T2K new results

Benjamin Quilain (Laboratoire Leprince-Ringuet) for the **T2K collaboration**

Outline :

1-Essential of T2K experiment

2-First discovery ν_e appearance

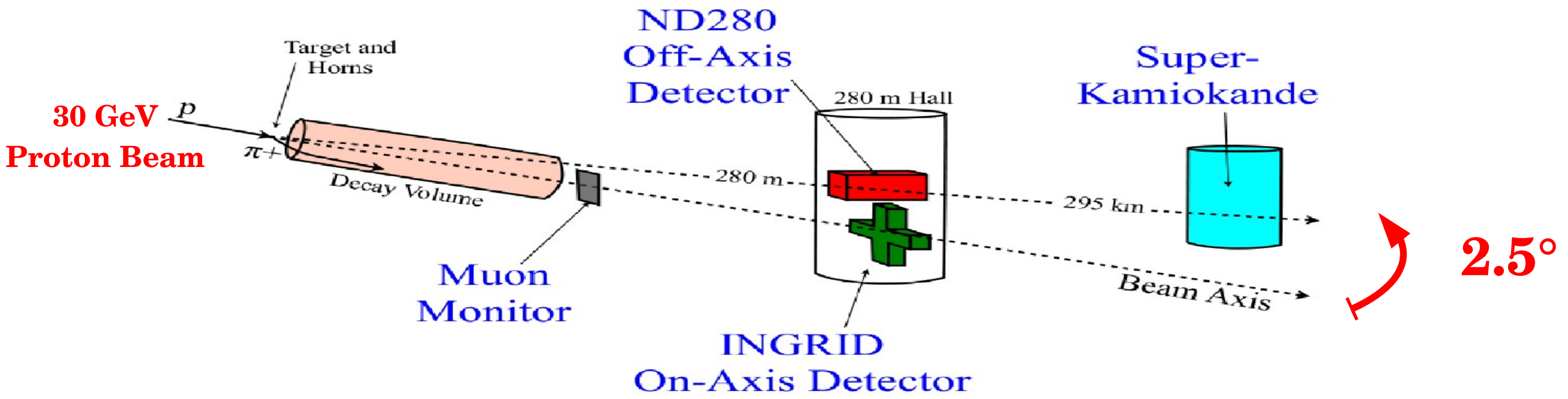
3-Results on ν_μ disapperance

4-Discussion on T2K future

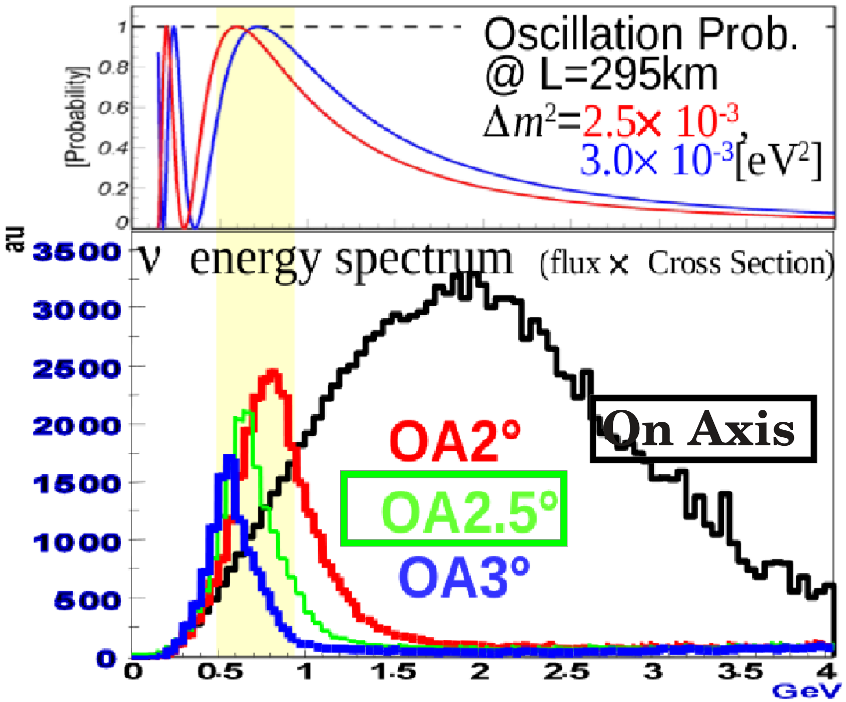
GDR Neutrino

The T2K Experiment

- Observation ν_e appearance in a ν_μ beam & ν_μ disapperance



- **Off-axis experiment :**
  - => **Tune energy spectrum** to 600 MeV, to maximize oscillation probability at 295km
    - **Higher statistics** of oscillated neutrinos
    - **Reduce contamination** from non oscillated high energy neutrinos



Flux knowledge is absolutely necessary (Rate & Shape)

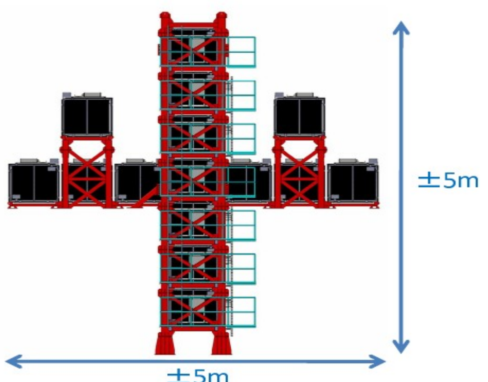
« On axis » constraints on flux

Complementary near detectors :

On Axis measurements :

- Direct measurements by detectors on proton beam line
- **Hadron production** Xsections & directions (measured thanks to **NA61/SHINE collaboration** on a replica target)
- **On Axis** near detector: **INGRID**
    - Monitor beam stability
    - Monitor off-axis angle : indirect constraints on neutrino spectra

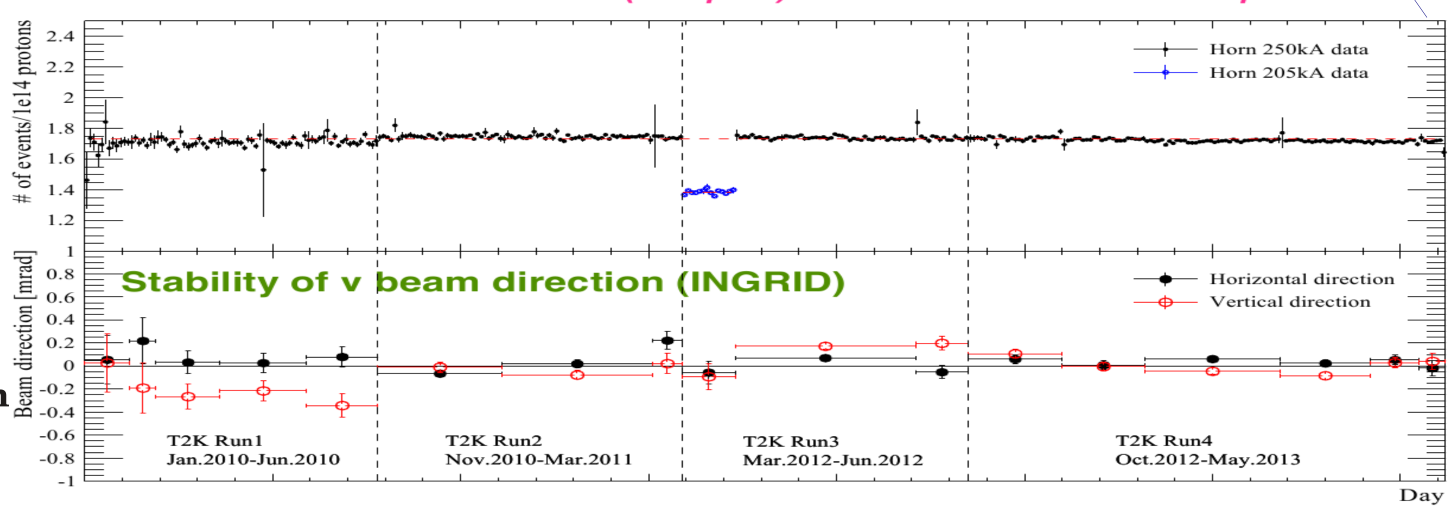
Since the beginning of T2K, 6.6 . 10^{20} POTs of data



2 % on peak

Stability of ν interaction rate normalized by # of protons (INGRID)

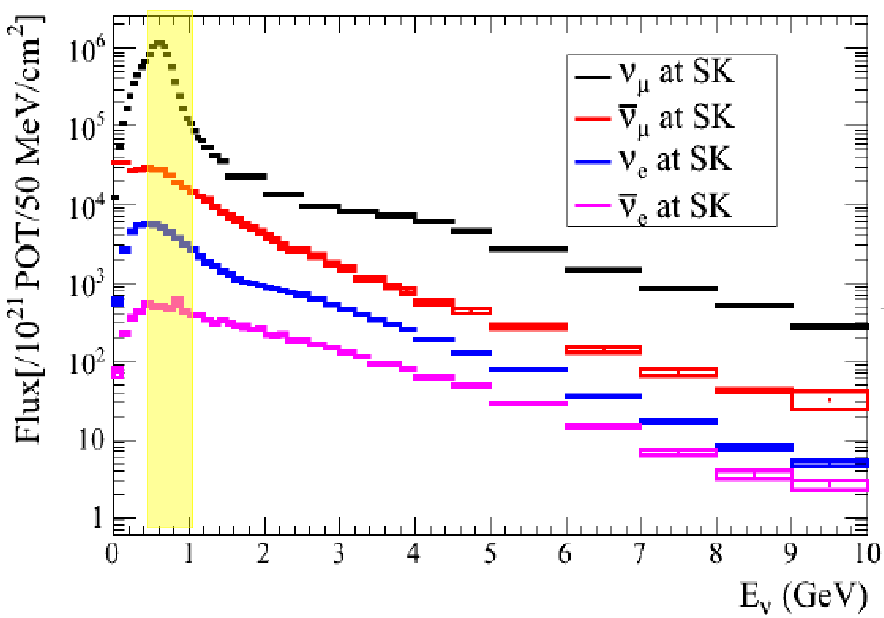
Fluctuation of ν interaction rate (/10^{19}p.o.t) is less than 0.7% whole run period



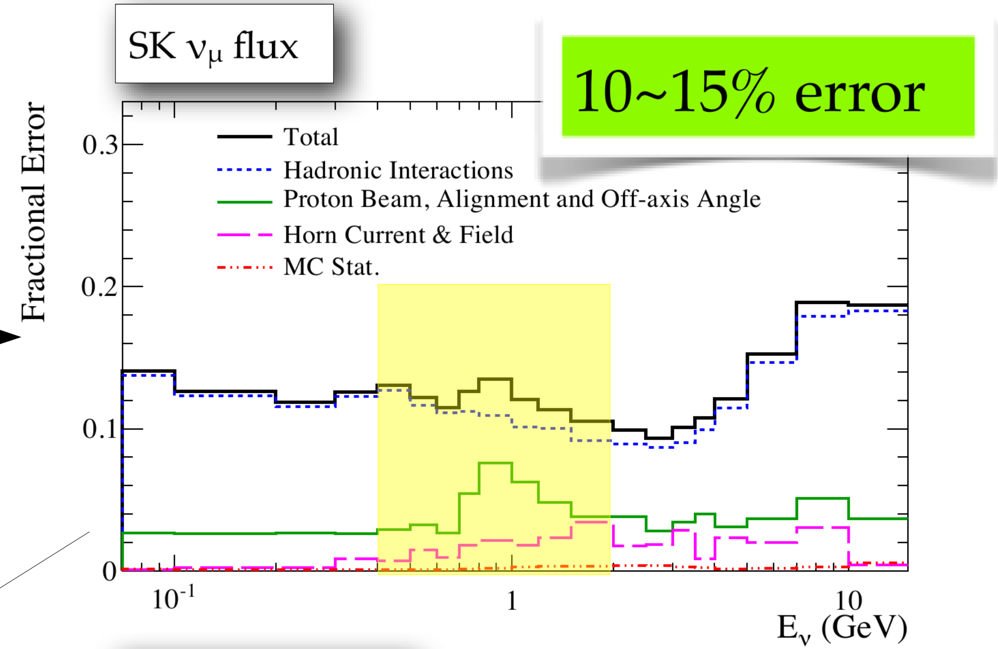
Stability of beam direction is much better than 1mrad during whole run period

Direct constraints on flux

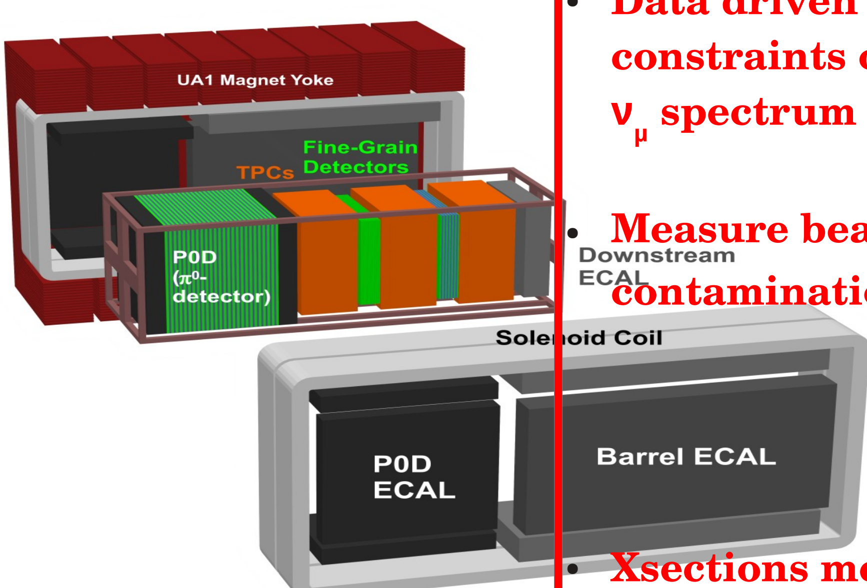
Neutrino flux from on-axis measurements



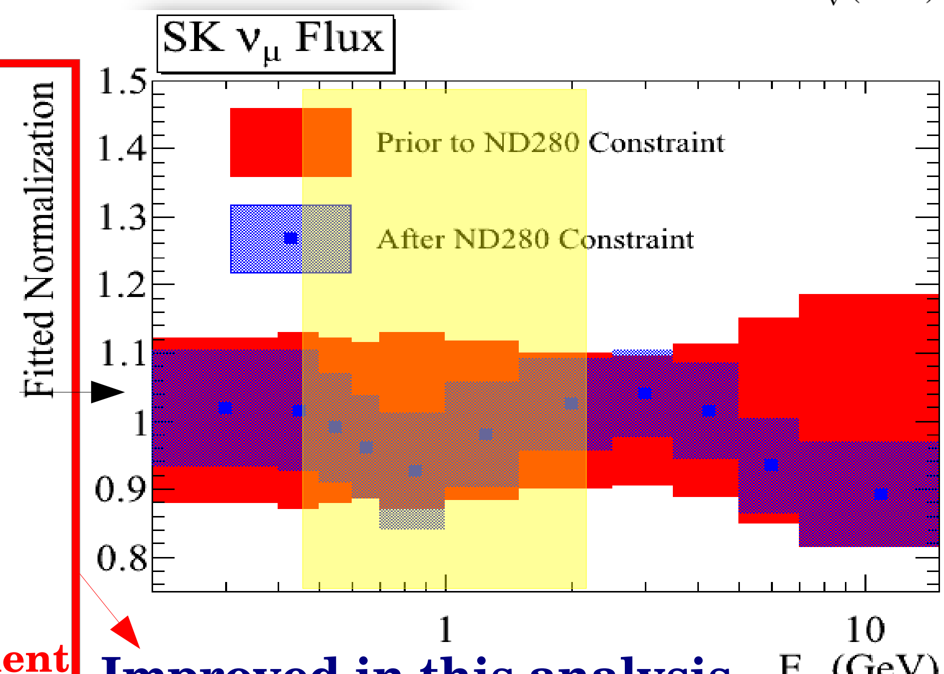
But



Off axis near detector: **ND280**



- **Data driven add. constraints on ν_μ spectrum**
- **Measure beam ν_e contamination**
- **Xsections measurement**



Improved in this analysis

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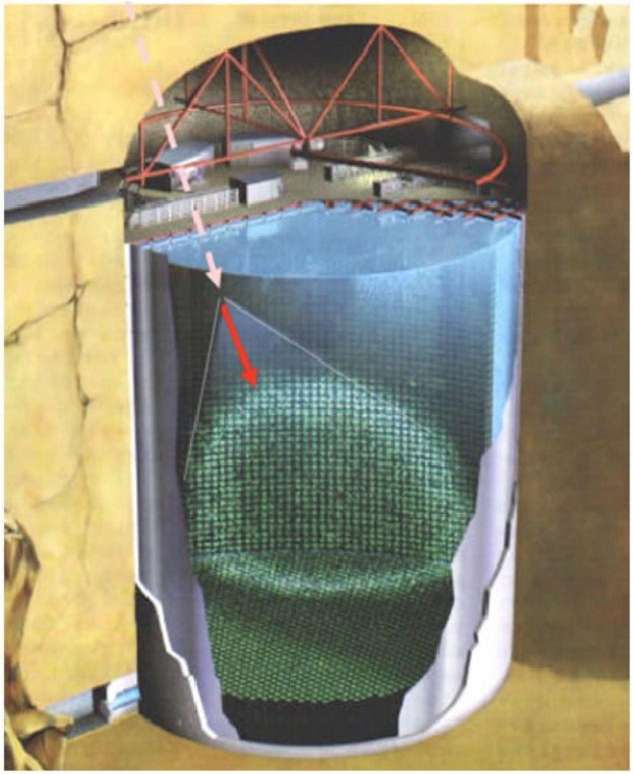
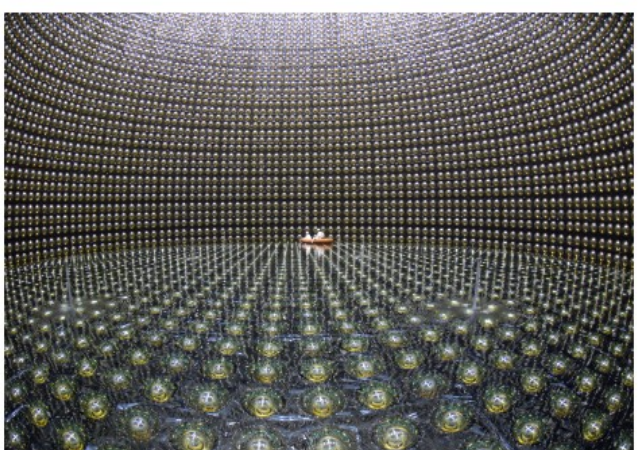
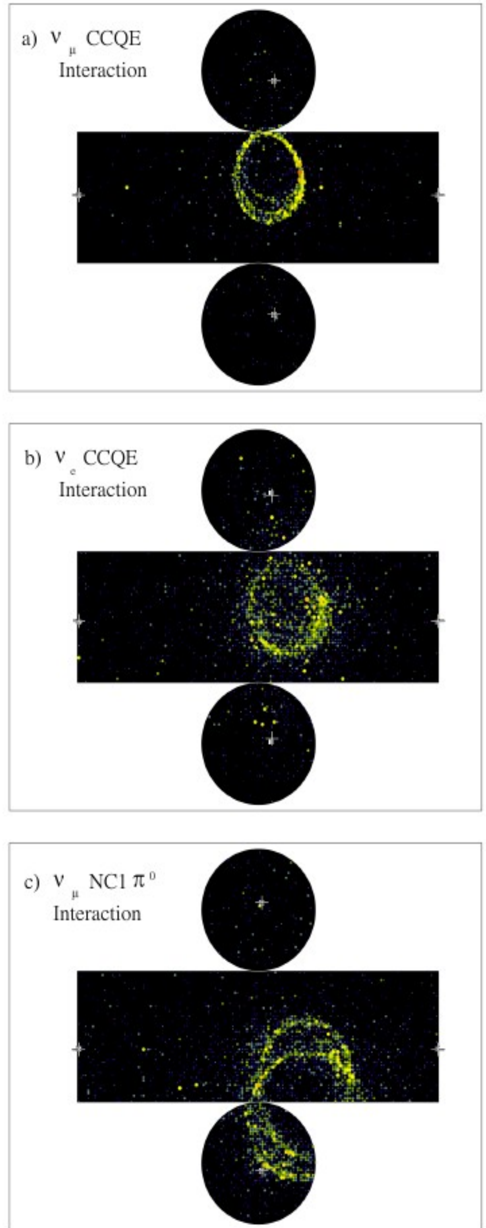
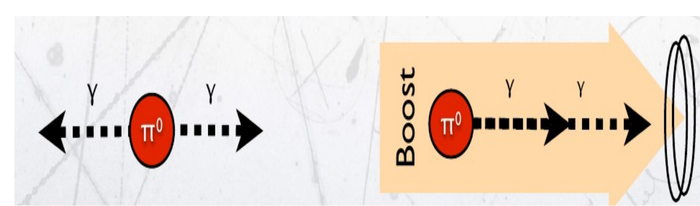
Far Detector : Super Kamiokande







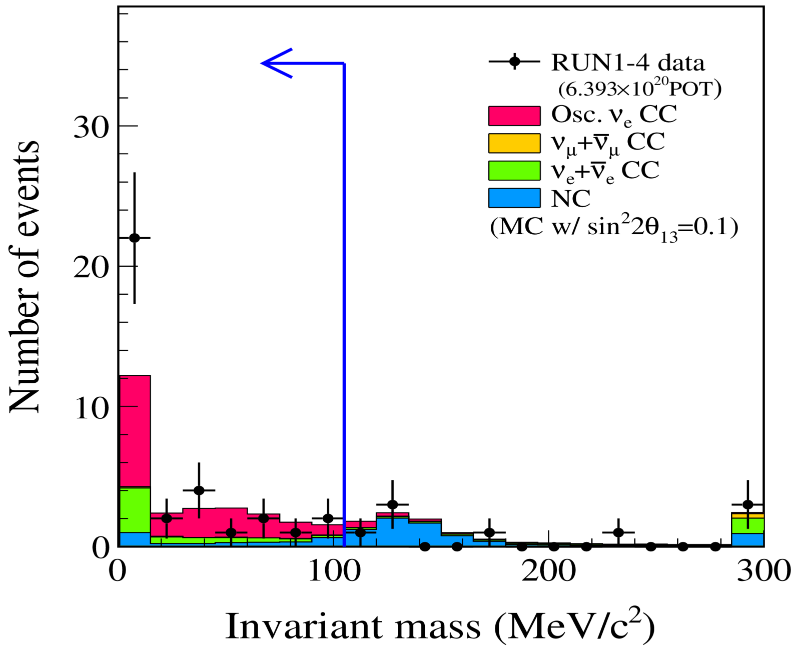
- 50 kT water Tcherenkov detector (FV = 22.5 kT)
- T2K event selection is based on a [-2, 10] µs time window around beam trigger
- **<u>Very good µ/e separation</u>** <u>(ring shape):</u>
  - 97.7 % purity on ν_e sample for 62.9 % efficiency
- π^0 contamination to ν_e sample for asymmetric decays



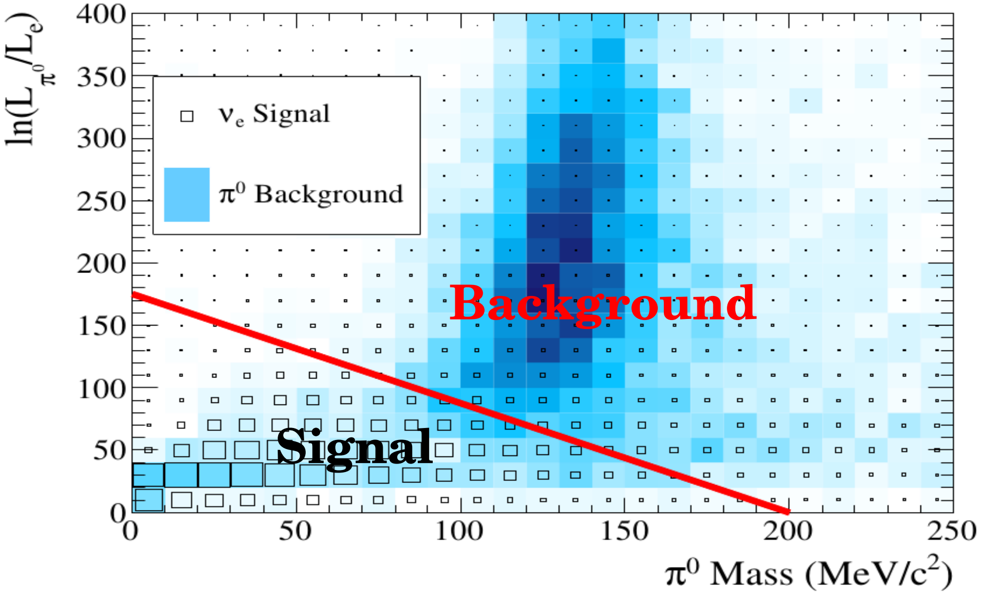
Recent update on ν_e selection

- A new reconstruction algorithm has been developped at SK
- Improved PID and more specifically, better π^0 fitter
- In this study, only used for the π^0 mass cut

