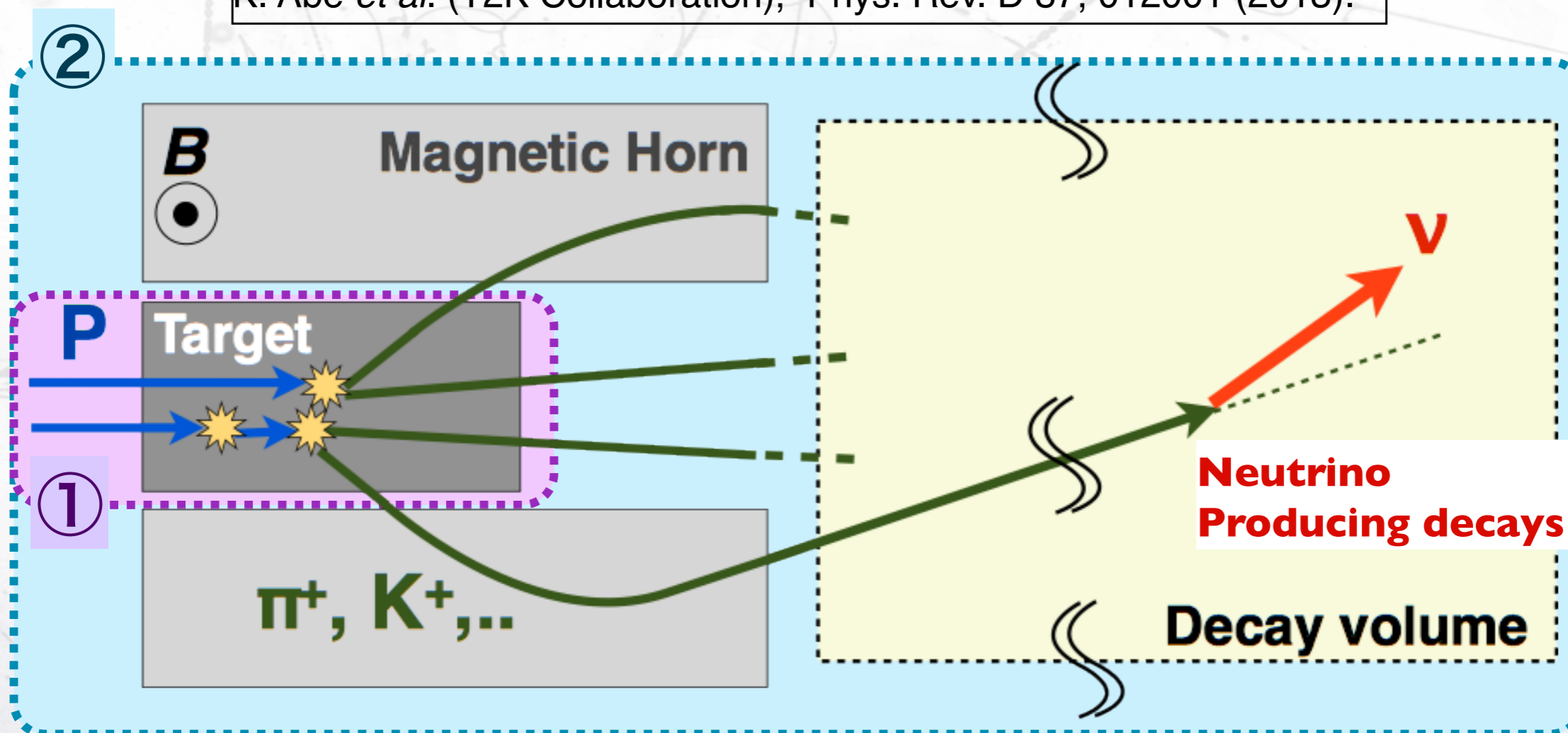
x~2 PoT in Run4!



Flux prediction



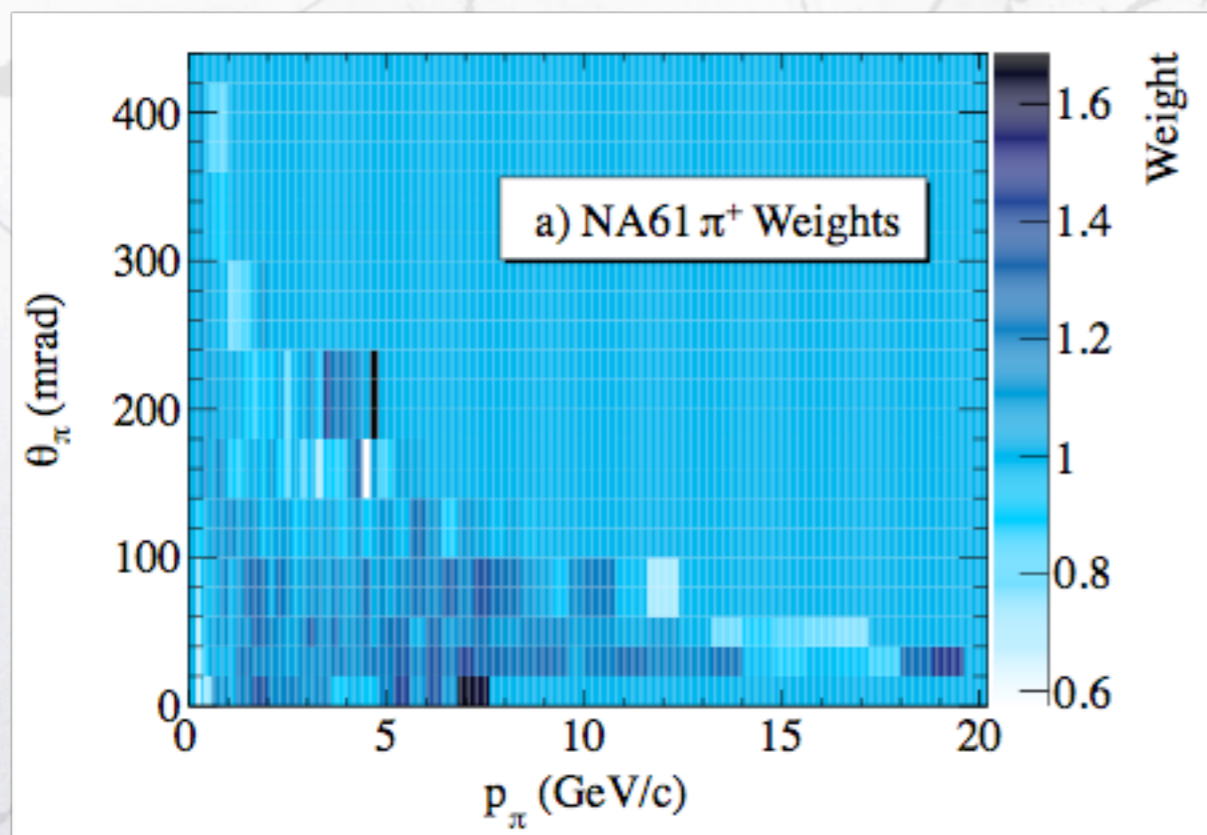
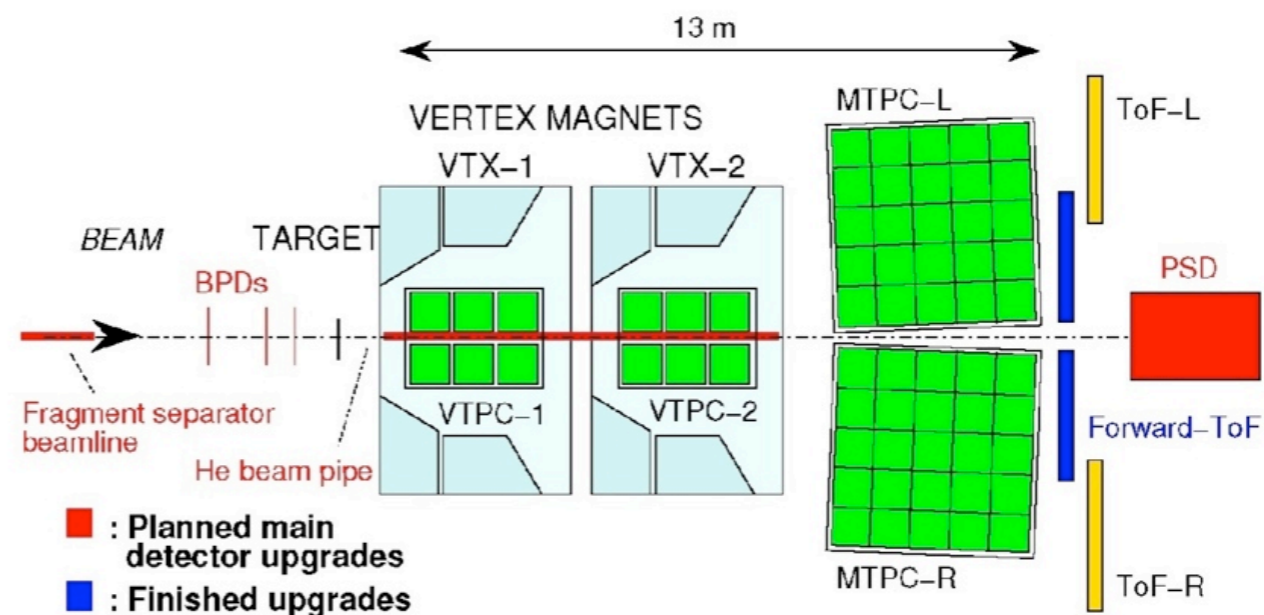
K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



NA61: Shine



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



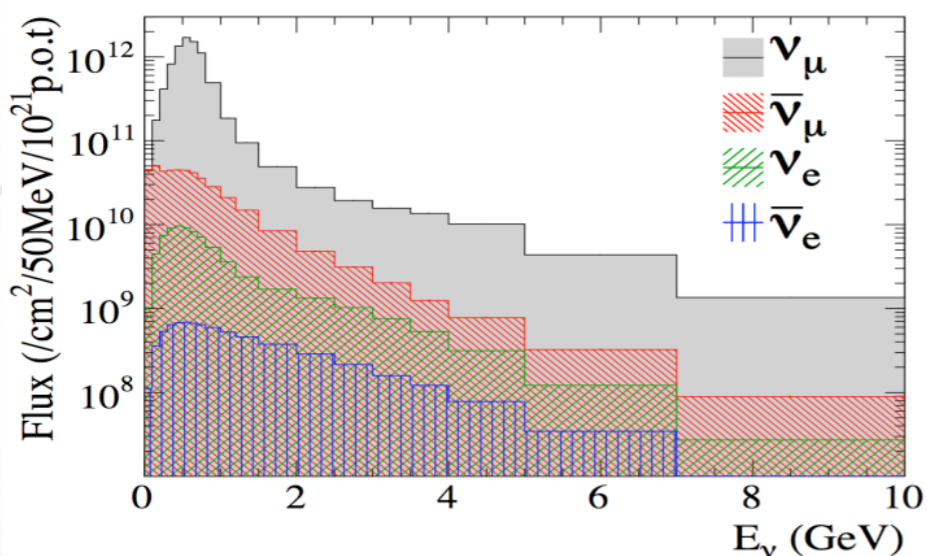
NA61/Shine measures a thin target for absolute production and thick target that is a copy of T2K target and provides also the reinteractions.



Flux prediction

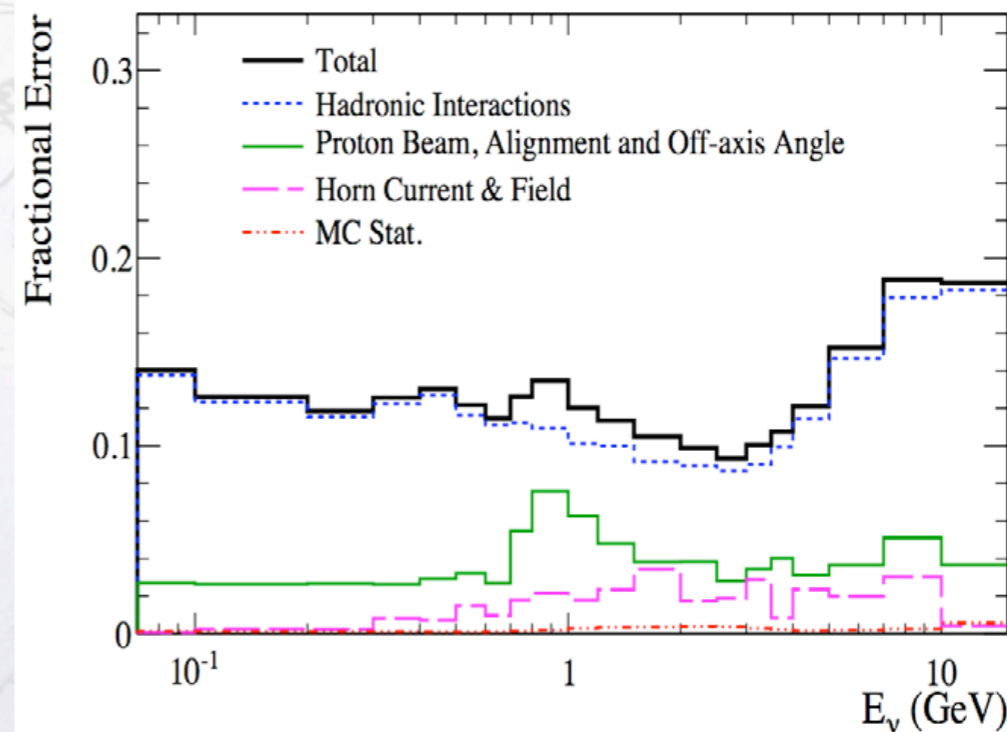
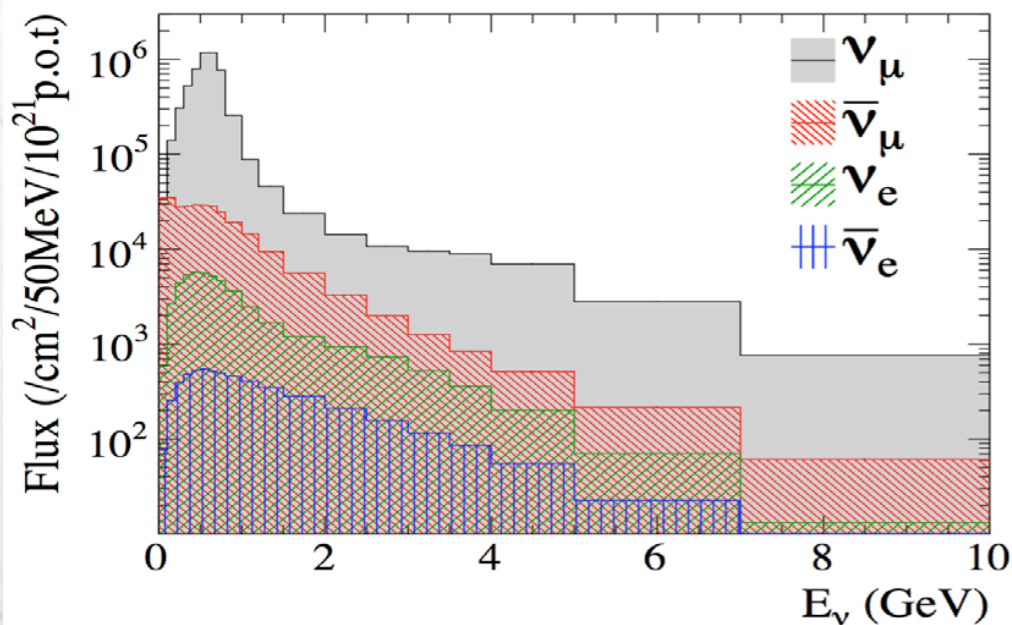


T2K Run1-4 Flux at ND280

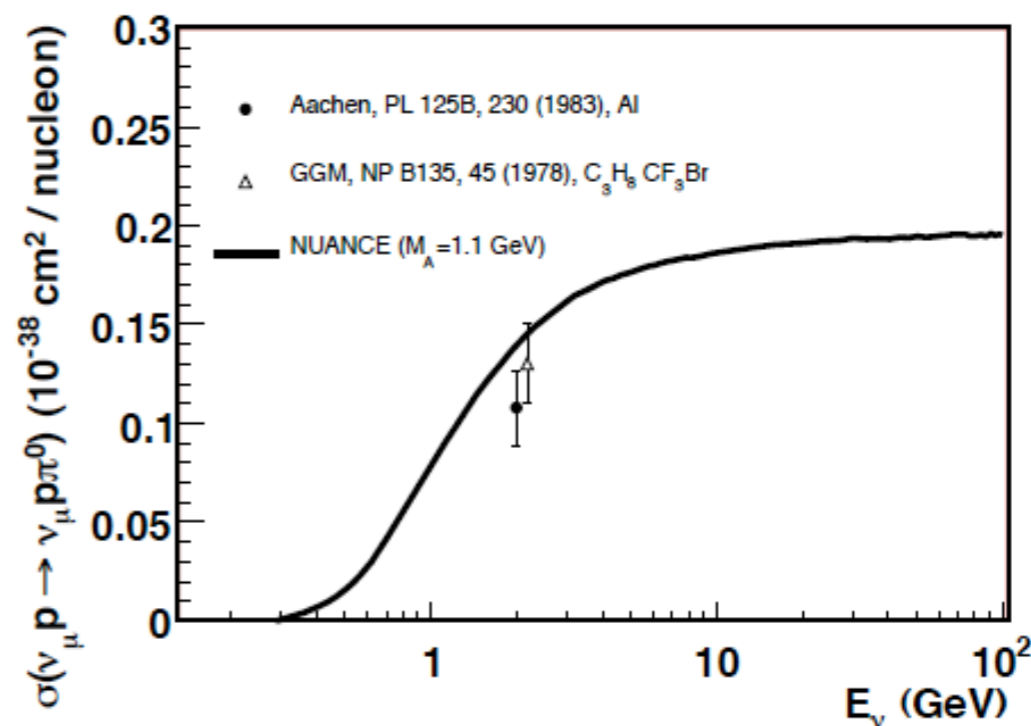
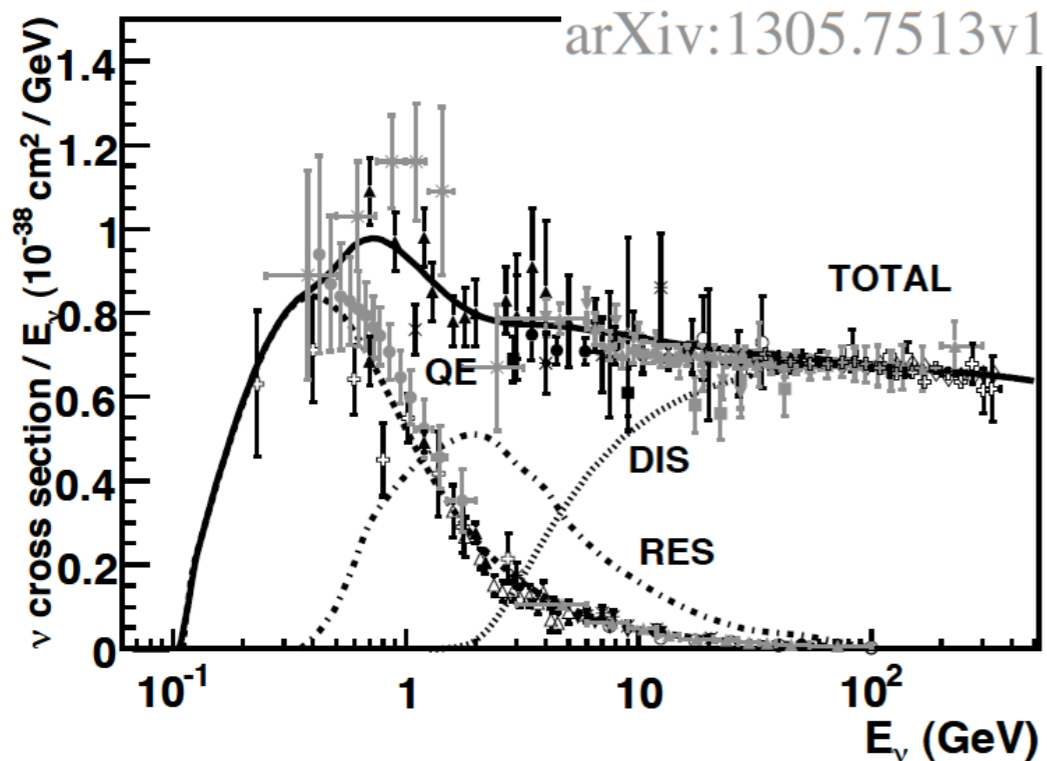


- Simulation is carried out by Fluka2008 3d.
- The pion and kaon production is weighted to the results from NA61-Shine.
- “A priori” flux error: ~15% below @ 1 GeV.
- Strong correlation between near and far detector.

T2K Run1-4 Flux at Super-K



When $E_\nu > 100\text{MeV}$ the ν -Nucleus cross-section dominates.



Charge current

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

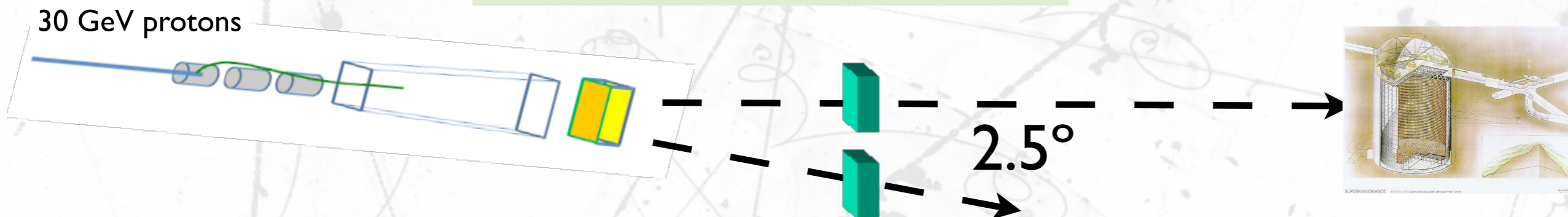
Neutral current

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

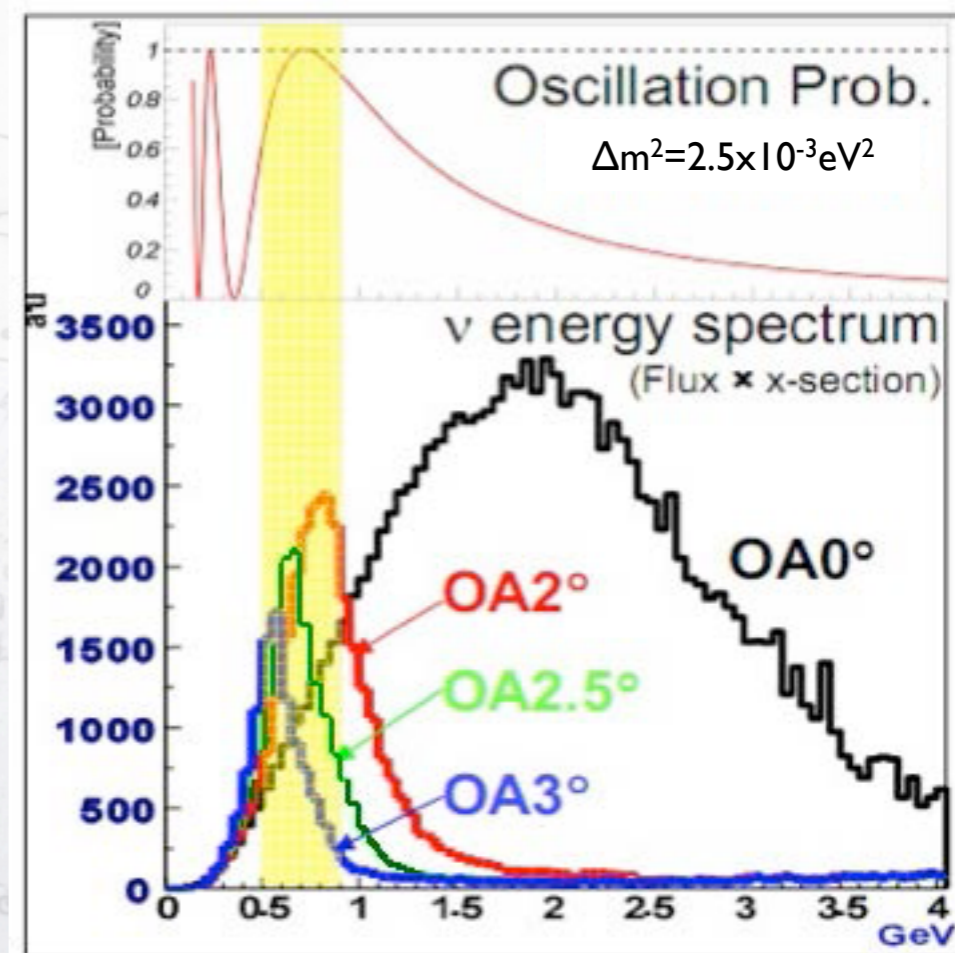
Off-axis concept



T2K runs 2.5° off-axis



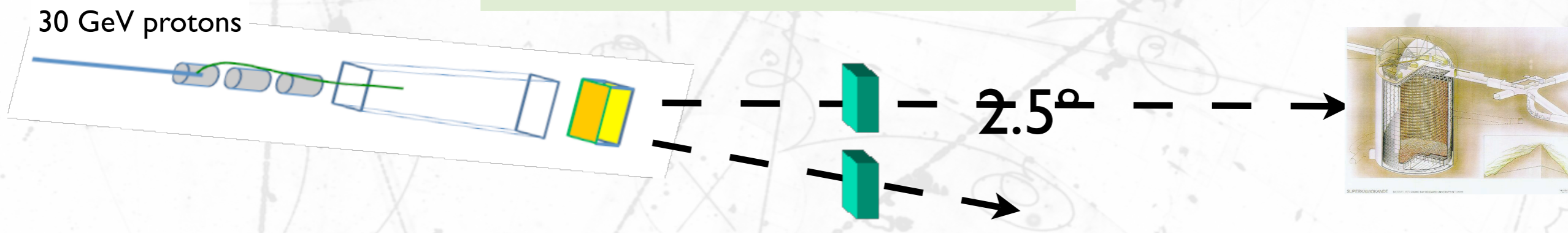
- off-axis optimises the flux at the maximum of the oscillation.



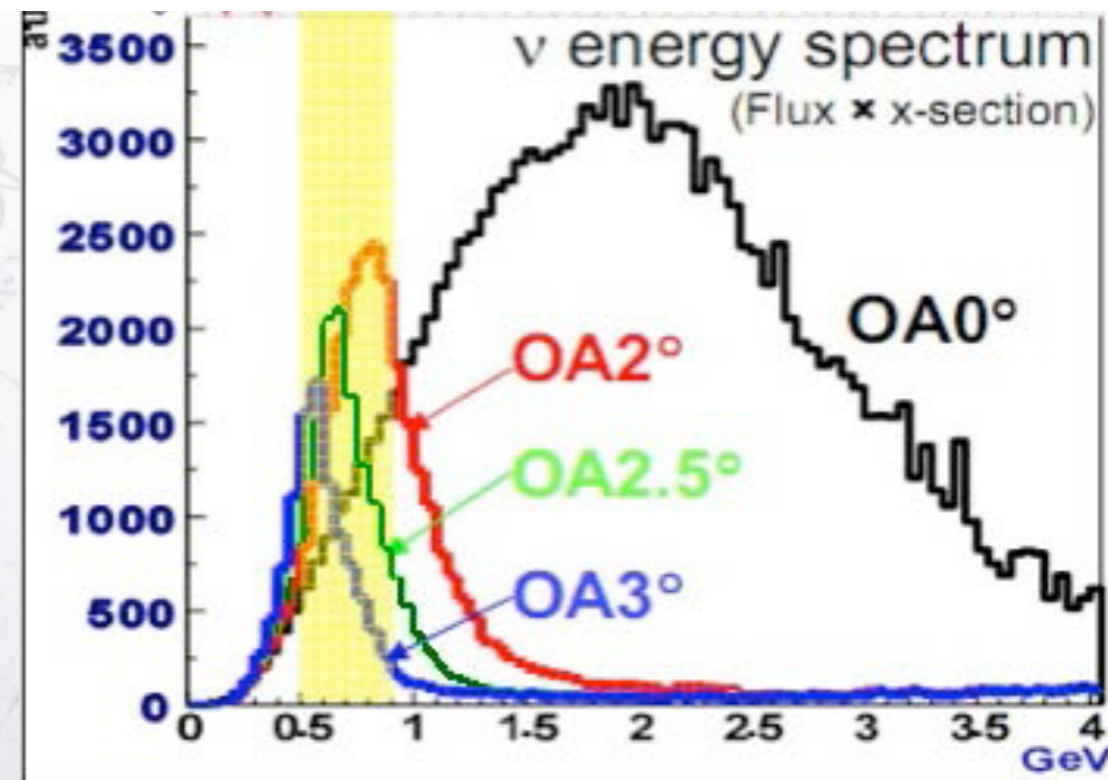
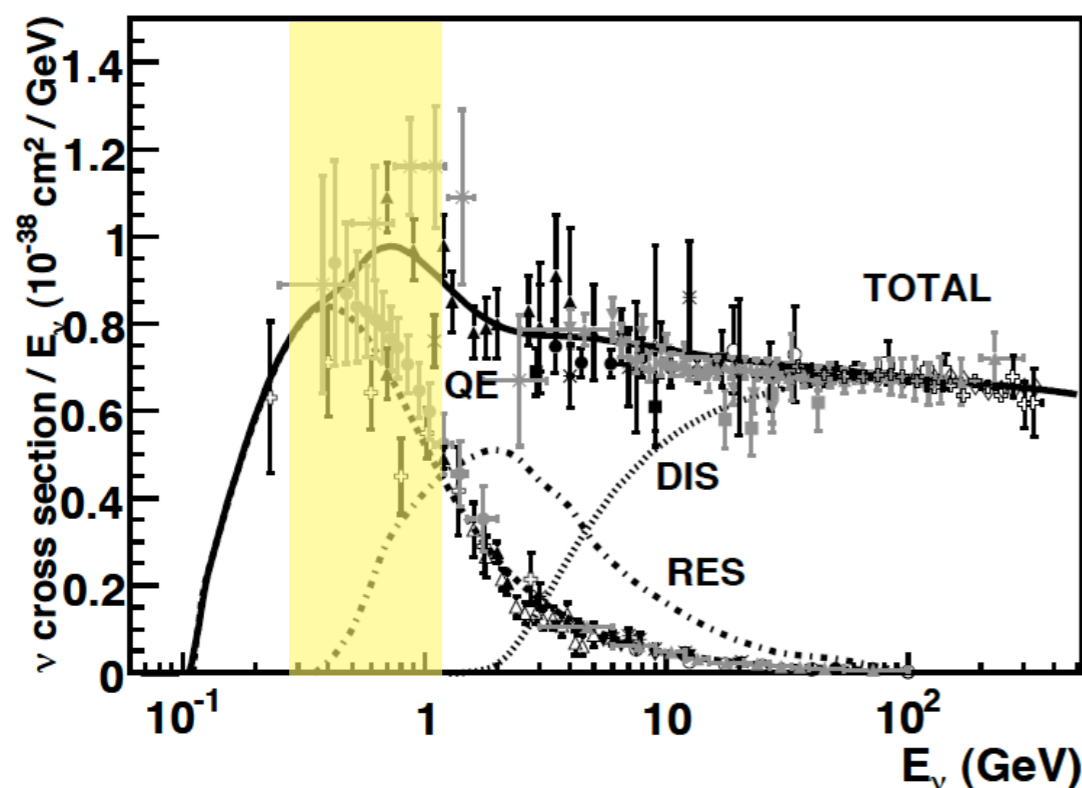
Off-axis concept



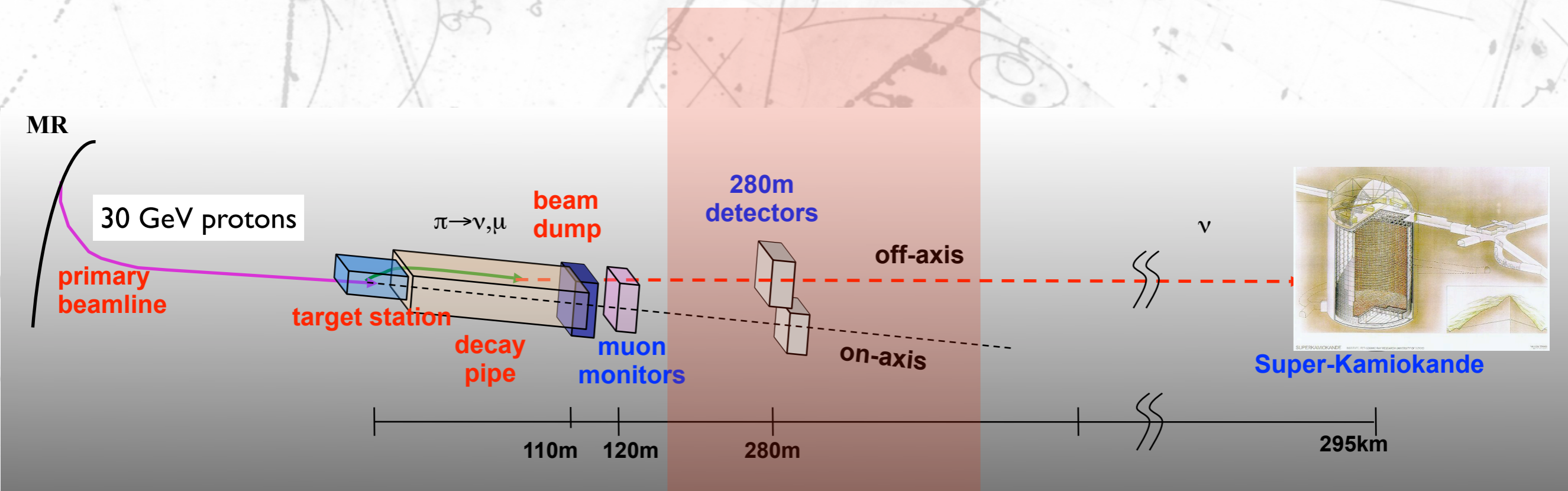
T2K runs 2.5° off-axis



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



ND280

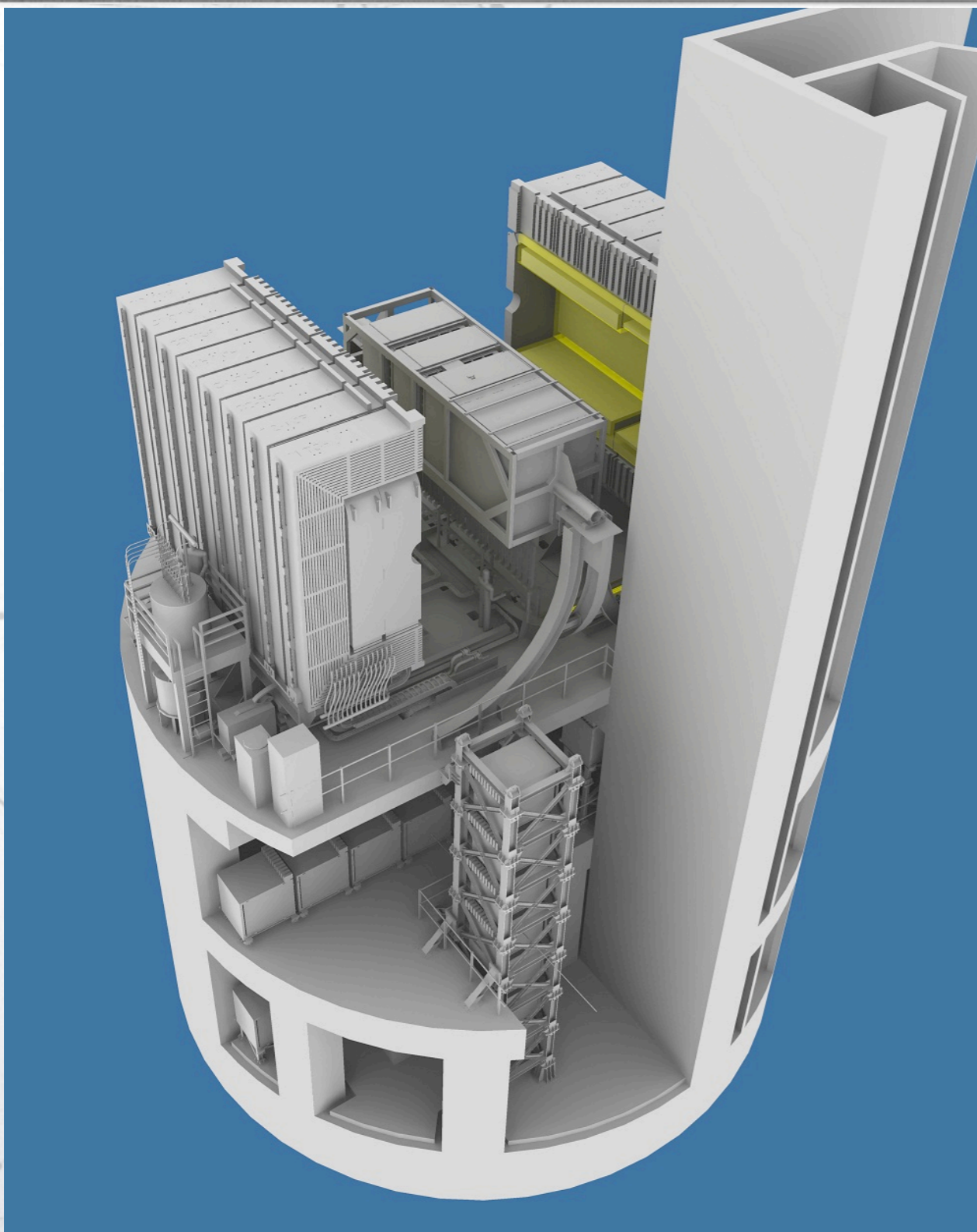


Beam

ND280

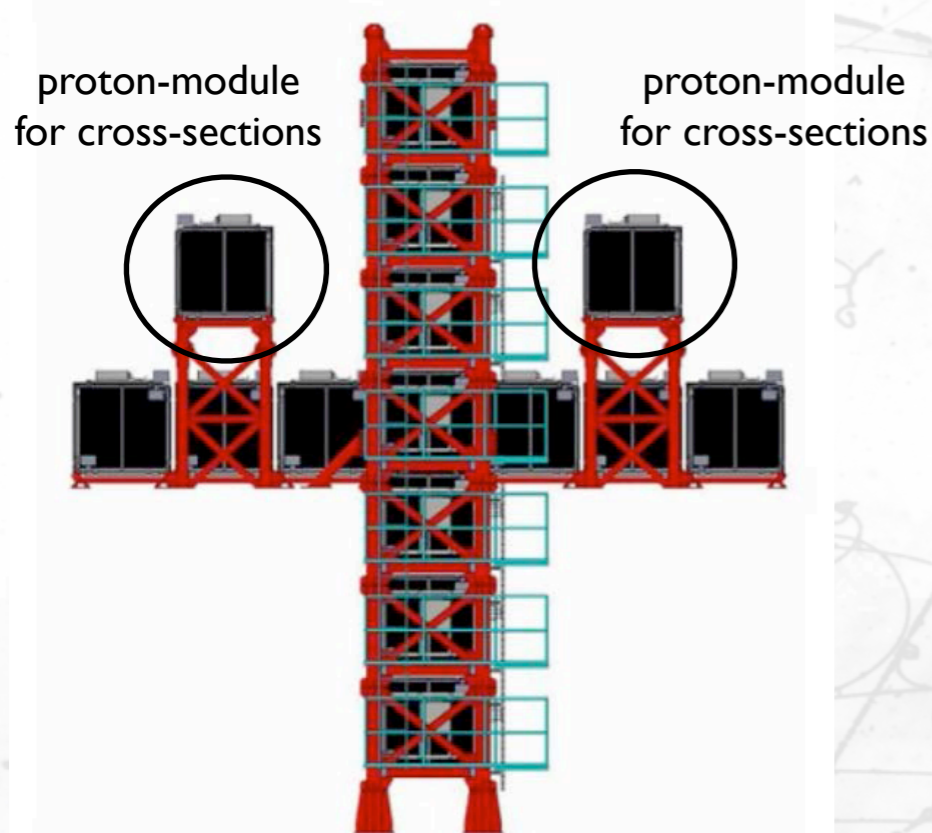
Super-Kamiokande

ND280

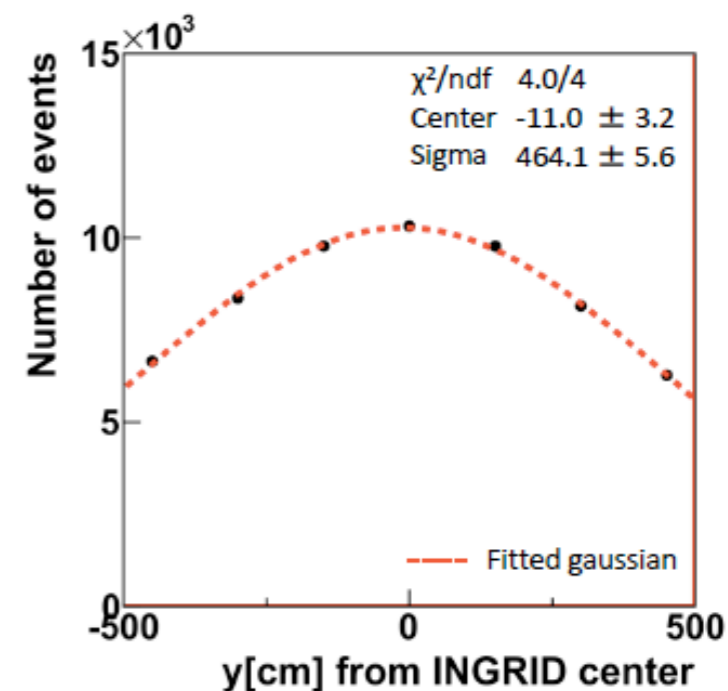
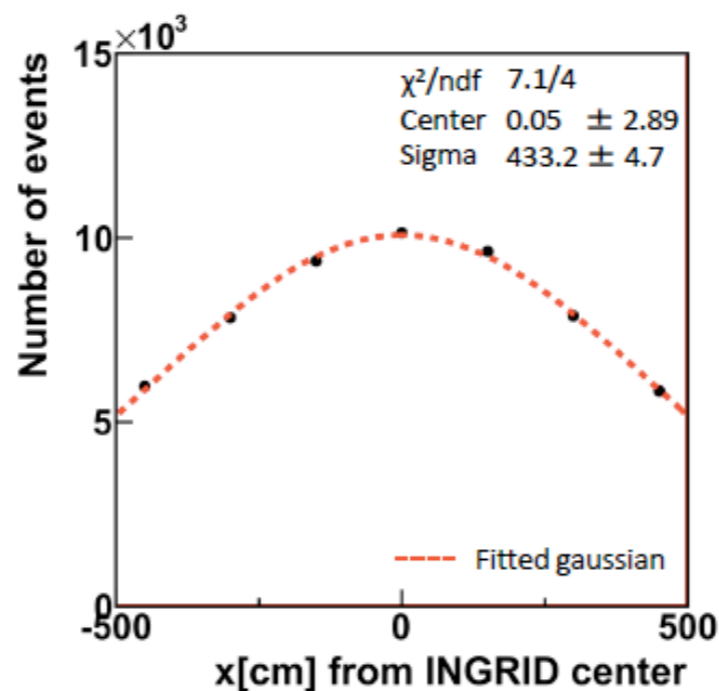
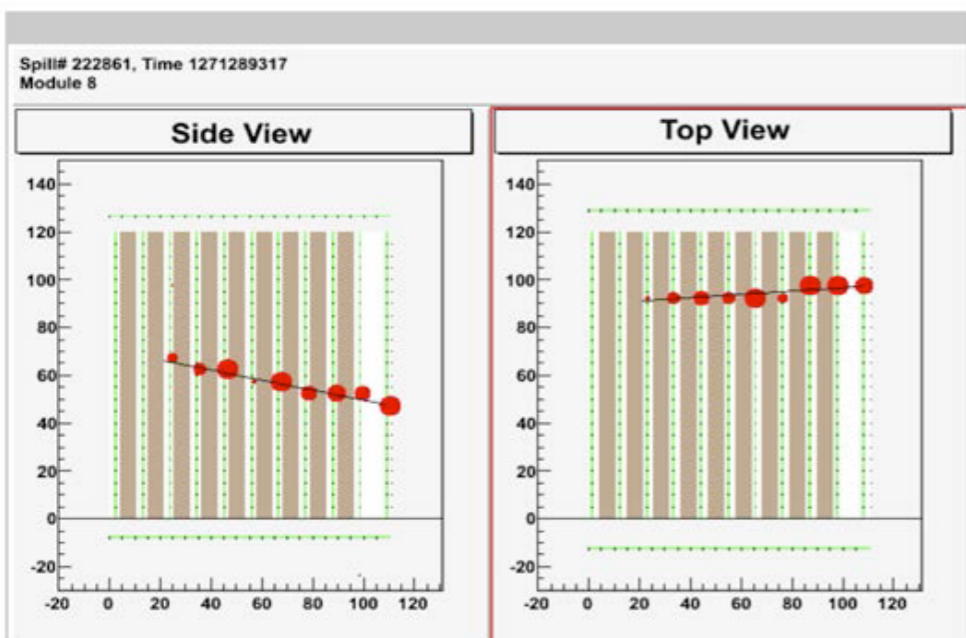


- ND280 is the near detector facility with two main detectors located 280m from the proton interaction point:
 - On-axis INGRID.
 - Off-axis ND280m.
- Three main purposes:
 - ν beam stability.
 - ν cross-sections.
 - ν beam flux constraint.

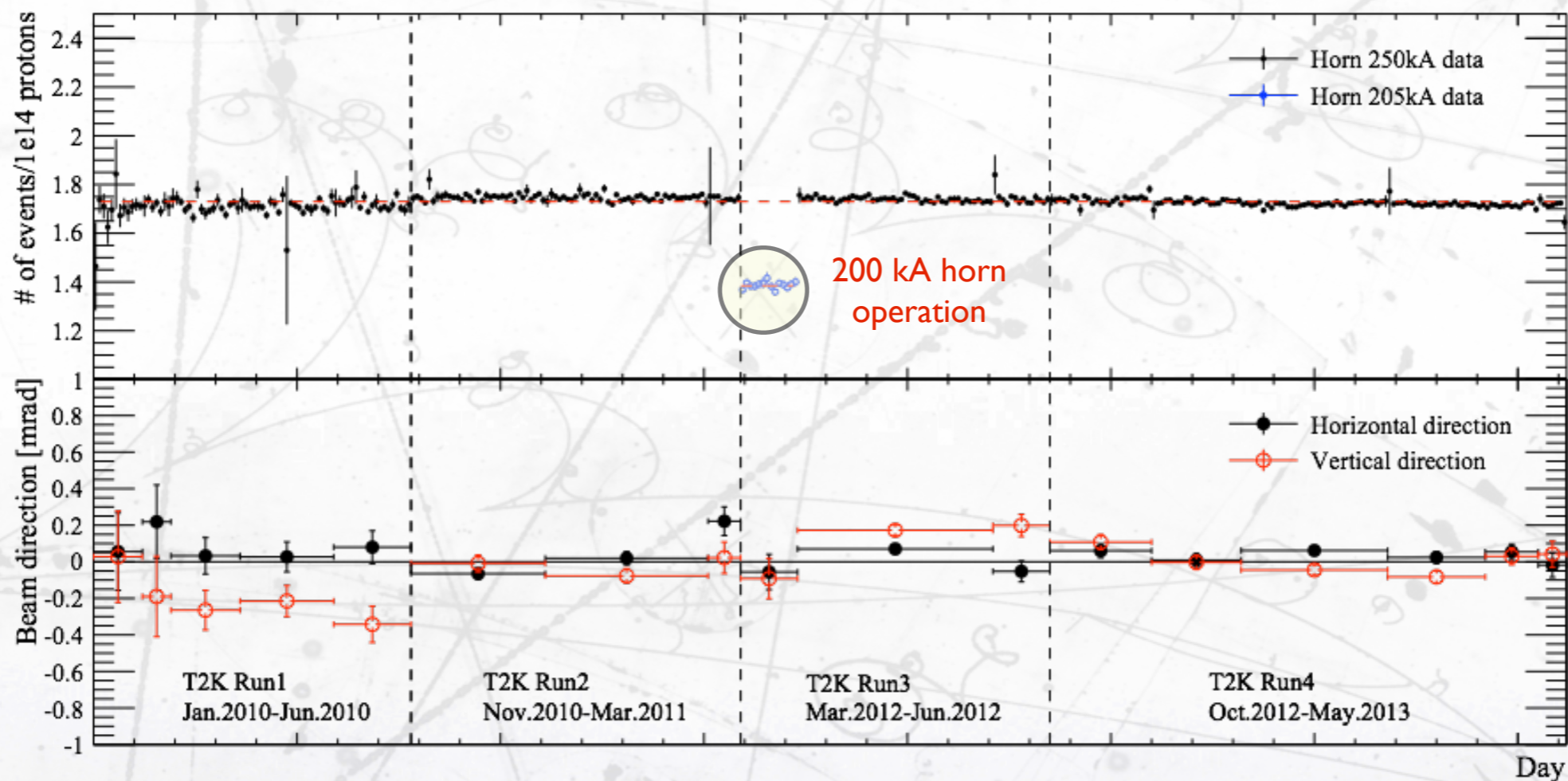
On-axis (INGRID)



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



On-axis: beam stability



Beam alignment and flux measured with neutrinos

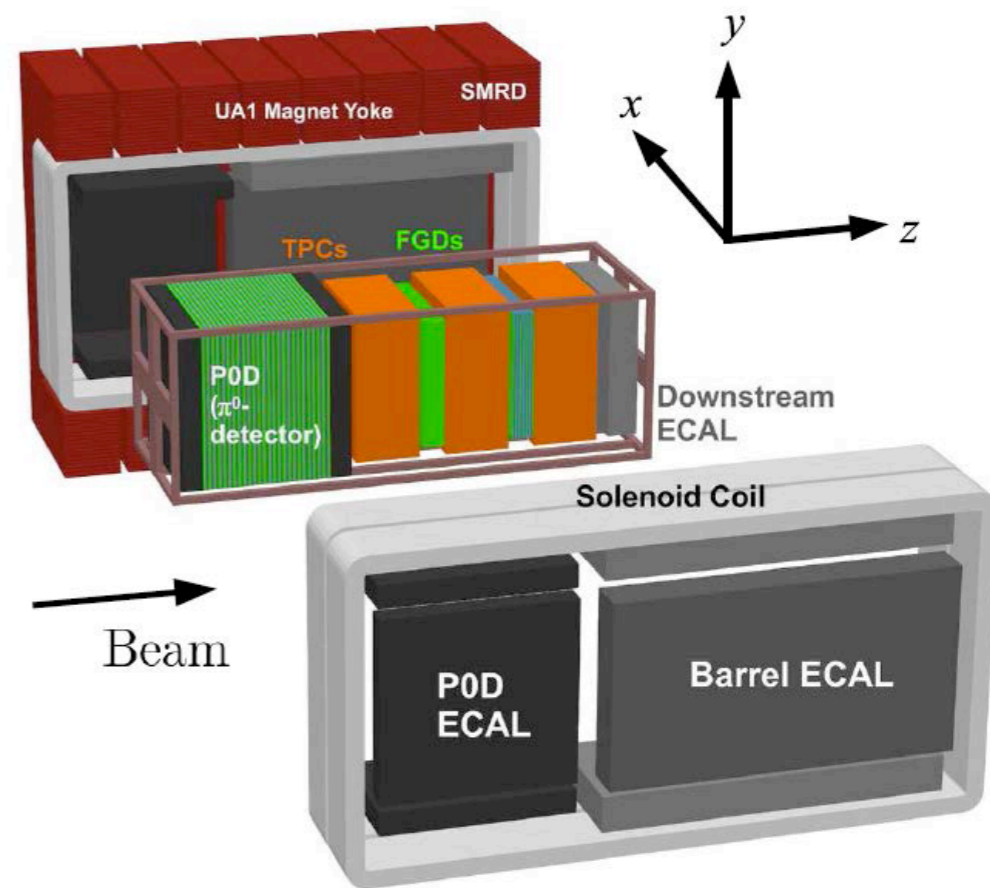
- Neutrino rate stable within 0.7%.
- Beam direction variation \ll 1 mrad.

- 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.



