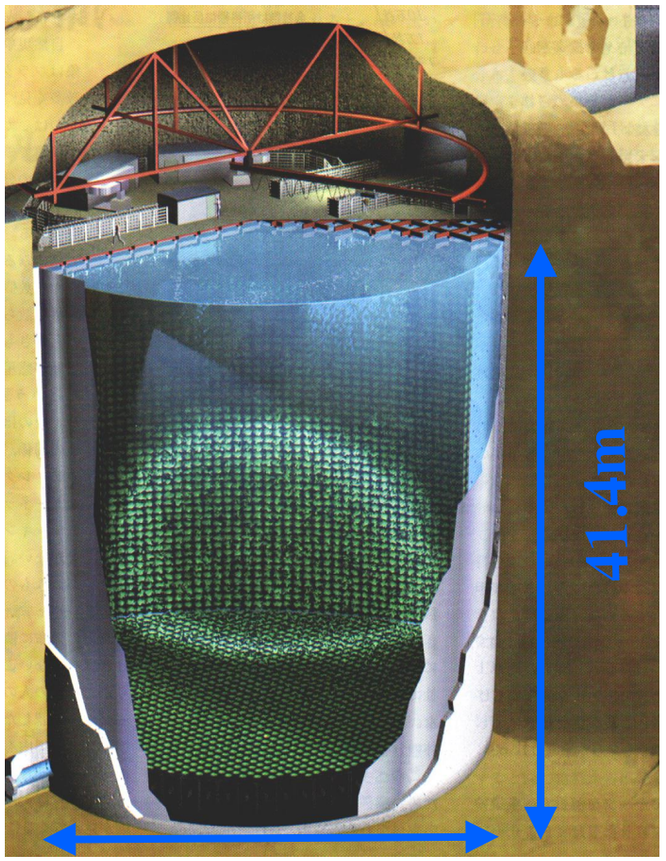
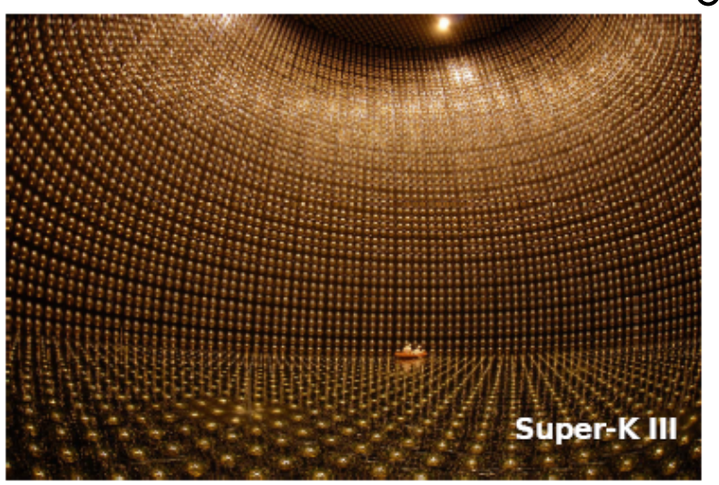
6. Super-Kamiokande

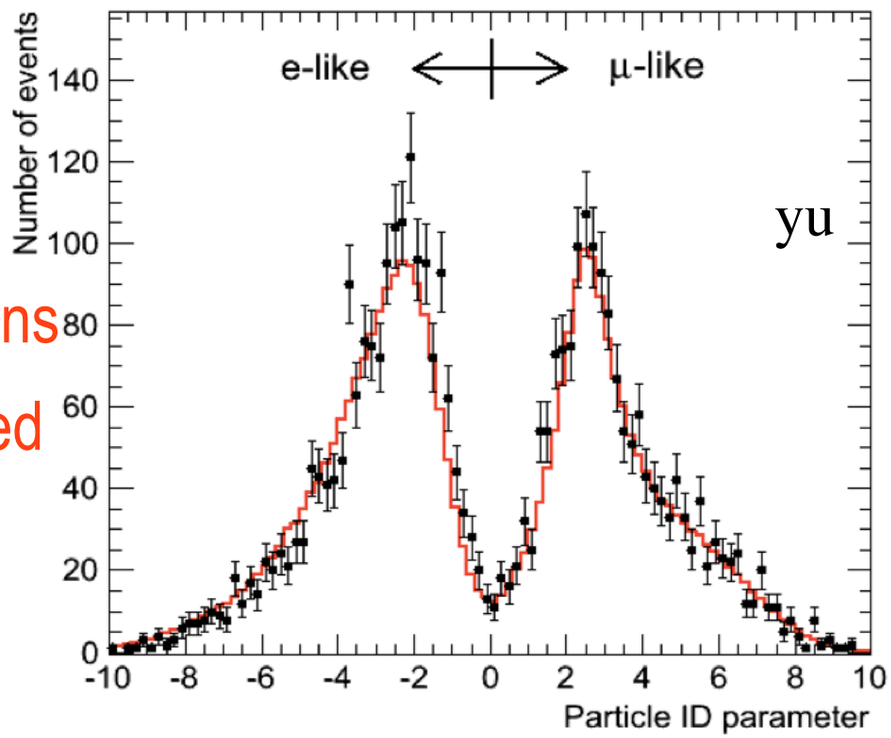
- Far Detector -

T2K-Far Detector: Super-Kamiokande

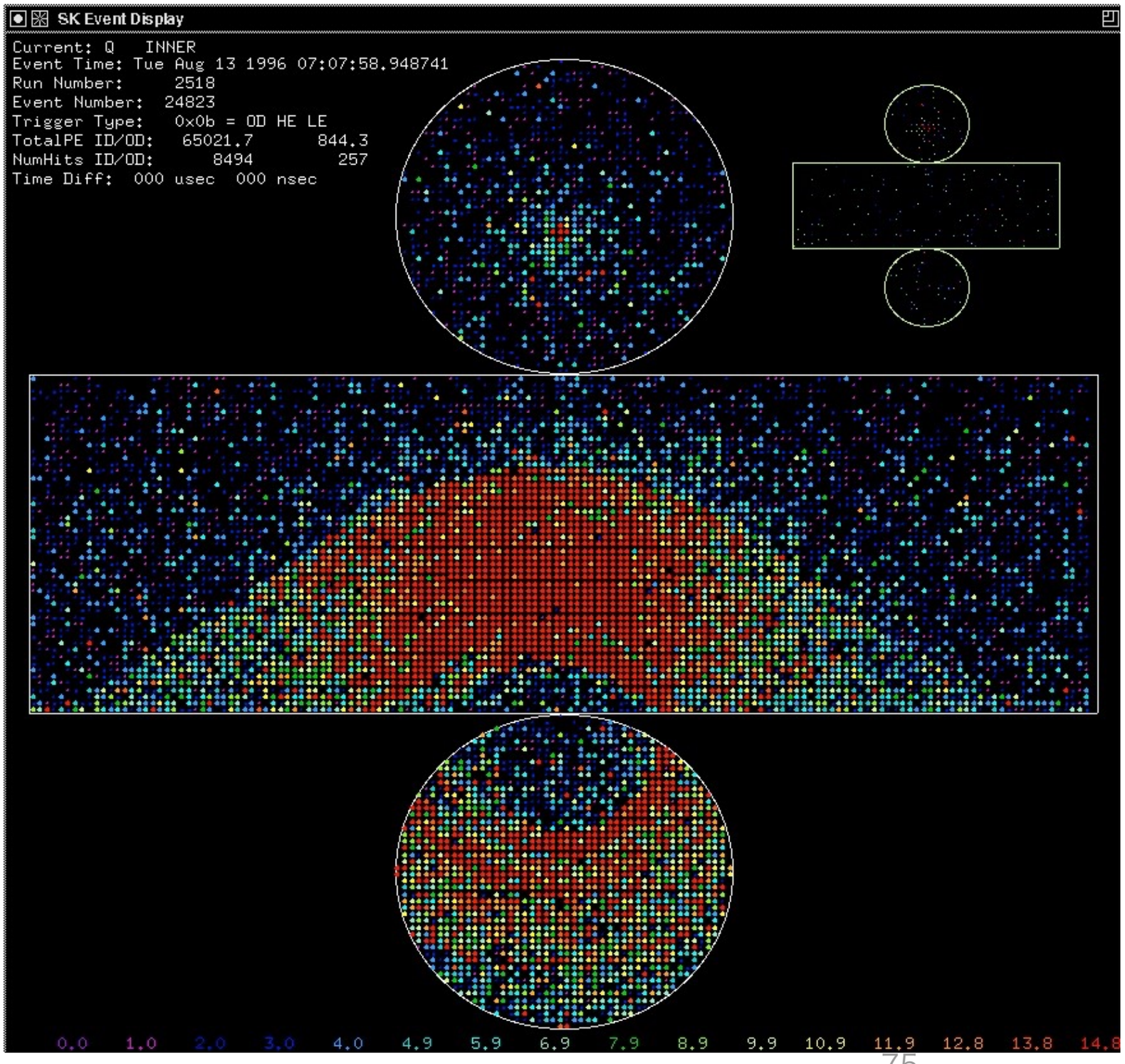


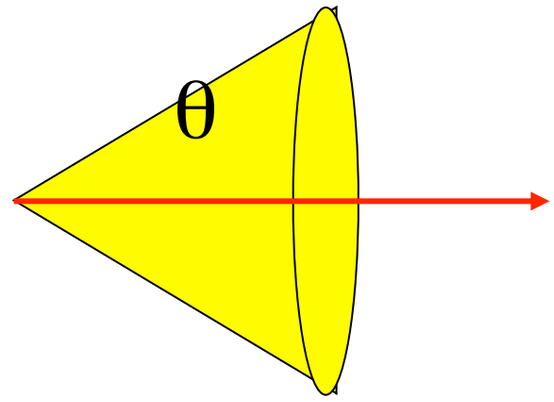


- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with 95% NC-1π^0 rejection
    - Inner tank (32 kton) :11,129 20inch PMT
    - Outer tank:1,885 8inch PMT
- Dead-time-less DAQ
- GPS timing information is recorded real-time at every accelerator spill
  - T2K recorded events: All interactions within a ±500μsec window centered on the the neutrino arrival time.



• Cherenkov Imaging





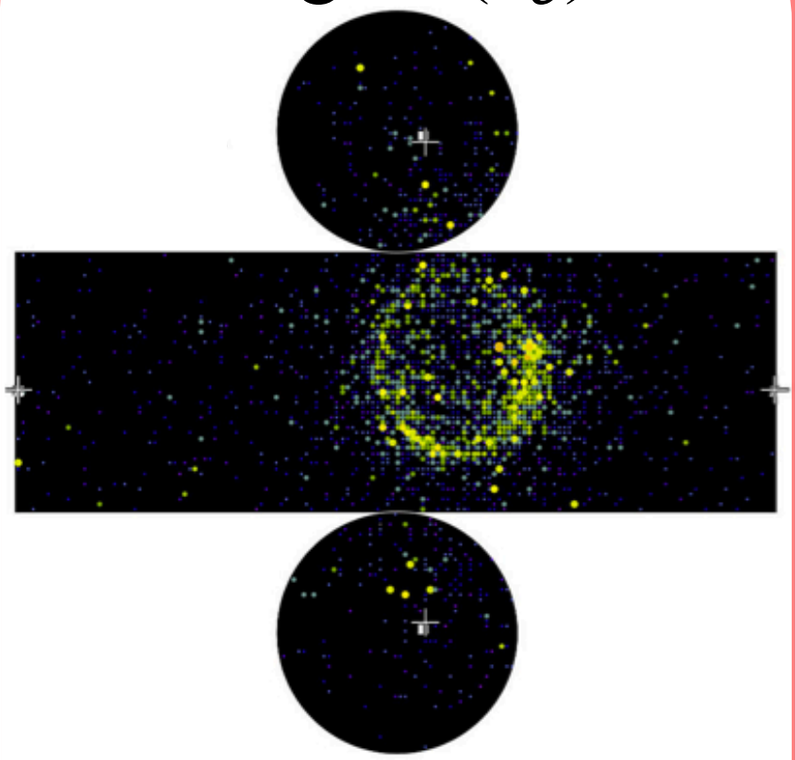
$\beta > 1/n$ (n=1.)

$\cos\theta = 1/n\beta$

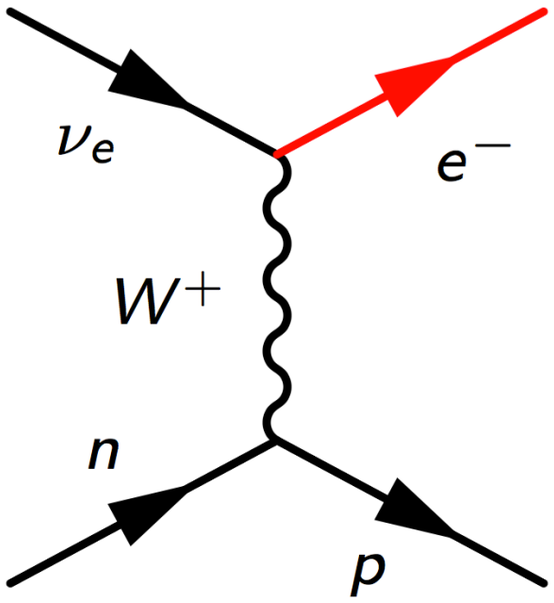
- **Particle ID.**
  - By the Cherenkov ring edge and the opening Angle.
- **Momentum**
  - The amount of light-yield inside a ring with PID
- **Vertex**
  - Timing of the PMT at the ring edge with PID

Neutrino Detection at SK Far Detector

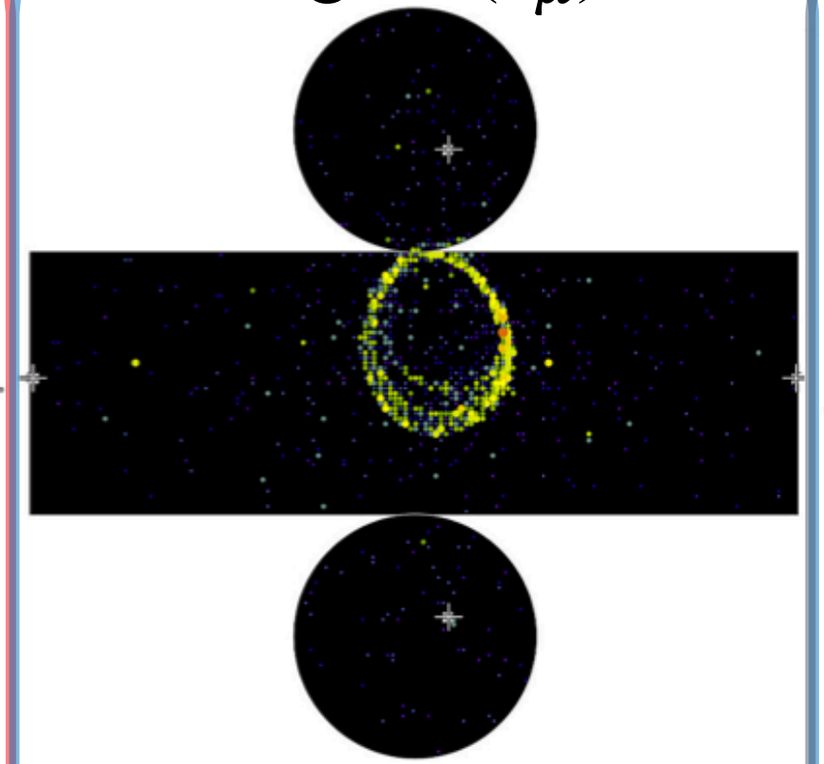
Signal (ν_e)



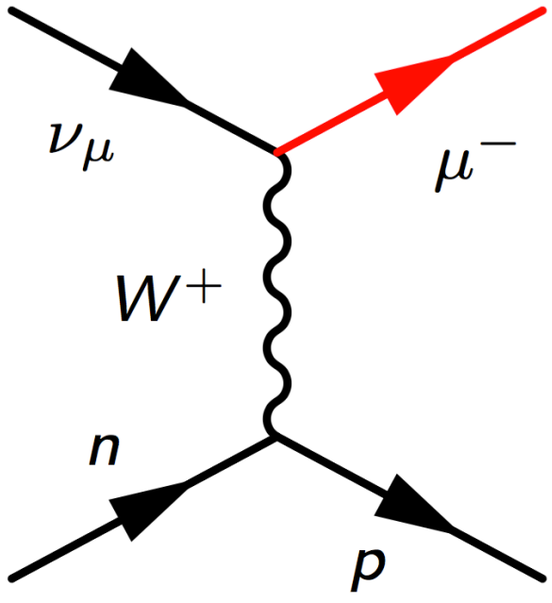
ν_e CCQE



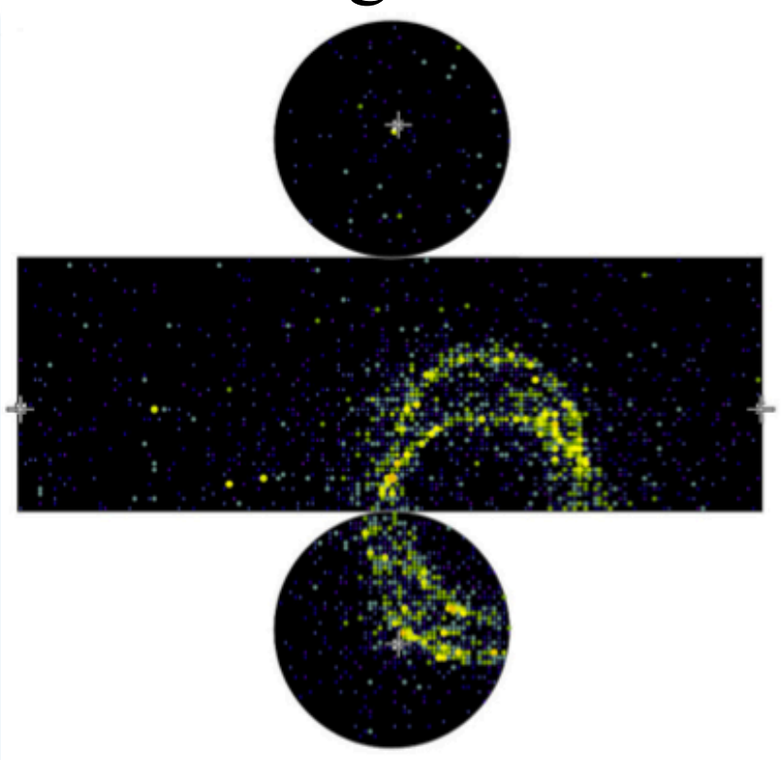
Signal (ν_μ)



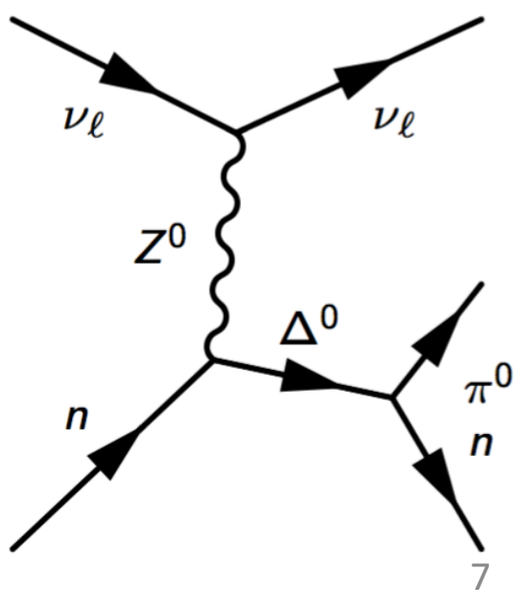
ν_μ CCQE



Background

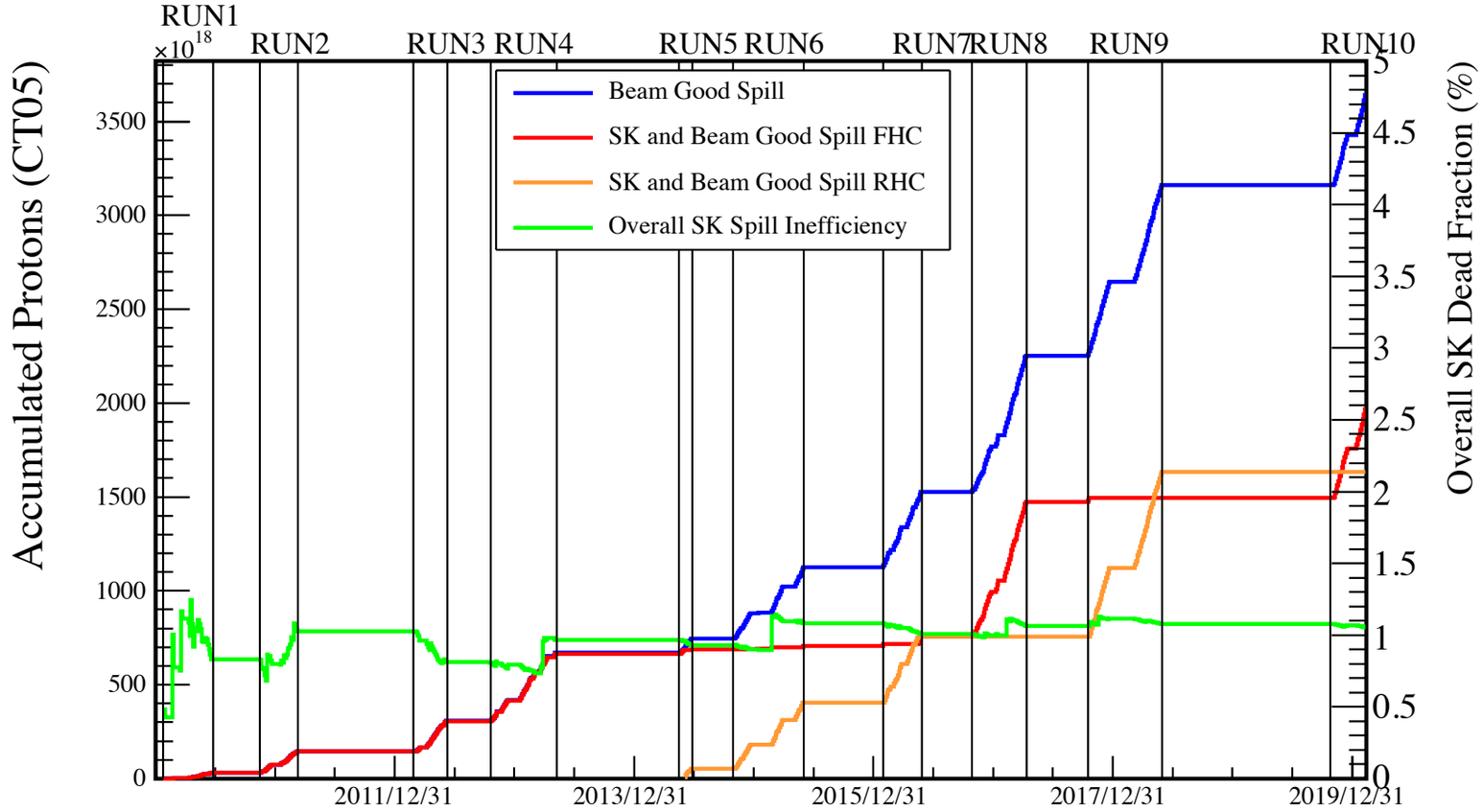


ν_ℓ NC1π^0



Initial Data Reduction

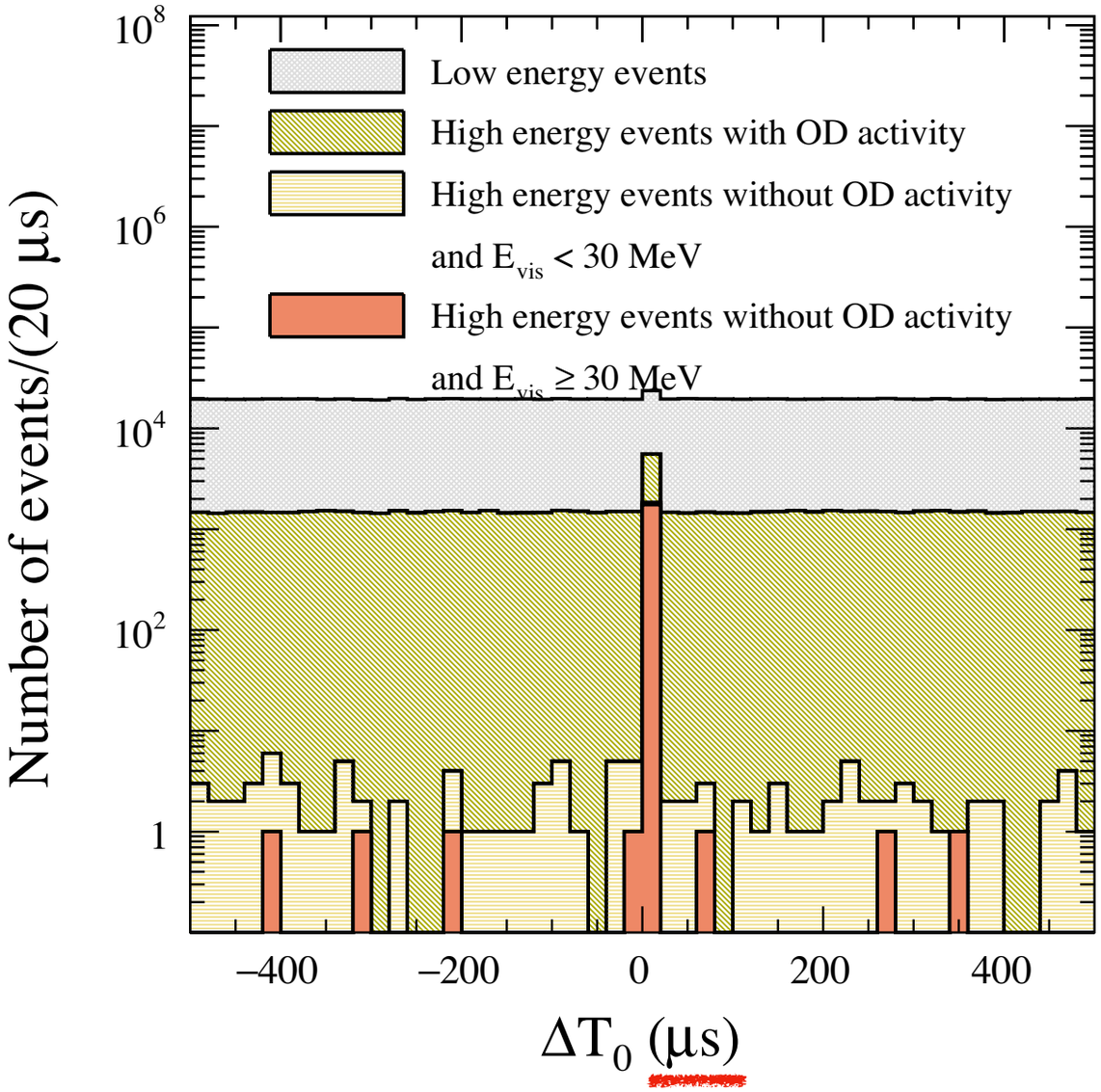
- Total POT
  - Neutrino beam
  - Anti-neutrino beam



	Number of spills			Inefficiency
	Runs 1-9	Run 10	Total	
Beam good spills	20,122,743	1,883,688	22,006,431	
(1) SK DAQ alive	20,085,525	1,881,924	21,967,449	0.18 %
(2) Bad subrun cut	20,039,874	1,881,636	21,921,510	0.21 %
(3) Incomplete data / GPS error cut	20,030,596	1,880,827	219,11,423	0.05 %
(4) Special data block cut	20,014,244	1,879,260	21,893,504	0.08 %
(5) Pre-activity cut	19,915,932	1,866,252	21,782,184	0.51 %
Total	19,915,932	1,866,252	21,782,184	1.02 %
POT ($\times 10^{20}$)	31.2836	4.7256	36.0092	

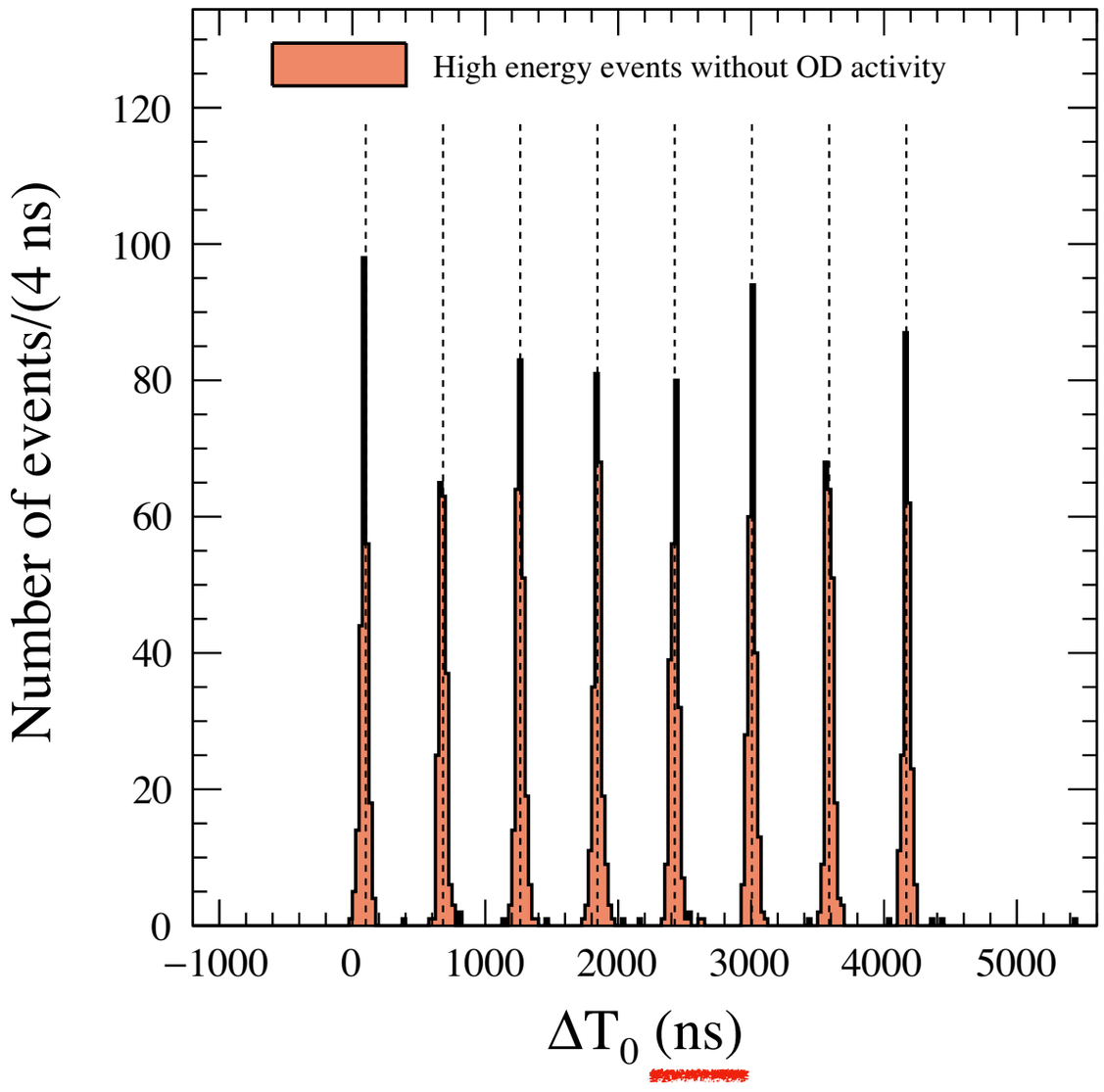
Timing Selection of accelerator neutrinos

Timing



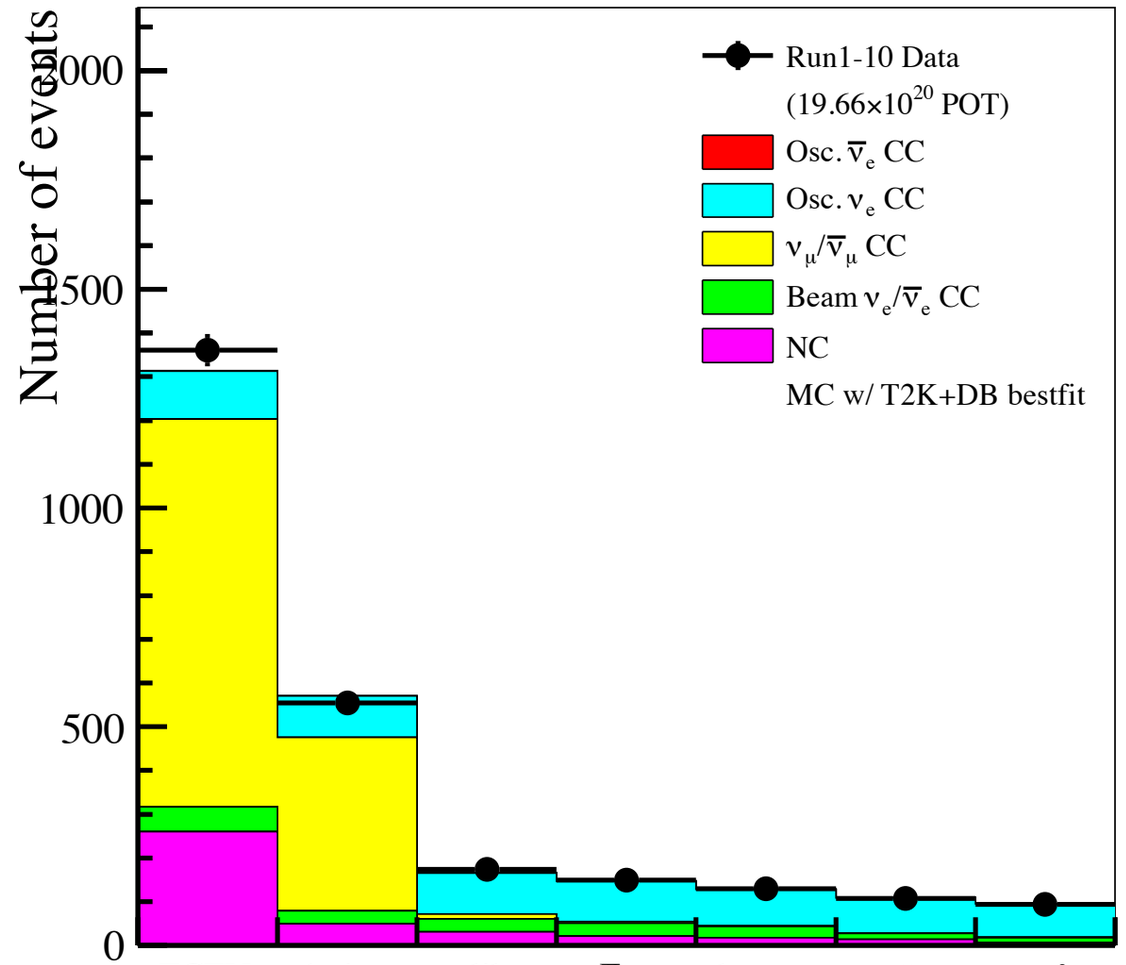
Timing

— Zoom —



Electron Neutrino Selection

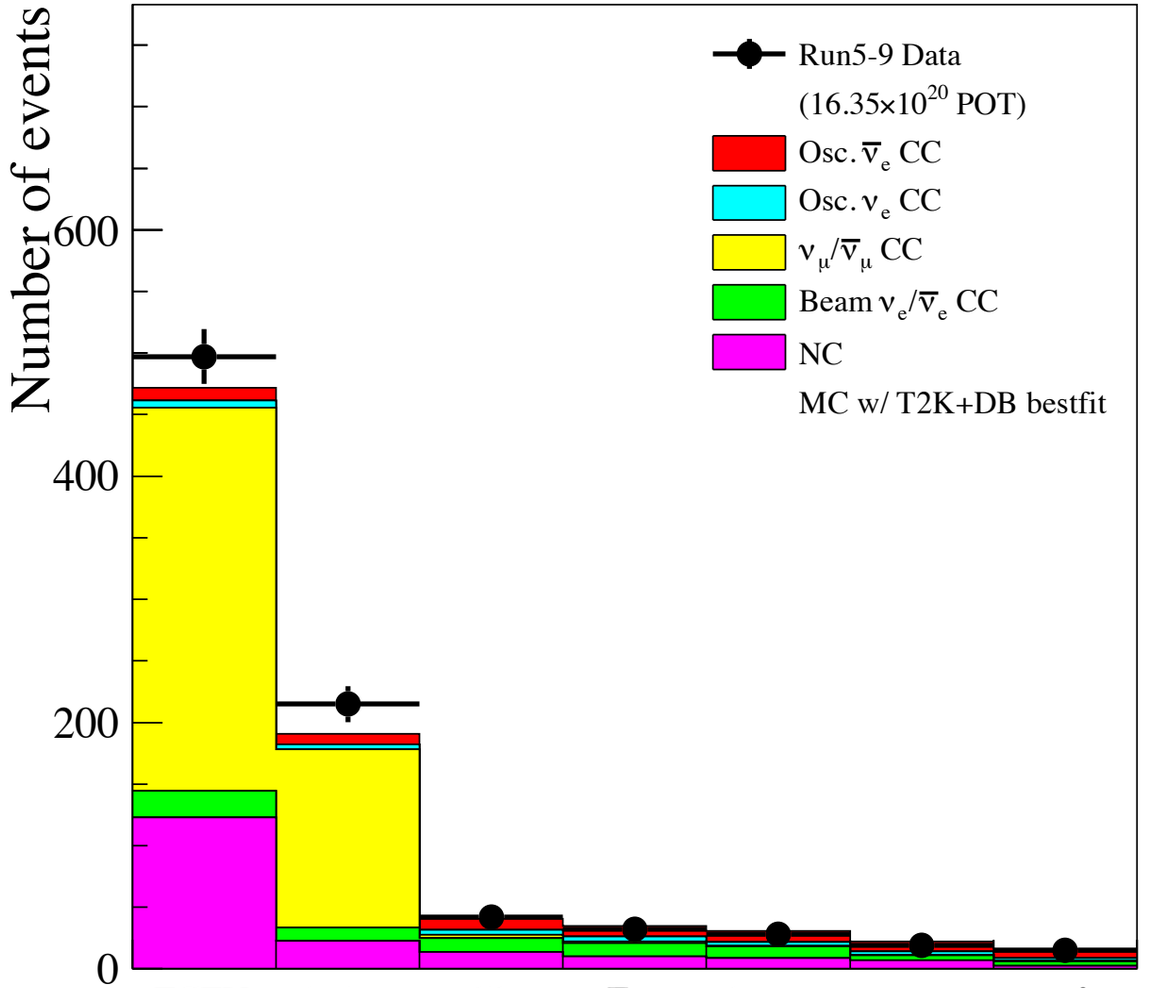
Parameter	Value
Δm^2_{21}	$7.53 \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{23}	$2.54 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{12}$	0.304
$\sin^2\theta_{13}$	0.0219
$\sin^2\theta_{23}$	0.550
δ_{CP}	-1.728
Mass Hierarchy	Normal
ν Travel Length	295 km
Earth Density	$2.6\,\mathrm{g\cdot\ cm^{-3}}$



Runs 1-10	Expected							Data
	$\nu_\mu + \bar{\nu}_\mu$ CC	Beam $\nu_e + \bar{\nu}_e$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.359	110.486	0.959	1246.704	1279
FCFV	886.362	56.685	260.508	1203.555	109.753	0.979	1314.287	1361
Single Ring	397.177	29.511	49.246	475.934	94.001	0.765	570.700	554
Electron-like PID	11.353	29.491	30.897	71.740	93.885	0.764	166.389	174
Evis $>$ 100 MeV	4.339	29.317	21.197	54.853	92.680	0.760	148.294	150
No Decay-e	1.196	24.903	18.205	44.304	83.884	0.738	128.927	130
Erec	0.764	13.129	14.137	28.029	81.240	0.540	109.809	107
π^0 rejection cut	0.423	11.661	6.607	18.691	76.164	0.461	95.315	94
Efficiency from FCFV	0.000	0.206	0.025	0.016	0.694	0.470	0.073	-

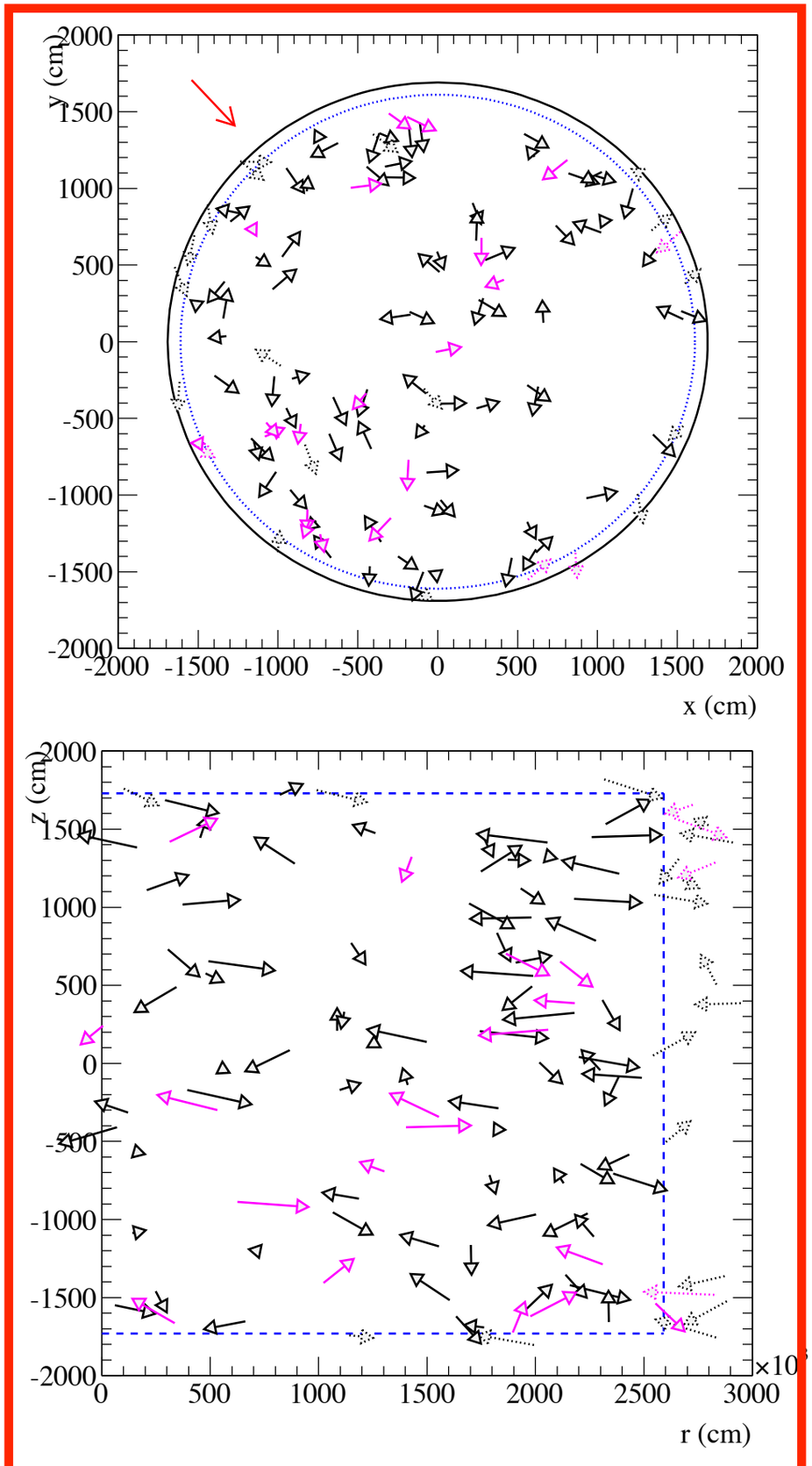
Electron Anti-Neutrino Selection

Parameter	Value
Δm^2_{21}	$7.53 \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{23}	$2.54 \times 10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{12}$	0.304
$\sin^2\theta_{13}$	0.0219
$\sin^2\theta_{23}$	0.550
δ_{CP}	-1.728
Mass Hierarchy	Normal
ν Travel Length	295 km
Earth Density	$2.6\,\mathrm{g}\cdot\,\mathrm{cm}^{-3}$



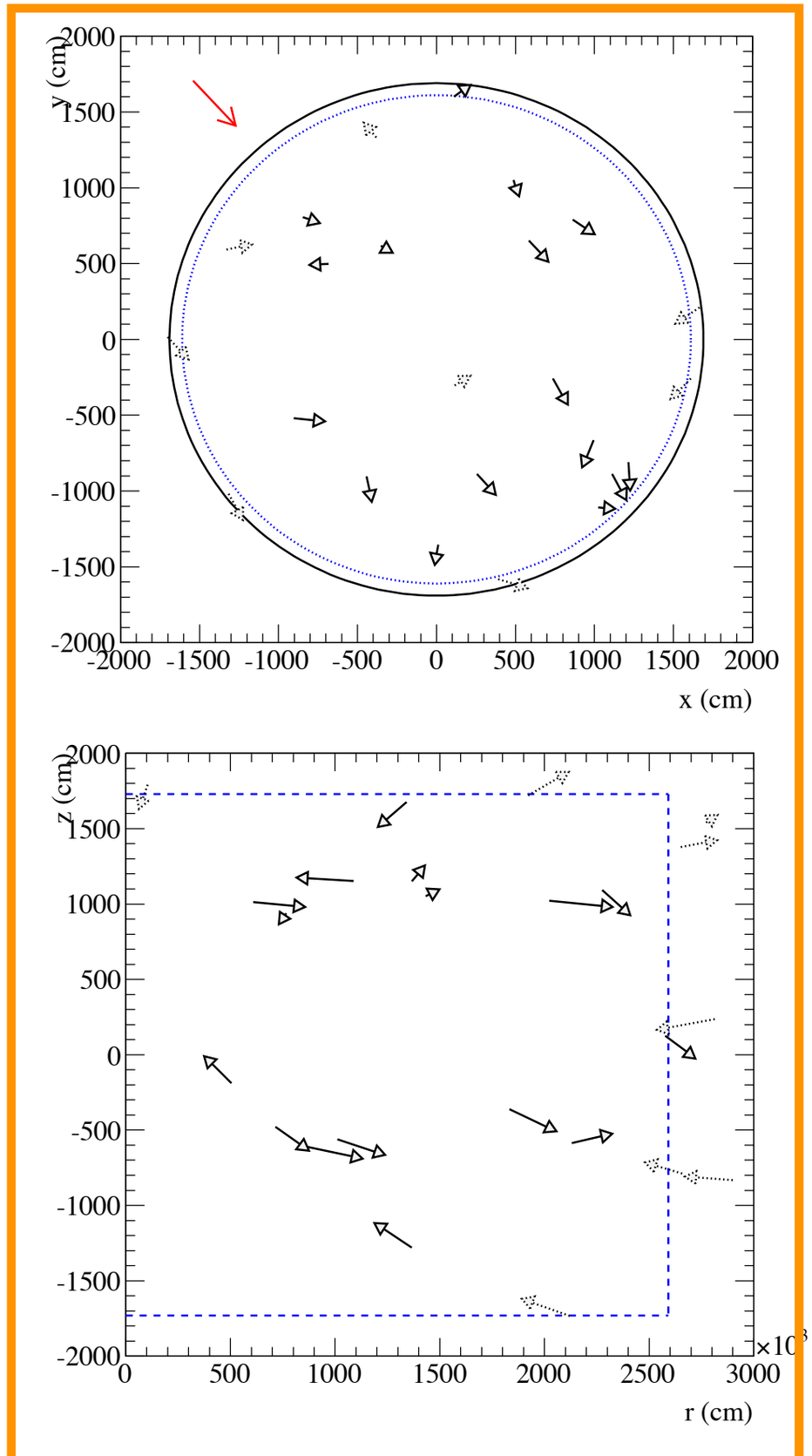
Runs 5-9	Expected							Data
	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	MC total	
Floor-FCFV	290.199	19.106	120.797	430.102	4.202	10.349	444.653	460
Sample-FCFV	311.203	21.476	122.864	455.543	5.810	10.312	471.665	497
Single Ring	144.493	10.884	22.609	177.986	4.133	8.809	190.927	215
Electron-like PID	2.806	10.875	13.831	27.512	4.126	8.802	40.440	42
Evis > 100 MeV	1.410	10.830	9.916	22.156	4.062	8.748	34.966	32
No Decay-e	0.406	9.479	8.600	18.485	3.465	8.581	30.532	28
Erec	0.277	4.272	6.770	11.318	2.914	8.133	22.365	19
π^0 rejection cut	0.130	3.701	2.404	6.235	2.646	7.374	16.255	**16**
Efficiency from FCFV	0.000	0.172	0.020	0.014	0.455	0.715	0.034	-

