New Oscillation results from T2K

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(On Behalf of the T2K Collaboration)

Lake Louise 2017 Winter Institute
23/02/2017

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Tokai to Kamioka

$\nu_\mu \nu_\tau \nu_e$
$\nu_\tau \nu_e \nu_\tau \nu_\mu$
$\nu_\tau \nu_\tau \nu_\tau$

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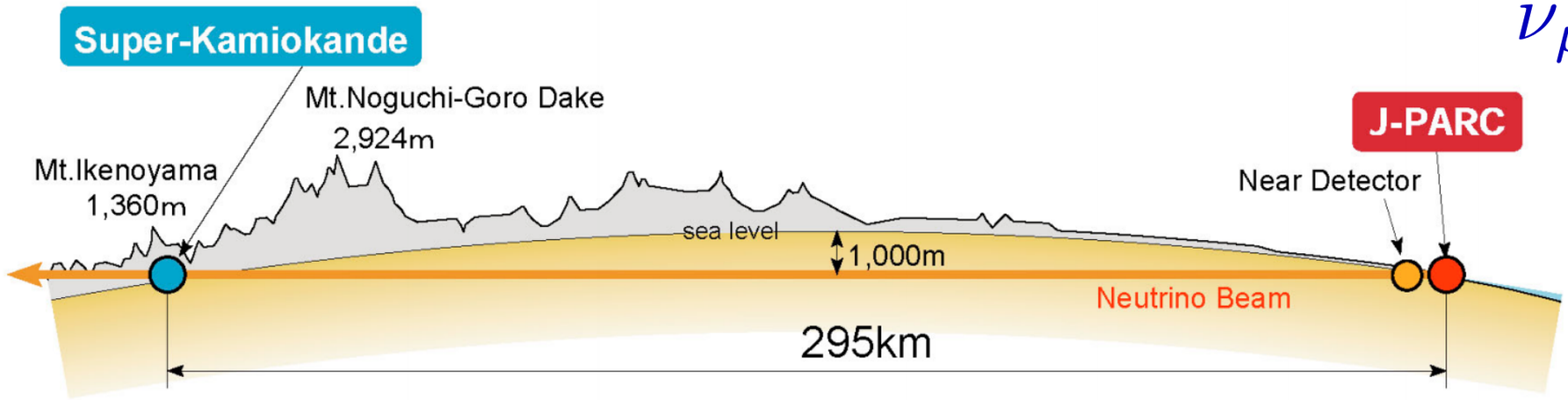
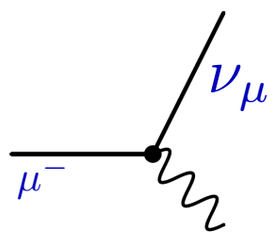
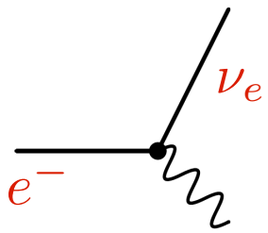
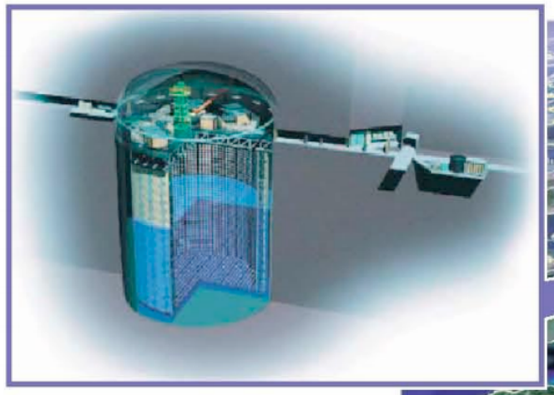








Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

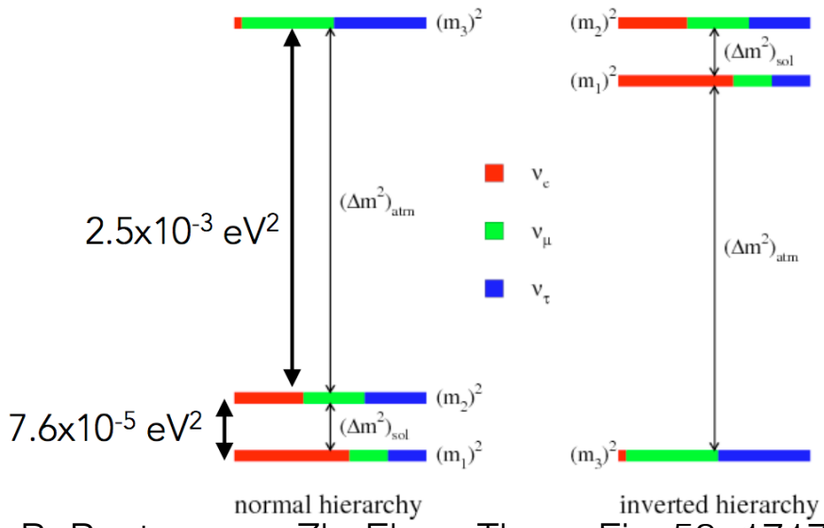
ν-Oscillation

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

$$s_{ij} = \sin(\theta_{ij})$$
$$c_{ij} = \cos(\theta_{ij})$$

U_{PMNS}:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Three rotation angles: θ_{12}, θ_{13}, θ_{23}
  - θ_{12}: Solar and reactor expts.
  - θ_{13}: Long-baseline and reactor expts.
- Complex CPV phase δ_{cp}

* B. Pontecorvo, Zh. Eksp. Theor. Fiz. 53, 1717 (1967) [Sov. Phys. JETP 26, 984 (1968)]

* Z. Maki, M. Nakagawa, S Sakata, Prog. Theor. Phys. 28, 1962

***Dirac ν oscillation**

T2K Sensitivity

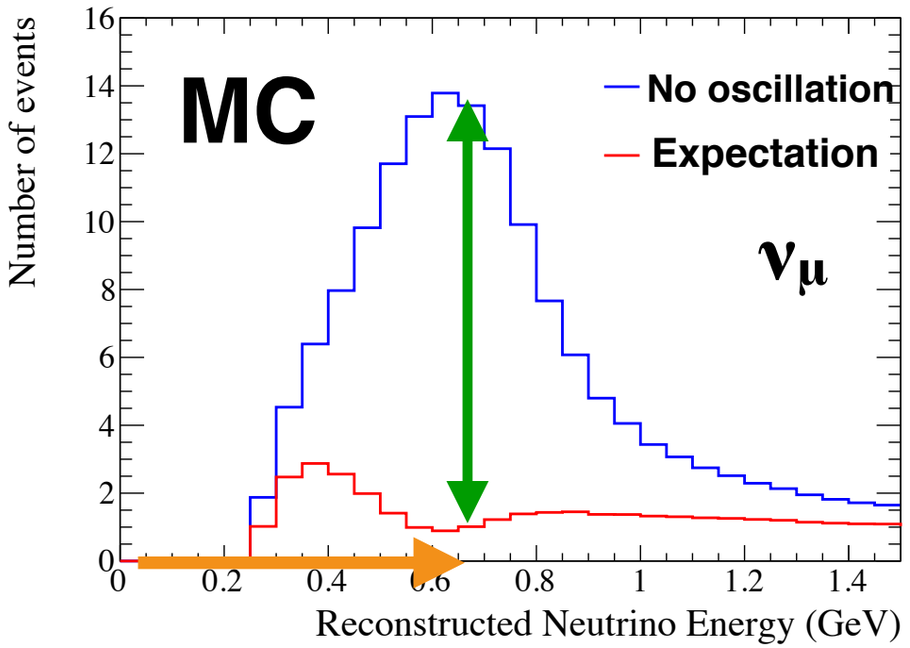
3 Flavour PMNS w/ Matter effects

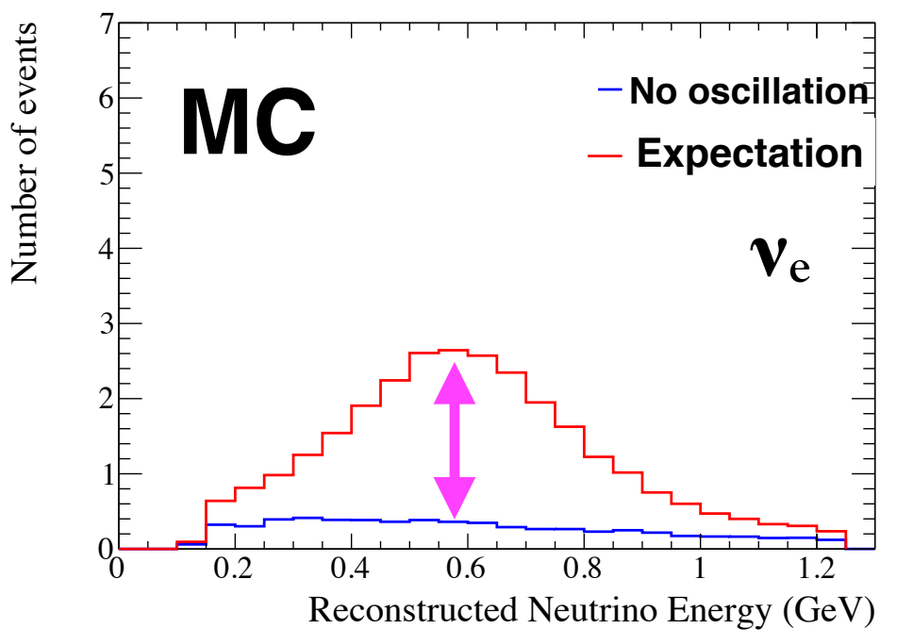
<u>ν_μ Disappearance data sets ($\nu + \bar{\nu}$)</u>

- $\sin^2(2\theta_{23})$ depth of osc dip
- Δm^2_{32} position of osc dip in energy
- Insensitive to PMNS CPV

<u>ν_e Appearance data sets</u>

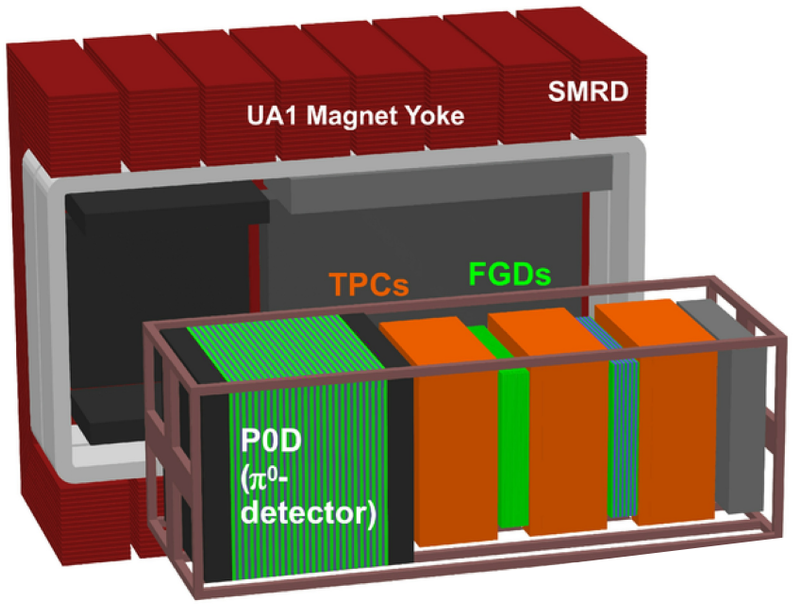
- Appearance prob. proportional to $\sin^2(\theta_{23})$, $\sin^2(2\theta_{13})$ for $\nu + \bar{\nu}$
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) \propto \sin(\delta_{cp})$ up to *~20%*
- Normal hierarchy: enhanced $P(\nu_\mu \rightarrow \nu_e)$ *~10%*
- Inverted hierarchy: enhanced $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ *~10%*



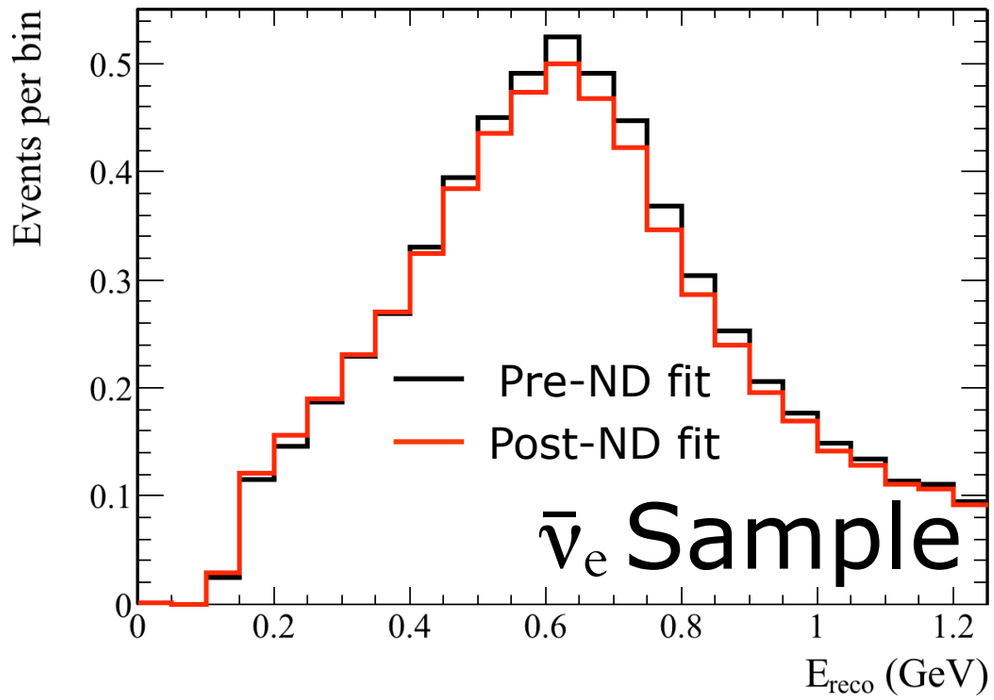


Analysis strategy

Data driven far detector prediction



ND280 Fit



Tracking

Time Projection Chambers 1,2,3

Target (Fine-Grained)

FGD1: Plastic

FGD2: Plastic+Water(Passive)

SK Oscillation Fit

Oscillation Parameters

SK: Super-K

Analysis strategy

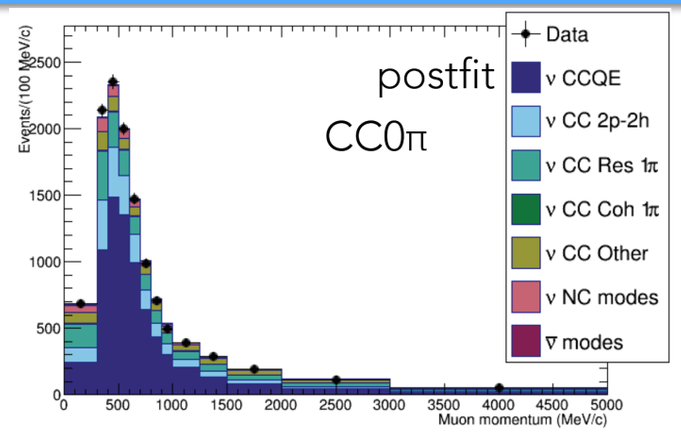
Data
Ingrid
Hadron Prod.

Flux Model MC

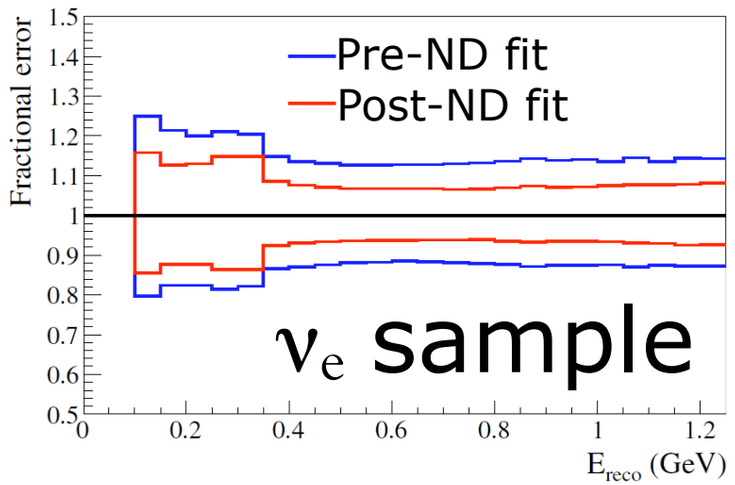
Cross-section Model MC

ND280 Fit

ND280 Data



- ν-mode and $\bar{\nu}$-mode data sets
- Significant ν contamination in $\bar{\nu}$ data set
- Super-K ν_e sample error 12.7% → 6.8%



Neutrino interaction cross sections from T2K S. Dolan Fri @ 8:30

Analysis strategy

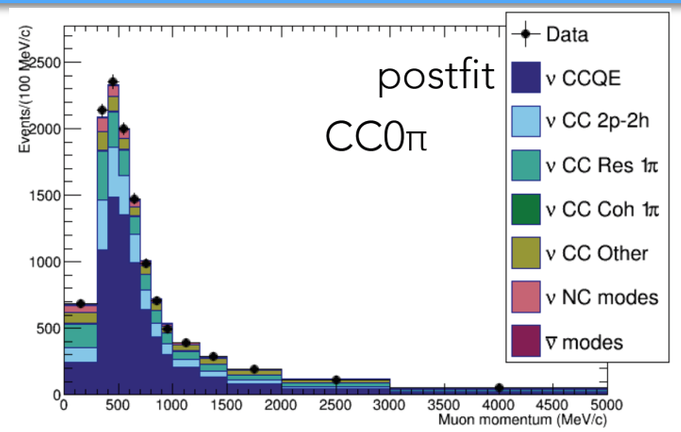
Data
Ingrid
Hadron Prod.

Flux Model MC

Cross-section Model MC

ND280 Fit

ND280 Data



SK Model MC

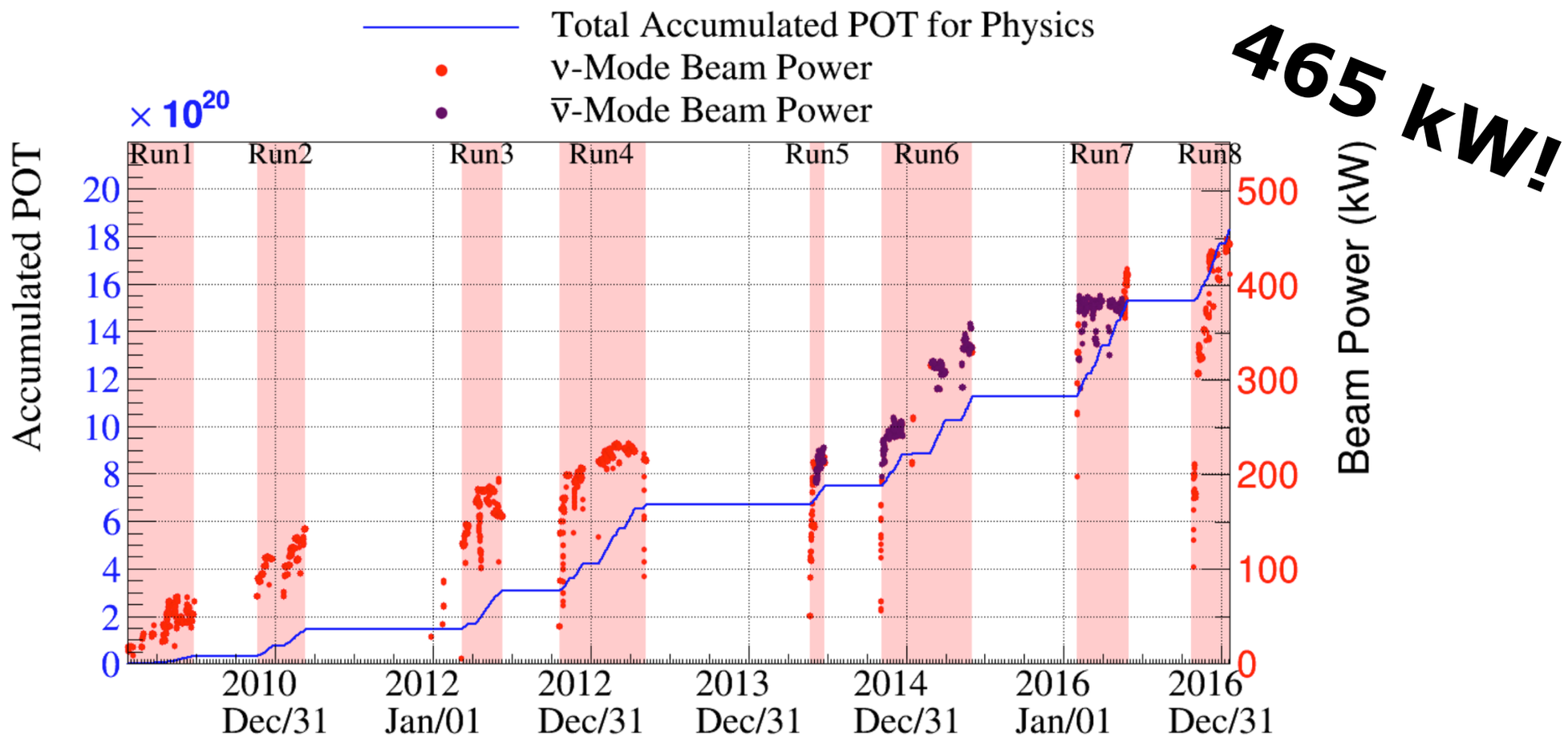
SK Data

SK Oscillation Fit

Oscillation Parameters

SK: Super-K

Data acquired



465 kW!