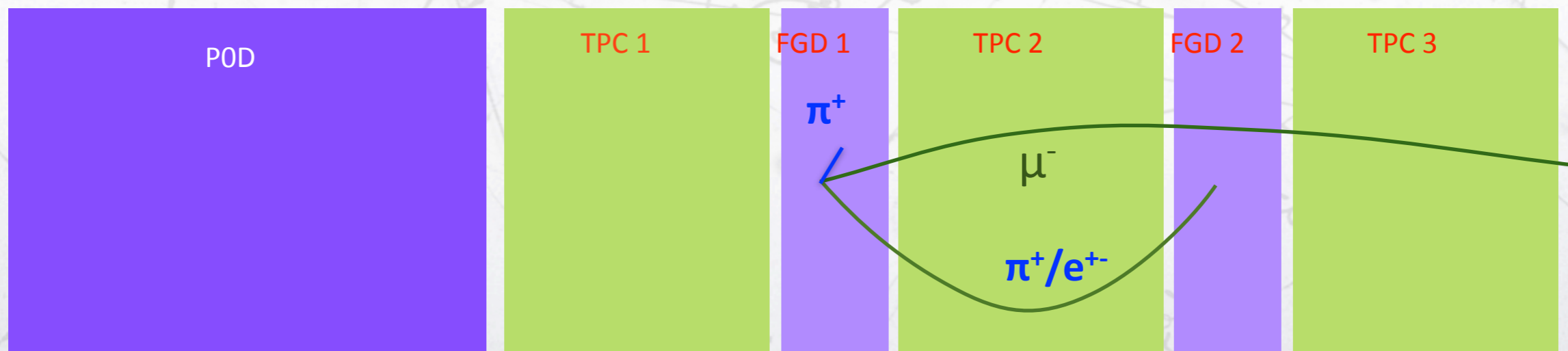
Magnet was granted by CERN



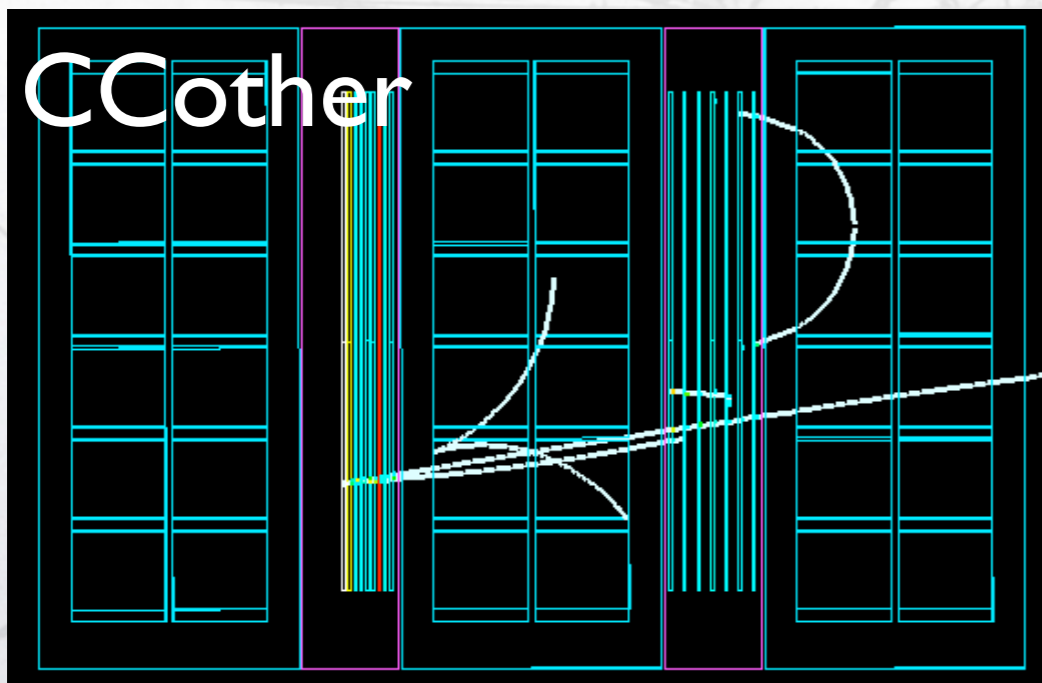
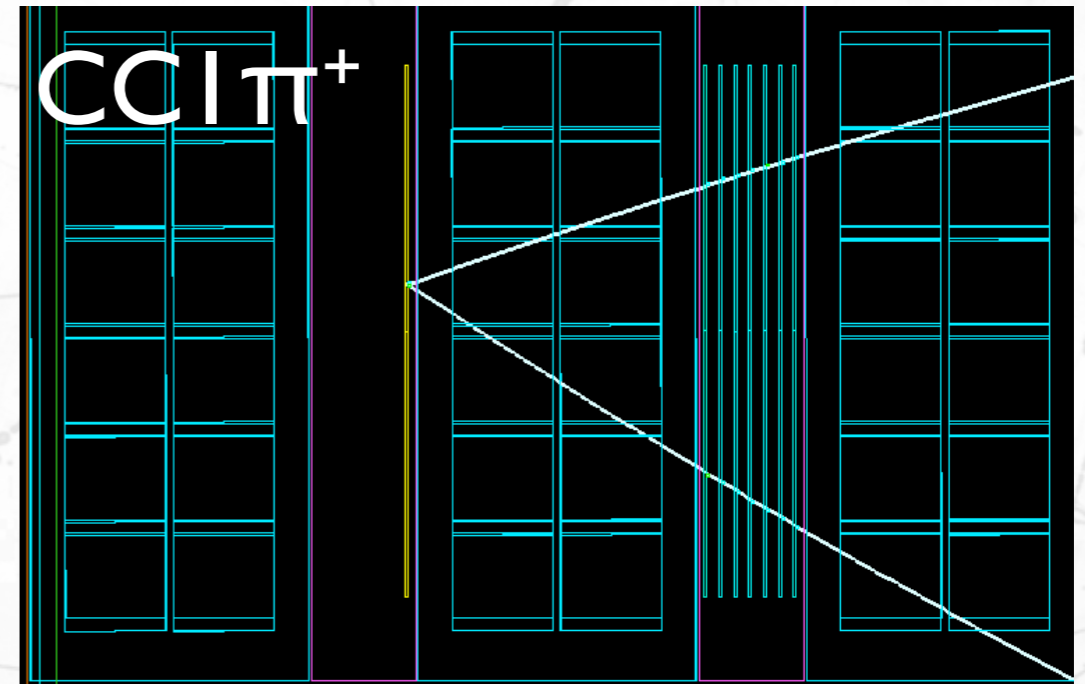
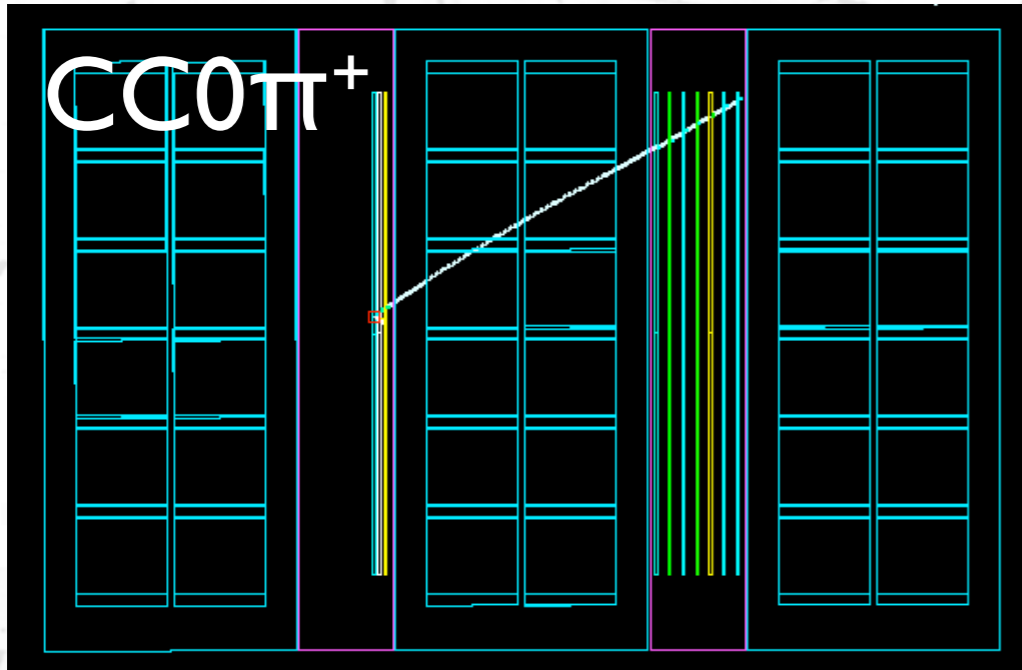
Off-axis: ν_μ analysis



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

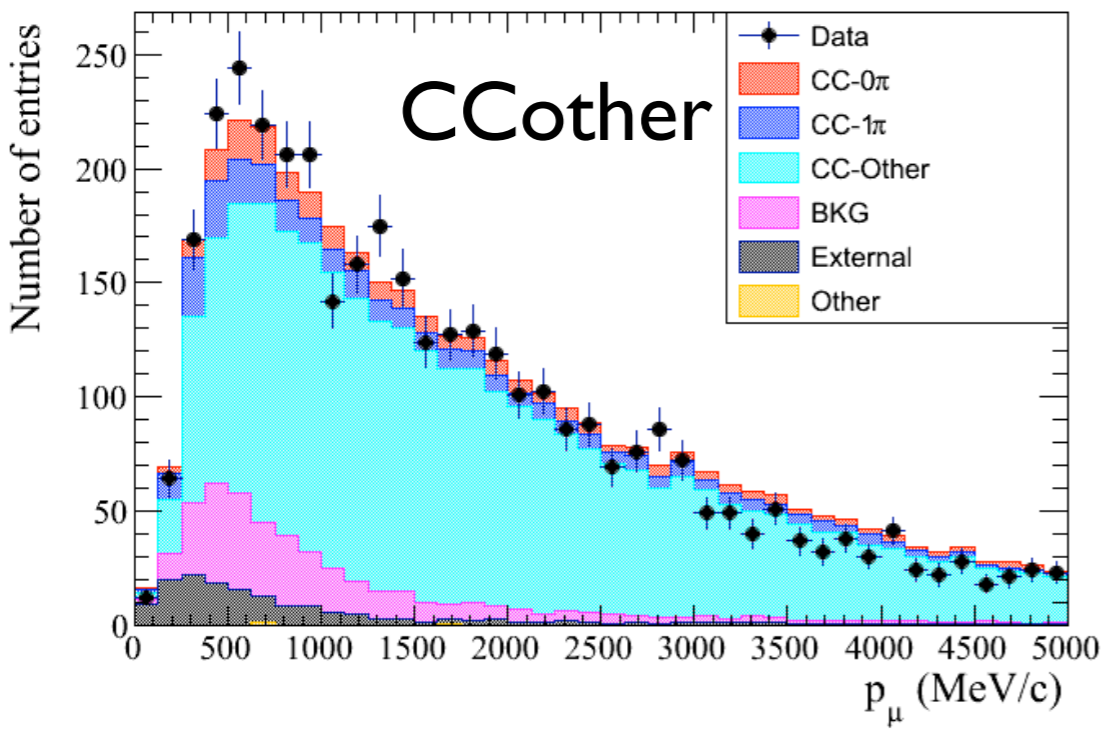
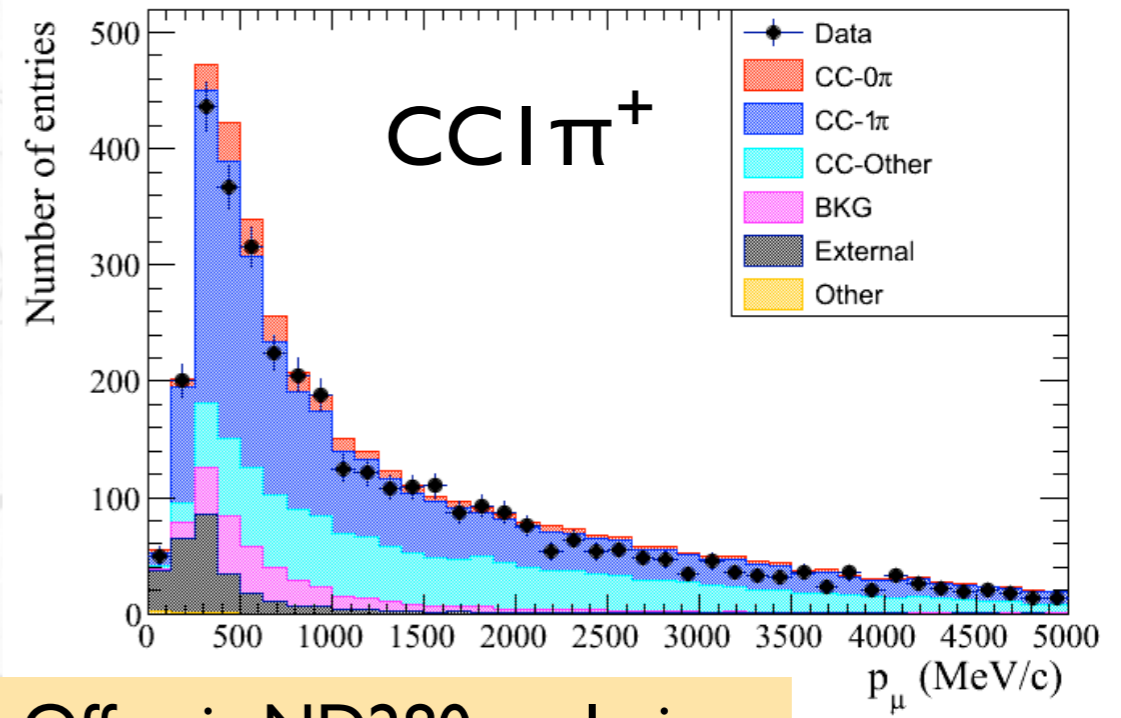
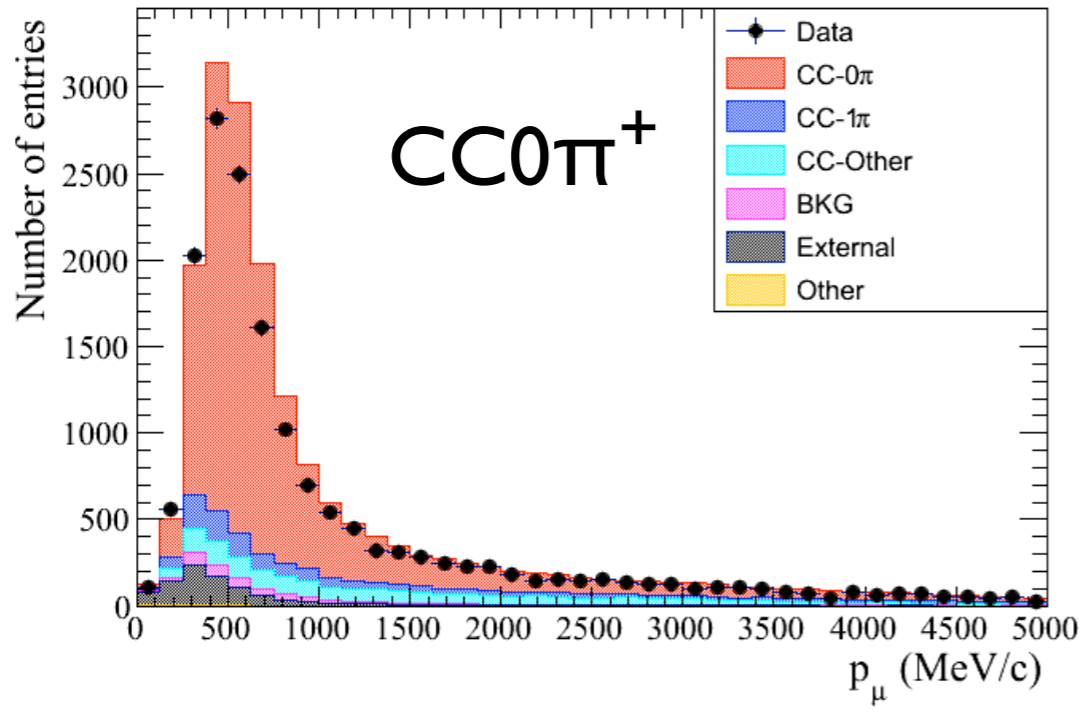
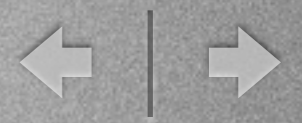


Off-axis: ν_μ analysis



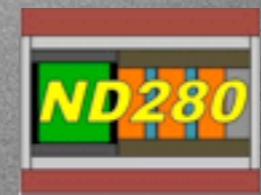
Off-axis ND280 analysis
real events

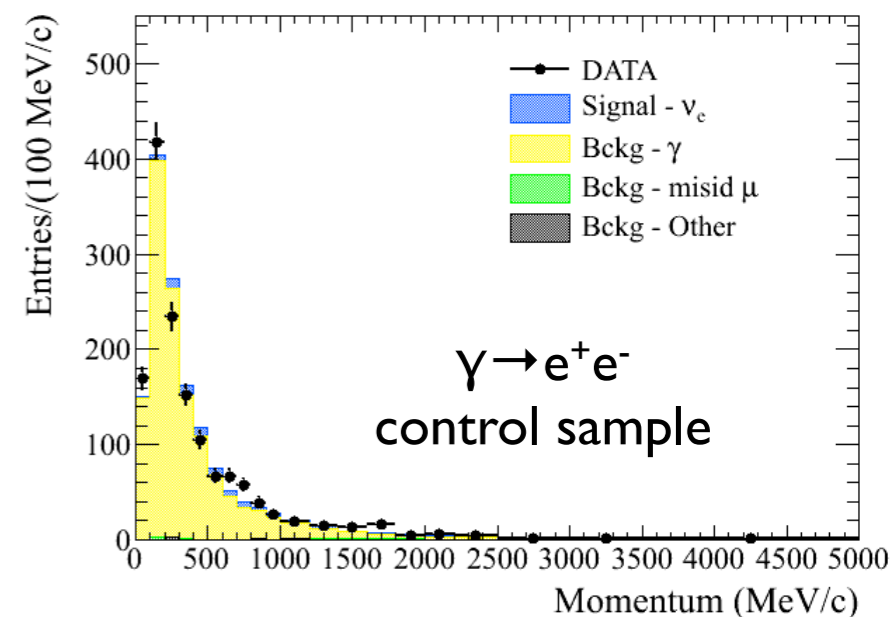
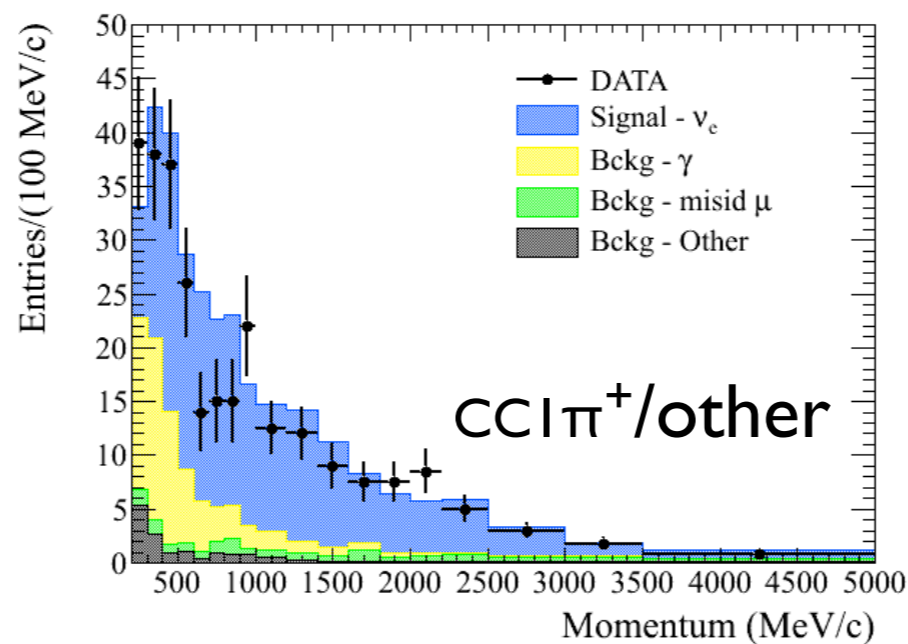
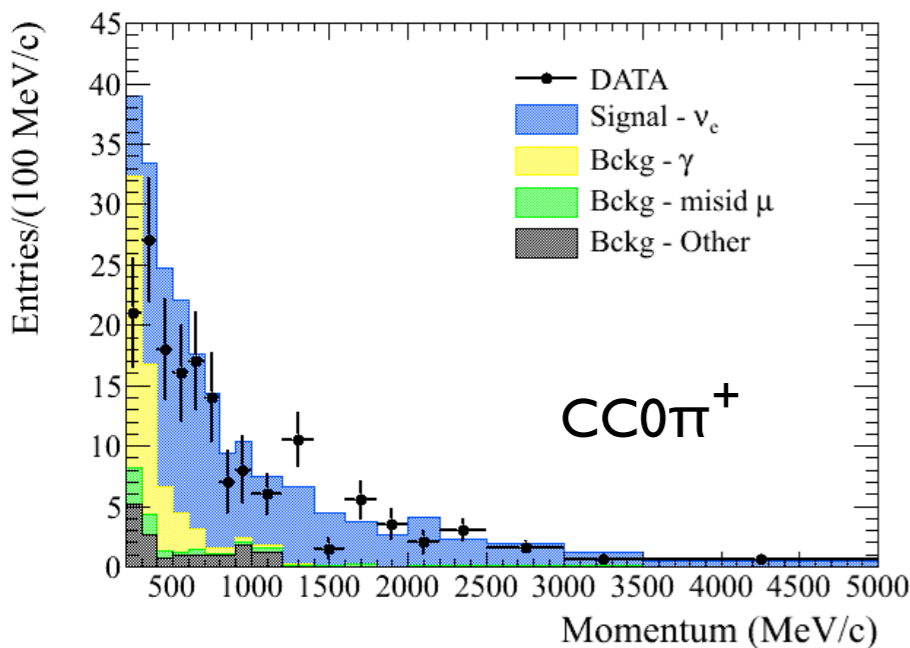
Off-axis: ν_μ analysis



Off-axis ND280 analysis

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





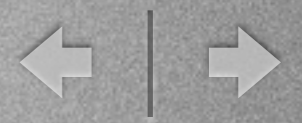
Off-axis ND280 analysis

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

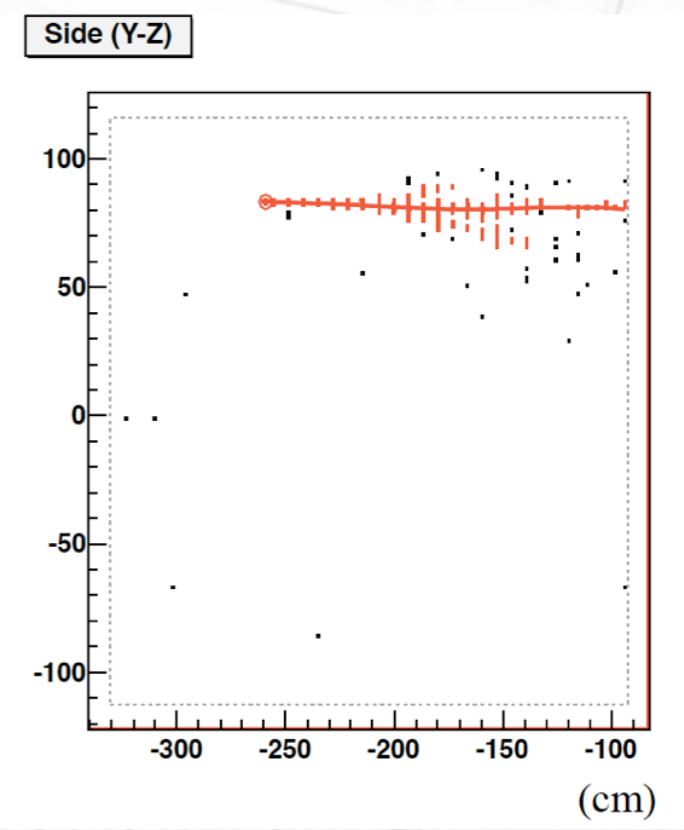
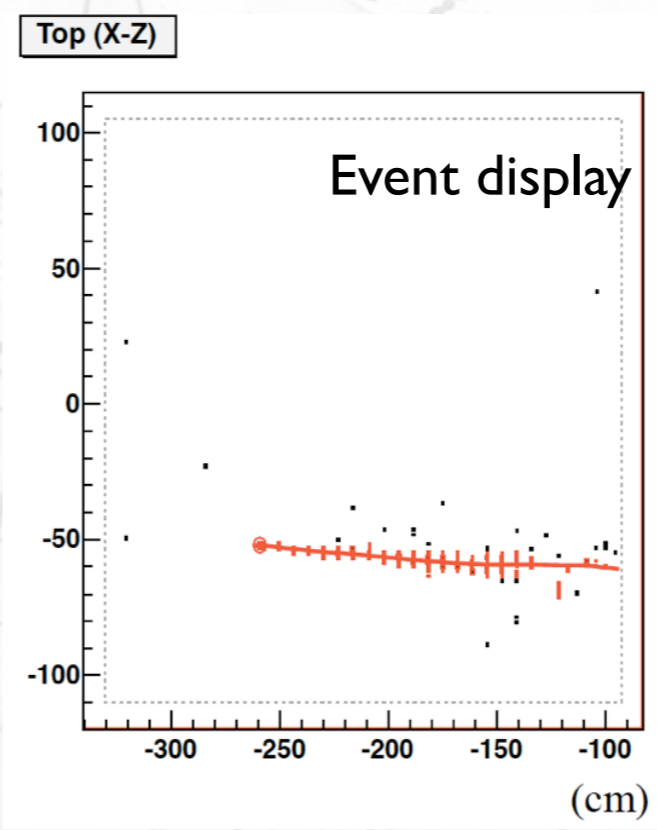
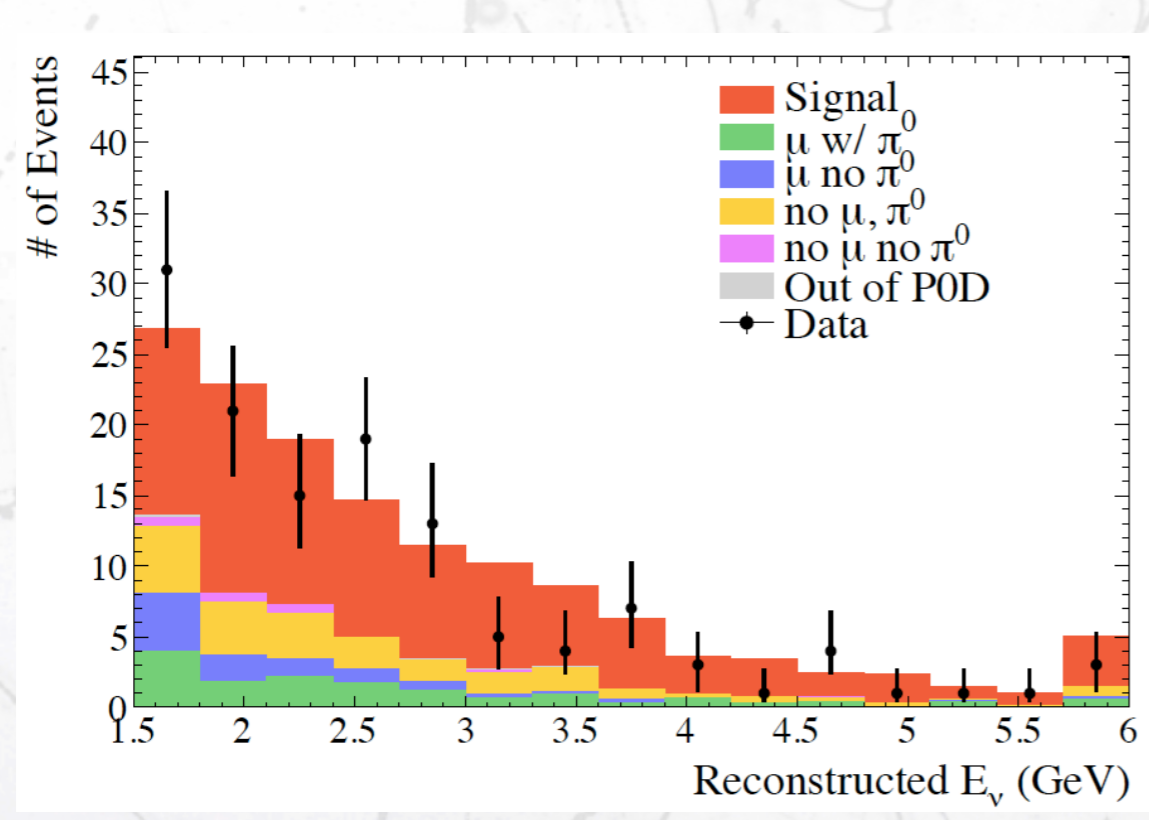
$$\frac{N_e^{meas}}{N_e^{pred}} = 1.06 \pm 0.06(stat) \pm 0.08(syst)$$

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

Off-axis: ν_e analysis



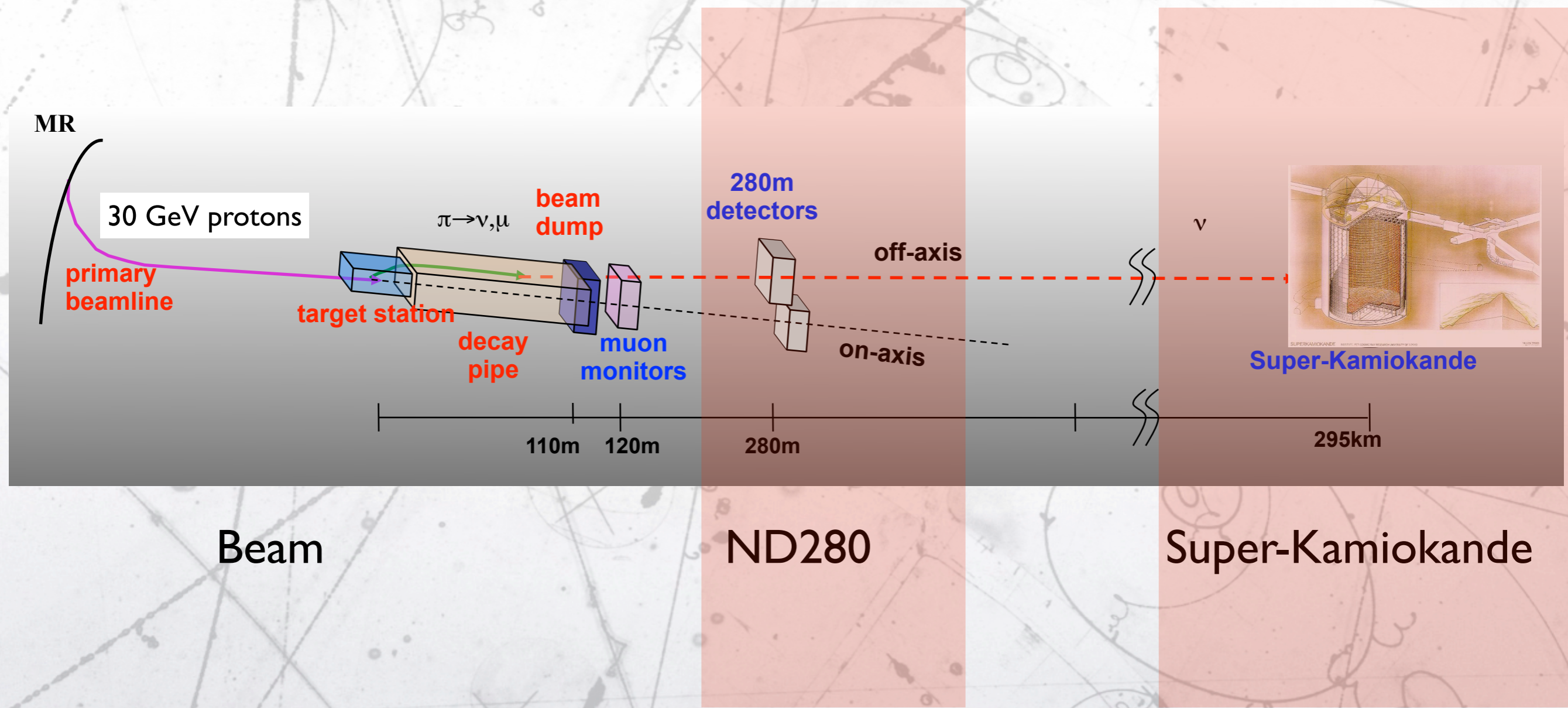
- ν_e events at the ND280 P0D detector calculated with 8.6×10^{19} PoT.



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

In good agreement with the tracker ν_e measurement

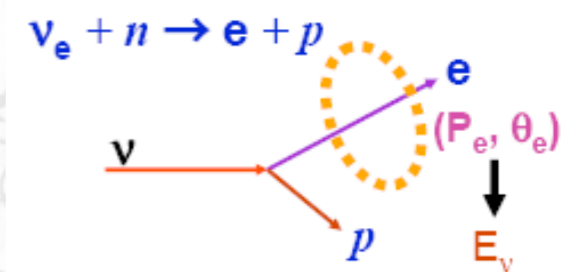
Cross sections



Cross-sections



- The T2K signal is the CCQE events. The 2 body kinematics allow to estimate the neutrino energy.



- Other channels can be seen as backgrounds to the CCQE signal.

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

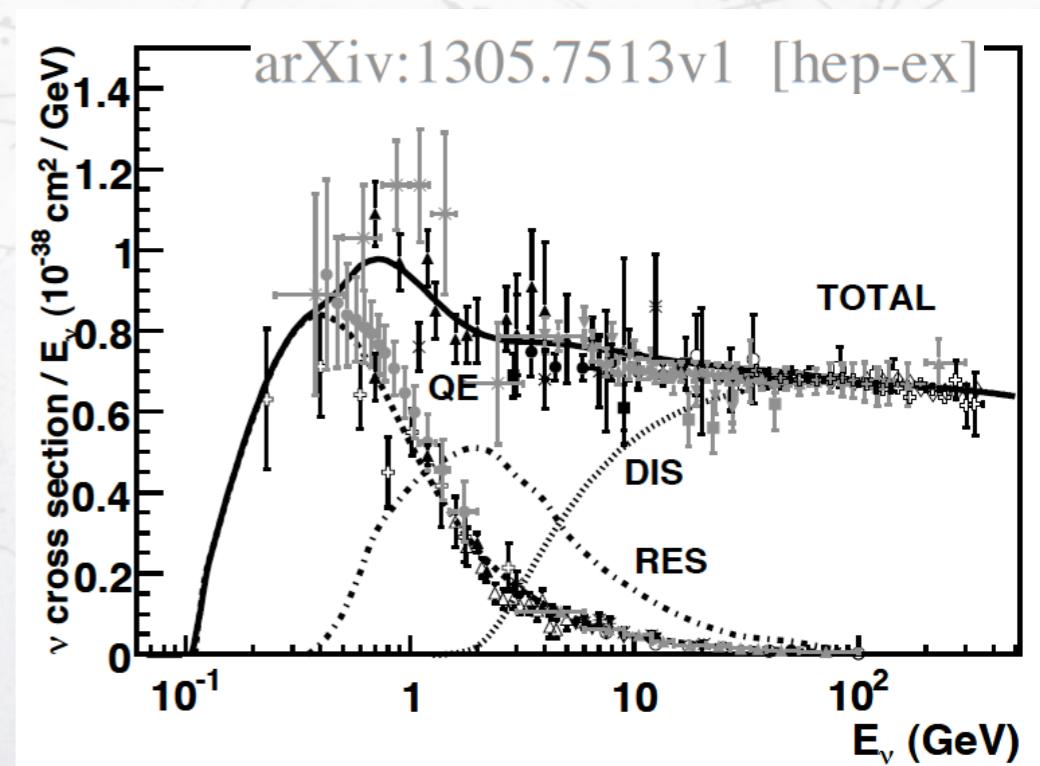
E_b is the binding energy

- We need to identify the channel by using the hadronic component of the interactions.

- At T2K energies there are many channel thresholds (CC π^+ , CC π^0 , CC Deep Inelastic Scattering, ...)

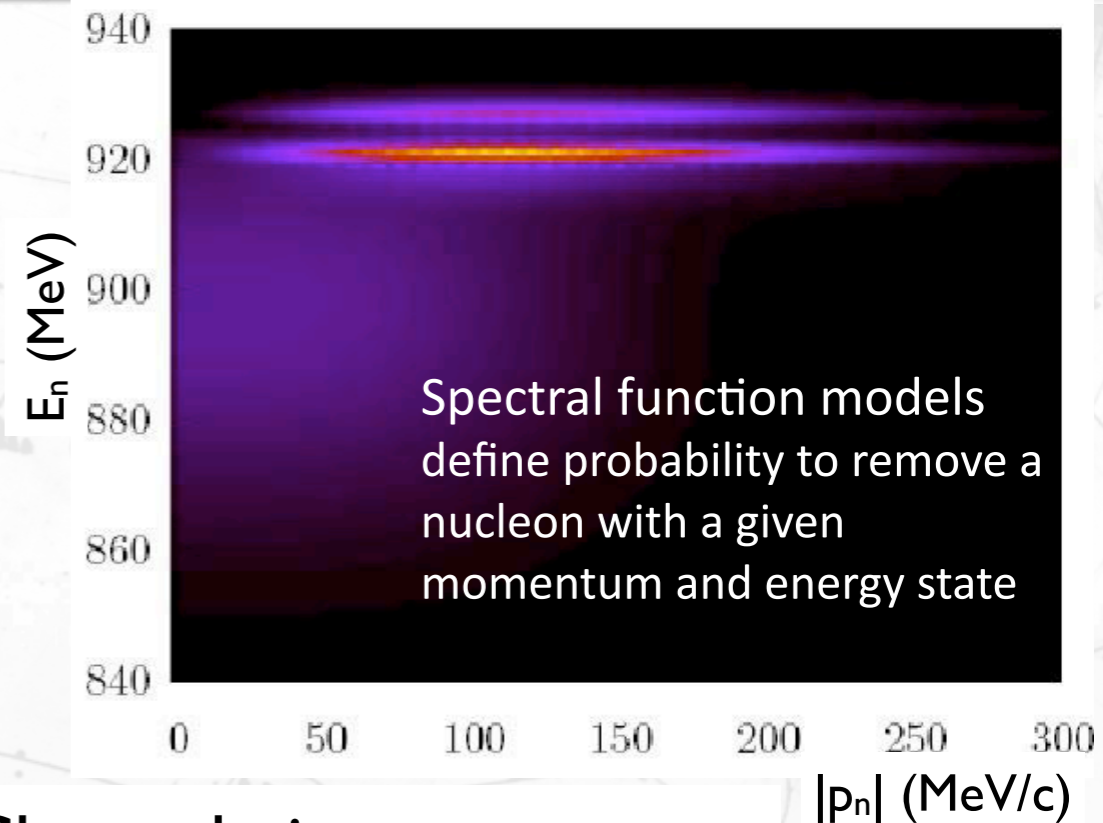
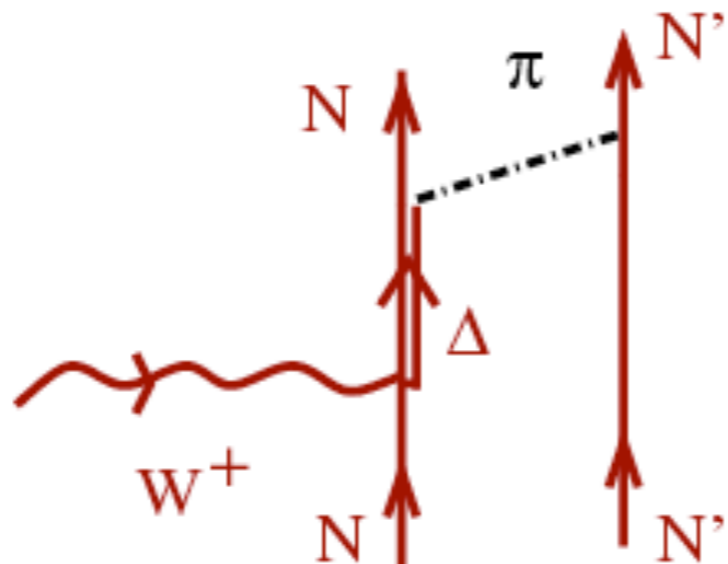
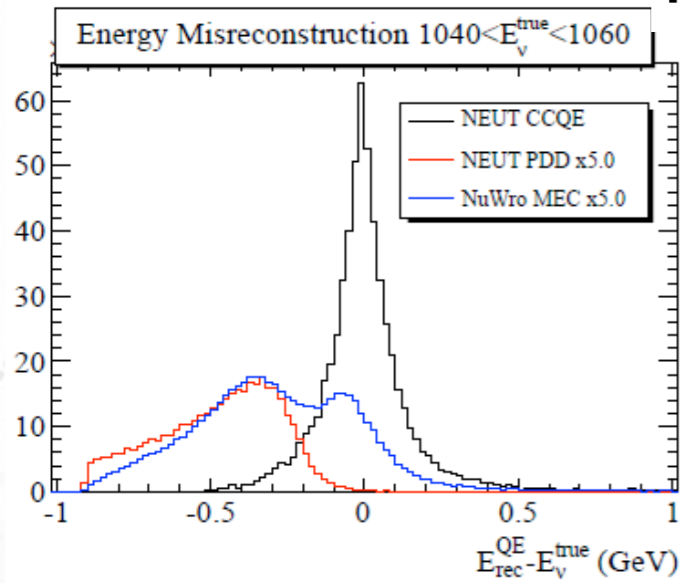
- Cross-section models are not precise.

- Final state interactions inside the nucleus alter the hadronic component.



Cross-sections: unknowns

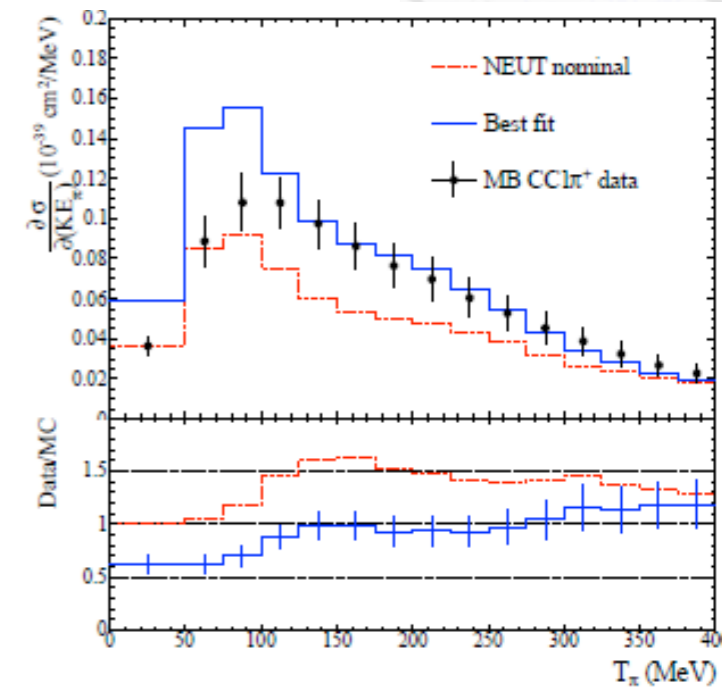
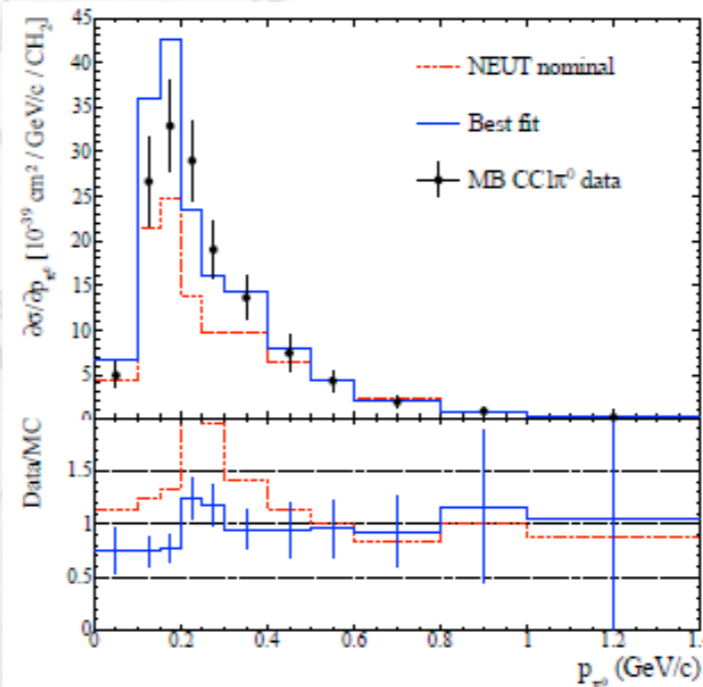
Multi-nucleon interactions



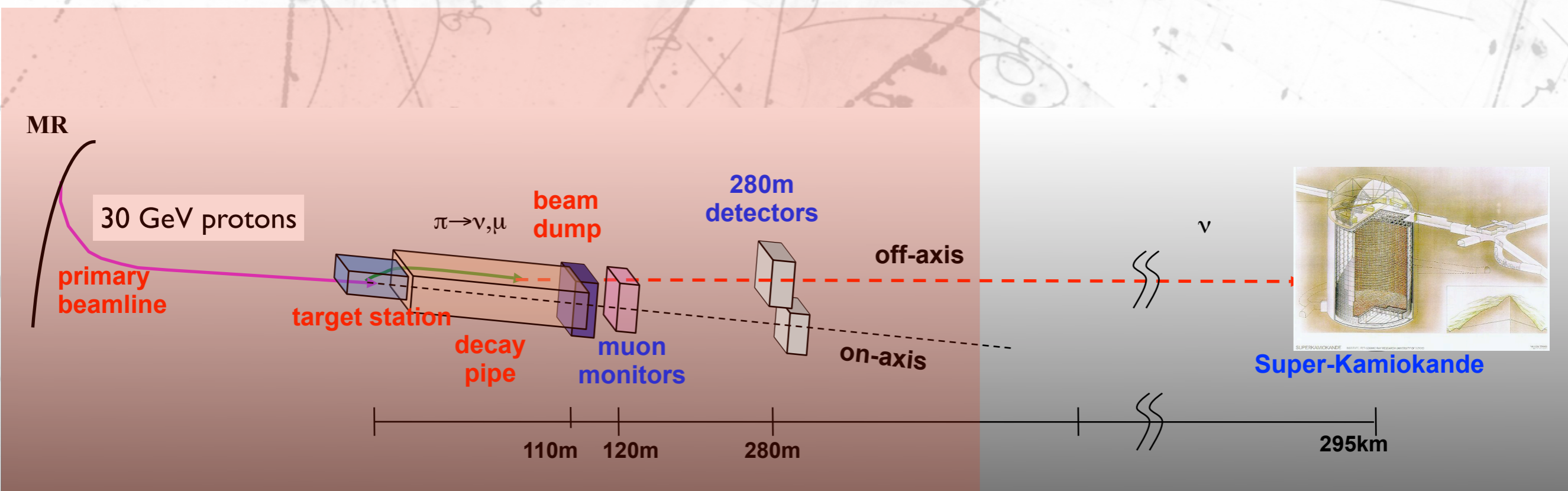
Charged pion momentum

T2K approach

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



Flux prediction



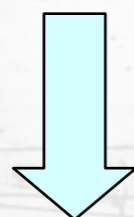
Beam

ND280

Super-Kamiokande

Neutrino Flux Model:

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



Neutrino Cross Section Model (NEUT):

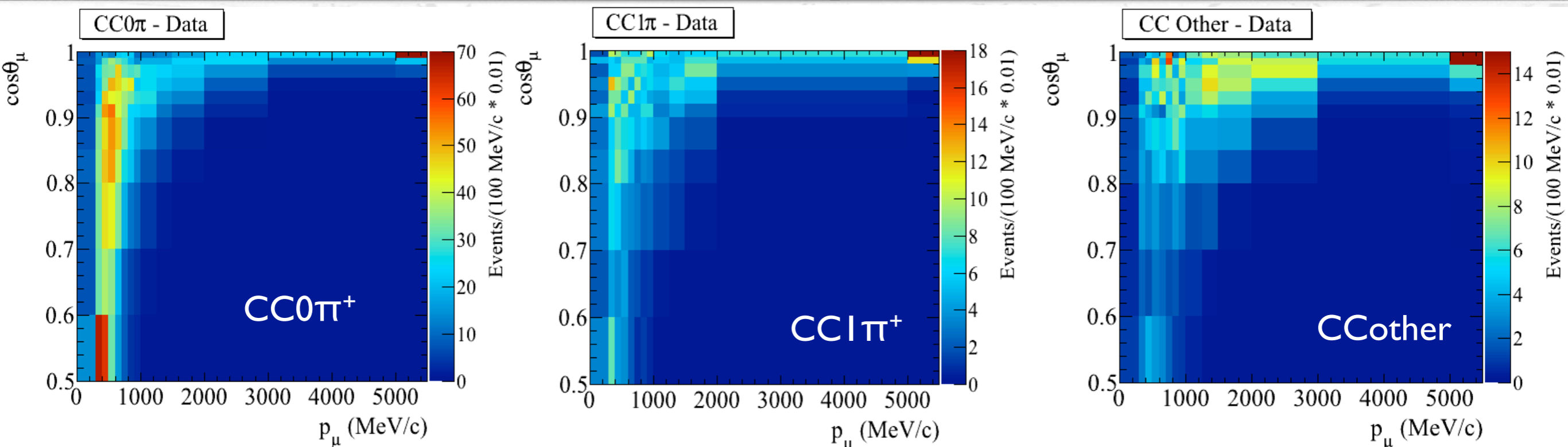
- Data-driven: External neutrino, electron, pion scattering data
- Uncertainties: modeled by variations of model parameters (M_A, p_F, E_b) and ad-hoc parameters



Constraint from ND280 Data

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

ND280 input data



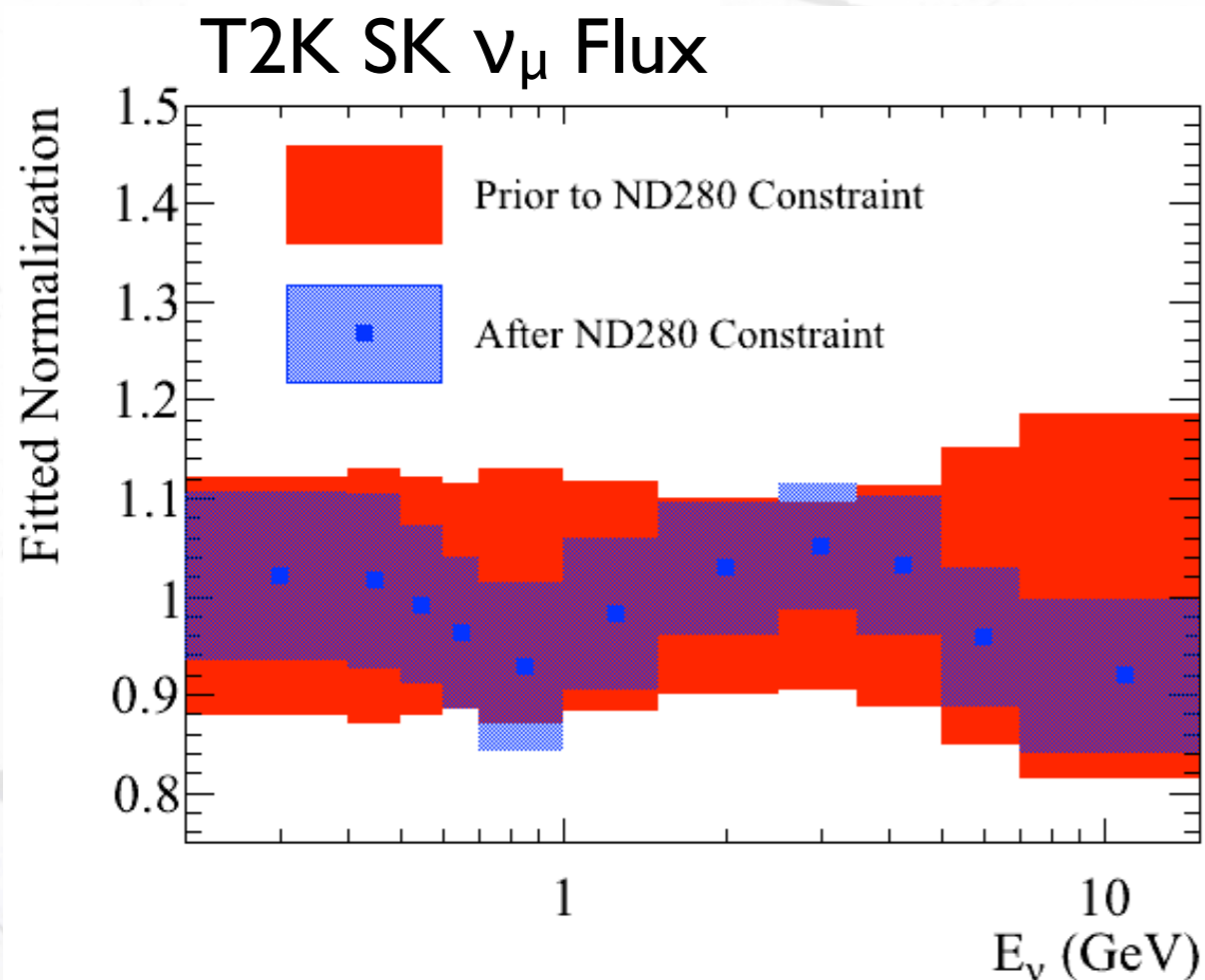
Data from T2K Runs 1-4: 5.9×10^{20} protons on target

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 ($\cos\theta$) preserving information on neutrino energy and interaction q^2

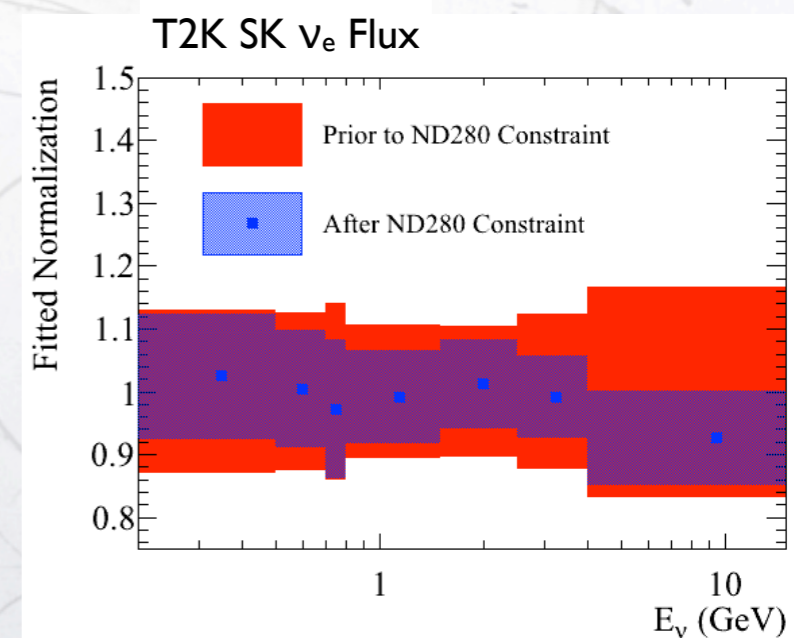


Constrained flux



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
CC1 π Norm.	1.15 ± 0.32	1.22 ± 0.16
NC1 π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25



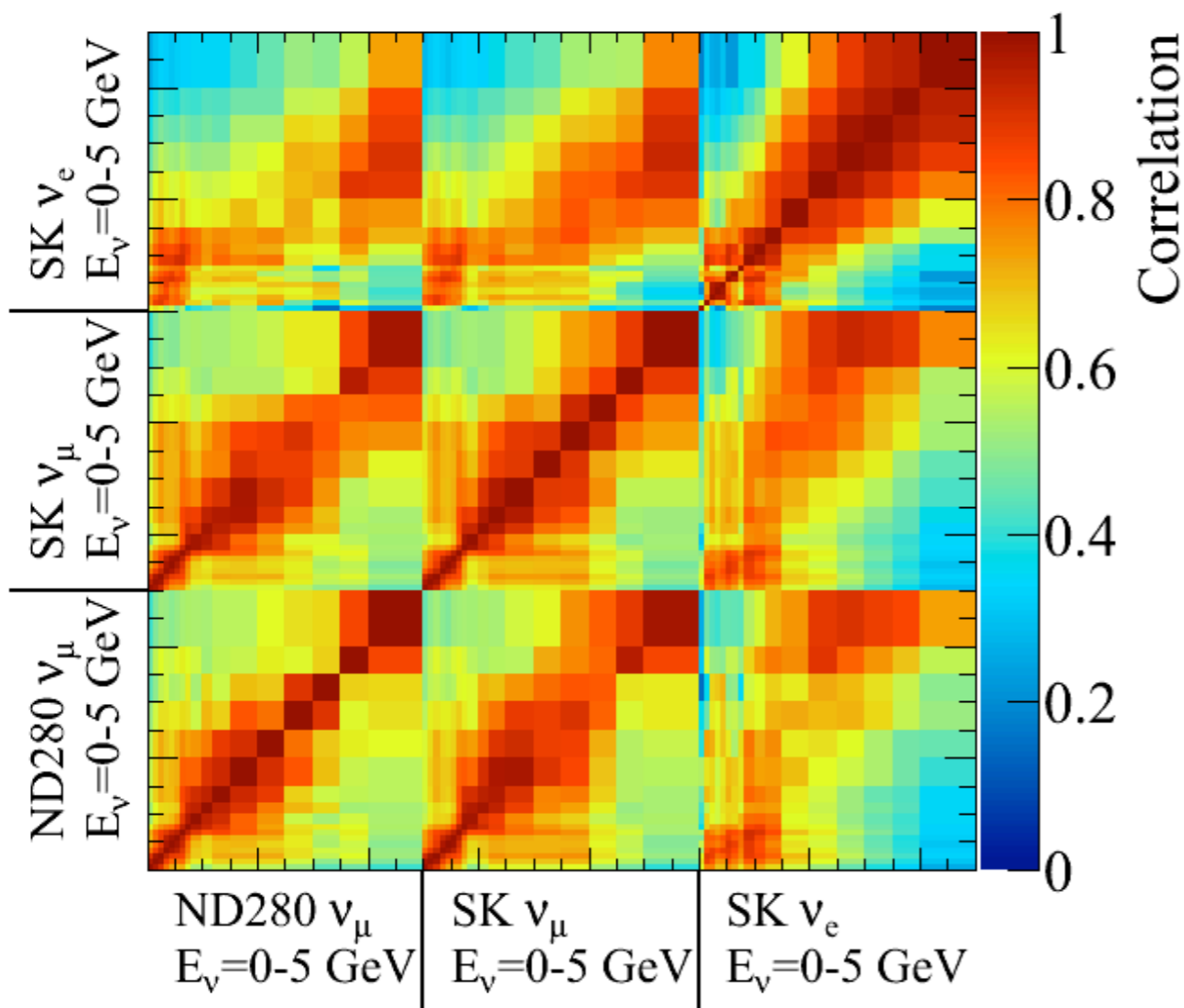
- T2K ν_μ and ν_e flux predictions are constrained by the fit.
- The cross-section parameters are also constrained.
- Plots show central values and error bands for normalisation parameters.