Fiducial Volume

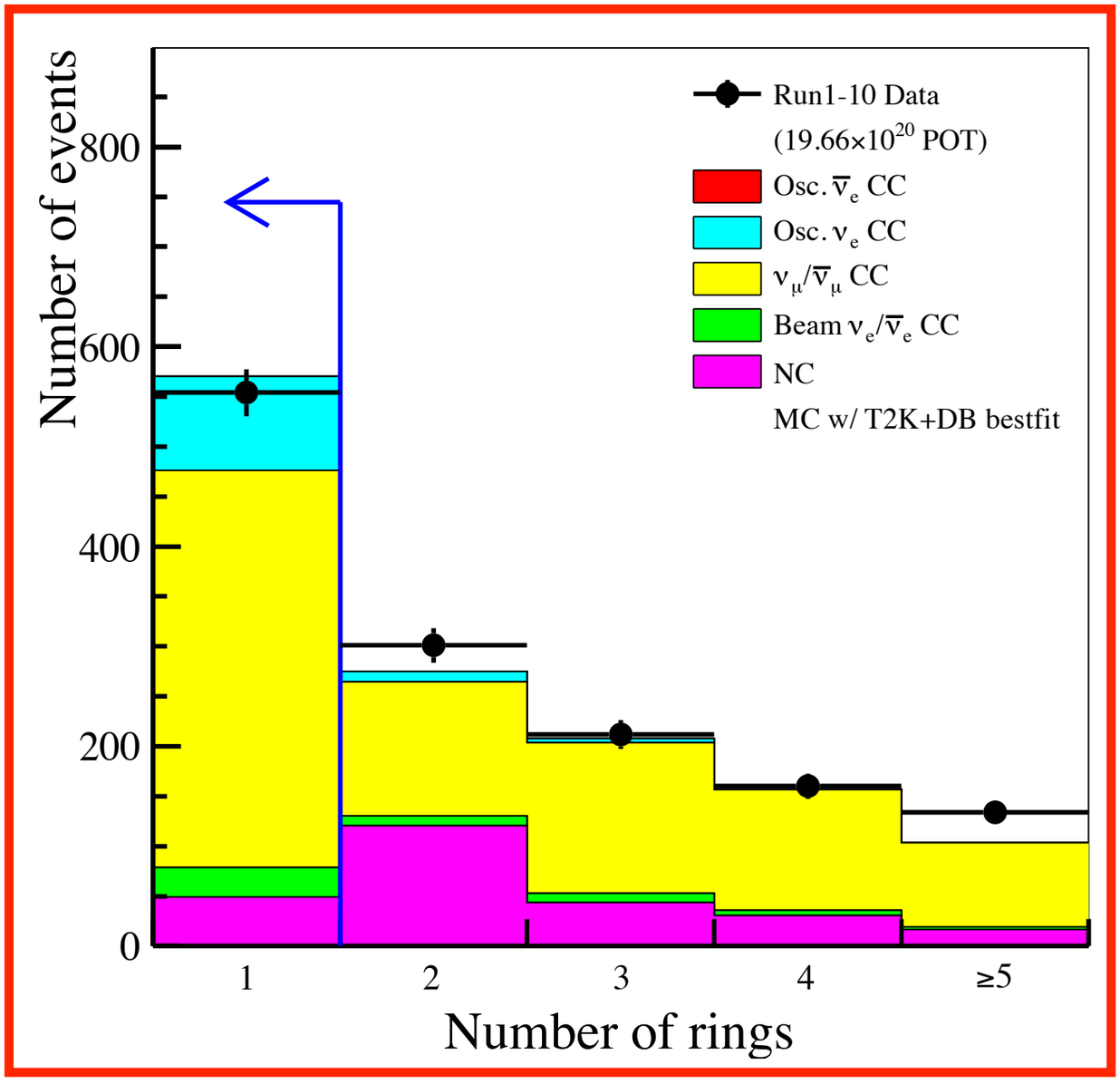


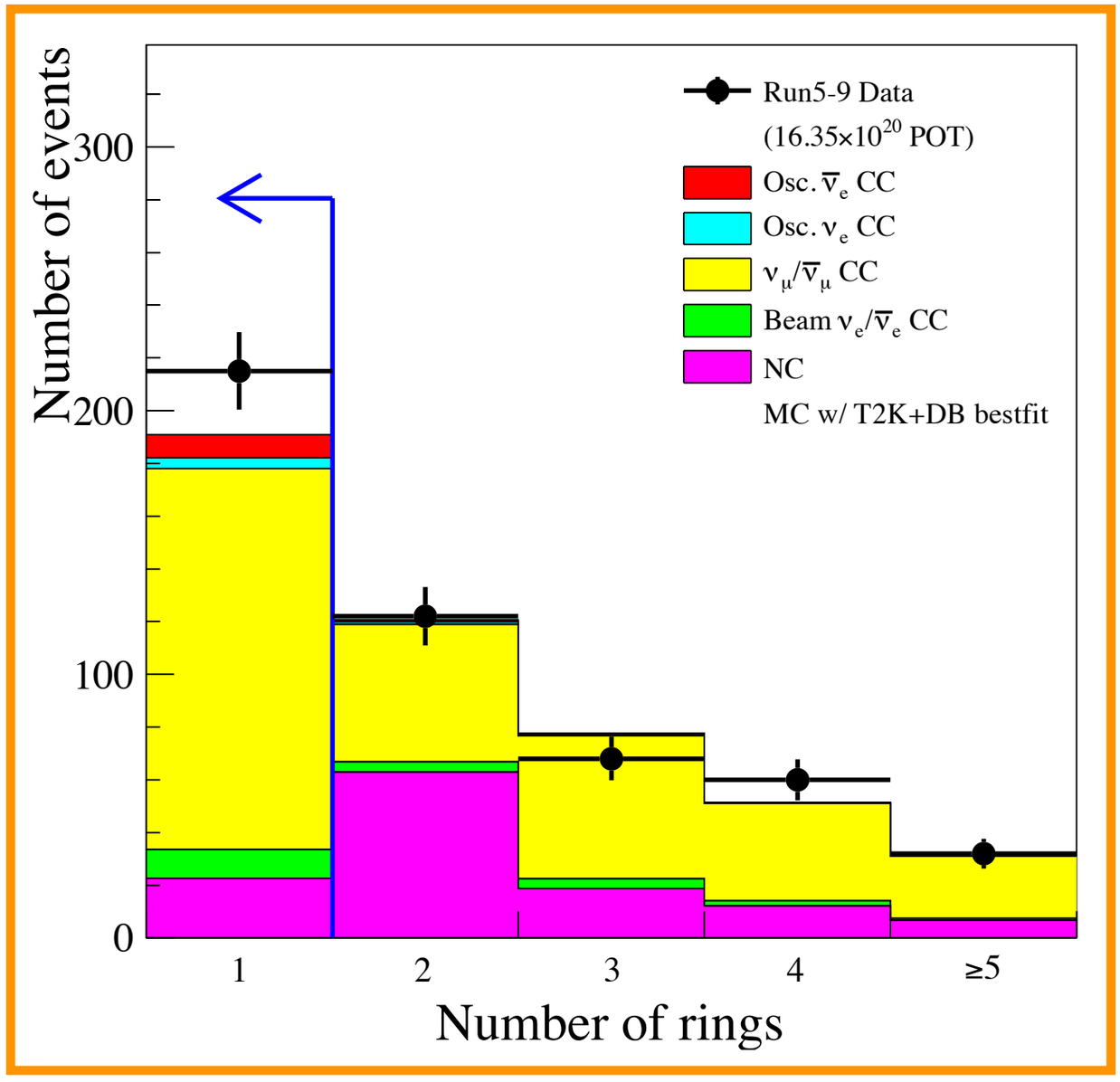
wall > 80 cm

to_wall > 170 cm

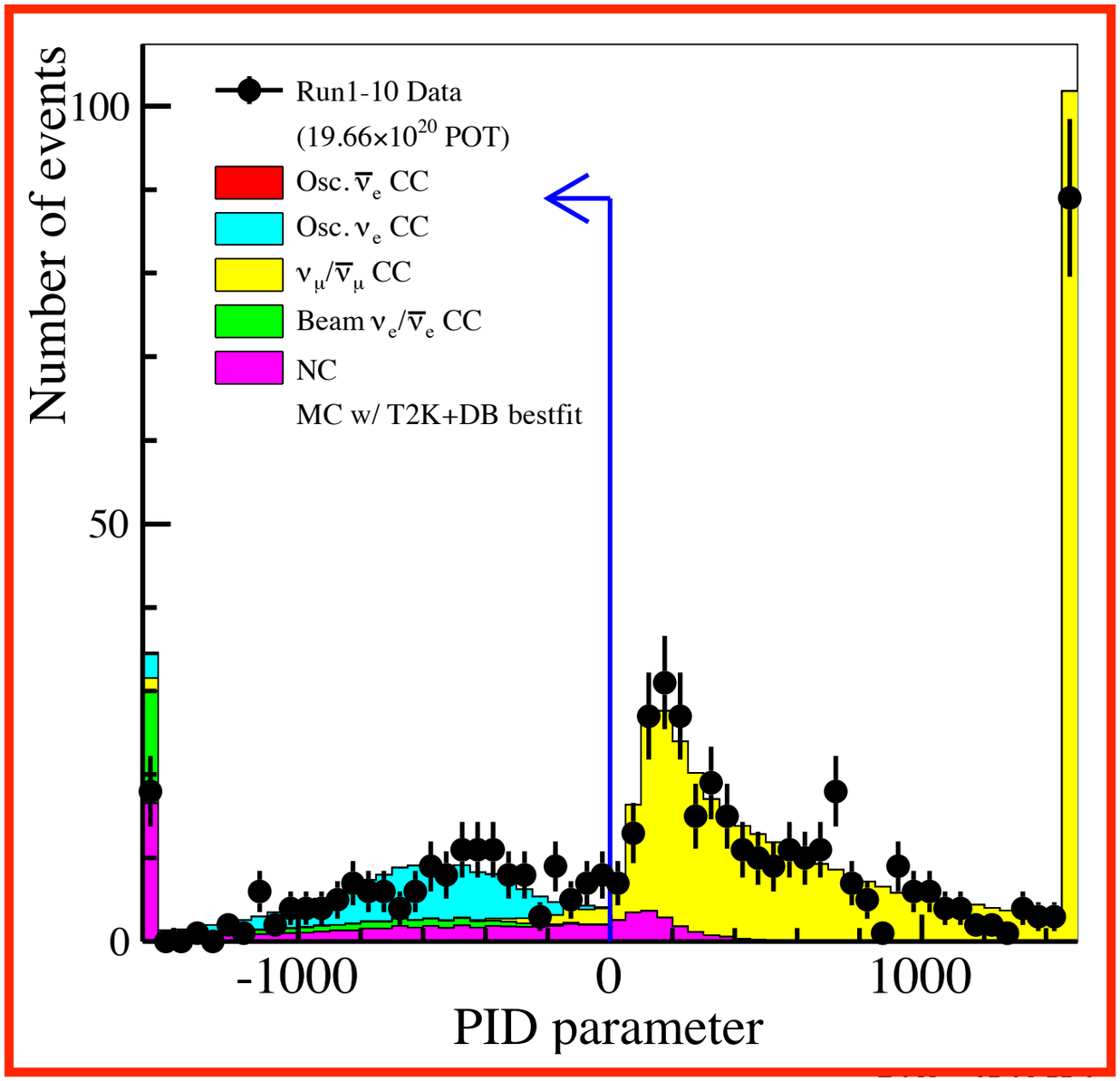


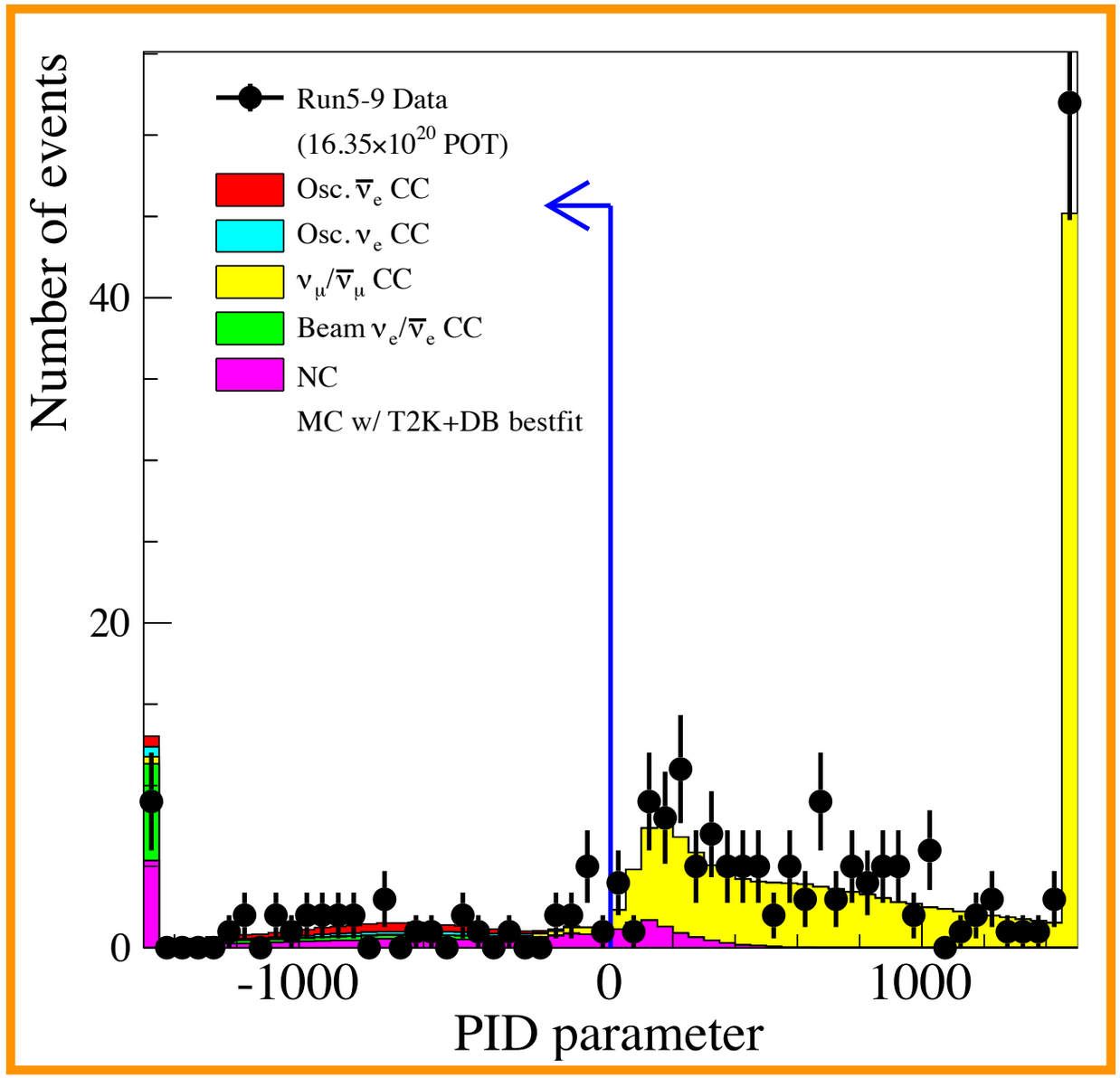
Number of Rings (=1)



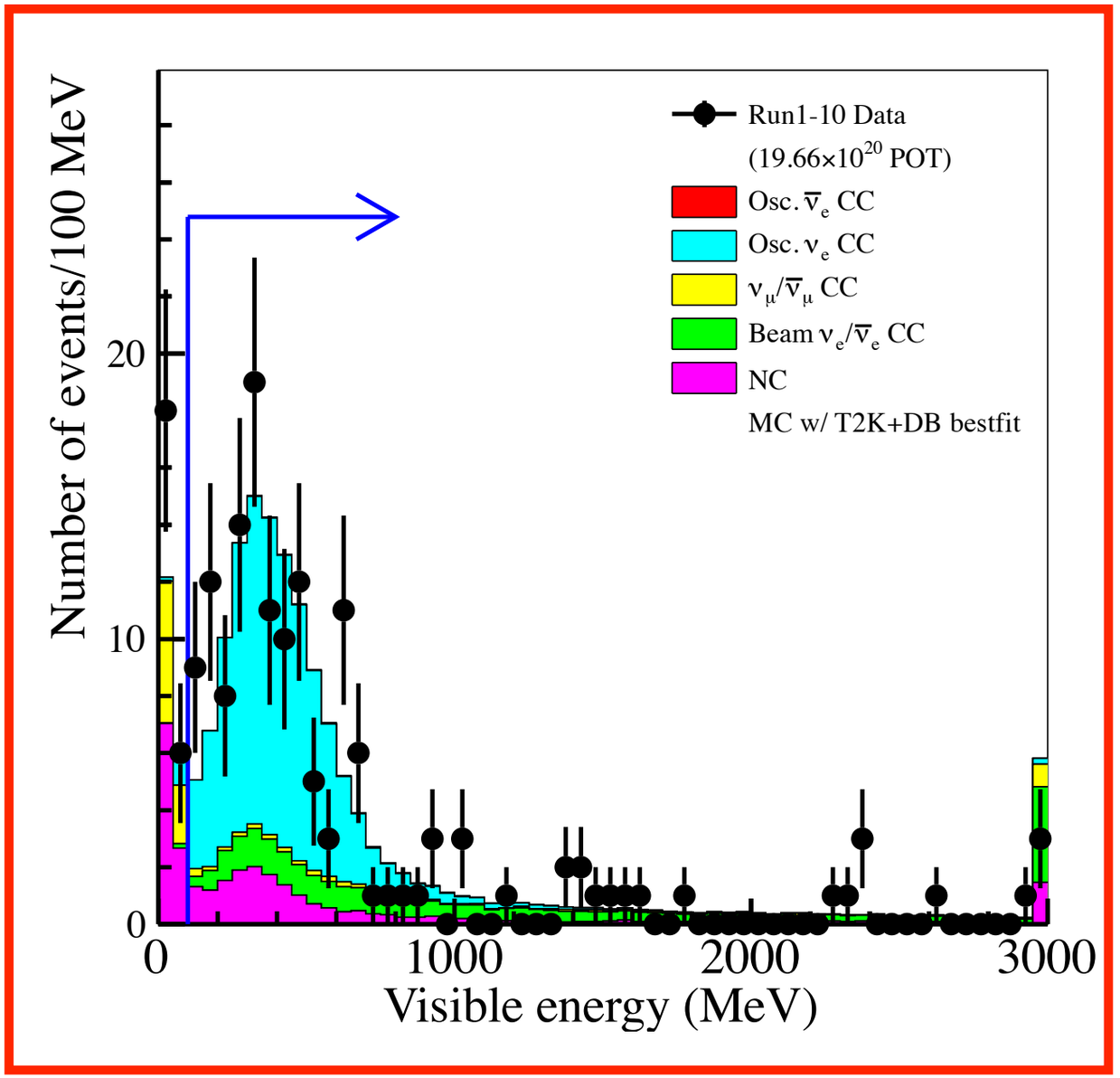


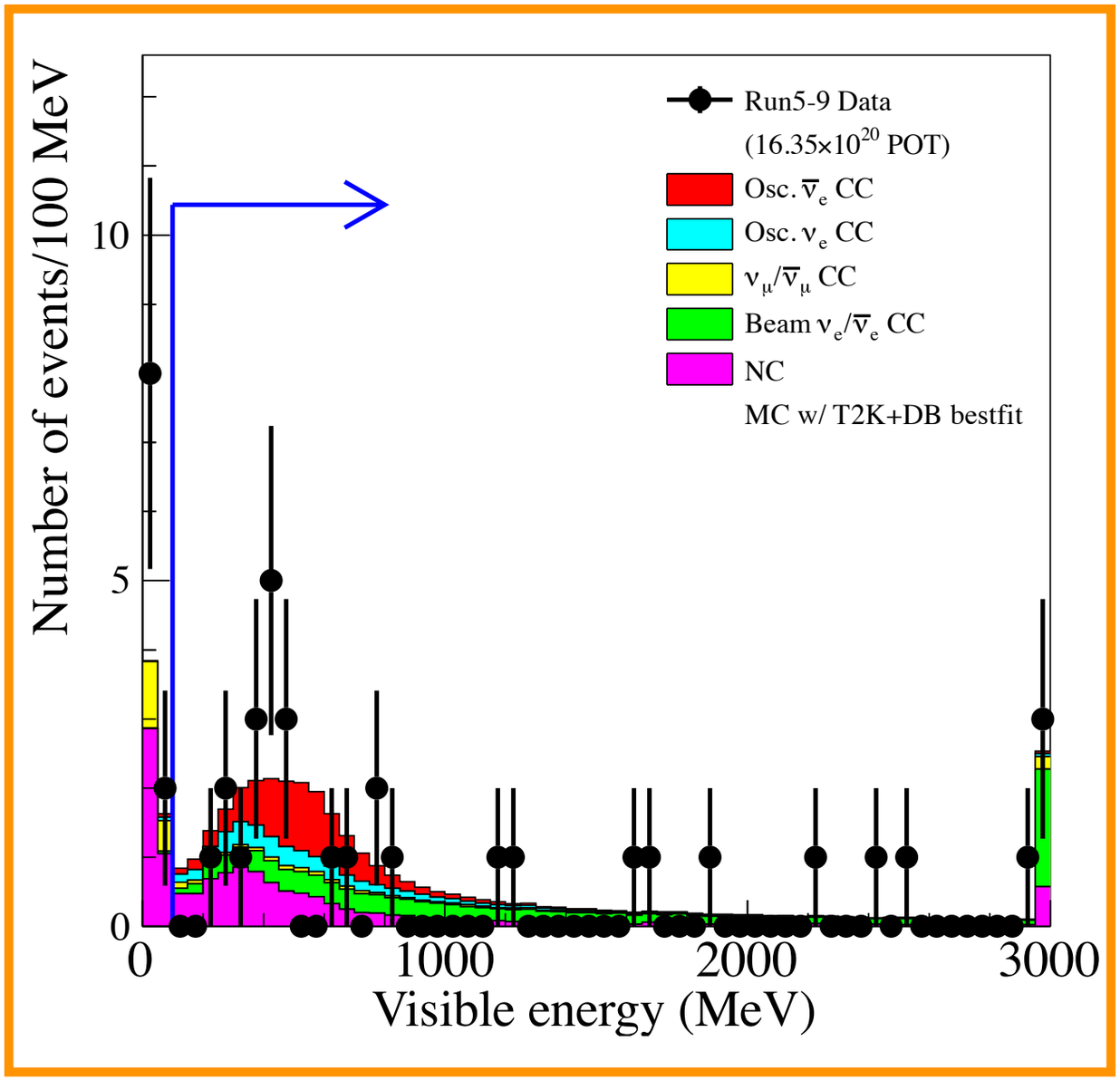
Particle ID (= e-like)



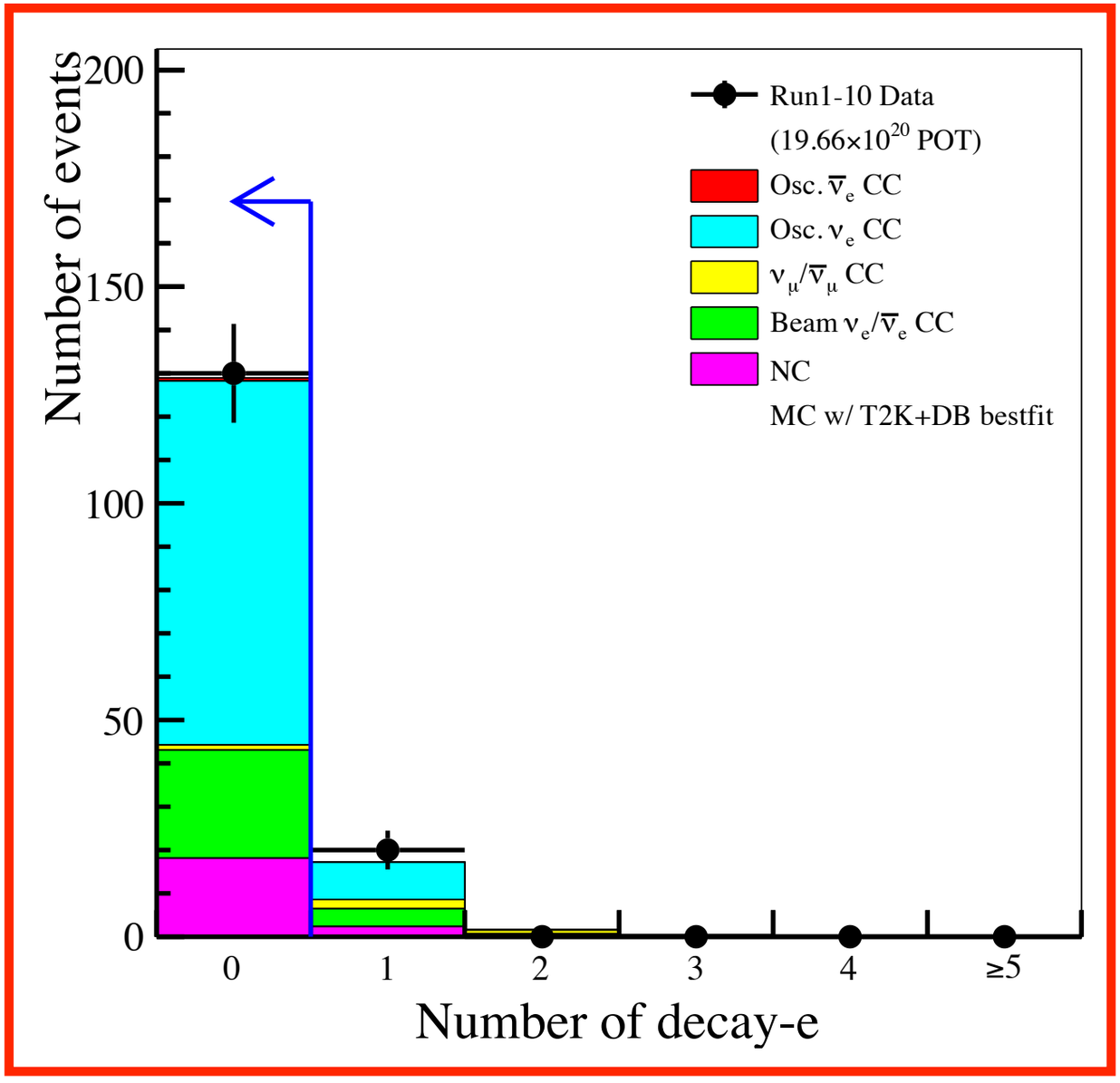


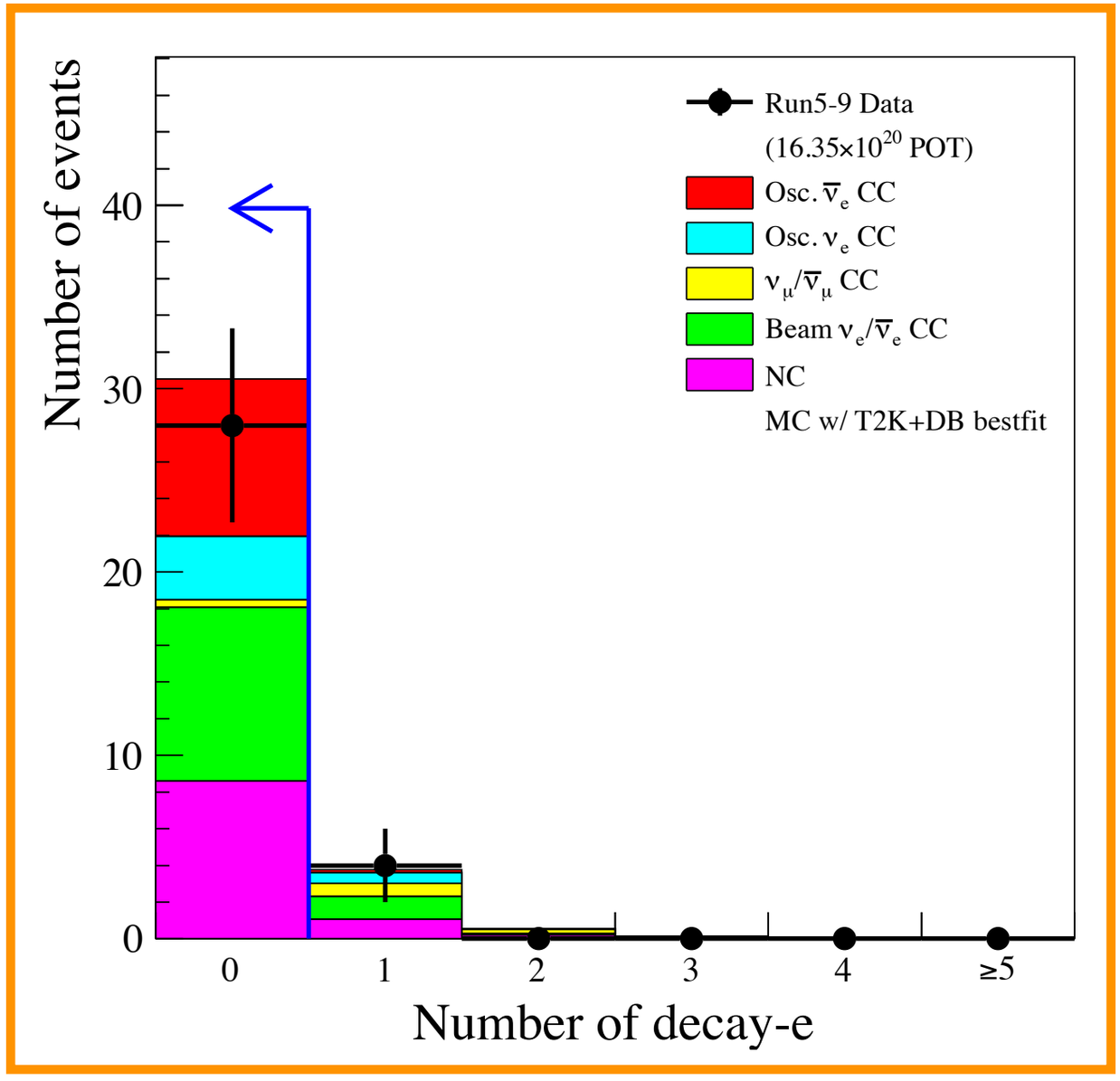
Visible Energy (> 100 MeV)



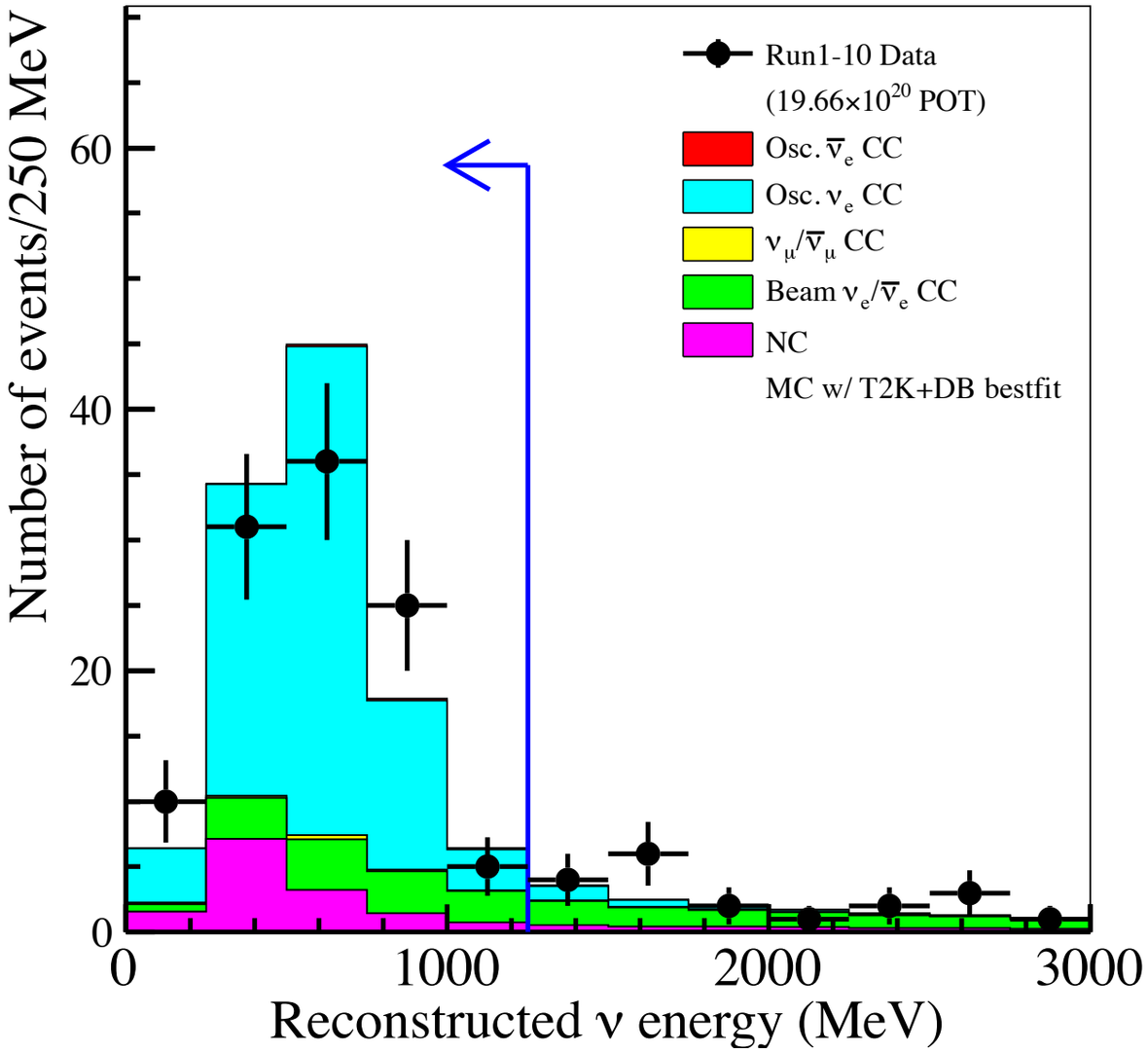


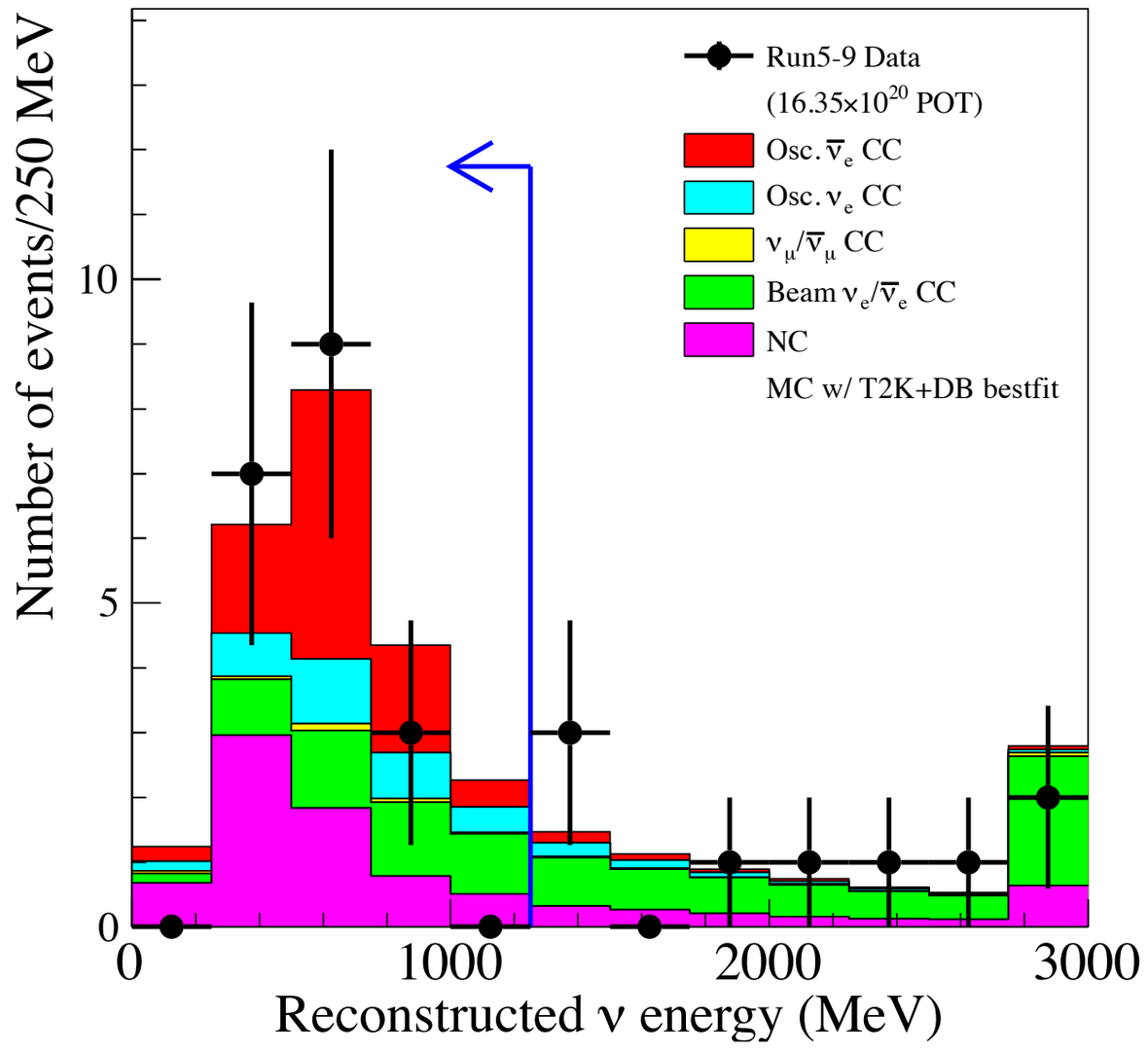
#Decay-electrons (=0)



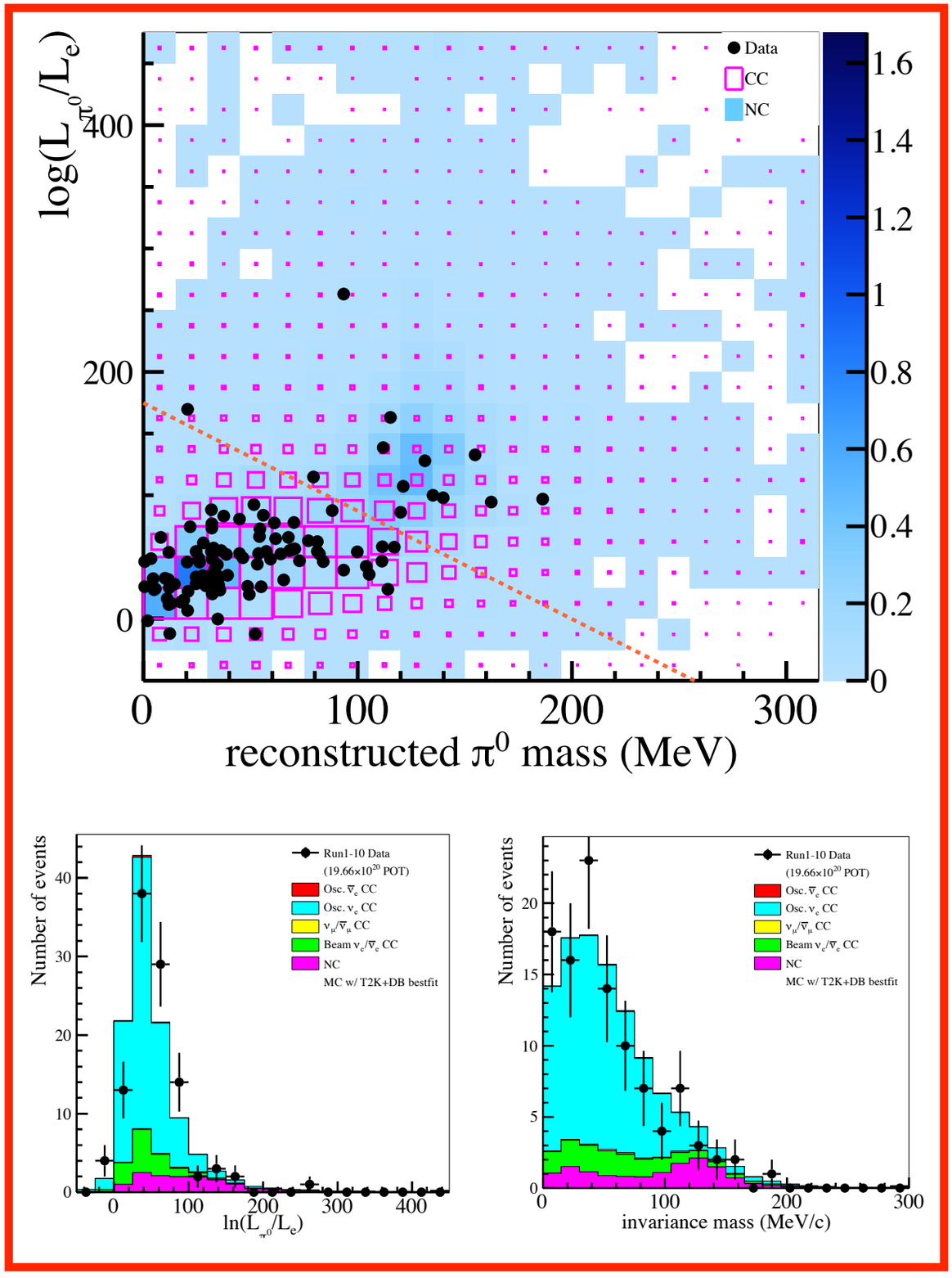


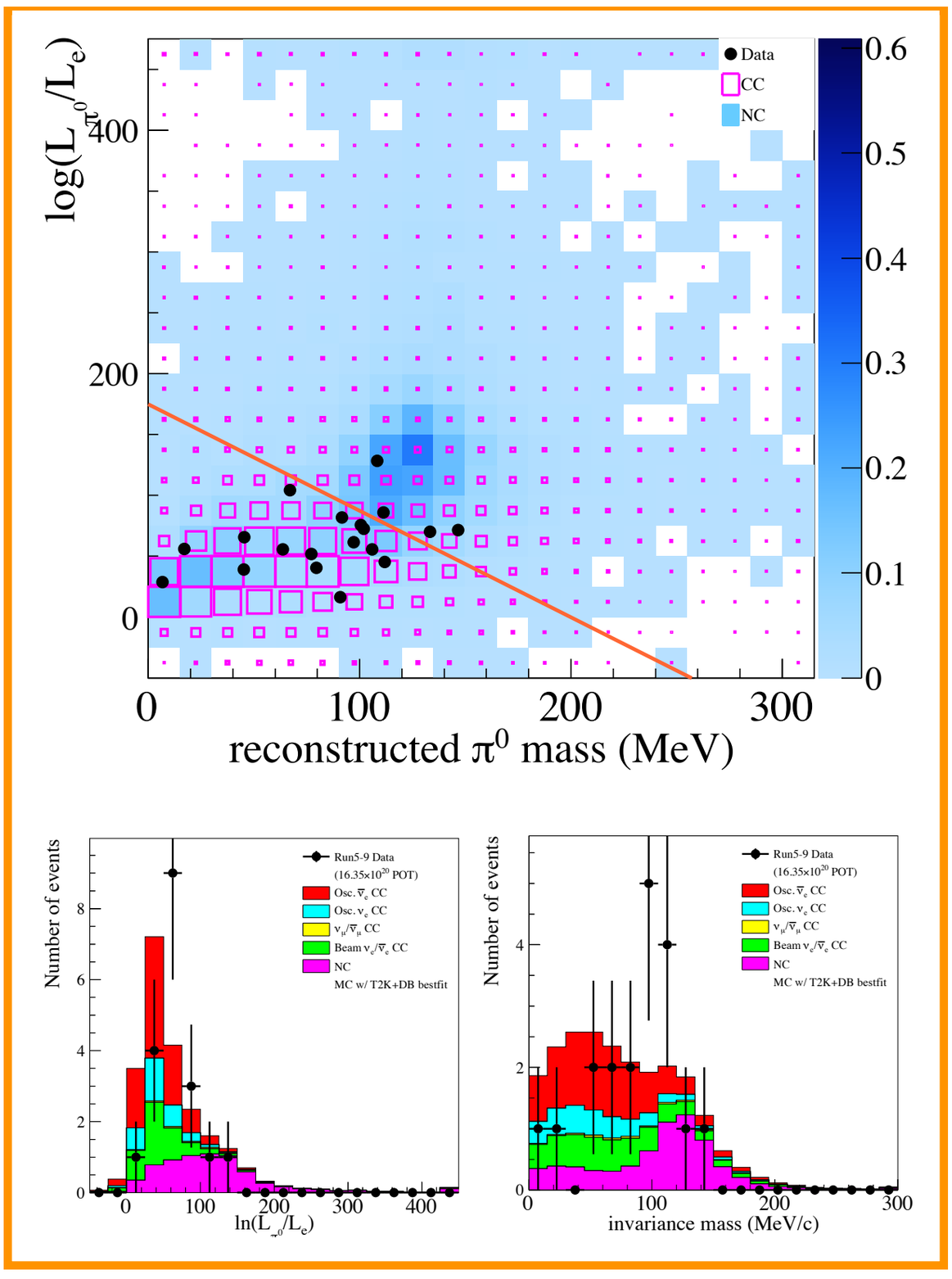
Reconstructed ν energy (<1250 MeV)





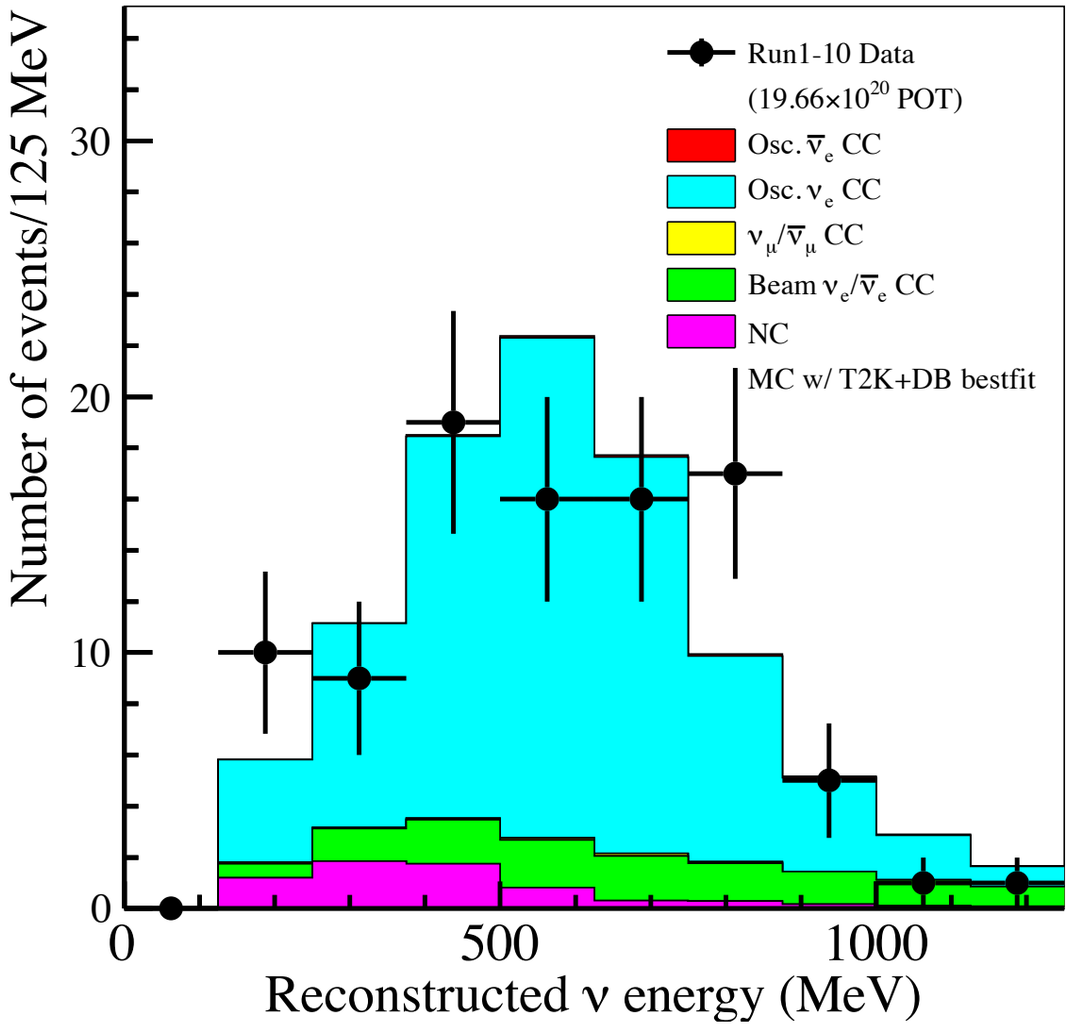
π^0 CUT

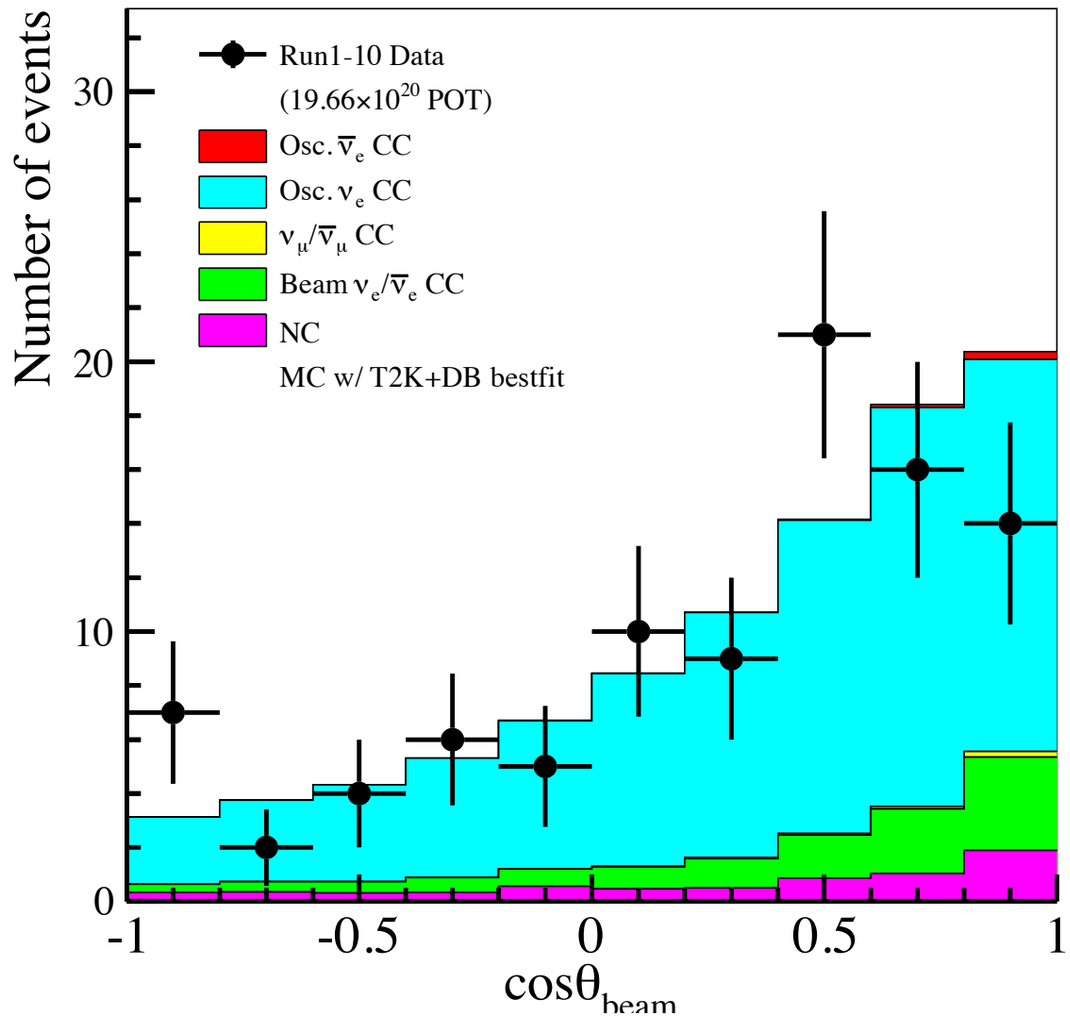

Data
CC
NC
log(L_π0/L_e)
reconstructed π0 mass (MeV)
Run1-10 Data
(19.66×10^20 POT)
Osc. ν̄_e CC
Osc. ν_e CC
ν_μ/ν̄_μ CC
Beam ν_e/ν̄_e CC
NC
MC w/ T2K+DB bestfit
Number of events
ln(L_π0/L_e)
invariance mass (MeV/c)