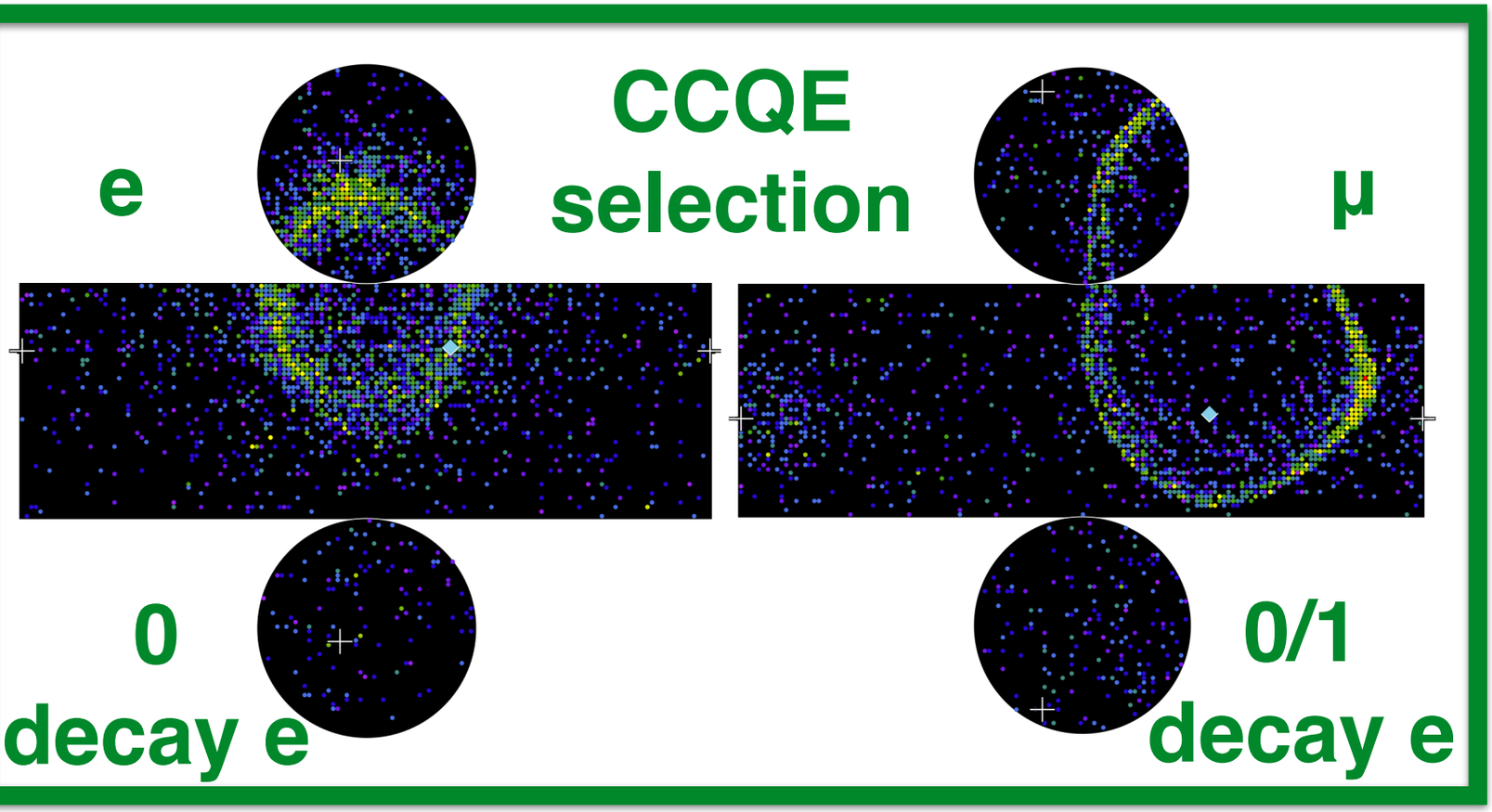
Today

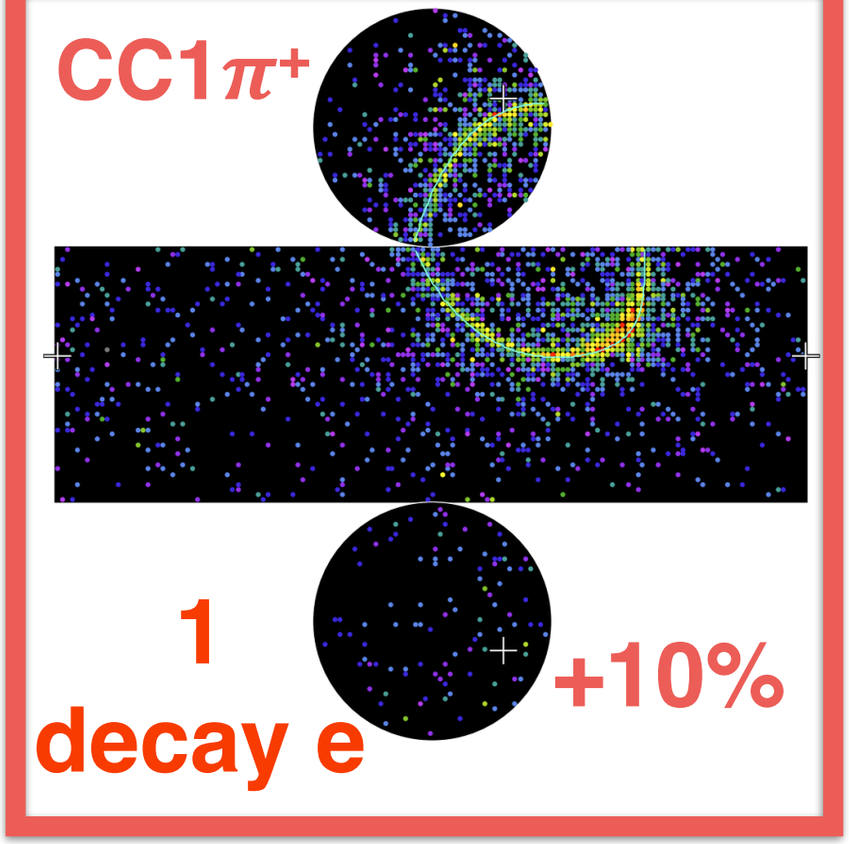
- ν-mode 7.48x10^{20} POT
- ν̄-mode 7.47x10^{20} POT

} ICHEP 2016

- **Additional ν_e CC1π^+ Super-K sample!**

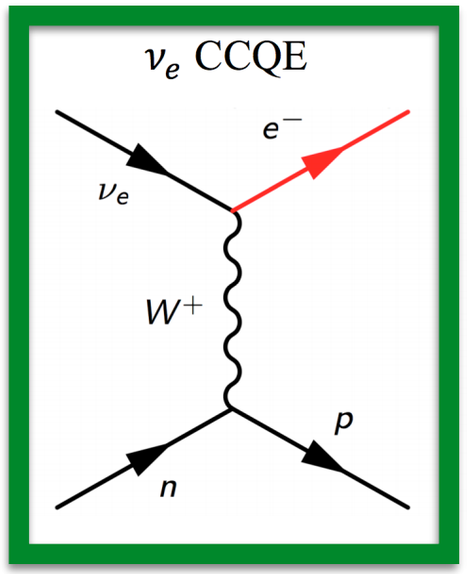
CC1π^+ Selection

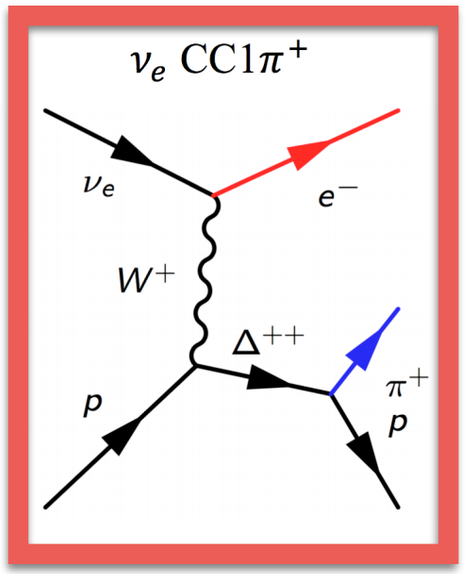




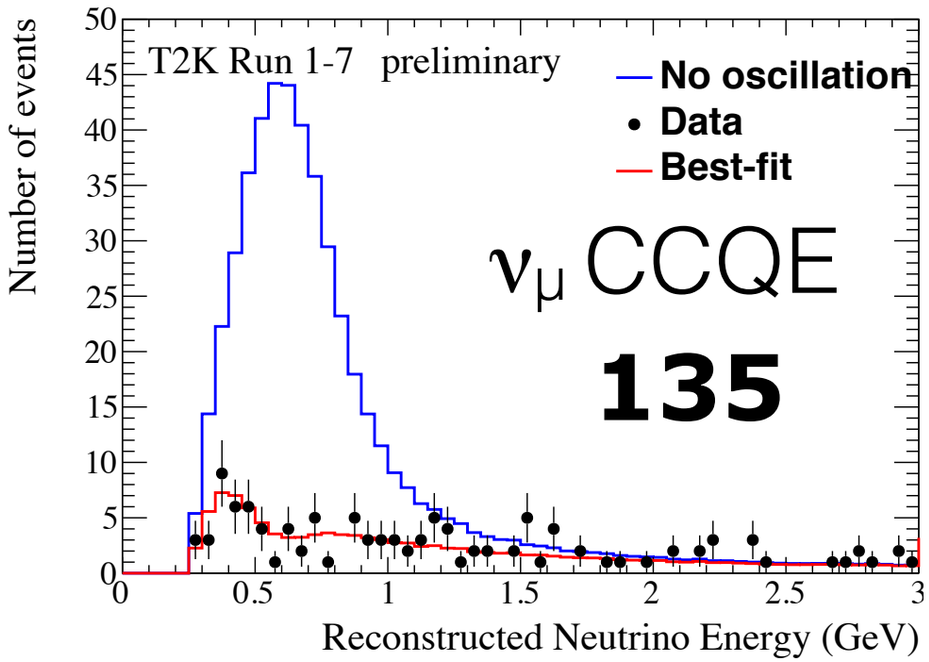
MC Expectation

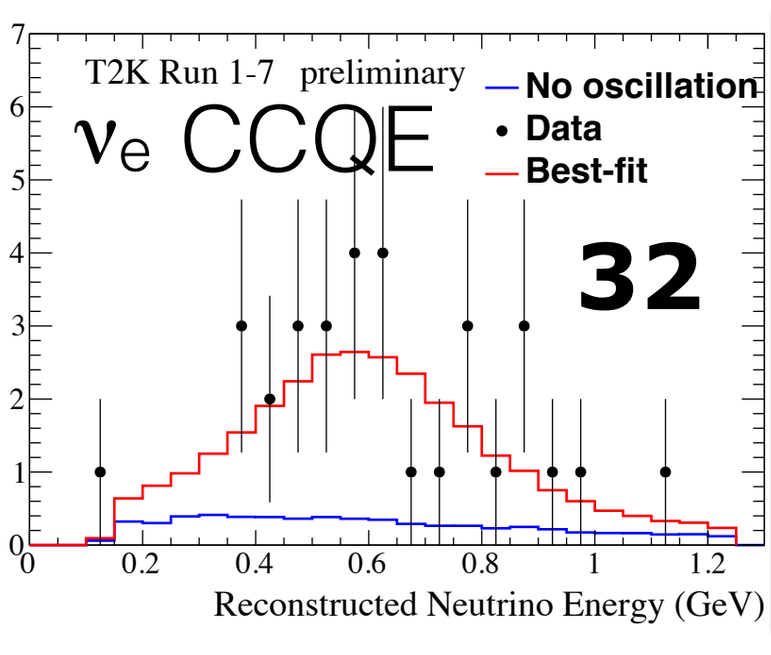
$\delta_{cp}=-\pi/2$	$\nu_\mu \rightarrow \nu_e$ (CCQE)	$\nu_\mu \rightarrow \nu_e$ (CC1π)	$\nu_\mu \rightarrow \nu_e$ (Total)
CCQE e	17.13	1.82	23.21
CC1π^+	0.01	1.93	2.29