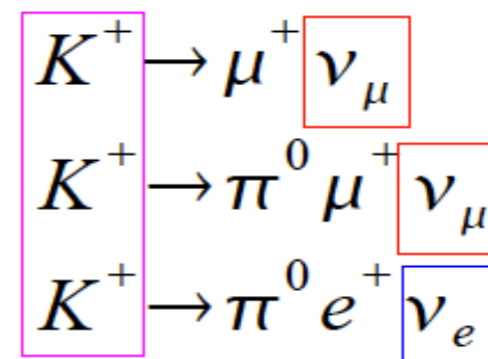
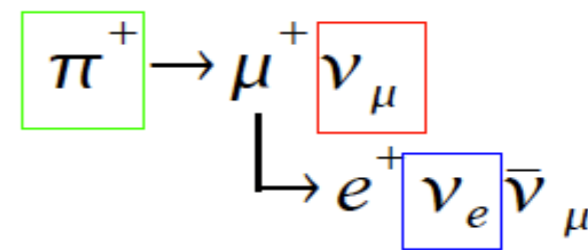
Covariance matrix



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



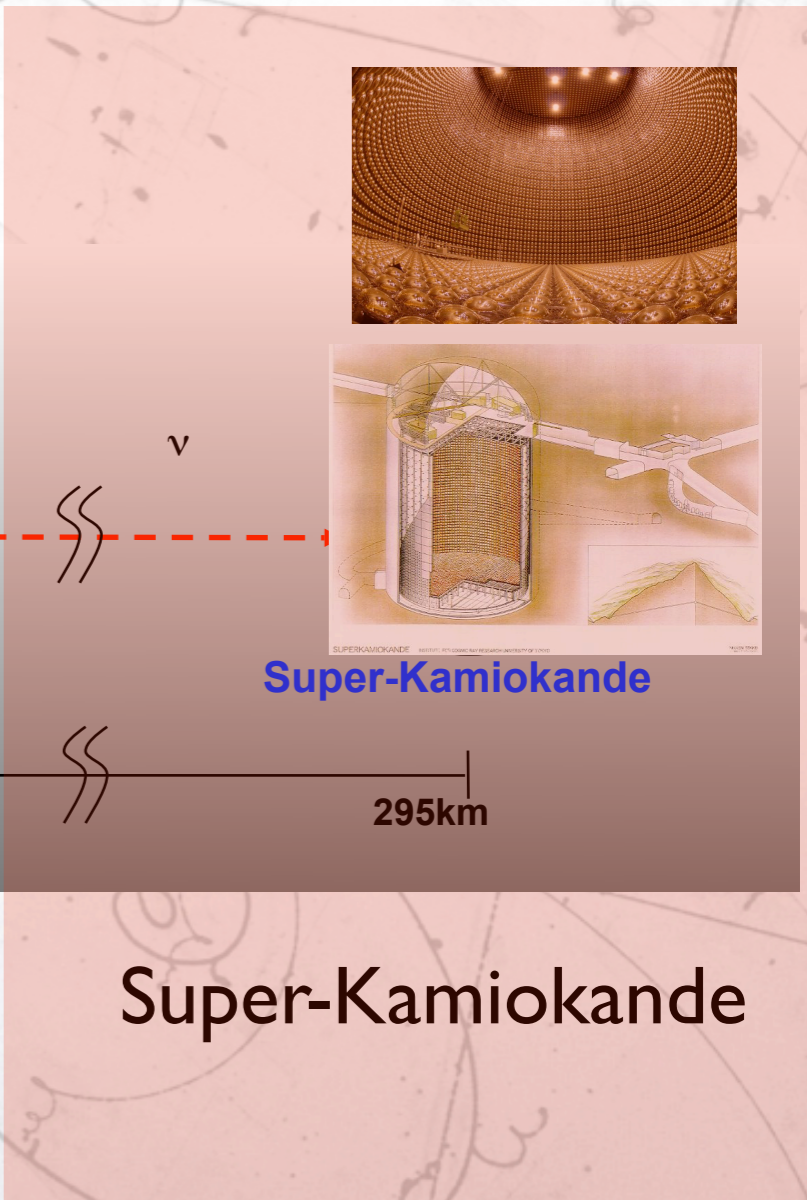
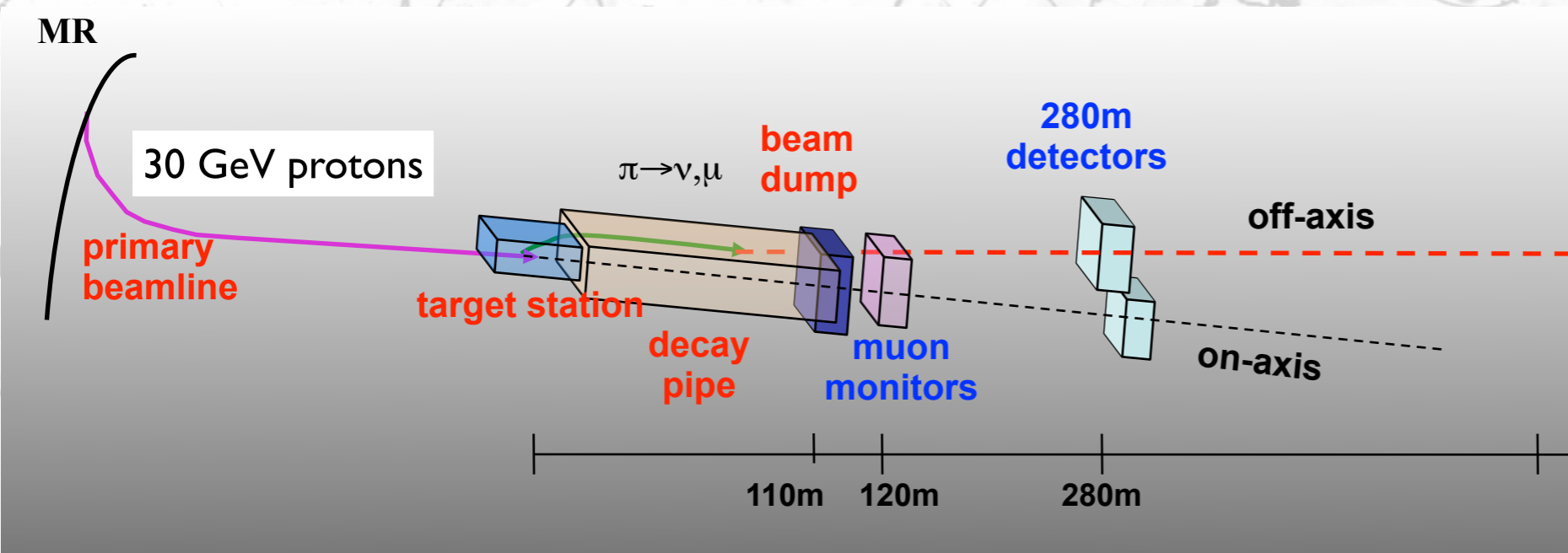
ν_e and ν_μ fluxes are correlated through parent hadrons



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



Super-Kamiokande

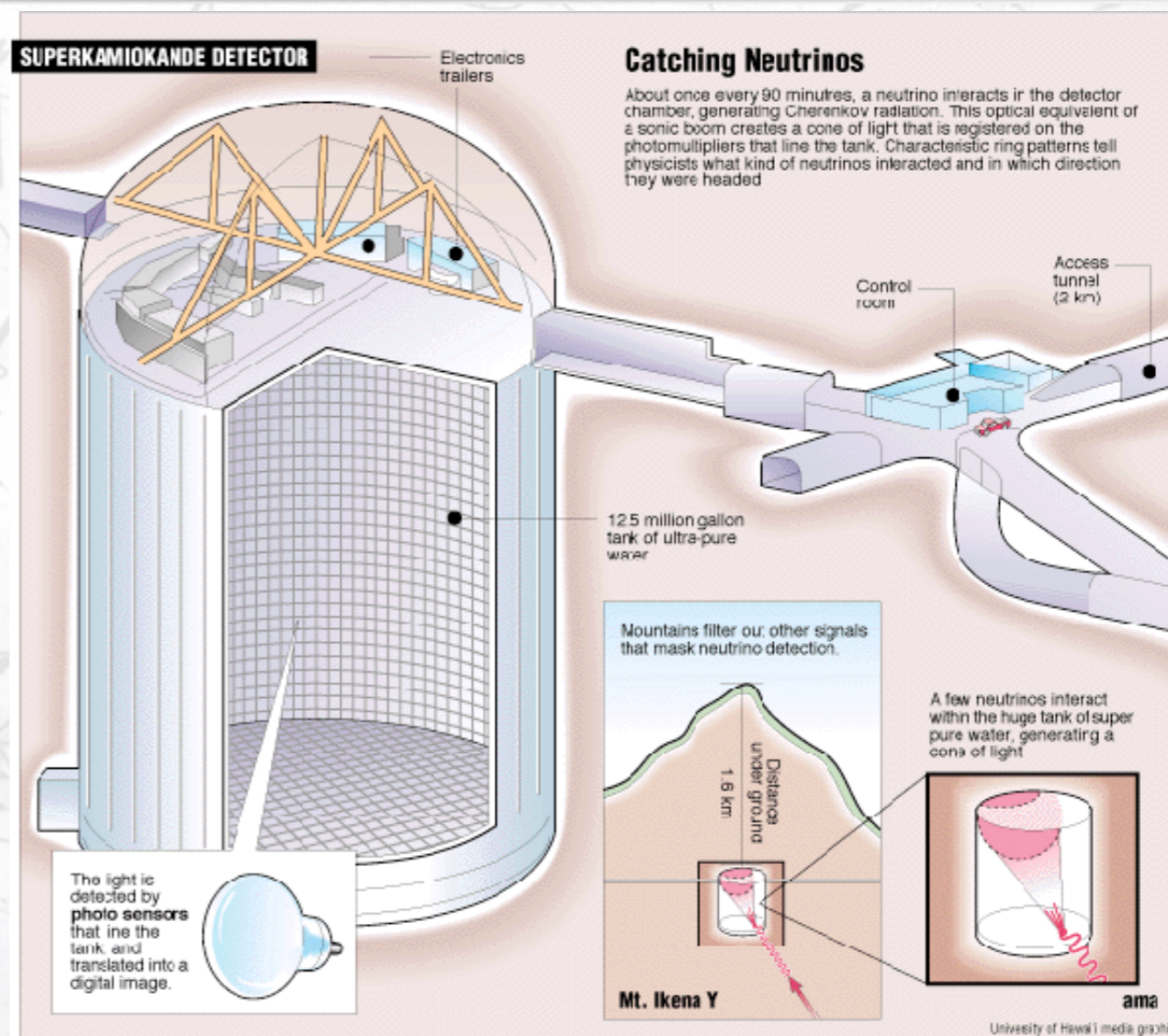
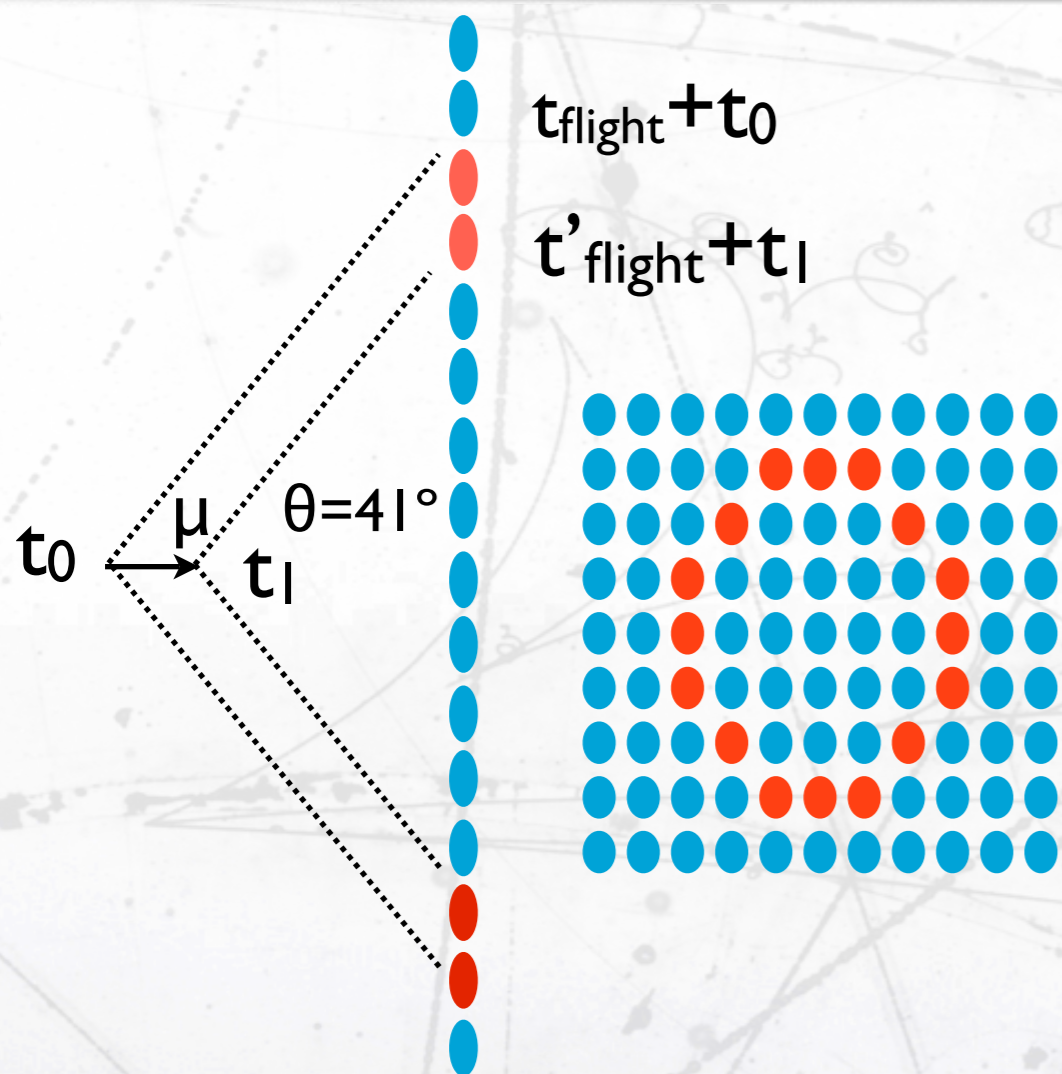


Beam

ND280

Super-Kamiokande

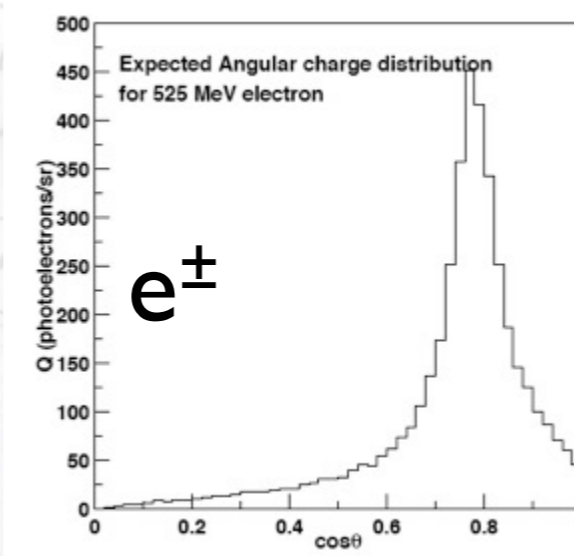
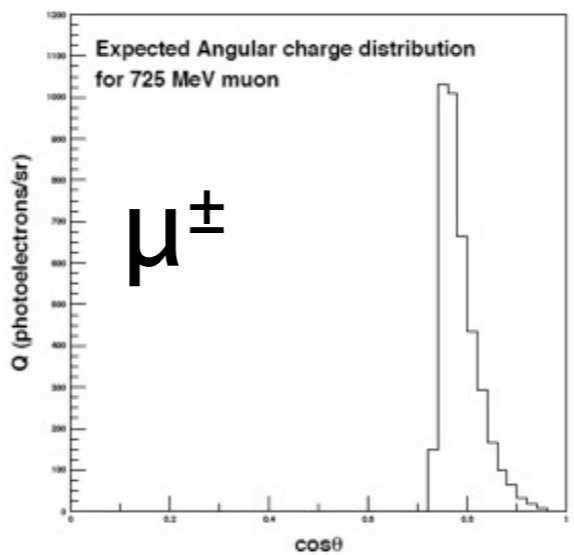
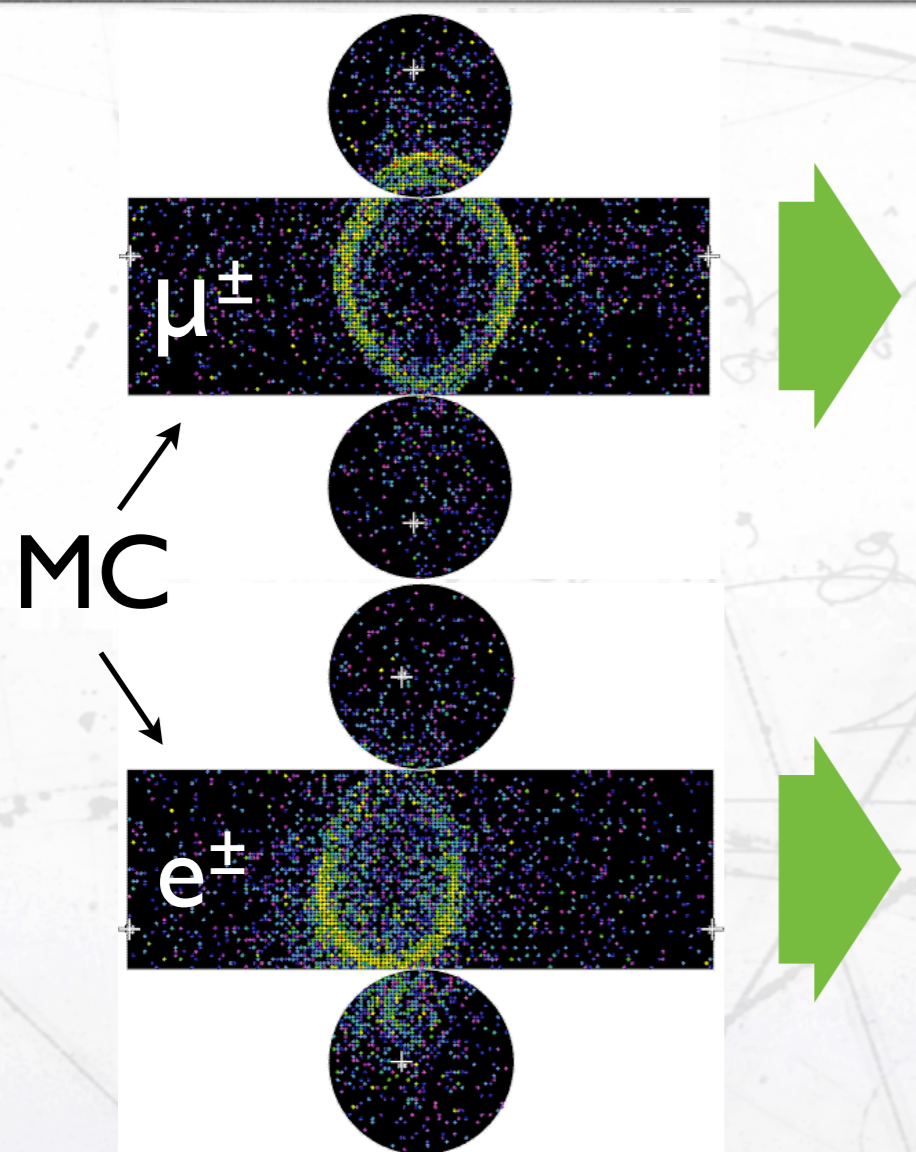
Super-Kamiokande



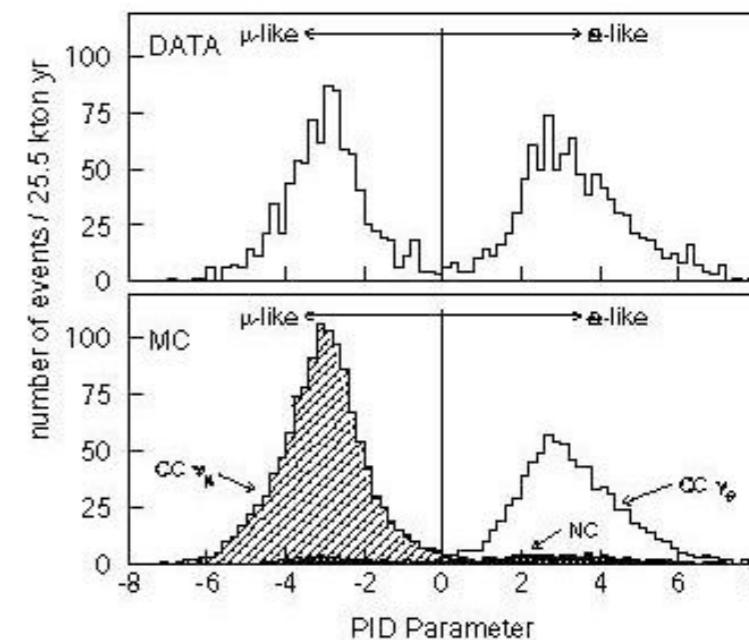
- 50 kTon water Cherenkov detector. (22.5 KTon fiducial).
- ~11 000 20" PMT inner detector.
- ~2000 8" PMT outer detector to veto external background.



SK: particle ID



Likelihood PID

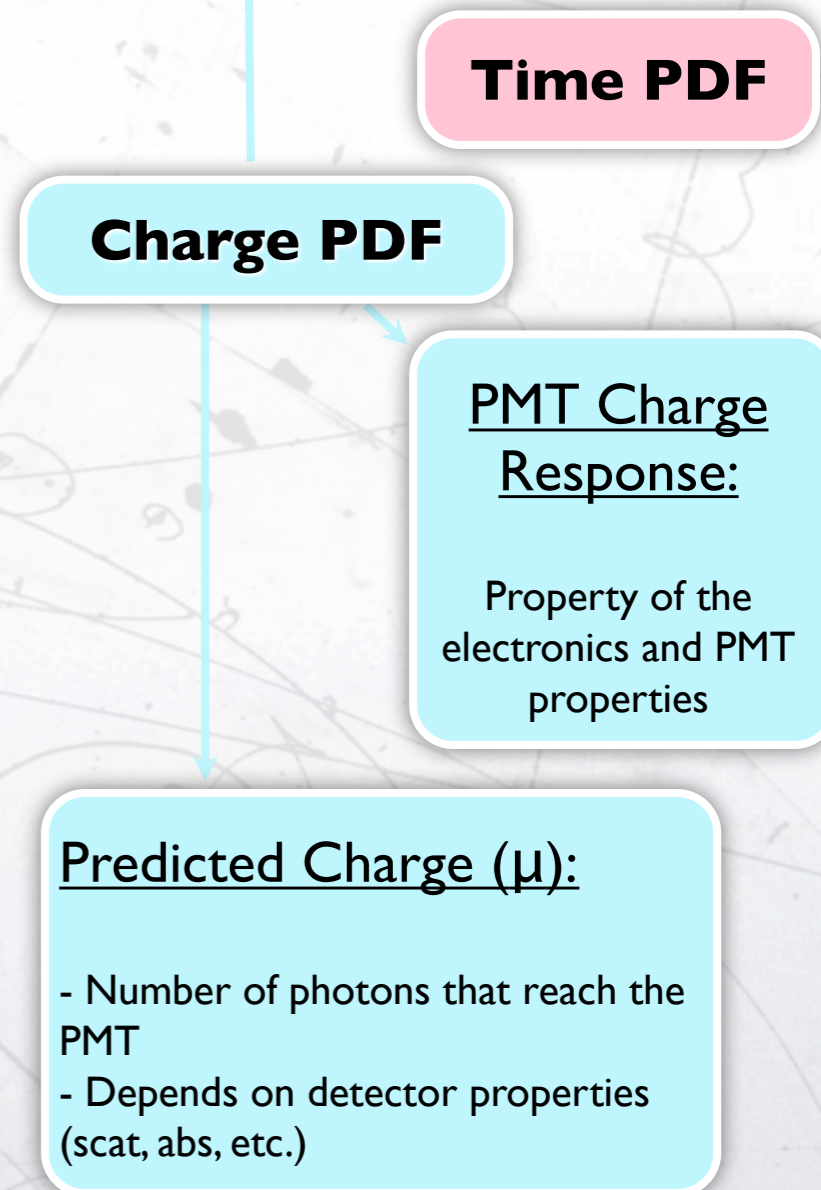


- The expected angular distribution of Cherenkov photons along the primary particle direction is different in electrons and muons:
- The electron is not sharp due to Multiple Scattering & showering.

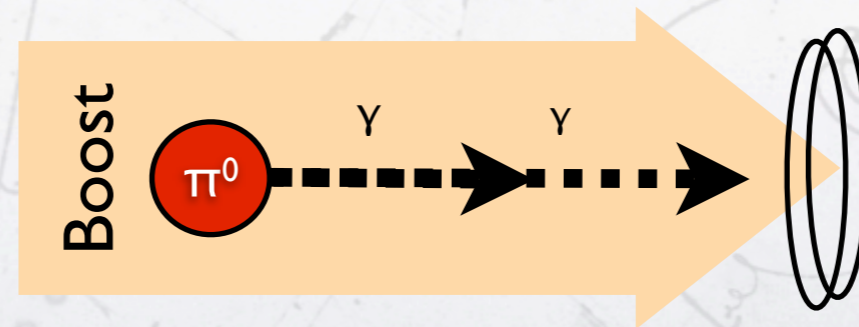


$$L(\mathbf{x}) = \prod_{\text{unhit}} P(i_{\text{unhit}}; \mathbf{x}) \prod_{\text{hit}} P(i_{\text{hit}}; \mathbf{x}) f_q(q_i; \mathbf{x}) f_t(t_i; \mathbf{x})$$

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

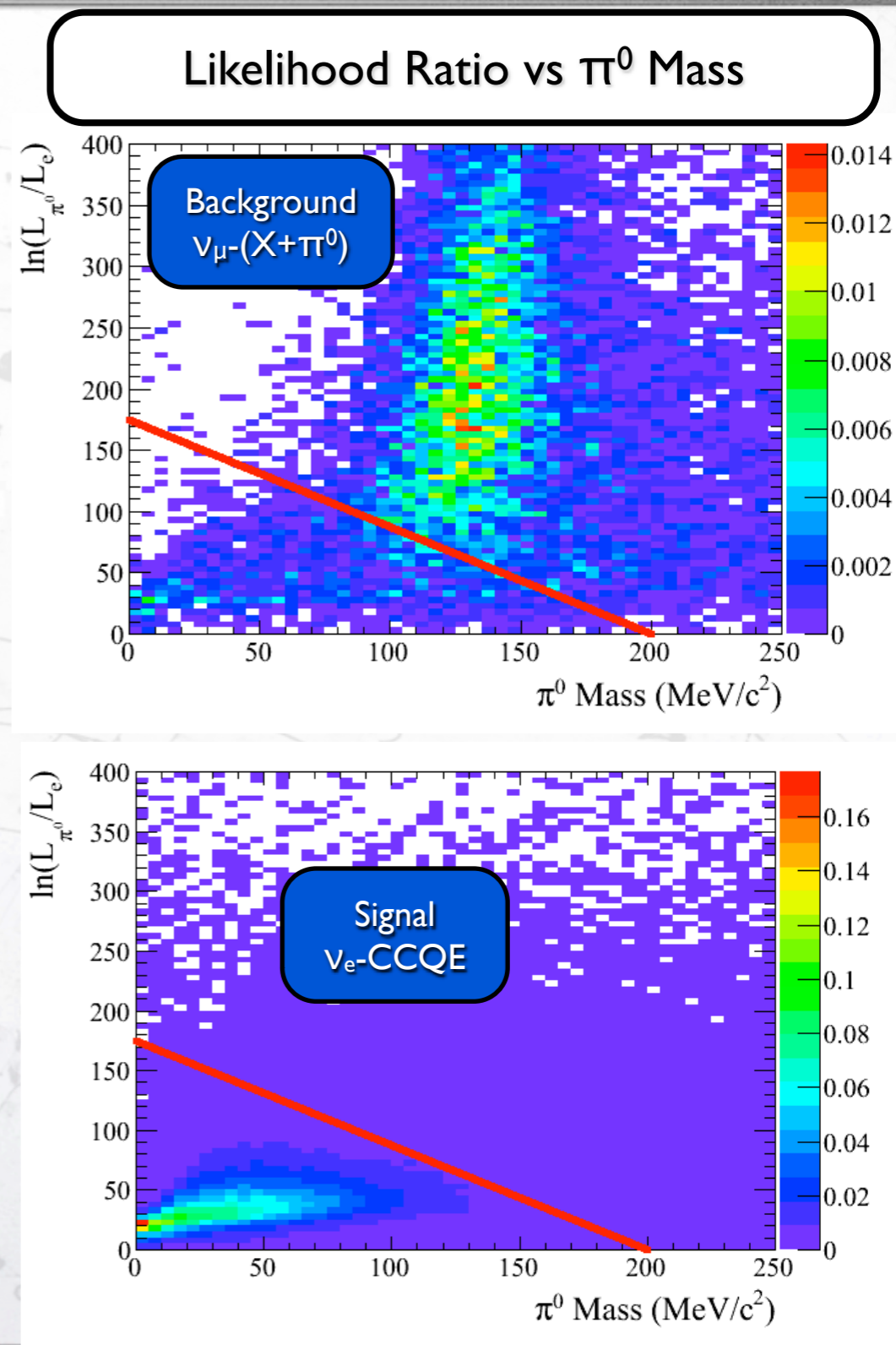


- The misidentification of π^0 and electrons happens when one photon is not identified:
- The two electron-like rings overlap.
- One of the two e-like rings is faint and it is lost in the Cherenkov light of the other photon.
- Or with 2 γ , the invariant mass of the photons has poor resolution.



Super-Kamiokande & π^0

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



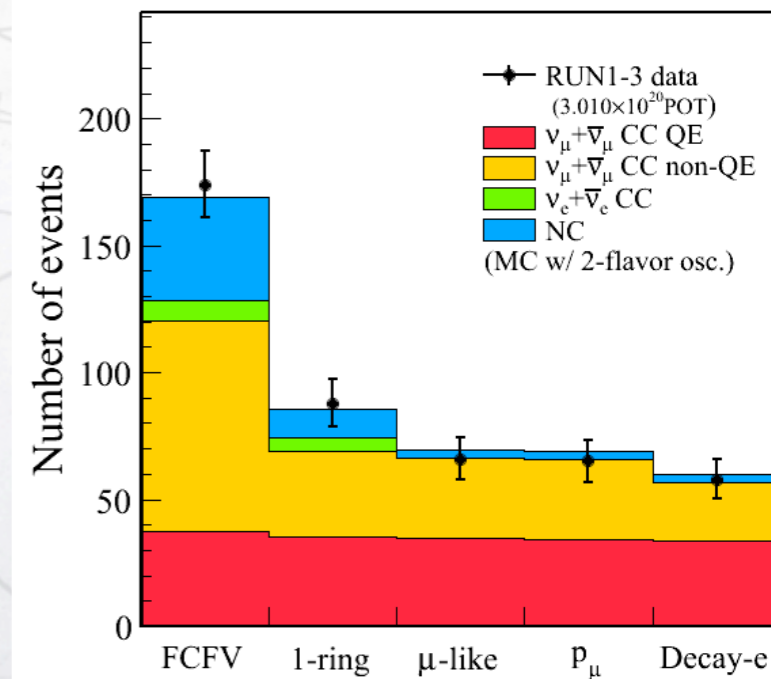
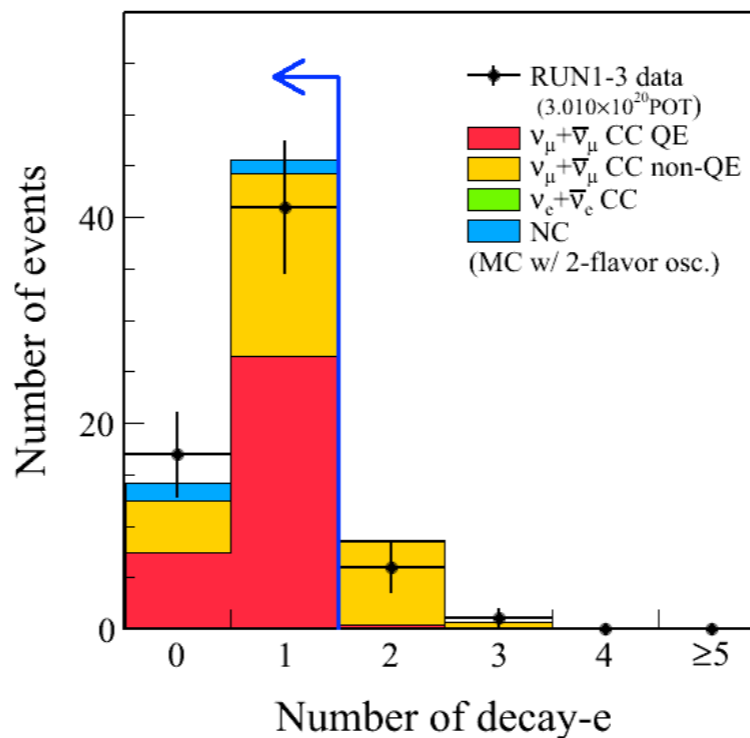
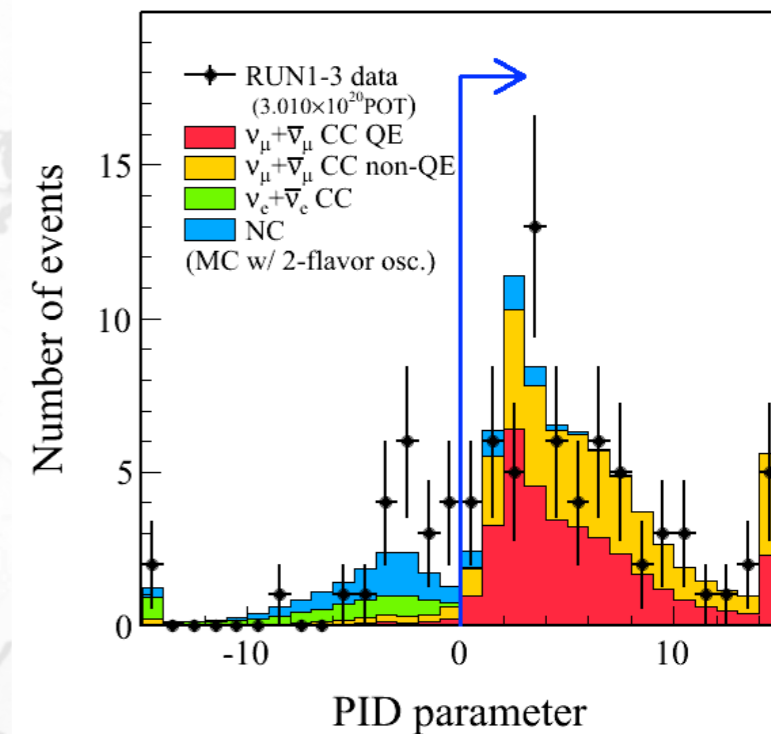
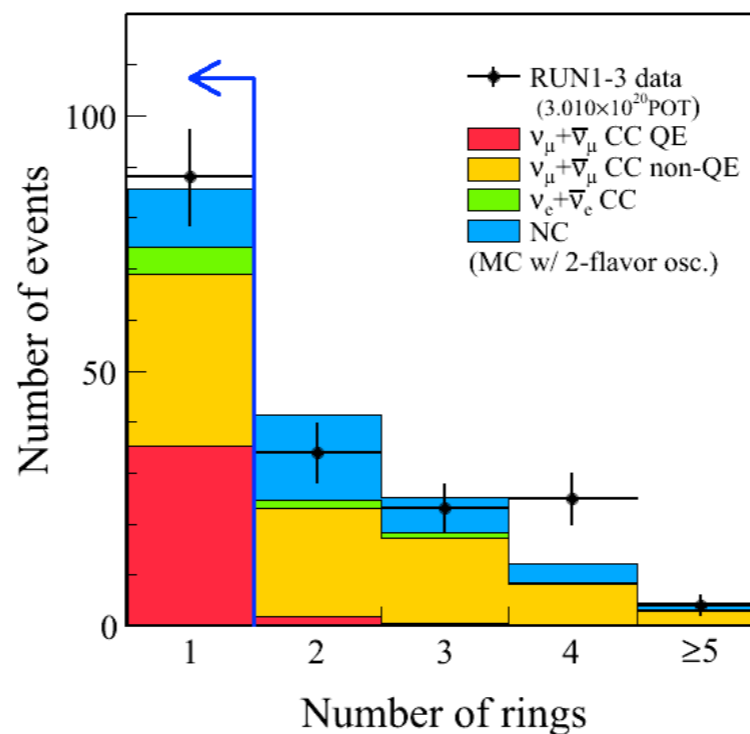
ν_μ selection



ν_μ Selection Cuts

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

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



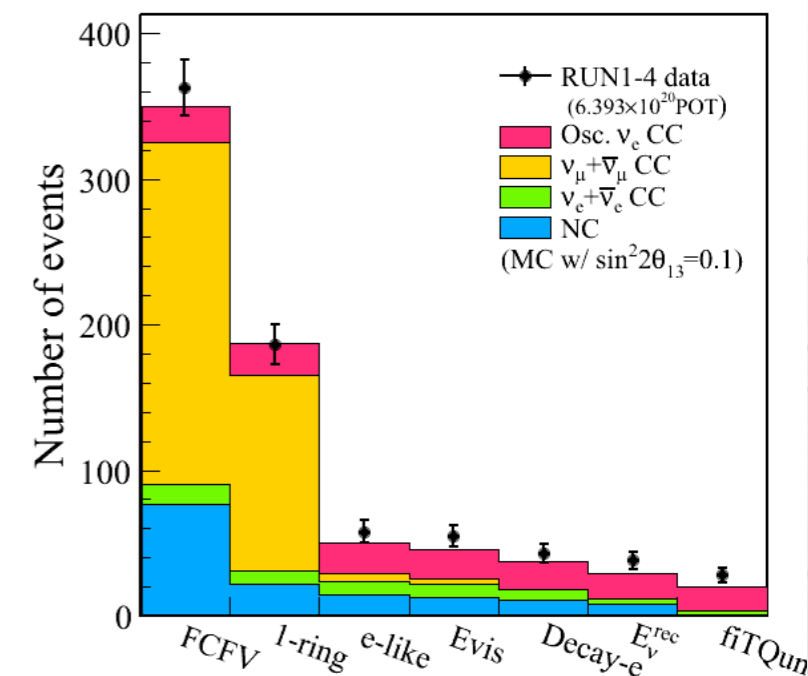
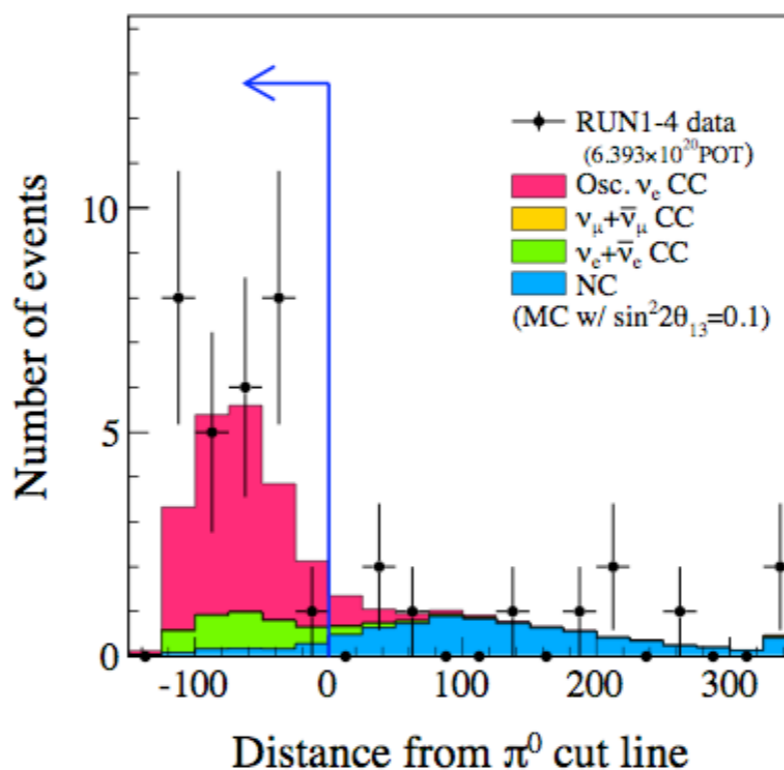
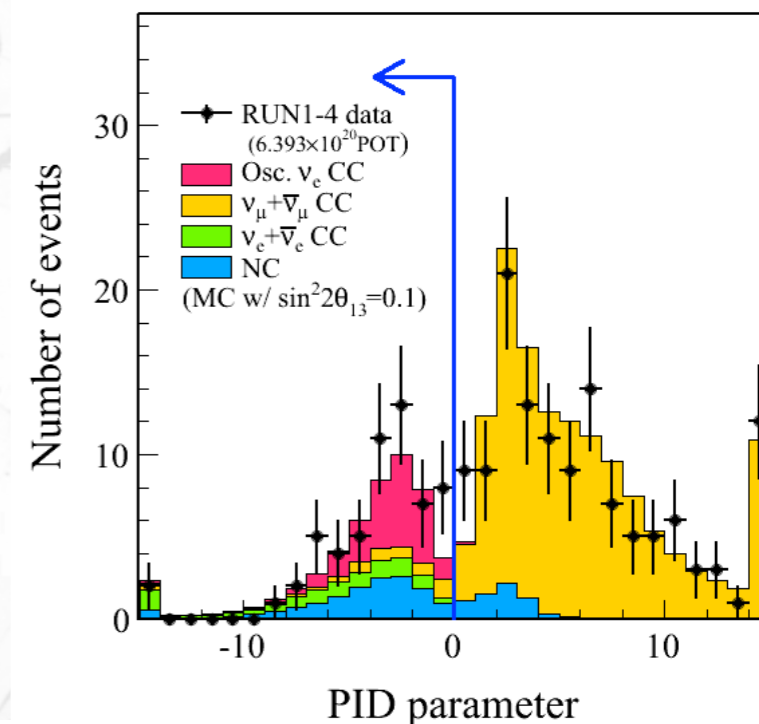
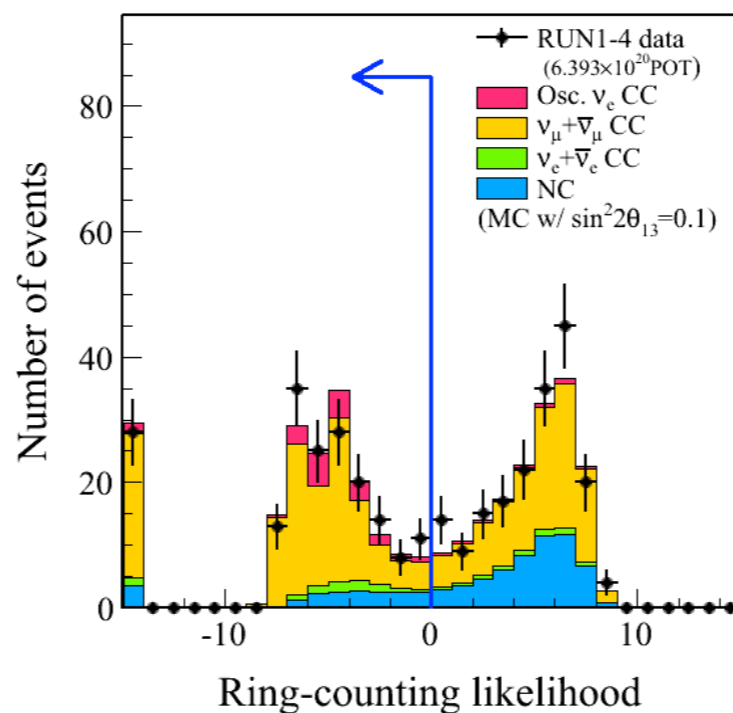
ν_e selection



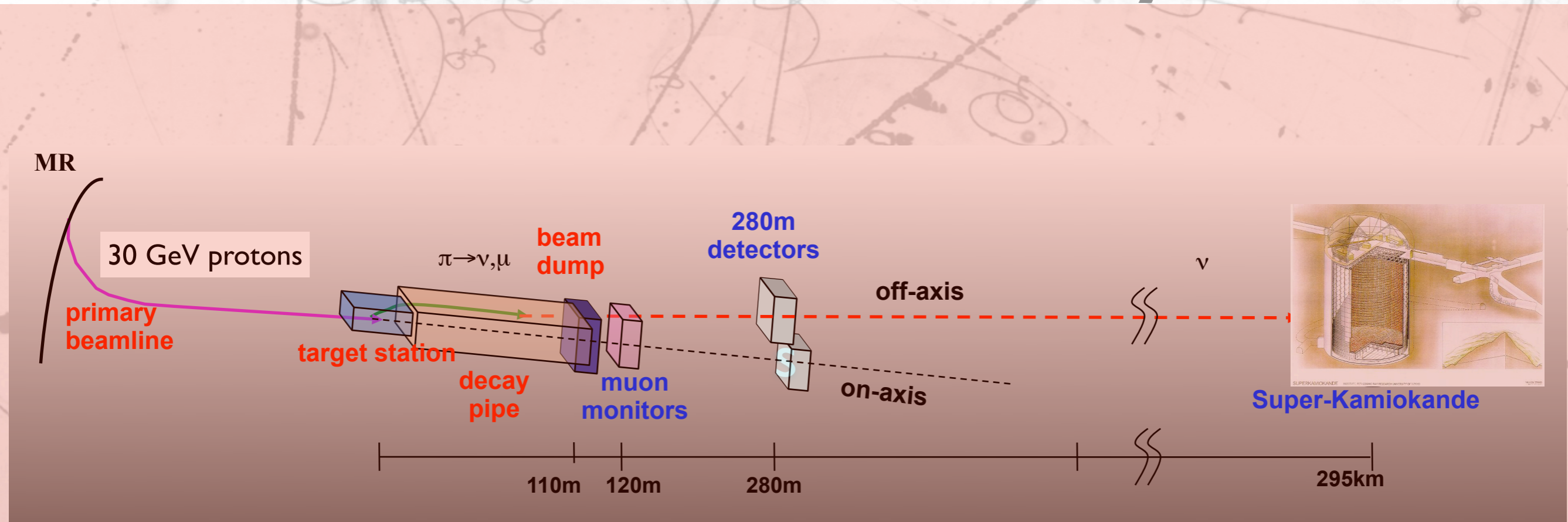
ν_e Selection Cuts

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

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



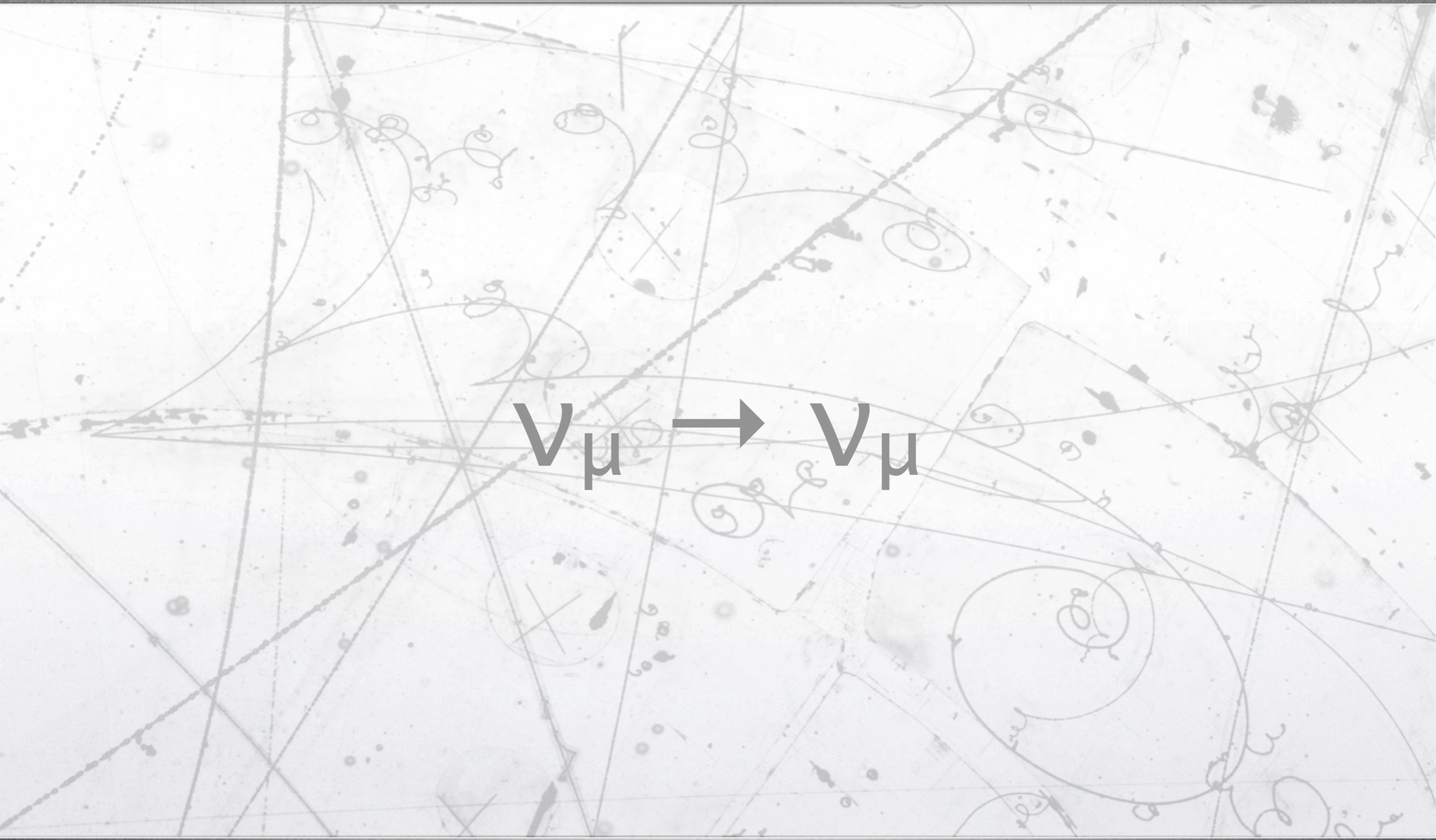
ν oscillation analysis



Beam

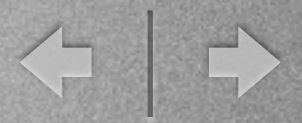
ND280

Super-Kamiokande

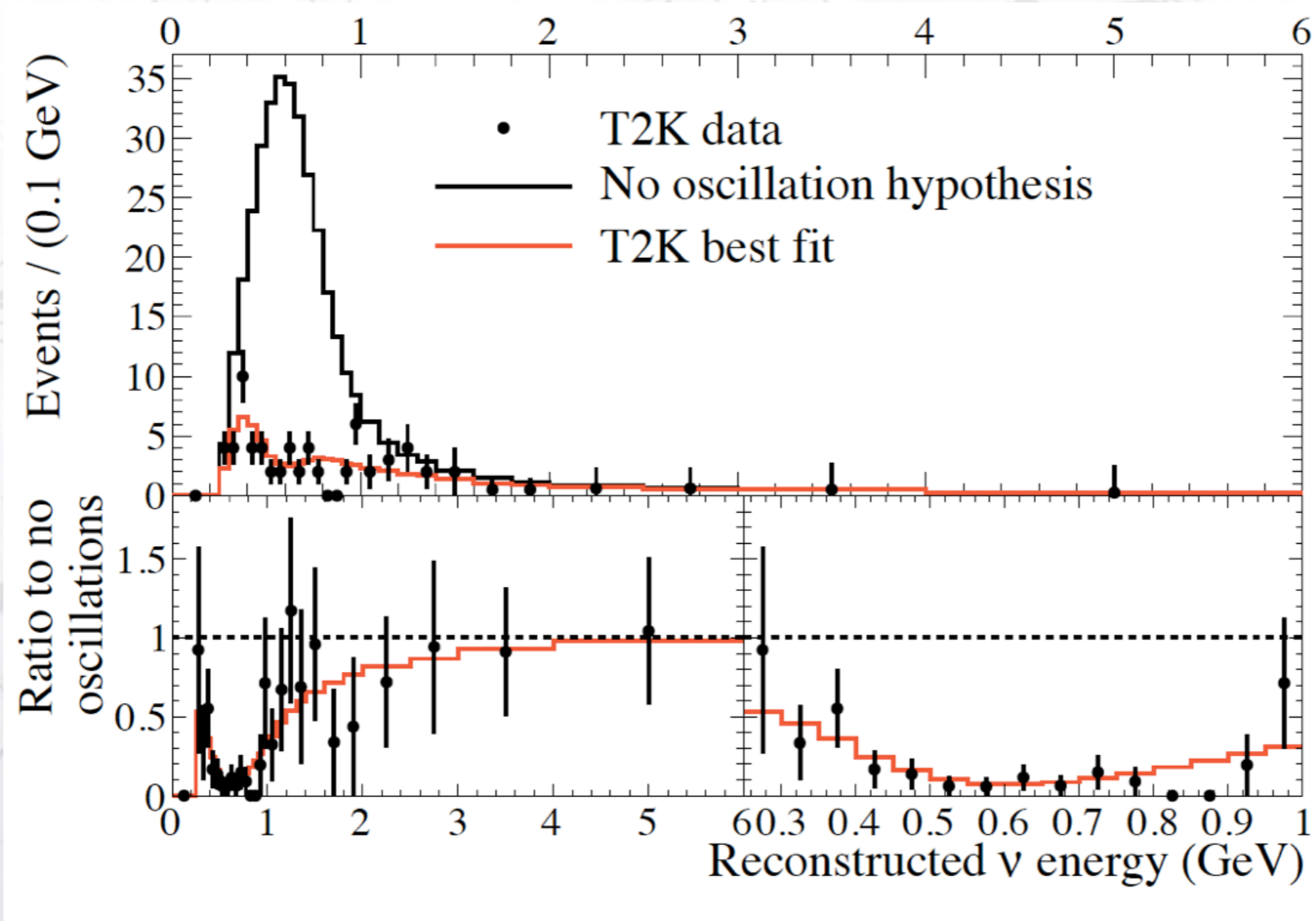


$$\nu_{\mu} \rightarrow \nu_{\mu}$$

ν_μ disappearance



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



3.01×10^{20} PoT

Energy reconstruction assuming CCQE



The θ_{23} octant



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

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

- If $\theta_{13} = 0$

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

- If $\theta_{13} \neq 0$ and $\theta_{23} \sim 45^\circ$, the ν_μ disappearance is sensitive to the octant

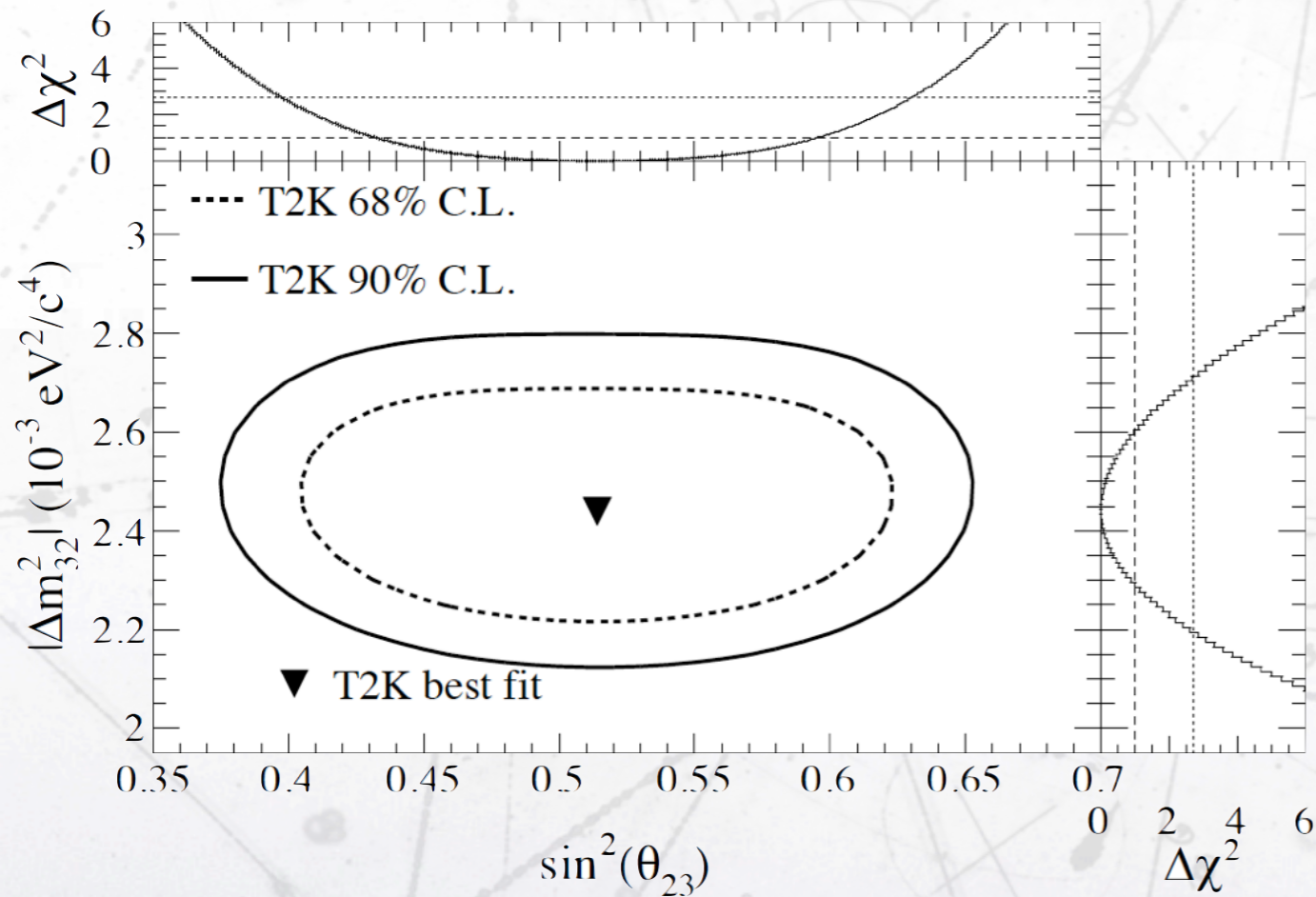
$$(i.e. P_{\nu_\mu \rightarrow \nu_\mu}(\theta_{23} > 45^\circ) \neq P_{\nu_\mu \rightarrow \nu_\mu}(\theta_{23} < 45^\circ))$$

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

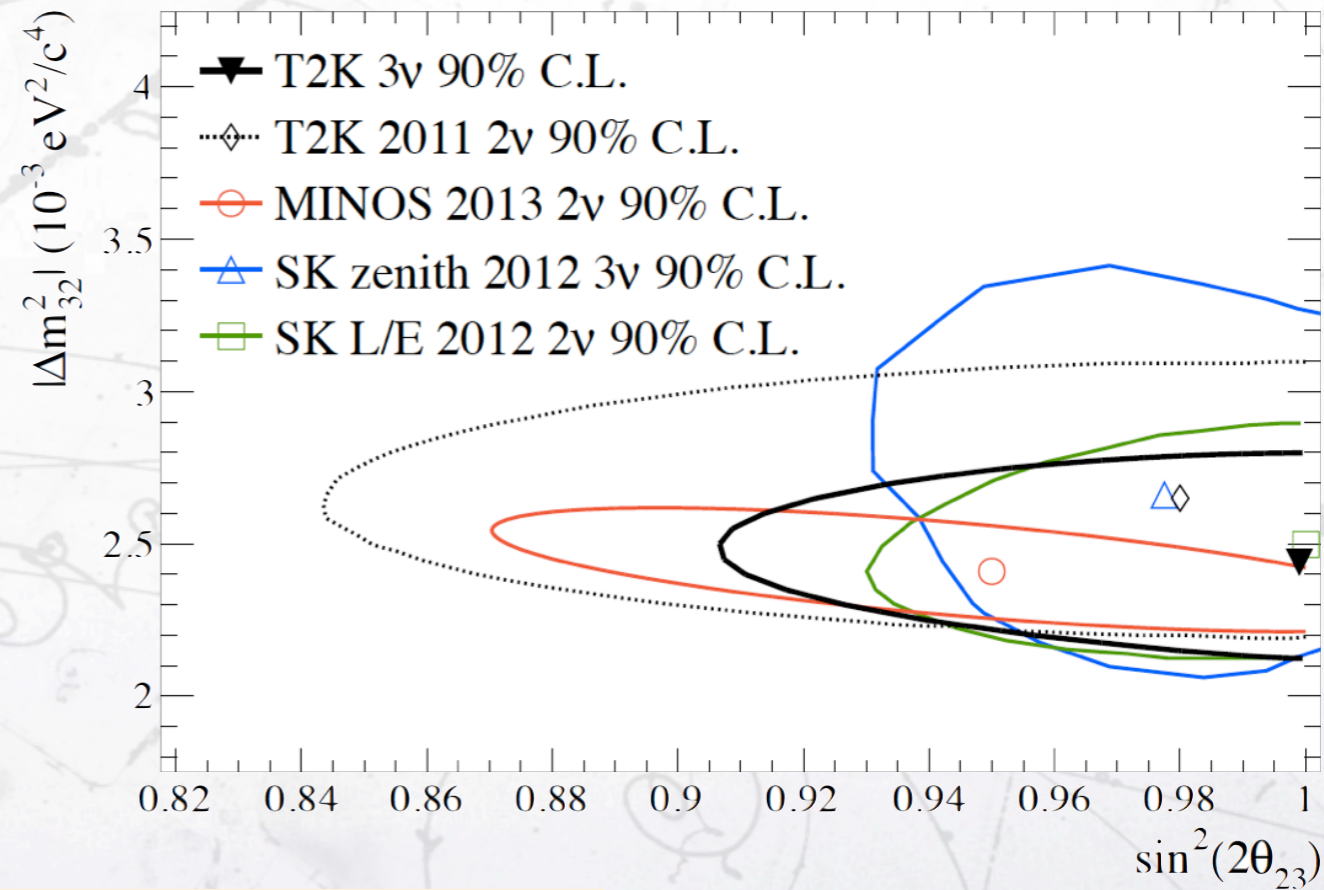
ν_μ disappearance



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



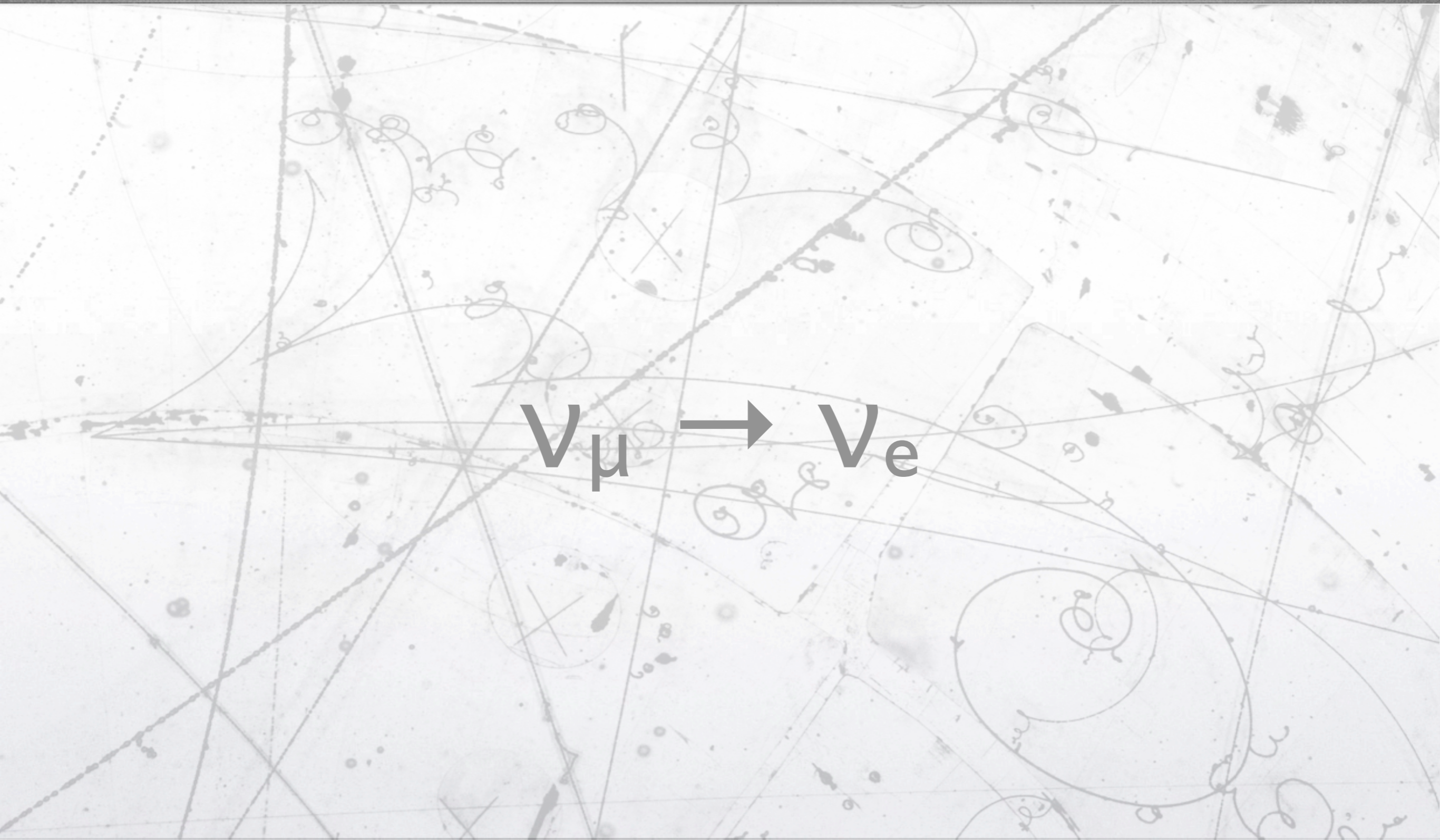
Old representation for comparisons!



