Updated results from T2K experiment with 3.13×10^{21} POT

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T2K (Tokai to Kamioka) (2010~)

- Long baseline neutrino oscillation experiment with high intensity muon neutrino beam from J-PARC MR to Super-Kamiokande (Super-K)
- Goals:
  - Precise measurement of ν_μ disappearance
  - Measurement of ν_e appearance → Discovery

    → Search for leptonic CP violation (δ_{CP})
  - Search for non-standard oscillation, Cross section measurements


T2K collaboration
12countries, ~500 members
Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.
France
CEA Saclay
LLR E. Poly.
LPNHE Paris
Germany
Aachen U.
Italy
INFN, U. Bari
INFN, U. Naples
INFN, U. Padua
INFN, U. Rome
Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.
Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.
Russia
INR
Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid
Switzerland
ETH Zurich
U. Bern
U. Geneva
United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. London
Royal Holloway U. London
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick
Texas
U. of Houston
USA
Boston U.
Colorado St U.
Duke U.
Louisiana State U.
Michigan St. U.
SLAC
Stony Brook U.
U. C. Irvine
U. of Colorado
U. of Pittsburgh
U. Rochester
U. Washington
Vietnam
IFIRSE
IOP, VAST
T2K Breakthrough Prize Celebration, 2016

Neutrino Oscillation

Flavor state
(Interaction)

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

Mass state
(Propagation)

$$\mathrm{U_{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

Atmospheric, LBL

$$\Delta m^2_{32} \simeq 2.4 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.4 \sim 0.6$$

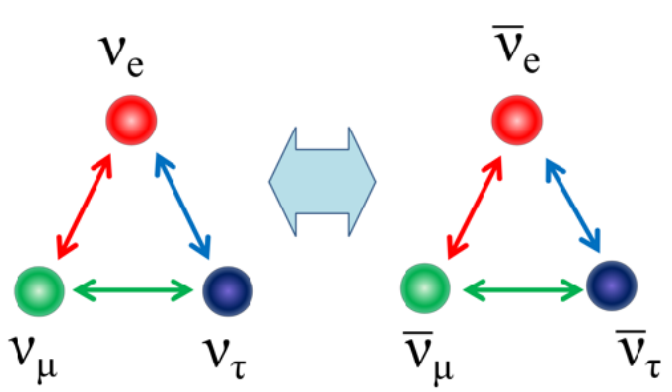
Reactor, LBL

$$\sin^2\theta_{13} \simeq 0.021$$

Solar, KamLAND

$$\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\mathrm{eV}^2$$
$$\sin^2\theta_{12} \simeq 0.30$$

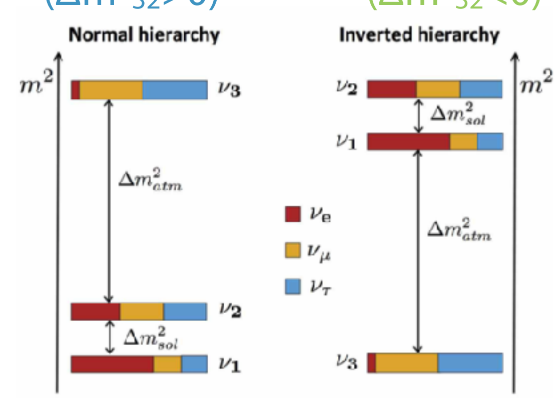
Still unknown:



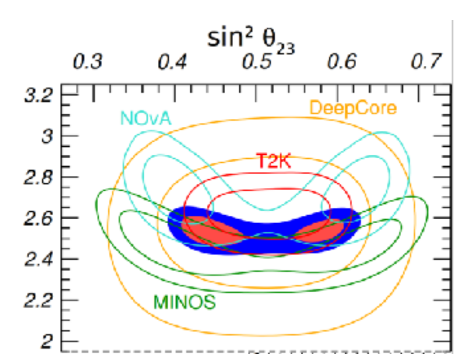
Leptonic CP (δ_{CP})

Normal ($\Delta m^2_{32}>0$)

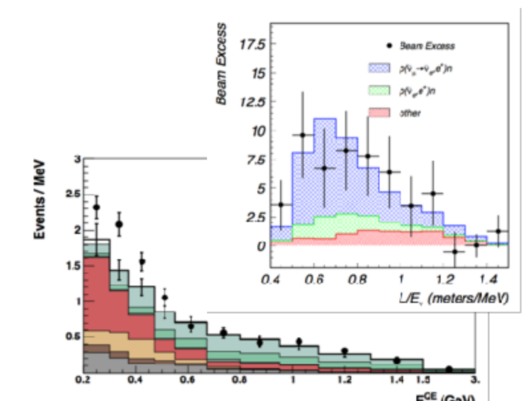
Inverted ($\Delta m^2_{32}<0$)



Mass Hierarchy
(Mass Ordering)



θ_{23} Octant



Sterile neutrino

Neutrino Oscillation in T2K

- Disappearance of muon neutrino (θ_{23}, Δm^2_{32}) :

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\underbrace{\cos^4\theta_{13}\sin^2 2\theta_{23}}_{} + \sin^2\theta_{23}\sin^2 2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

↑ Leading term

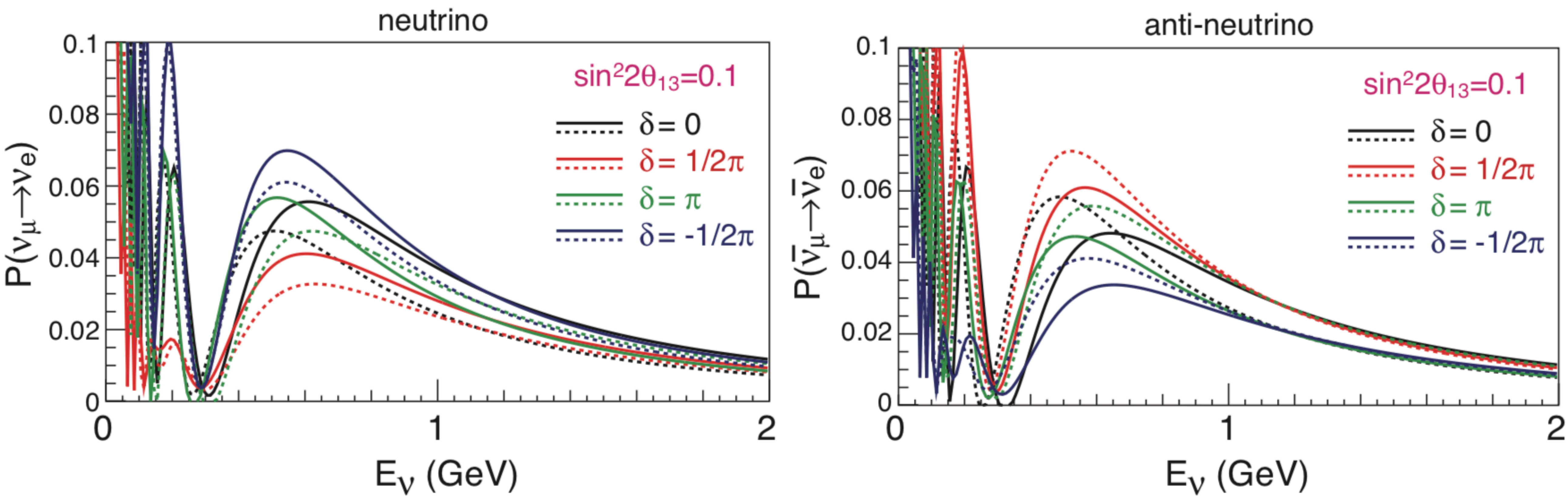
- Appearance of electron neutrino (θ_{13}) and CP measurement (δ_{CP})

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\left(1 + \frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1 - 2\sin^2\theta_{13})\right)$$ ← Leading term

$$- \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

↖CP violating term

CP effect on electron appearance



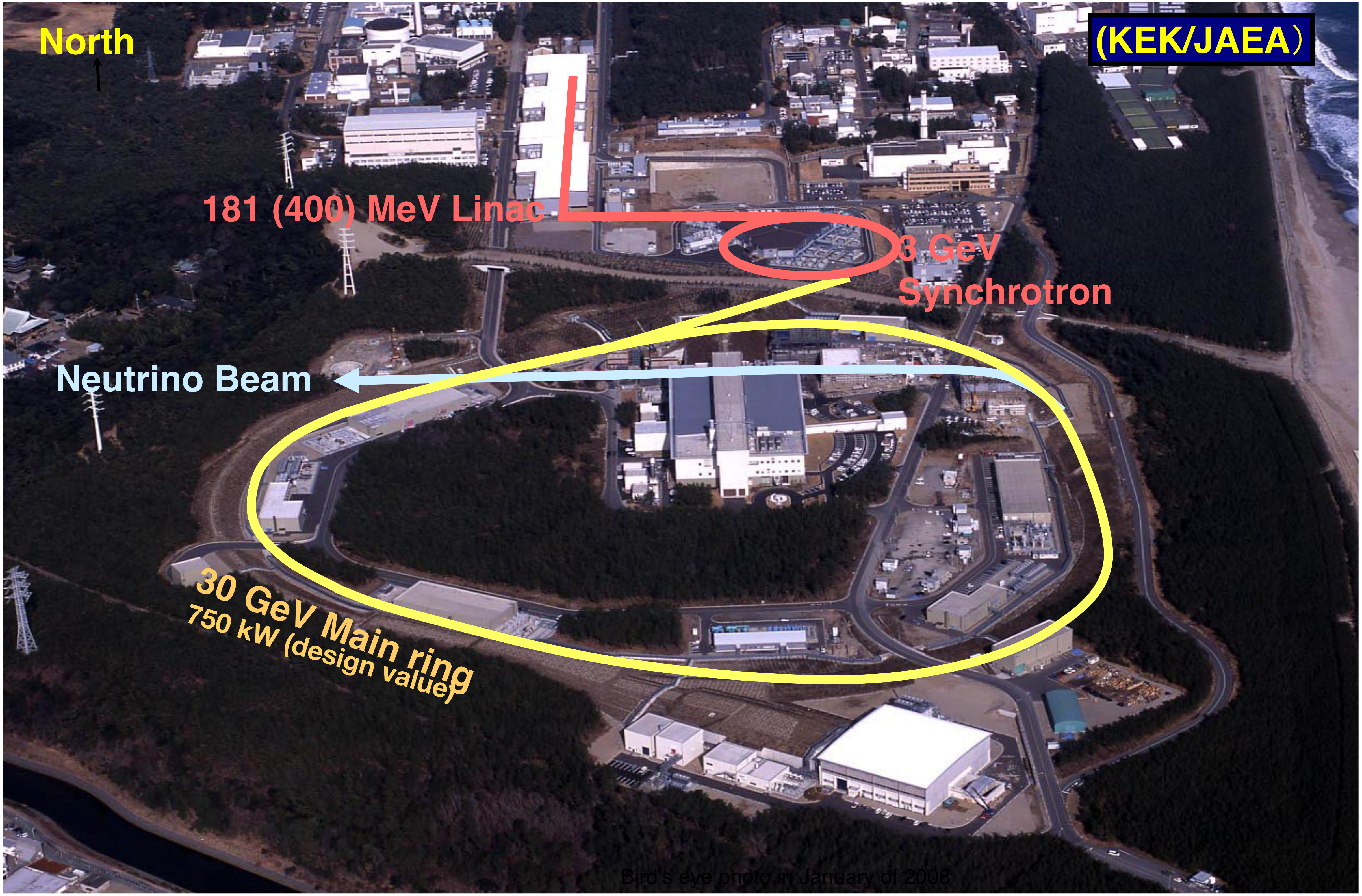
- ~25% change at oscillation peak between δ=-1/2π and 1/2π
- Opposite direction for neutrino and anti-neutrino