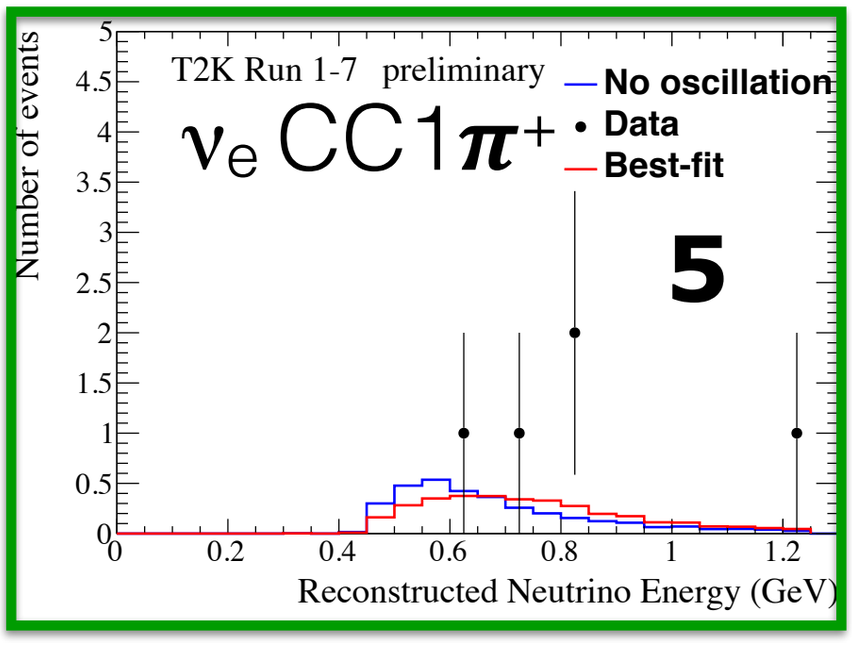


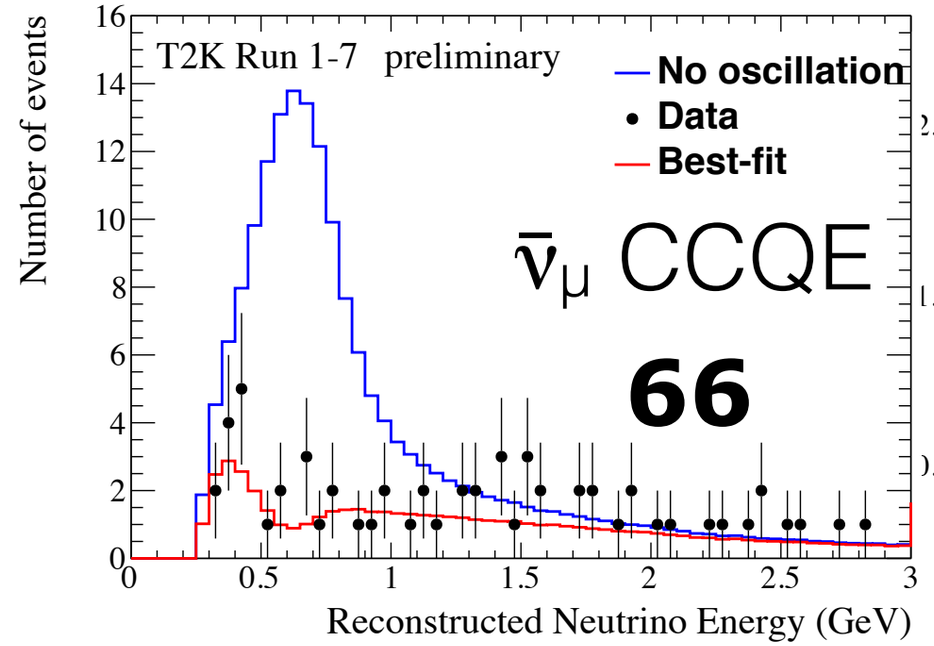


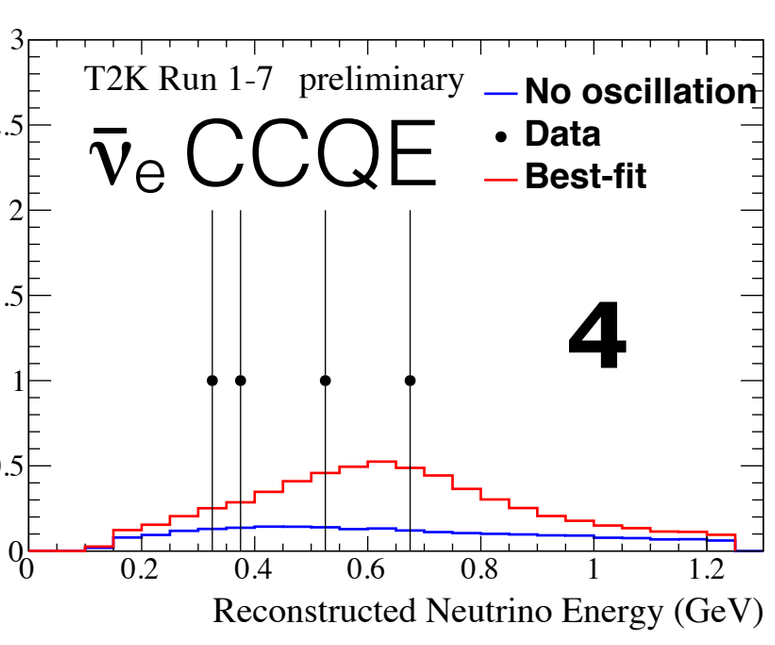
Super-K Data







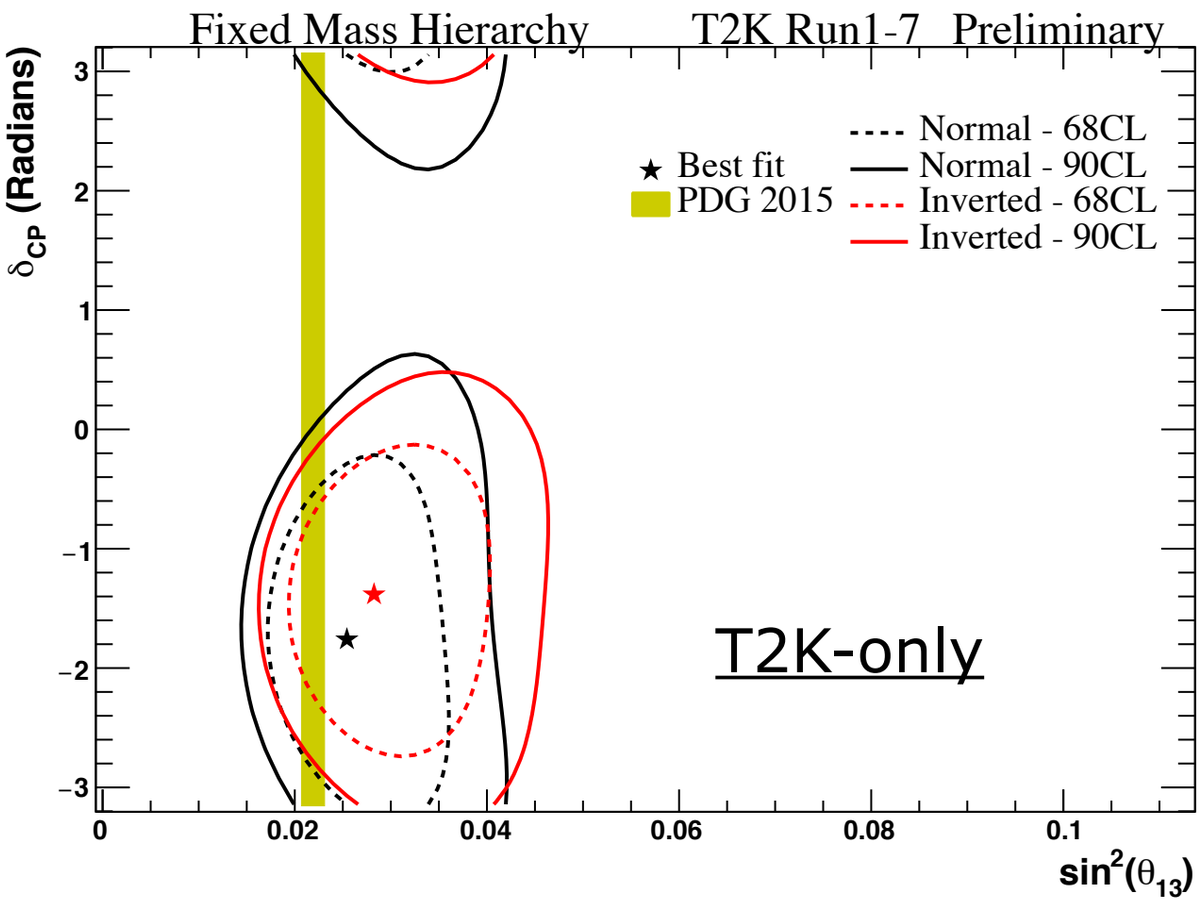


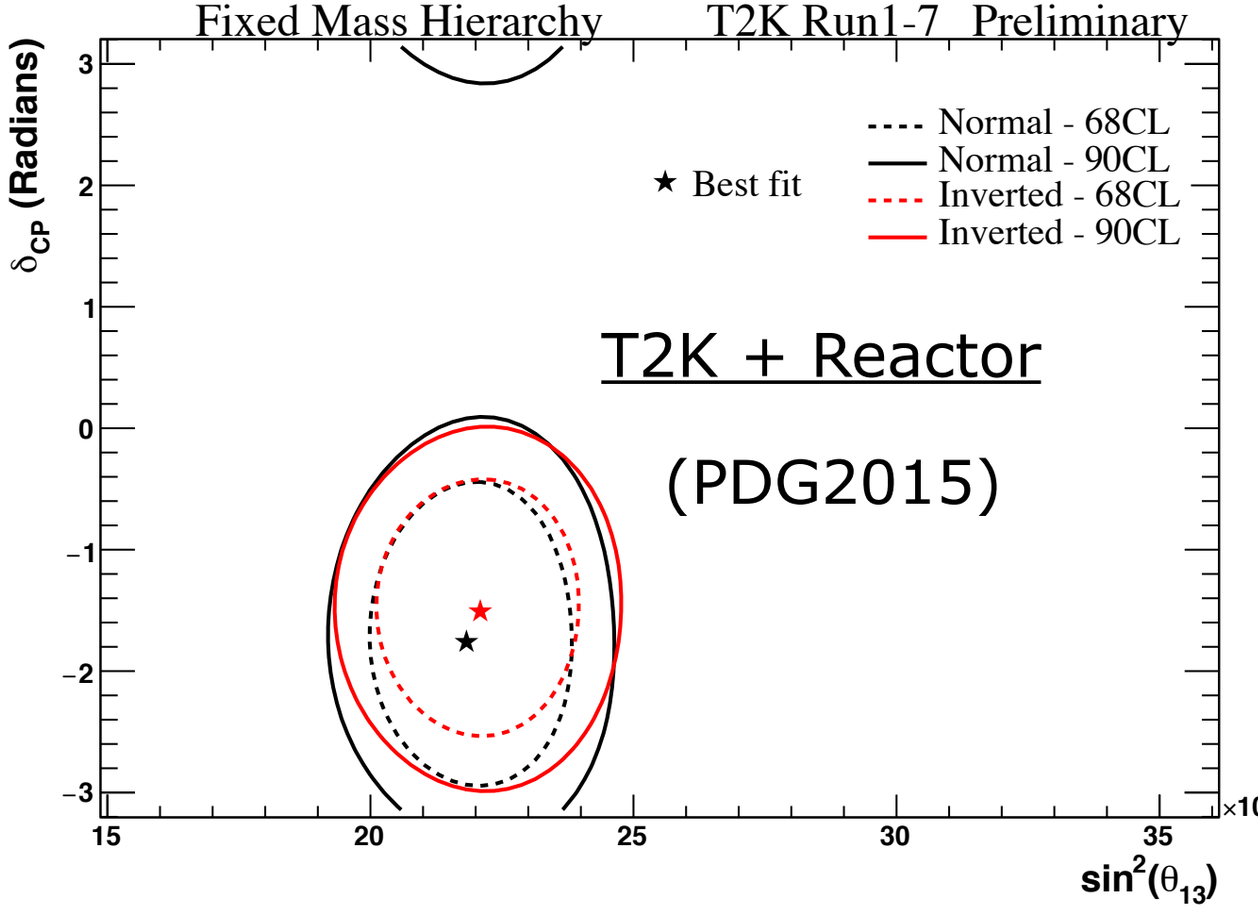


δcp	π/2	-π/2	Obs
νe CCQE	19.6	28.7	32
CC1π+	2.3	3.1	5
ν̄e CCQE	7.7	6.0	4

δ_{cp} and θ_{13} Results

All nuisance parameters marginalised
Independent hierarchy fits

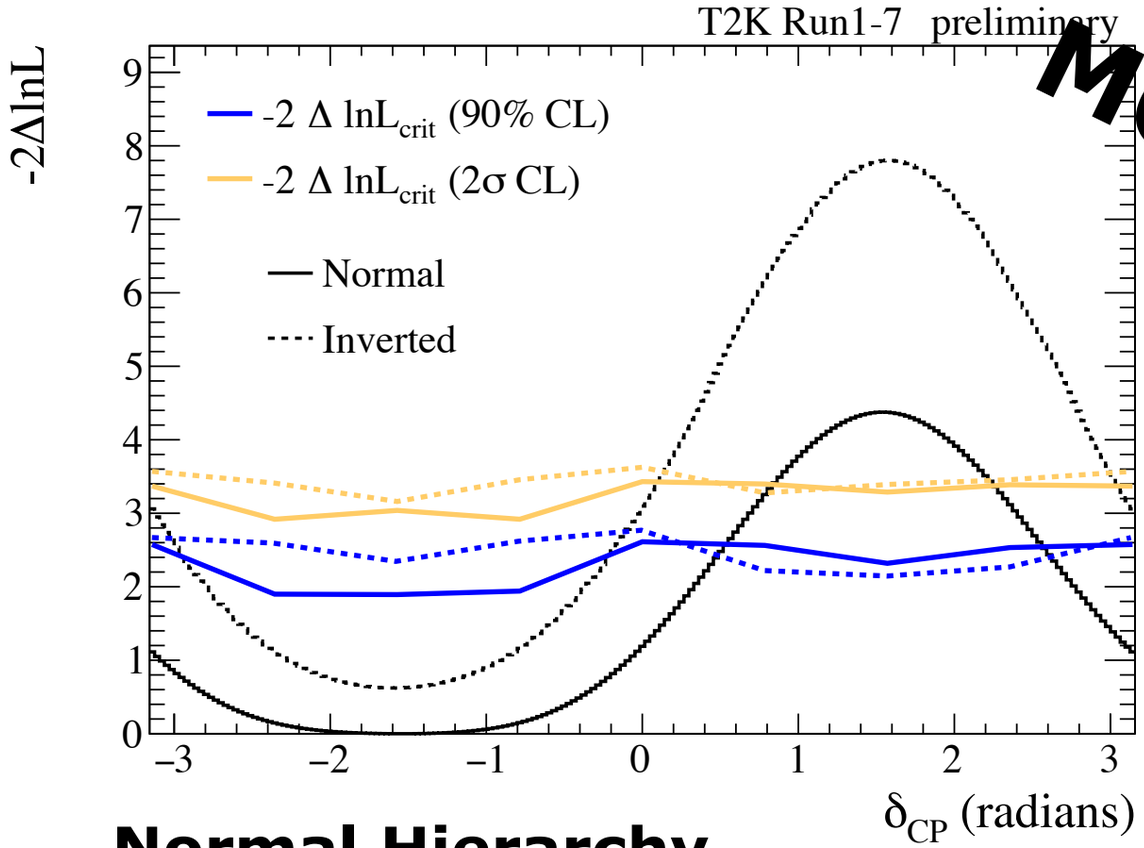


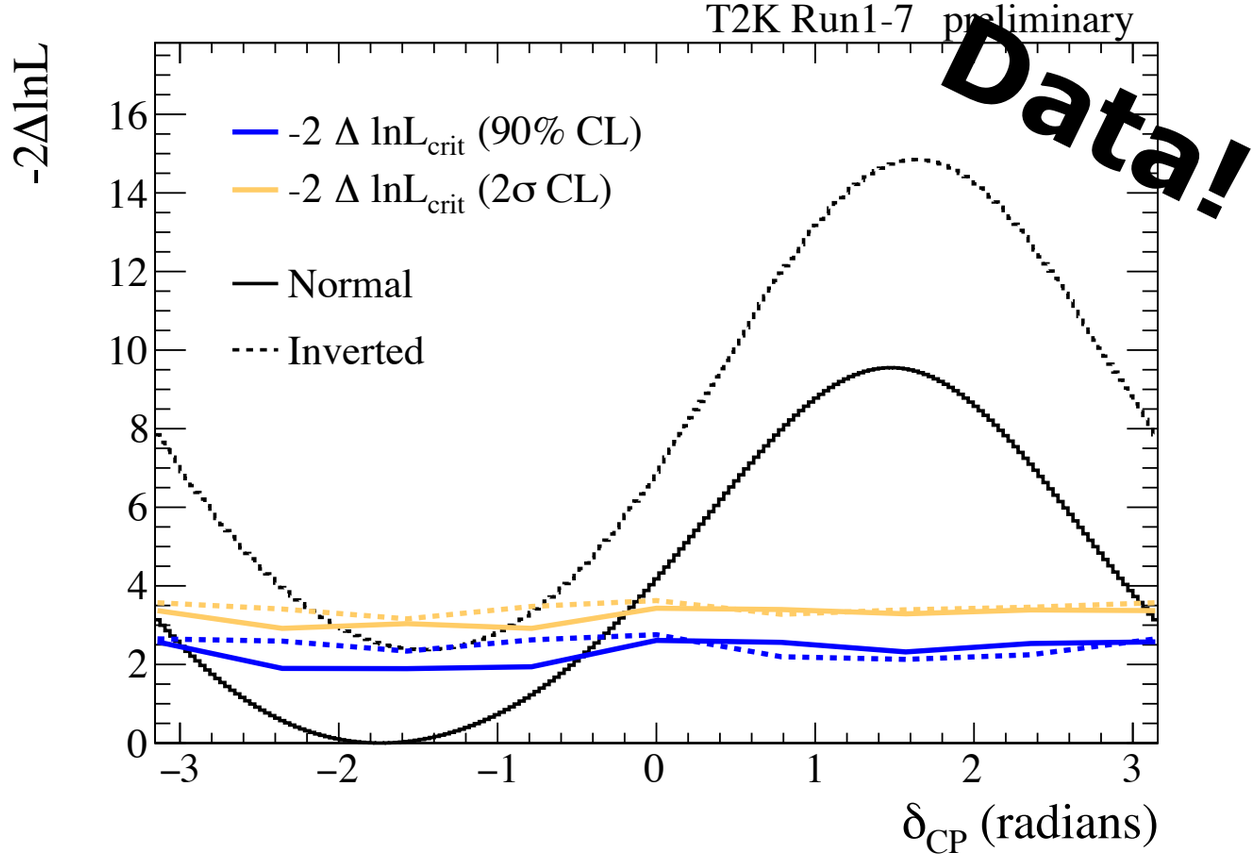


Closed T2K-only 90% CL contour
Consistent w/ reactor within 68% CL

Weaker δcp - θ_{13} degeneracy
IH: $\sin(\delta_{cp}) \neq 0$ @ 90% for all θ_{13}

δcp Fit T2K+Reactor





Normal Hierarchy

PDG 2015

$\sin^2(\theta_{13}) = 0.0217$

$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2$

$\sin^2(\theta_{12}) = 0.306$

T2K Best fit

$\sin^2(\theta_{23}) = 0.528$

$\delta_{CP} =$ -1.601

$\Delta m^2_{32} = 2.51 \cdot 10^{-3} eV^2$

MC (sensitivity)

Exclude IH sin(δcp) = 0 @ 90% CL

Data

90%CL [-2.978; -0.467] NH

[-1.466; -1.272] IH

$\delta_{cp} \neq 0$ @ 2σ, $\sin(\delta_{cp}) \neq 0$ @ 90% CL

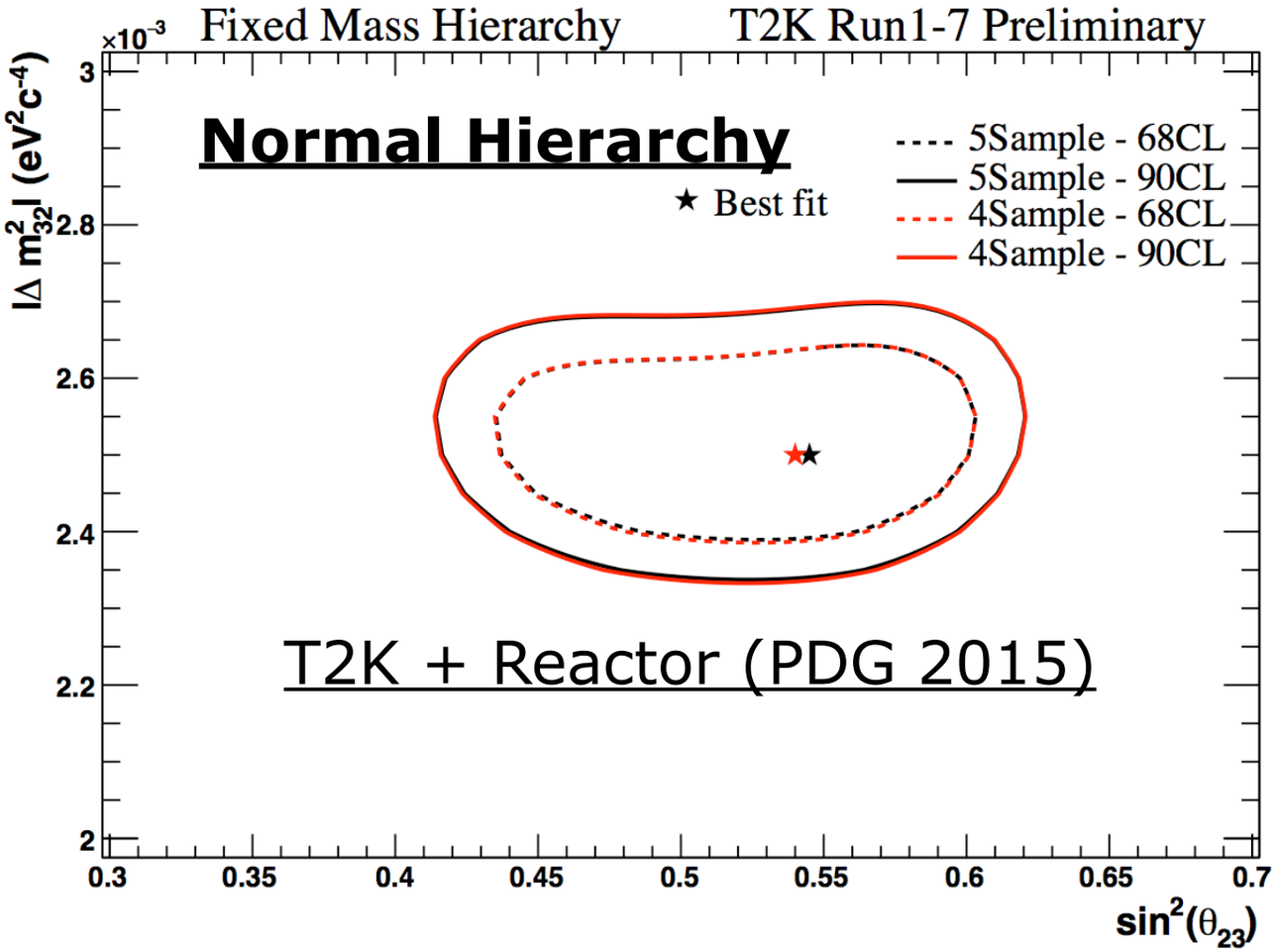
Summary+Future

- θ_{13} measurement consistent with reactor experiments
- Stronger than expected δcp constraint (resolved with more data)

- More Data
  - Currently record beam power in ν-mode
  - 750 kW expected soon
- CC1π^+ ν_μ selection (and more)
- Gadolinium doping at Super-K
- Near detector upgrades
- Additional ND280 selections (See Stephen Dolan's Talk)

Backups

$\sin^2(\theta_{23})$ vs Δm^2_{32} sensitivity



True Parameters^{MC}

PDG 2015

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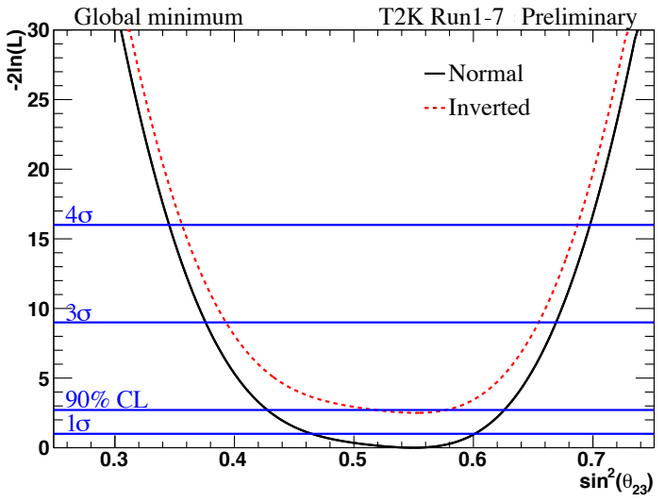
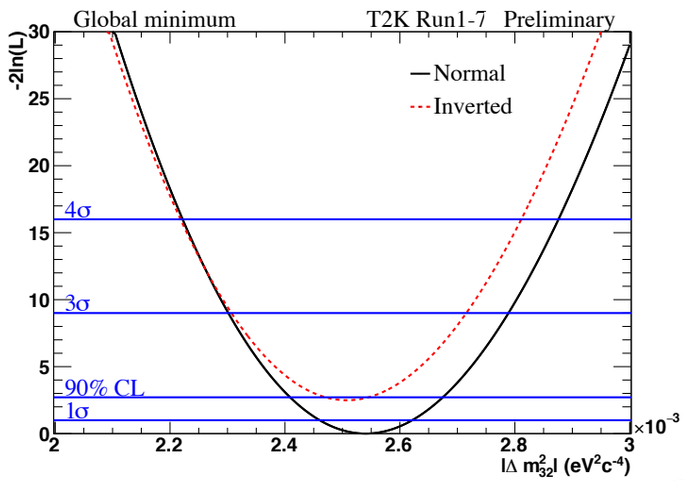
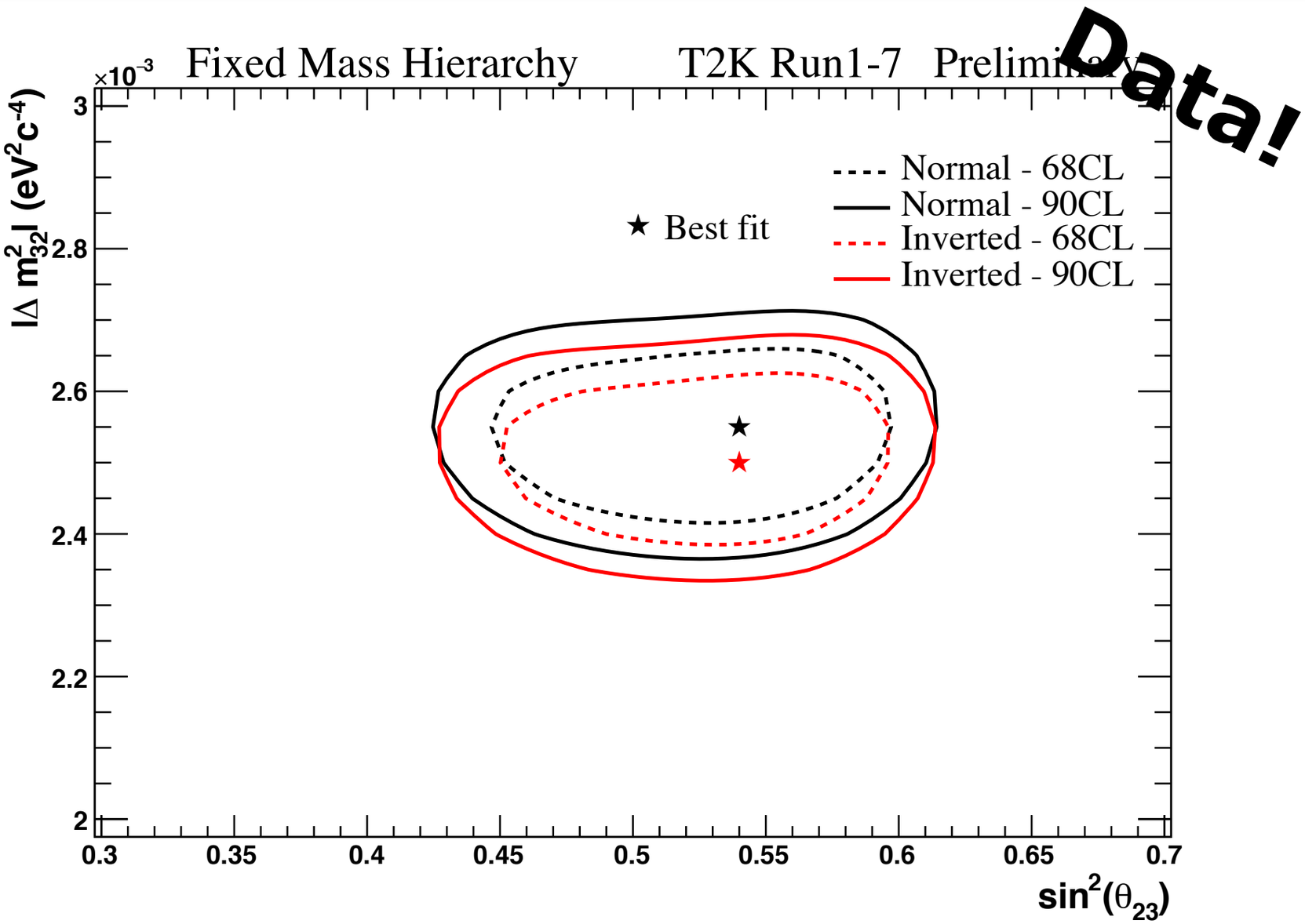
$\sin^2(\theta_{23})$ vs Δm^2_{32}