Old algorithm: 1D cut on π^0 mass



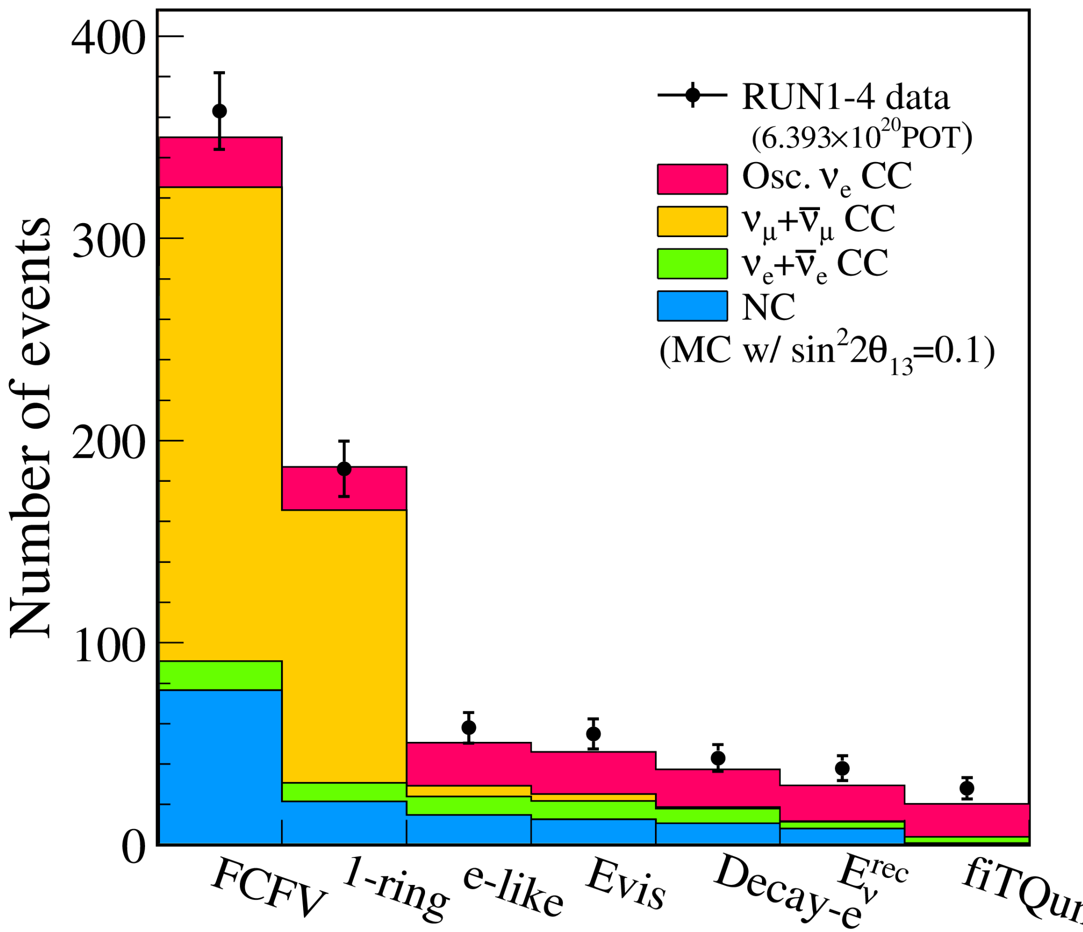
New algorithm : 2D cut on π^0 mass and π^0 /e Likelihood ratio



	Old + E_υ^{rec}	New+ E_υ^{rec}
Efficiency	90.1 %	88.5 %
NC rejection efficiency	79.7 %	92.0 %

Super Kamiokande ν_e selection

Breakdown



Selection	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	$\nu_\mu\rightarrow\nu_e$ CC	Data
Interactions in FV	337.92	17.77	281.32	28.29	-
FCFV	255.29	17.08	86.59	27.34	363
+Single-ring	146.24	10.82	24.73	23.27	186
+Electron-like PID	5.80	10.74	17.33	22.99	58
$+p_e>$ 100MeV	3.73	10.67	14.92	22.50	55
+No decay-e	0.70	8.52	12.72	19.58	43
$+E_\nu^{rec}<$ 1250MeV	0.22	3.93	9.54	18.78	38
+Non-π^0-like	0.07	3.40	1.02	17.32	28
Efficiency [%]	0.0	19.9	1.2	63.3	-

Improved analysis
(ND280 constraints
& π^0 rejection)
& **statistics**

2012 : 11 ν_e events observed for 3.3 background events

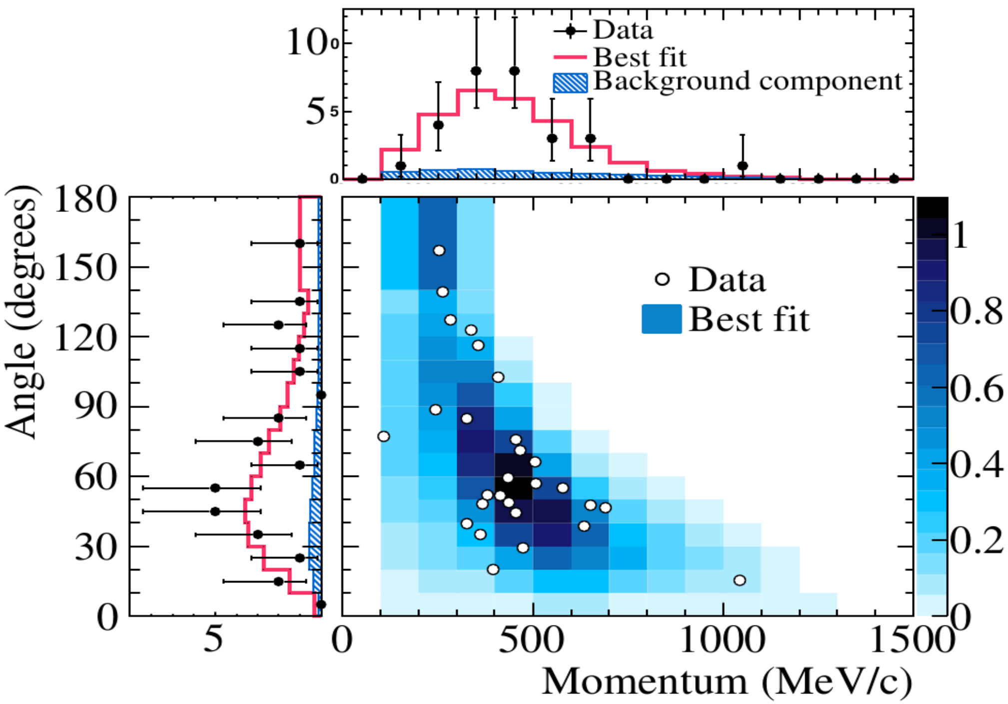
2013 : 28 ν_e events observed for 4.9 background events

Observation of ν_e appearance

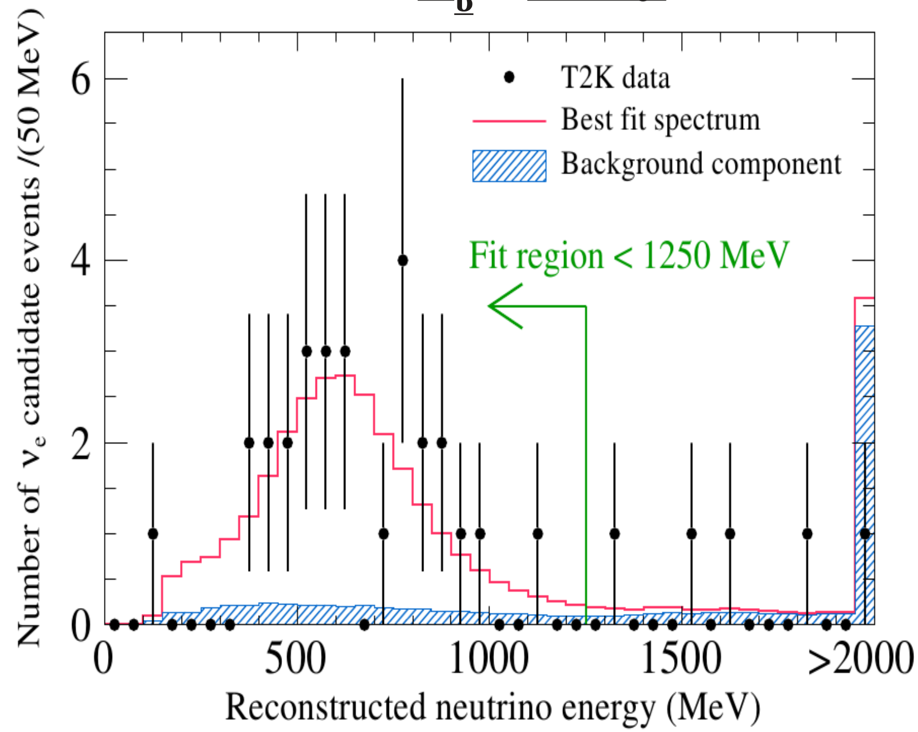
- **Fix all parameters except θ_{13}, do not take into account error on osc. param**

θ_{23} set to π/4 $|\Delta m^2_{32}|$ = 2.4.10^{-3} eV²   **δ_{cp} = 0**

(p_e, θ_e) study :



E_ν^{rec} study



These 2 methods gives nearly identical best fit values and 68 % CL (and both hierarchies)

for δ_{cp} =0

Normal hierarchy

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

7.3σ significance on $\theta_{13} \neq 0$

Inverted hierarchy

$$\sin^2(2\theta_{13}) = 0.170^{+0.045}_{-0.037}$$

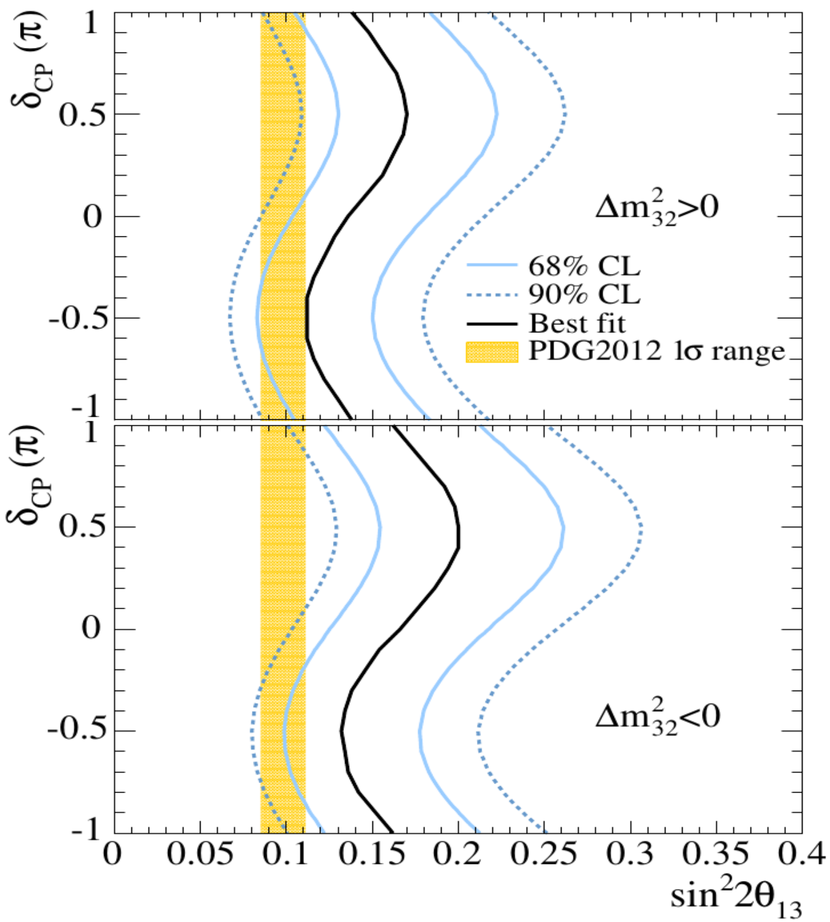
→ **First discovery of ν_e appearance in a ν_μ beam**

The δ_{cp} Fit

If δ_{cp} =0 : very high $\sin^2(2\theta_{13})$ as compared to reactor value: $\sin^2(2\theta_{13}) = 0.096$

→ What if this tension is due to δ_{cp} ?

δ_{cp} / $\sin^2(2\theta_{13})$ common fit (marginalized over $\sin^2(\theta_{23})$ and Δm^2_{32})



Best Fit Value for δ_{cp} / assuming reactor $\sin^2(\theta_{23})$:

$\delta_{cp}=-\pi/2$

From high number of ν_e observed, a maximal δ_{cp} violation is favoured

Exclusion at 90 % CL :

$0.19 < \delta_{cp}/\pi < 0.80$ for Normal Hierarchy

$-0.04 < \delta_{cp}/\pi < 1$ & $-1 < \delta_{cp}/\pi < -0.97$ for Inverted Hierarchy

Aiming to constrain δ_{cp} : Now, θ_{23} is the limiting factor towards δ_{cp} knowledge (with MH)

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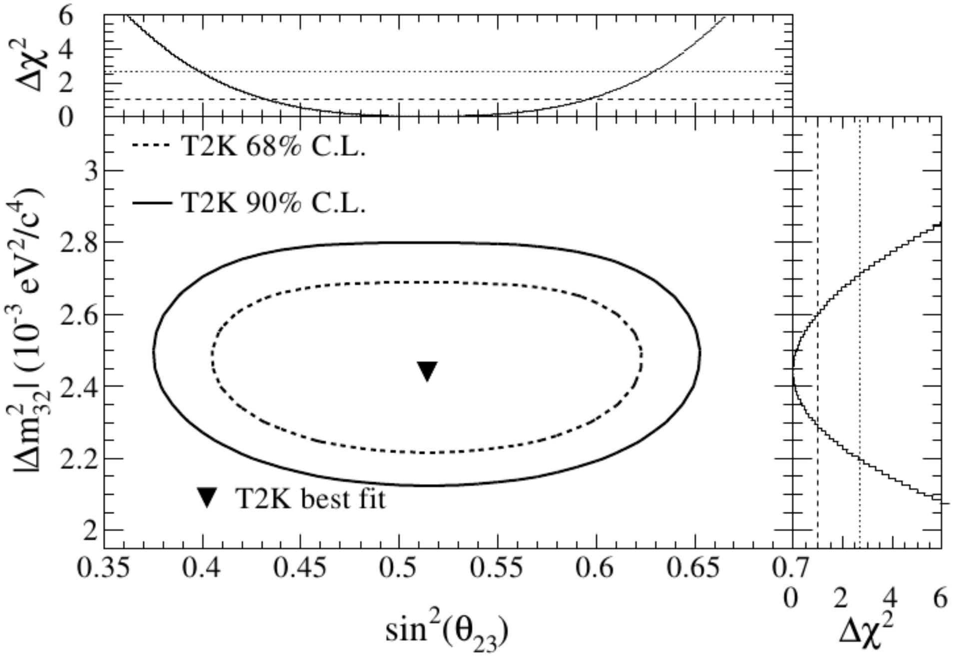
The ν_μ disappearance

- Presented at last GDR : **Accepted for PRL publication**



Fix all parameters to PDG values except θ_{23} and $|\Delta m^2_{32}|$:

$\sin^2(2\theta_{13})=0.098$ $\Delta m^2_{21} = 7.5*10^{-5}$ eV²/c⁴

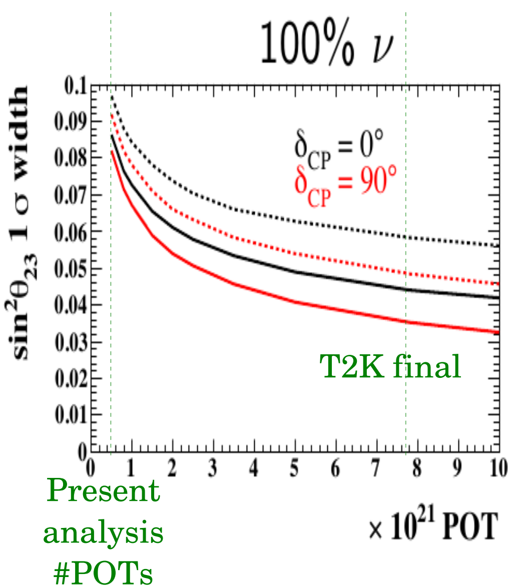
$\sin^2(2\theta_{12})=0.857$ $\delta_{cp} = 0$

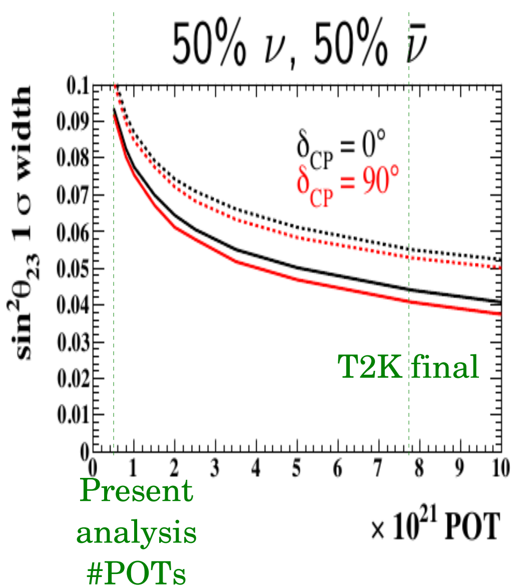
Best Fit Point :

$\sin^2(\theta_{23})=0.514 \pm 0.082$

$|\Delta m^2_{32}| = 2.44^{+0.17}_{-0.15}*10^{-3}$ eV²/c⁴

- **Compatible with maximal mixing angle**
- **Higher octant is barely favoured**





$\sin^2 2\theta_{13} = 0.1,\ \sin^2\theta_{23} = 0.5,\ \Delta m^2_{32} = 2.4\times10^{-3}\ \mathrm{eV}^2$

- Sensitivity to possible maximal mixing & octant degeneracy will increase in upcoming years (careful : Sensitivity to θ_{23} > predictions)

- Combined fit with SK is studied

Future sensitivity on δ_{cp}

- What will be T2K sensitivity on δ_{cp} with T2K full stat (7.8×10^{21} POTs) ?

$$P(\nu_\mu \to \nu_e) = \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}}$$ Leading term

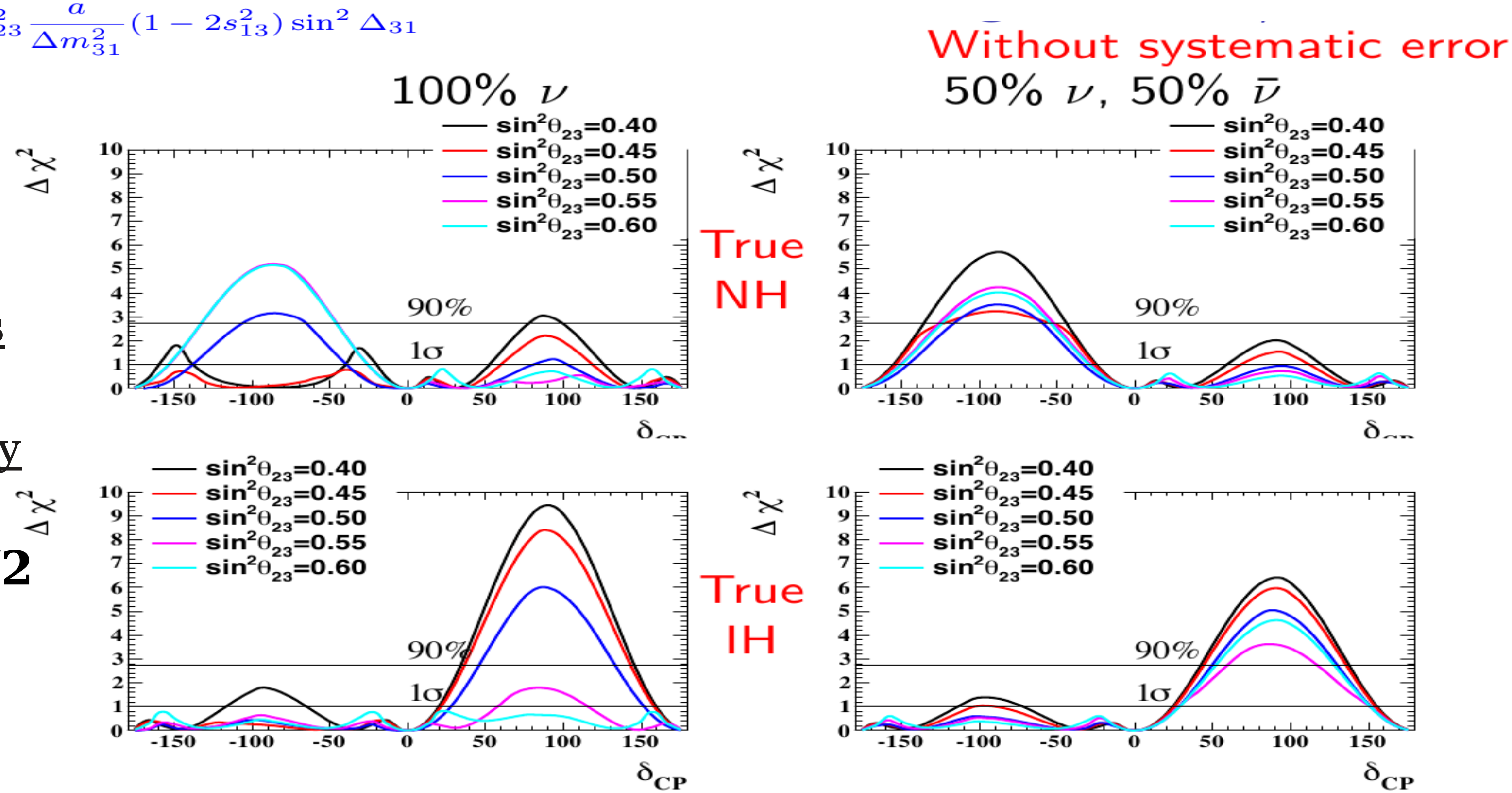
$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

$$\boxed{-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}}$$ CP violating term

$$+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$

$$-8c_{13}^2 s_{12}^2 s_{23}^2 \frac{aL}{4E}(1-2s_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$

$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2)\sin^2\Delta_{31}$$



If CP violation is maximal (&Mass Hierarchy solved):

$\leq 2.5\,\sigma$ on δ_{cp} **=-π/2**

$\leq 3\sigma$ on δ_{cp} **=π/2**

Assuming true: $\sin^2 2\theta_{13} = 0.1$, $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV^2

θ_{13} constrained by the ultimate reactor sensitivity

- What is best neutrino/antineutrino data taking strategy to achieve it? → On-going studies

Conclusions & Future

Conclusions : So far, T2K accumulated **8.3 % of total #POTs :**

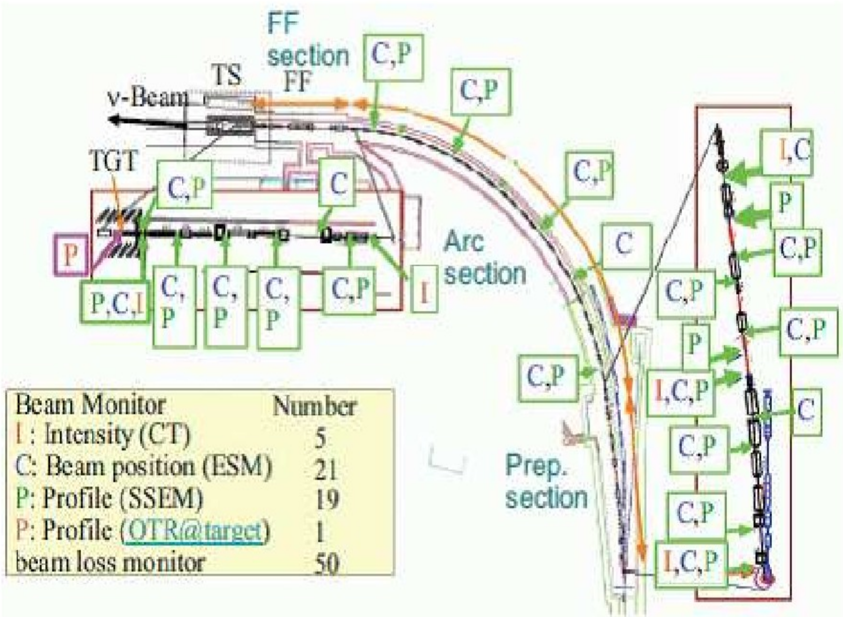
- First discovery of **ν_e appearance in a ν_μ beam**
- ν_μ disappearance measurement **favours maximal mixing :** T2K is now experiment with **best sensitivity on $\sin^2(2\theta_{23})$**

Future:

- Combined θ_{23}/θ_{13} fit
- Θ_{23} / $|\Delta m^2_{32}|$ high precision measurement
- Dedicated task force defining **future data taking policy to constraint MH & δ_{cp}**
- **Anti-Neutrino test run is forecast** : Switch horn current in 2014 ($1*10^{20}$ POT)
- **LINAC upgrade** by April 2014 to operate MR from 220 kW today to 400kW : $8*10^{20}$ POT/year
- Future MR upgrade to operate at 750 kW (accepted, done by 2018)

Additionnal slides

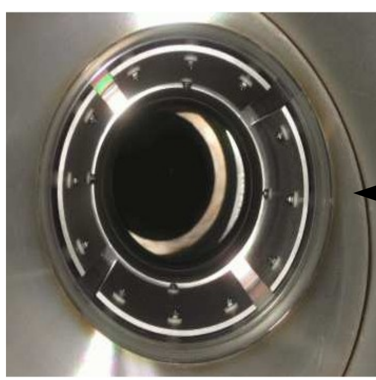
Primary Beam Informations



Beam is, only for understanding, divided in 2 parts :
primary (before target) and secondary (after) beam line.