Data
CC
NC
log(L_π0/L_e)
reconstructed π0 mass (MeV)
Run5-9 Data
(16.35×10^20 POT)
Osc. ν̄_e CC
Osc. ν_e CC
ν_μ/ν̄_μ CC
Beam ν_e/ν̄_e CC
NC
MC w/ T2K+DB bestfit
Number of events
ln(L_π0/L_e)
invariance mass (MeV/c)

Electron Neutrino events

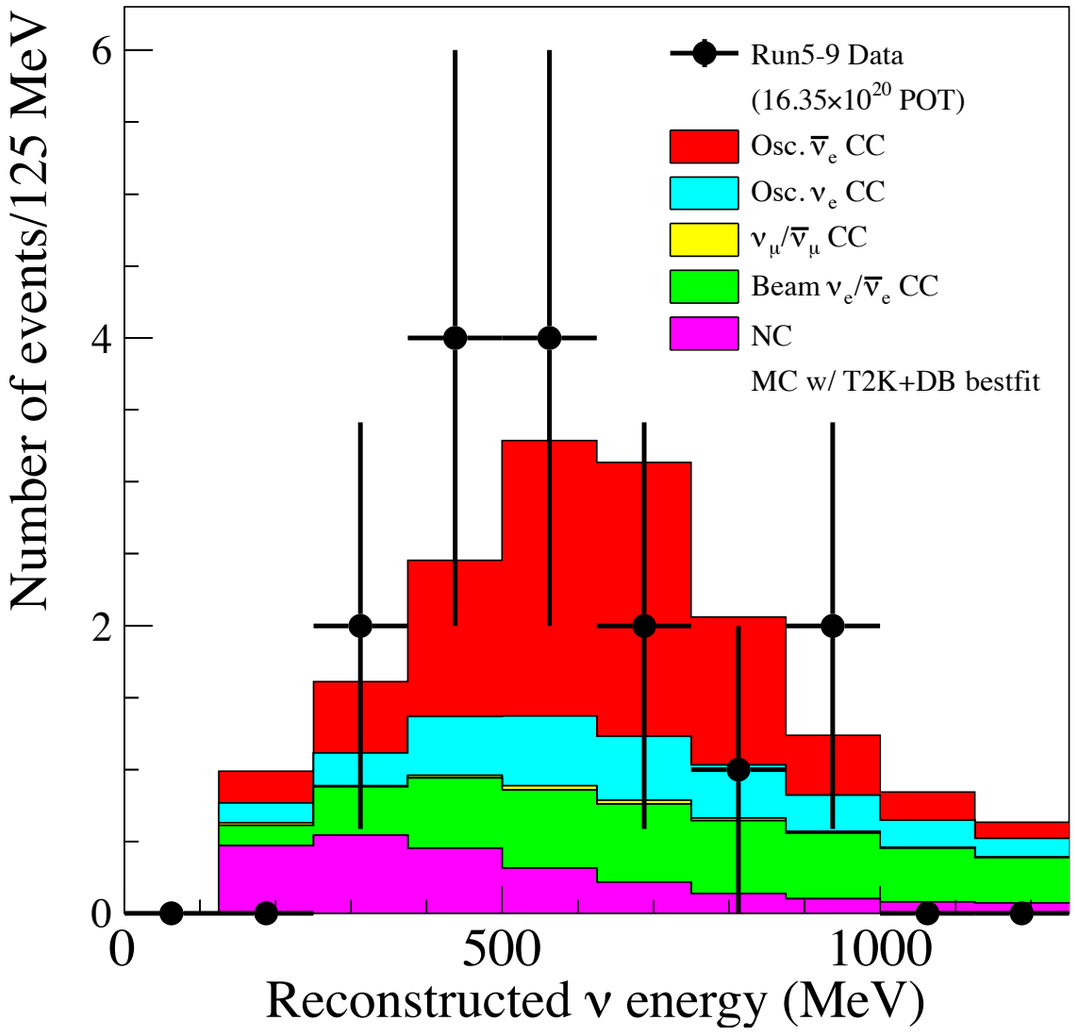
- Neutrino:
  - Data: 94
  - MC: 95.315

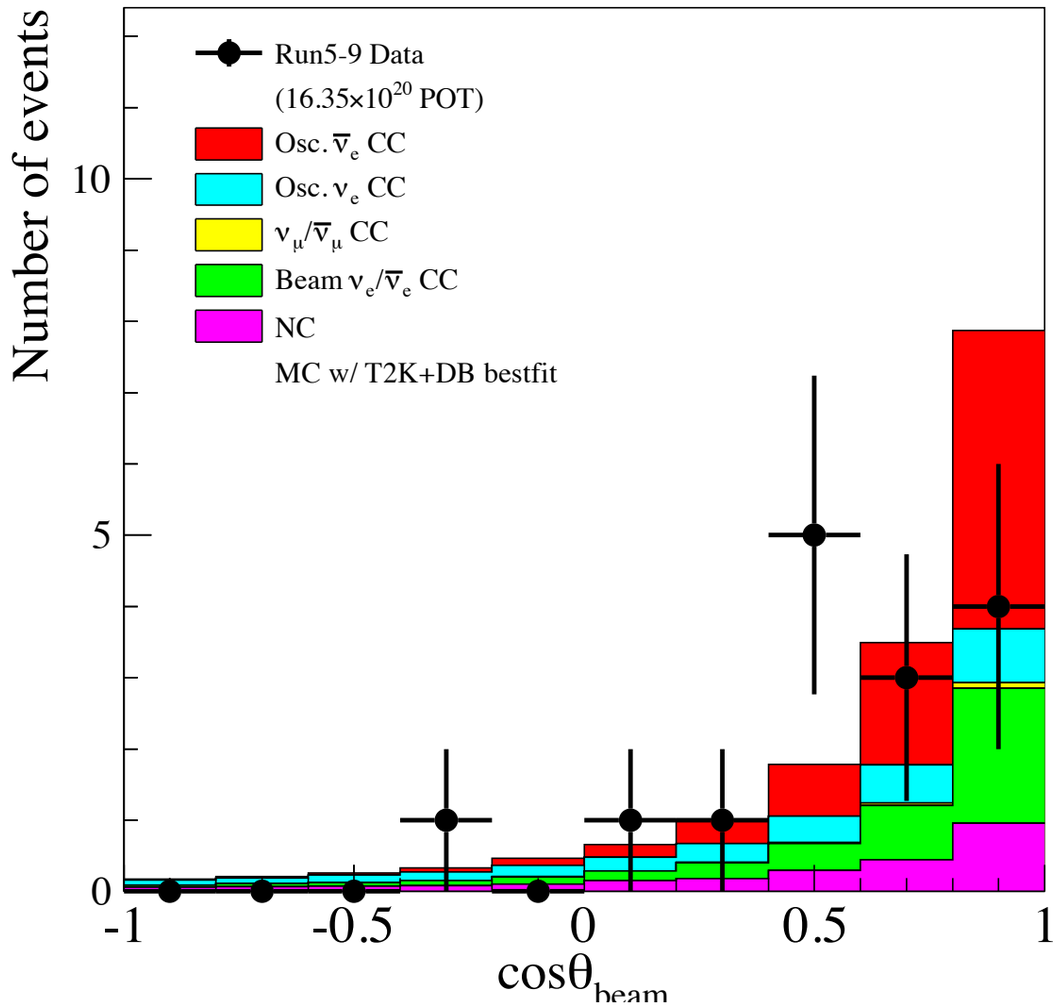




Electron Anti-Neutrino events

- Anti-neutrino:
  - Data: 16
  - MC: 16.255





FINAL Electron (anti-)neutrino events

Runs 1-10	Expected							Data
	$\nu_\mu + \bar{\nu}_\mu$ CC	Beam $\nu_e + \bar{\nu}_e$ CC	NC	BG Total	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.359	110.486	0.959	1246.704	1279
FCFV	886.362	56.685	260.508	1203.555	109.753	0.979	1314.287	1361
Single Ring	397.177	29.511	49.246	475.934	94.001	0.765	570.700	554
Electron-like PID	11.353	29.491	30.897	71.740	93.885	0.764	166.389	174
Evis $>$ 100 MeV	4.339	29.317	21.197	54.853	92.680	0.760	148.294	150
No Decay-e	1.196	24.903	18.205	44.304	83.884	0.738	128.927	130
Erec	0.764	13.129	14.137	28.029	81.240	0.540	109.809	107
π^0 rejection cut	0.423	11.661	6.607	18.691	76.164	0.461	95.315	94
Efficiency from FCFV	0.000	0.206	0.025	0.016	0.694	0.470	0.073	-
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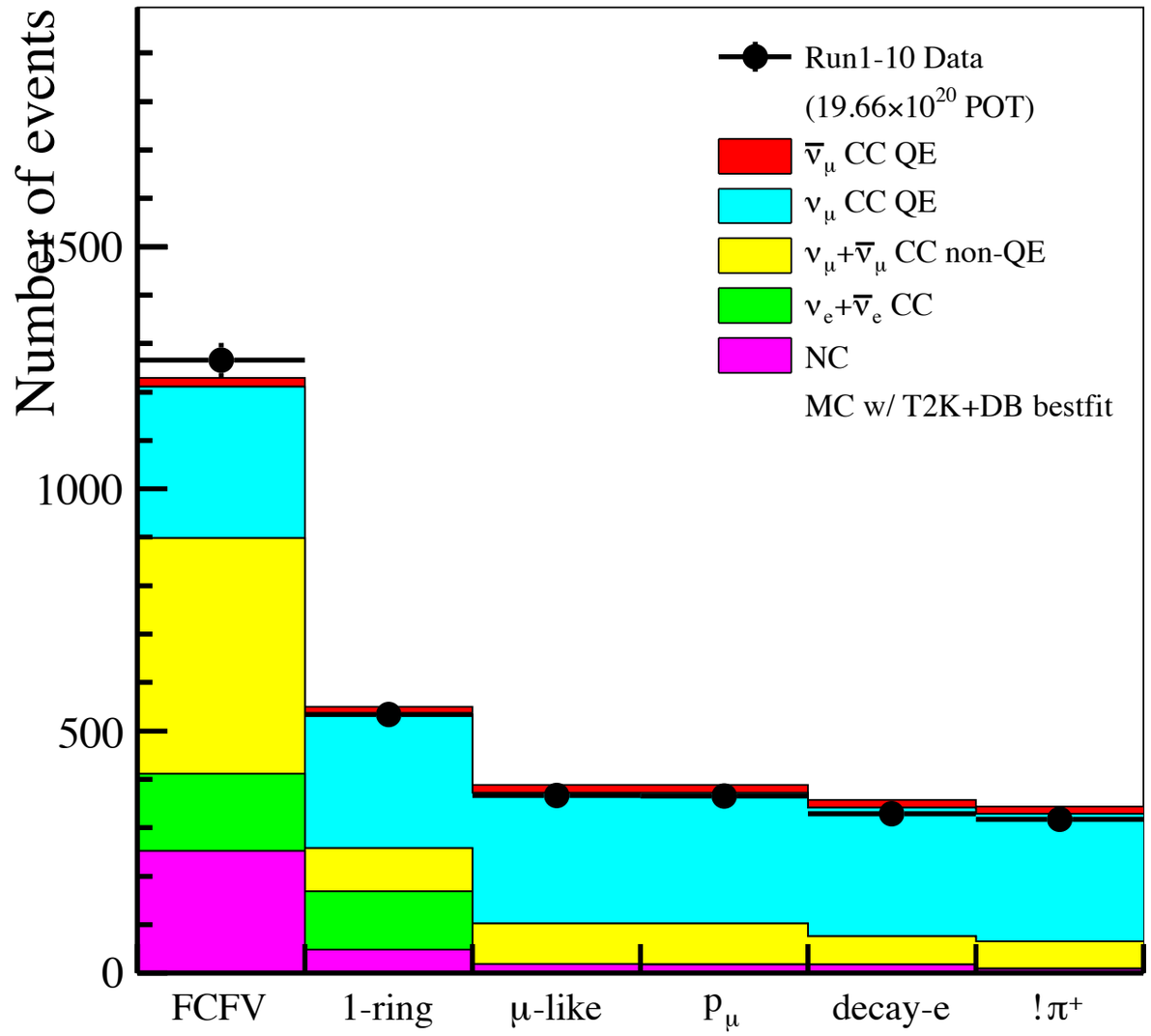
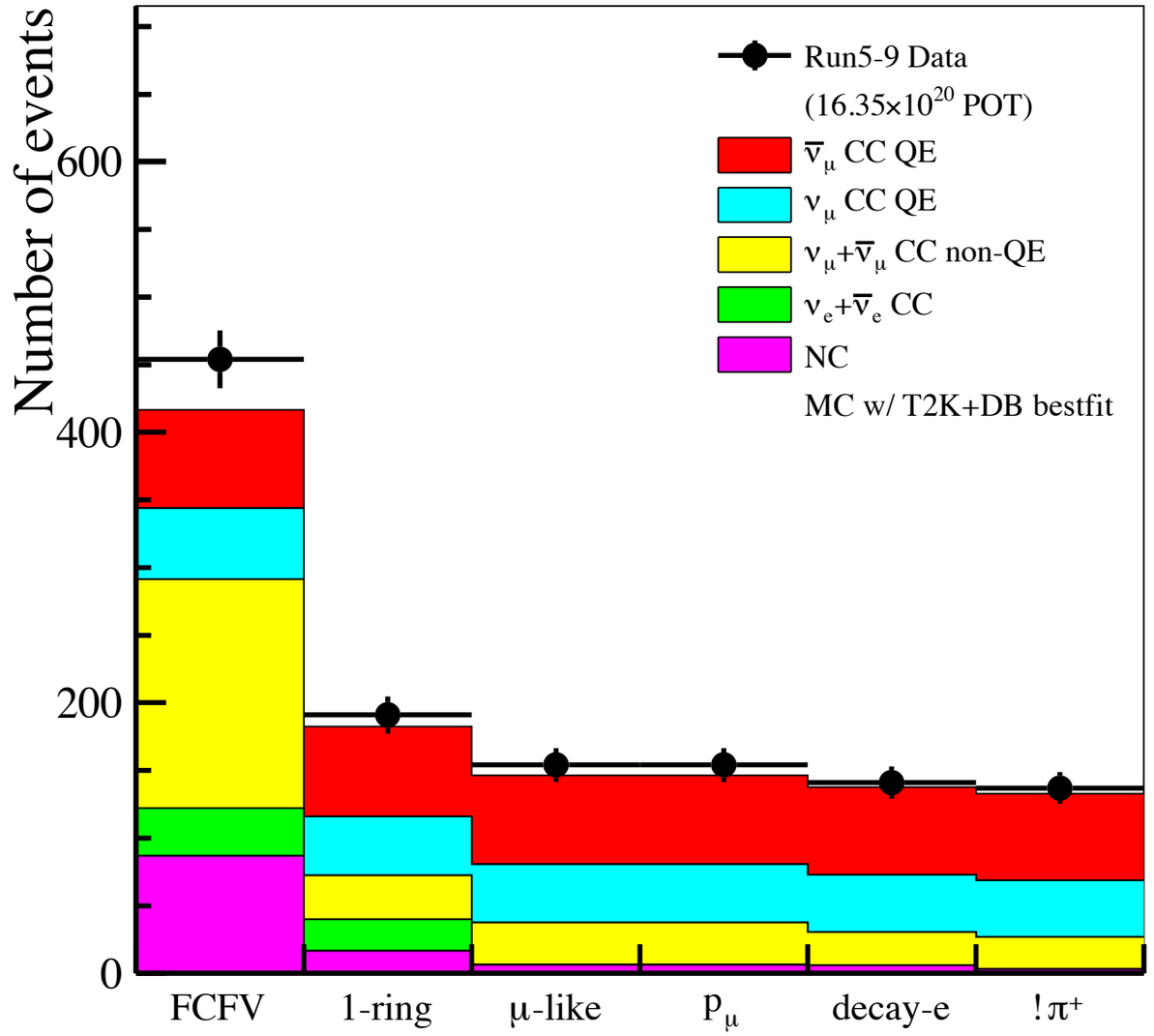
Sample-FCFV	311.203	21.476	122.864	455.543	5.810	10.312	471.665	497
Single Ring	144.493	10.884	22.609	177.986	4.133	8.809	190.927	215
Electron-like PID	2.806	10.875	13.831	27.512	4.126	8.802	40.440	42
Evis $>$ 100 MeV	1.410	10.830	9.916	22.156	4.062	8.748	34.966	32
No Decay-e	0.406	9.479	8.600	18.485	3.465	8.581	30.532	28
Erec	0.277	4.272	6.770	11.318	2.914	8.133	22.365	19
π^0 rejection cut	0.130	3.701	2.404	6.235	2.646	7.374	16.255	**16**
Efficiency from FCFV	0.000	0.172	0.020	0.014	0.455	0.715	0.034	-

Muon Neutrino Selection



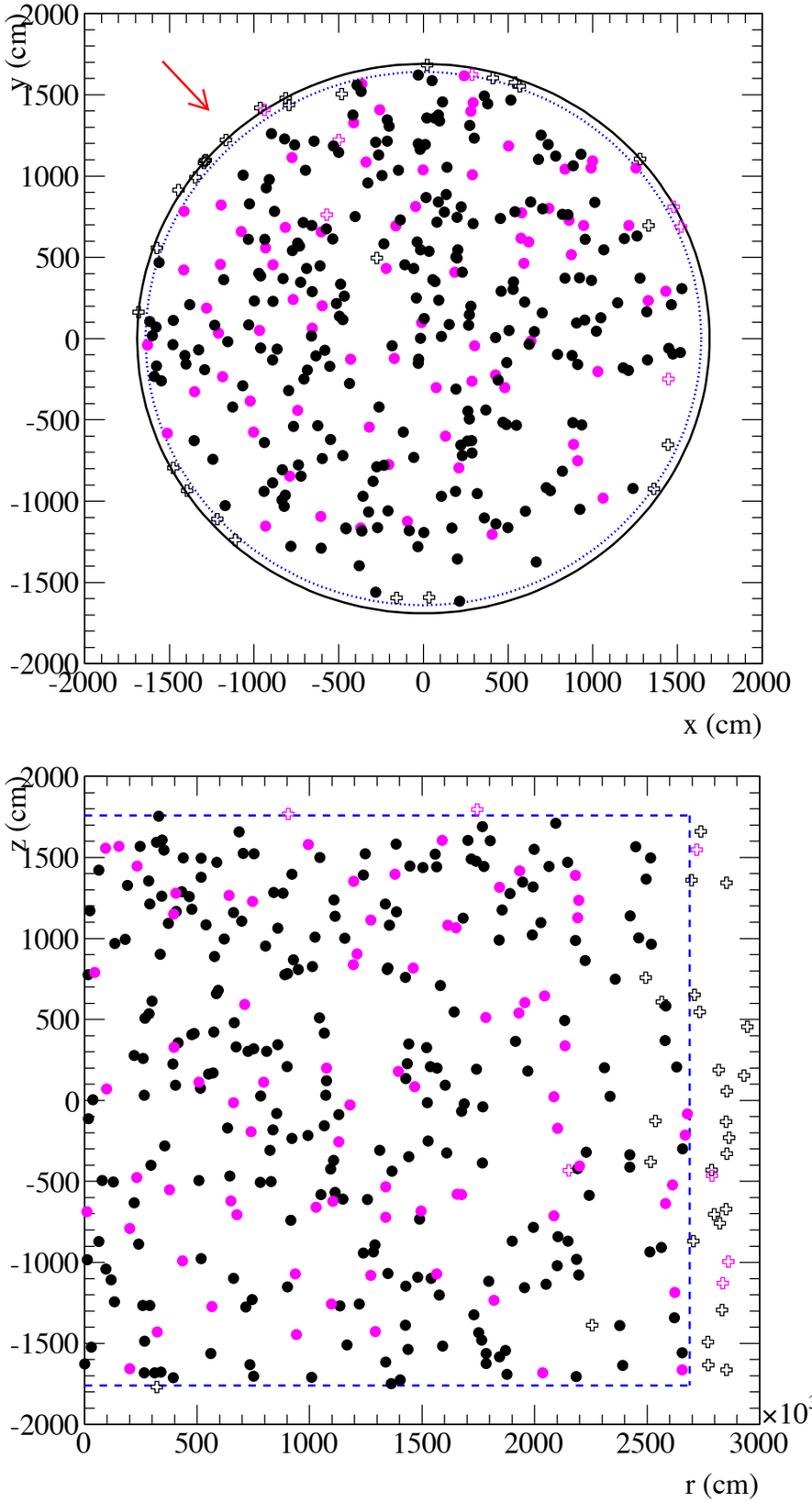
Runs 1-10	Expected							Data
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.259	110.486	0.959	1246.704	1279
FCFV	159.210	252.169	487.223	898.601	312.544	18.239	1229.385	1266
Single Ring	120.241	48.469	89.208	257.919	276.480	16.037	550.436	534
Muon-like PID	0.130	18.270	84.397	102.797	270.330	15.927	389.055	367
Momentum	0.130	18.127	84.351	102.608	269.977	15.924	388.509	366
0 or 1 Decay-e	0.128	17.606	57.972	75.706	266.412	15.751	357.869	329
π^+ rejection cut	0.121	8.896	56.723	65.740	263.084	15.597	344.422	318
Efficiency from FCFV	0.001	0.035	0.116	0.073	0.842	0.855	0.280	-

Muon Anti-Neutrino Selection



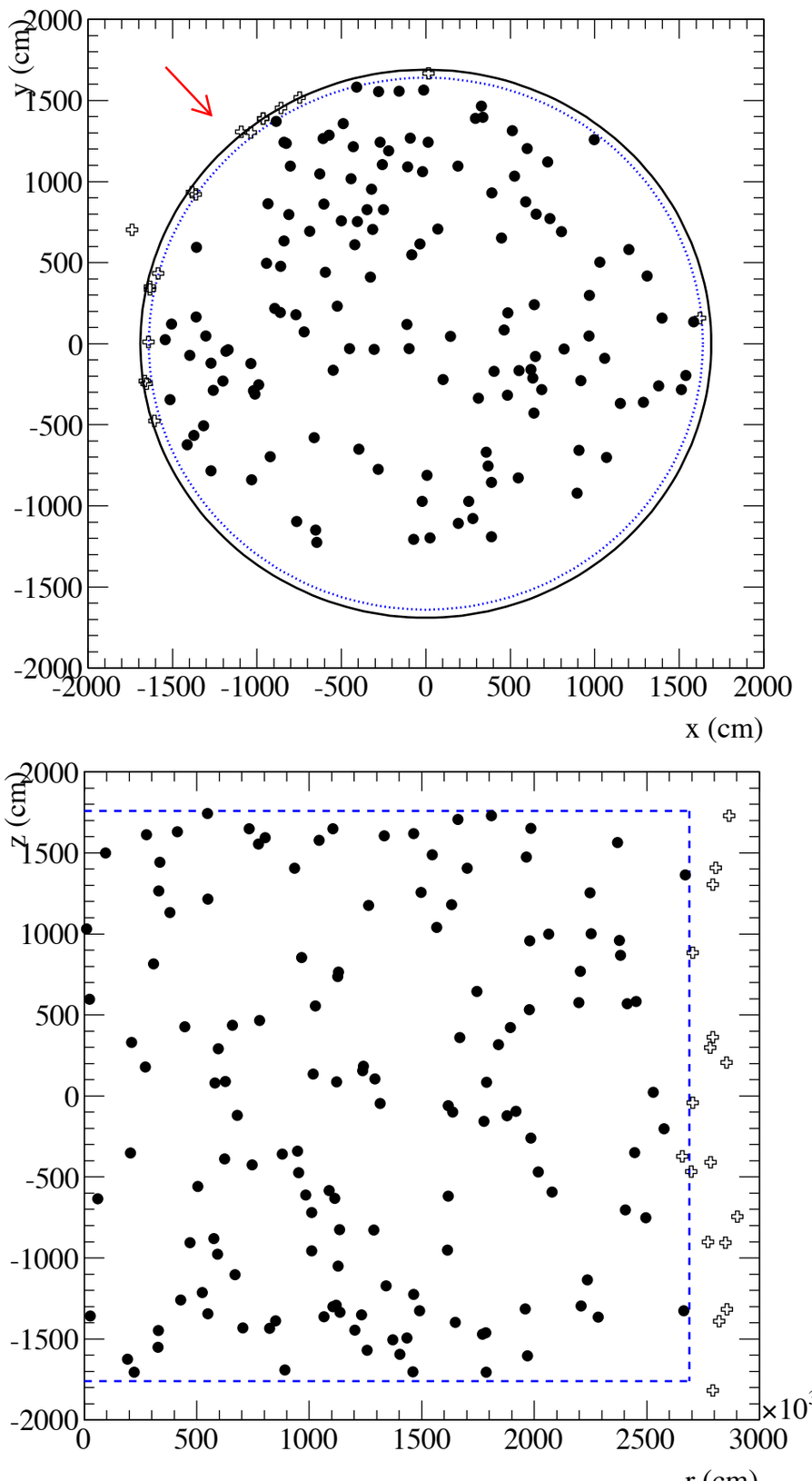
Runs 5-9			Expected				Data	
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC total	
Floor-FCFV	19.908	87.827	170.146	277.881	53.225	74.086	405.192	459
FCFV	35.324	86.630	169.259	291.213	52.663	72.699	416.575	454
Single Ring	23.313	16.622	32.691	72.626	43.306	66.692	182.624	191
Muon-like PID	0.013	6.290	31.379	37.682	42.884	65.768	146.333	154
Momentum	0.013	6.232	31.373	37.618	42.865	65.729	146.213	154
0 or 1 Decay-e	0.013	6.031	24.437	30.481	42.160	64.931	137.572	141
π^+ rejection cut	0.011	2.849	24.025	26.885	41.673	64.251	132.809	137
Efficiency from FCFV	0.000	0.033	0.142	0.092	0.791	0.884	0.319	-

Fiducial Volume

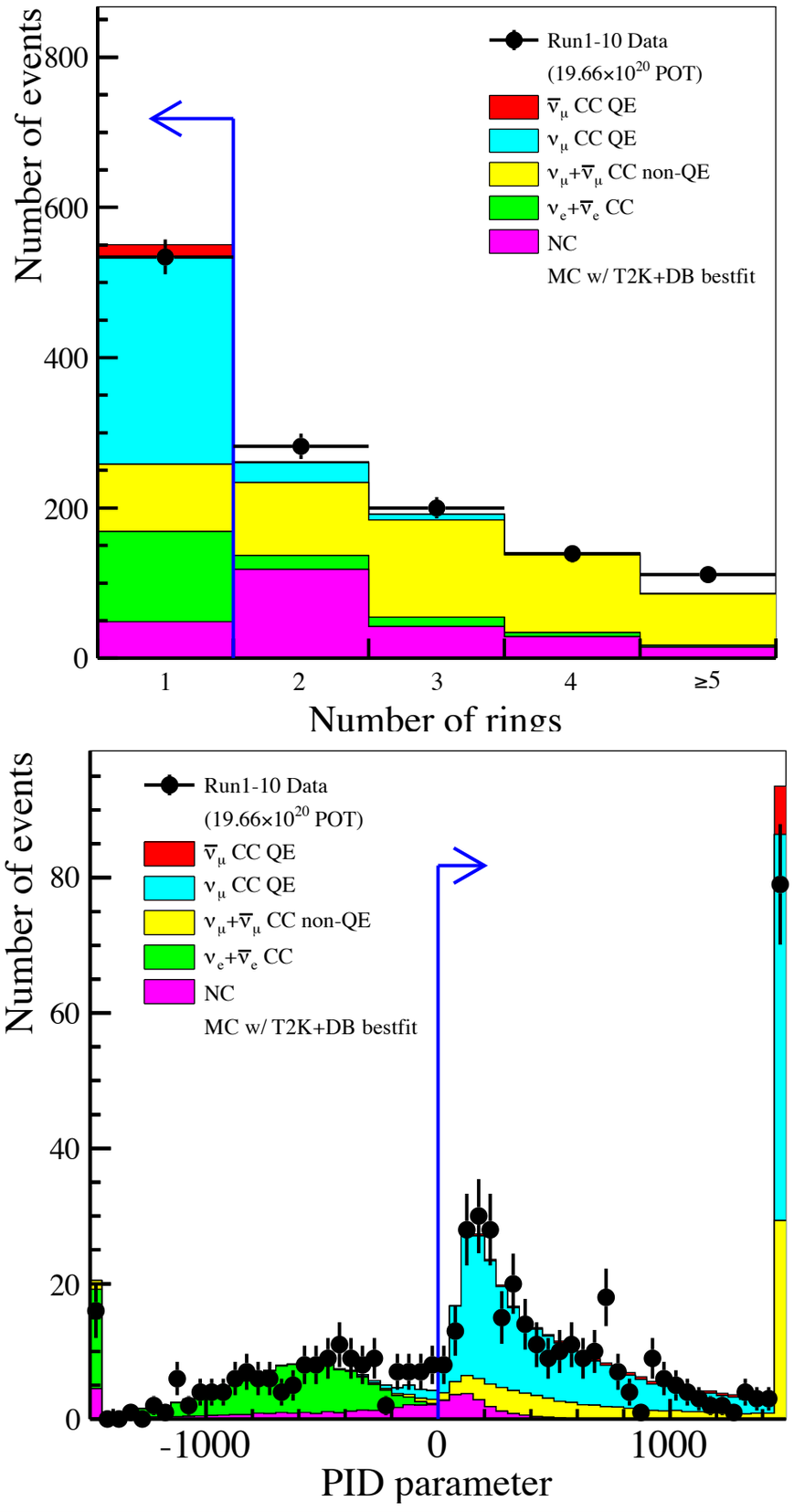


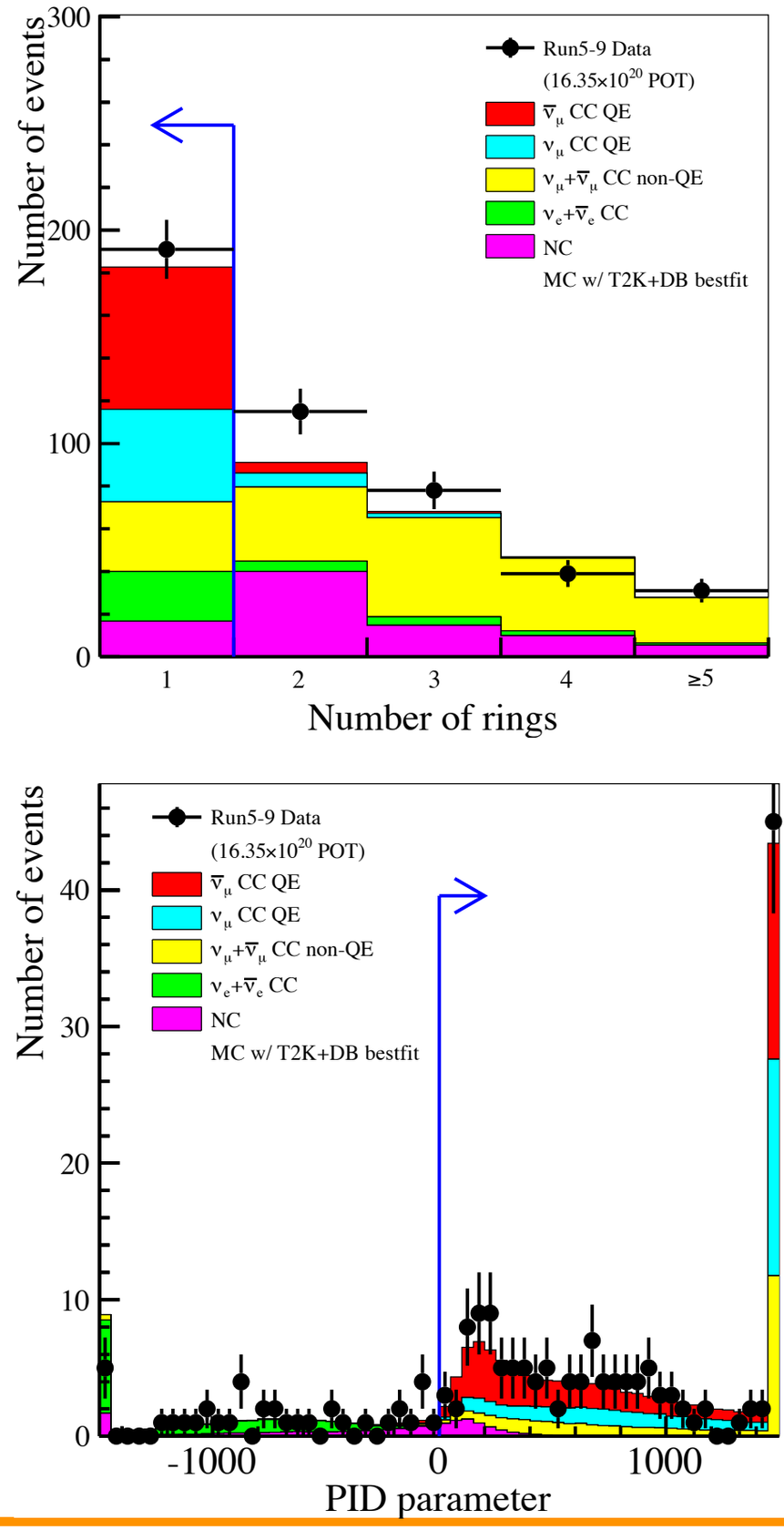
wall > 50 cm

to_wall > 250 cm

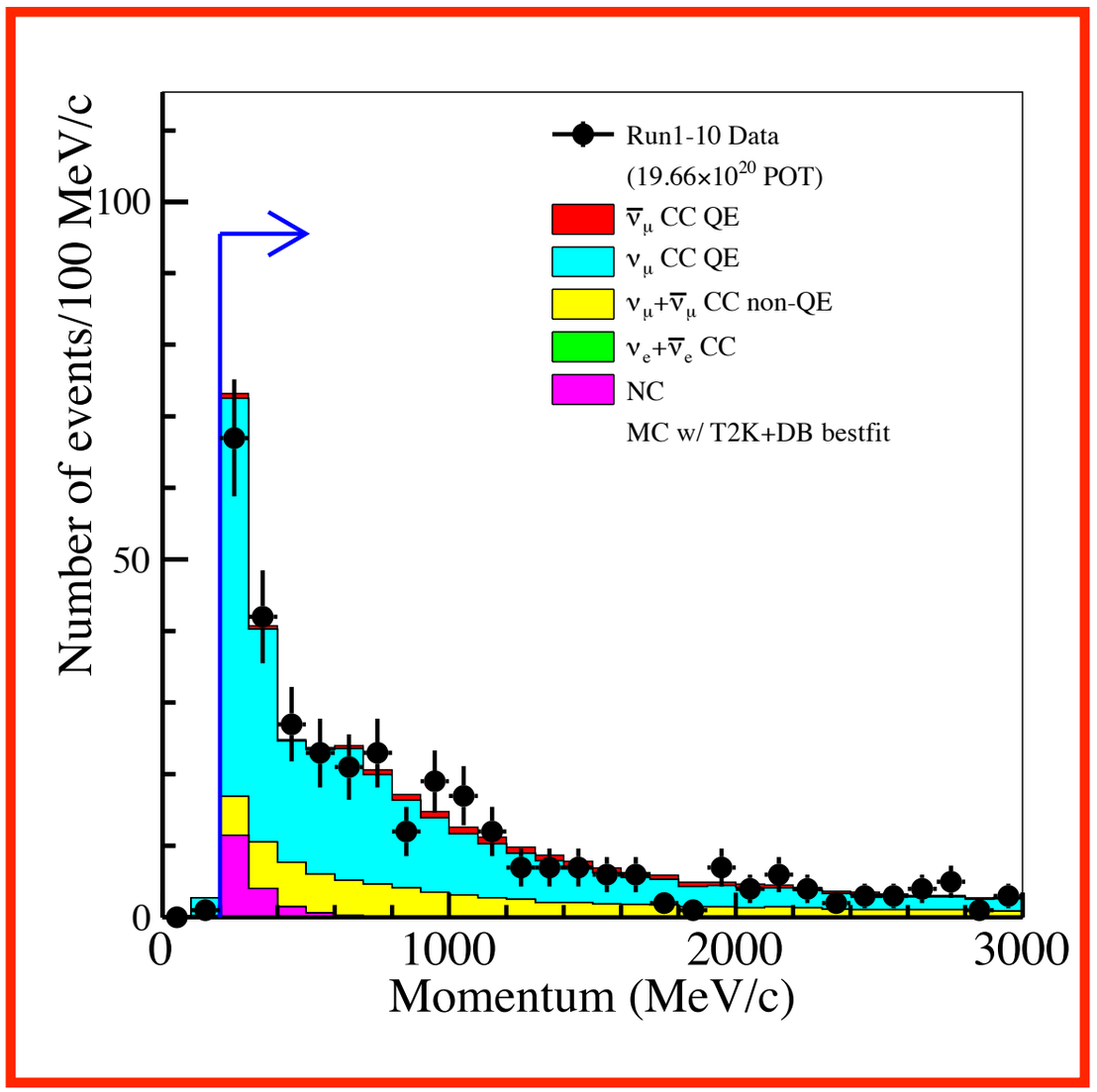


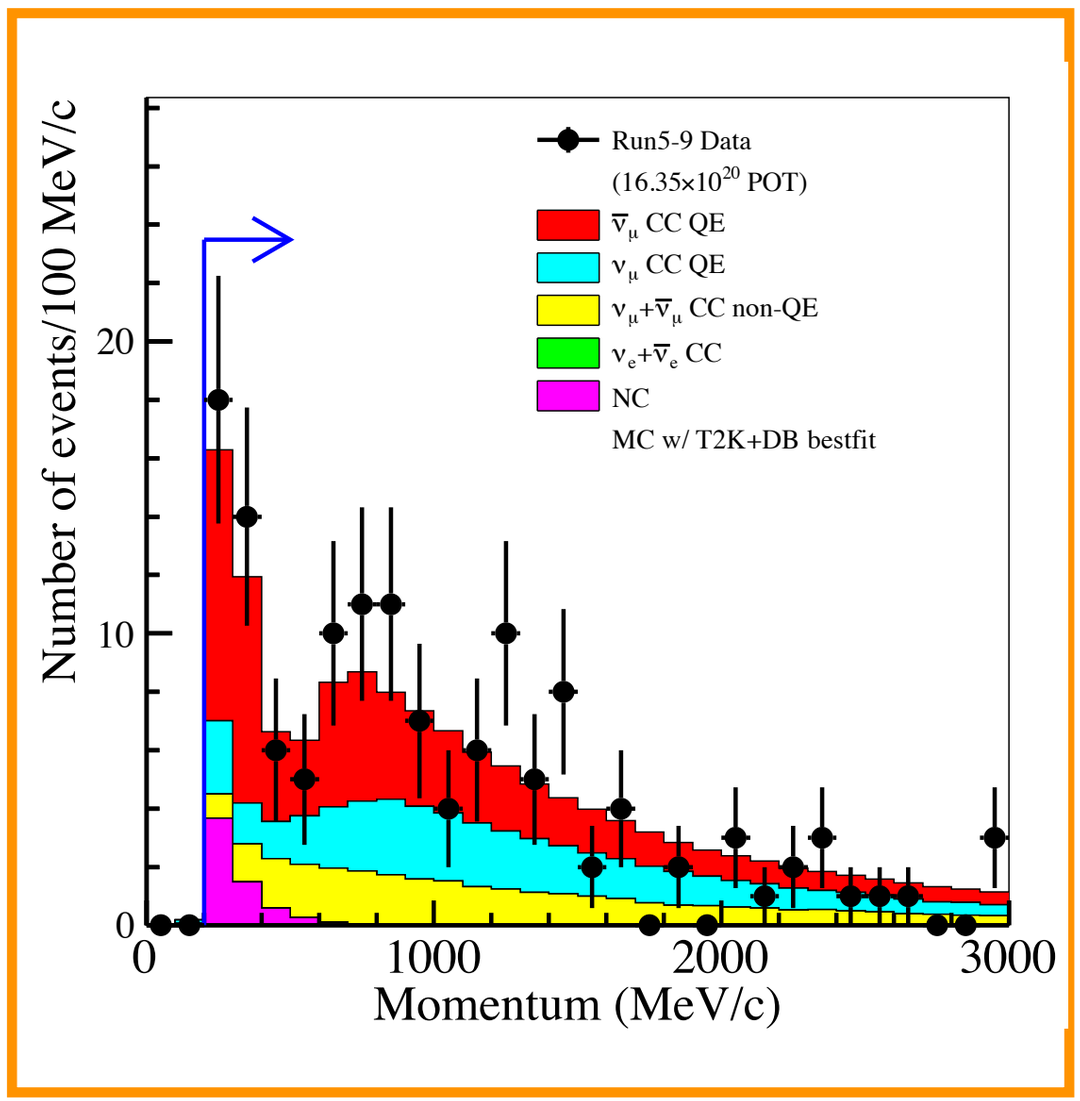
Rings (=1); Particle ID (= μ-like)



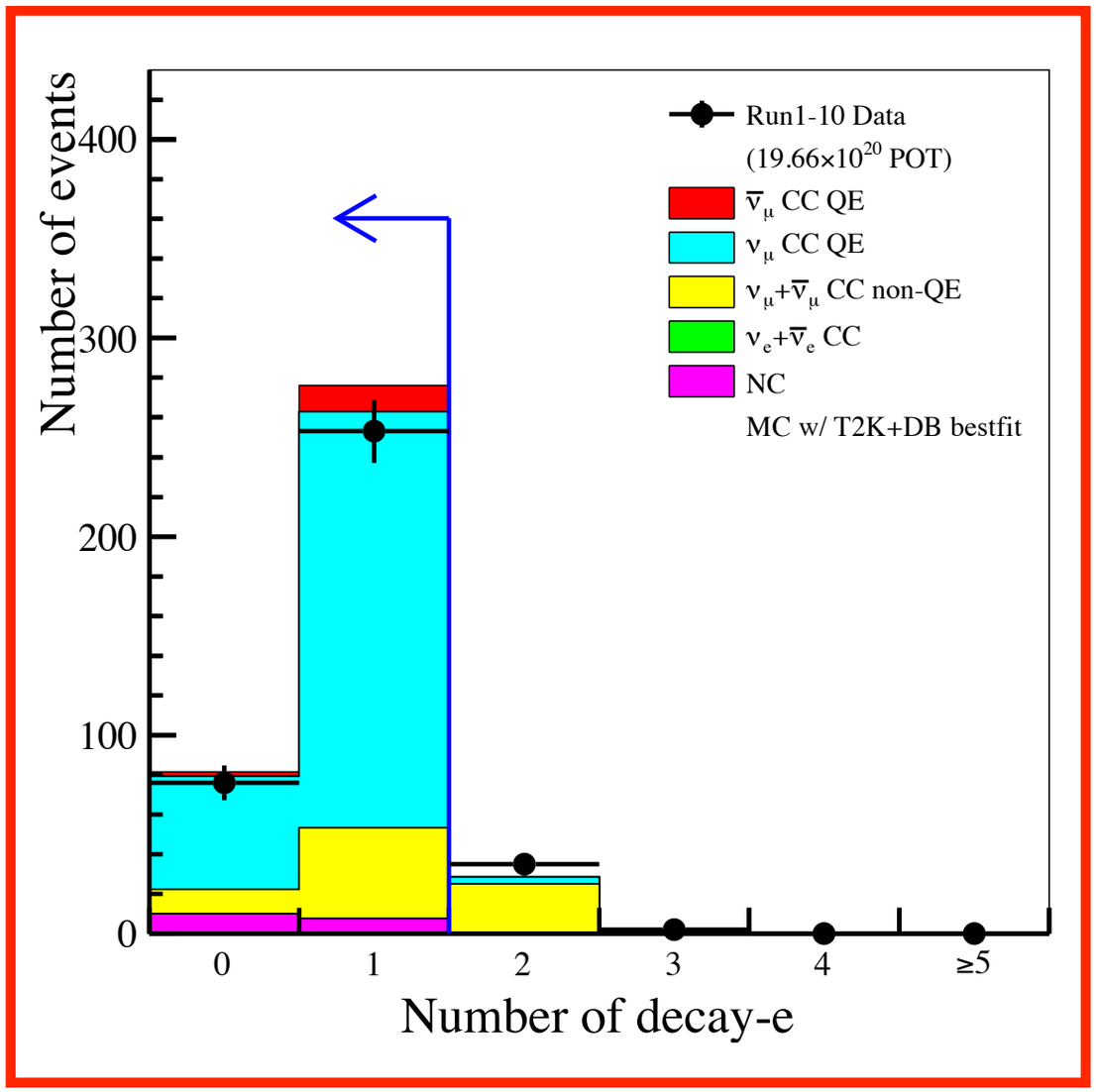


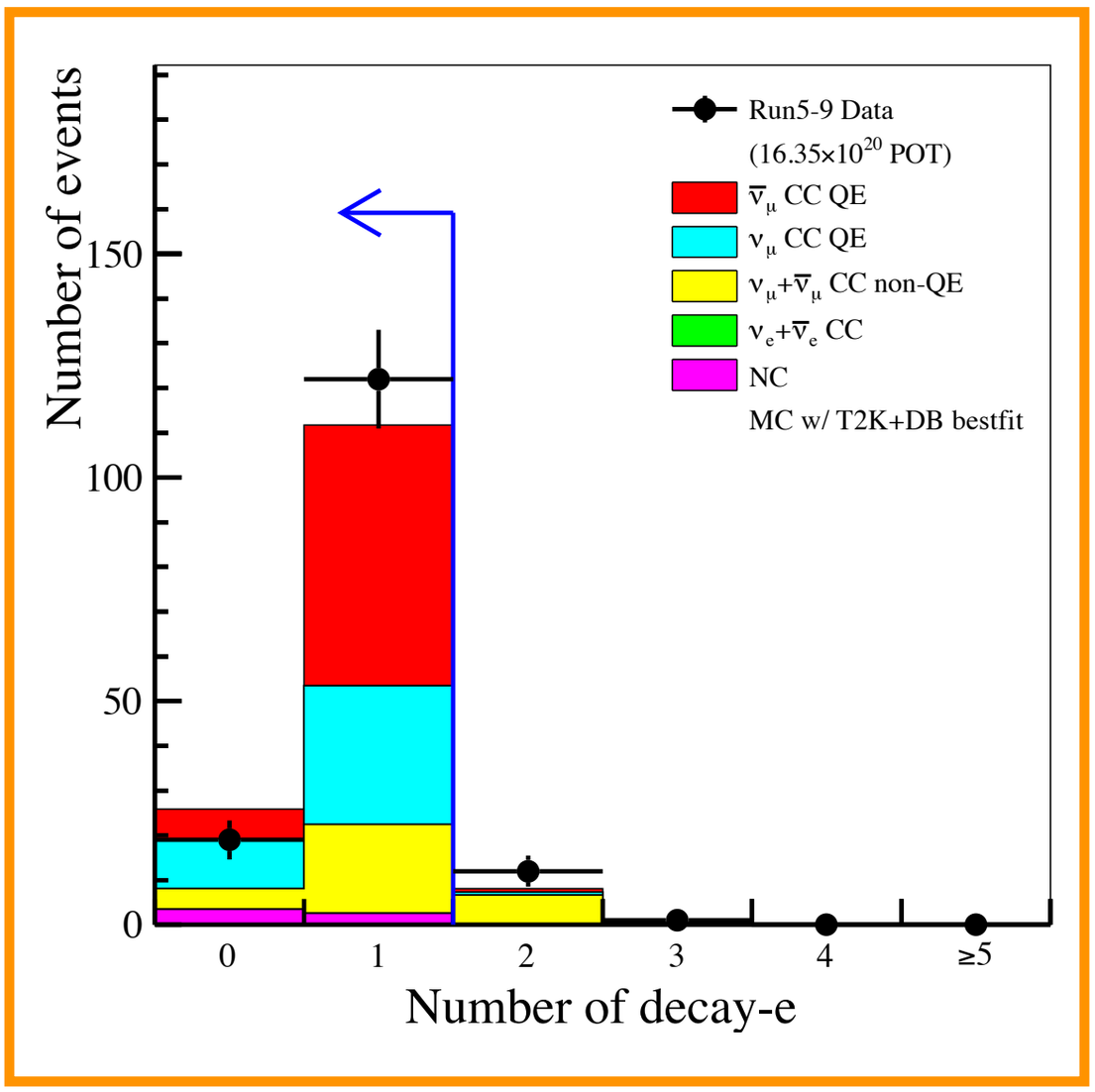
pμ> 200 MeV/c


Run1-10 Data
(19.66×10^20 POT)
ν̄μ CC QE
νμ CC QE
νμ+ν̄μ CC non-QE
νe+ν̄e CC
NC
MC w/ T2K+DB bestfit
Number of events/100 MeV/c
Momentum (MeV/c)
0
50
100
0
1000
2000
3000