1σ CL: [0.47; 0.60]



1σ CL: [2.46; 2.62] 10^{-3}



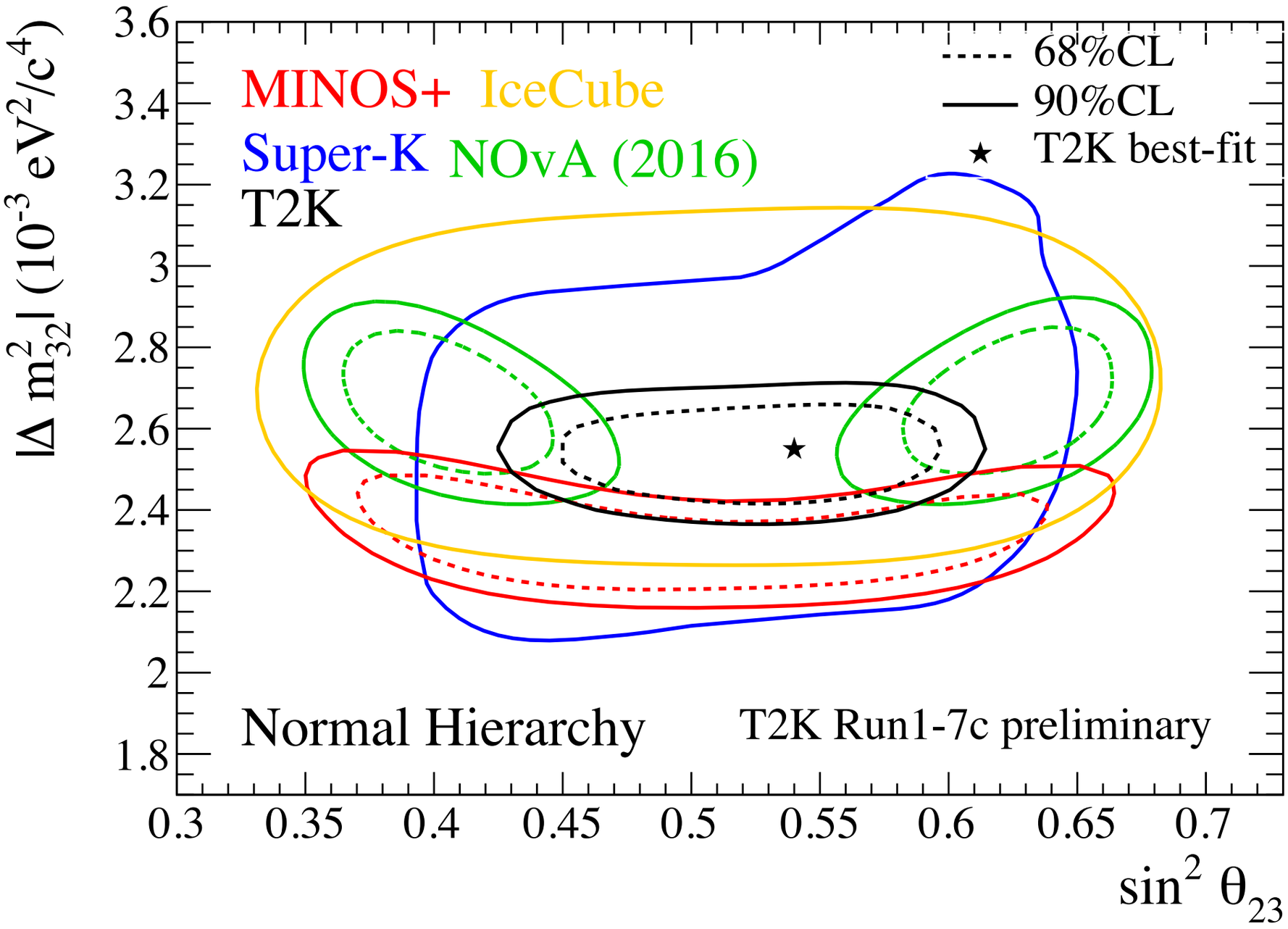
Consistent with sensitivity

Best fit: Maximal disappearance

Consistent with maximal 2-3 mixing

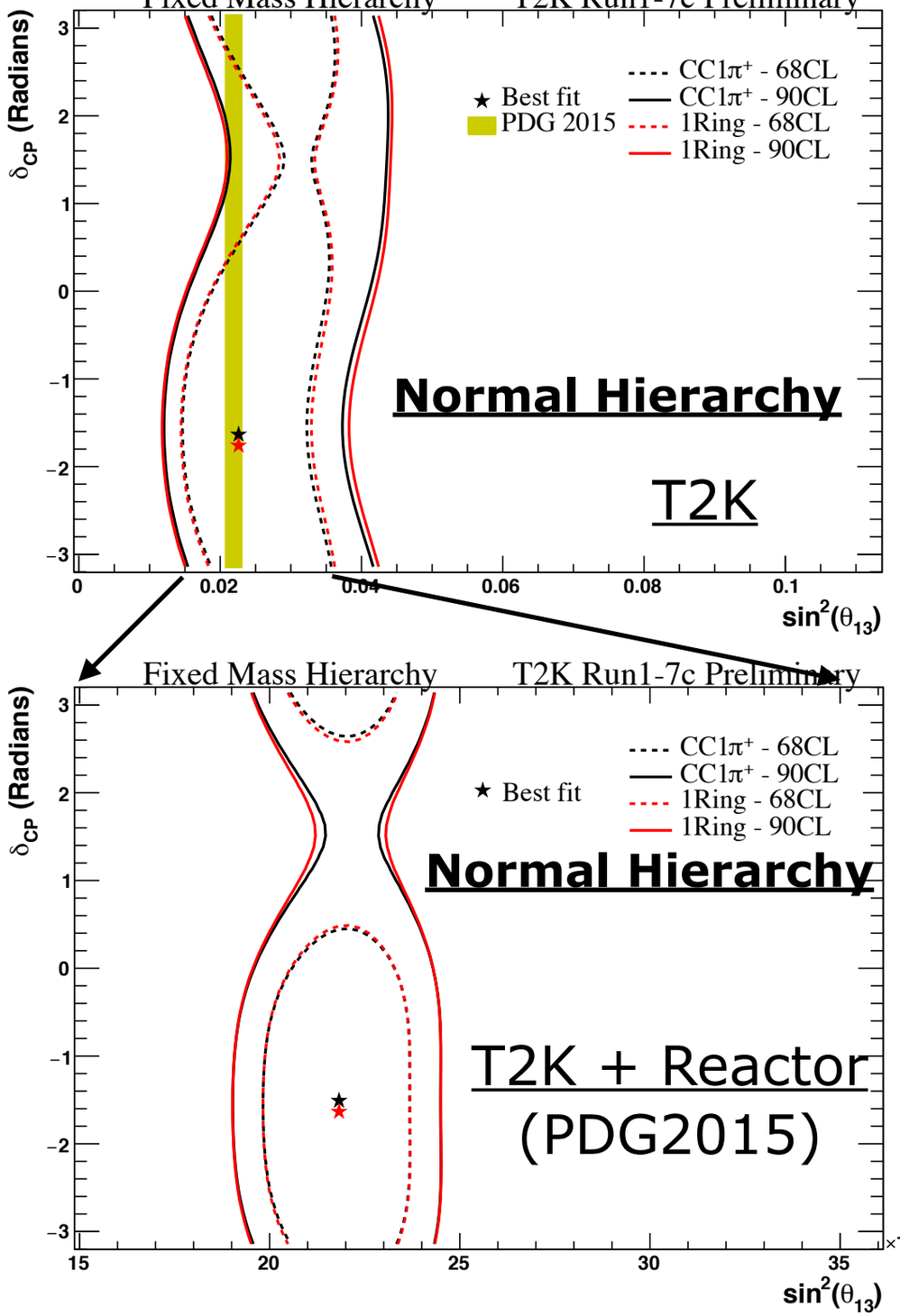
Experiment Comparison

Data!

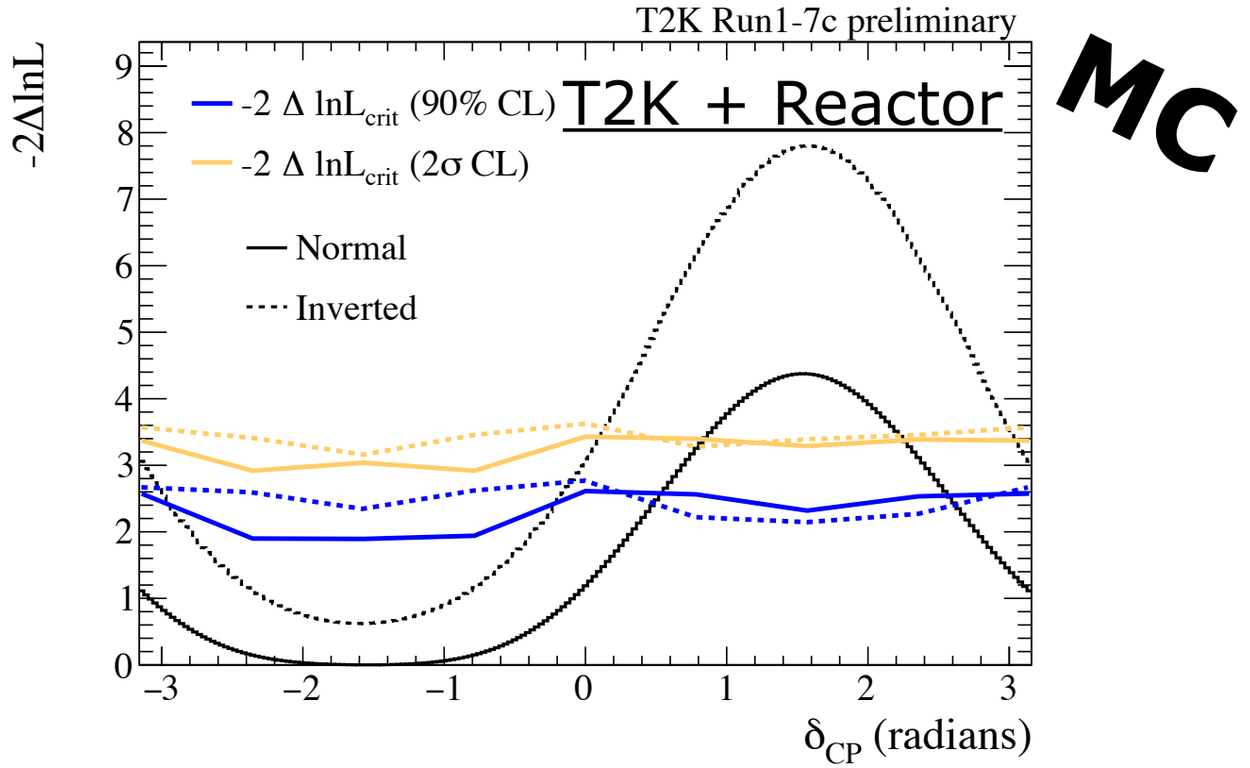


δ_{cp} and θ_{13} Sensitivity

MC



MC



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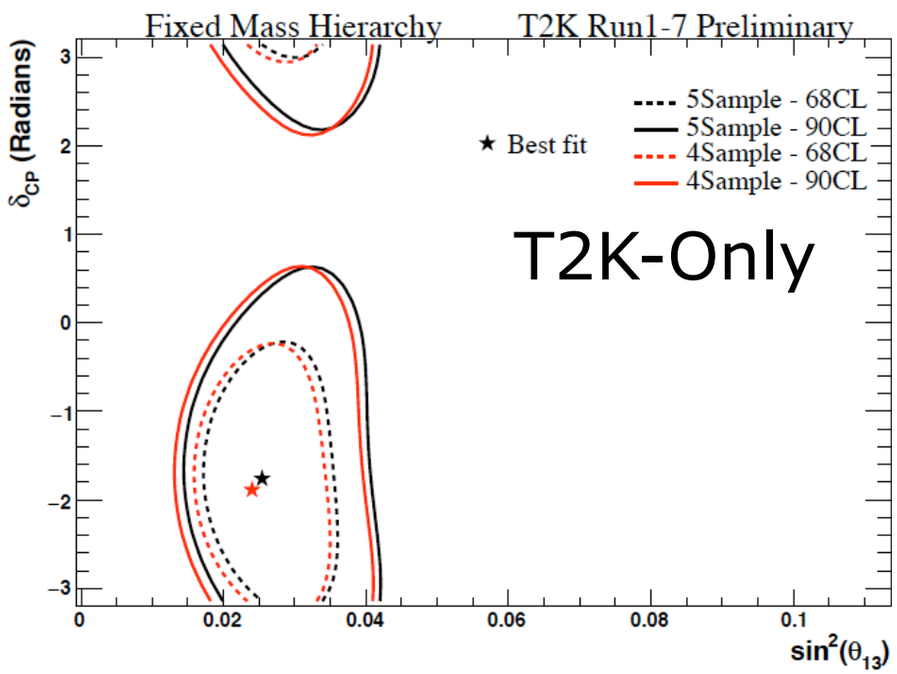
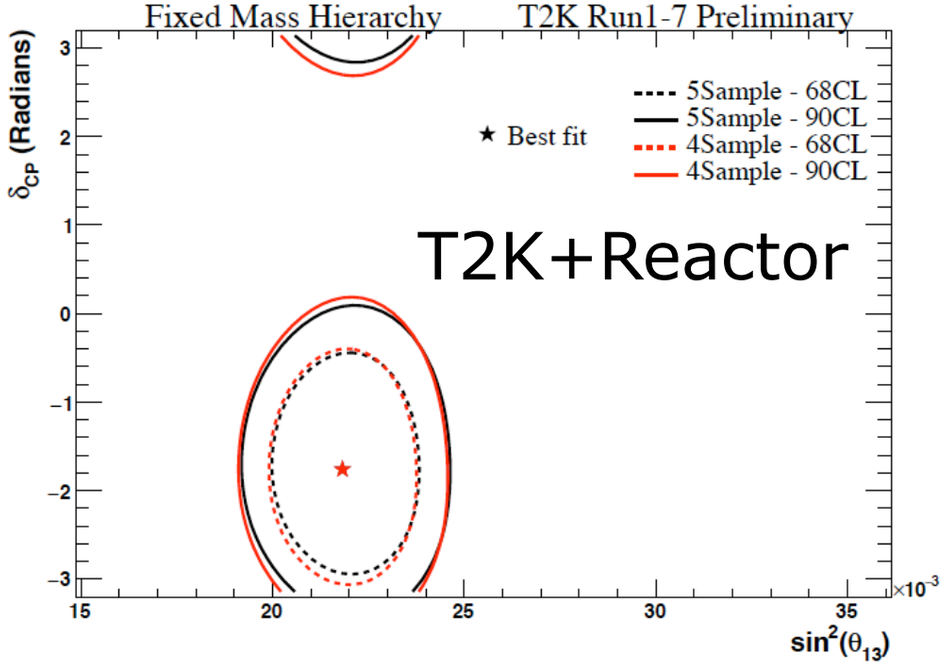
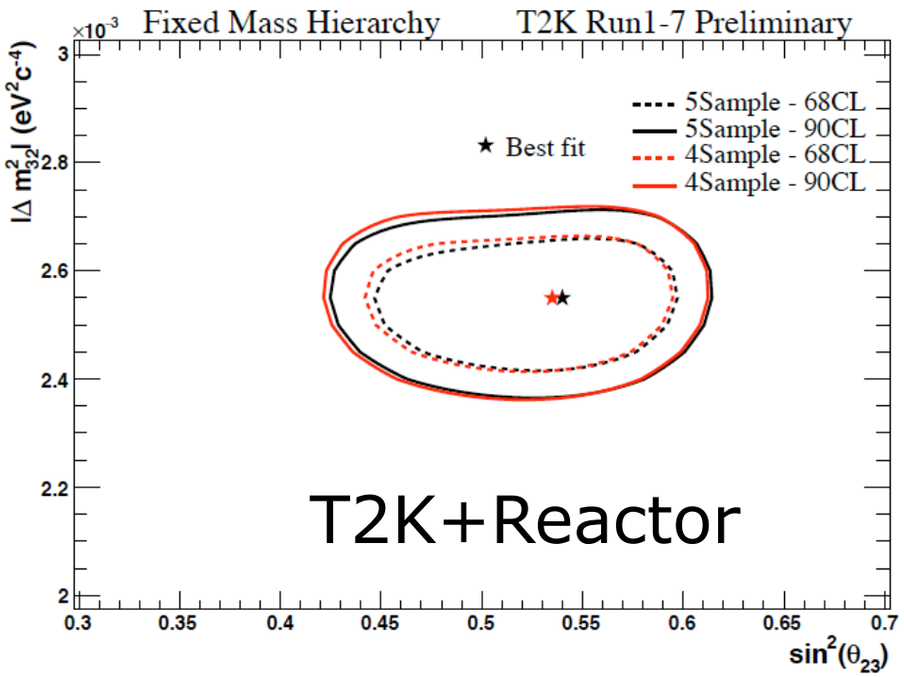
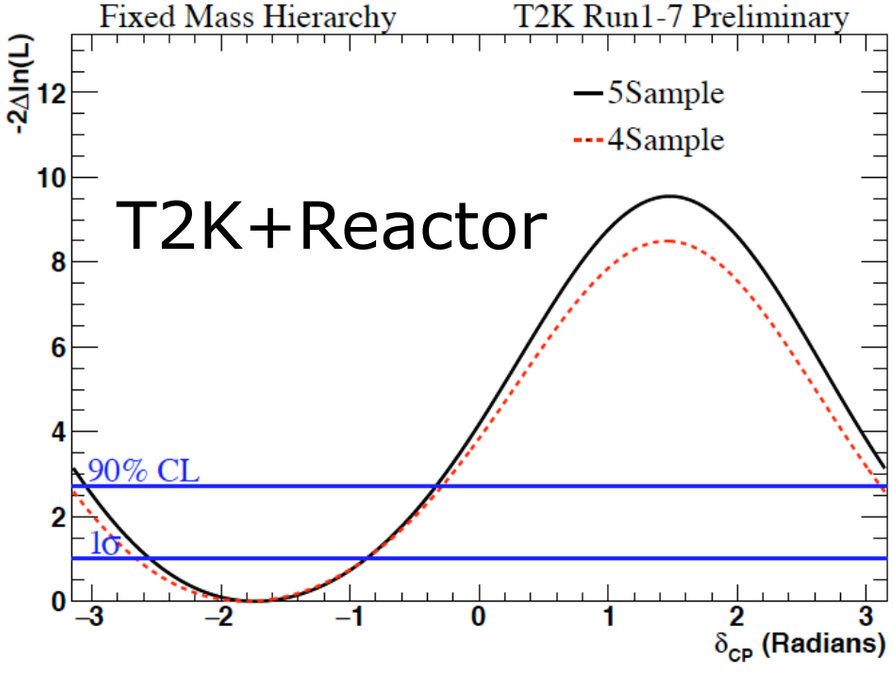
CC1π^+ Comparison Data