There are different detectors to monitore each beam parameter on the primary beamline:

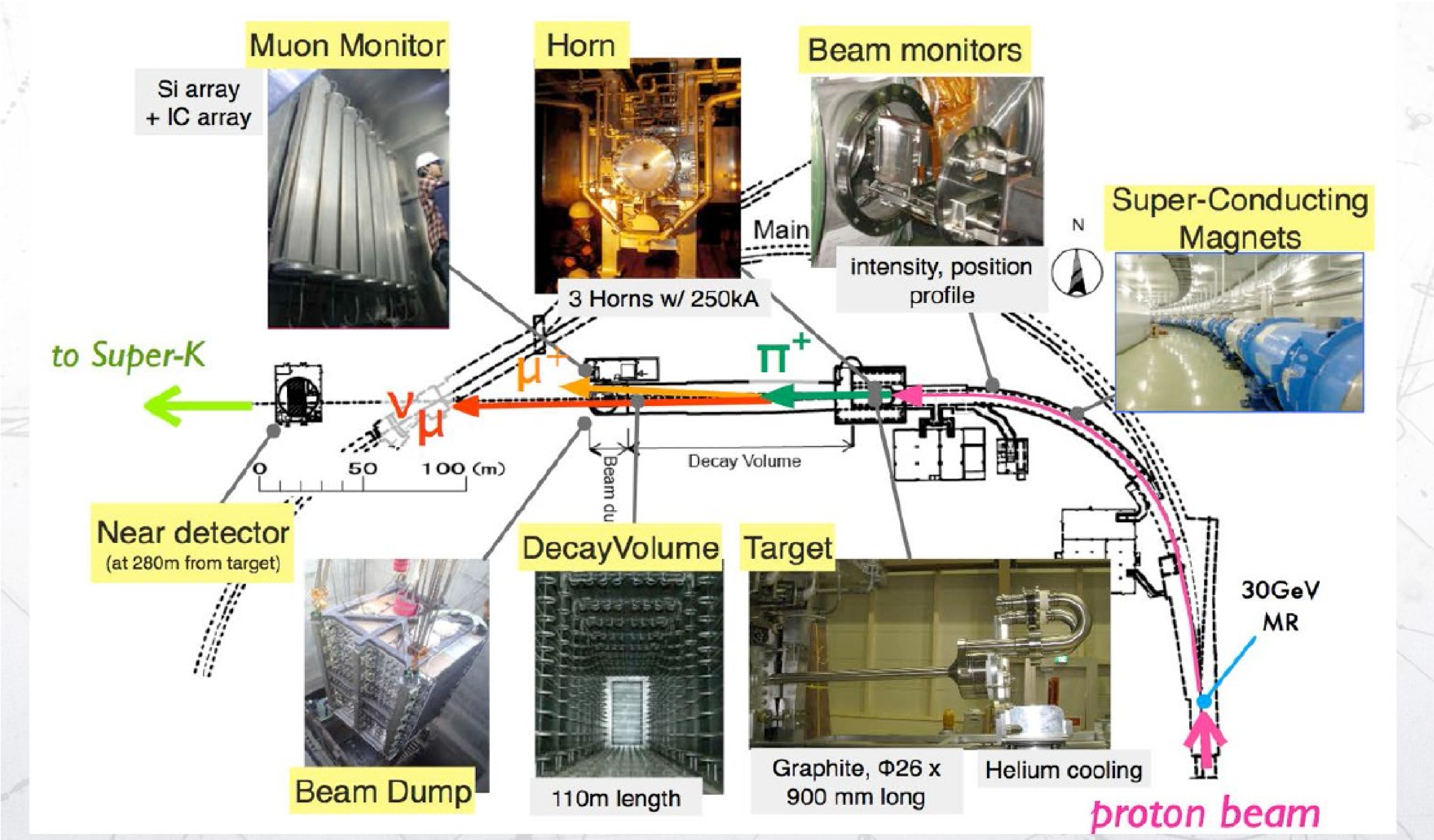
1-**Intensity** is monitored by CTs (5 current transformers) which are solenoid => passage of protons creats induced current : 2 % absolute uncertainty on #POT, 0.5 % in relative



2-**Position** is monitored by electrostatic monitors (21) and secondary emission monitors (19)

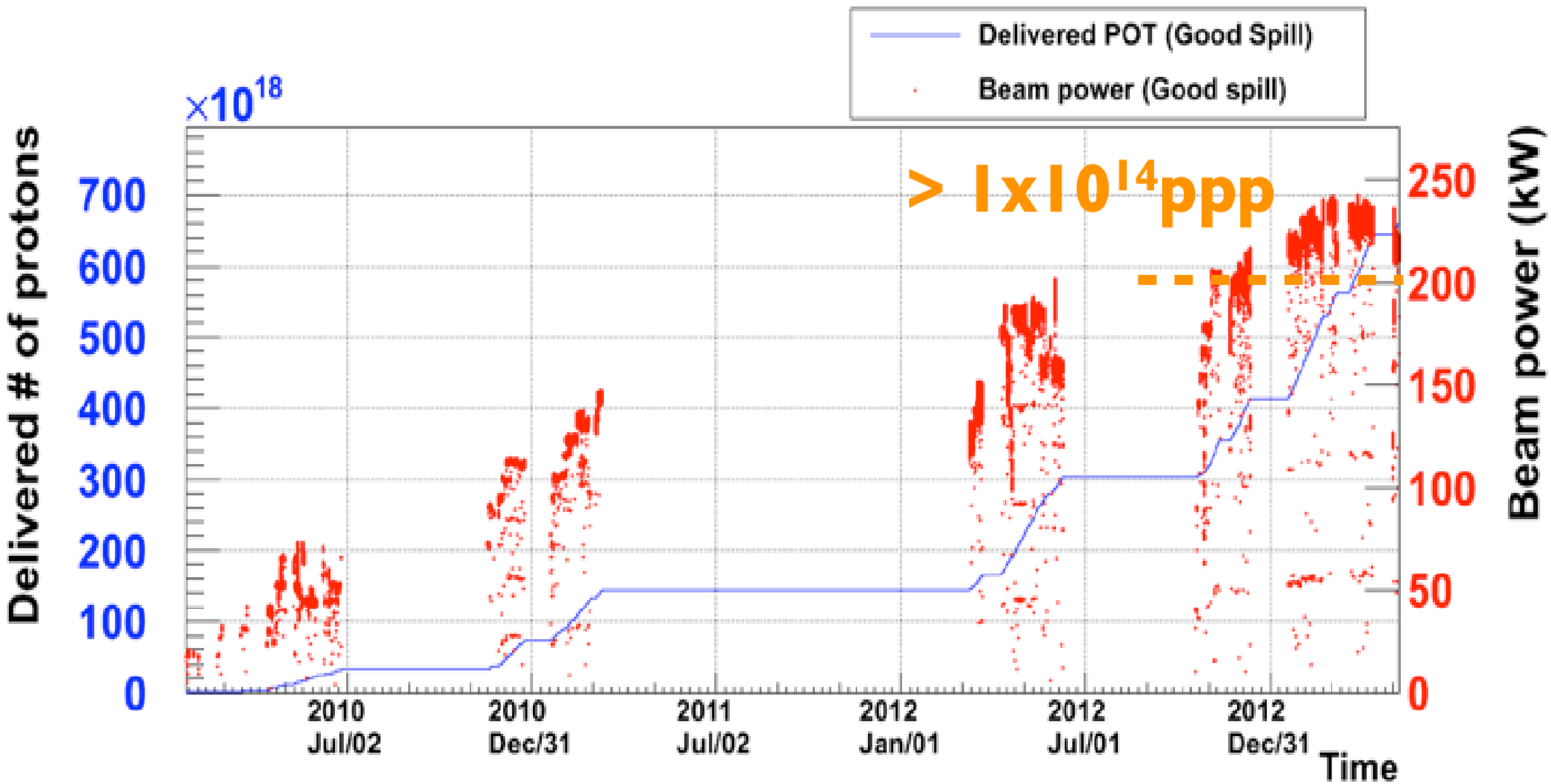
3-**Proton loss** is monitored by beam loss monitors

Secondary Beam Informations

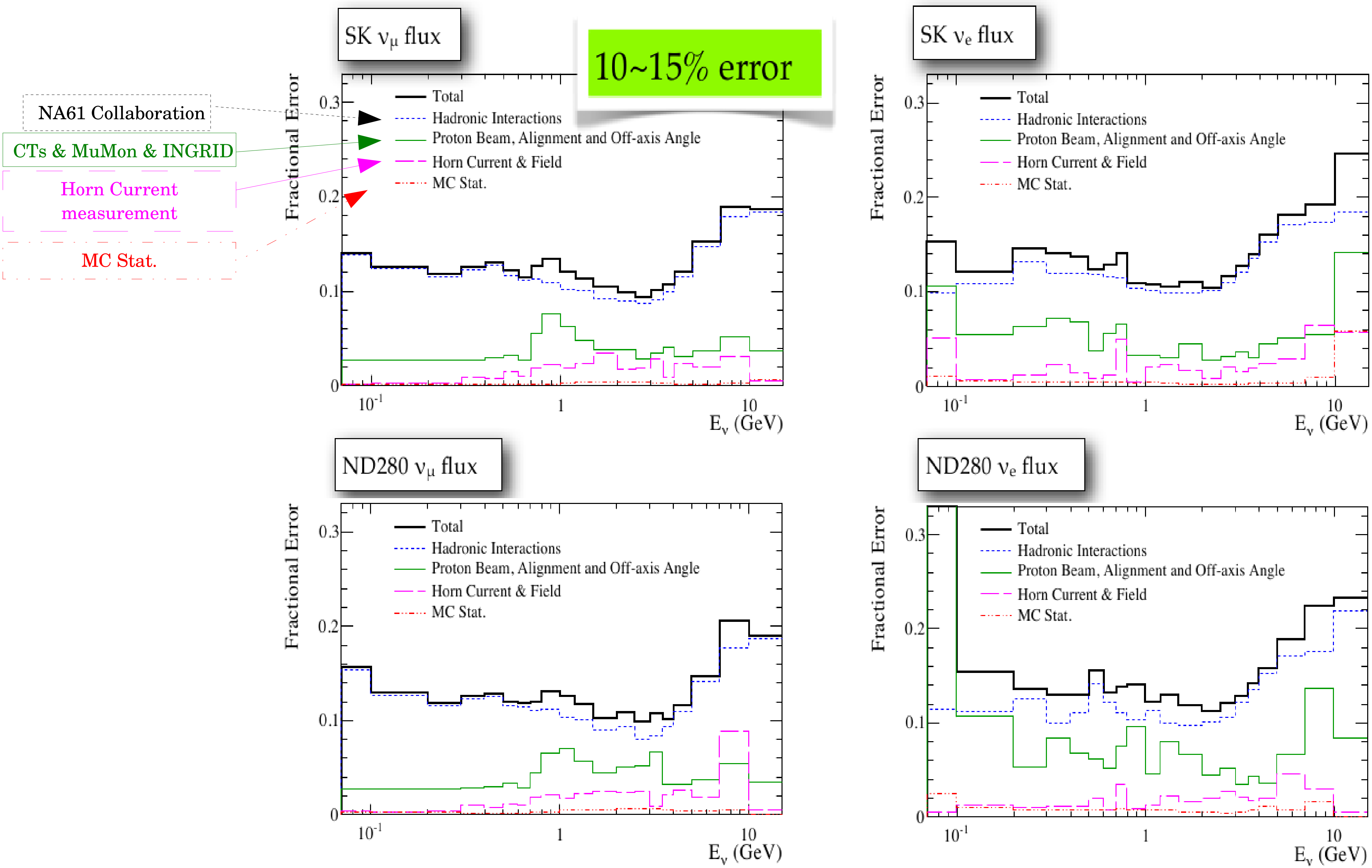


Data taking history

Integrated POT so far (Power history)

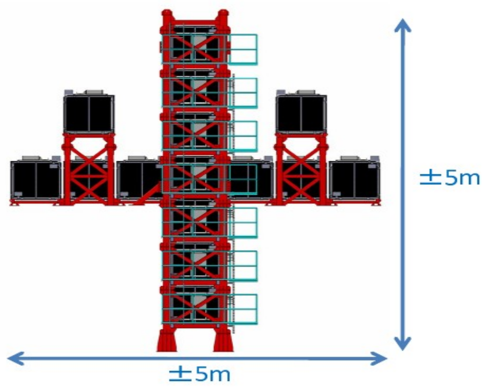


Constraints on flux



Near Detector complex

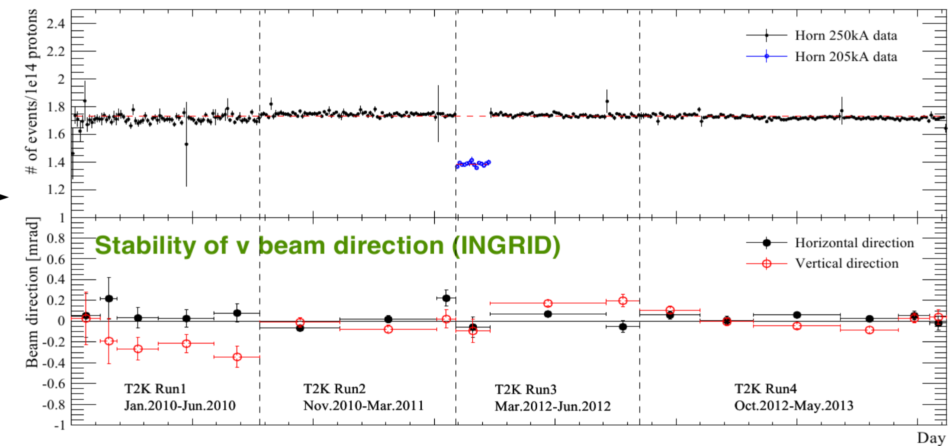
On Axis : INGRID detector



- Constraint on rate : Monitor ν_μ beam stability : constraint spectrum rate
- Indirect constraint on Shape : Off-axis angle (<1 mrad) to constraint spectrum shape

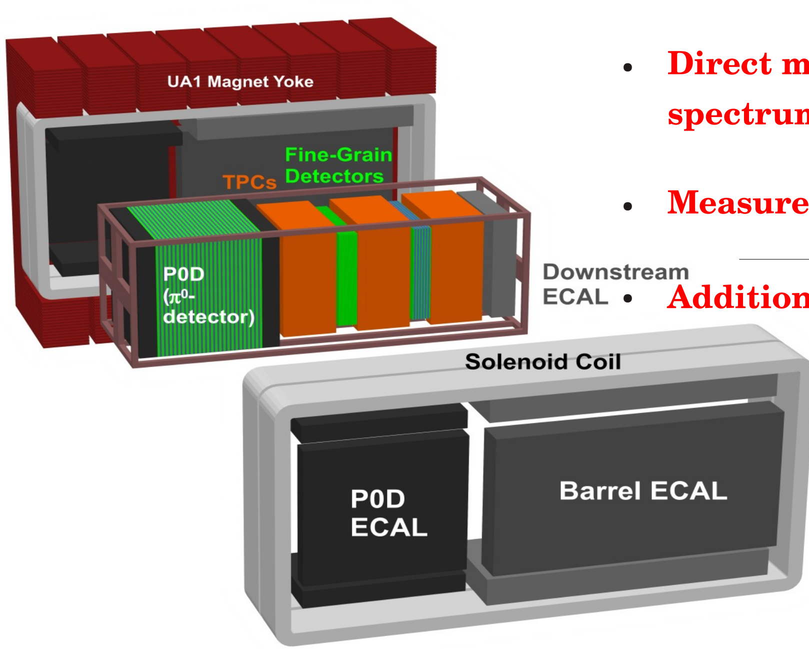
Stability of ν interaction rate normalized by # of protons (INGRID)

Fluctuation of ν interaction rate (/10[19]p.o.t) is less than 0.7% whole run period

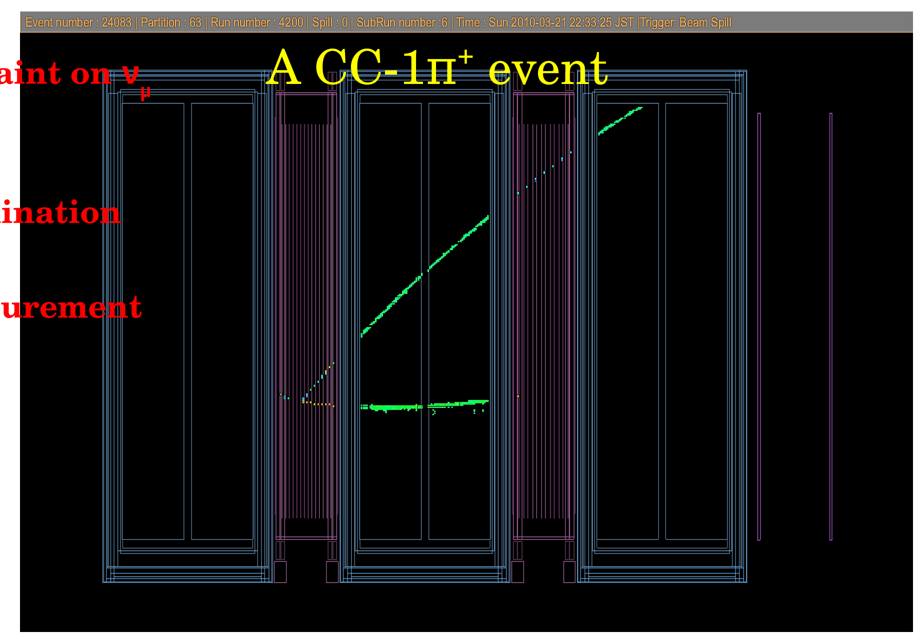


Stability of beam direction is much better than 1mrad during whole run period

Off Axis : ND280 detector complex



- Direct monitoring & constraint on ν_μ spectrum
- Measure intrinsic ν_e contamination
- Additionnal Xsections measurement



Interaction ID in ND280

1-CCNuMu : Muon 1st identification, geometric only:

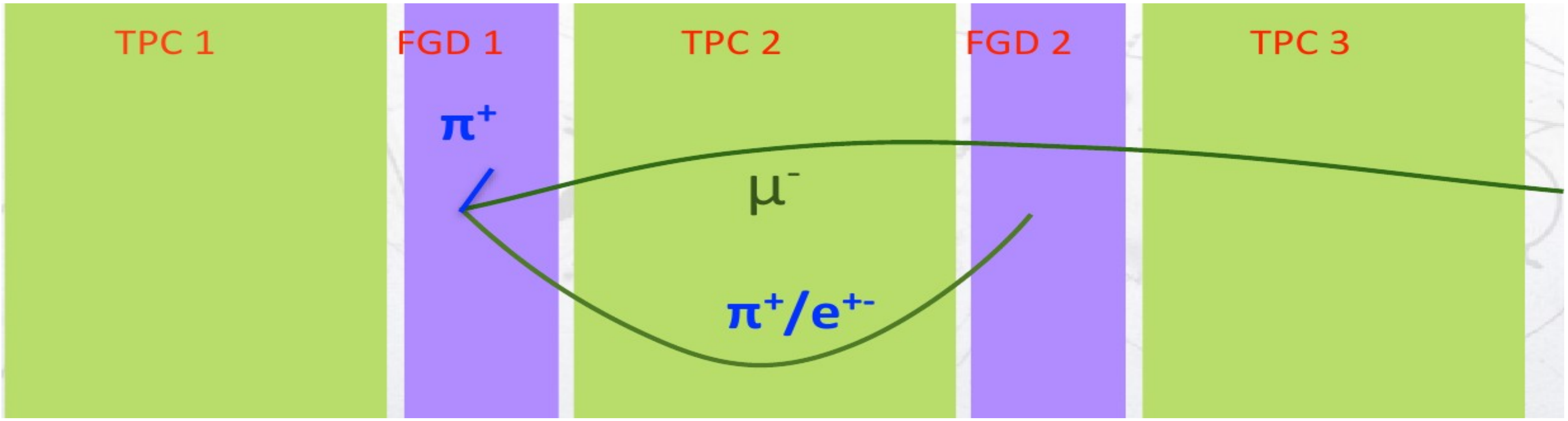
1-Starting in FGD1 FV
2-Propagating at least in TPC2
3-If several pass 1 & 2, select highest momentum track among them
4-Check negative curvature in the B field

Cutting all tracks that going in TPC1 : reduce BG & also, remove possible backward going particles from vertex in FGD1 => predominant foward-going muons

Then second identification starts, based on a PID (dE/dX based mainly) **=> select final CC NuMu inclusive sample**

2-This CC inclusive sample is divided in 2 : **CCQE and CcnonQE**. CCQE is selected:

A-Only one muon-like track
B-No additionnal tracks passing trough FGD1 & TPC2
C-No electrons from muon decay at rest in FGD1 (Michel electron) which correspond in most of the case to a **stopped or low energy Pion**



Interaction ID in ND280

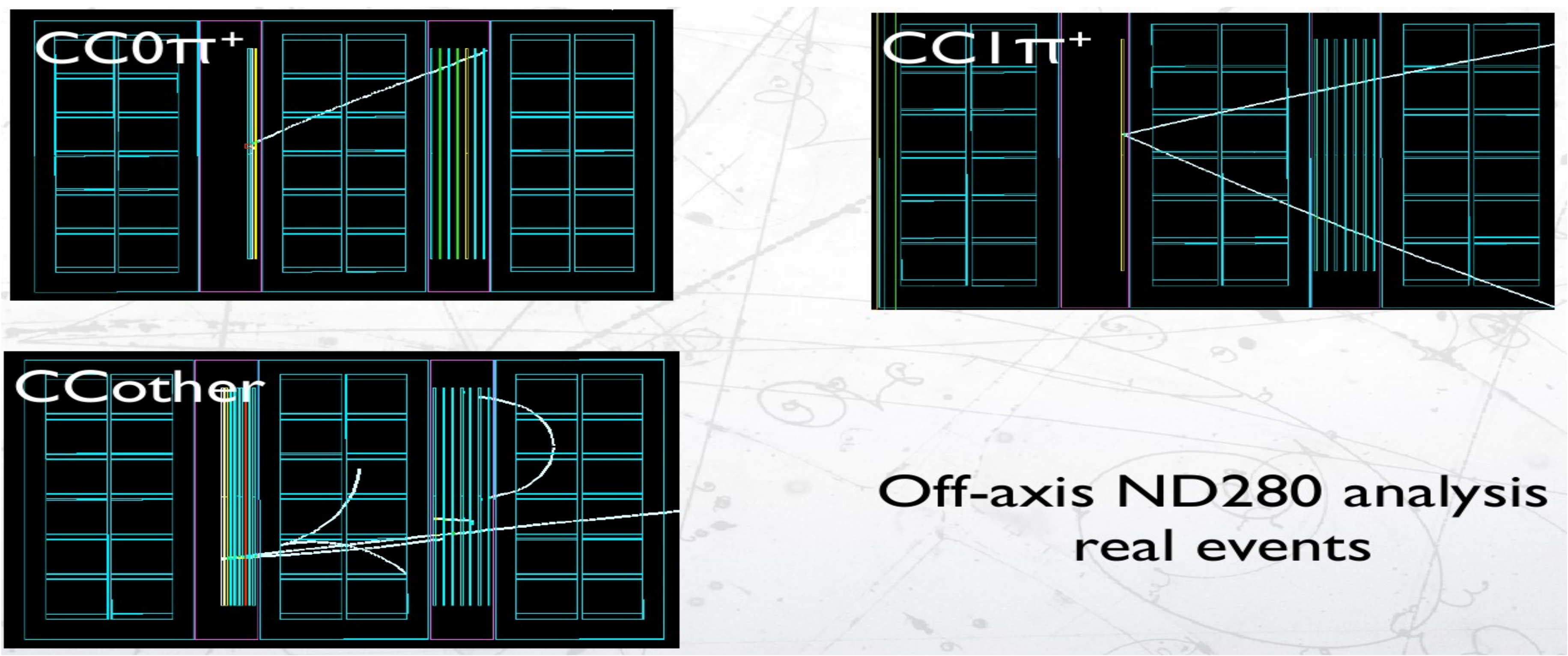
From the previous slide that **CC0Pi+ corresponds to our former CCQE interaction, while, while CCnonQE is divided in 2 samples : CC1Pi+ & CCOther**

a Pi+ is identified with a specific PID, in 3 different ways :