Physical Review Letters in Press. Arxiv:1308.0465

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



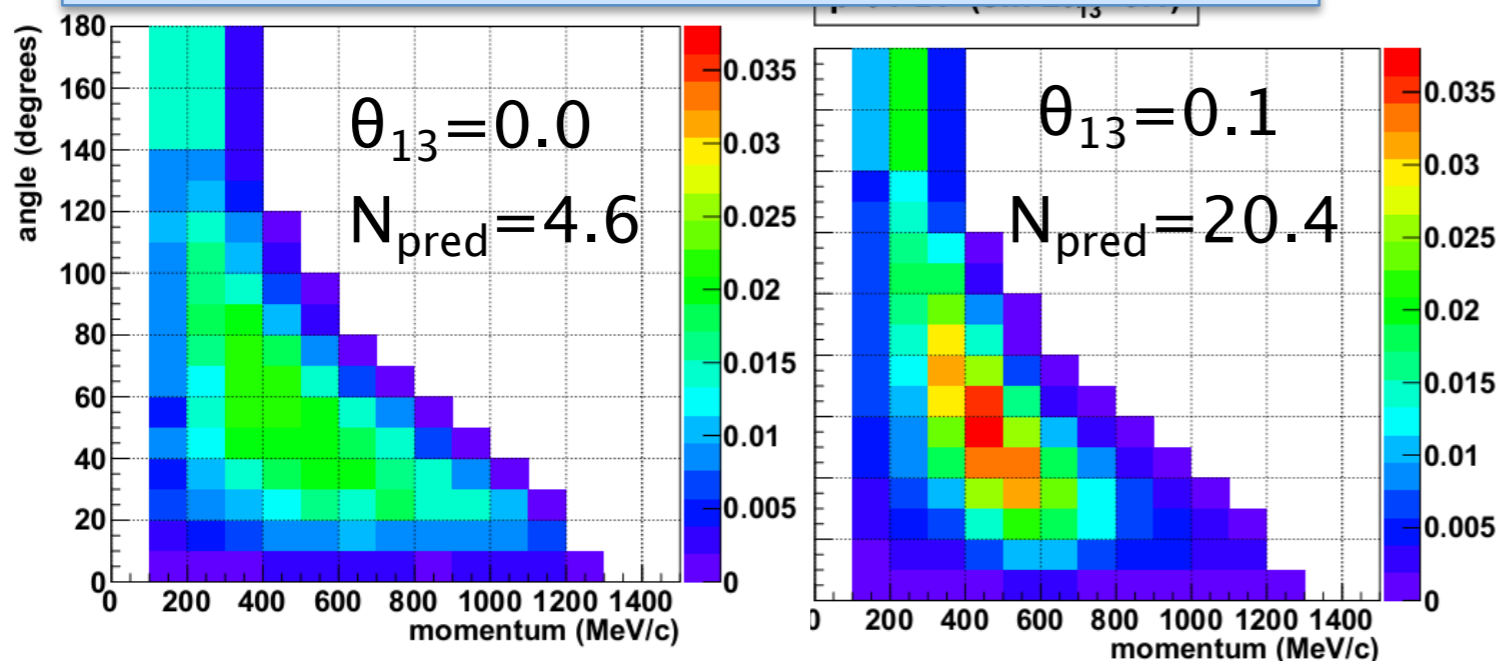


$$\nu_{\mu} \rightarrow \nu_e$$

ν_e appearance



Electron momentum vs. angle distribution (MC)

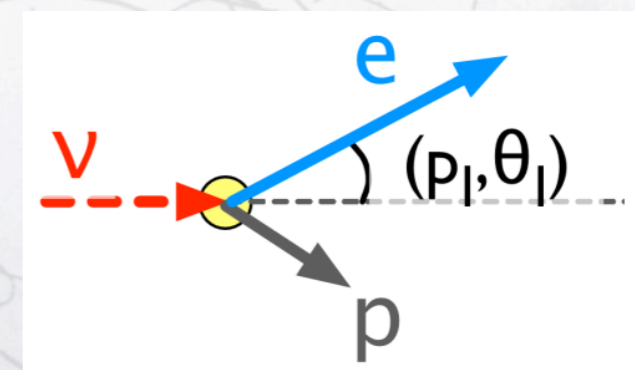


Fixed oscillation parameters

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

Analysis method

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



V_e appearance



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

Systematic parameter constraint term

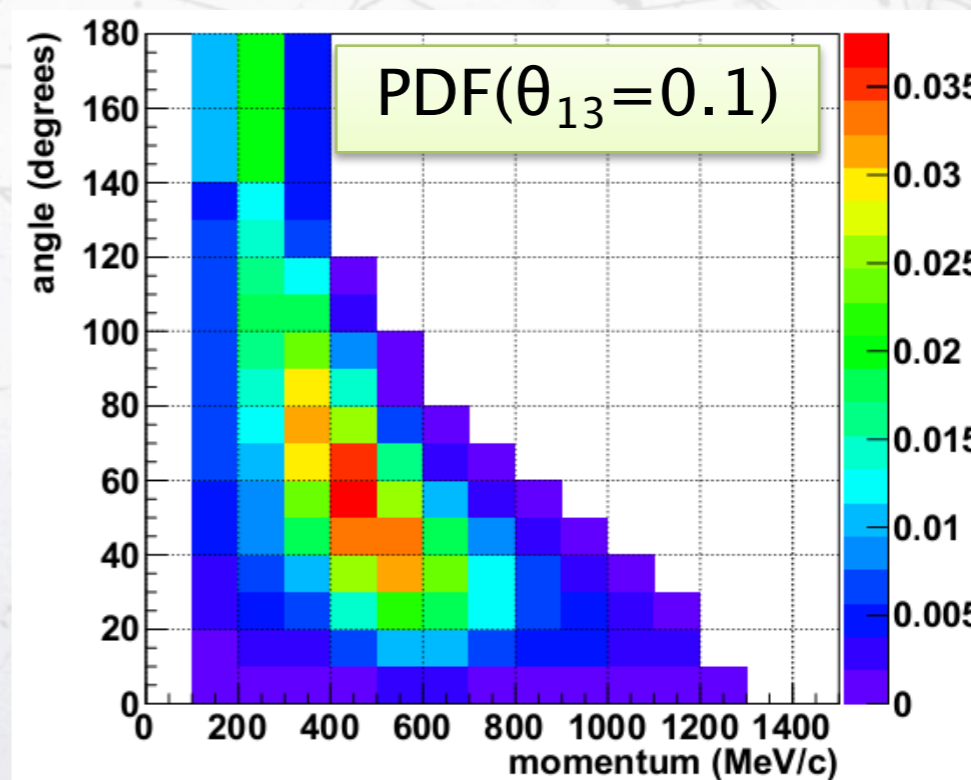
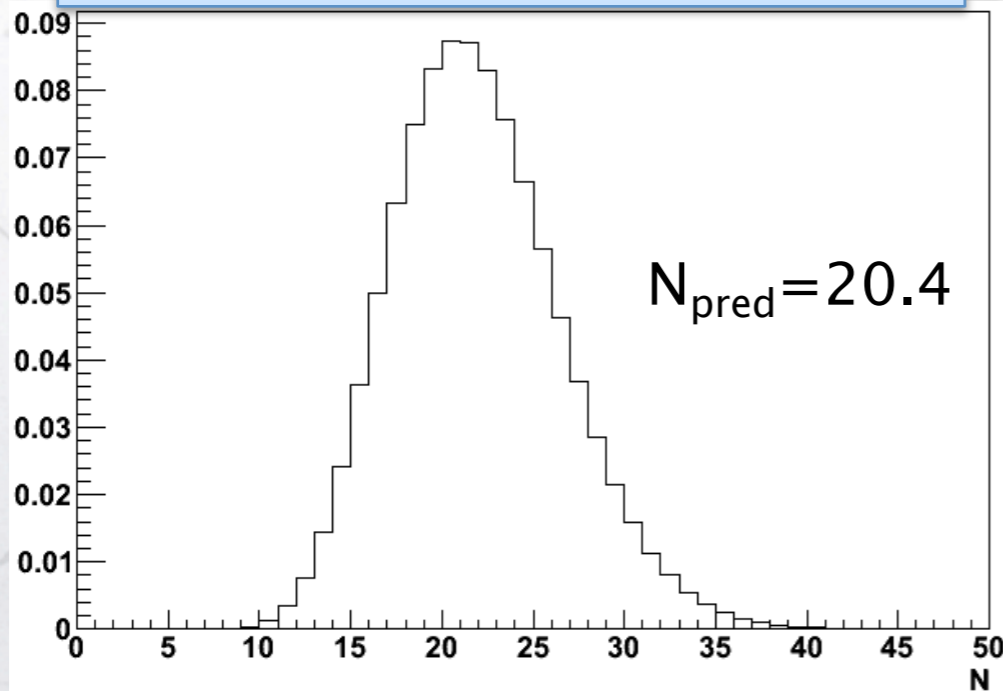
$$Poisson(N_{obs})_{\text{mean}=N_{pred}}$$

$$\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$$

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

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

Poisson distribution ($\theta_{13}=0.1$)



ν_e appearance



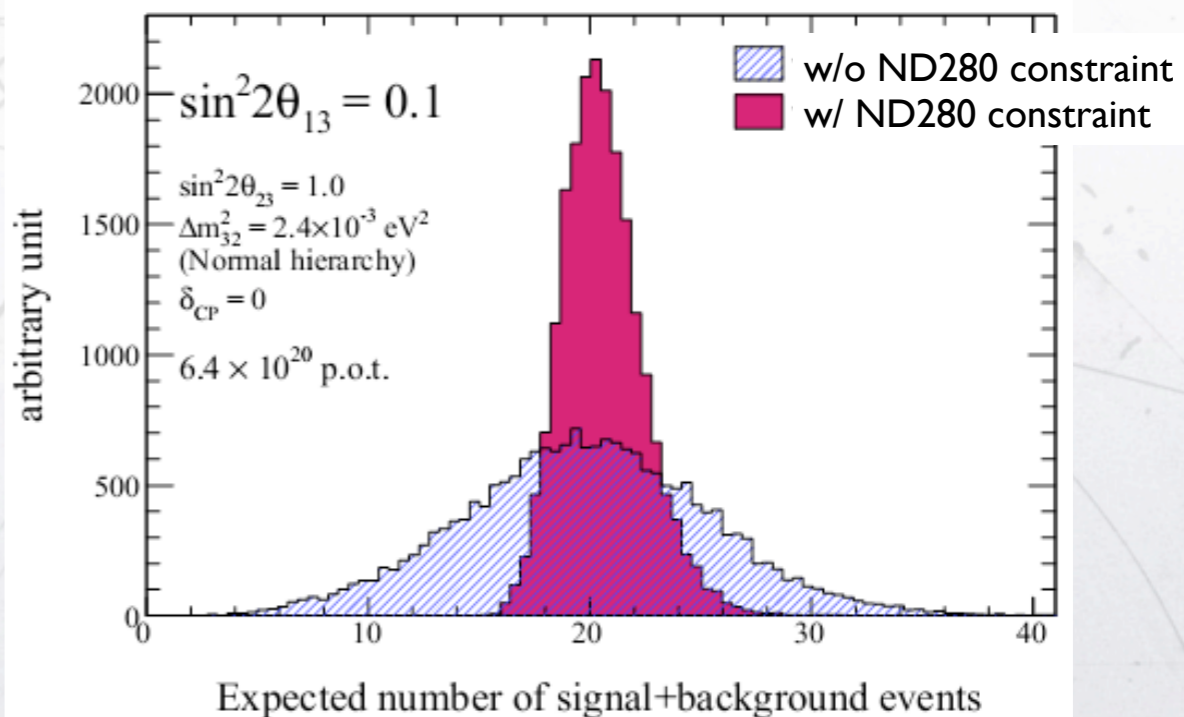
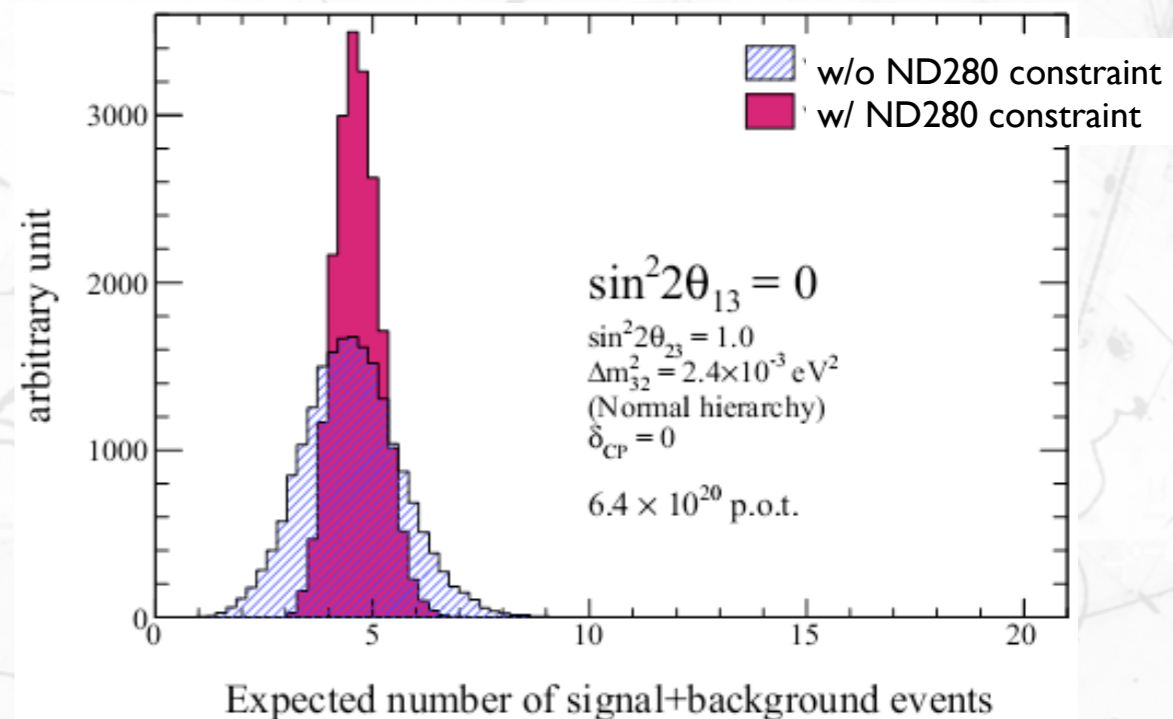
6.4×10^{20} PoT

Event prediction

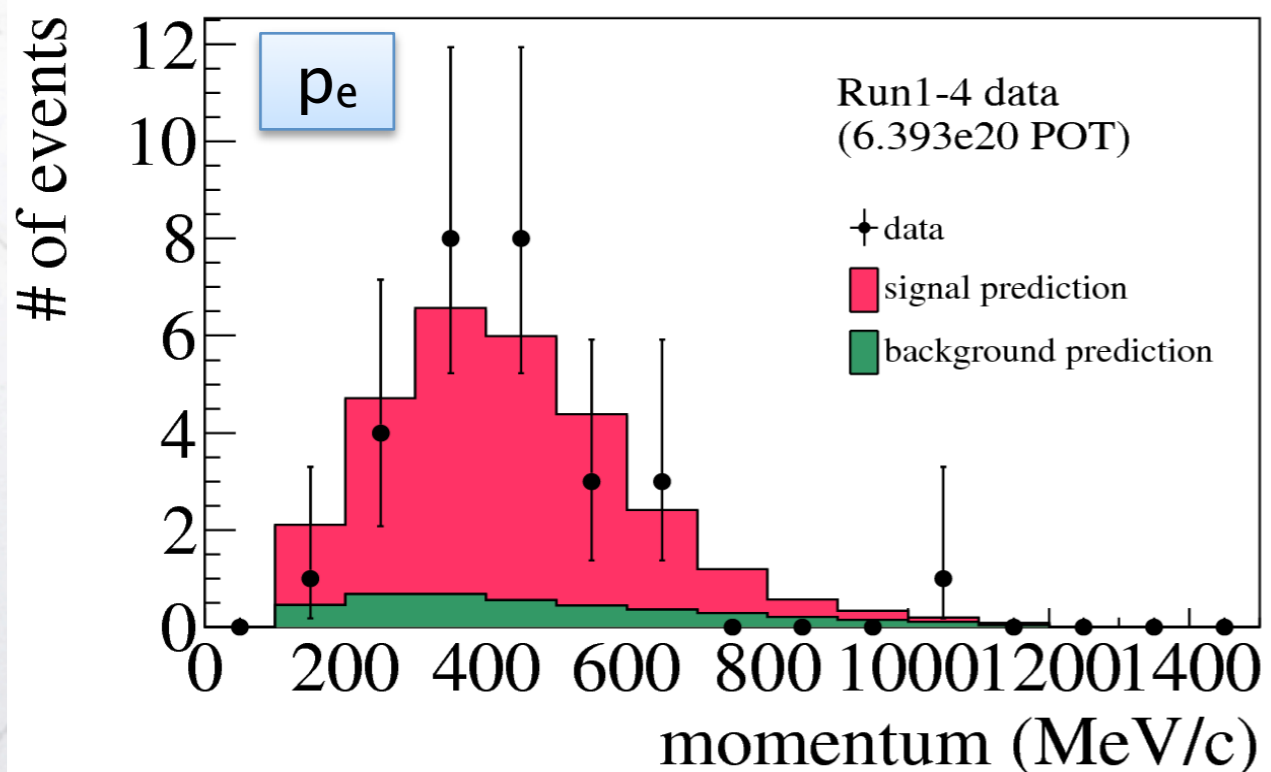
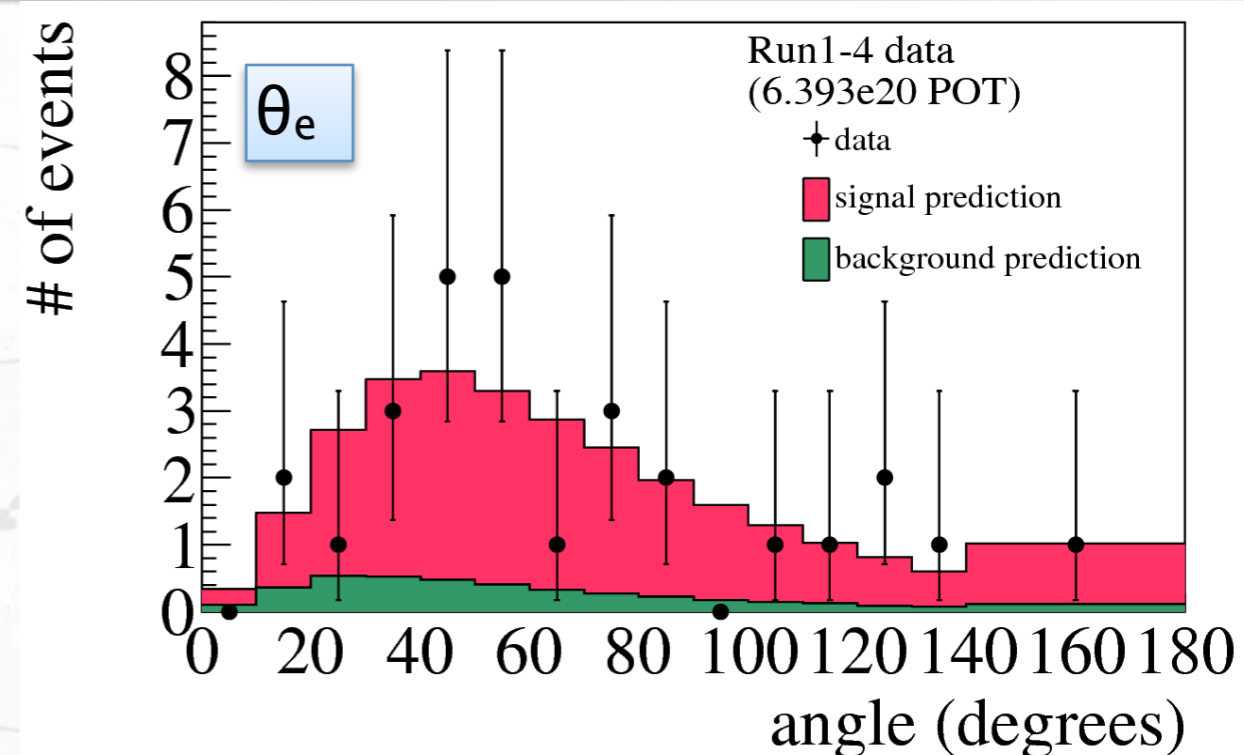
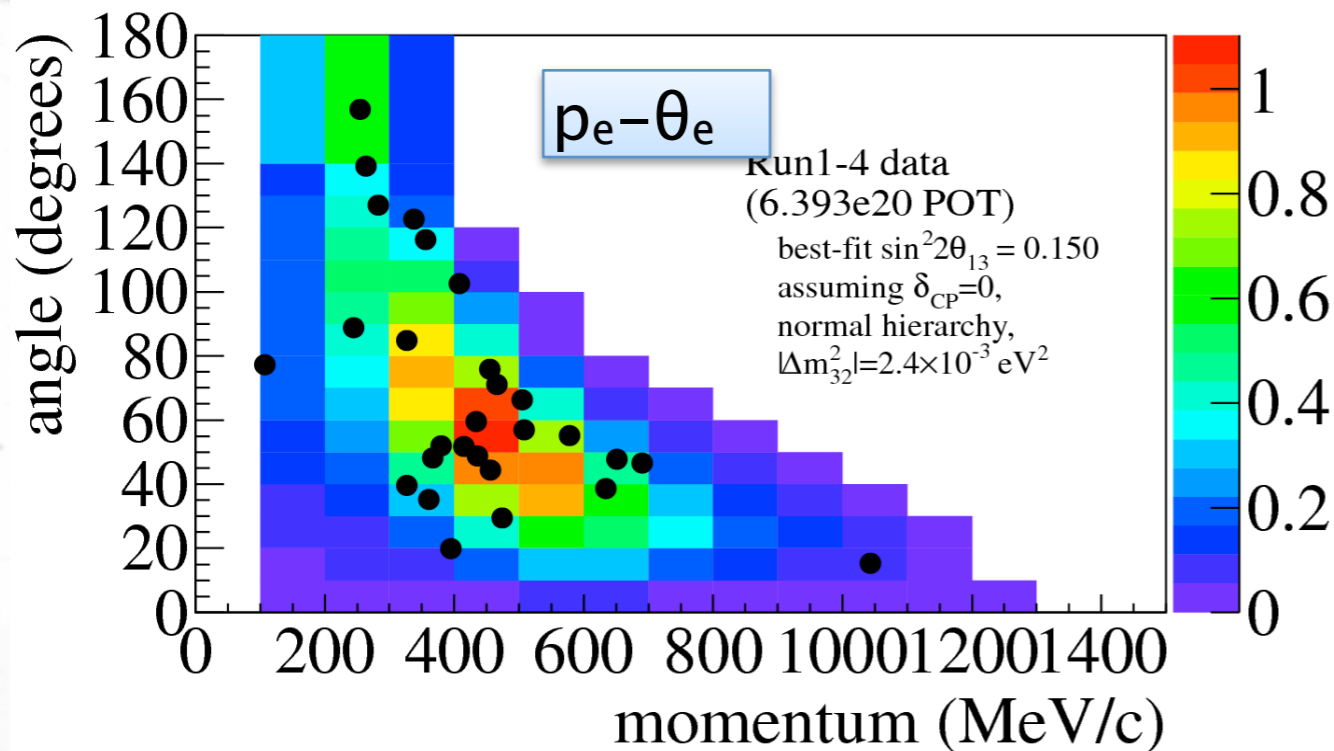
Event cath.	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
ν_e signal	0.38	16.42
ν_e back.	3.17	2.93
ν_μ back.	0.89	0.89
$\nu_\mu + \nu_e$ back.	0.20	0.19
Total	4.64	20.44

Systematic error

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



ν_e appearance



Assuming $\delta_{CP}=0$, normal hierarchy, $|\Delta m^2_{32}|=2.4 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23}=1$

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

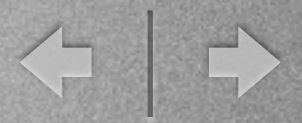
$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

90% allowed region:

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



ν_e appearance



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

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

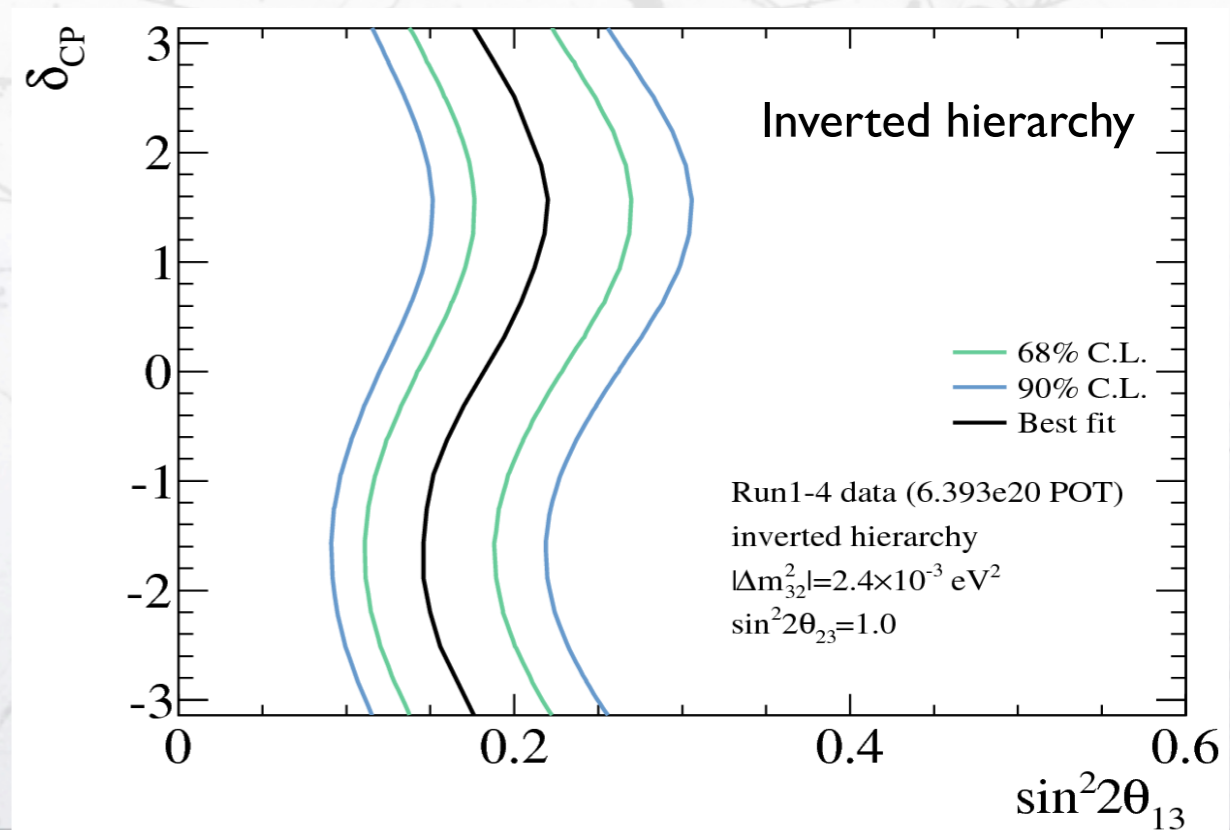
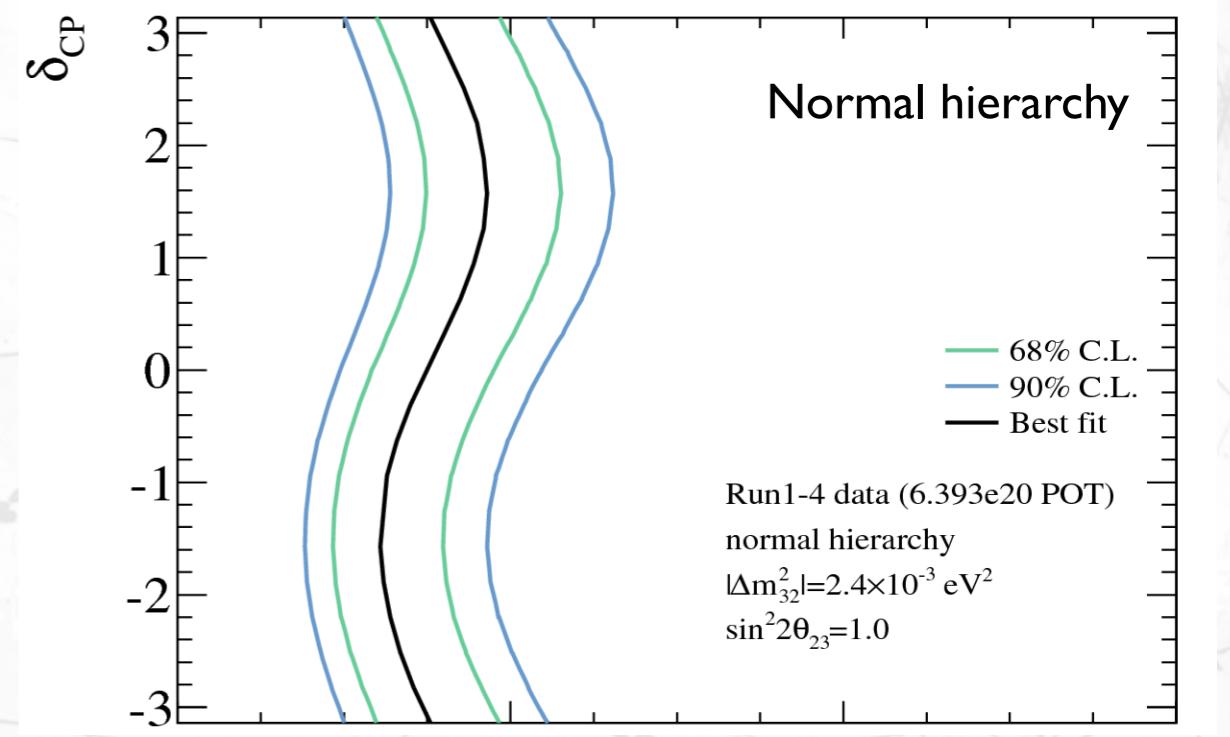
Normal hierarchy:

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

Inverted hierarchy:

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

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



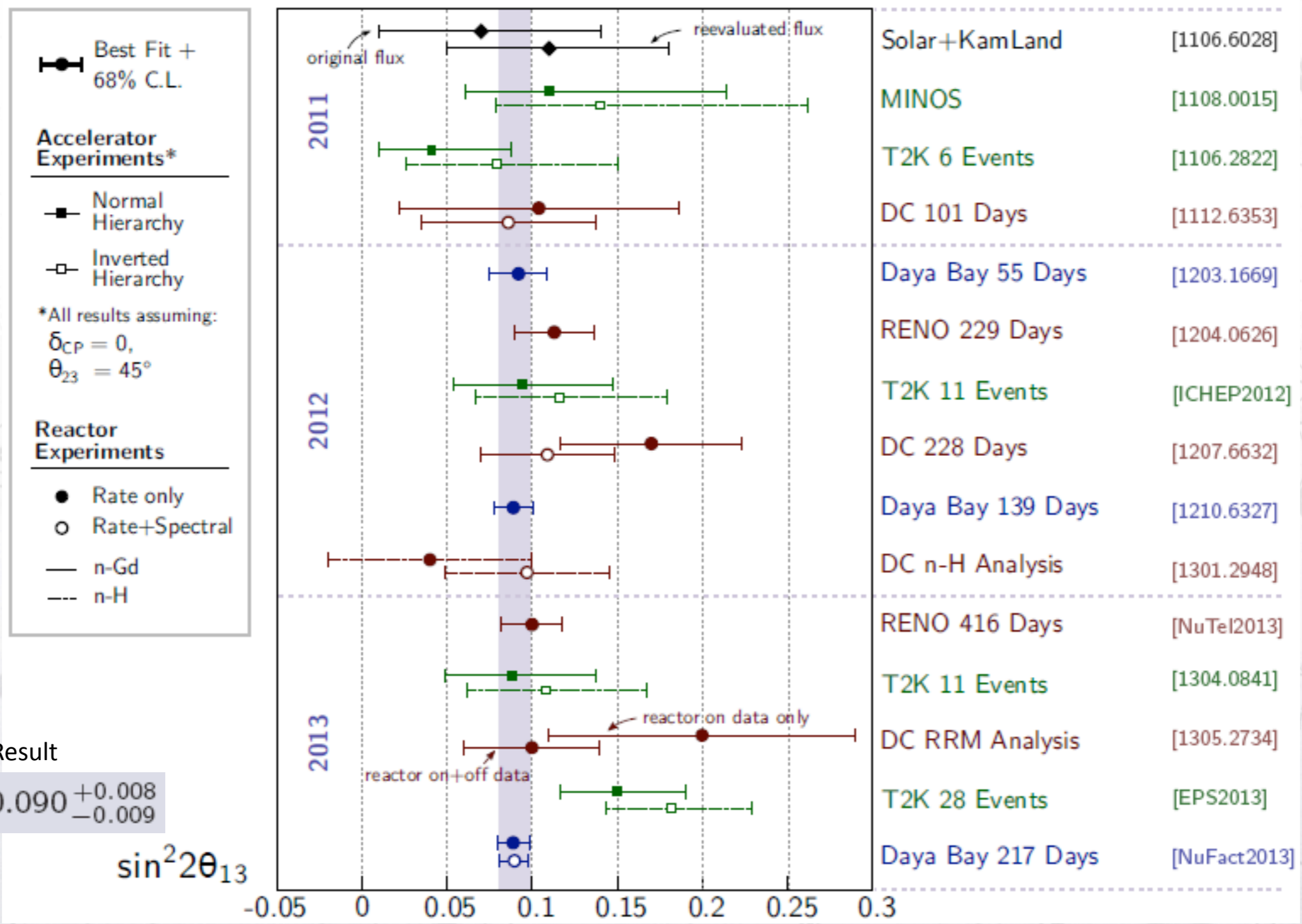
NOTE: These are 1D contours for values of δ_{CP} , not 2D contours in $\delta_{CP}-\theta_{13}$ space



Global θ_{13}



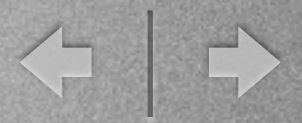
Compilation from Soeren Jetter (HEP), NuFact 2013



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



ν_e appearance



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

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

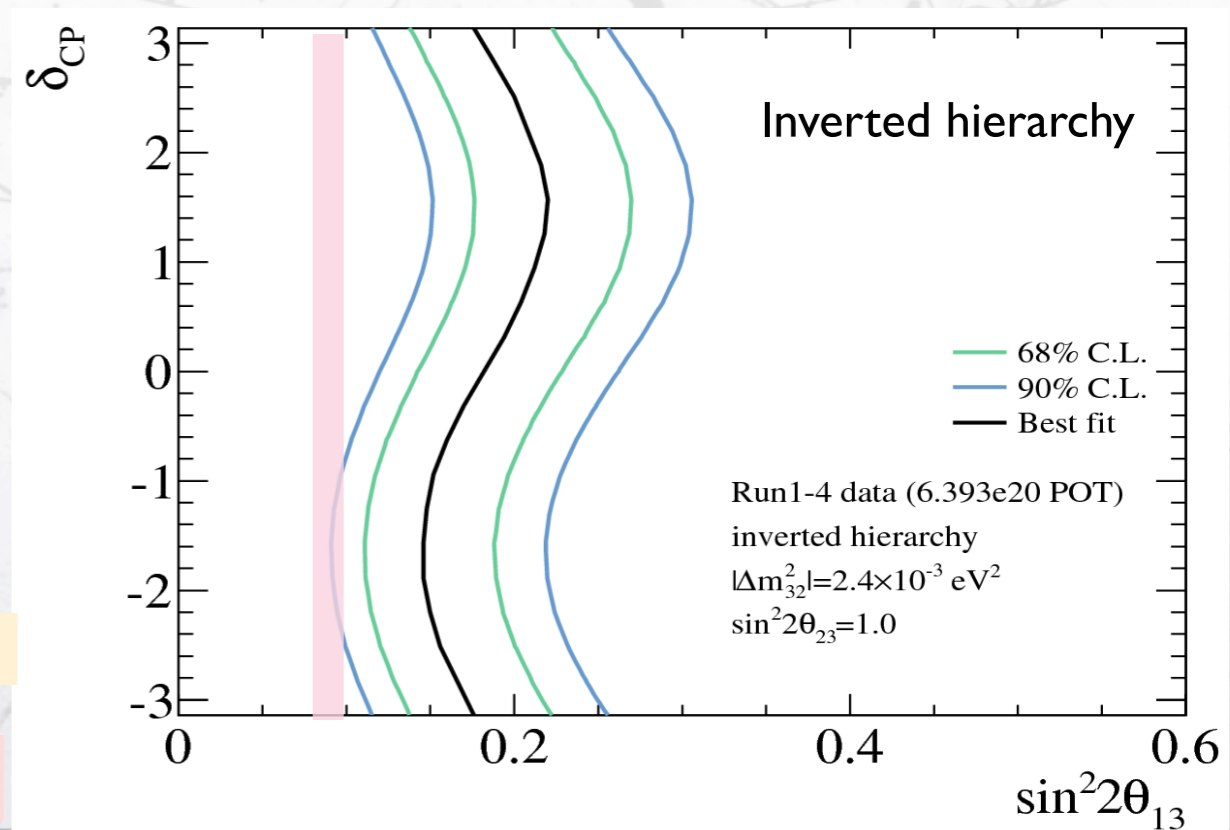
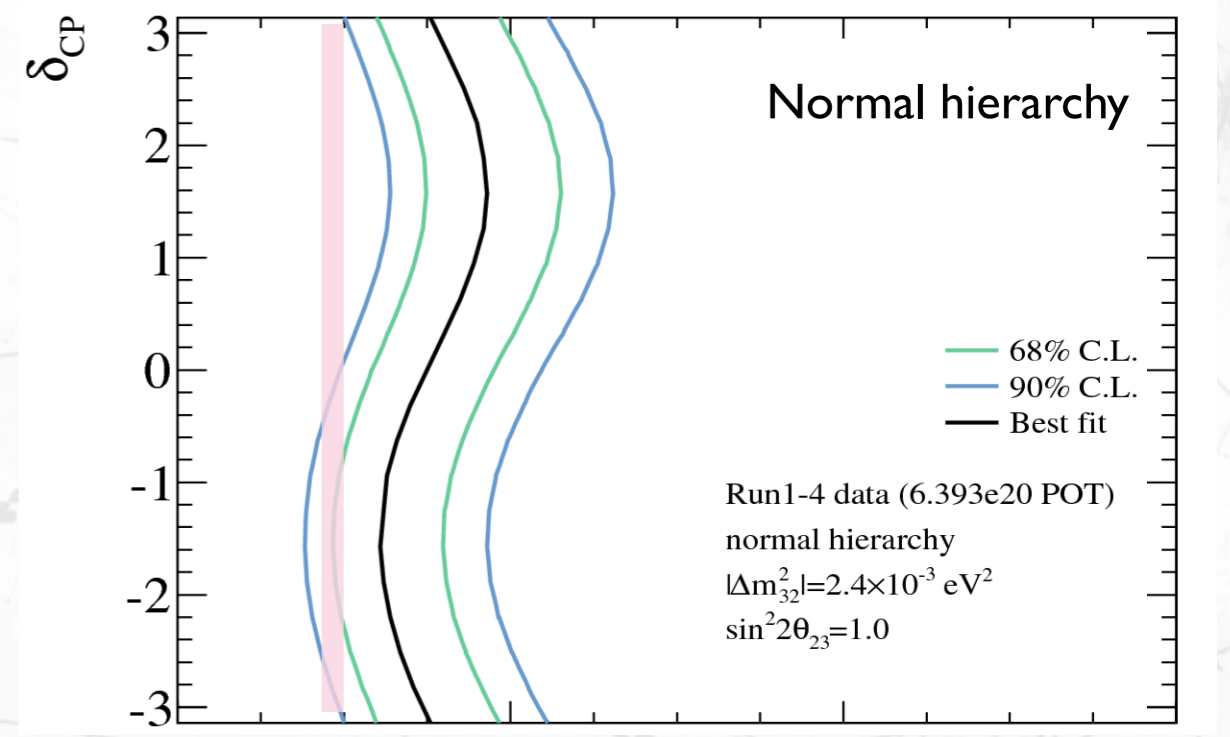
Normal hierarchy:

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

Inverted hierarchy:

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

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



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

New Daya-Bay result. (NUFACT13)



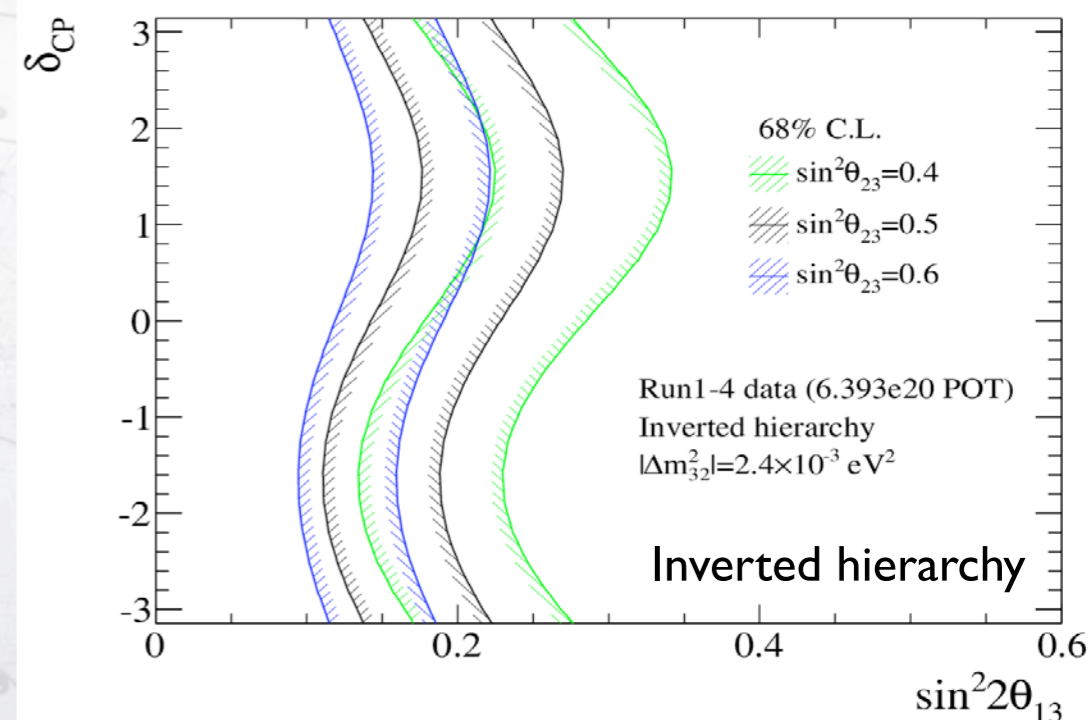
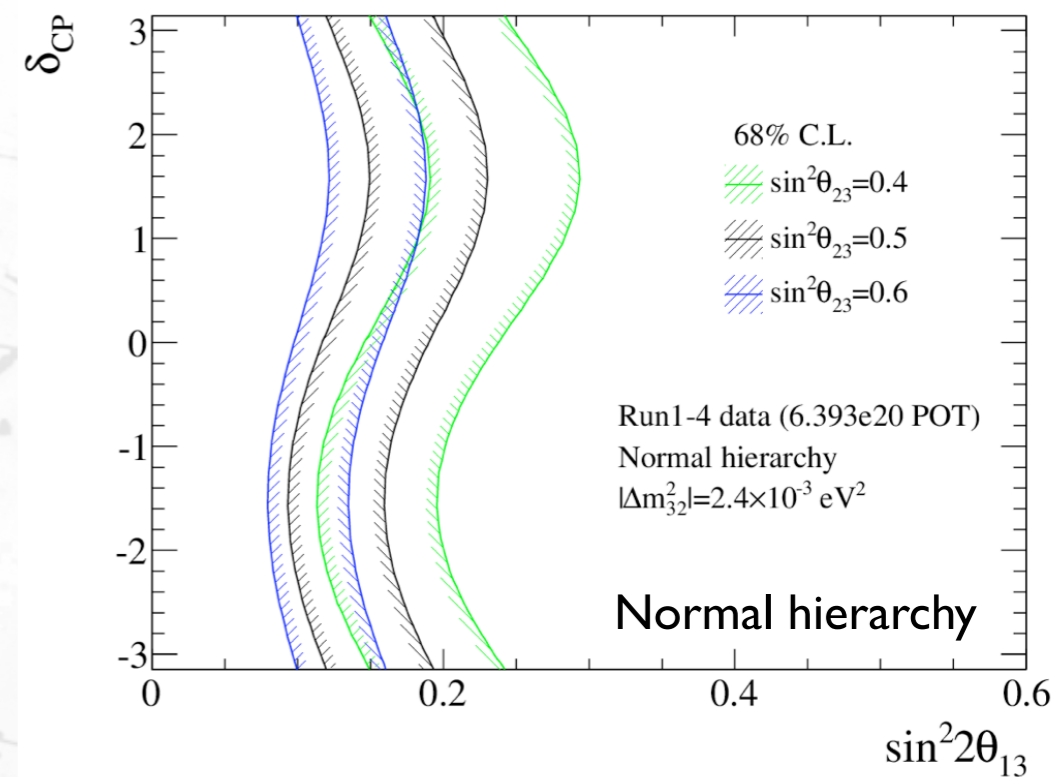
V_e appearance



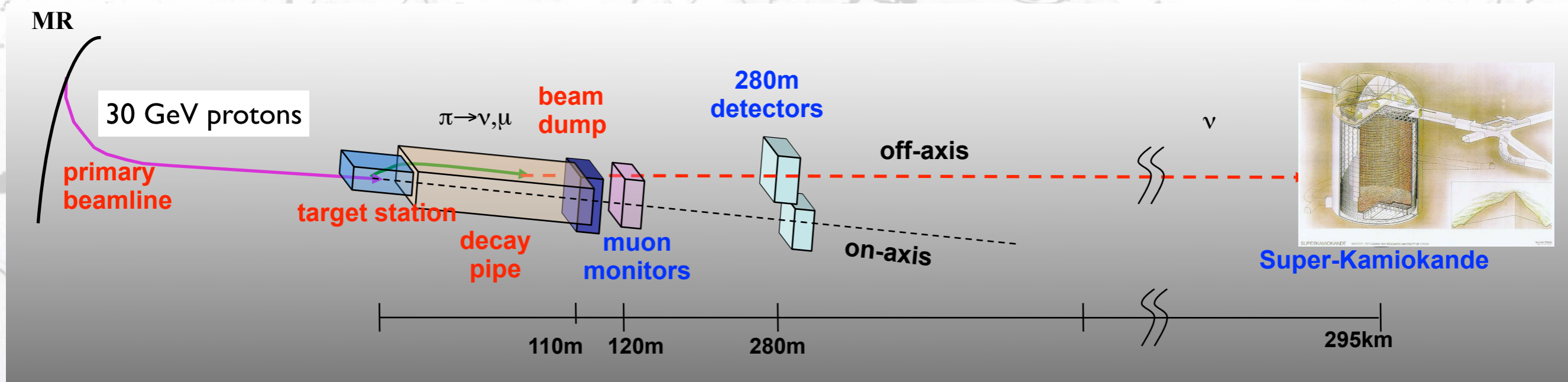
The uncertainty in the atmospheric mixing angle.