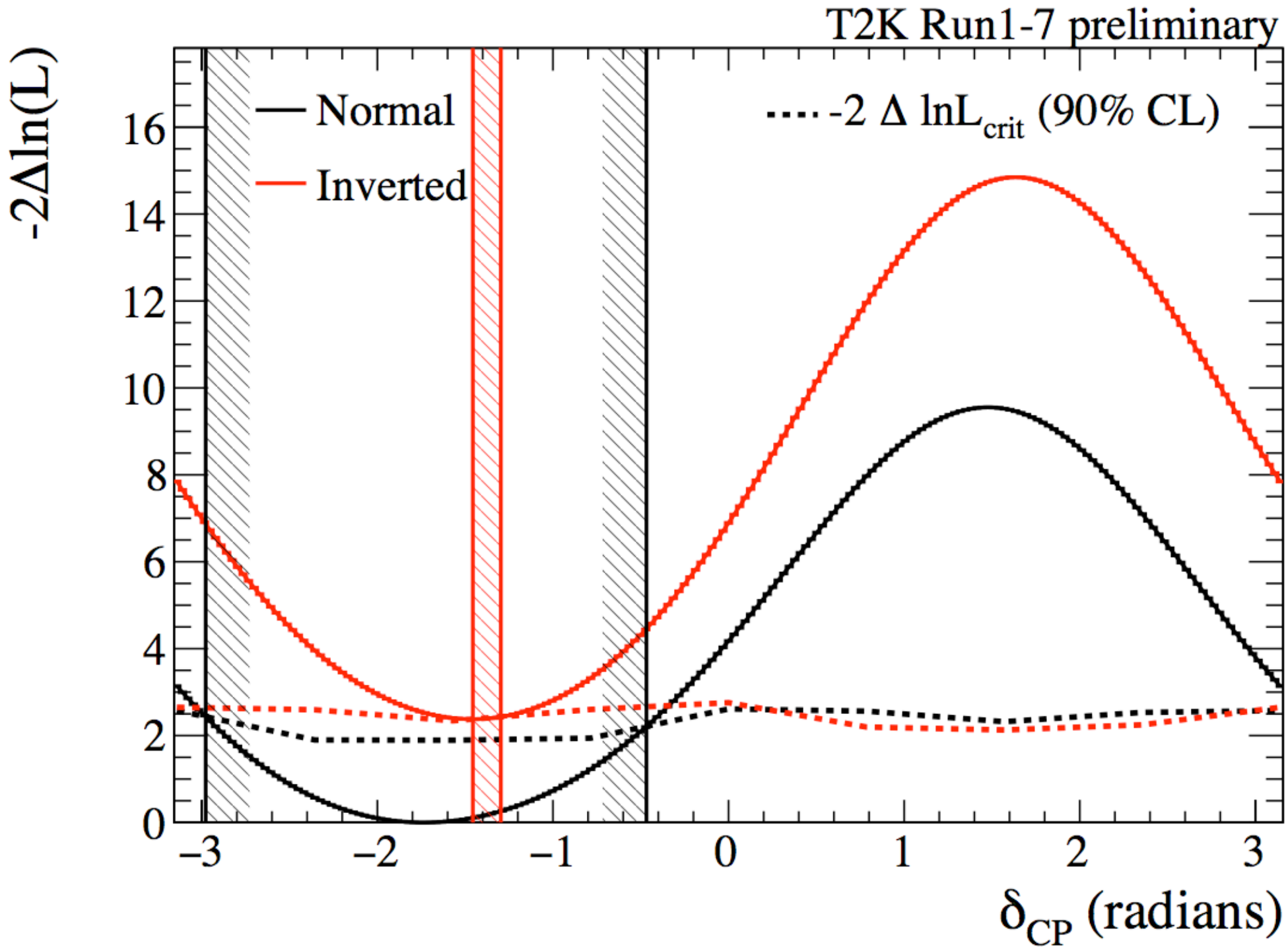




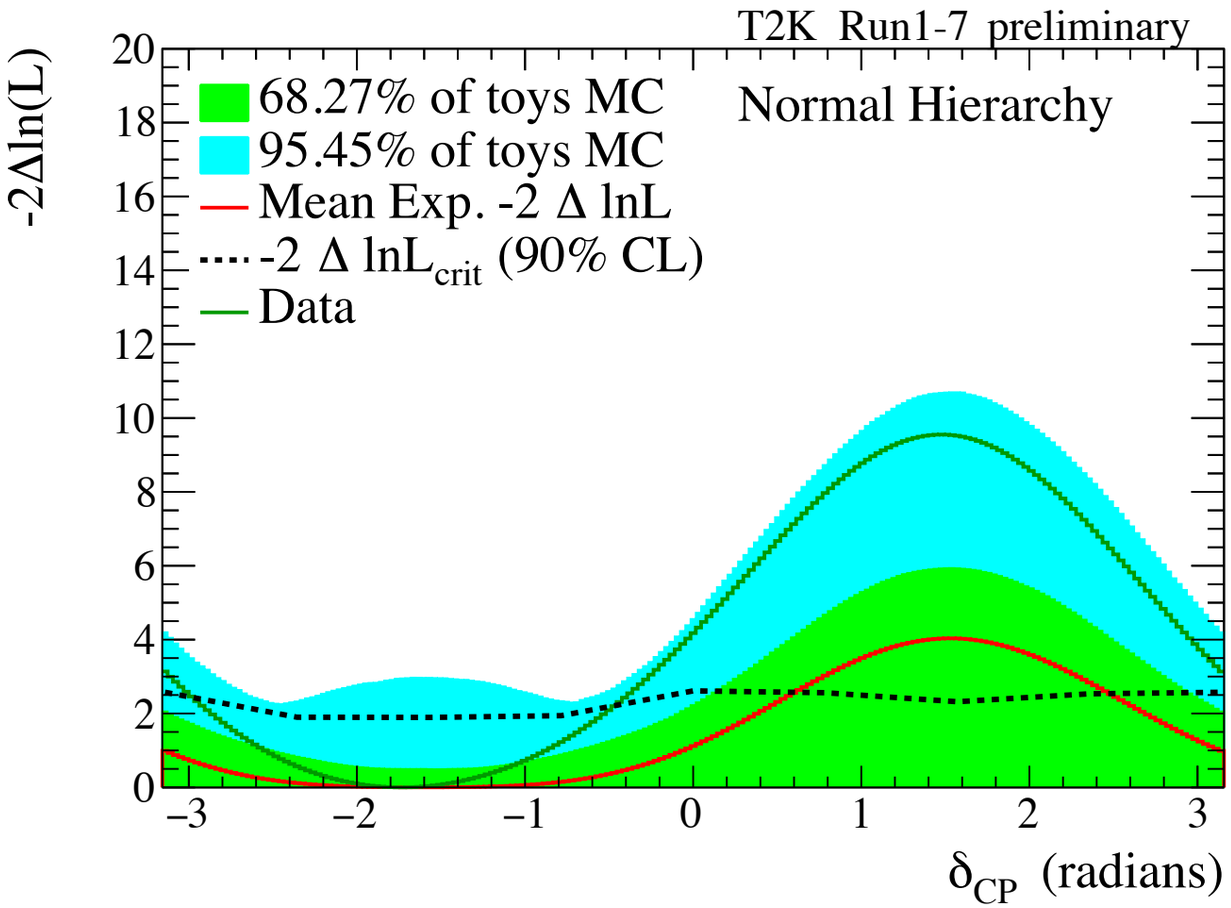


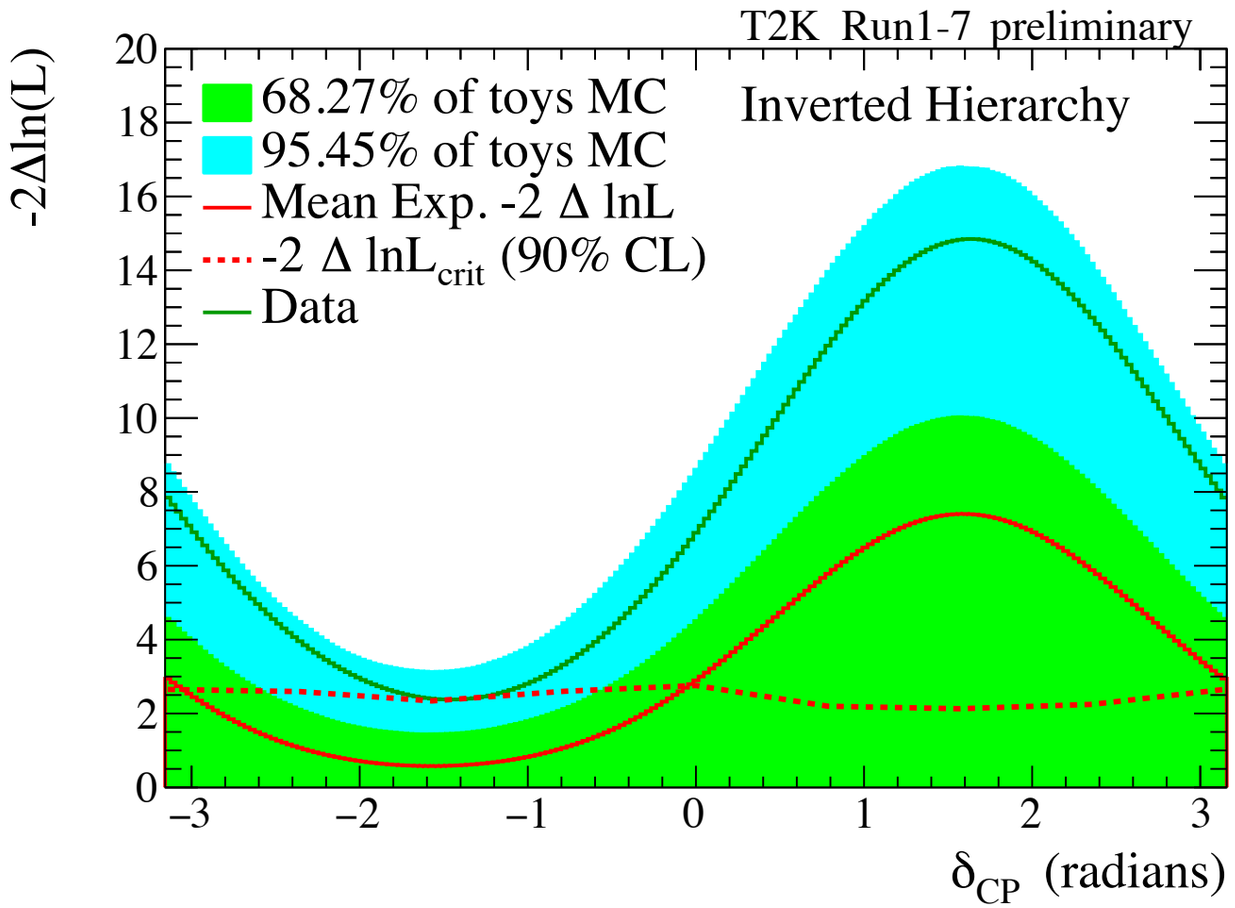


δ_{cp} 90% Exclusion



δcp exclusion





10k toy experiments with true δcp = $-\pi/2$

$\Delta\chi^2_{bin} = \chi^2_{bin} - \chi^2_{bf}$ (ordered from min to max)

NH & IH data constraint within a 2σ fluctuation

Octant + Hierarchy

Posterior probability table

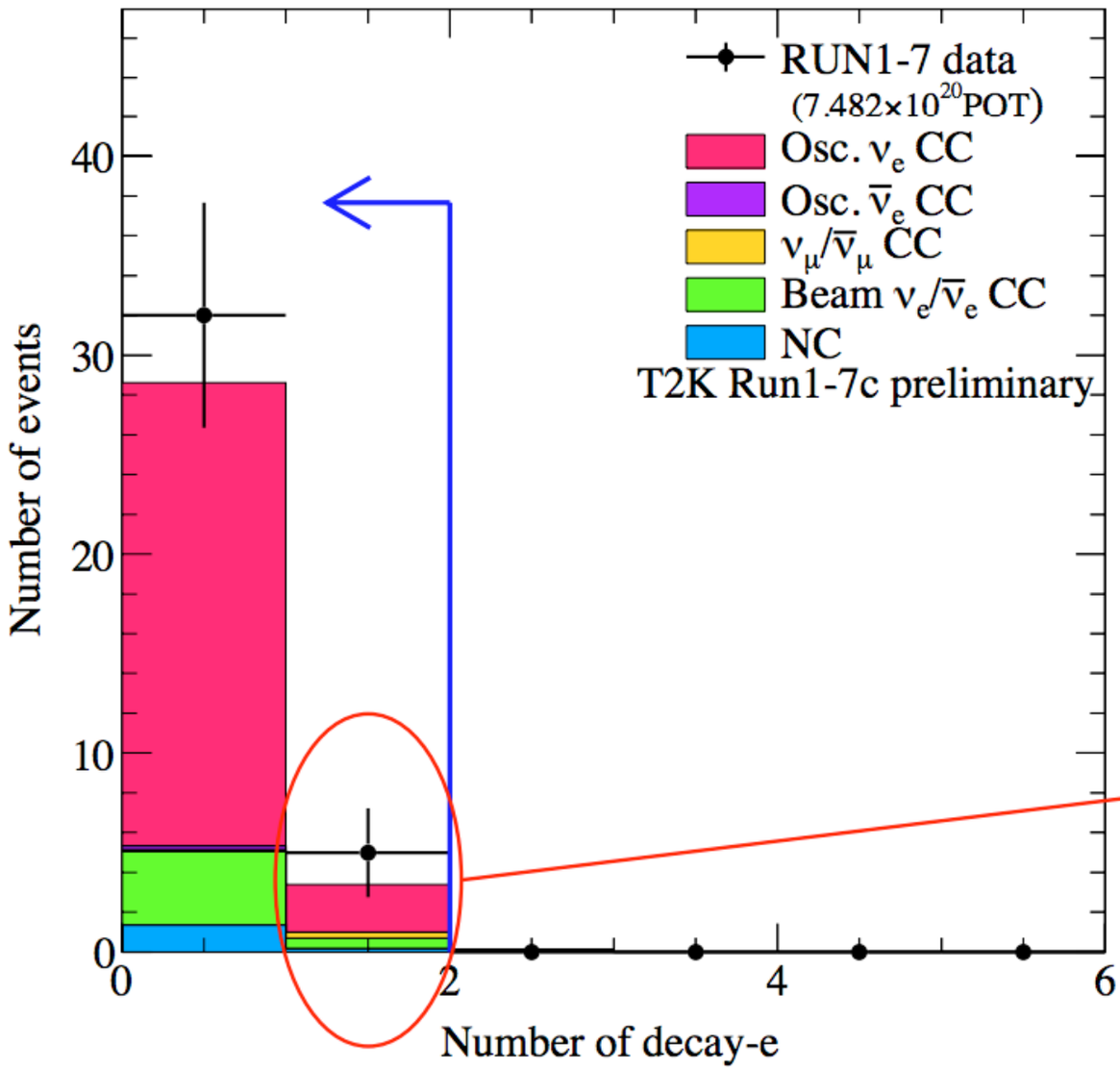
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line Total
Inverted Hierarchy	0.055	0.150	0.205
Normal Hierarchy	0.232	0.563	0.795
Column Total	0.287	0.713	1

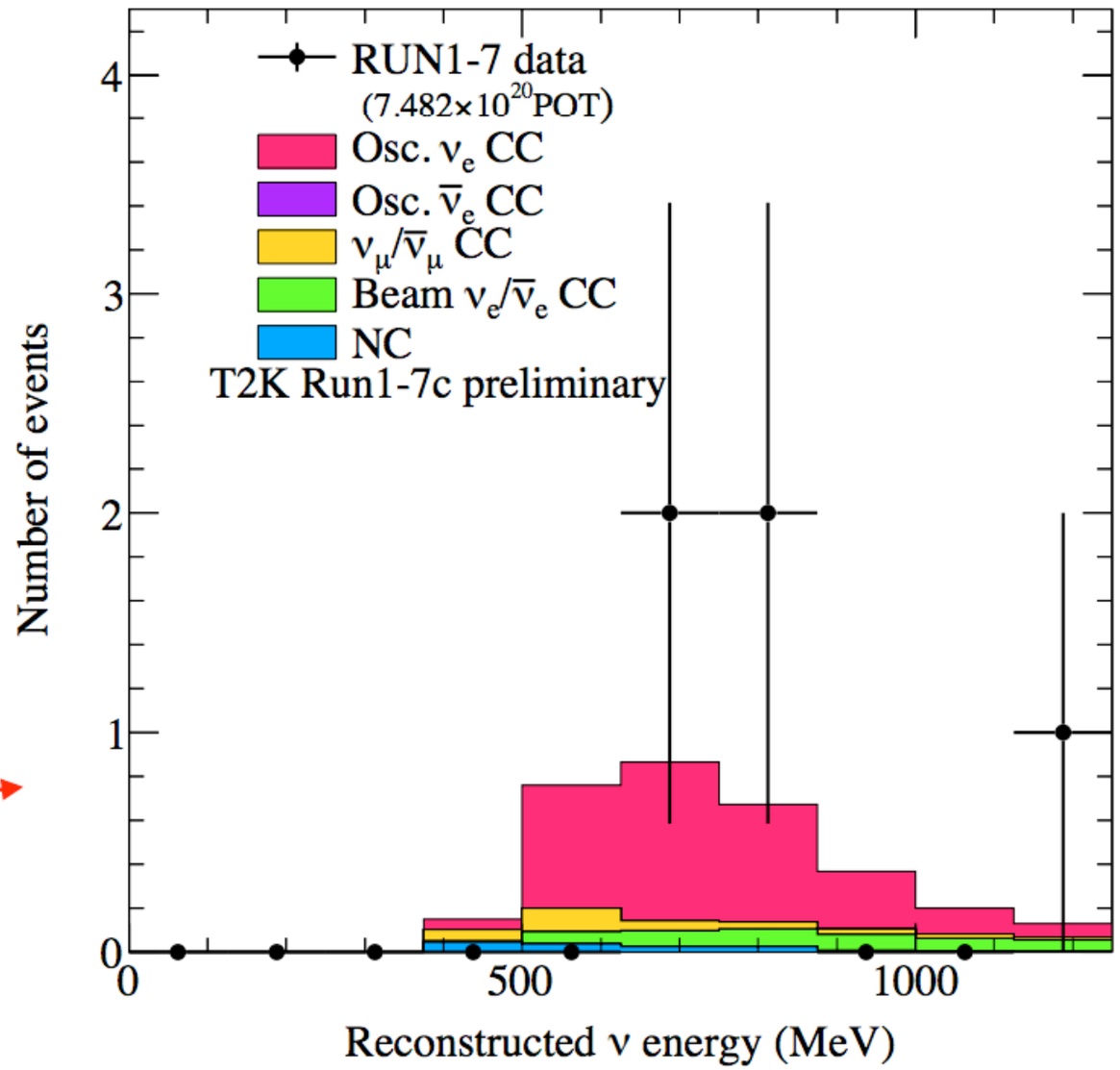
Upper octant and Normal Hierarchy preferred

Bayes factor (assuming flat priors)

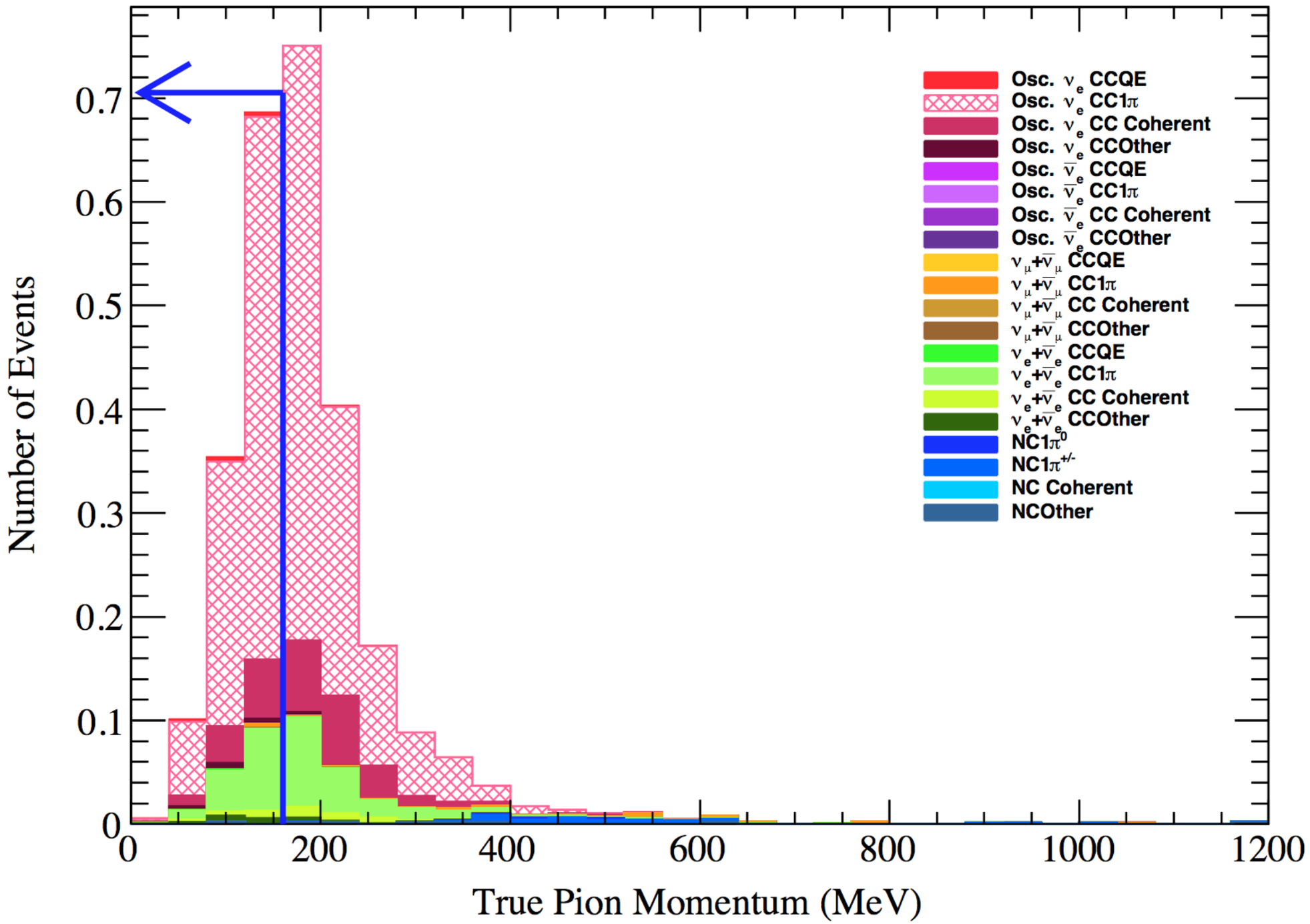
Normal / Inverted: 3.88 not significant (Jeffery's scale)
Upper / Lower octant: 4.48 not significant (Jeffery's scale)