1-FGD1+TPC2 track consistent with a Pion

2-A FGD contained track consistent with a Pion

3-With a Michel electron arising from late Pi=>Mu (electron + timing shift)



Interest of this division in 3 samples : better constraint on flux & Xsections than previous 2 samples (CCQE and CcnonQE)

Constraints on flux from ND280

Predicted Neutrino Flux :
Direct beam, INGRID and NA61/SHINE data

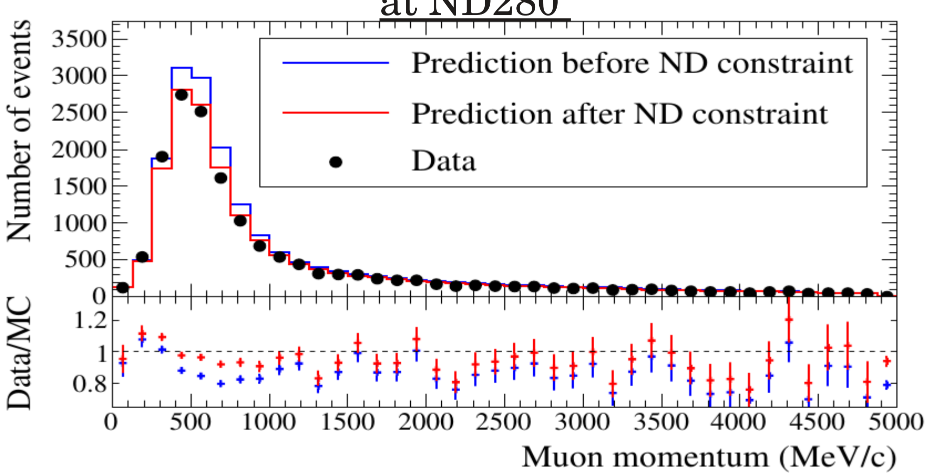
Xsections Model :
Based on NEUT (data driven by other experiments)

MC predictions compared to constraints from ND280 data:

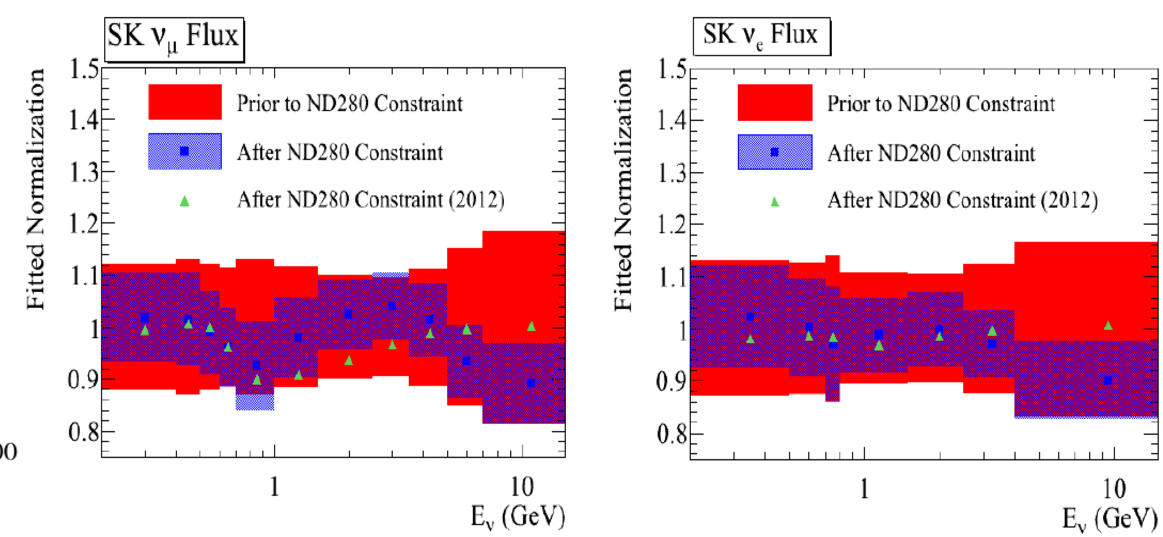
- Data sample enhanced in 0,1 or multiple pions
- Fit of model to data constrains flux, normalization, NEUT parameters (correlations)

Constraints on Flux prediction at SK and associated systematics

Muon momentum distribution for CC-0π sample at ND280



SK flux prediction re-weighting



SK uncertainty reduction

	$\sin^2 2\theta_{13}=0.1$		$\sin^2 2\theta_{13}=0.0$	
	ν_e Prediction (Events)	Error from Constrained Parameters	ν_e Prediction (Events)	Error from Constrained Parameters
No ND280 Constraint	22.6	26.5%	5.3	22.0%
ND280 Constraint (2012, Runs 1-3)	21.6	4.7%*	5.1	6.1%*
ND280 Constraint (this analysis)	20.4	3.0%	4.6	4.9%

ND280 Analysis	ND280 Data	SK Selection	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
No Constraint	--	Old	22.6%	18.3%
No Constraint	--	New	26.9%	22.2%
2012 method*	Runs 1-2	Old	5.7%	8.7%
2012 method**	Runs 1-3	Old	5.0%	8.5%
2012 method	Runs 1-3	New	4.9%	6.5%
2012 method***	Runs 1-3	New	4.7%	6.1%
2013 method	Runs 1-3	New	3.5%	5.2%
2013 method	Runs 1-4	New	3.0%	4.9%

Factor 2.4 more ND280 POT

Improved SK π^0 rejection

New ND280 reconstruction, selection, binning

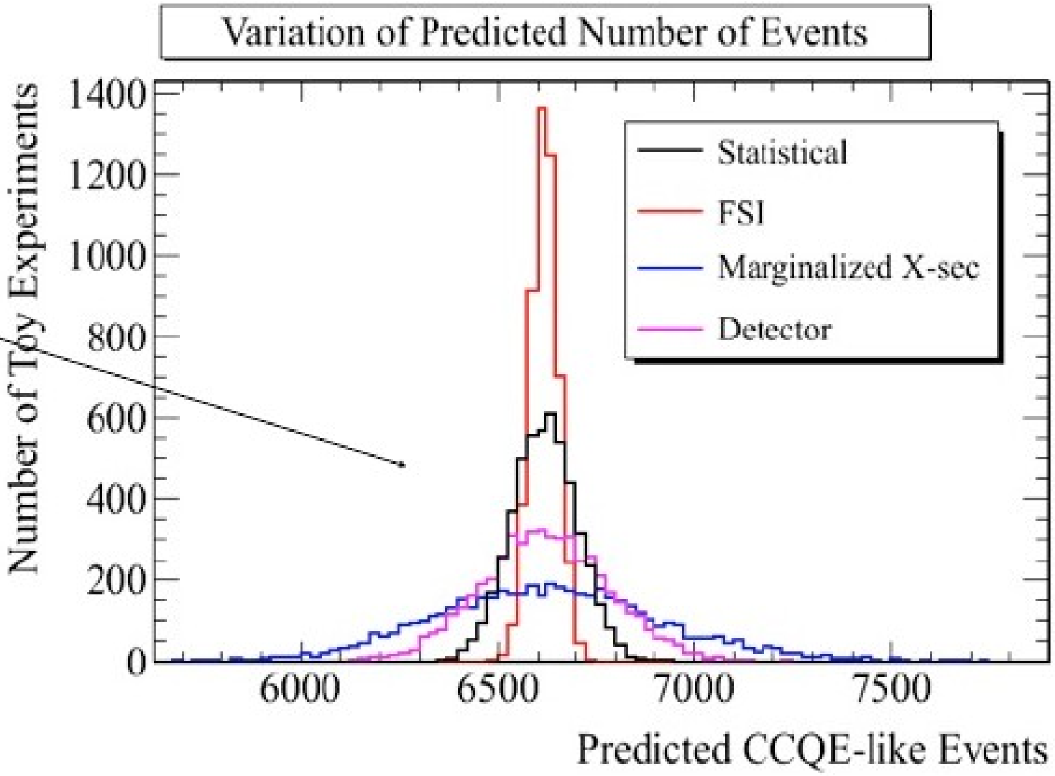
Factor 2.2 more ND280 POT

*Results presented at Neutrino 2012 conference
**Published results, arXiv:1304.0841v2
***Update to NEUT tuning with MiniBooNE data

Systematic limited

We study the dependence of the event rate prediction on marginalized nuisance parameters

Compare to statistical variations



Dominant uncertainties from:

1) Marginalized cross section parameters: CC Coherent cross section, high energy CC1π cross section, etc.

2) Detector response uncertainties

Solutions:

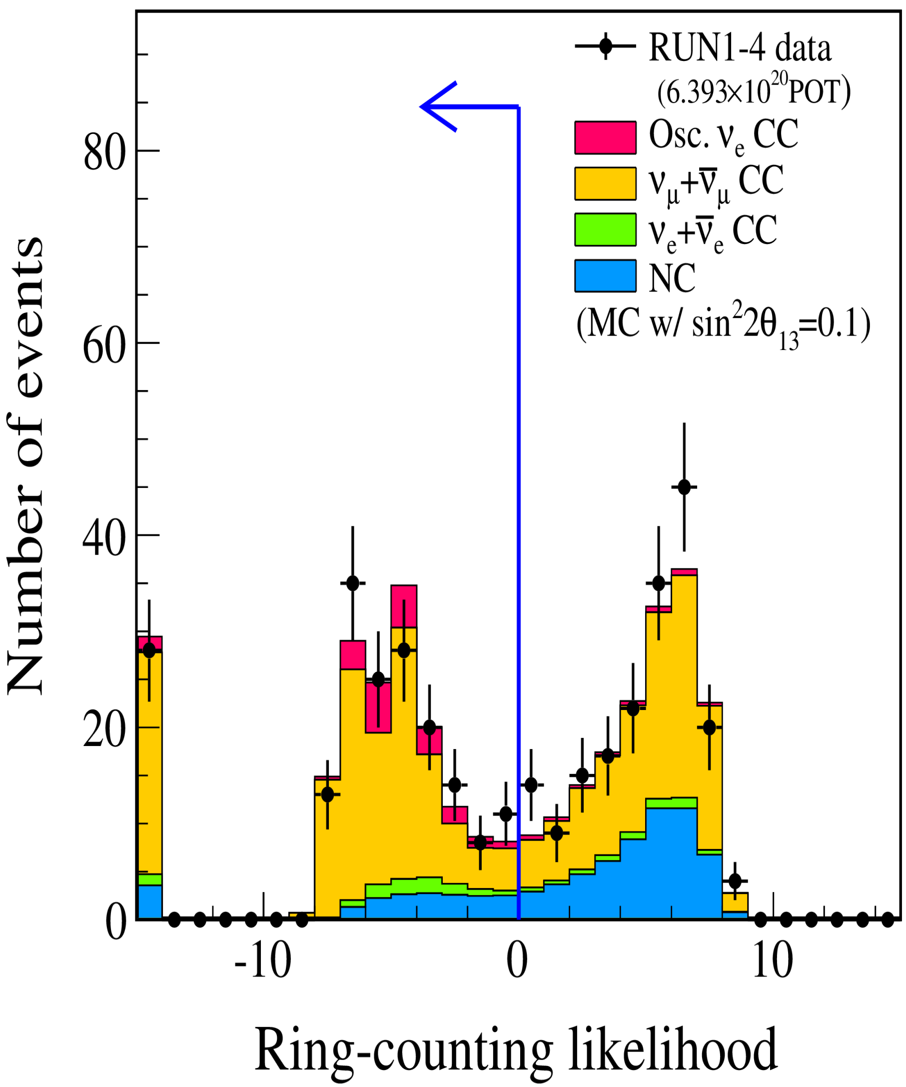
A) More optimized binning and selection of the data to better constrain the marginalized cross section uncertainties

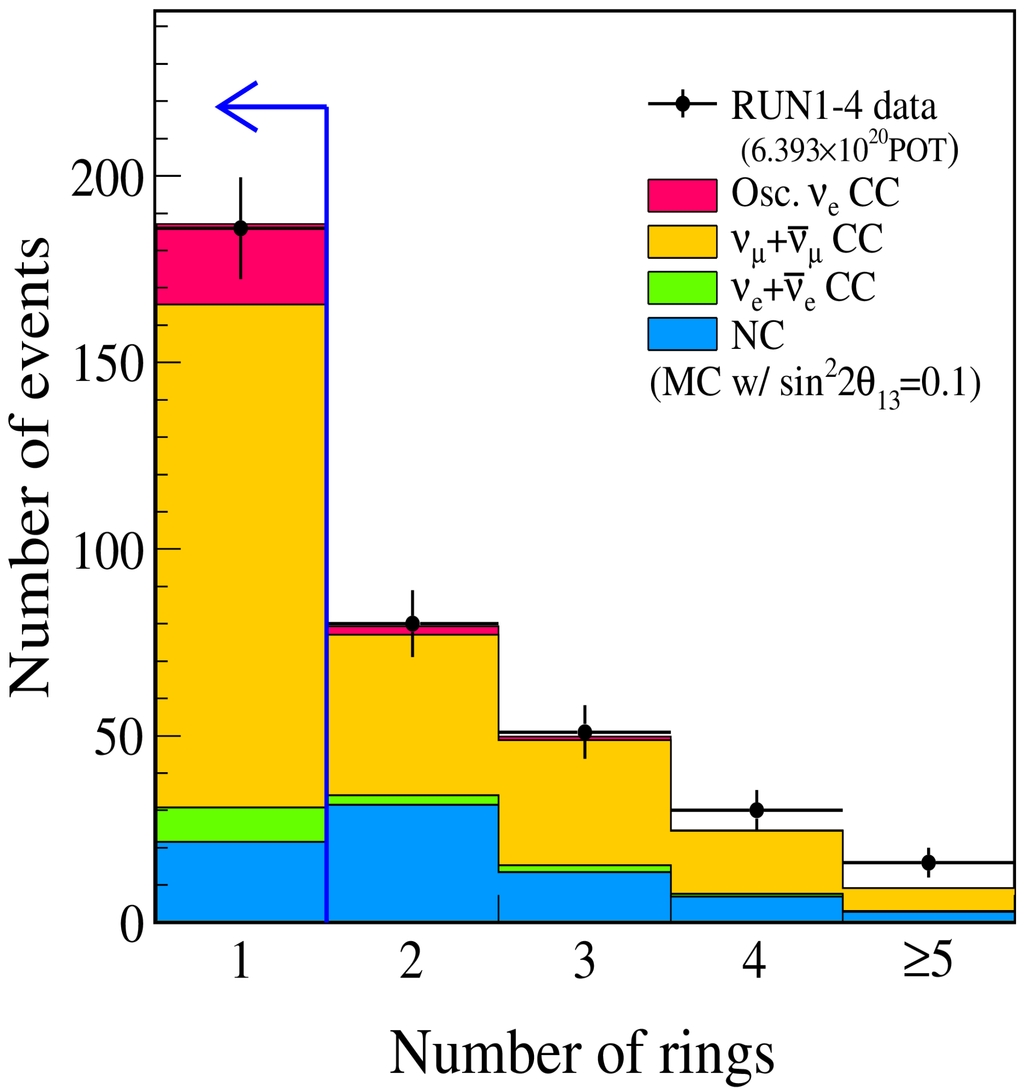
B) Improved understanding of the detector response and reconstruction to reduce the uncertainty

SK ν_e selection

1 ring

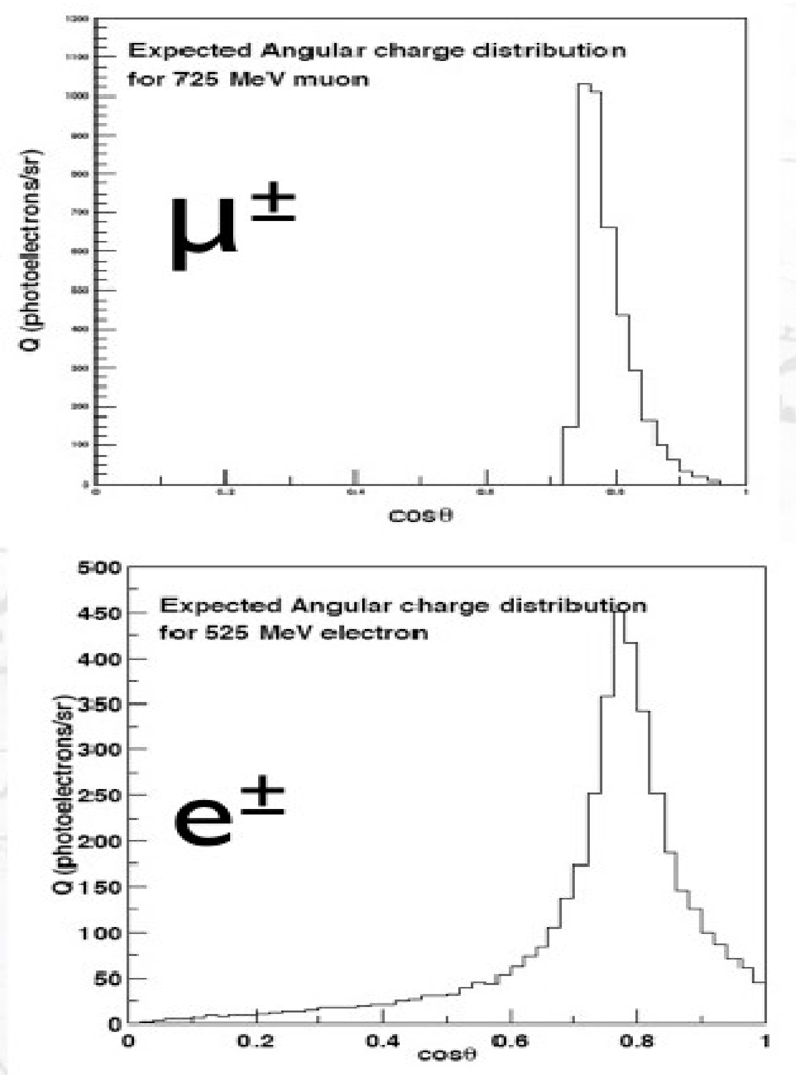
Based on the Hough transformation to find the ring