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

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



T2K: the future



Beam

ND280

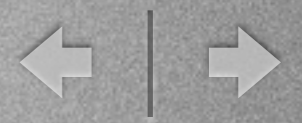
Super-Kamiokande

Upgrade plan



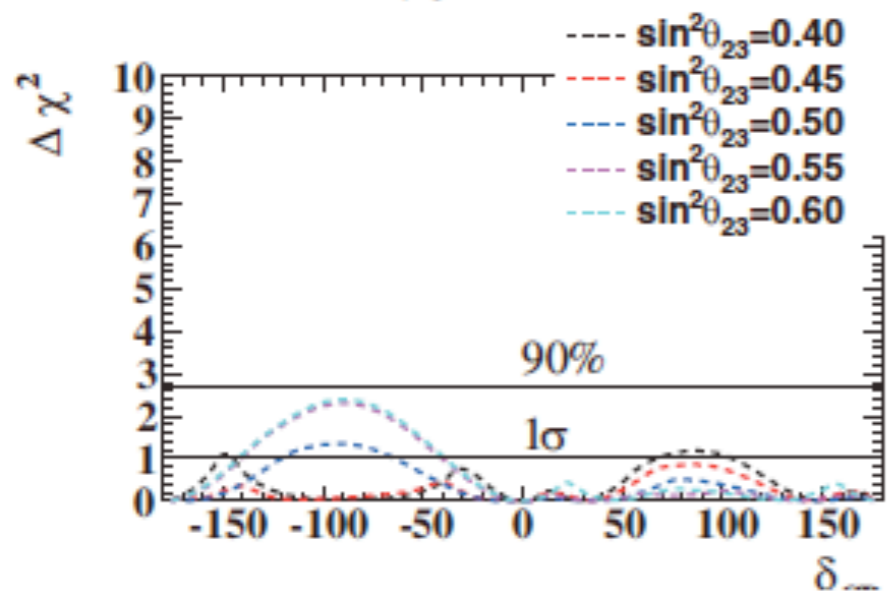
- Planned J-PARC Main Ring (MR) power improvements 220 kW operation in CY2013. Integrated 6.7×10^{20} PoT to date.
- Linac upgrade to be completed within a year. Expect range of steady MR operation for neutrino between 200-400 kW
- Planned MR upgrade (depends on funding). Up to 750 kW
- Possible staged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

Future δ_{CP} sensitivity



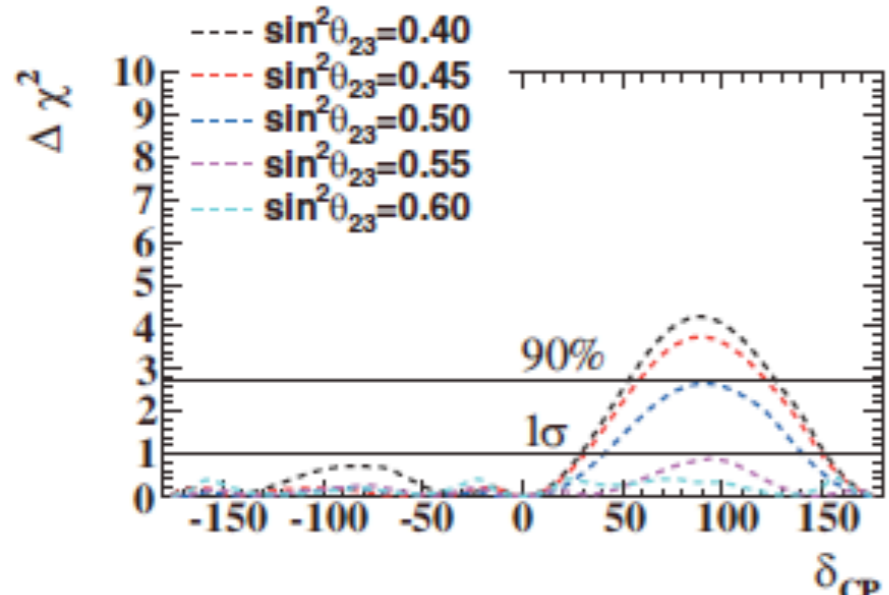
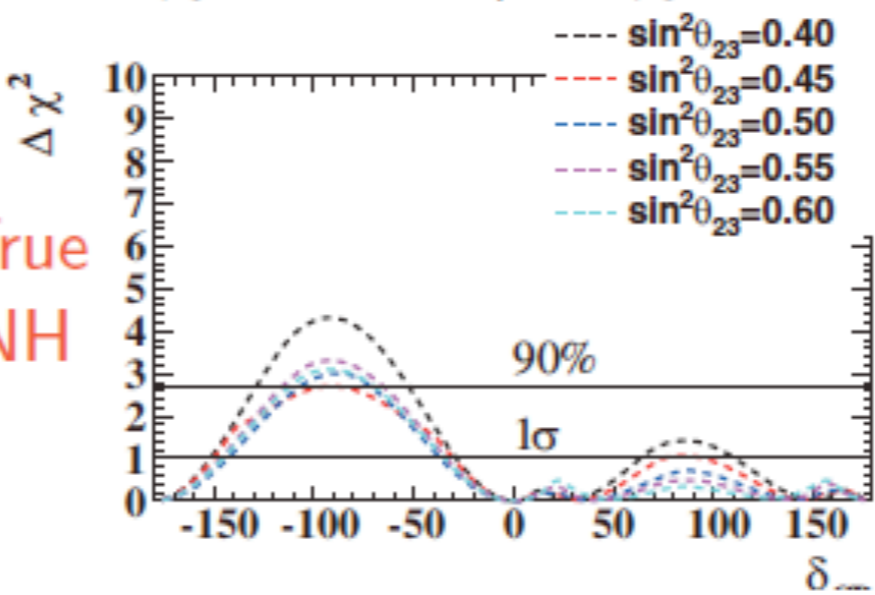
7.8x10²¹ PoT + 2012 systematics

100% POT ν

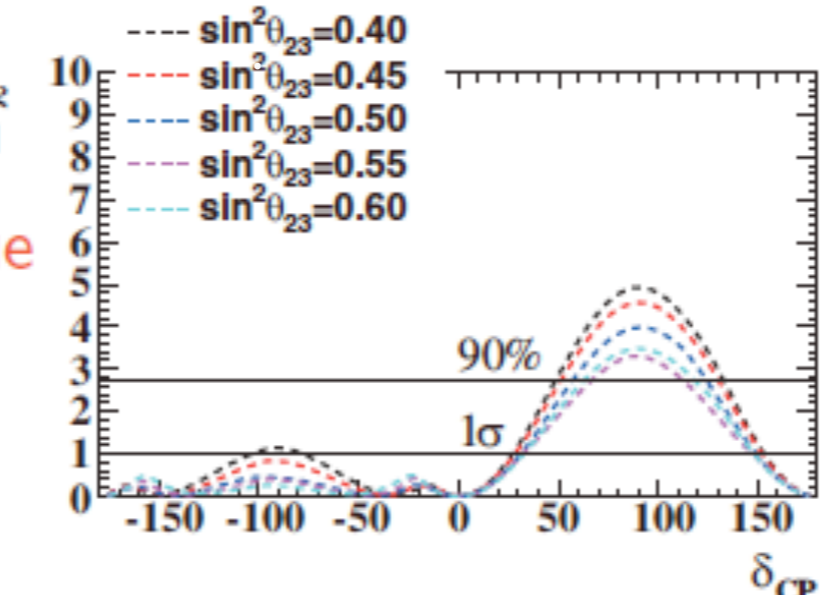


True
NH

50% POT ν + 50% POT $\bar{\nu}$



True
IH



T2K + reactor

Assumptions

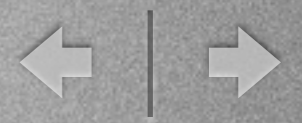
$$\sin^2 2\theta_{13} = 0.1$$

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

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



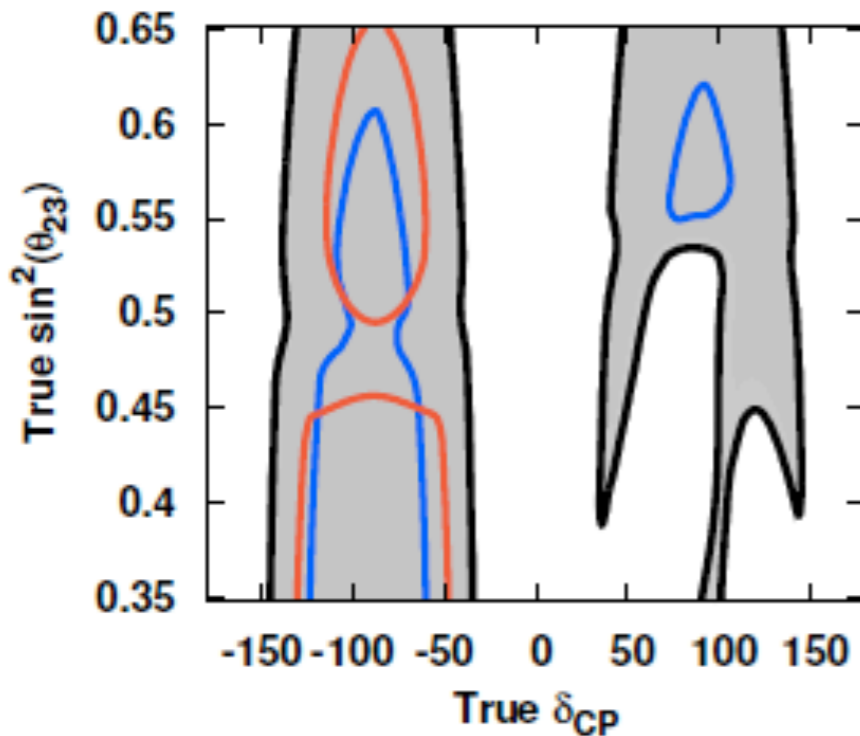
Future δ_{CP} sensitivity



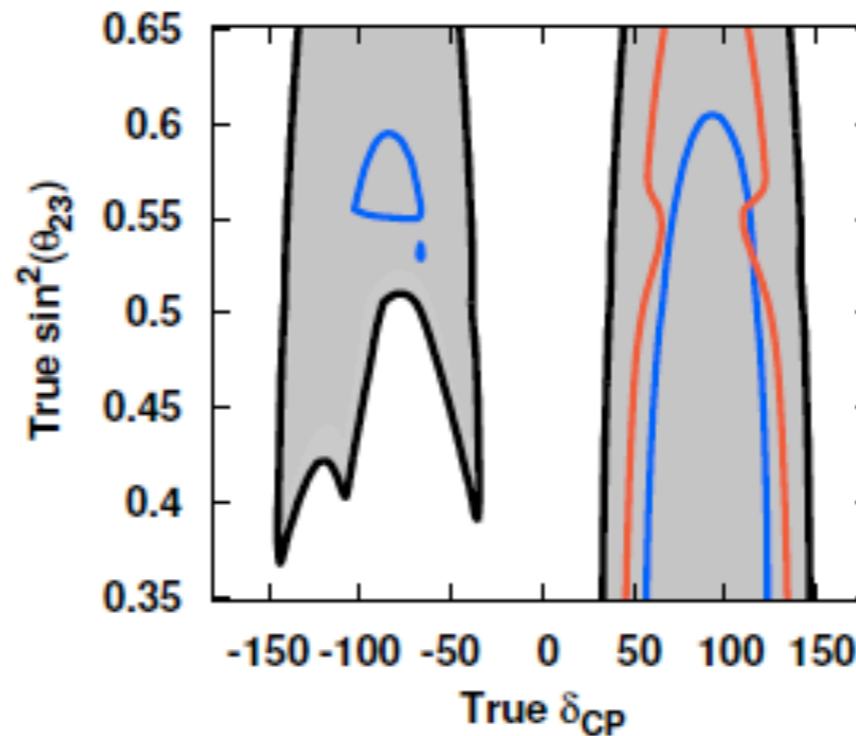
T2K + NoVa + reactor

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

True Normal MH



True Inverted MH



50% ν + 50% $\bar{\nu}$

T2K alone

Nova alone

T2K+ NoVa

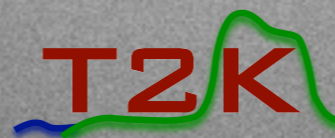
Assumptions

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

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

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

⊕ simple normalisation errors.



Conclusions



- T2K has shown the first evidence (7.4σ significance) of the appearance of ν_e in a ν_μ beam with only 8.3% of the total T2K statistics.
- Also measurement of $\nu_\mu \rightarrow \nu_\mu$ which favours maximal mixing. Oscillations at “atmospheric” baseline are now precision measurements
- This success is the result of a combined effort of JPARC accelerator increasing the PoT statistics (x2 in one year!) and T2K analysis improvements reducing the systematic errors.
- T2K will continue to run and benefit from planned J-PARC Main Ring (MR) power improvements 220 kW operation in CY2014.
- T2K horn system designed to easily switch from neutrino to anti-neutrino beams.
- Proposed a pilot run with antineutrinos in 2014.

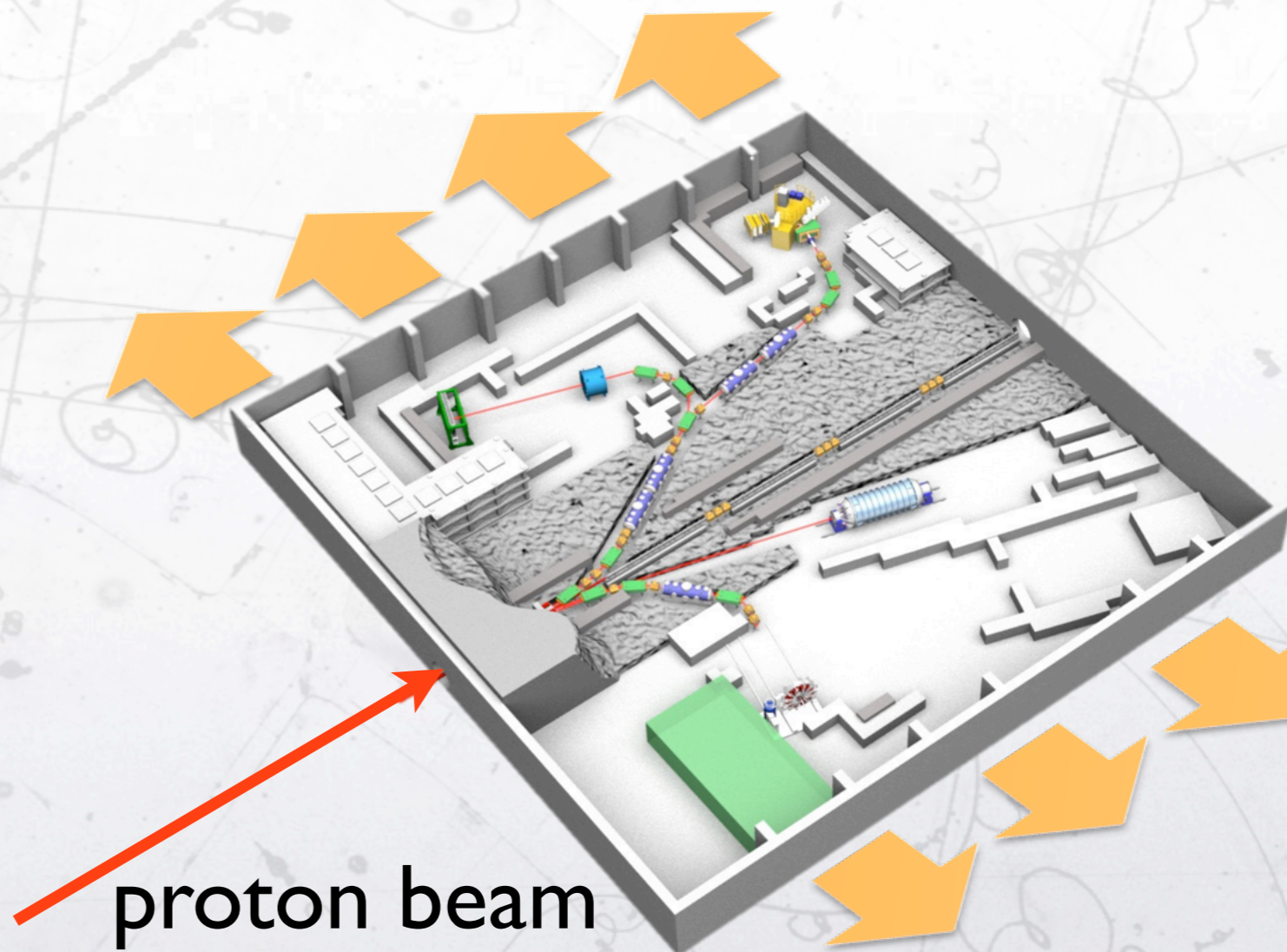
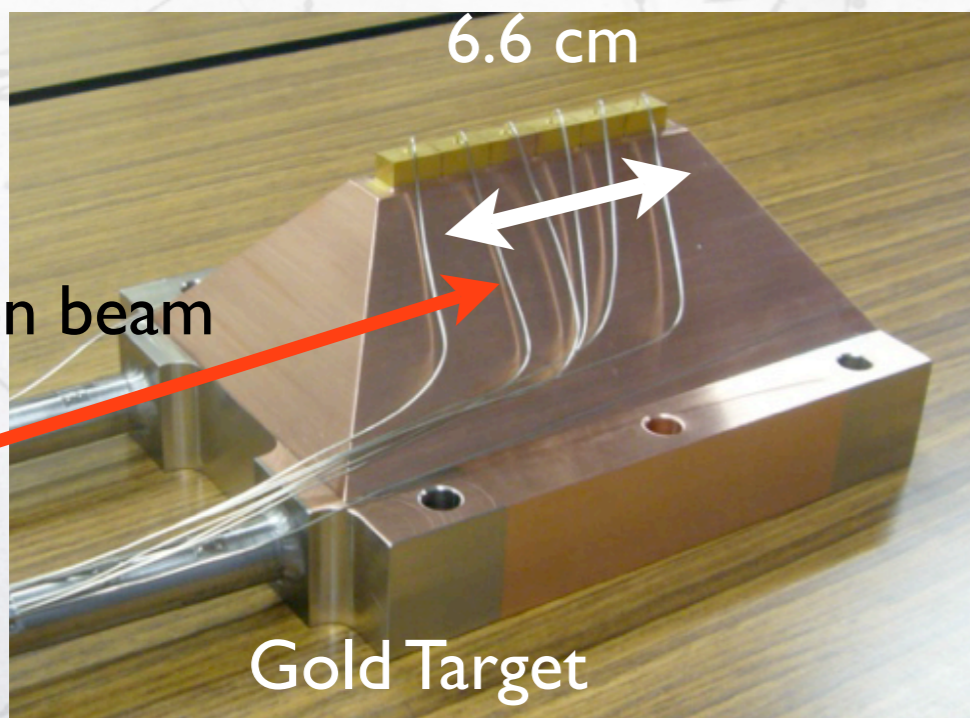
Support slides

J-PARC accident



11:55 on May 23

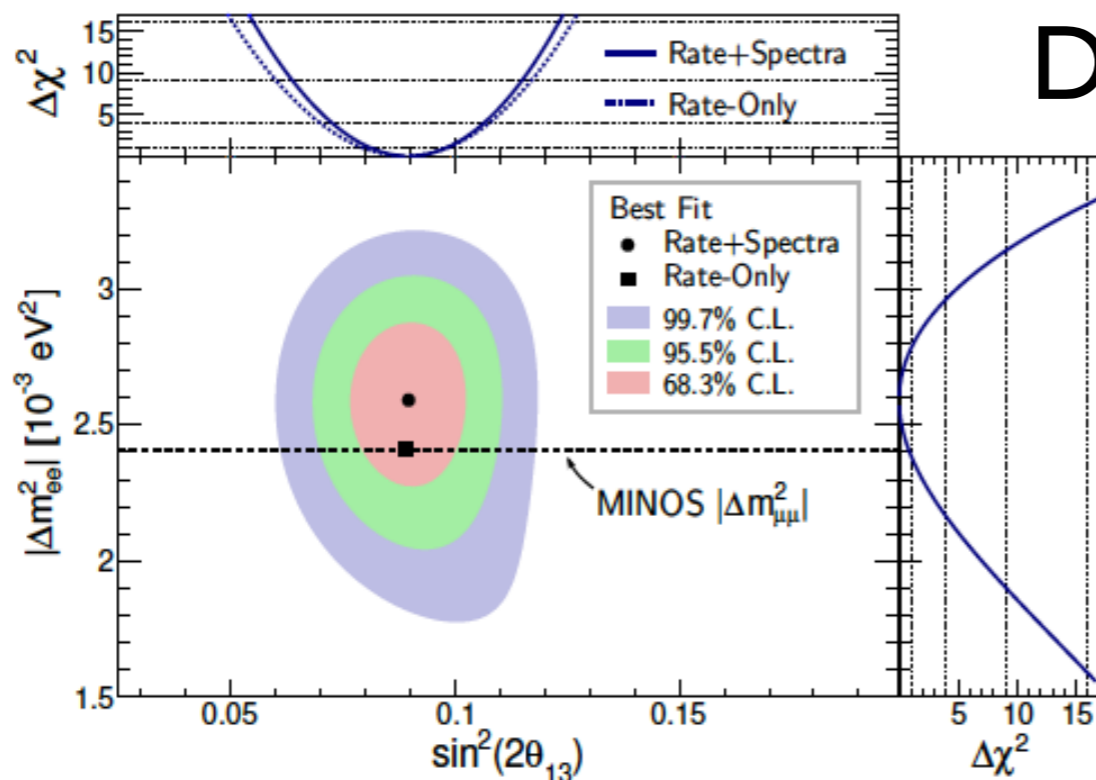
- An abnormal proton beam was injected to the gold target.
- The target heated up to a extraordinarily high temperature.
- Radioactive material was released from the target.
- The radioactive material was leaked into the HD hall: xWorkers were exposed to radiation.
- The radioactive material was released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



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

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

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

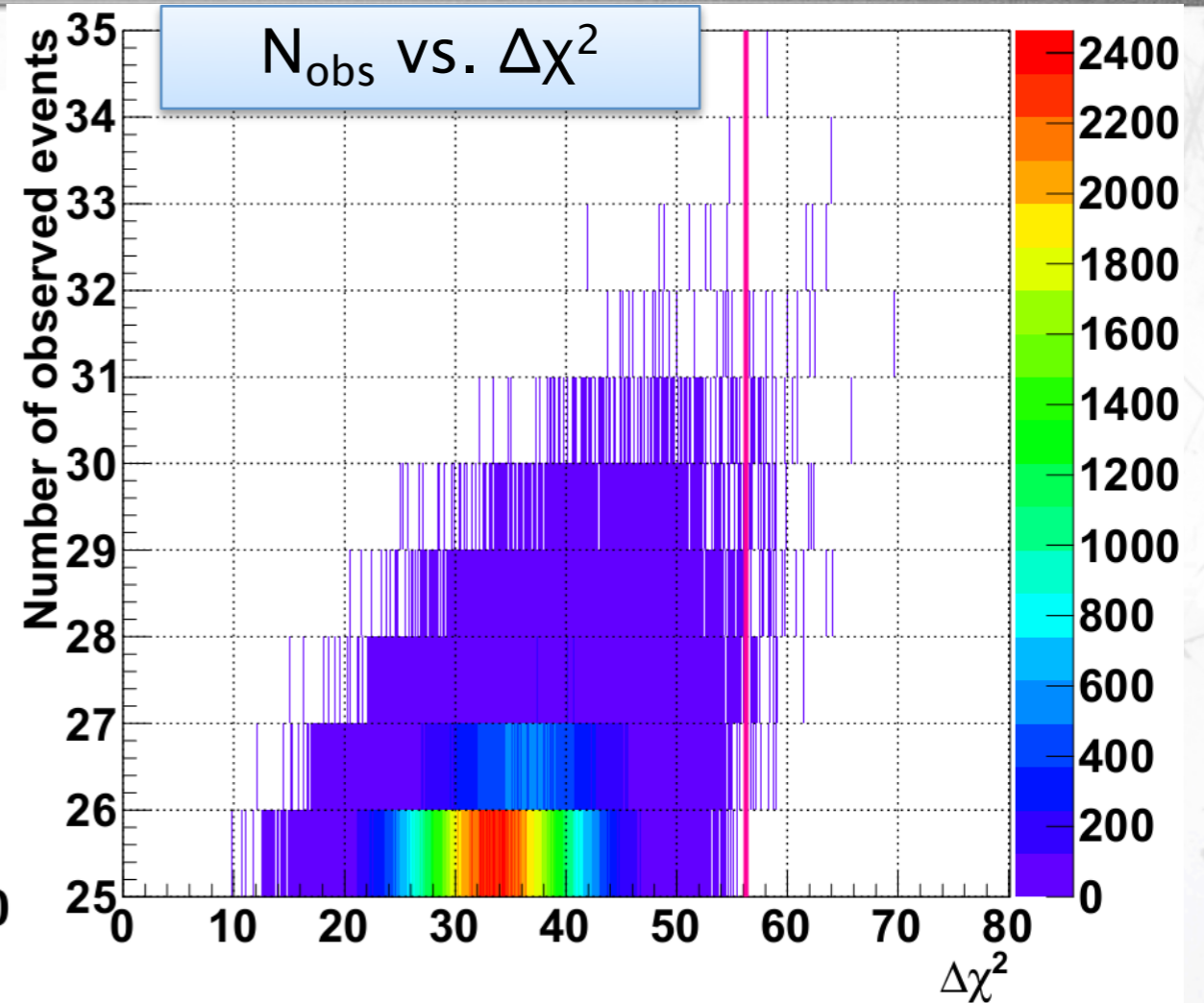
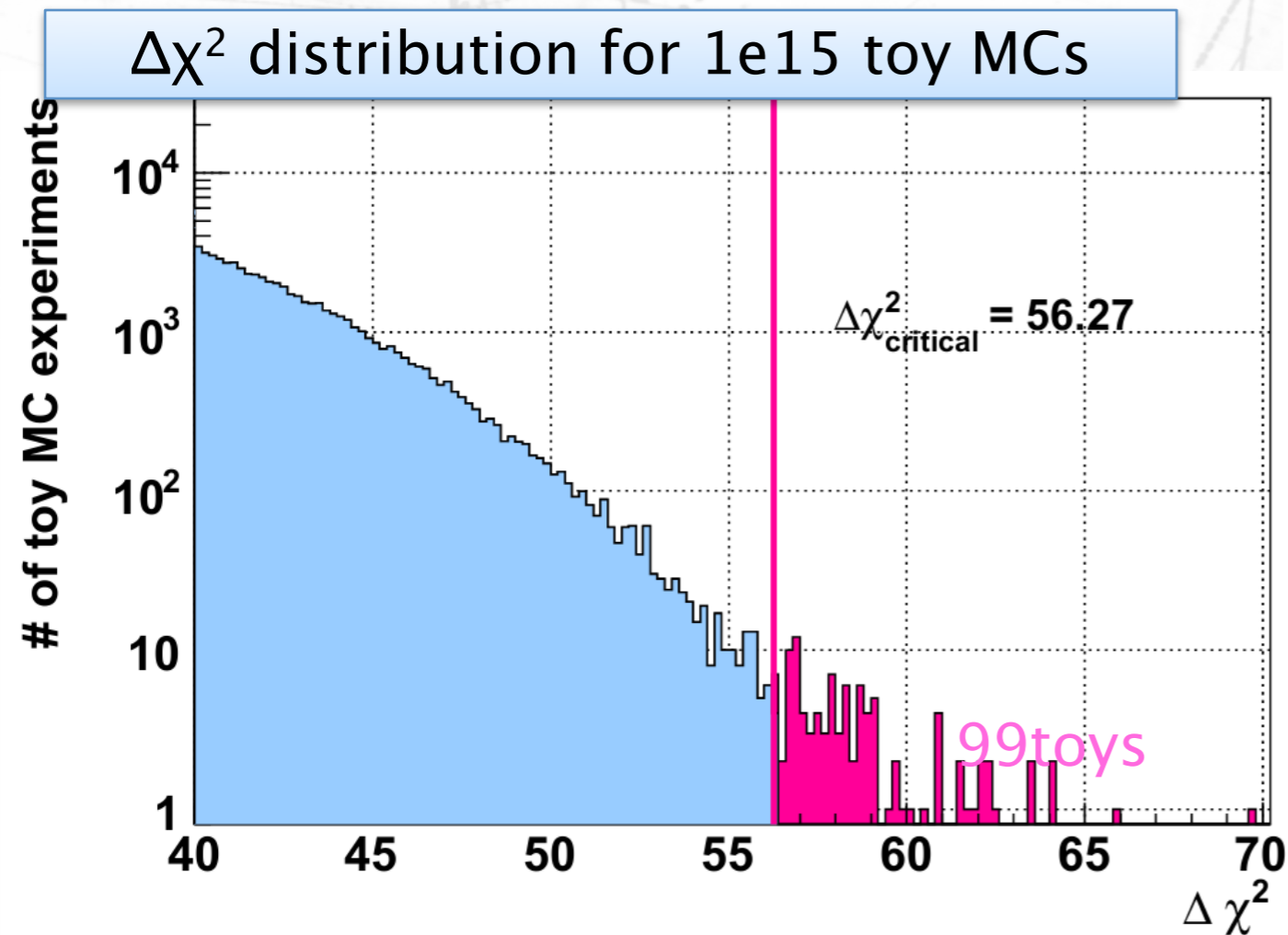
Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

	Normal MH Δm_{32}^2 [10^{-3}eV^2]	Inverted MH Δm_{32}^2 [10^{-3}eV^2]
From Daya Bay Δm_{ee}^2	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m_{\mu\mu}^2$ [João, NuFact2013]	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.12}_{-0.09}$

Reactor experiments measure θ_{13} with no degeneracies.



ν_e analysis



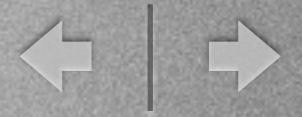
p-value is calculated as followings:

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 $\Delta\chi^2_{\text{data}}$

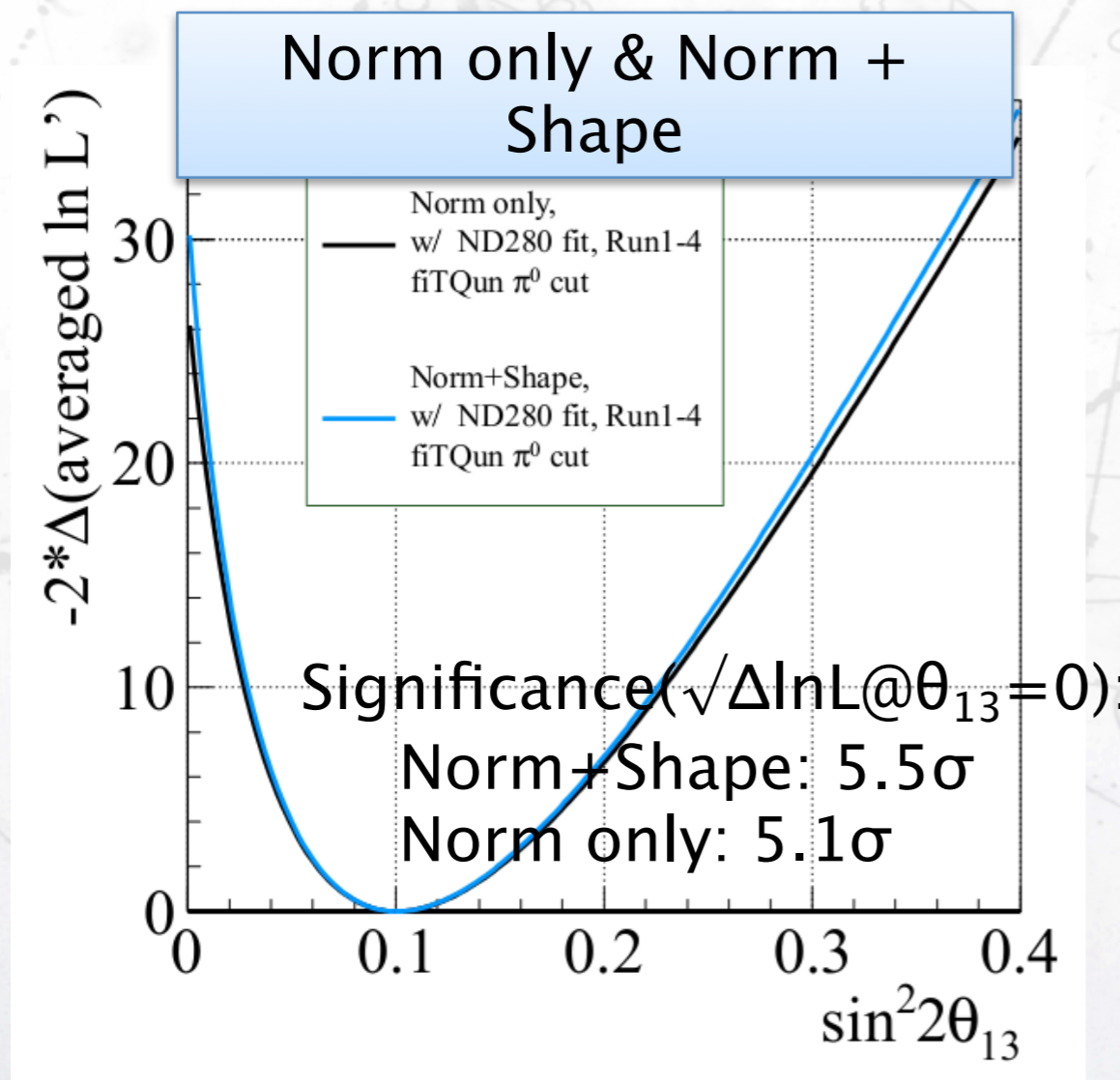
For the actual calculation, we use time saving method.

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

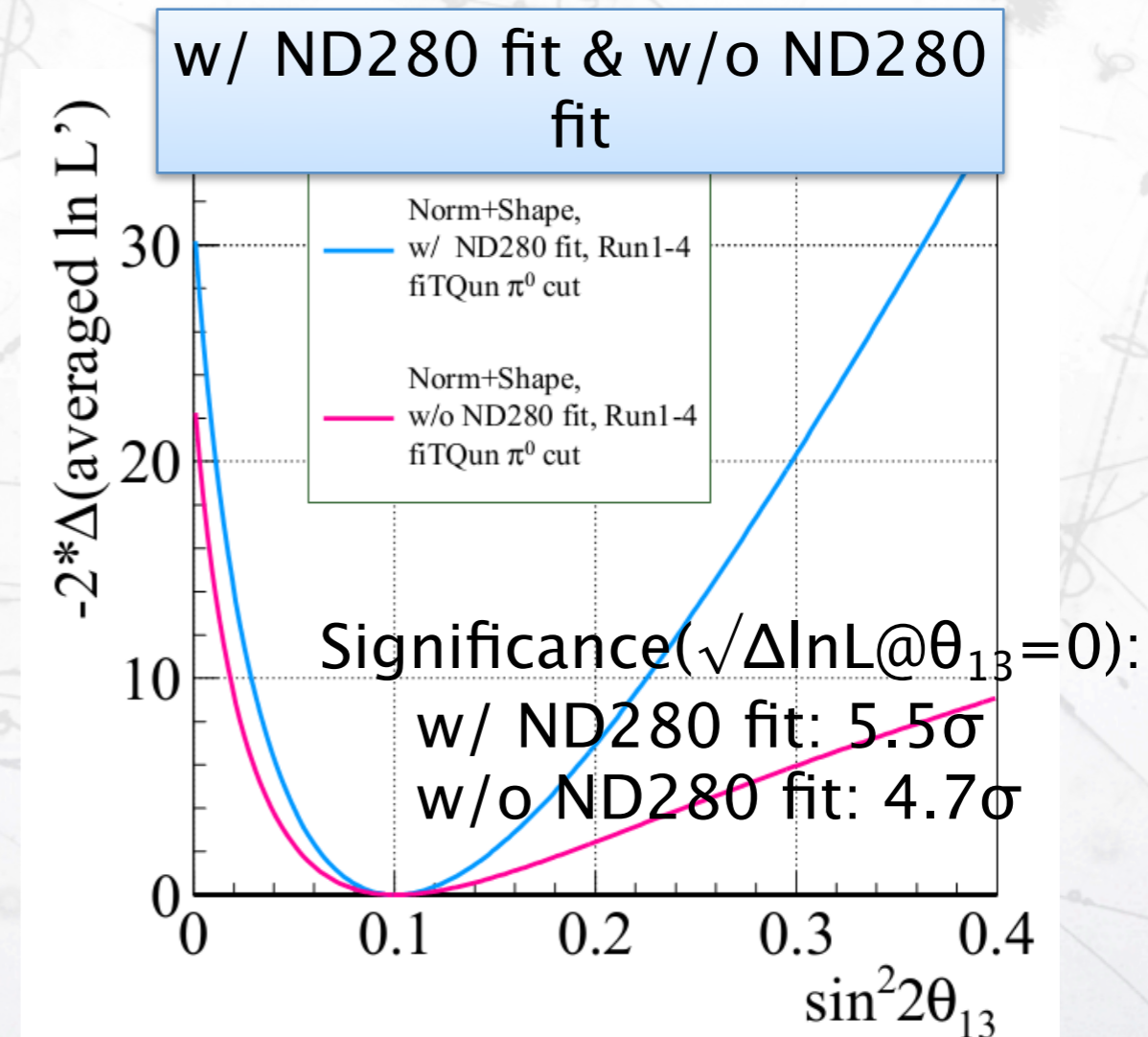
Sensitivity checks



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

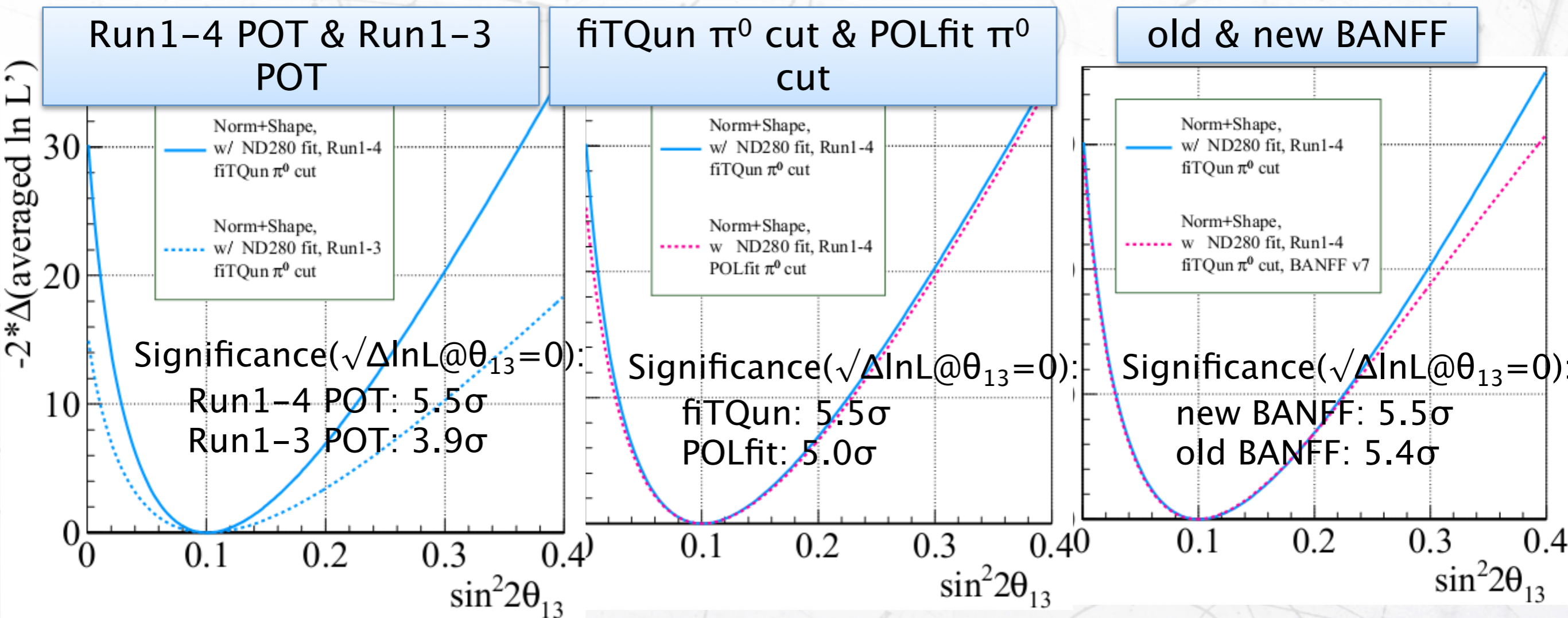


Effect of using shape information is not significant but important.



ND280 fit makes relatively large improvement.





Significance becomes much larger by adding Run4.

Effect of using fiTQun is not significantly large but important.

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_{21}^2 (eV ²)	7.6×10^{-5}	7.6×10^{-5}	7.6×10^{-5}	7.6×10^{-5}
Δm_{32}^2 (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

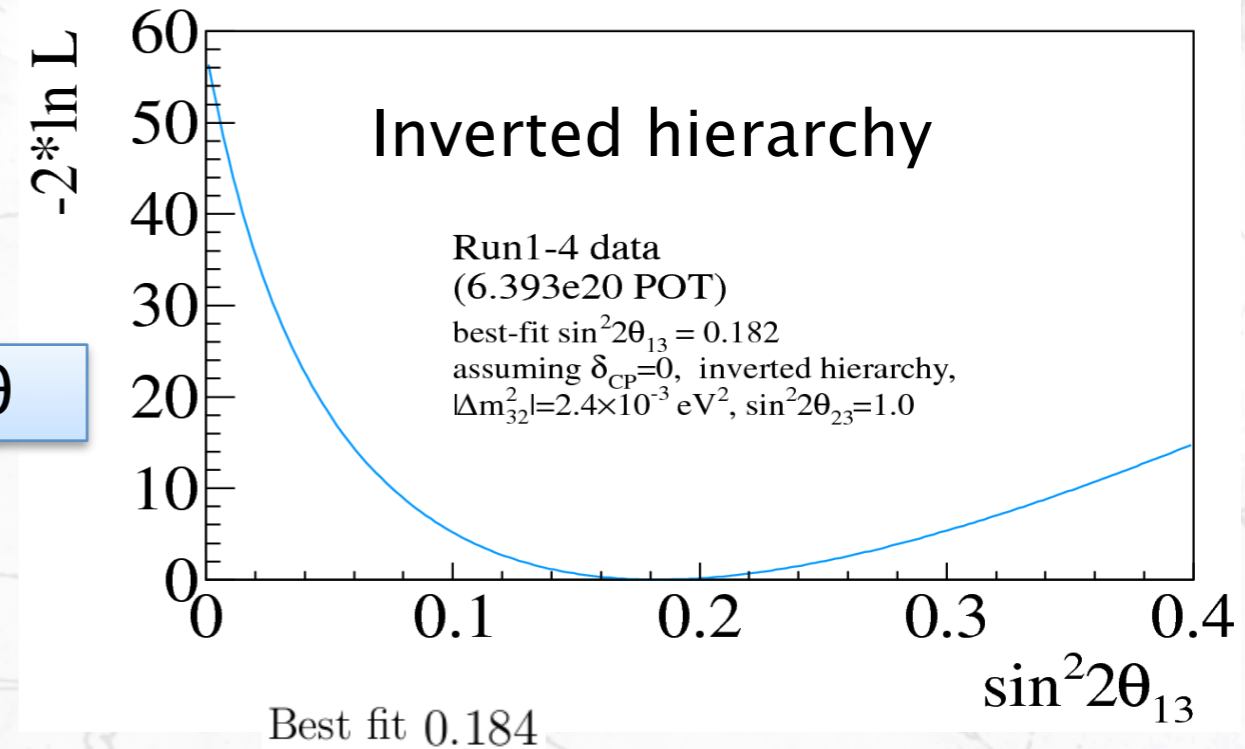
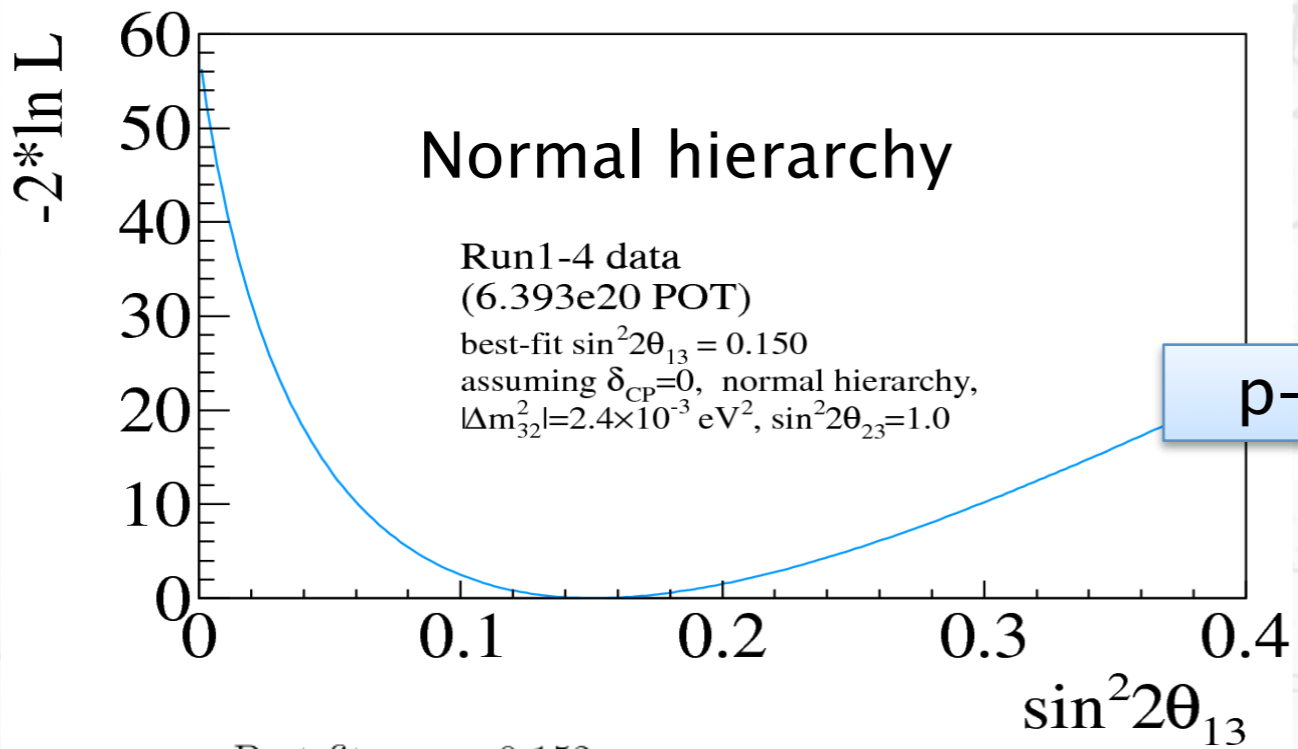
set		Normal hierarchy	Inverted hierarchy
set D	best-fit	0.090	0.110
	68% C.L. allowed	$0.063 < x < 0.121$	$0.077 < x < 0.147$
	90% C.L. allowed	$0.048 < x < 0.145$	$0.060 < x < 0.175$
set E	best-fit	0.174	0.210
	68% C.L. allowed	$0.139 < x < 0.216$	$0.168 < x < 0.259$
	90% C.L. allowed	$0.118 < x < 0.247$	$0.144 < x < 0.294$
set F	best-fit	0.026	0.032
	68% C.L. allowed	$0.010 < x < 0.046$	$0.012 < x < 0.057$
	90% C.L. allowed	$0.002 < x < 0.062$	$0.002 < x < 0.077$
set G	best-fit	0.140	0.170
	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. $p-\theta$ 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. $\sin^2 2\theta_{23} = 1.0$, $\Delta m_{32}^2 = 2.4 \times 10^{-3}$, $\delta = 0$)

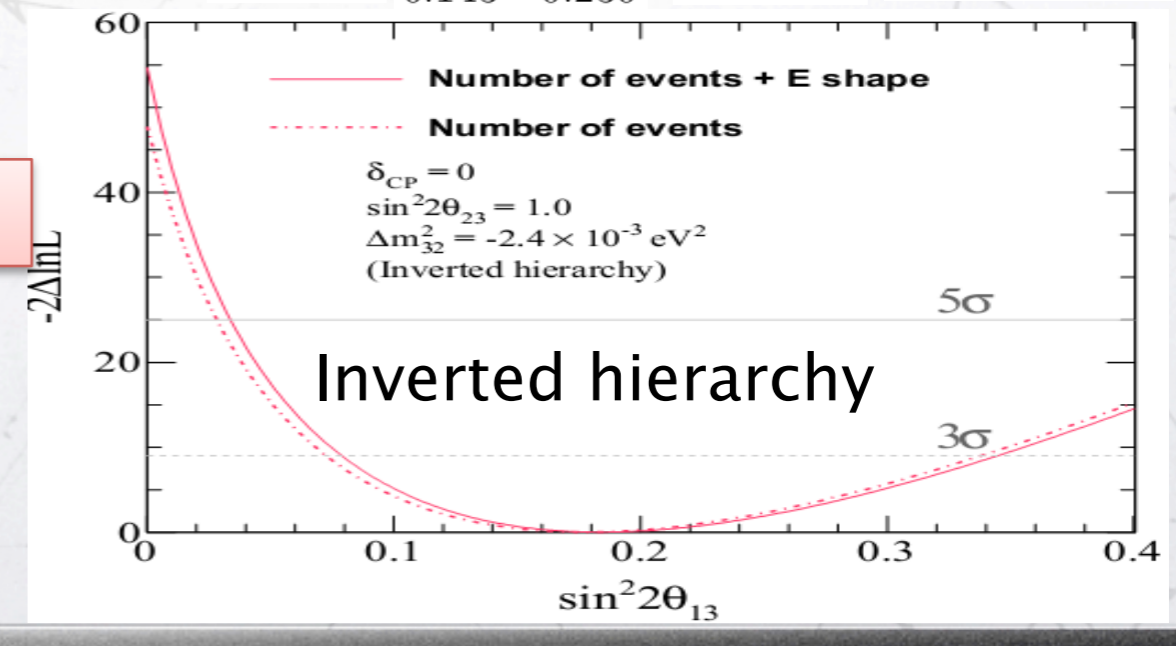
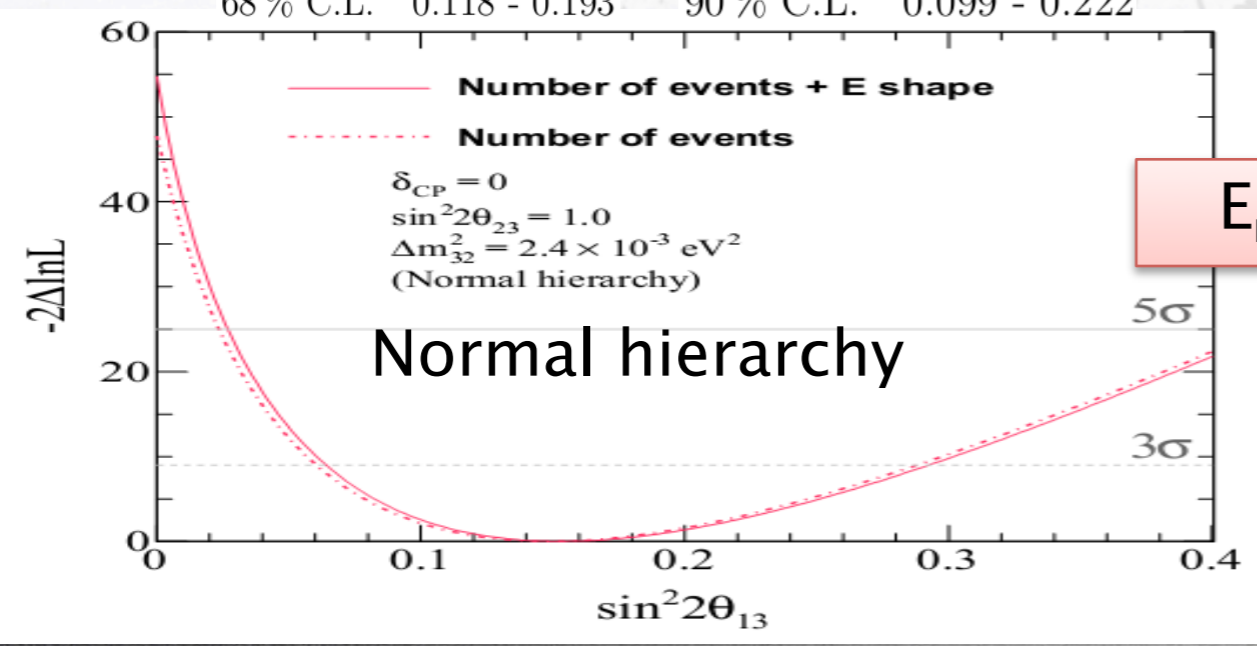


Likelihood curves for Run 1-4 data



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

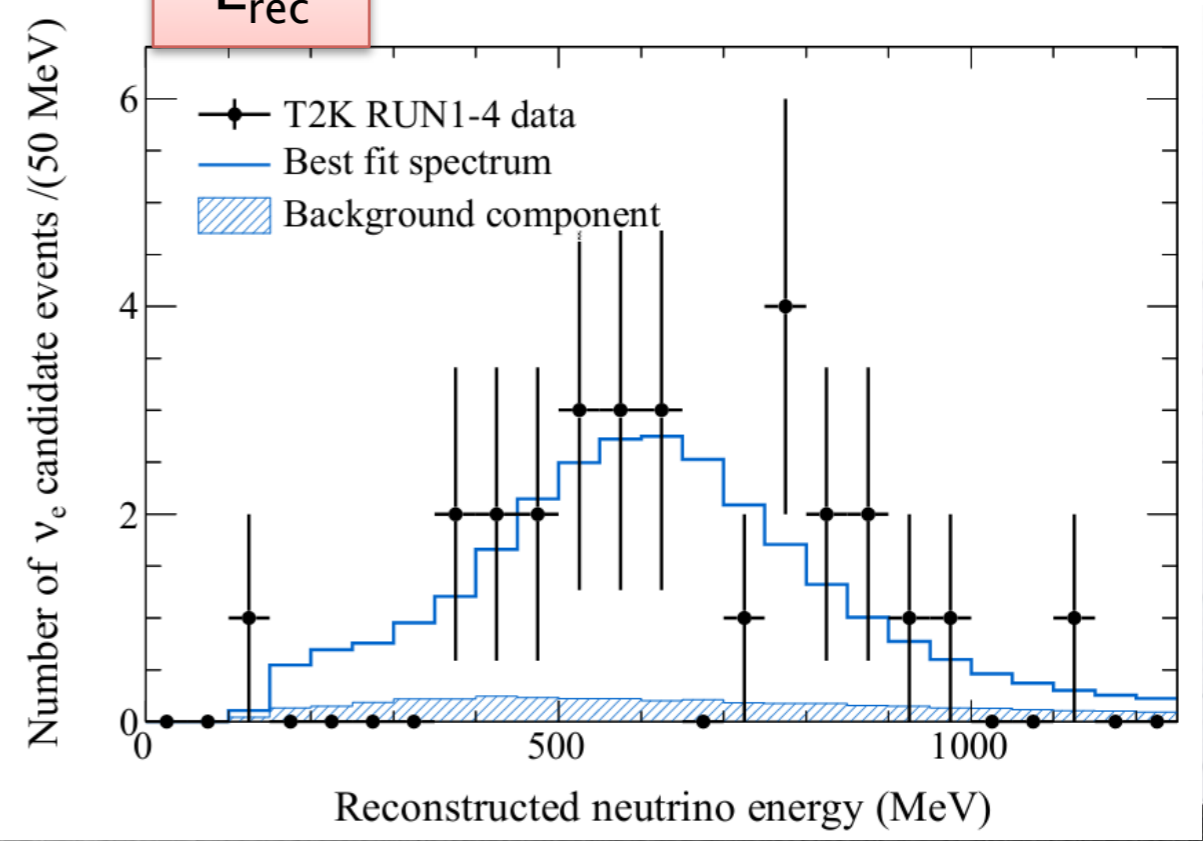
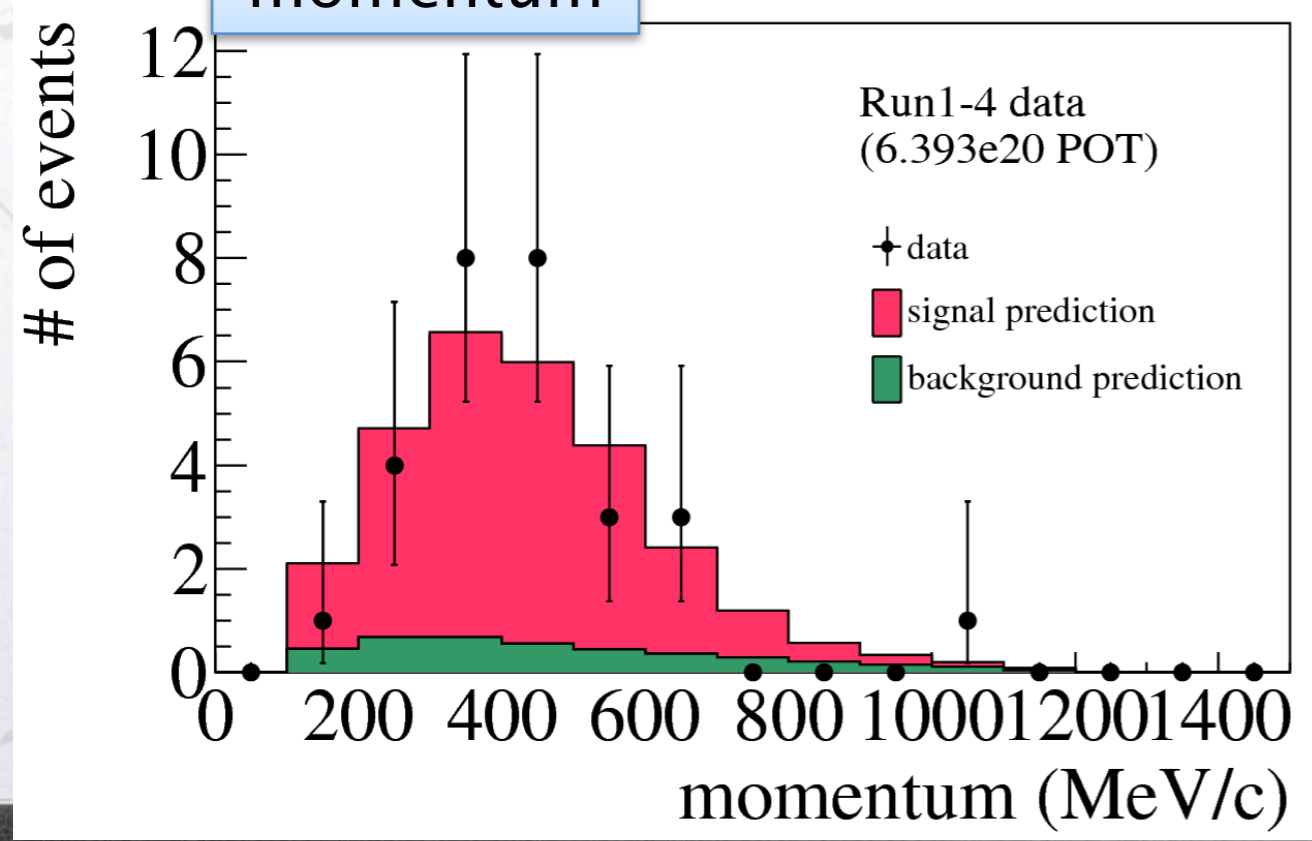
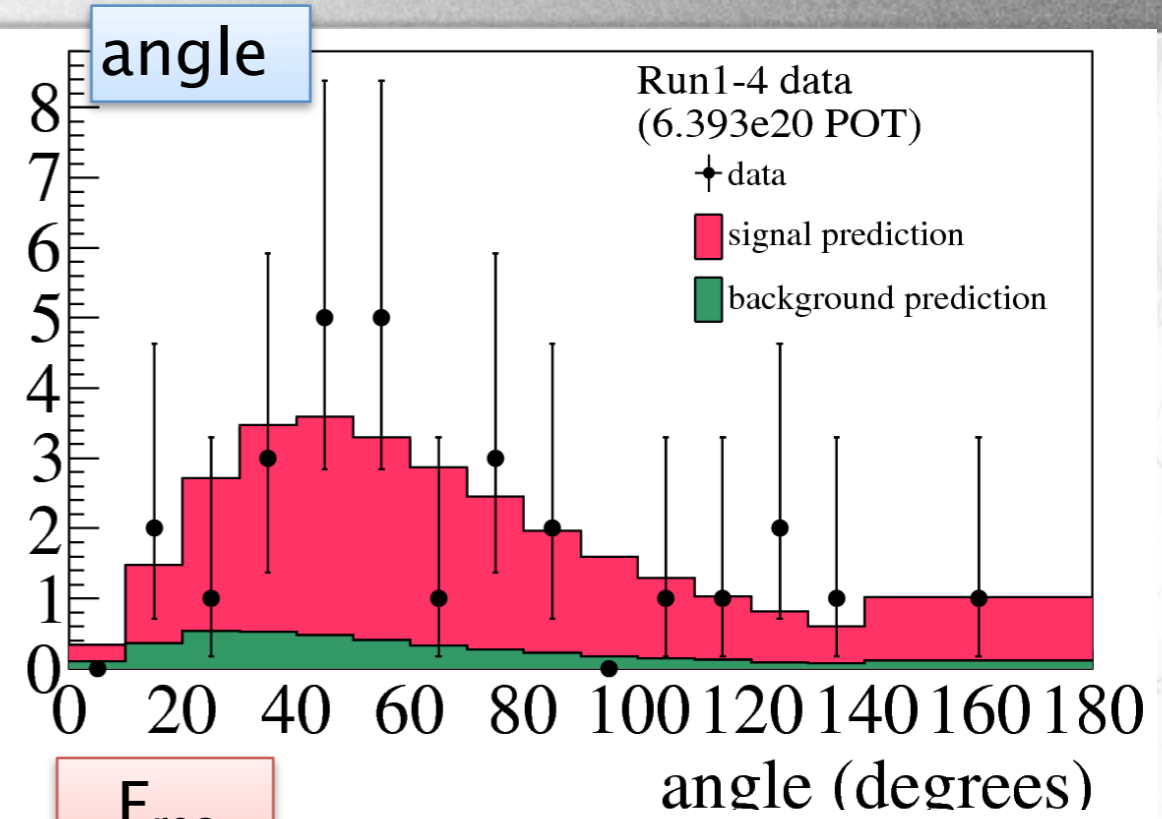
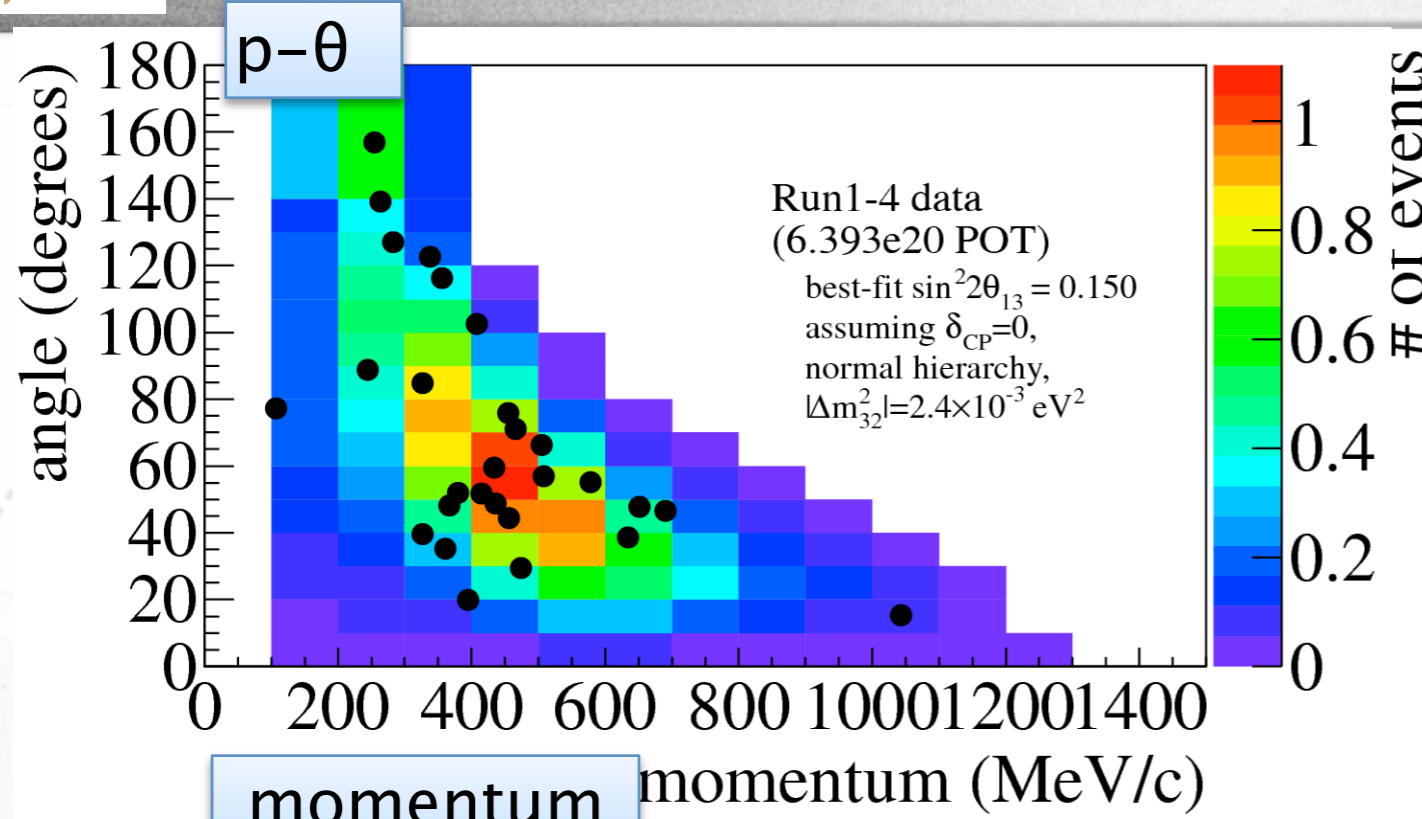
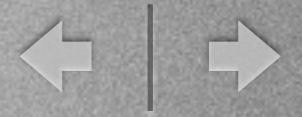
Best fit 0.184
68% C.L. 0.143 - 0.230 90% C.L. 0.120 - 0.264