CC1π^+ Selection



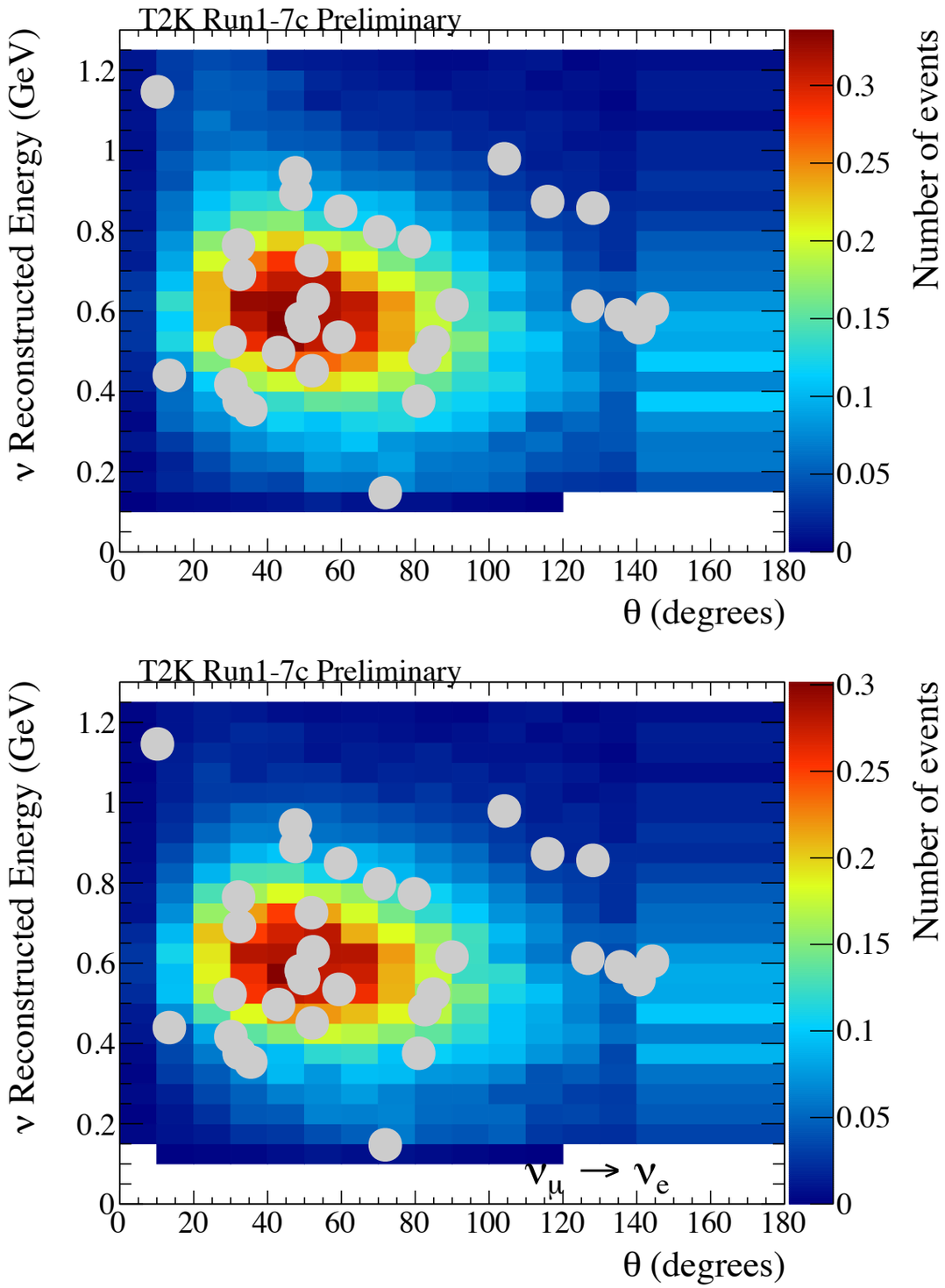


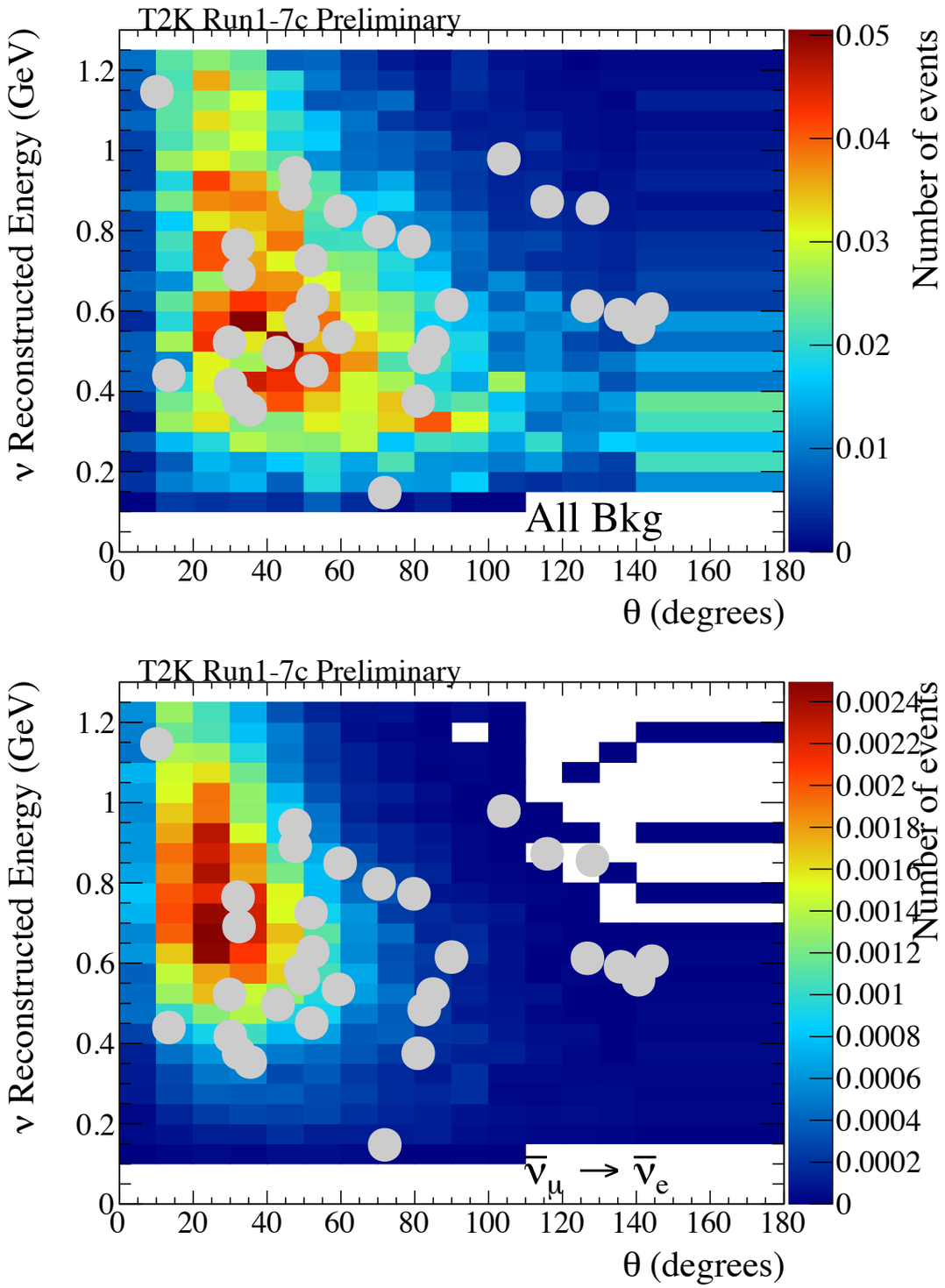
π^+ momentum


Number of Events
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
200
400
600
800
1000
1200
True Pion Momentum (MeV)
Osc. ν_e CCQE
Osc. ν_e CC1π
Osc. ν_e CC Coherent
Osc. ν_e CCOther
Osc. $\bar{\nu}_e$ CCQE
Osc. $\bar{\nu}_e$ CC1π
Osc. $\bar{\nu}_e$ CC Coherent
Osc. $\bar{\nu}_e$ CCOther
$\nu_\mu+\bar{\nu}_\mu$ CCQE
$\nu_\mu+\bar{\nu}_\mu$ CC1π
$\nu_\mu+\bar{\nu}_\mu$ CC Coherent
$\nu_\mu+\bar{\nu}_\mu$ CCOther
$\nu_e+\bar{\nu}_e$ CCQE
$\nu_e+\bar{\nu}_e$ CC1π
$\nu_e+\bar{\nu}_e$ CC Coherent
$\nu_e+\bar{\nu}_e$ CCOther
NC1π^0
NC1$\pi^{+/-}$
NC Coherent
NCOther

