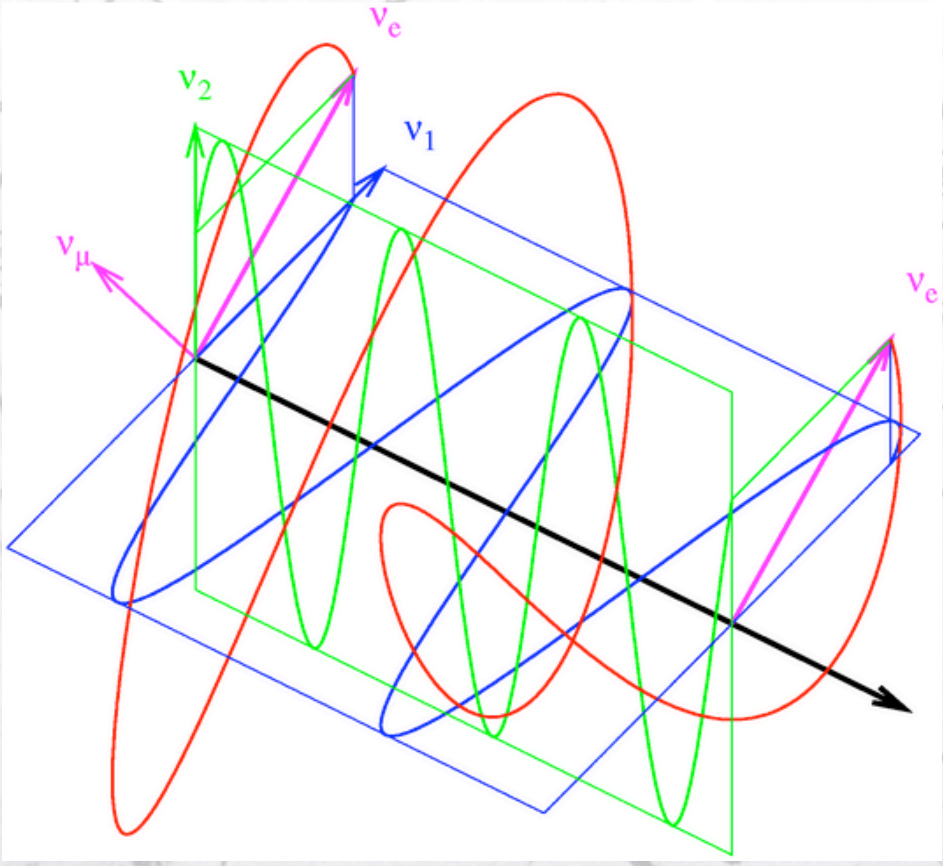
New T2K oscillation results

T2K

Federico Sánchez
IFAE (Barcelona)

Neutrino oscillations

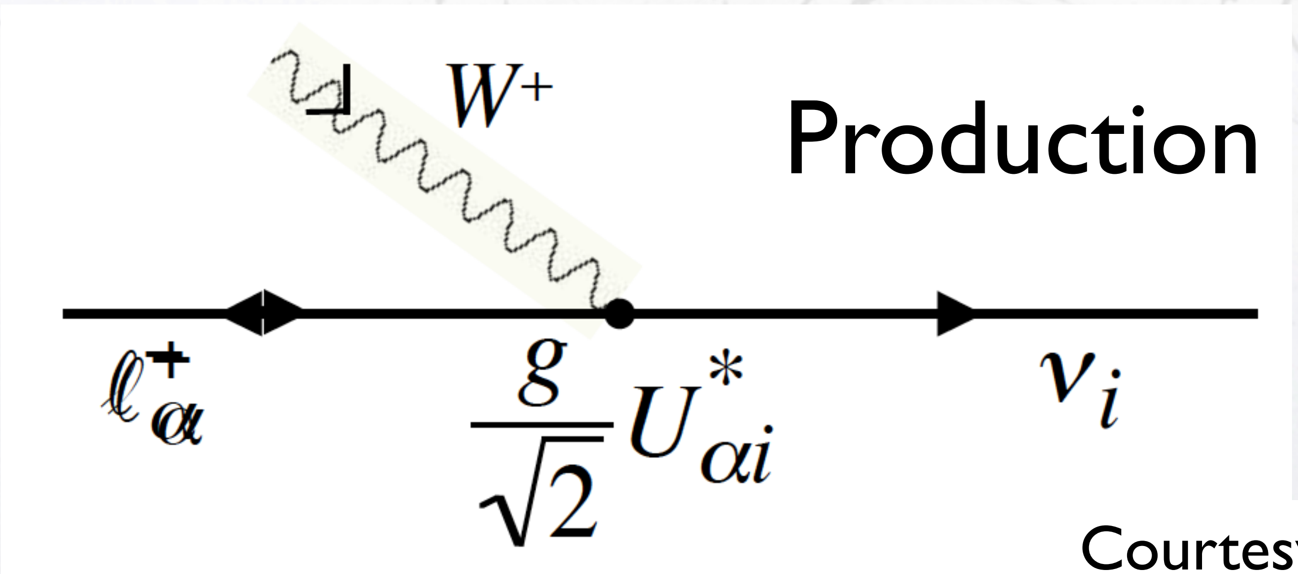


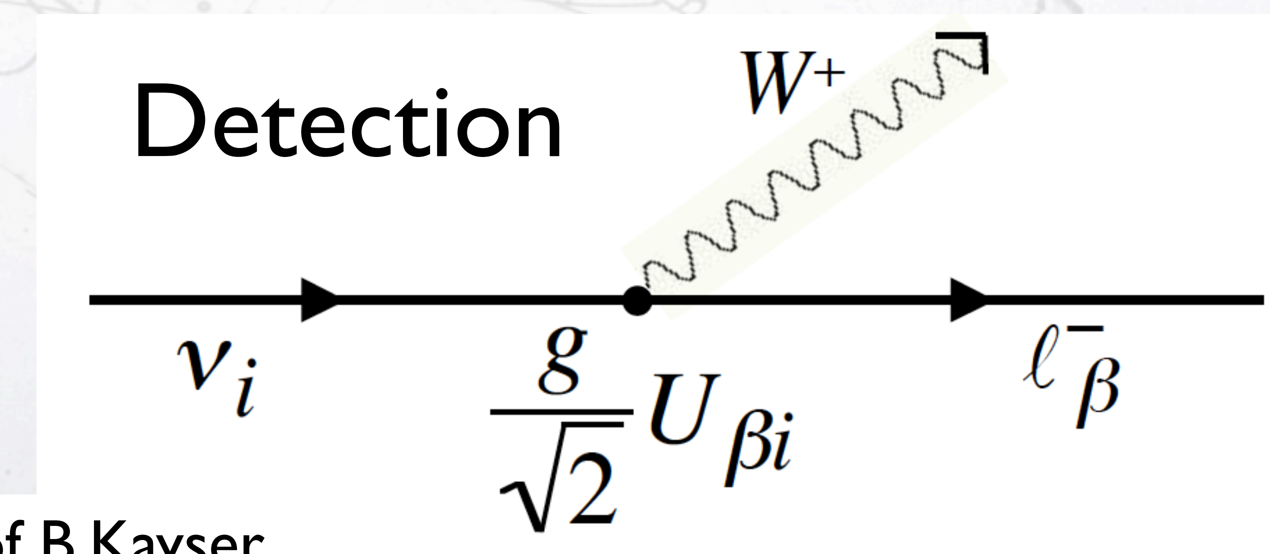
ν oscillations

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

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

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





Courtesy of B.Kayser

ν oscillations

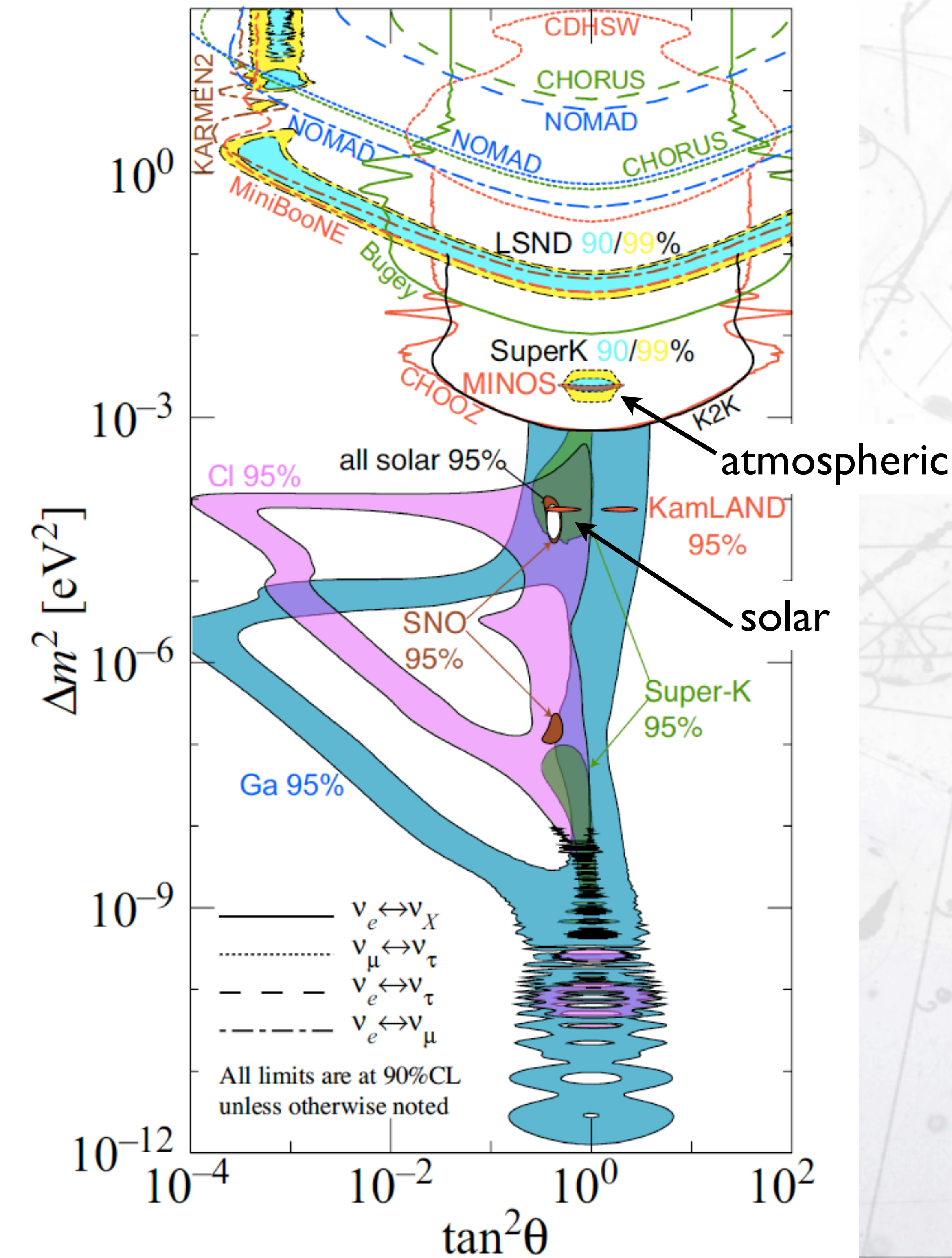
atmospheric   solar

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

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

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

ν oscillations



Particle Data Group neutrino review

Status as of 2012

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

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

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

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

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

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

ν oscillations

What is missing

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

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

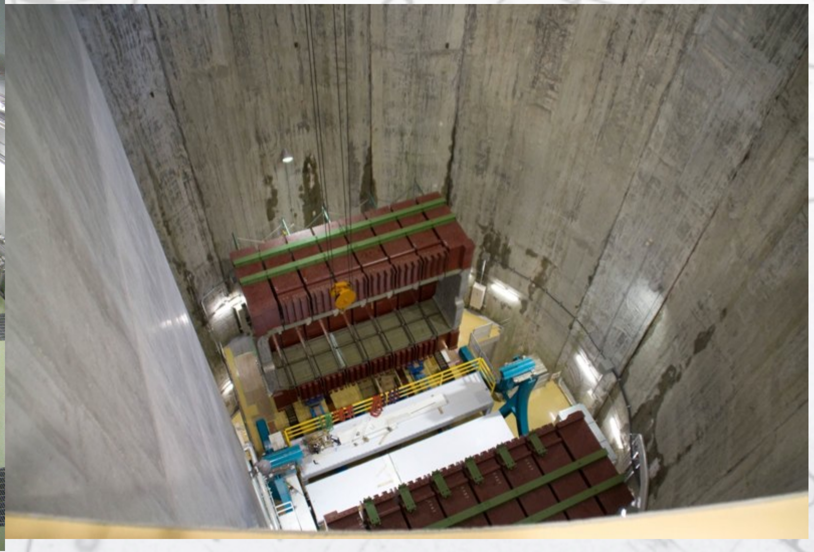
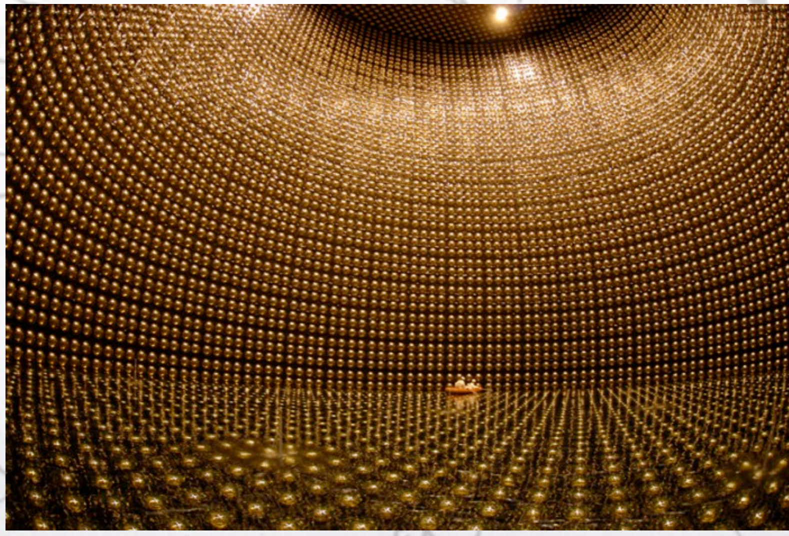
- The absolute neutrino mass.

- The mass hierarchy: is $m_3 > m_1$?

T2K ⊕ NOvA

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.

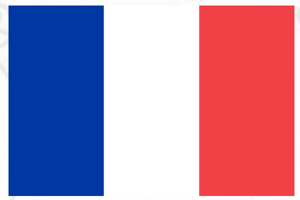





T2K collaboration

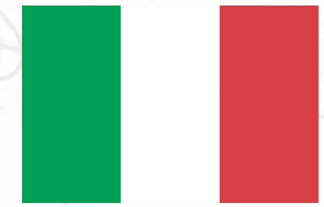
~500 member, 59 institutions, 11 countries.

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



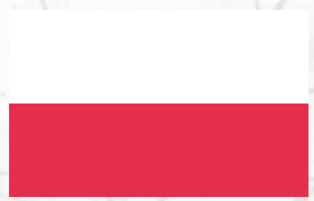
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

RWTH Aachen U.



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

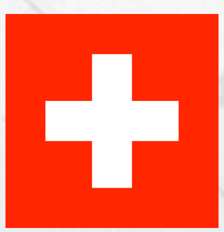
ICRR Kamioka
ICRR RCCN Kavli
IPMU KEK Kobe
U. Kyoto
U. Miyagi
U. Edu. Osaka City
U. Okayama
U. Tokyo Metropolitan
U. U. Tokyo



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

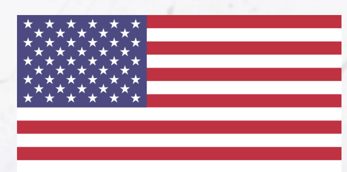
INR

IFAE, Barcelona
IFIC, Valencia

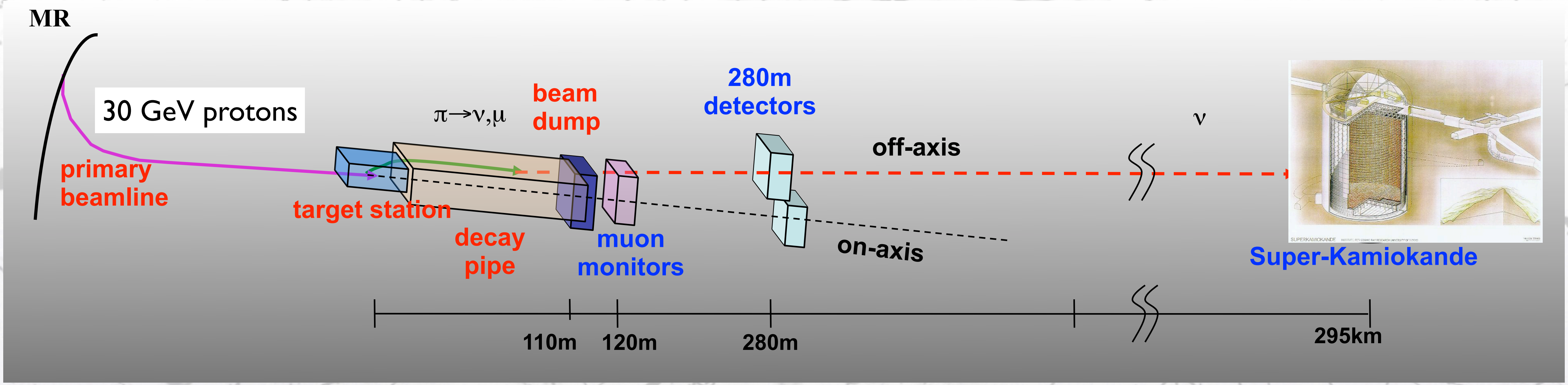


ETH Zurich
U. Bern
U. Geneva

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

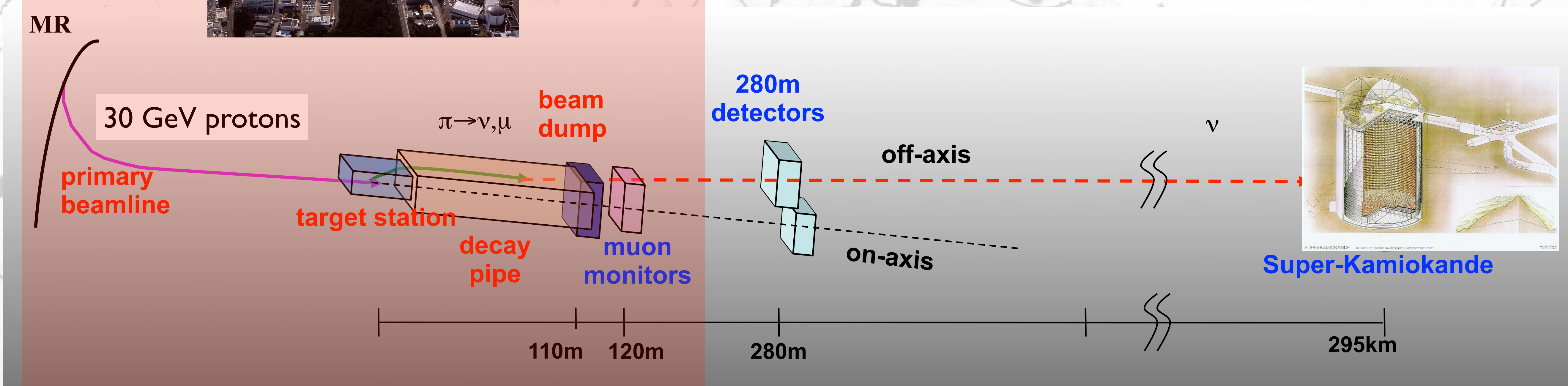


Beam

ND280

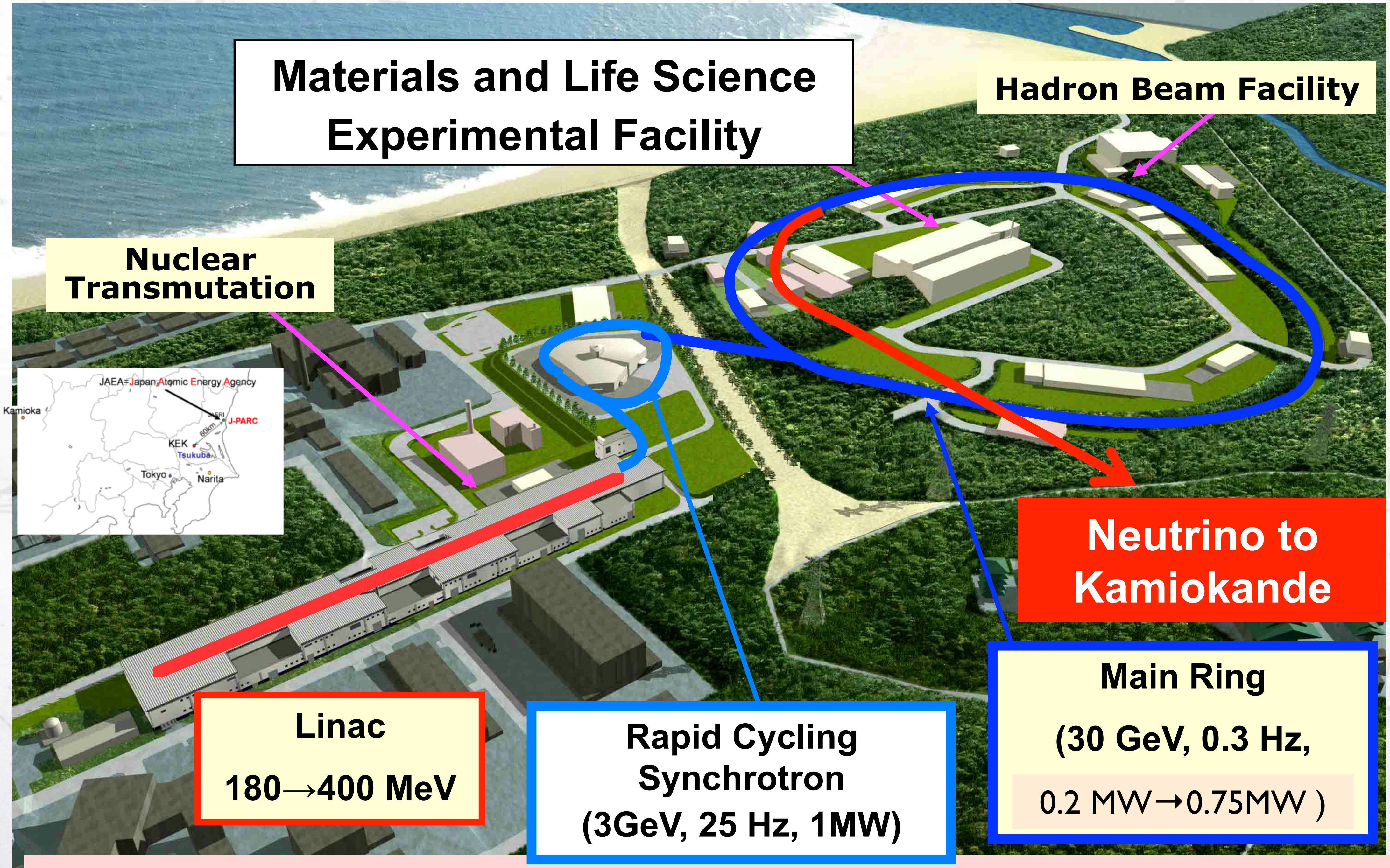
Super-Kamiokande

Beam



Beam ND280 Super-Kamiokande

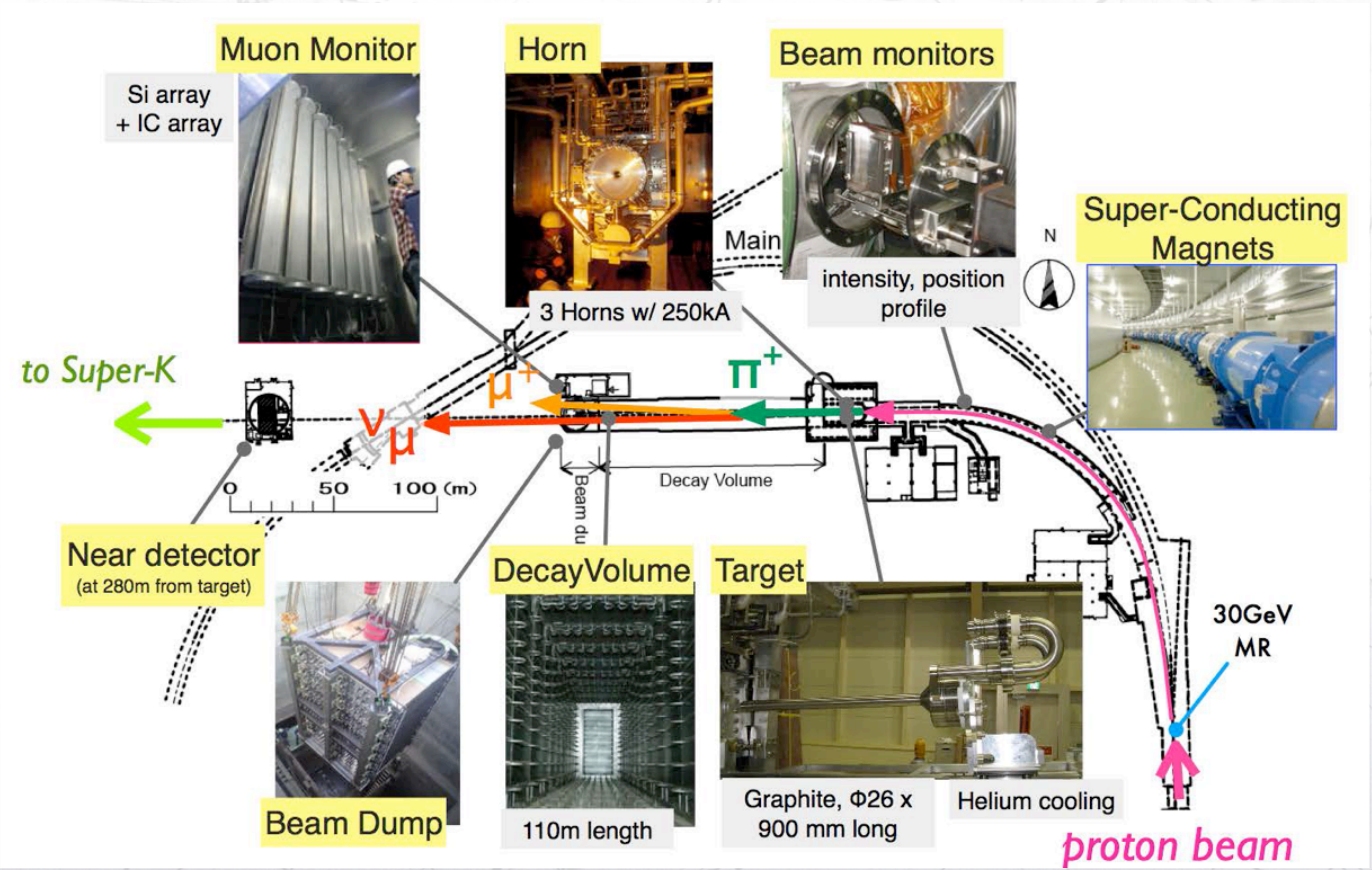
J-PARC



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

ν beam

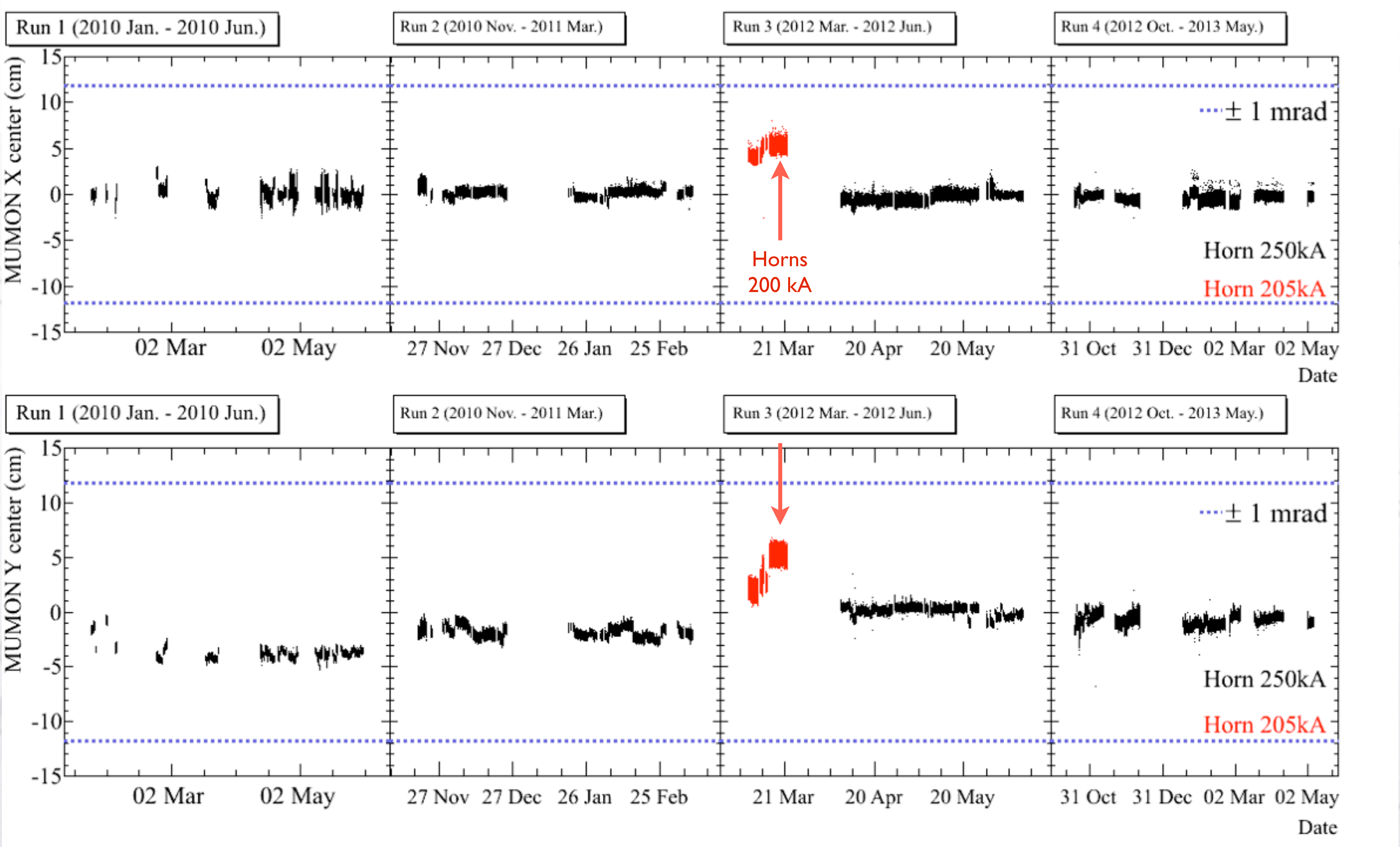


Muon Monitor
Si array
+ IC array
Horn
Beam monitors
Main
intensity, position profile
Super-Conducting Magnets
N
3 Horns w/ 250kA
to Super-K
μ^+
π^+
ν_μ
0 50 100 (m)
Decay Volume
Near detector
(at 280m from target)
DecayVolume
Target
30GeV MR
Beam Dump
110m length
Graphite, Φ26 x 900 mm long
Helium cooling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

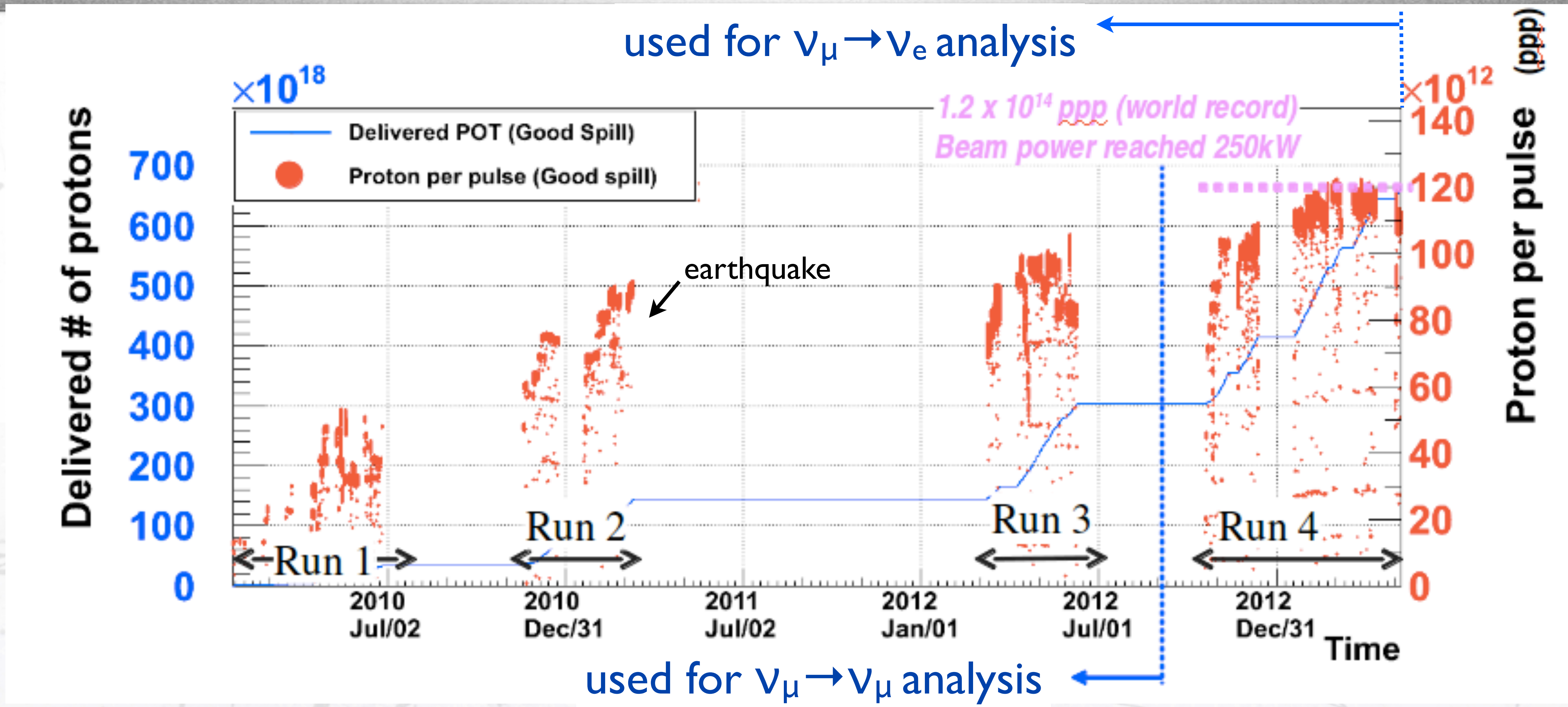
Beam stability

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

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



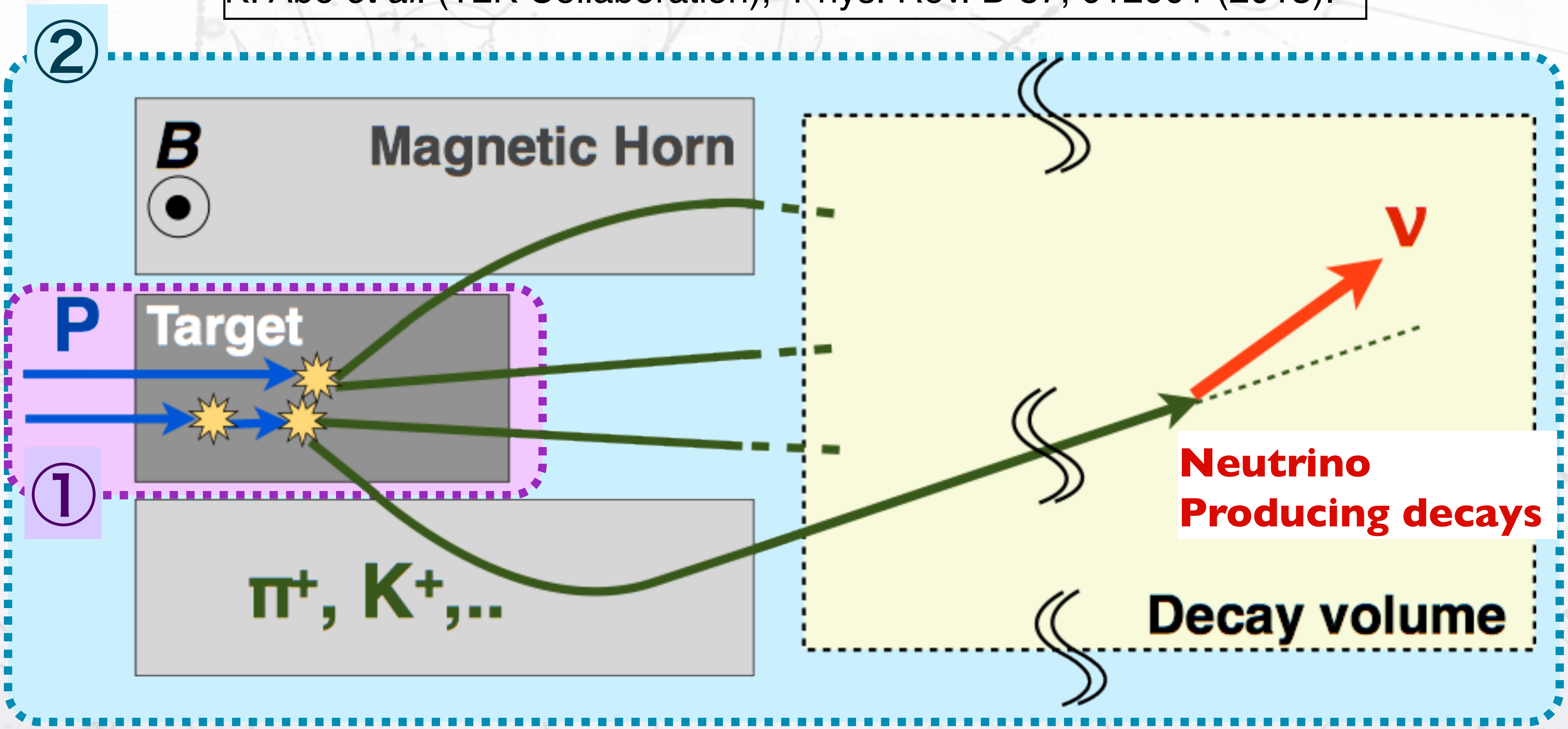
Data sets



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

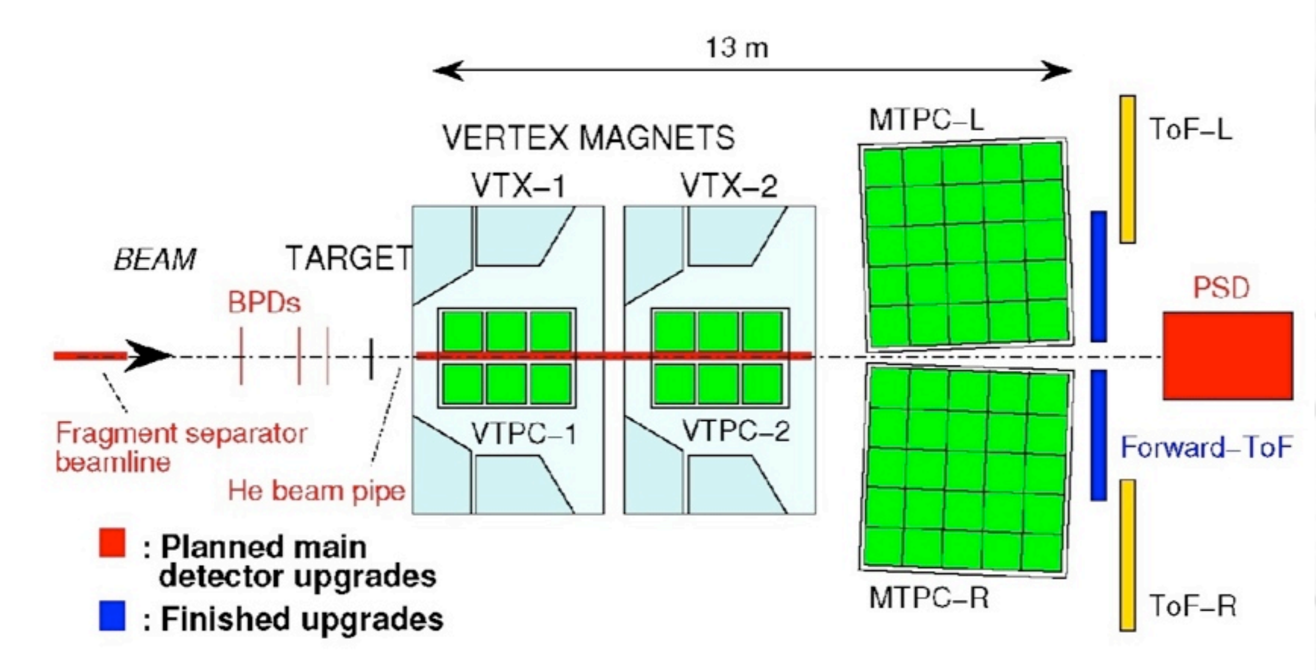
Flux prediction

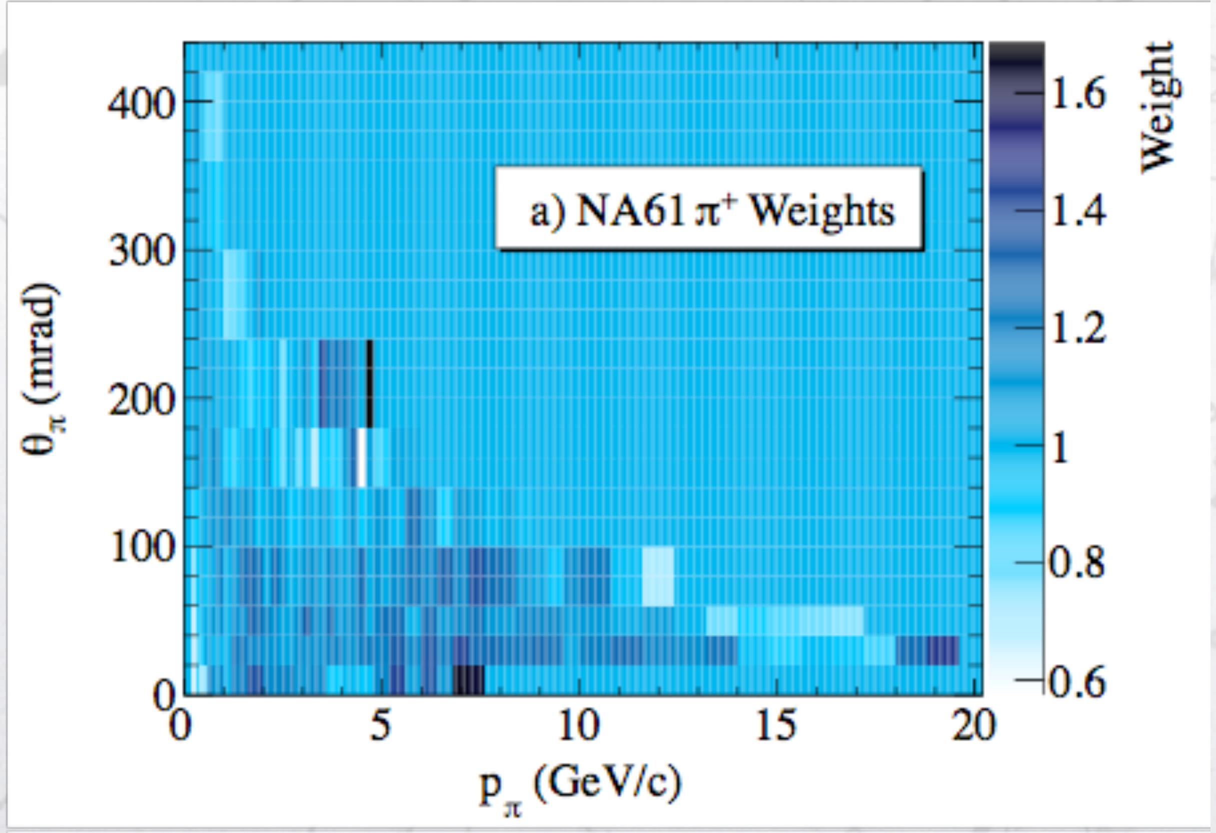
K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



NA61: Shine

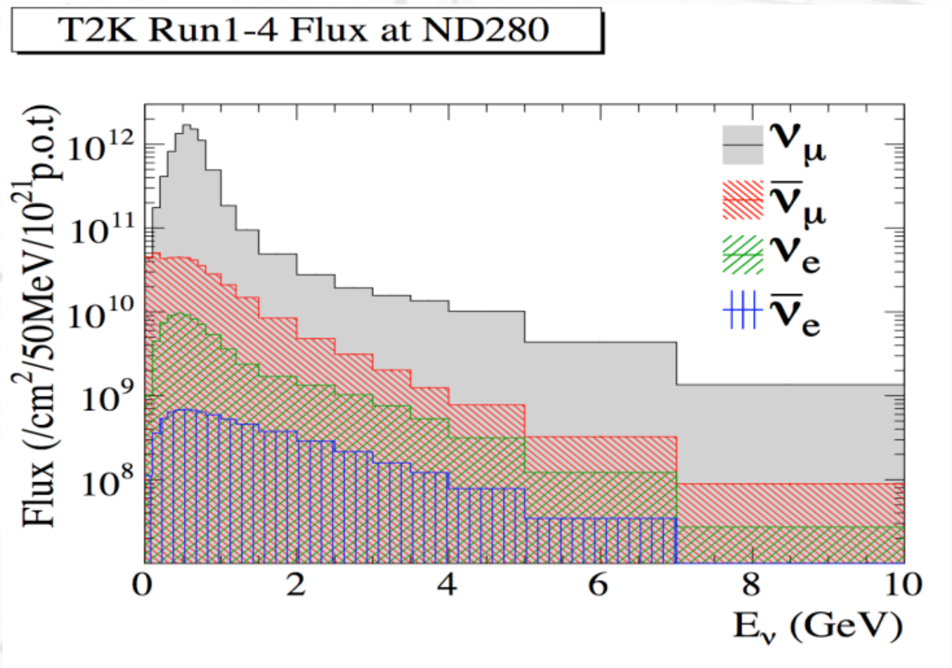
NA61/Shine measures for T2K the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.



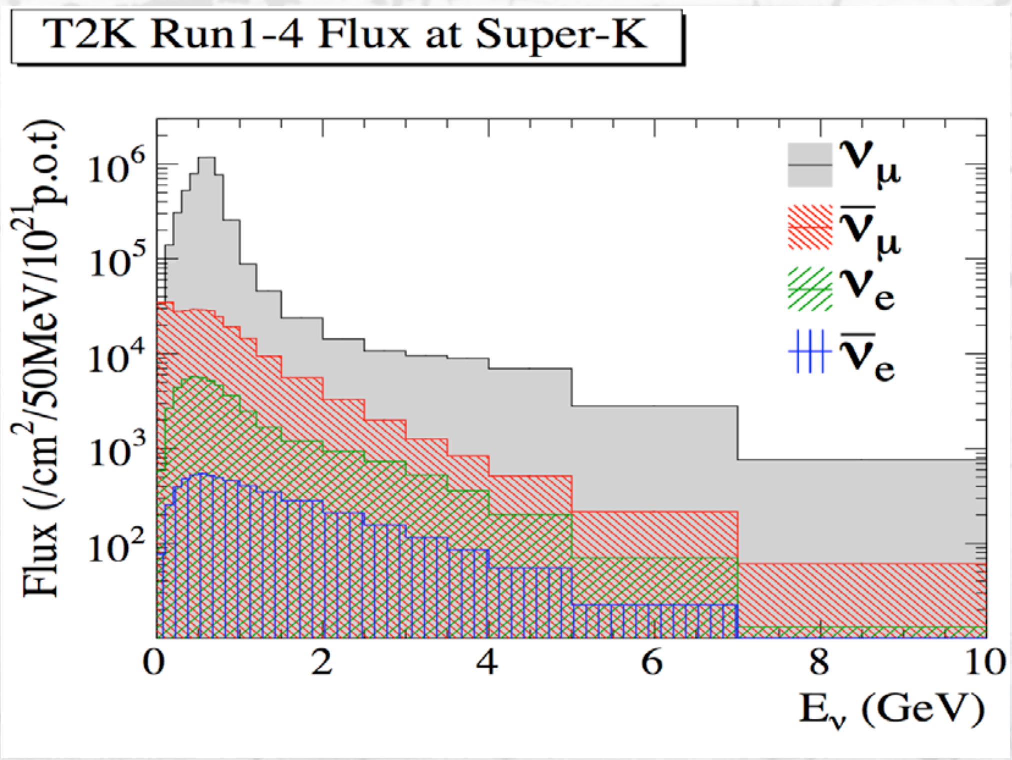


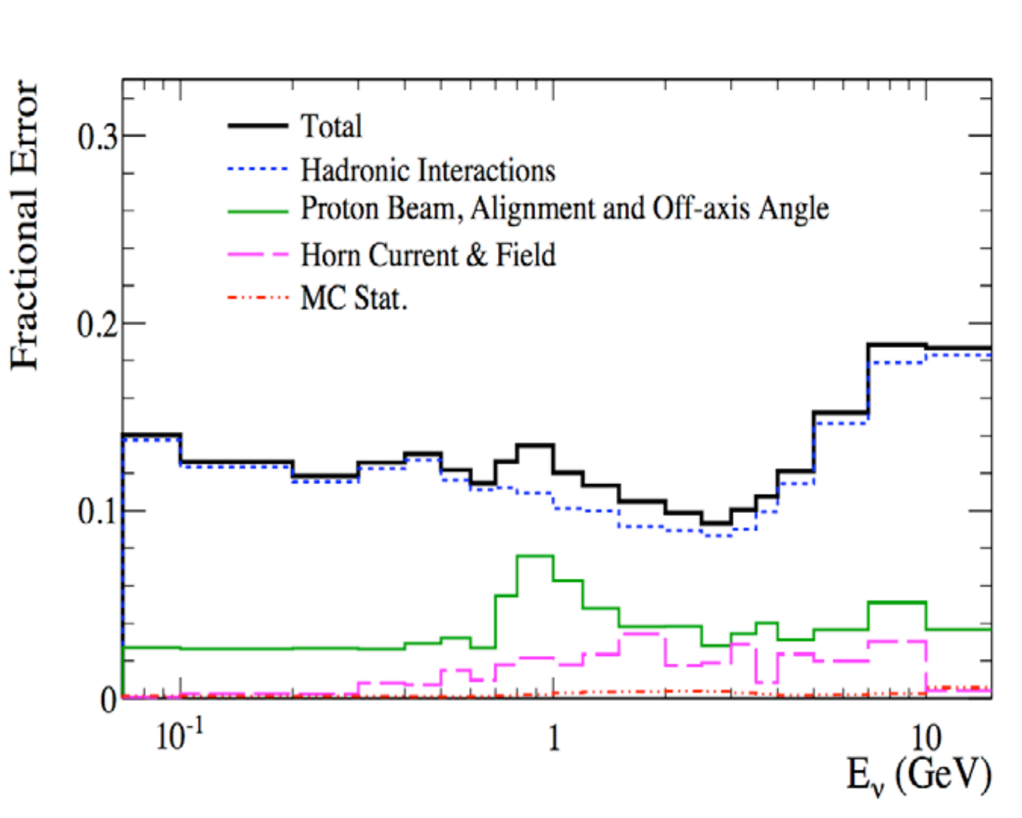
NA61/Shine measures a thin target for absolute production and thick target that is a copy of T2K target and provides also the reinteractions.

Flux prediction



- 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.