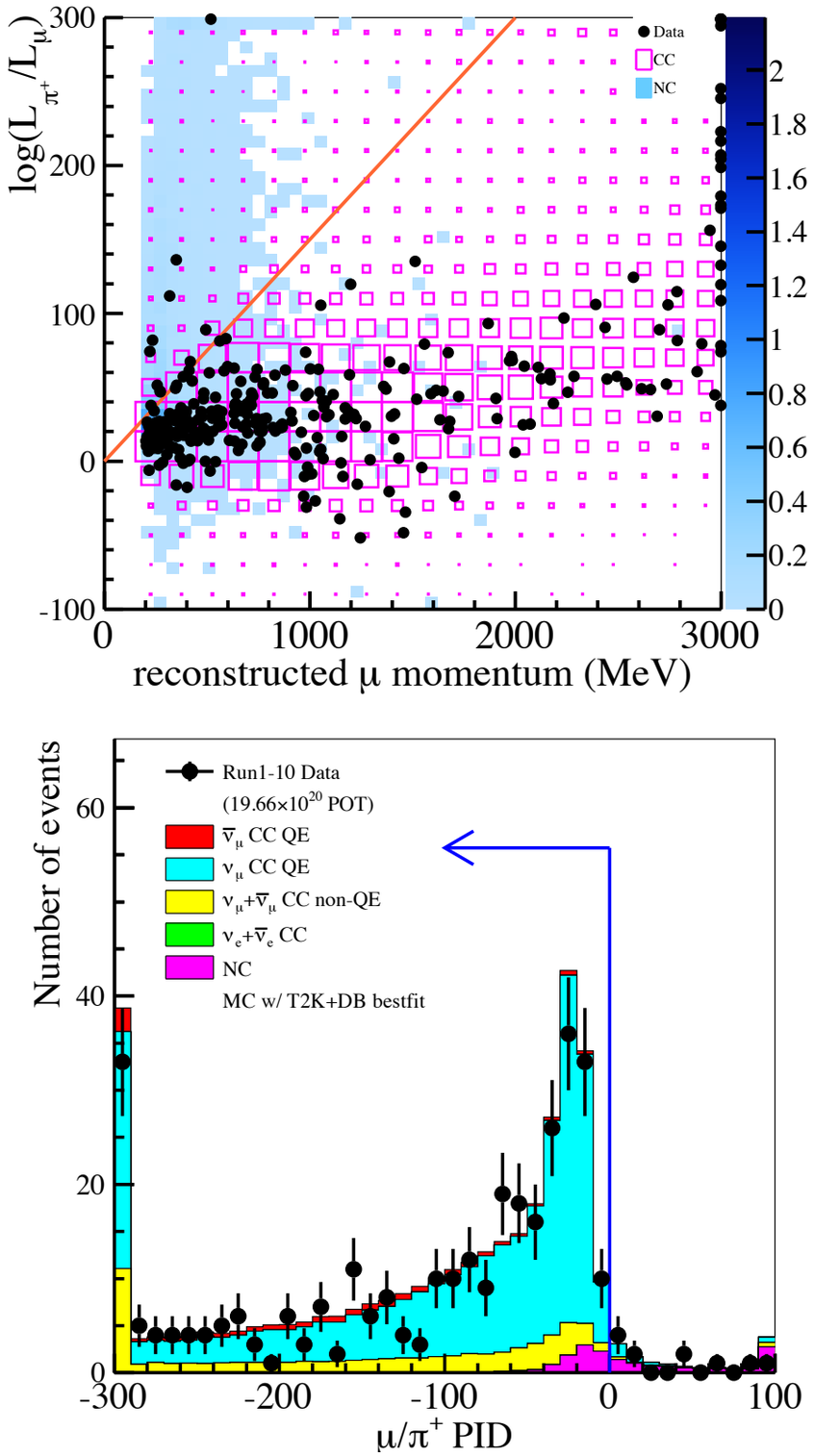

Run5-9 Data
(16.35×10^20 POT)
ν̄μ CC QE
νμ CC QE
νμ+ν̄μ CC non-QE
νe+ν̄e CC
NC
MC w/ T2K+DB bestfit
Number of events/100 MeV/c
Momentum (MeV/c)
0
10
20
0
1000
2000
3000

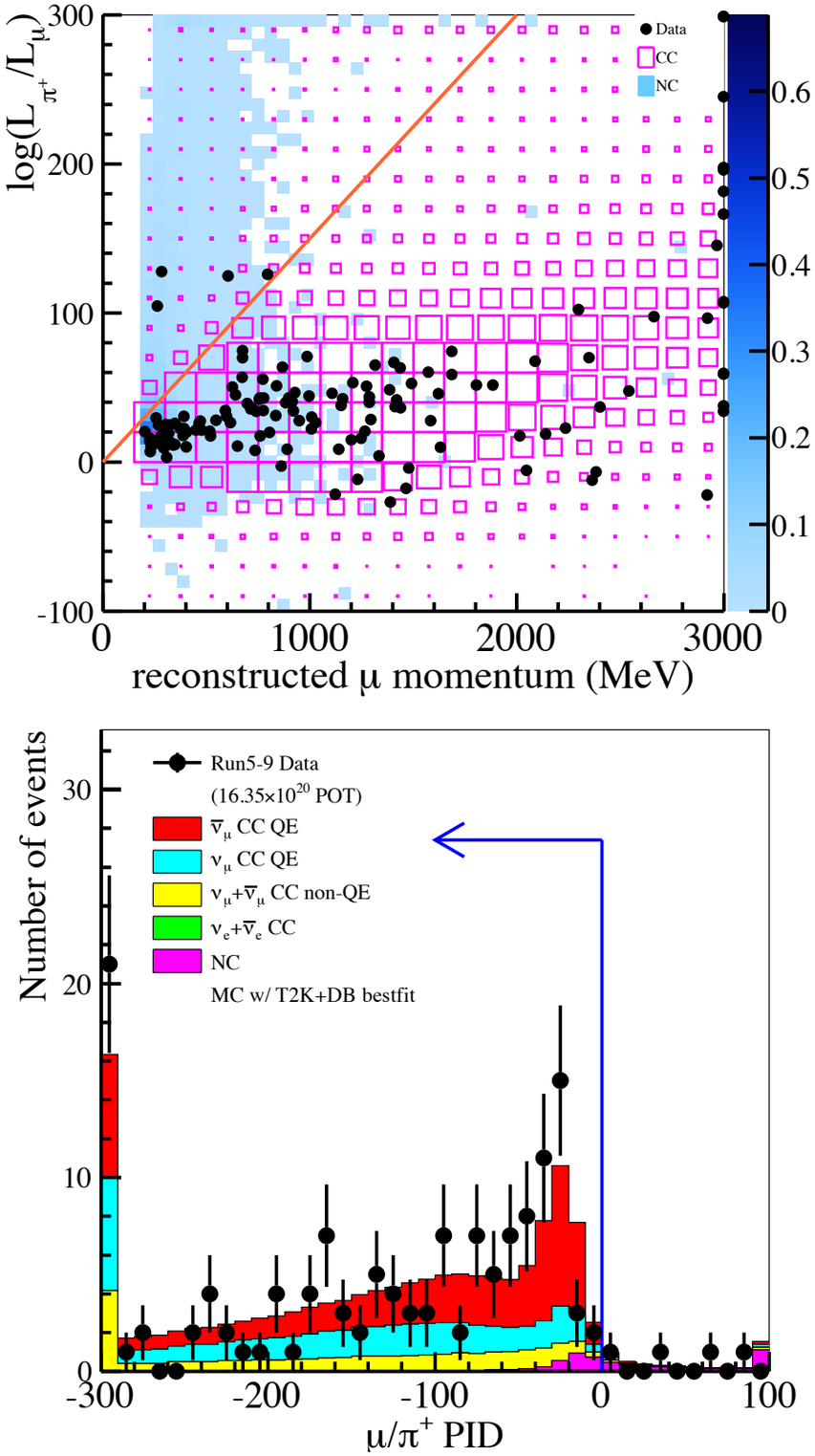
#Decay-electrons (<=1)





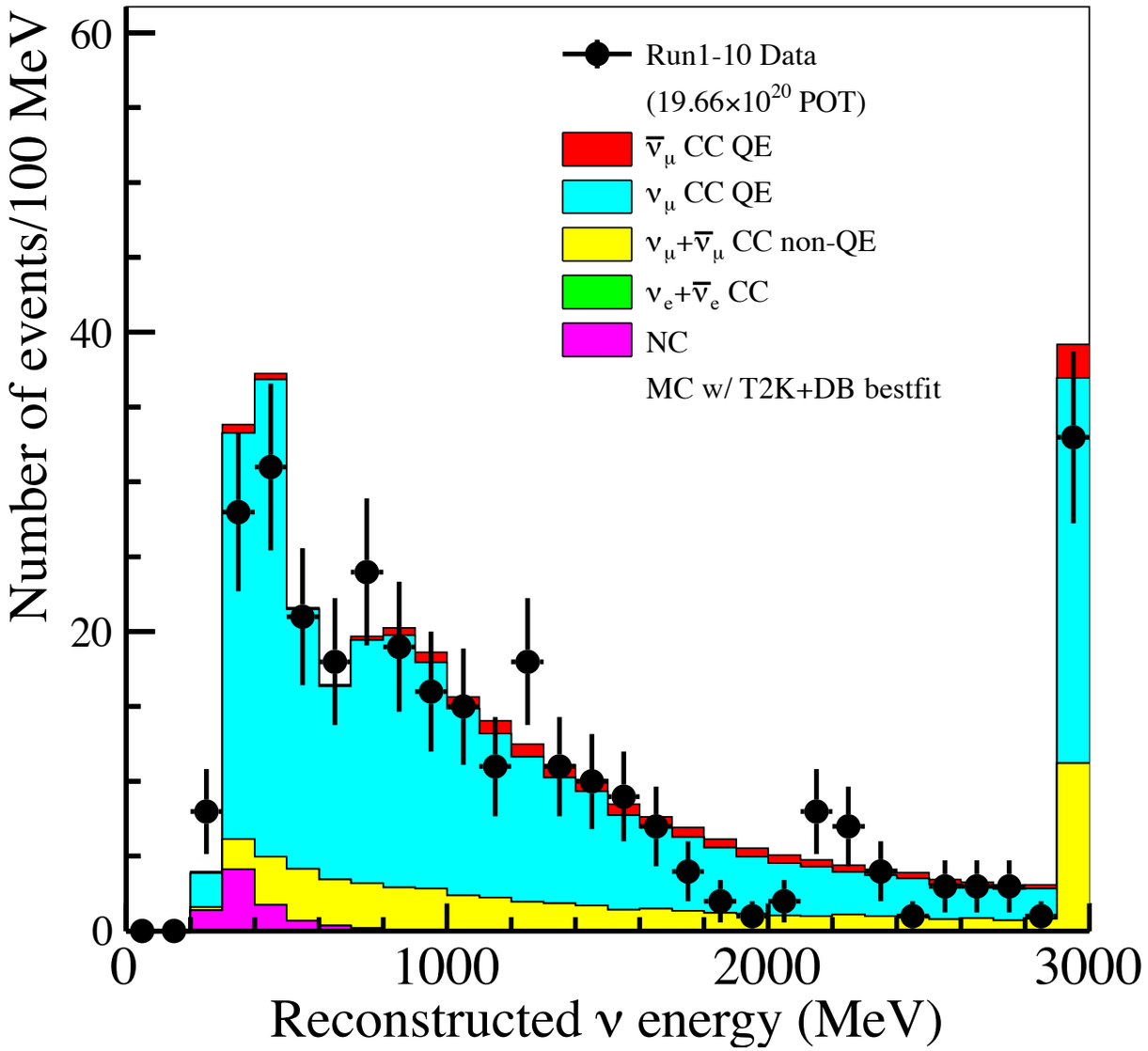
NOT π^+

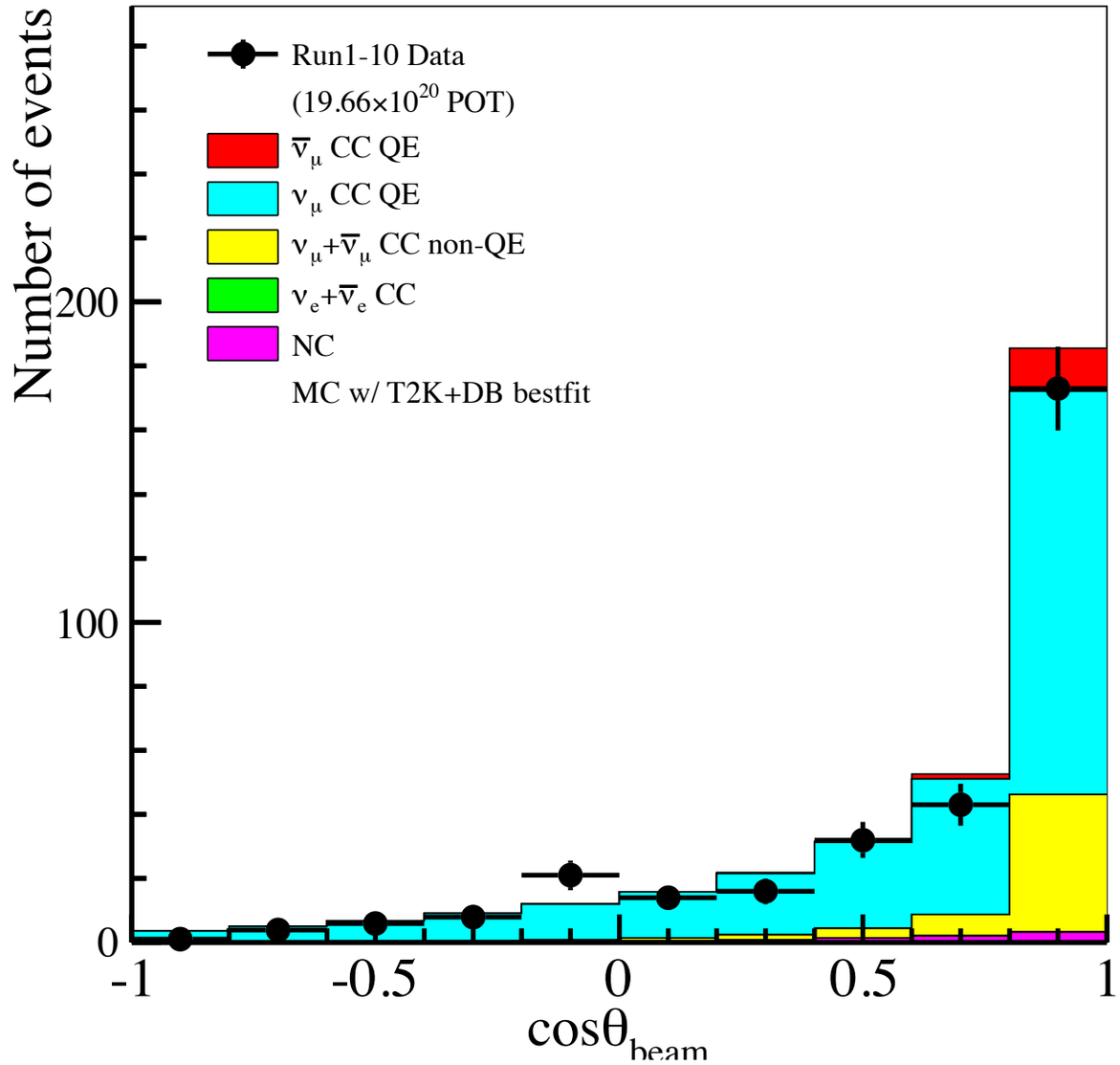

log(L_π+ /L_μ)
Data
CC
NC
reconstructed μ momentum (MeV)
Run1-10 Data
(19.66×10^20 POT)
ν̄_μ CC QE
ν_μ CC QE
ν_μ+ν̄_μ CC non-QE
ν_e+ν̄_e CC
NC
MC w/ T2K+DB bestfit
Number of events
μ/π+ PID


log(L_π+ /L_μ)
Data
CC
NC
reconstructed μ momentum (MeV)
Run5-9 Data
(16.35×10^20 POT)
ν̄_μ CC QE
ν_μ CC QE
ν_μ+ν̄_μ CC non-QE
ν_e+ν̄_e CC
NC
MC w/ T2K+DB bestfit
Number of events
μ/π+ PID

Muon Neutrino events

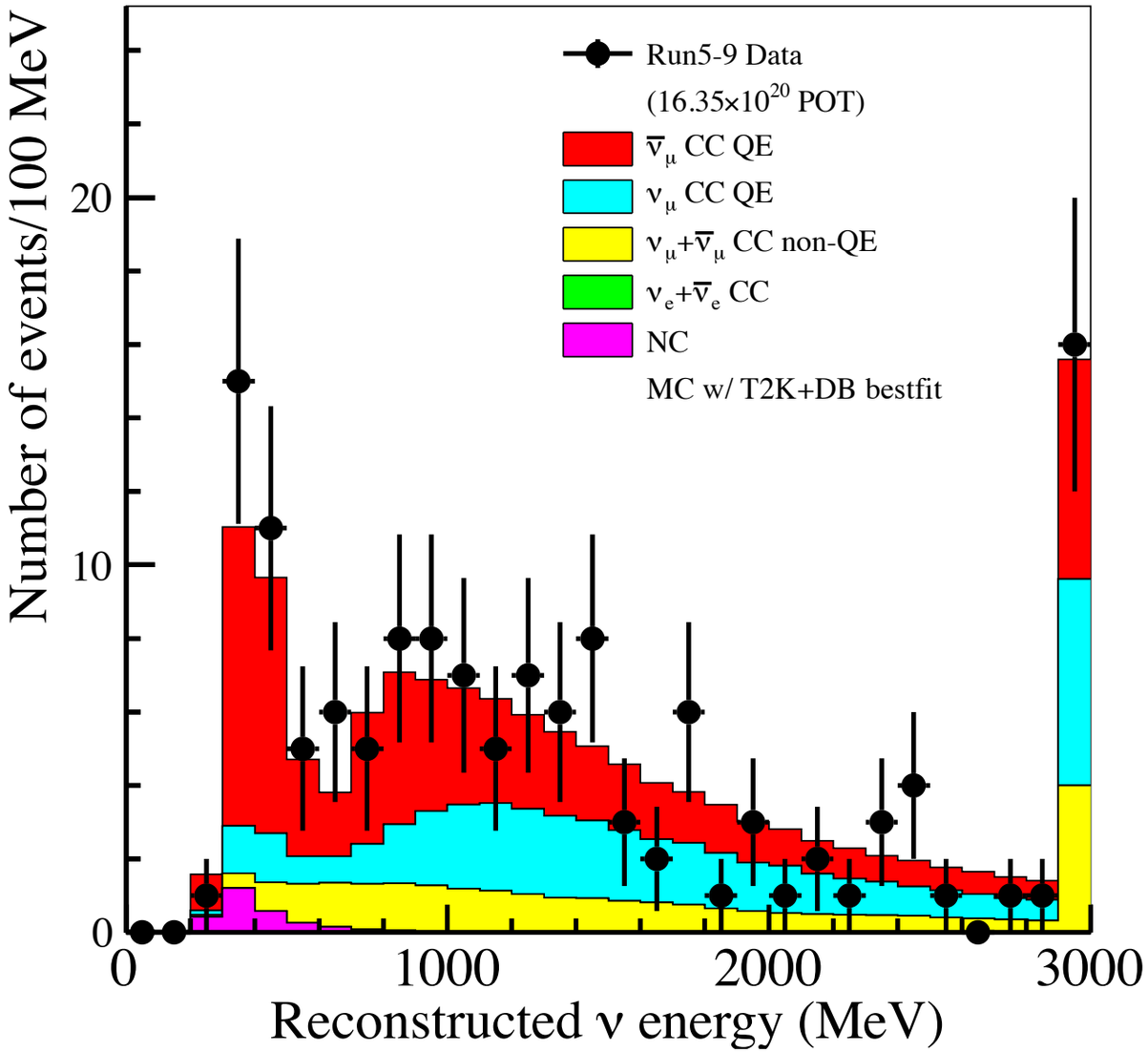
- Neutrino:
  - Data: 318
  - MC: 344.422

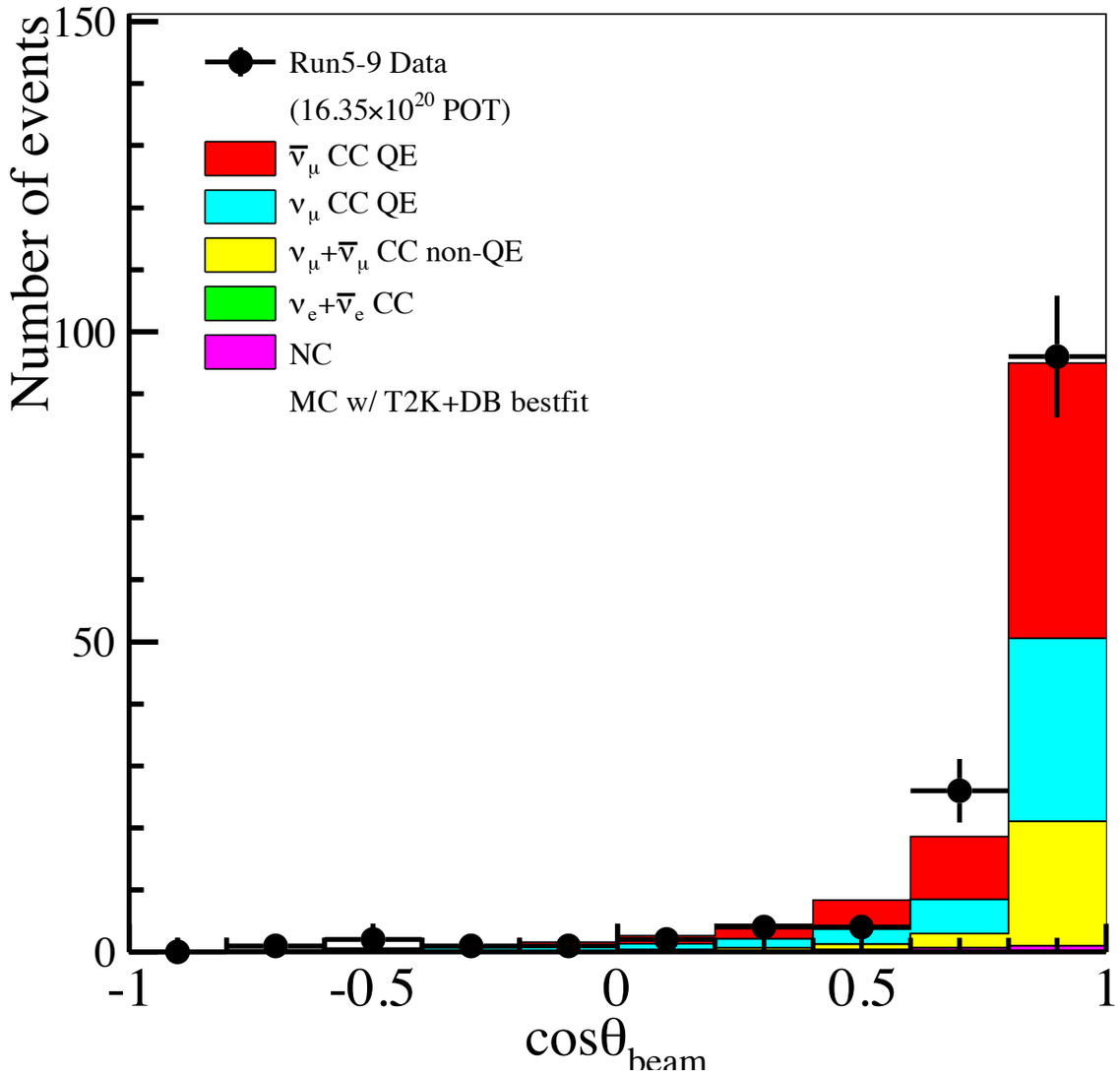




Muon Anti-Neutrino events

- Anti-neutrino:
  - Data: 137
  - MC: 132.809





FINAL muon (anti-)neutrino events

Runs 1-10	Expected							Data
	$\nu_e + \bar{\nu}_e$ CC	NC	$\nu_\mu + \bar{\nu}_\mu$ CC non-QE	Bckg Total	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE	MC total	
Floor-FCFV	828.065	51.574	255.620	1135.259	110.486	0.959	1246.704	1279
FCFV	159.210	252.169	487.223	898.601	312.544	18.239	1229.385	1266
Single Ring	120.241	48.469	89.208	257.919	276.480	16.037	550.436	534
Muon-like PID	0.130	18.270	84.397	102.797	270.330	15.927	389.055	367
Momentum	0.130	18.127	84.351	102.608	269.977	15.924	388.509	366
0 or 1 Decay-e	0.128	17.606	57.972	75.706	266.412	15.751	357.869	329
π^+ rejection cut	0.121	8.896	56.723	65.740	263.084	15.597	344.422	318
Efficiency from FCFV	0.001	0.035	0.116	0.073	0.842	0.855	0.280	-

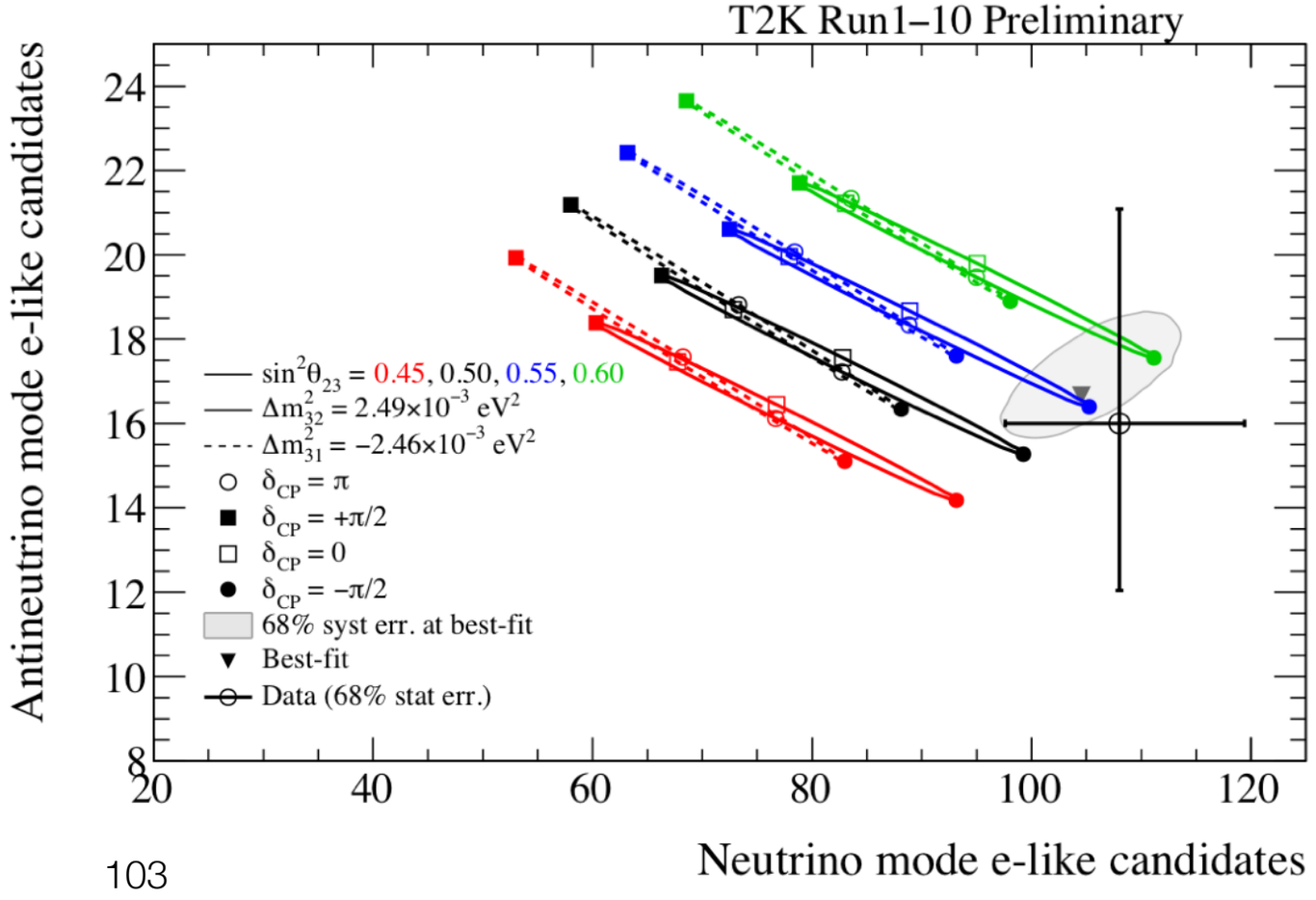
Floor-FCFV	19.908	87.827	170.146	277.881	53.225	74.086	405.192	459
FCFV	35.324	86.630	169.259	291.213	52.663	72.699	416.575	454
Single Ring	23.313	16.622	32.691	72.626	43.306	66.692	182.624	191
Muon-like PID	0.013	6.290	31.379	37.682	42.884	65.768	146.333	154
Momentum	0.013	6.232	31.373	37.618	42.865	65.729	146.213	154
0 or 1 Decay-e	0.013	6.031	24.437	30.481	42.160	64.931	137.572	141
π^+ rejection cut	0.011	2.849	24.025	26.885	41.673	64.251	132.809	137
Efficiency from FCFV	0.000	0.033	0.142	0.092	0.791	0.884	0.319	-

7. Oscillation Analysis

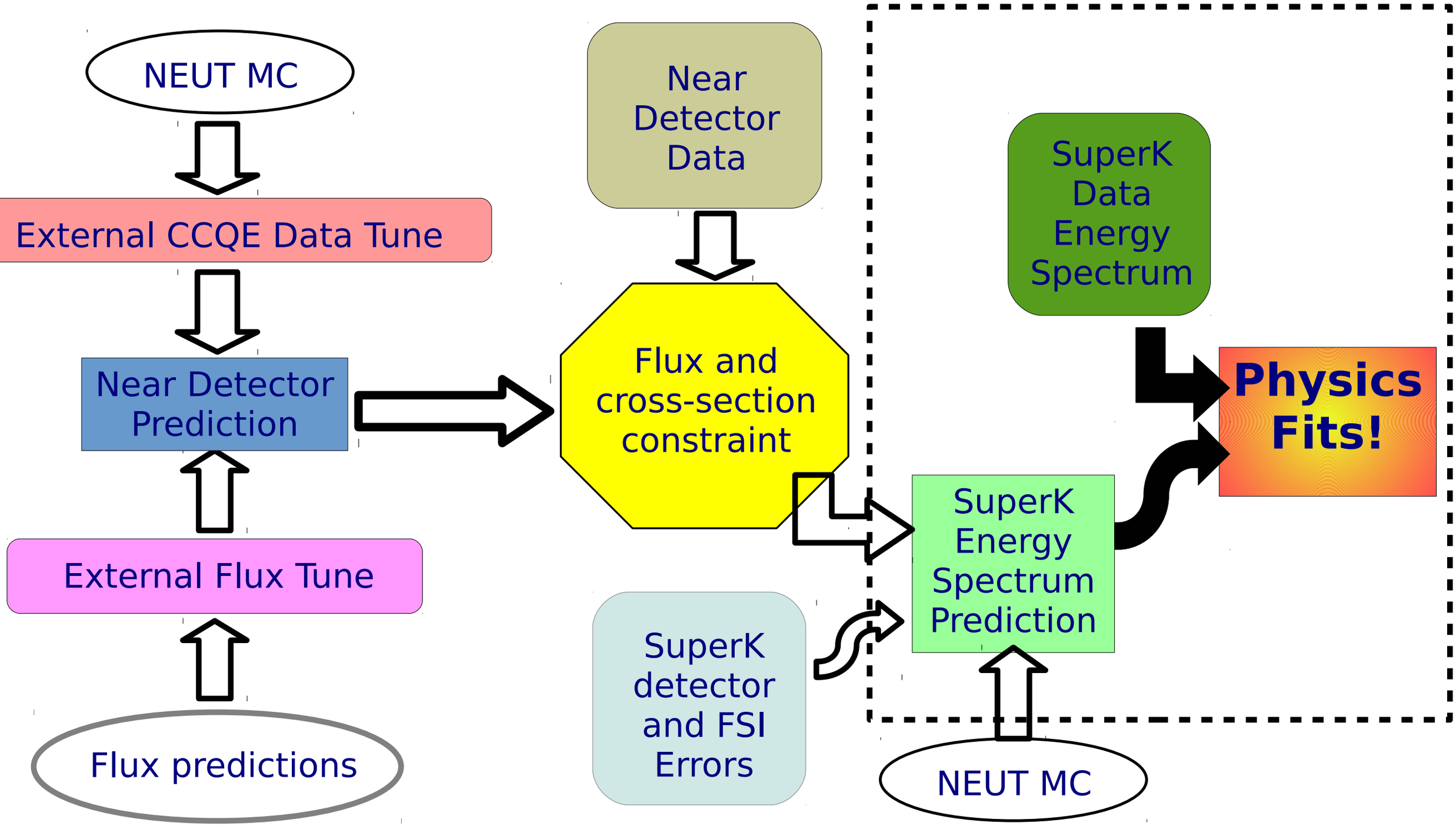
Event sample for OA

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Rμ	356.48	355.76	356.44	357.27	318
RHC 1Rμ	138.34	137.98	138.34	138.73	137
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1π^+	9.20	8.01	6.51	7.71	14
FHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	213.40	213.06	213.36	213.81	191
RHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	68.53	68.34	68.53	68.74	71

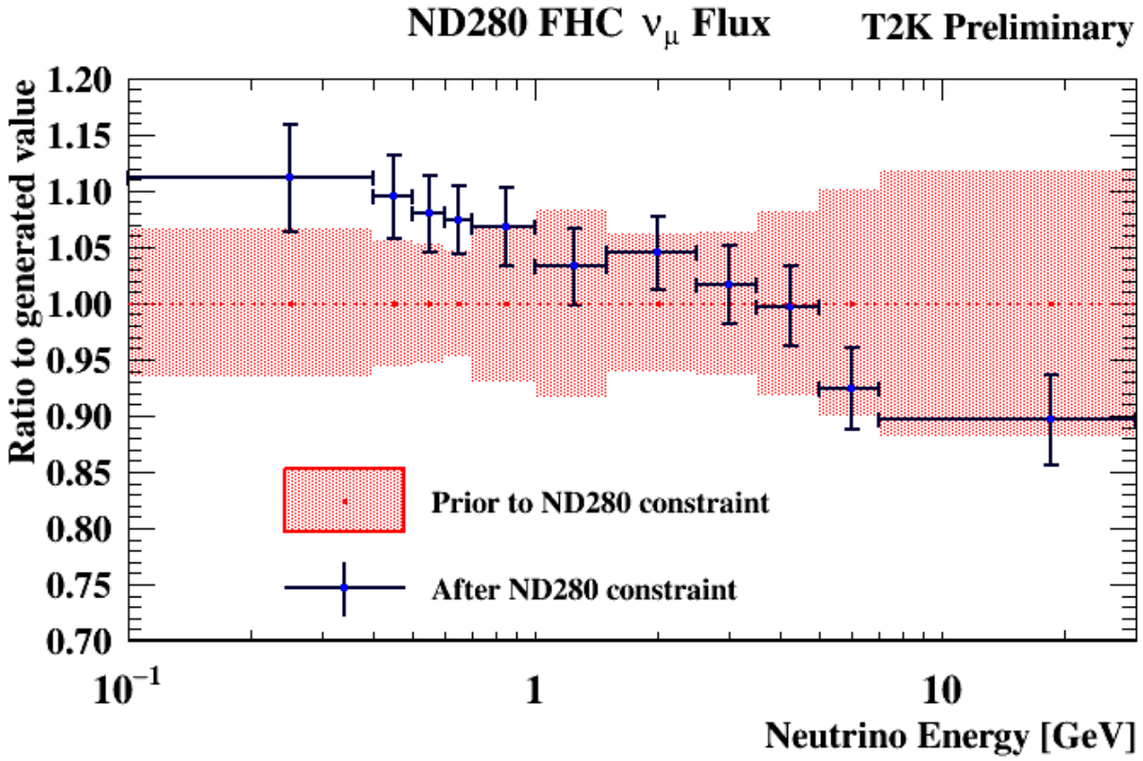
- **FHC (Forward Horn Current): Neutrino beam mode**
- **RHC (Riverse Horn Current): Anti-neutrino beam mode**