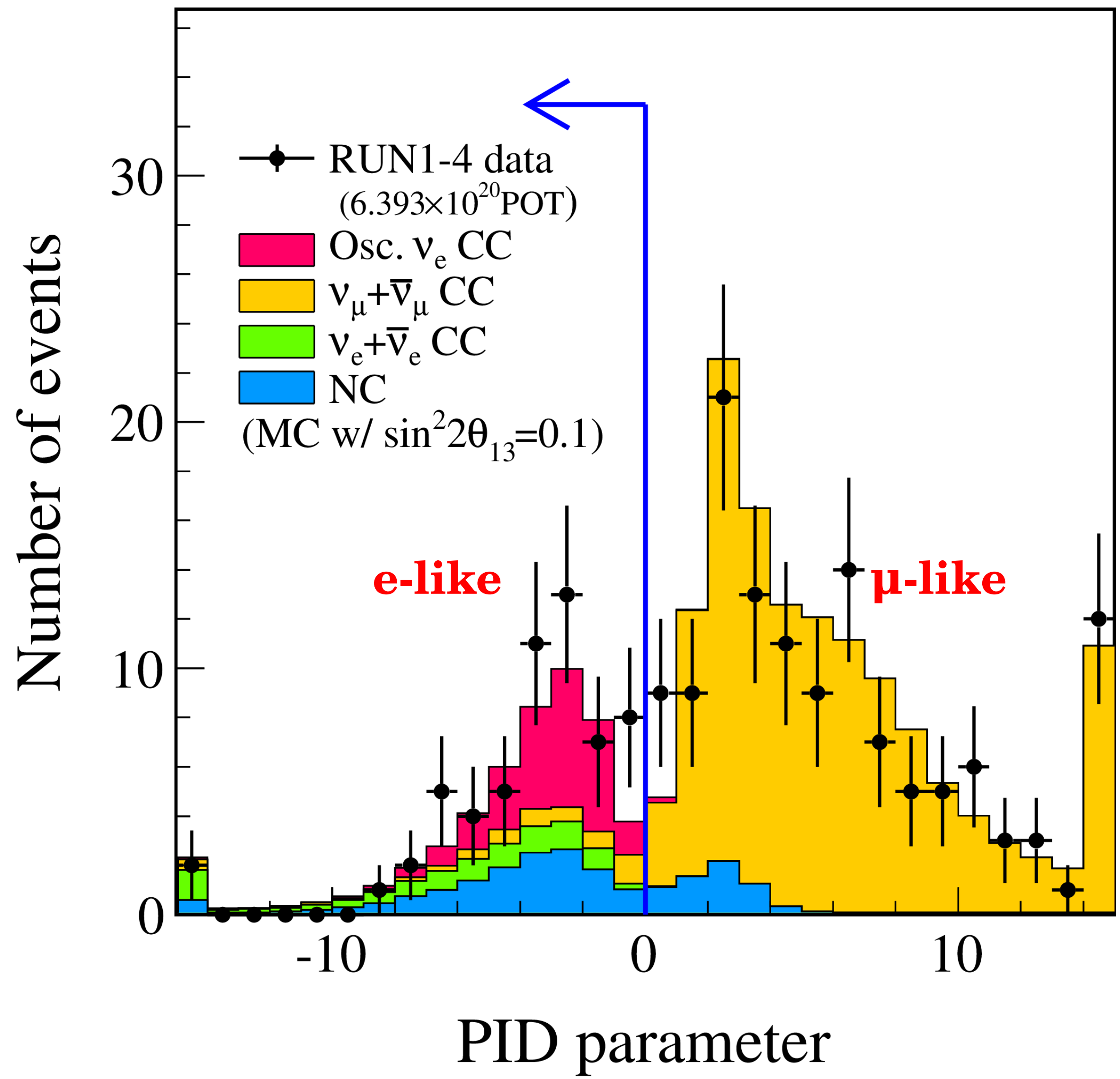




e-like

Charge Profiles

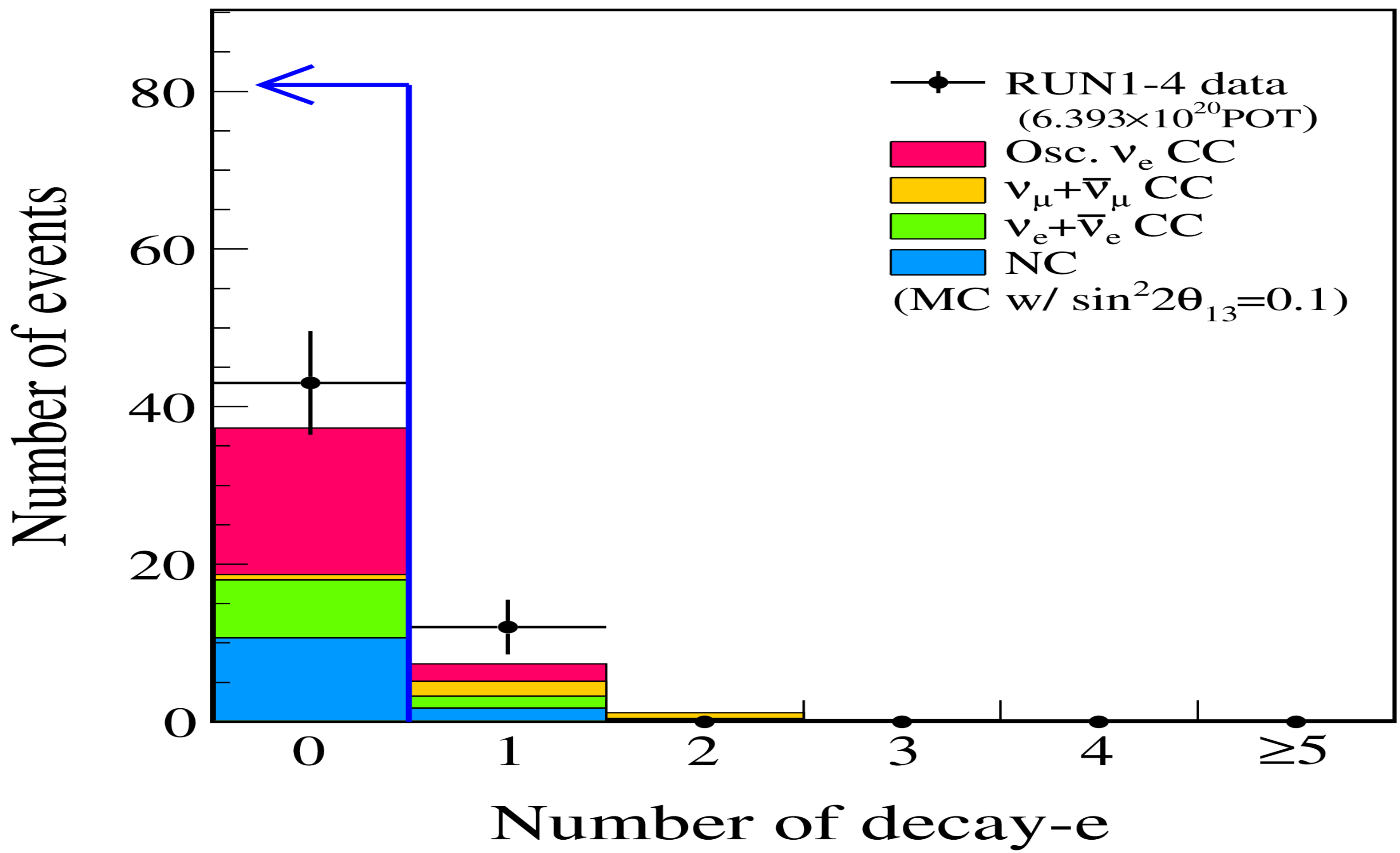




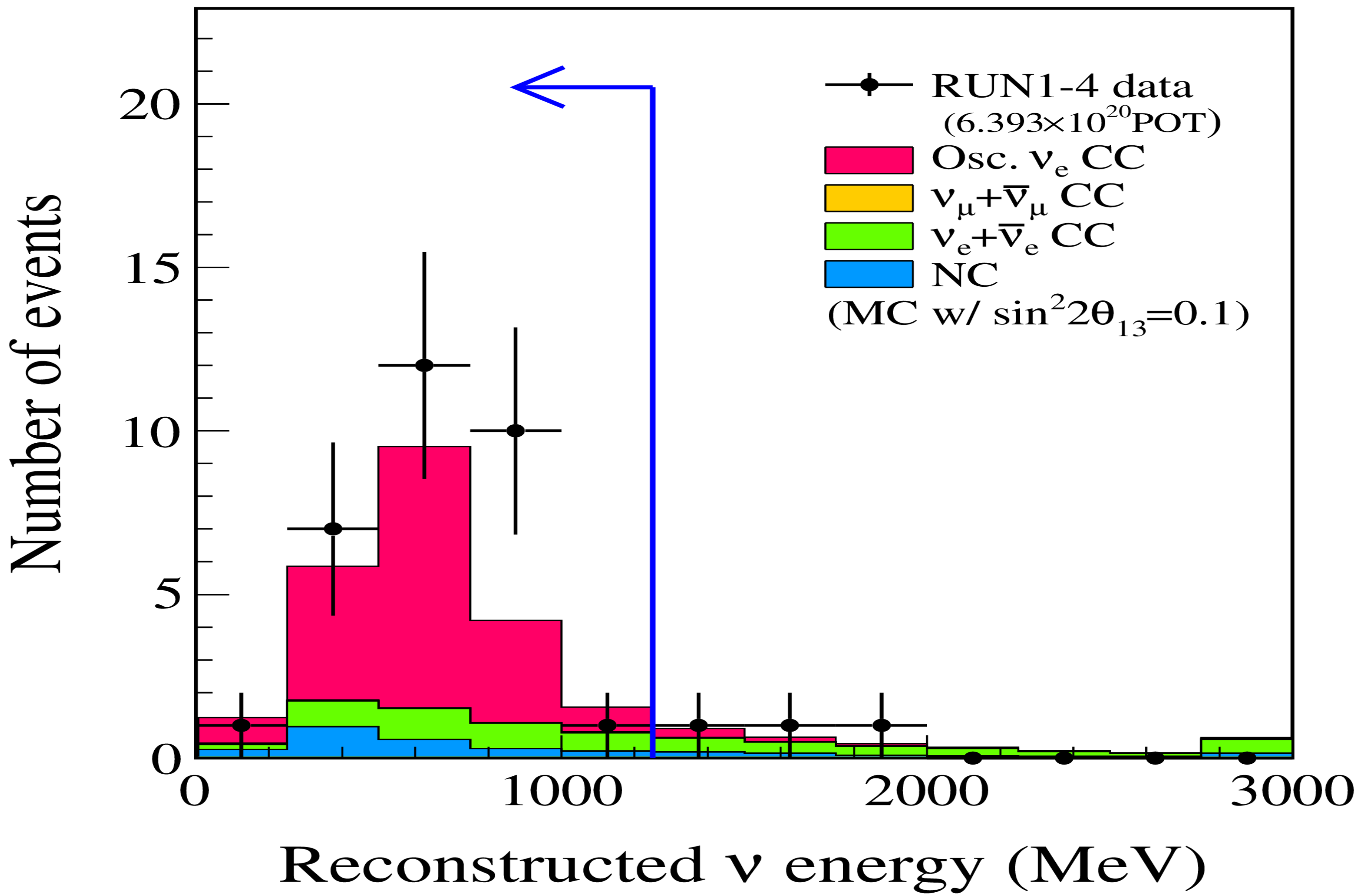
Electron is scattered due to its low mass => fuzzy ring

Decay Electrons

Search for a peak in the charge/time distribution after the main event :



Reconstructed Neutrino Energy

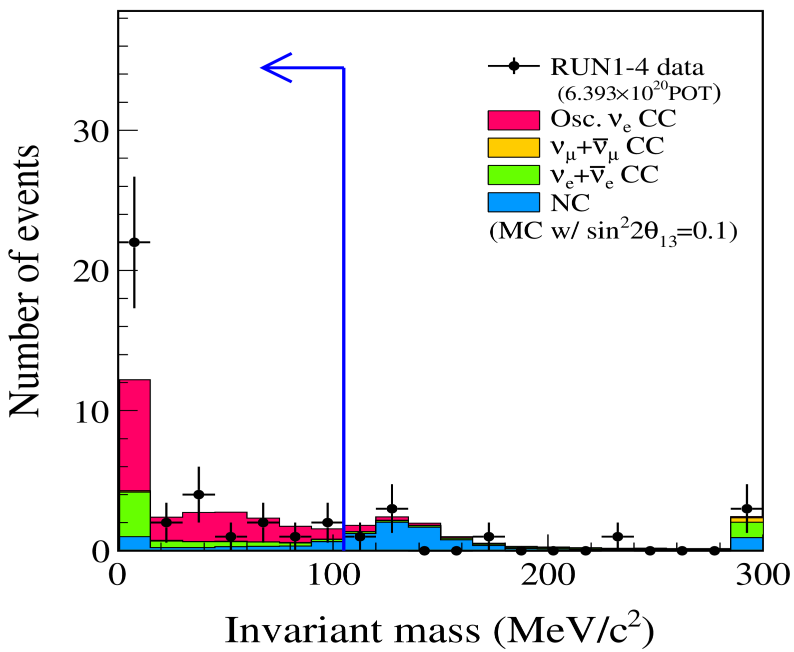


On this plot, this cut seem strange. Its existence is explained by really high systematic errors on high energy electron neutrino events. Therefore, it is wiser to remove those hits to remove also few intrinsic nuE that dominates at high energy

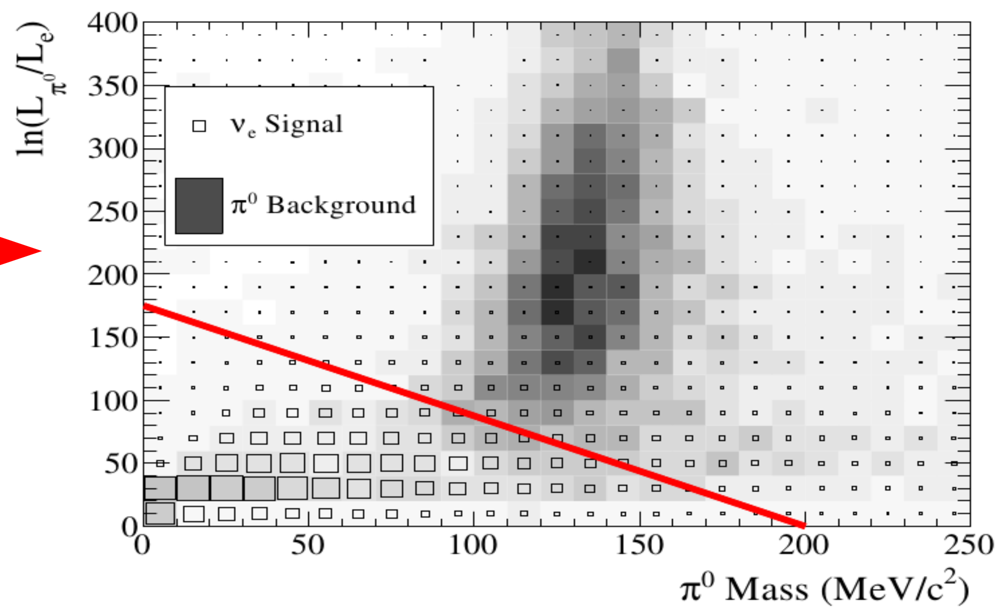
π^0 Mass

- A new reconstruction algorithm has been developped at SK
- Improved PID and more specifically, better π^0 fitter
- In this study, only used for the π^0 mass cut

Old algorithm: 1D cut on π^0 mass



New algorithm : 2D cut on π^0 mass and π^0 /e Likelihood ratio



This fit can be optimized but become highly model sensitive

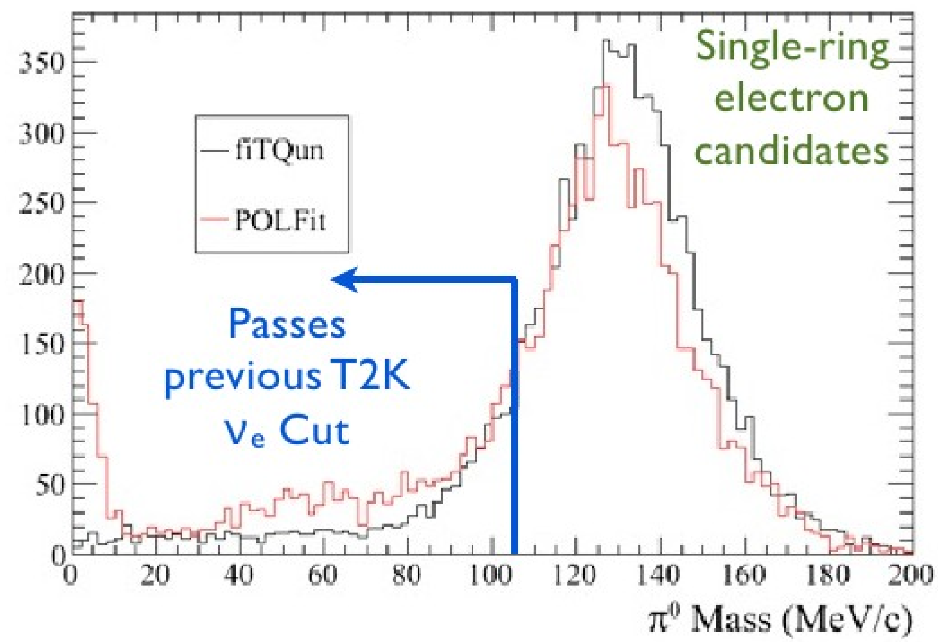
The fiTQun algorithm

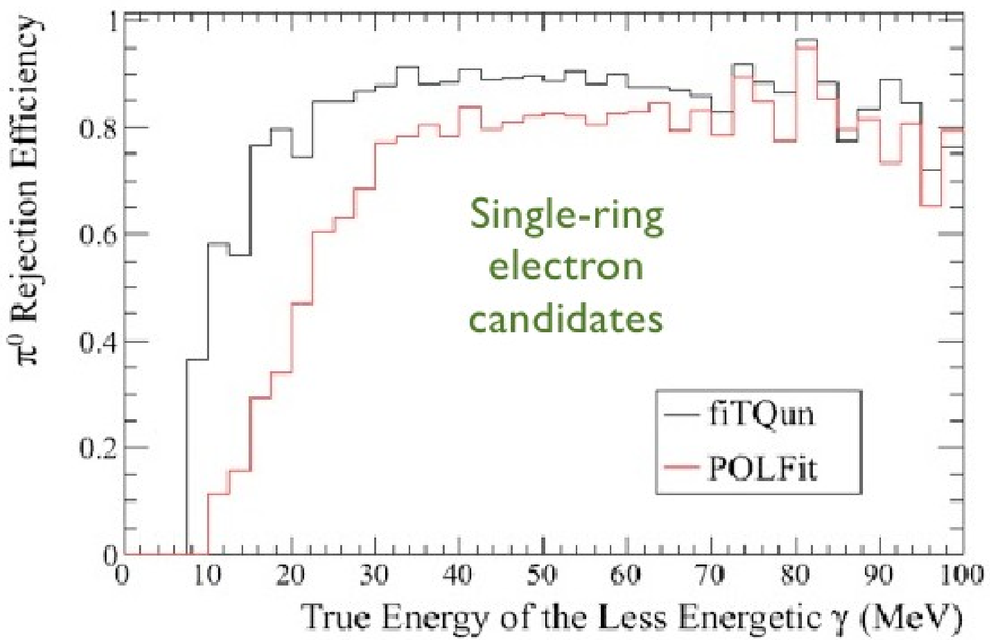
fiTQun: A New Event Reconstruction Algorithm for Super-K

- For each Super-K event we have, for every hit PMT
  - **A measured charge**
  - **A measured time**
- For a given event topology hypothesis, it is possible to produce a **change and time PDF for each PMT**
  - Based on the likelihood model used by MiniBooNE (NIM A608, 206 (2009))
- Framework can handle **any number of reconstructed tracks**
  - Same fit machinery used for all event topologies (e.g. e^- and π^0)
- Event hypotheses are distinguished by **comparing best-fit likelihoods**
  - electron vs muon
  - electron vs π^0
  - 1-ring vs 2-ring vs 3-ring ...

The fiTQun algorithm

- 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





Cuts Summary

RUN1+2+3+4 6.393x10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}$=0.0					Data
	ν_μ+antiν_μ CC	ν_e+antiν_e CC	NC	BG total	Signal	
Interactions in FV	308.01	15.48	271.56	595.05	0.53	-
FCFV	234.76	14.88	76.46	326.1	0.51	363
Single-ring	134.95	9.58	21.6	166.13	0.46	186
Electron-like PID	5.32	9.51	14.87	29.71	0.45	58
E_{vis}>100MeV	3.46	9.45	12.67	25.58	0.44	55
No decay-e	0.65	7.71	10.64	19	0.41	43
POLfit mass	0.19	5.47	2.99	8.64	0.39	34
E_ν^{rec}<1250MeV	0.12	3.45	2.3	5.87	0.39	31
Efficiency [%]	0.04	22.3	0.8	1	73.6	-

RUN1+2+3+4 6.393x10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}$=0.1					Data
	ν_μ+antiν_μ CC	ν_e+antiν_e CC	NC	BG total	Signal	
Interactions in FV	307.67	14.96	271.56	594.19	25.59	-
FCFV	238.67	14.38	76.46	325.26	24.78	363
Single-ring	134.76	9.19	21.6	165.55	21.5	186
Electron-like PID	5.32	9.12	14.87	29.31	21.24	58
E_{vis}>100MeV	3.45	9.06	12.67	25.19	20.87	55
No decay-e	0.65	7.37	10.64	18.66	18.61	43
POLfit mass	0.19	5.17	2.99	8.35	17.32	34
E_ν^{rec}<1250MeV	0.12	3.2	2.3	5.62	16.77	31
Efficiency [%]	0.04	21.4	0.8	0.9	65.5	-

Improvement from 2012 & Systematic error for each sample

Predicted number of events and systematic uncertainties

Predicted # of events w/ 6.4×10^{20} POT

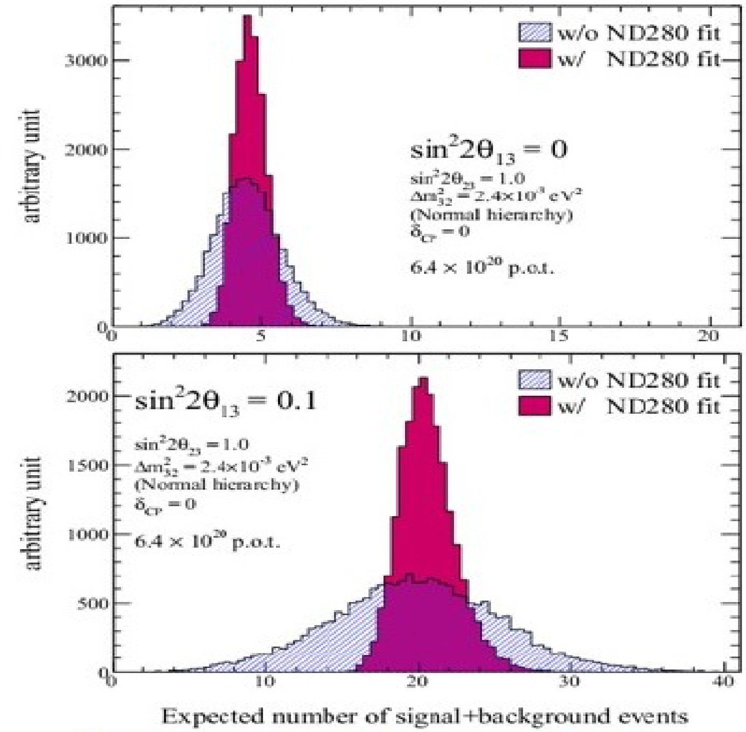
Event category	$\sin^2 2\theta_{13}=0.0$	$\sin^2 2\theta_{13}=0.1$
ν_e signal	0.38	16.42
ν_e background	3.17	2.93
ν_μ background (mainly NCπ^0)	0.89	0.89
$\nu_\mu + \nu_e$ background	0.20	0.19
Total	4.64	20.44
Total (w/ 2012 flux & cross section parameters)	5.15	21.77

Near detector fit in 2013 predicts smaller number of events compared to 2012.

Systematic uncertainties

Error source	$\sin^2 2\theta_{13}=0.0$	$\sin^2 2\theta_{13}=0.1$
Beam flux + ν int. in T2K fit	4.9 %	3.0 %
ν int. (from other exp.)	6.7 %	7.5 %
Far detector (+FSI+SI+PN)	7.3 %	3.5 %
Total	11.1 %	8.8 %
Total (2012)	13.0 %	9.9 %

The predicted number of events distribution

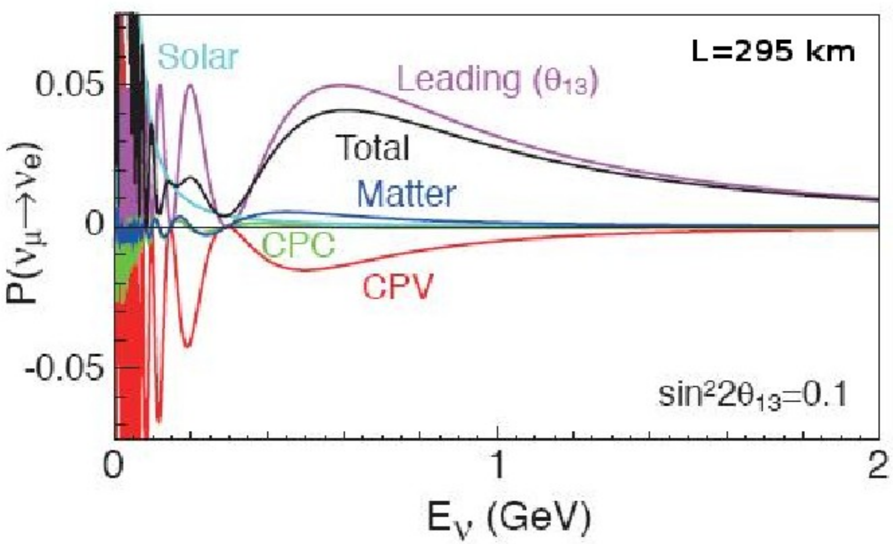


Errors are reduced from 2012 mainly due to near detector analysis improvement.

Still statistically limited (stat. Error = 18.9 %)

Appearance Formula

$$P(\nu_\mu \to \nu_e) = \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}}$$
$$+8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$+4s_{12}^2c_{13}^2(c_{12}^2c_{23}^2 + s_{12}^2s_{23}^2s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$
$$-8c_{13}^2s_{12}^2s_{23}^2\frac{aL}{4E}(1-2s_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$
$$+8c_{13}^2s_{13}^2s_{23}^2\frac{a}{\Delta m_{31}^2}(1-2s_{13}^2)\sin^2\Delta_{31}$$



Leading order :

- Sensitive theta13 & theta23

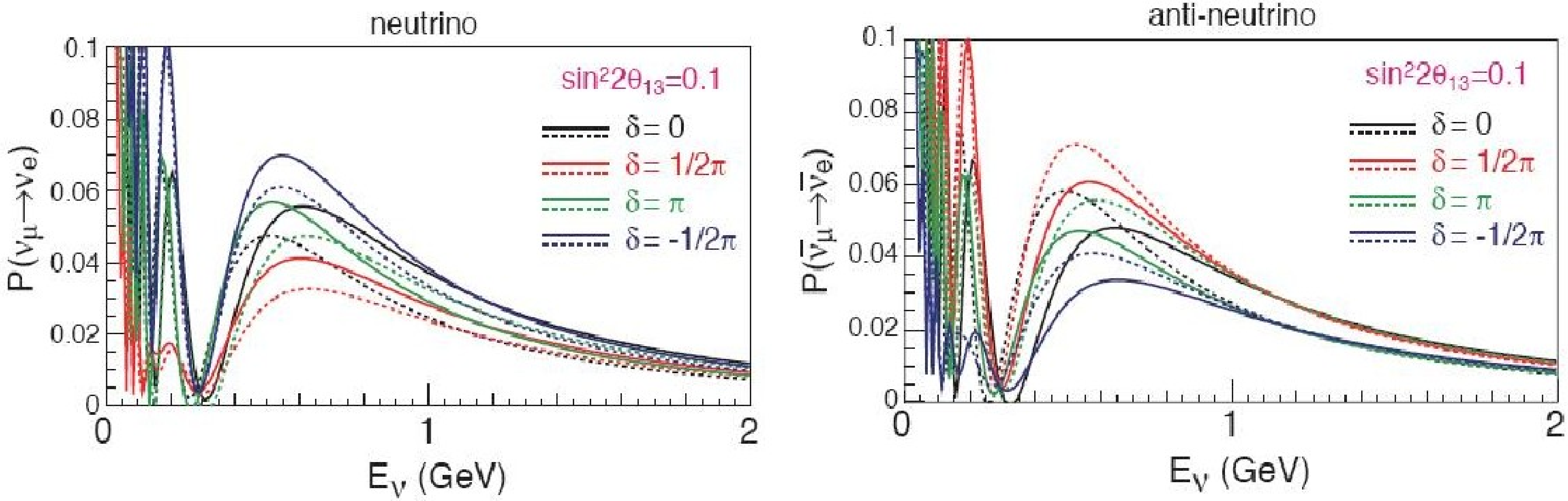
Higher orders :

- Dependence on solar parameters also
- Sensitivity to CP violation & matter effects

Matter Effects & CP violation term

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$
$$+8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$
$$\boxed{-8c_{13}^2 c_{12}c_{23} s_{12}s_{13}s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}}$$
$$+4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta) \sin^2\Delta_{21}$$
$$-8c_{13}^2 s_{12}^2 s_{23}^2 \frac{aL}{4E}(1-2s_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$
$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2)\sin^2\Delta_{31}$$

$$\boxed{P(\bar\nu_\mu \to \bar\nu_e) \qquad a \to -a \qquad \delta \to -\delta}$$



Observation of ν_e appearance

- $6.6 \,.\, 10^{20}$
- Off-Axis

- **Fix all parameters except θ_{13}, do not take into account error on osc. param**
  - θ_{23} set to $\pi/4$
  - **δ_{cp} set to 0**
  - $|\Delta m^2_{32}| = 2.4.10^{-3}$ eV², and then fit for normal and inverted hierarchy
- **<u>2 studies :</u>** (Angle, Momentum) of the electron & one in E_υ^{rec}

<u>For the (p, θ) study :</u>

We define the likelihood as following:

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

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

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

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

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

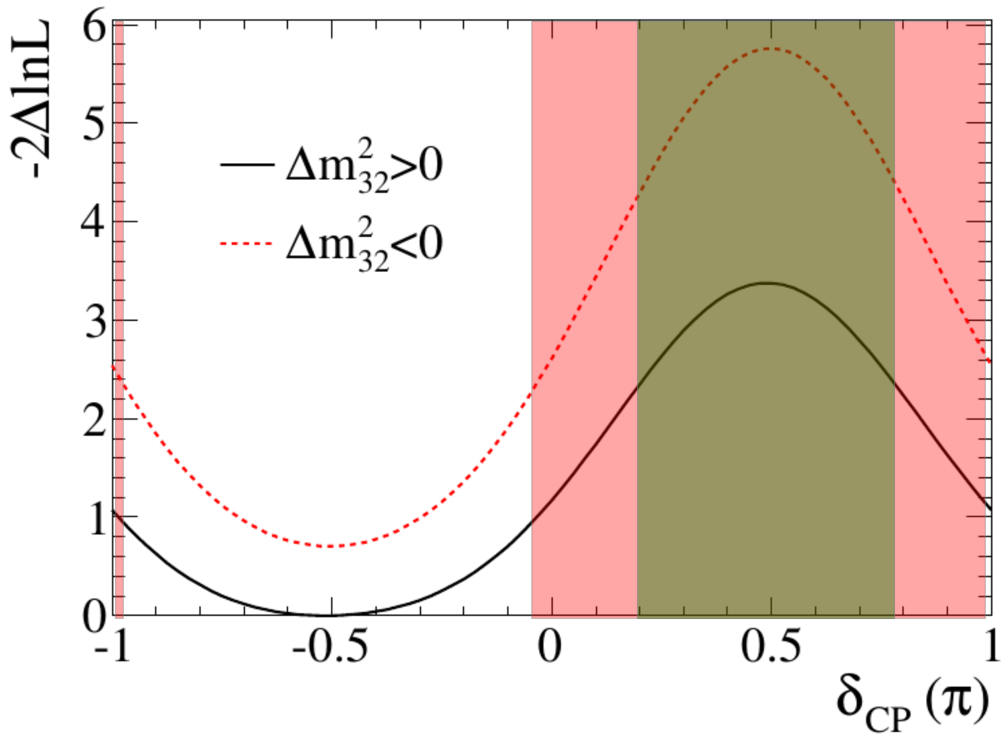
L_{shape} is the product of the probabilities that each event has (p_i, θ_i).
ϕ: Predicted p-θ distribution (PDF) .