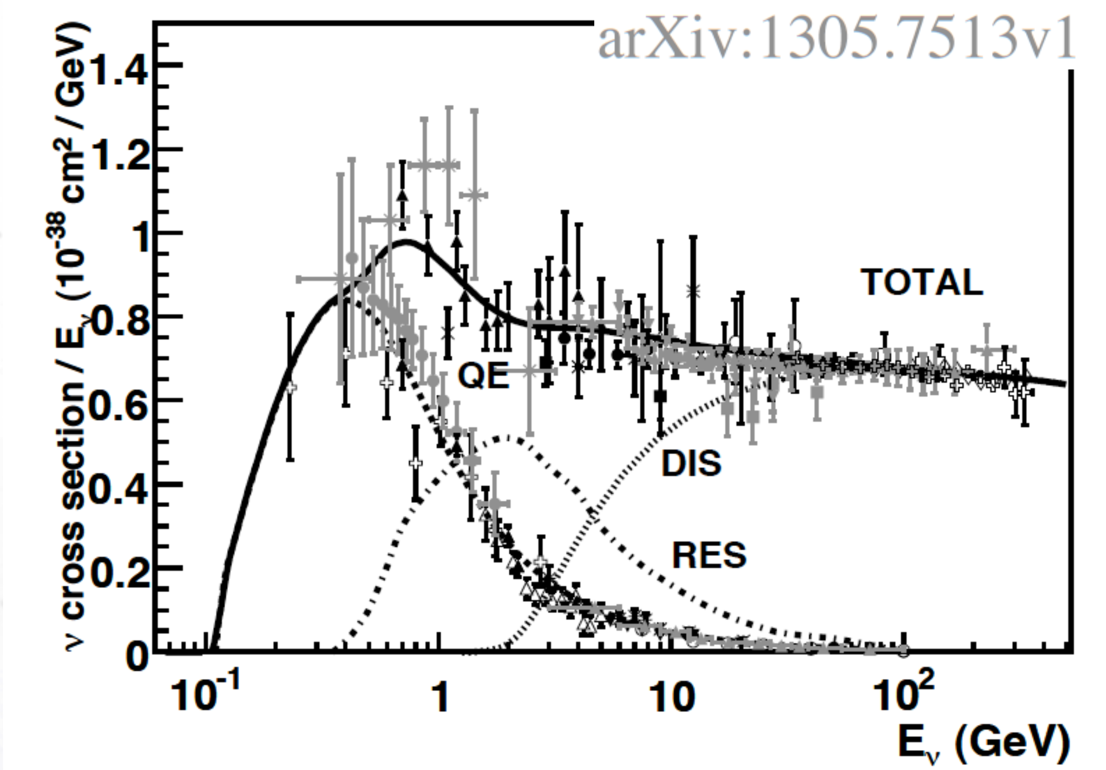


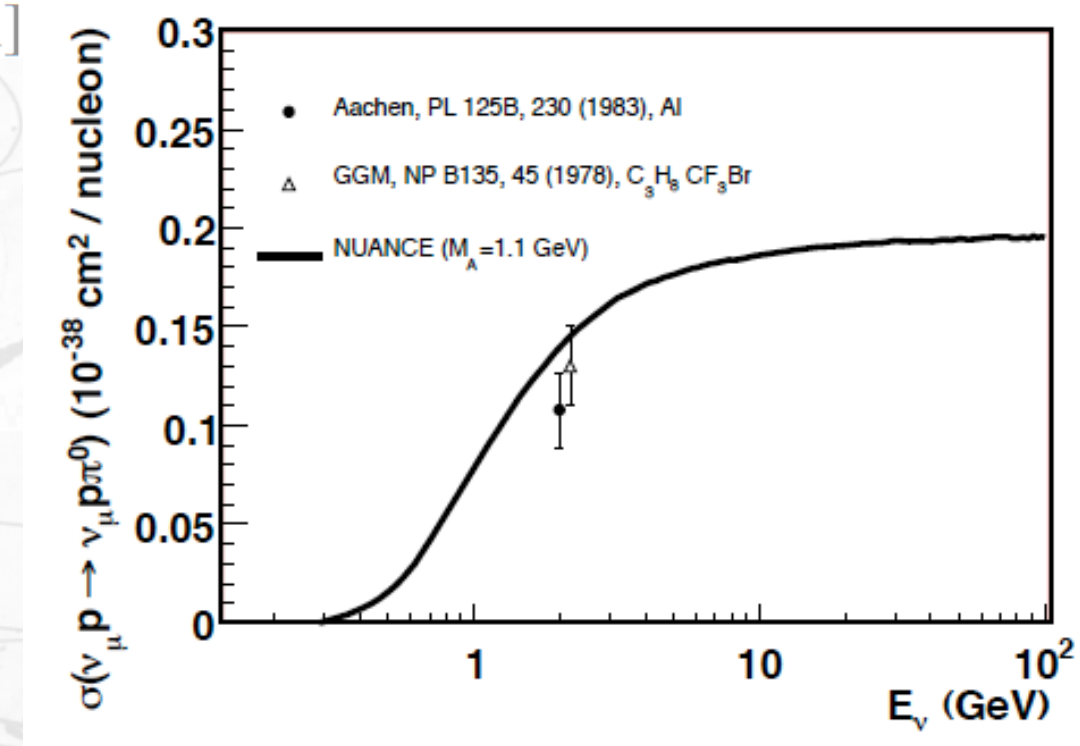


$\sigma_{\nu N}$

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

arXiv:1305.7513v1 [hep-ex]



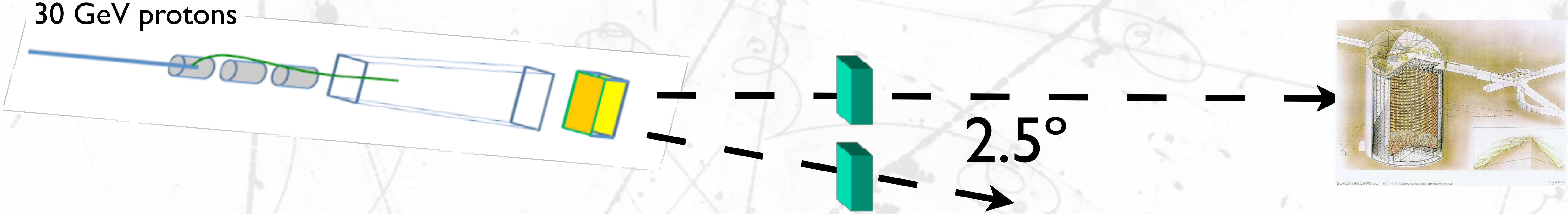


Charge current	
CC-QuasiElastic	$\nu_\mu n \rightarrow \mu^- p$
CC-Resonance	$\nu_\mu N \rightarrow \mu^- \pi^{+,0} N$
CC-Deep Inelastic	$\nu_\mu N \rightarrow \mu^- X$

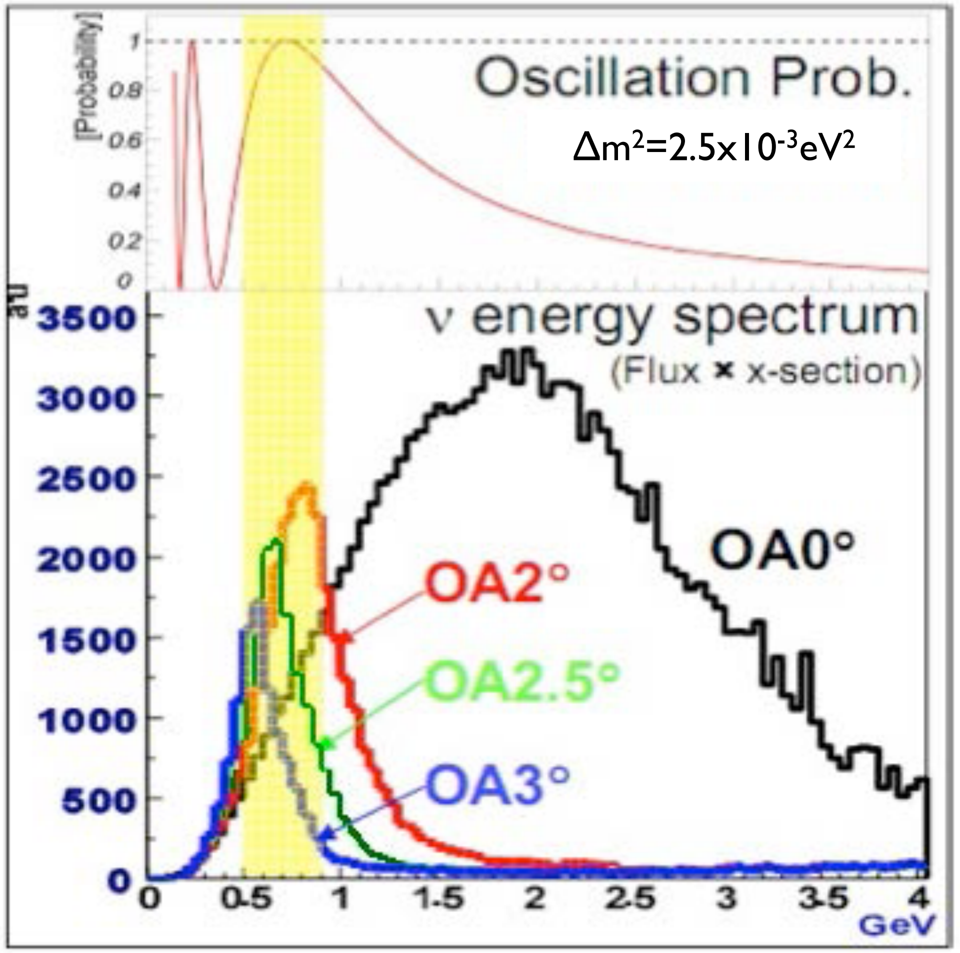
Neutral current	
NC-Elastic	$\nu_\mu (n,p) \rightarrow \nu_\mu (n,p)$
NC-Resonance	$\nu_\mu N \rightarrow \mu^- \pi^{+,0} N$
NC-Deep Inelastic	$\nu_\mu N \rightarrow \nu_\mu X$

Off-axis concept

T2K runs 2.5° off-axis

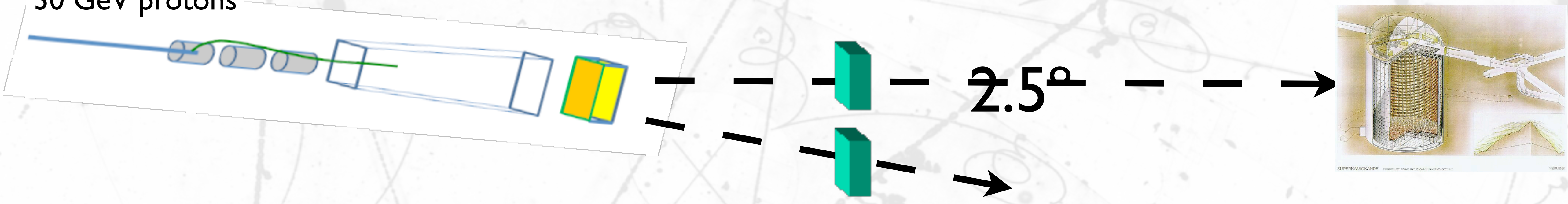


- off-axis optimises the flux at the maximum of the oscillation.

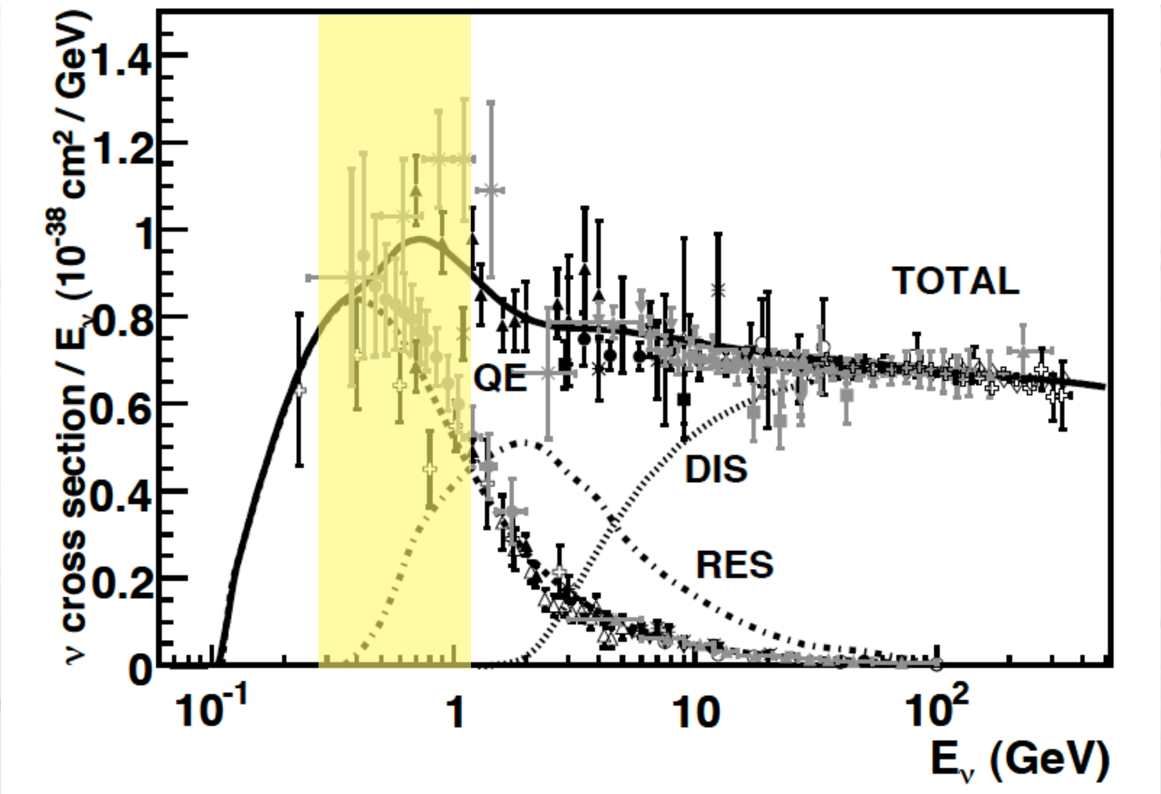


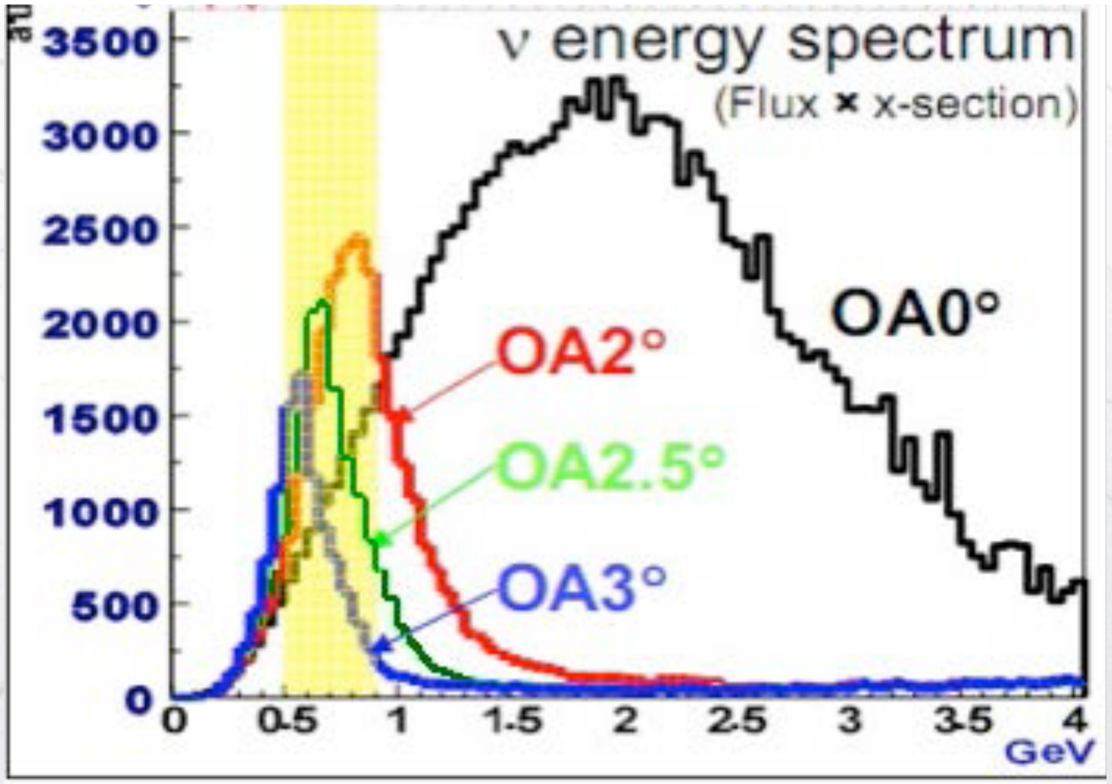
Off-axis concept

T2K runs 2.5° off-axis

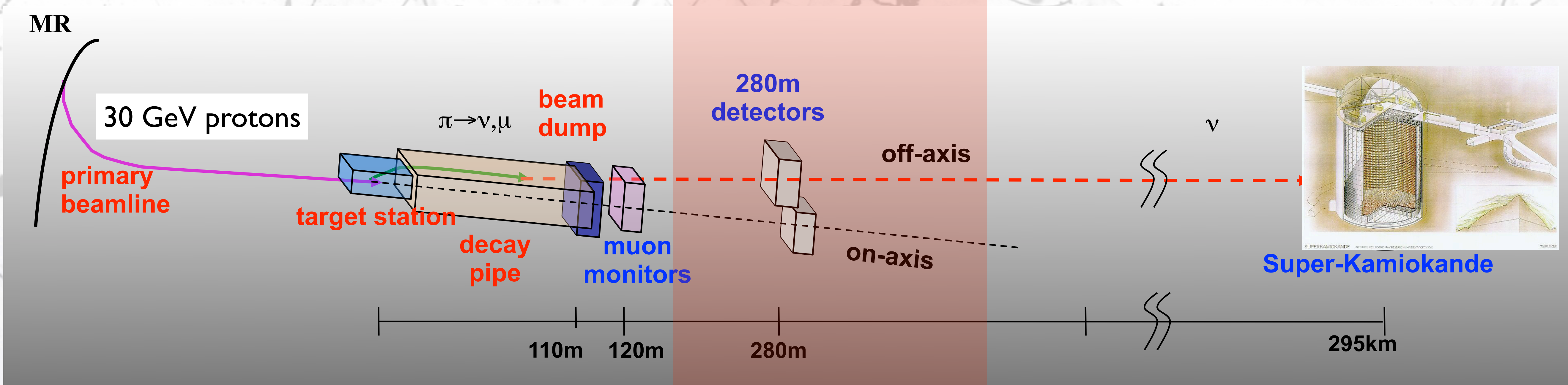


- off-axis reduces the high energy contamination ($NC\pi^0$ and non-CCQE backgrounds.)





ND280

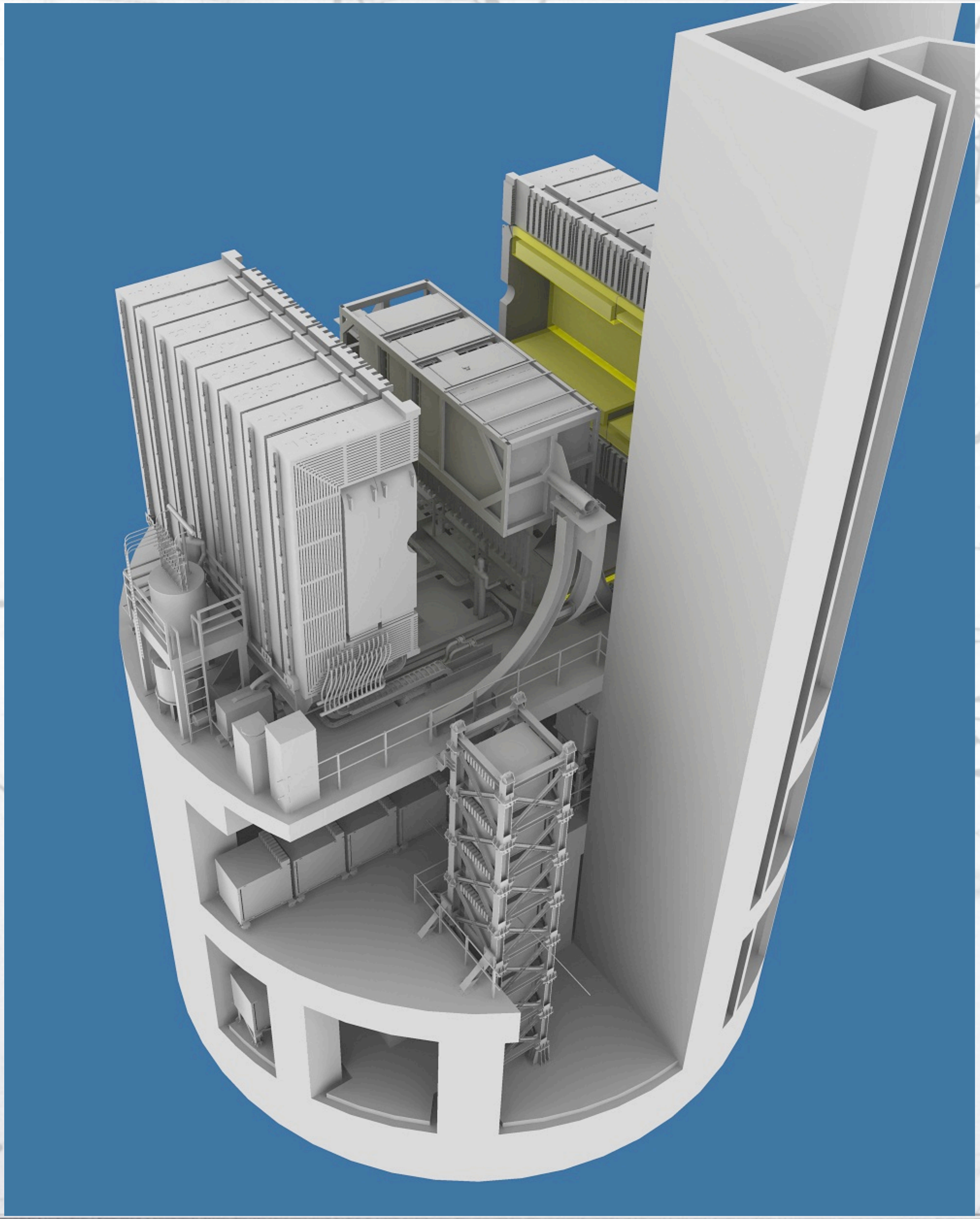


Beam

ND280

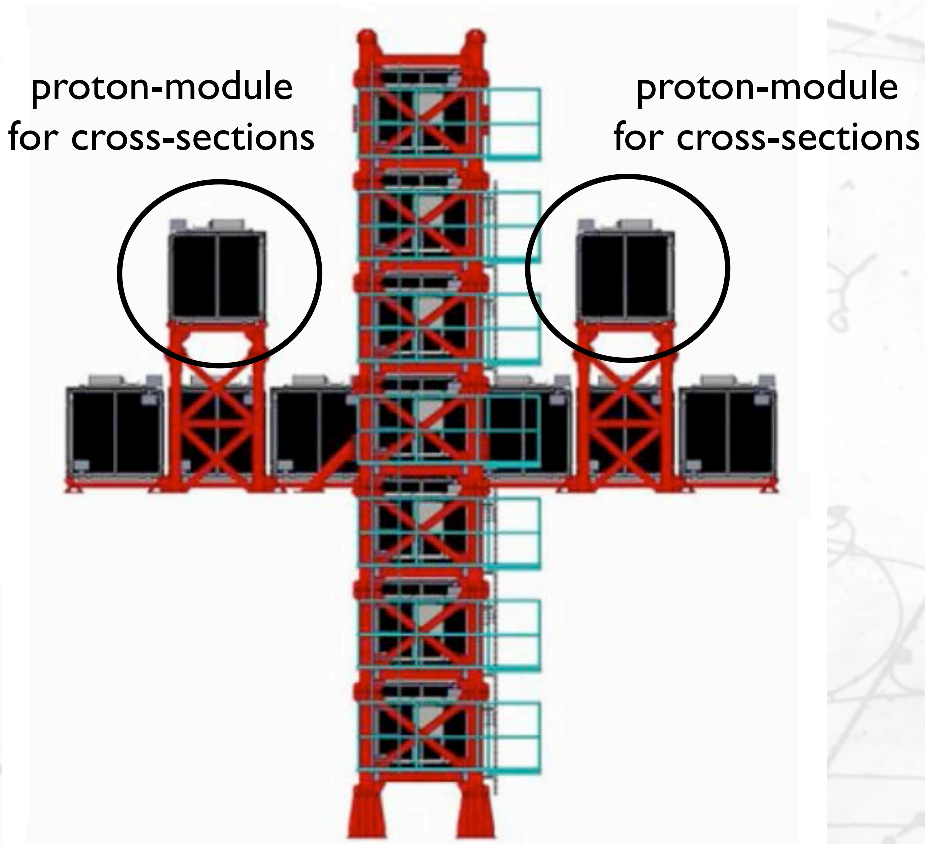
Super-Kamiokande

ND280

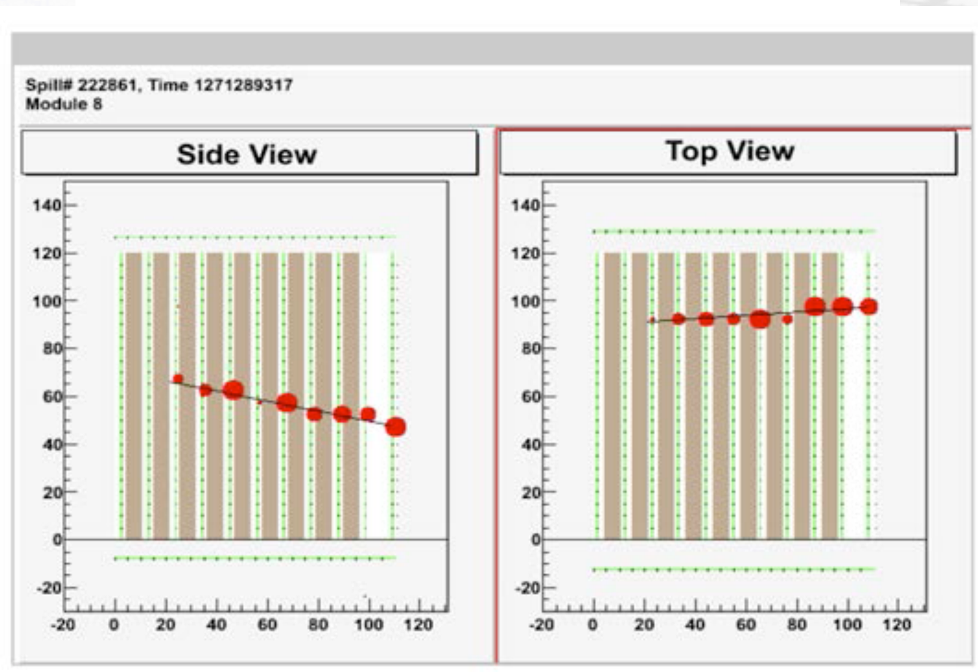


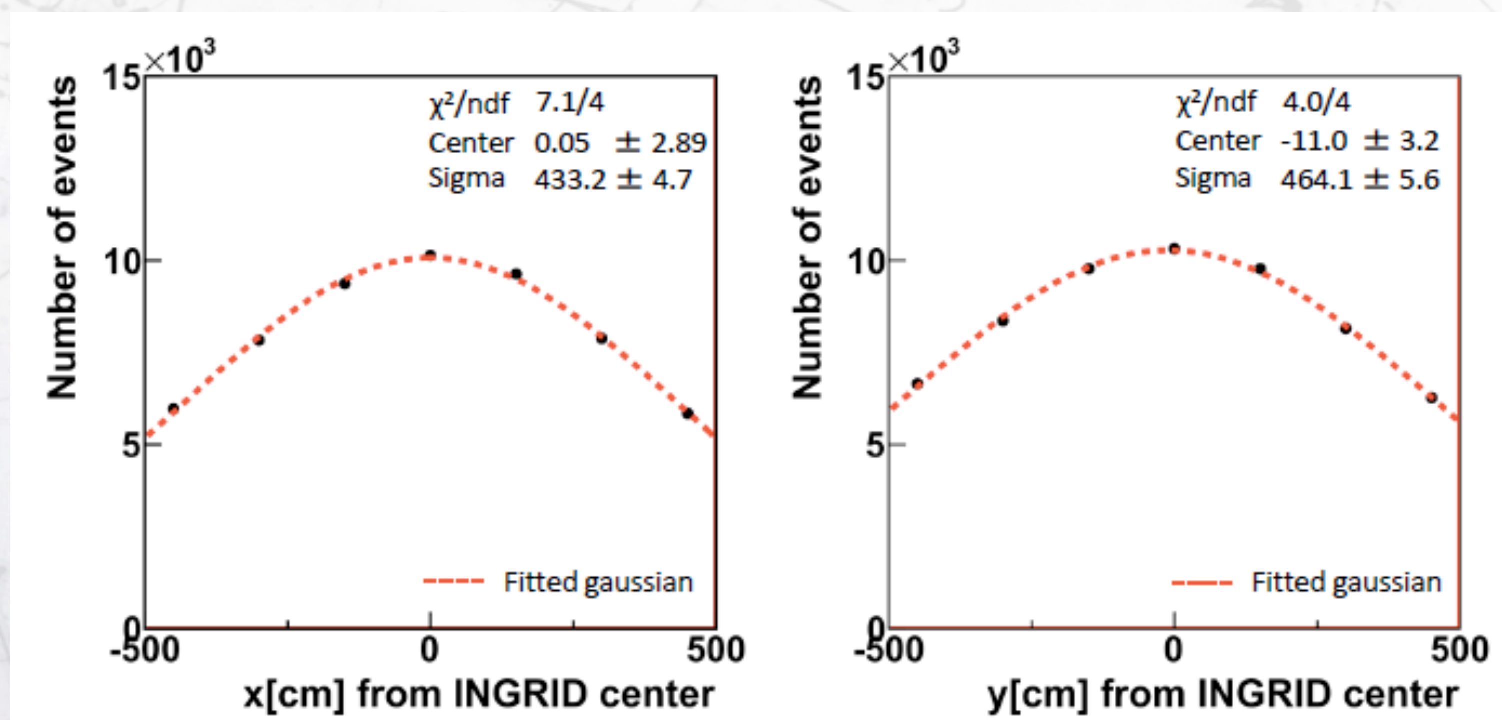
- ND280 is the near detector facility with two main detectors located 280m from the proton interaction point:
  - On-axis INGRID.
  - Off-axis ND280m.
- Three main purposes:
  - ν beam stability.
  - ν cross-sections.
  - ν beam flux constraint.

On-axis (INGRID)

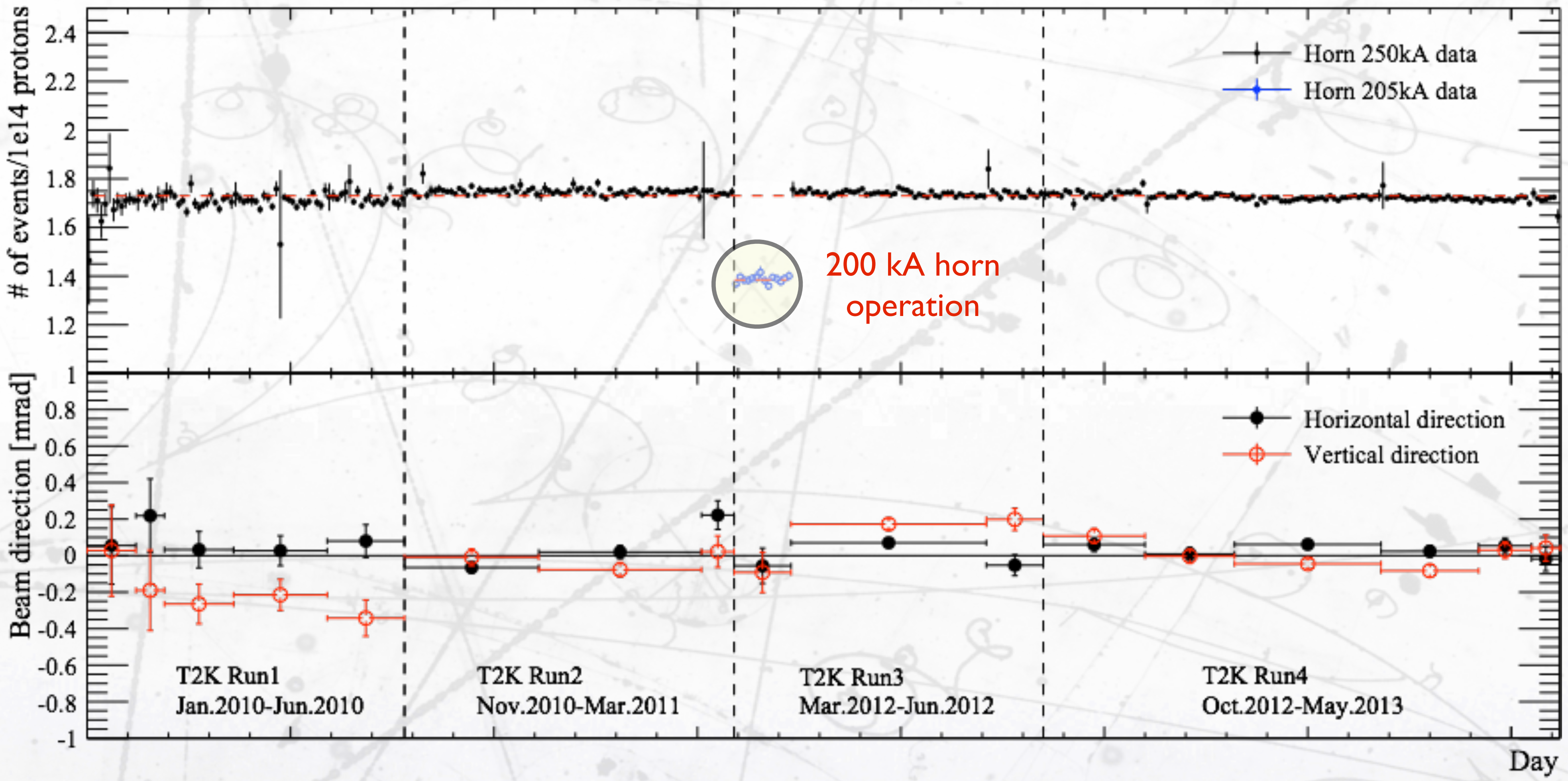


- INGRID counts ν CC events in a cross of 13 identical detectors:
  - total rate monitors beam intensity stability with respect to proton on target counting.
  - The relative event counts between modules monitor the beam direction stability.





On-axis: beam stability



Beam alignment and flux measured with neutrinos

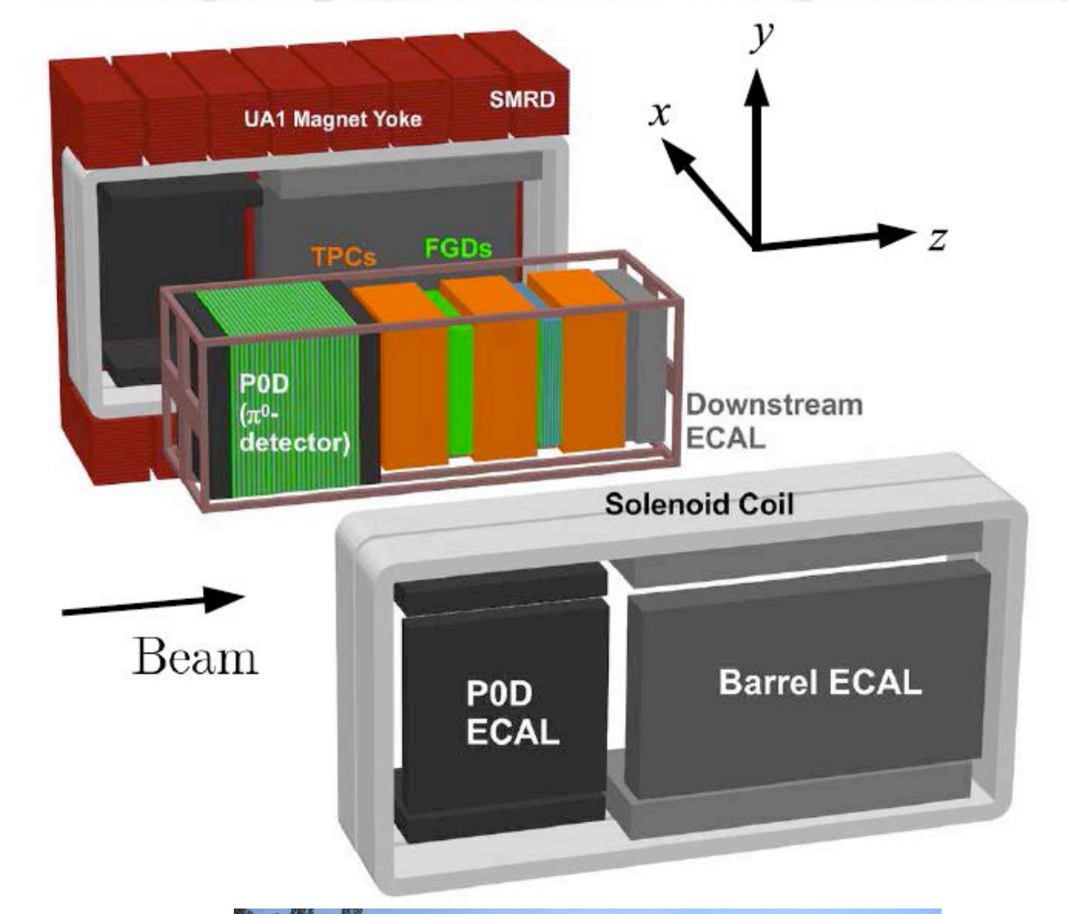
- Neutrino rate stable within 0.7%.
- Beam direction variation << 1 mrad.

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.

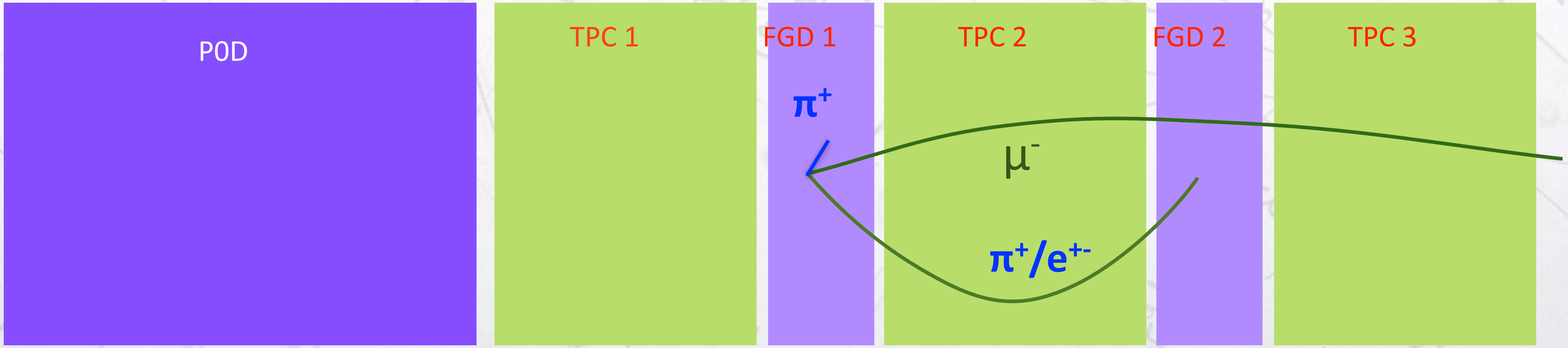
Magnet was granted by CERN



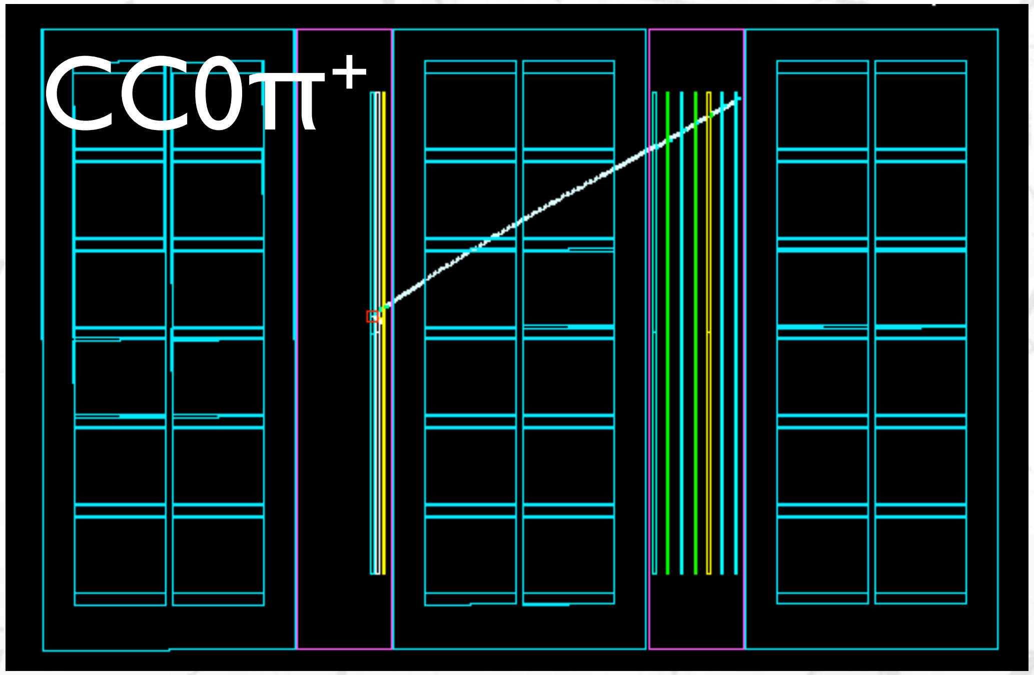
Magnet @ CERN Prévessin

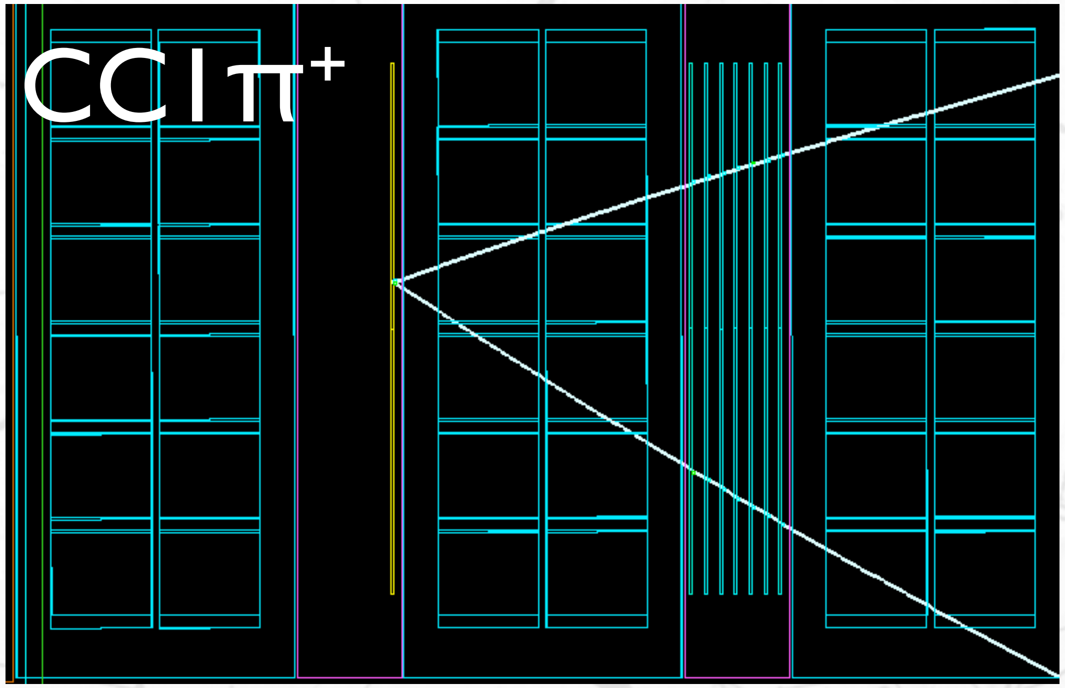
Off-axis: ν_μ analysis

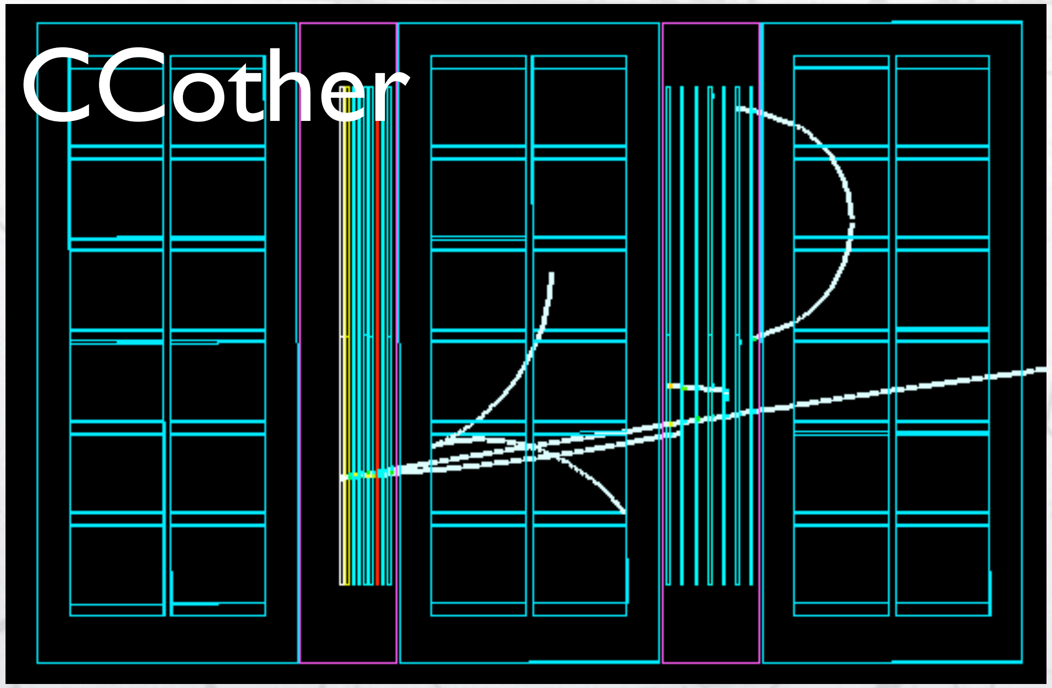
- The ND280 constrains flux and cross-section.
- Sample of CC events is selected. Muon as highest momentum negative track in the event in the target fiducial volume compatible with muon Pid in TPC.
- The sample is divided in 3 categories: $0\pi^+$, $1\pi^+$ and others (mainly Deep Inelastic Scattering)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



Off-axis: ν_μ analysis

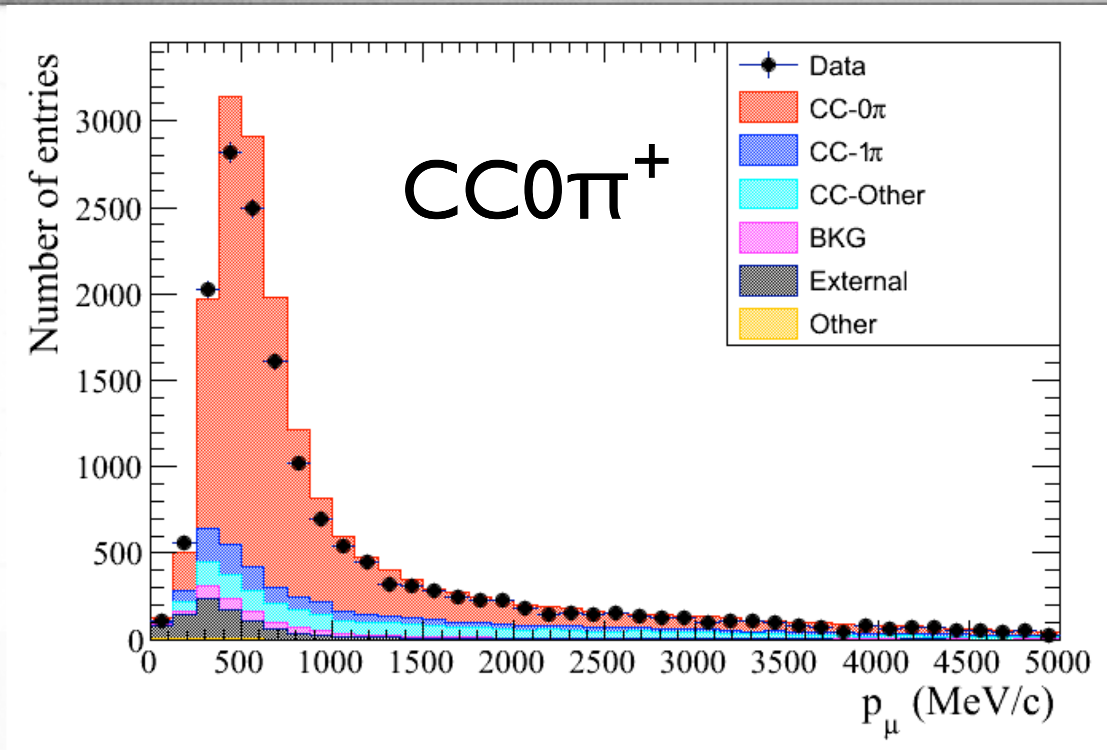


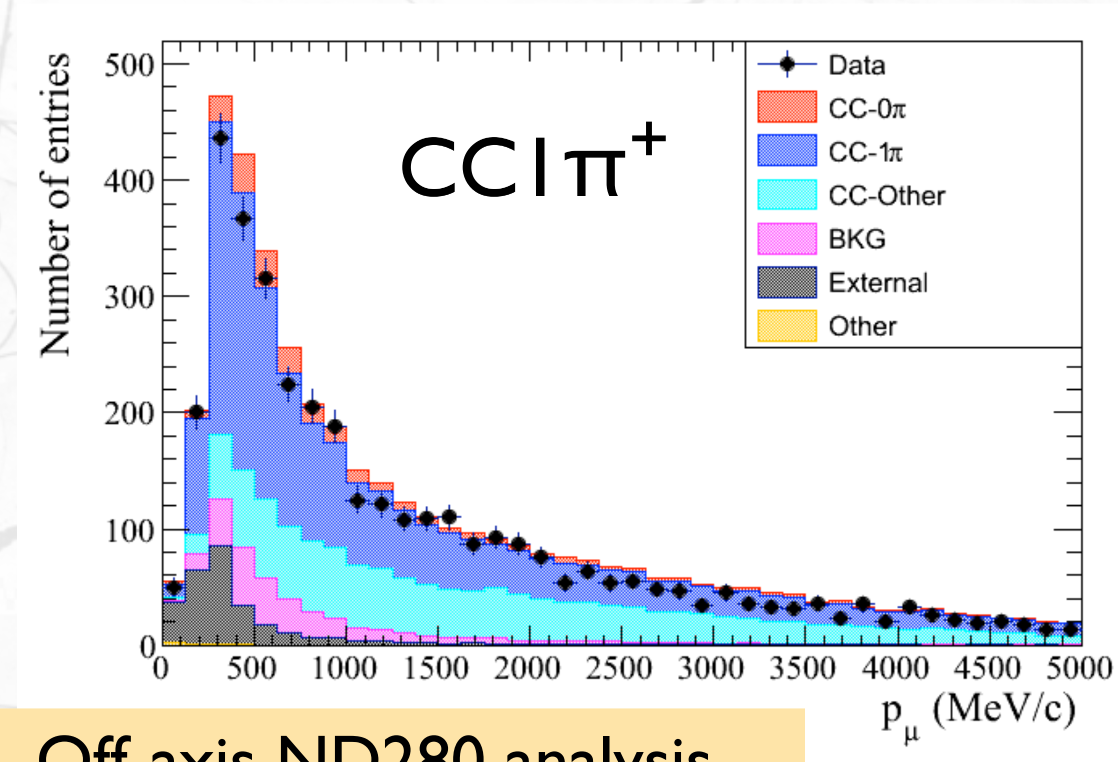


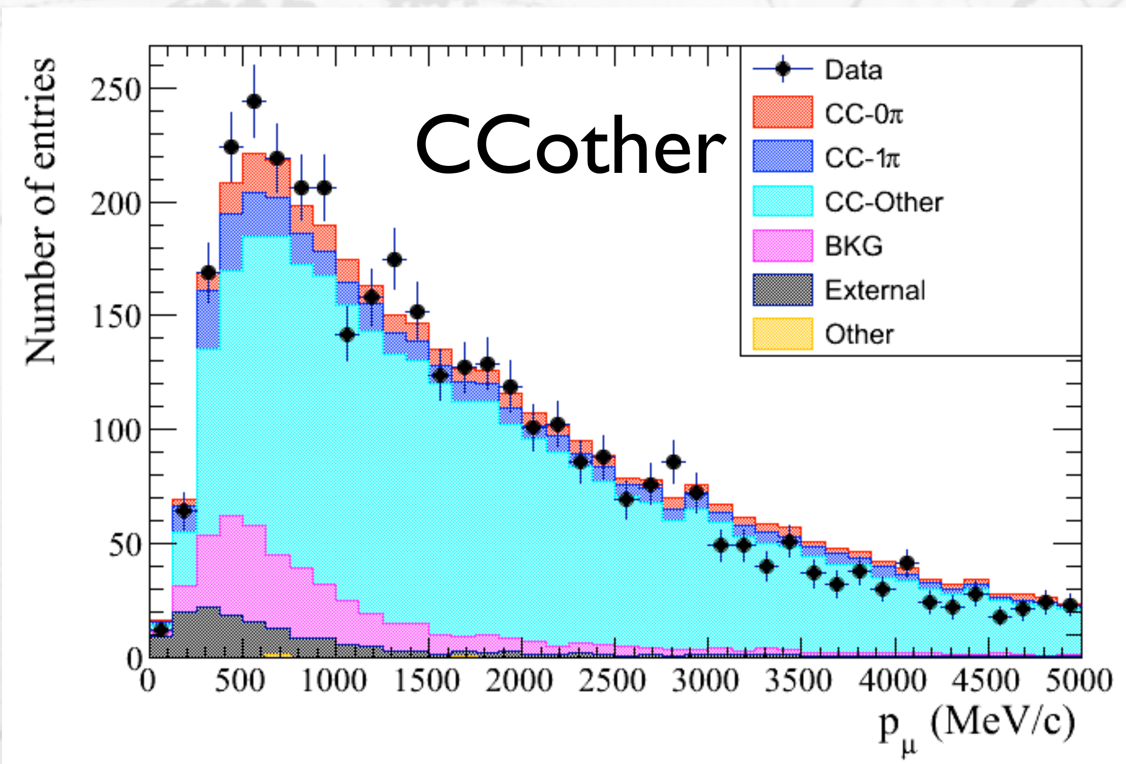


Off-axis ND280 analysis real events

Off-axis: ν_μ analysis



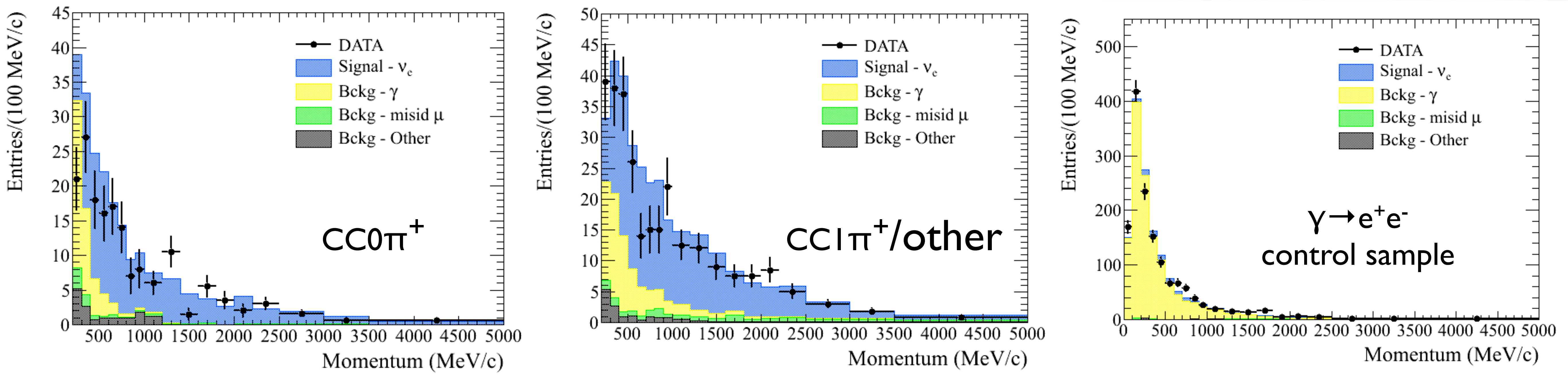




Off-axis ND280 analysis

	Purities			Efficiency
	CC0π	CC1π	CCOther	
CC0π	73,5%	6,5%	6,1%	50,1%
CC1π	8,5%	50,5%	8,3%	29,5%
CCOther	10,9%	29,8%	72,9%	35,2%
Background	2,2%	6,8%	8,7%	
Out of FV	4,9%	6,4%	4,0%	