  → Possible to measure CP by independent ν and $\bar{\nu}$ measurements

- Marginal effect due to neutrino mass hierarchy

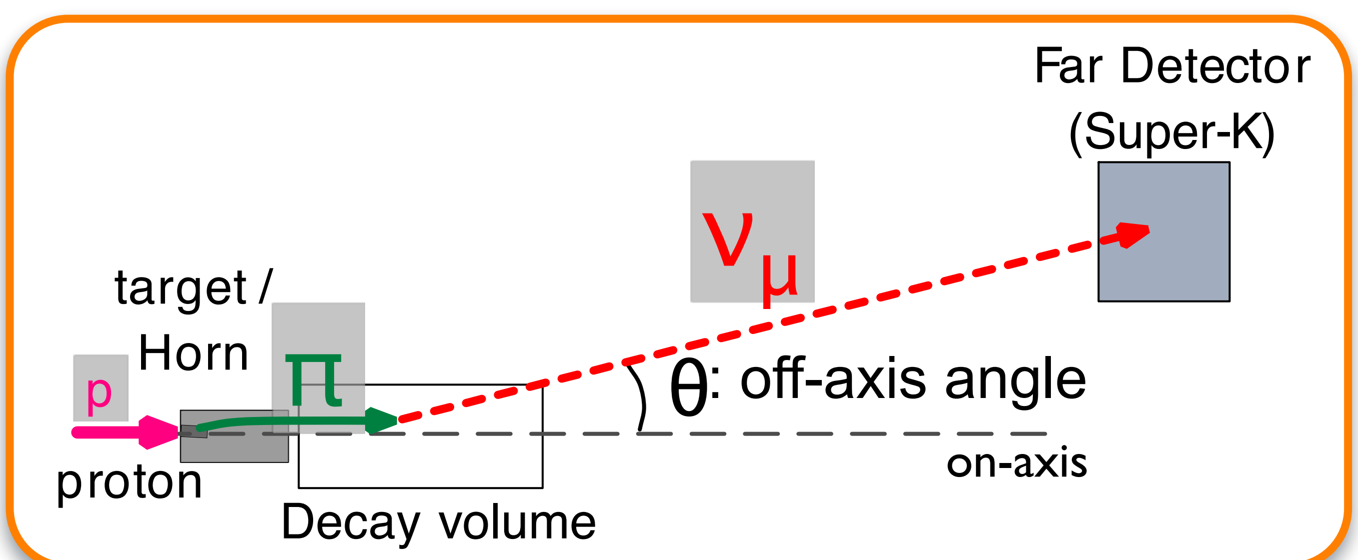
T2K experiment

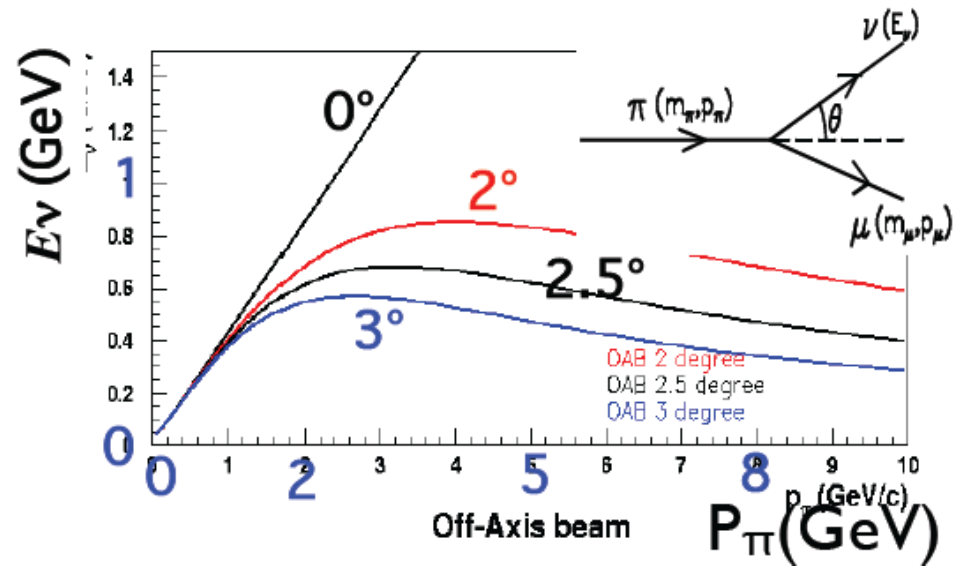
J-PARC Accelerator

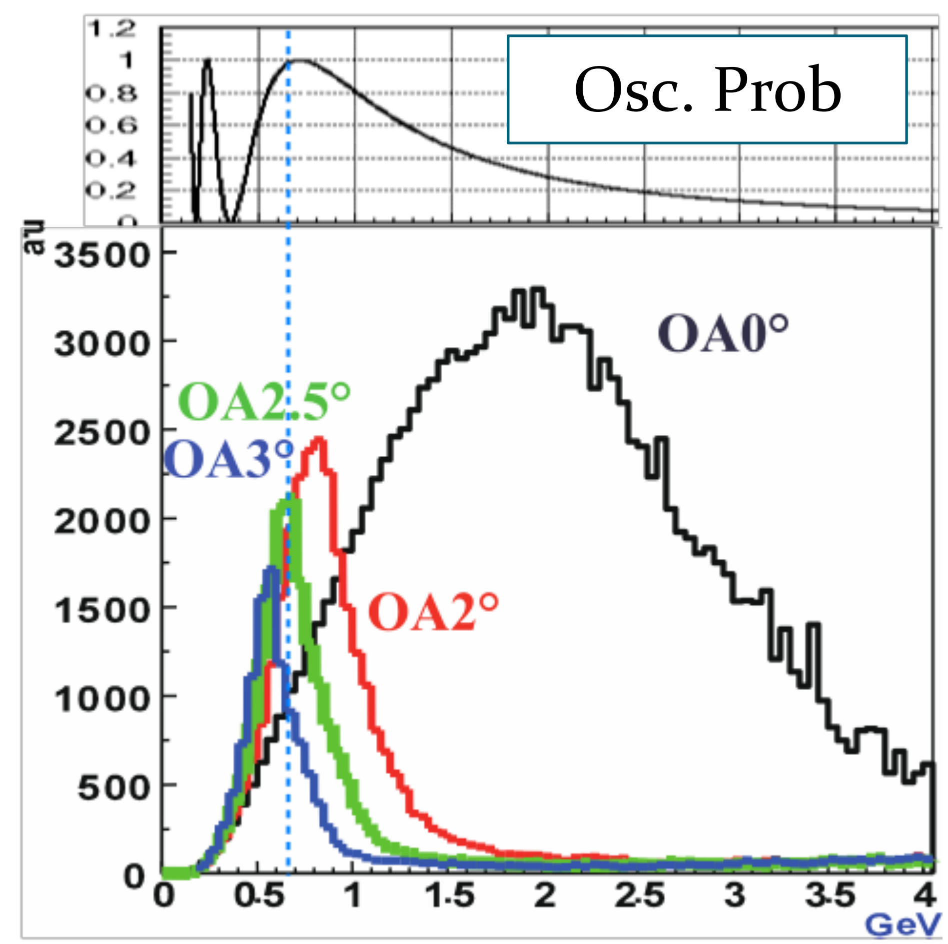


Off-Axis Beam

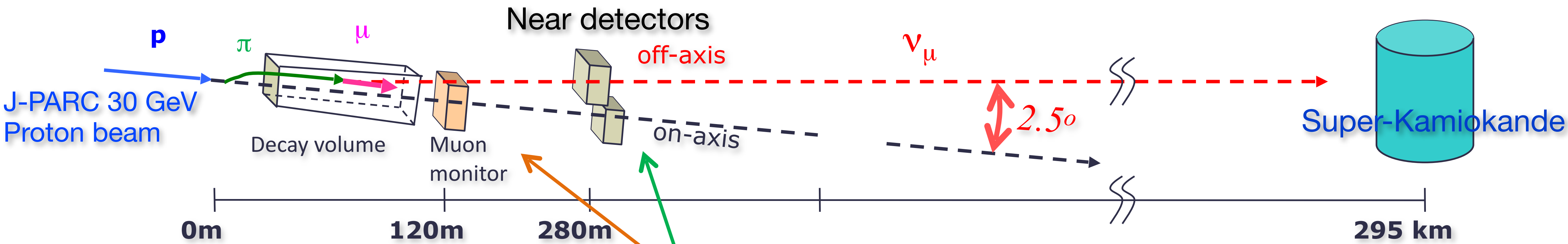
- Neutrino beam are pointed to 2.5° off-axis direction from SK direction
  - Produce intense narrow-band beam
  - Optimize peak energy by off-axis angle (~0.6GeV)
  - Suppress high energy flux　(Eν>1GeV) producing ν_e backgrounds
- *First experiment to utilize off-axis beam*







T2K overview



Off-axis (2.5 °) ν_μ beam

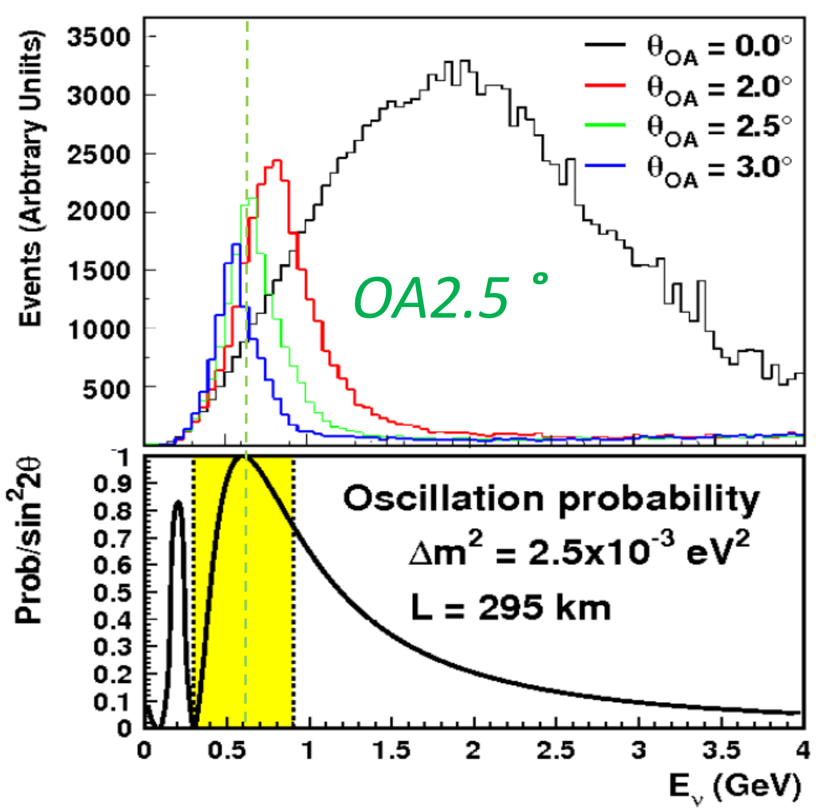
- Intense, low energy narrow-band
- Peak E_ν tuned for oscillation max. (~0.6 GeV)
- Reduce BG from high energy tail
- Small ν_e fraction (~1%)

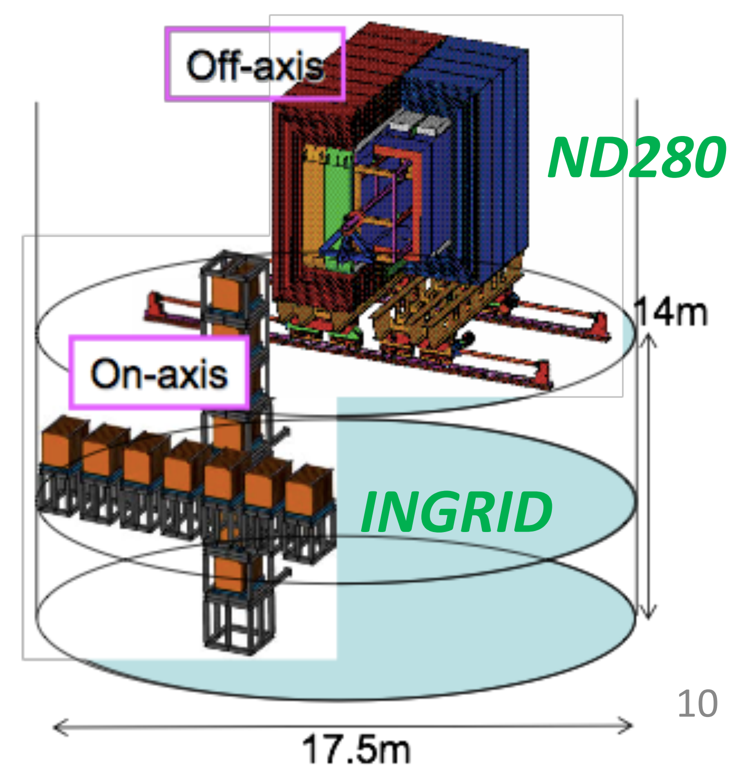
Muon monitor

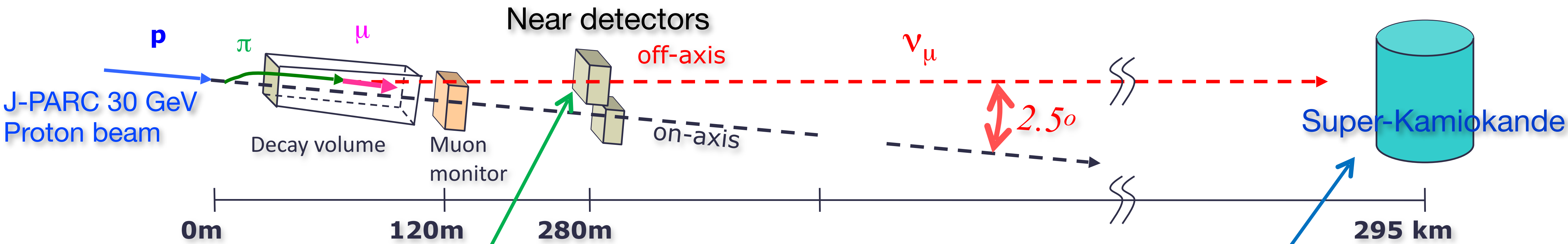
- Monitor intensity and profile spill-by-spill

On-axis detector (INGRID)

- Monitor ν beam day-by-day
- Detector coverage is 10m x 10m





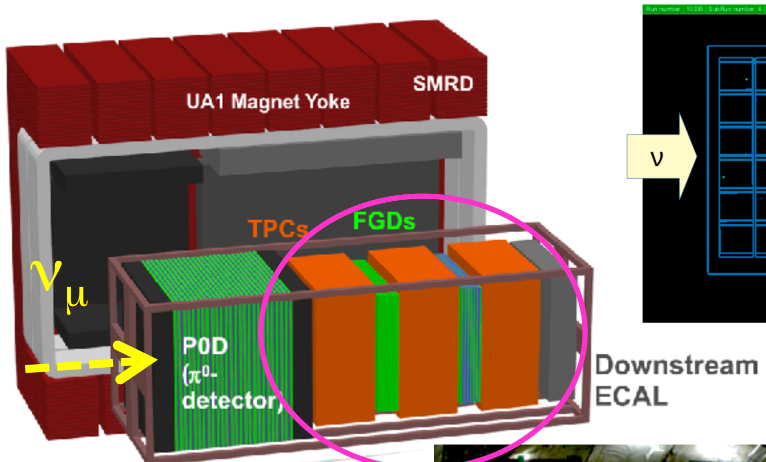


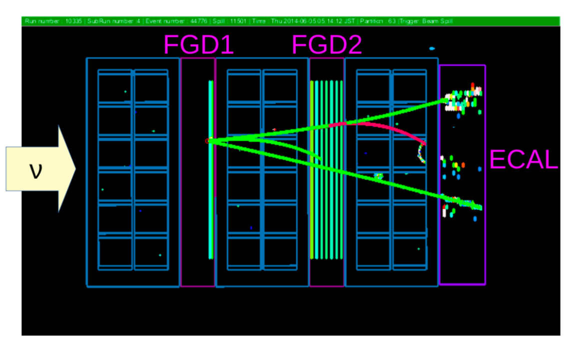
Off-axis detector (ND280)