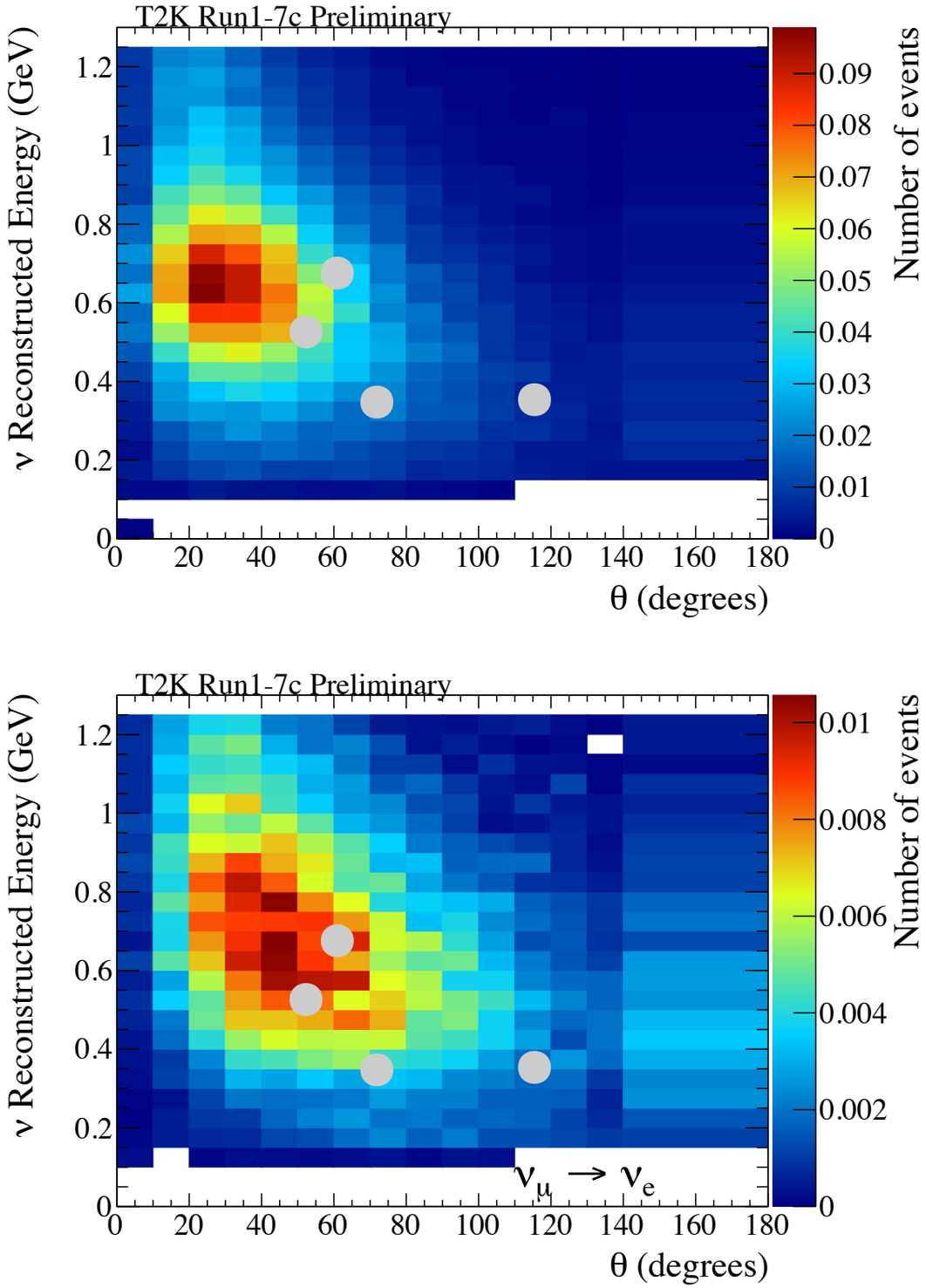
Signal Background Separation

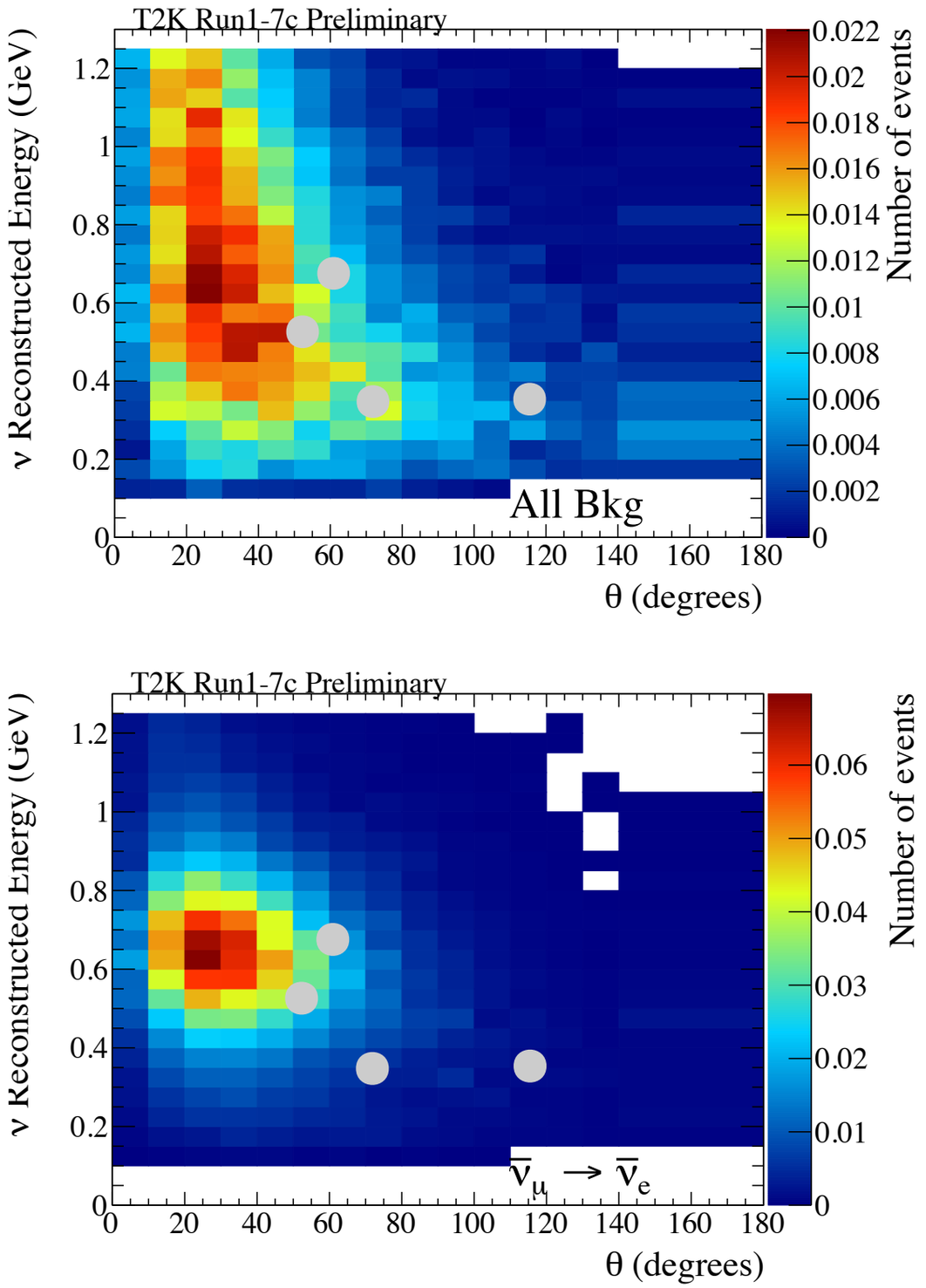
FHC electron like



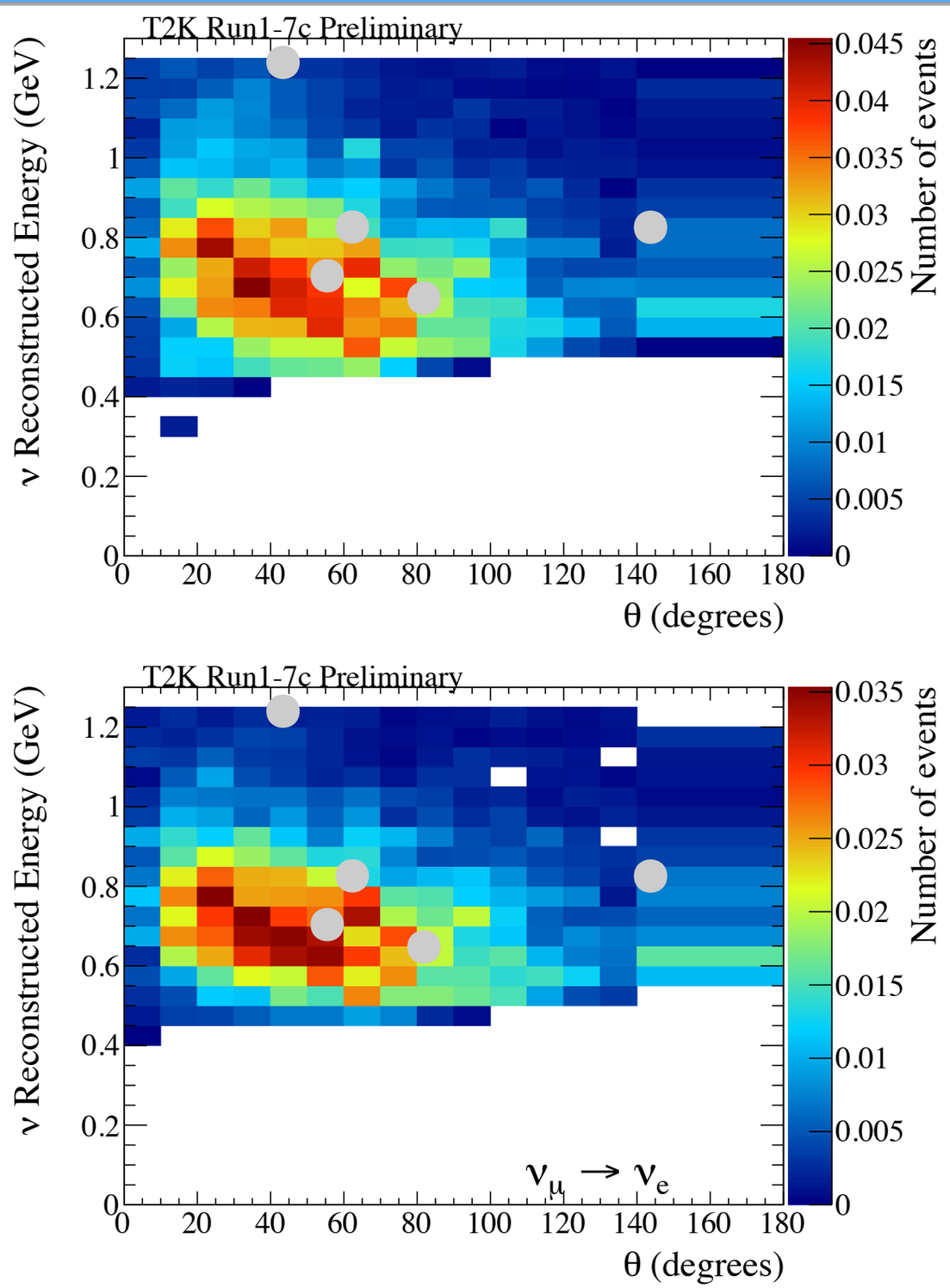


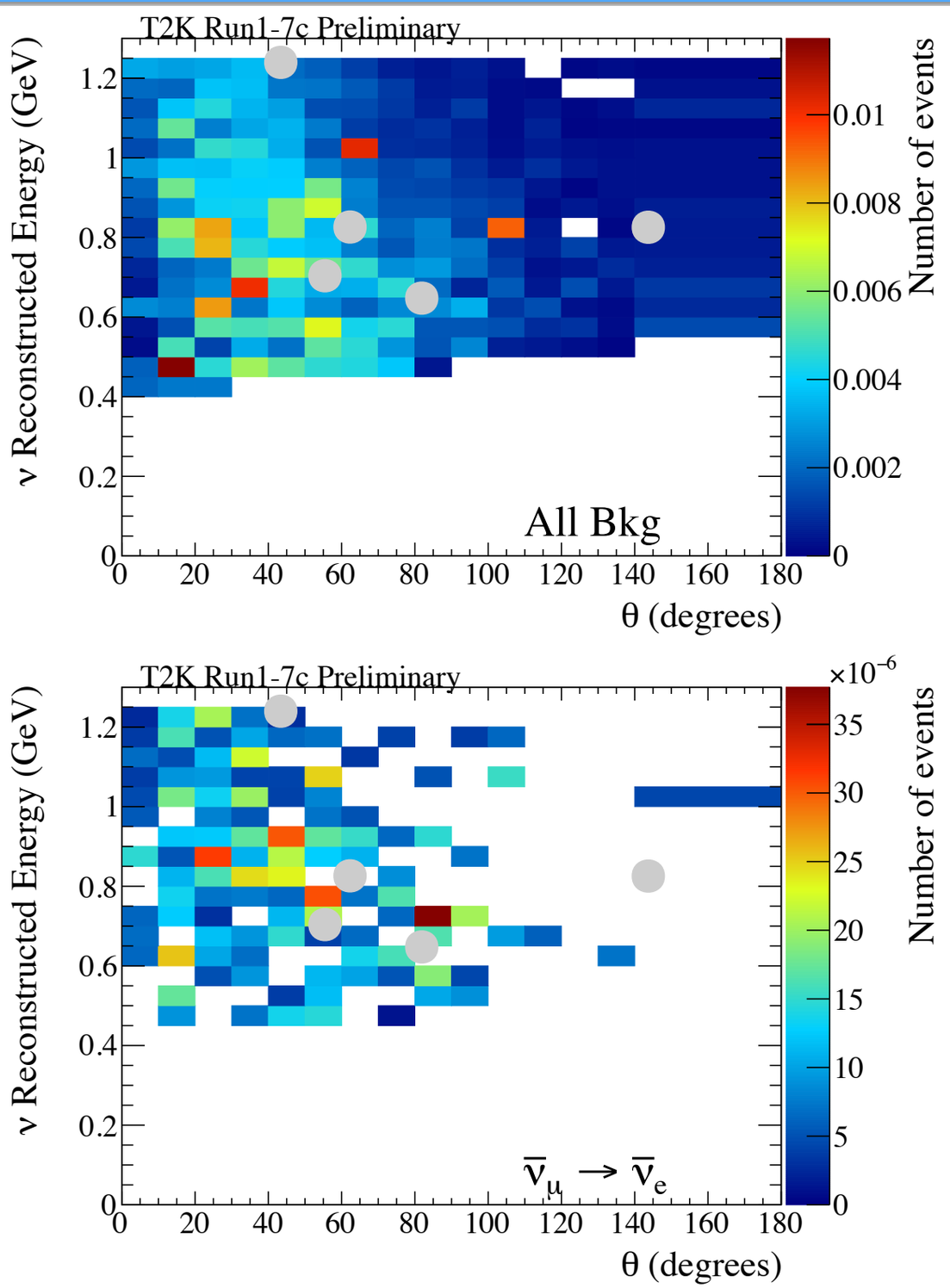
RHC electron line



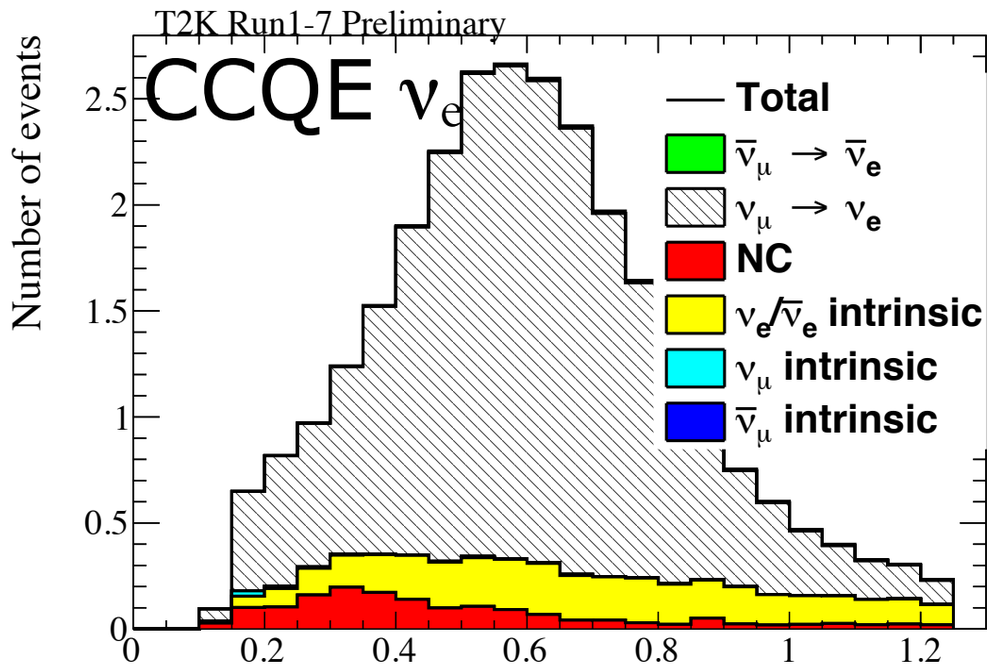


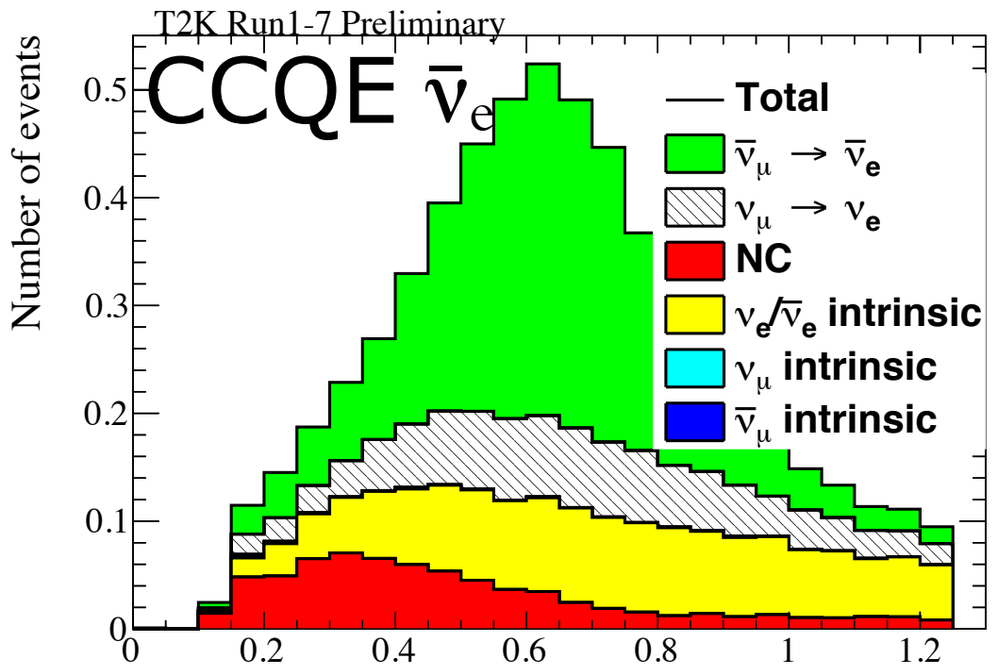
CC1π^+-like

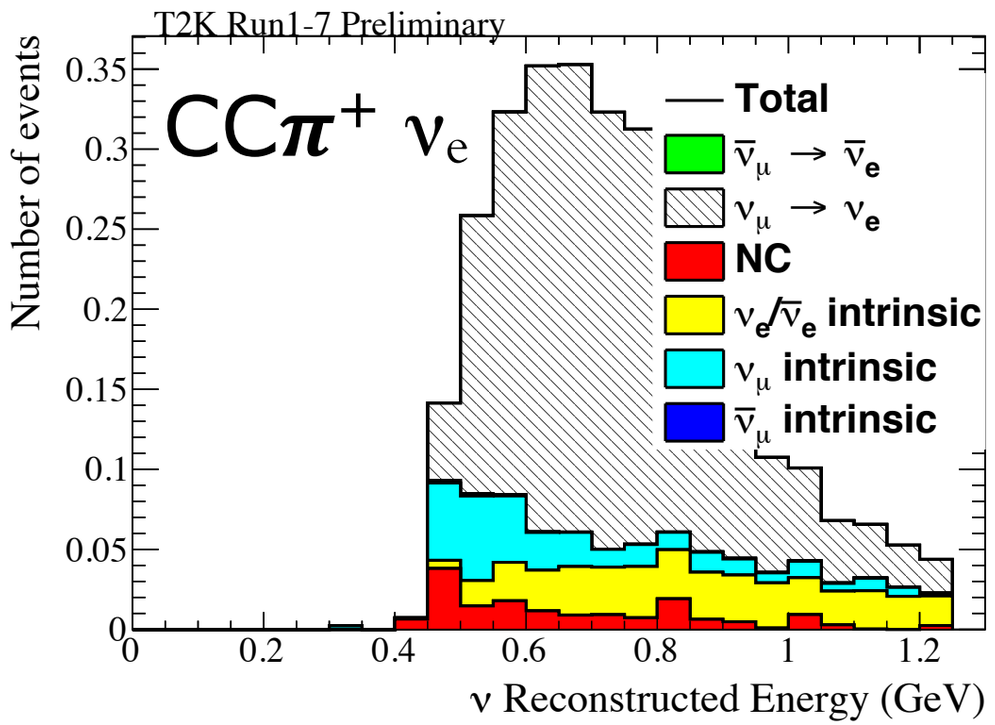

T2K Run1-7c Preliminary
ν Reconstructed Energy (GeV)
θ (degrees)
Number of events
$\nu_\mu \rightarrow \nu_e$


T2K Run1-7c Preliminary
ν Reconstructed Energy (GeV)
θ (degrees)
Number of events
All Bkg
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
×10⁻⁶

e-Like

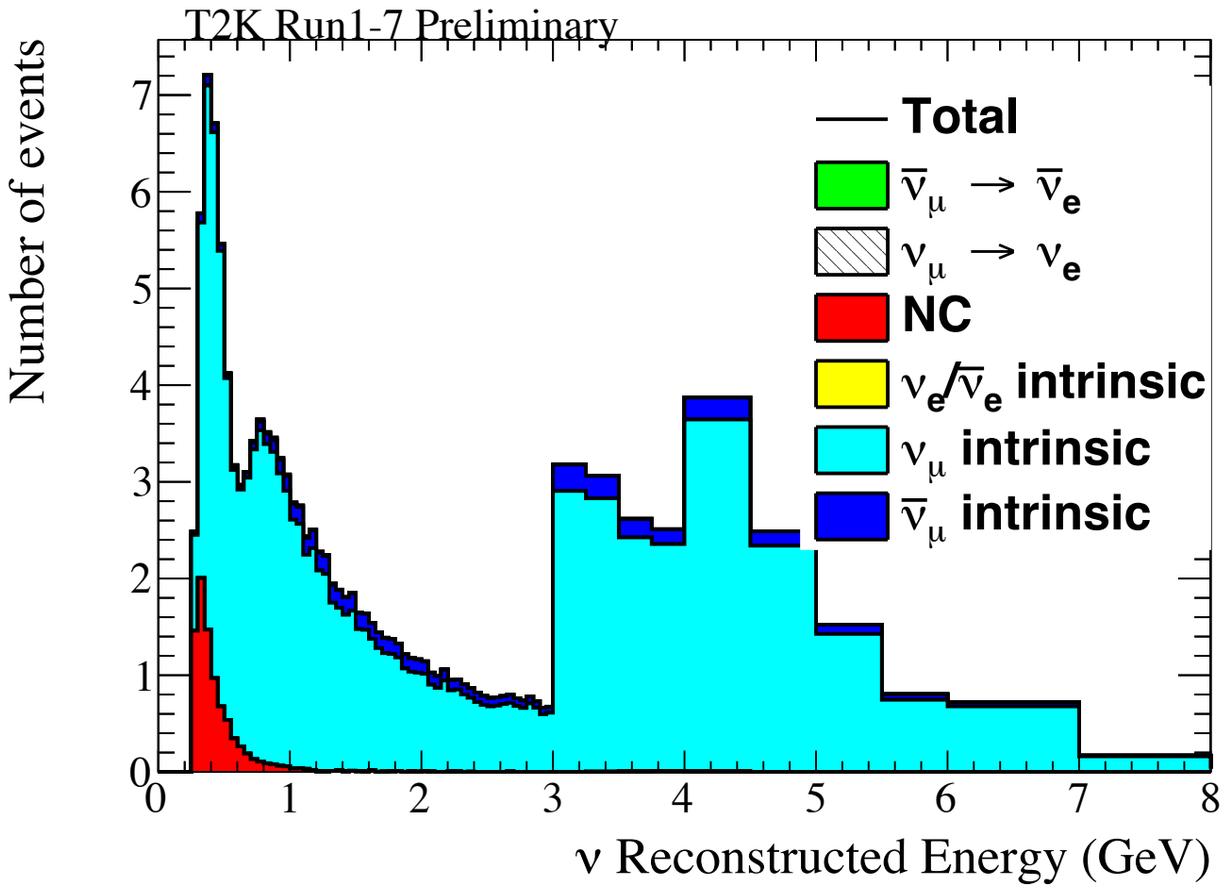

T2K Run1-7 Preliminary
CCQE ν_e
Total
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\nu_\mu \rightarrow \nu_e$
NC
$\nu_e/\bar{\nu}_e$ intrinsic
ν_μ intrinsic
$\bar{\nu}_\mu$ intrinsic
Number of events
ν Reconstructed Energy (GeV)


T2K Run1-7 Preliminary
CCQE $\bar{\nu}_e$
Total
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\nu_\mu \rightarrow \nu_e$
NC
$\nu_e/\bar{\nu}_e$ intrinsic
ν_μ intrinsic
$\bar{\nu}_\mu$ intrinsic
Number of events
ν Reconstructed Energy (GeV)

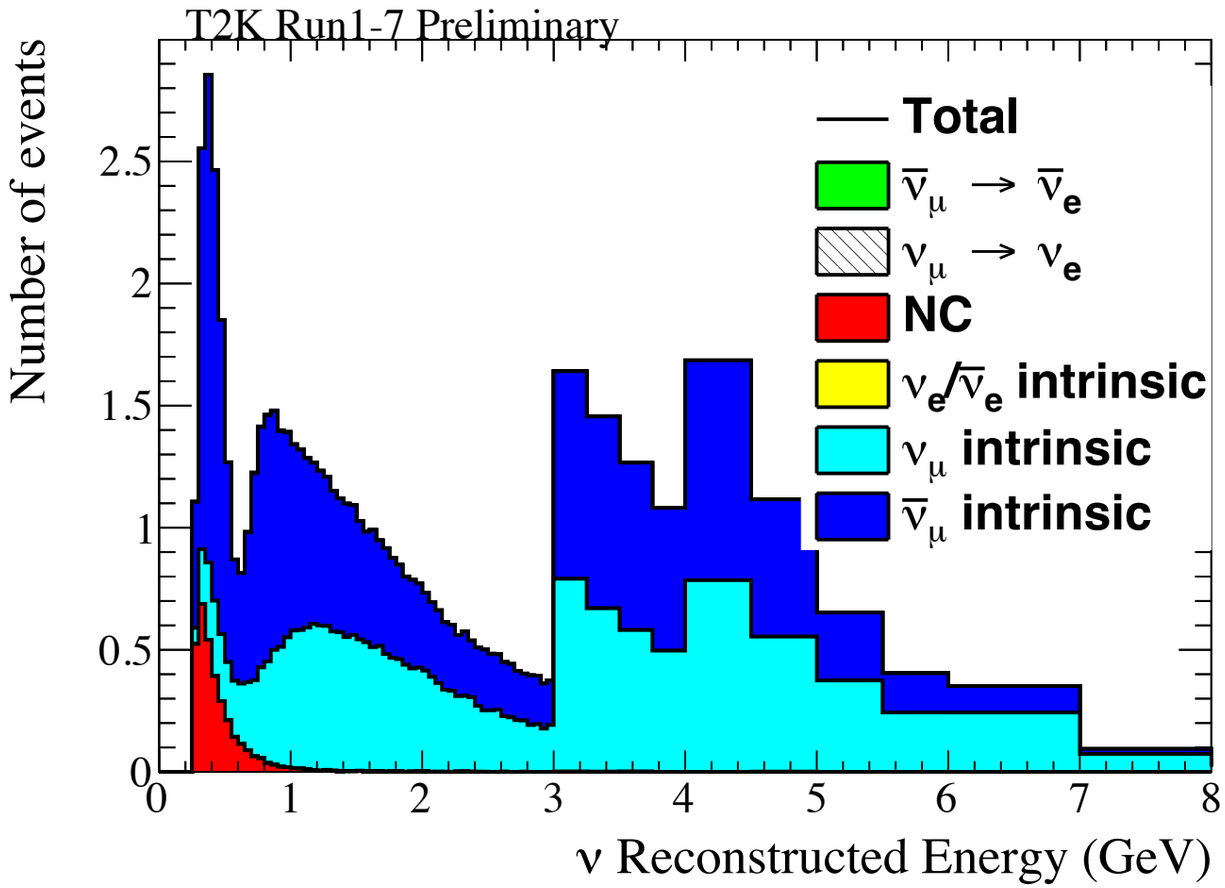

T2K Run1-7 Preliminary
CCπ^+ ν_e
Total
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\nu_\mu \rightarrow \nu_e$
NC
$\nu_e/\bar{\nu}_e$ intrinsic
ν_μ intrinsic
$\bar{\nu}_\mu$ intrinsic
Number of events
ν Reconstructed Energy (GeV)

μ-Like

CCQE ν_μ



CCQE $\bar{\nu}_\mu$



Uncertainty μ

ν_μ CCQE

Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	4.16%
Flux	3.56%
MEC (corr)	3.51%
MECbar (corr)	0.21%
NC 1gamma (uncorr)	0.00%
XSec nue/numu	0.01%
XSec Tot	4.03%
Flux+XSec	2.93%
Oscillations	0.03%
All	5.11%
All prefit	12.02%

$\bar{\nu}_\mu$ CCQE

Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	11.15%
Flux	3.80%
MEC (corr)	2.95%
MECbar (corr)	1.82%
NC 1gamma (uncorr)	0.00%
XSec nue/numu	0.00%
XSec Tot	4.23%
Flux+XSec	3.45%
Oscillations	0.03%
All	11.69%
All prefit	17.92%

Uncertainty e

ν_e CCQE

Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	3.52%
Flux	3.66%
MEC (corr)	3.90%
MECbar (corr)	0.05%
NC 1gamma (uncorr)	1.49%
XSec nue/numu	2.62%
XSec Tot	5.12%
Flux+XSec	4.20%
Oscillations	4.22%
All	6.81%
All prefit	12.71%

$\bar{\nu}_e$ CCQE

Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	3.98%
Flux	3.80%
MEC (corr)	2.98%
MECbar (corr)	2.32%
NC 1gamma (uncorr)	2.97%
XSec nue/numu	1.50%
XSec Tot	5.49%
Flux+XSec	4.67%
Oscillations	4.00%
All	7.42%
All prefit	14.46%

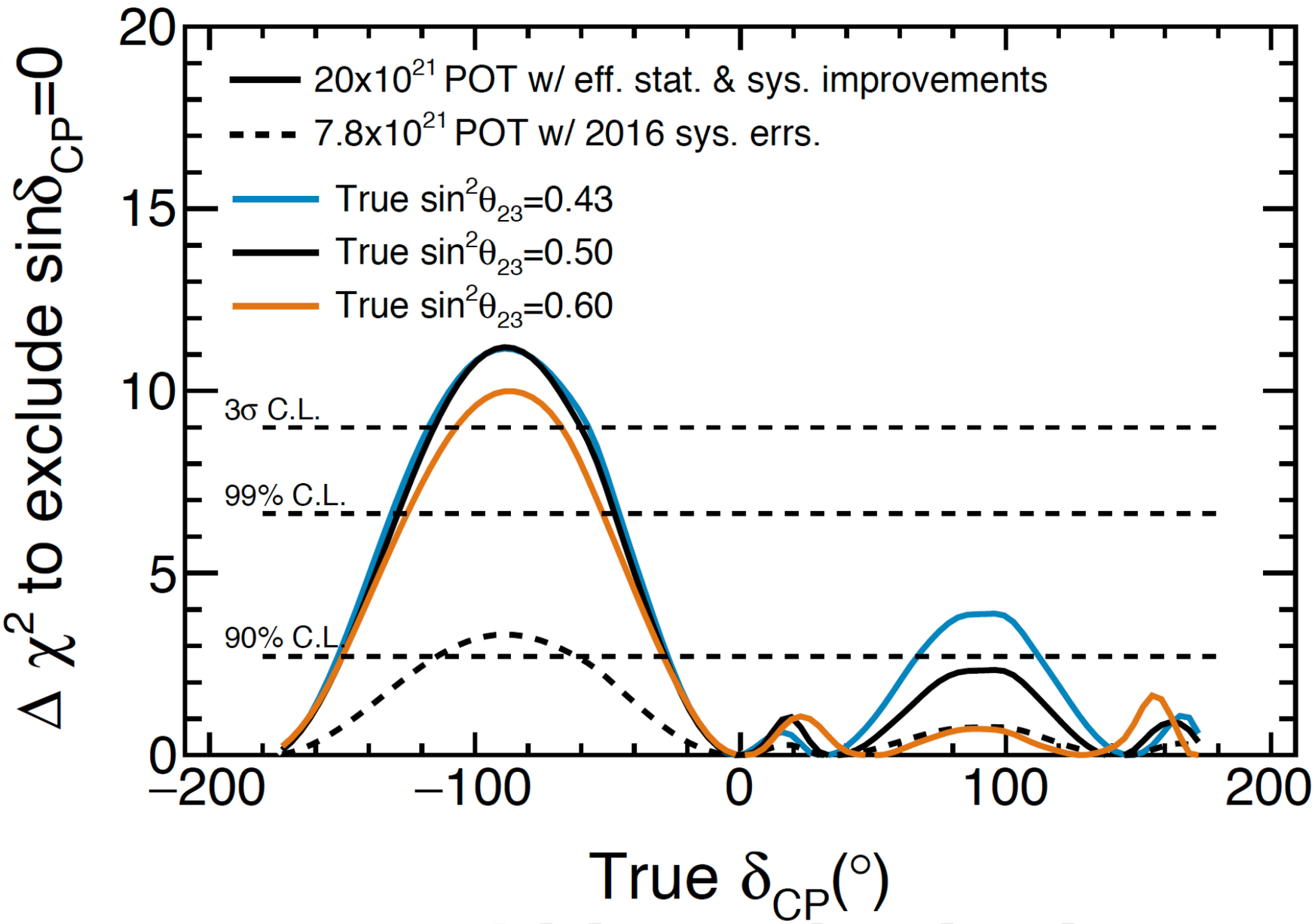
Uncertainty CC1π^+

ν_e CC1π^+

Source of uncertainty	$\delta N_{SK}/N_{SK}$ Asimov A
SKDet+FSI+SI	13.97%
Flux	3.58%
MEC (corr)	0.49%
MECbar (corr)	0.01%
NC 1gamma (uncorr)	0.43%
XSec nue/numu	2.44%
XSec Tot	4.87%
Flux+XSec	5.02%
Oscillations	3.77%
All	15.33%
All prefit	21.88%