Off-axis: ν_e analysis



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

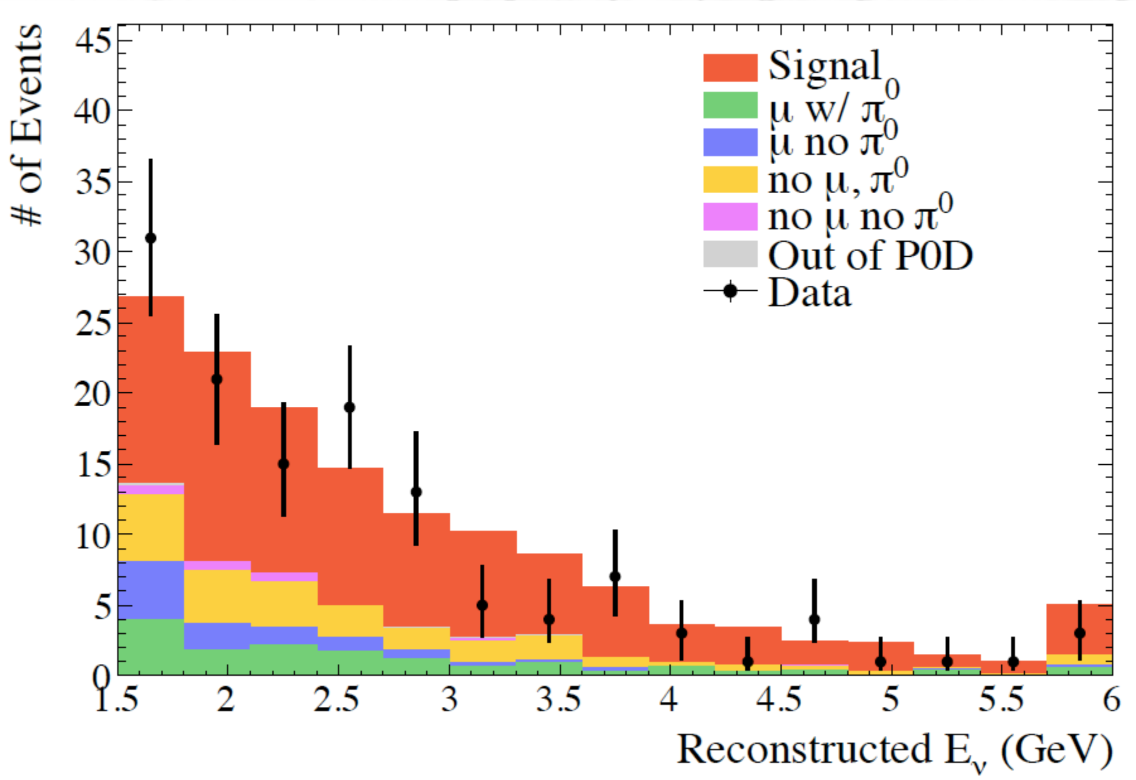
arXiv:1403.2552

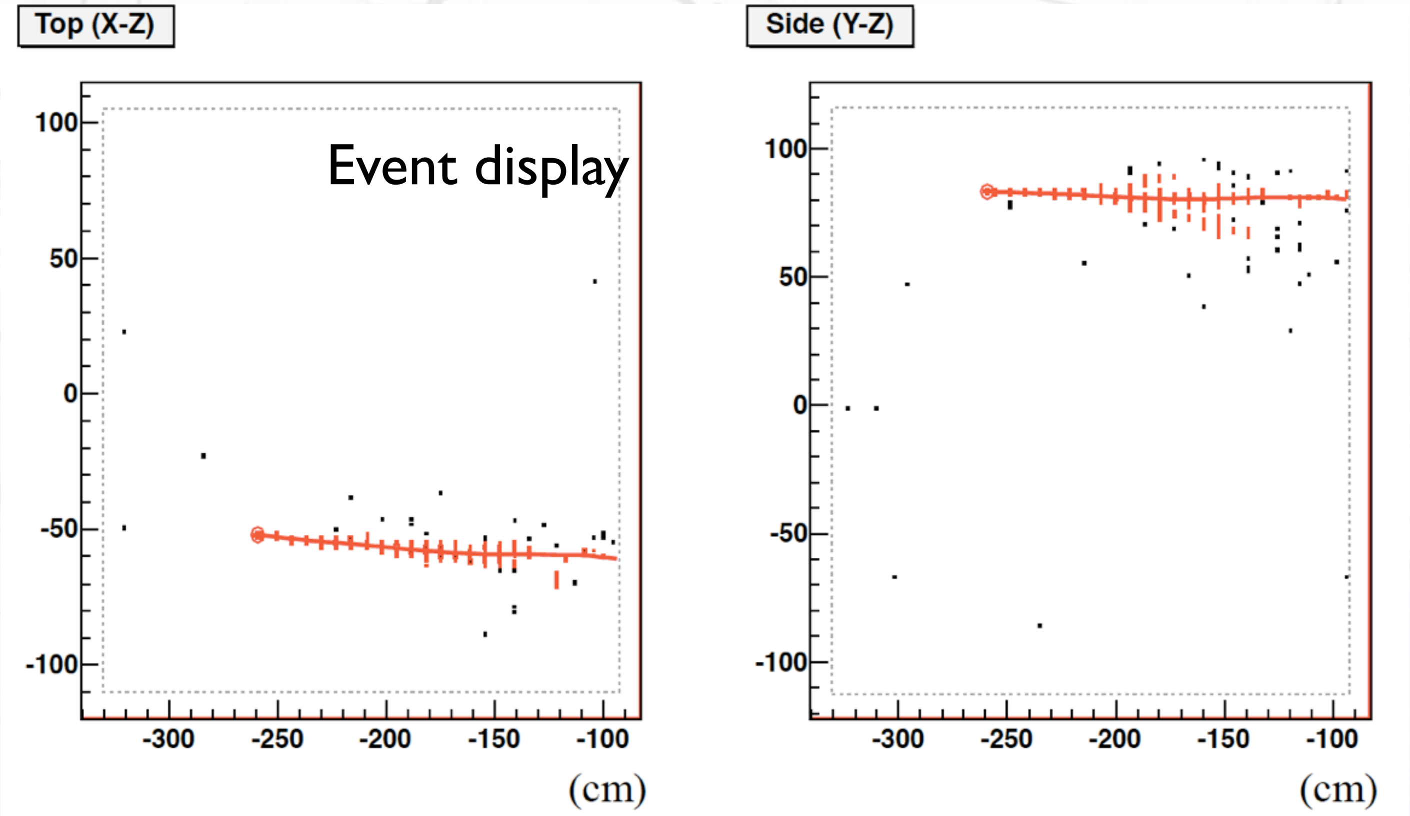
$$\frac{N_e^{meas}}{N_e^{pred}} = 1.01 \pm 0.06(stat) \pm 0.06(flux \oplus x.sec) \pm 0.05(det \oplus FSI)$$

$$\frac{N_\gamma^{meas}}{N_\gamma^{pred}} = 0.64 \pm 0.10$$

Off-axis: ν_e analysis

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

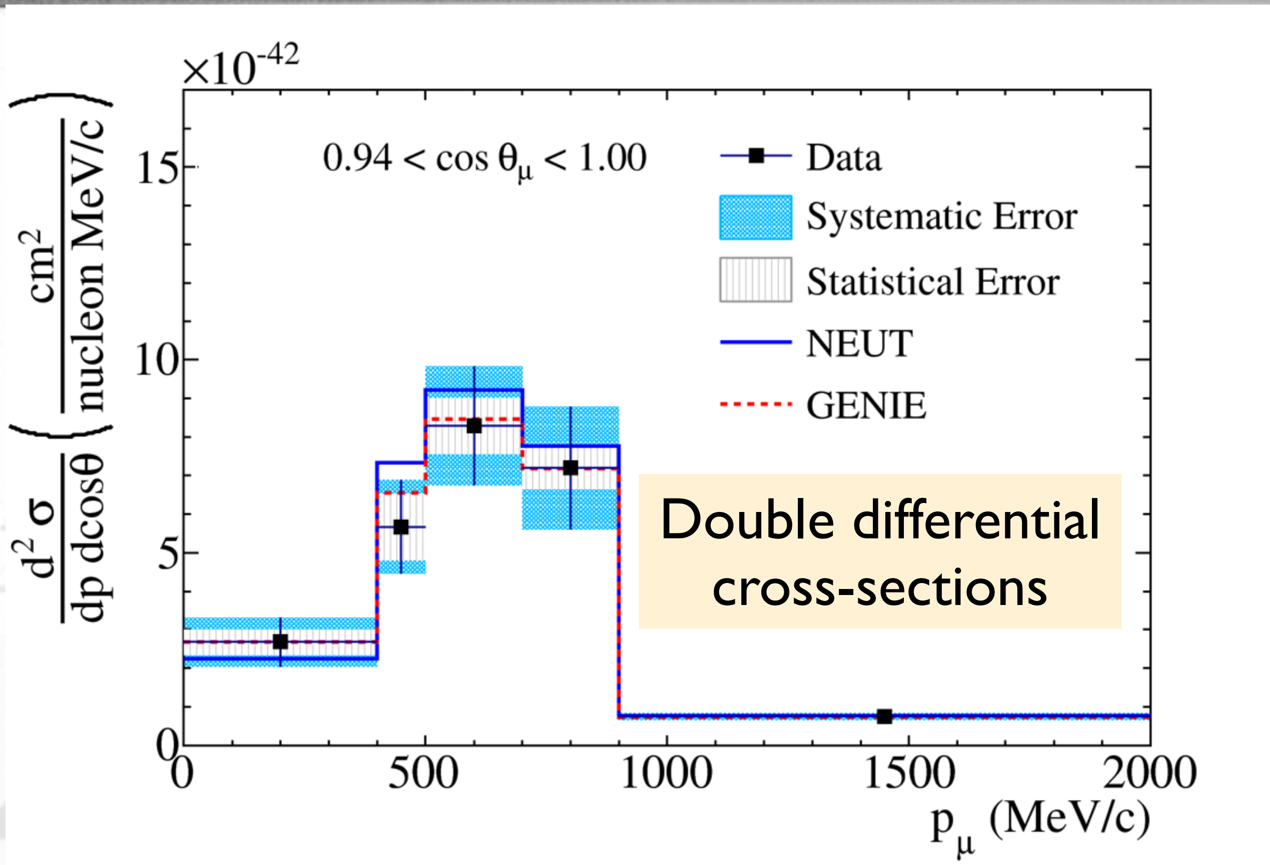




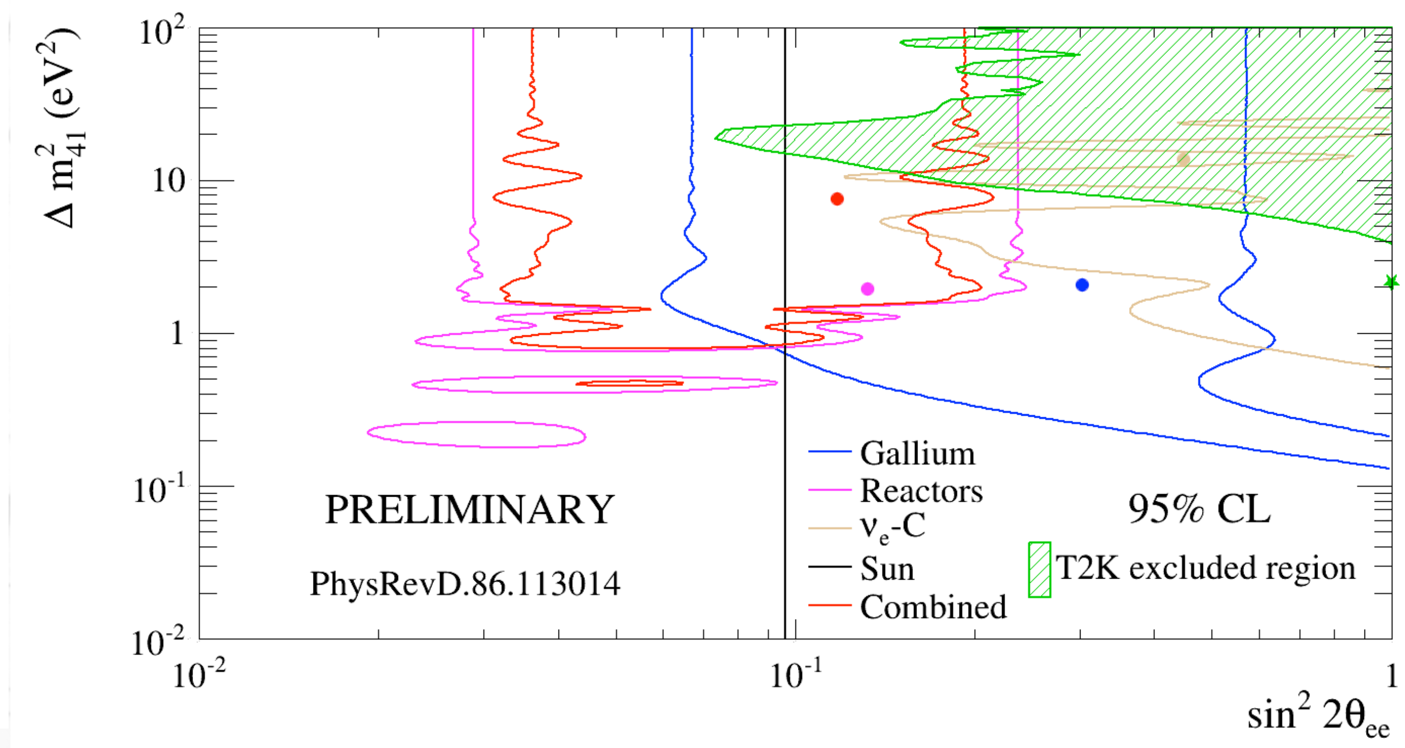
$$\frac{Data - Back_{MC}}{Sign_{MC}} = 0.91 \pm 0.13(stat) \pm 0.18(det) \pm 0.13(flux)$$

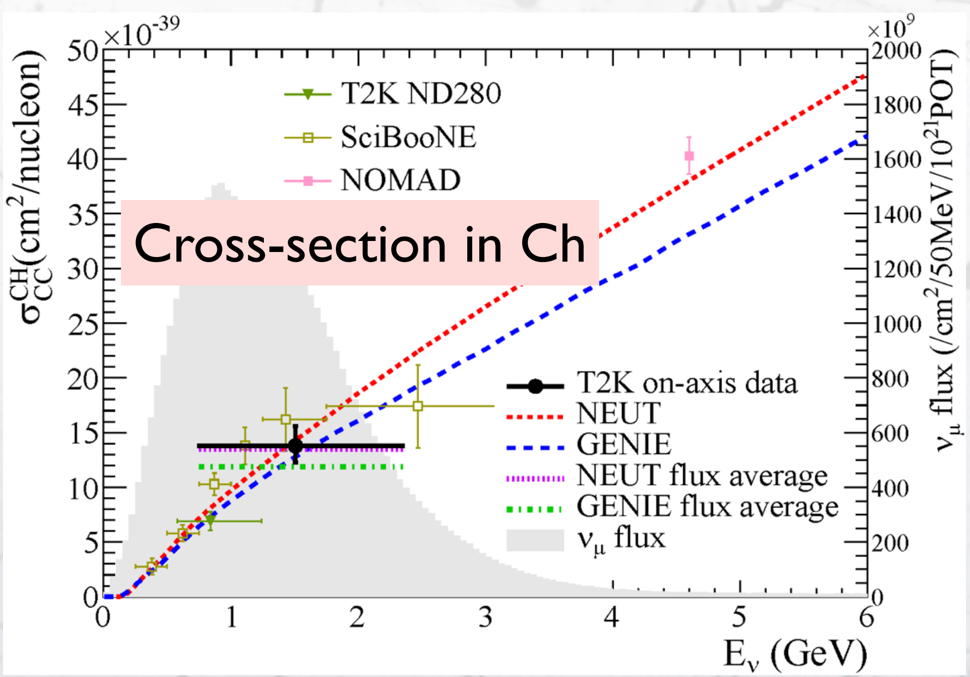
In good agreement with the tracker ν_e measurement

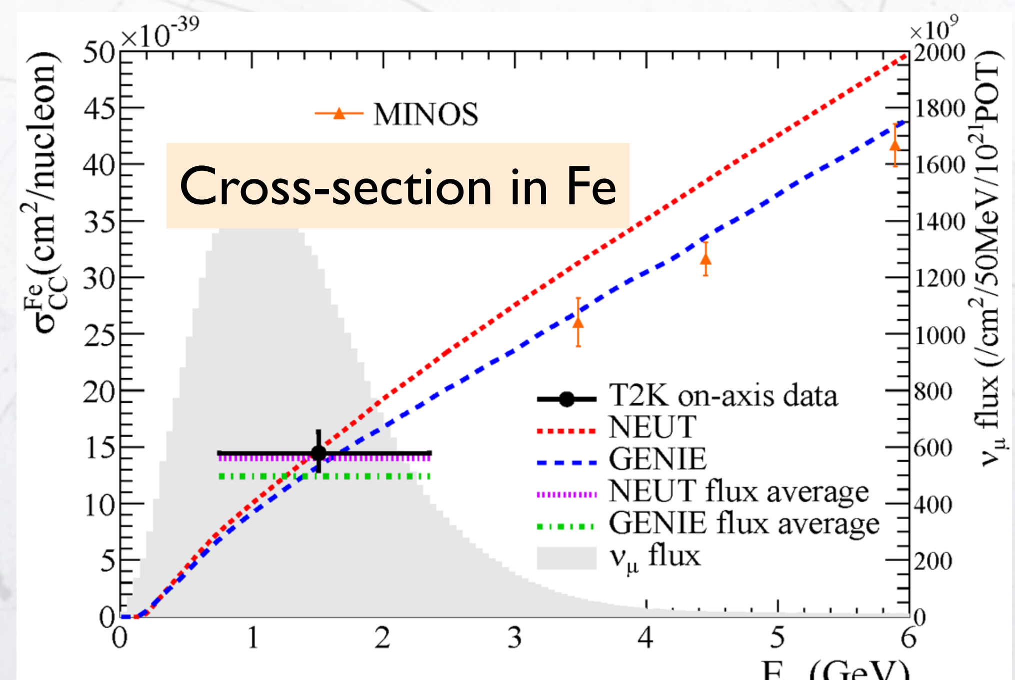
ND280 other analysis



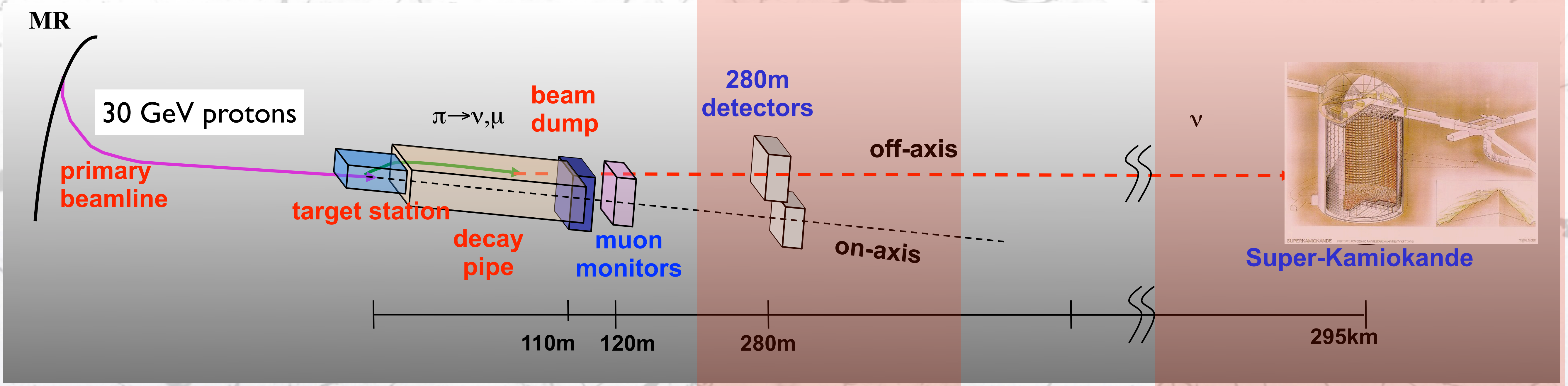
ν_e disappearance for sterile searches







Cross sections



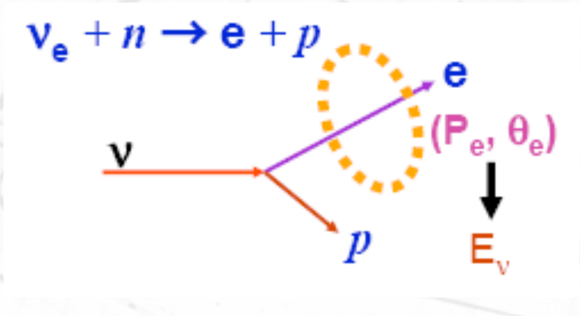
Beam

ND280

Super-Kamiokande

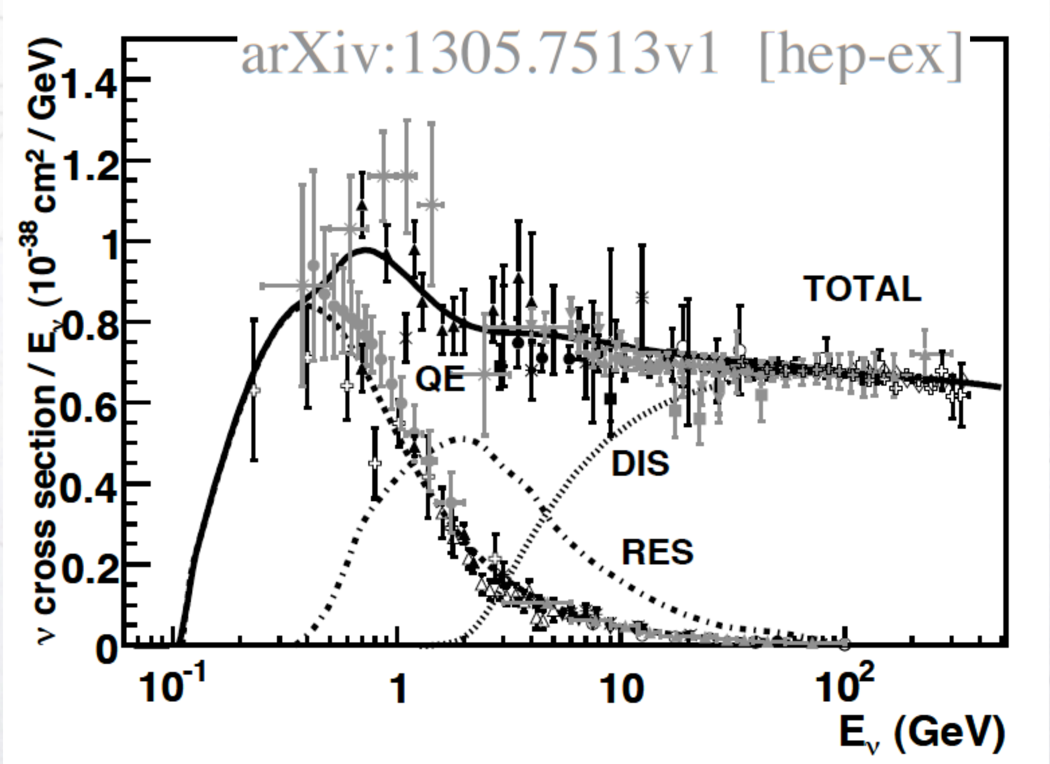
Cross-sections

- The T2K signal is the CCQE events. The 2 body kinematics allow to estimate the neutrino energy. $\nu_\mu n \to \mu^- p$
- Other channels can be seen as backgrounds to the CCQE signal.
  - We need to identify the channel by using the hadronic component of the interactions.
- At T2K energies there are many channel thresholds (CC1π^+, CC1π^0, CC Deep Inelatic Scattering, …)
- Cross-section models are not precise.
- Final state interactions inside the nucleus alter the hadronic component.



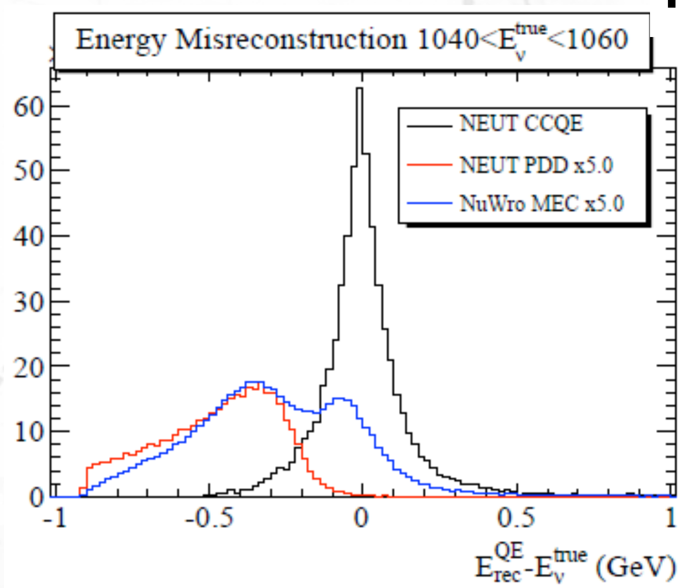
$$E_{reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

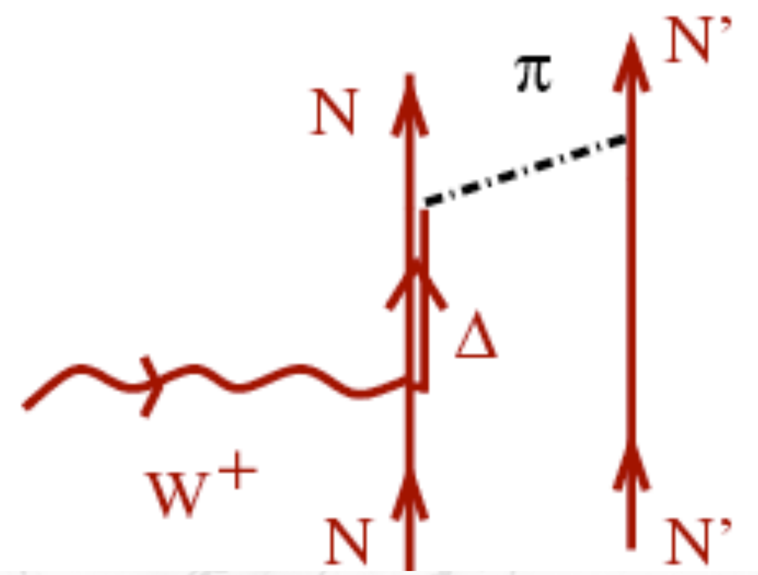
E_b is the binding energy

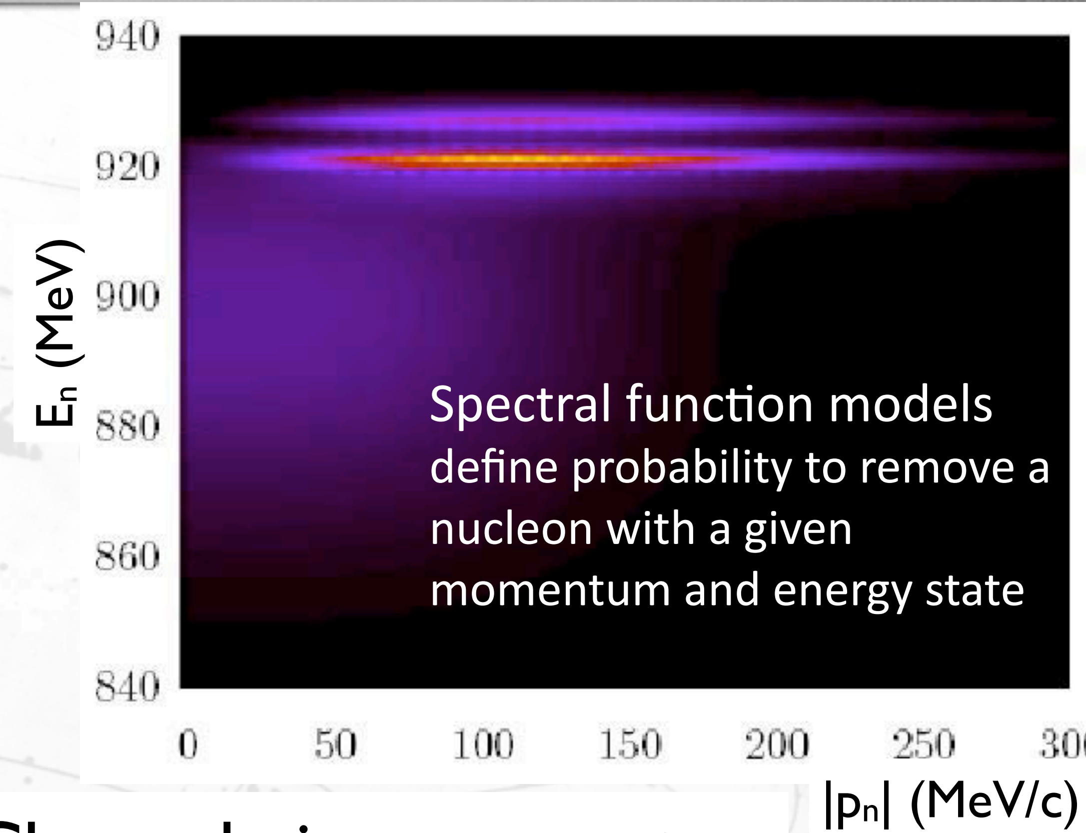


Cross-sections: unknowns

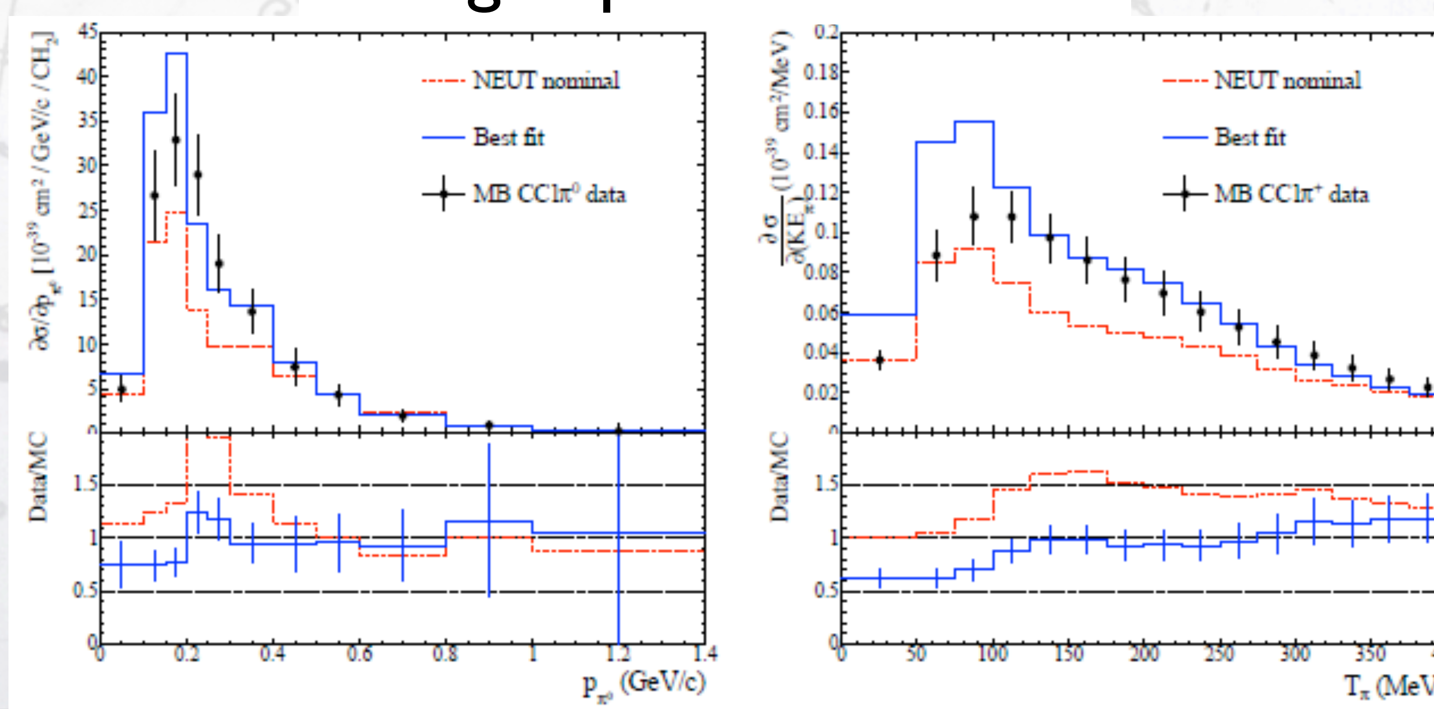
Multi-nucleon interactions







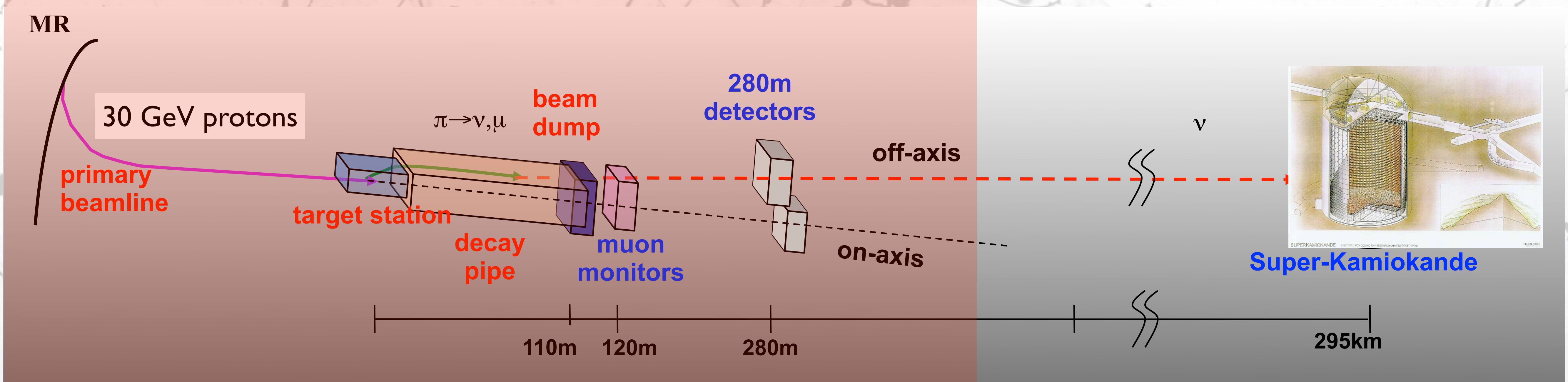
Charged pion momentum



T2K approach

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

Flux prediction



Beam ND280 Super-Kamiokande

Flux constraint

Neutrino Flux Model:

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

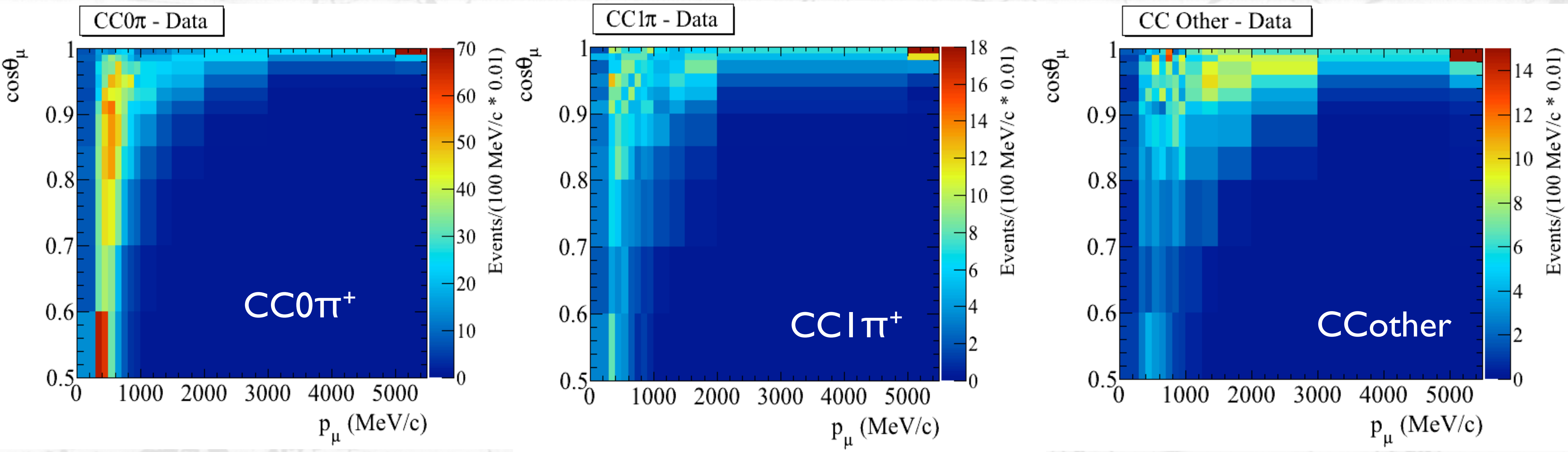
Neutrino Cross Section Model (NEUT):

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

Constraint from ND280 Data

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

ND280 input data

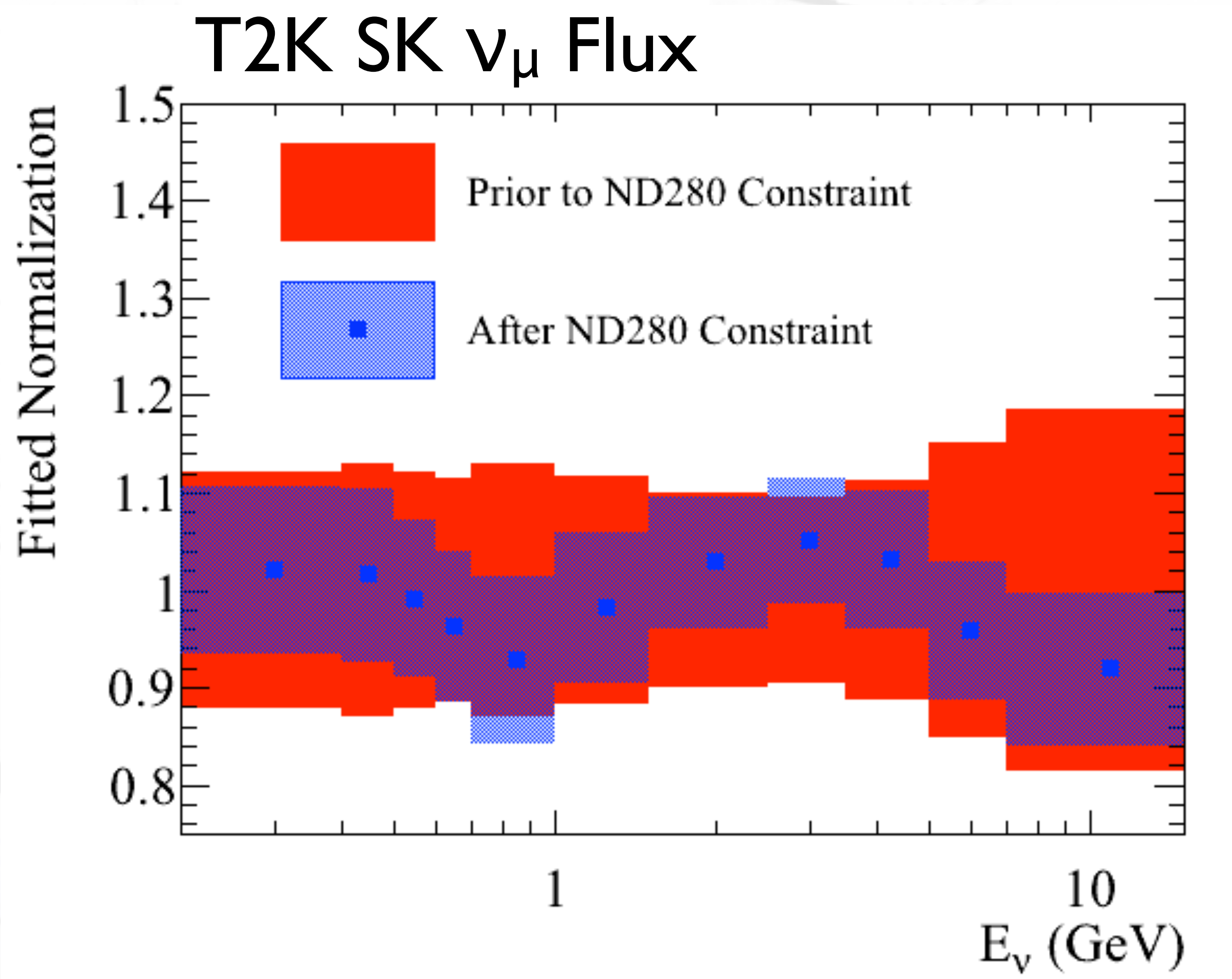


Data from T2K Runs 1-4: 5.9×10^{20} protons on target

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

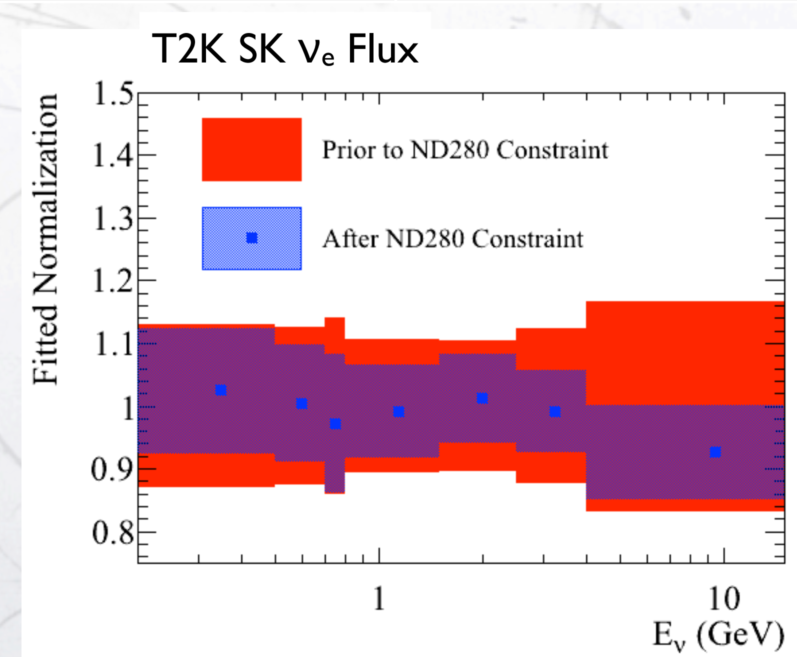
Data are binned in two dimensions: muon momentum (p) and angle (cosθ) preserving information on neutrino energy and interaction q^2

Constrained flux



Cross-section parameters

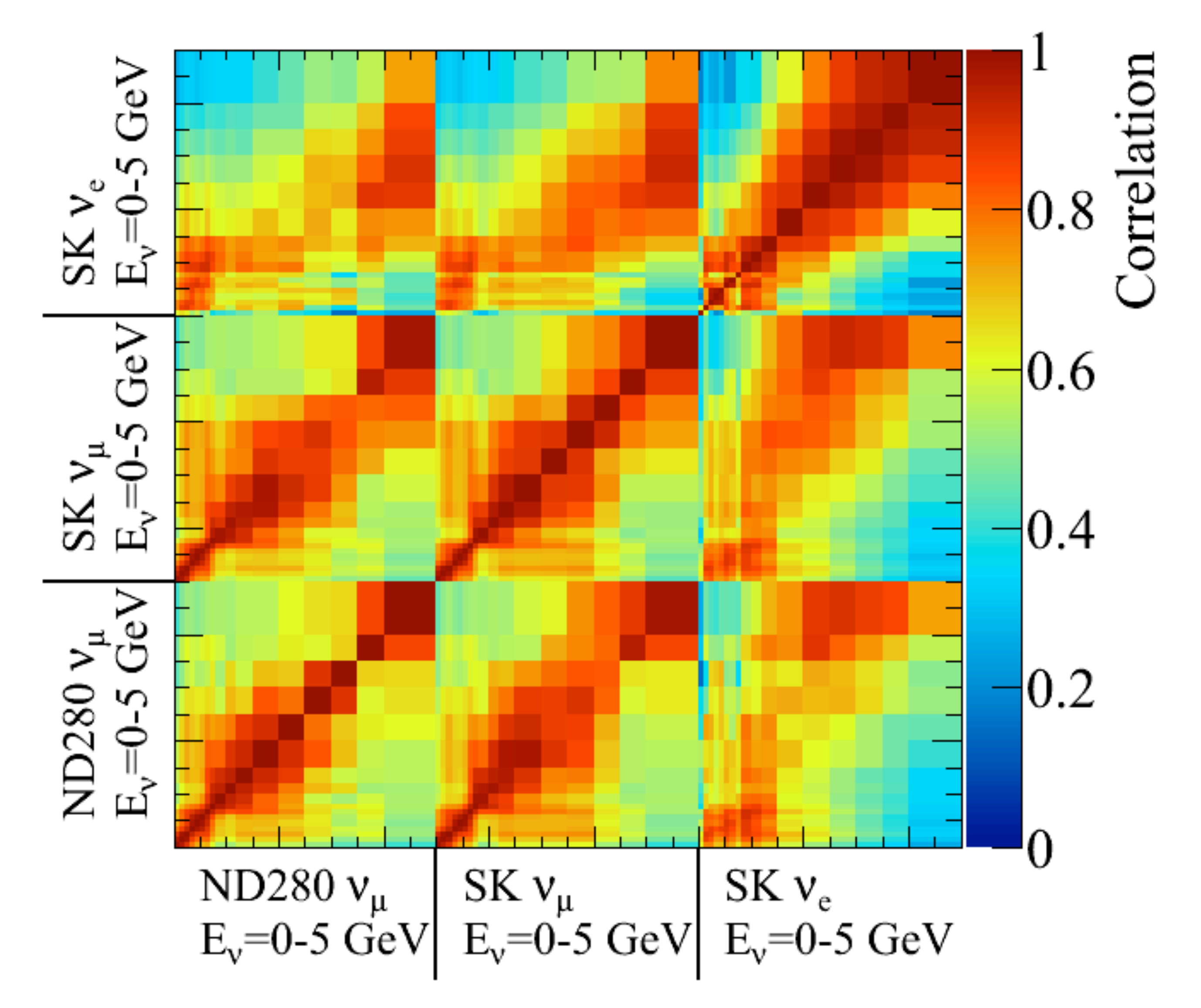
Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
CCQE Norm.	1.00 ± 0.11	0.961 ± 0.076
CC1π Norm.	1.15 ± 0.32	1.22 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.10 ± 0.25



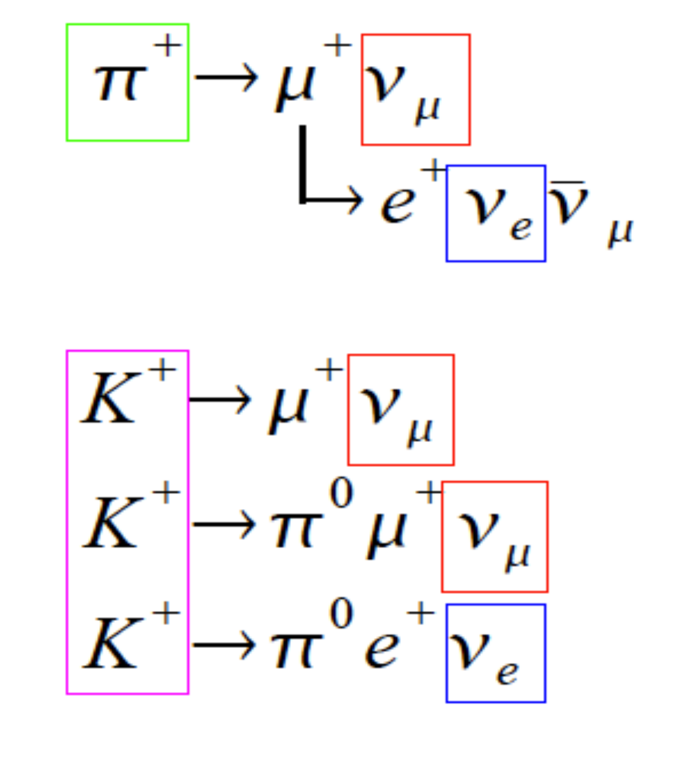
- T2K ν_μ and ν_e flux predictions are constrained by the fit.
- The cross-section parameters are also constrained.
- Plots show central values and error bands for normalisation parameters.