- Predict interaction rate before oscillation
- UA1 magnet
- Fine grained detector (FGD)
  FGD1: CH target, FGD2: 42% water
- Time projection chamber (TPC), ECAL, P0D

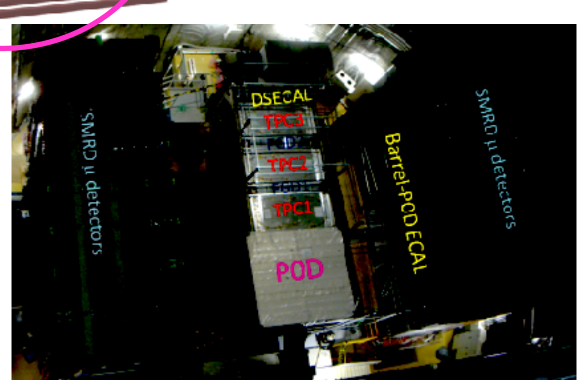
Far detector (Super-Kamiokande)

- Water Cherenkov detector (total mass ~50 kton)
- Excellent particle ID for μ / e particle with ~99% efficiency



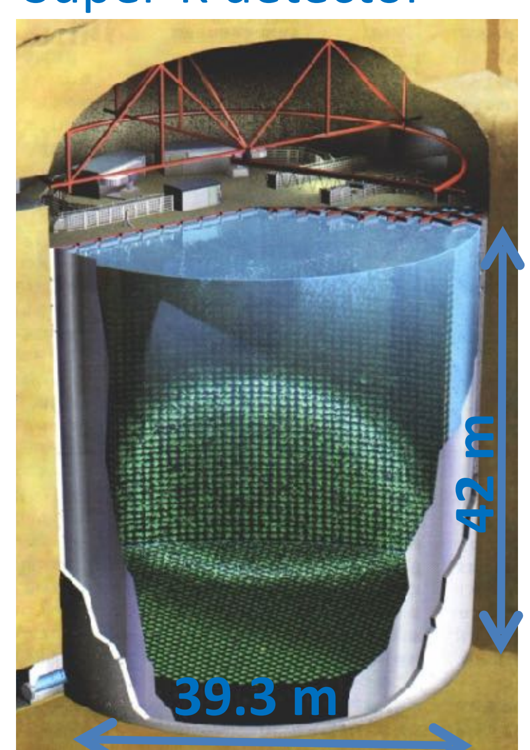


ND280

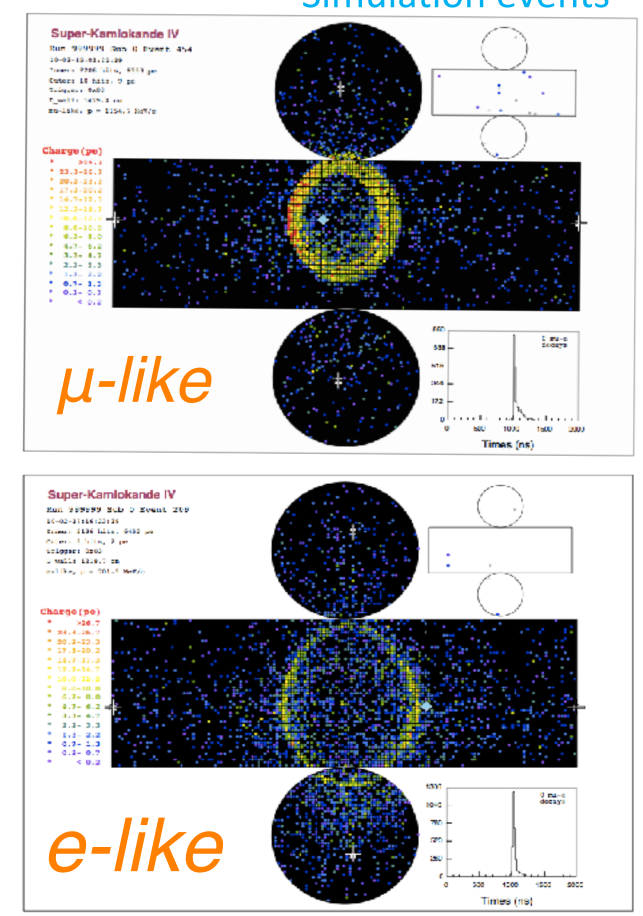


Top view of detector

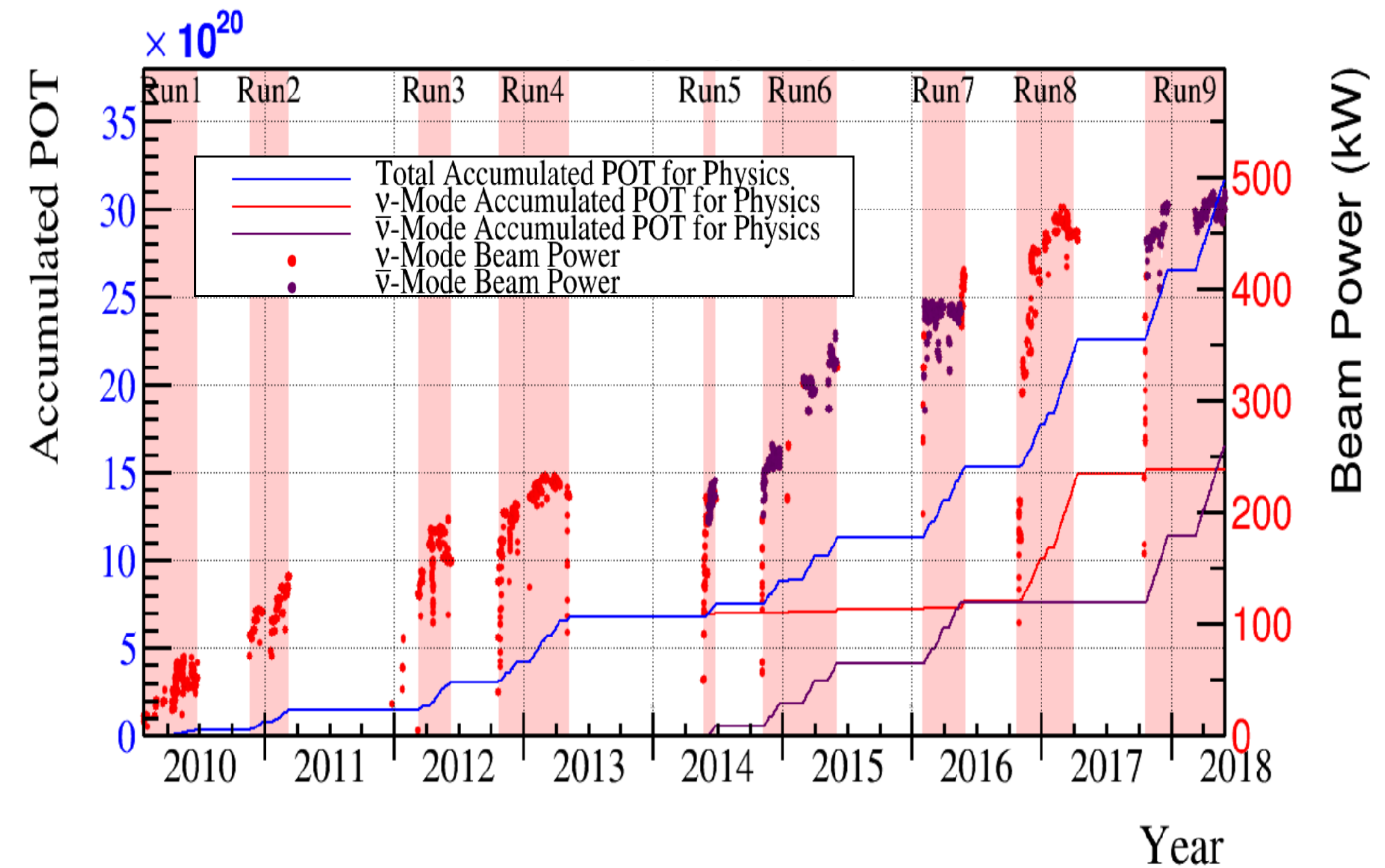
Super-K detector



Simulation events

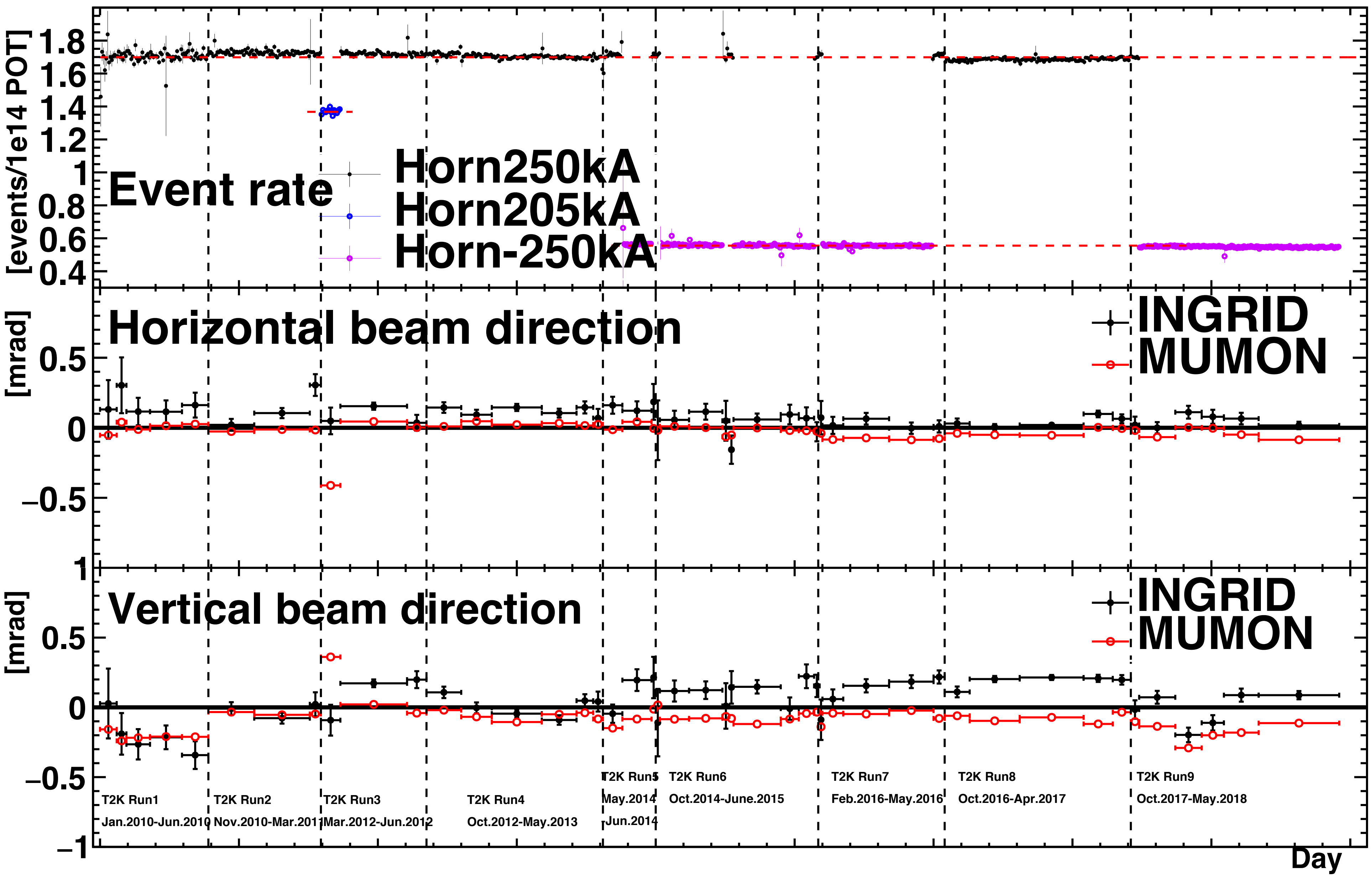


Beam Power and Accumulated POT



- 3.16 x 10^{21} Proton On Target (POT) accumulated until May 2018
- neutrino: 1.51 x 10^{21} POT, anti-neutrino: 1.65 x 10^{21} POT
- ~30% increase of anti-neutrino data from previous result