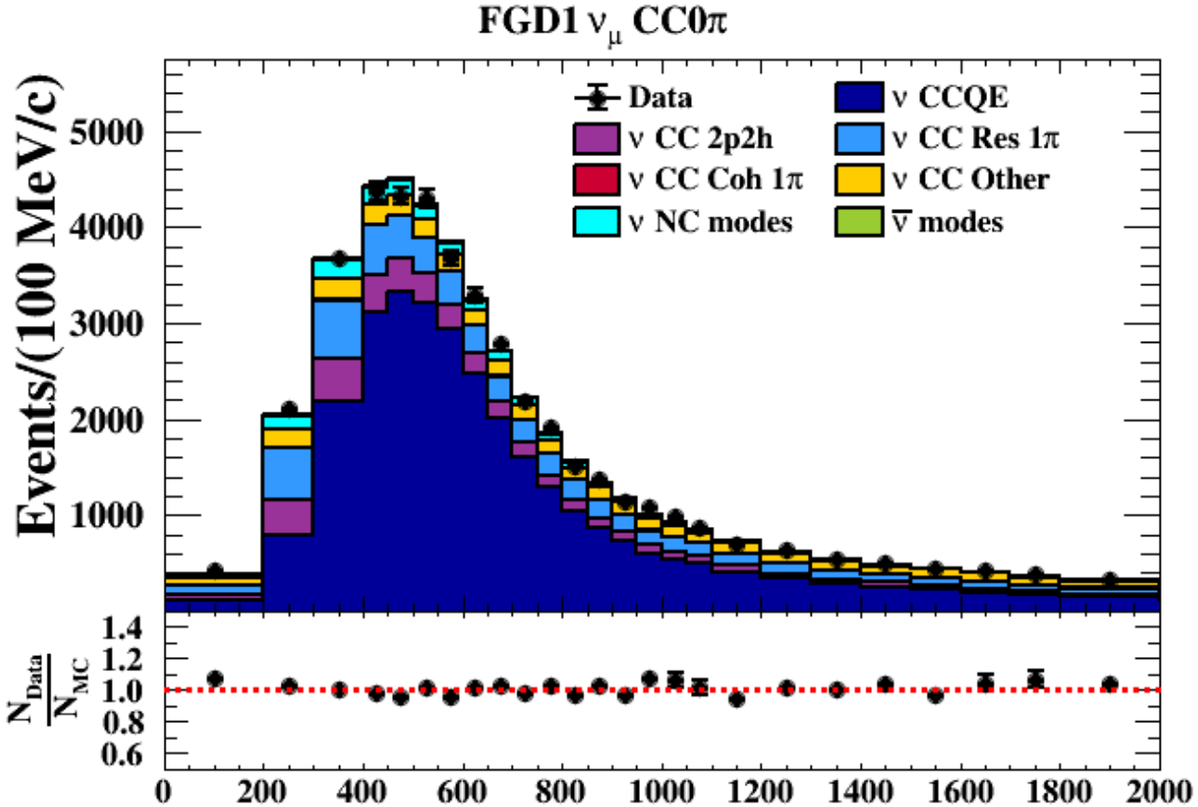


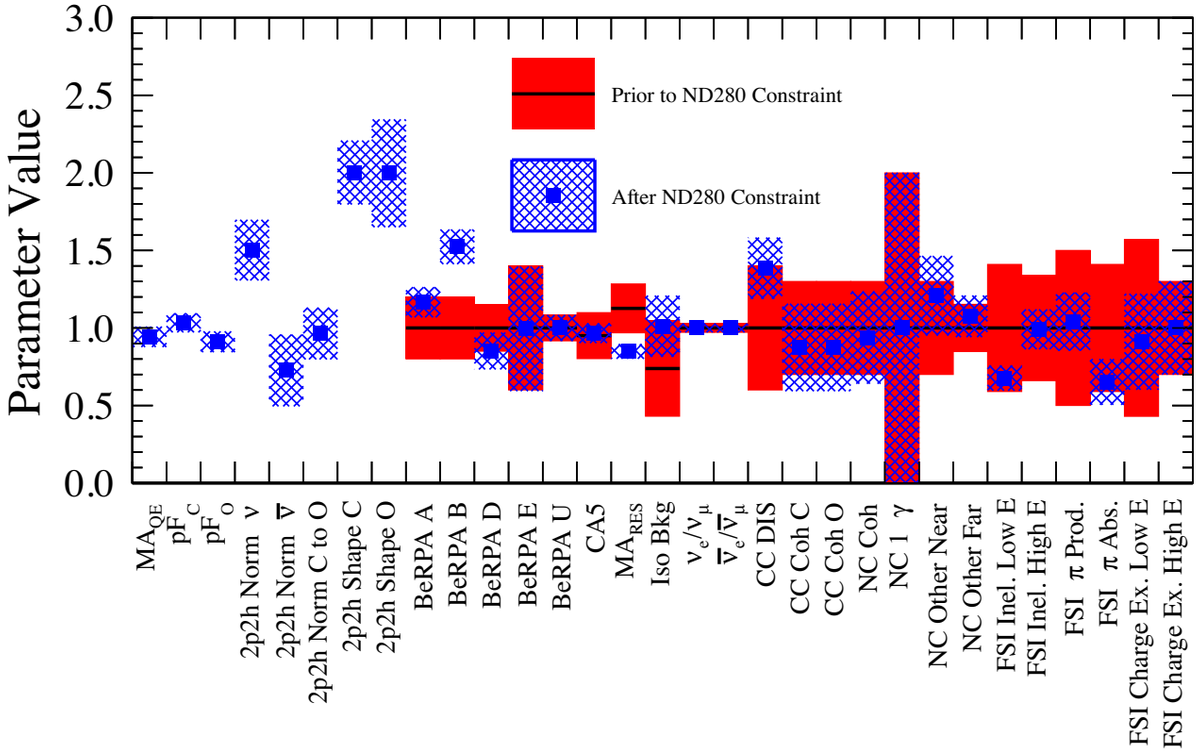
REMINDER: OA overview

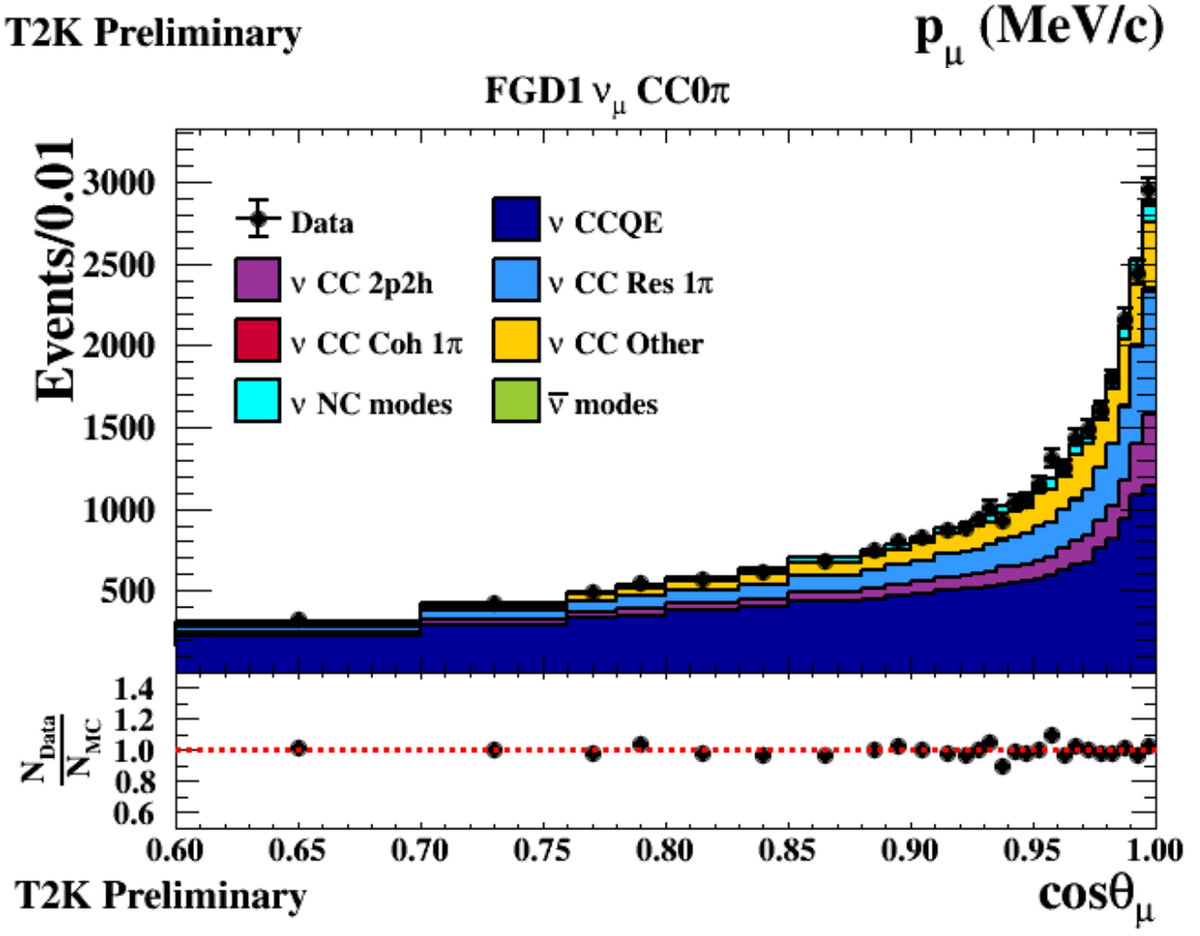


Near Detector measurements → constraints

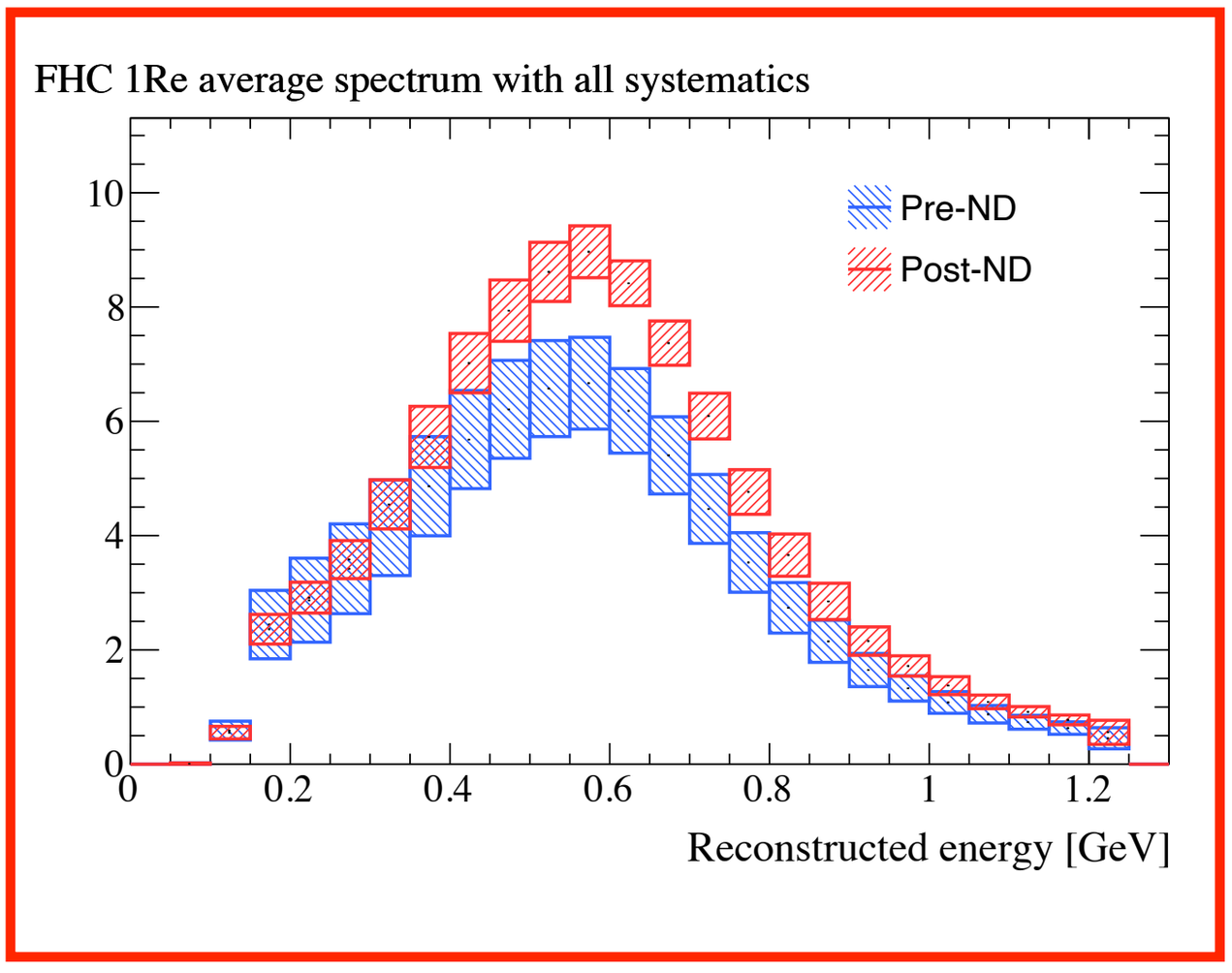


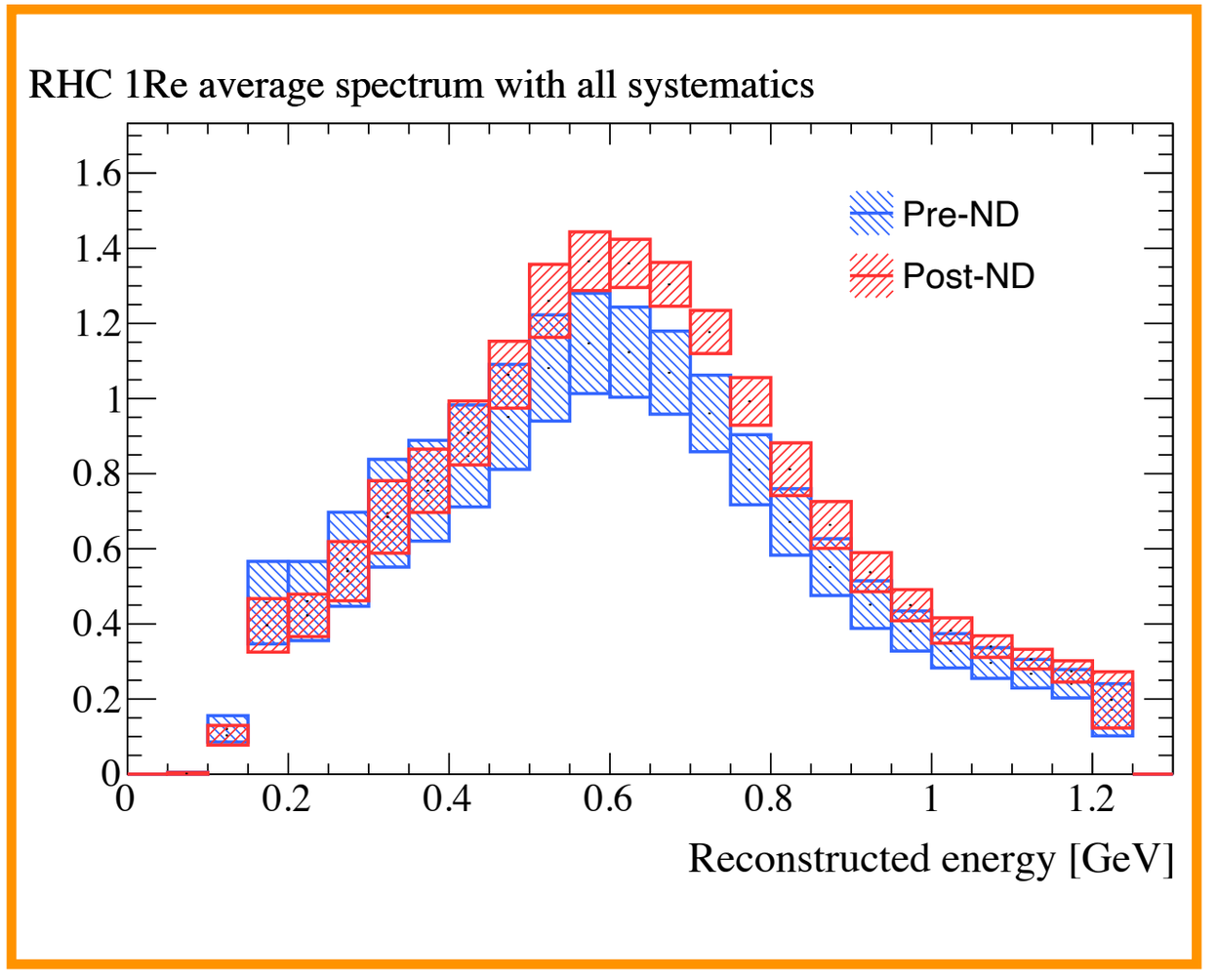




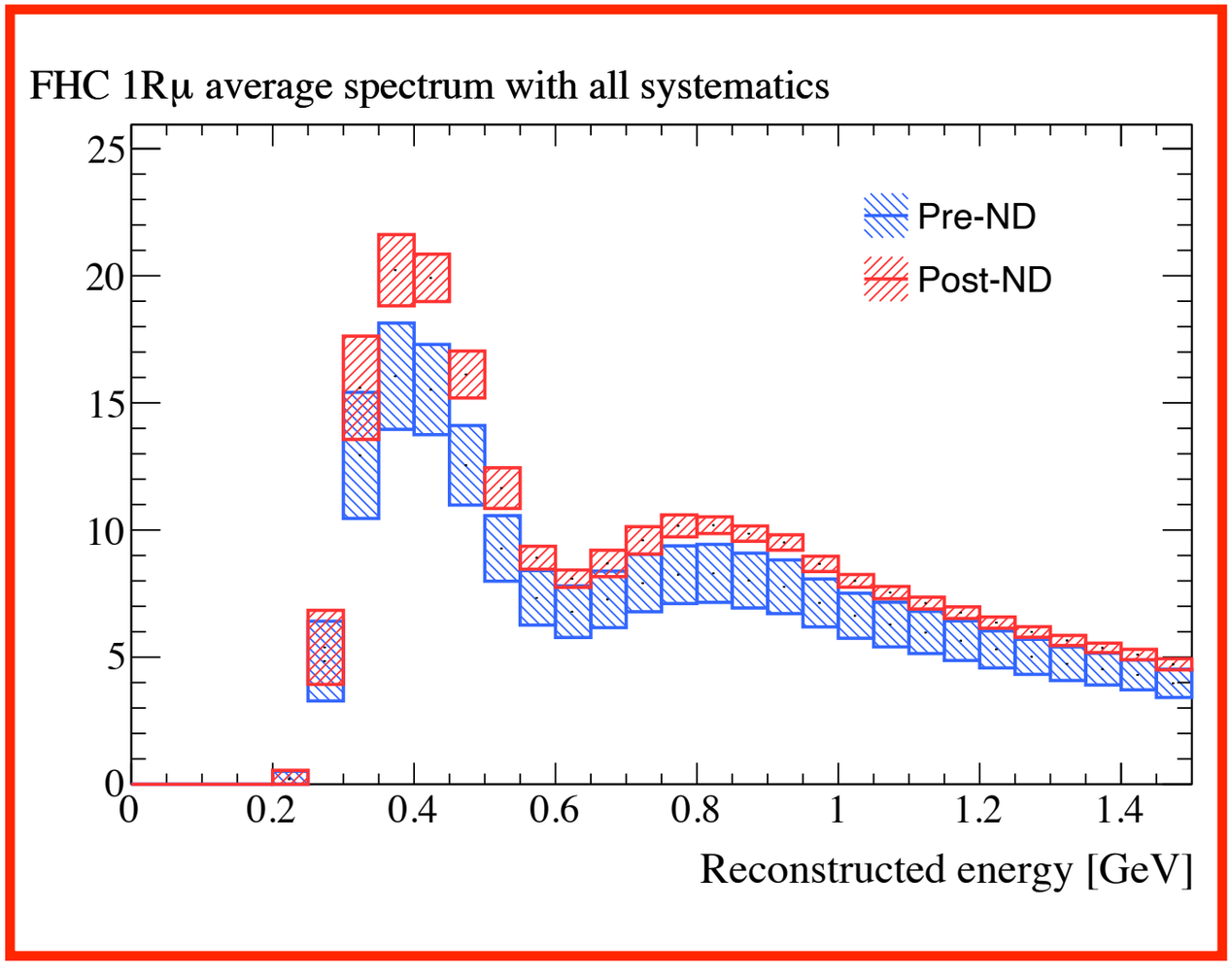


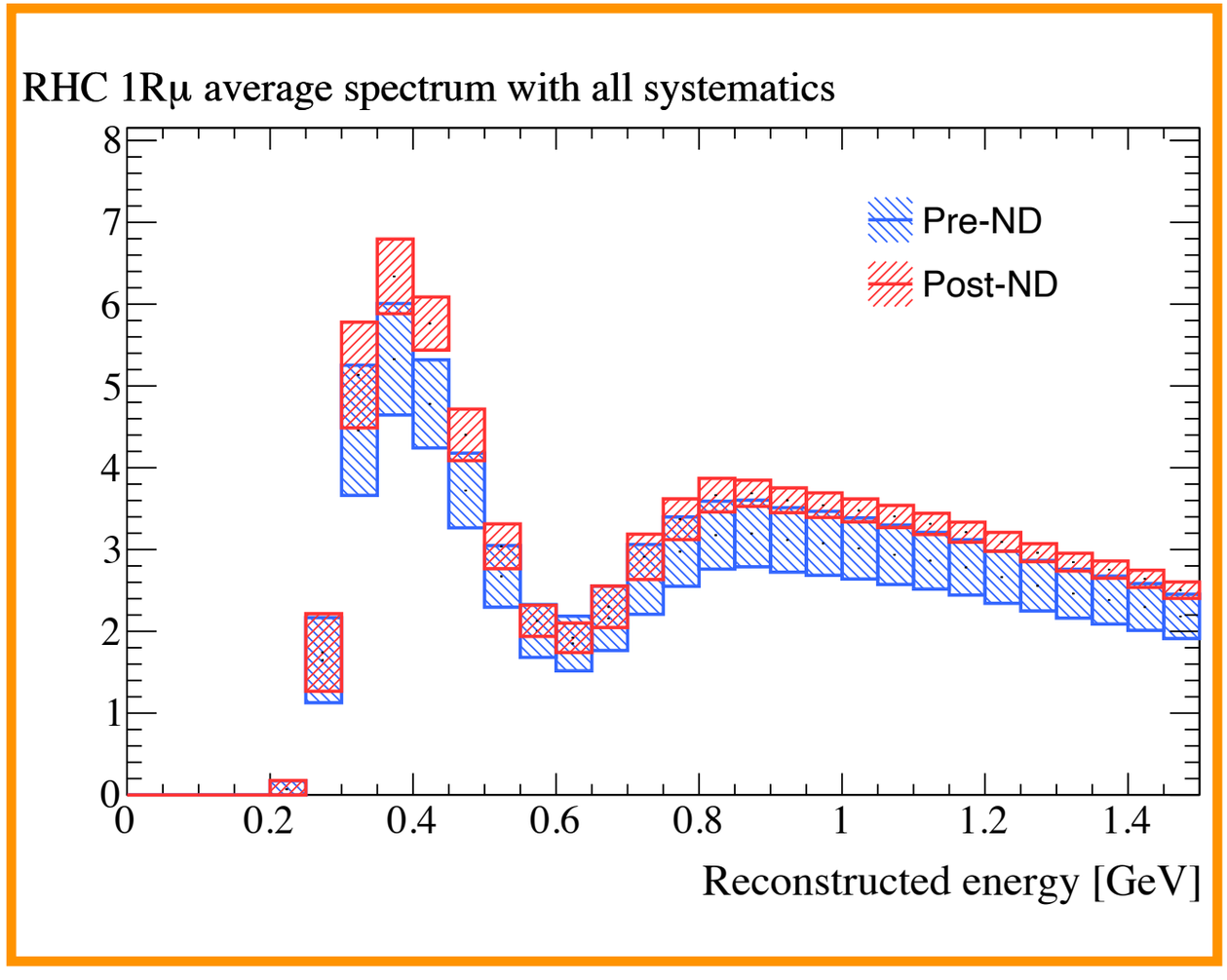
Electron Neutrino Predictions





Muon Neutrino Predictions





Systematic uncertainties

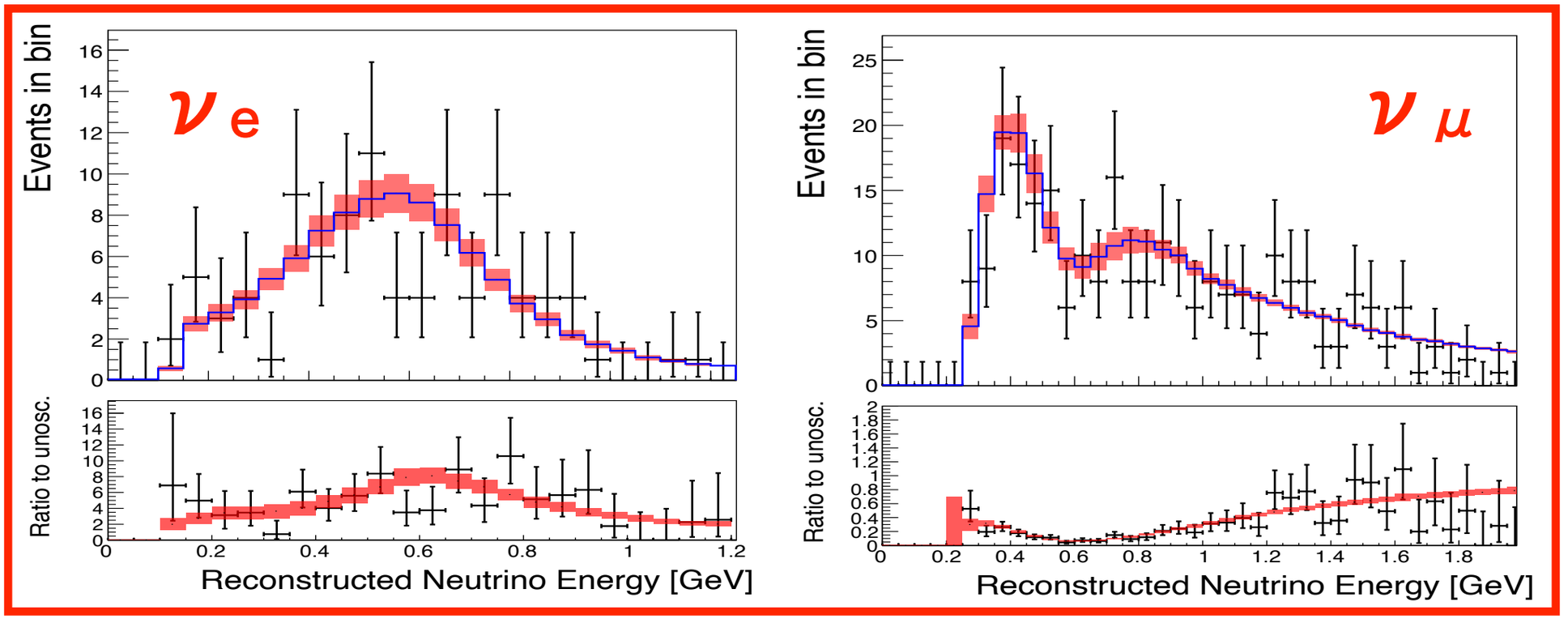
Before ND280 Constraint

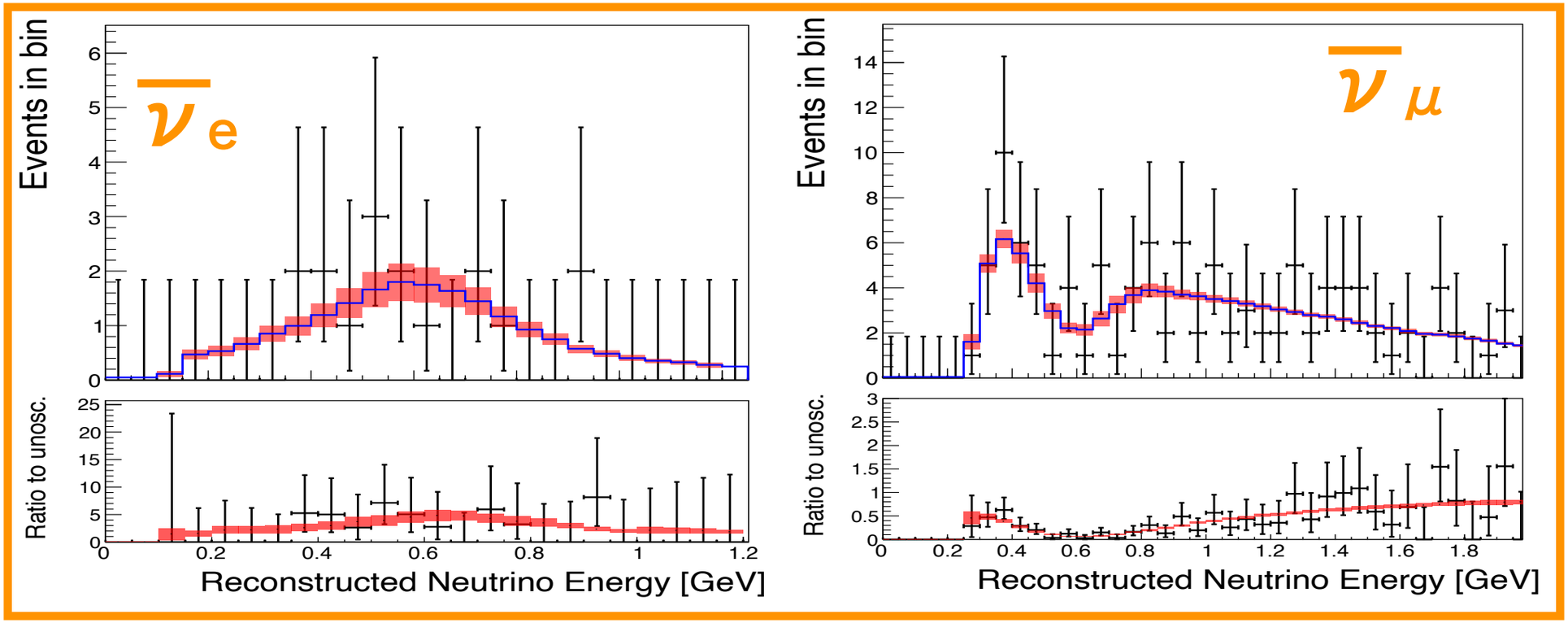
Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

After ND280 Constraint

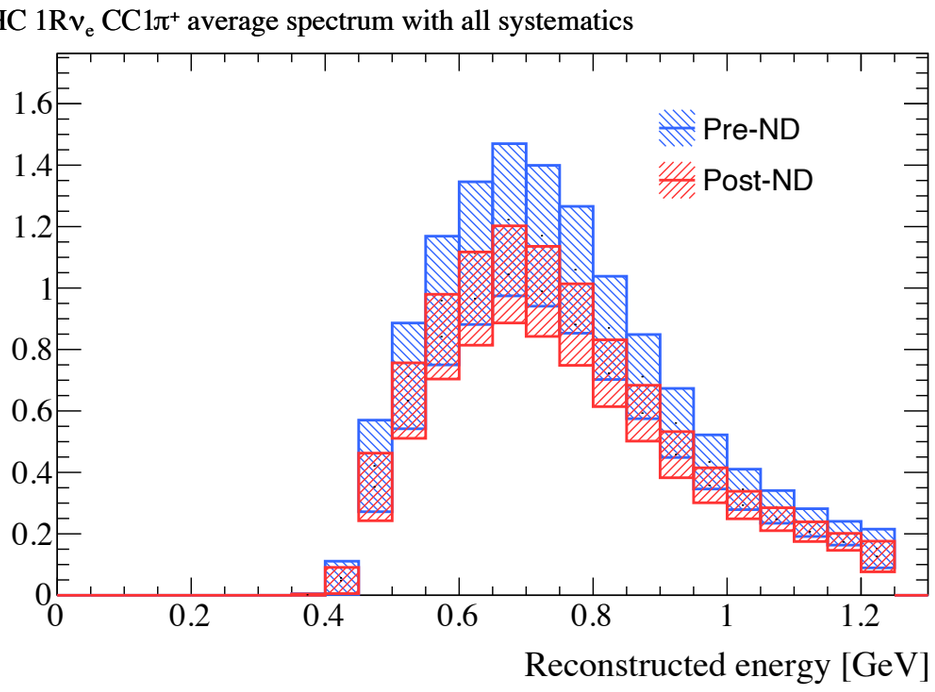
Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

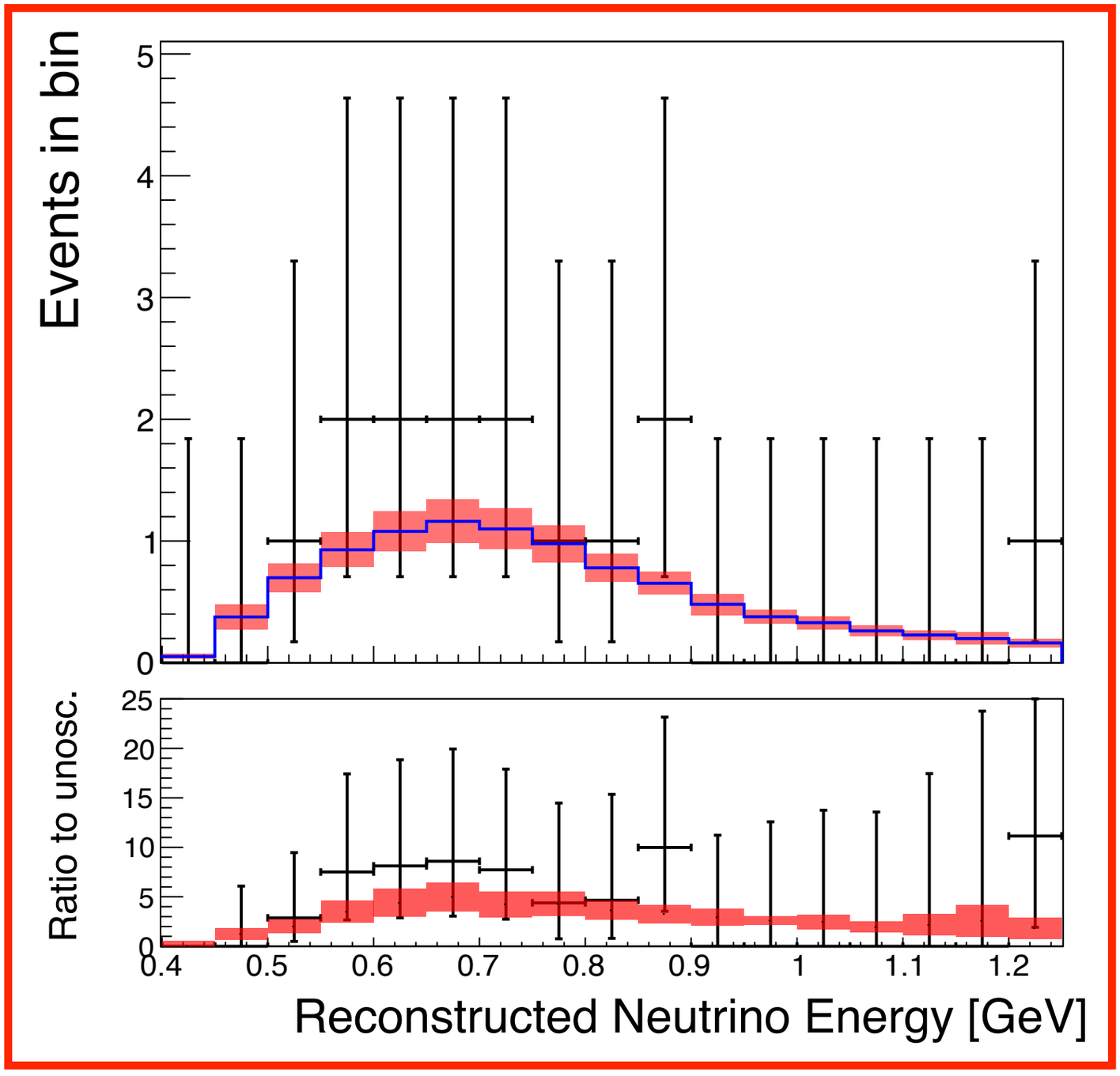
Oscillation FIT





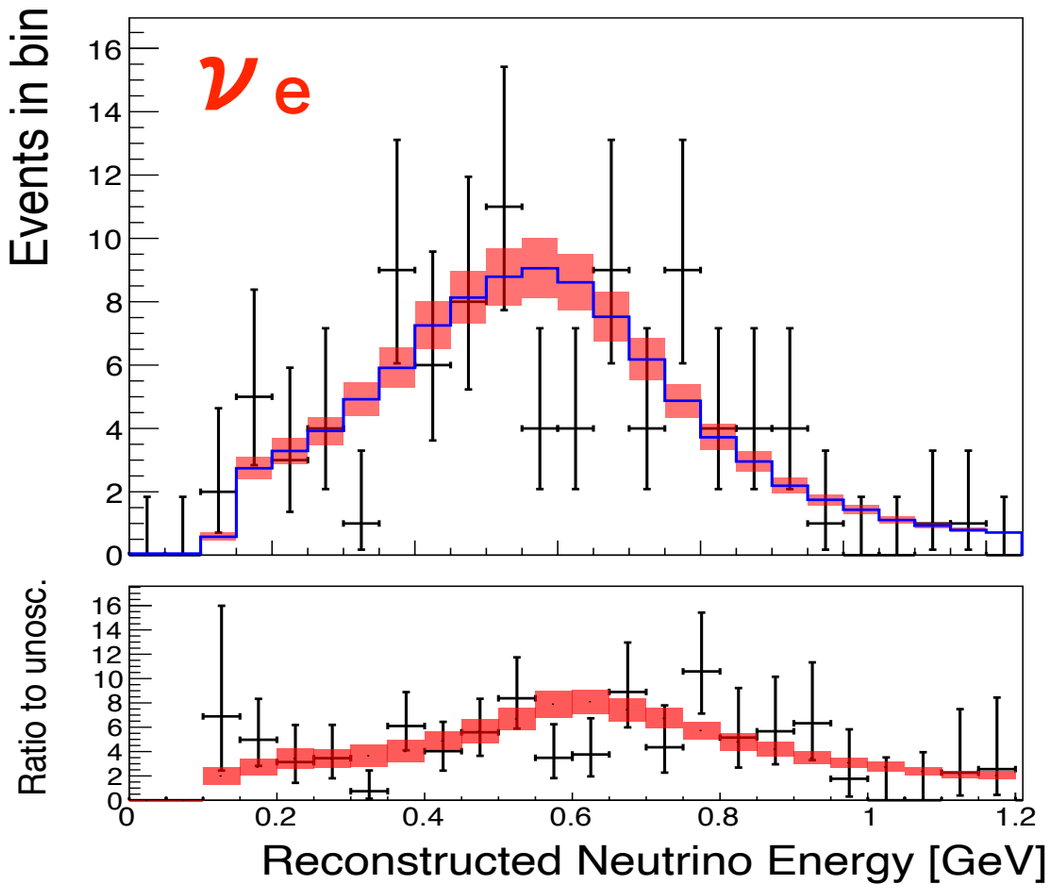
Oscillation FIT w/ CC ν_e-1π^+

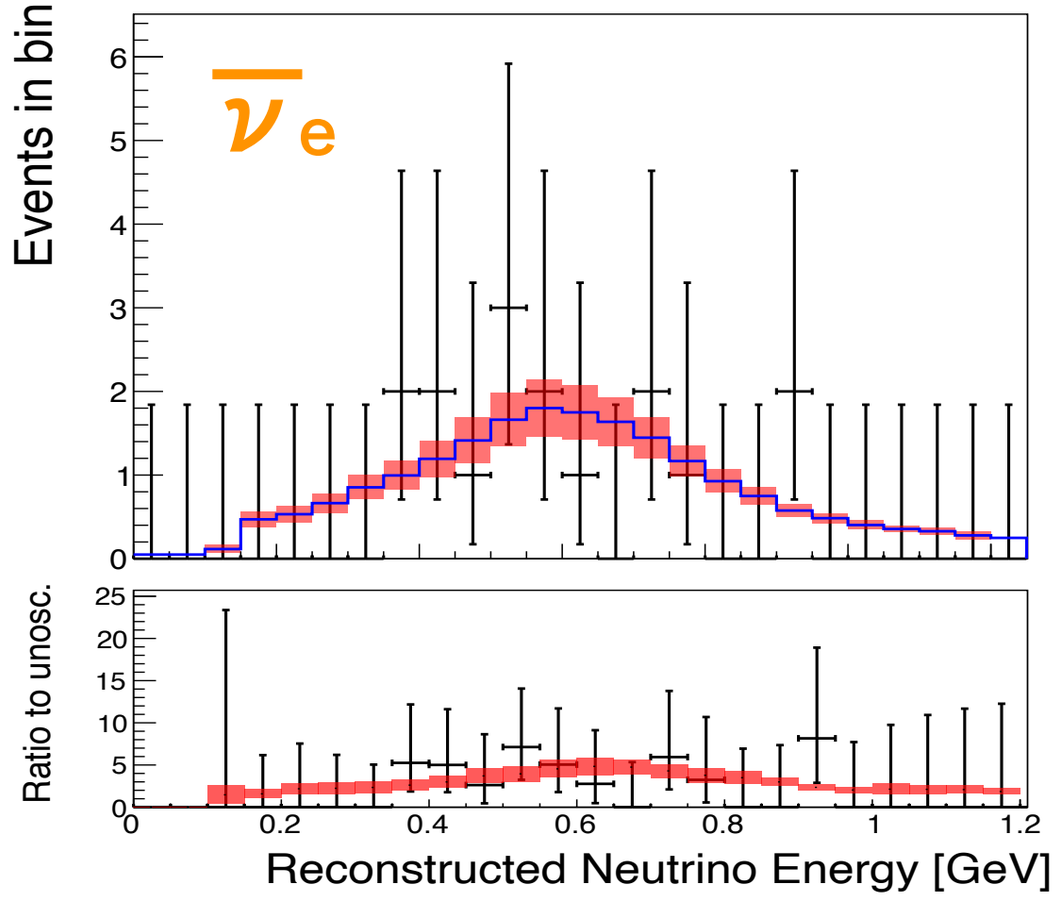




9. Latest OA results

Best Fit oscillation parameters





- **Data: 94**
- **Best fit w/δ_{CP}=-π/2: 97.62**

- **Data: 16**
- **Best fit w/δ_{CP}=-π/2: 16.69**

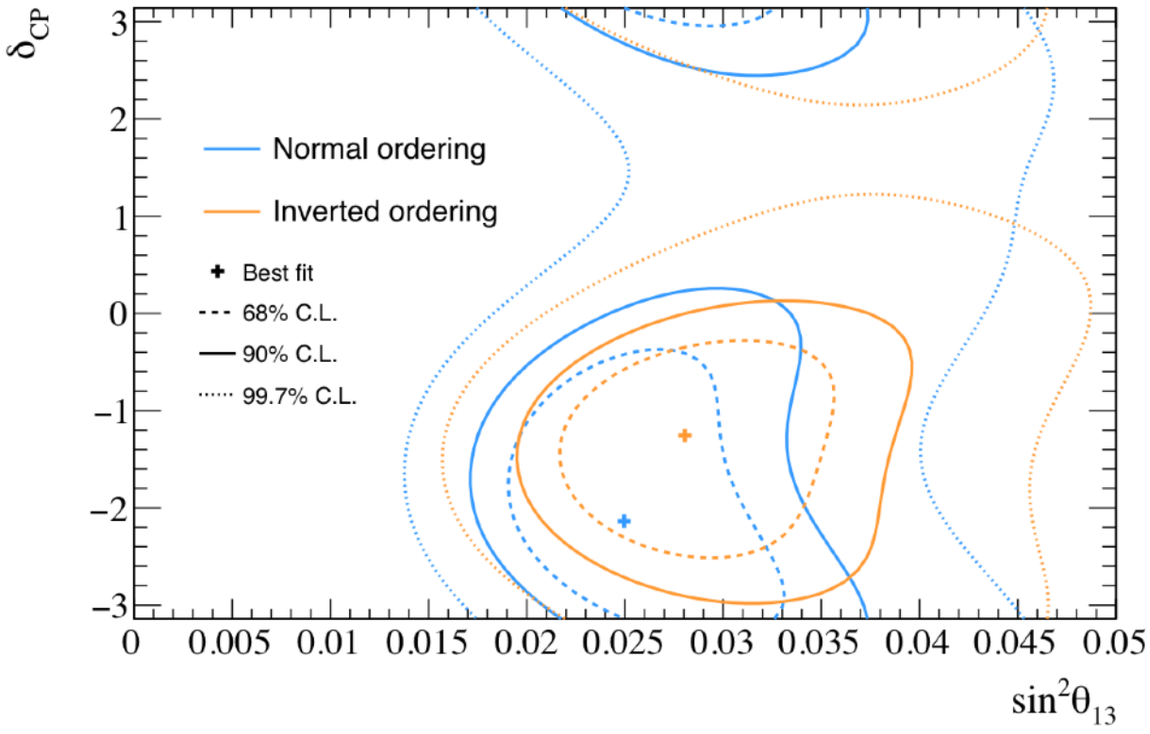
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1π^+	9.20	8.01	6.51	7.71	14

T2K Best fit osc. parameters

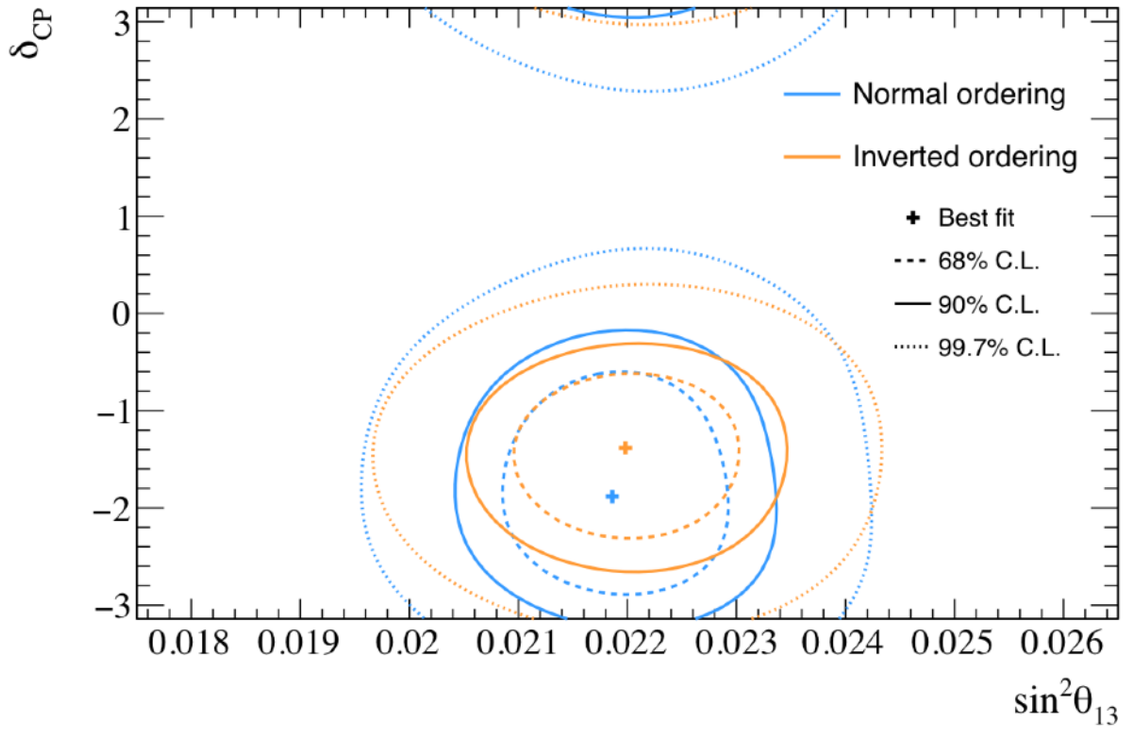
Parameter	Best fit			
Data	T2K only		T2K + reactor	
Hierarchy	Normal	Inverted	Normal	Inverted
$\sin^2(2\theta_{13})$	0.107	0.118	0.0856	0.0860
$\sin^2(\theta_{13})$	27.5×10^{-3}	30.5×10^{-3}	21.9×10^{-3}	22.0×10^{-3}
δ_{CP}	-2.22	-1.30	-1.93	-1.44
Δm^2_{32} (NH)/$\lvert\Delta m^2_{31}\rvert$ (IH) [eV^2/c^4]	2.486×10^{-3}	2.453×10^{-3}	2.485×10^{-3}	2.456×10^{-3}
$\sin^2(\theta_{23})$	0.476	0.475	0.553	0.558
$-2 \ln L$	298.75	299.56	299.14	301.25

θ_{13} versus δ_{CP}

T2K only



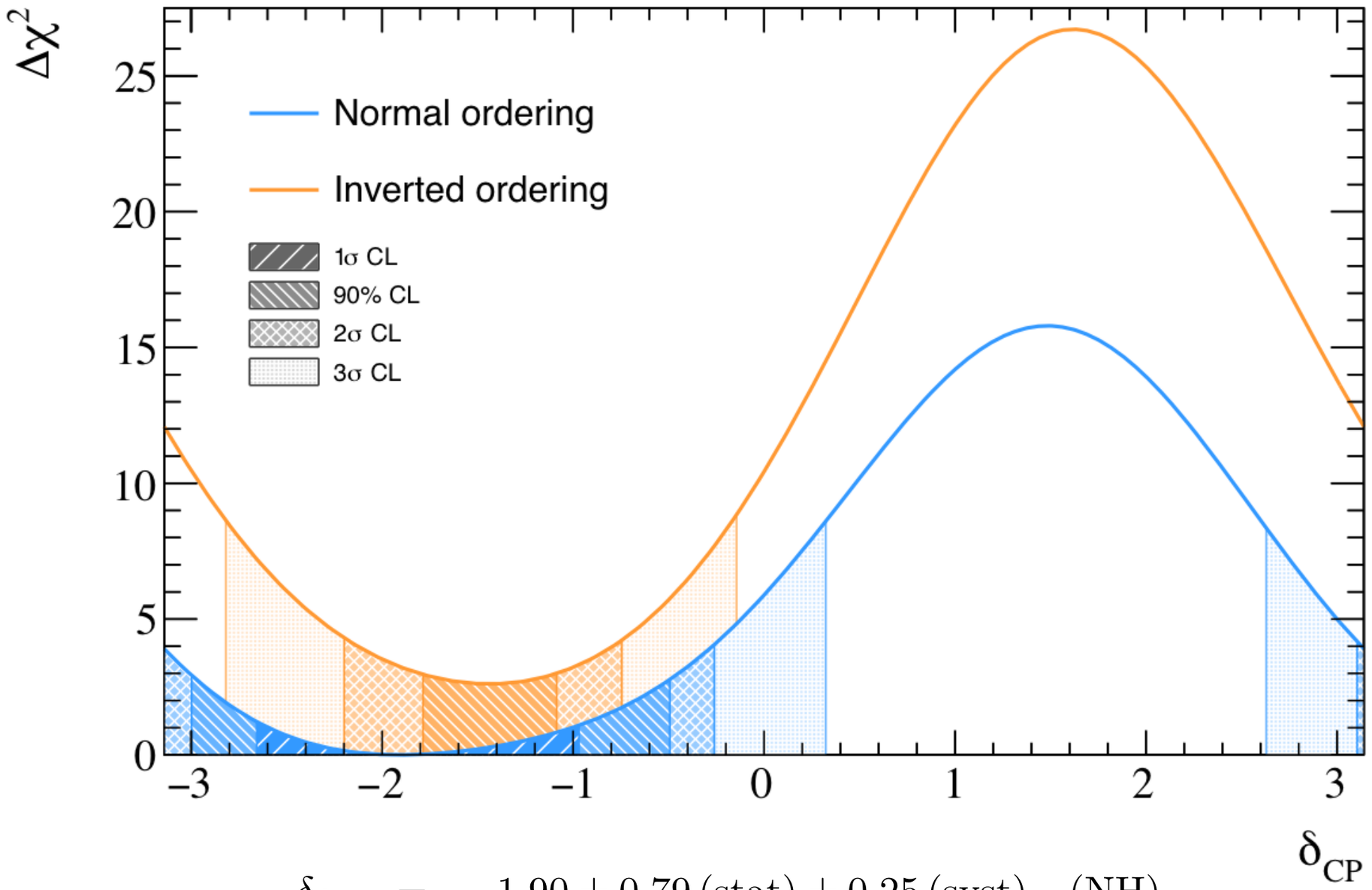
T2K + reactor θ_{13}



δ_{CP}

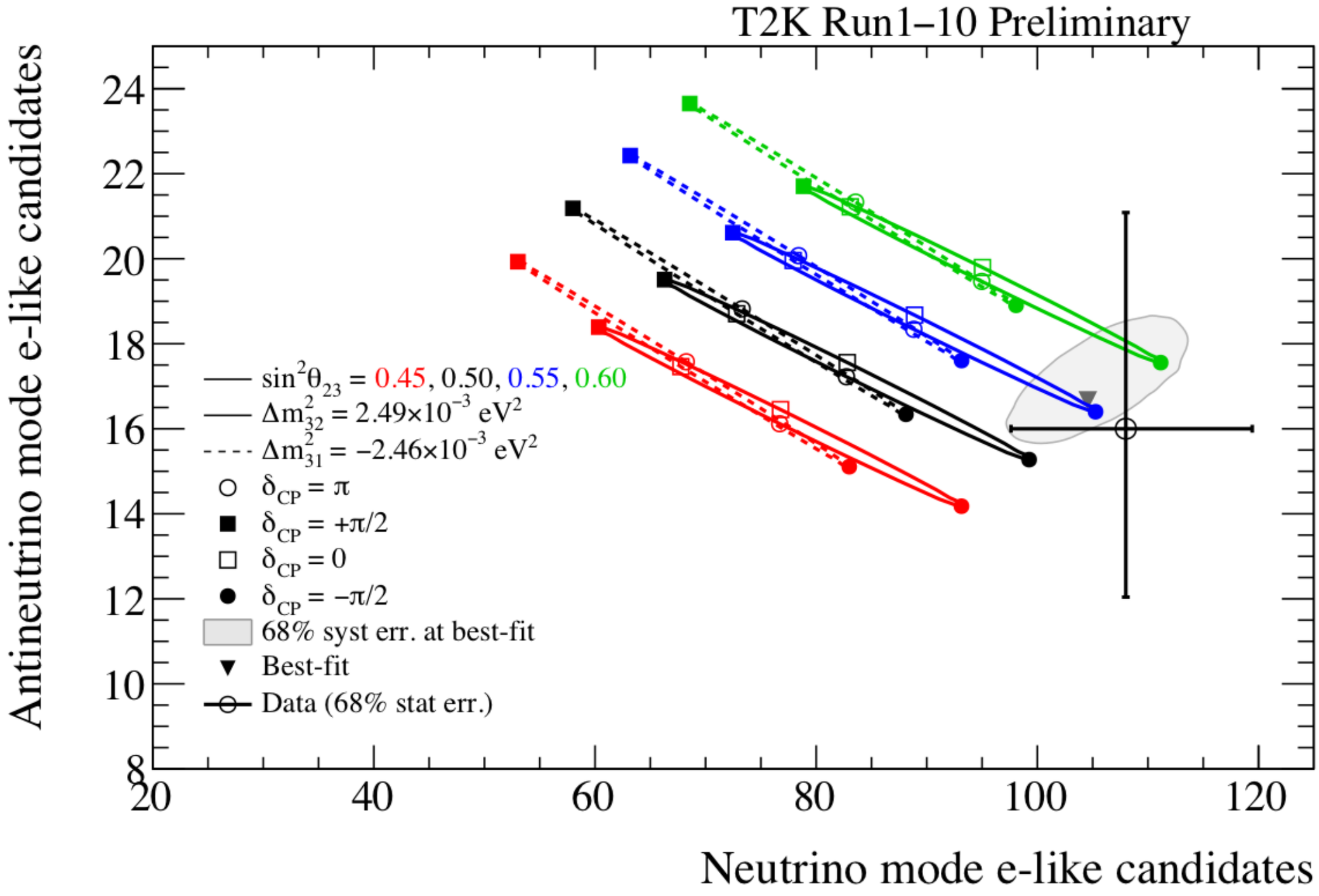
	Hierarchy	Most Probable Value	Range (1σ)
T2K only	Normal	-2.23	$[-3.03, -0.94]$
	Inverted	-1.29	$[-2.09, -0.58]$
	Both	-1.68	$[-2.71, -0.72]$
T2K + reactor	Normal	-1.90	$[-2.55, -1.07]$
	Inverted	-1.43	$[-2.00, -0.89]$
	Both	-1.74	$[-2.44, -0.99]$

δ_{CP} w/ reactor θ_{13}

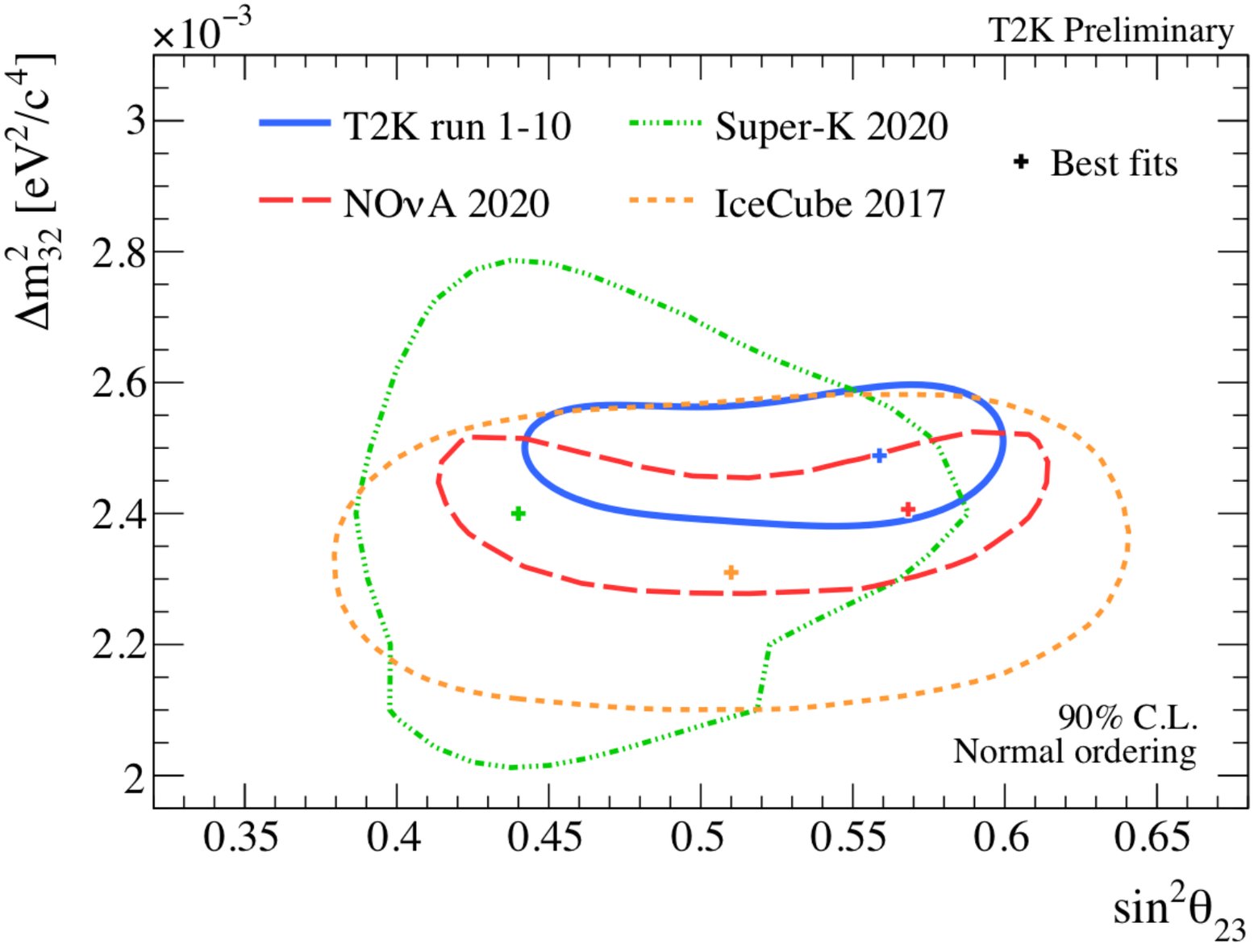


$$\delta_{\rm CP} = -1.90 \pm 0.79\,({\rm stat}) \pm 0.25\,({\rm syst}) \quad ({\rm NH})$$
$$\delta_{\rm CP} = -1.43 \pm 0.52\,({\rm stat}) \pm 0.15\,({\rm syst}) \quad ({\rm IH})$$