Covariance matrix

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

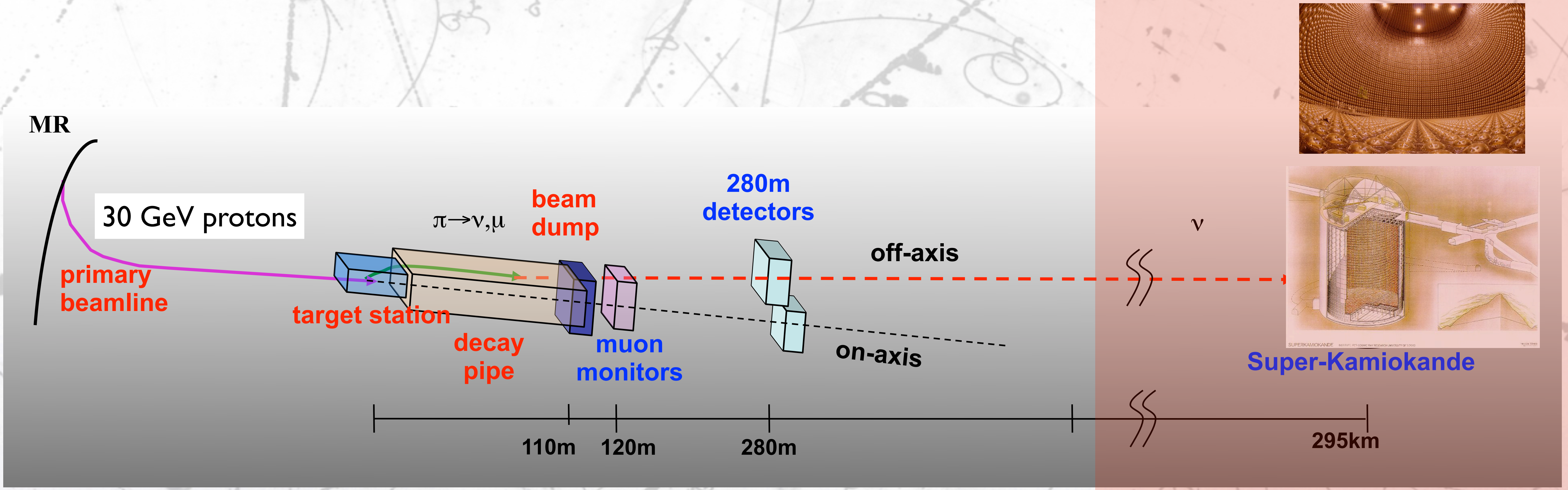


ν_e and ν_μ fluxes are correlated through parent hadrons



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

Super-Kamiokande

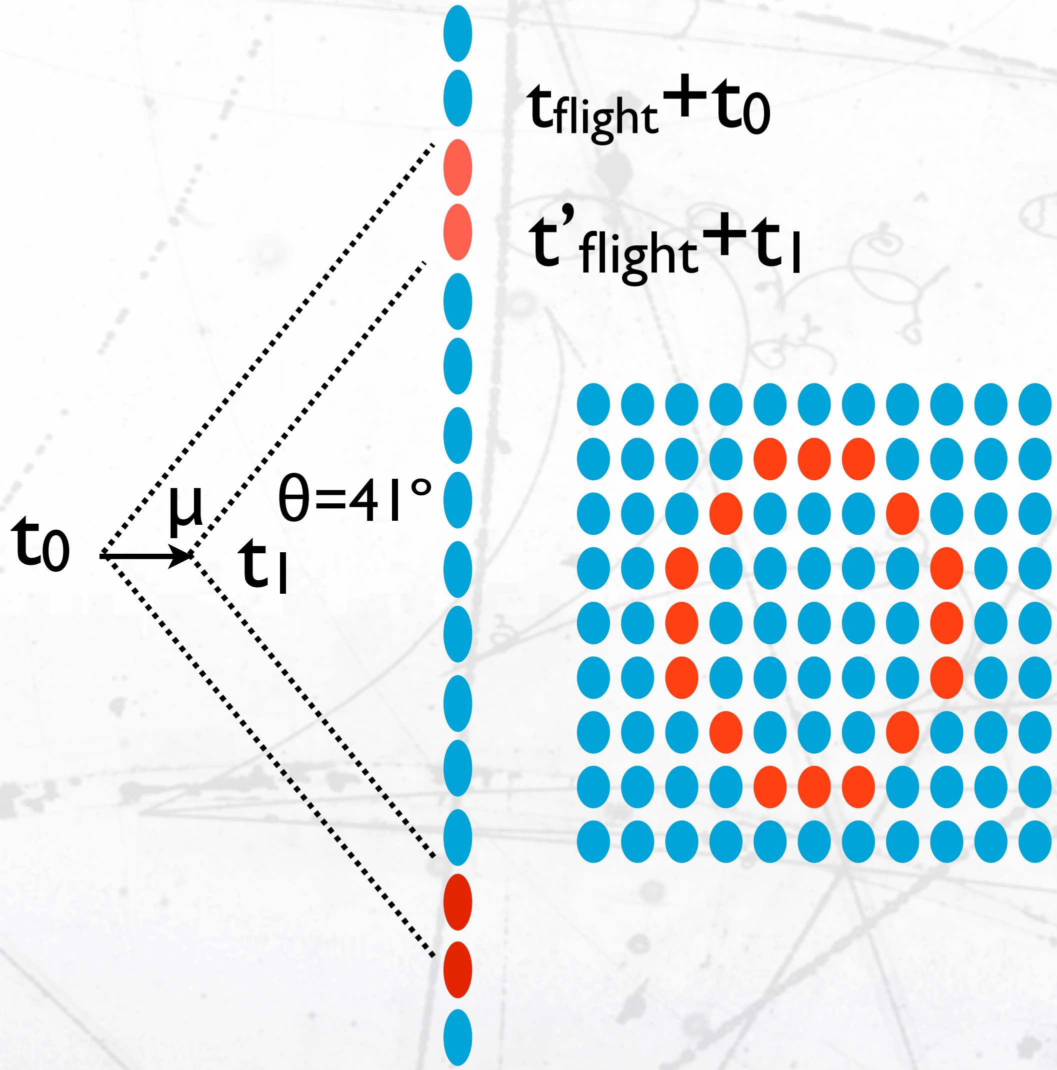


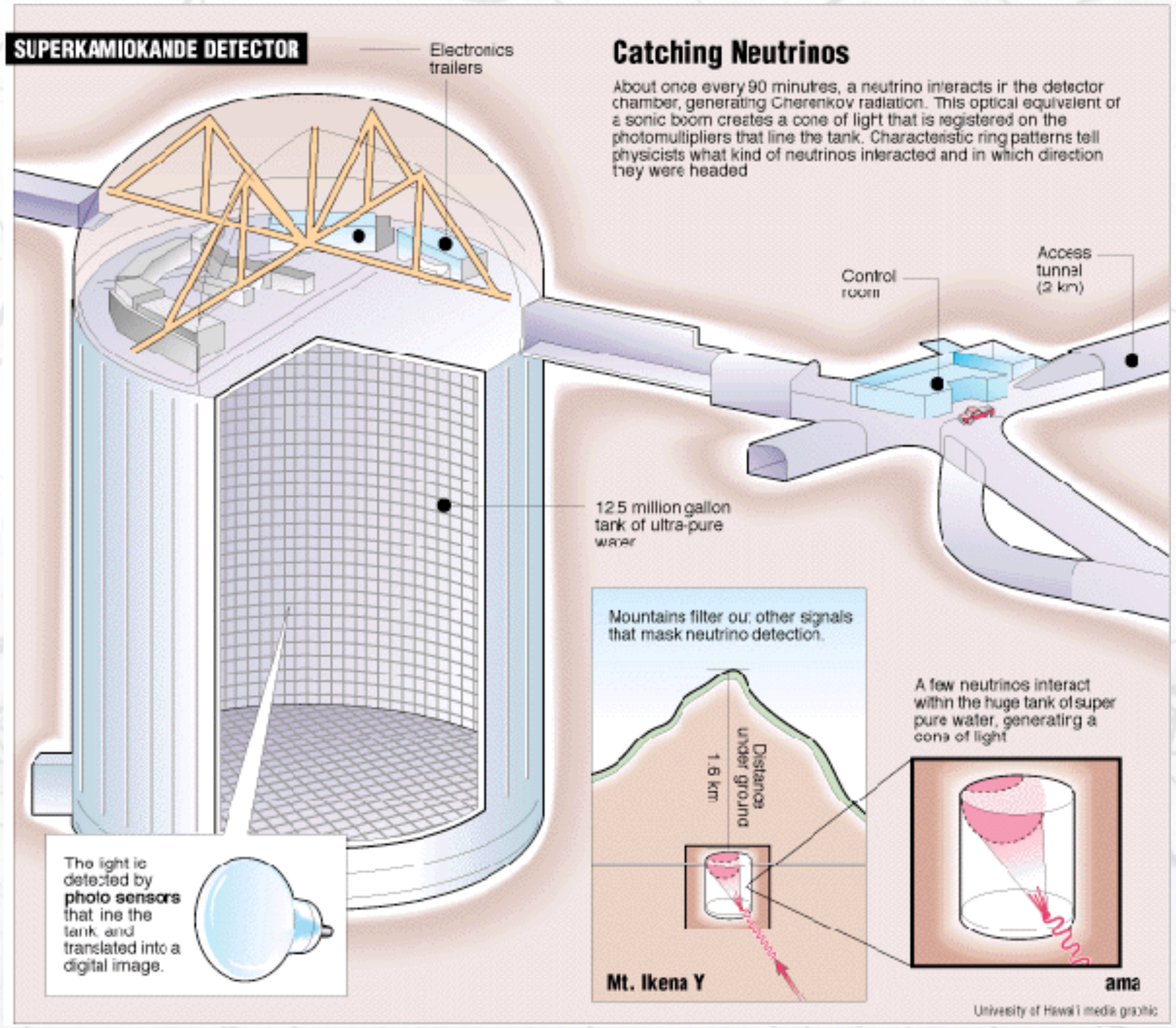
Beam

ND280

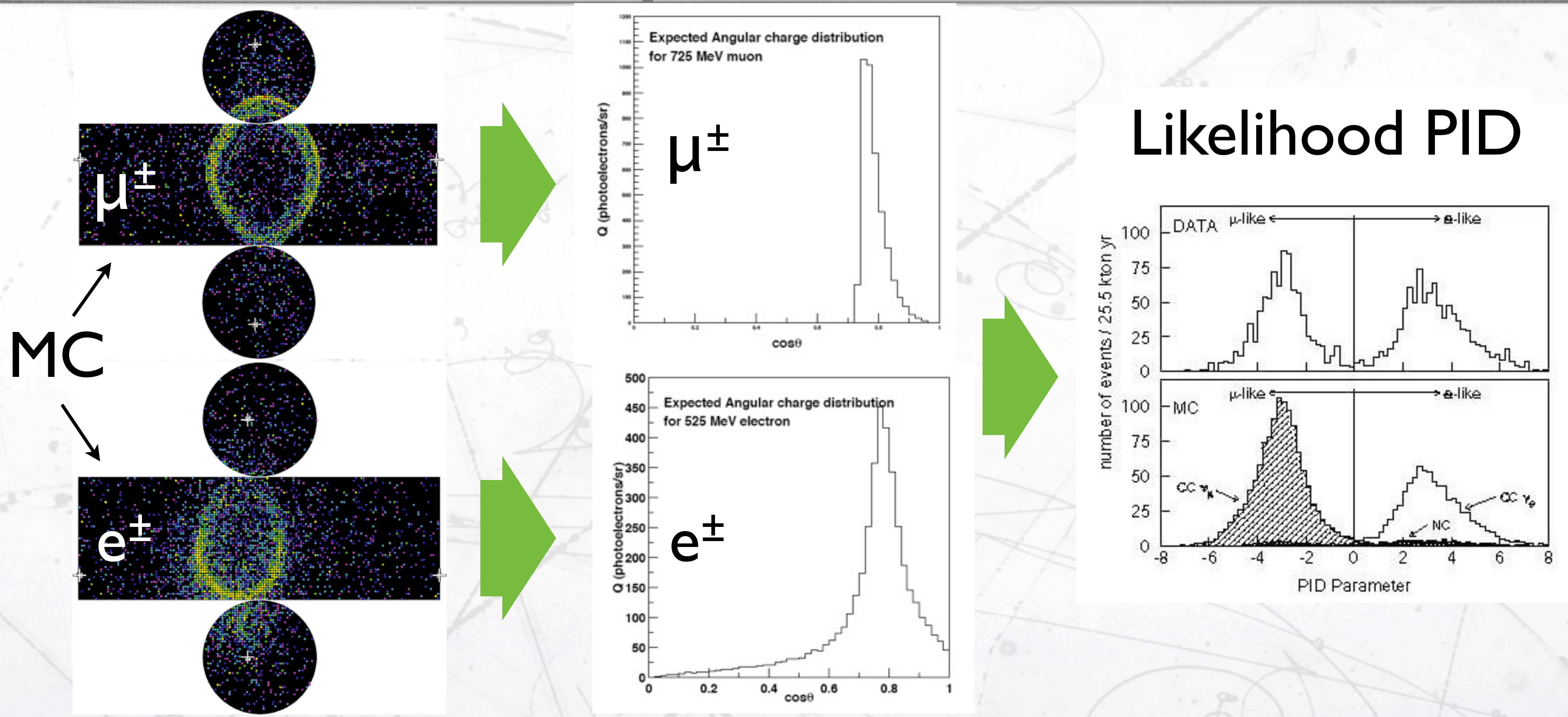
Super-Kamiokande

Super-Kamiokande





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



- 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.

SK: new reconstruction

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

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

Time PDF

Charge PDF

PMT Charge Response:

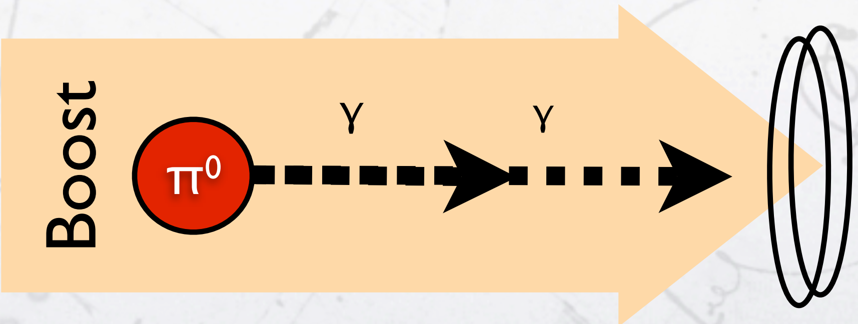
Property of the electronics and PMT properties

Predicted Charge (μ):

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

Super-Kamiokande & π^0

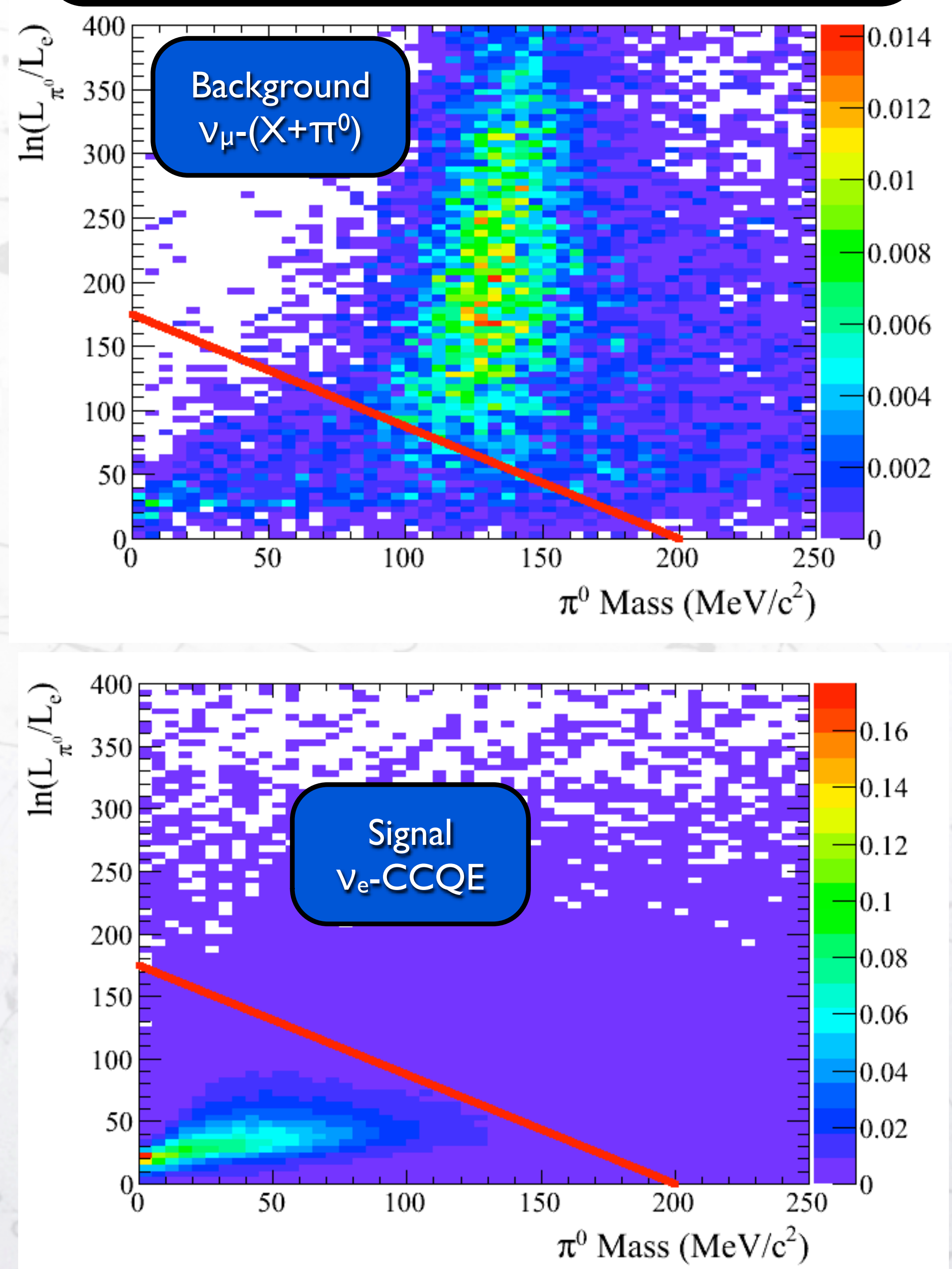
- The misidentification of π^0 and electrons happens when one photon is not identified:
  - The two electron-like rings overlap.
  - One of the two e-like rings is faint and it is lost in the Cherenkov light of the other photon.
- Or with 2 γ, the invariant mass of the photons has poor resolution.



Super-Kamiokande & π^0

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

Likelihood Ratio vs π^0 Mass

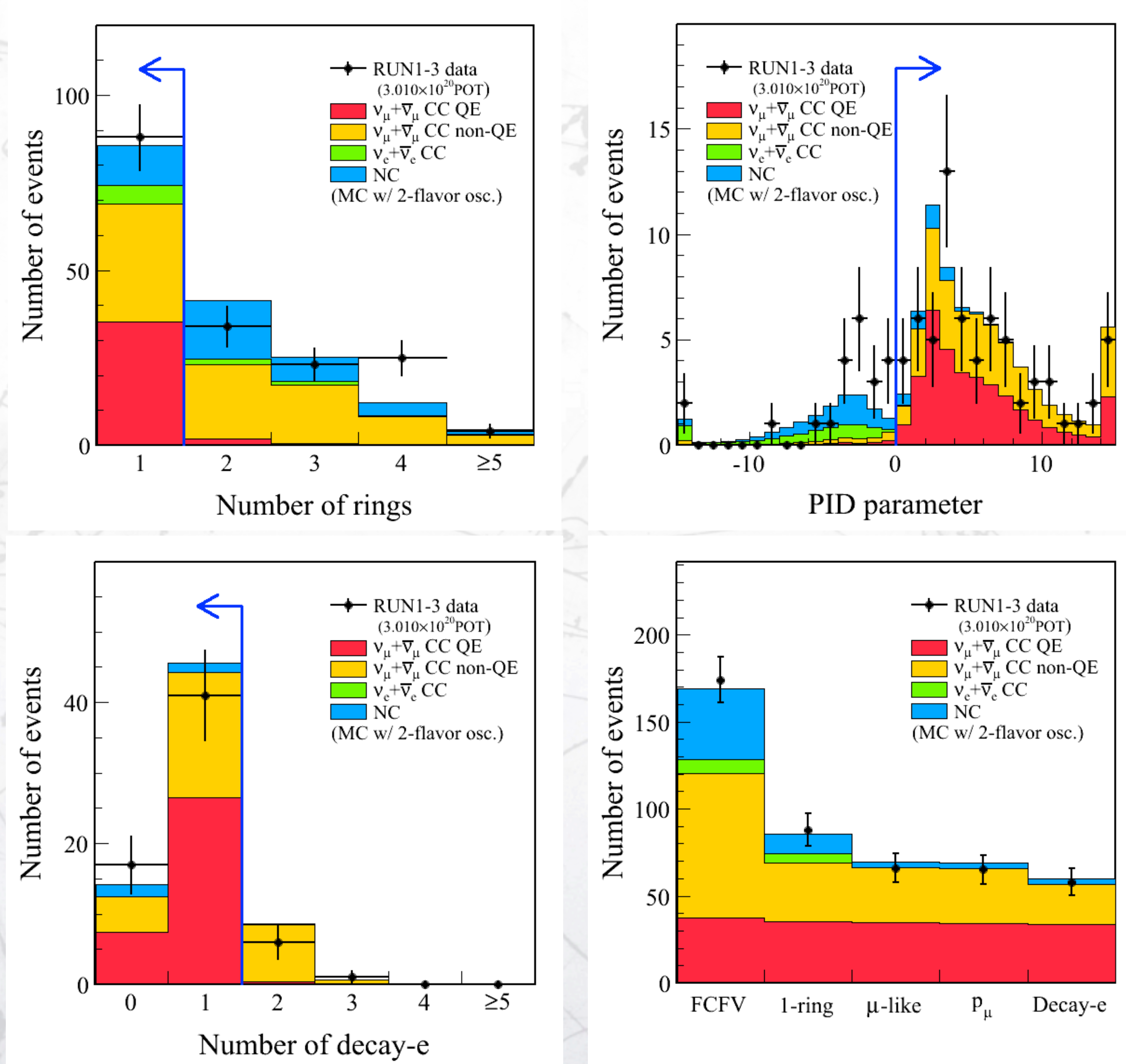


ν_μ selection

ν_μ Selection Cuts

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

120 events for
6.4 x10^{20} proton on target

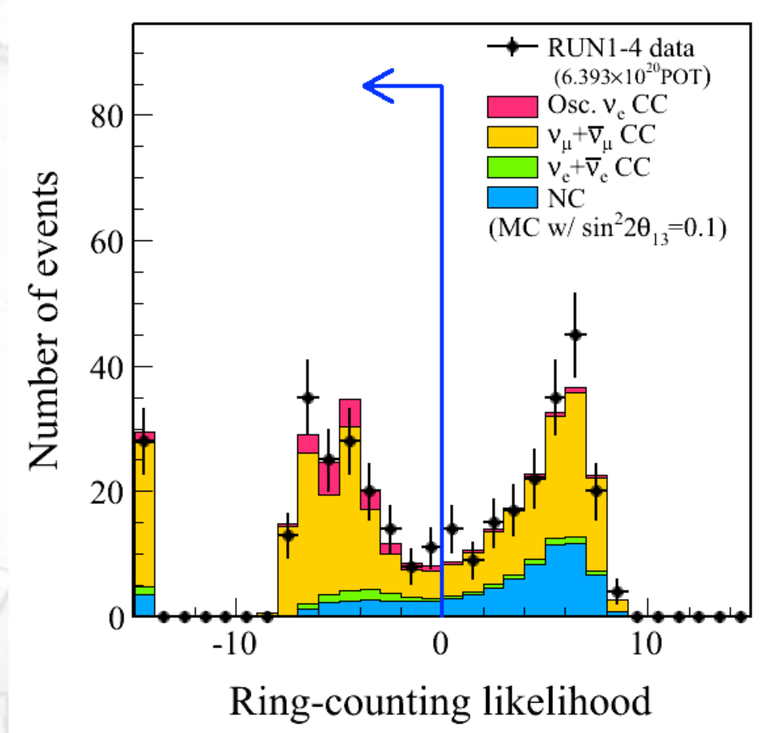


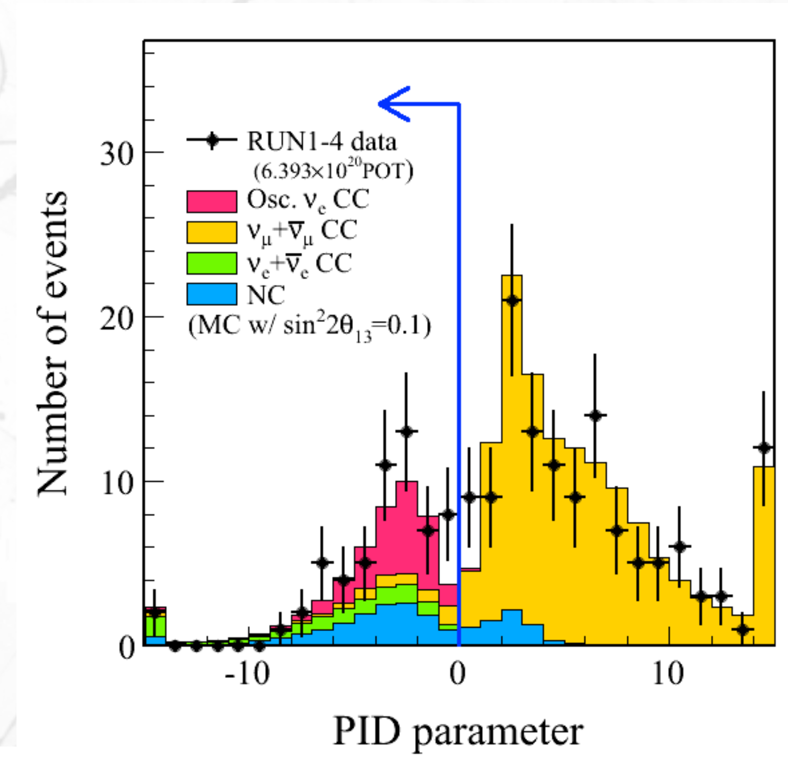
ν_e selection

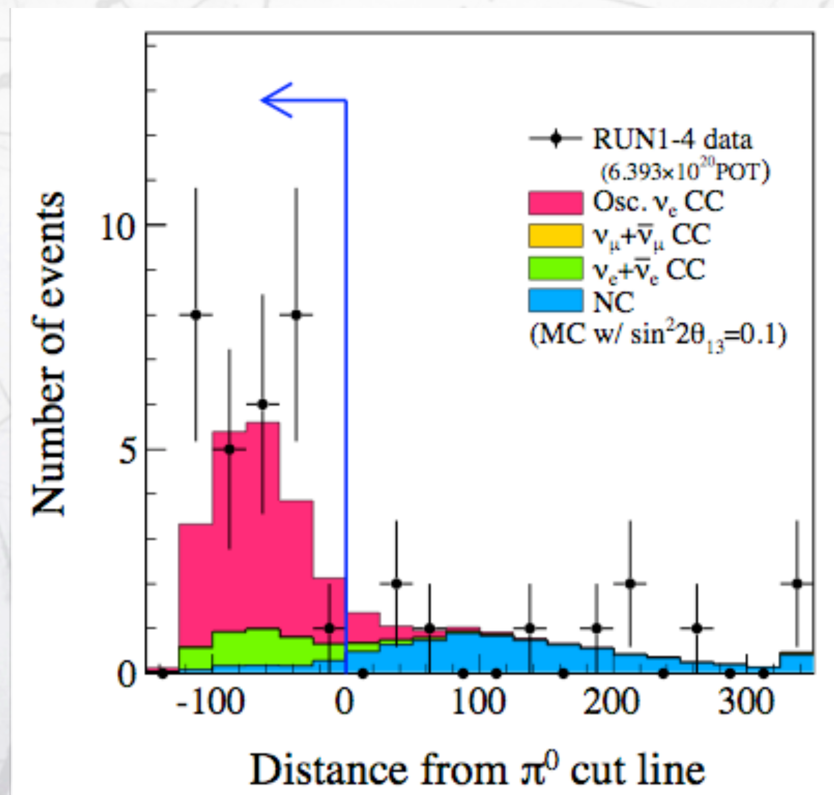
ν_e Selection Cuts

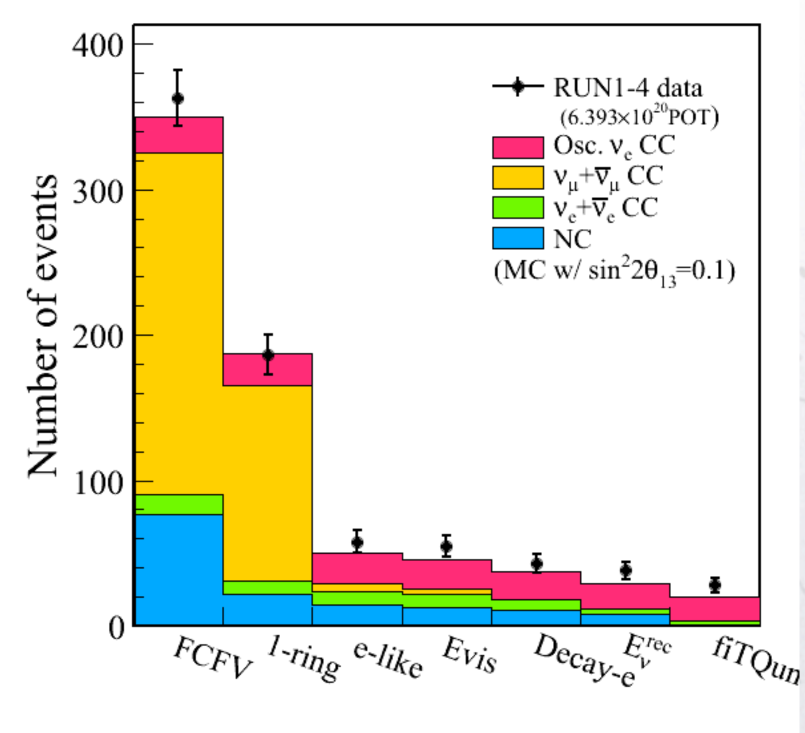
- Number veto hits < 16
- Fiducial Volume=200cm
- number of rings = 1
- Ring is electron-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- new analysis π^0 cut
- 0 < E_ν < 1250 MeV

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

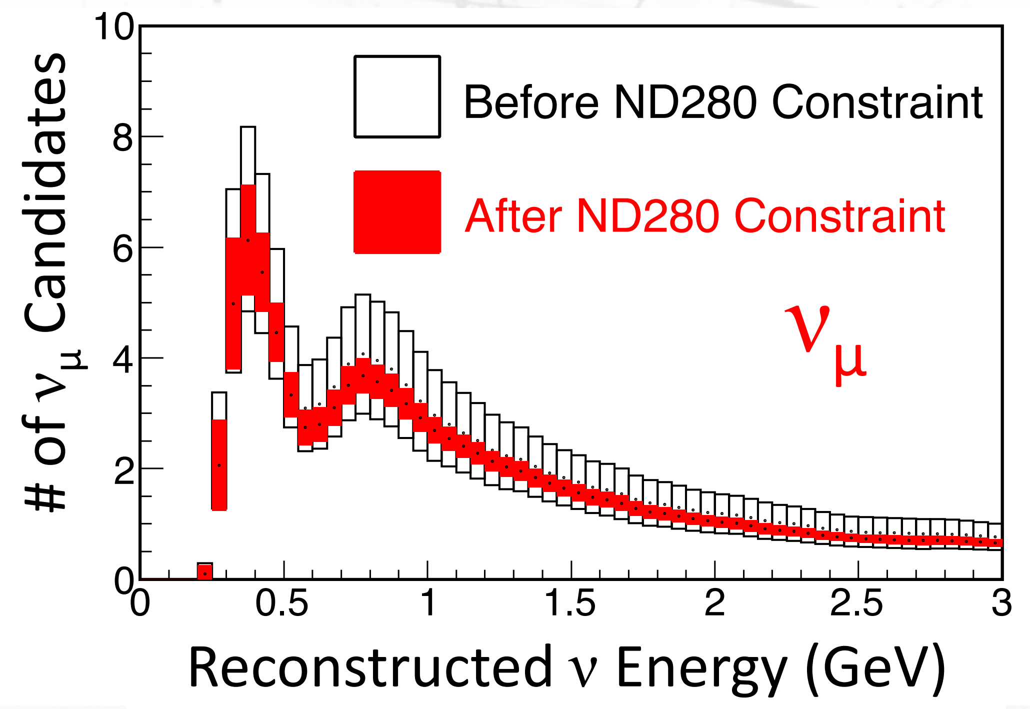




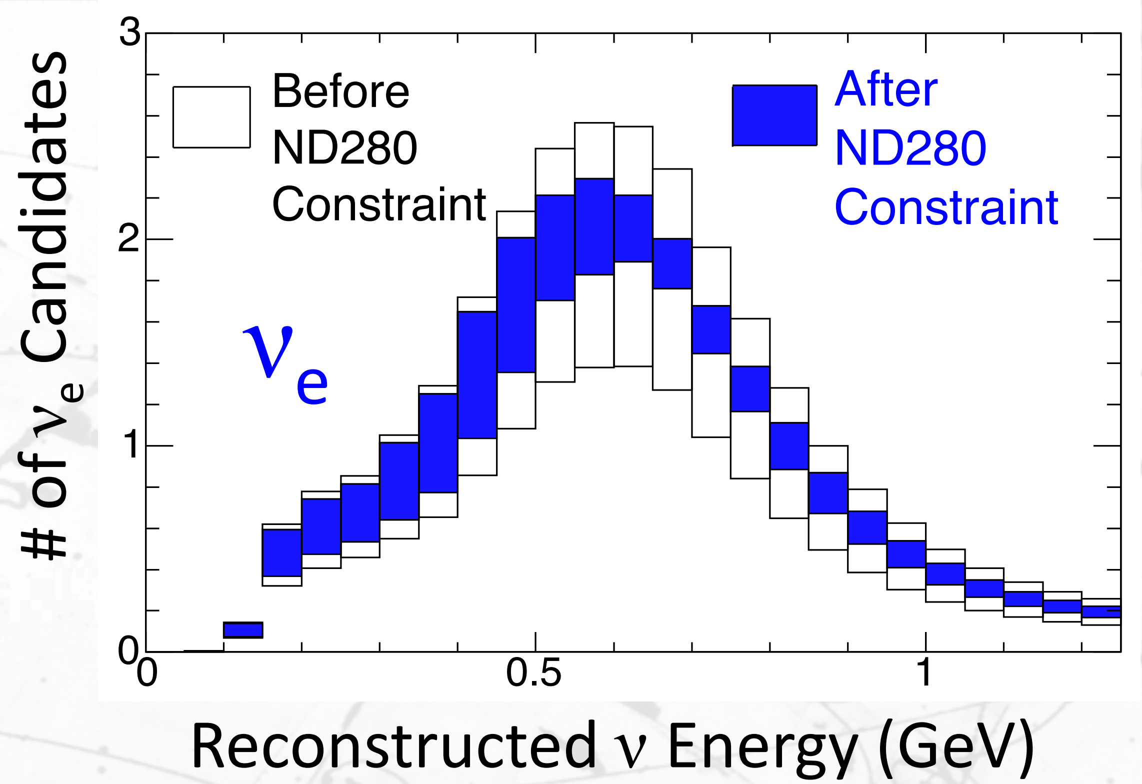




Prediction systematics

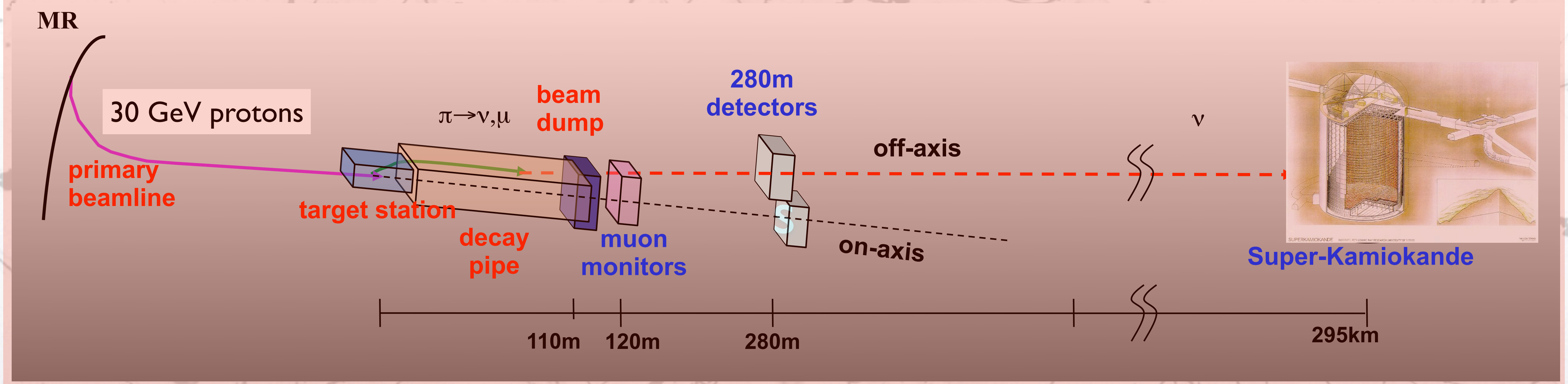


$\sin^2 2\theta_{13} = 0.1$,
$\sin^2 2\theta_{23} = 1$
$\Delta m_{32}^2 = 2.4\times10^{-3} eV^2$
NH
$\delta_{CP}=0$



elative Uncertainty in # of ν_μ Candidates (%)	**Systematic Error Source**	Relative Uncertainty in # of ν_e Candidates (%)
2.7	Flux + Xsec. (ND280 constrained)	2.9
4.9	Xsec. (ND280 independent)	4.7
3.5	π Hadronic Interactions	2.3
4.4	SK Detector	2.6
8.1	Total	6.8

ν oscillation analysis

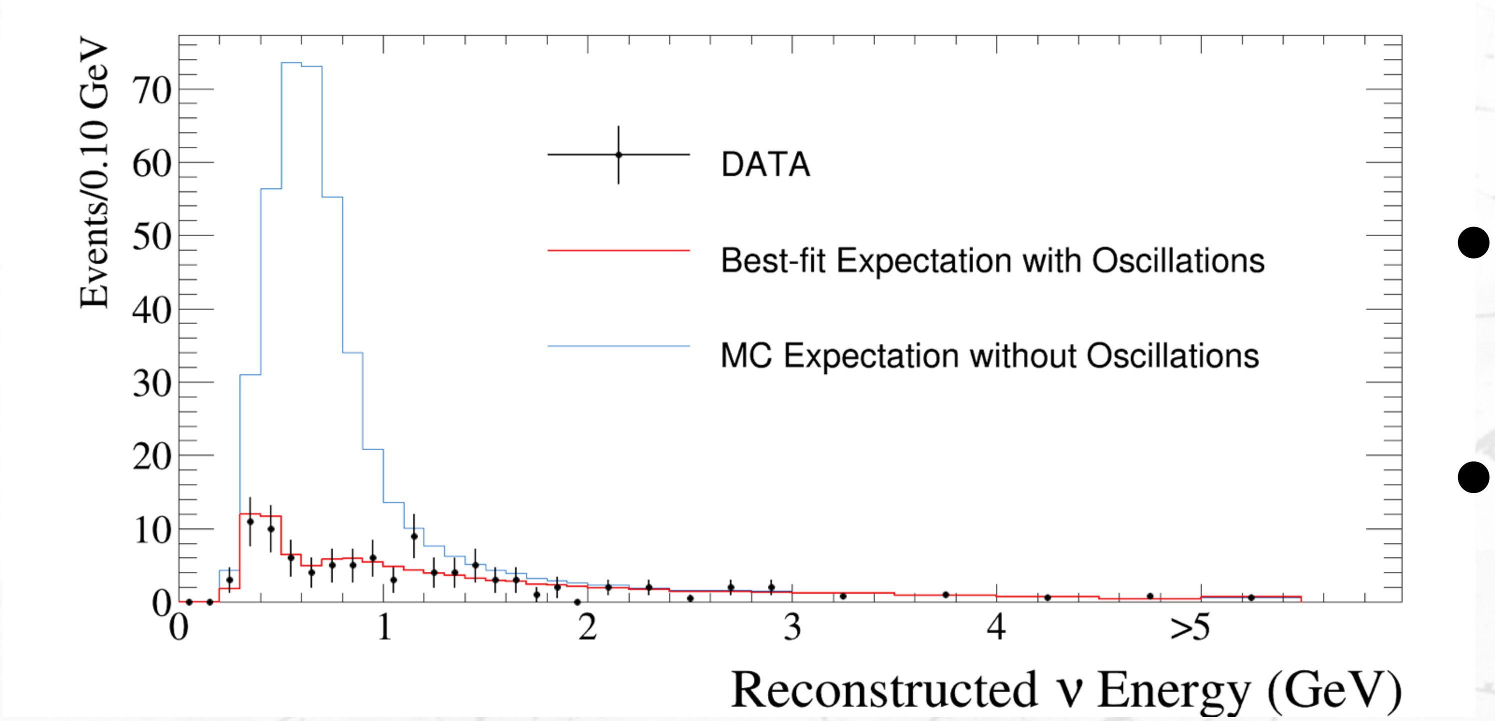


Beam | ND280 | Super-Kamiokande

EXCELENCIA SEVERO OCHOA

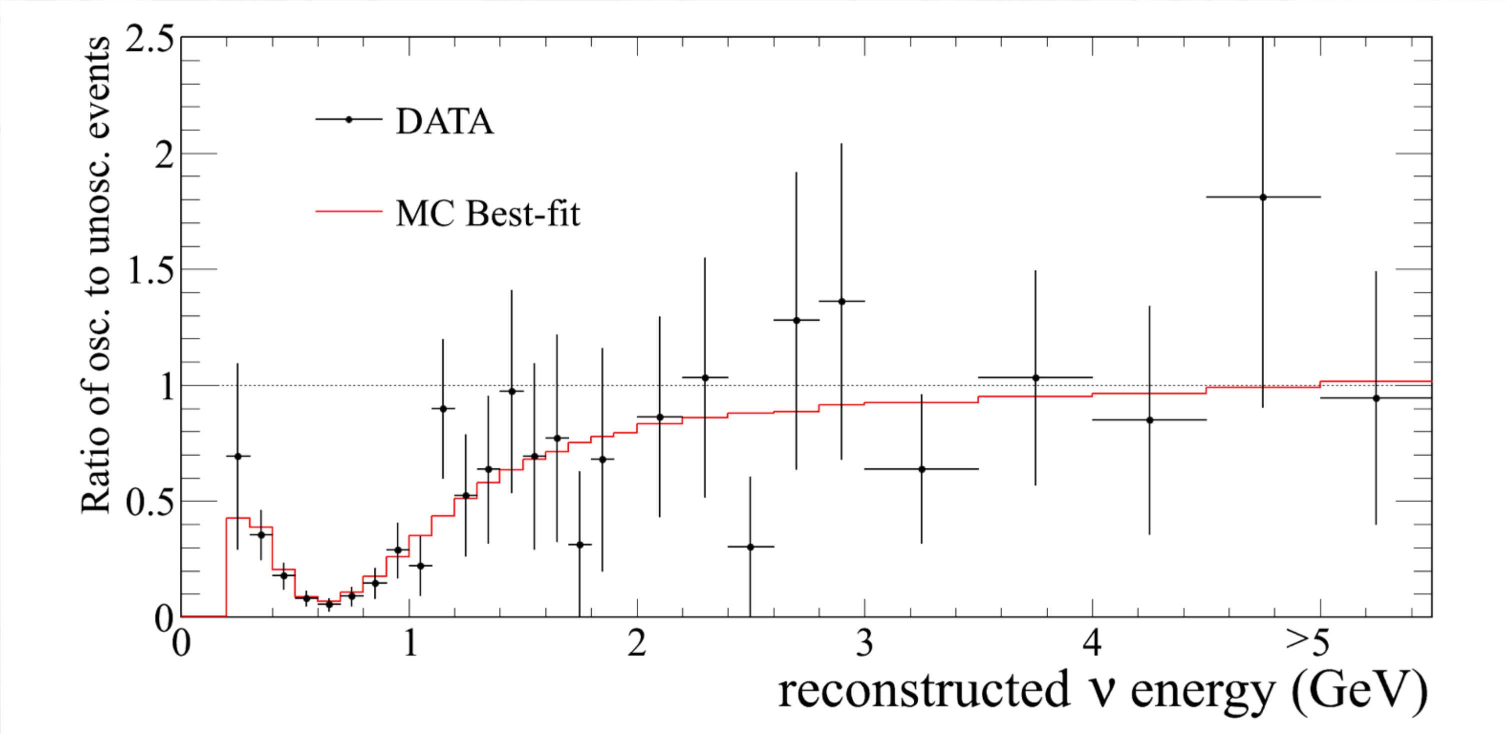
$\nu_\mu \rightarrow \nu_\mu$

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 x 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 $\theta_{13} = 0$

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

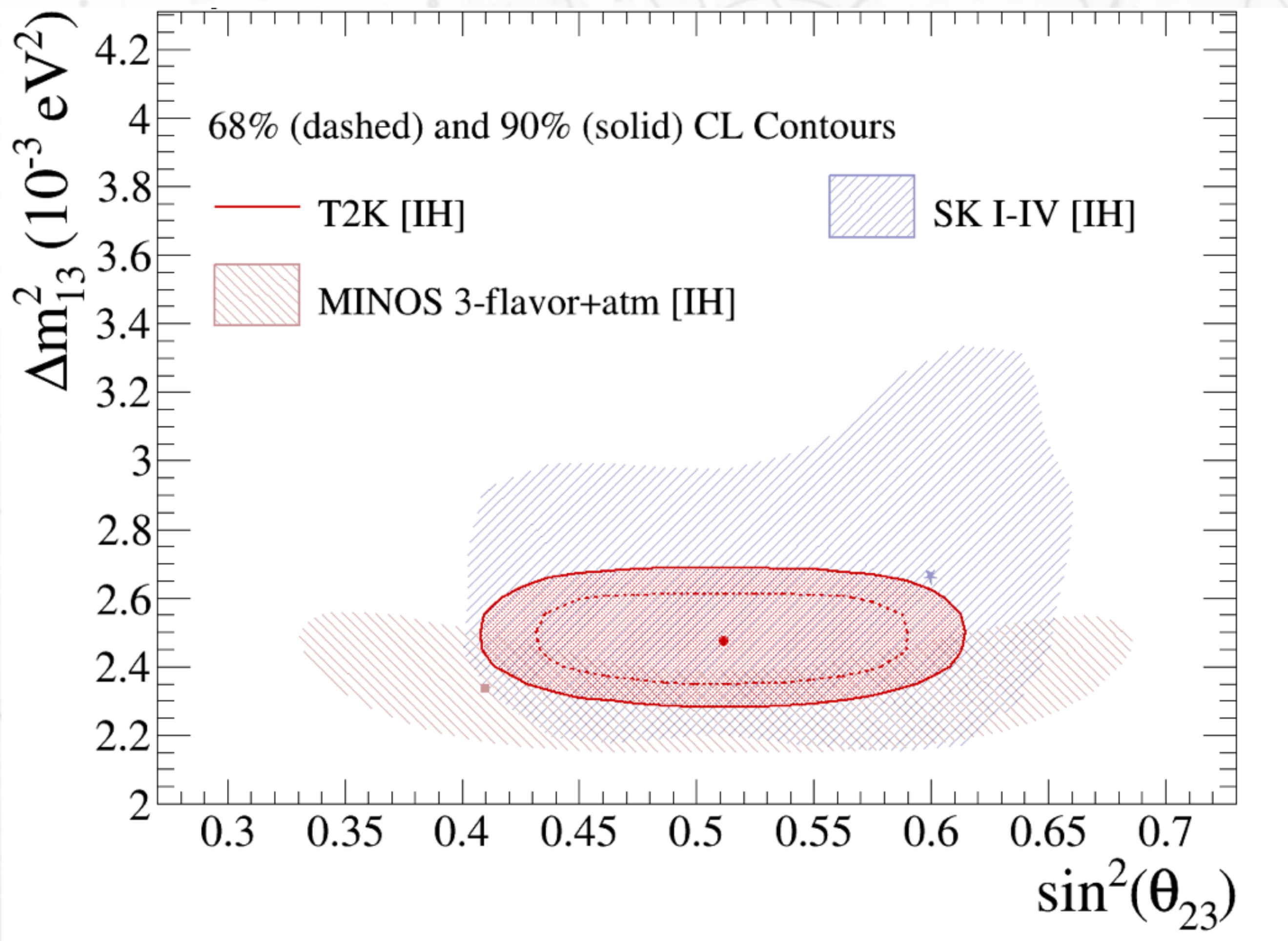
- If θ_{13} != 0 and θ_{23}~45°, the ν_μ disappearance is sensitive to the octant

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

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

ν_μ disappearance

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

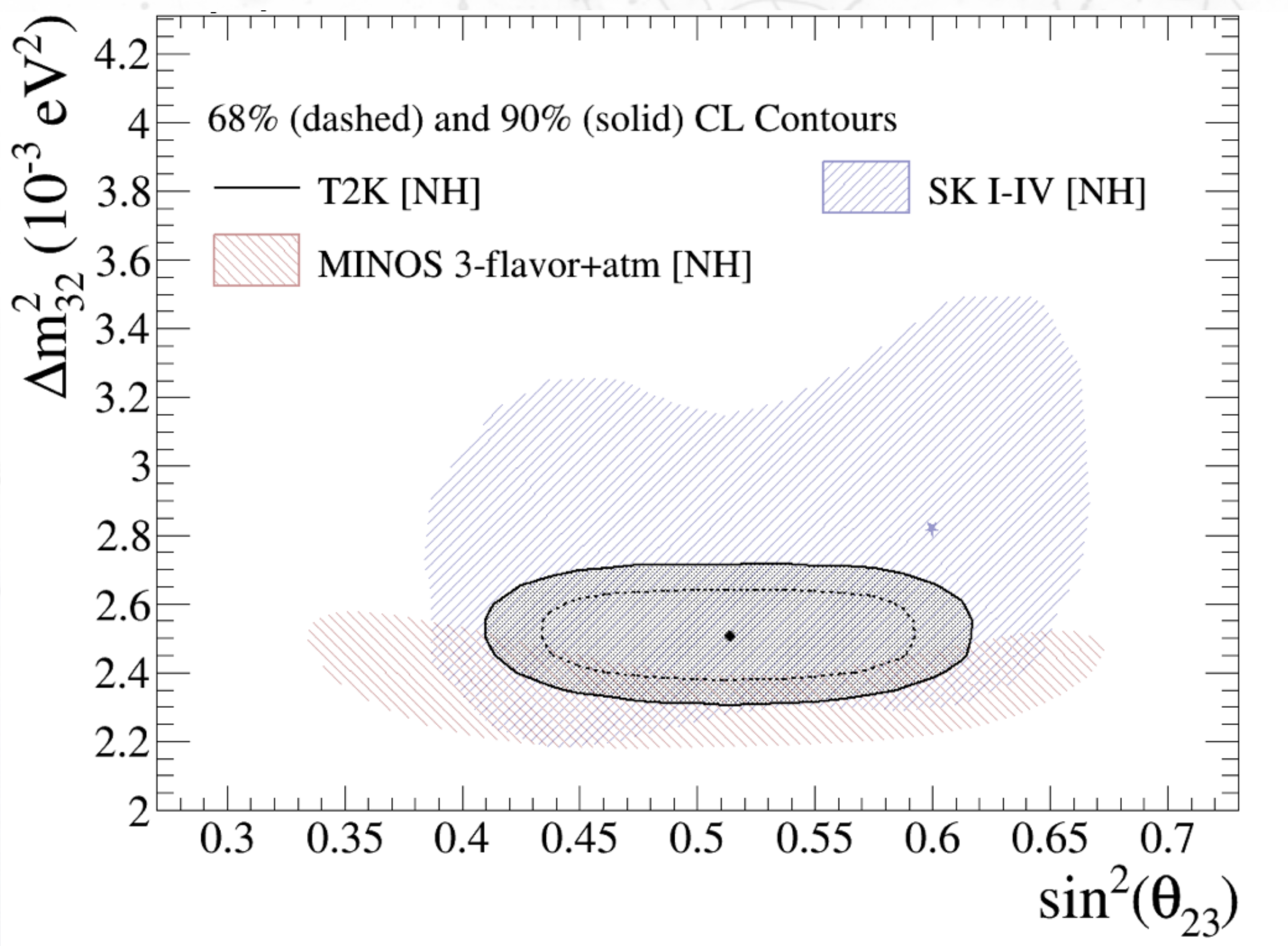


arXiv:1403.1532 (2014)		Best-fit ± FC 68% CL
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{23} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{23} (10^{-3} eV^2)	2.48 ± 0.10

- T2K already dominates the measurement of mixing angle.