- Rate and shape analysis => $\sin^2(2\theta_{13})$ for normal and inverted hierarchies

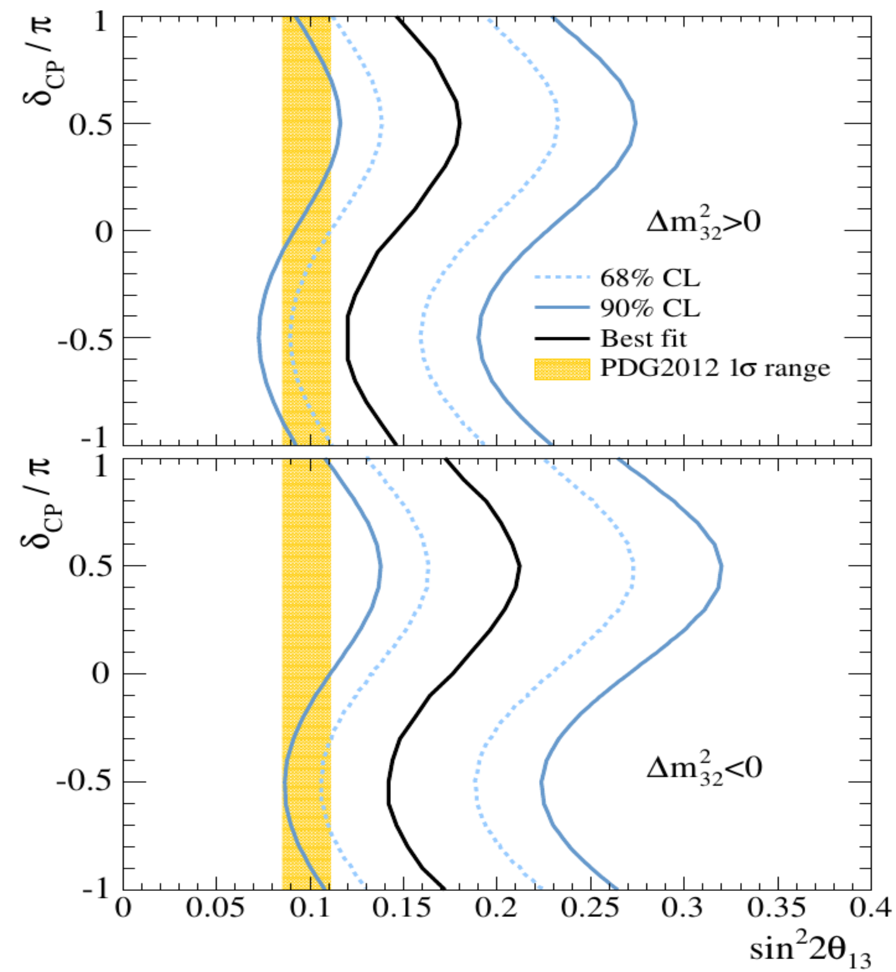
- We deduce significance comparing Likelihood value between θ_{13} best fit value & $\theta_{13}=0$

The δ_{cp} Fit

δ_{cp} fit only (marginalized over $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$ and Δm^2_{32})



δ_{cp} / $\sin^2(2\theta_{13})$ common fit (marginalized over $\sin^2(\theta_{23})$ and Δm^2_{32})



Exclusion at 90 % CL :

$0.19 < \delta_{cp}/\pi < 0.80$ for Normal Hierarchy

$-0.04 < \delta_{cp}/\pi < 1$

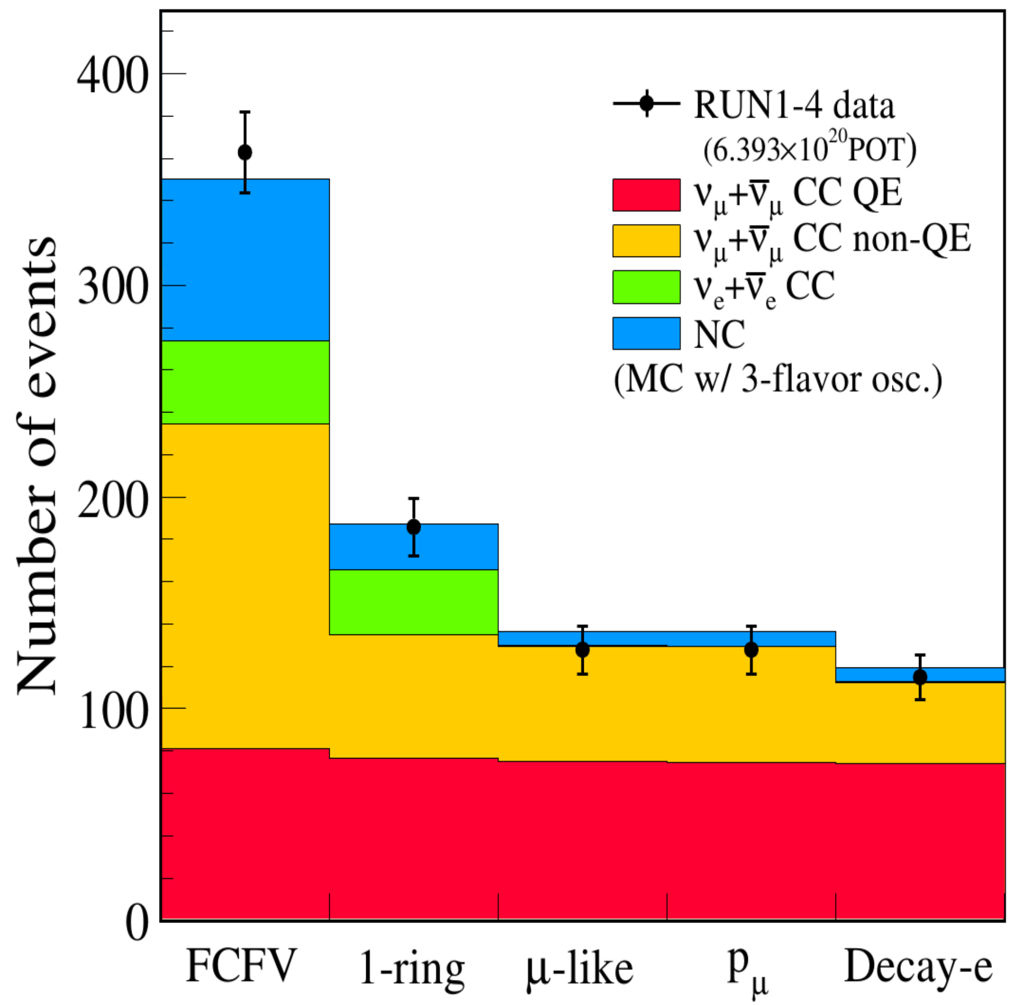
& $-1 < \delta_{cp}/\pi < -0.97$ for Inverted Hierarchy

→ **From T2K results, a maximal δ_{cp} violation is favoured**

SK ν_μ selection

SK ν_μ selection

RUN1+2+3+4 6.393×10^{20}POT	Data	MC Expectations w/ $\sin^2 2\theta_{13}=0.1$				
		MC total	ν_μ+antiv$_\mu$ CCQE	ν_μ+antiv$_\mu$ CC non-QE	ν_e+antiv$_e$ CC	NC
Interactions in FV	532	630.97	104.54	208.65	40.44	277.34
FCFV	363	356.53	79.92	158.75	39.04	78.83
Single-ring	186	188.96	75.3	60.92	30.37	22.37
μ-like PID	128	138.14	73.85	56.98	0.33	6.99
p_μ>200MeV/c	128	137.87	73.68	56.95	0.33	6.91
$N_{dcy\text{-}e}$<=1	115	120.13	72.84	40.29	0.32	6.67
Efficiency [%]	-	19.0	69.7	19.3	0.8	2.4

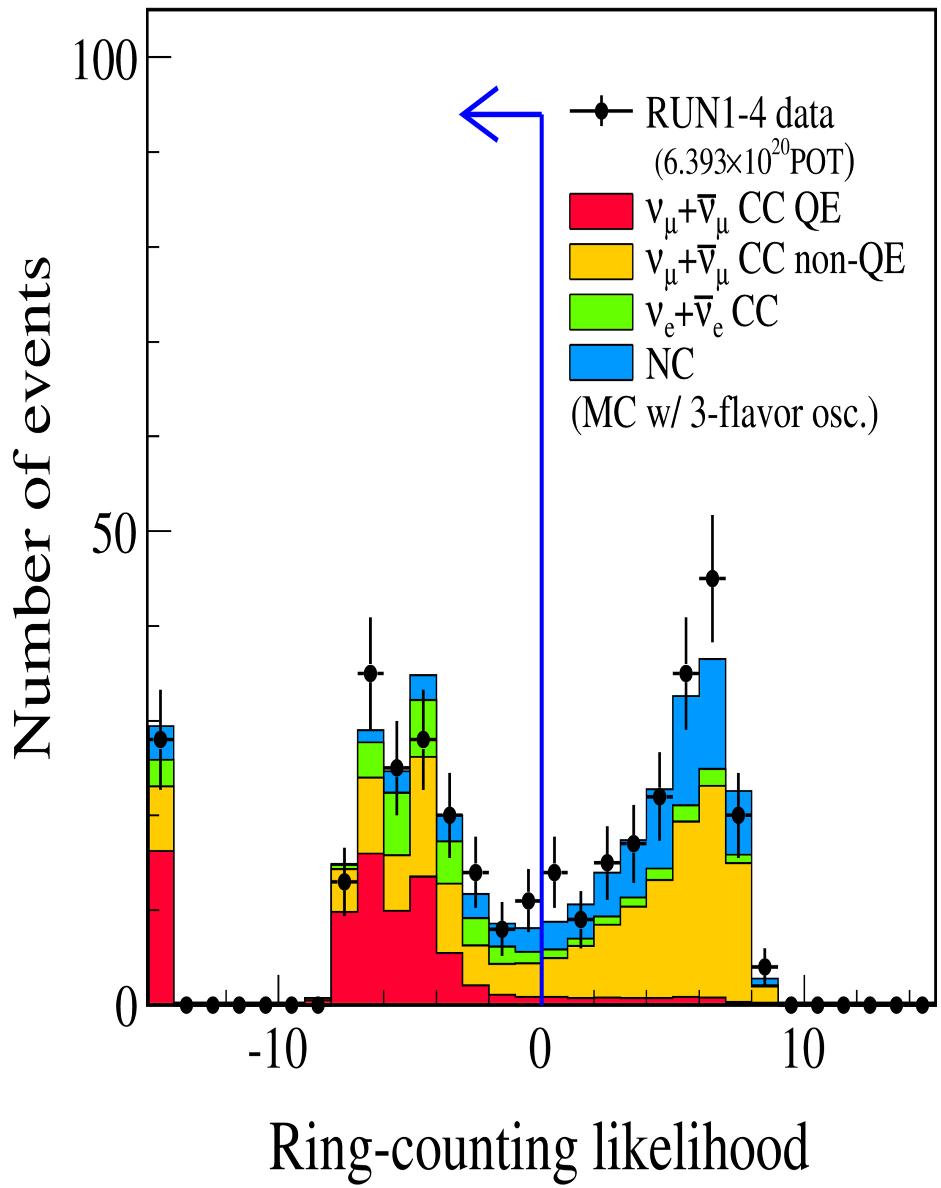


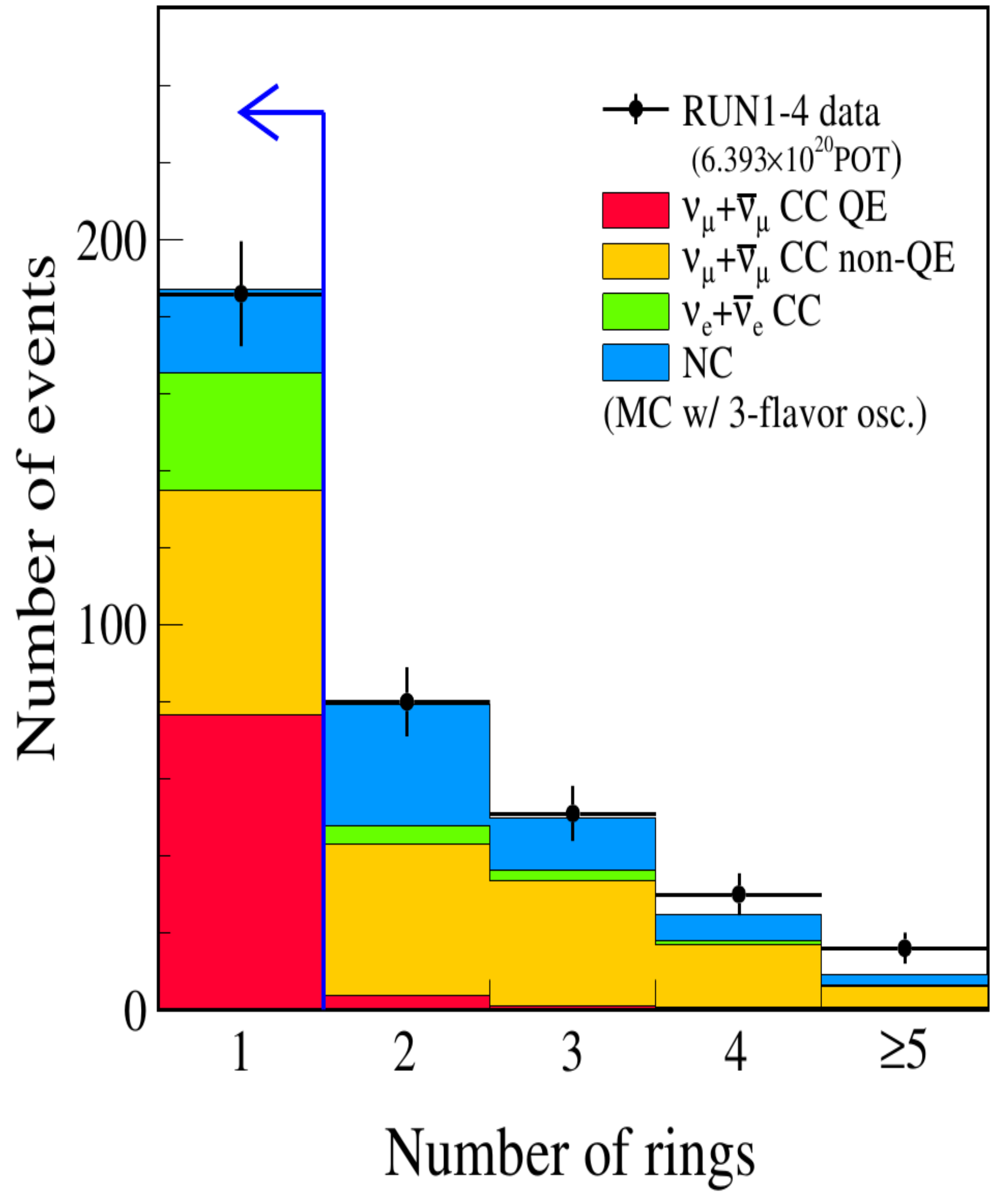
Remove intrinsic & oscillated electron Neutrino

Remove NC events (Tau Neutrinos)

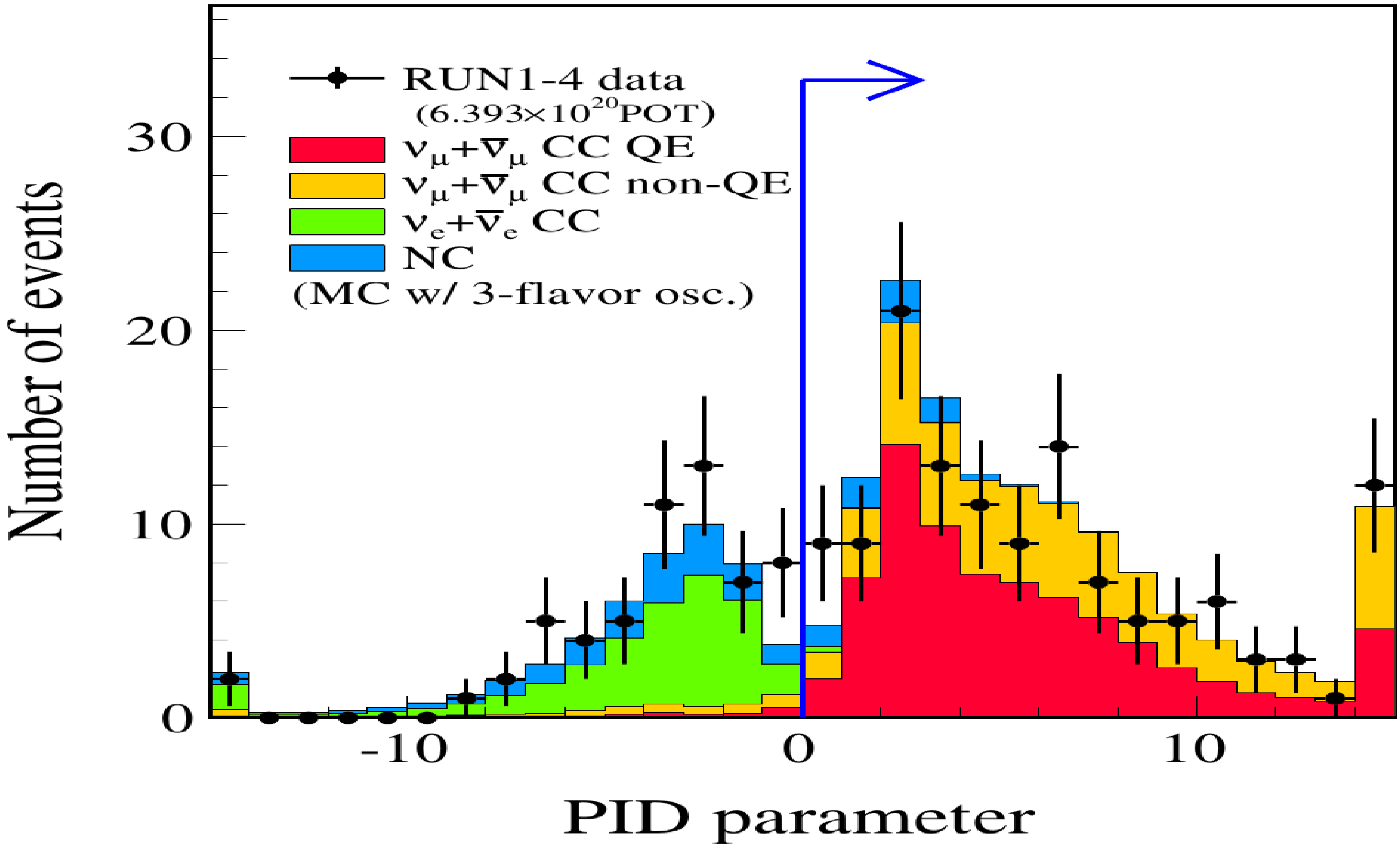
1 Ring Muon like

Ring Counting



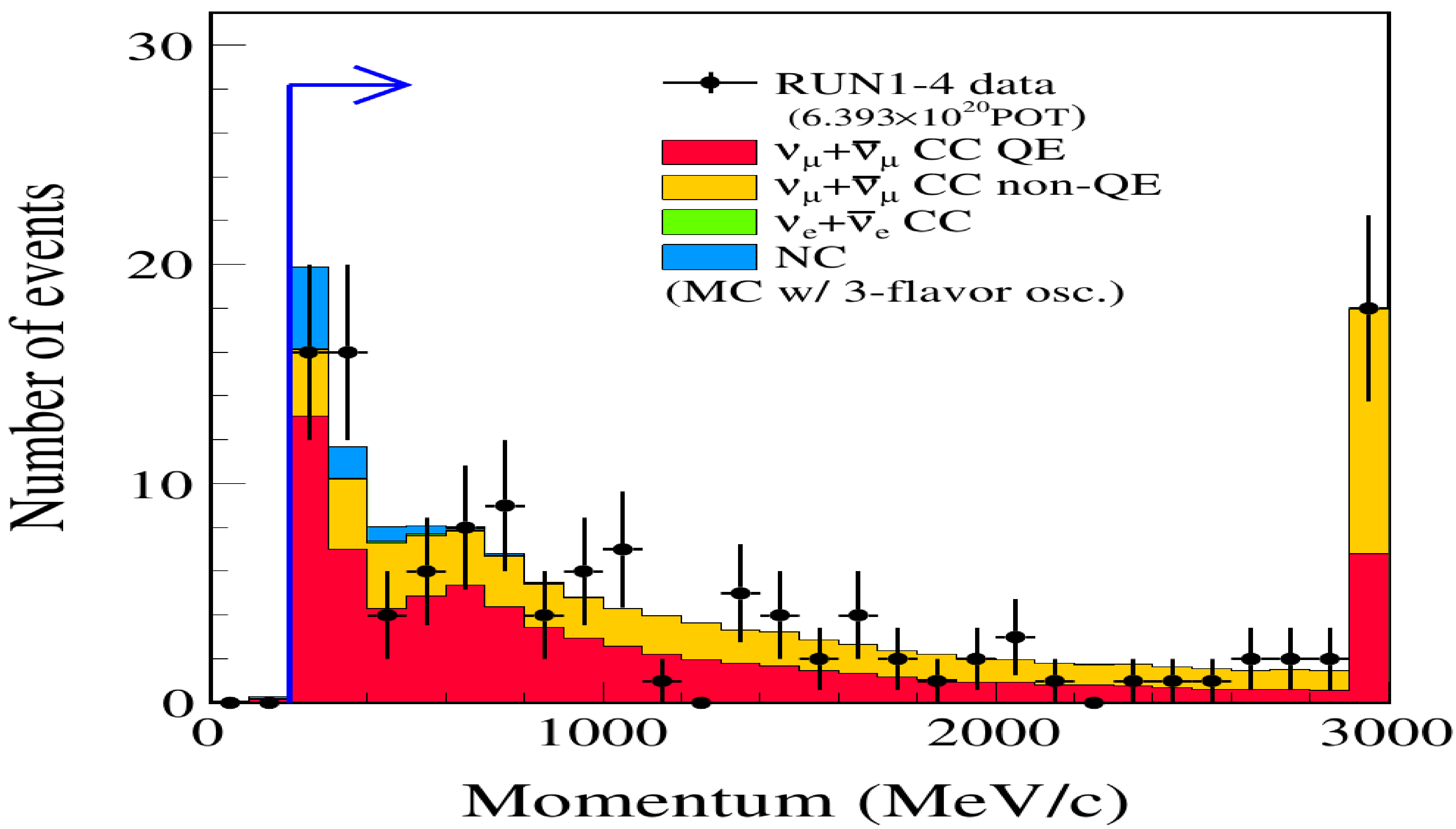


μ Like



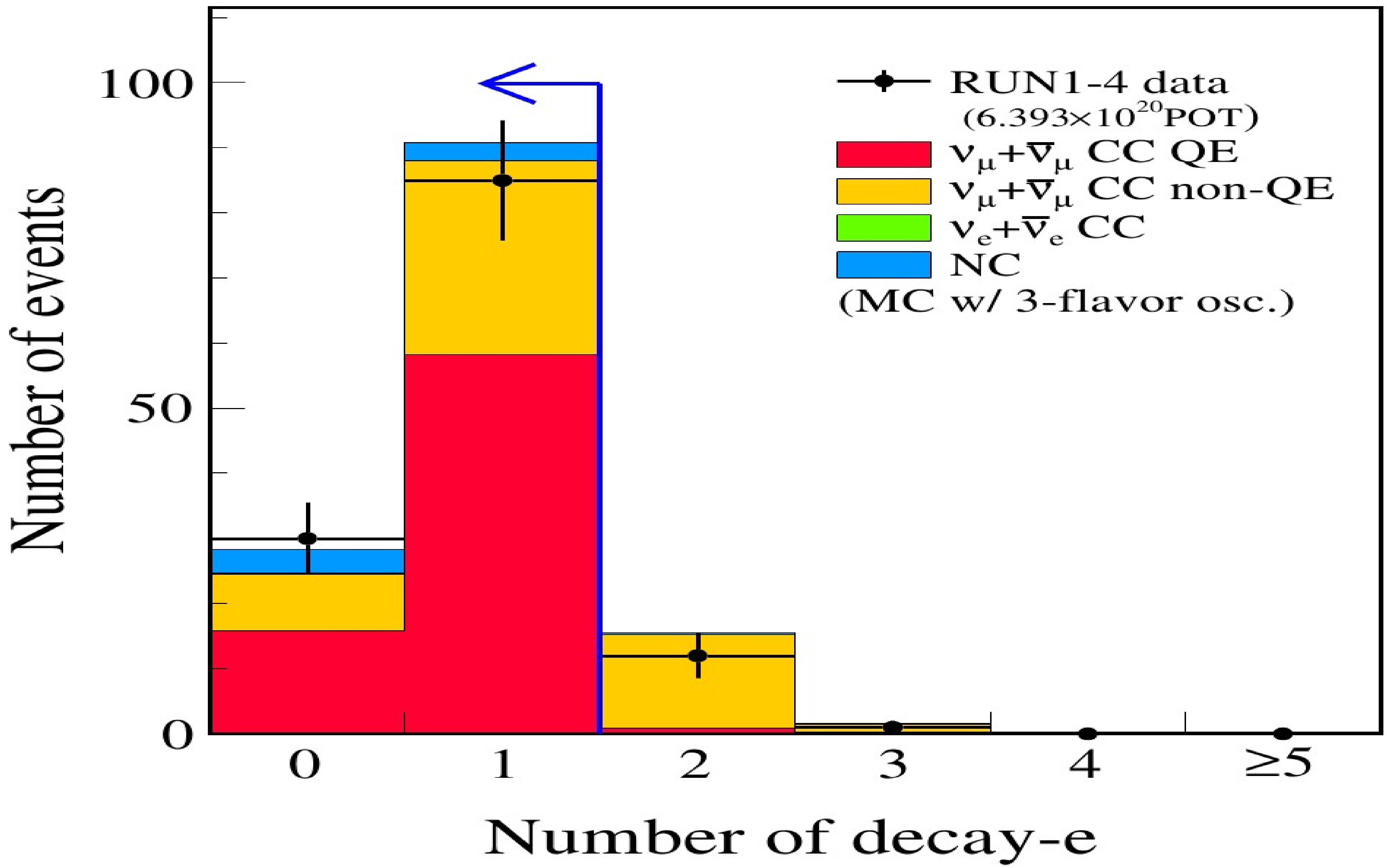
RUN1-4 data
(6.393×10^20 POT)
νμ+ν̄μ CC QE
νμ+ν̄μ CC non-QE
νe+ν̄e CC
NC
(MC w/ 3-flavor osc.)
Number of events
PID parameter
30
20
10
0
-10
0
10