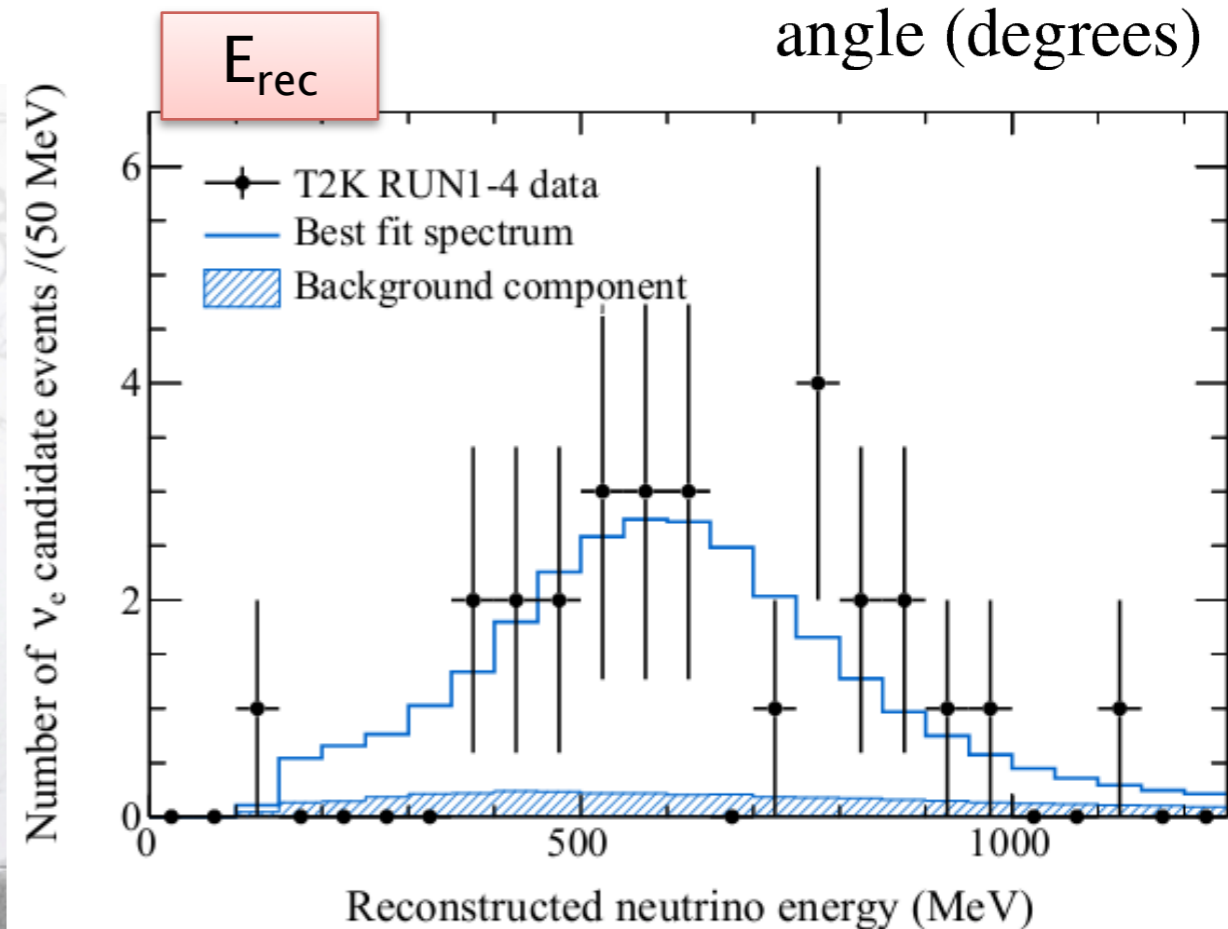
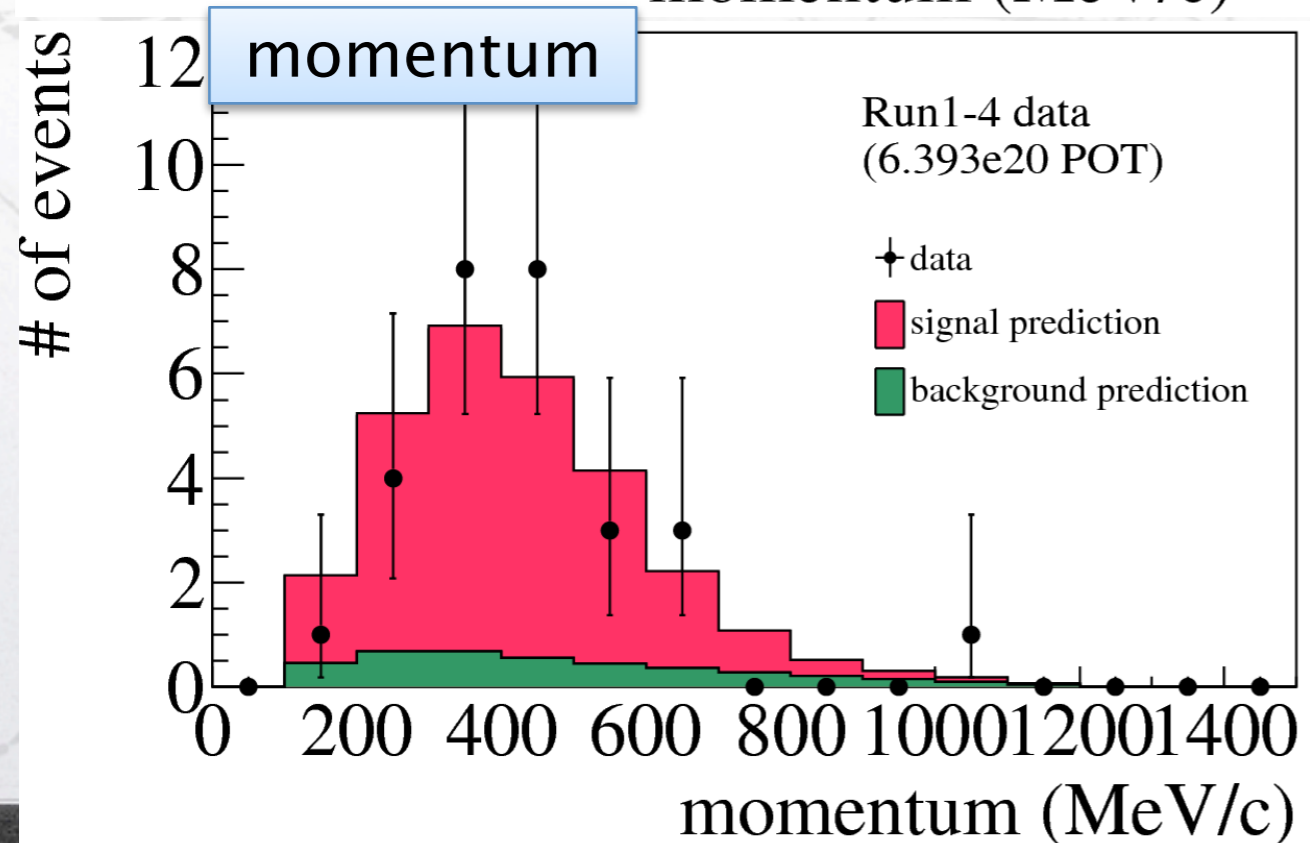
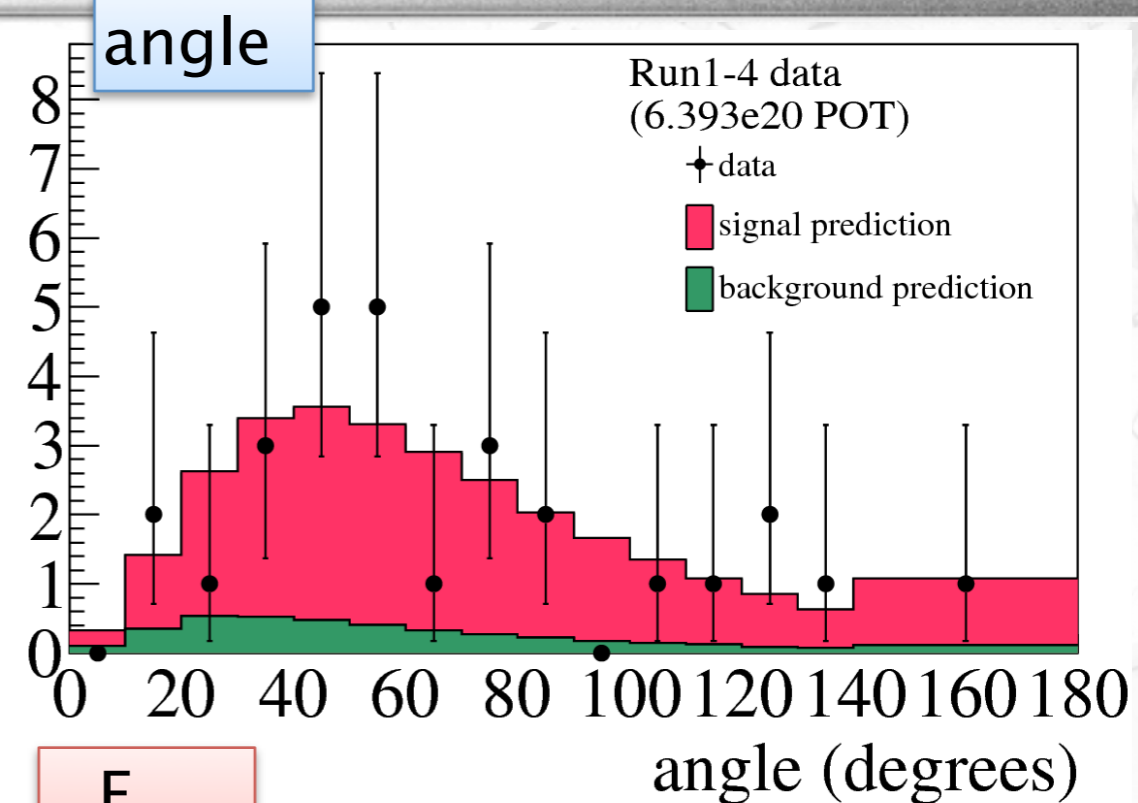
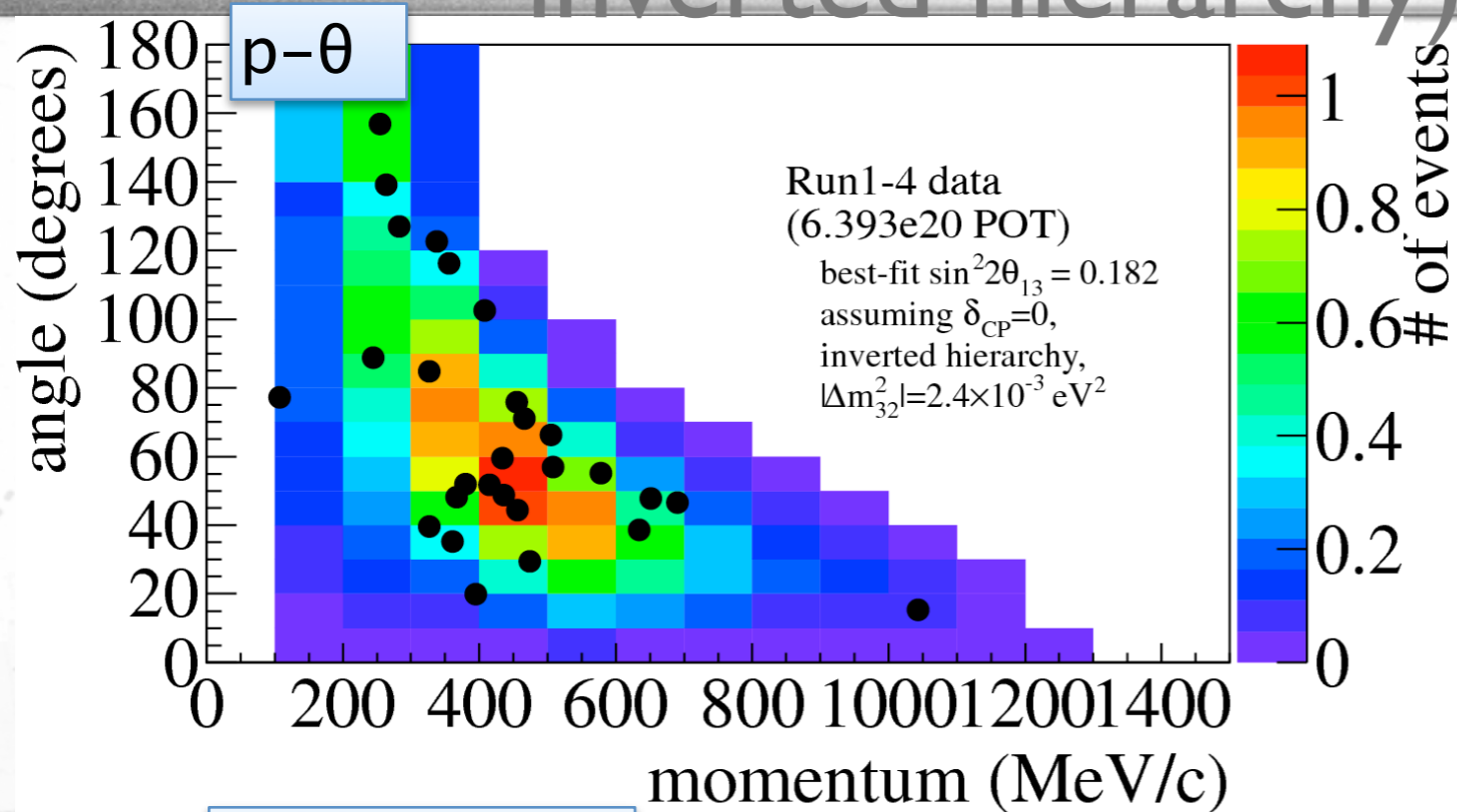
(summary table will be shown later.)



Best fit distributions (Run 1-4, normal)



Best fit distributions (Run 1-4, inverted hierarchy)



Fit summary table



	Run1-4 ($p-\theta$)	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
<u>Normal hierarchy</u>					
Best fit	0.150	0.152	0.180	0.112	0.088
90% C.L.	0.097 - 0.218	0.099 - 0.222	0.105 - 0.280	0.050 - 0.204	0.030 - 0.175
68% C.L.	0.116 - 0.189	0.118 - 0.193	0.131 - 0.237	0.072 - 0.164	0.049 - 0.137
<u>Inverted hierarchy</u>					
Best fit	0.182	0.184	0.216	0.136	0.108
90% C.L.	0.119 - 0.261	0.120 - 0.264	0.129 - 0.332	0.062 - 0.244	0.038 - 0.212
68% C.L.	0.142 - 0.228	0.143 - 0.230	0.160 - 0.283	0.088 - 0.198	0.062 - 0.167



(unit: %)

Error source	Black: 2013		$\sin^2 2\theta_{13} = 0$				$\sin^2 2\theta_{13} = 0.1$			
	Blue: 2012		w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	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
CC1 π norm. ($E_\nu < 2.5$ GeV)			4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1 π^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

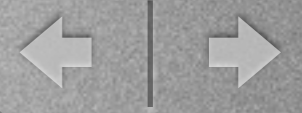
Systematic errors for N_{exp}

(unit: %)

Error source	Black: 2013	$\sin^2 2\theta_{13} = 0$				$\sin^2 2\theta_{13} = 0.1$			
	Blue: 2012	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	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
CC1 π norm. ($E_\nu < 2.5$ GeV)		4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1 π^0									
CC oth									
Spectra									
p_F									
CC col									
NC col									
NC oth									
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$									
W sha									
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}

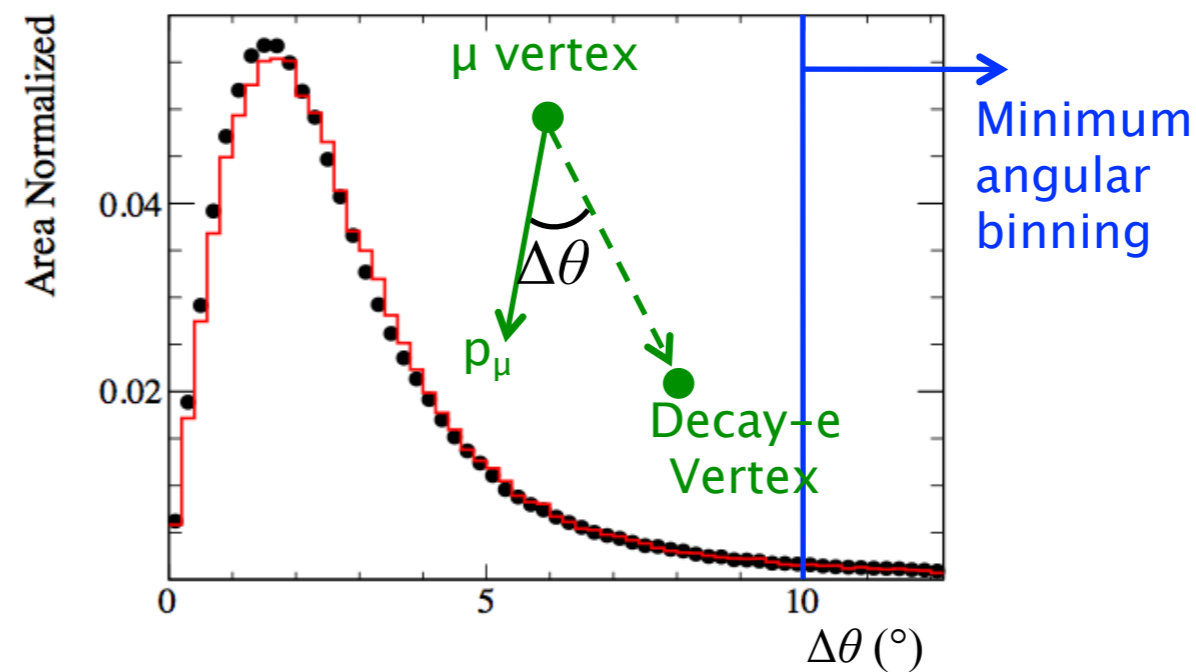
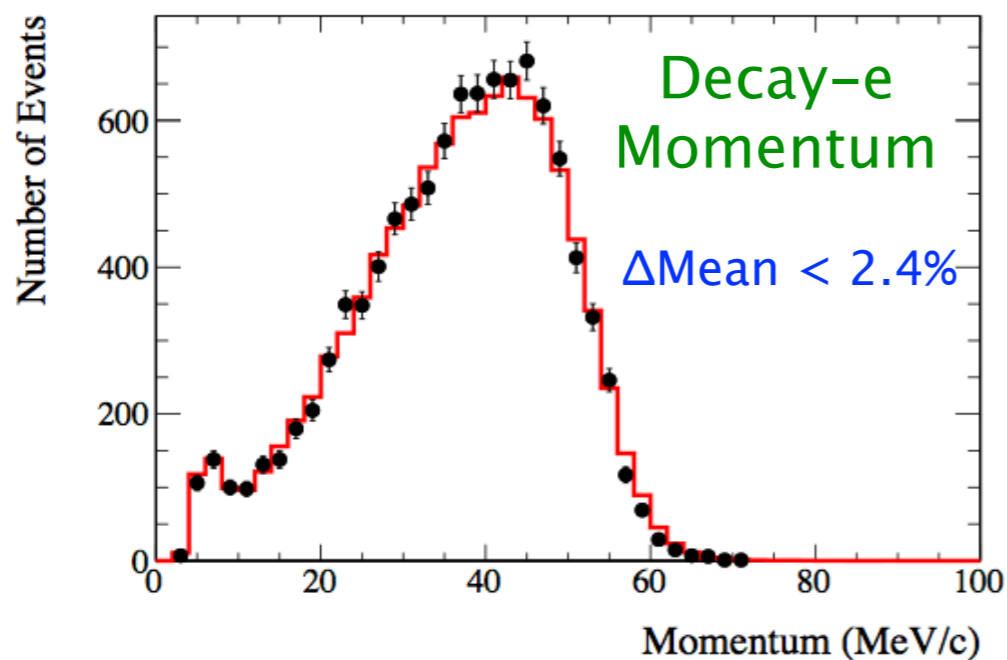
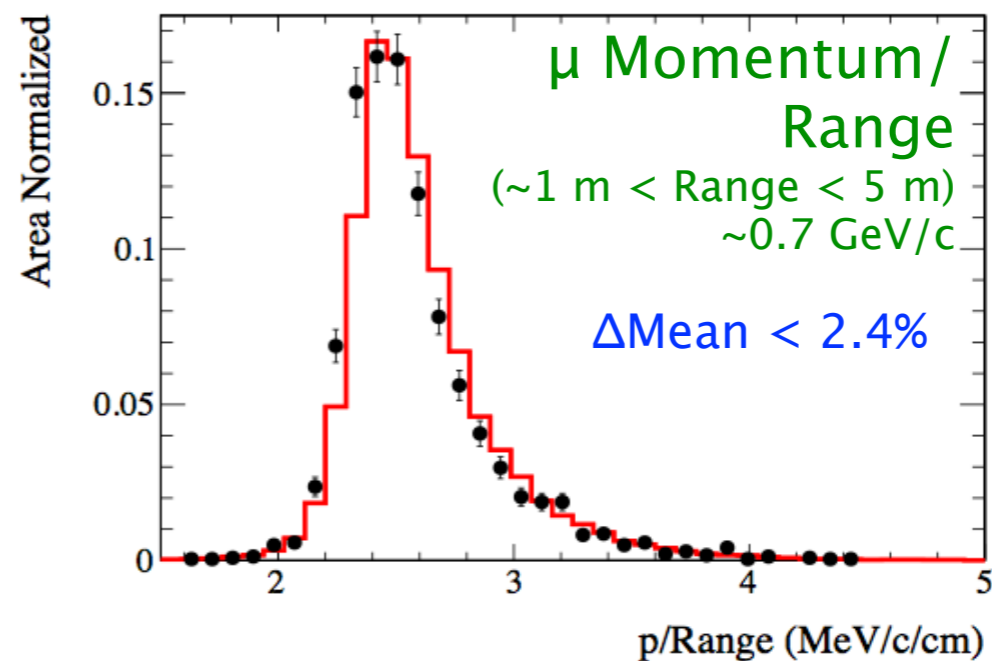
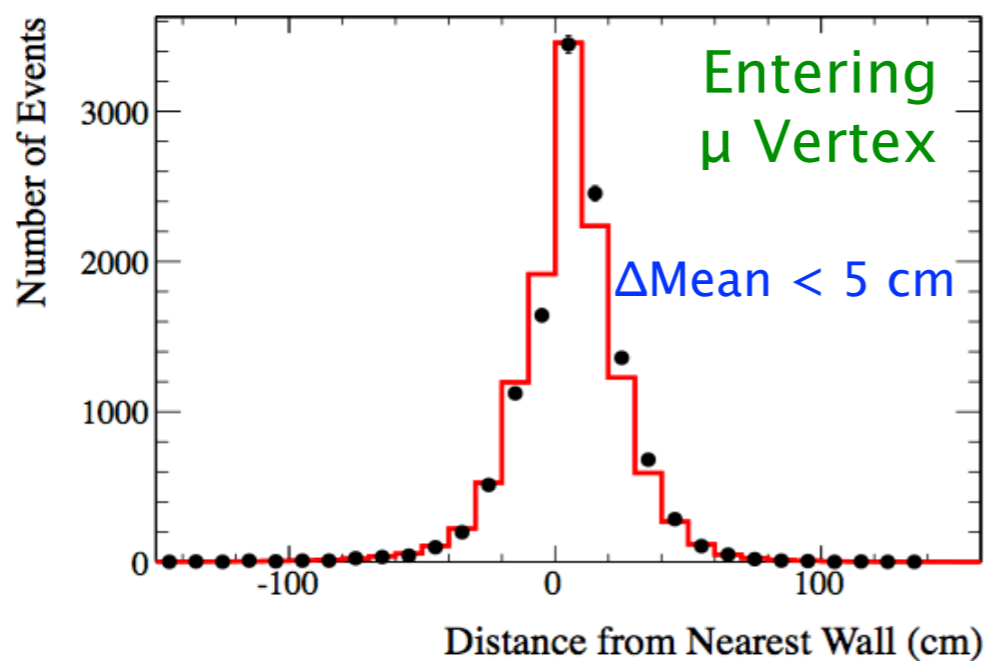


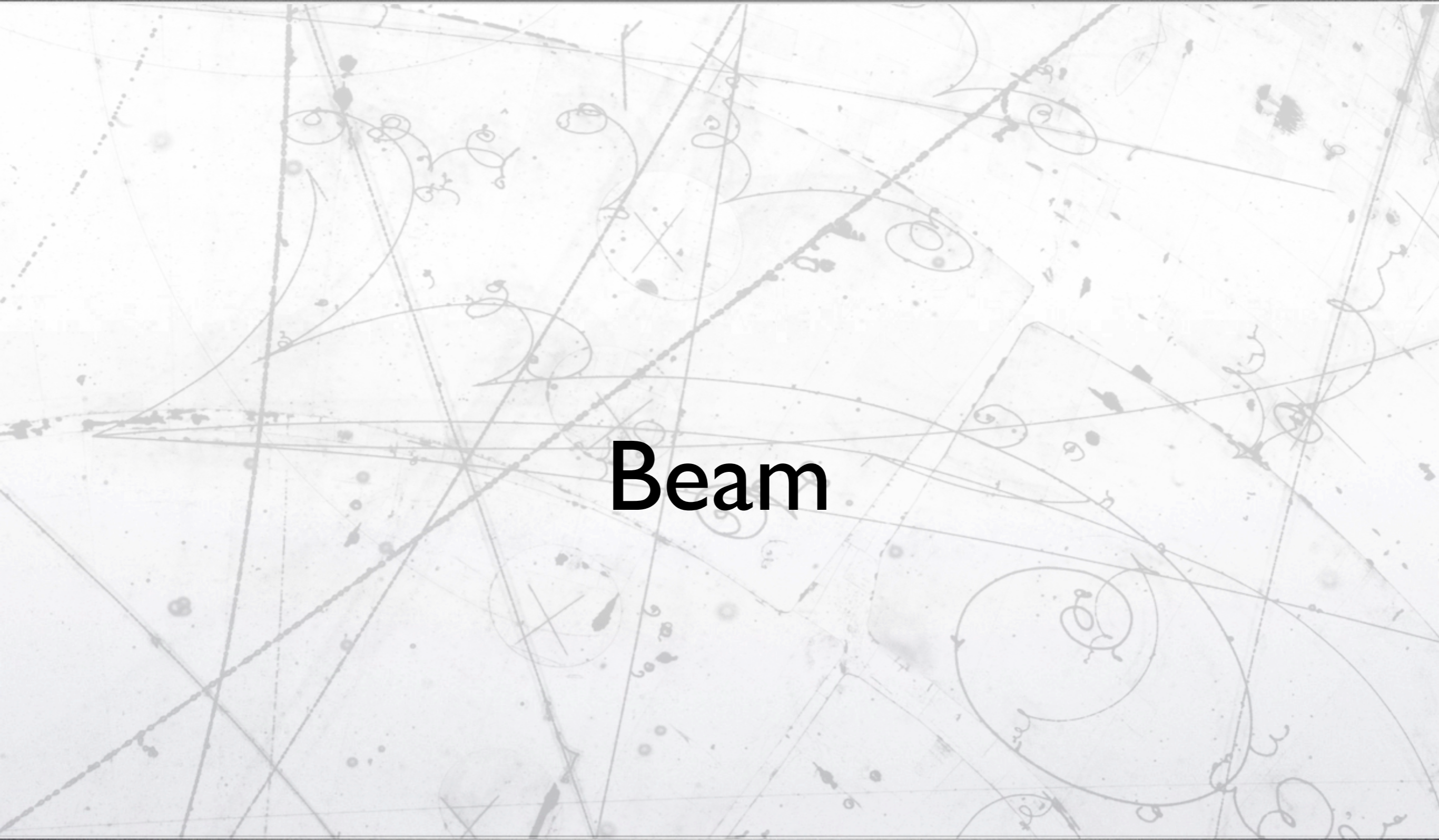
(unit: %)

Error source	Black: 2013		$\sin^2 2\theta_{13} = 0$		$\sin^2 2\theta_{13} = 0.1$					
	Blue: 2012		w/o ND280 fit	w/ ND280 fit	w/o ND280 fit	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
CC1 π norm. ($E_\nu < 2.5$ GeV)			4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1 π^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.)

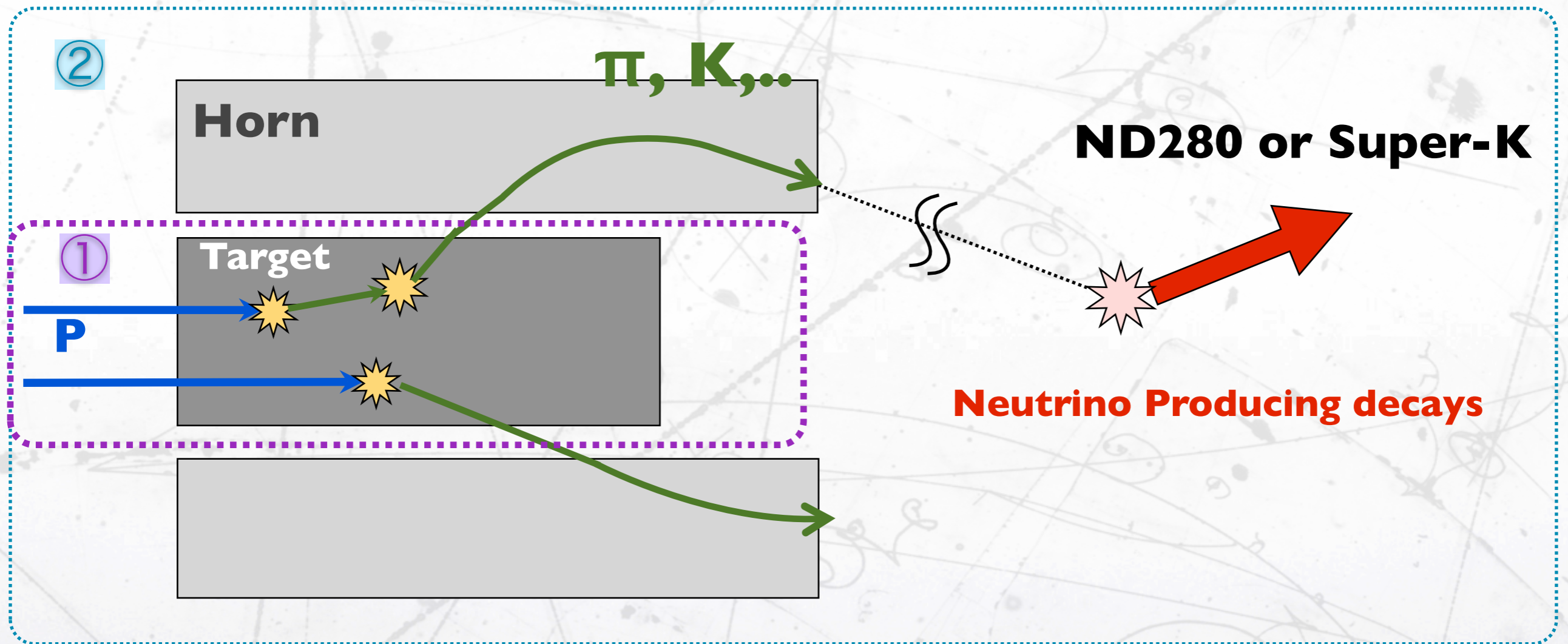
Validation with stopping muons





Beam

Simulating neutrino flux



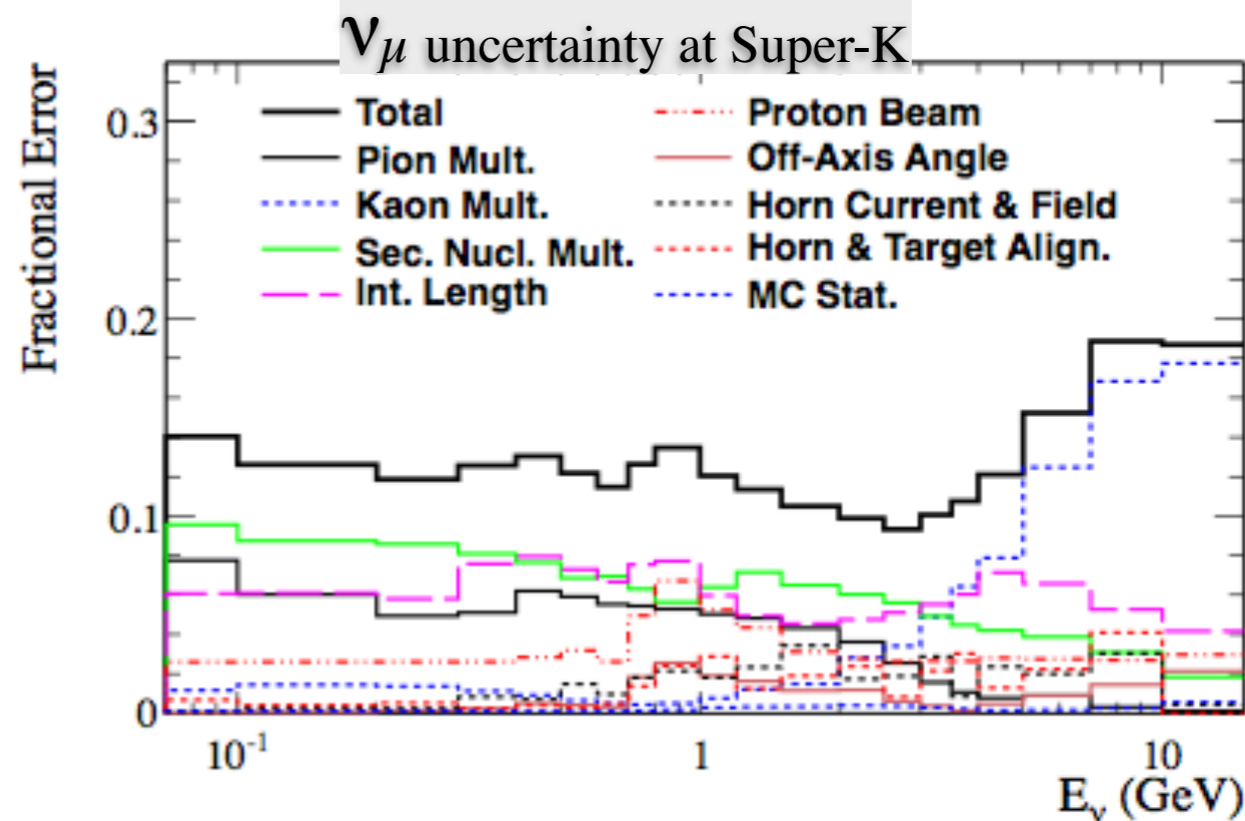
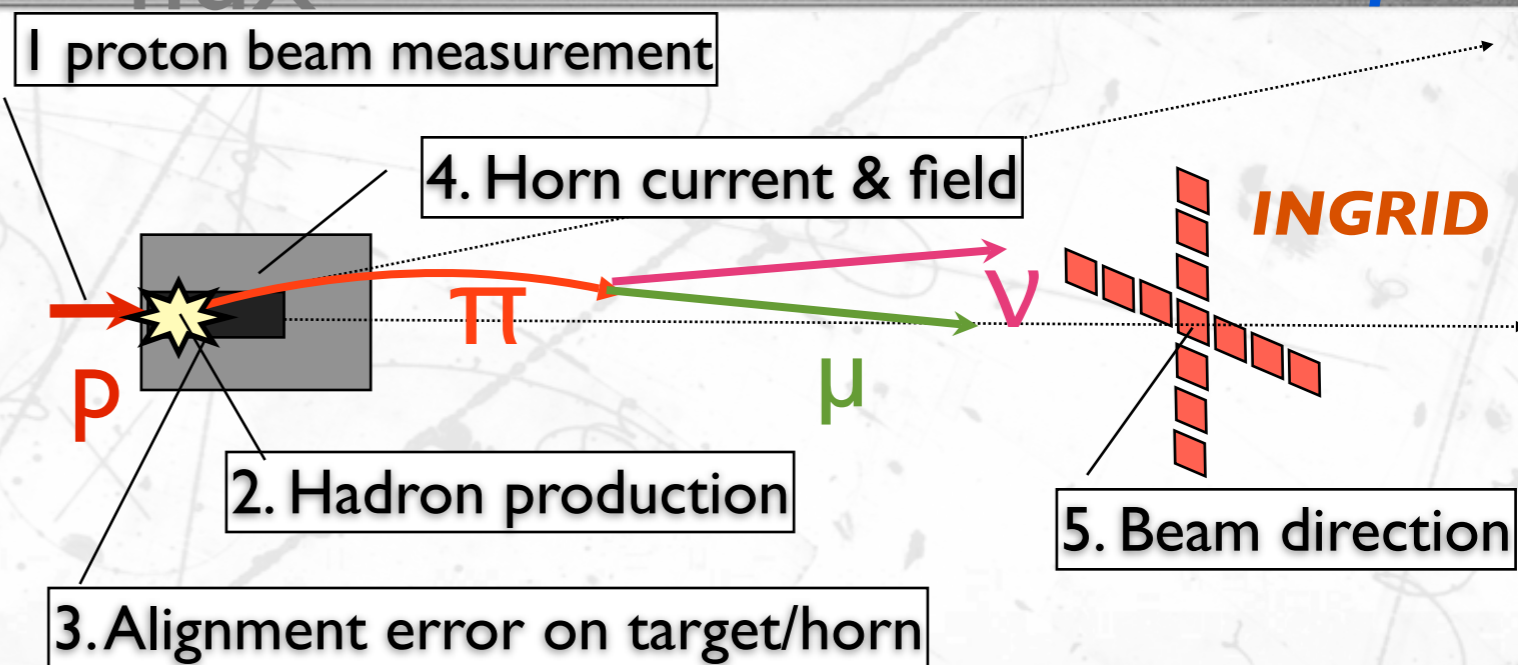
1. p interaction inside the carbon target with FLUKA2008.3d

2. Tracking through horn fields and decay volume using GEANT3 with GCALOR

Calculate neutrino producing decays

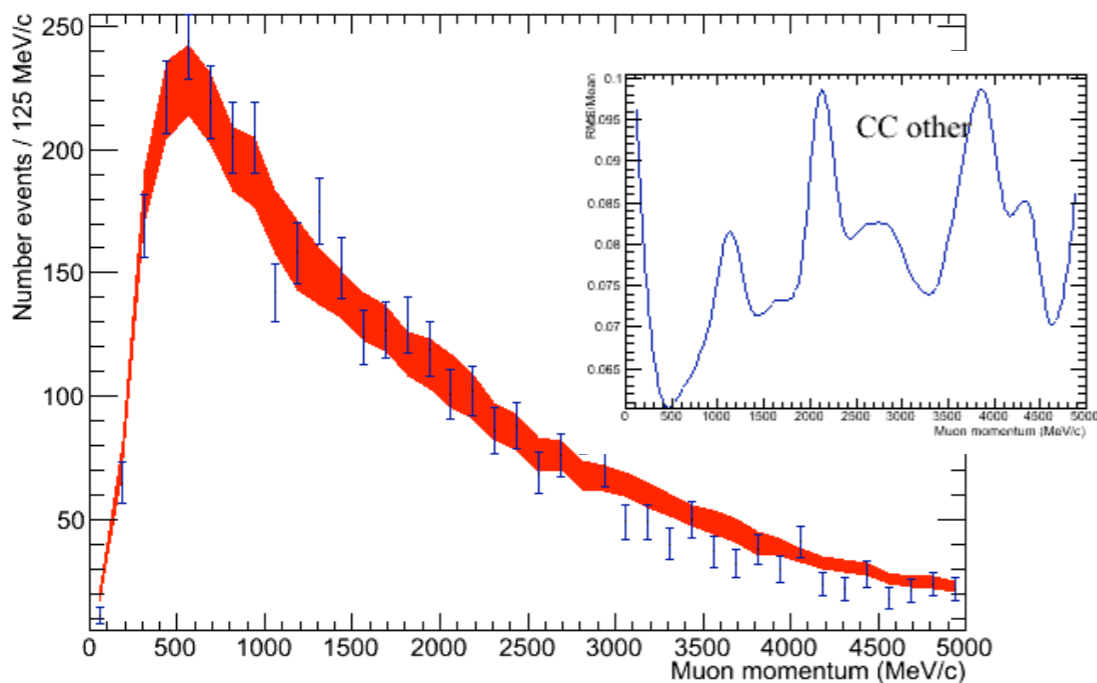
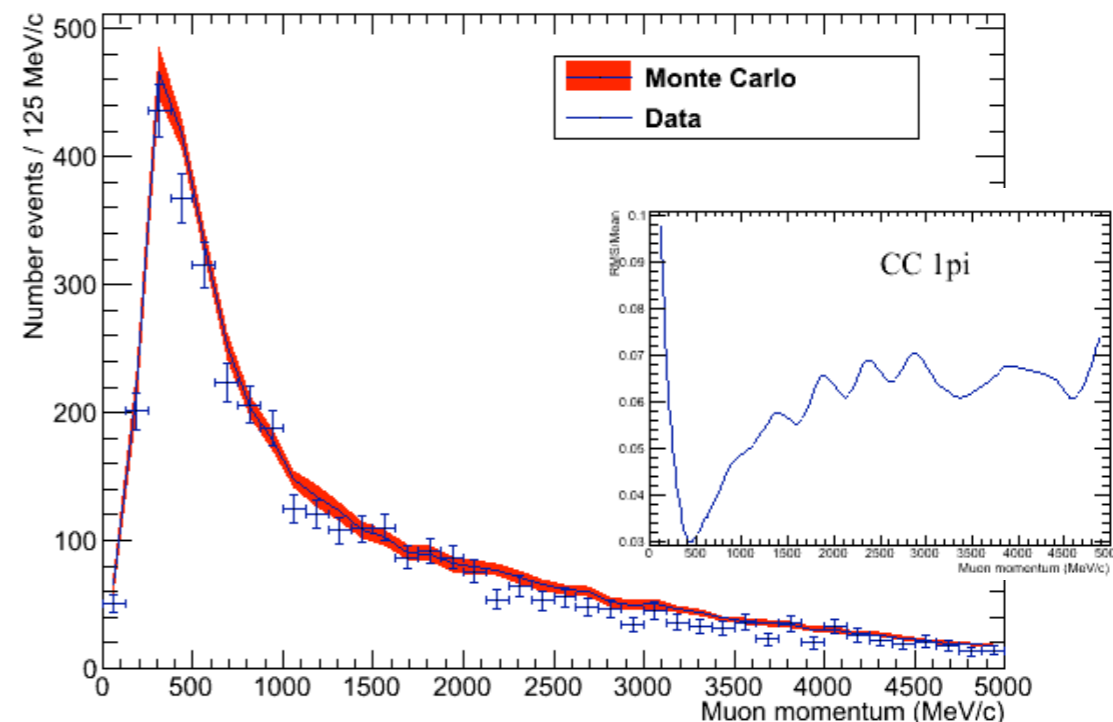
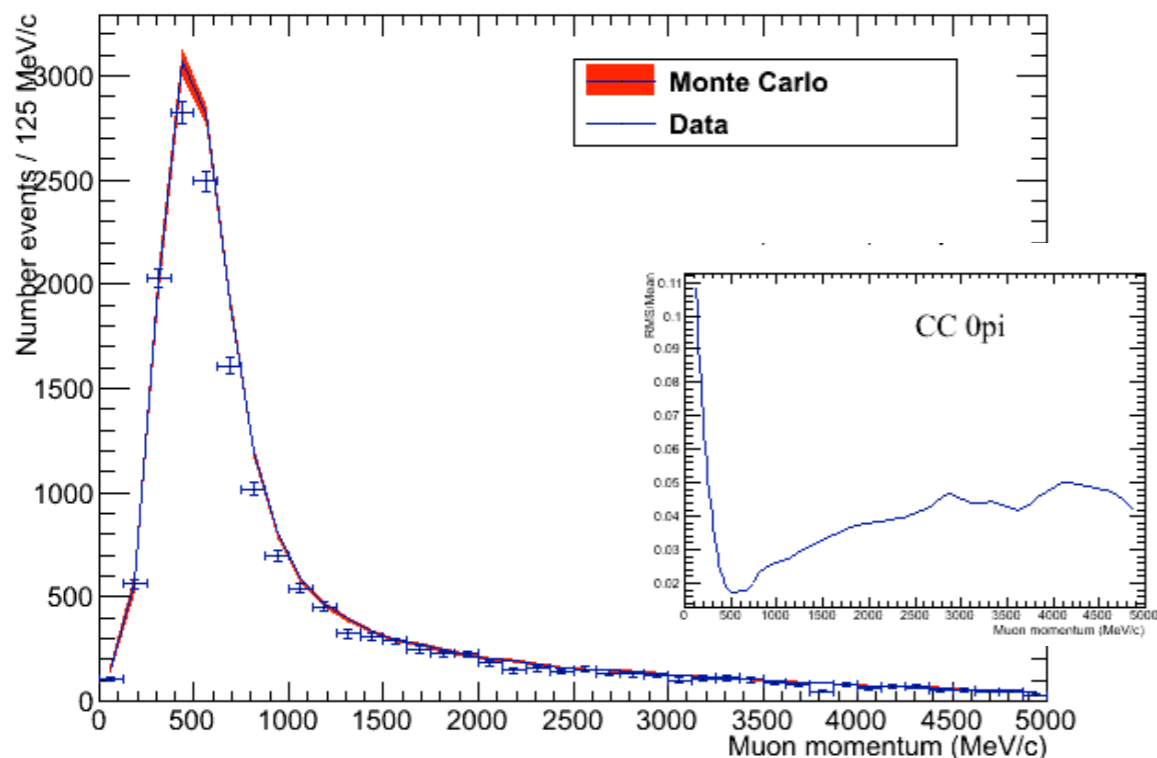
Estimate the flux at the near/far detector

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)

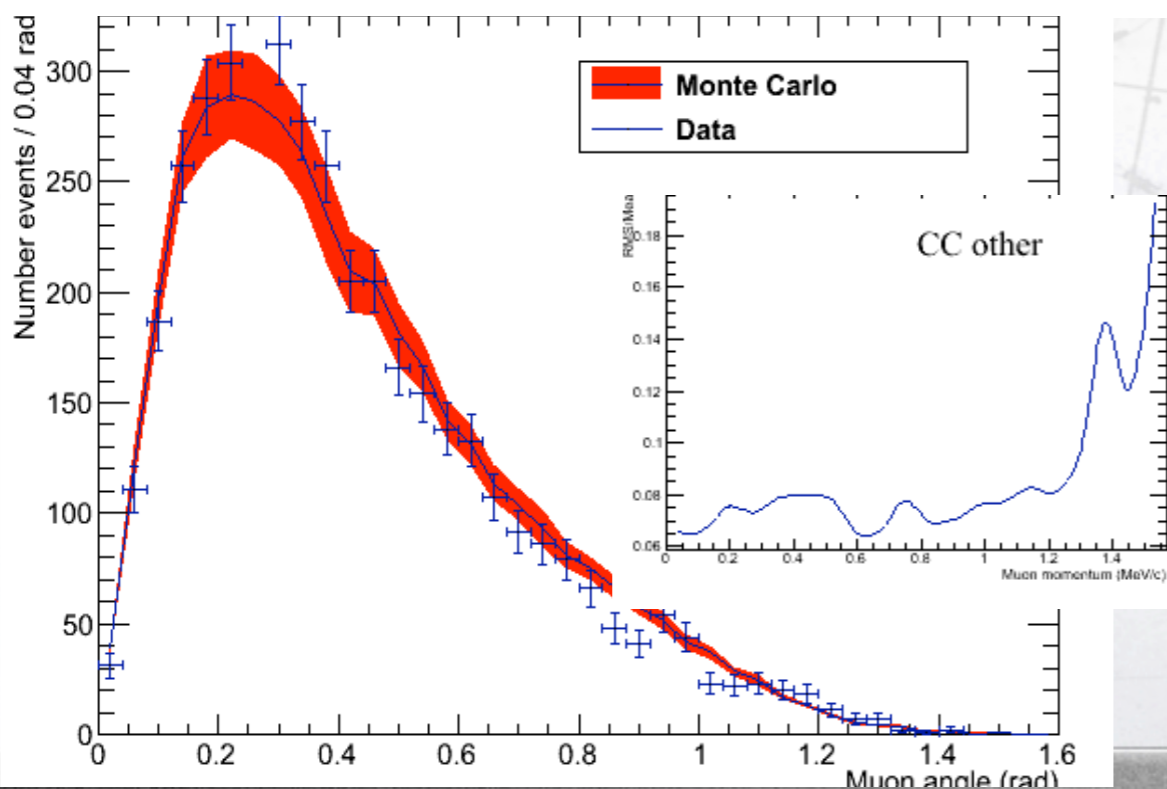
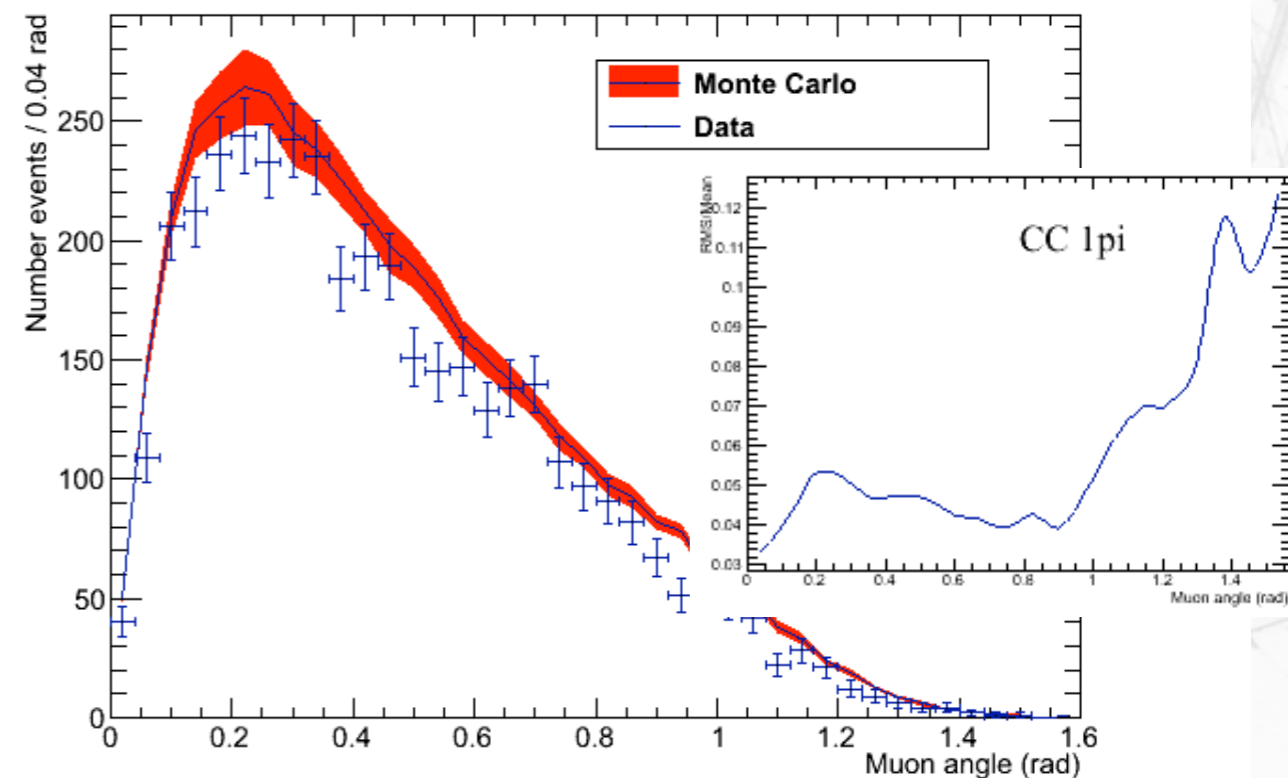
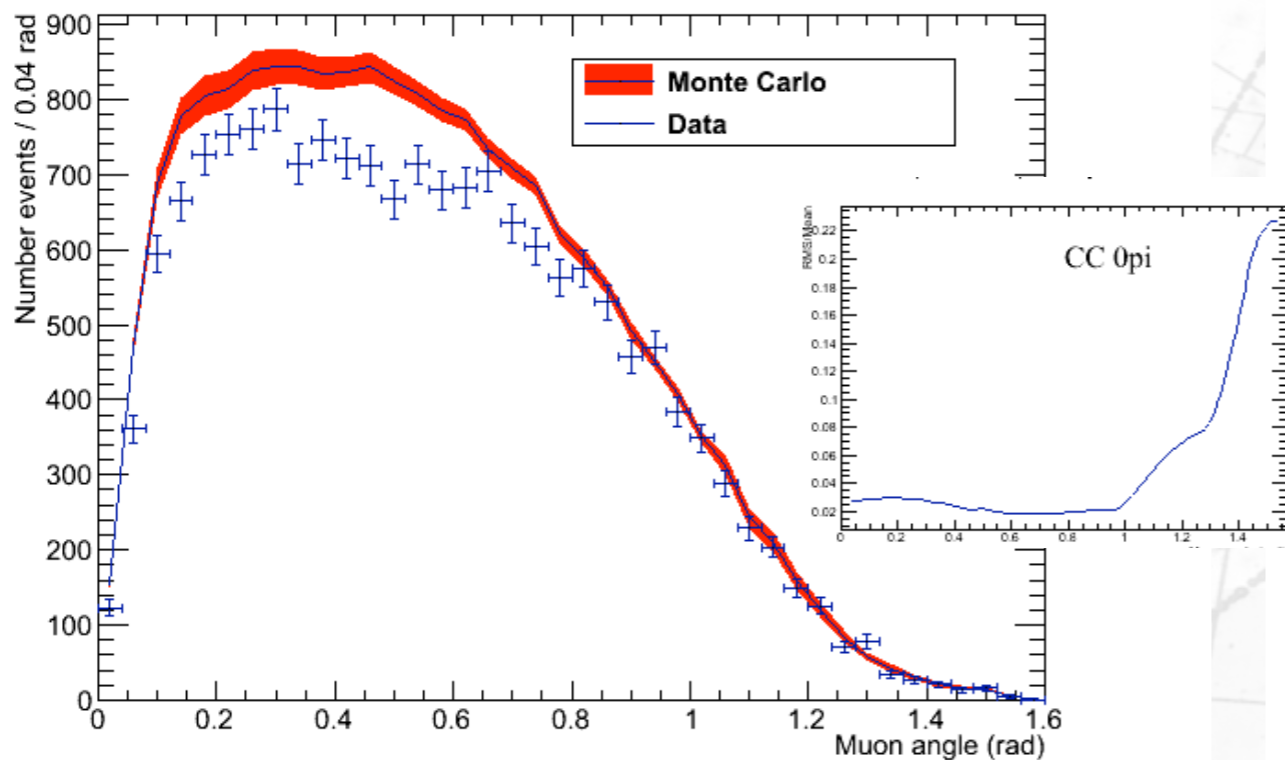