ν_μ disappearance

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



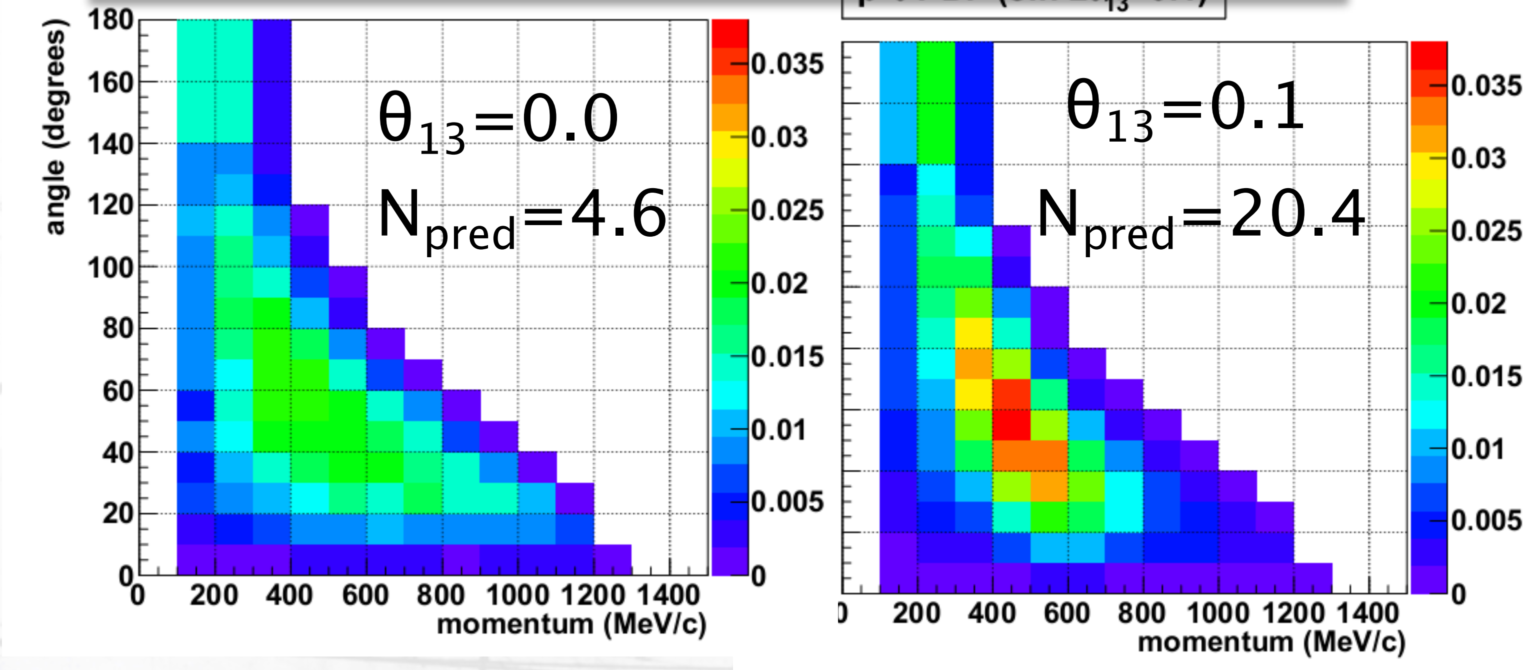
arXiv:1403.1532 (2014)		Best-fit ± FC 68% CL
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{23} (10^{-3} eV^2)	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{23} (10^{-3} eV^2)	2.48 ± 0.10

- T2K already dominates the measurement of mixing angle.

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

ν_e appearance

Electron momentum vs. angle distribution (MC)

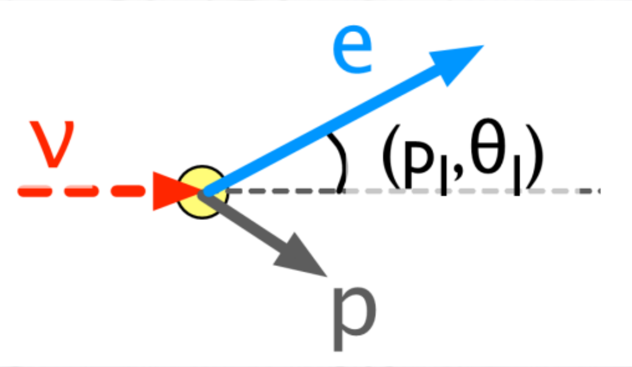


Fixed oscillation parameters

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

Analysis method

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



ν_e appearance

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

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

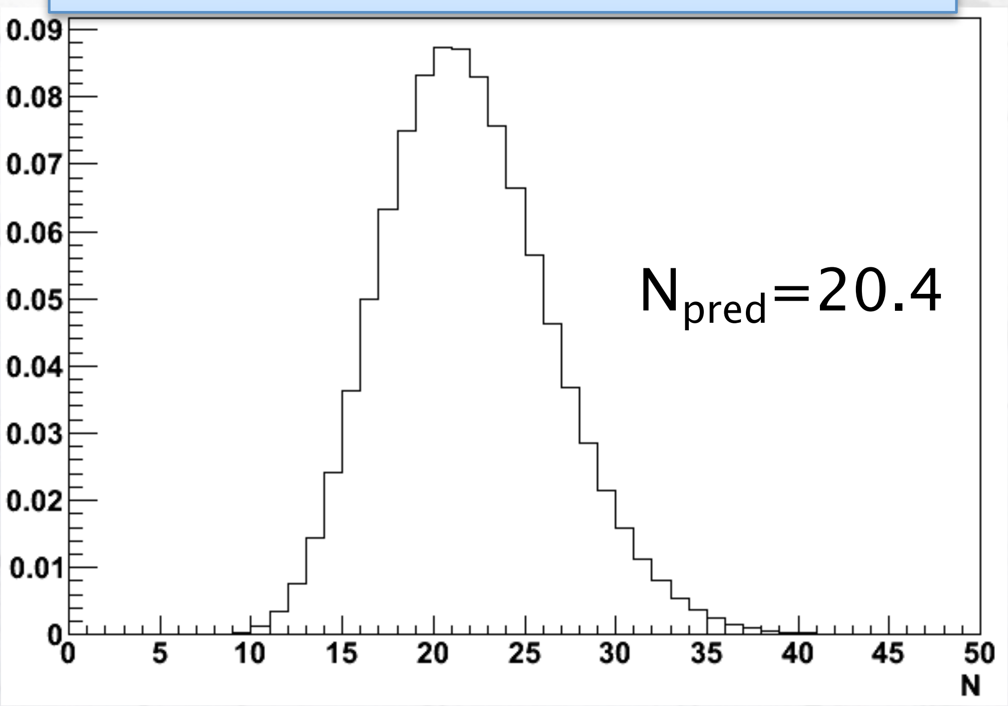
$\mathcal{L}_{norm}$: $Poisson(N_{obs})_{\text{mean}=N_{pred}}$

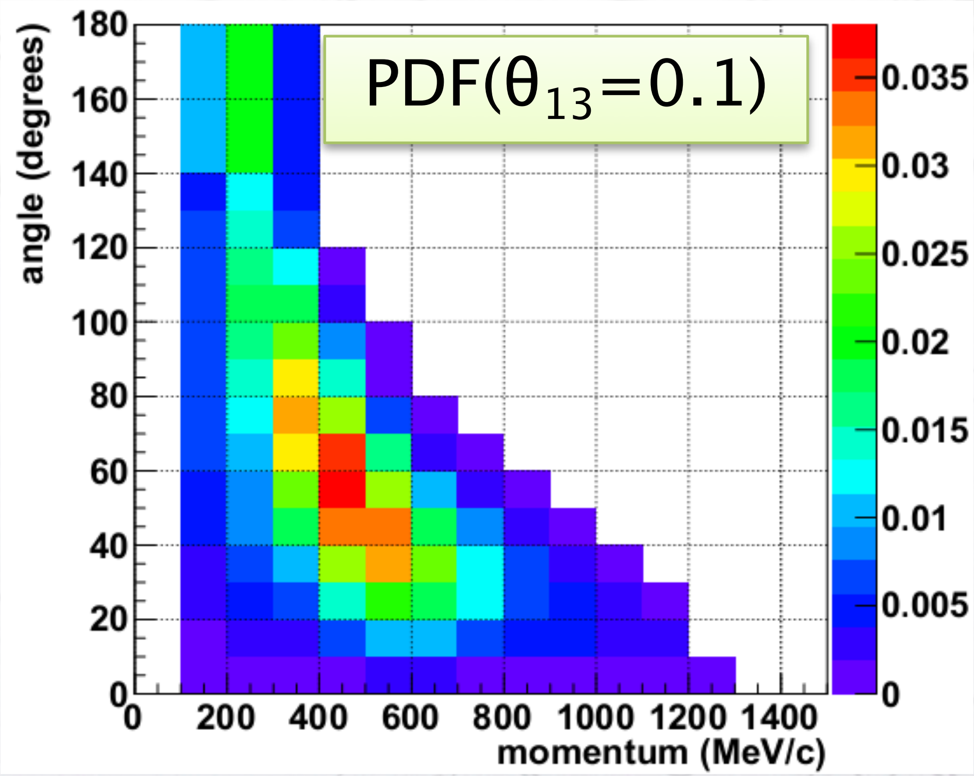
$\mathcal{L}_{shape}$: $\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$

$\mathcal{L}_{norm}$ 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 (θ_{13}=0.1)





ν_e appearance

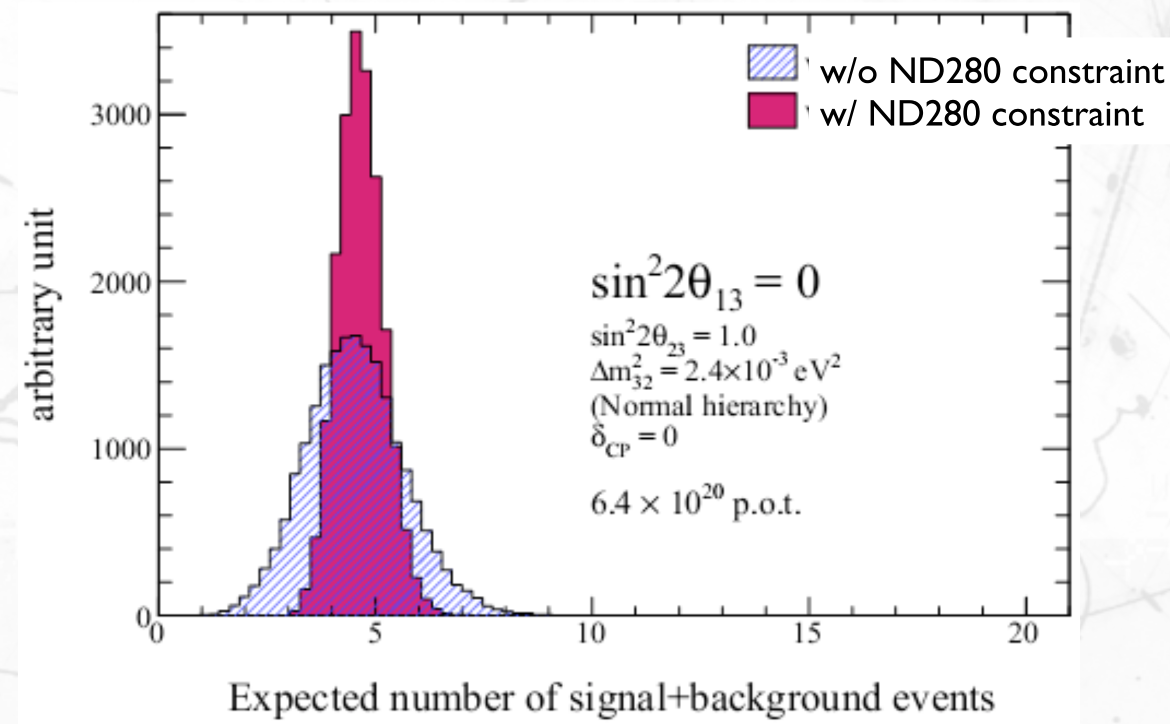
6.4×10^{20} PoT

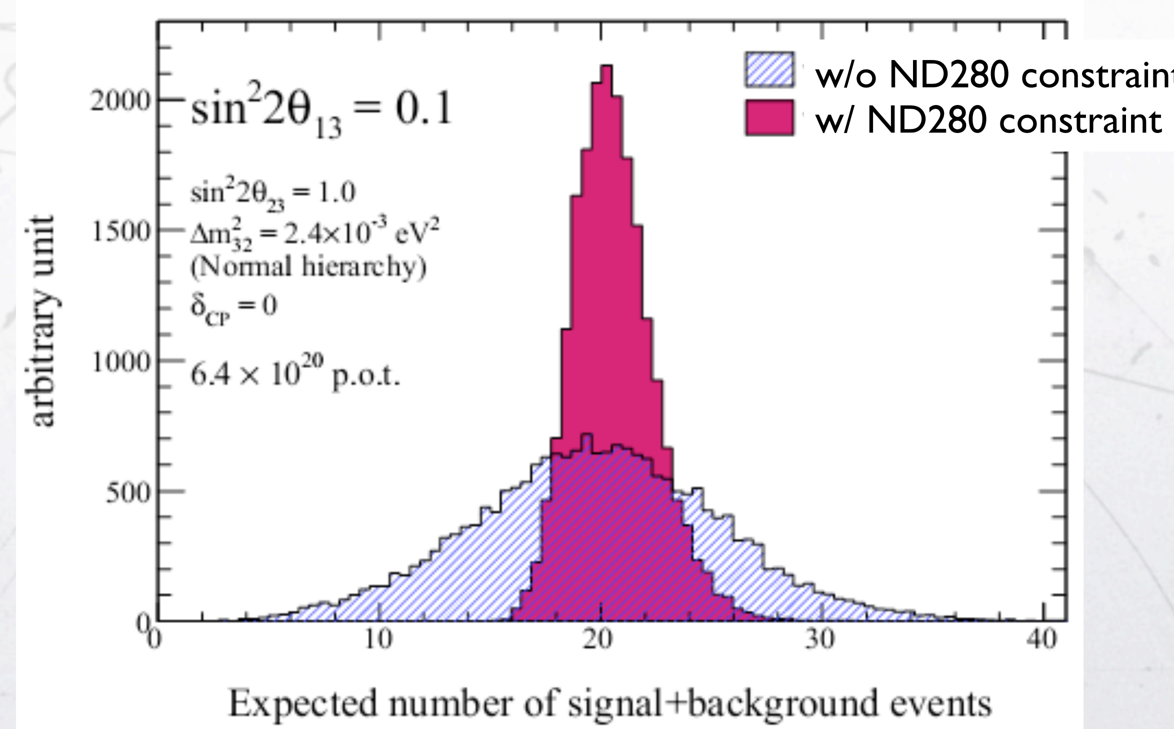
Event prediction

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

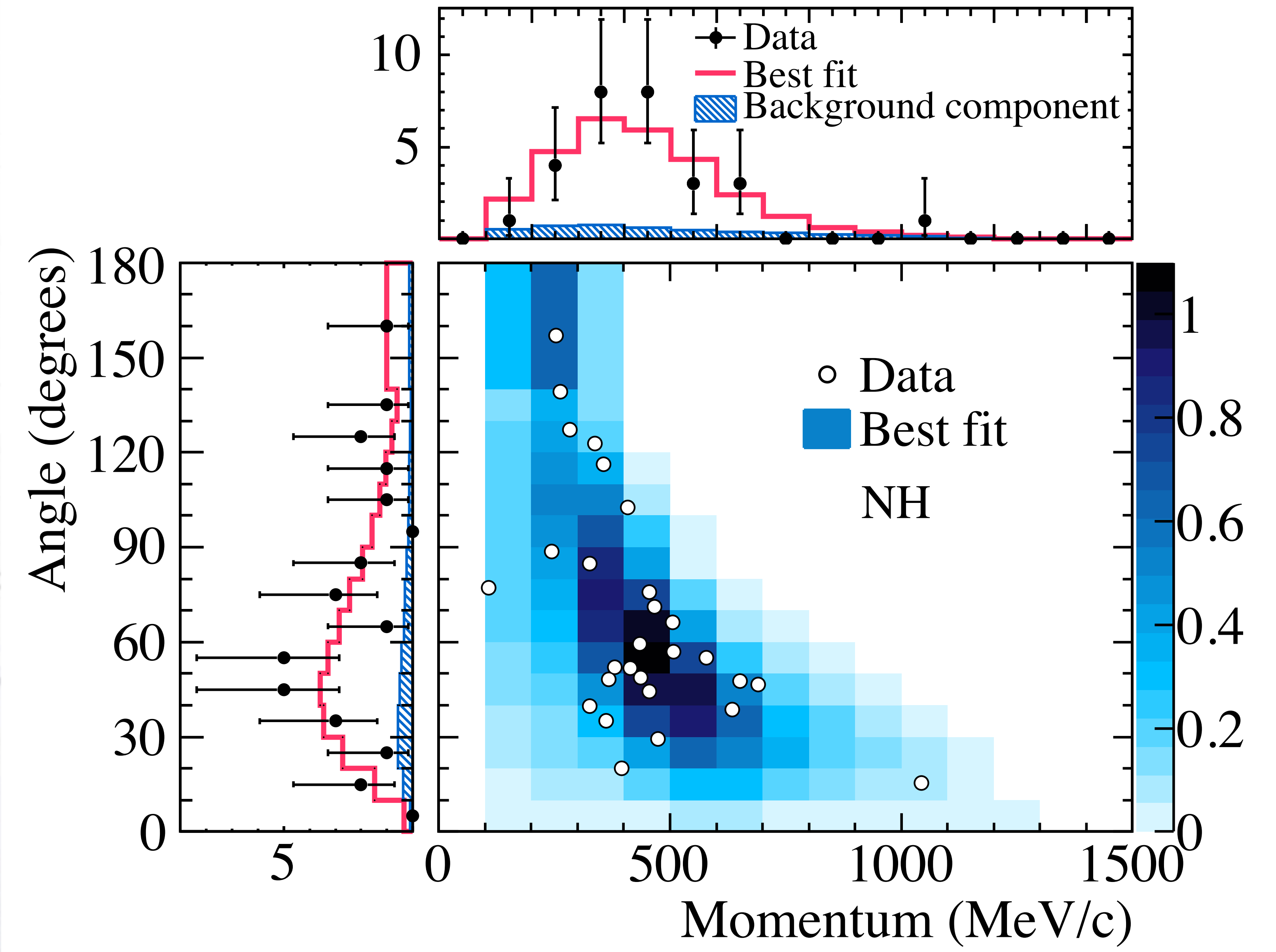
Systematic error

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



Best fit with 68% C.L. error:

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

PRL 112, 061802 (2014)

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

Joint analysis

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

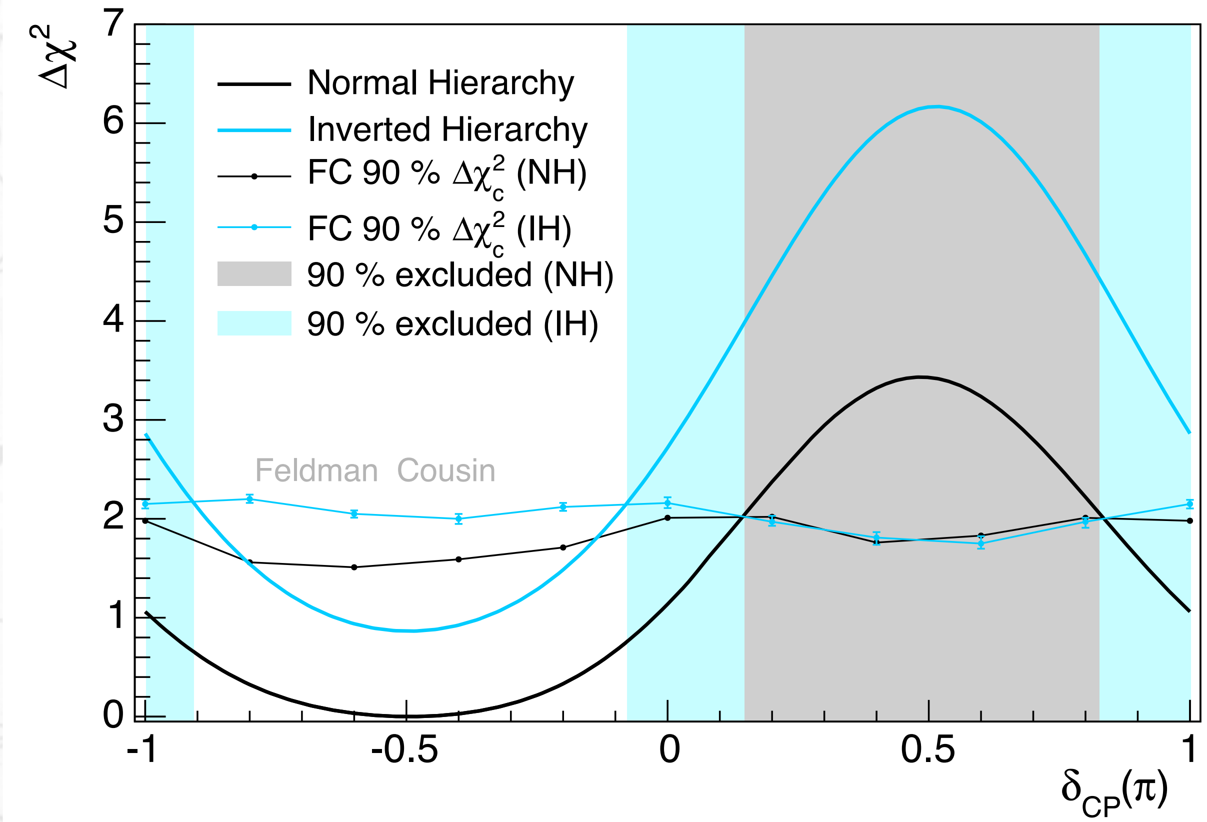
Accounting for correlations in the parameter space

$$(\theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{32})$$

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	$\delta_{CP} \in [-0.9, -0.08\ ]\ \pi$

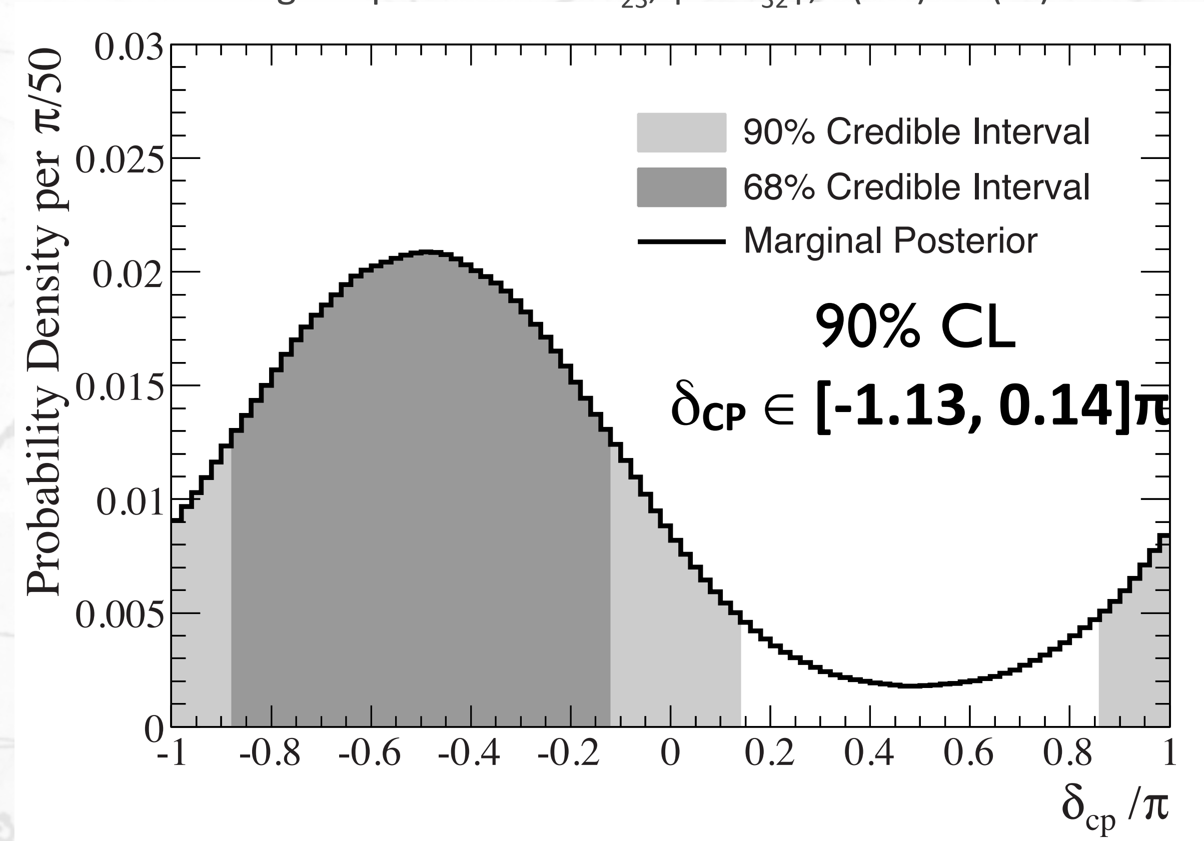
Joint analysis (Bayes)

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)

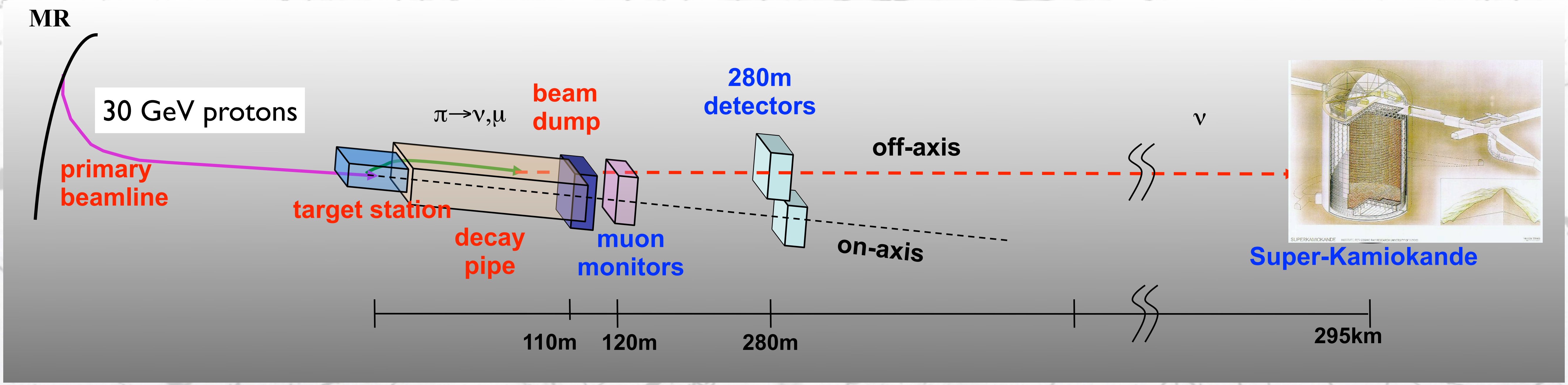
And compare the probabilities for each MH and θ_{23} octant combination

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%	

T2K: the future



Beam

ND280

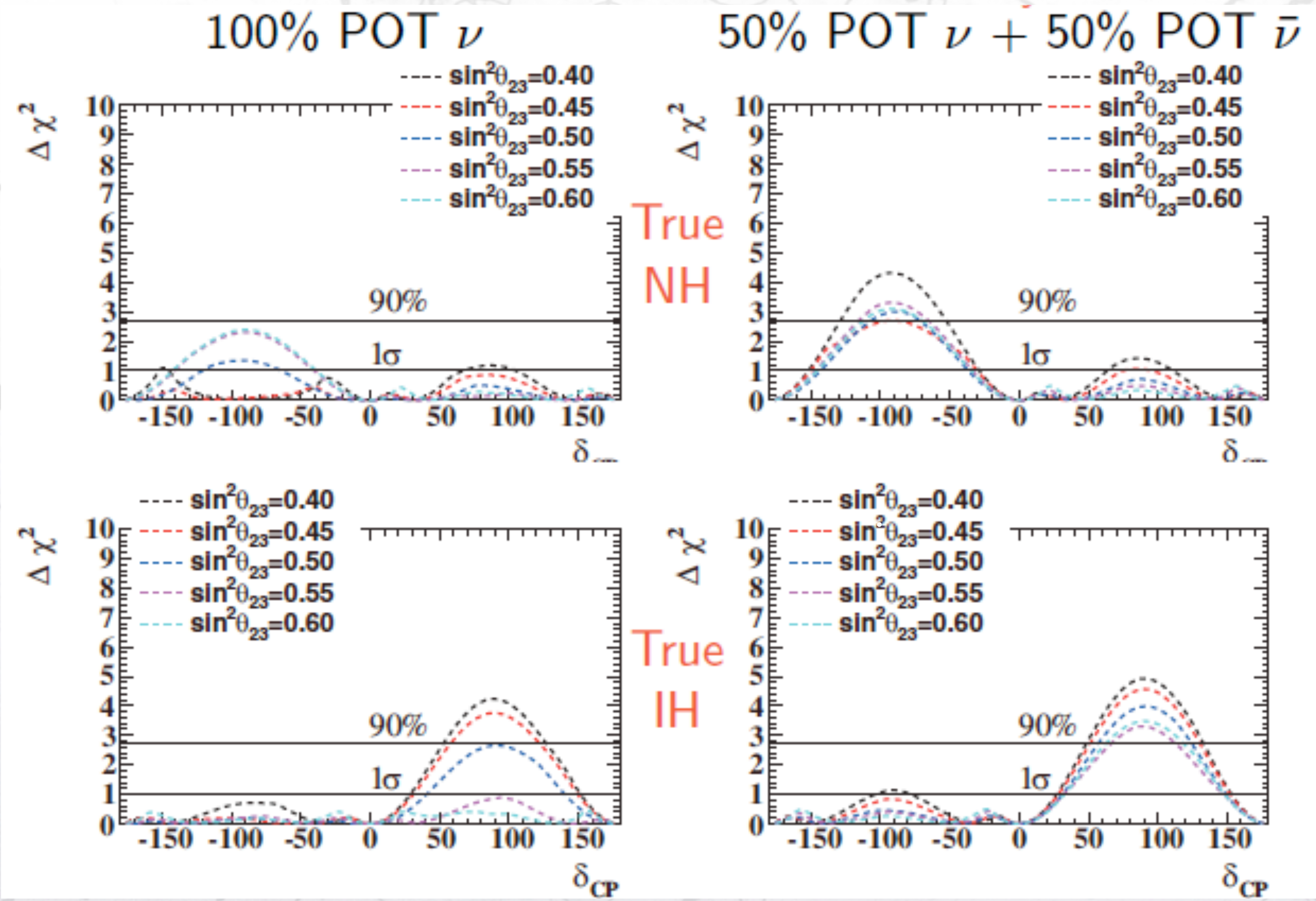
Super-Kamiokande

Upgrade plan

- Planned J-PARC Main Ring (MR) power improvements 220 kW operation in CY2014. 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

7.8×10^{21} PoT + 2012 systematics



T2K + reactor

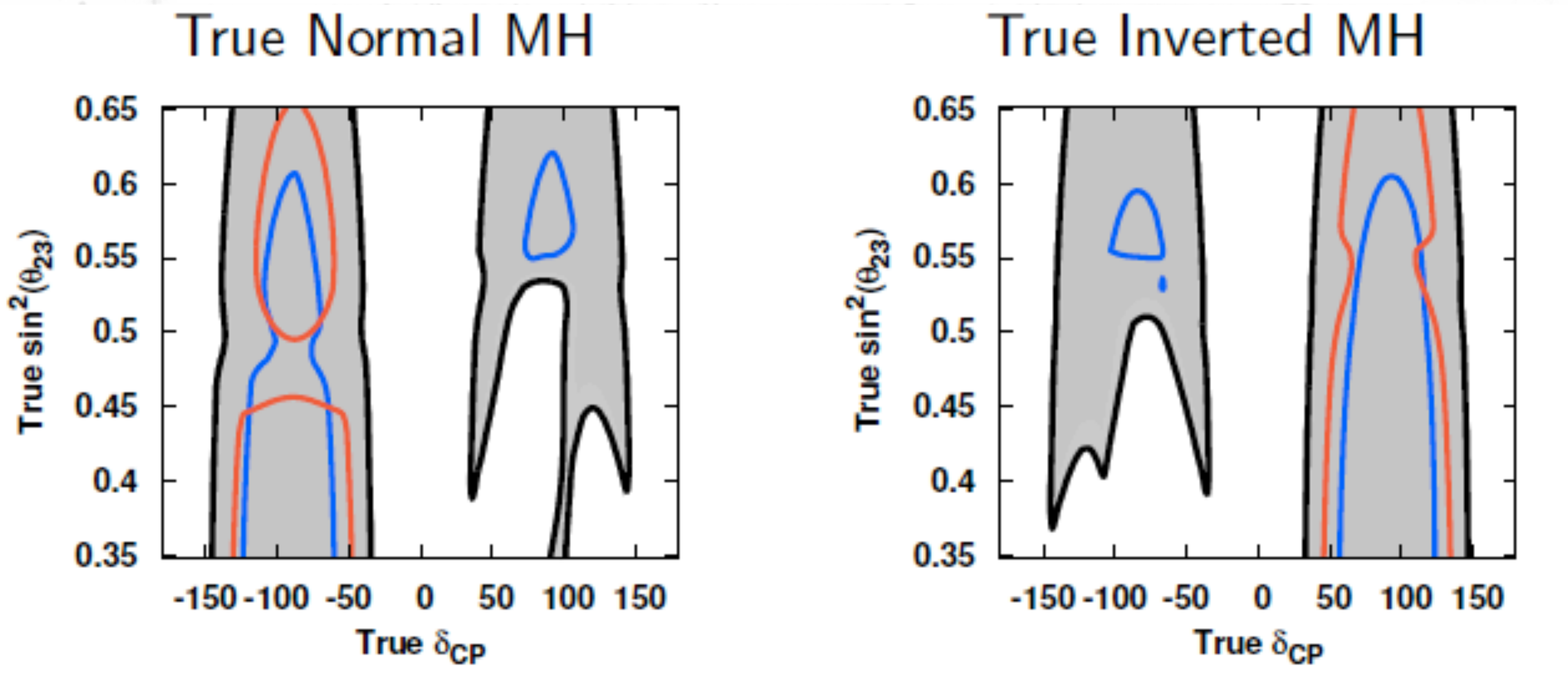
Assumptions

$$\sin^2 2\theta_{13} = 0.1$$
$$\Delta m^2_{32} = 2.4\times10^{-3} eV^2$$
$$\delta(\sin^2\theta_{13}) = 0.005$$

Future δ_{CP} sensitivity

T2K + Nova + reactor

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



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

T2K alone

Nova alone

T2K+ Nova

Assumptions

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

⊕ simple normalisation errors.

Concluding remarks

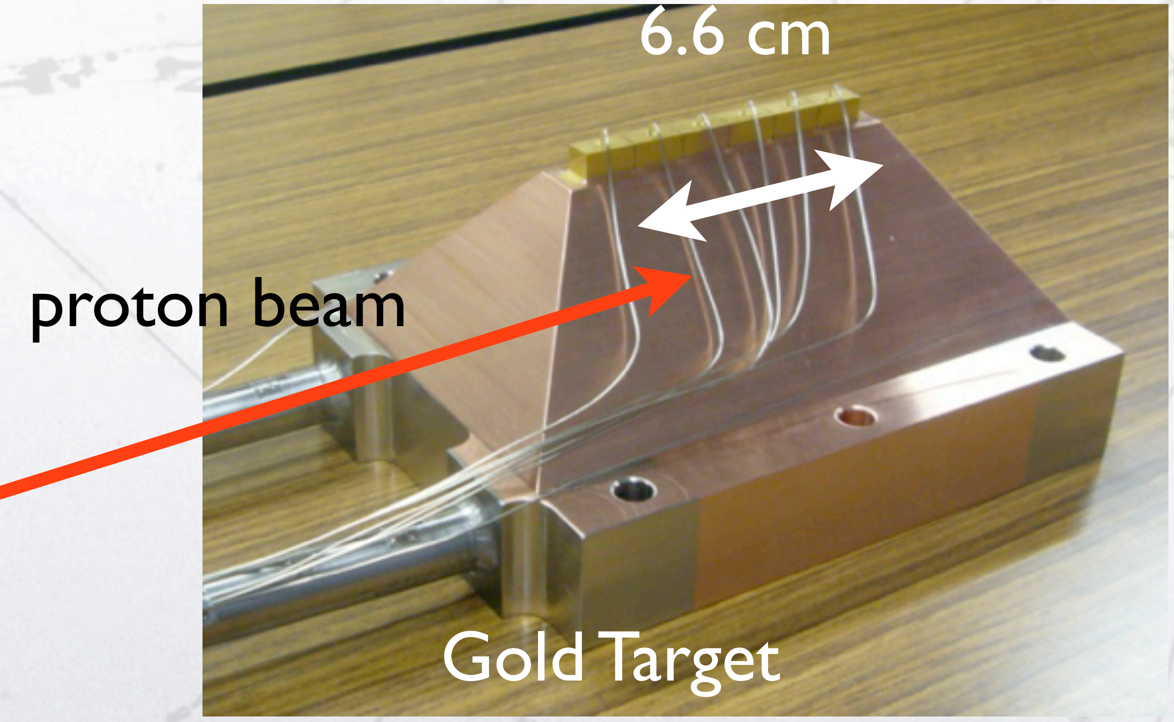
- T2K has shown the first evidence (7.4 σ significance) of the appearance of ν_e in a ν_μ beam with only 8.3% of the total T2K statistics.
- Also measurement of $\nu_\mu \rightarrow \nu_\mu$ which favours maximal mixing. Oscillations at "atmospheric" baseline are now precision measurements
- This success 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 May 2014.

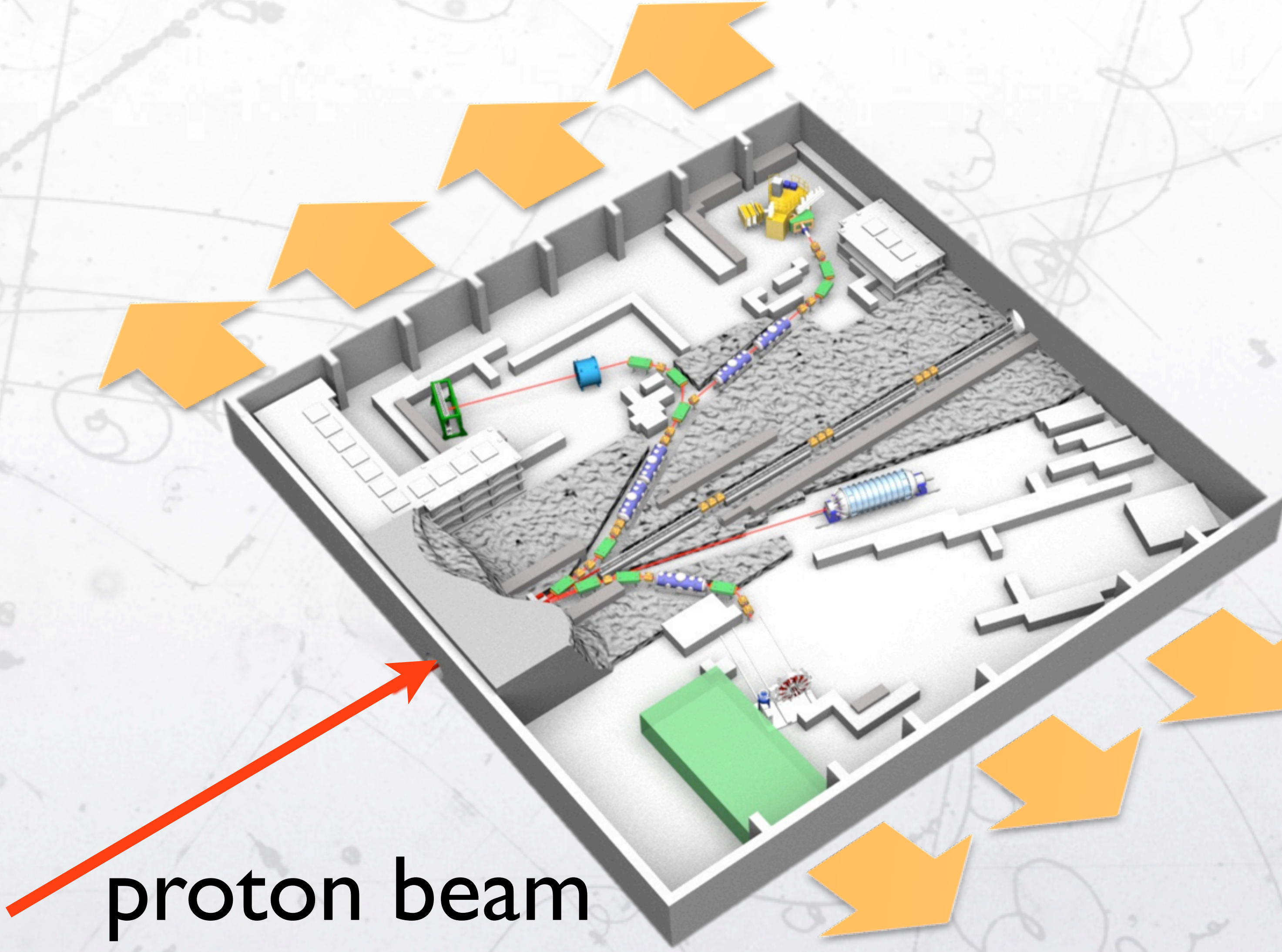
Support slides

J-PARC accident

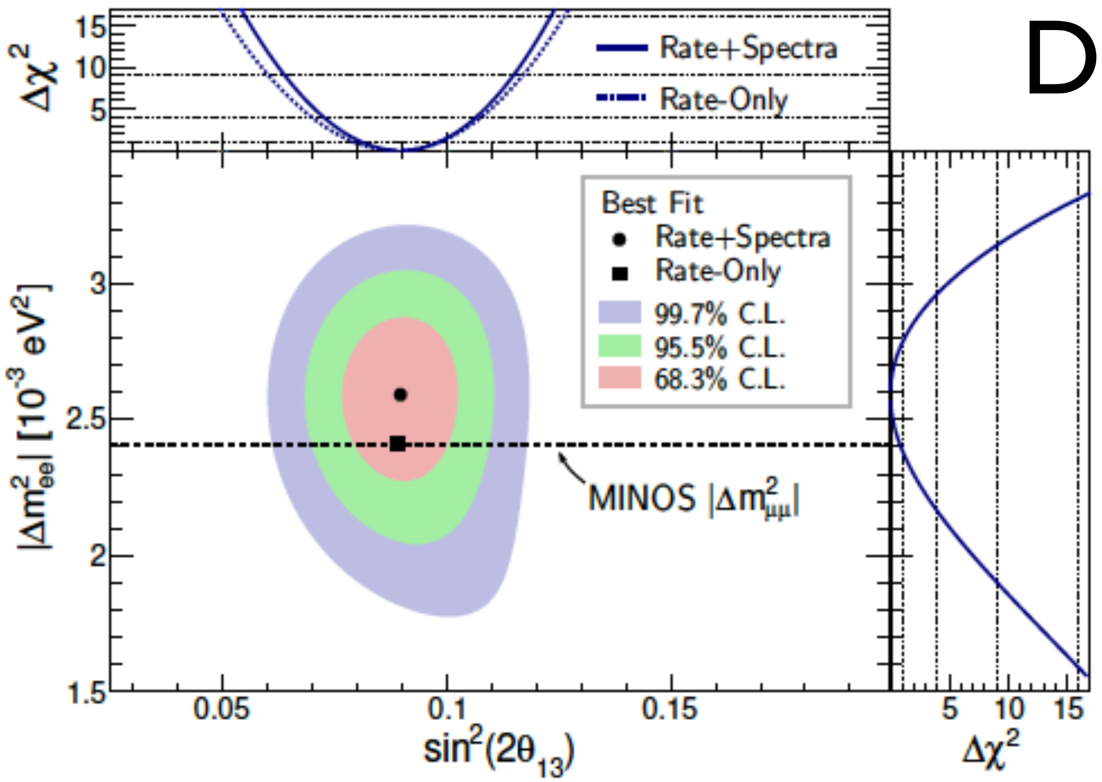
11:55 on May 23

- 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

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

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

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

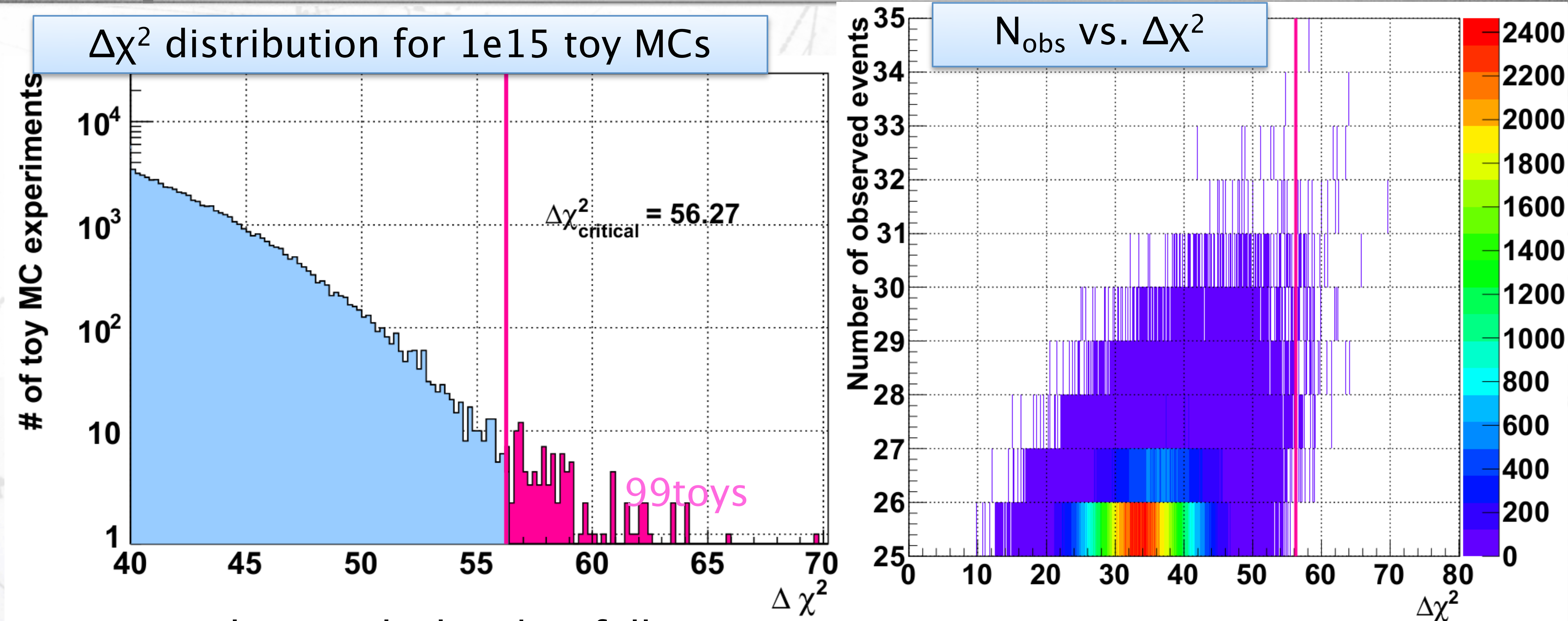
Strong confirmation of oscillation-interpretation of observed $\bar{\nu}_e$ deficit

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

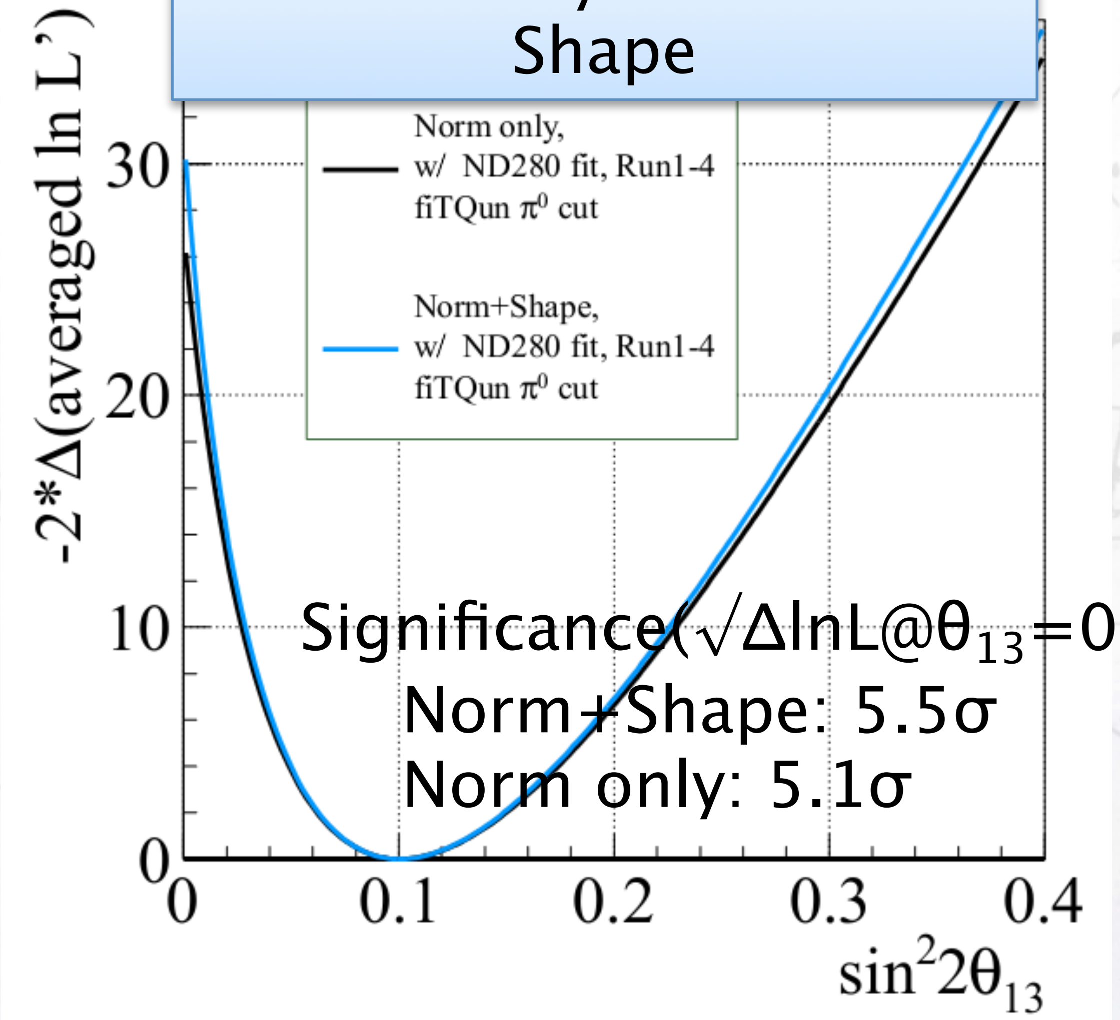
For the actual calculation, we use time saving method.

- 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.