Number of events as a function of θ_{23}

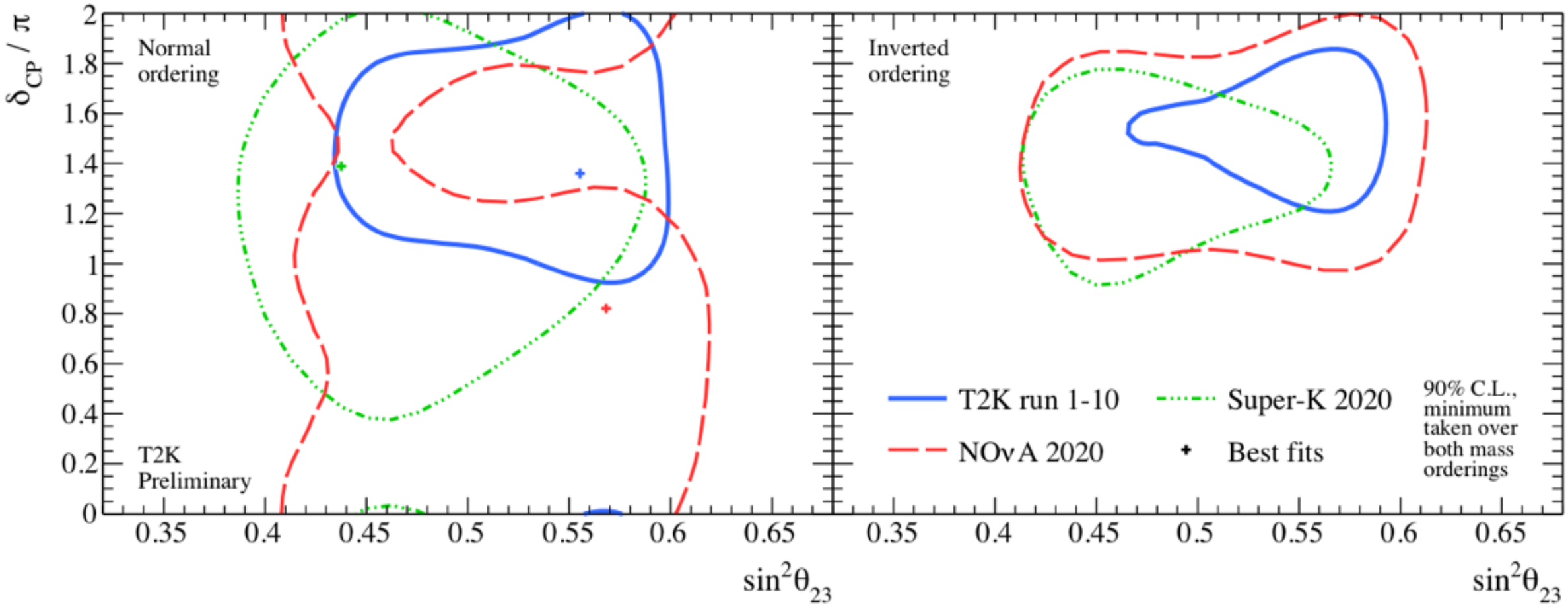


$\sin^2\theta_{23}$ versus Δm^2_{32}

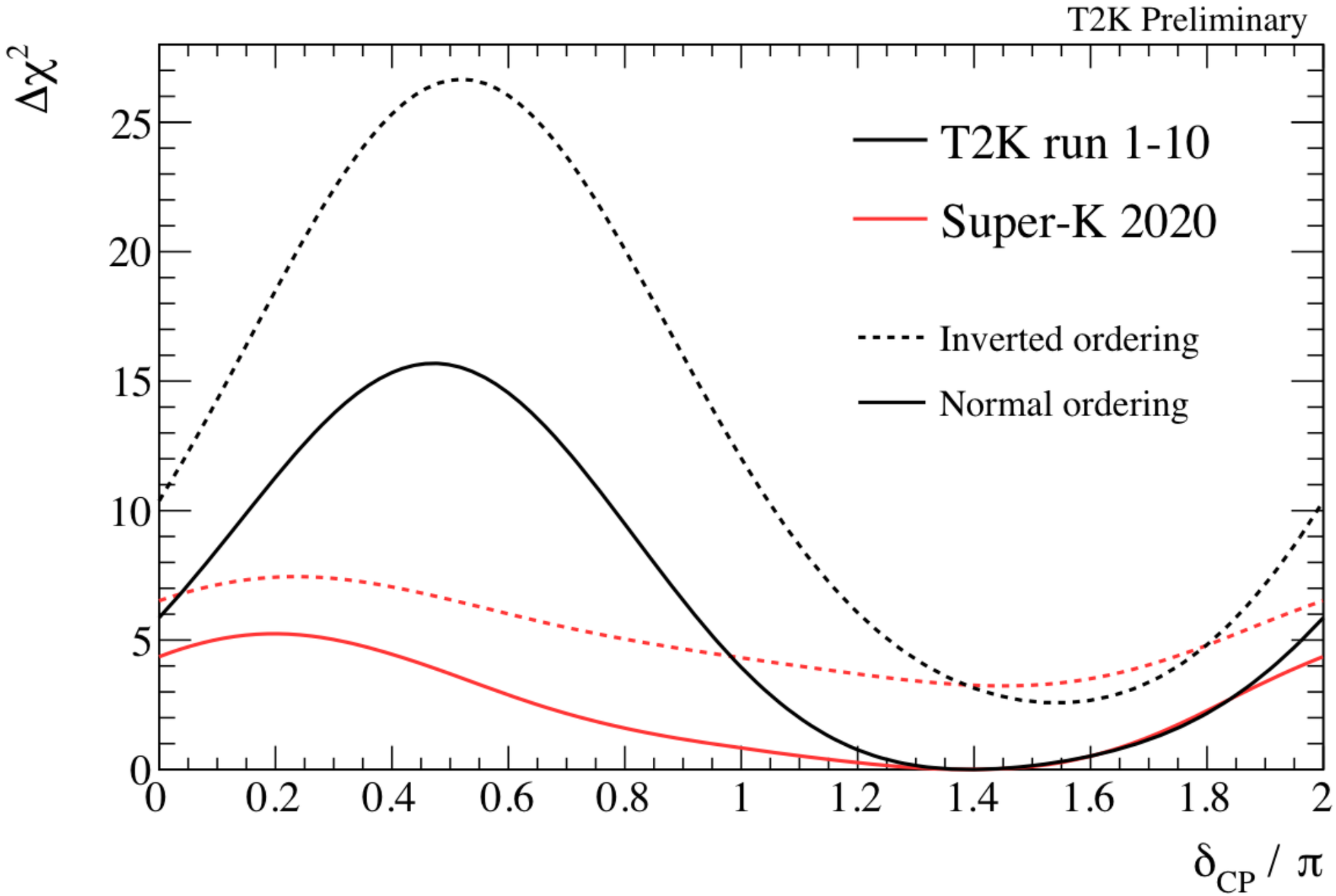


	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Normal ordering	0.19	0.65	0.83
Inverted ordering	0.03	0.14	0.17
Column total	0.21	0.79	1.00

$\sin^2\theta_{23}$ versus δ_{CP}

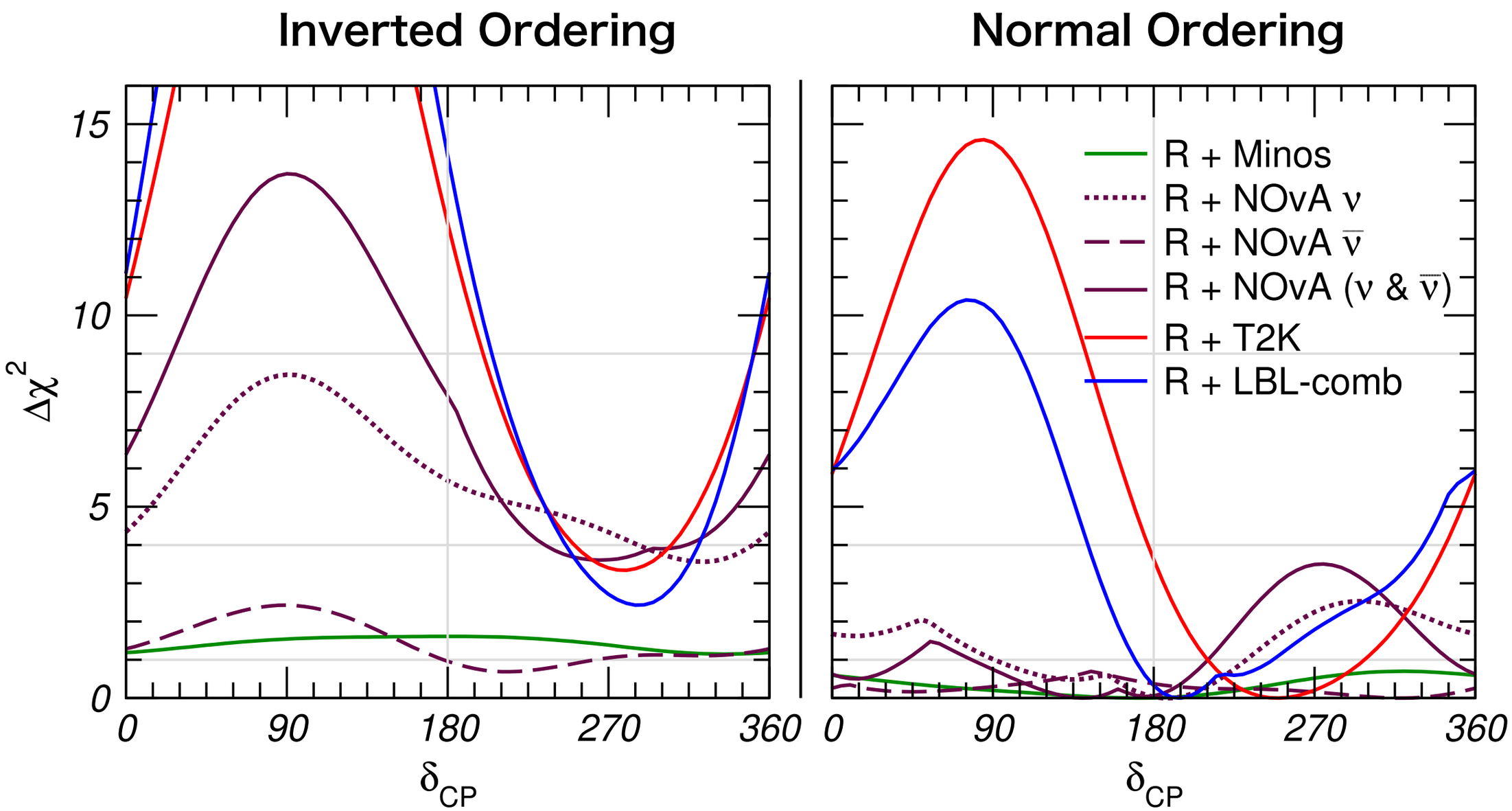


δ_{CP} by T2K and Super-K atm. ν



NuFIT 5.0 (2020)

http://www.nu-fit.org

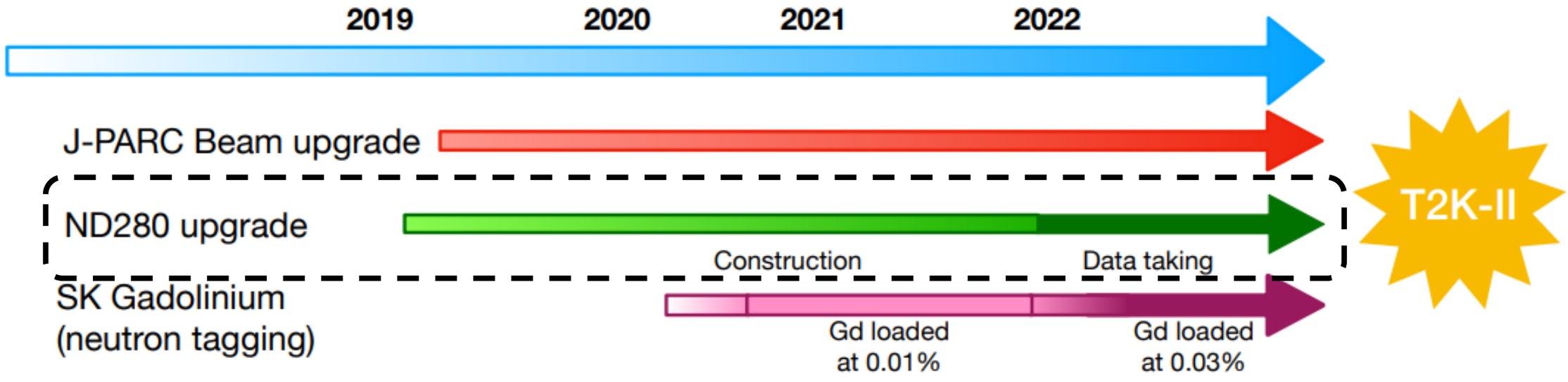


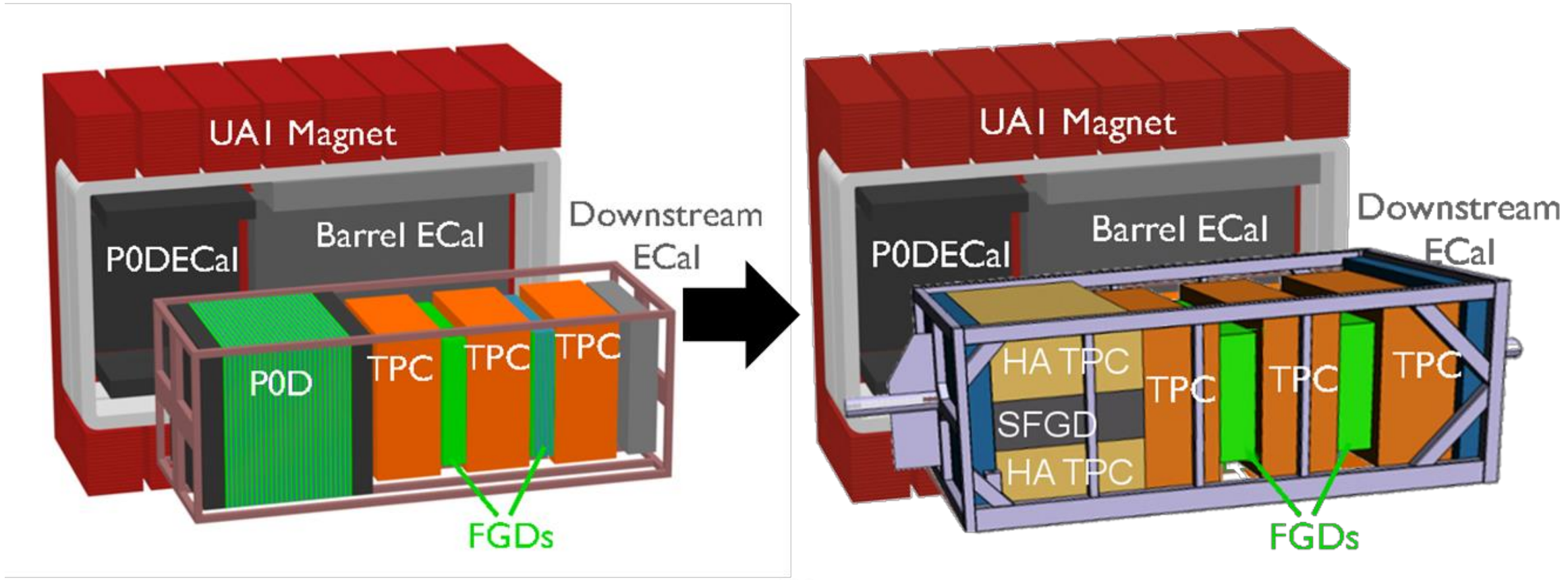
10. Future Prospect

- T2K-II w/ ND280 Upgrade
- (SK-Gd)
- Hyper-Kamiokande

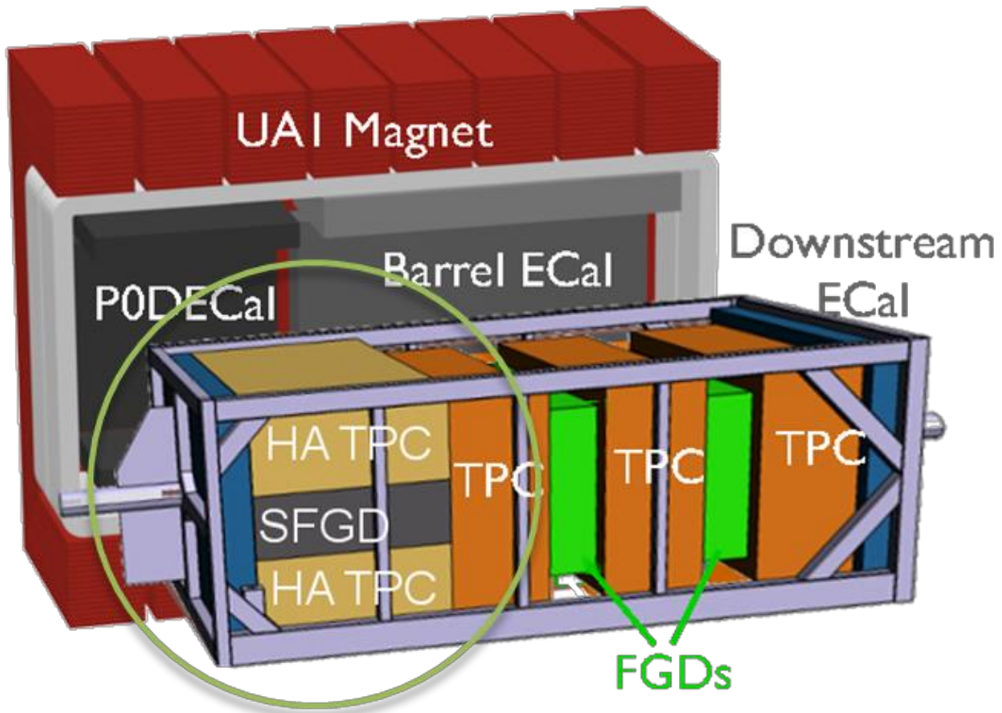
Seamless program to ν CPV From T2K to Hyper-Kamiokande

T2K-II w/ ND280 Upgrade

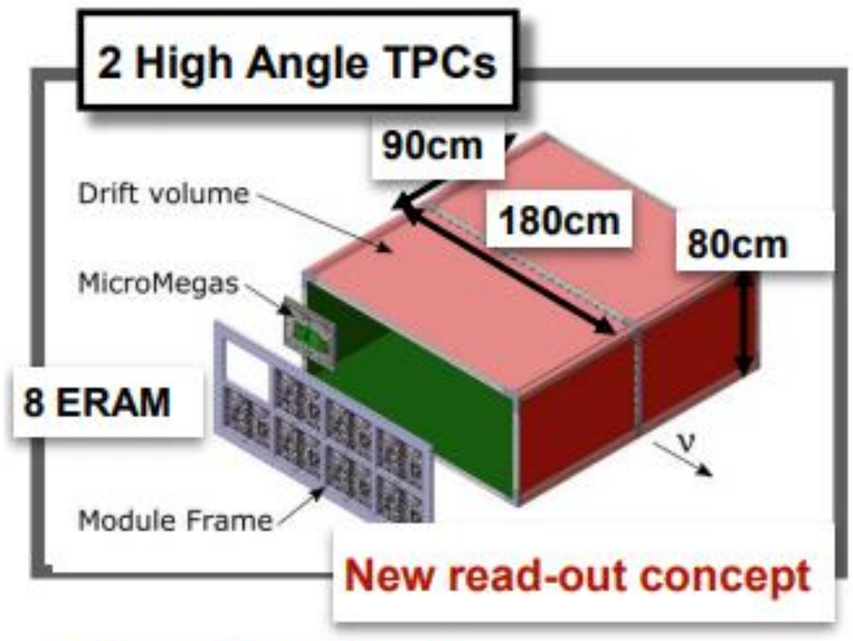




ND280 Upgrade



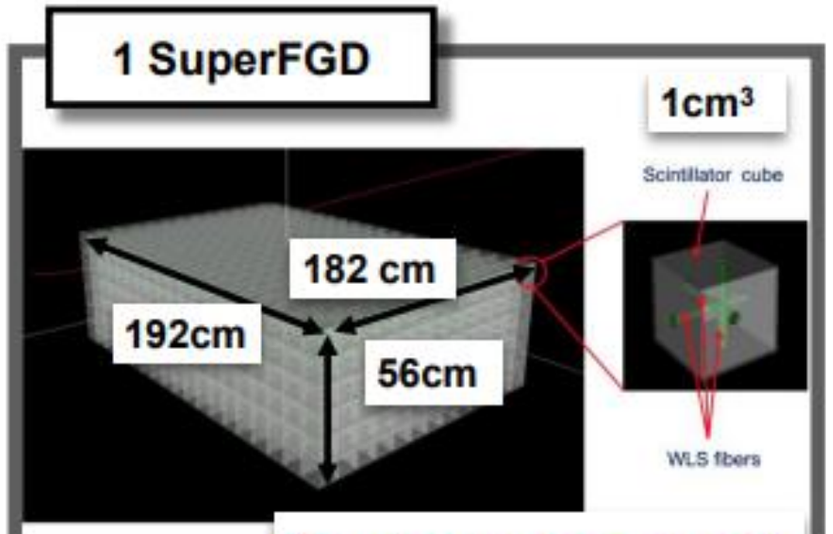
2 High Angle TPCs



New read-out concept

NIM A 957 163286 (2020)

1 SuperFGD



Novel detector concept

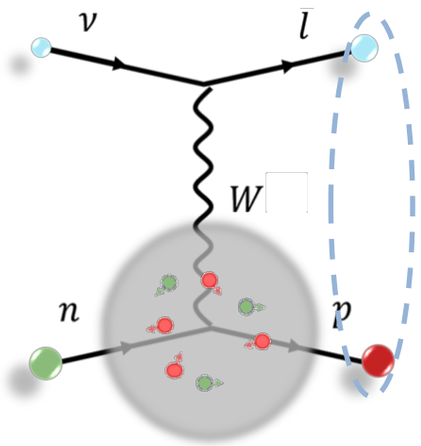
JINST 13, P02006 (2018)
JINST 15 P12003 (2020)

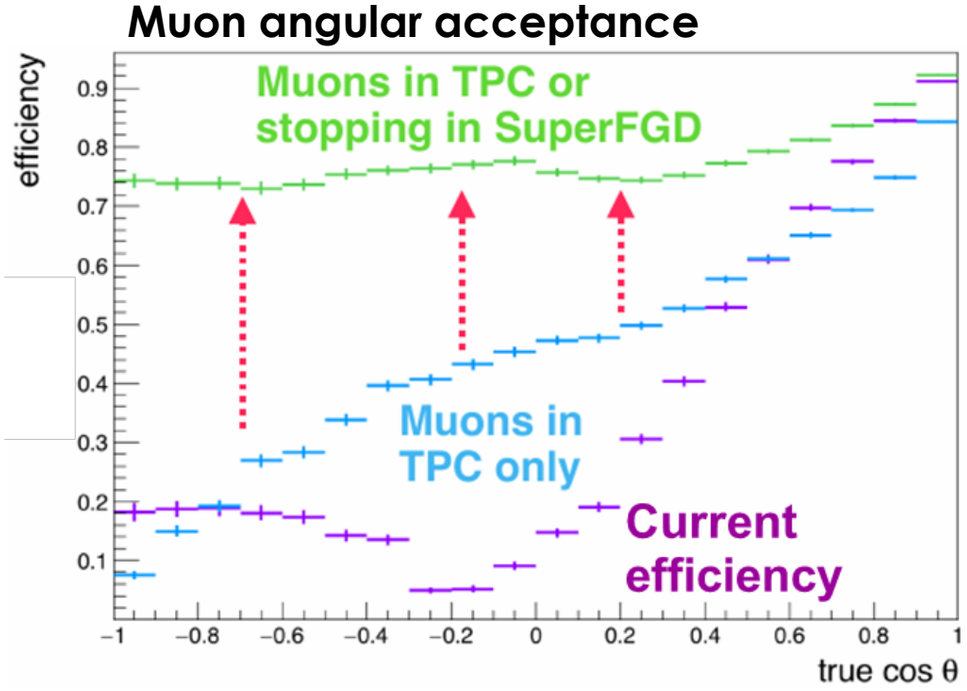
6 ToF panels

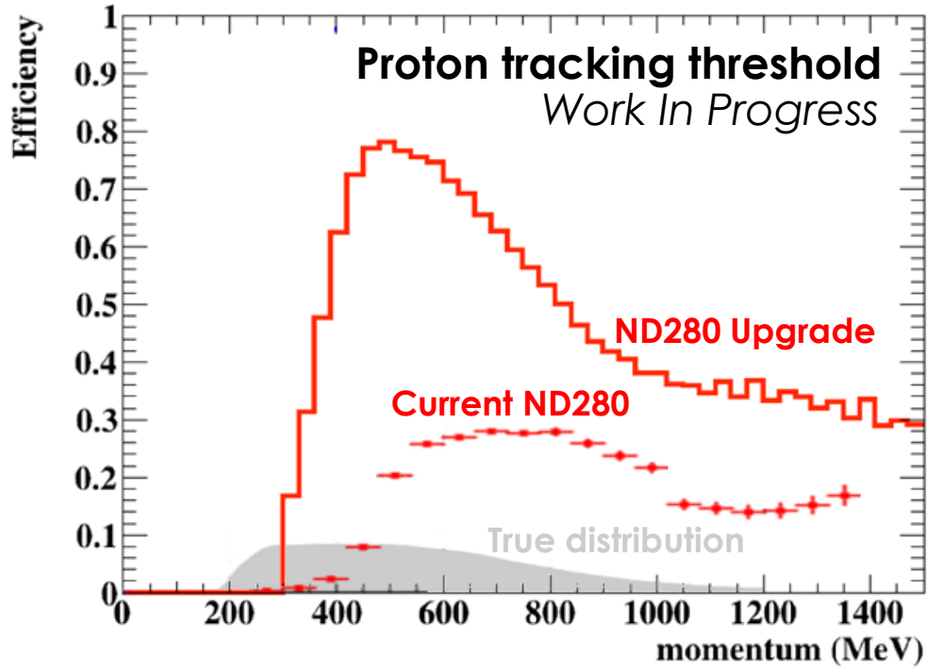
150 ps time resolution resolution

JPS Conf. Proc. 27, 011005 (2019)

Physics motivation of Upgrade



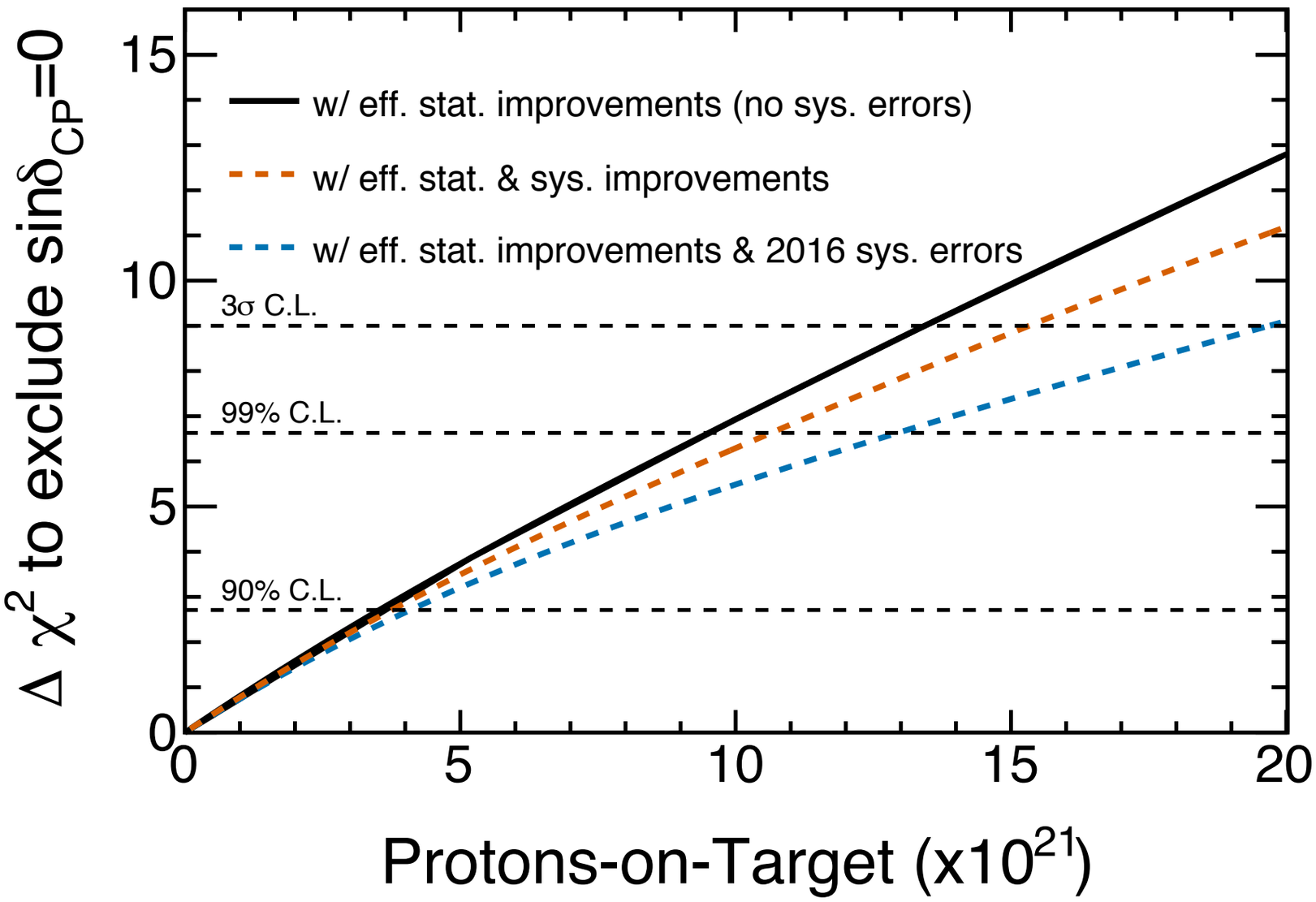




- Detailed study of neutrino interactions to reduce the systematic uncertainty with less ambiguous model constraints.
  - Dramatically improved angular acceptance for a muon.
  - Much lower tracking thresholds for a proton.
  - ~18% (2011) → ~9% (2014) → ~6% (2016) → ~5% (2020) [→ <4% (2025)]

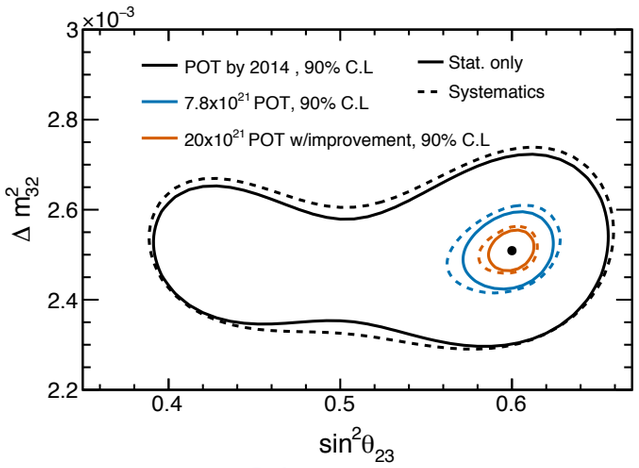
T2K-II Physics Sensitivity

- As a function of POT in the case of $\sin^2\theta_{23}=0.5$, $\delta_{CP}=-\pi/2$ and normal MH

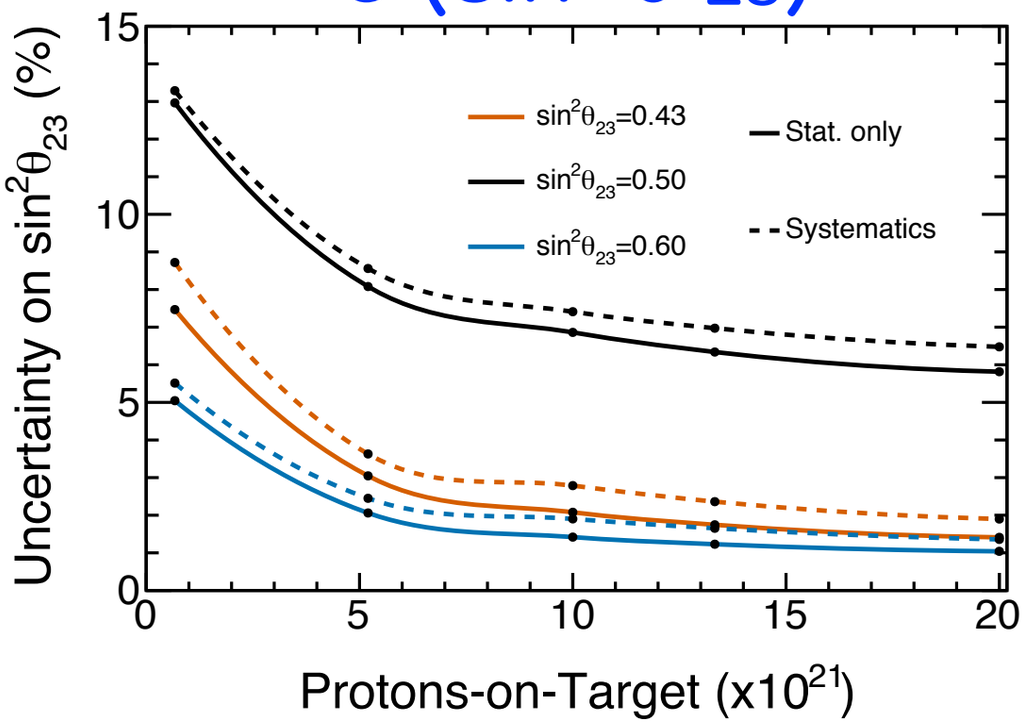


T2K-II Physics Sensitivity

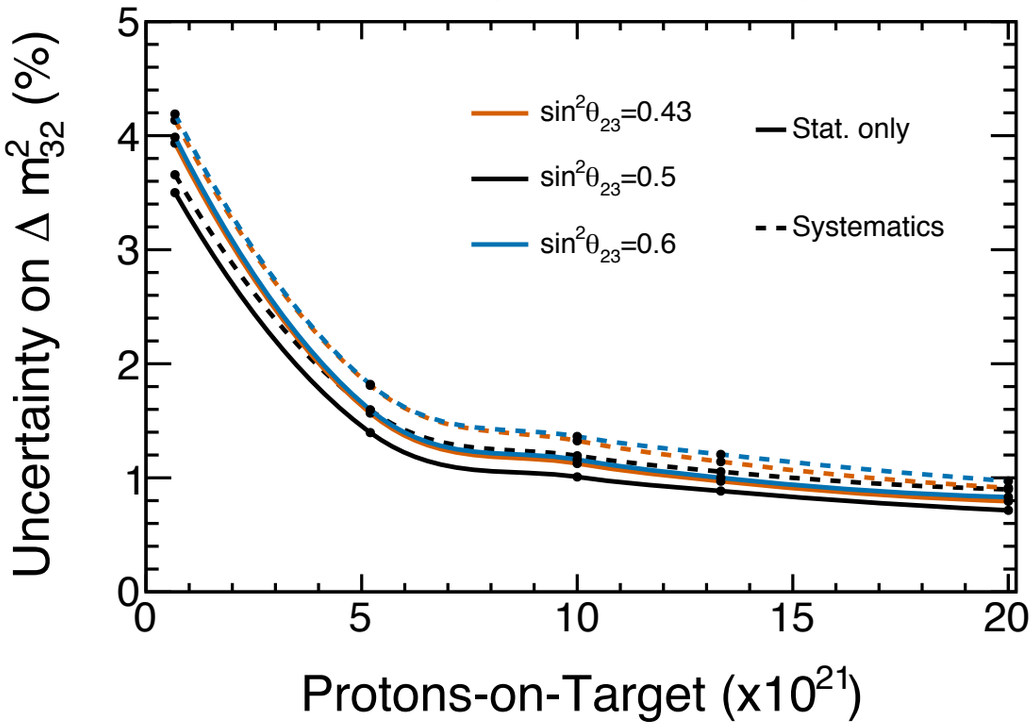
- Precisions of $\sin^2\theta_{23}$ and Δm^2_{32}



$\delta(\sin^2\theta_{23})$

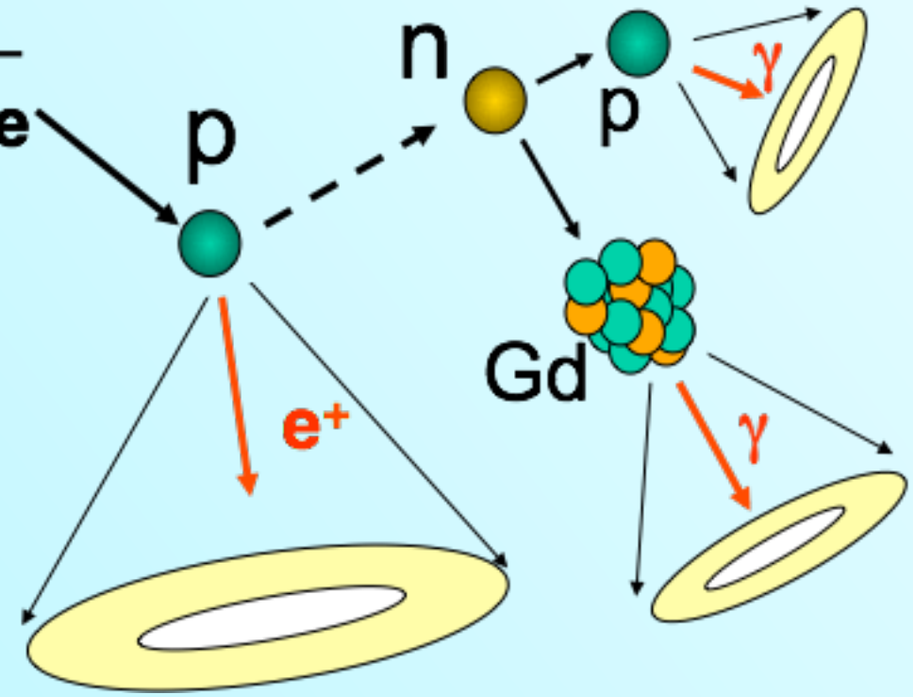


$\delta(\Delta m^2_{32})$



- More physics for Neutrino Interactions and non-standard models

SK-Gd



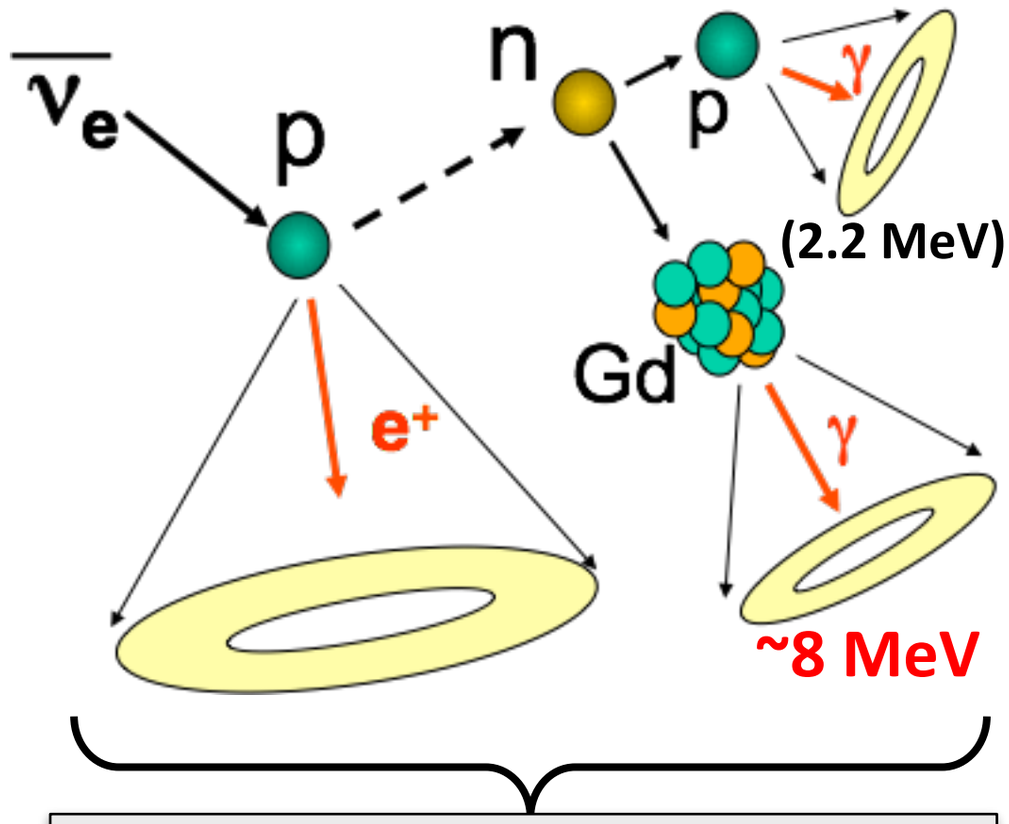
Next phase: SK-Gd

SK-Gd Phase:

Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:

- Detect the world's first Supernova Relic Neutrinos (SRN) (or Diffuse Supernova Neutrino Background, DSNB)
- Improve pointing accuracy for supernova
- Early warning of nearby supernova from pre-burst signal (silicon burning)
- Enhance ν or $\bar{\nu}$ discrimination in atmospheric ν & T2K analysis
- Reduce backgrounds in proton decay search



- Reduce BG of $\bar{\nu}_e$ signal
  - Delayed coincidence
  - $\Delta T \sim 30\ \mu s$
  - Vertices within ~ 50 cm

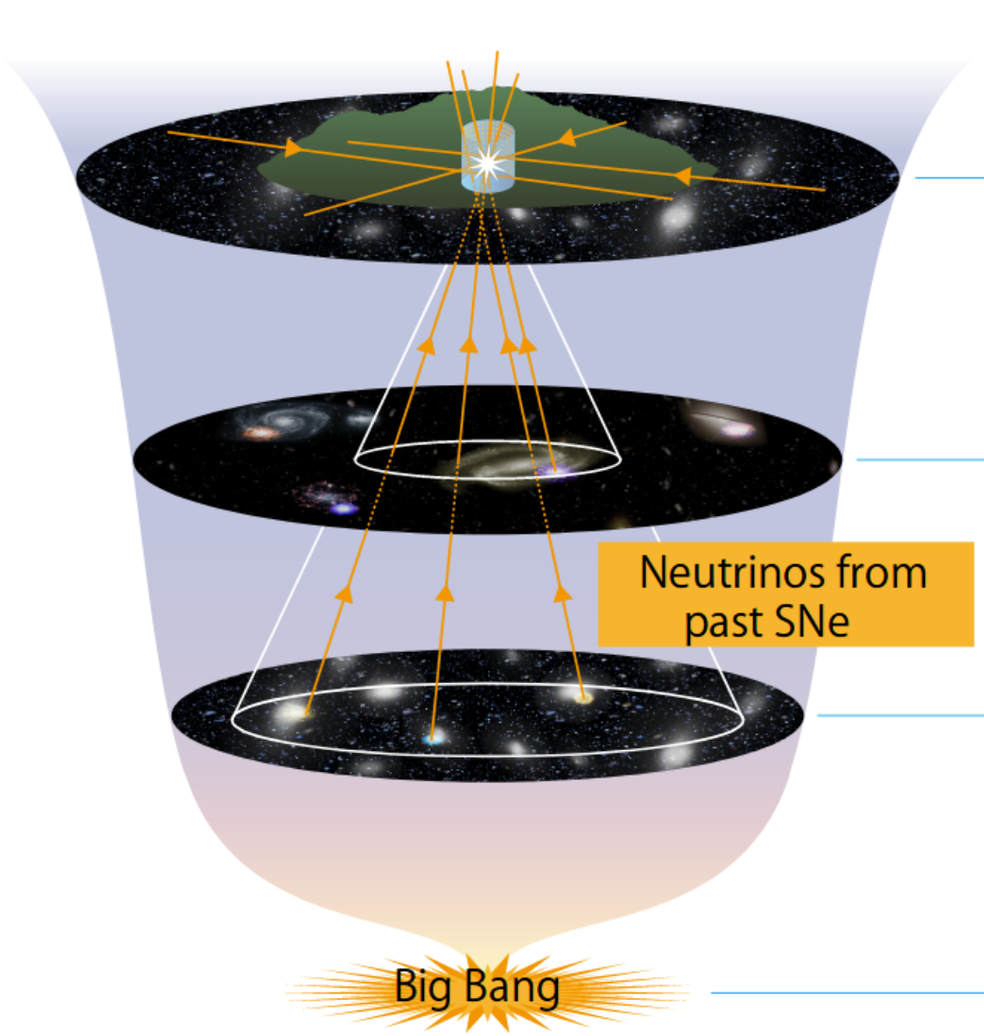
SK refurbishment has been completed.