ND280



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%)



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%)

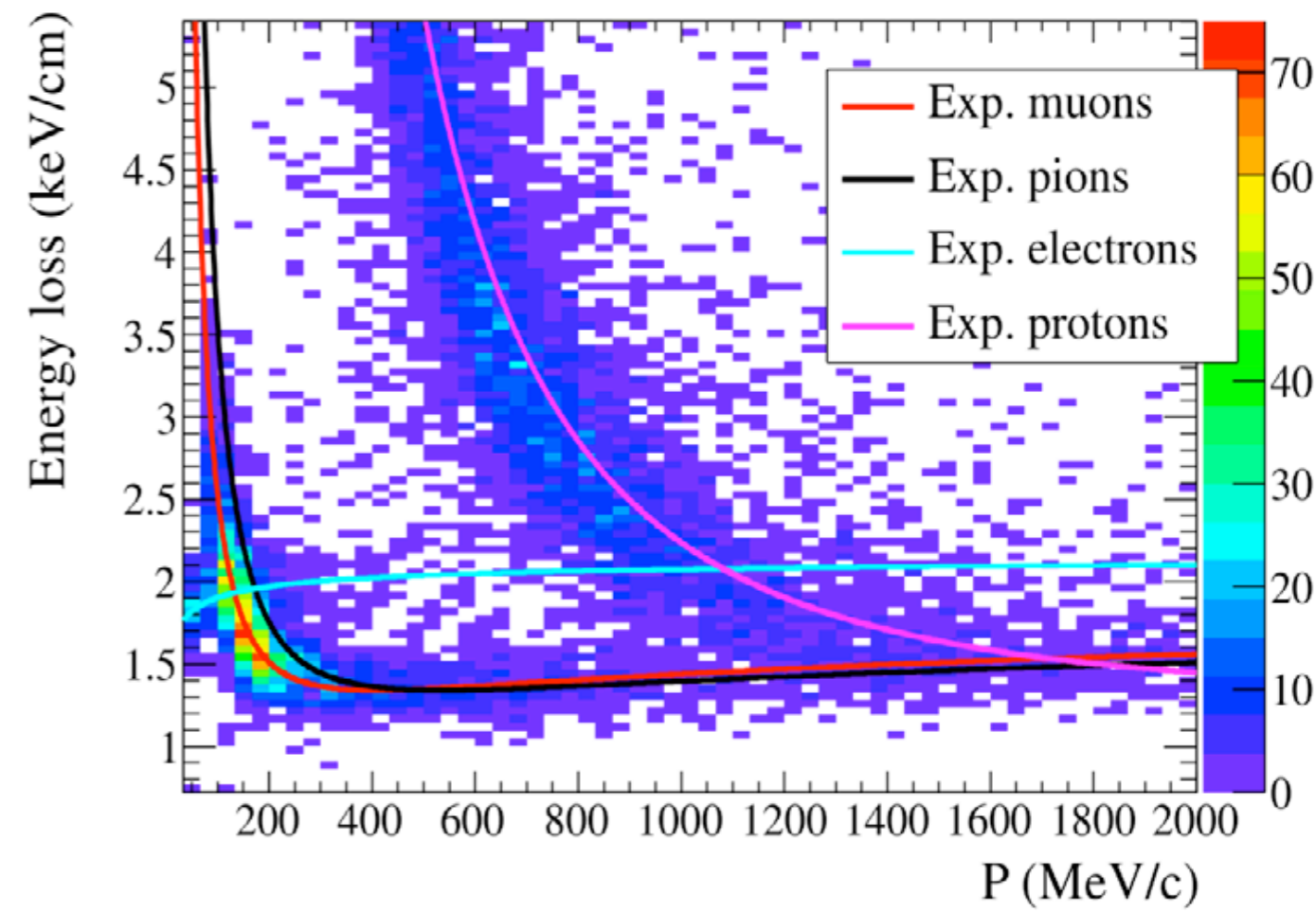
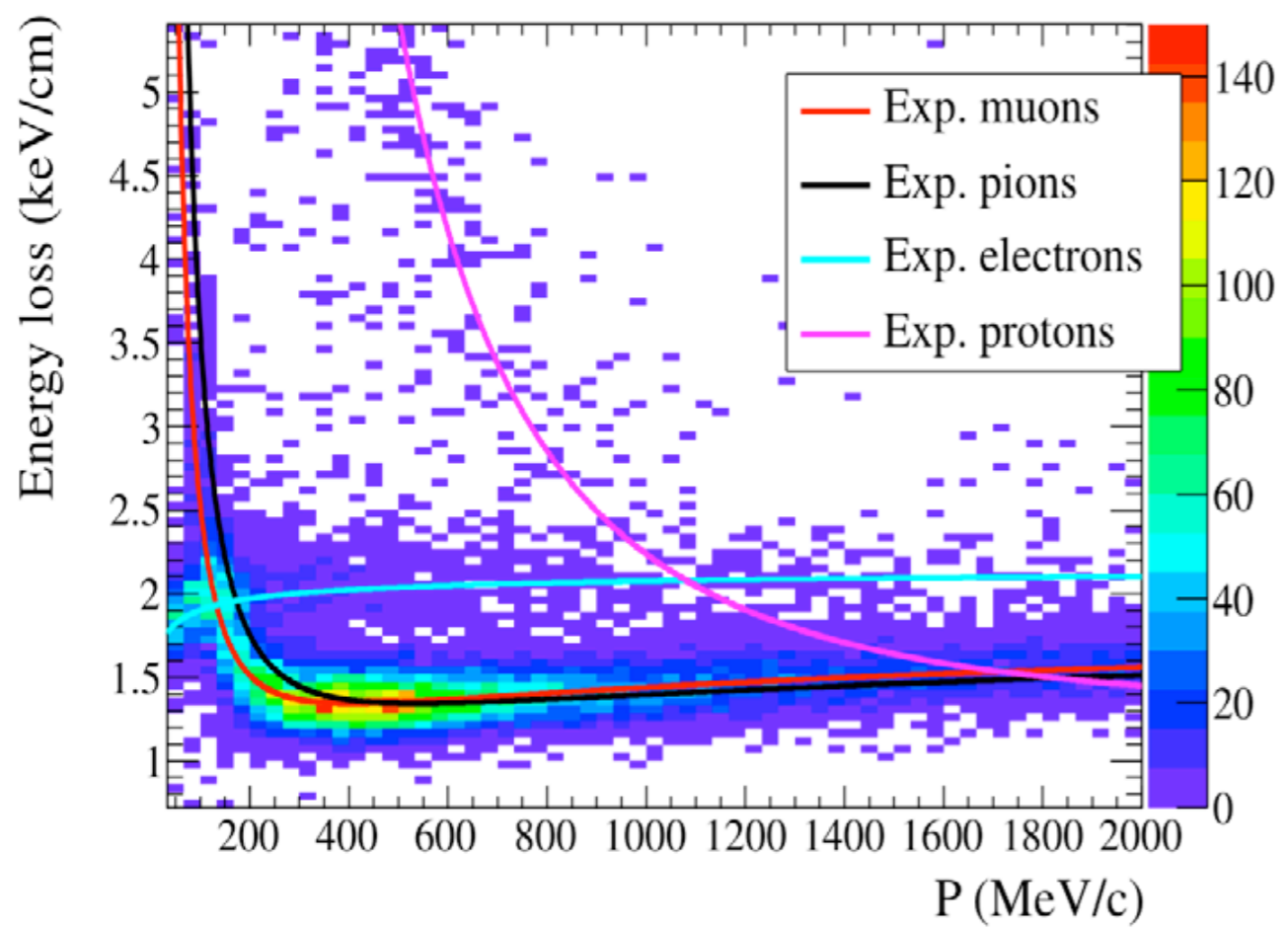
FGD PID (0.3%)

FGD tracking efficiency (1.4%)

Pion secondary interaction (8%)

Negative Tracks in TPC

Positive Tracks in TPC

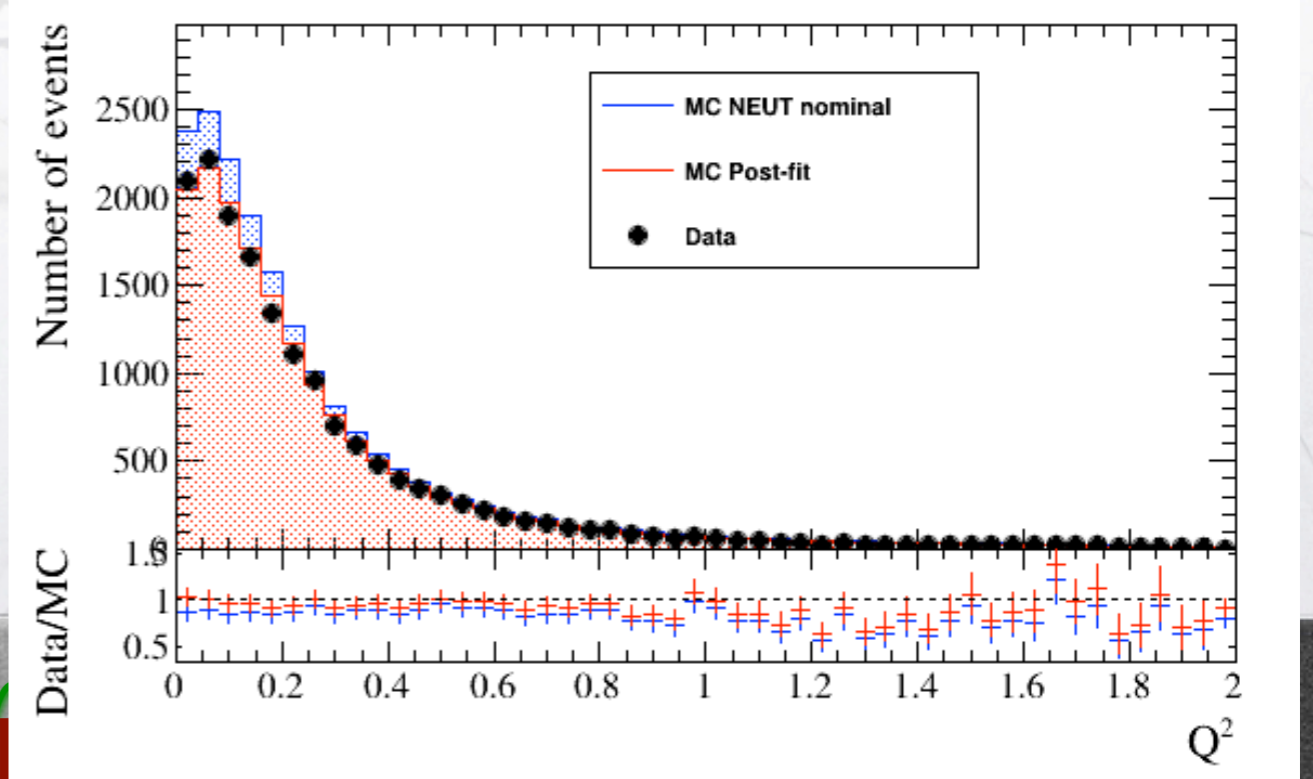
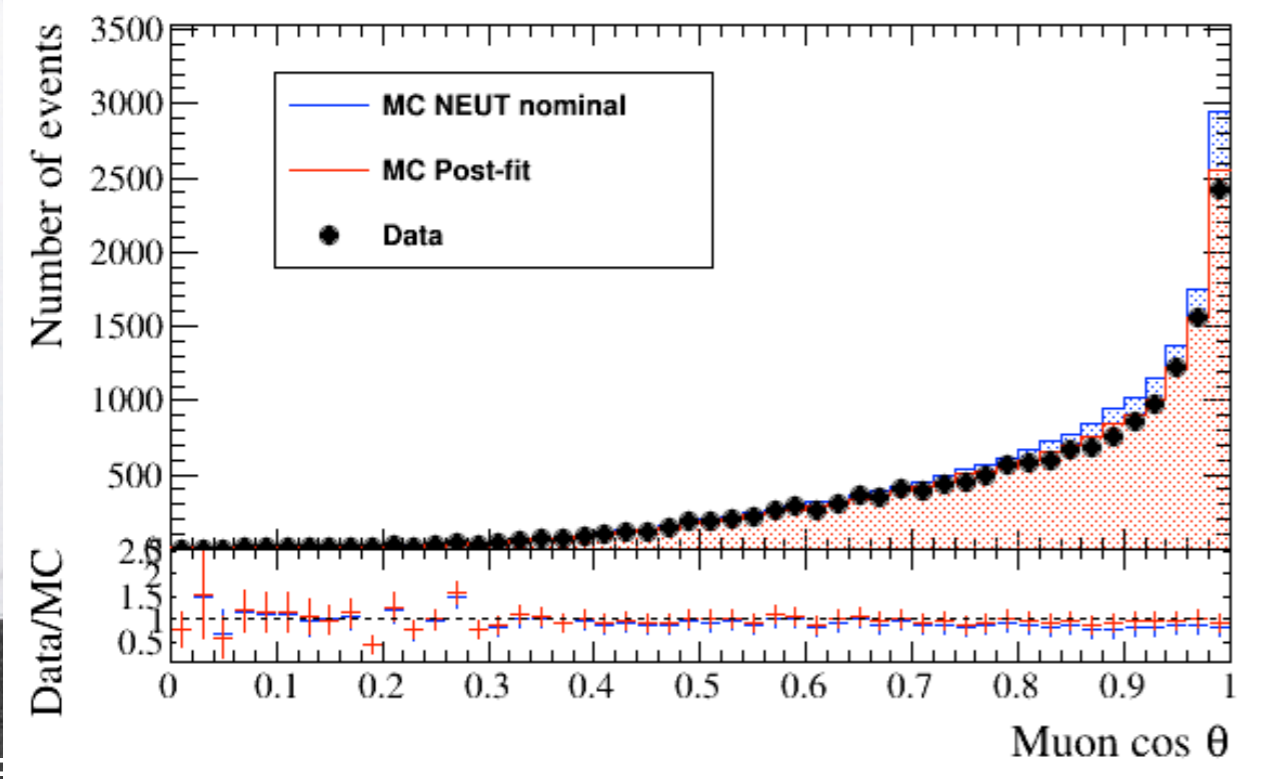
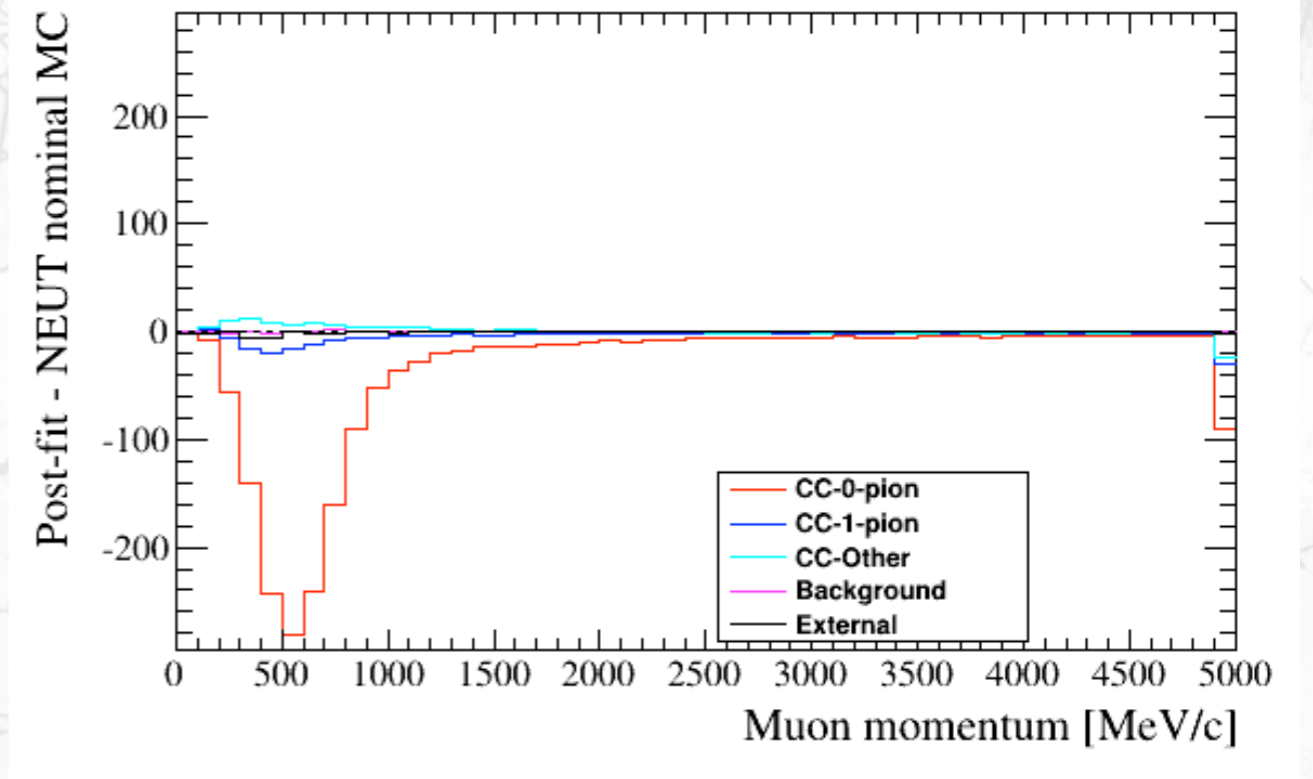
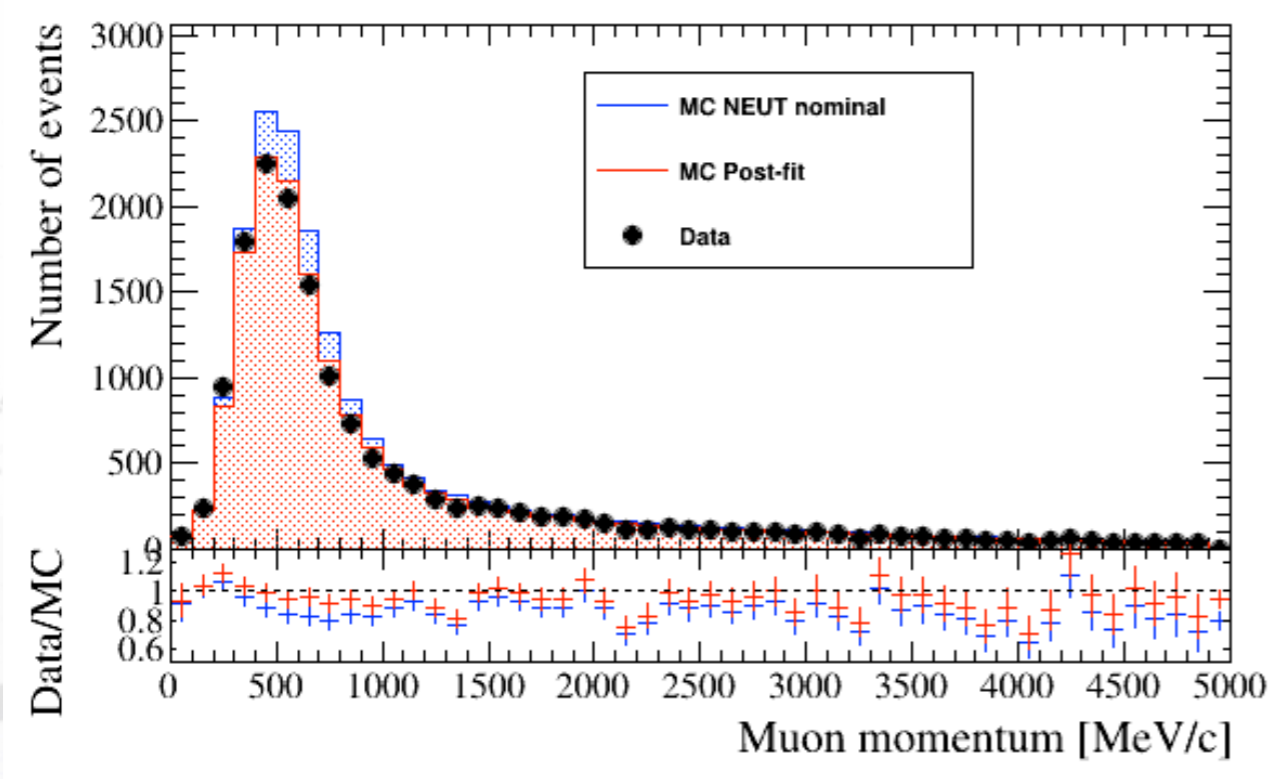
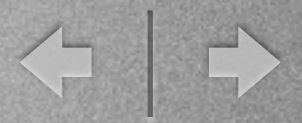


Post-fit ν_μ ND280

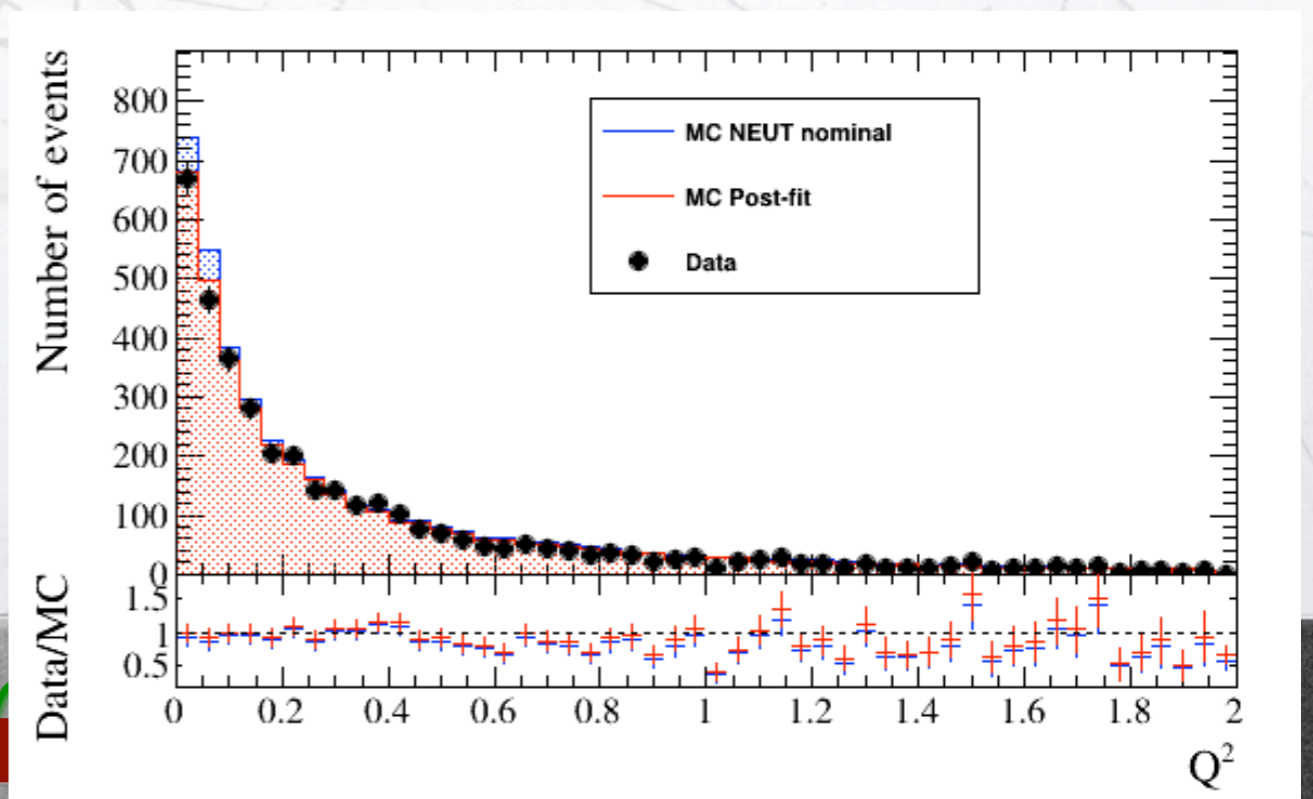
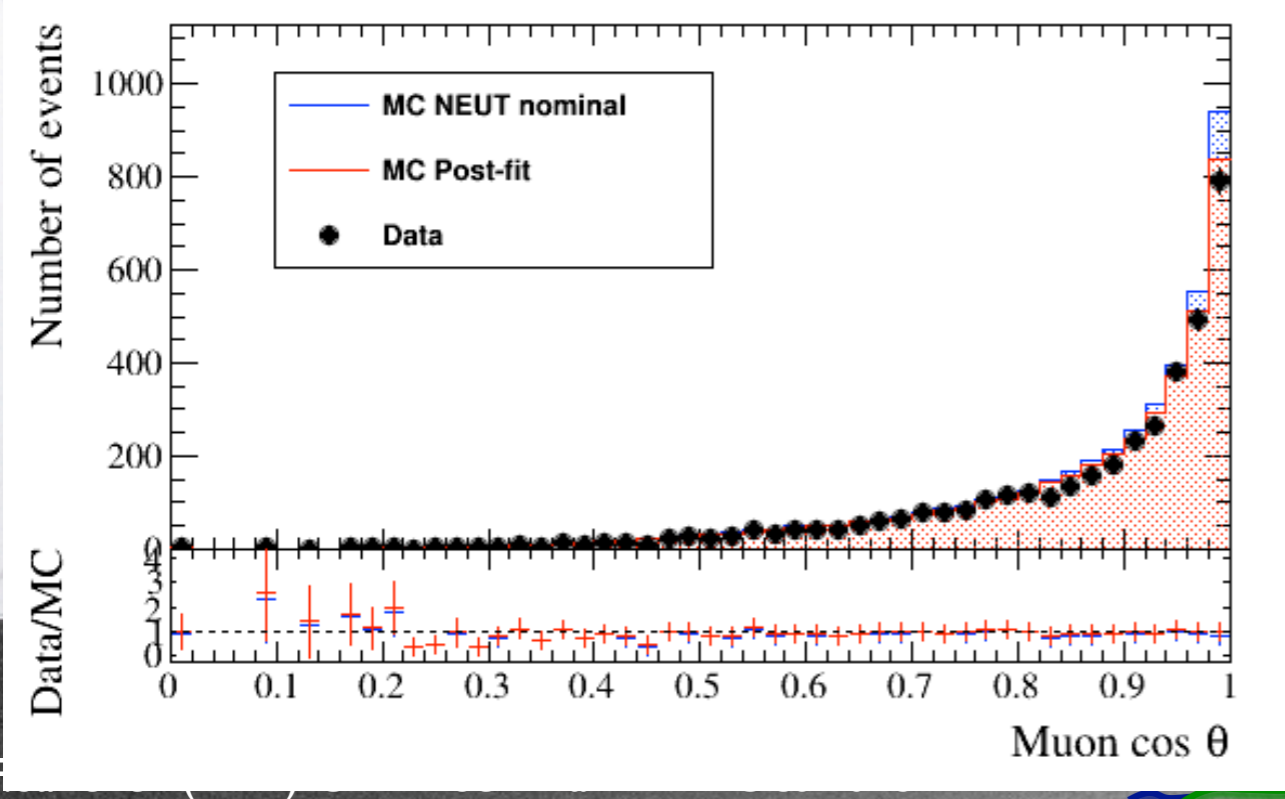
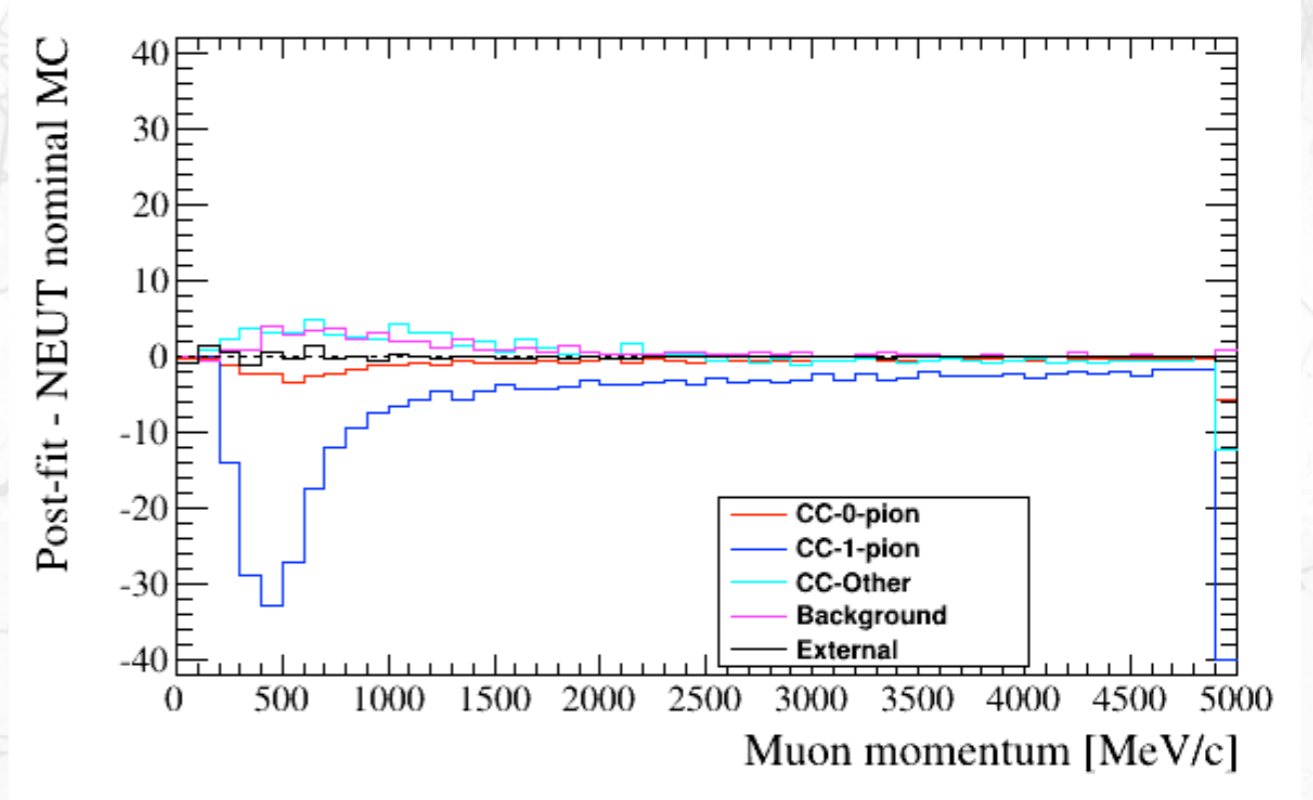
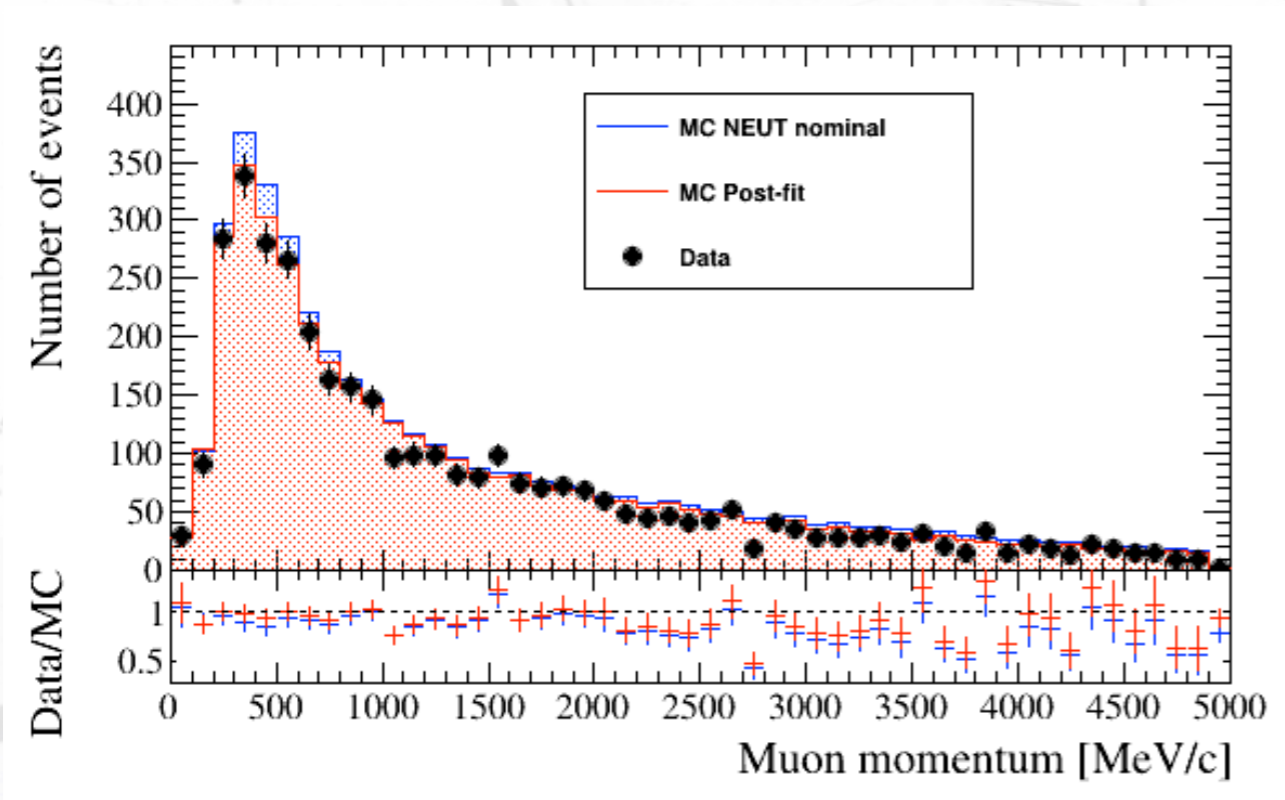
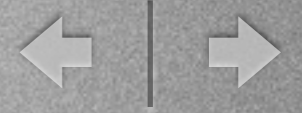


- Use beam and cross section parameters obtained from the constrained fit to the ND280 $\nu_\mu(p_\mu, \cos\theta_\mu)$ spectra to re-weight the MC.
- Improved agreement between the MC distributions, after post-fit re-weight, and the data.

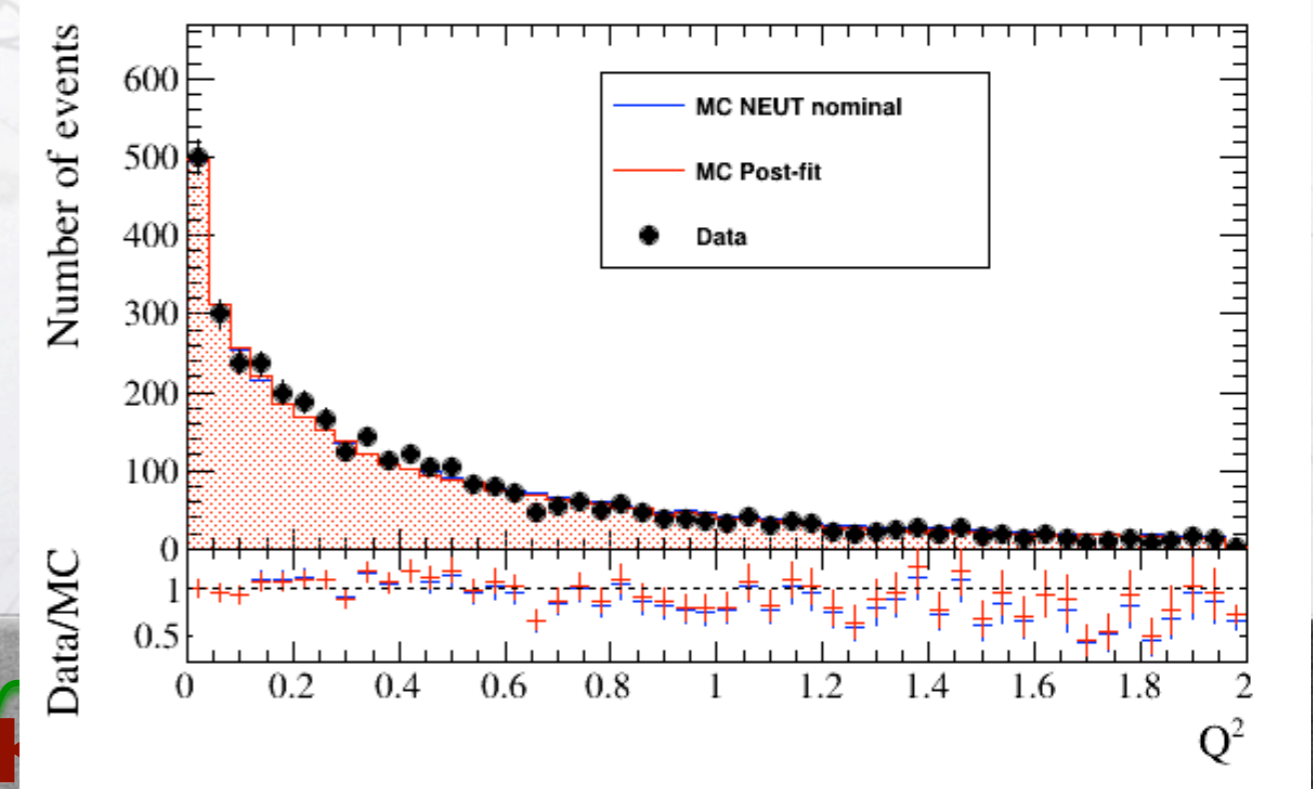
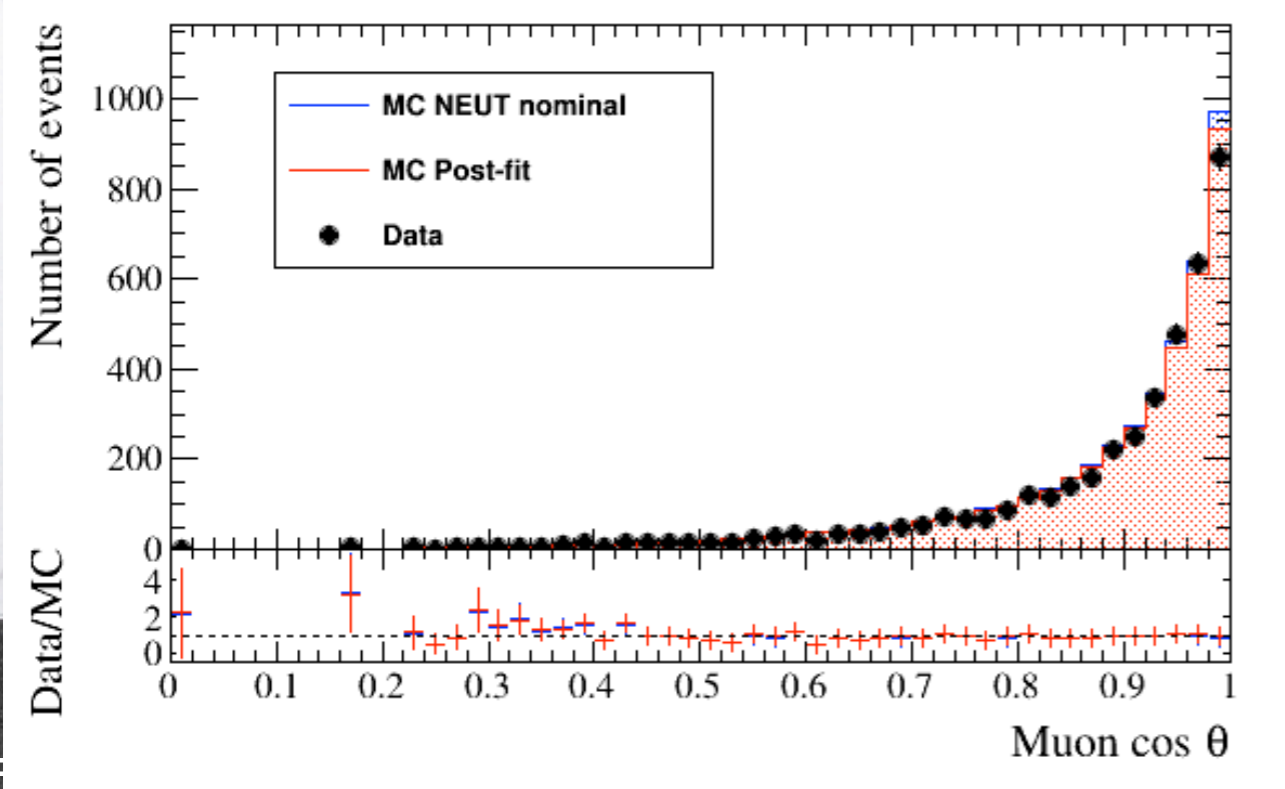
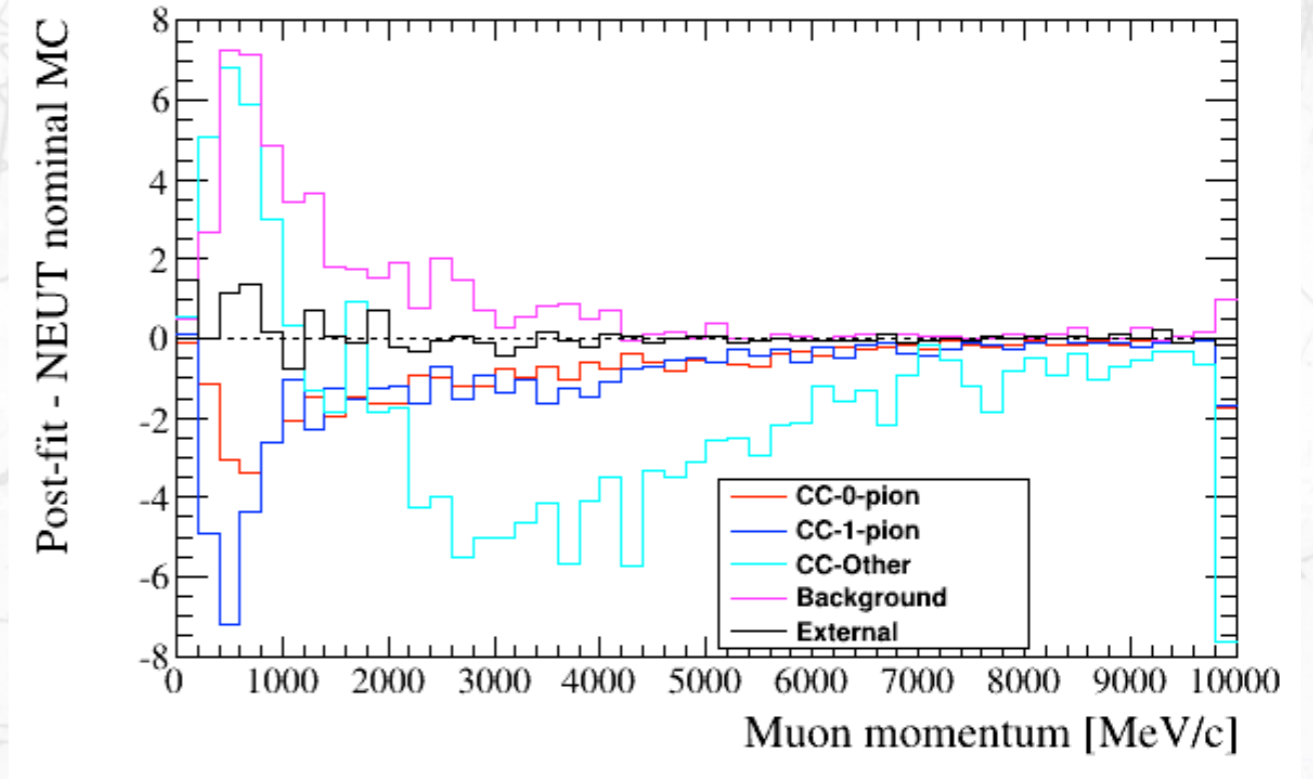
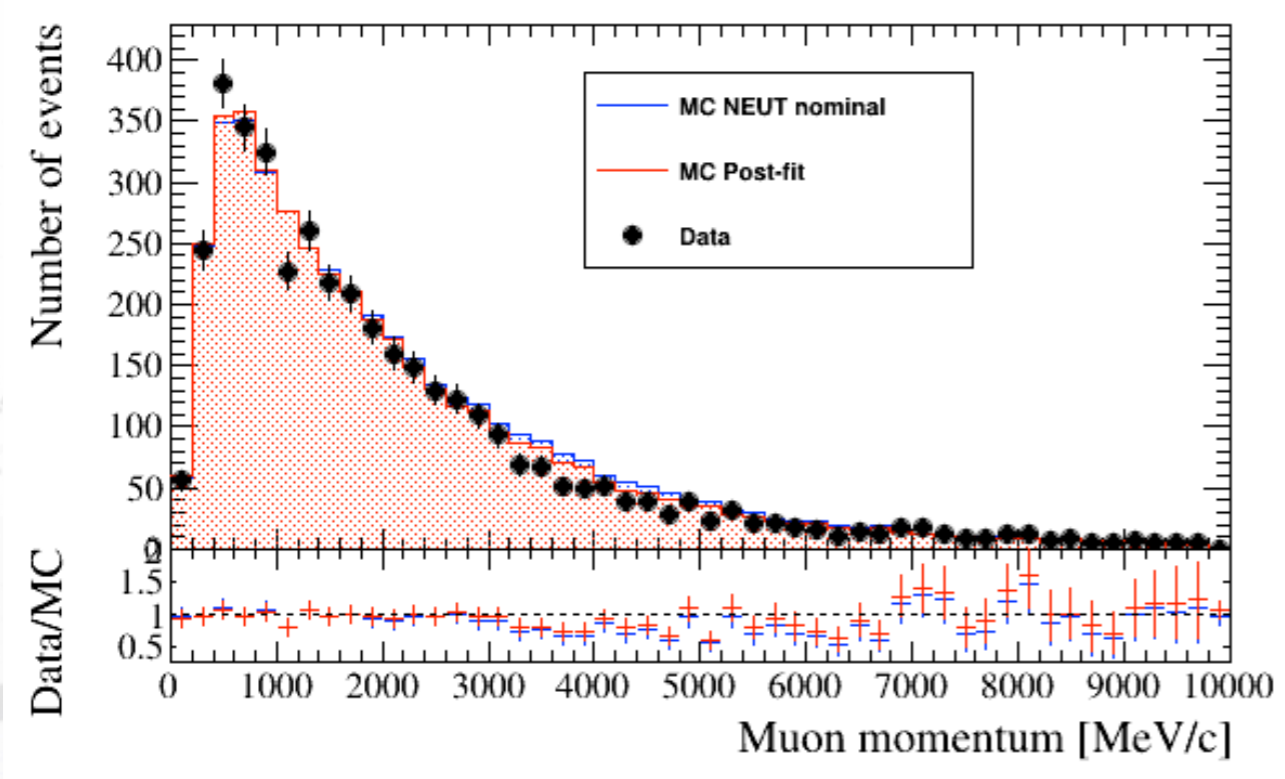
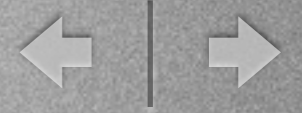
CC-0-pion post-fit



CC-1-pion post-fit



CC-Other post-fit





Flux fit

ND280 Fit $\Delta\chi^2$



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

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

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

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)

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

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

Selection	Number of Events (Data)	Number of Events (MC before ND280 constraint)	Number of Events (MC after ND280 constraint)
CC0 π	16912	20016	16803
CC1 π	3936	5059	3970
CC Other	4062	4602	4006
CC Inclusive	24910	29678	24779

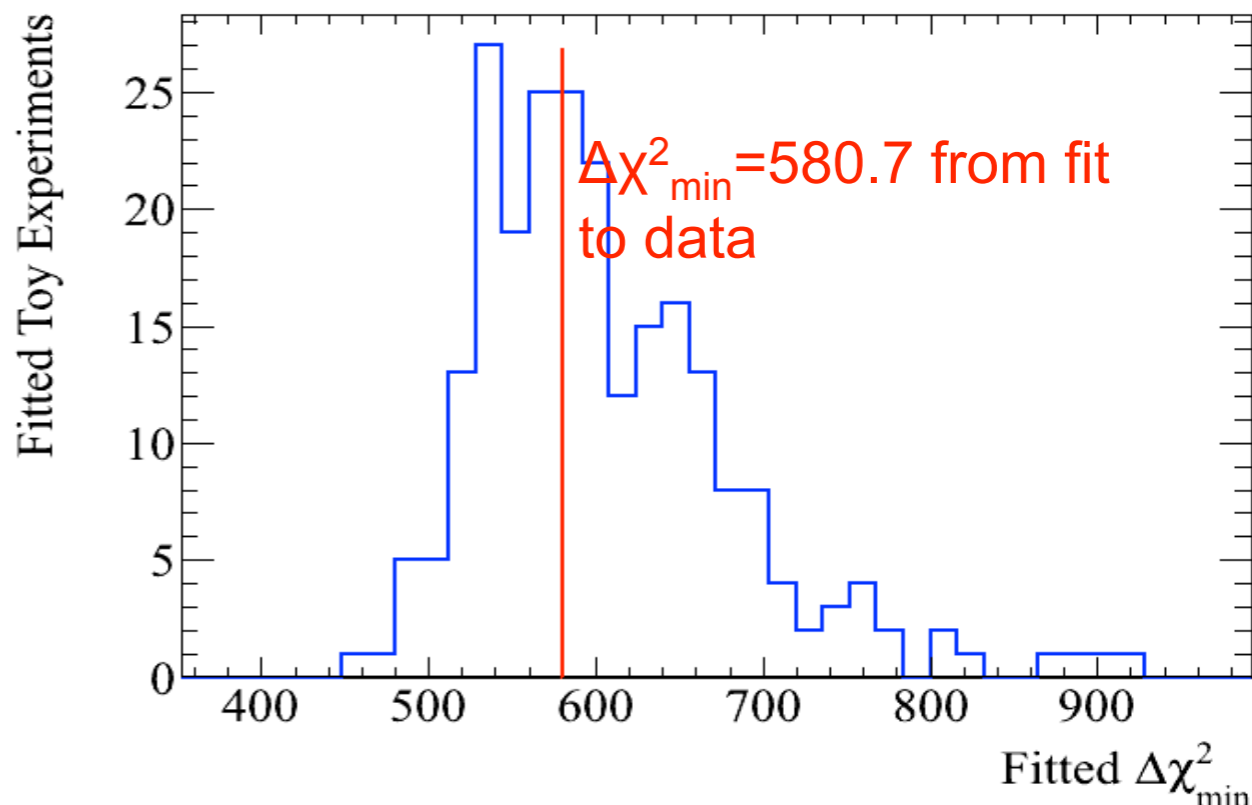
Test the data and constrained MC agreement with toy experiments:

Generated variations of models within prior uncertainties

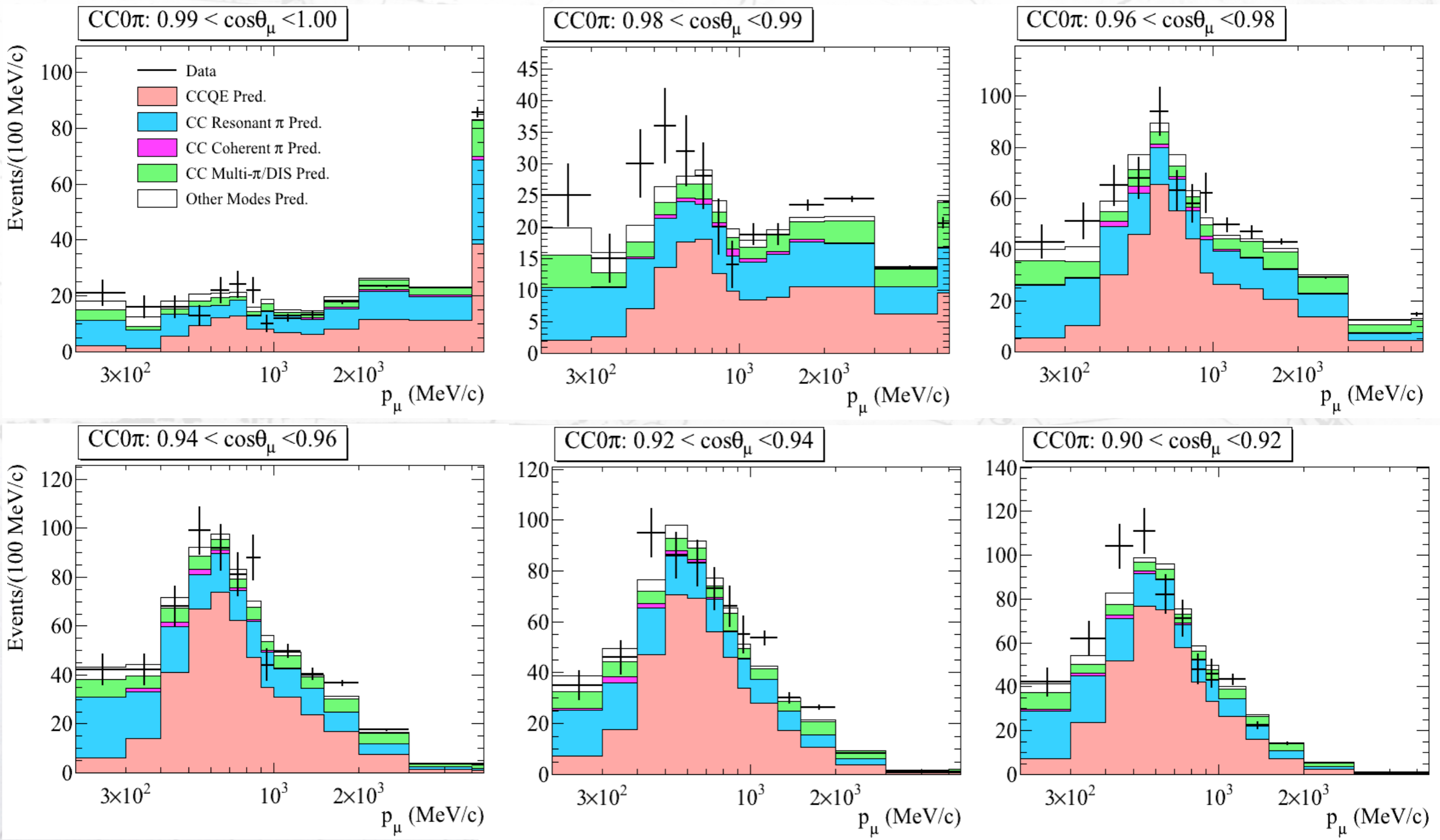
Fit toy data in same manner as data

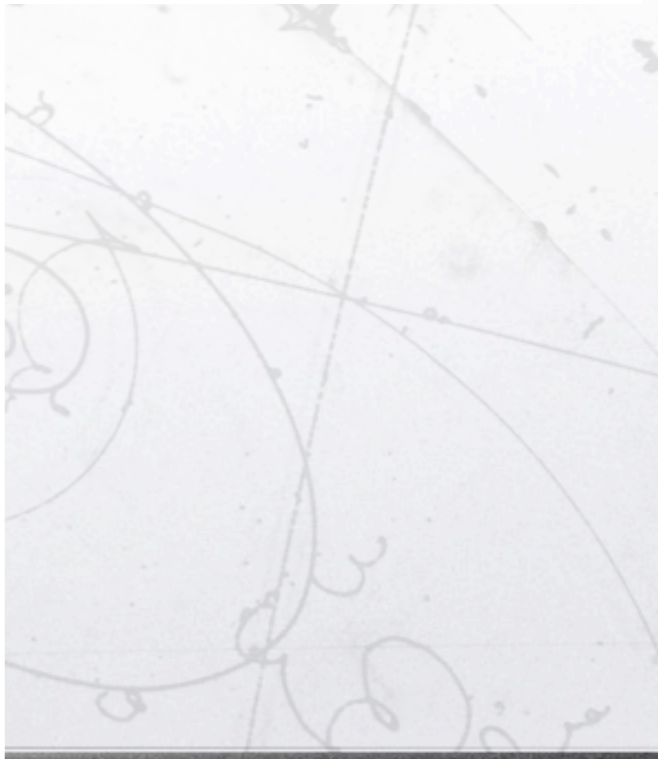
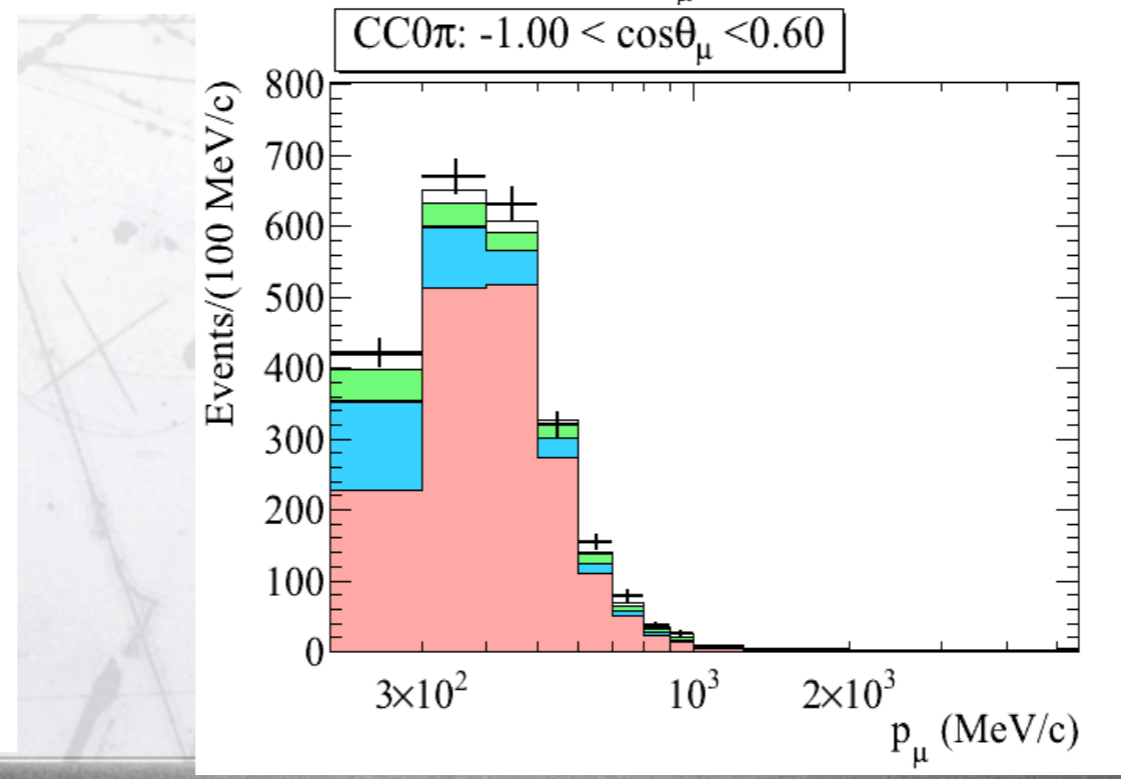
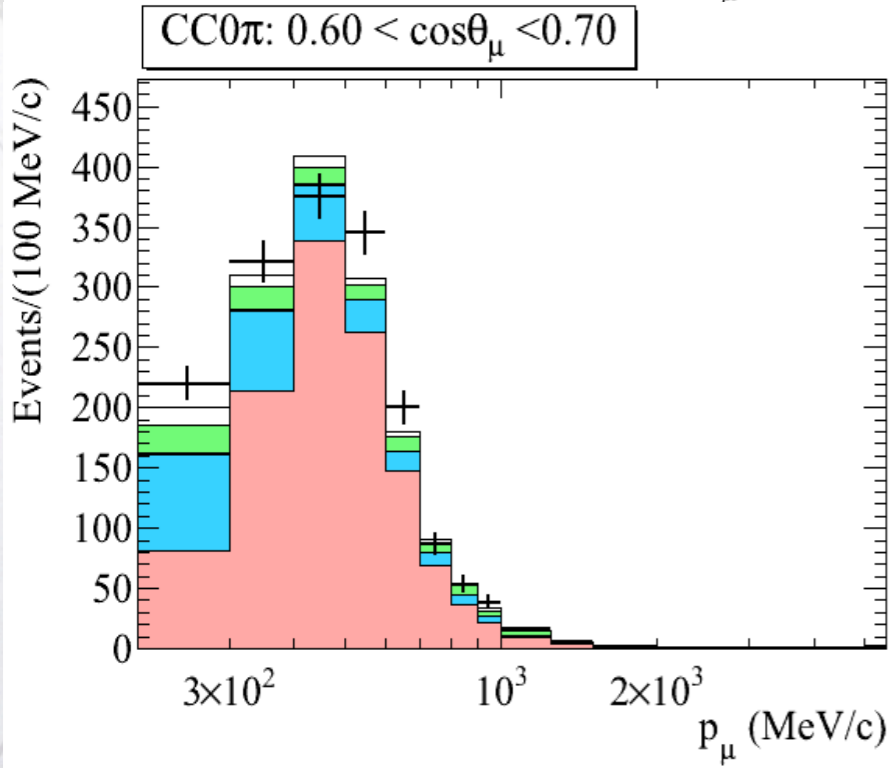
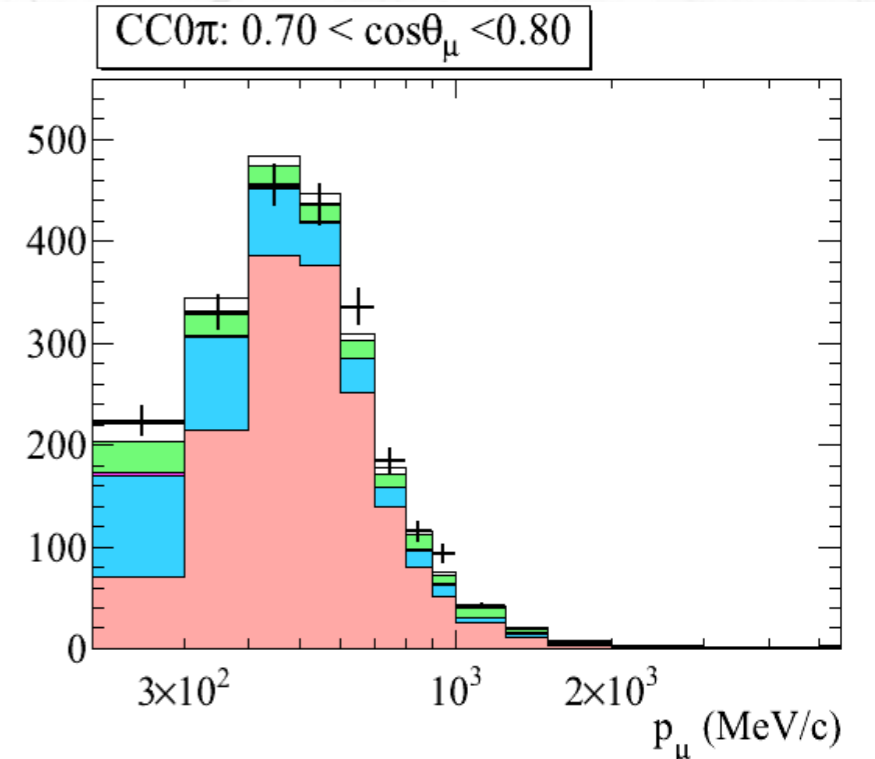
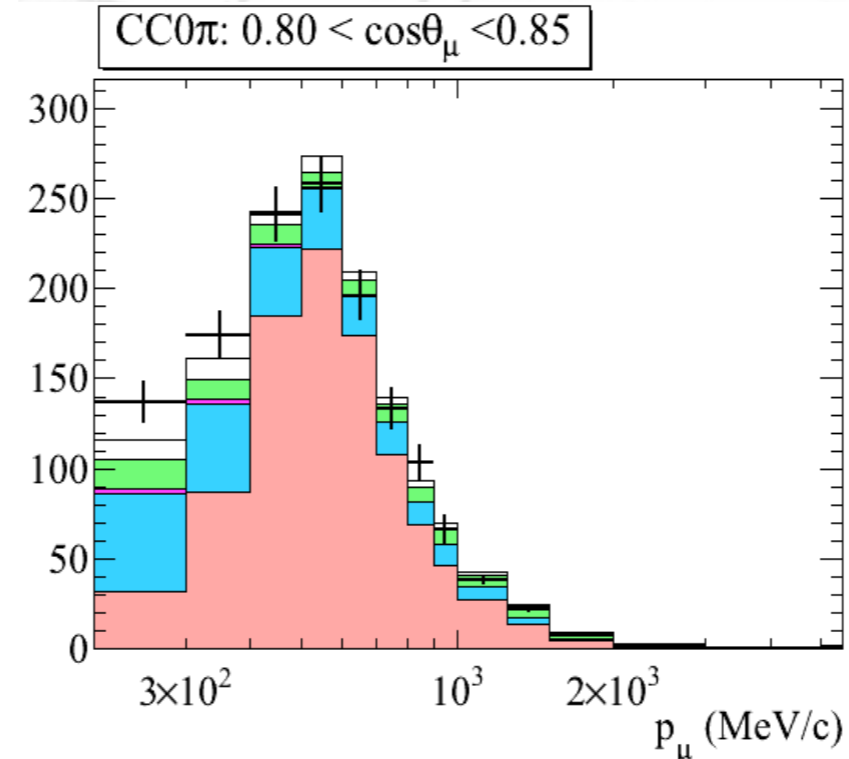
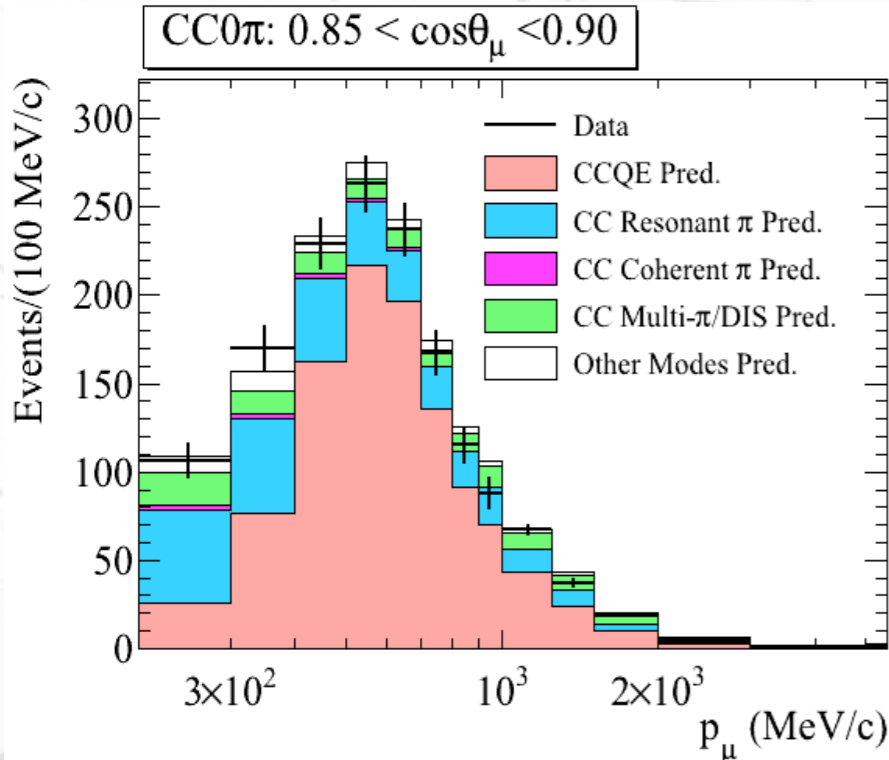
Record $\Delta\chi^2$ at minimum for each toy fit

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



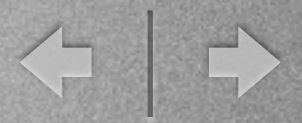
Data and Constrained Model (CC0 π)



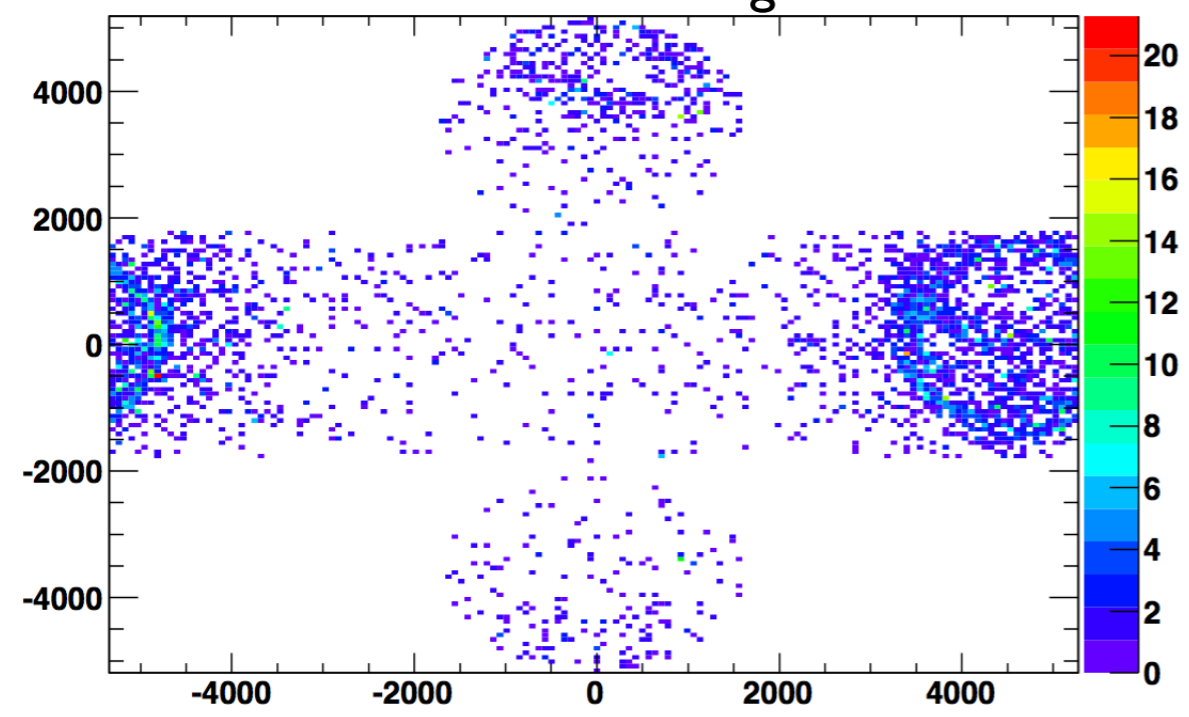


New SK π^0 analysis

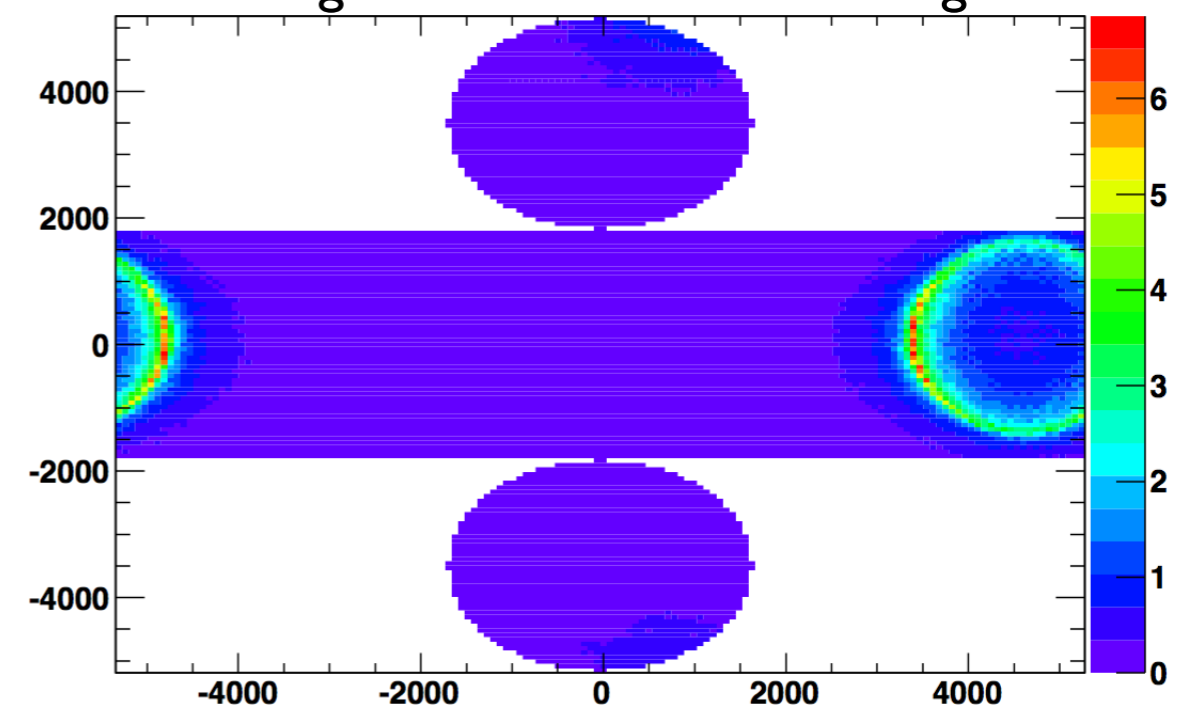
Event Display: π^0 Fit



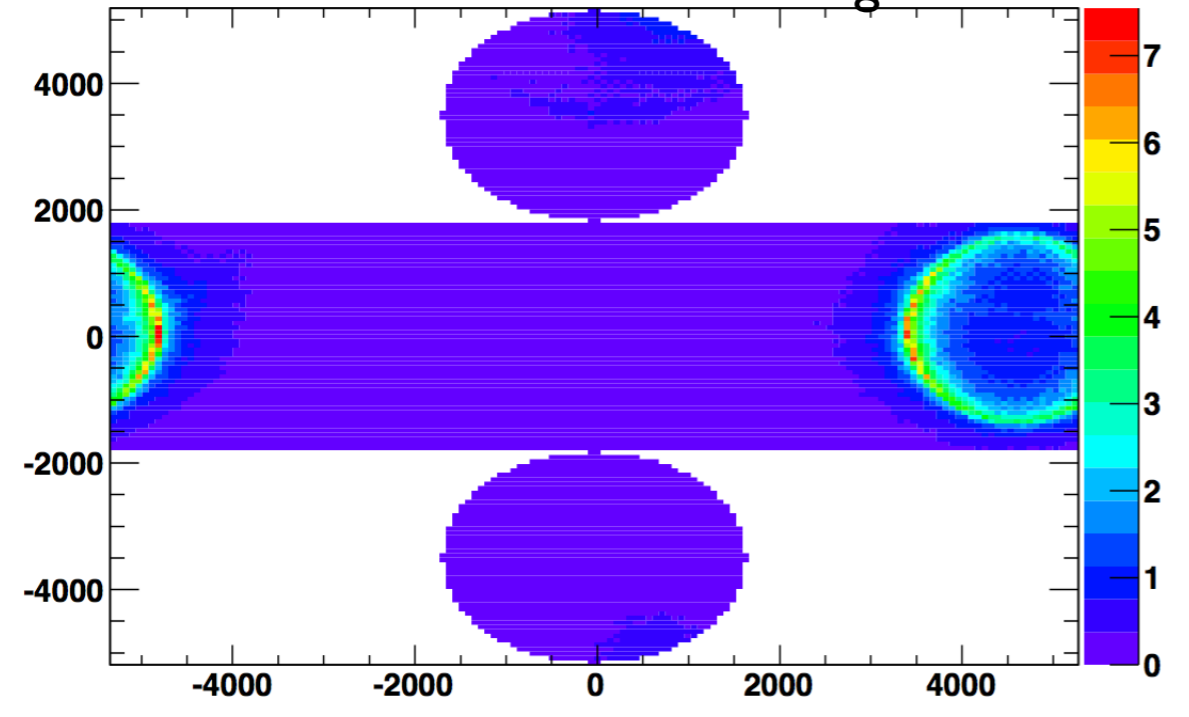
Measured Charge



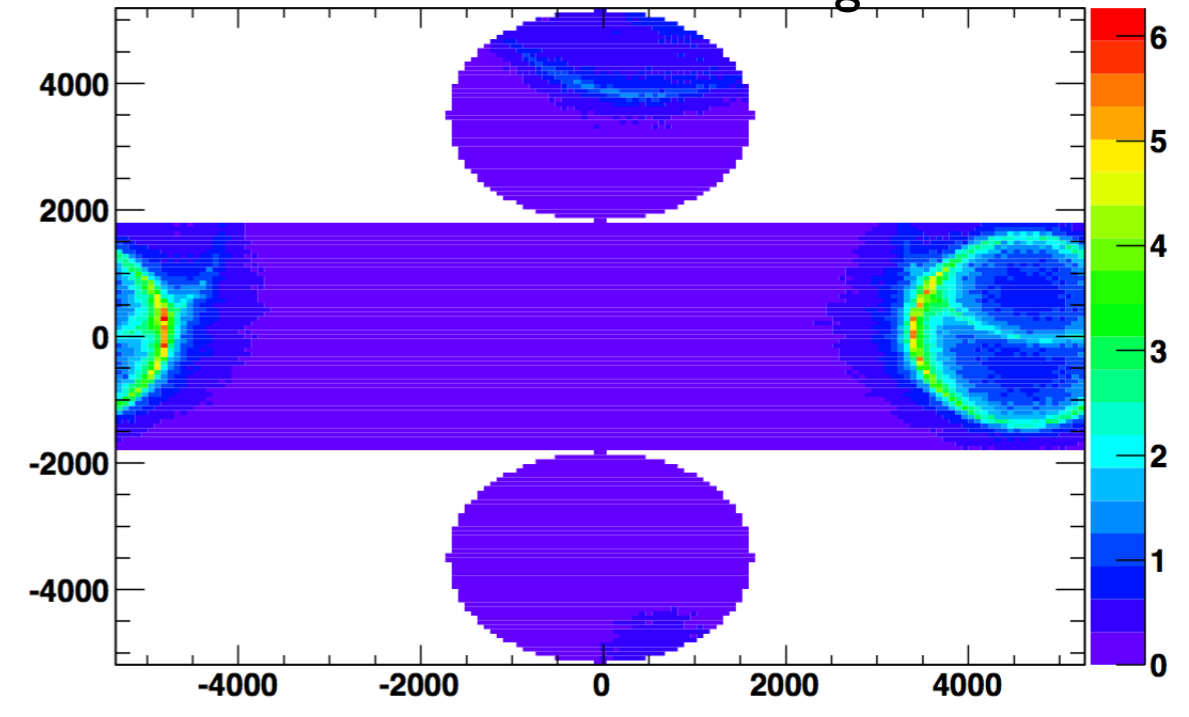
I-ring e-like Fit Predicted Charge



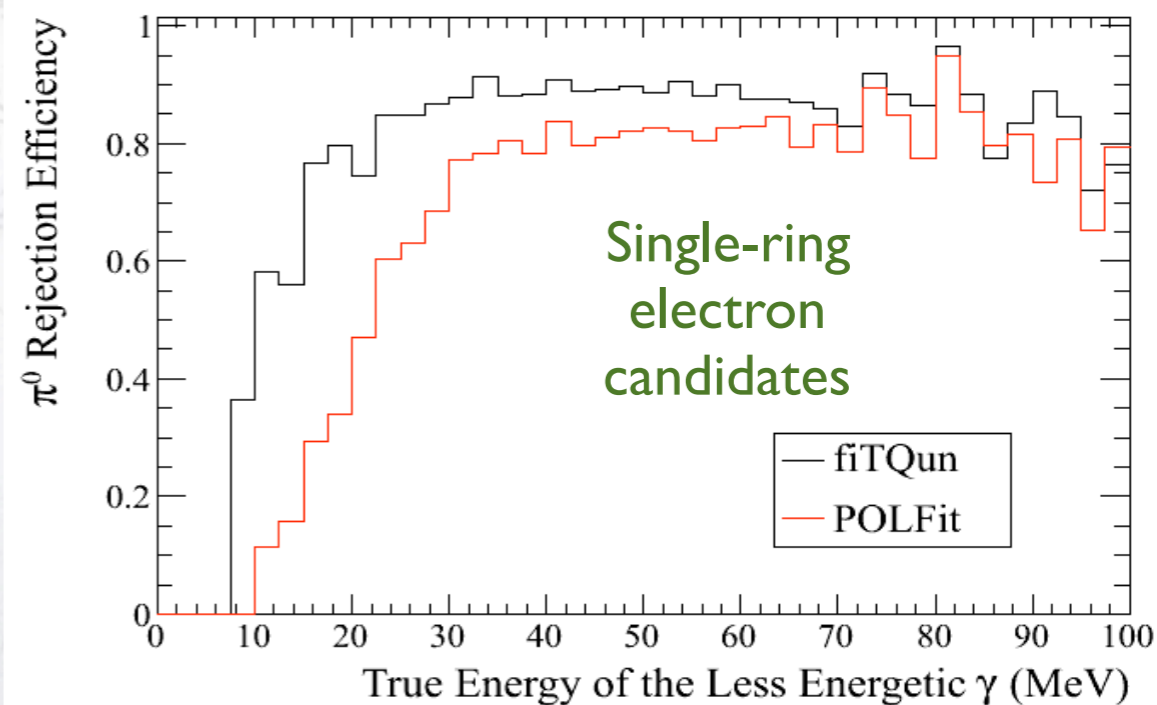
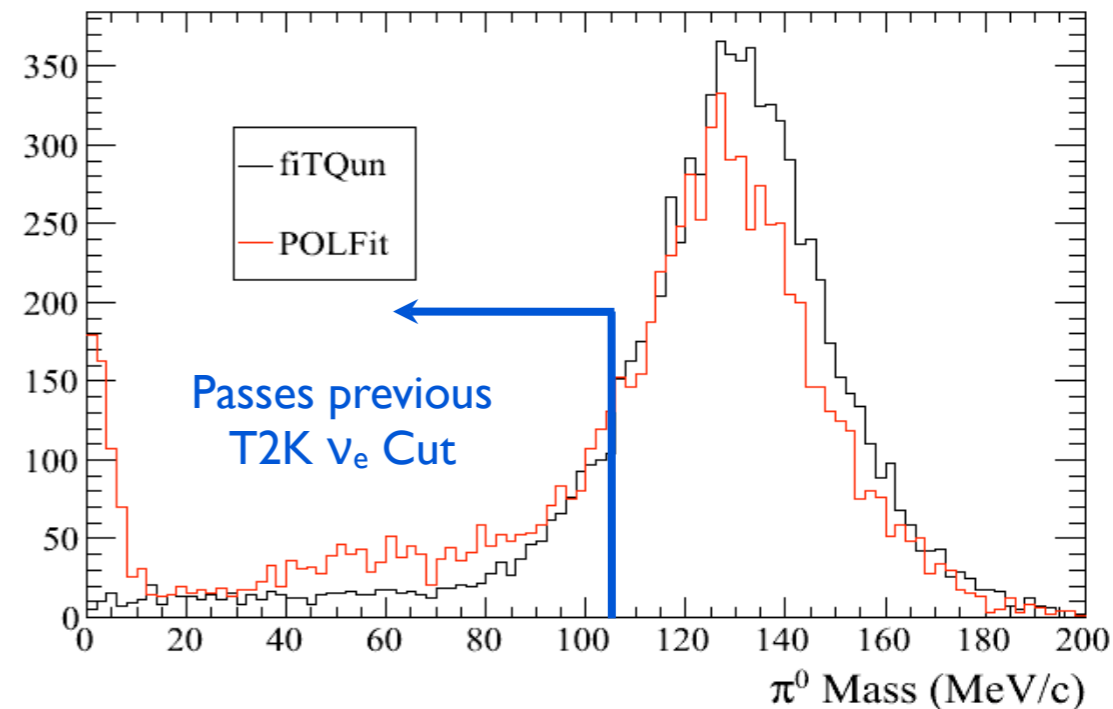
π^0 Seed Predicted Charge



π^0 Fit Predicted Charge



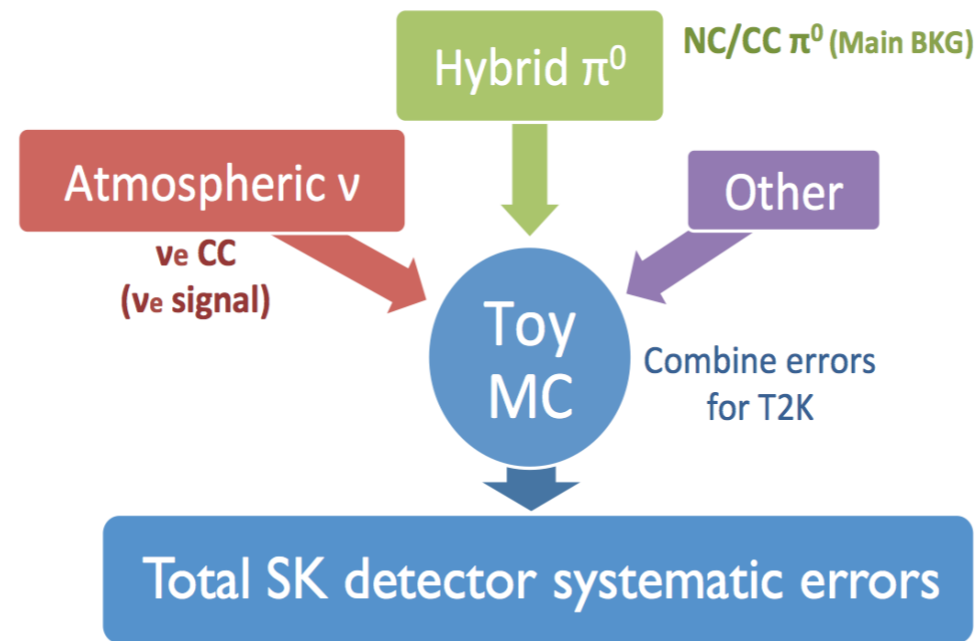
- Previous T2K ν_e appearance cut:
 $m_{\pi^0} < 105 \text{ MeV}/c^2$
- The π^0 mass tail is much smaller for fiTQun
- Significant spike at zero mass in standard fitting algorithm (POLFit)
- Lower plot: π^0 rejection efficiency vs lower photon energy
- fiTQun is more sensitive to lower energy photons



candidates

SK systematics and control sample

SK detector error estimation



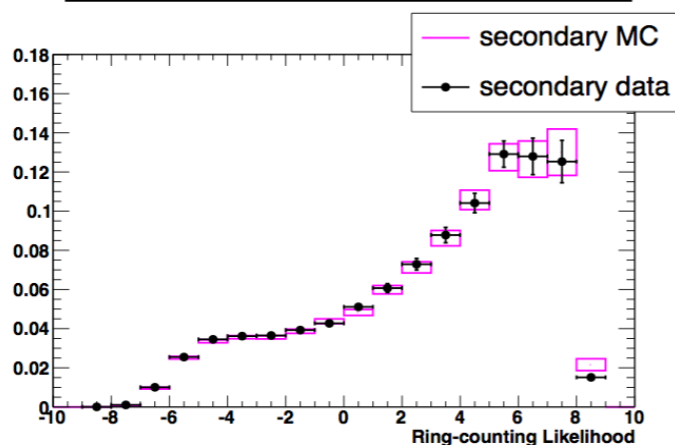
- To evaluate SK detector systematic uncertainties, employ several control samples:
 - Atmospheric ν_e samples (errors on ν_e 's), "Hybrid- π^0 " samples (errors on π^0 's), Cosmic-ray muon samples, ...
 - The errors evaluated with the control samples are combined with Toy MC method

3

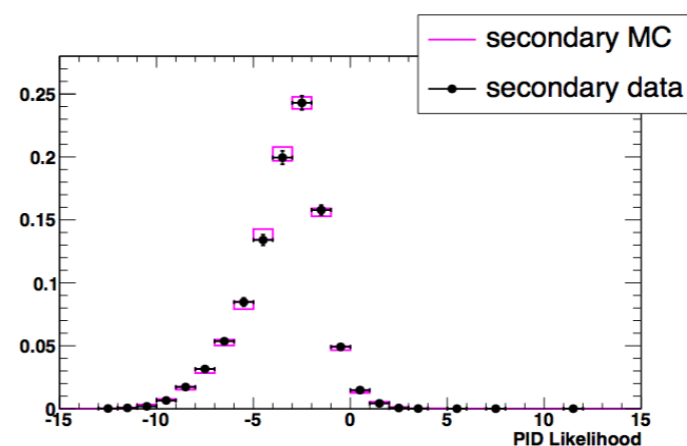
Monday, July 15, 13

Basic distributions

Ring Counting

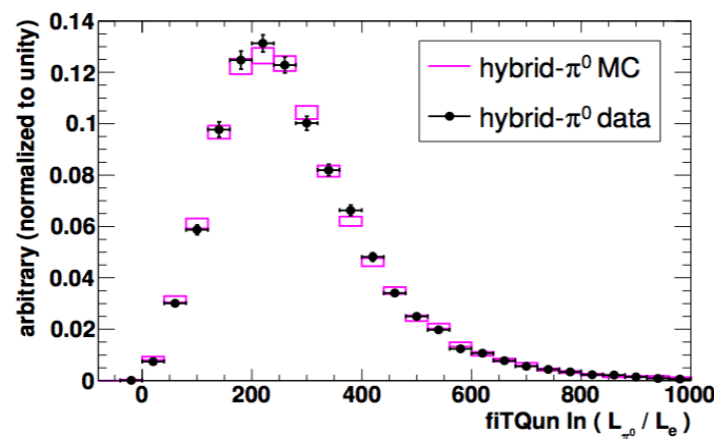


PID

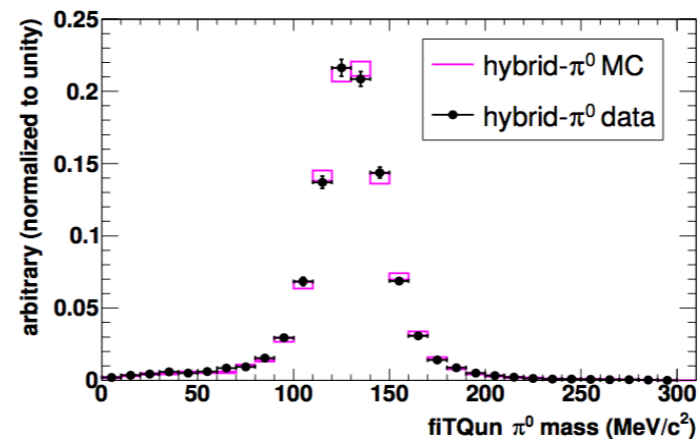


π^0 rejection

π^0/e likelihood ratio



π^0 mass

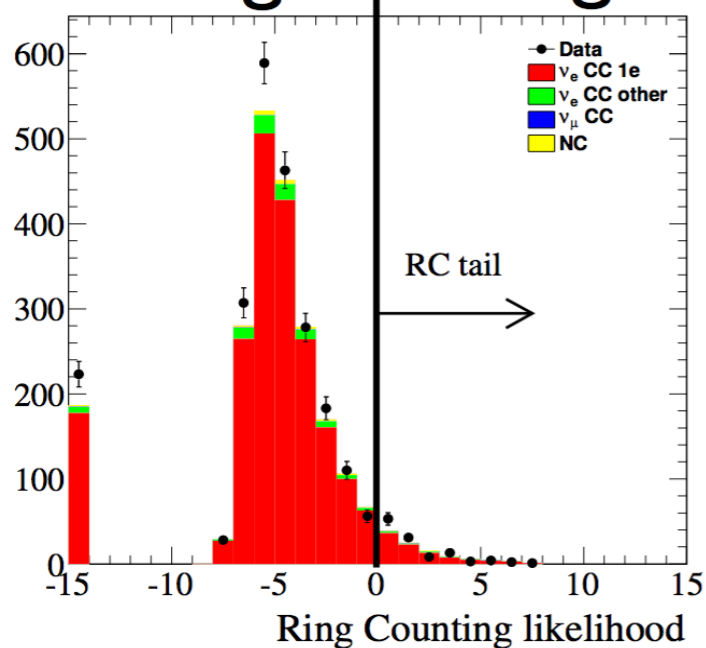


Control Samples

- ν_e candidate sample (“core” sample) + rejected samples (three “tail” samples)
 - Selections: ring counting, PID, and π^0 rejection
 - (cf. ν_e candidates: 1-ring & e-like & none π^0 -like)

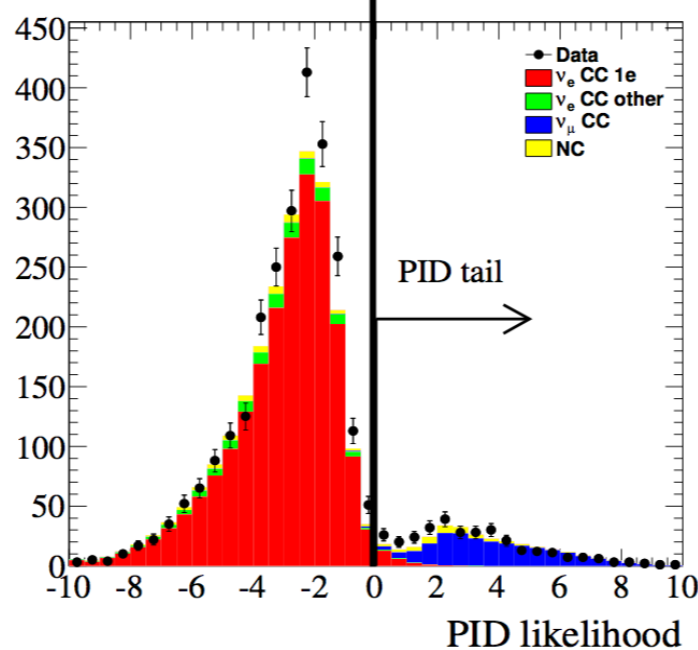
Ring Counting

Single ring Multi-ring



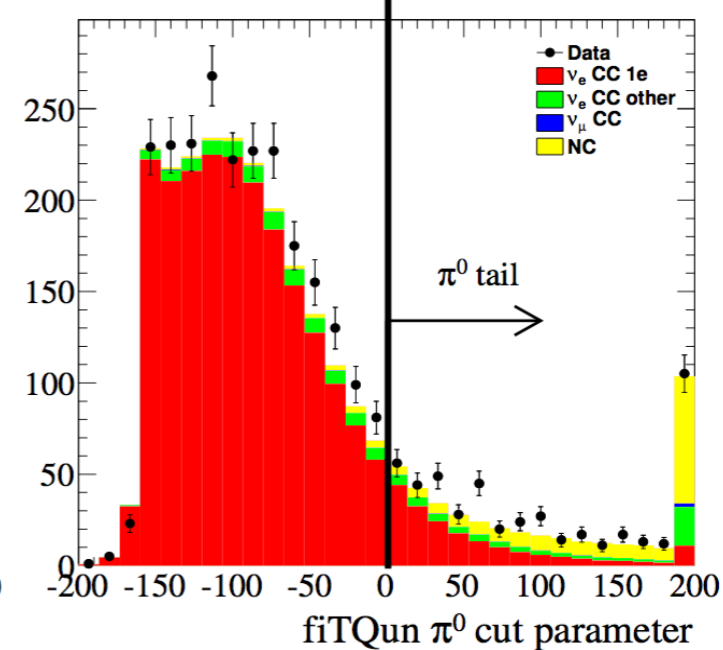
PID

e-like μ -like



π^0 rejection

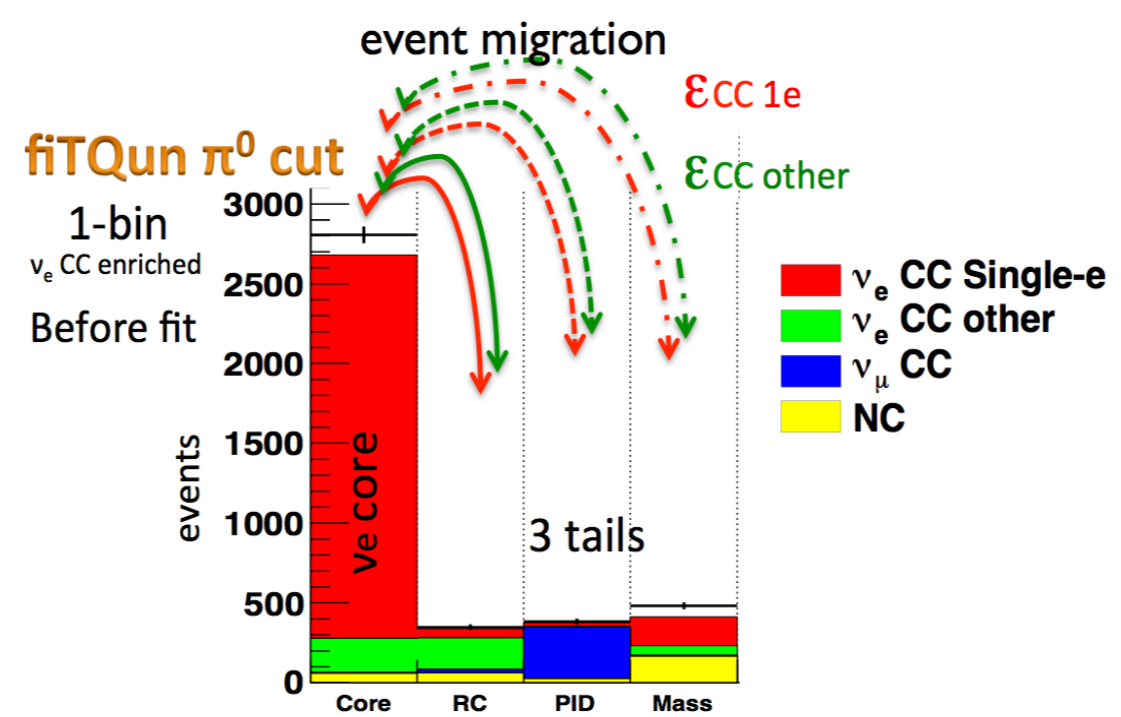
none π^0 -like π^0 -like



Monday, July 15, 13

Atmospheric ν fit

- Evaluate errors on ' ν_e 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.

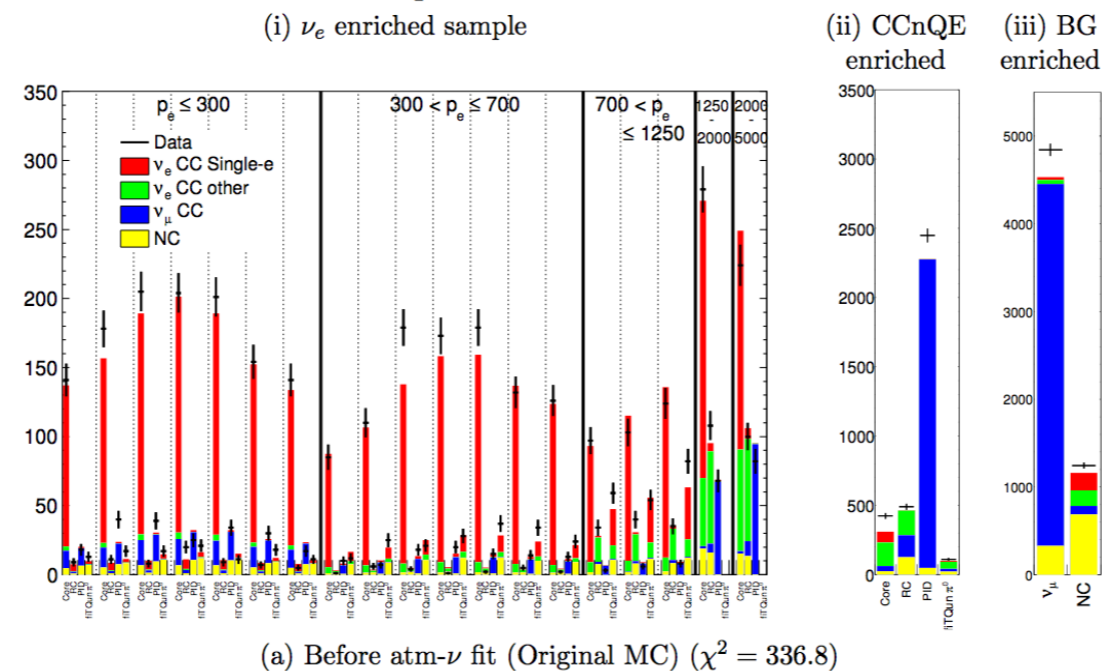


7

atm- ν fit results

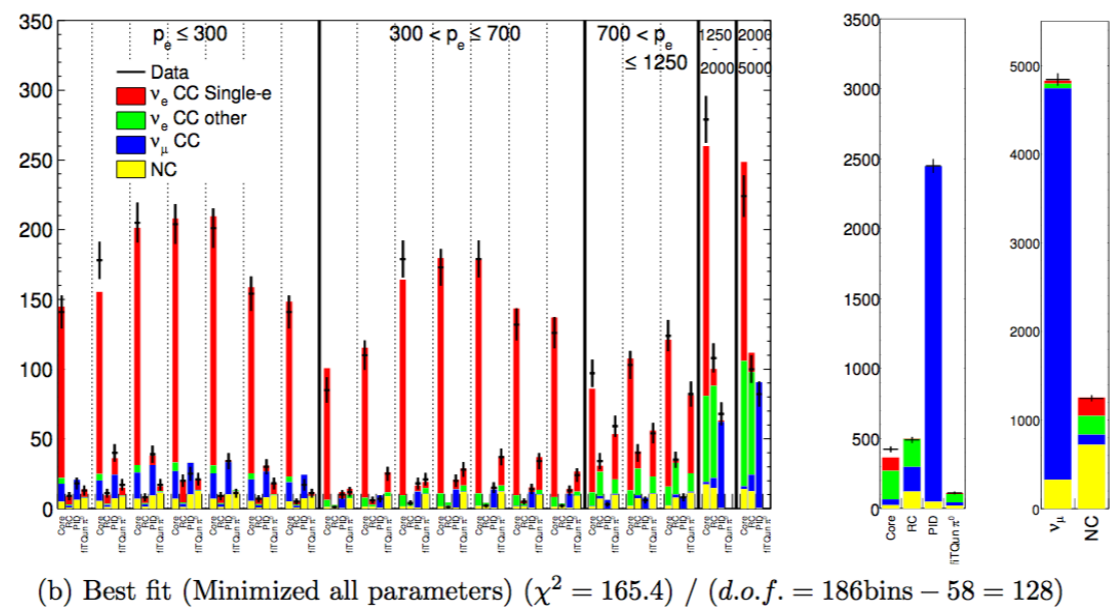
Number of events in p - θ bins and control samples.

Before fit



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

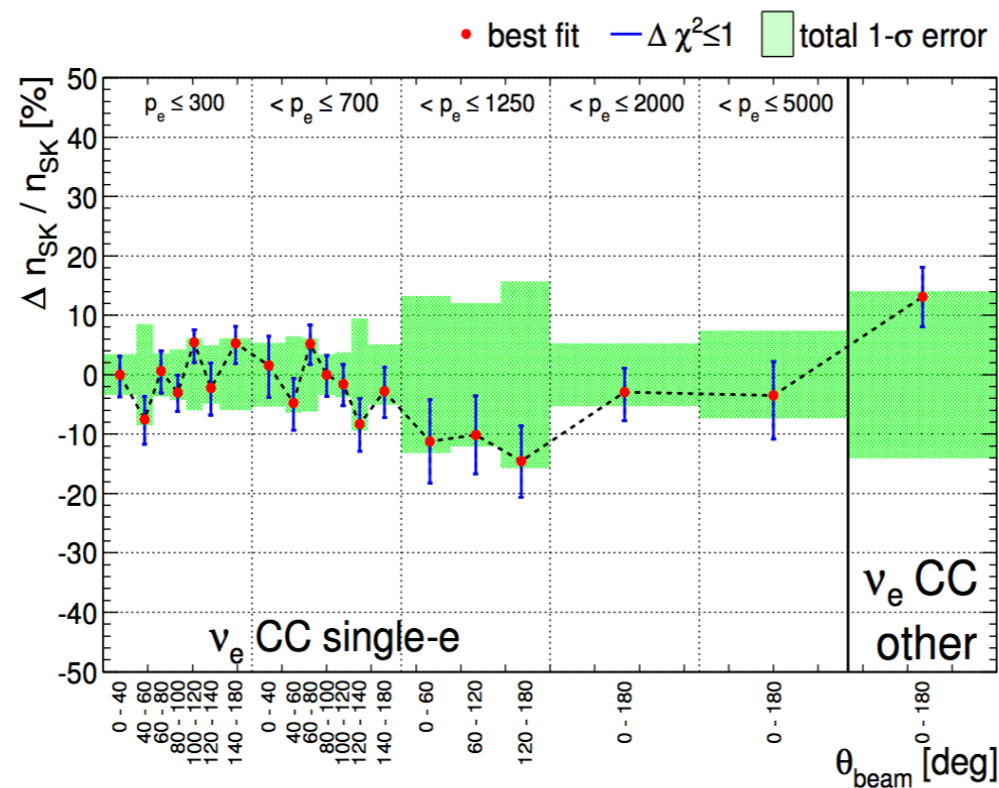
Best fit



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

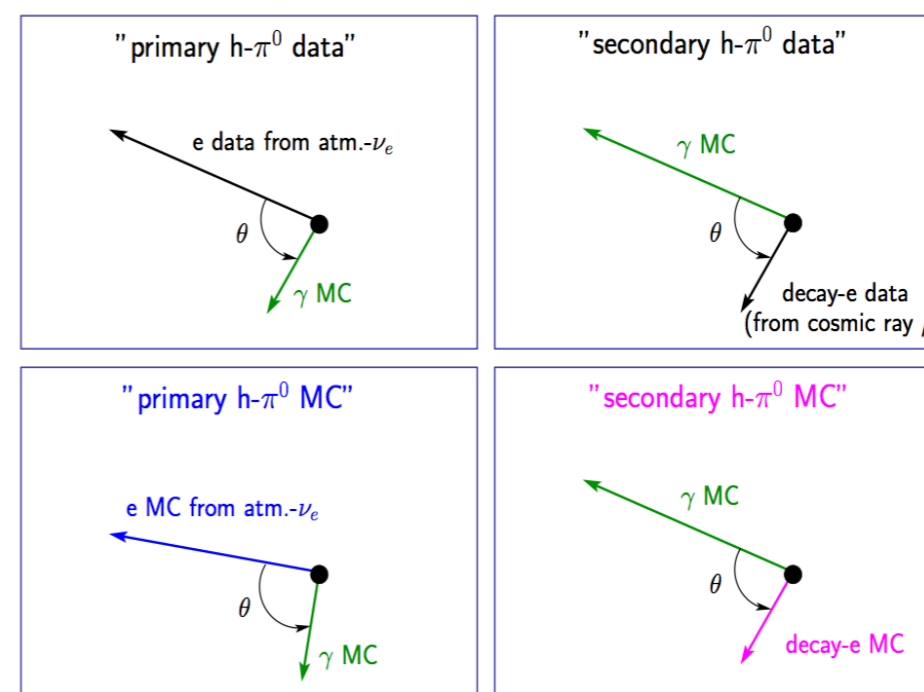
SK error w/ atm- ν fit

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



“Hybrid- π^0 ” samples

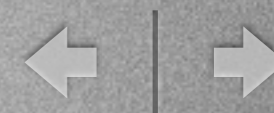
- “Hybrid- π^0 ” samples
 - Electron track from atm- ν data is combined with γ from MC following π^0 decay kinematics



- 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- ν_e (and decay-e from cosmic-ray μ) is the lower energy “ γ ”, and higher energy γ from MC

11

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 ($\theta_1, \varphi_1, \theta_2, \varphi_2$)

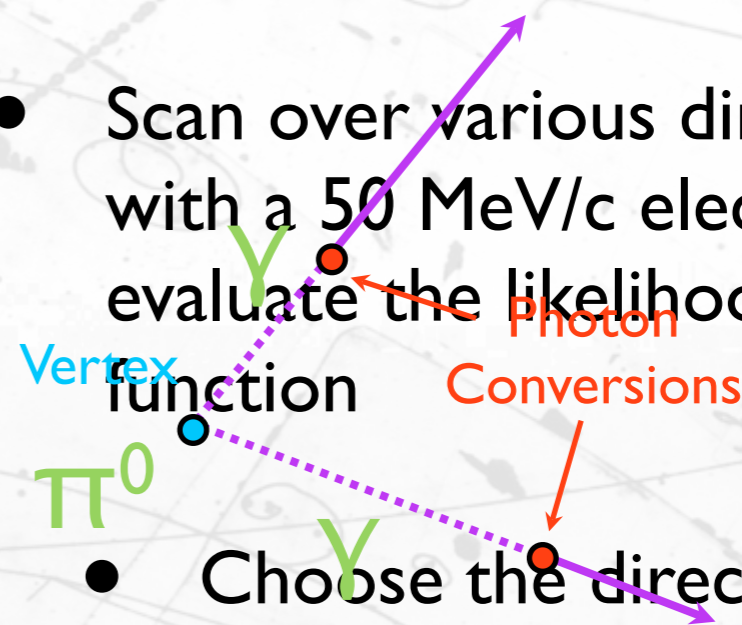
- Momenta (p_1, p_2)

- 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

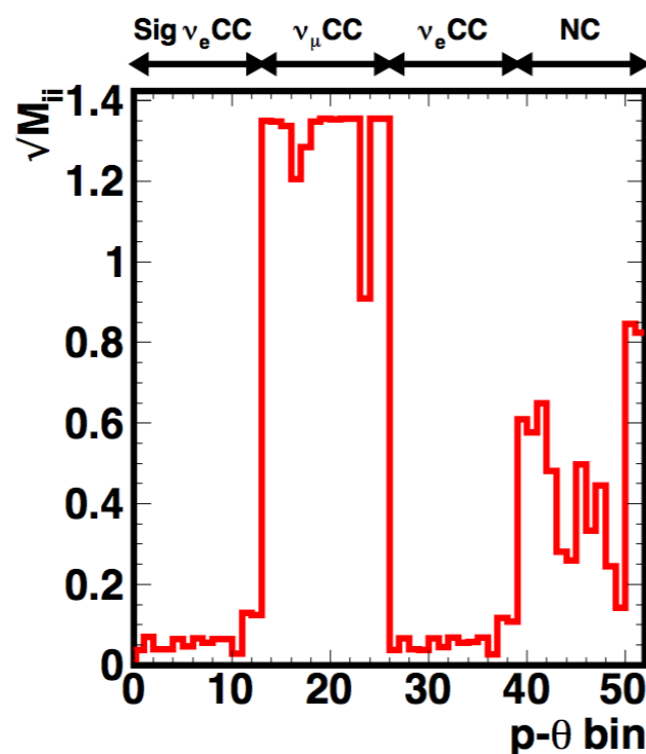
- **Do full 12 parameter fit**



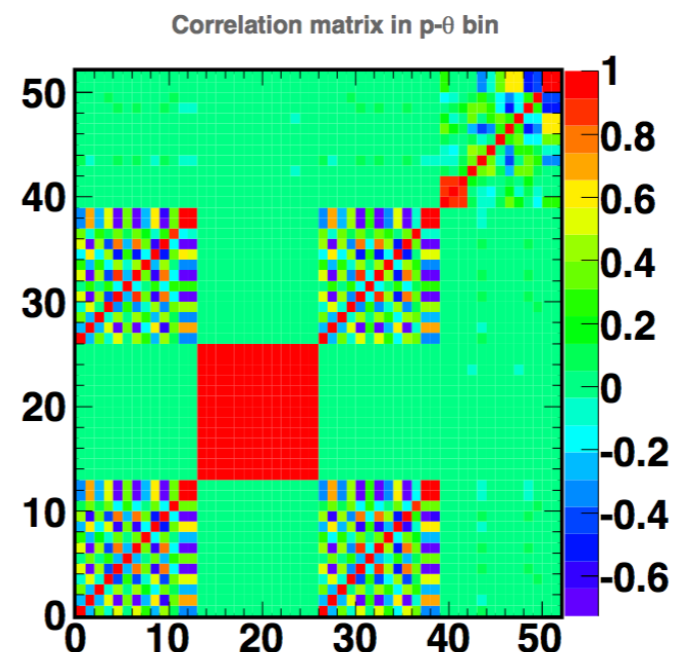
Error matrices in p - θ

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

Square-root of diagonal elements of covariance matrix



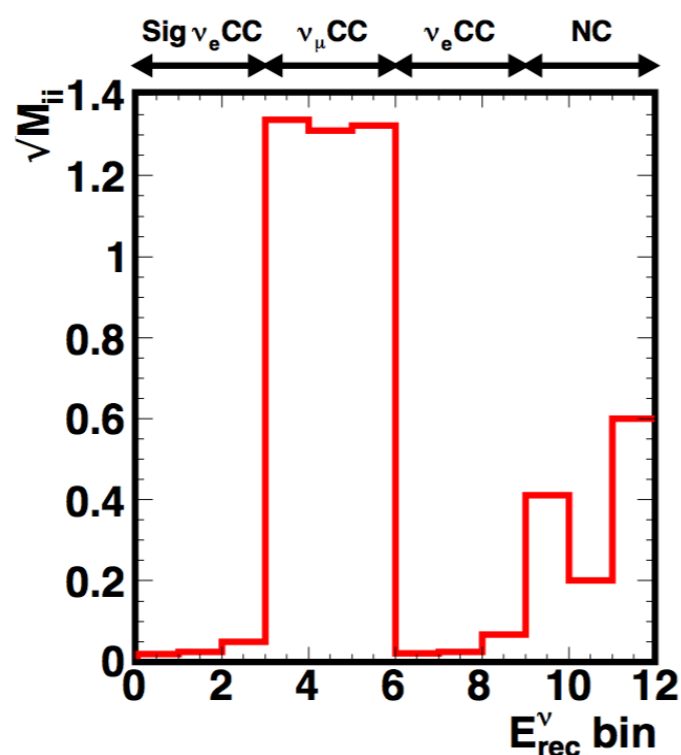
Correlation matrix



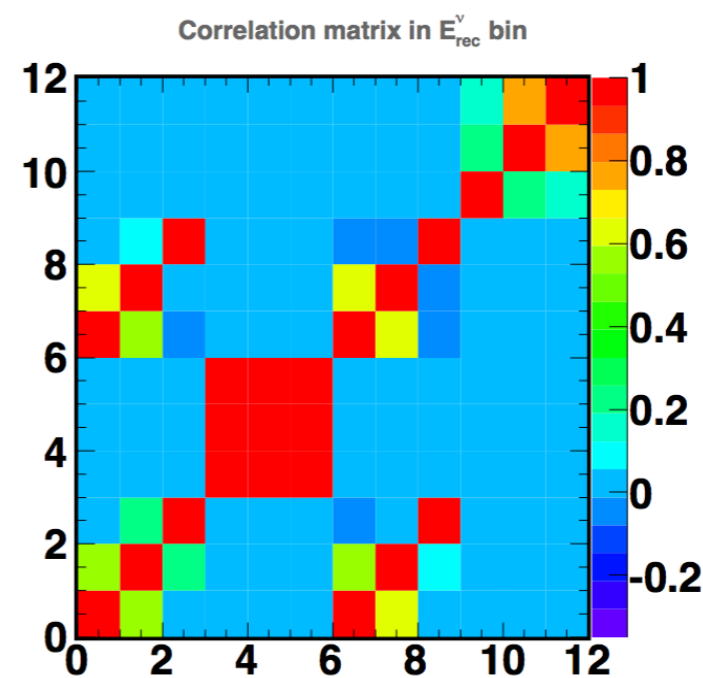
Error matrices in rec E_ν

- Error matrices for inputs to oscillation analyses in E_ν bins

Square-root of diagonal elements of covariance matrix



Correlation matrix



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.