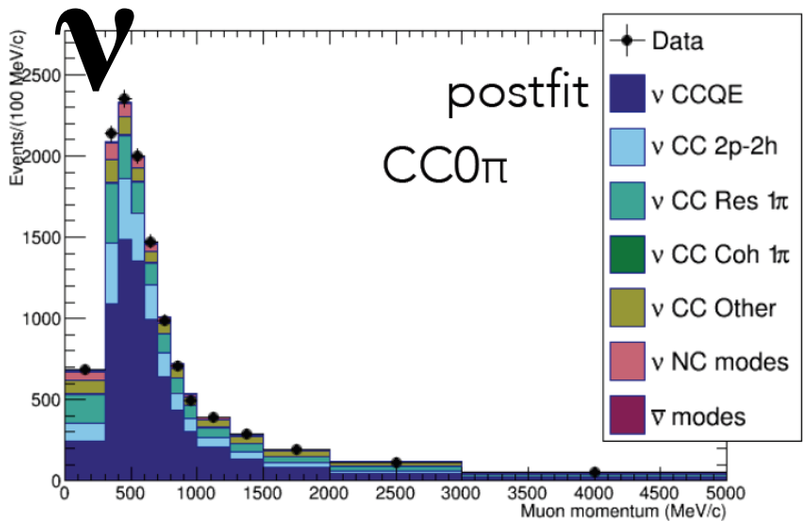
T2K Phase 2

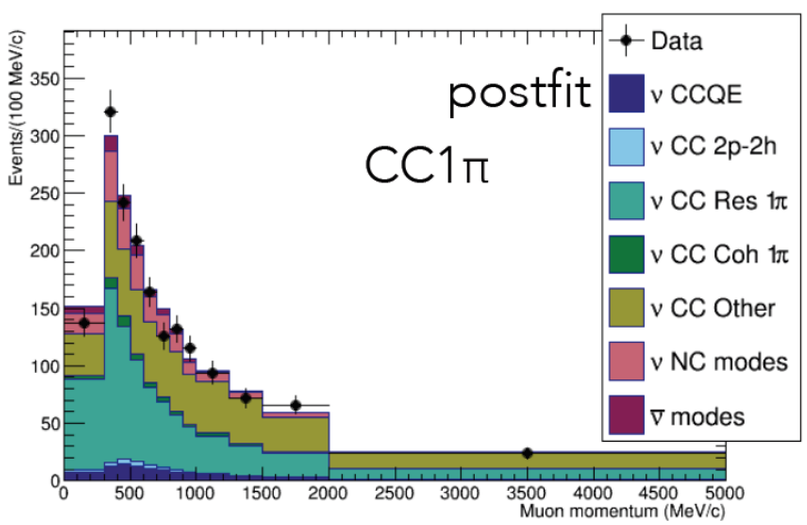
sin(δcp)=0 exclusion vs True δcp

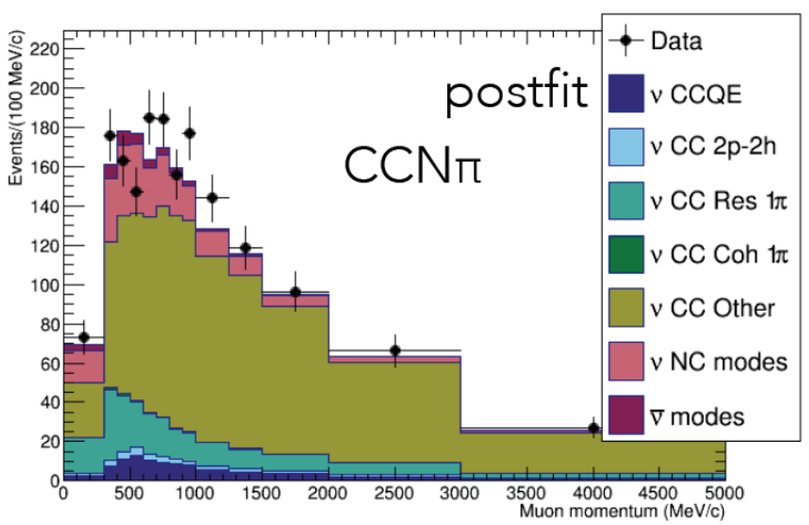


True Normal hierarchy (unknown)

ND280 Fit



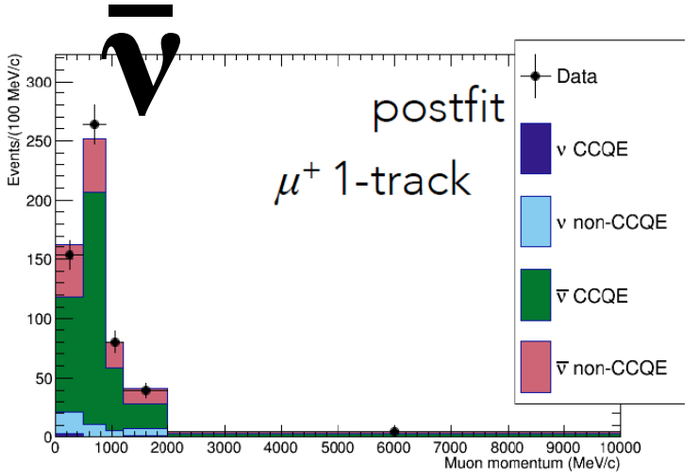


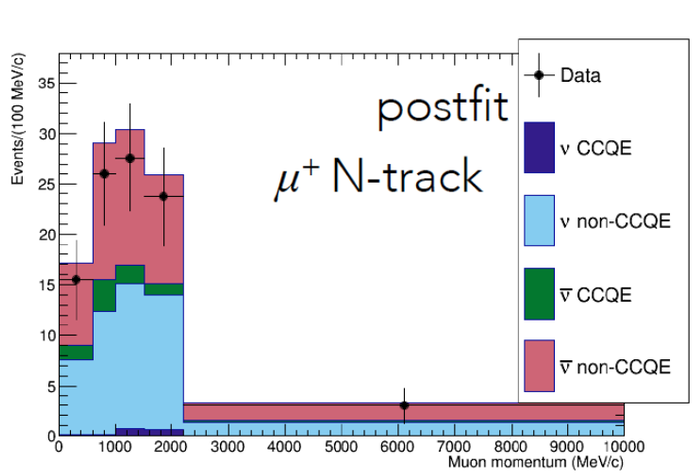


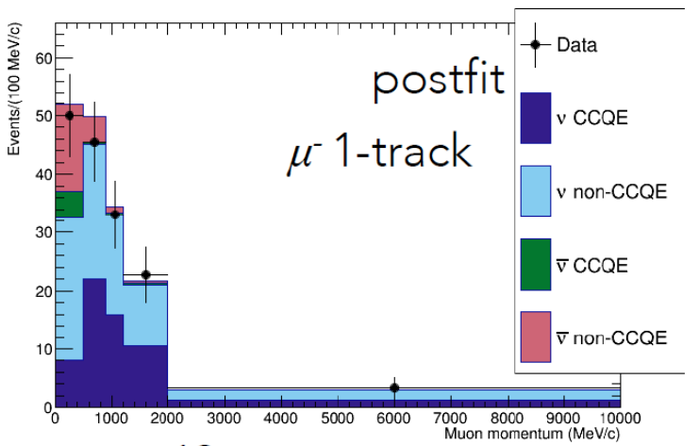
FGD2 (Water)

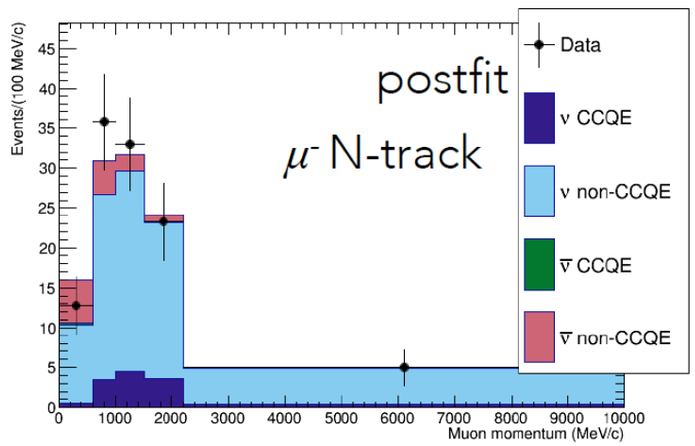
3 ν-mode samples
5.8e20 POT
4 $\overline{\nu}$-mode samples
2.8e20 POT

Total x2 (FGD1)









$\bar{\nu}_e$ Appearance

1. Determine significance of $\bar{\nu}_e$ candidate event excess under no appearance

2. Determine the consistency with the PMNS prediction given the ν-mode data

7.47e20 POT

Signal	Background (3.22)		
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	Beam ν_e	NC
2.786	1.04	1.47	0.71

4 events observed!

Normal Hierarchy

$$\sin^2(\theta_{13}) = 0.0217,$$
$$\sin^2(\theta_{23}) = 0.528$$
$$\delta_{CP} = \text{-}1.601,$$
$$\sin^2(\theta_{12}) = 0.306,$$
$$\Delta m^2_{21} = 7.5 \cdot 10^{-5} eV^2,$$
$$\Delta m^2_{32} = 2.51 \cdot 10^{-3} eV^2$$

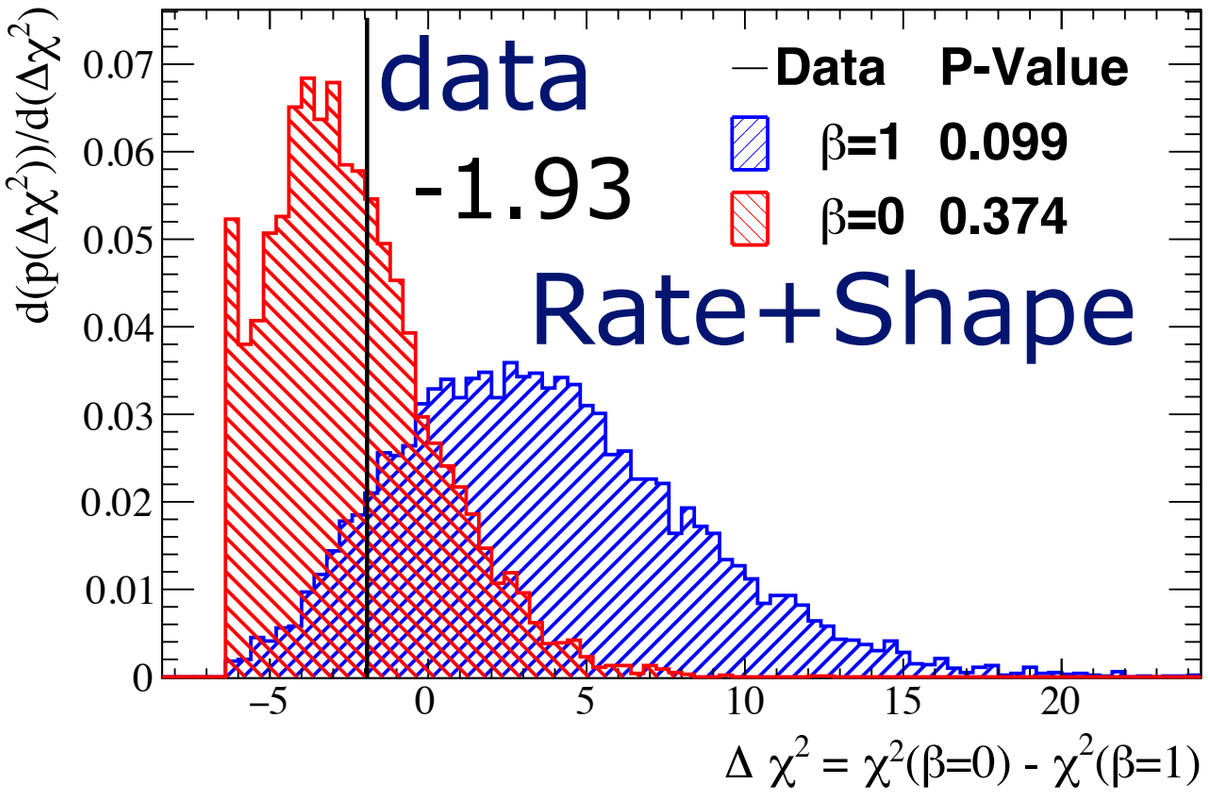
$\bar{\nu}_e$ Appearance

Null Hypotheses

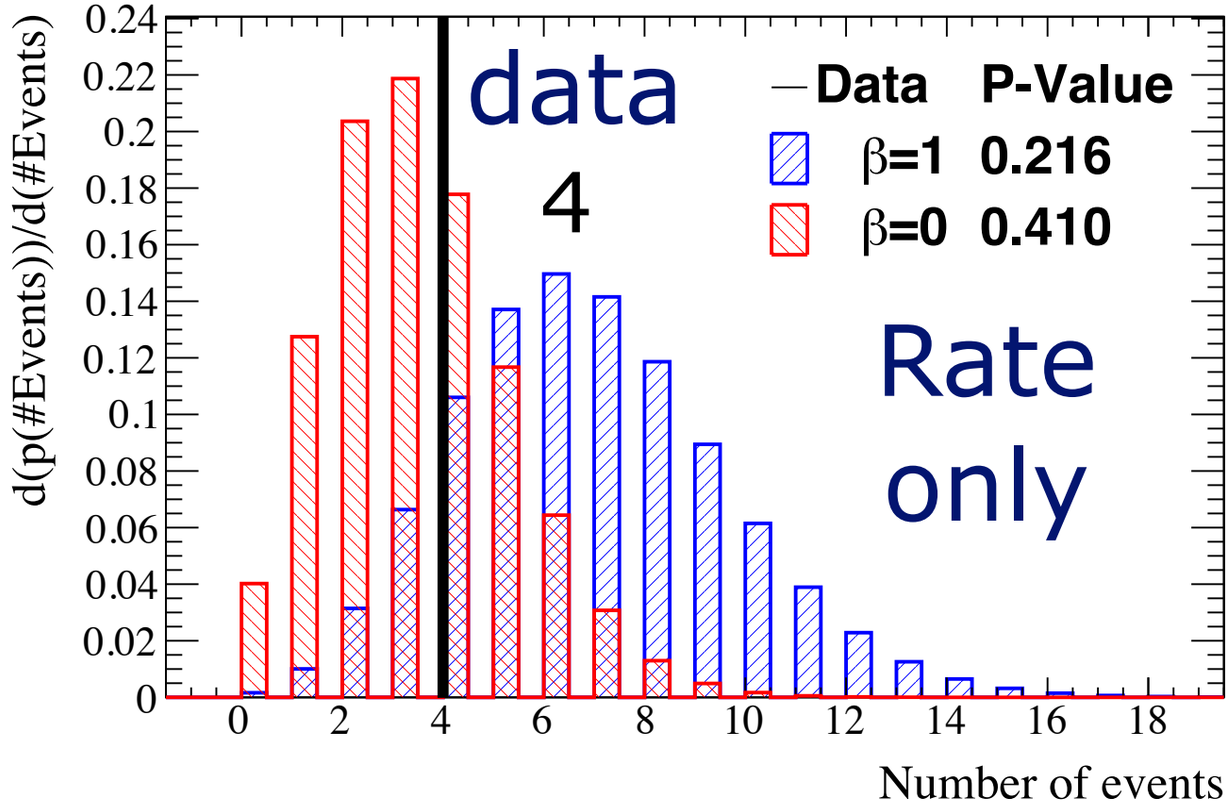
No $\bar{\nu}_e$ appearance (β=0)

PMNS $\bar{\nu}_e$ appearance (β=1)

$P_{osc}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \cdot P_{osc}(\text{PMNS})$



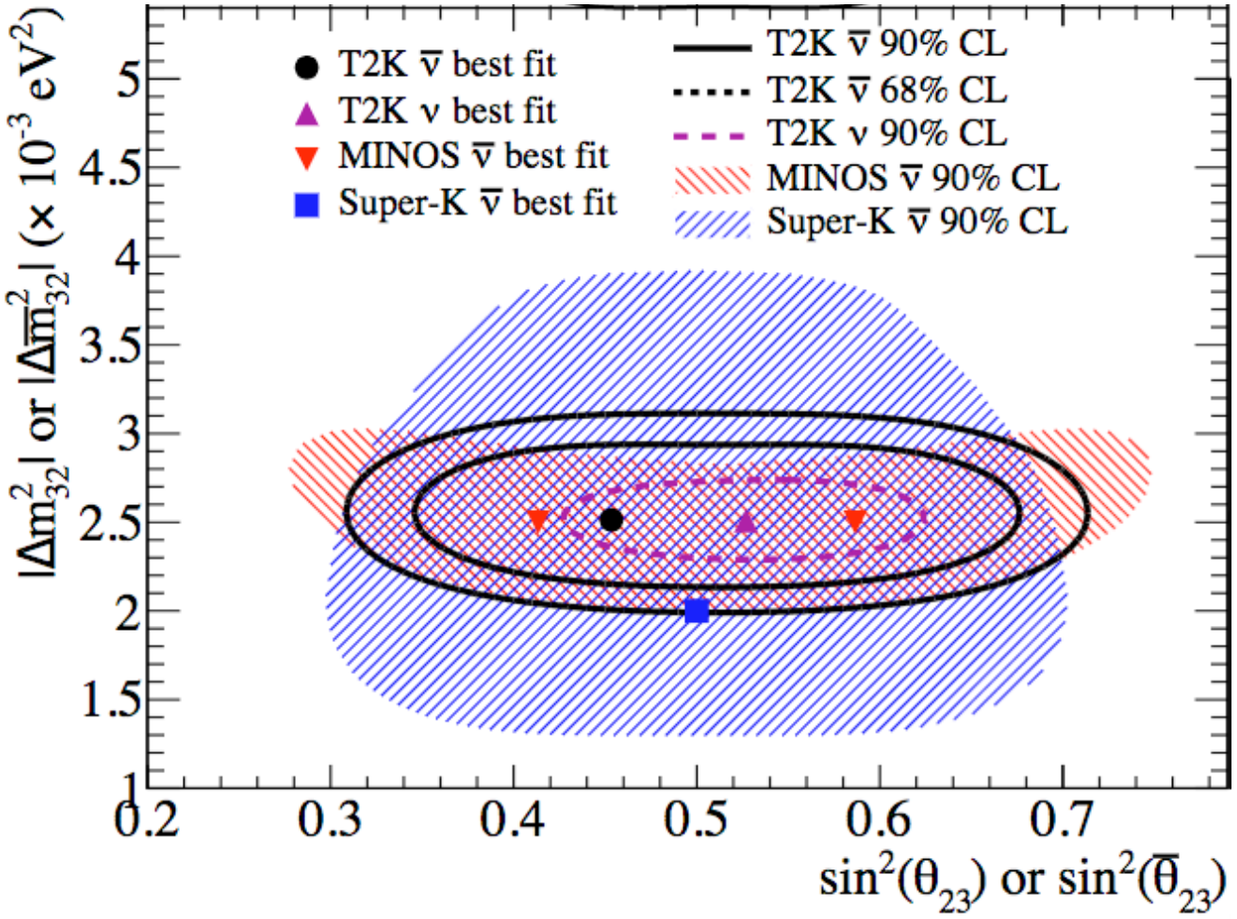
$P_{osc}(\nu_x \rightarrow \nu_y) = P_{osc}(\text{PMNS})$



B_{01} = 2.62 : Weak preference for β=0

$\bar{\nu}_\mu$ Disappearance

- Introduce new separate parameters $\sin^2(\bar{\theta}_{23})$ and $\Delta\bar{m}^2_{32}$ for $\bar{\nu}$ oscillations.
- Fix all ν oscillation (background) PMNS parameters $\sin^2(\theta_{23})=0.528$ and $\Delta m^2_{32}=2.509\text{e-}3\ eV^2$



$\bar{\nu}$: $6.57\times10^{20}_{POT}$

$\bar{\nu}$: $4.01\times10^{20}_{POT}$