- Fix water leakage
- Replace dead PMTs
- Improve water piping in the SK detector

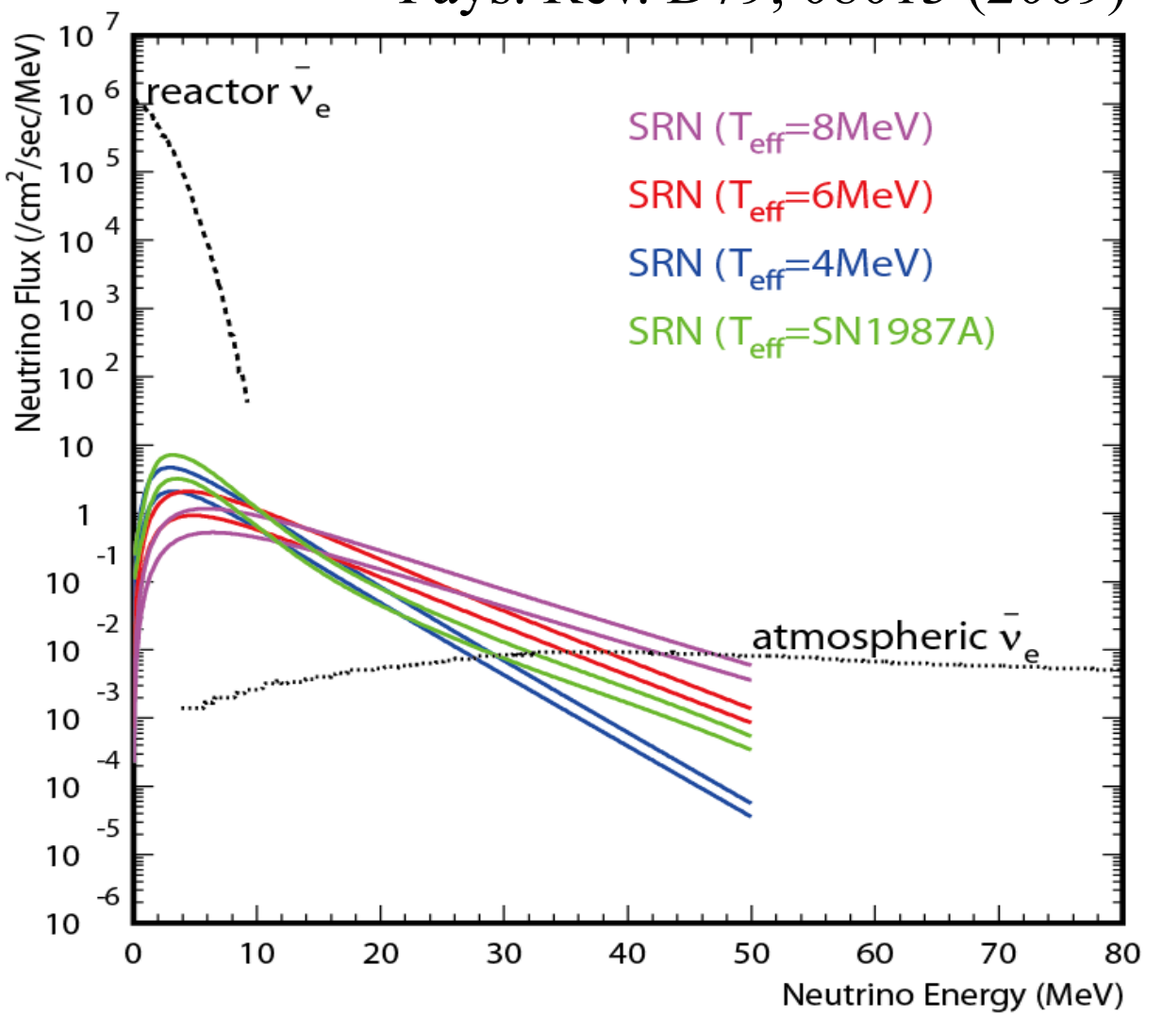
Capture efficiencies in water

- 0.01% Gd [$Gd_2(SO_4)_3$ 10t] : ~50%
- 0.1% Gd [$Gd_2(SO_4)_3$ 100t] : ~90%

Supernova relic neutrinos in SK-Gd



Pays. Rev. D79, 08013 (2009)

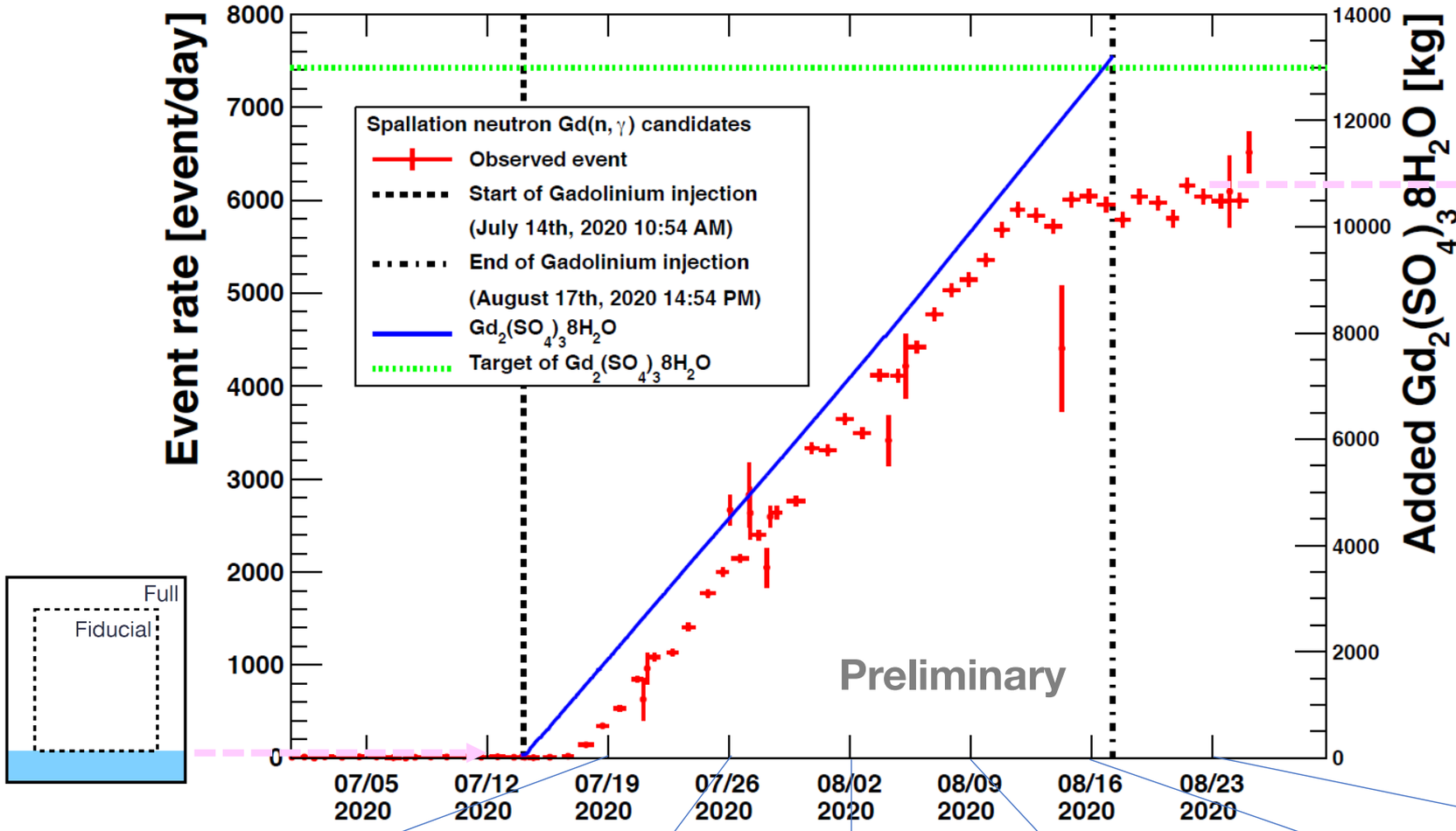


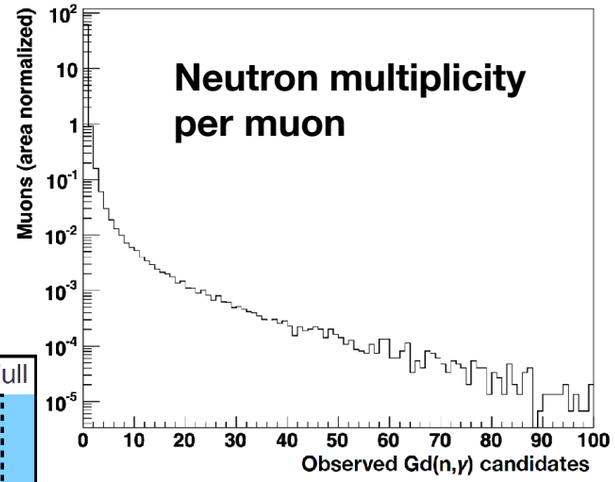
10 years observation

HBD models	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	significance (2 energy bin)
T_{eff} 8MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

Gd-loading in 2020

Neutron event rates vs. Gd-loading

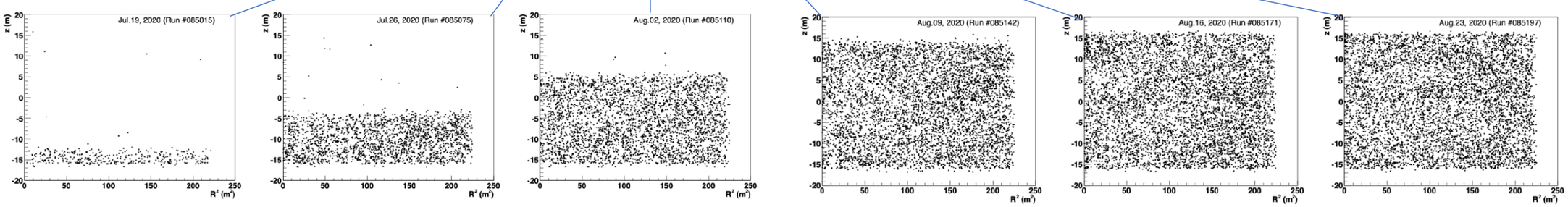




Neutron yields in water is under calculation

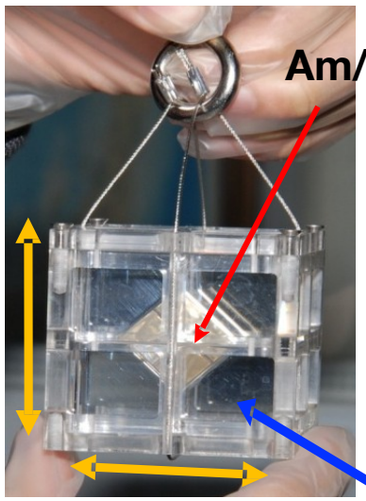
$$Y_n = \frac{N_n}{N_\mu \, L_\mu \, \rho \, V_{\mathrm{corr}}}$$

- N_n : The number of neutrons produced by cosmic-ray muons
- N_μ : The number of selected muons
- L_μ : The average path length of muons
- ρ : The density of Gd water
- V_{corr} : Fiducial volume / Full volume



SK-Gd is ongoing

neutron source special run



Am/Be source

100~200 neutrons/s

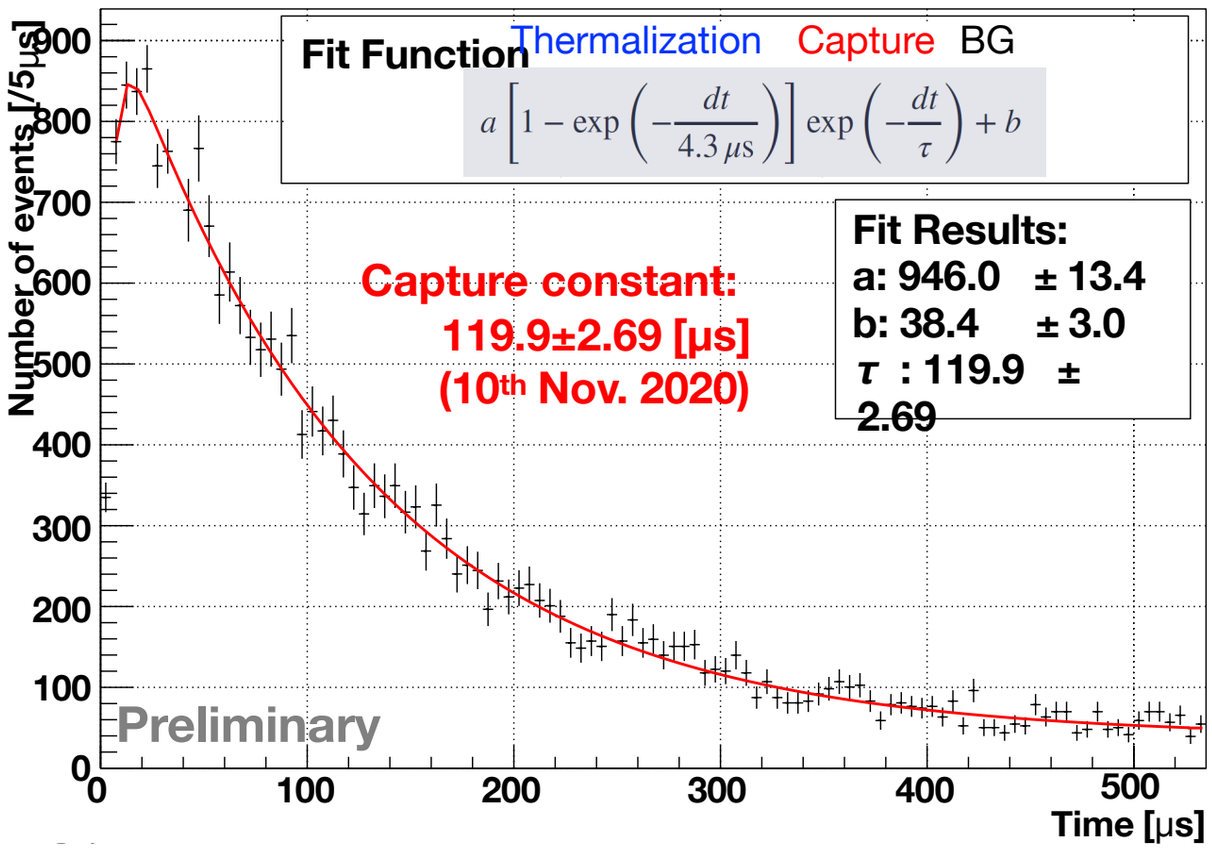
$^{241}Am \rightarrow {}^{237}Np + \alpha$

$^{9}Be + \alpha \rightarrow {}^{13}C^{*} + n$ (2-6 MeV)

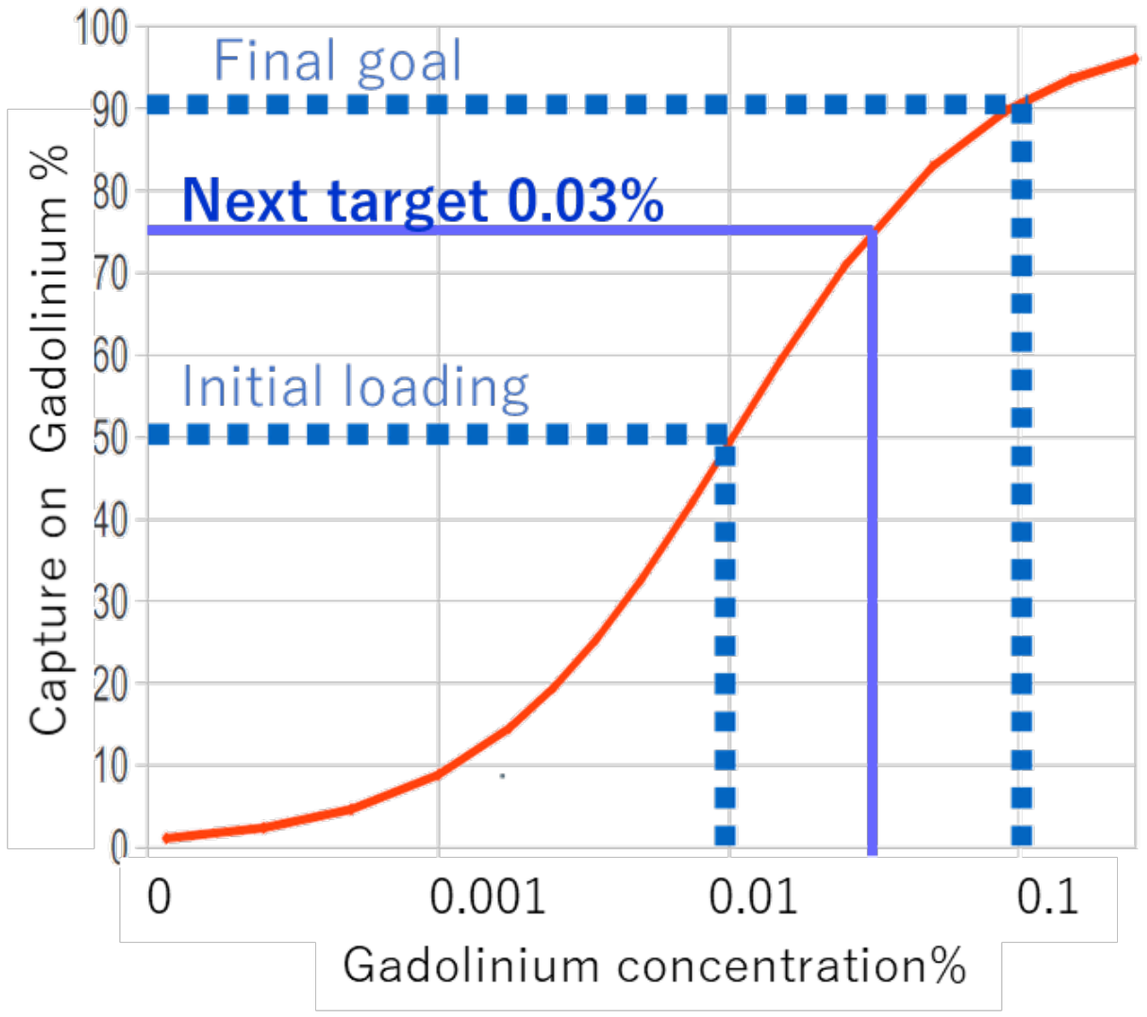
$^{13}C^{*} \rightarrow {}^{12}C + \gamma$ (4.43 MeV)

5cm

8 BGO Crystals

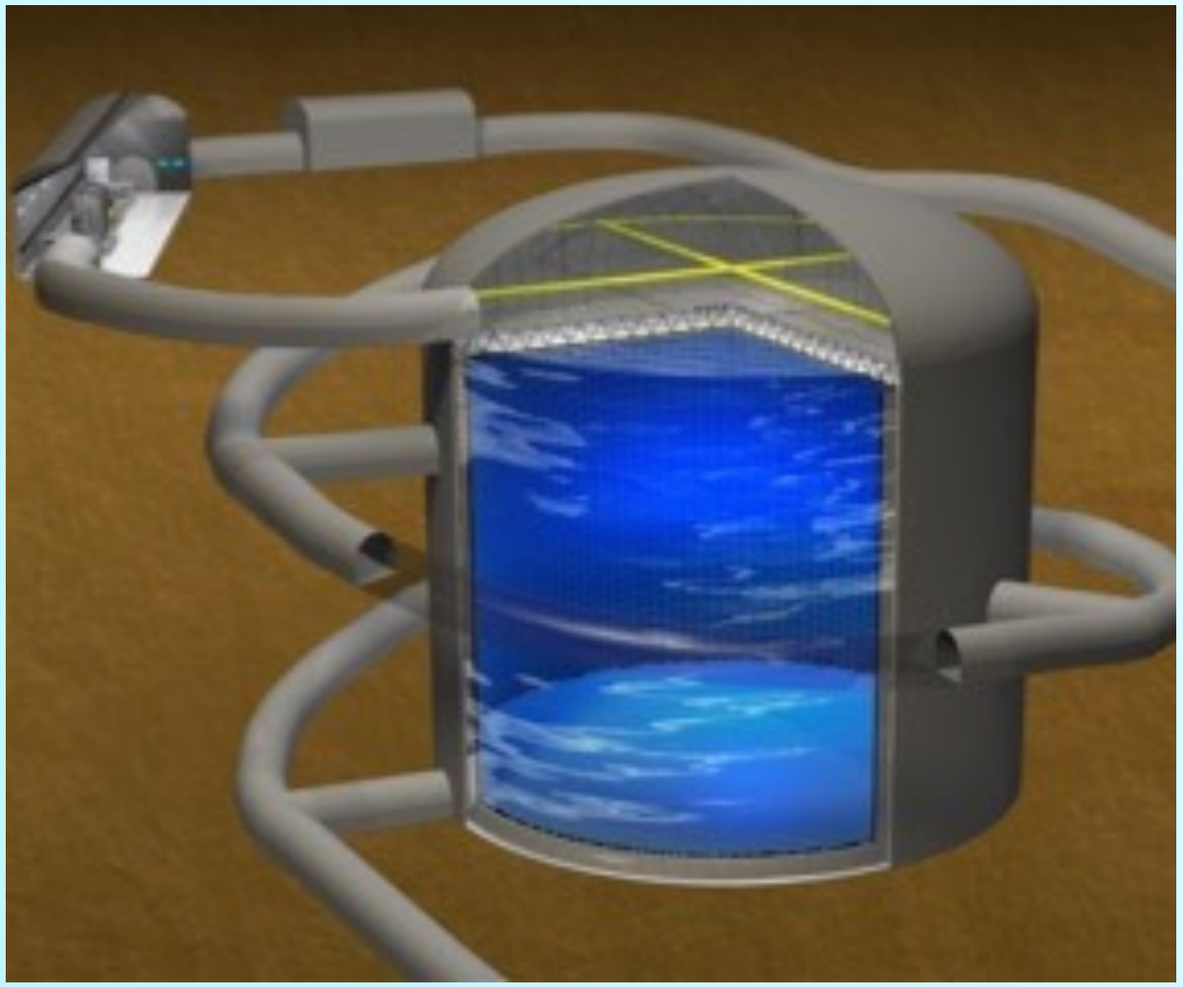


more Gd in 2022

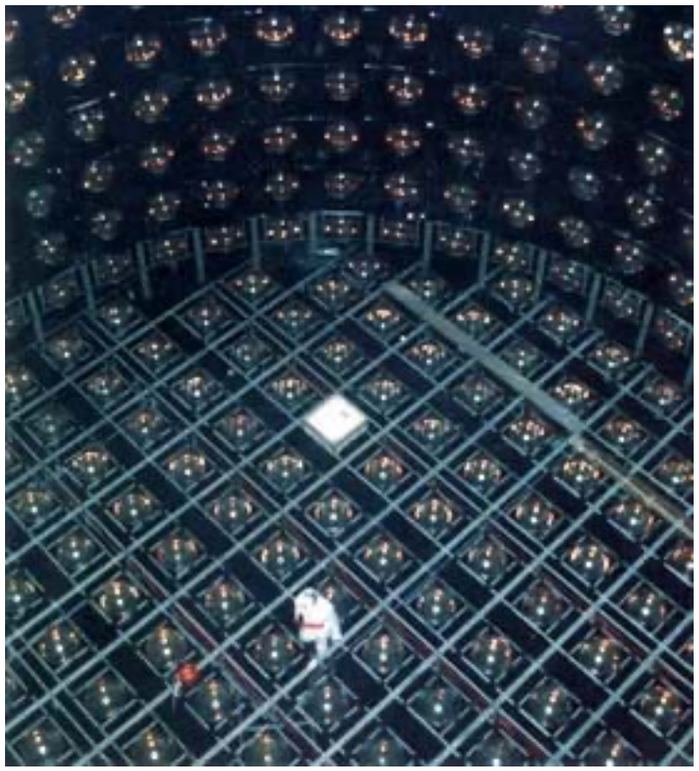


Hyper-Kamiokande

(now under construction, and operation in 2027)



Three generations of Water Cherenkov Detectors at Kamioka, Japan

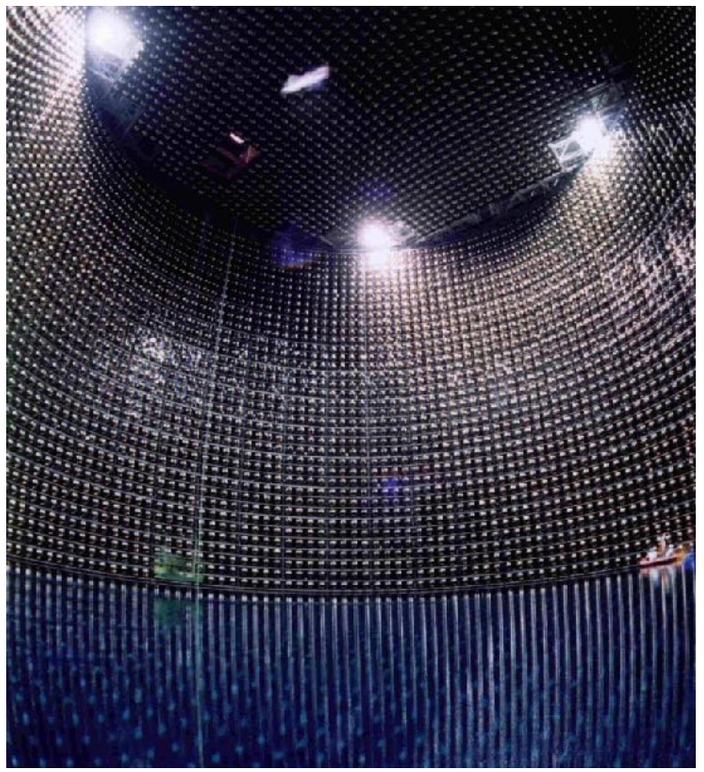


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino "anomaly"
- Supernova 1987A

Birth of neutrino astrophysics

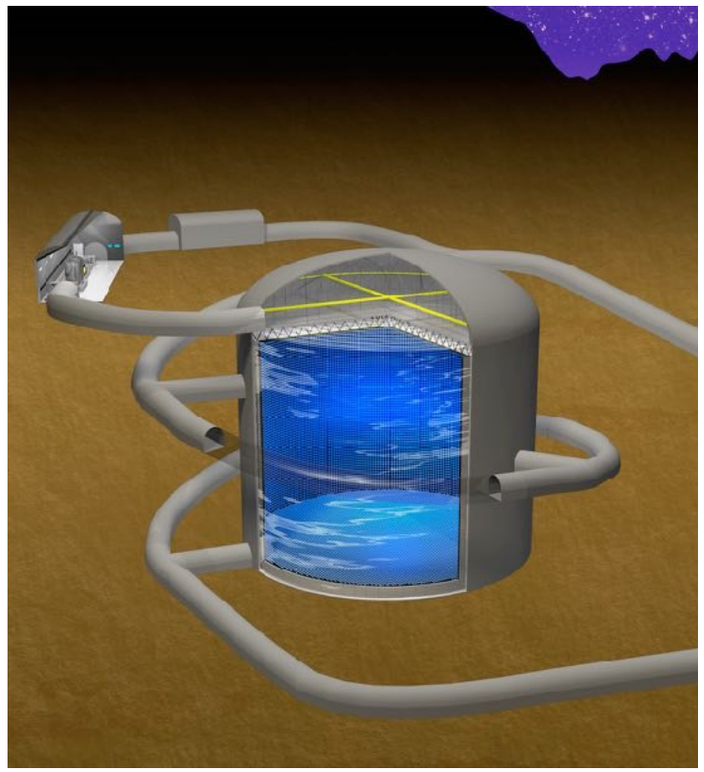


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - ➢ All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



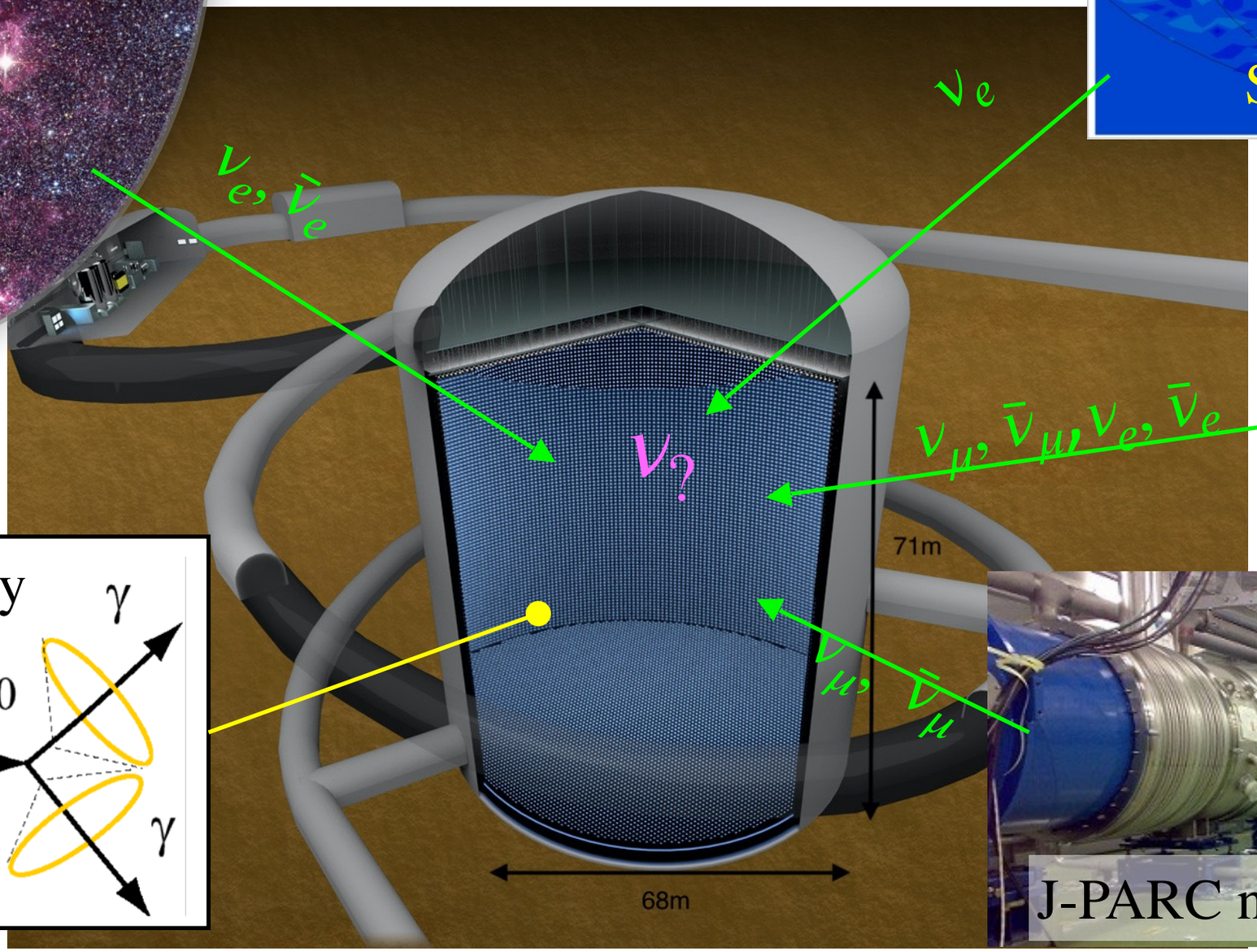
Hyper-Kamiokande

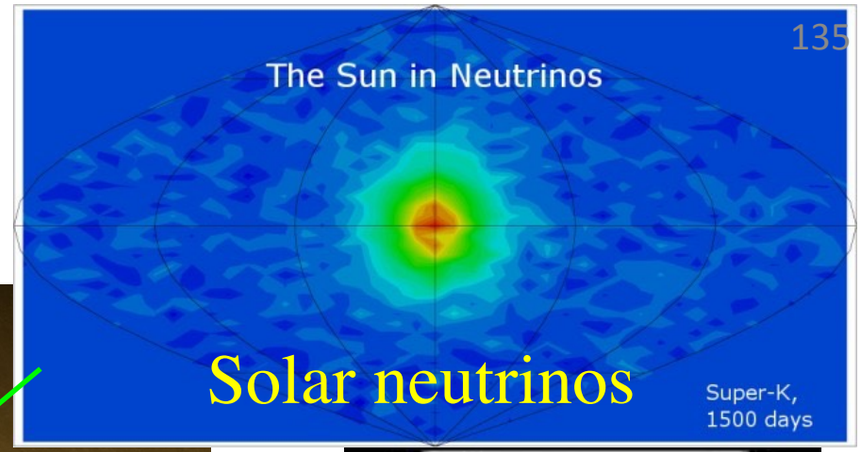
(start operation in 2027)

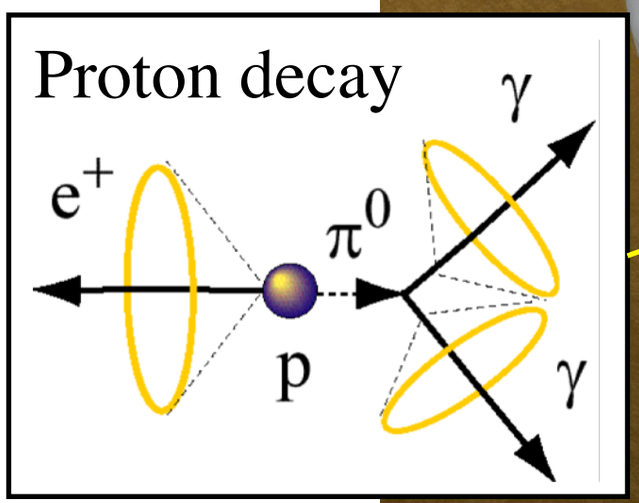
- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

Physics in Hyper-Kamiokande





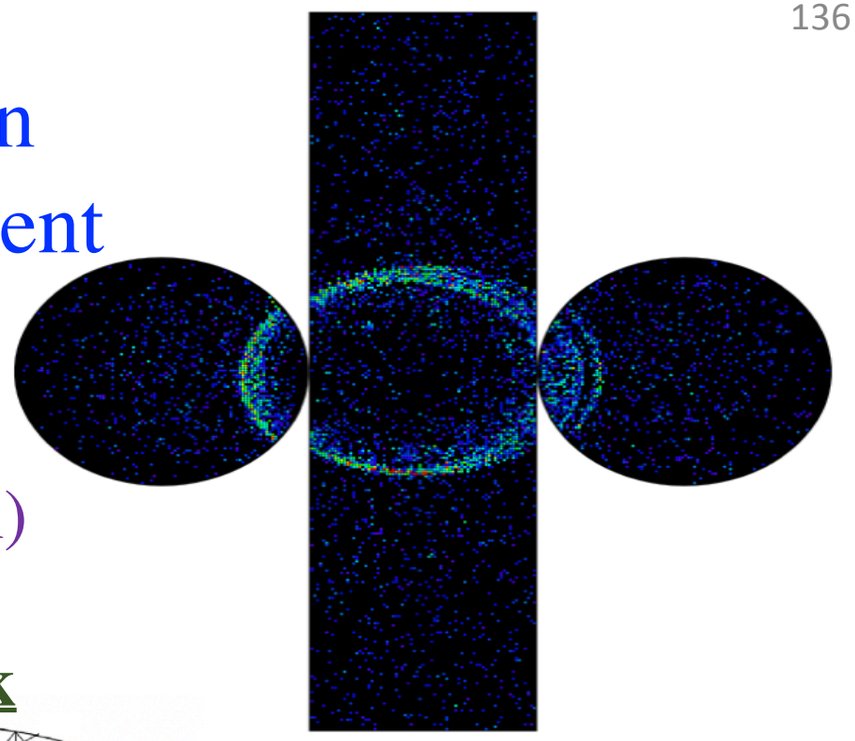


The Hyper-Kamiokande detector

High QE Box&Line PMT

× 2 photon detection
× 2 timing resolution

Precision measurement



Recent update:

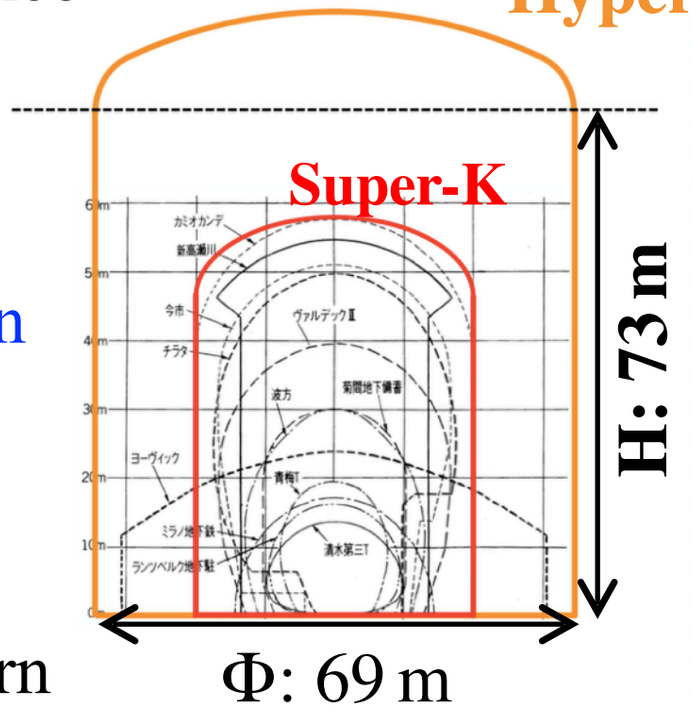
- Lower dark rate (similar level to SK)
- Lower radioactive contamination

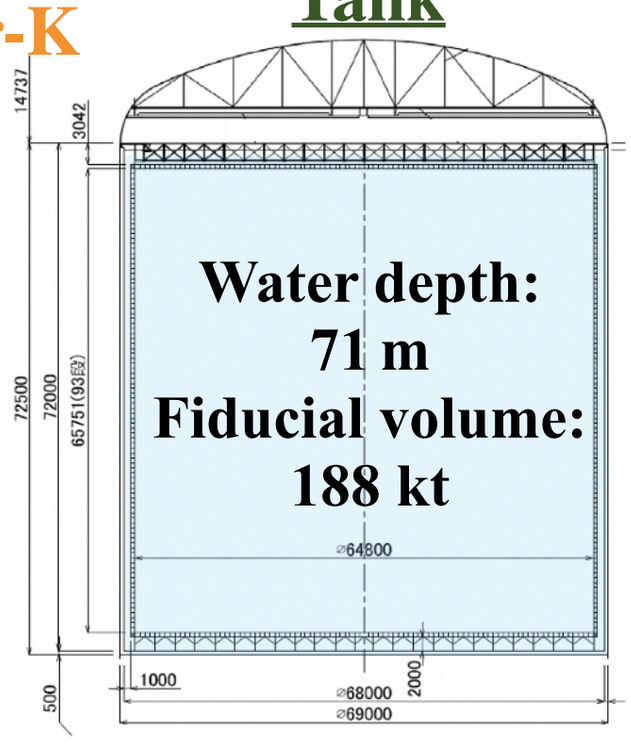
× 2 pressure tolerance

Cavern

Hyper-K

Tank





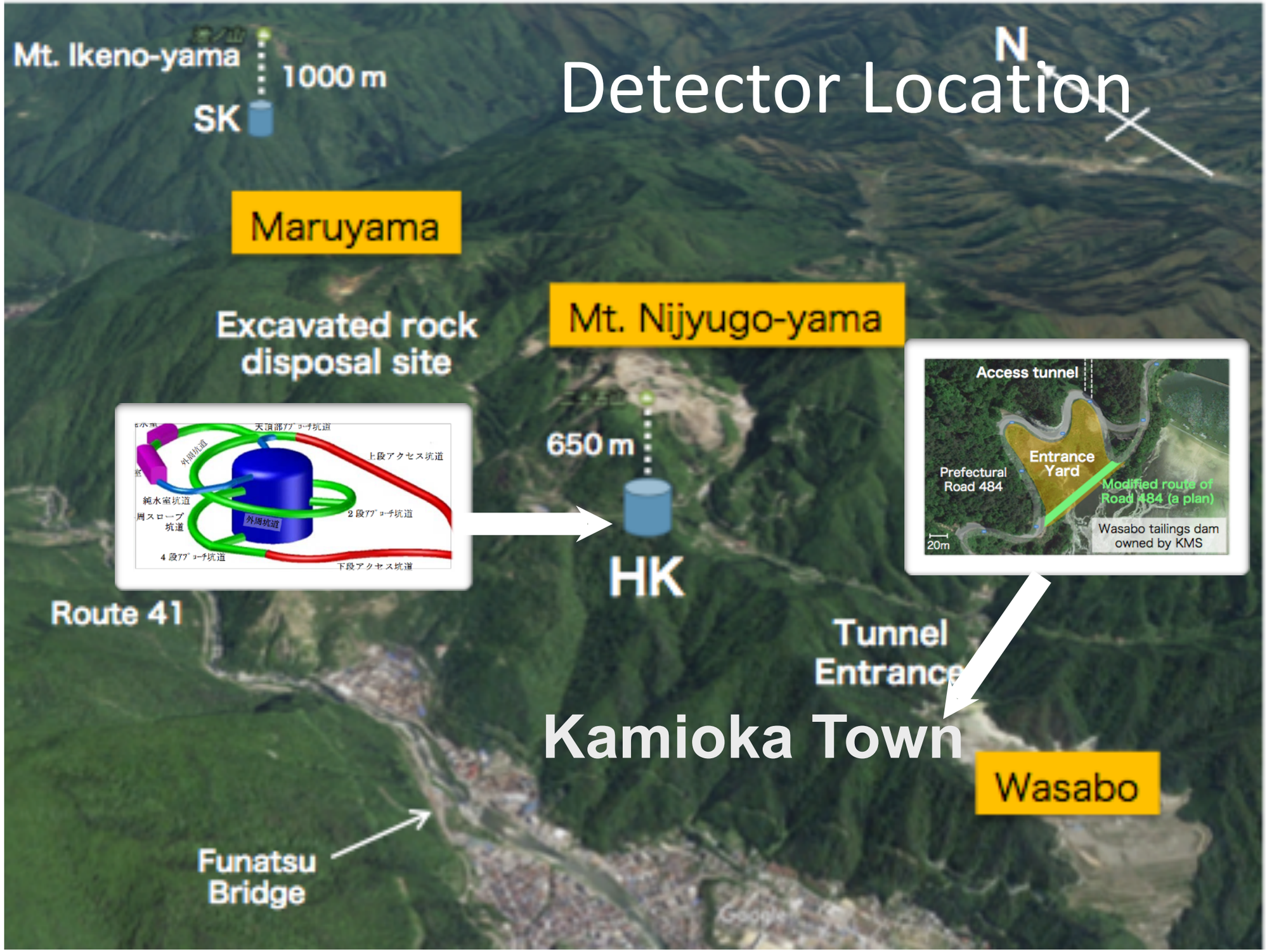
New detector design (cost reduction)

R&D for large cavern

High statistics neutrino data

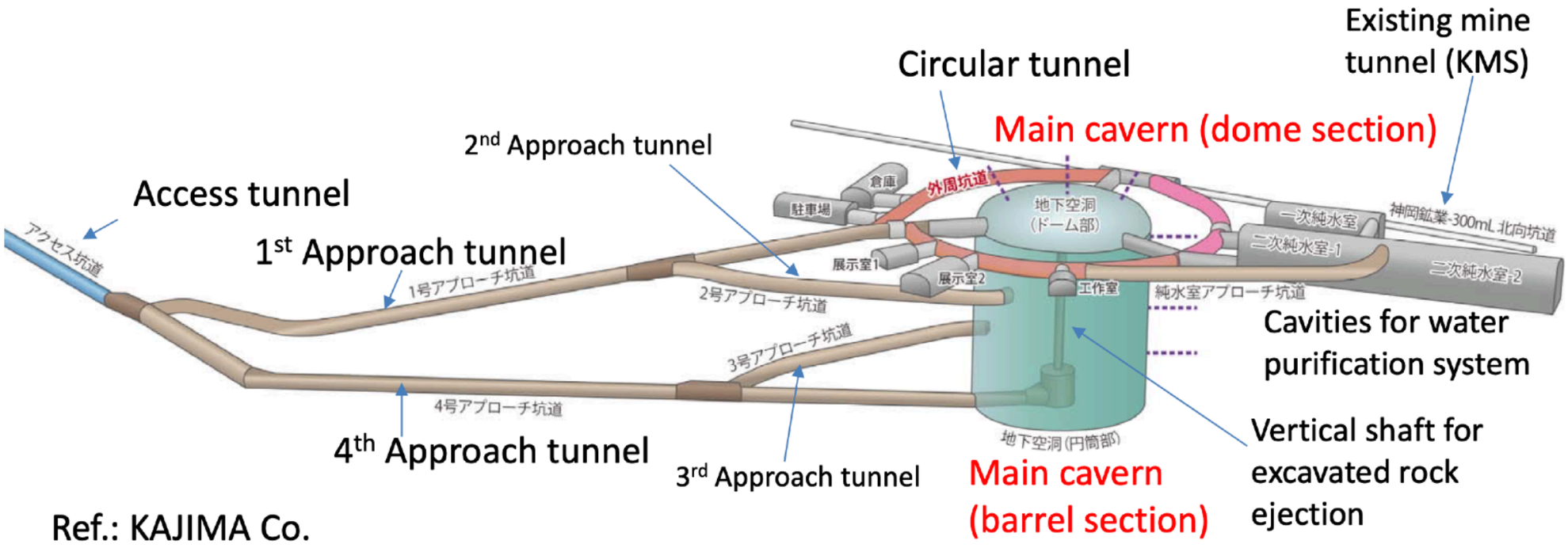
New detector design by synergy of different technologies

- 8km south of Super-K
- 295km from J-PARC and 2.5 deg. off-axis (same as Super-K)
- 650m rock overburden



Tunnel & Cavern excavation started !

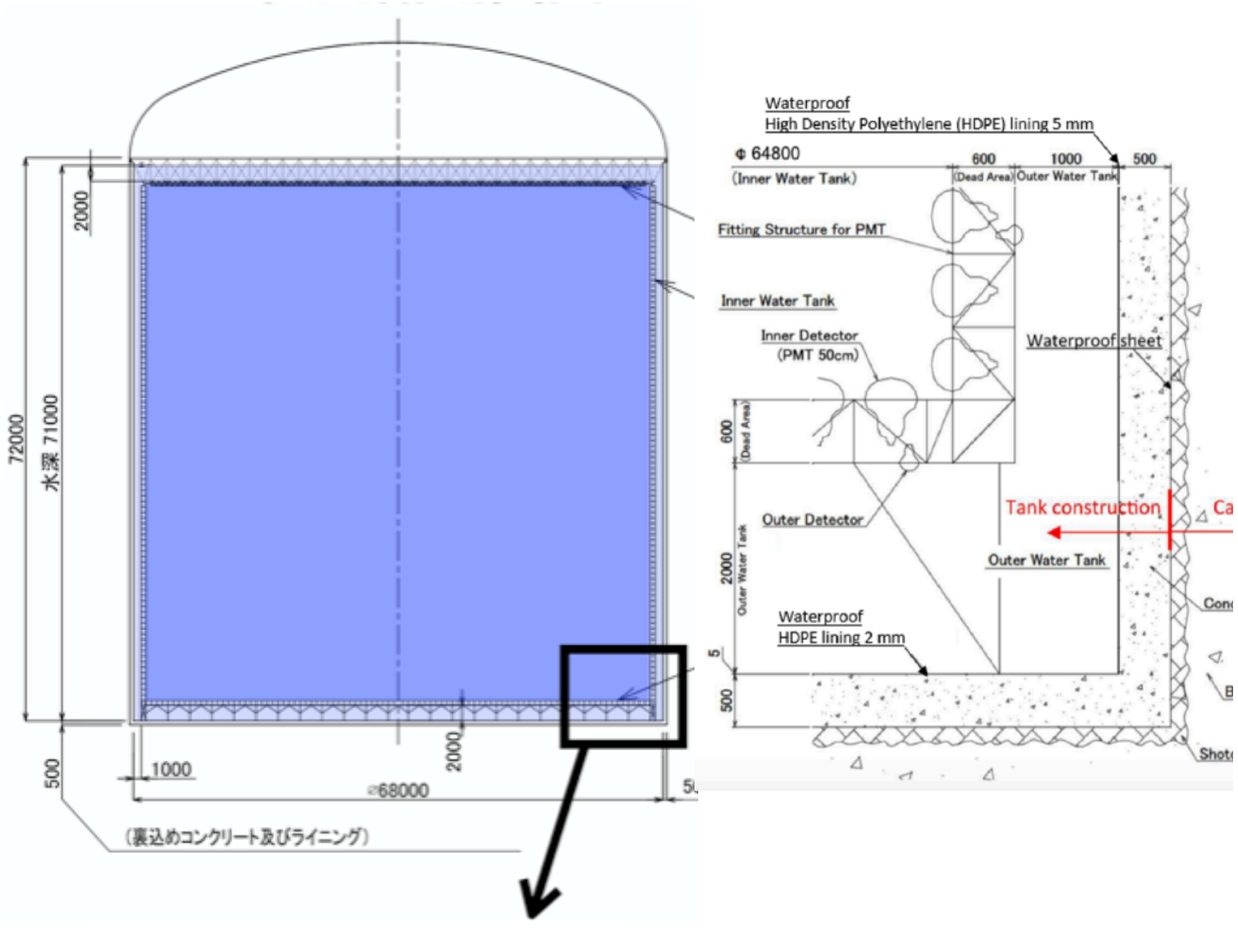
- Site construction officially started in 2020, entrance yard prepared.
- Geological survey performed and confirmed rock quality is excellent !
- Access tunnel excavation started 2021, followed by main cavity excavation in 2022

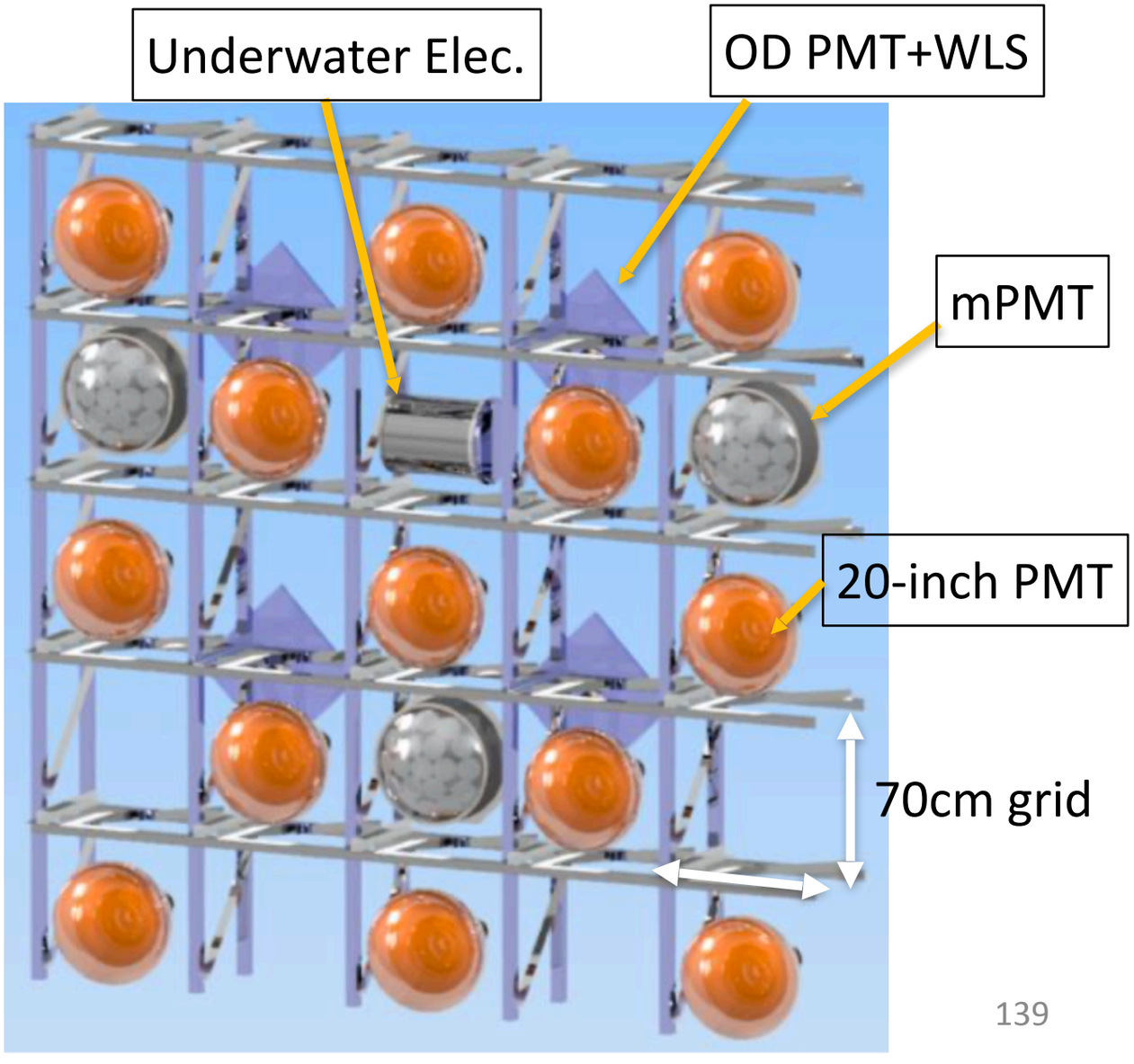


Ref.: KAJIMA Co.