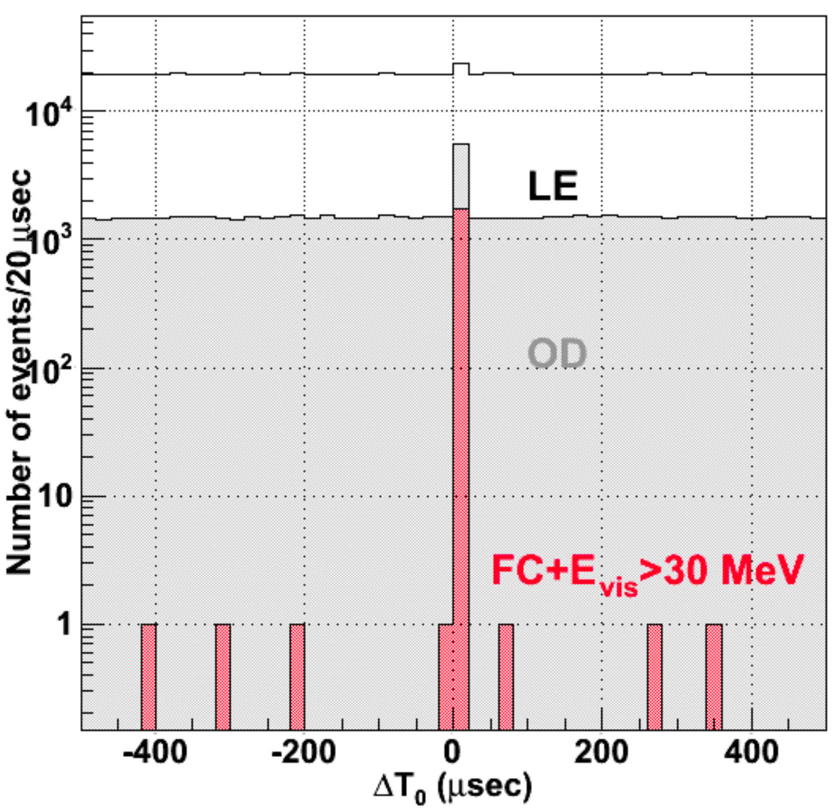
Neutrino Beam Stability

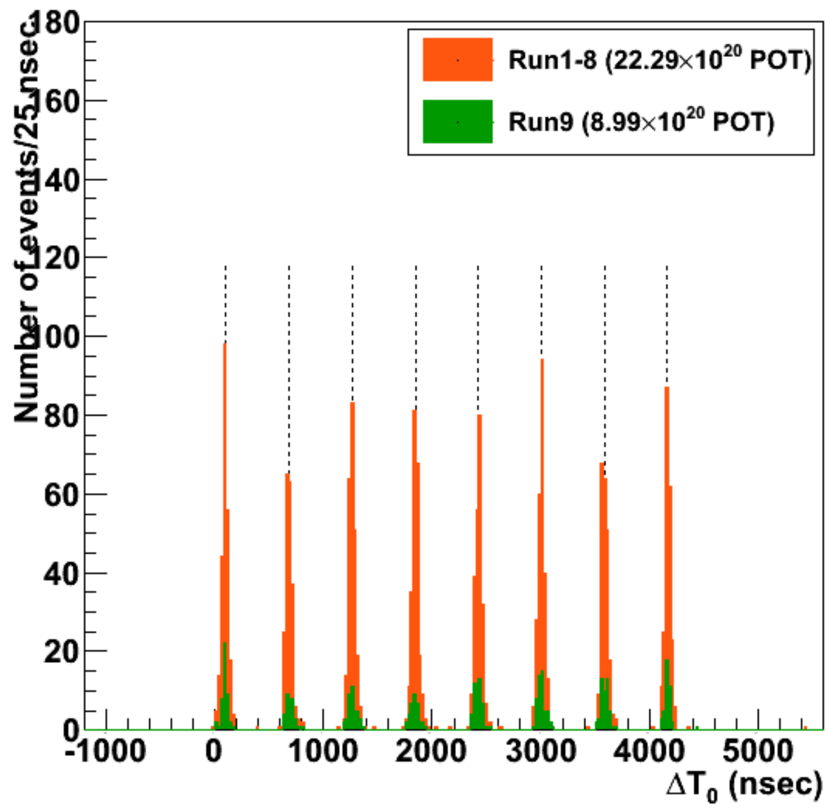


- Neutrino event rate and direction are stable

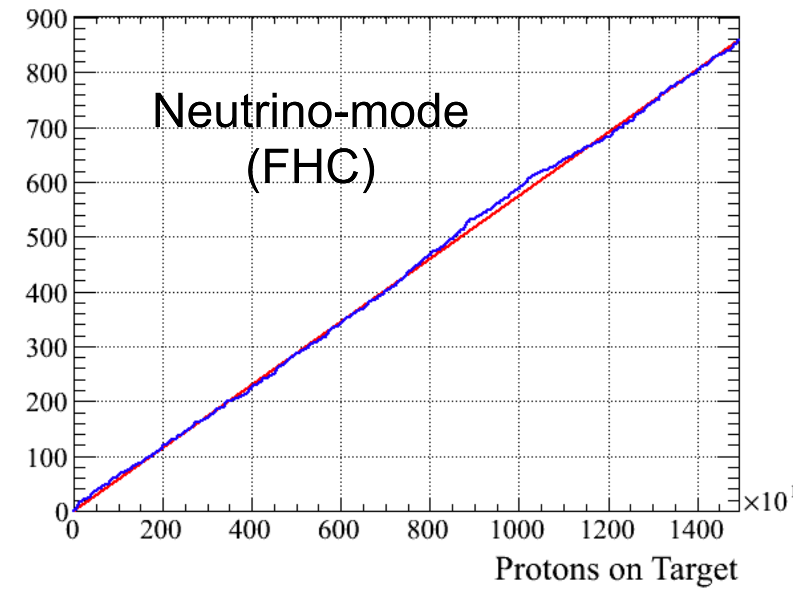
Super-K Data Quality

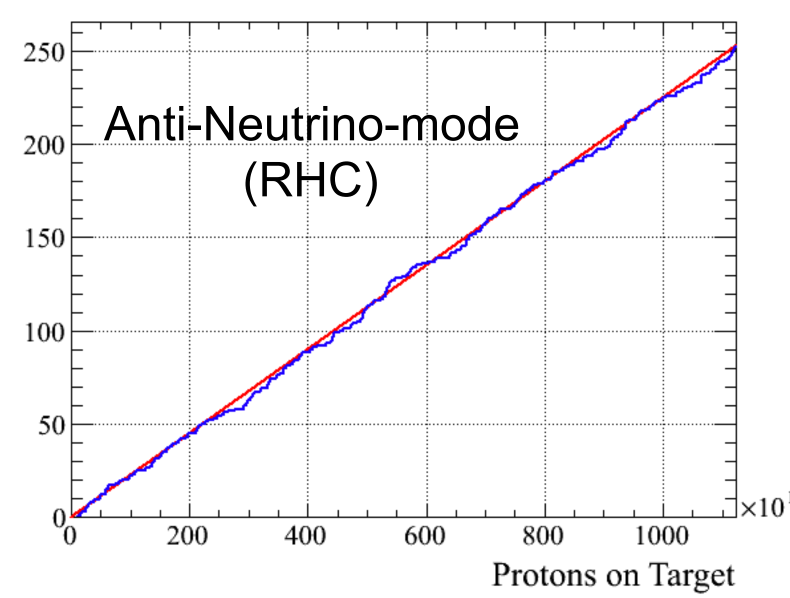
Beam timing





Neutrino Rate Stability

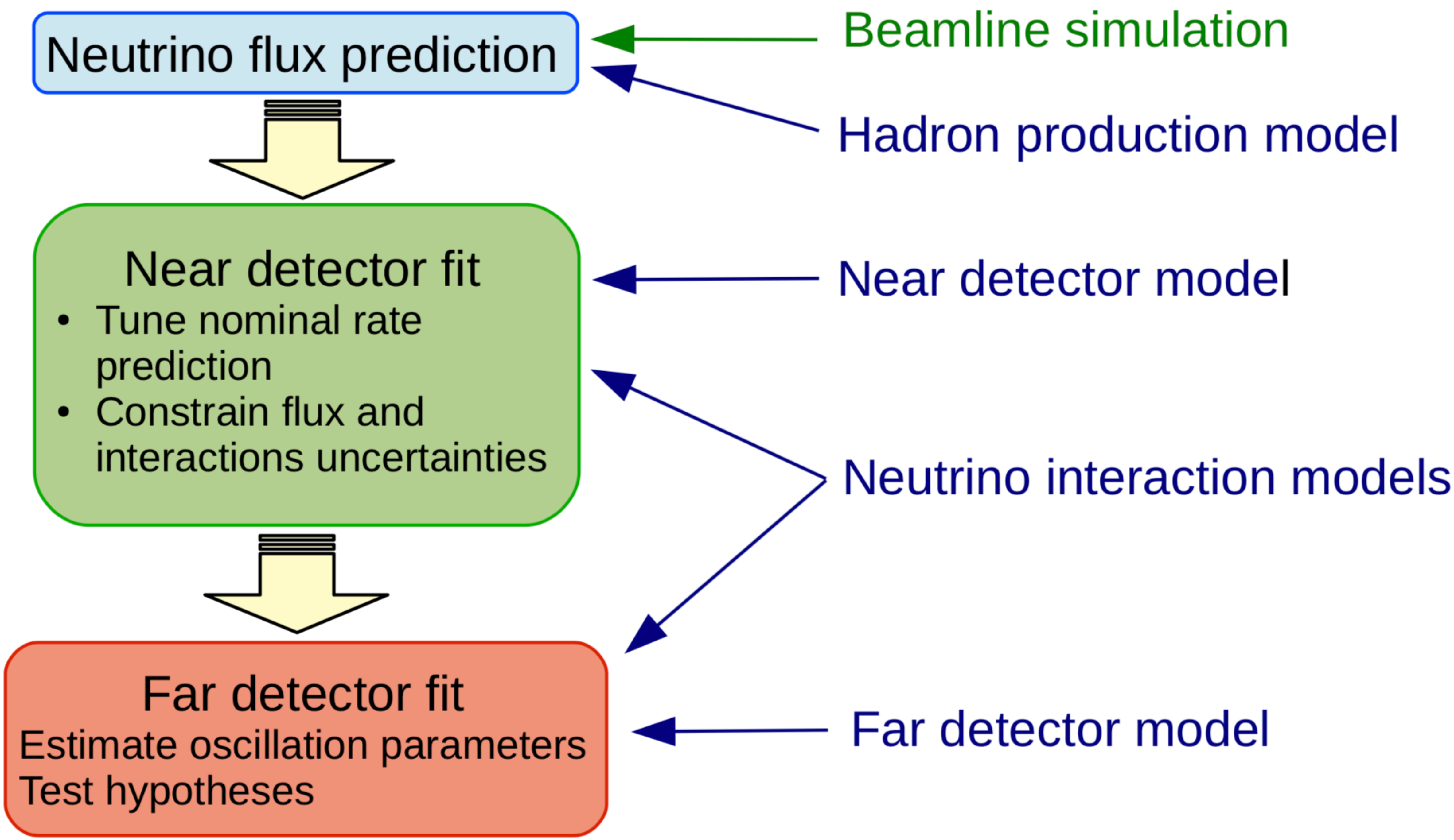




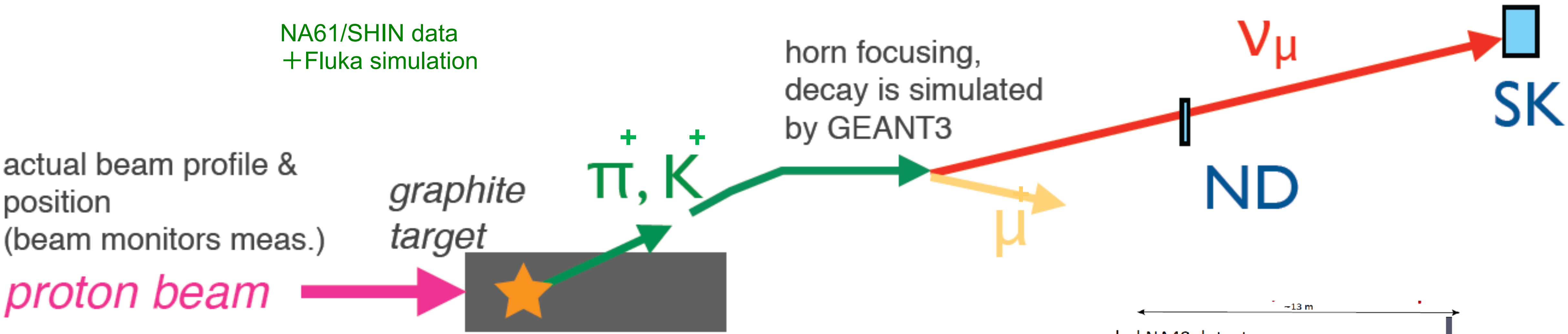
- Data taking is stable and efficient (~1% inefficiency)
- Clear bunch structure in beam timing
- Stable event rates for both ν and $\overline{\nu}$ mode