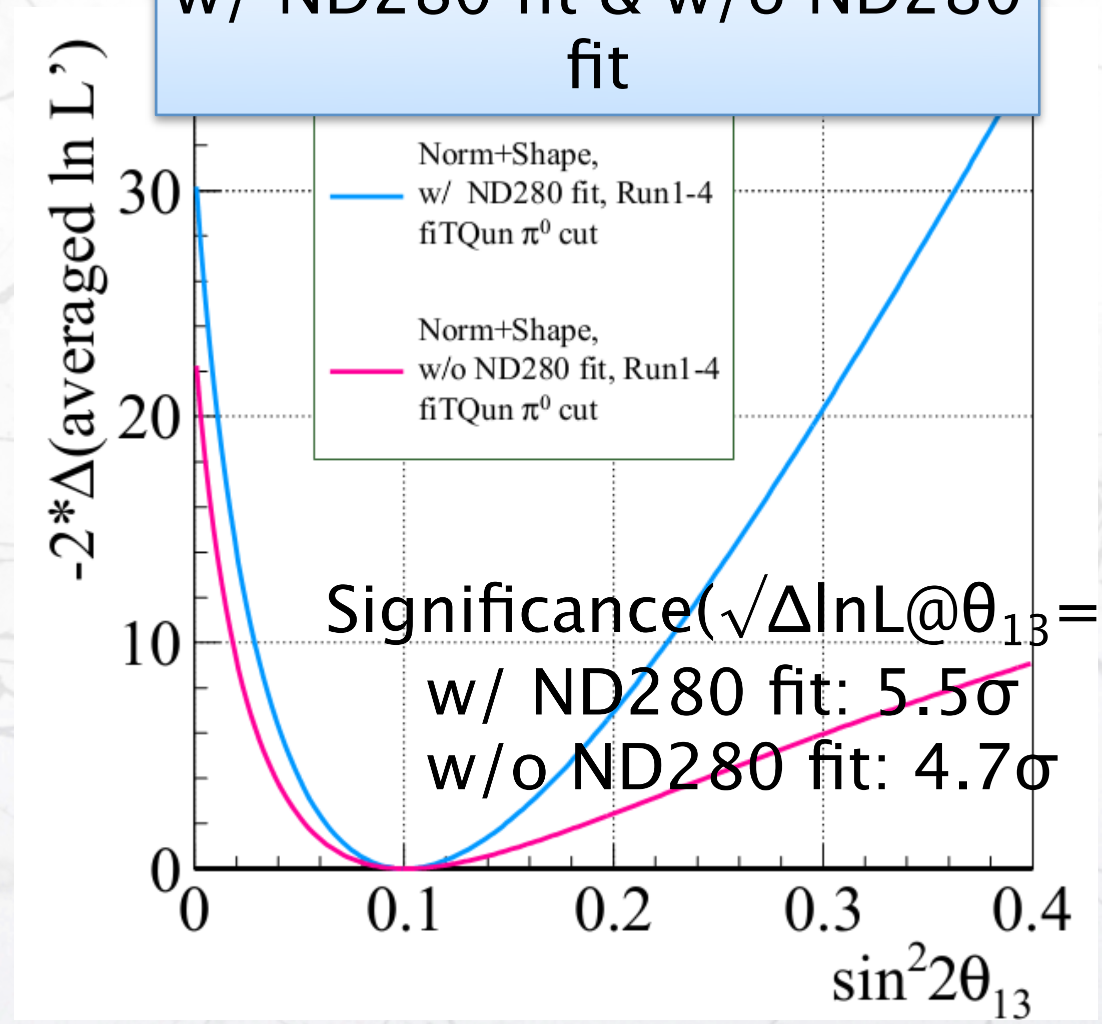
Norm only & Norm + Shape



Significance($\sqrt{\Delta \ln L}$@θ_{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

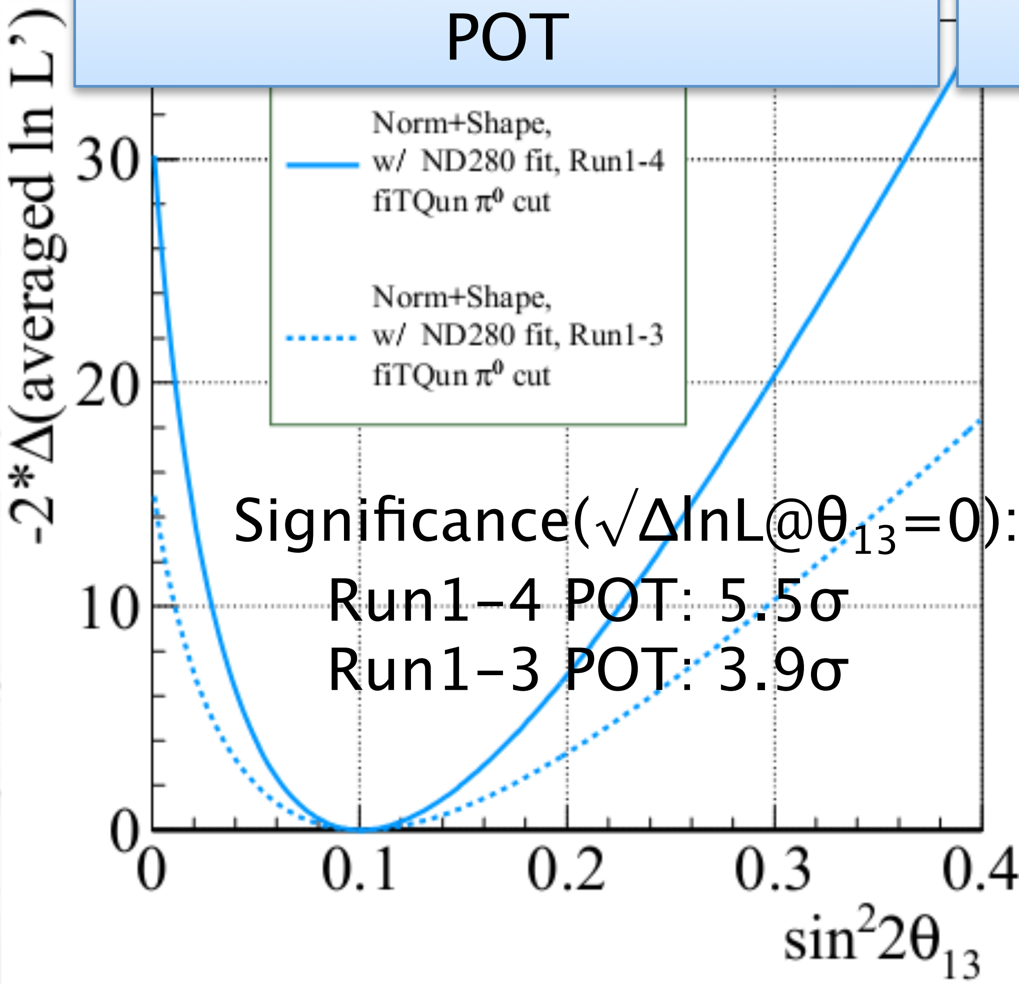


Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
w/ ND280 fit: 5.5σ
w/o ND280 fit: 4.7σ

ND280 fit makes relatively large improvement.

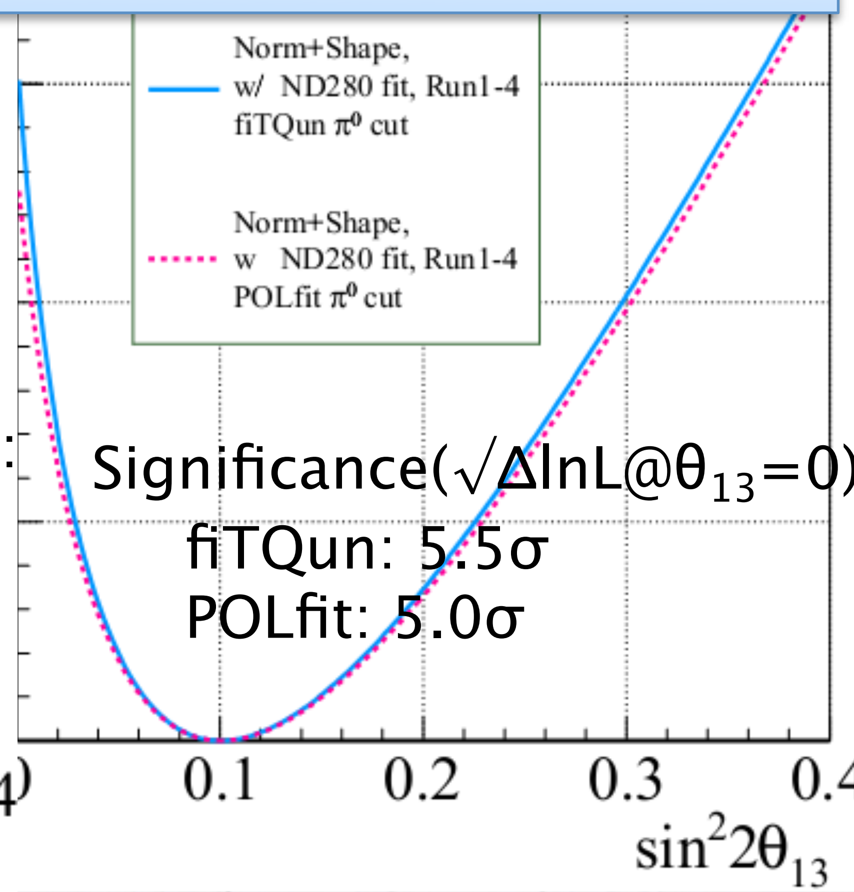
Sensitivity checks

Run1-4 POT & Run1-3 POT



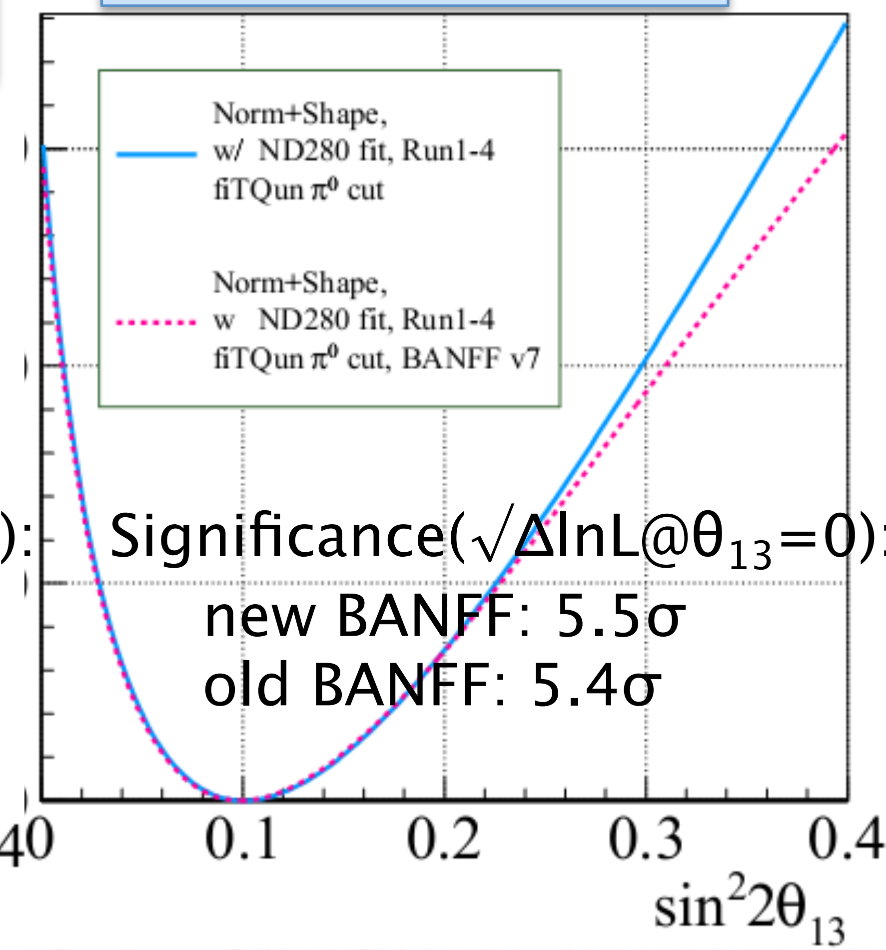
Significance($\sqrt{\Delta \ln L}$@θ_{13}=0):
Run1-4 POT: 5.5σ
Run1-3 POT: 3.9σ

fiTQun π^0 cut & POLfit π^0 cut



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

old & new BANFF



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

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^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.

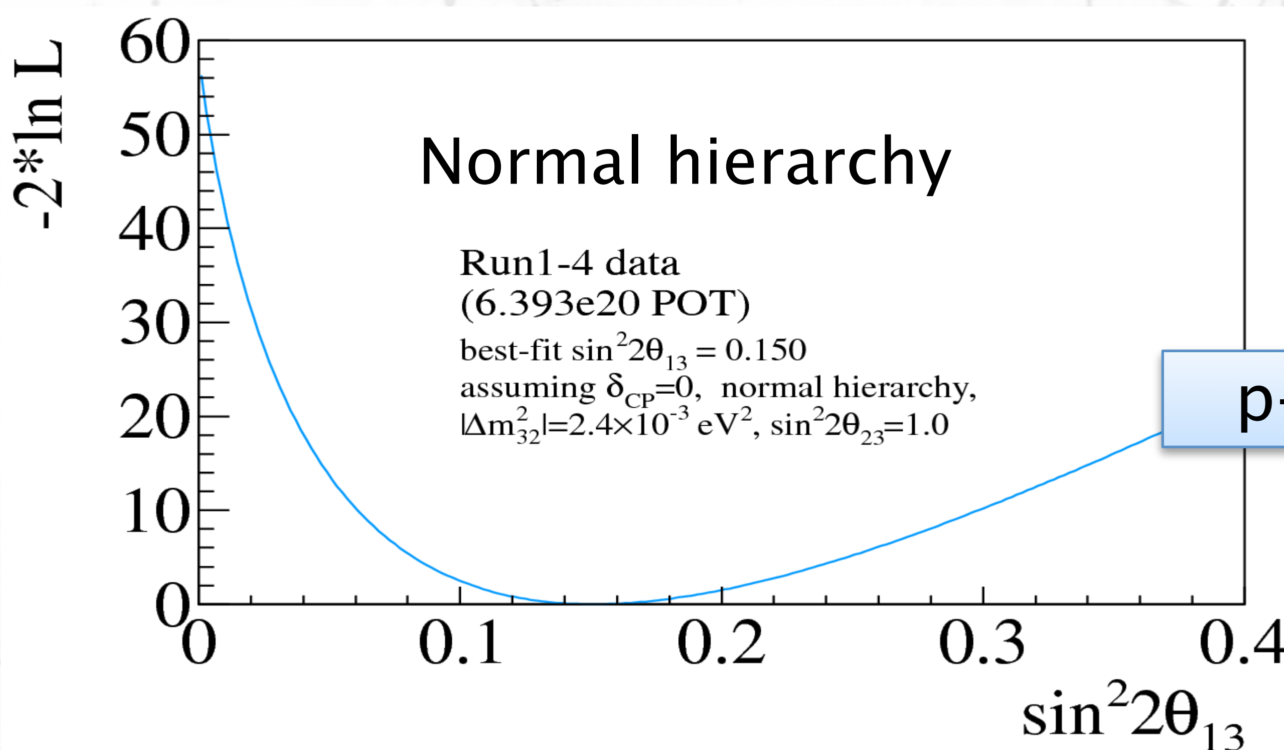
Fitted values

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	$0.089 < x < 0.206$	$0.110 < x < 0.249$

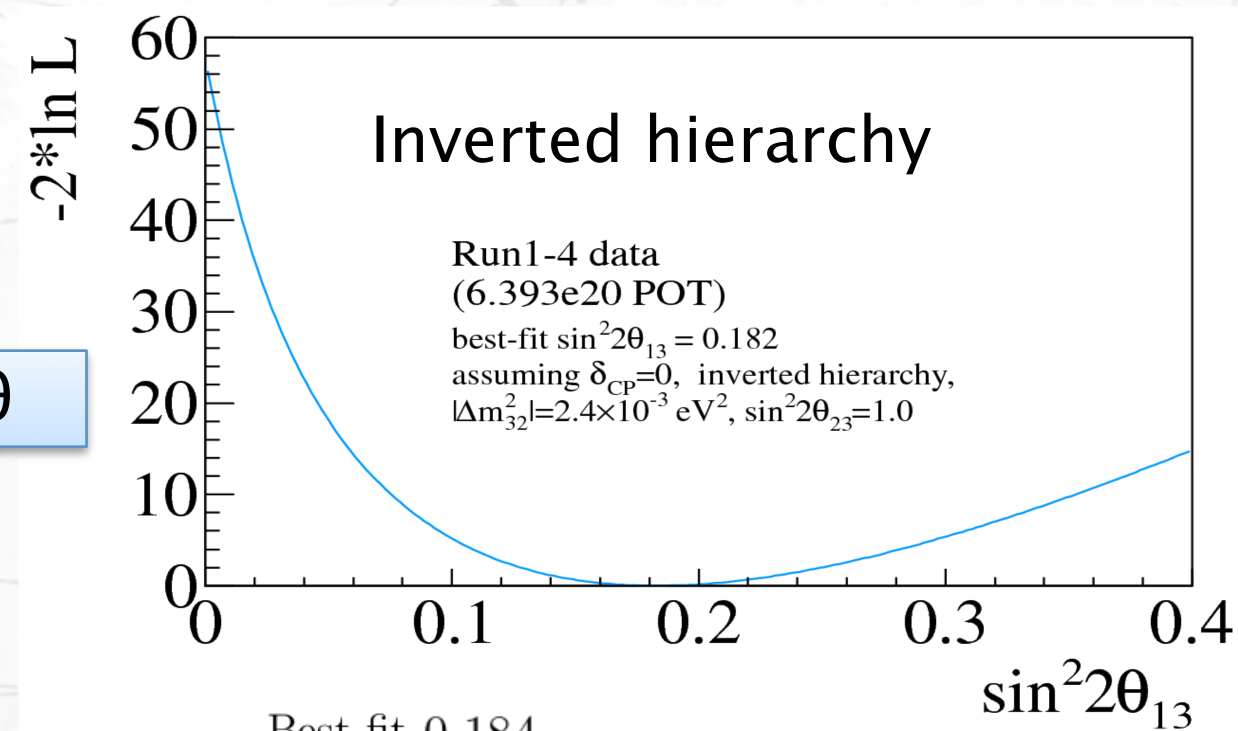
The fitted values were consistent with the true values. p–θ and E_{rec} were also consistent with each other.

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

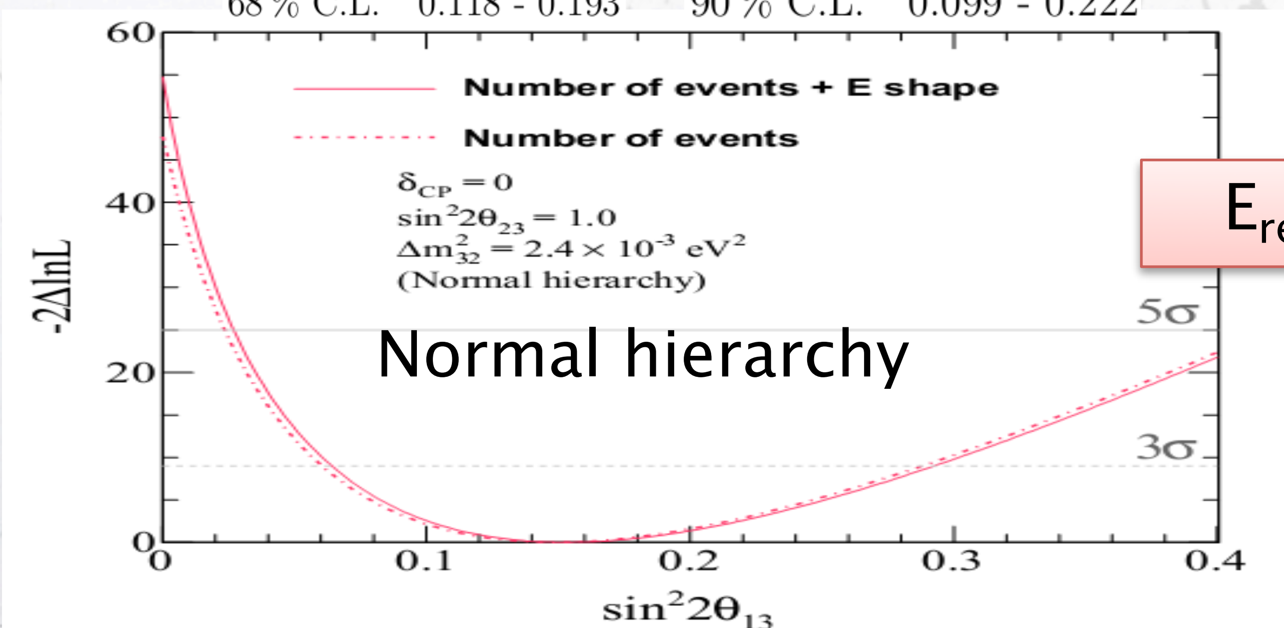
Likelihood curves for Run1-4 data



p−θ

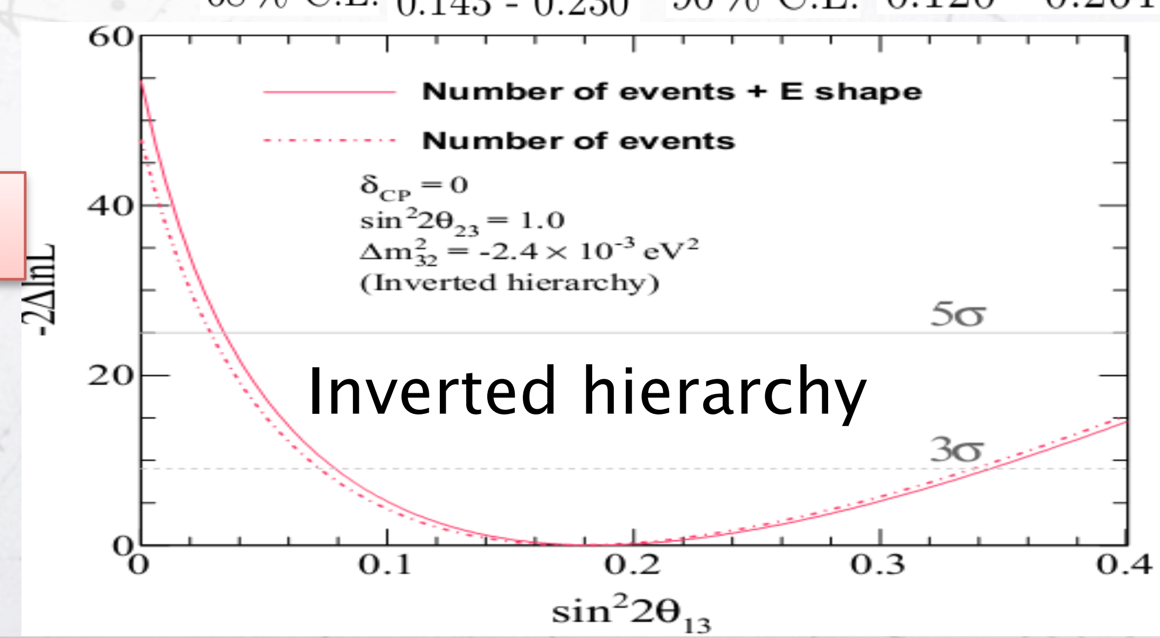


Best fit 0.152
68 % C.L. 0.118 - 0.193 90 % C.L. 0.099 - 0.222



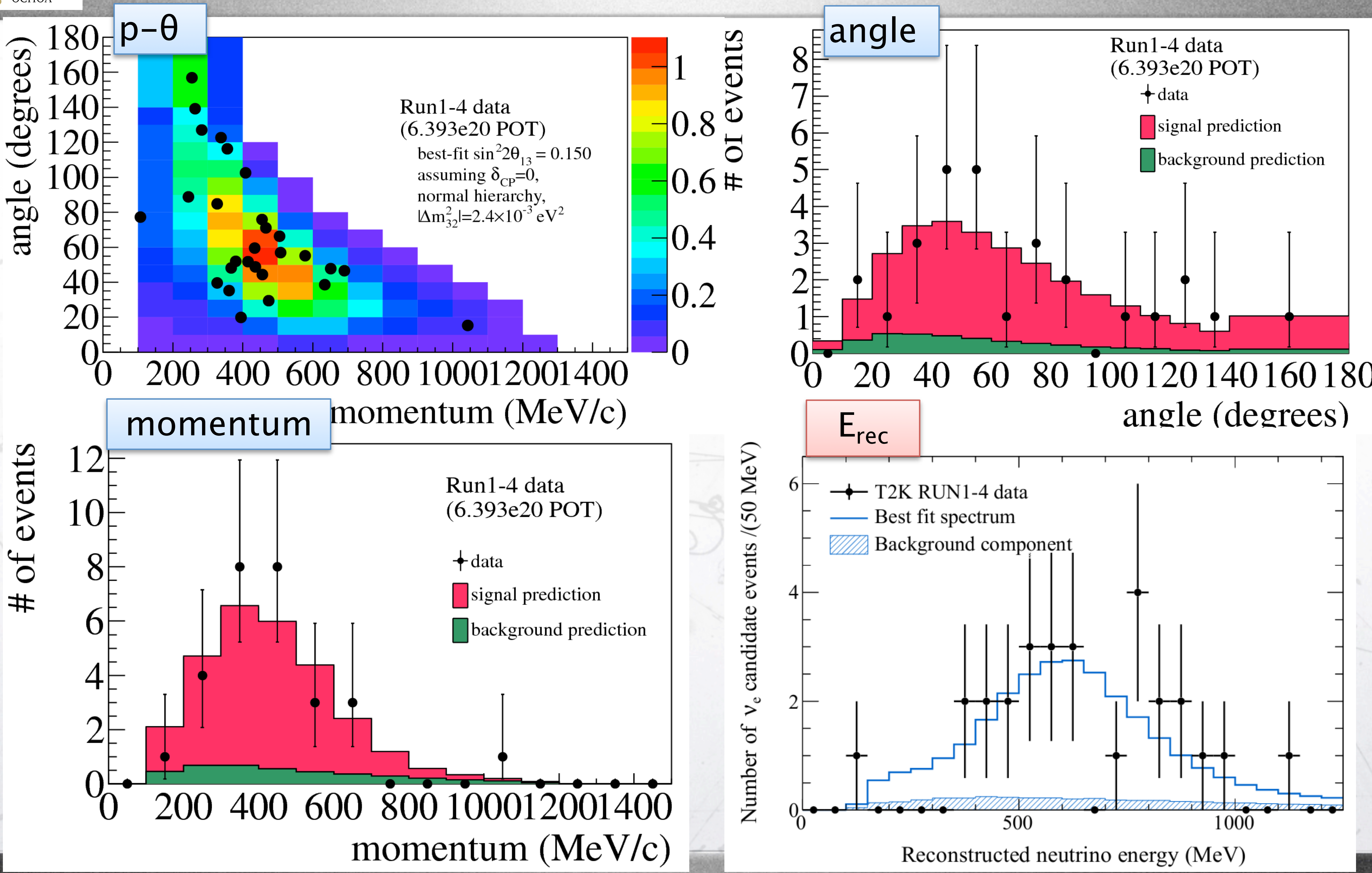
E_{rec}

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

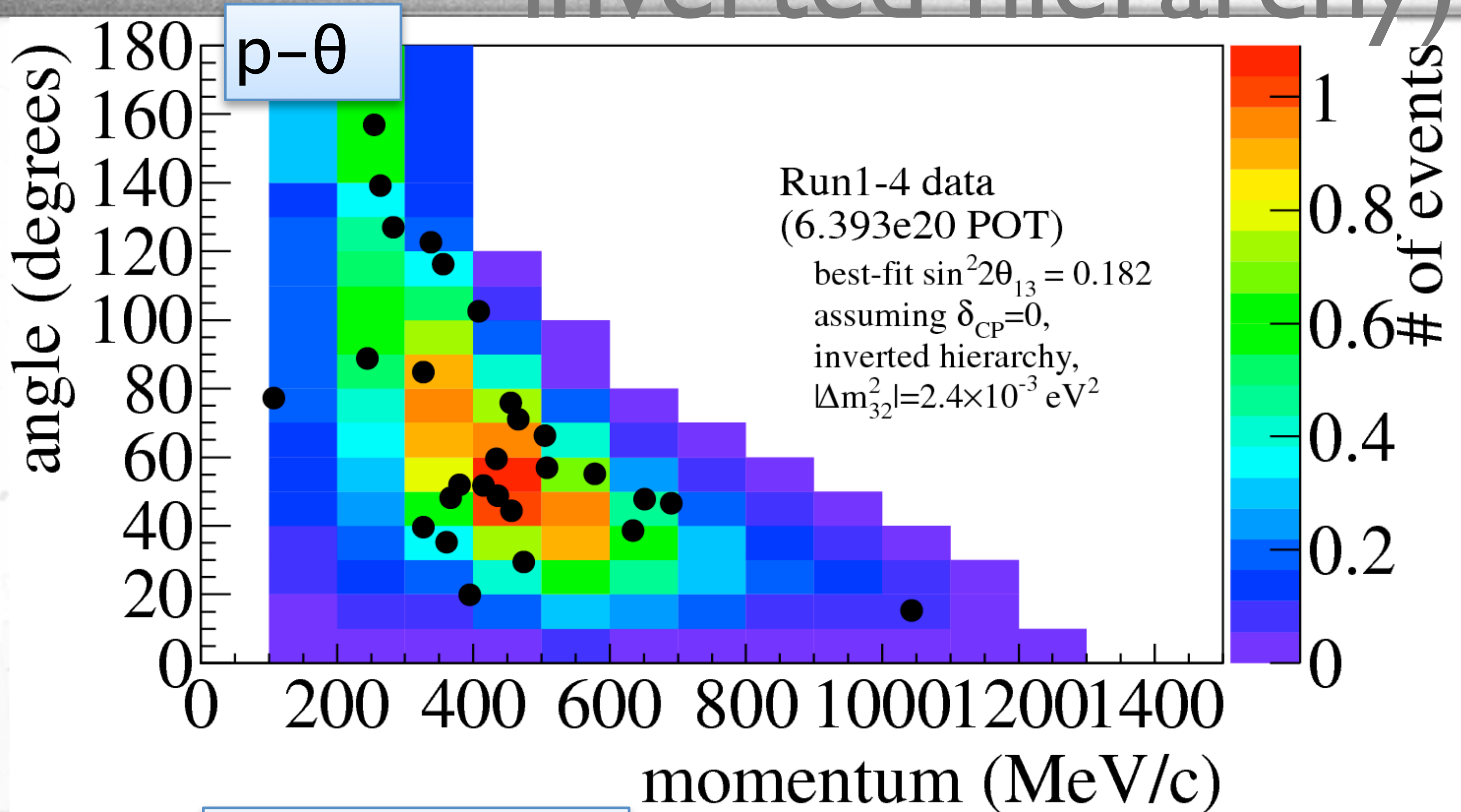


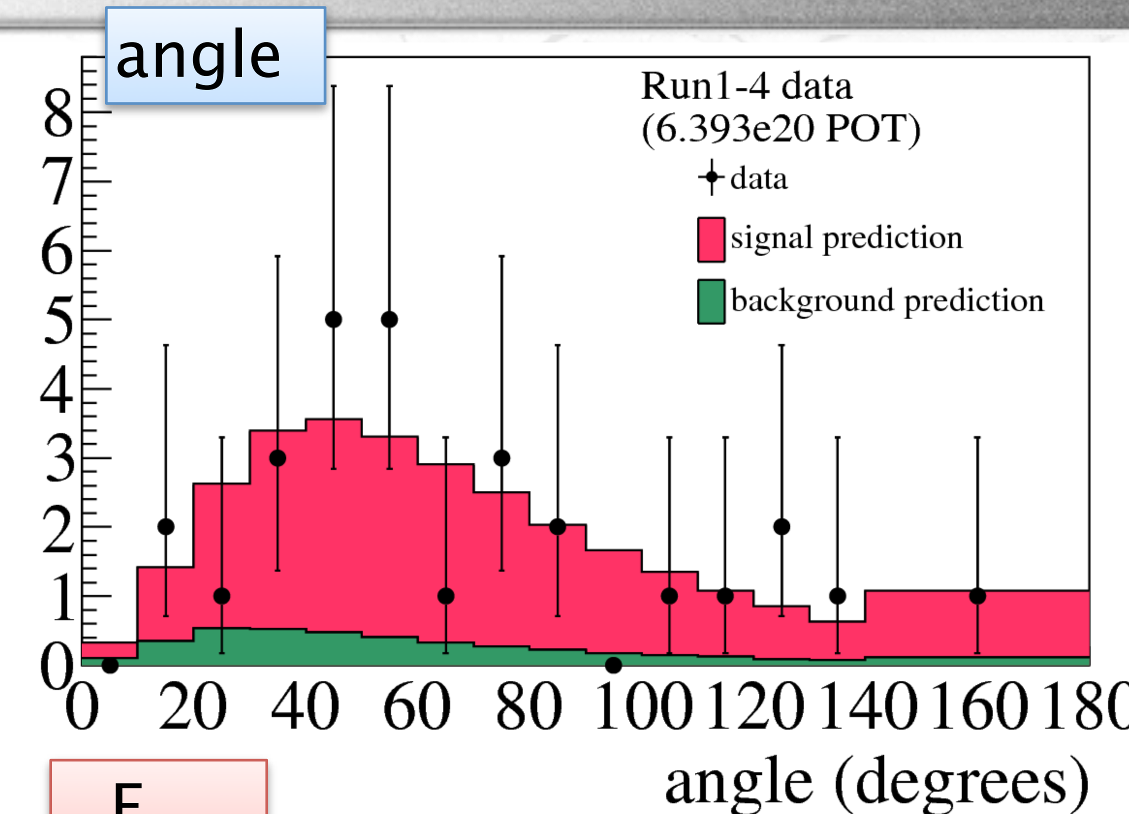
(summary table will be shown later.)

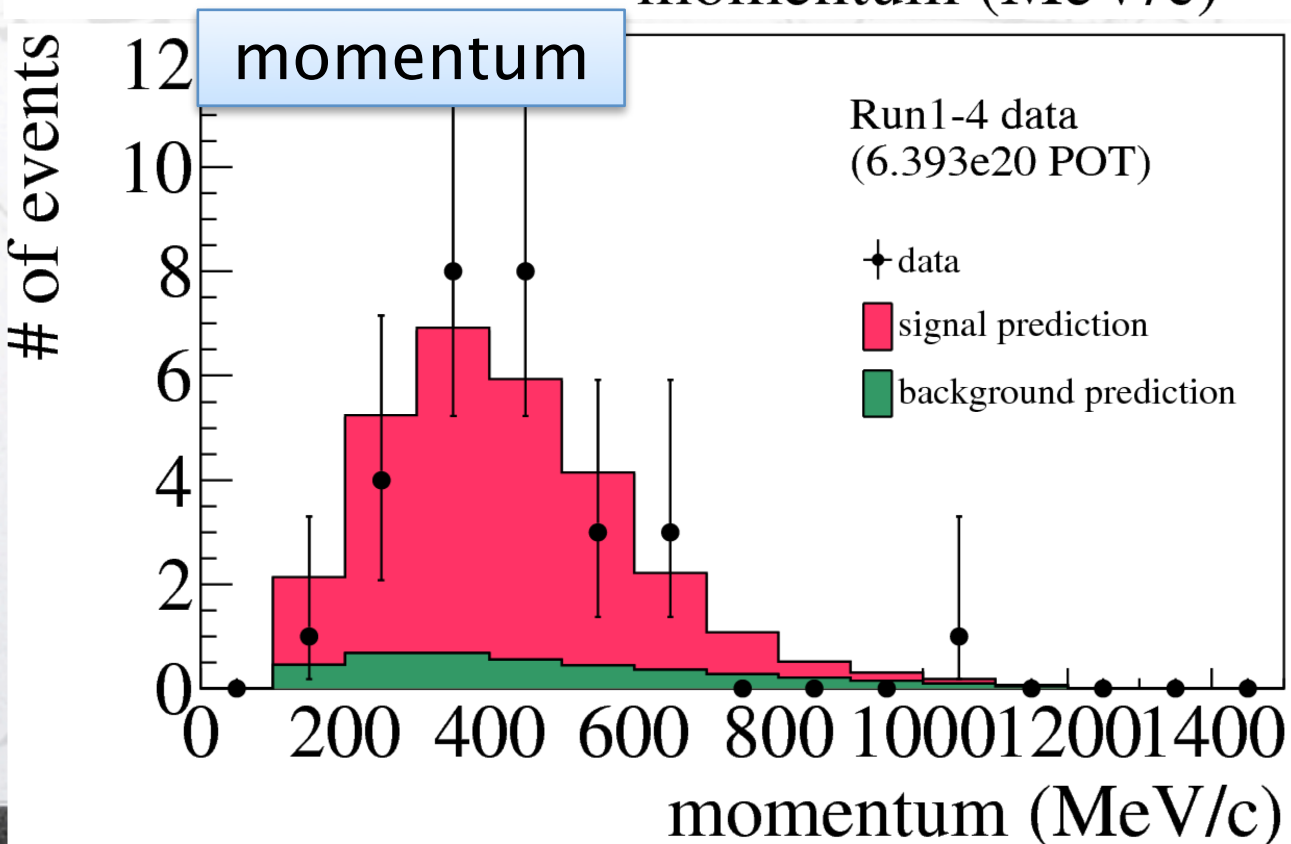
Best fit distributions (Run1-4, normal

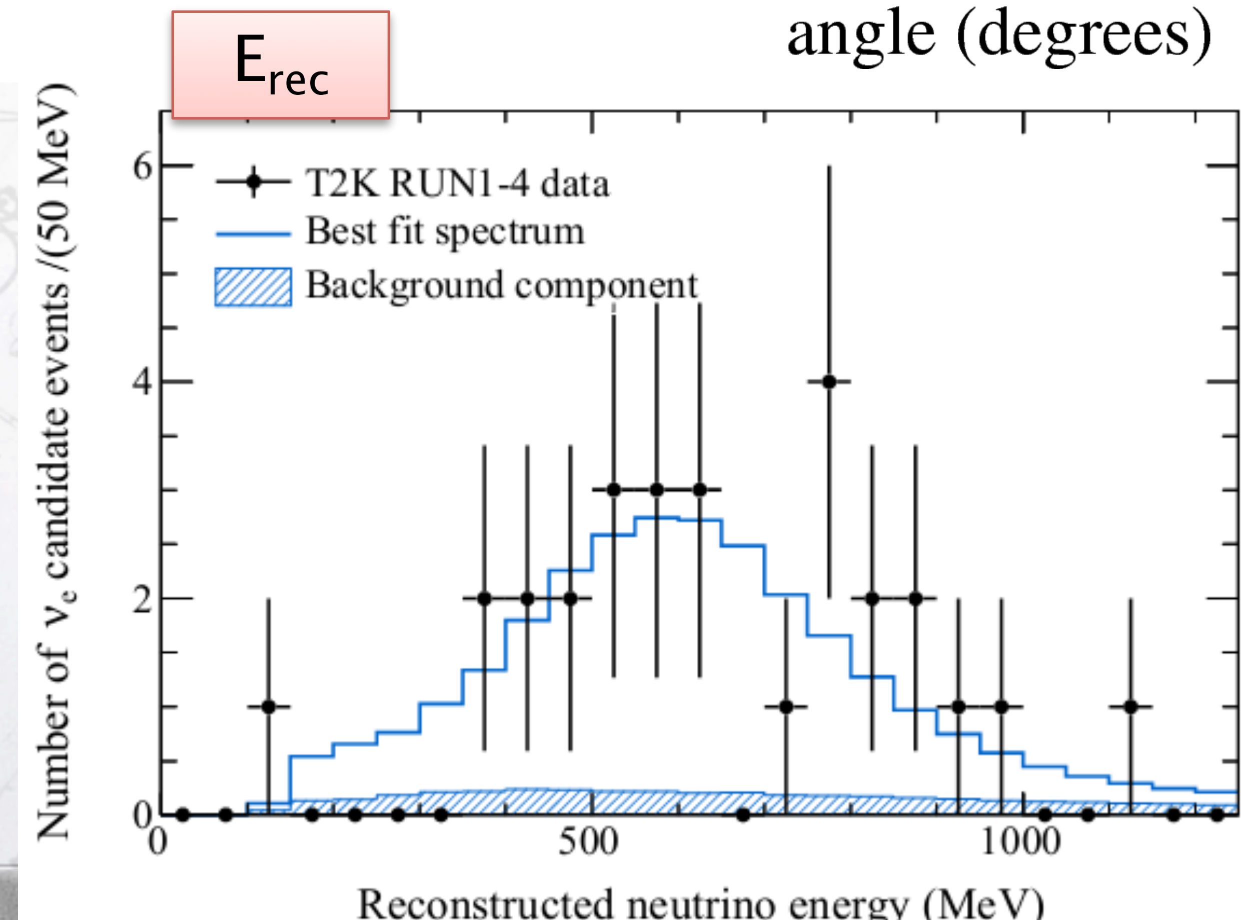


Best fit distributions (Run1-4, inverted hierarchy)









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 (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.	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 co				
NC co				
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: %)

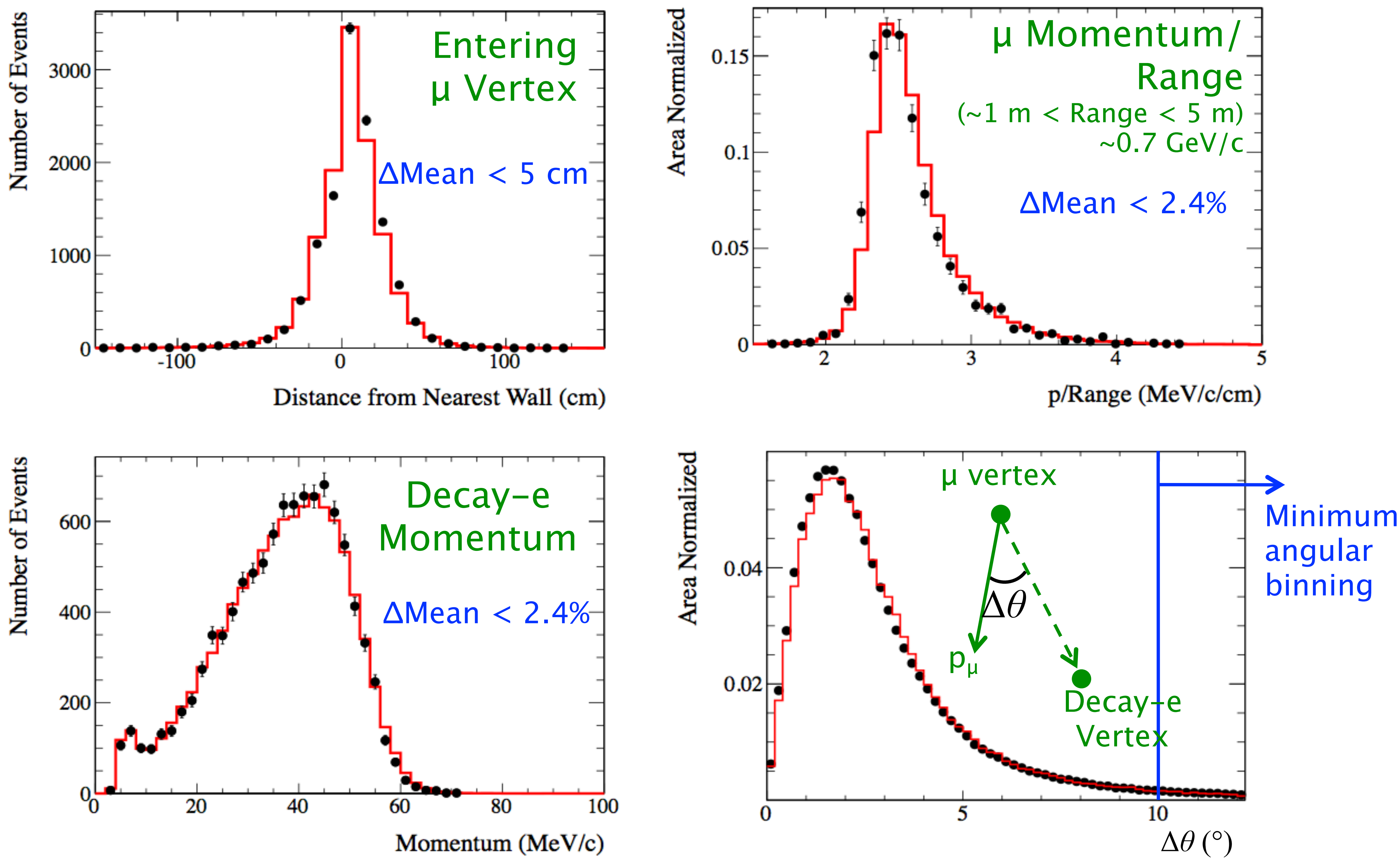
Black: 2013
Blue: 2012

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.)

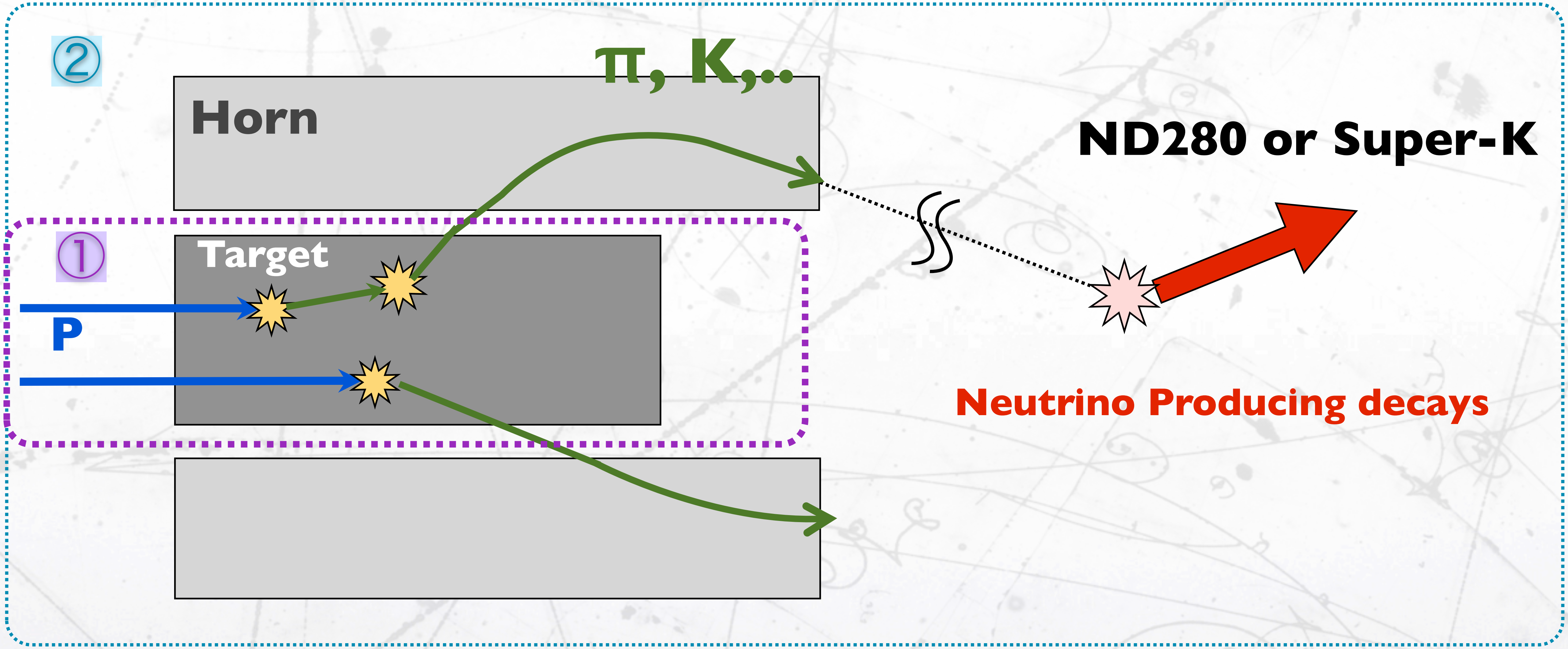
New reconstruction validation

Validation with stopping muons



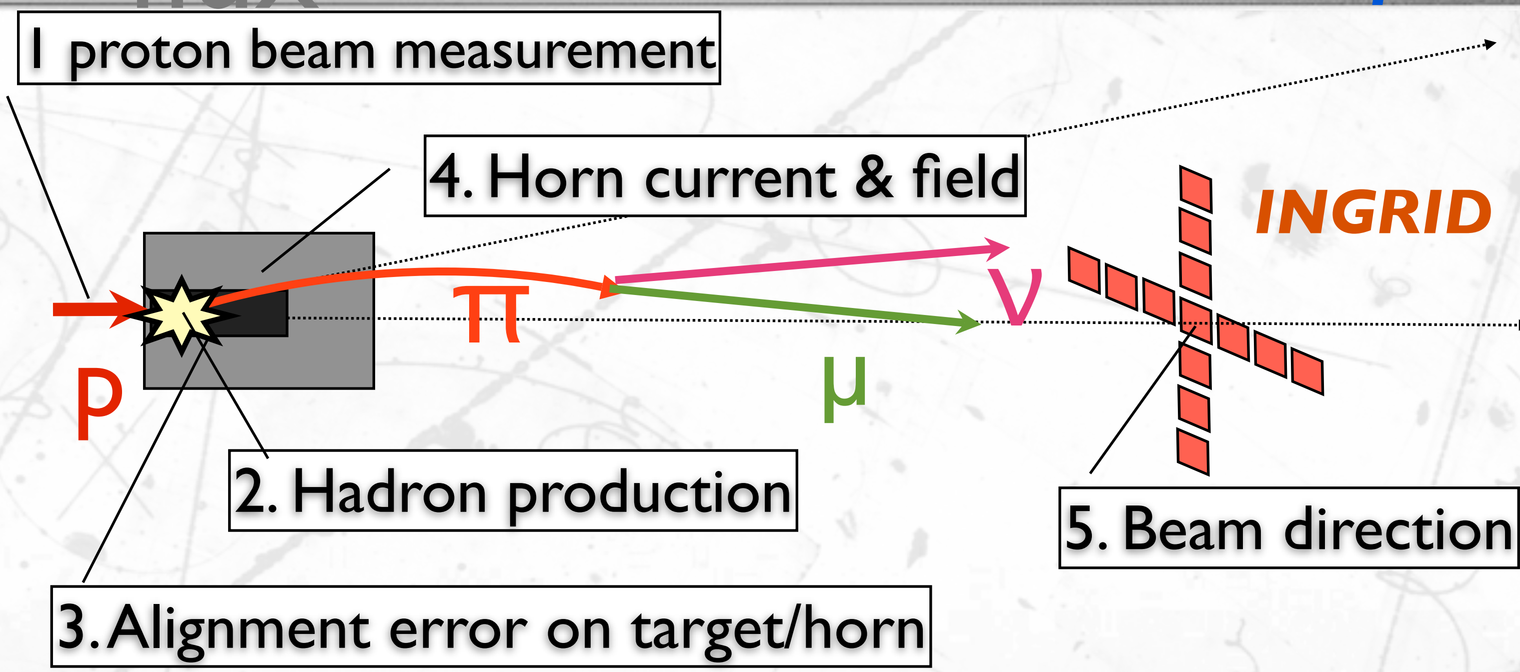
Beam

Simulating neutrino flux

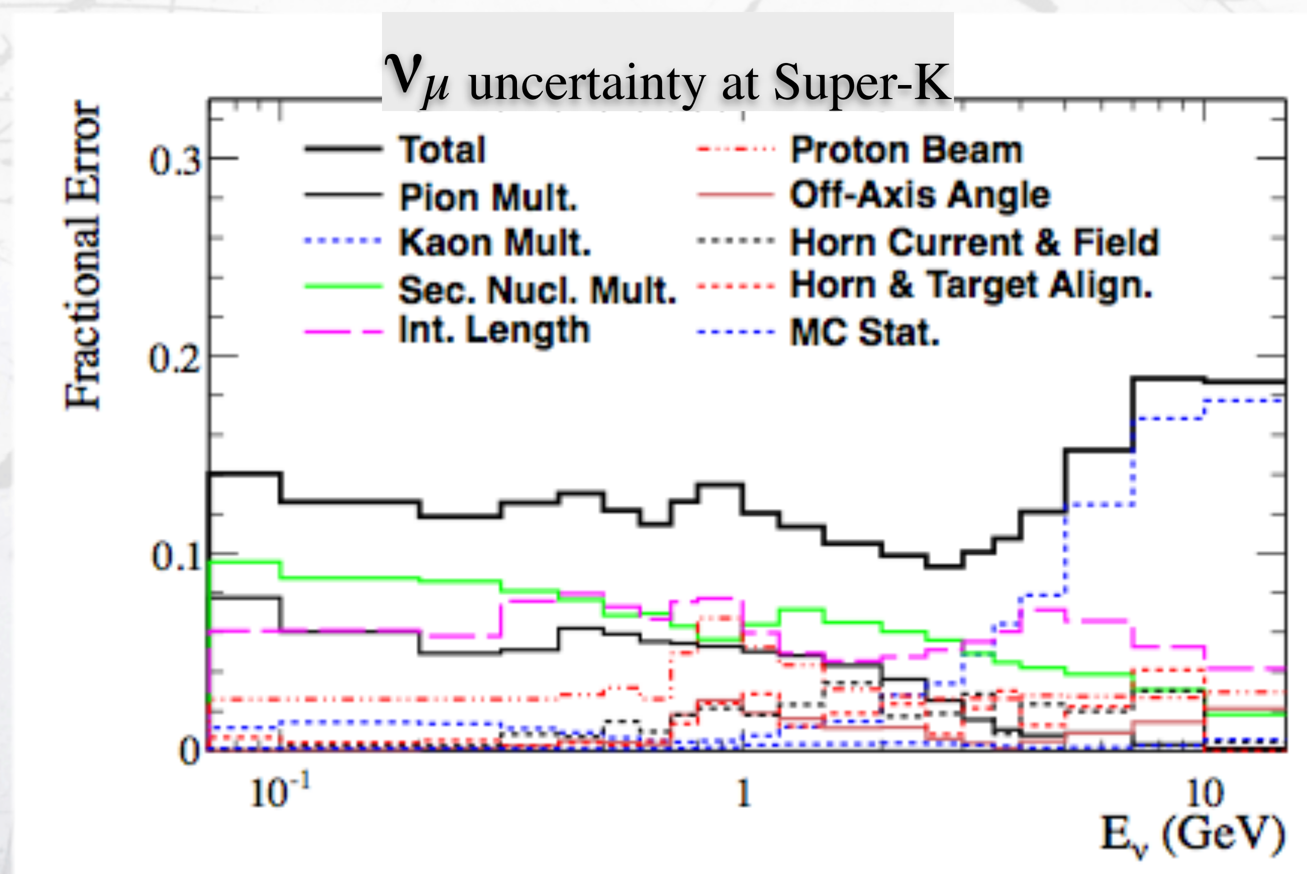


1. p interaction inside the carbon target with FLUKA2008.3d
2. Tracking through horn fields and decay volume using GEANT3 with GCALOR
   Calculate neutrino producing decays
   Estimate the flux at the near/far detector