Far detector : ID and OD configuration

- 67mΦx66m Inner Detector (fiducial 186kt)
  - Aiming 40% photo-coverage with HighQE (x2 SK)
  - 20,000 HPK HiQE 20-inch PMTs will be installed
  - mPMT modules will be integrated as hybrid configuration.
- 1m(wall) or 2m(top/bottom) thick Outer Detector
  - 3” PMTs + WLS boards
- Under-water electronics module
  - Mitigate disadvantage of long cables



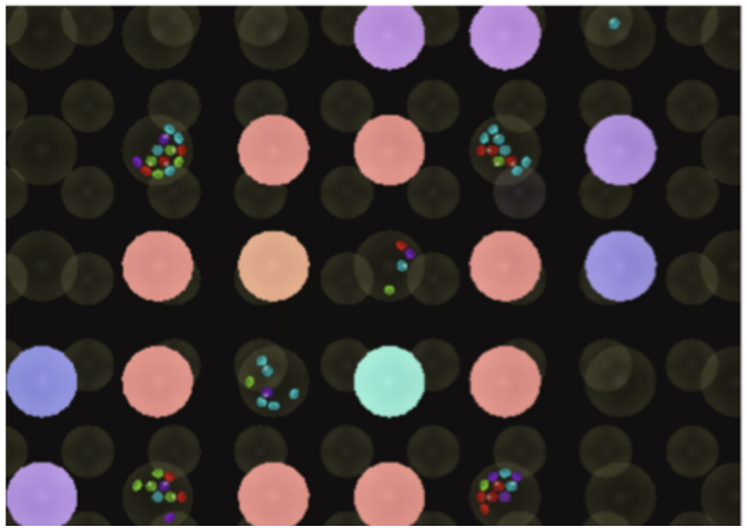


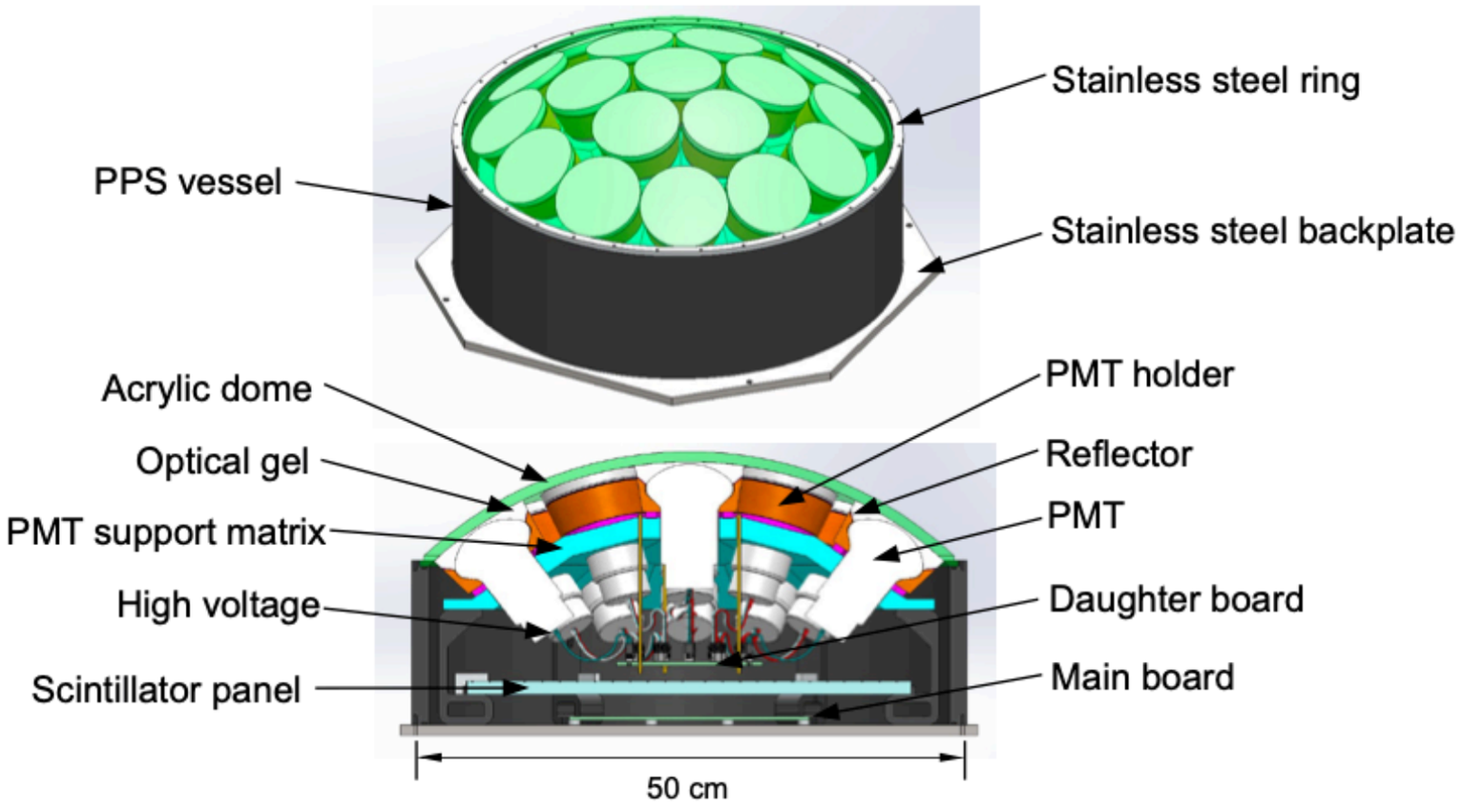
ID photo-detectors: 20-inch PMT

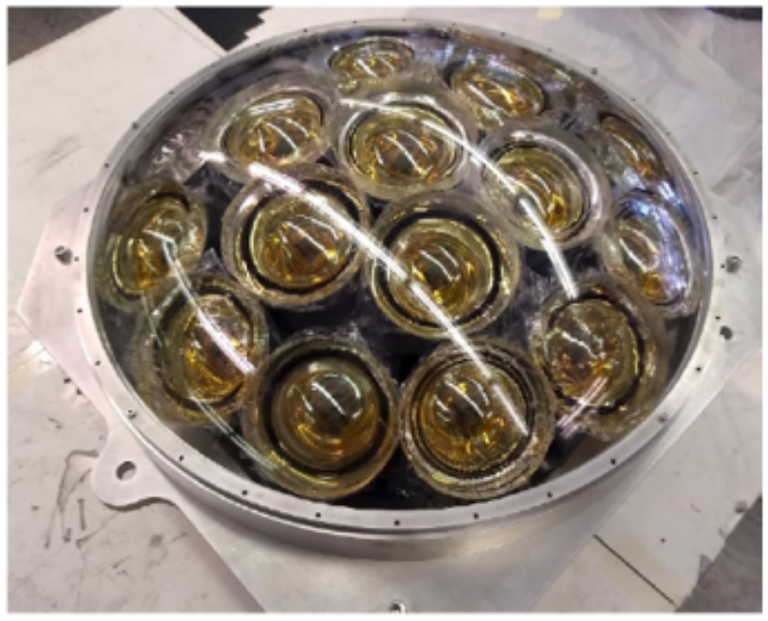
- New HPK Box&Line 20-inch PMT (R12860) R&D completed. Excellent performance.
  - High QE (x2 SK) w/ similar dark rate as SK (4kHz),
  - Better charge and timing resolution
  - 1.25MPa pressure tolerance
- 136 prototype PMTs installed in SK since 2018 for long term test.
- Mass production started. Total 20,000 20”PMTs delivered until 2026.
  - First 1,000 20”PMTs are delivered to Kamioka. Detail inspection is on-going.
- Prototypes PMT covers have been developed. Final test and design fix soon.

ID photo-sensors: mPMT module

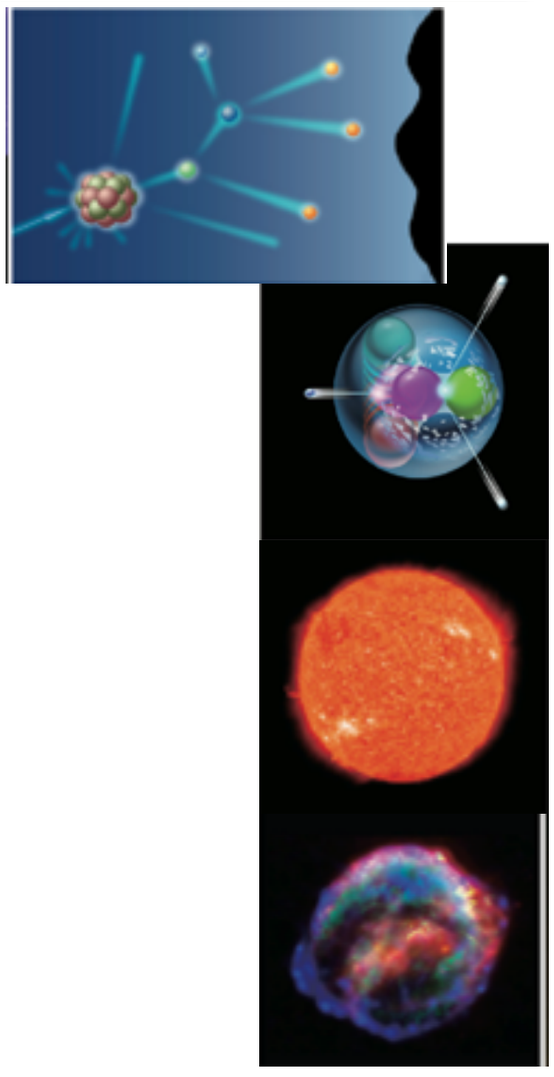
- Multi PMT module : 19 x 3-inch PMT with in-case electronics
- Increase photo-coverage (870 cm^2/module)
- Good TTS (1.3ns) and dark rate of 3-inch PMT
- High granularity and photon directional information
- Improve reconstruction at the fiducial edge, calibration reference







Many physics targets

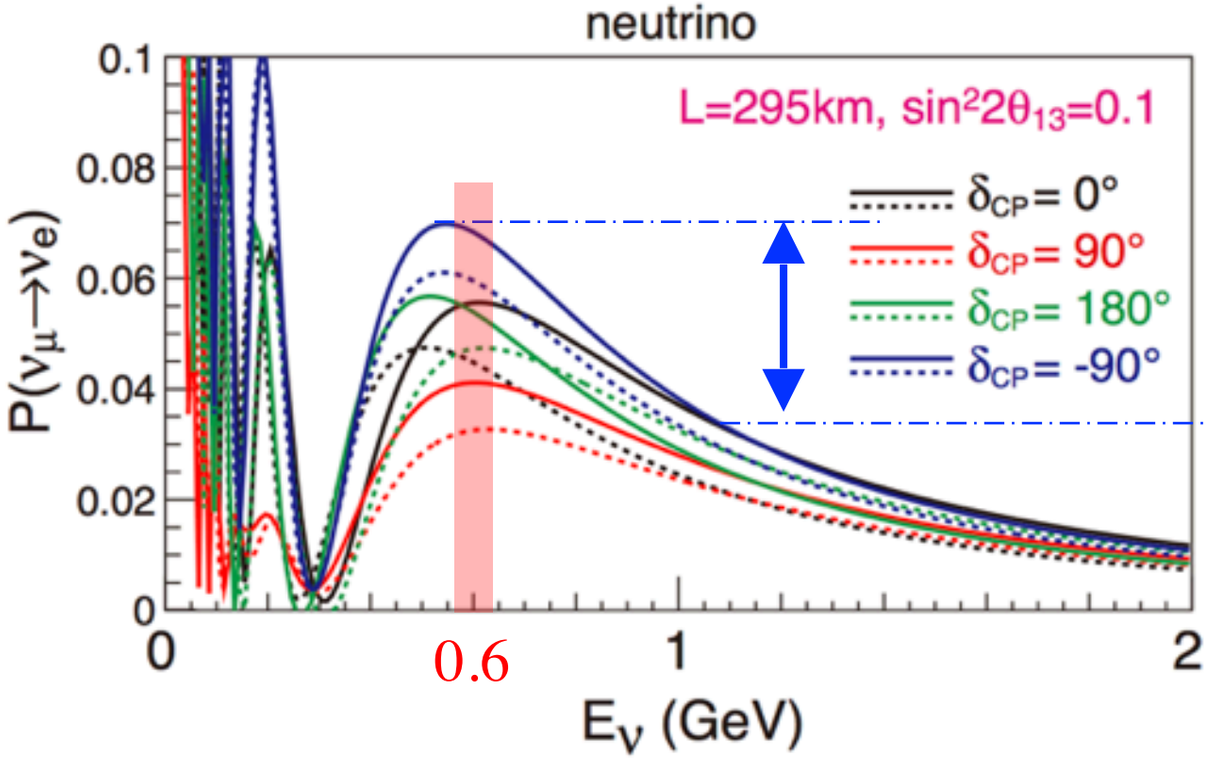


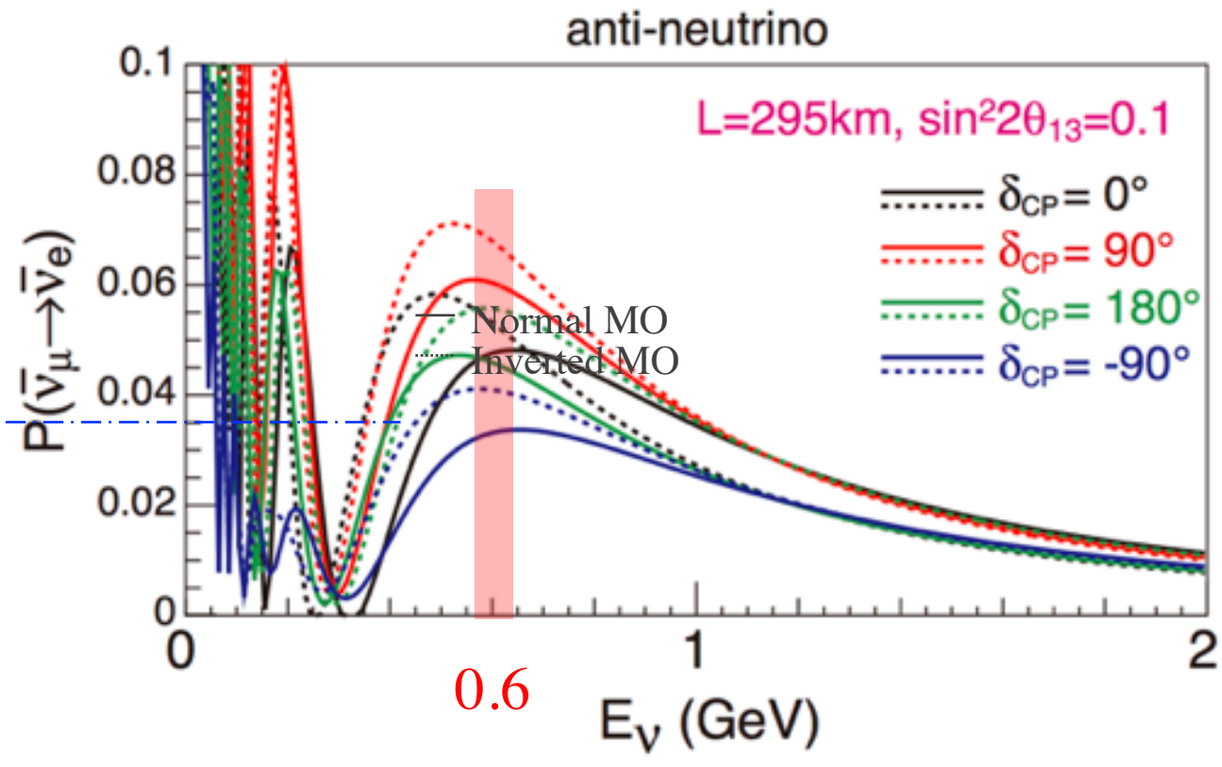
LBL (1.3MW×10years)	δ precision	7°-22°
	CPV coverage (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}-45°\rvert>2°$
Proton Decay (20 years)	$e^+\pi^0$ (3σ)	1×10^{35}
	$\bar{\nu}K$ (3σ)	3×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	8σ/4σ
	Upturn	>3σ
Supernova	Burst (10kpc)	54k-90k
	Relic	70ν's / 10 years

Long-baseline program with the J-PARC neutrino beam

Experimental setup

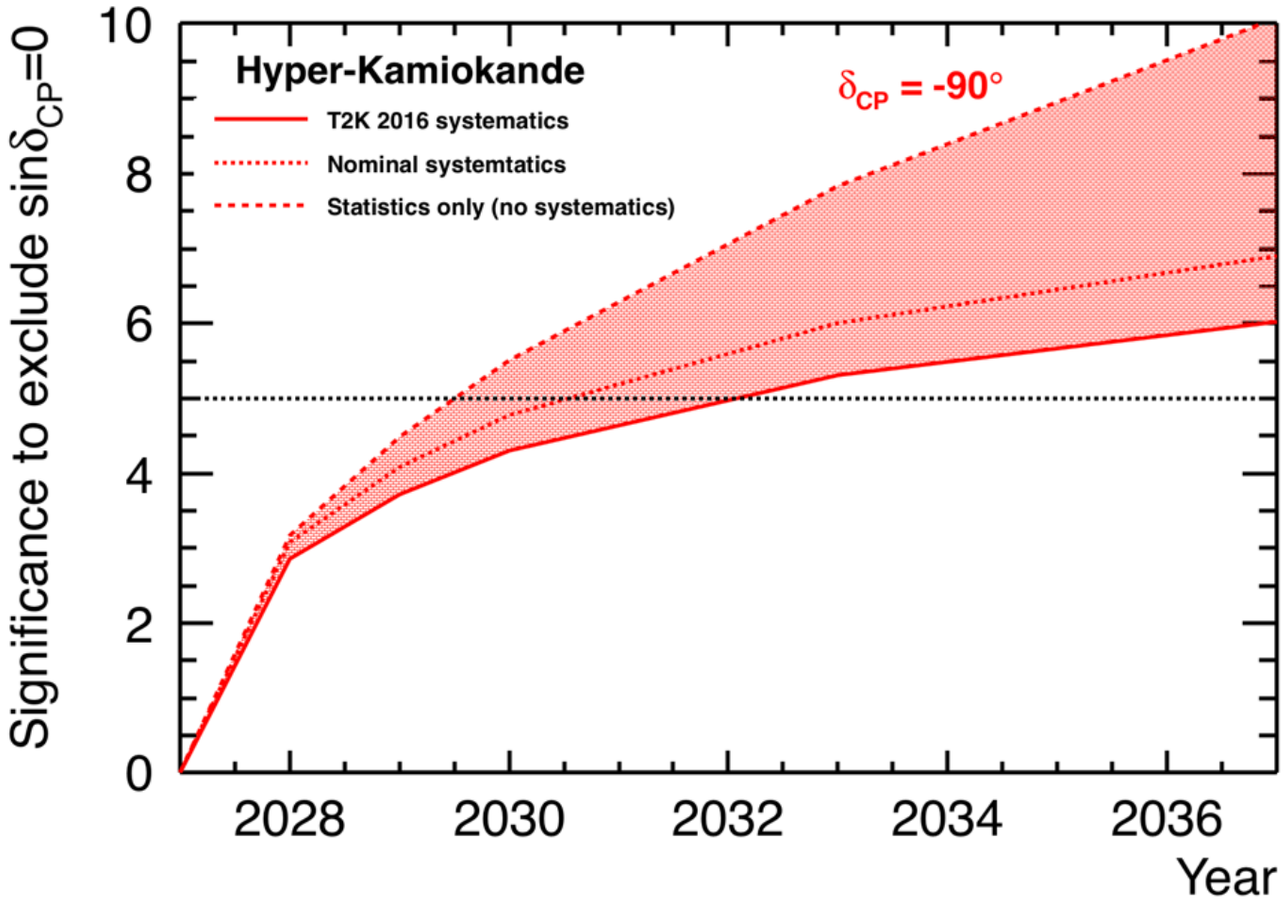
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - ➢ Major component is QE: E_ν determined from (p, θ) of charged lepton
- Measures CP violation in neutrinos by comparing $P\left(\nu_\mu \to \nu_e\right)$ and $P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$





- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

Prospects for CP violation measurement



Projected sensitivity to CPV

Stat. only

Impact of systematic uncertainties after 10 years

T2K syst. (2016)

- **Reduction of systematic uncertainties** has impact to CPV measurement
  - ➢ Uncertainties on neutrino interaction models are major components

    ⇒ **Near detector measurements and constraints**

θ_{23} and Δm^2_{32}

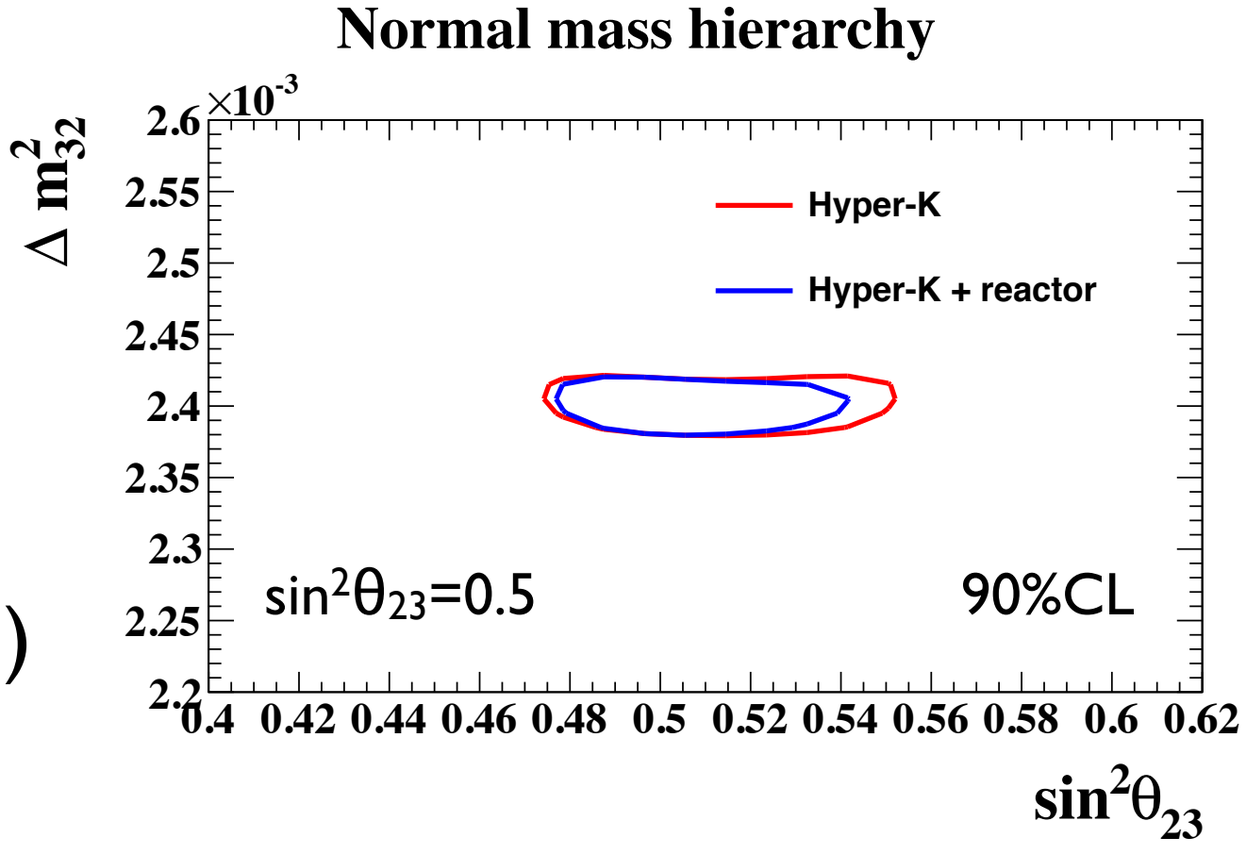
$\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5} eV^2$

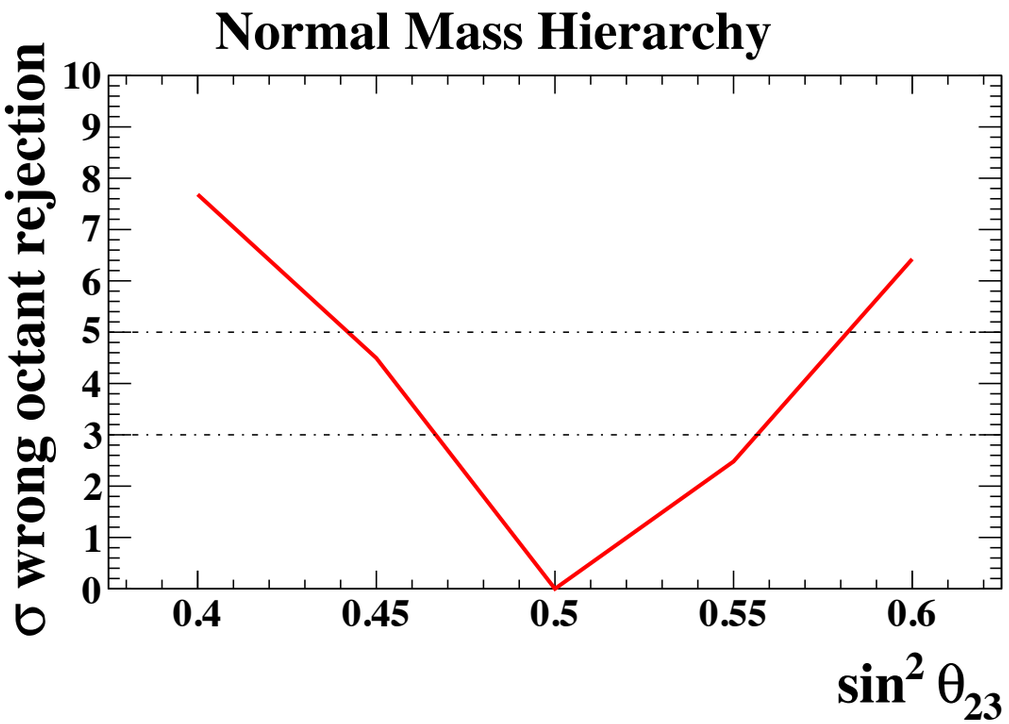
→ Mass hierarchy sensitivity in combination with reactor

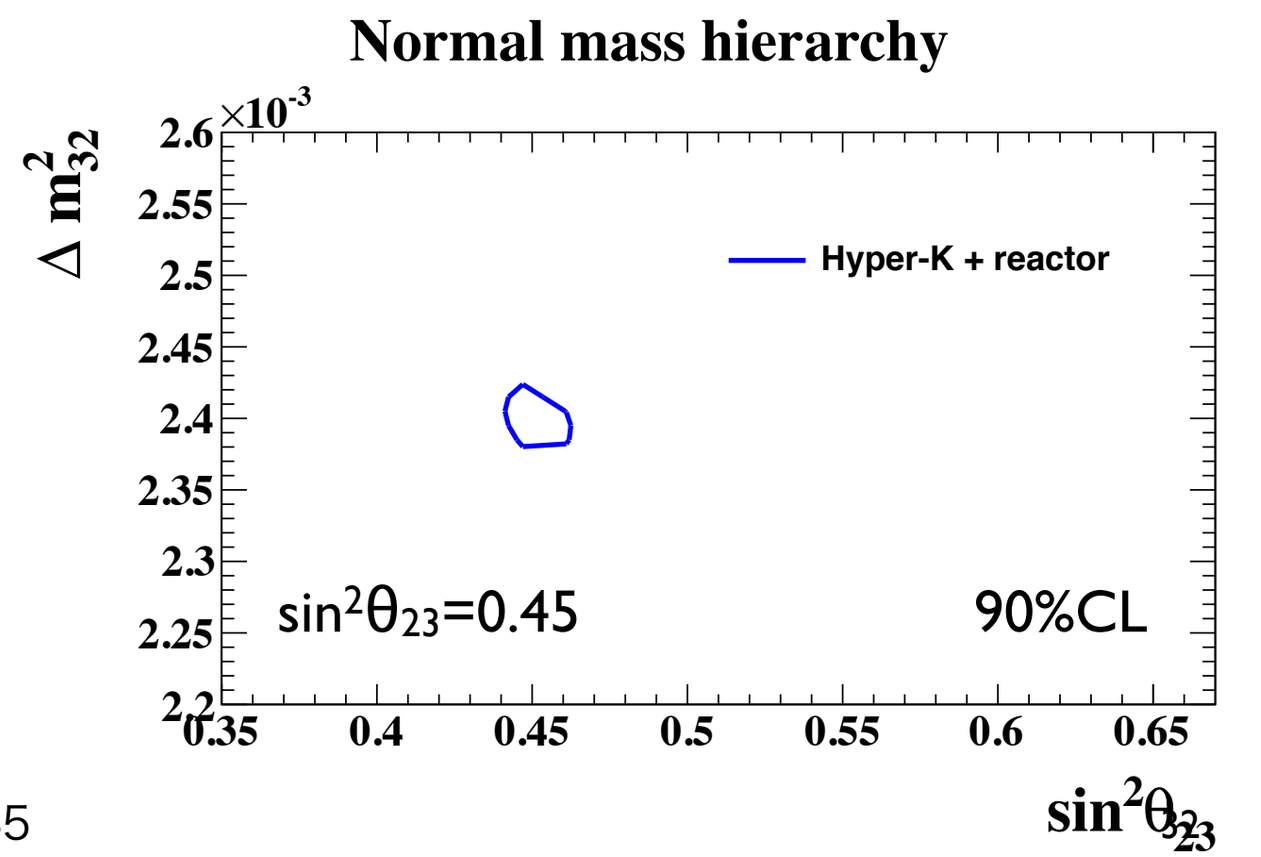
$\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}=0.5$)

~ 0.006 (for $\sin^2\theta_{23}=0.45$)

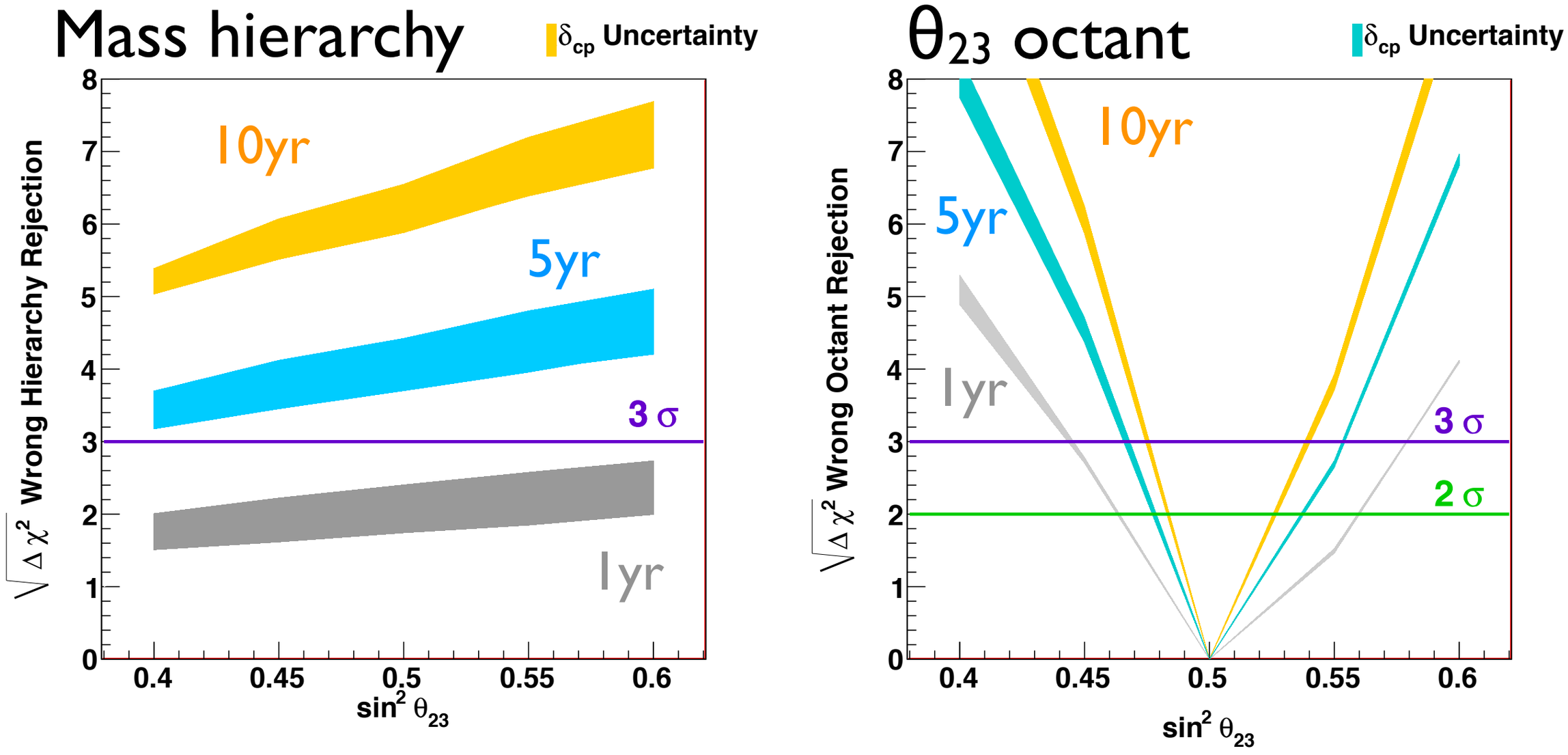
→Octant determination, input to models





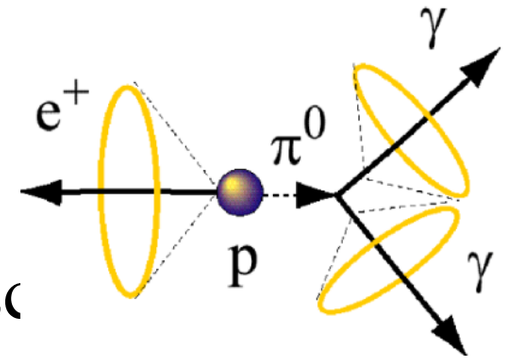


Beam + Atm ν combination



- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

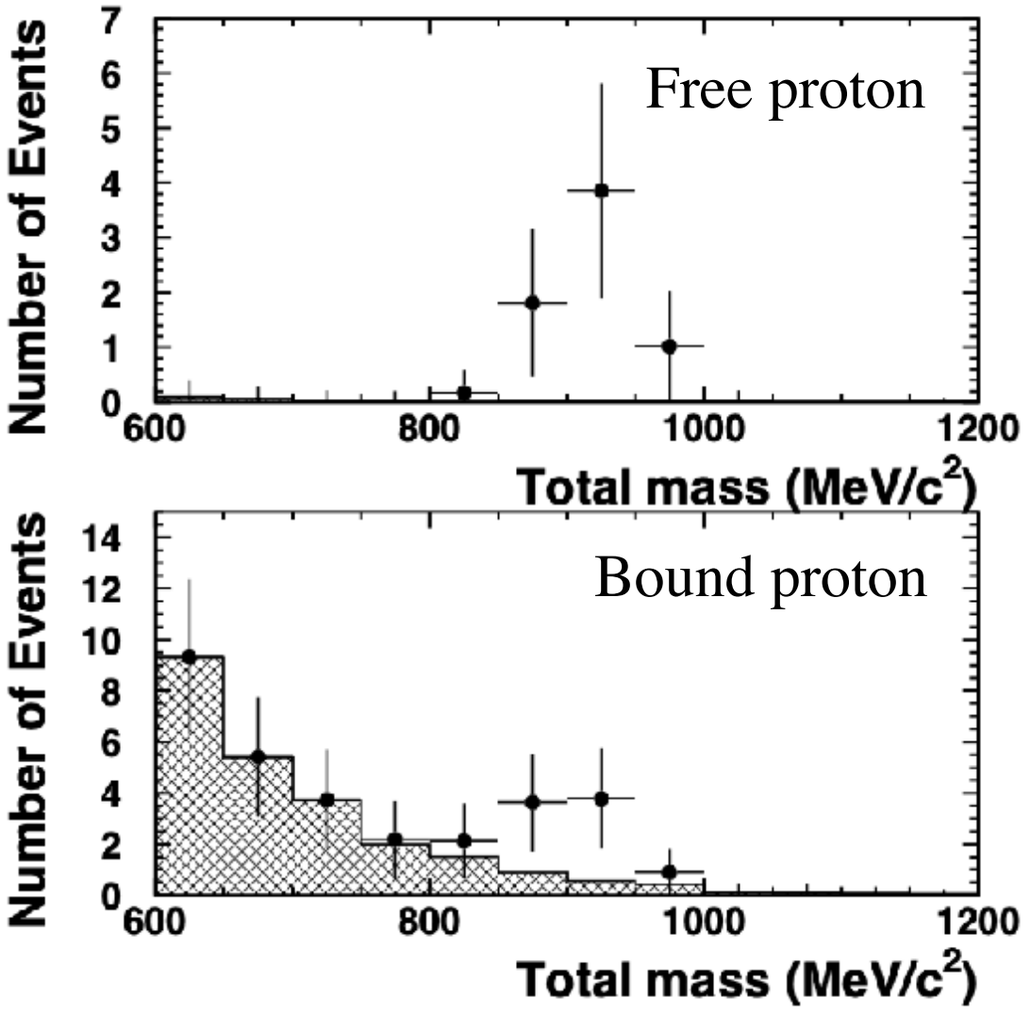
Proton decay search

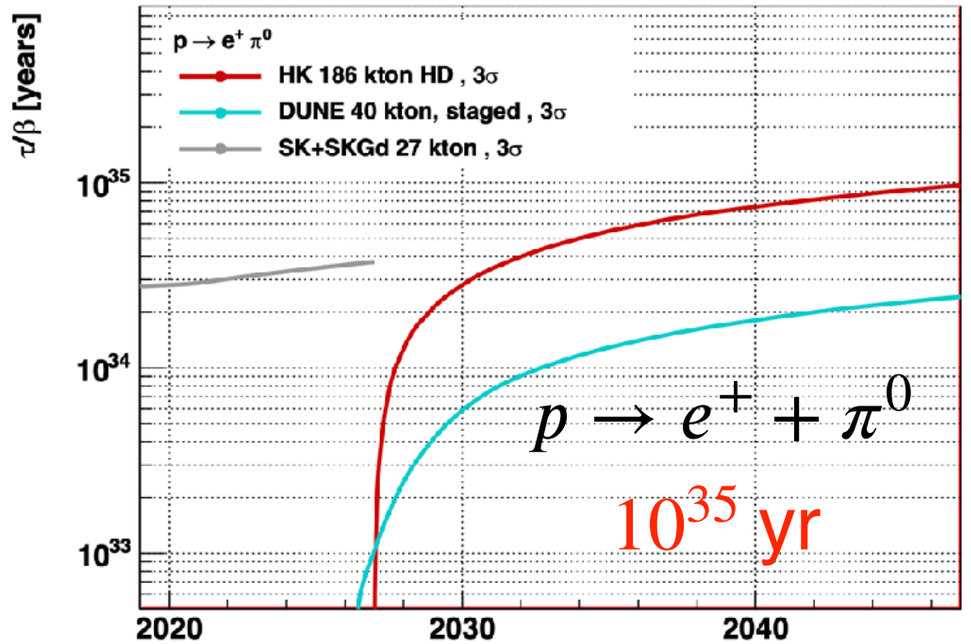


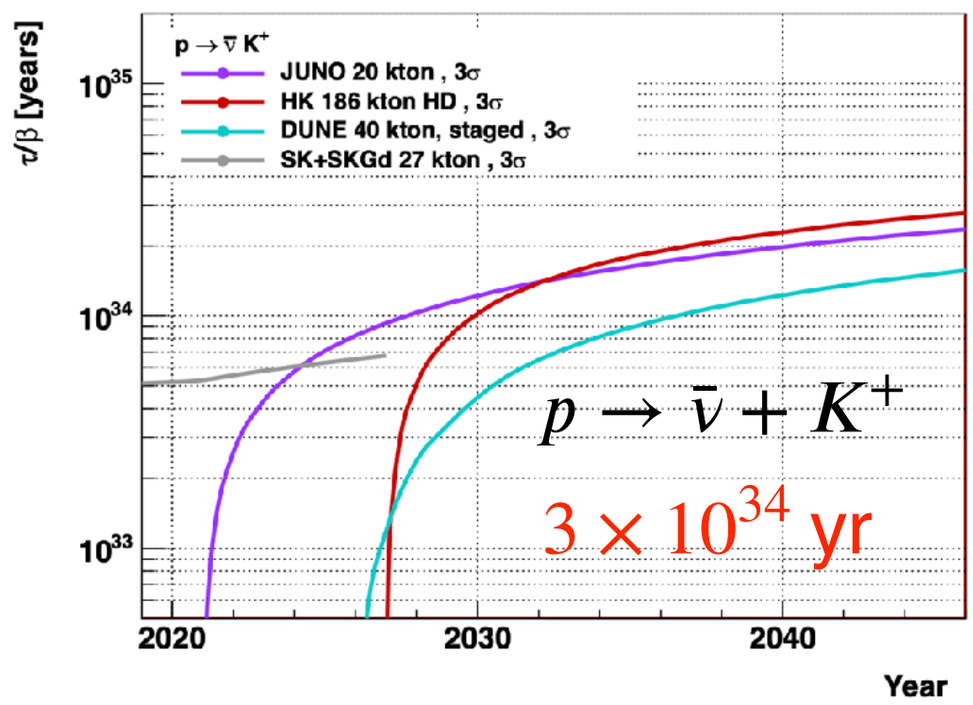
GUT

- One possible approach to reach GUT energy sc
- Extend proton decay search by one order of magnitude beyond the current limits

After 10 years of HK
if $\tau = 1.7 \times 10^{34}$ years ···







Hyper-Kamiokande schedule

FY2020 FY2021 FY2022 FY2023 FY2024 FY2025 FY2026 FY2027 FY2028

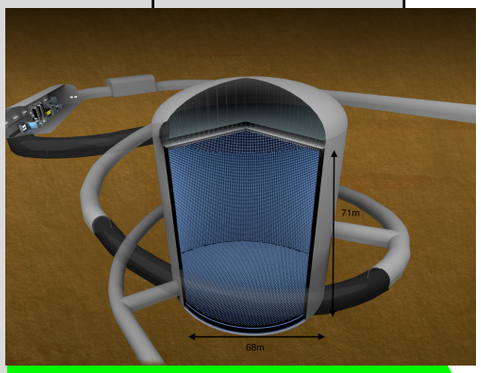
Geo. survey

Access/ Cavern design

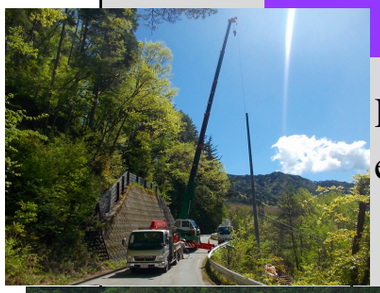
Cavern excavation

Tank const.

PMT installa tion



PMT production



Power line to entrance yard

PMT cases, mirrors, electronics etc.

Operation

Entrance yard

Water system

Filling water

Upgrade of J-PARC accelerator and neutrino beamline

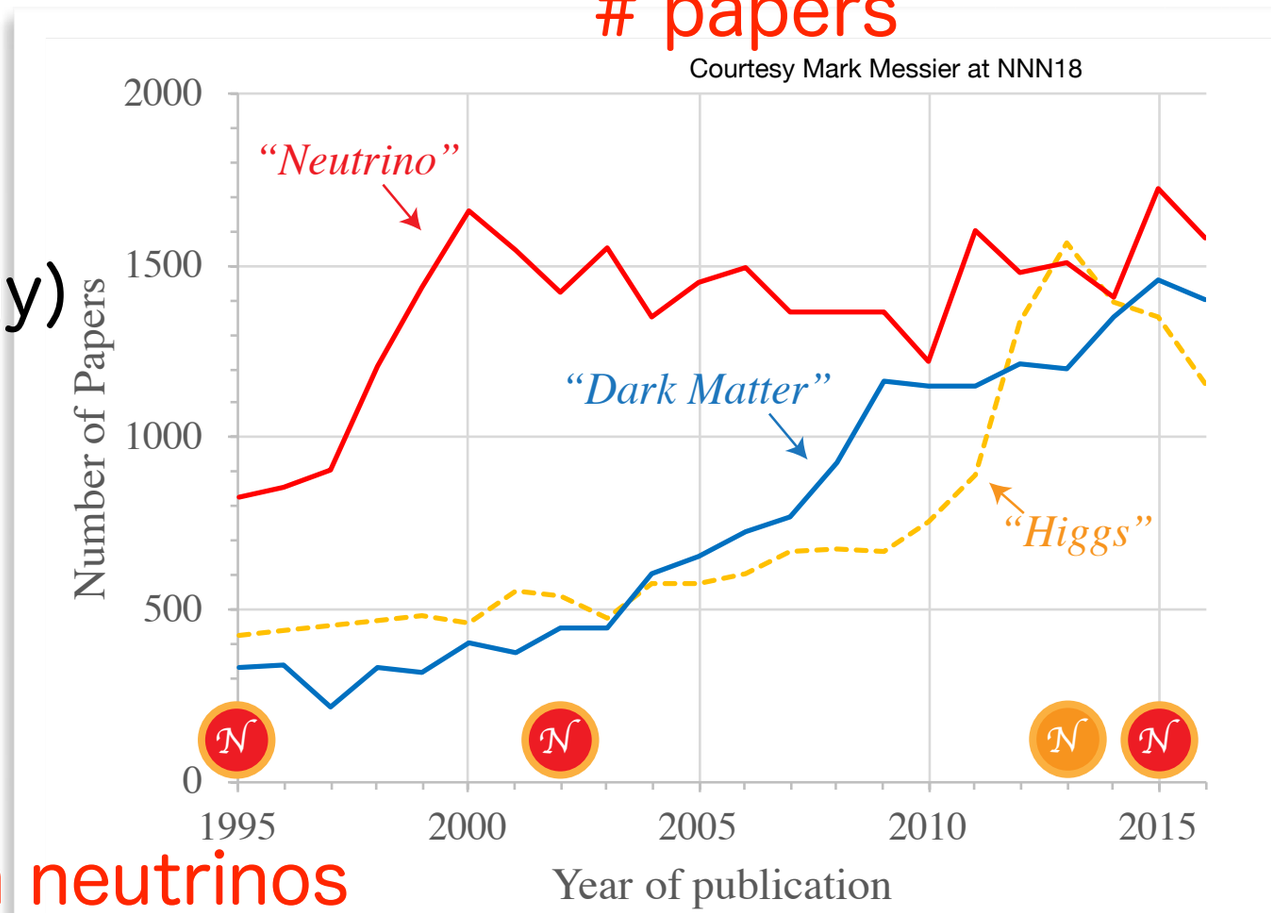
Near detector facility, R&D, production

ND construction

Finally,

Big problems in Particle Physics

- Unification: Unification of forces [and particles]
- Origin of neutrino mass
- Family structure (3 families in quarks and leptons)
- Imbalance between matter and anti-matter (almost no anti-matters in our universe)
- Dark Matter
- Accelerating Universe (Dark Energy)
- Inflation



➡ Let's explore new physics with neutrinos

Data based on INSPIRES search "find ti Neutrino and date 2000", eg

https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/files/NF-pamph-EN.pdf

END

HiggsTan
http://higgstan.com

HiggsTan Cartoon

登録情報

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