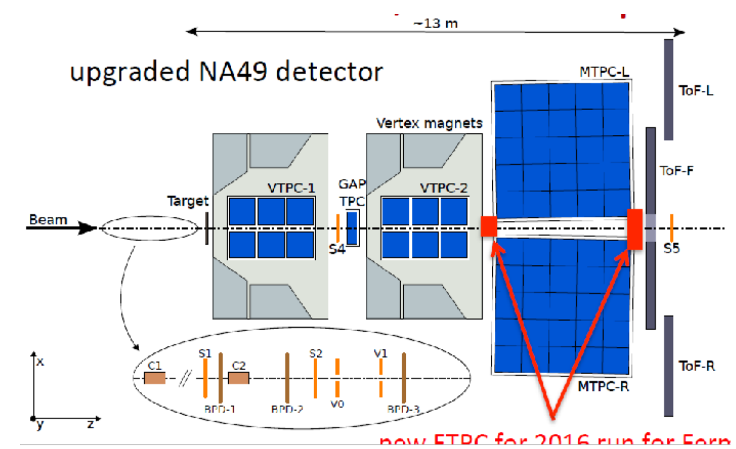
Oscillation Analysis

Oscillation Analysis Strategy



Neutrino Flux Predictions

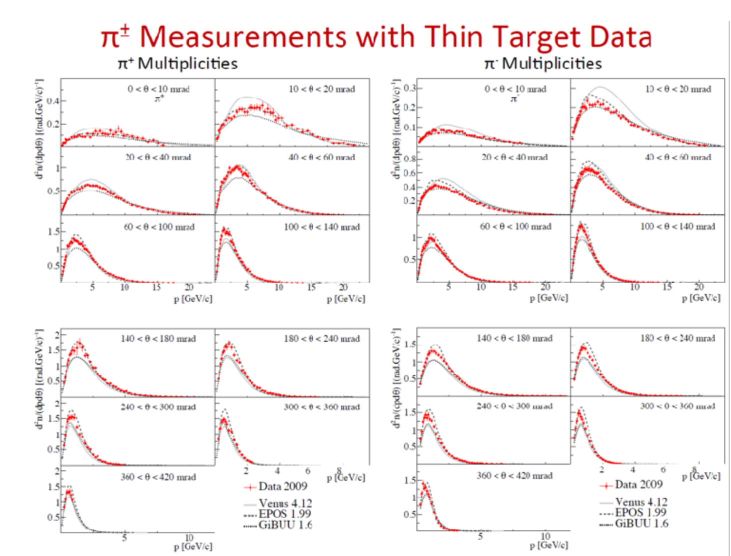




Hadron production in 30GeV proton + C

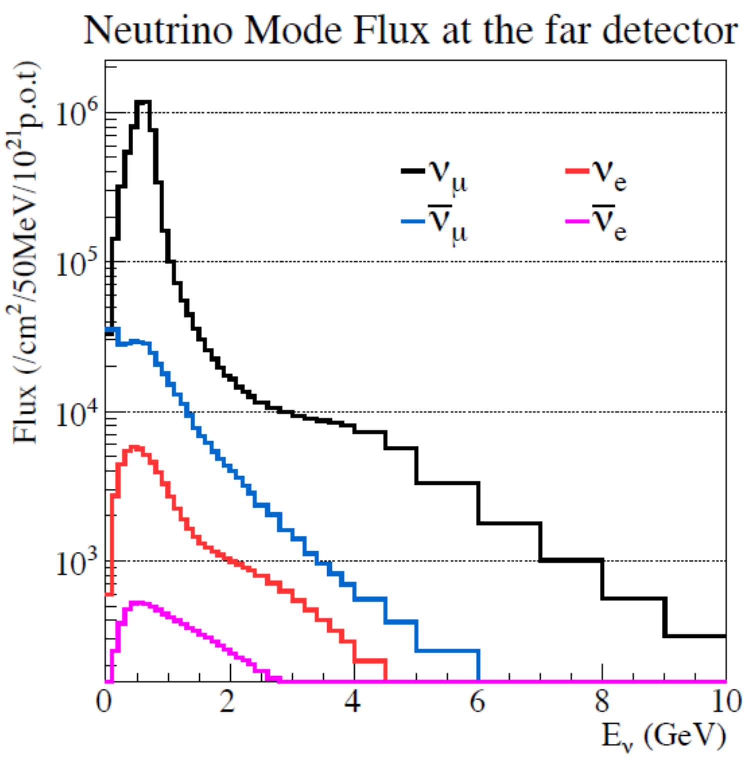
- ***Use CERN NA61/SHINE pion measurement (large acceptance: >95% coverage of ν parent pions)***
- *Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation*
- *Secondary interaction x-sections outside the target were based on experimental data*

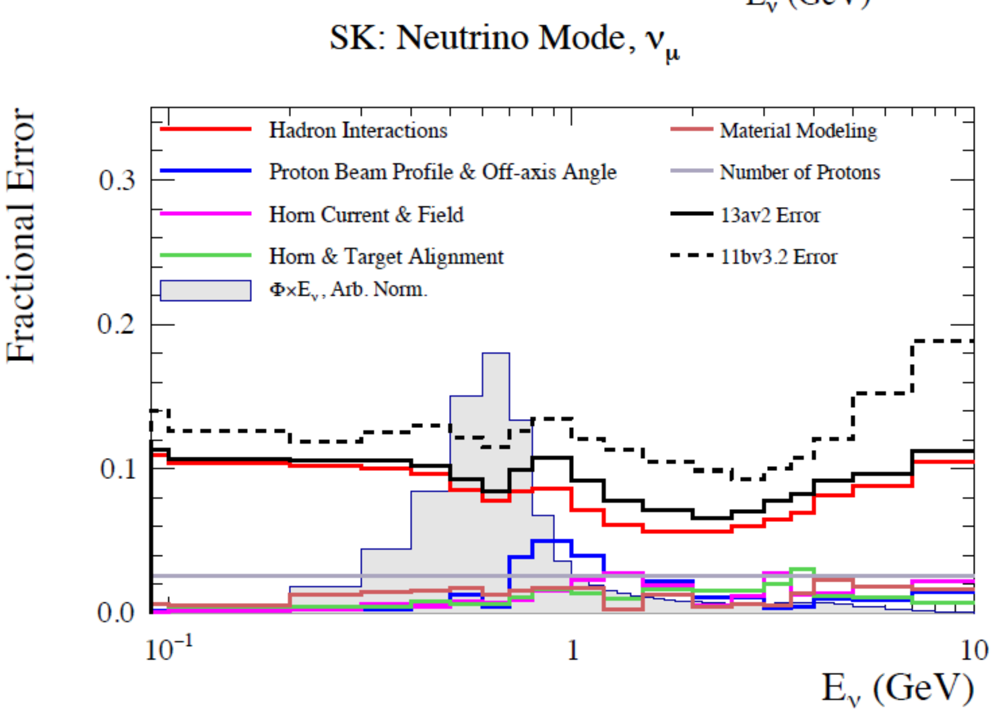
NA61 / SHINE



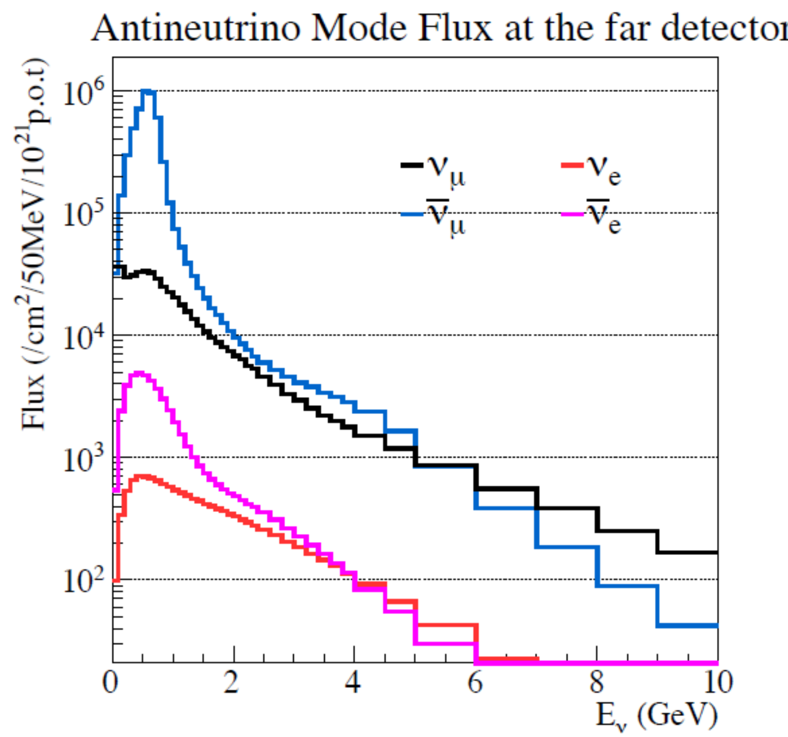
Neutrino Flux Predictions

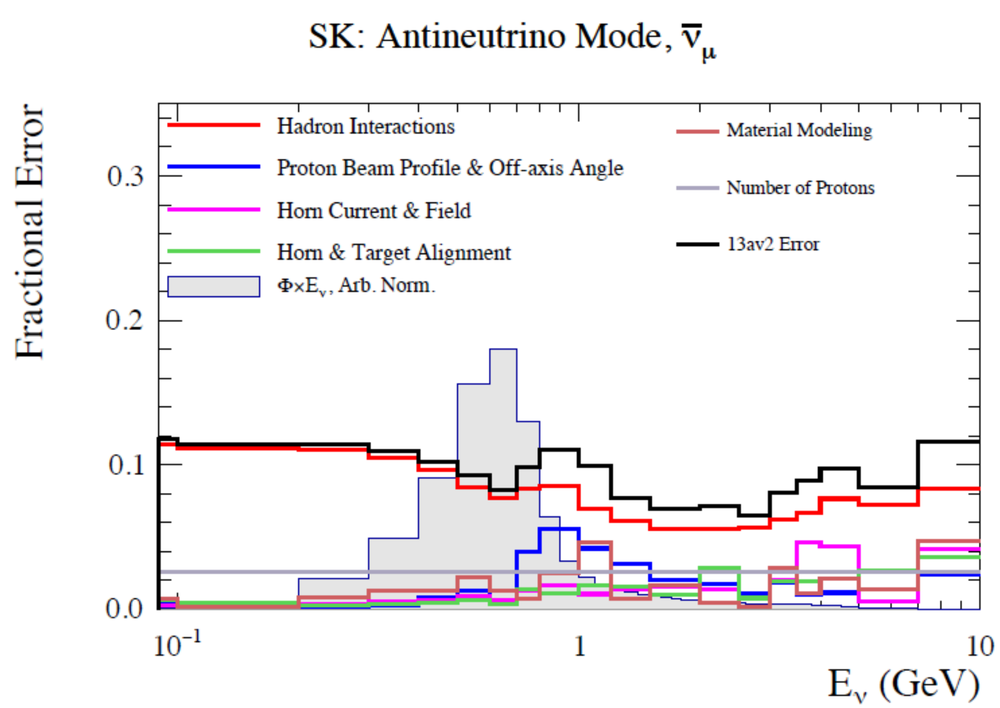
Neutrino-mode
(Forward Horn Current: FHC)





Anti-neutrino-mode
(Reverse Horn Current: RHC)

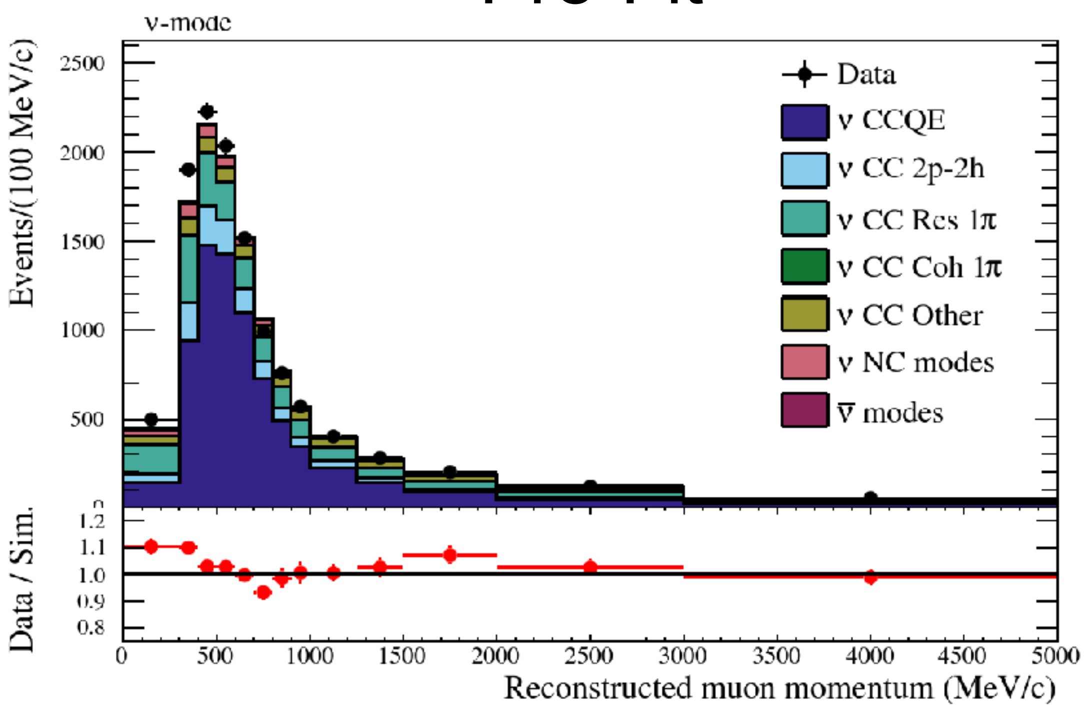




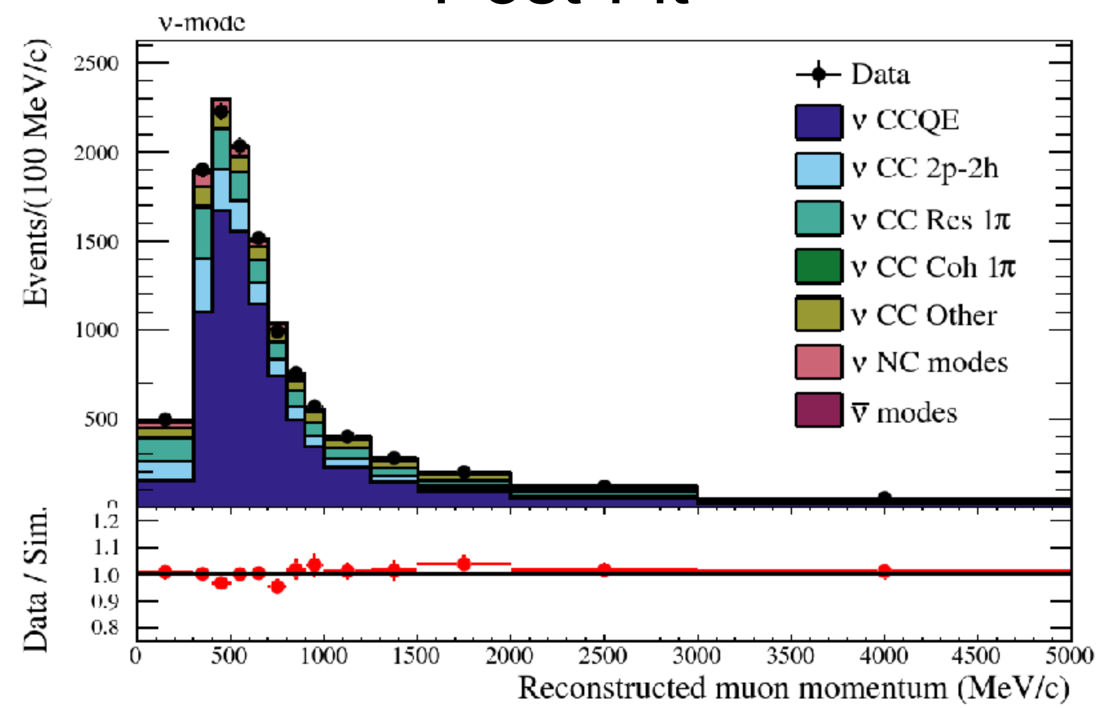
- ~8% absolute error
- Still hadron prod. uncertainty is dominant