μ momentum



RUN1-4 data
(6.393×10^20 POT)
νμ+ν̄μ CC QE
νμ+ν̄μ CC non-QE
νe+ν̄e CC
NC
(MC w/ 3-flavor osc.)
Number of events
Momentum (MeV/c)
0
10
20
30
0
1000
2000
3000

Decay electron



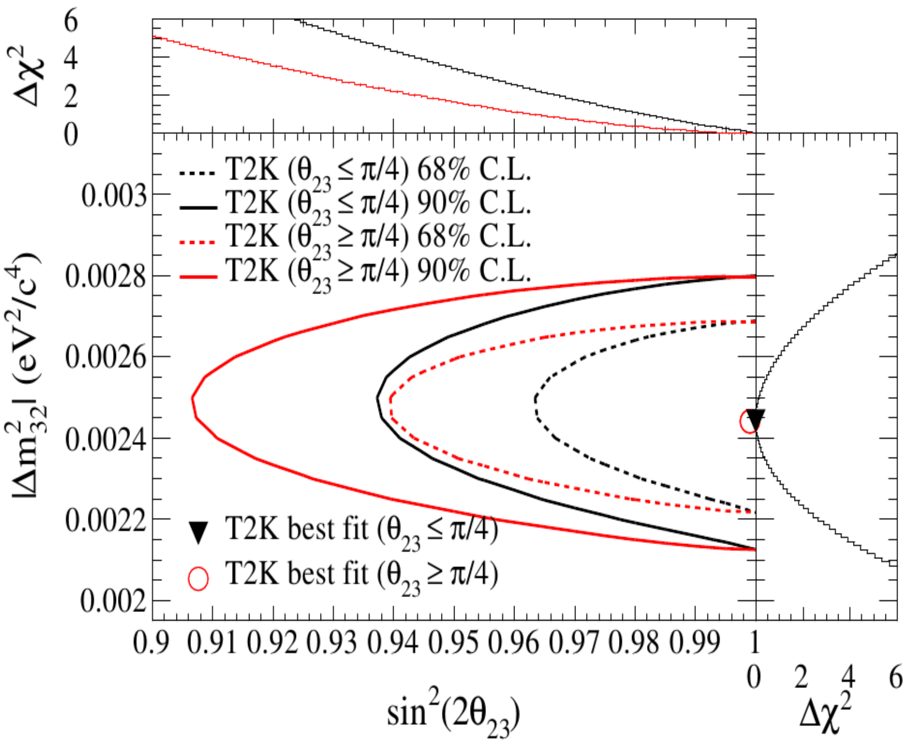
The ν_μ disappearance

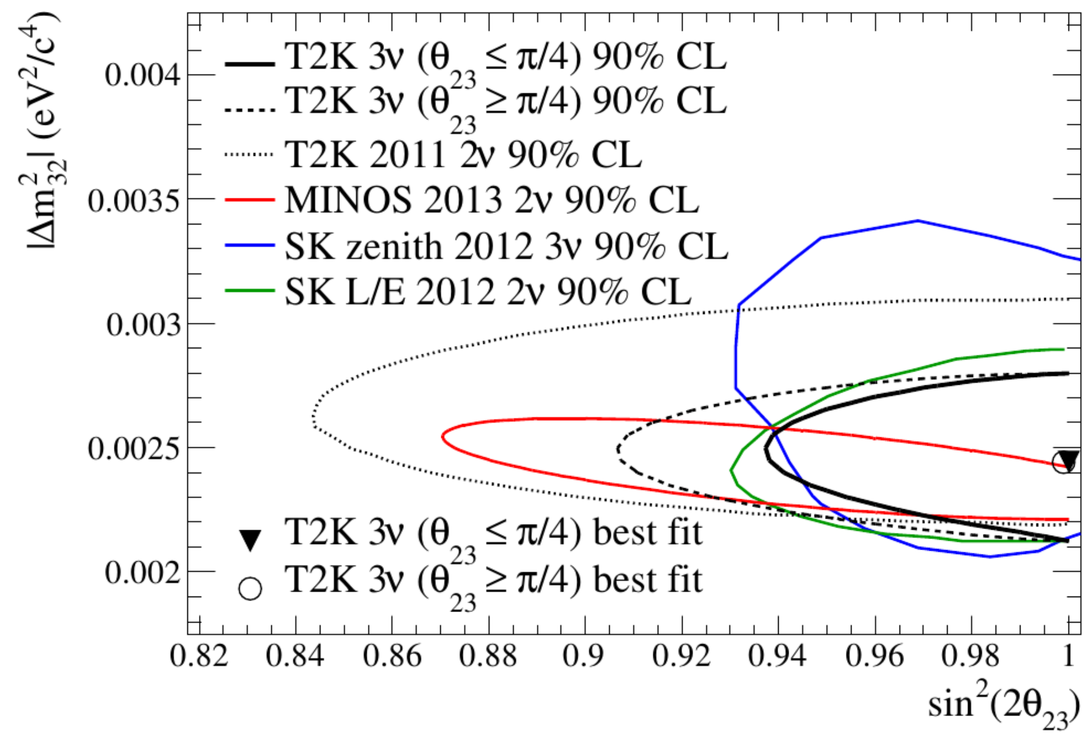
- Presented at last GDR => no update on the analysis method but…

Accepted for PRL publication

- **Fix all parameters to PDG values except θ_{23} and $|\Delta m^2_{32}|$:**

$\sin^2(2\theta_{13})=0.098$ $\Delta m^2_{21}= 7.5*10^{-5}$ eV²/c⁴ $\sin^2(2\theta_{12})=0.857$ $\delta_{cp}=0$



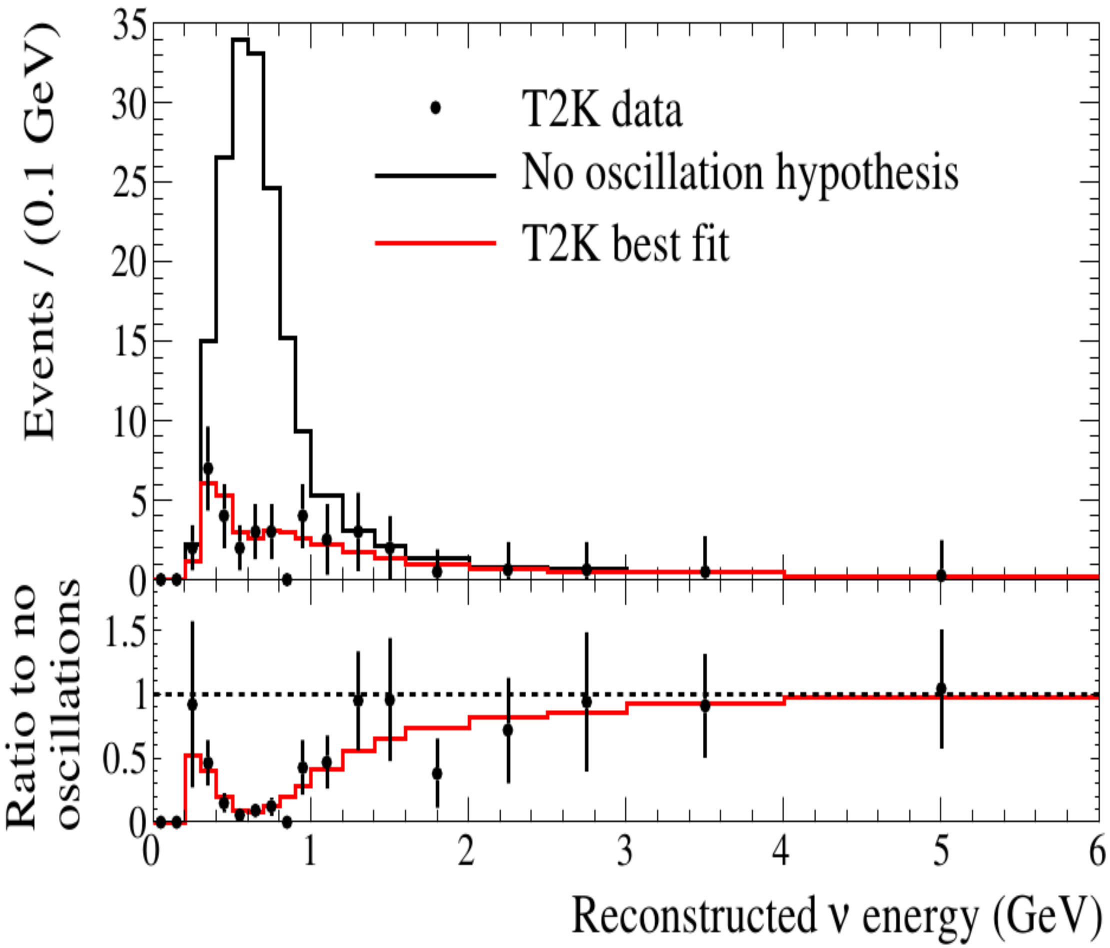


Best Fit Value for both Octants $\sin^2(2\theta_{23})=1.000$

→ **Favours Maximal Mixing**
No Octant sensitivity for now

The ν_μ disappearance

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



Source of uncertainty (no. of parameters)	$\delta n^{exp}_{SK} / n^{exp}_{SK}$
ND280-independent cross section (11)	6.3%
Flux & ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%

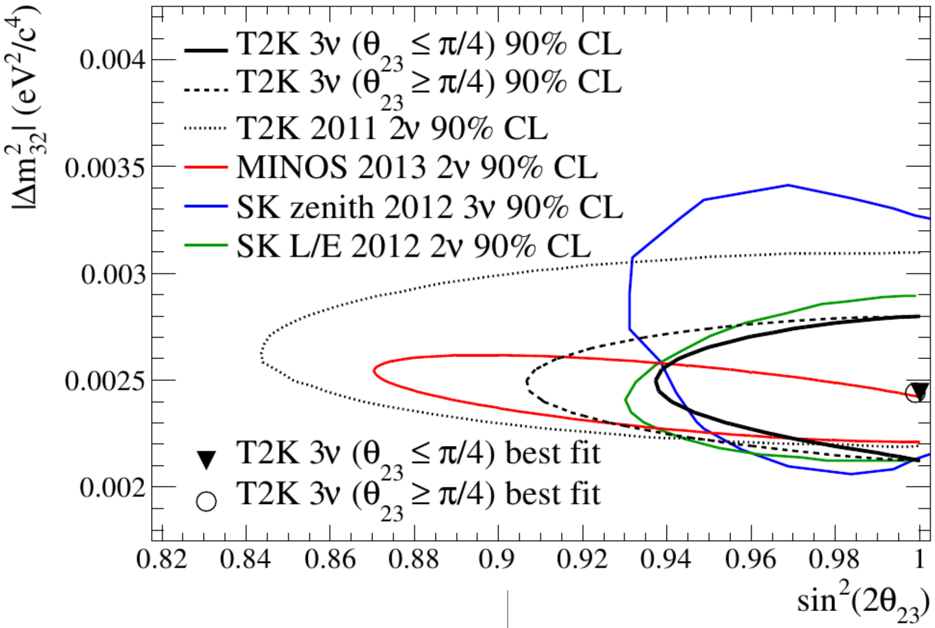
58 events : stat uncertainty on norm is 7.6 %

=> syst dominated in this channel

Benjamin Quilain

The ν_μ disappearance

- Presented at last GDR : **Accepted for PRL publication**



Fix all parameters to PDG values except θ_{23} and $|\Delta m^2_{32}|$:

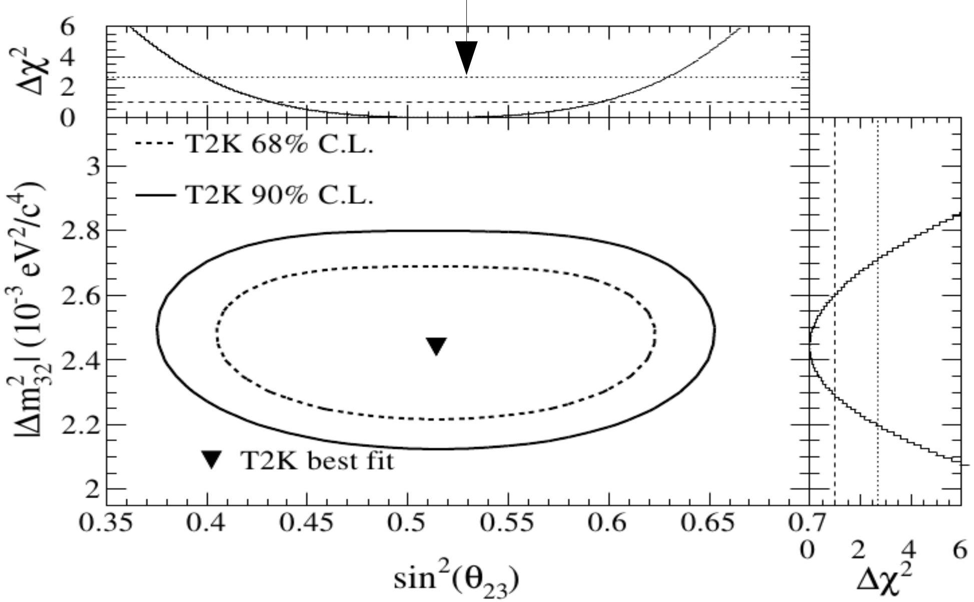
$\sin^2(2\theta_{13})=0.098$ $\Delta m^2_{21}= 7.5*10^{-5}\ eV^2/c^4$

$\sin^2(2\theta_{12})=0.857$ $\delta_{cp}=0$

Best Fit Value for both Octants $\sin^2(2\theta_{23})=1.000$

→ **Favoured Maximal Mixing**
Small Octant sensitivity for now

Now



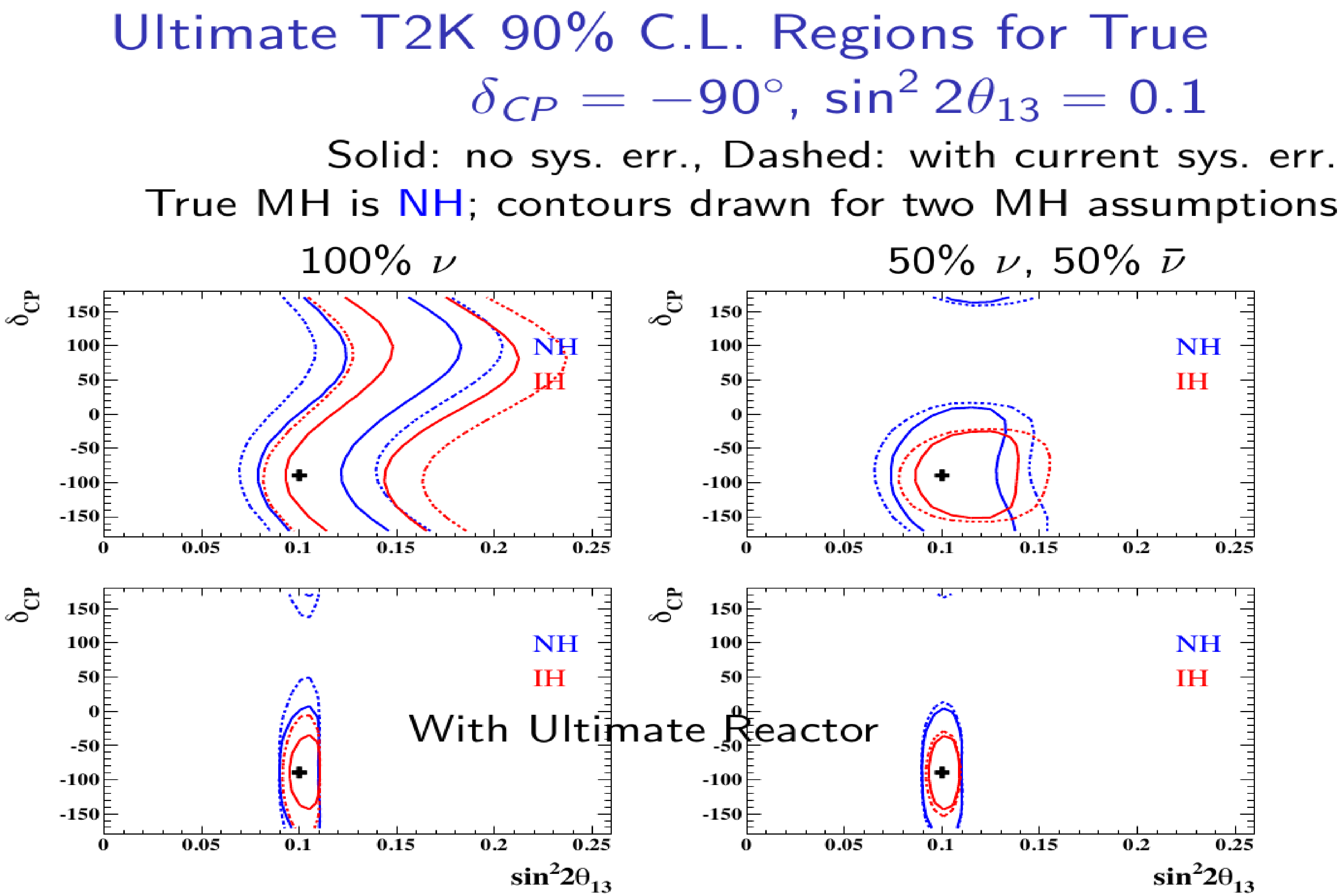
Best Fit Point :
$\sin^2(\theta_{23})=0.514 \pm 0.082$
$\Delta m^2_{32}= 2.44^{+0.17}*10^{-3}\ eV^2/c^4$

- **Compatible with maximal mixing angle**
- **Higher octant is barely favoured**

→ Will be updated with current T2K statistics

Future

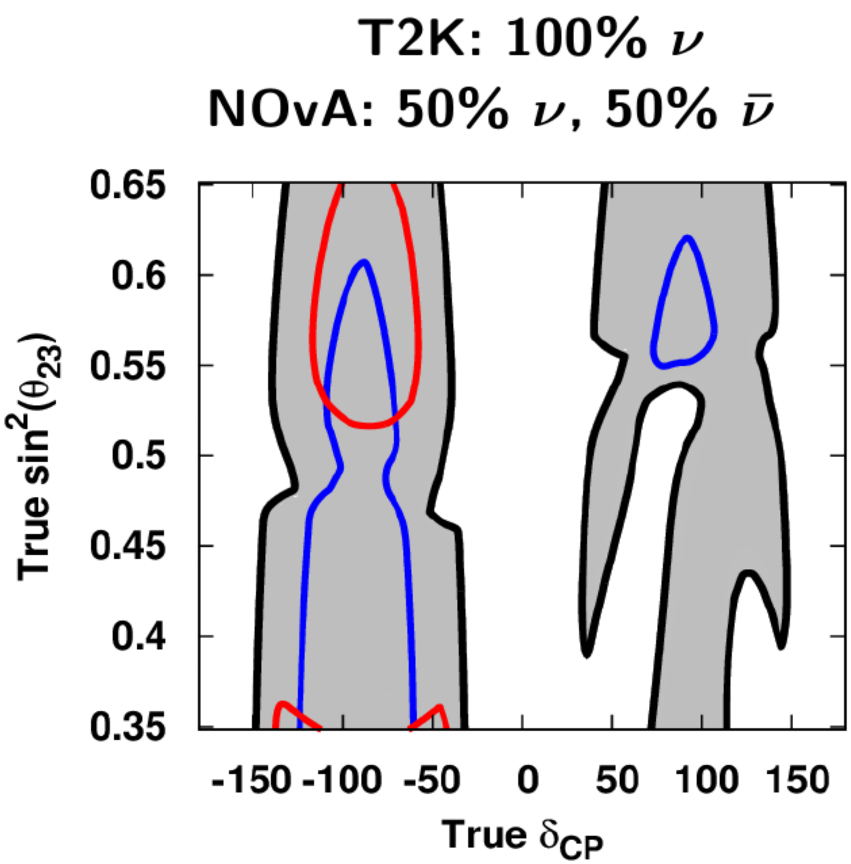
Mass hierarchy dependence

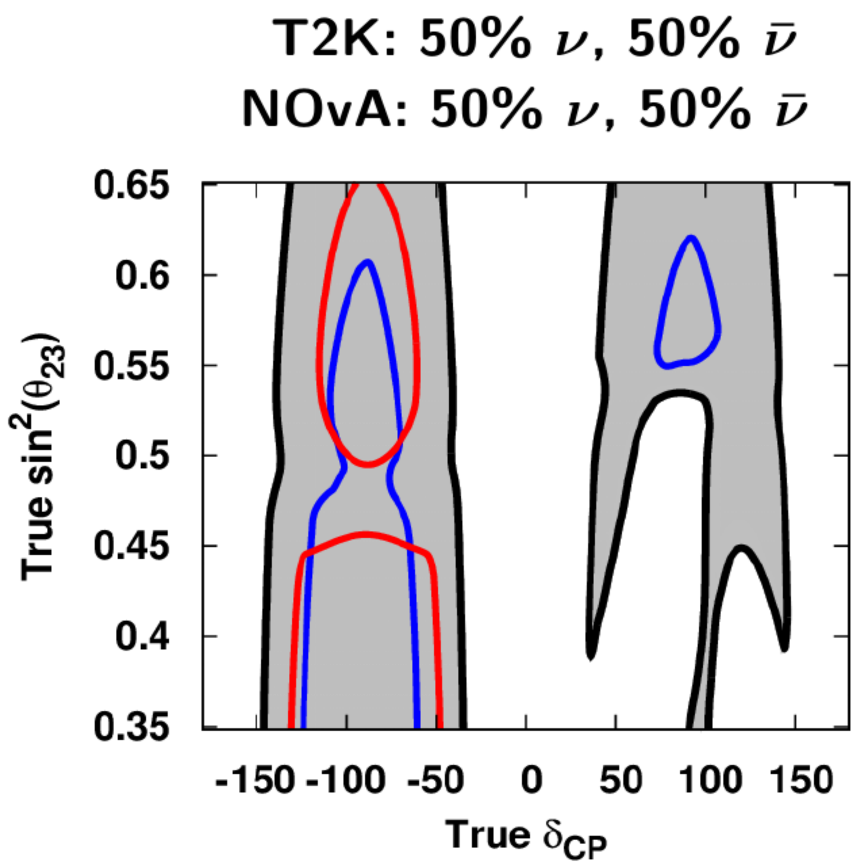


- Low sensitivity to mass hierarchy
- With reactor constraints, dependence on Mass hierarchy exist but is not huge : but without mass hierarchy not even 2 Sigma on non 0 CP violation