Systematic error sources for neutrino flux

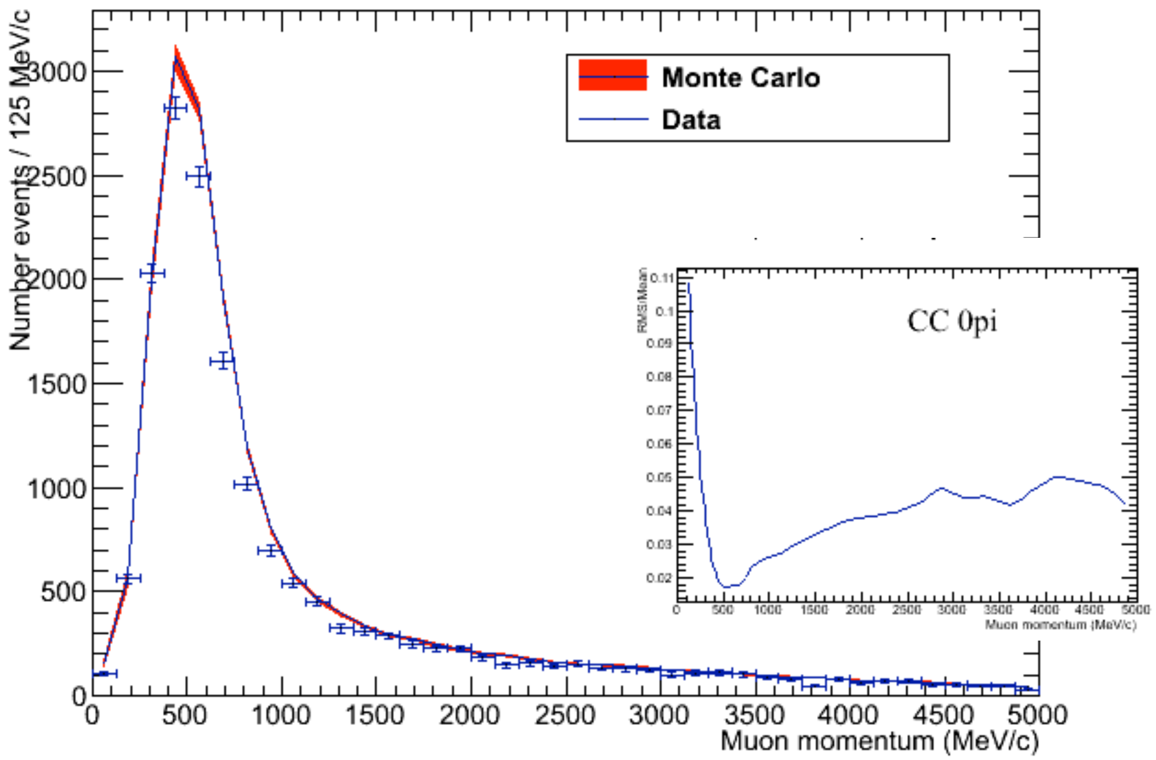


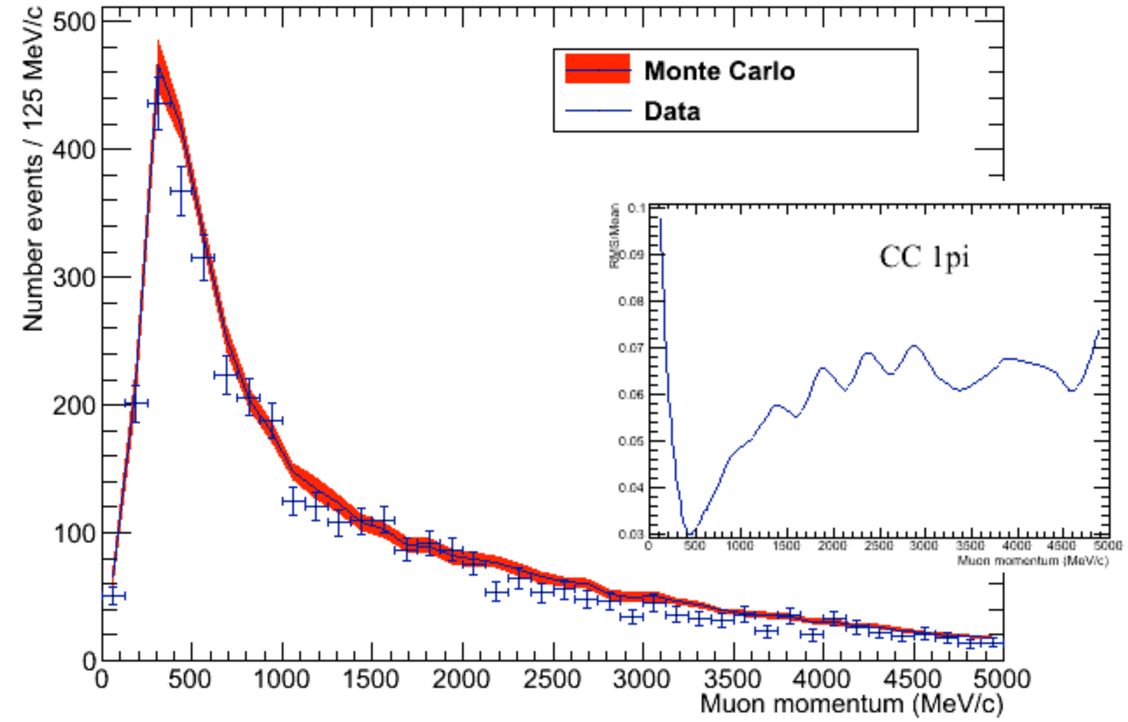
1. Measurement error on monitoring proton beam
2. Hadron production
3. Alignment error on the target and the horn
4. Horn current & field
5. Neutrino beam direction (Off-axis angle)

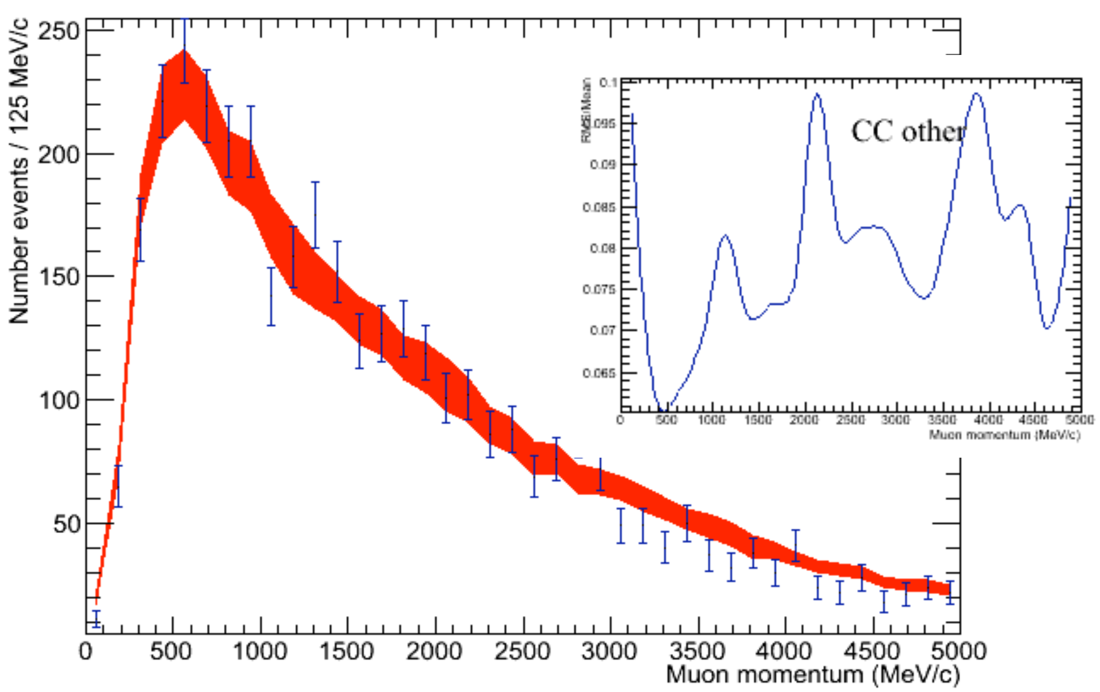


ND280

Detector systematics

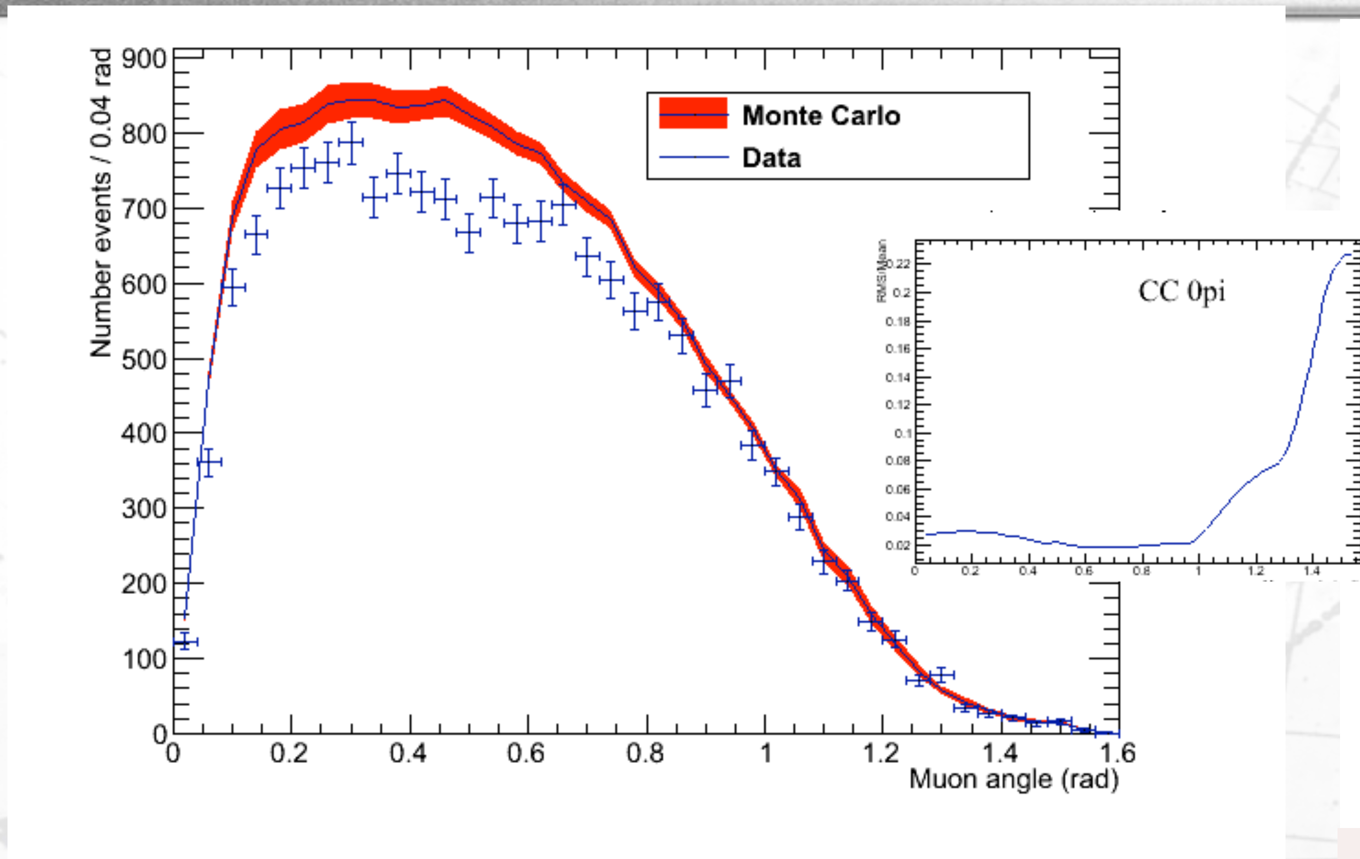


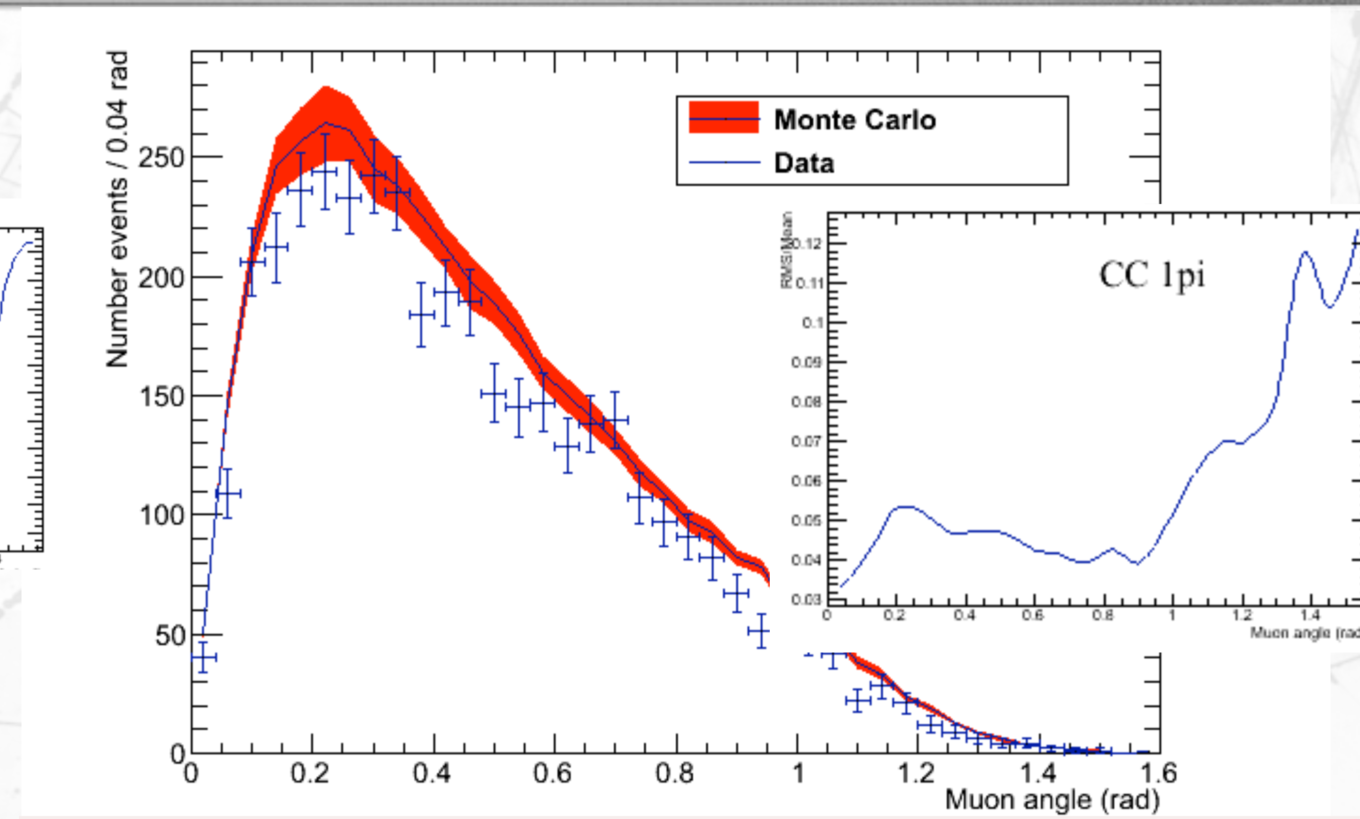


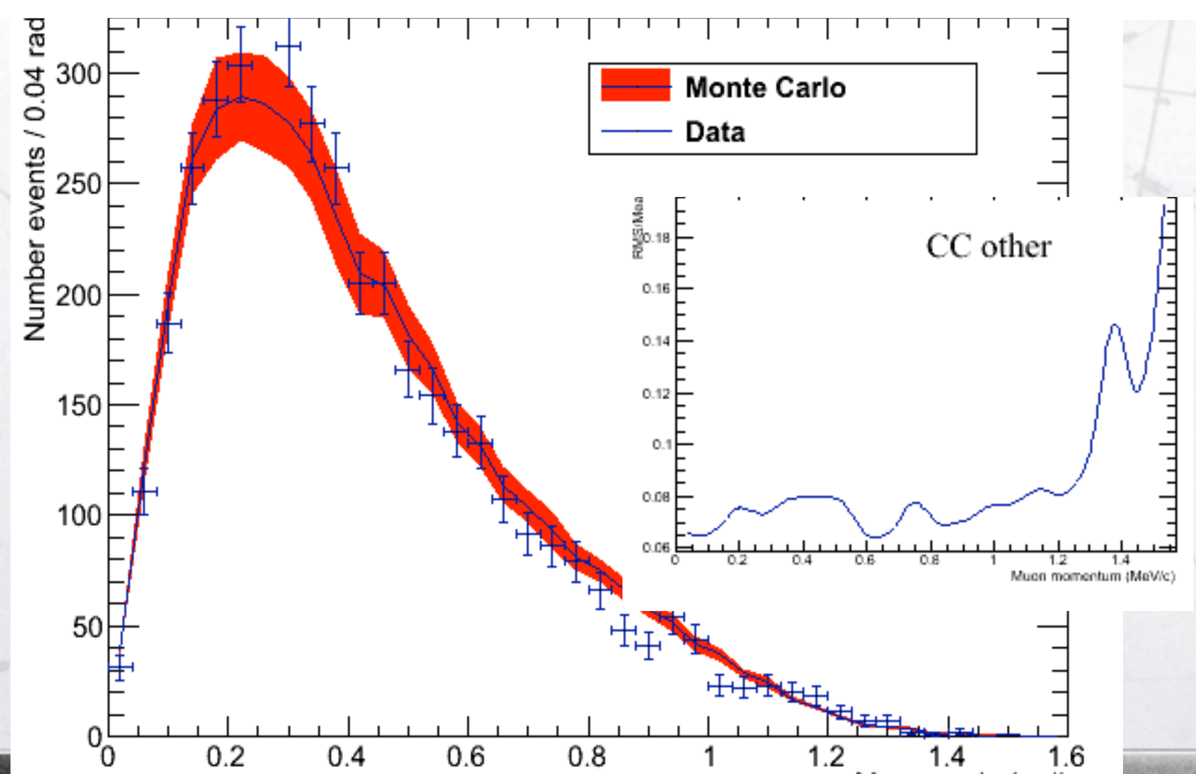


B Field distortion (0.3%)	TPC Tracking efficiency (0.6%)
TPC-FGD matching efficiency (1%)	***TPC Charge confusion (2.2%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (10%)***
Pile-up (0.07%)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

Detector systematics

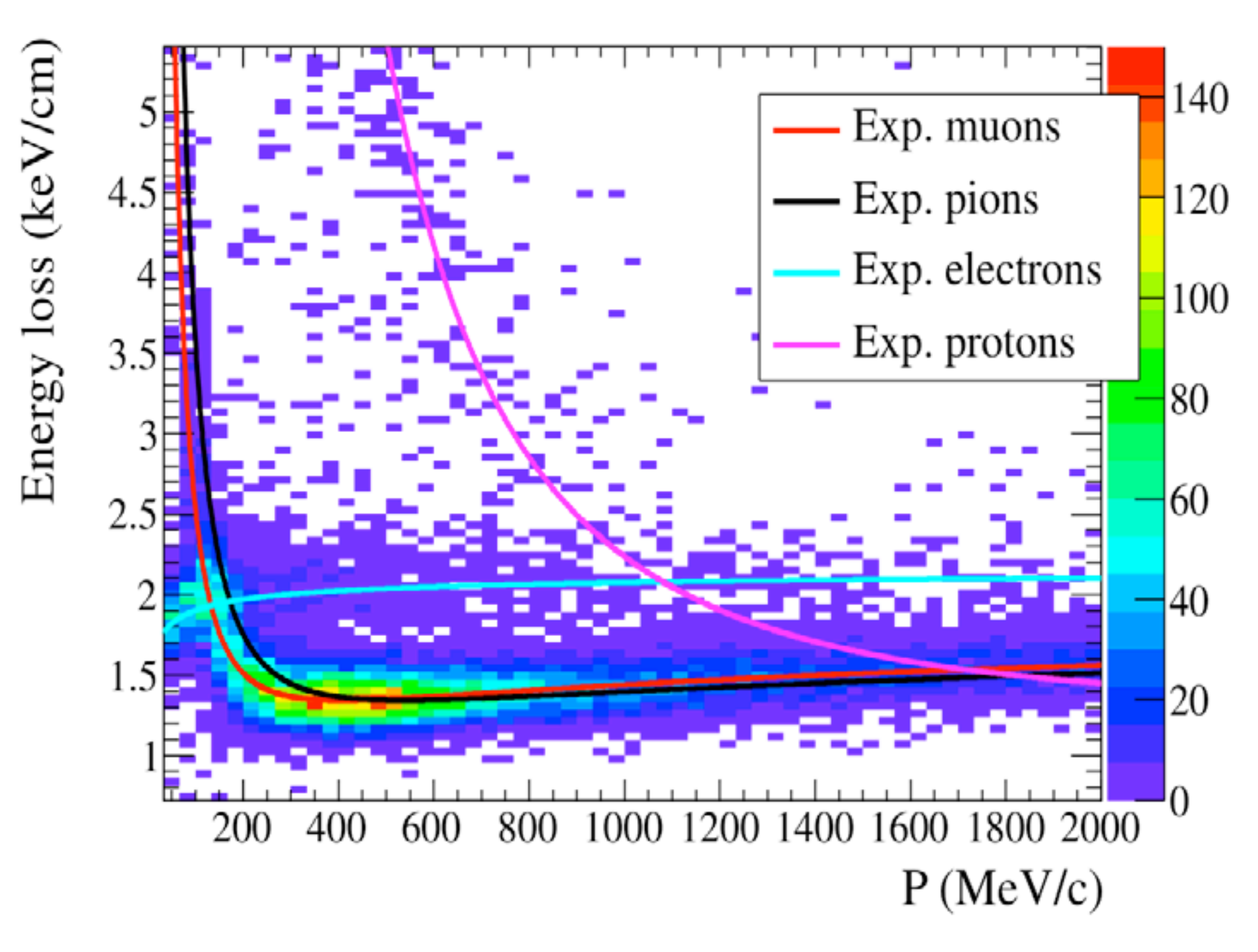




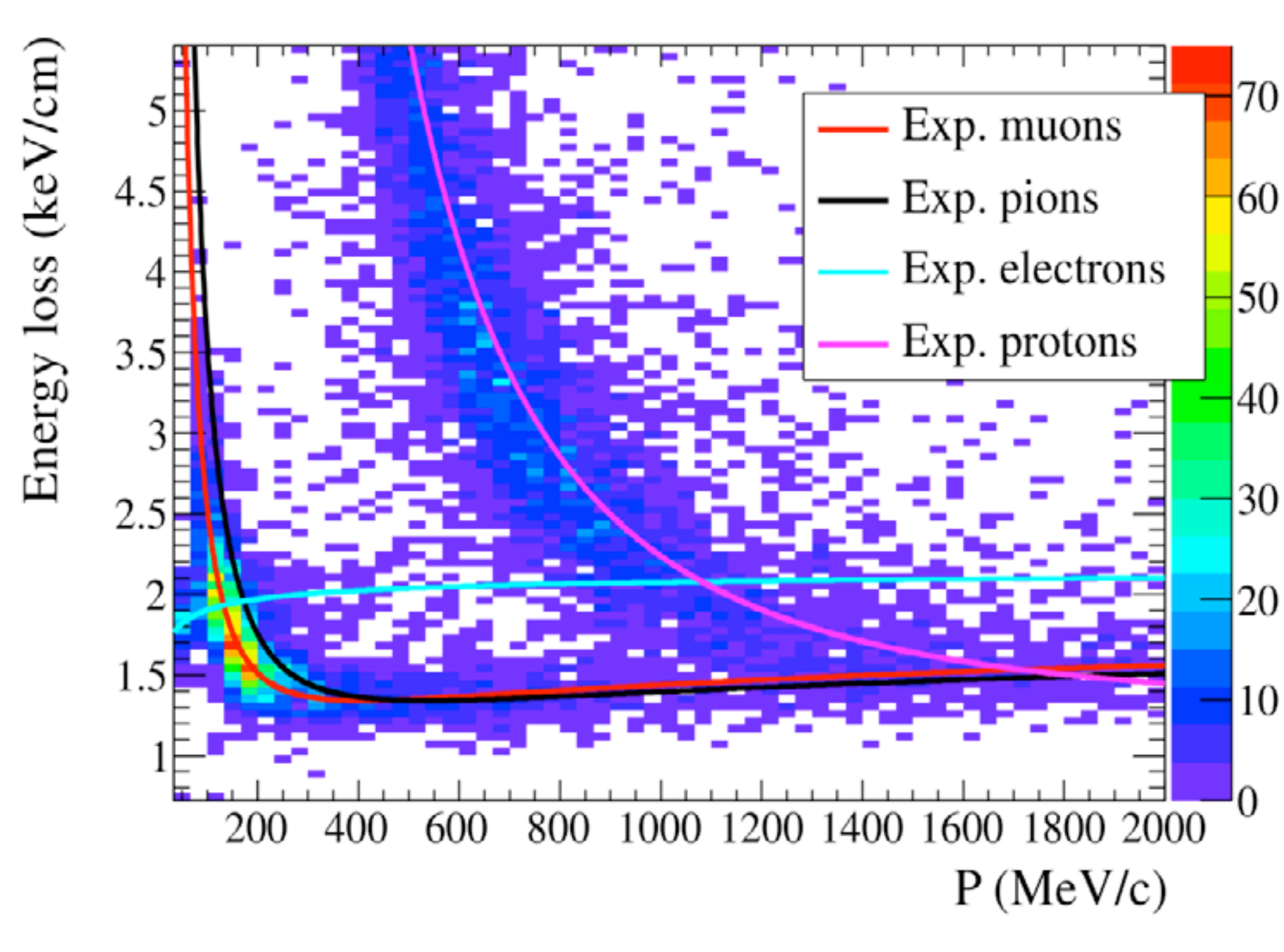


B Field distortion (0.3%)	TPC Tracking efficiency (0.2%)
TPC-FGD matching efficiency (1.8%)	***TPC Charge confusion (5.0%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (22%)***
Pile-up (0.07%)	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



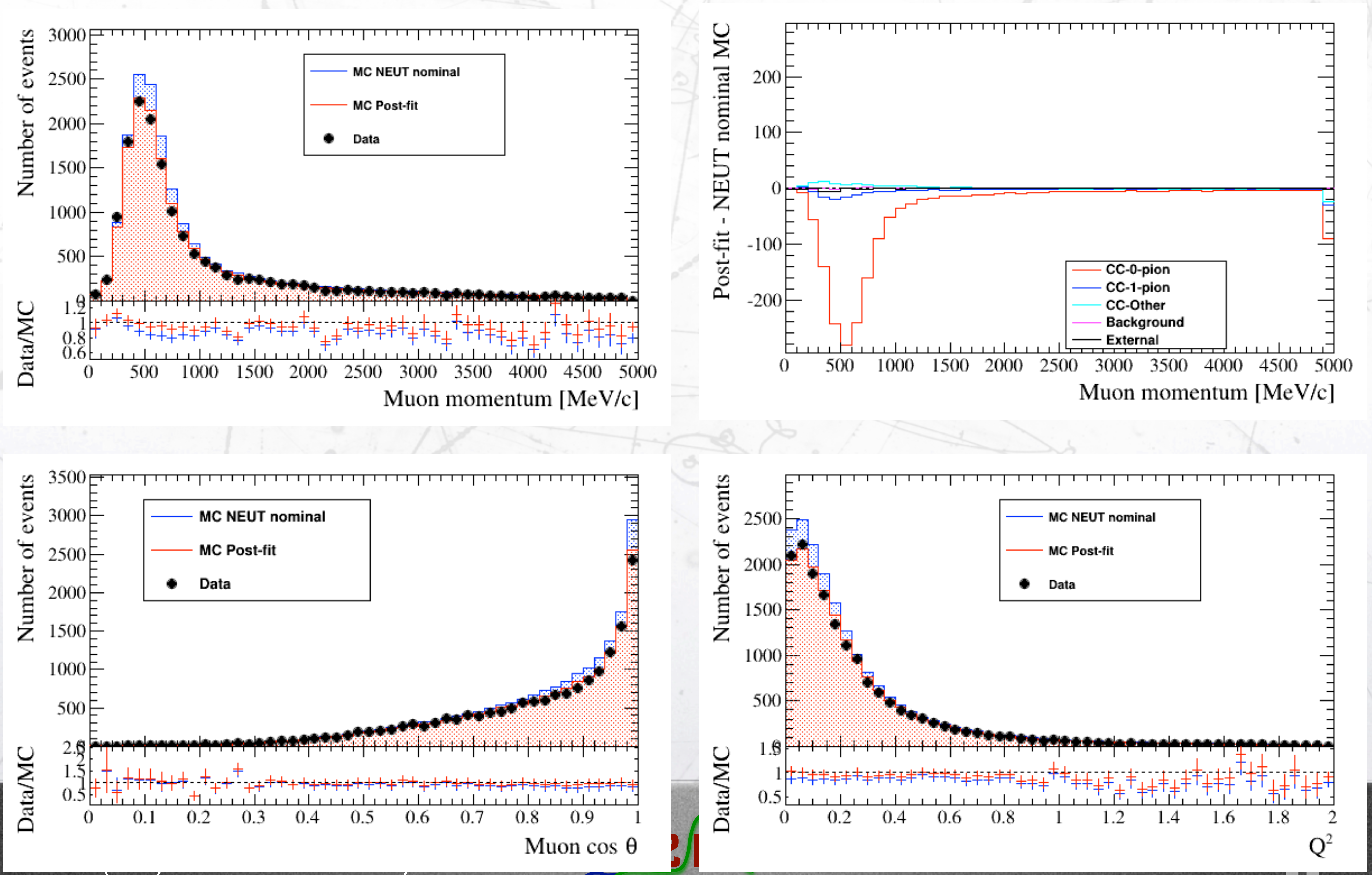
Positive Tracks in TPC



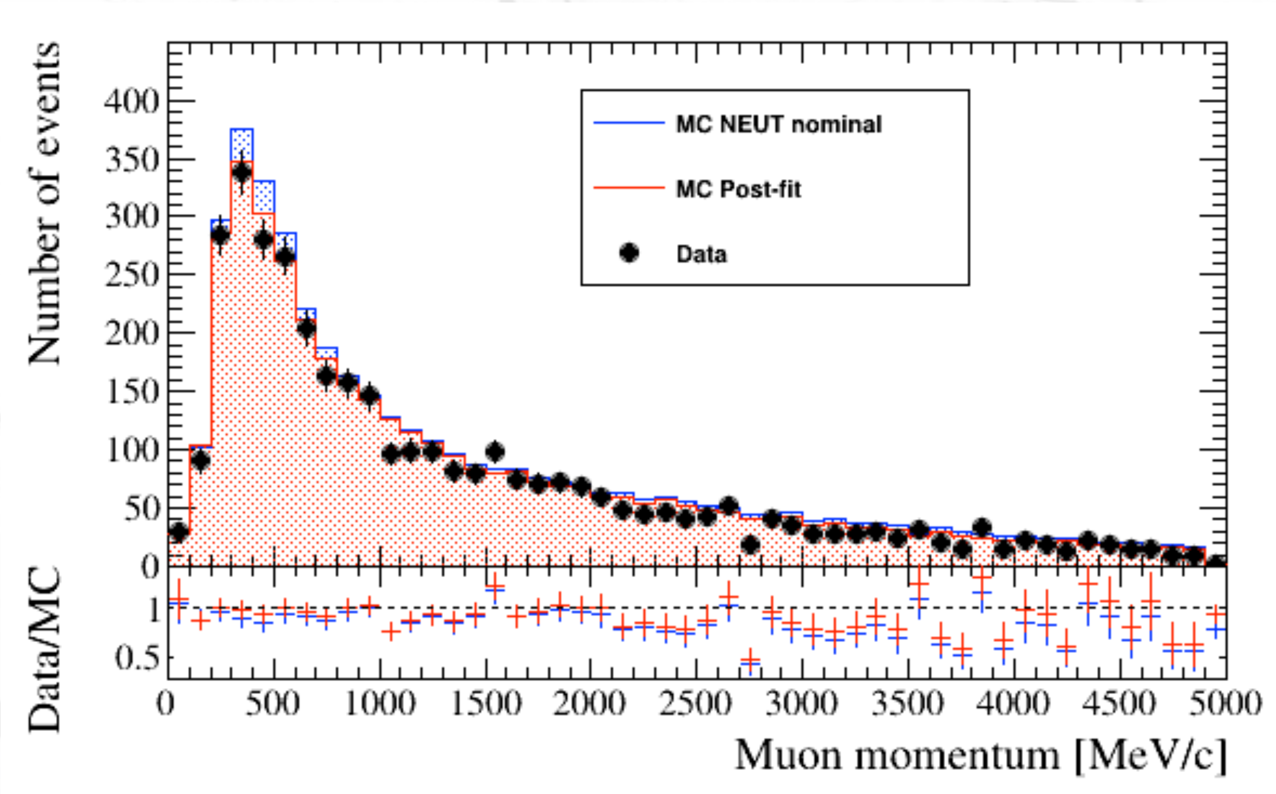
Post-fit ν_μ ND280

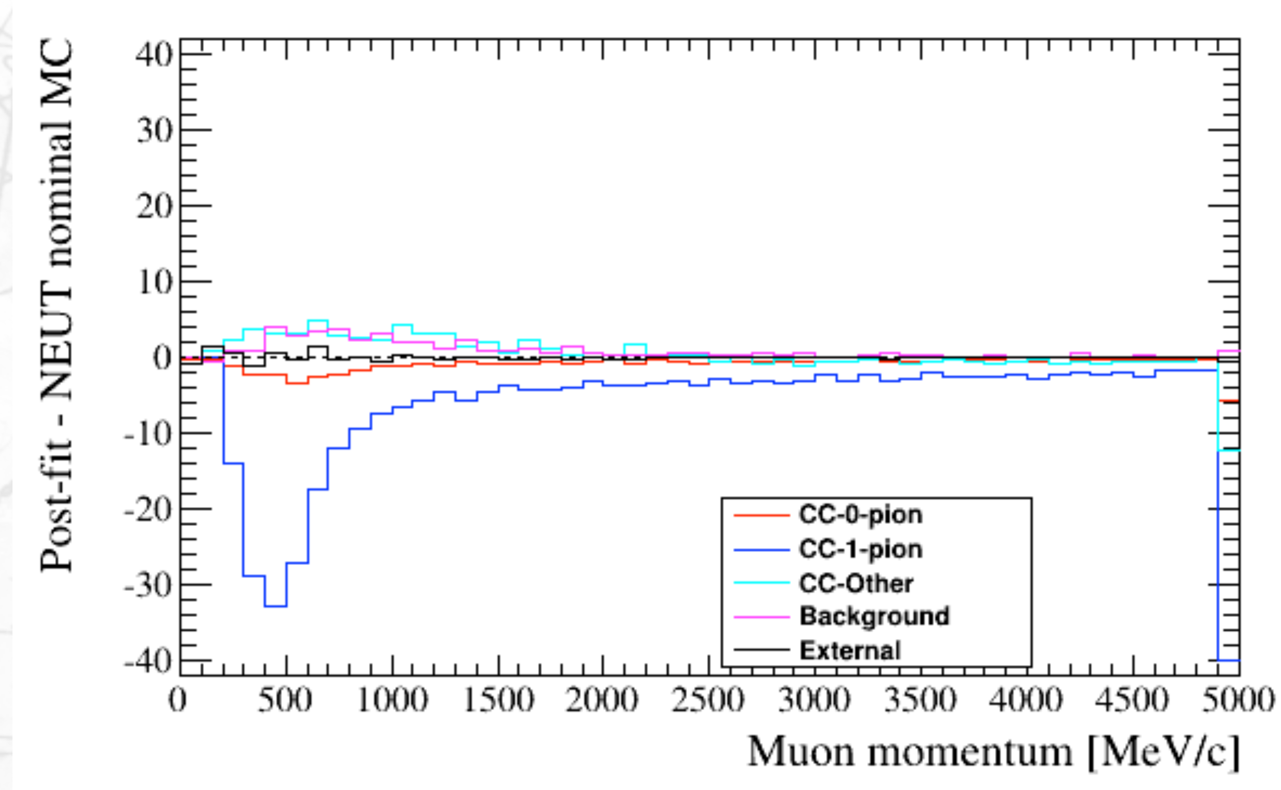
- Use beam and cross section parameters obtained from the constrained fit to the ND280 ν_μ (p_μ, $\cos\theta_\mu$) spectra to re-weight the MC.
- Improved agreement between the MC distributions, after post-fit re-weight, and the data.

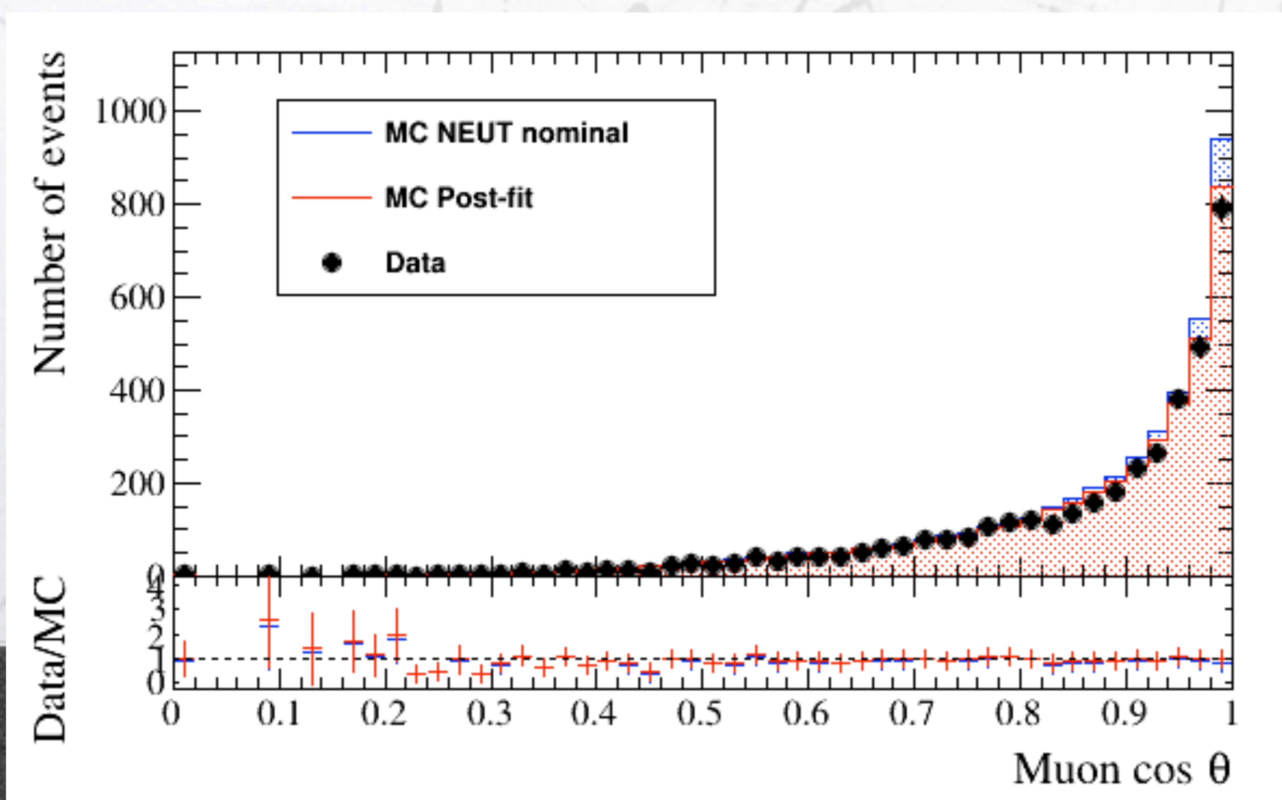
CC-0-pion post-fit

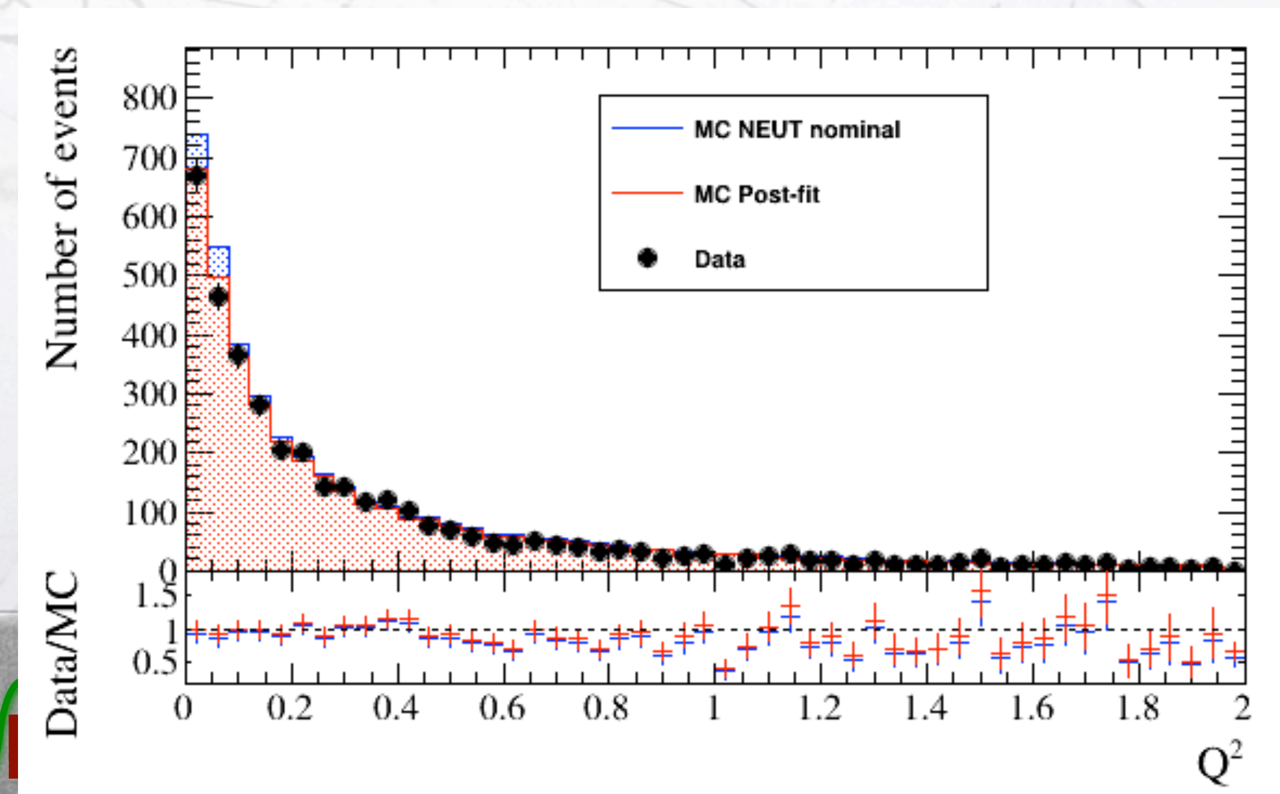


CC-1-pion post-fit

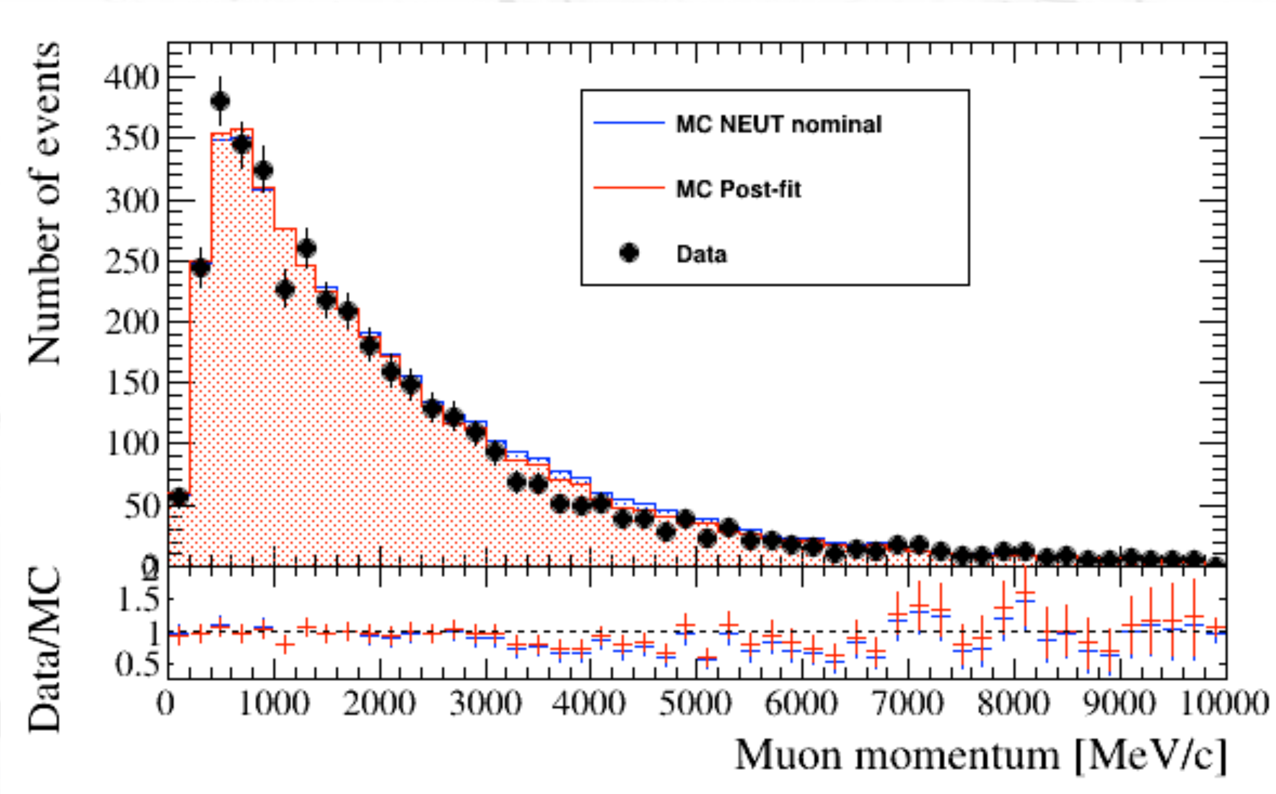


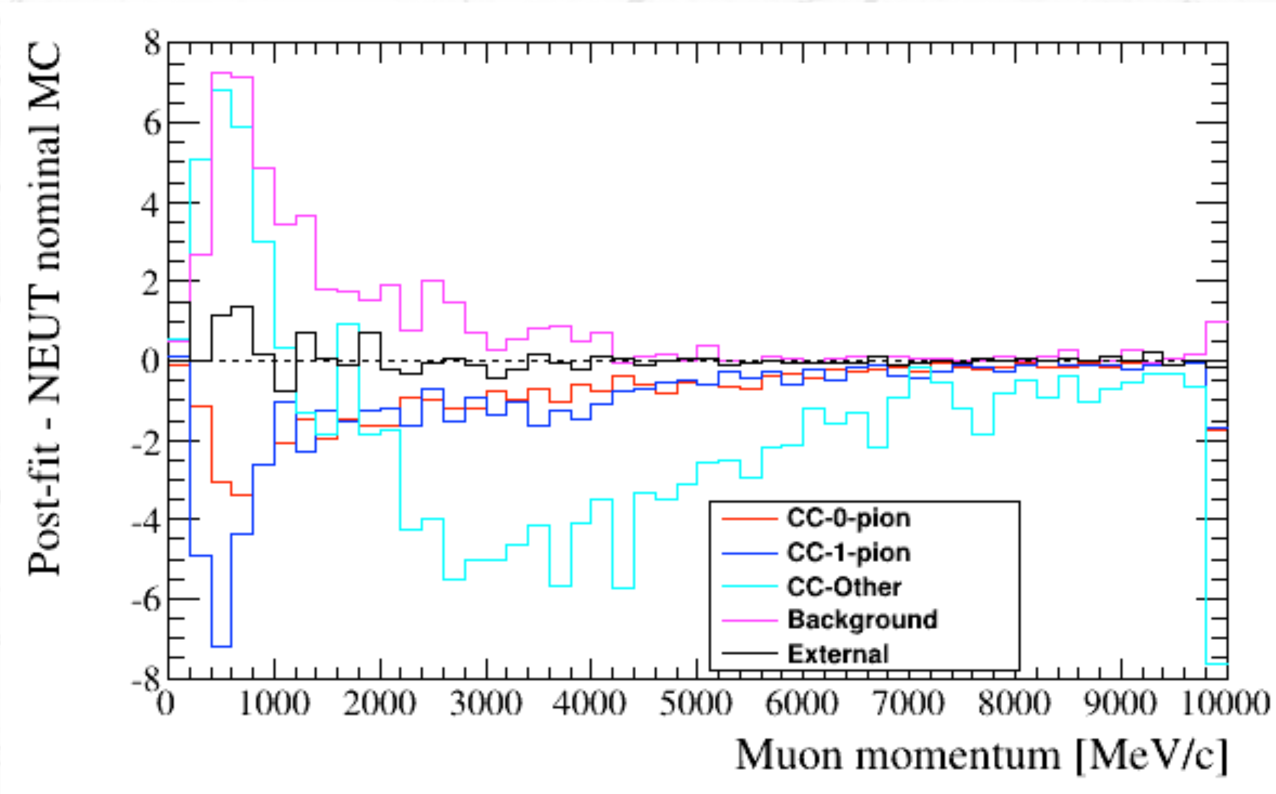


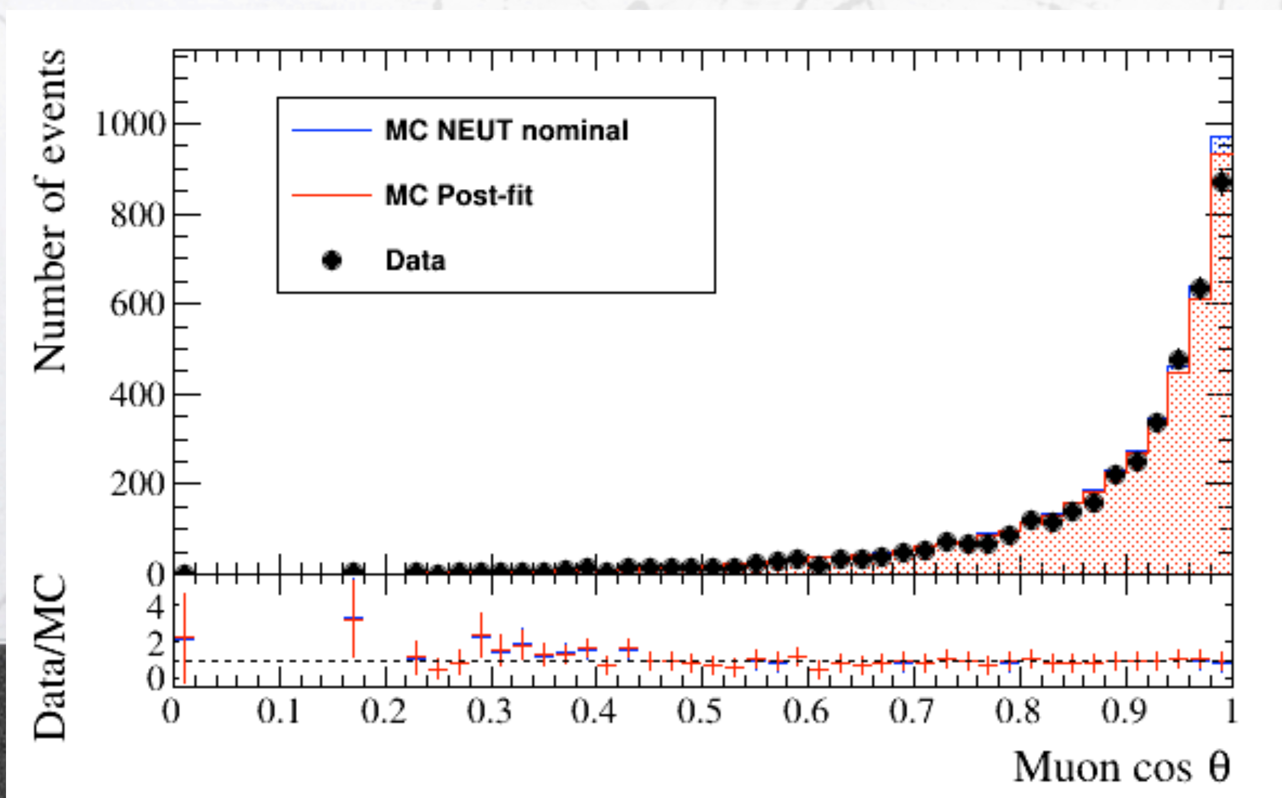


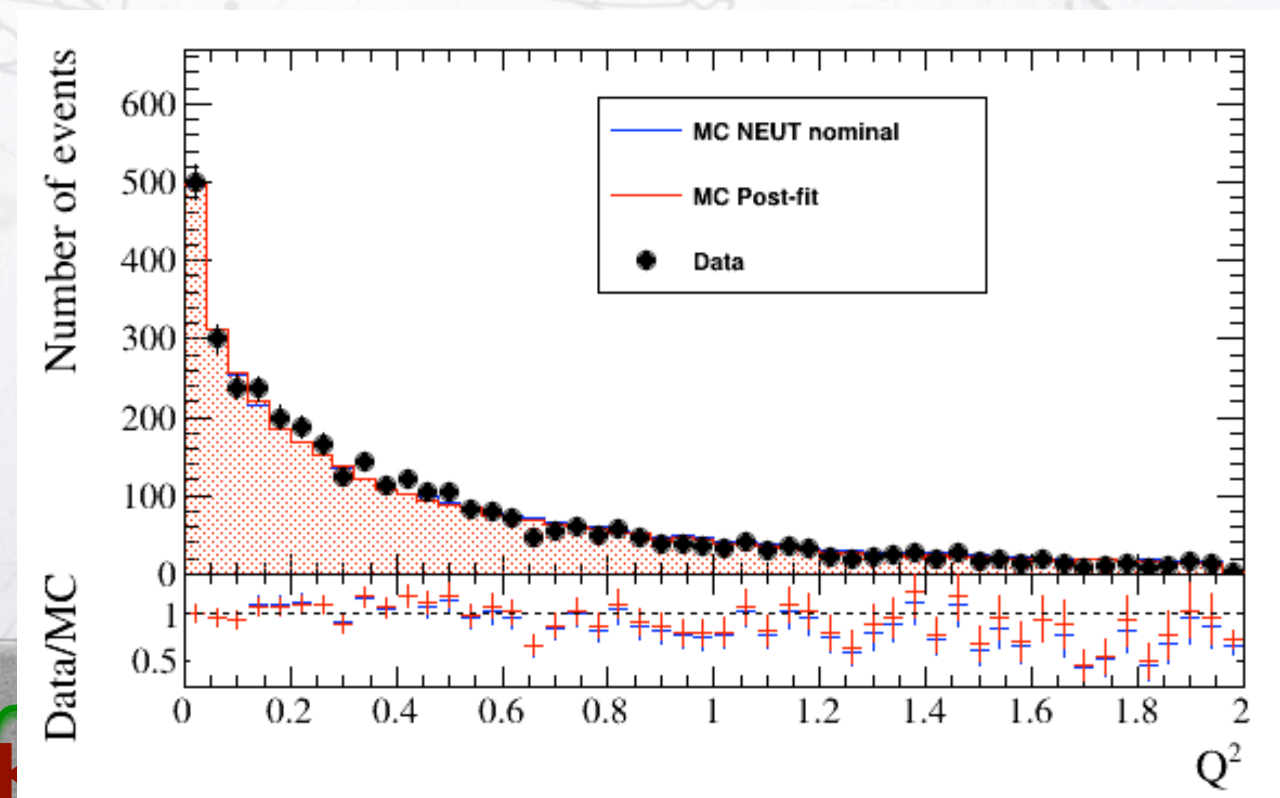


CC-Other post-fit









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

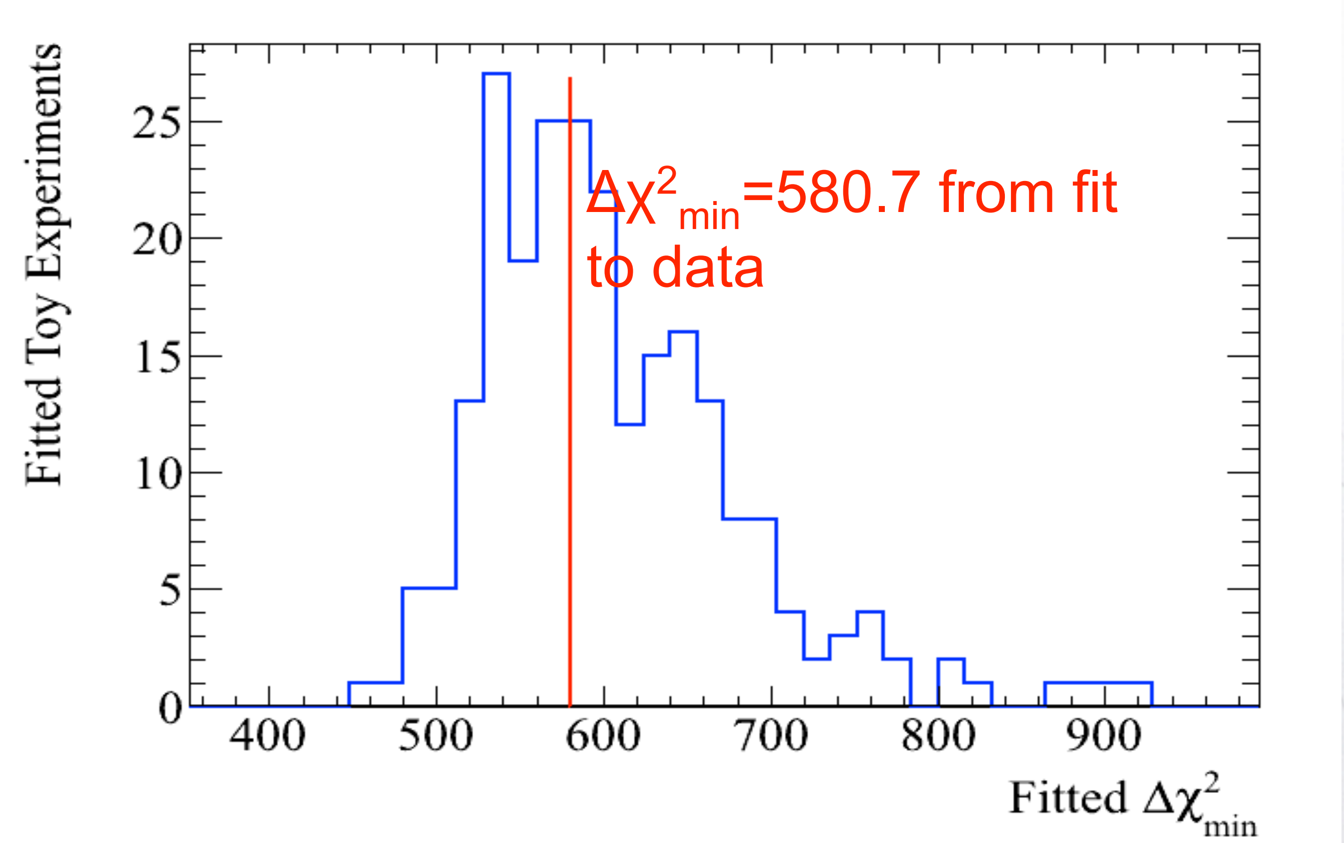
Test the data and constrained MC agreement with toy experiments:

Generated variations of models within prior uncertainties

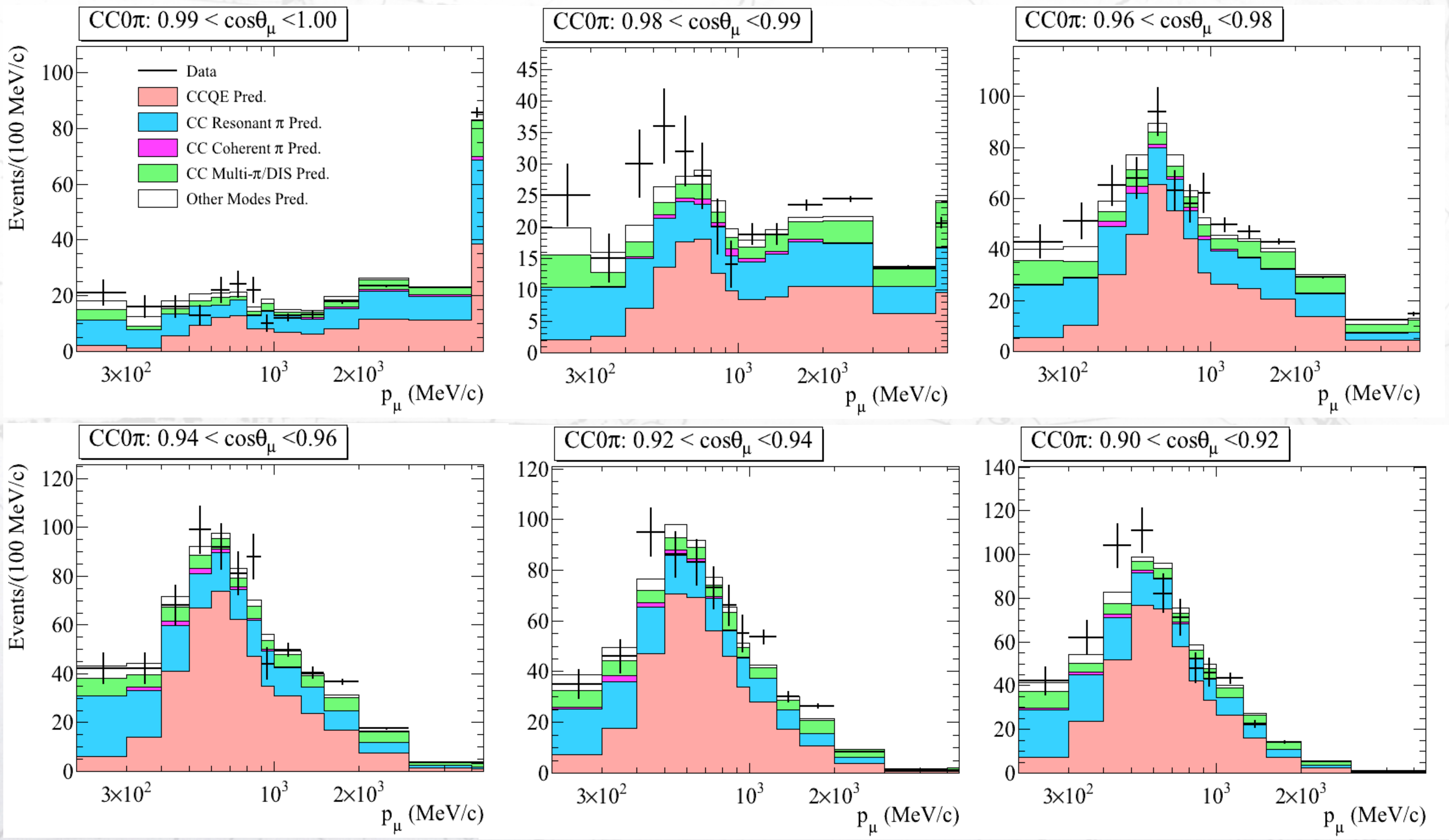
Fit toy data in same manner as data

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

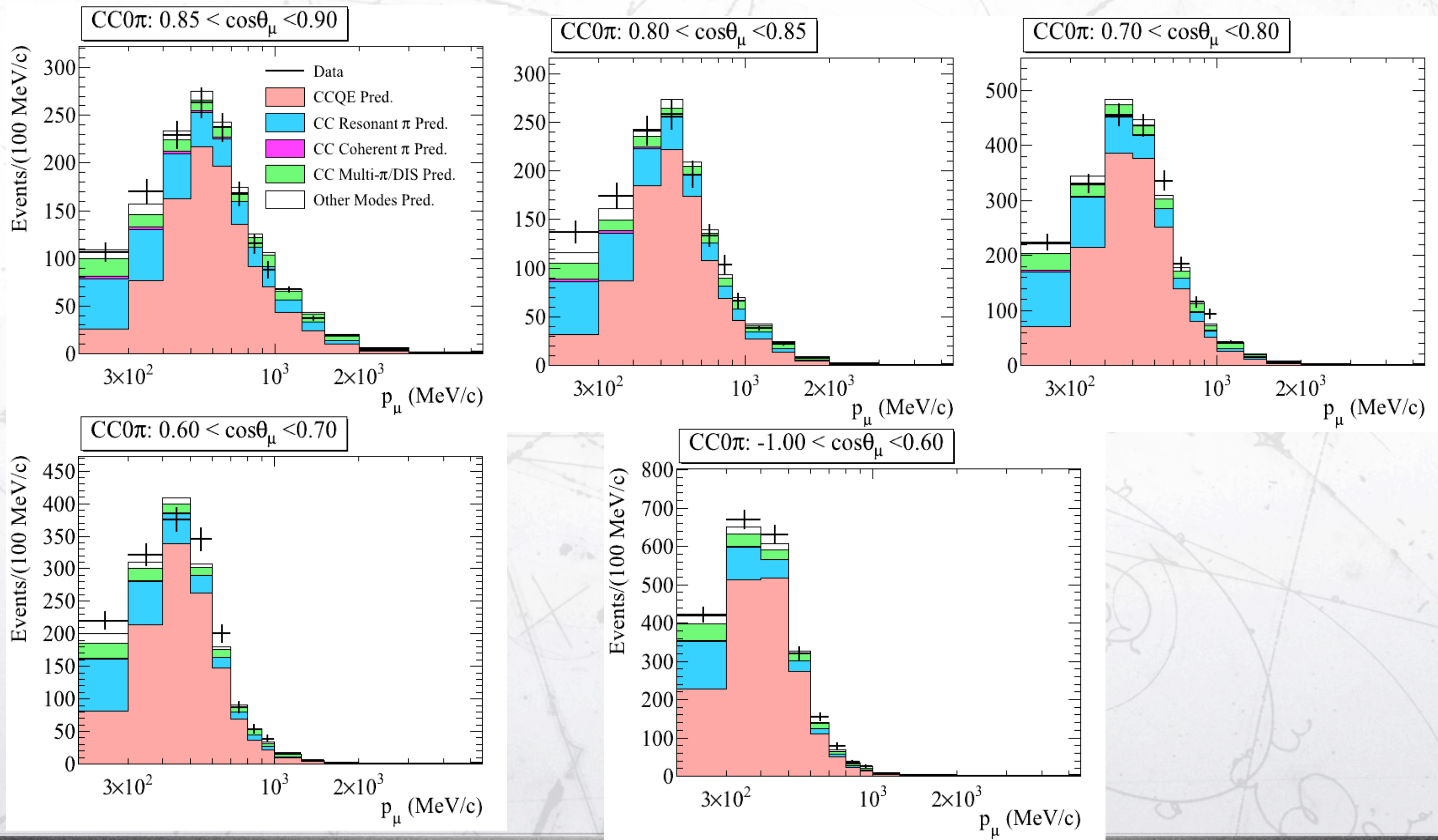
$\Delta\chi^2_{min}$=580.7 for data has p-value of 0.57



Data and Constrained Model (CC0π)

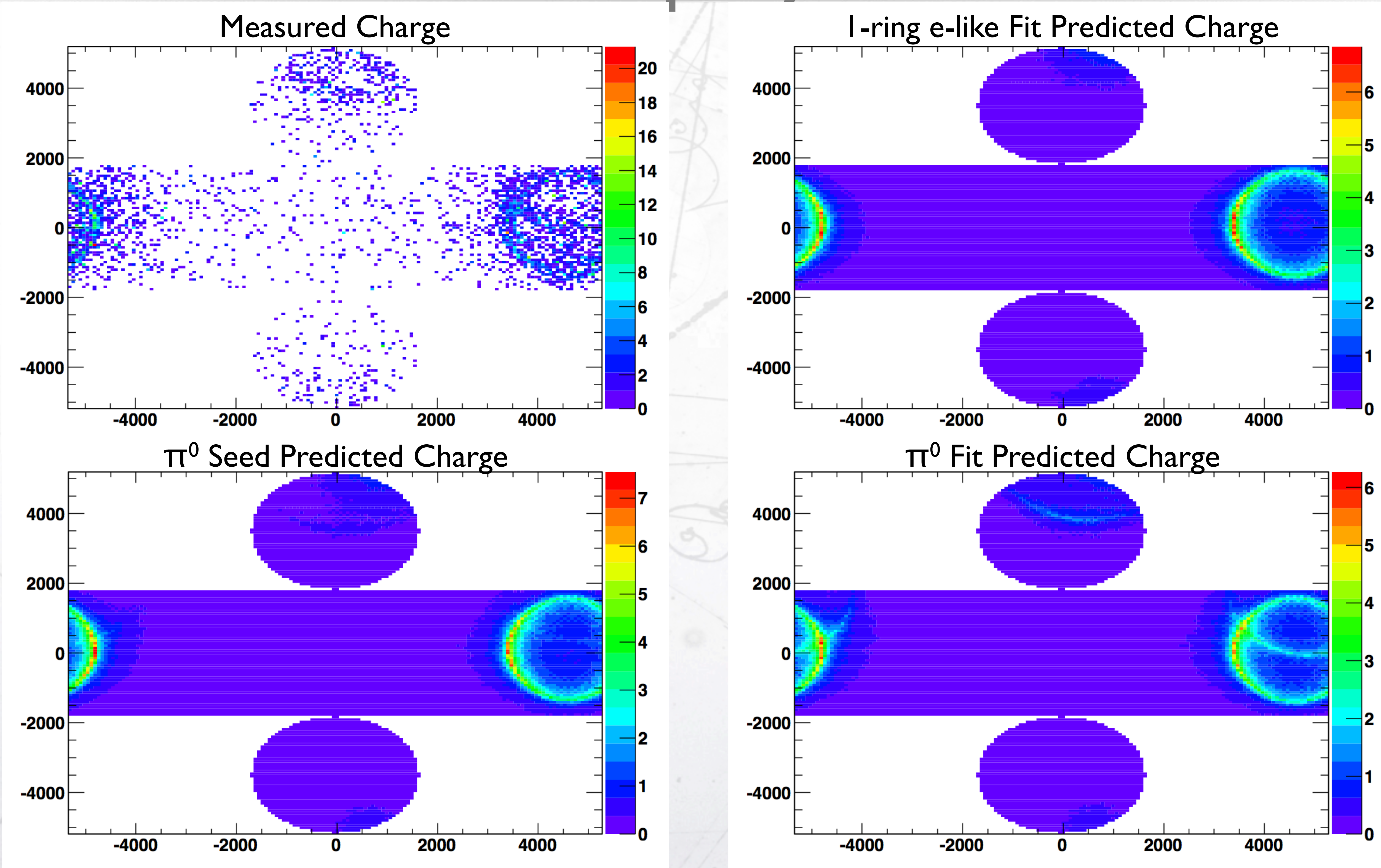


Data and Constrained Model (CC0π)



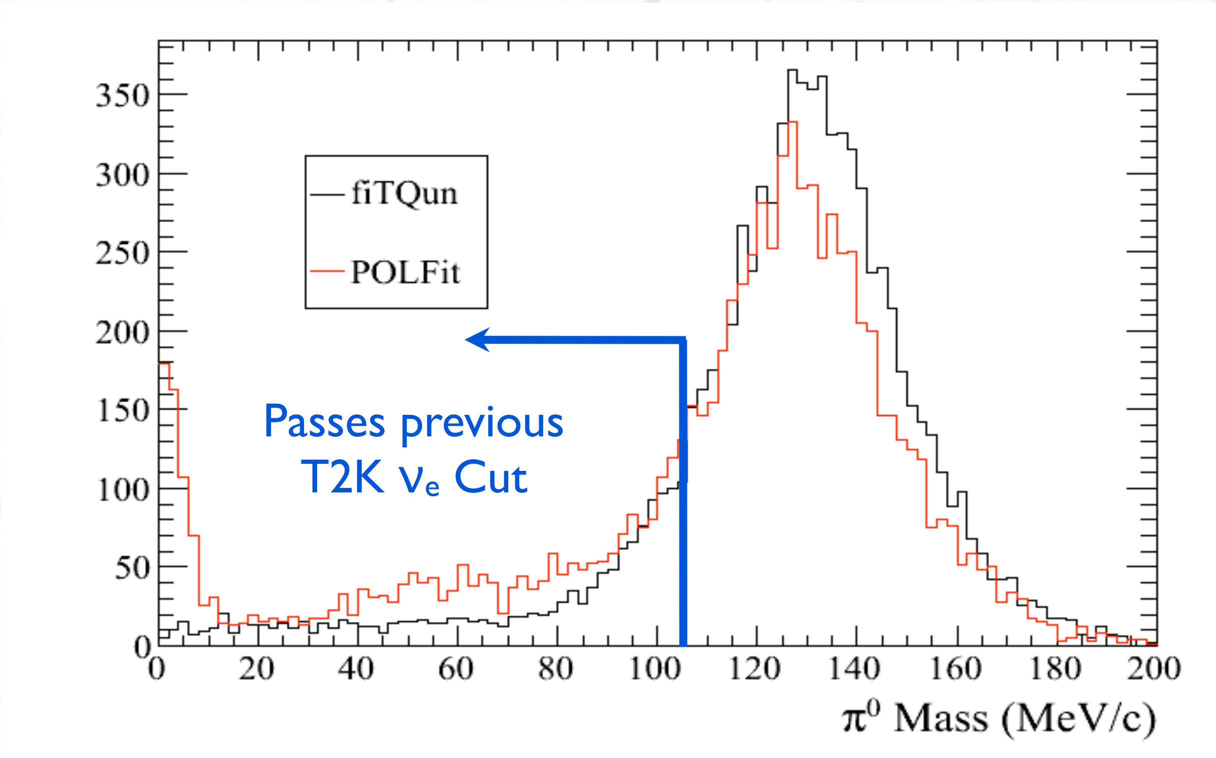
New SK π^0 analysis

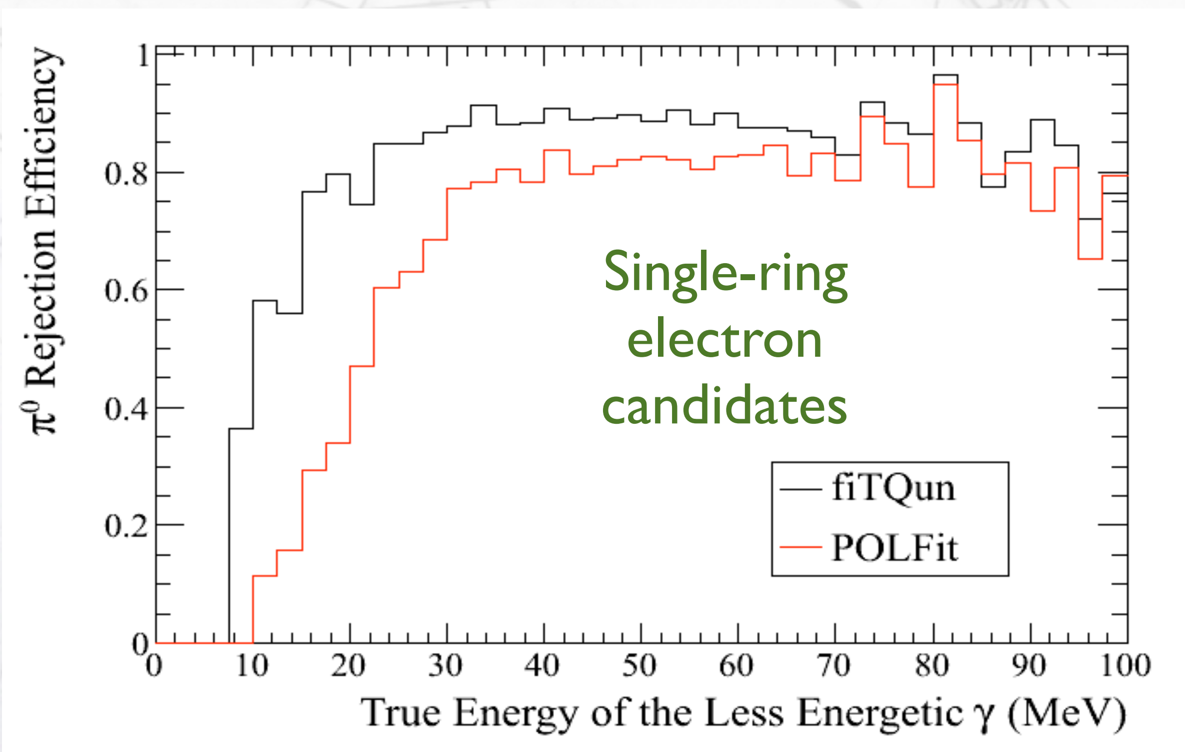
Event Display: π^0 Fit



π^0 Fit Performance

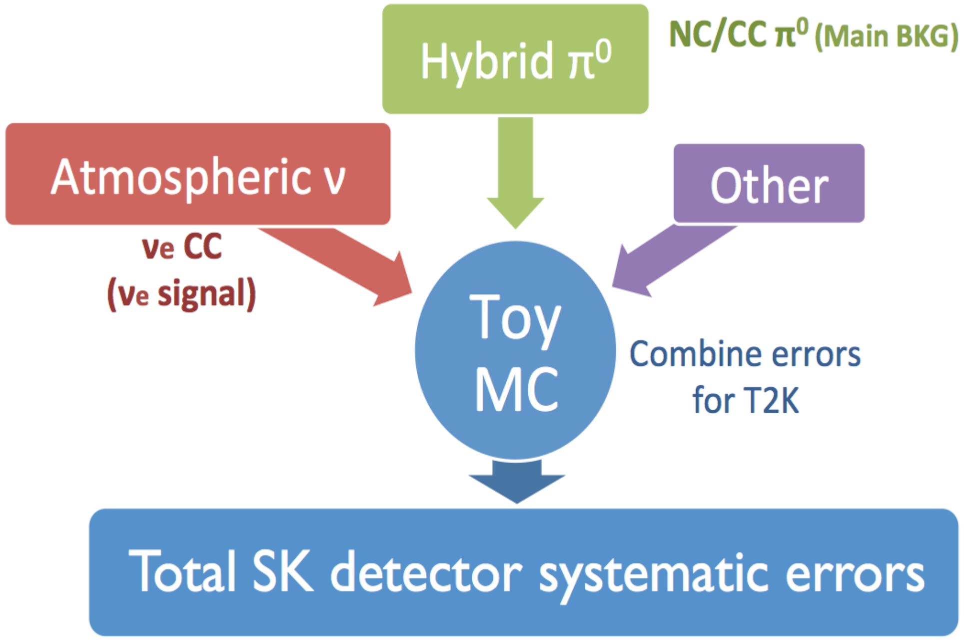
- Previous T2K ν_e appearance cut: $m_{\pi 0} < 105$ MeV/c^2
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in standard fitting algorithm (POLFit)
- Lower plot: π^0 rejection efficiency vs lower photon energy
  - fiTQun is more sensitive to lower energy photons





SK systematics and control sample

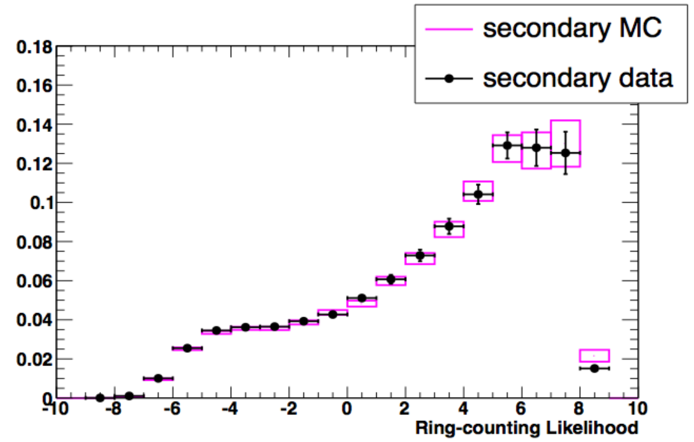
SK detector error estimation



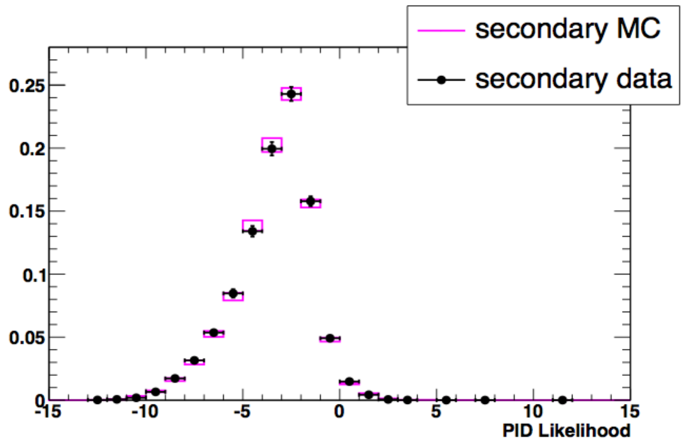
- To evaluated SK detector systematic uncertainties, employ several control samples:
  - Atmospheric νe samples (errors on νe's), "Hybrid-π0" samples (errors on π0's), Cosmic-ray muon samples, ...
- The errors evaluated with the control samples are combined with Toy MC method

Basic distributions

Ring Counting

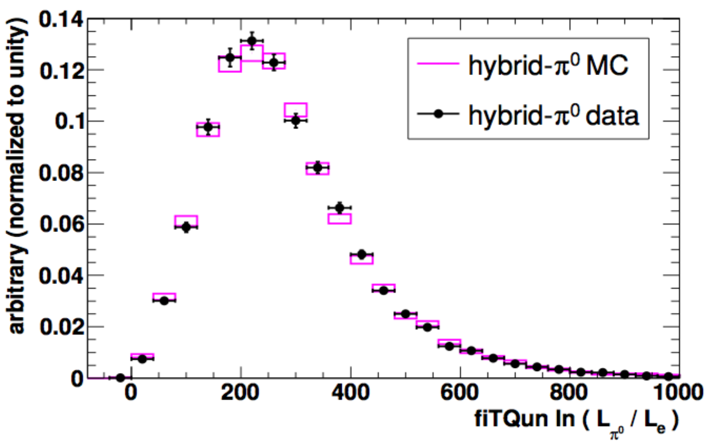


PID

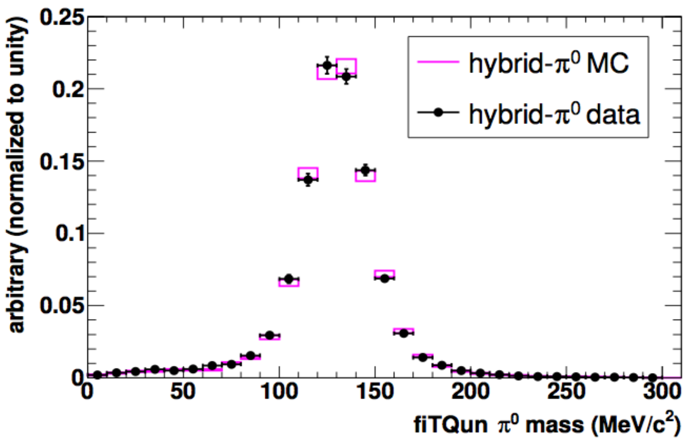


π0 rejection

π0/e likelihood ratio



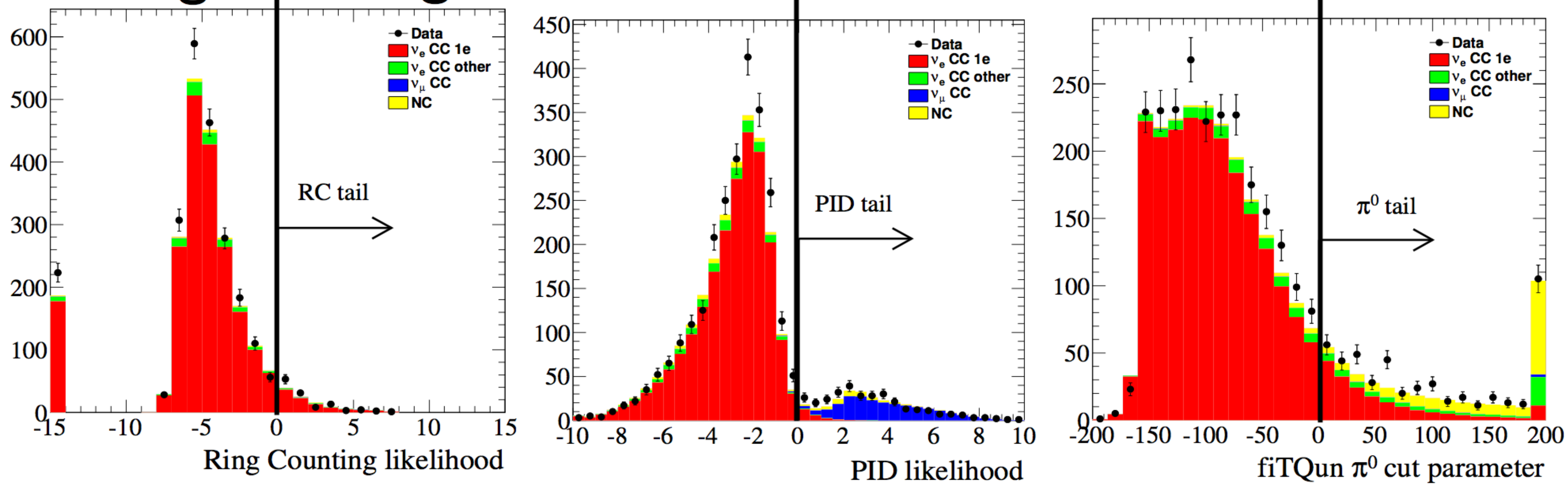
π0 mass



Control Samples

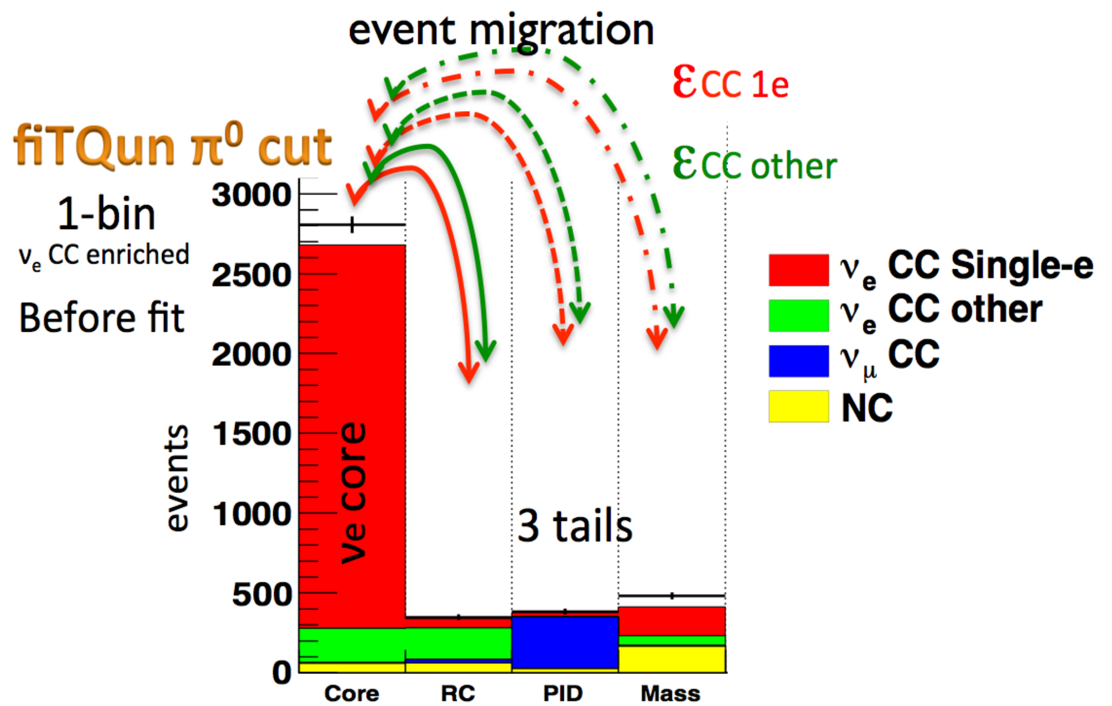
- νe candidate sample ("core" sample) + rejected samples (three "tail" samples)
  - Selections: ring counting, PID, and π0 rejection
  - (cf. νe candidates: 1-ring & e-like & none π0-like)

Ring Counting	PID	π0 rejection
Single ring / Multi-ring	e-like / μ-like	none π0-like / 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

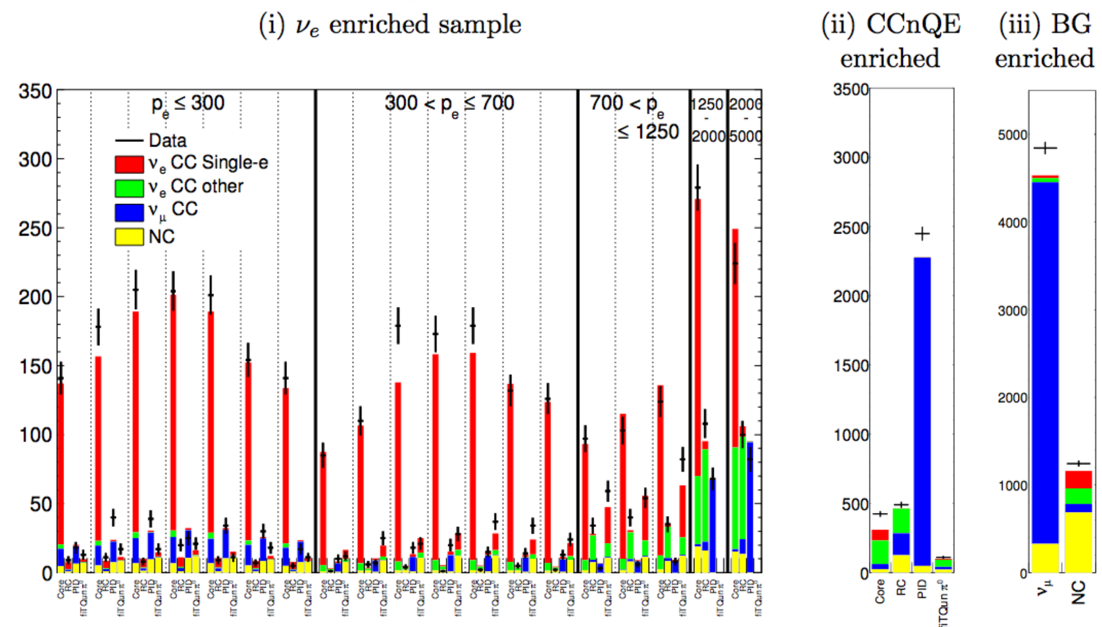


- Evaluate the errors in bins of momentum (p) and scattered angle (θ)
  - p bins: 100, 300, 700, 1250, 2000, 5000 MeV/c
  - θ bins: 0, 40, 60, 80, 100, 120, 140, 180 deg.

atm-ν fit results

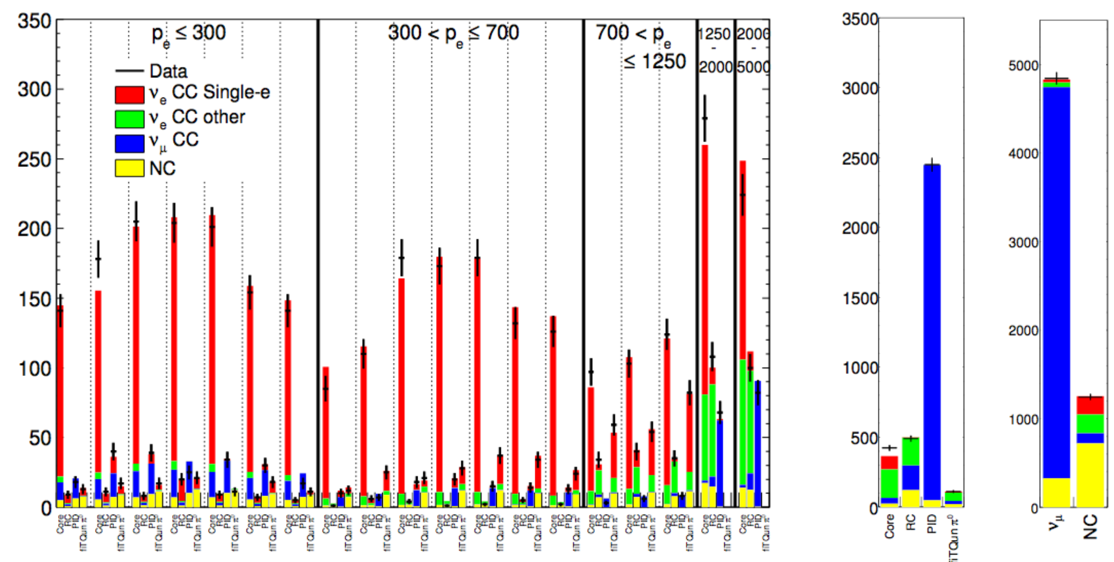
Number of events in p-θ bins and control samples.

Before fit



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

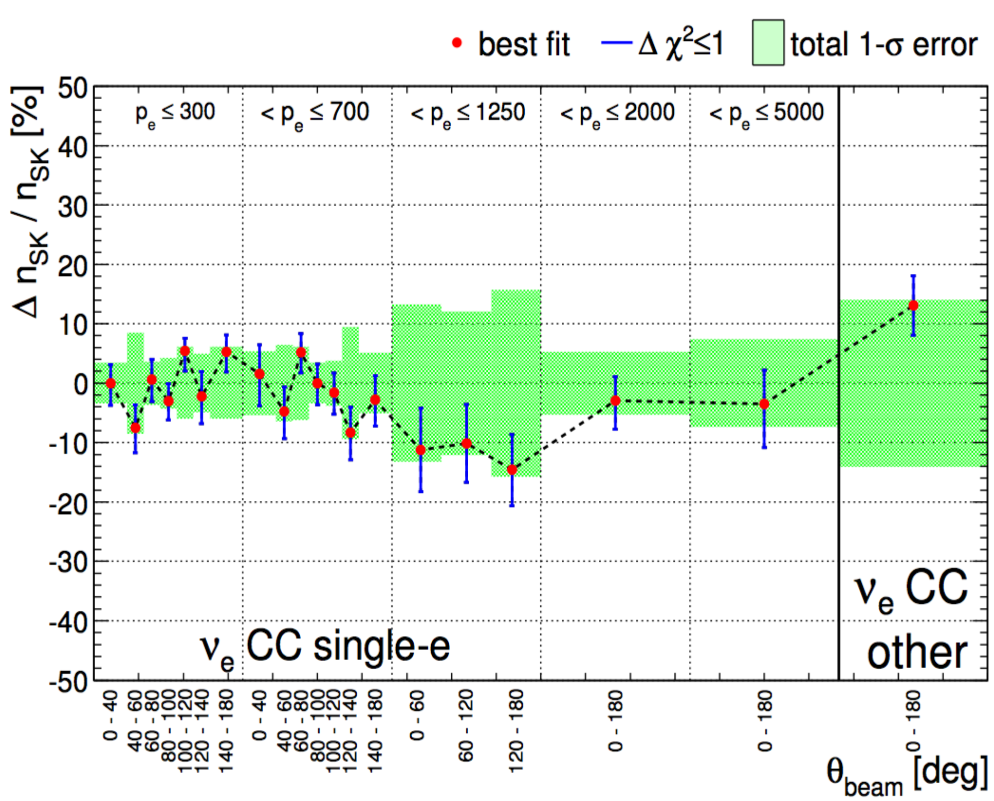
Best fit



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

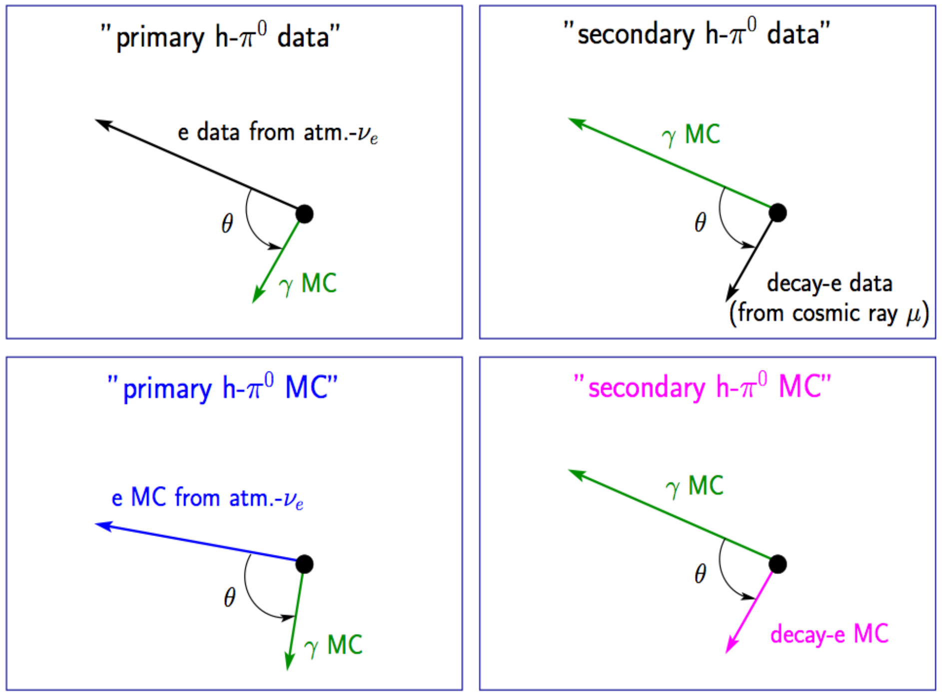
SK error w/ atm-ν fit

- 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

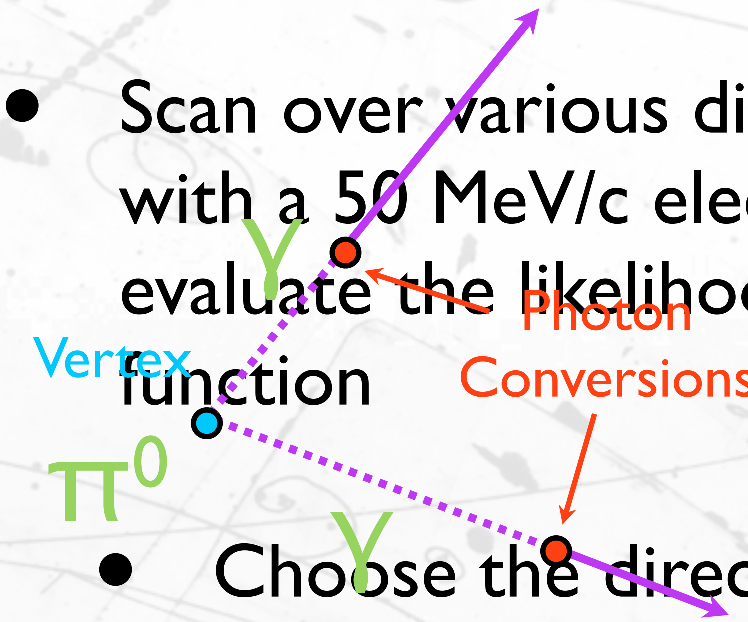


- Control samples:
  - Primary: electron from atm-ν is used for the higher energy “γ”, and the lower energy γ from MC
  - Secondary: electron of atm-νe (and decay-e from cosmic-ray μ) is the lower energy “γ”, and higher energy γ from MC

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

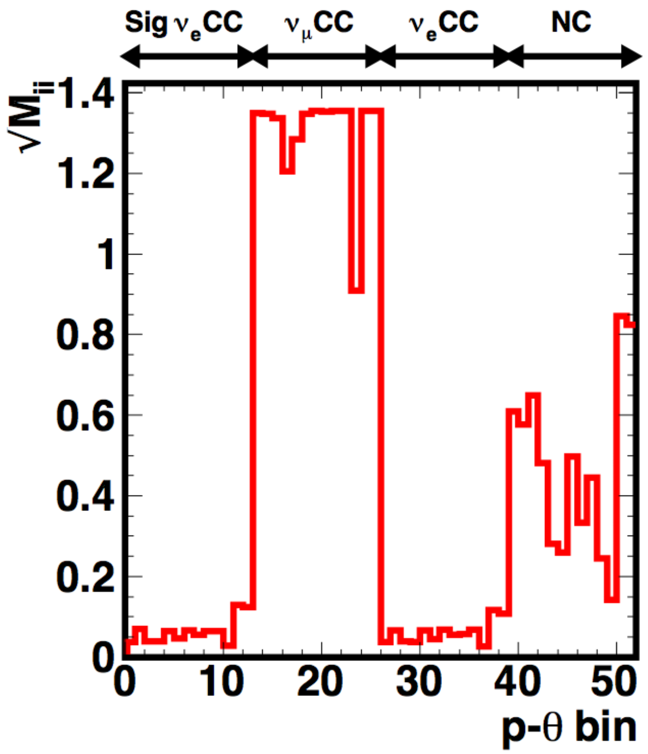


- First, fit while floating only p_1 and p_2
- **Do full 12 parameter fit**

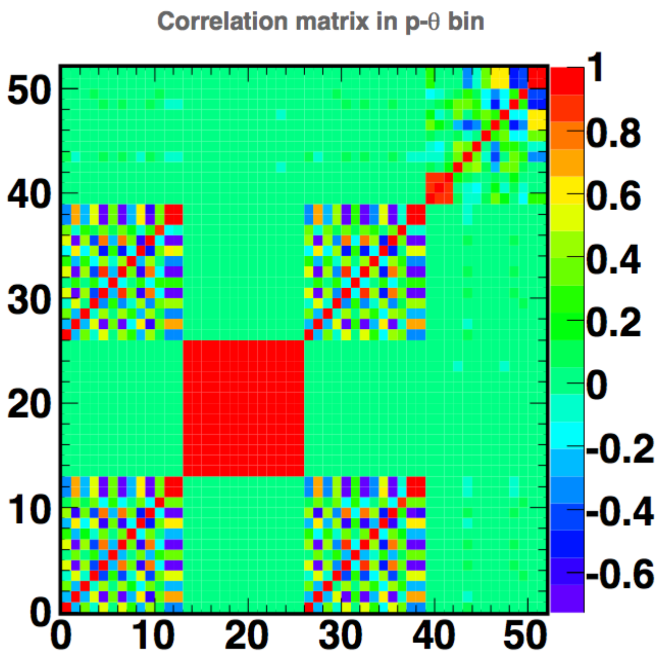
Error matrices in p-θ

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

Square-root of diagonal elements of covariance matrix



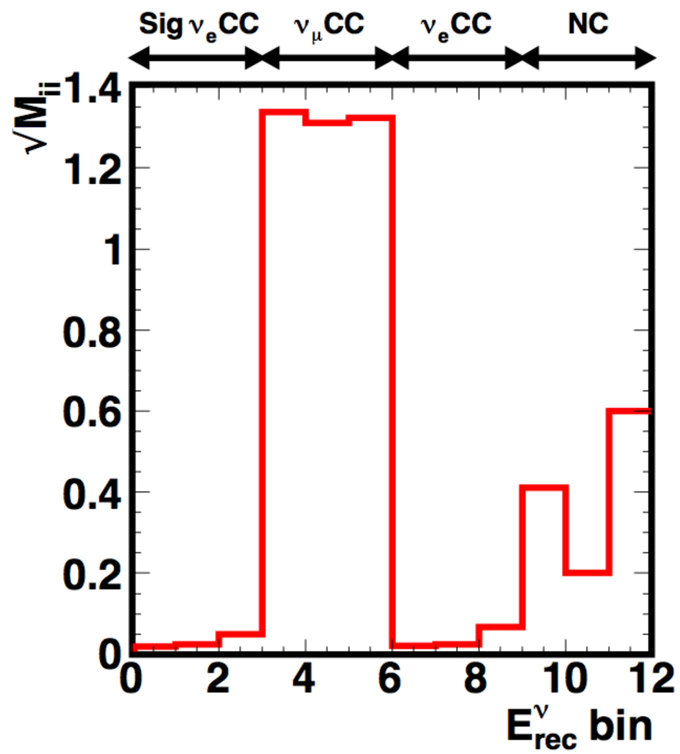
Correlation matrix



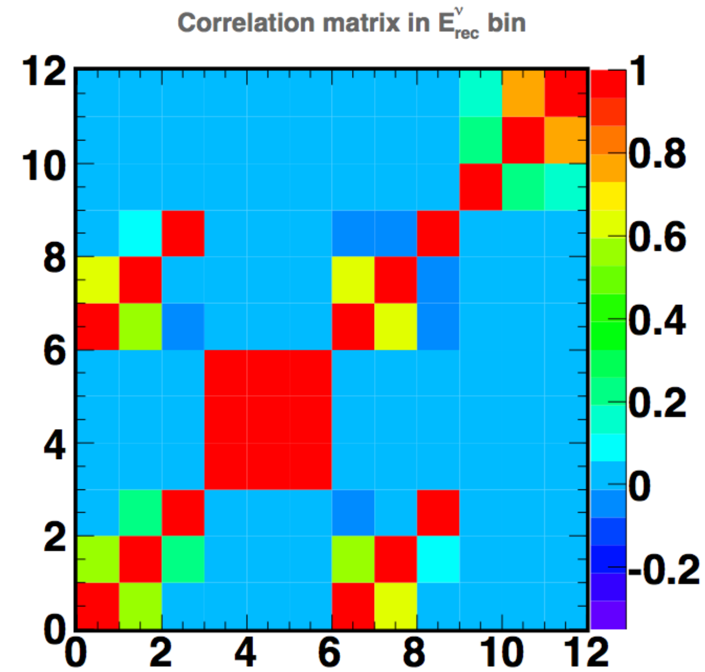
Error matrices in rec E_ν

- Error matrices for inputs to oscillation analyses in $E\nu$ bins

Square-root of diagonal elements of covariance matrix



Correlation matrix



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.