Near Detector Fit

Pre-Fit



Post-Fit



- Initial uncertainties on flux and cross section are further constrained by ND280 data
- Significant reduction on SK prediction uncertainties

Uncertainties on SK event rate w/ and w/o ND fit

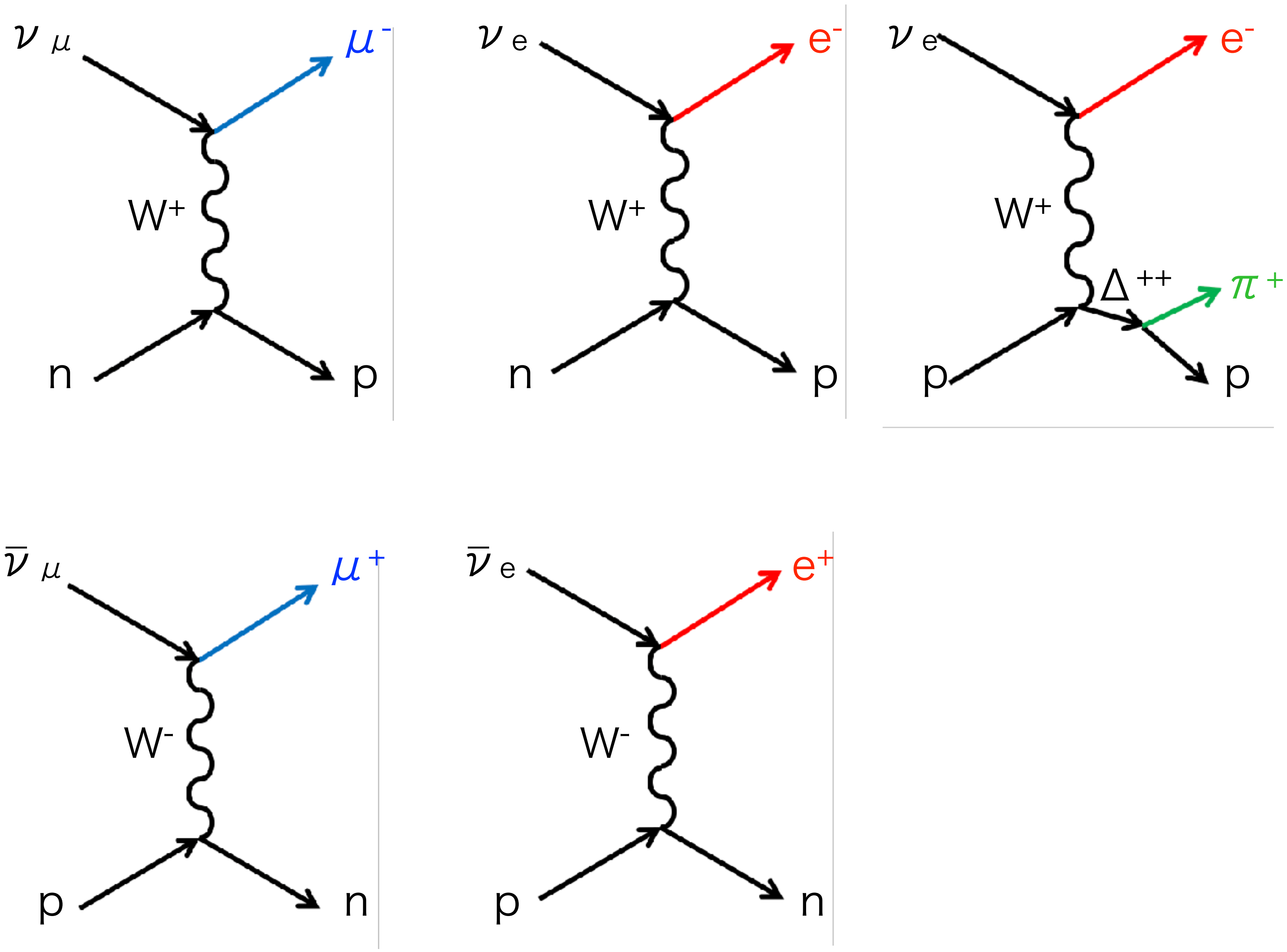
Sample	Pre-fit	Post-fit
ν-mode 1Rμ	14.6%	5.1%
ν̄-mode 1Rμ	12.5%	4.5%
ν -mode 1Re	16.9%	8.8%
ν̄-mode 1Re	14.4%	7.1%

Super-K neutrino data sample

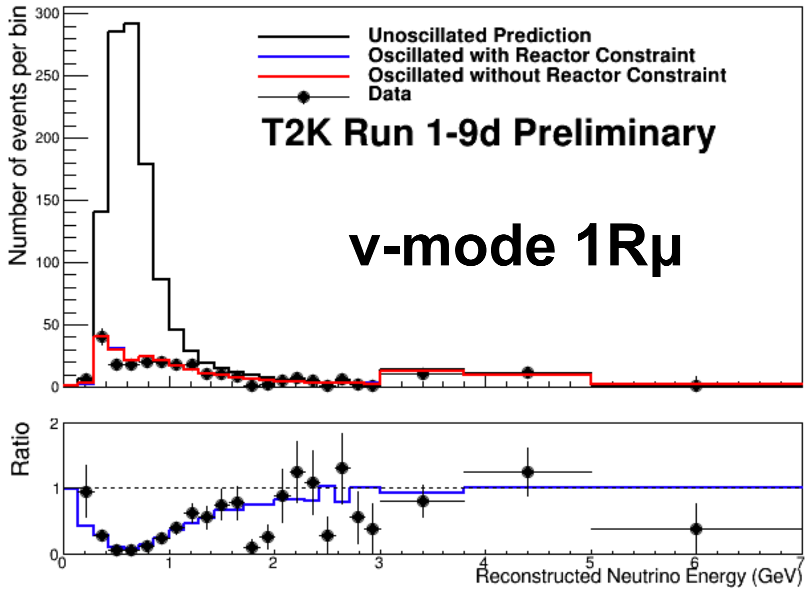
1Ring μ-like | 1Ring e-like | 1Ring CC1π^+

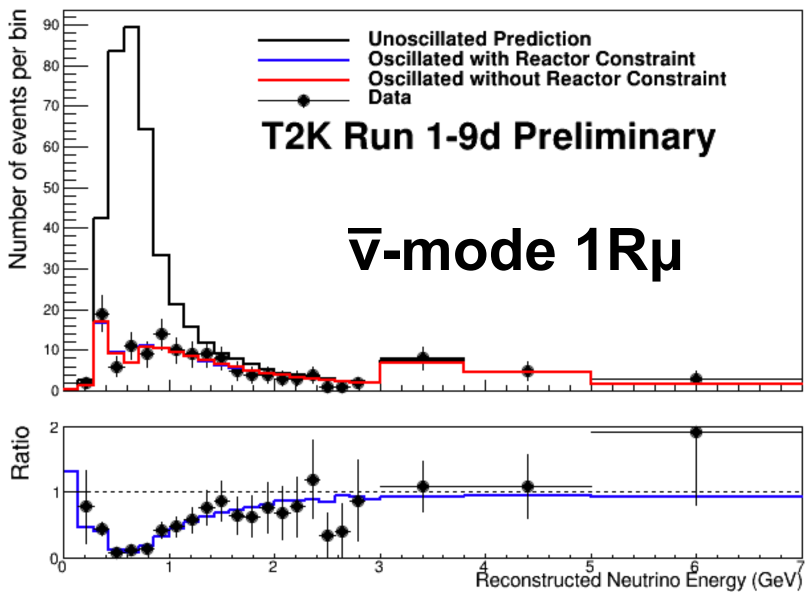
Neutrino-mode (FHC)

Anti-Neutrino-mode (RHC)



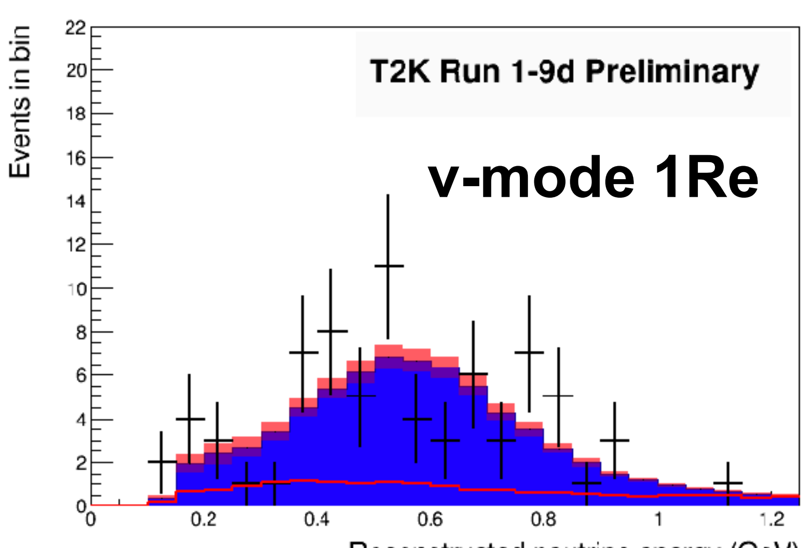
Super-K Data

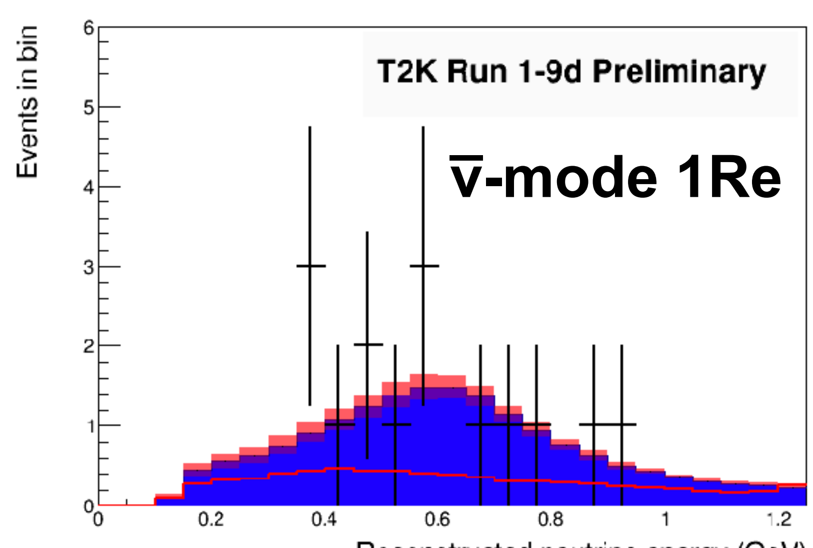


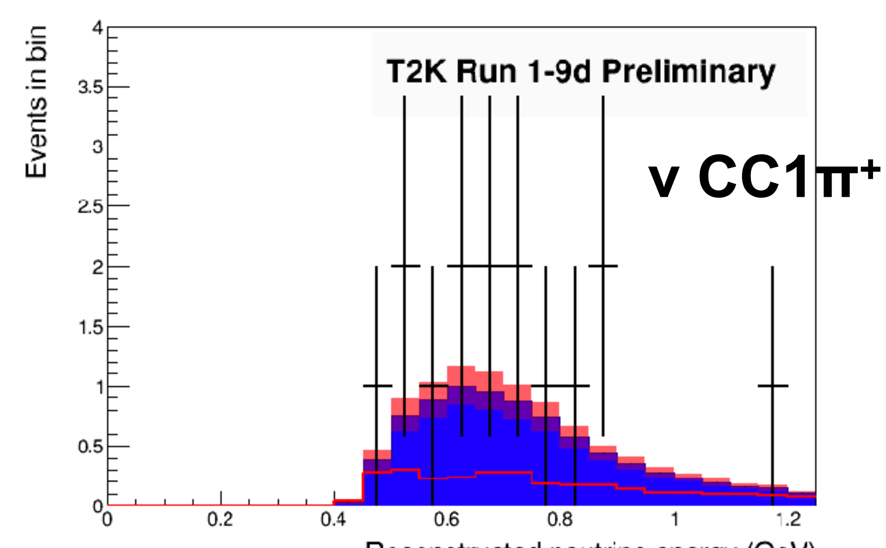


Predictions with: $\sin^2\theta_{13}=0.0212$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.51\times10^{-3}$, NH

Sample	δ=-π/2	δ=0	δ=π/2	δ=π	Obs.
ν-mode 1Rμ	272.4	272.0	272.4	272.8	243
ν̅-mode 1Rμ	139.5	139.2	139.5	139.9	140
ν-mode 1Re	74.4	62.2	50.6	62.7	75
ν̅-mode 1Re	17.1	19.6	21.7	19.3	15
ν CC1π⁺	7.0	6.1	4.9	5.9	15