Future sensitivity & Nova common fit

- Regions where $\sin\delta \neq 0$ can be determined to 90% CL for normal hierarchy
- Gray regions: T2K+NOvA combined fit
- Curves: T2K alone, NOvA alone



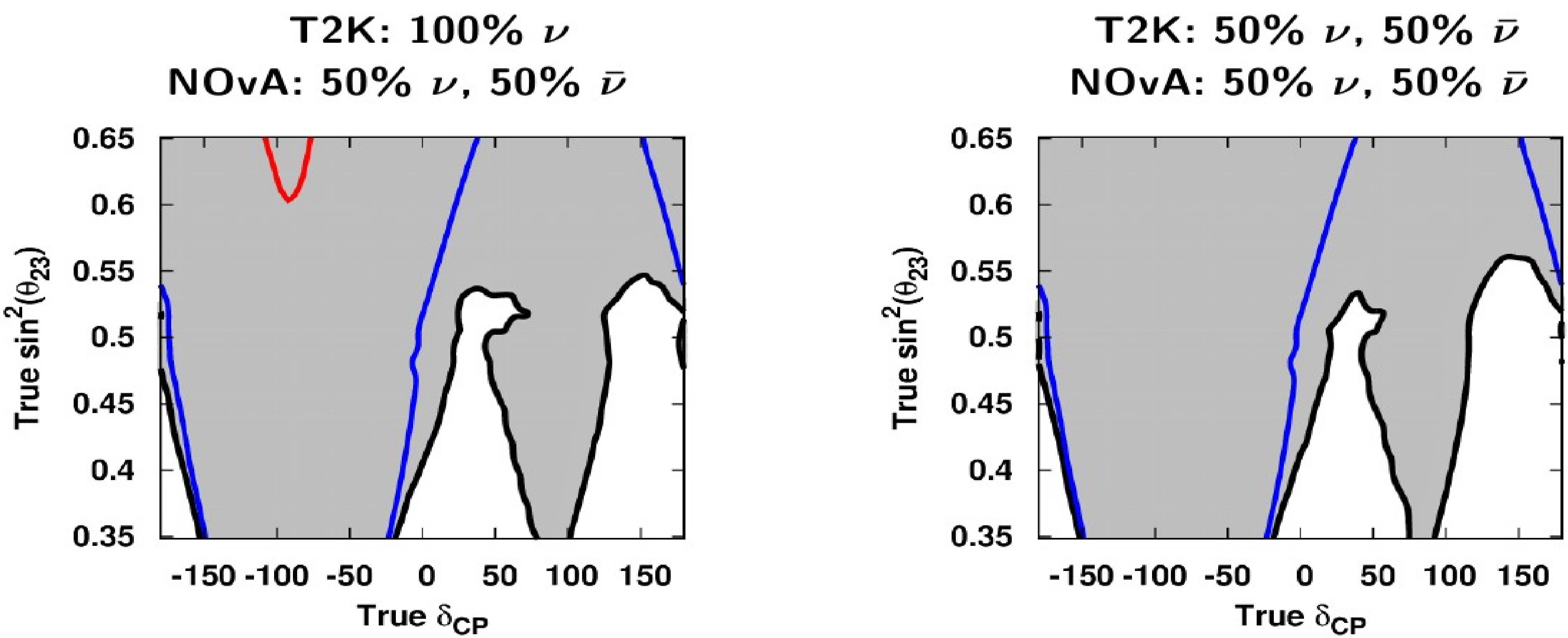


Beam time in Neutrino/Anti : Now studied by a dedicated task force

Mass Hierarchy sensitivity & Nova common fit

90% CL Mass Hierarchy Resolution

- Regions where the **mass hierarchy** can be determined to 90% CL for normal hierarchy
- Gray regions: T2K+NOvA combined fit
- Curves: T2K alone, NOvA alone

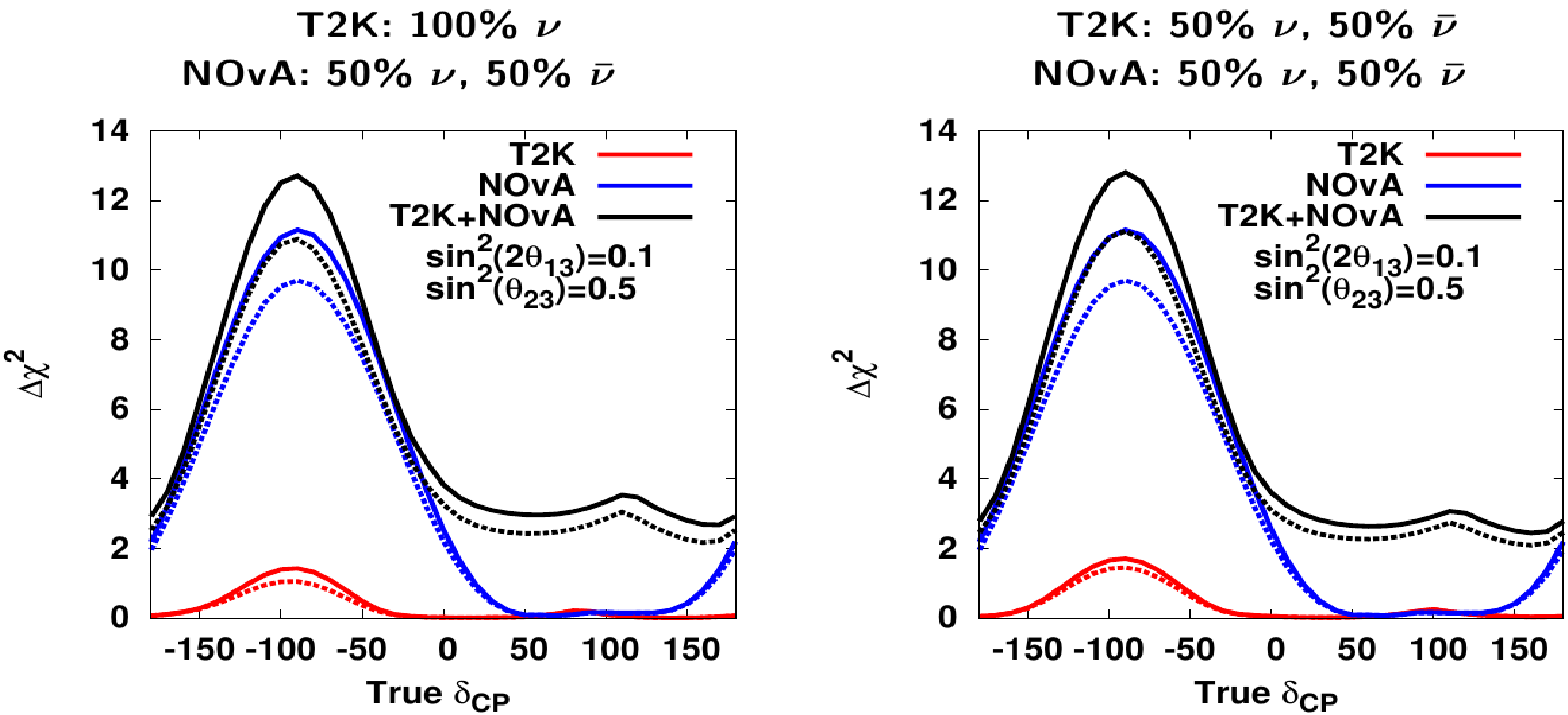


T2K alone could not solve the mass hierarchy problem

CP dependence on Mass Hierarchy sensitivity

90% CL Mass Hierarchy Resolution

- $\Delta\chi^2$ vs δ_{CP} for mass hierarchy determination
- $\sin^2(\theta_{23}) = 0.5$
- Curves: T2K alone, NOvA alone, T2K+NOvA combined fit



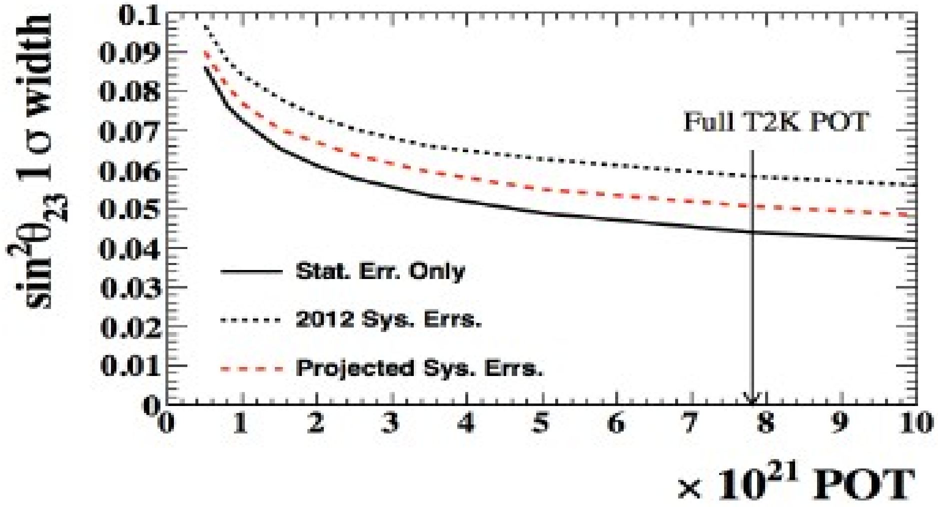
Disappearance Formula

In limits : |Δm^2_{32}| >> |Δm^2_{21}| :

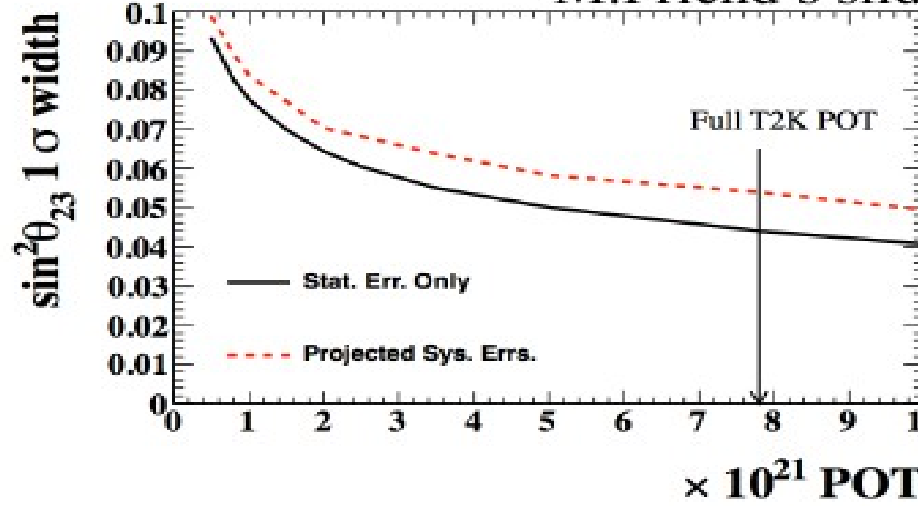
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - [\cos^4(\theta_{13}) \sin^2(2\theta_{23}) + \sin^2(\theta_{23}) \times \sin^2(2\theta_{13})] \sin^2(\Delta m^2_{32} L/4E_\nu),$$

Θ_{23} Sensitivity prediction

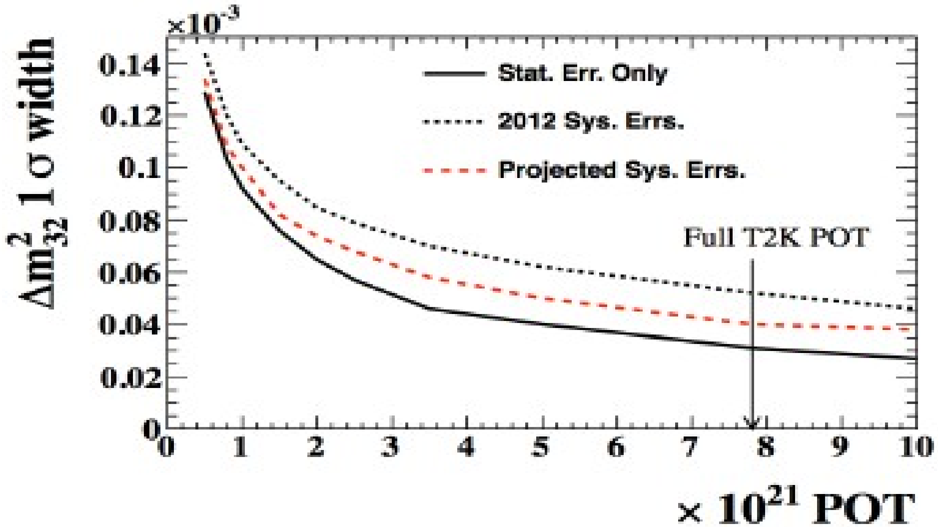
M.Friend's slide



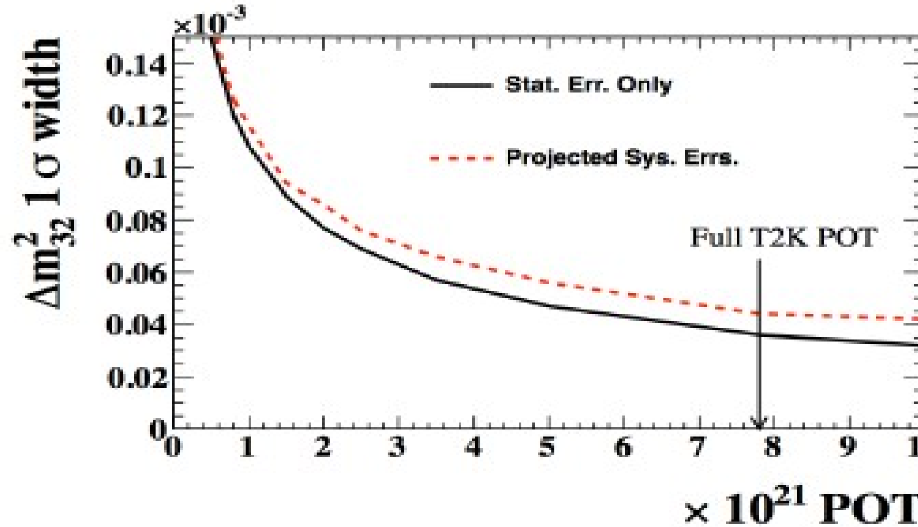
(a) 100% ν-running.



(b) 50% ν, 50% $\bar{\nu}$-running.

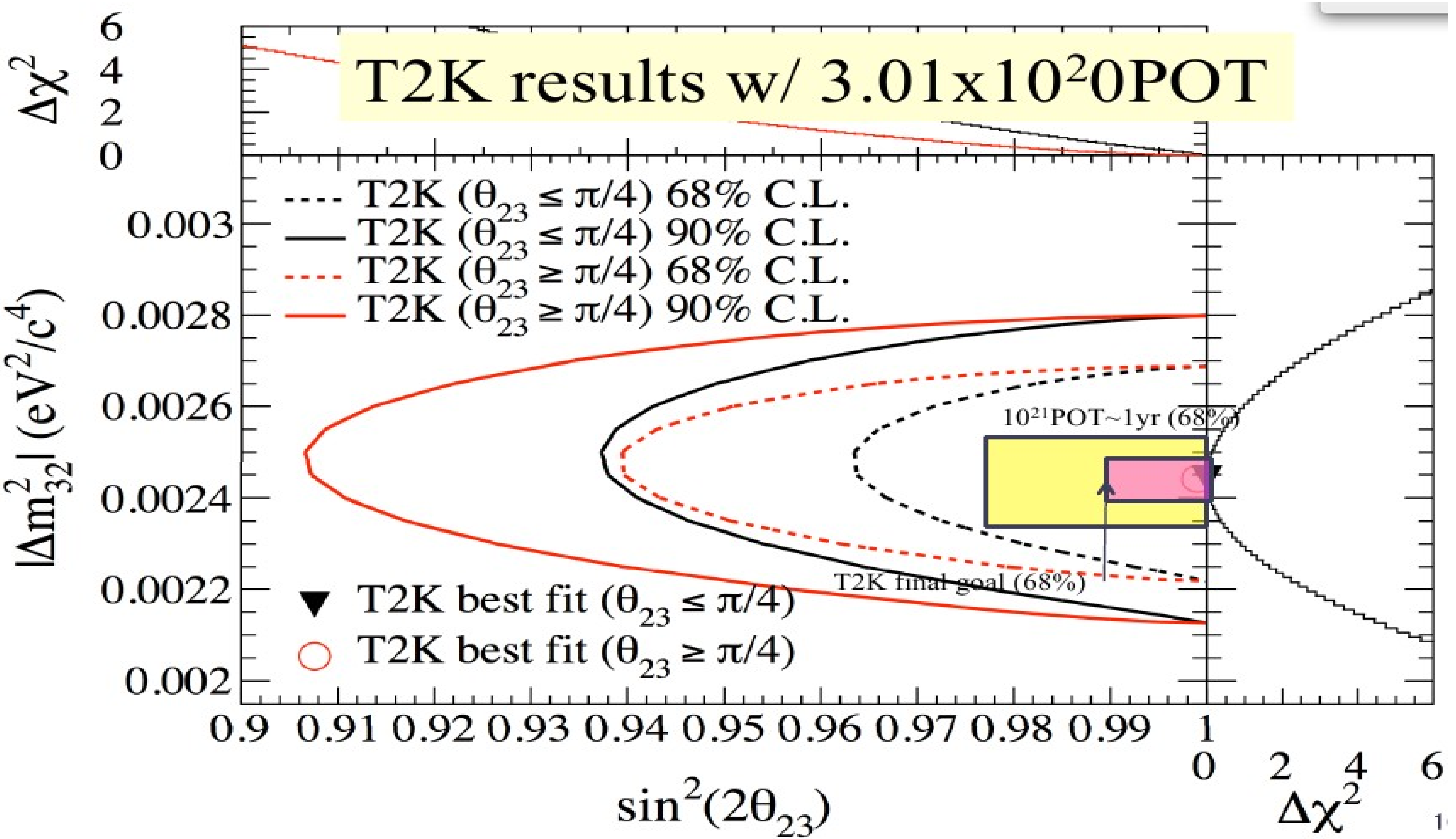


(c) 100% ν-running.



(d) 50% ν, 50% $\bar{\nu}$-running.

Maximal mixing sensitivity

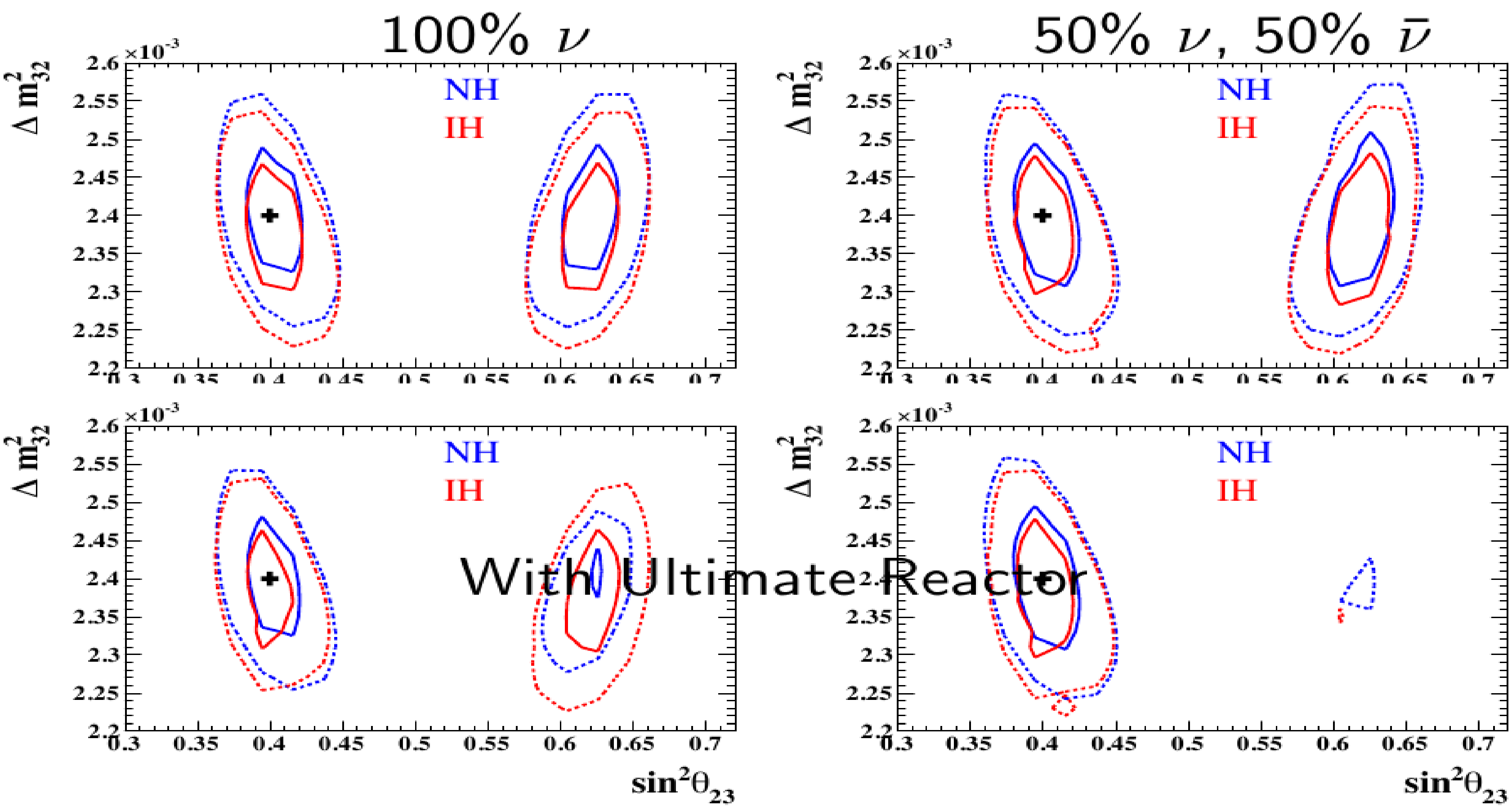


Octant sensitivity

Ultimate T2K 90% C.L. Regions for True $\sin^2\theta_{23} = 0.4$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions



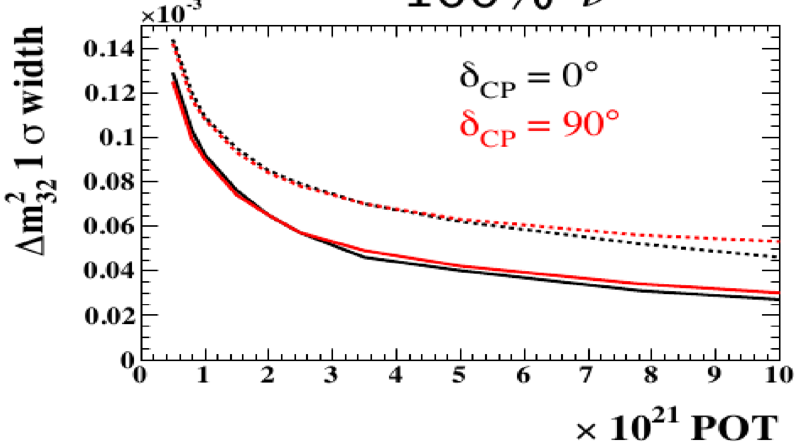
$\sin^2\theta_{23}$ octant determination!

$|\Delta m^2_{32}|$ sensitivity

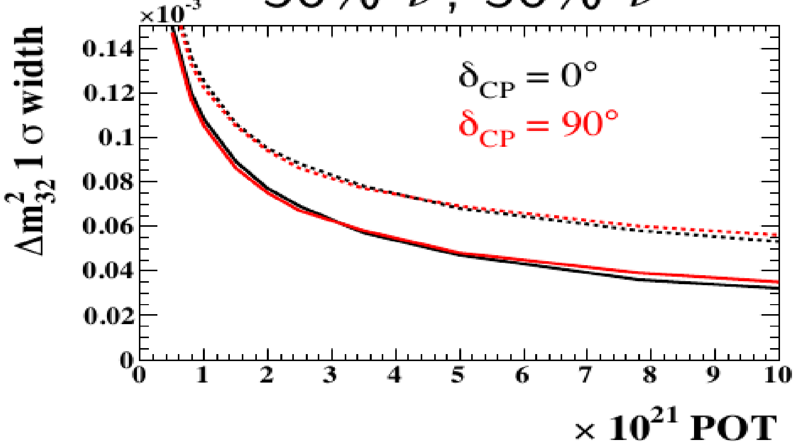
T2K Δm^2_{32} 1σ Precision vs. POT

Solid: no sys. err., Dashed: with current sys. err.

100% ν



50% ν, 50% $\bar{\nu}$



Assuming true:
$\sin^2 2\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2
θ_{13} constrained by the ultimate reactor sensitivity