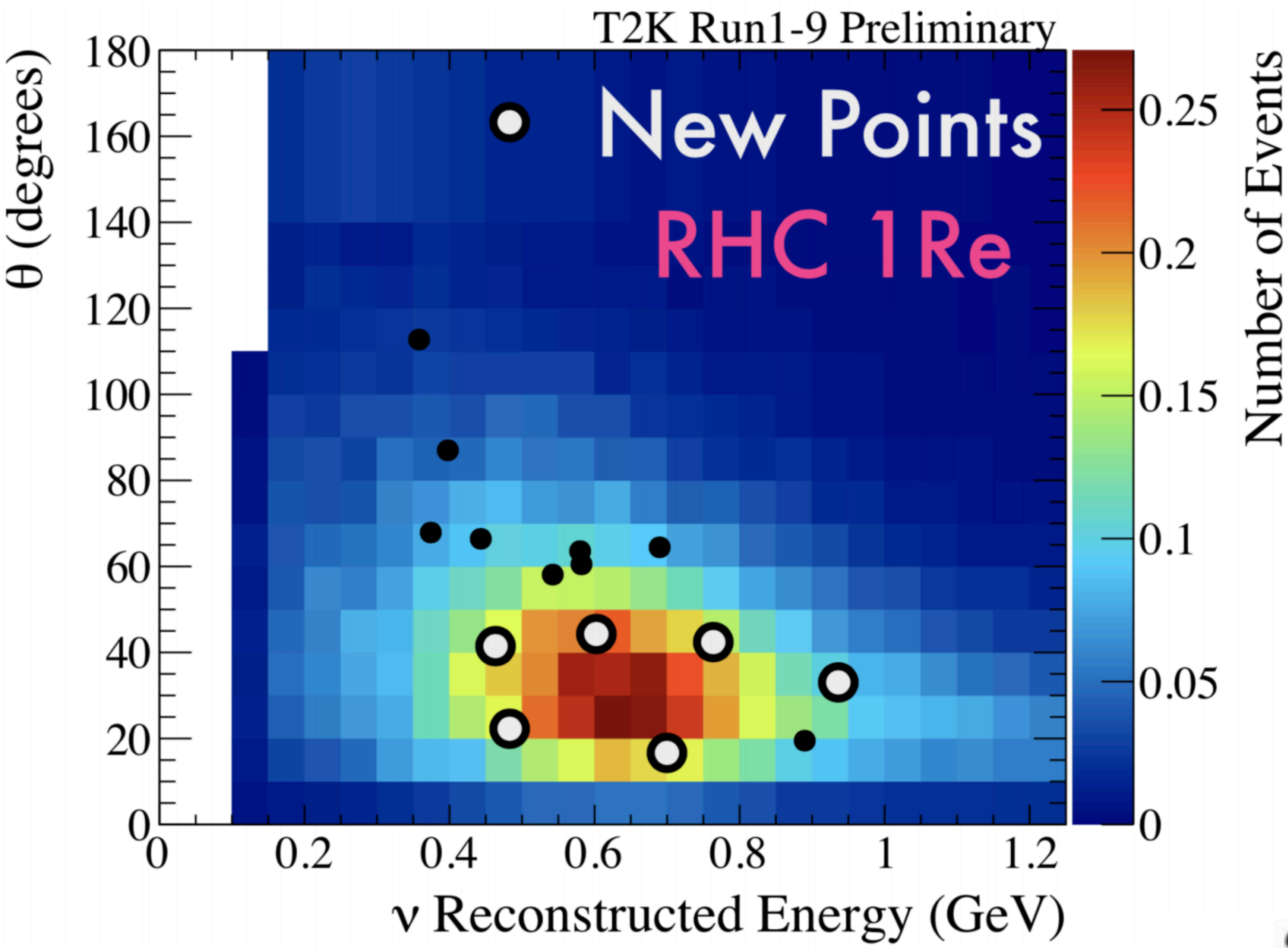




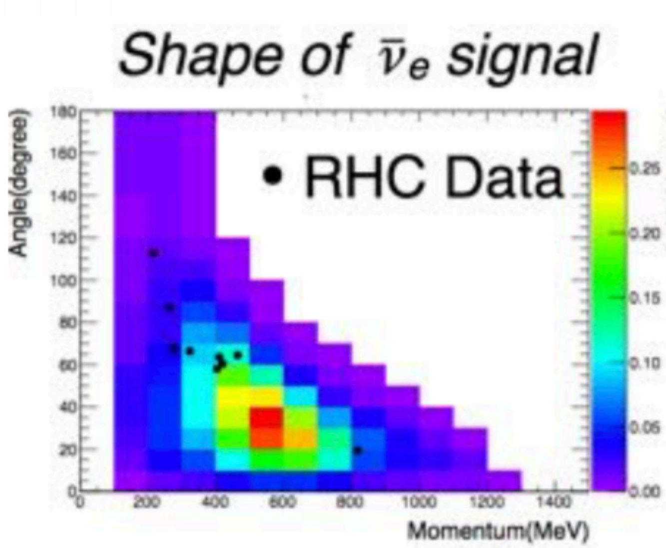


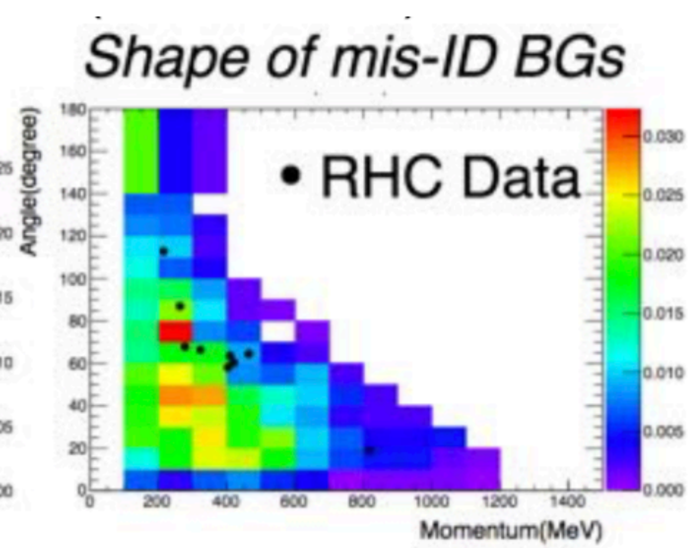
New $\overline{\nu}_e$ appearance data

Full Run1-9 Data (~May 2018)



- Number of $\overline{\nu}_e$ 1Re events:
  9 (prev.) → 15 events
- Distribution of new data points agrees better with $\overline{\nu}_e$ signal
- Convincing that T2K is really observing $\overline{\nu}_e$ appearance



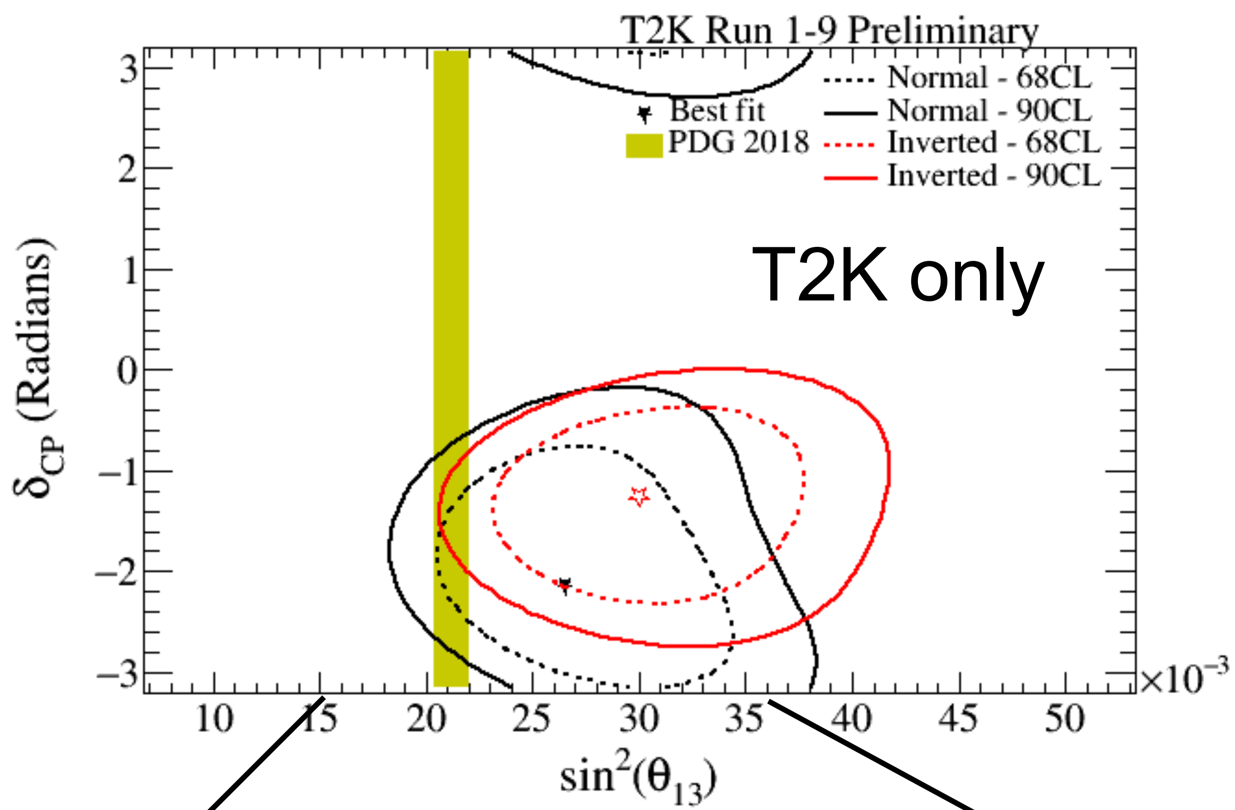


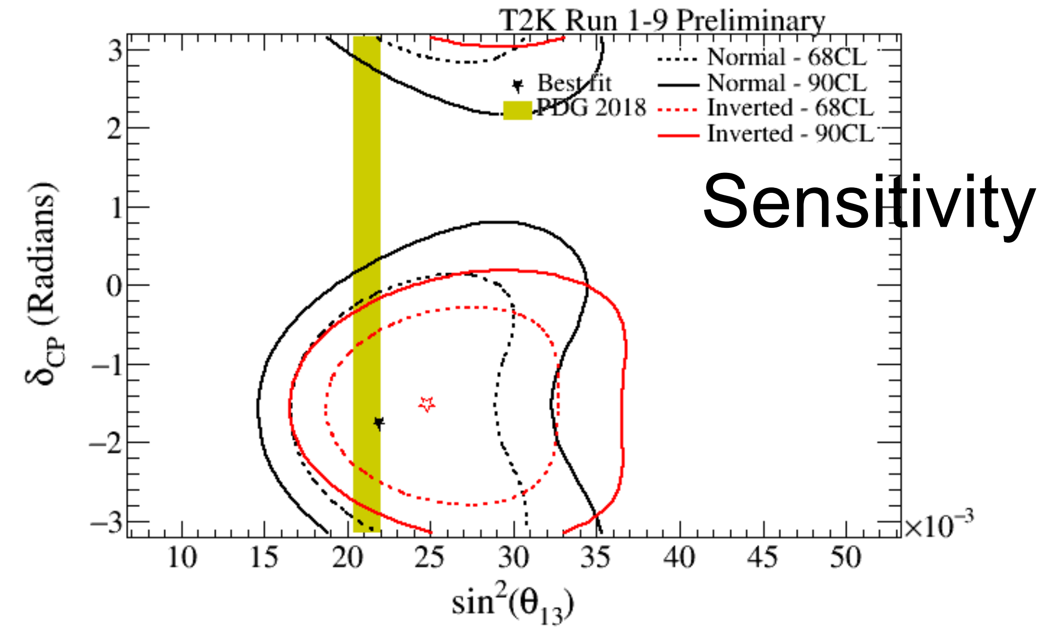
Previous Data (~Dec 2017)

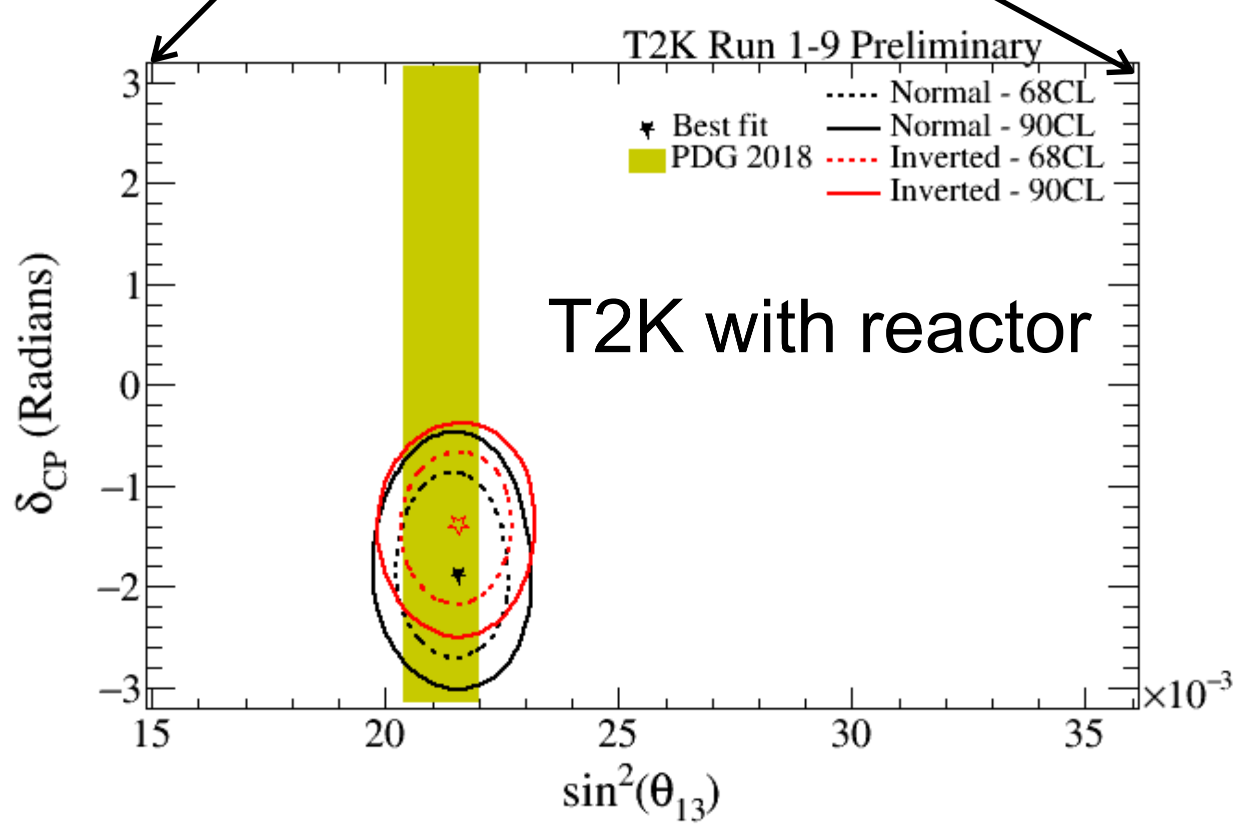
Systematic uncertainties in N_{SK}

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03

Oscillation fit result: θ_{13} vs δ_{CP}



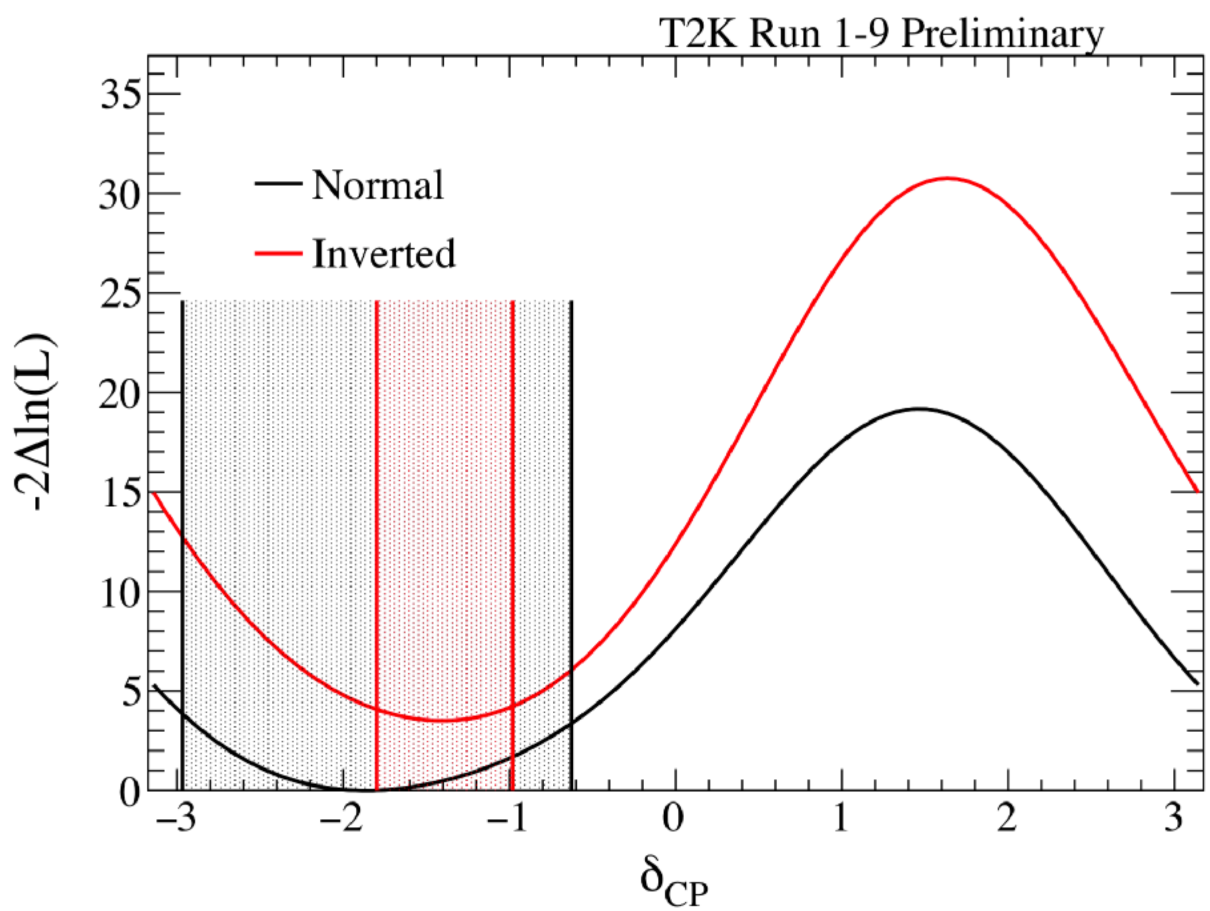




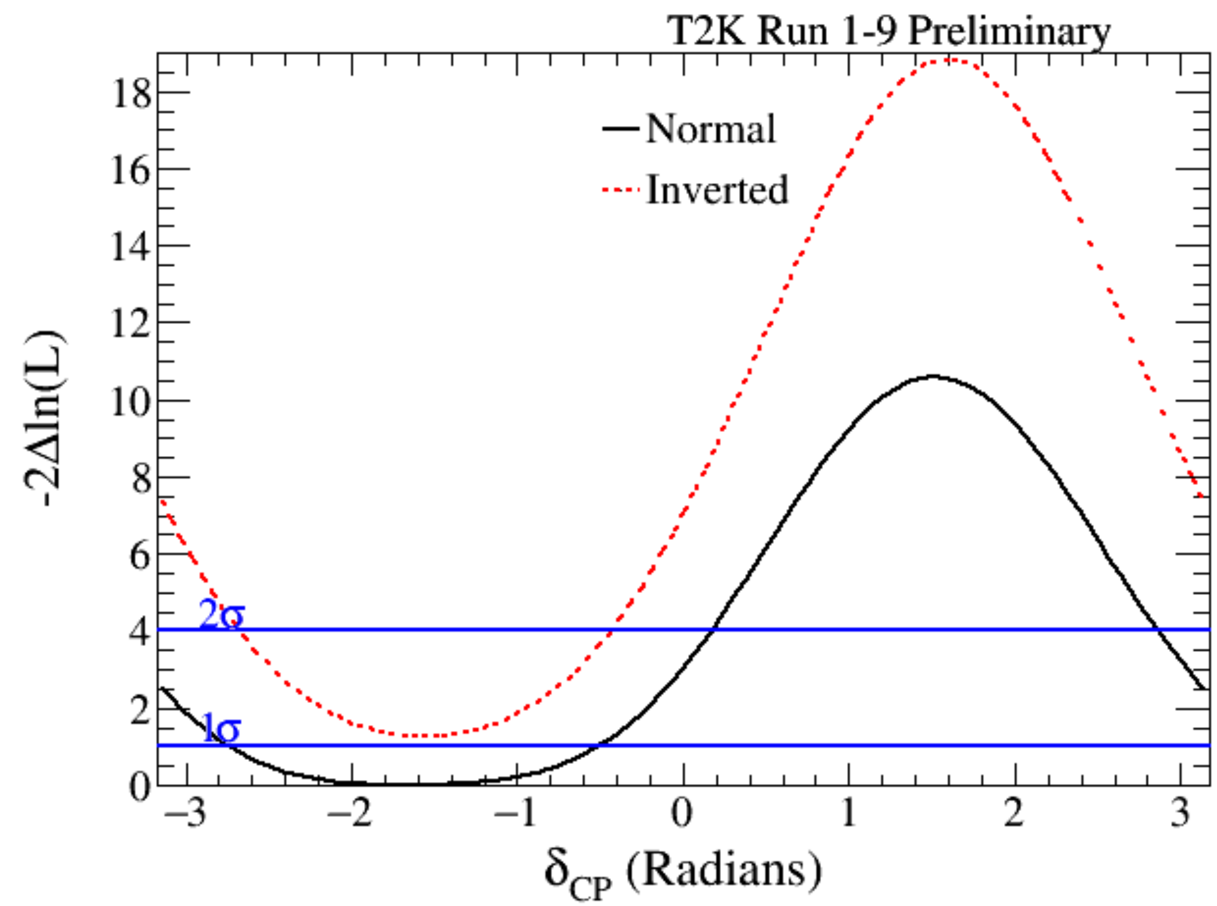
- Update reactor constraint:
  $\sin^2\theta_{13} = 0.0219 \pm 0.0012$
  $\rightarrow$ 0.0212 ± 0.0008 (PDG2018)
  ($\sin^2 2\theta_{13} = 0.0857 \rightarrow 0.0830$)
- Preferred $\delta_{CP} \sim -\pi/2$
- Better fit result than sensitivity

Constraint on δ_{CP}

Data (2σ CL)

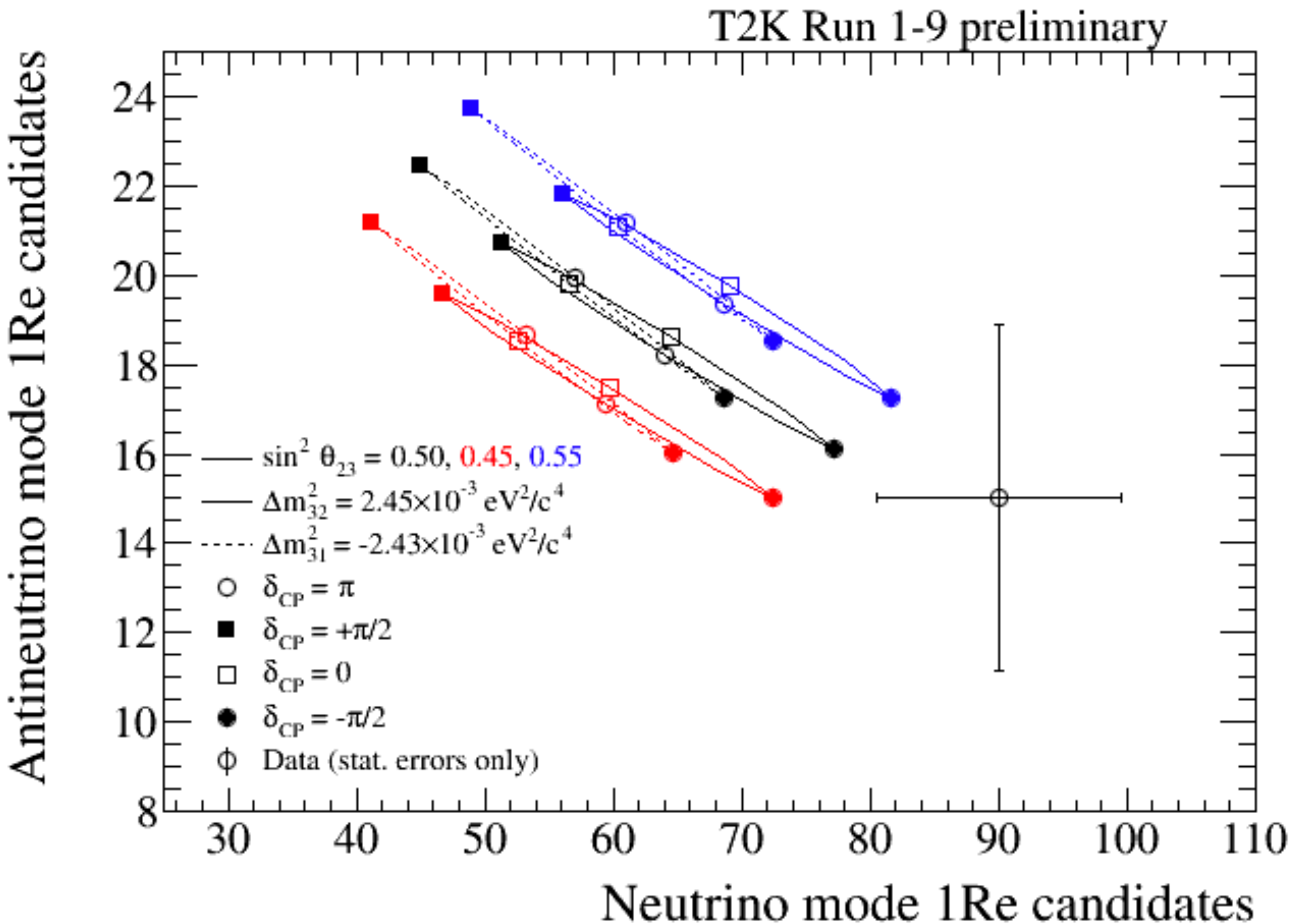


Sensitivity

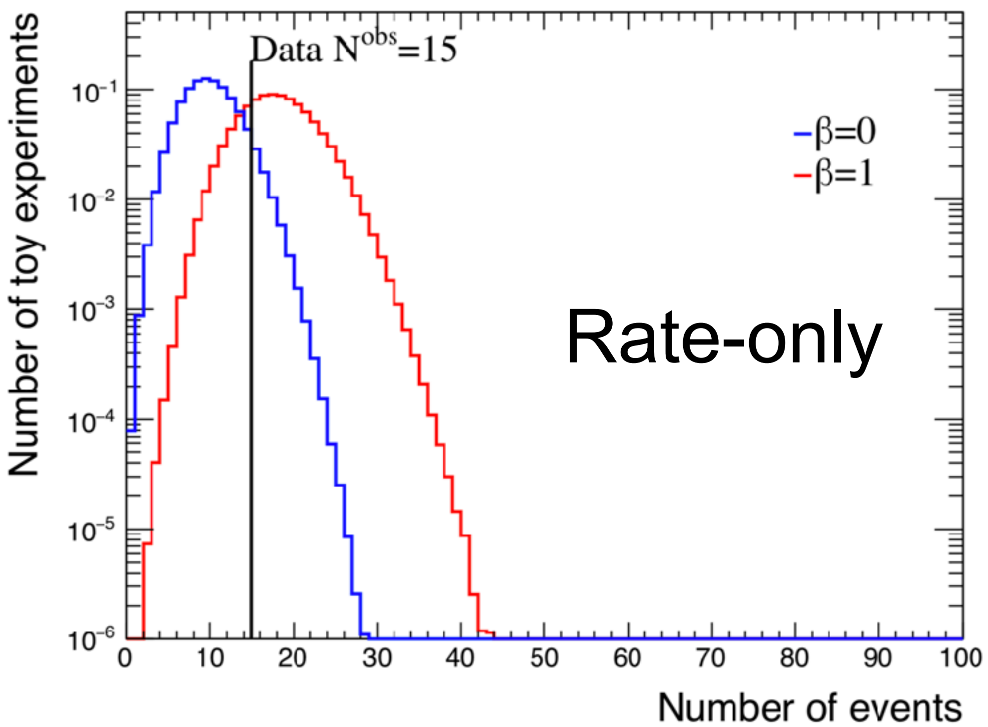


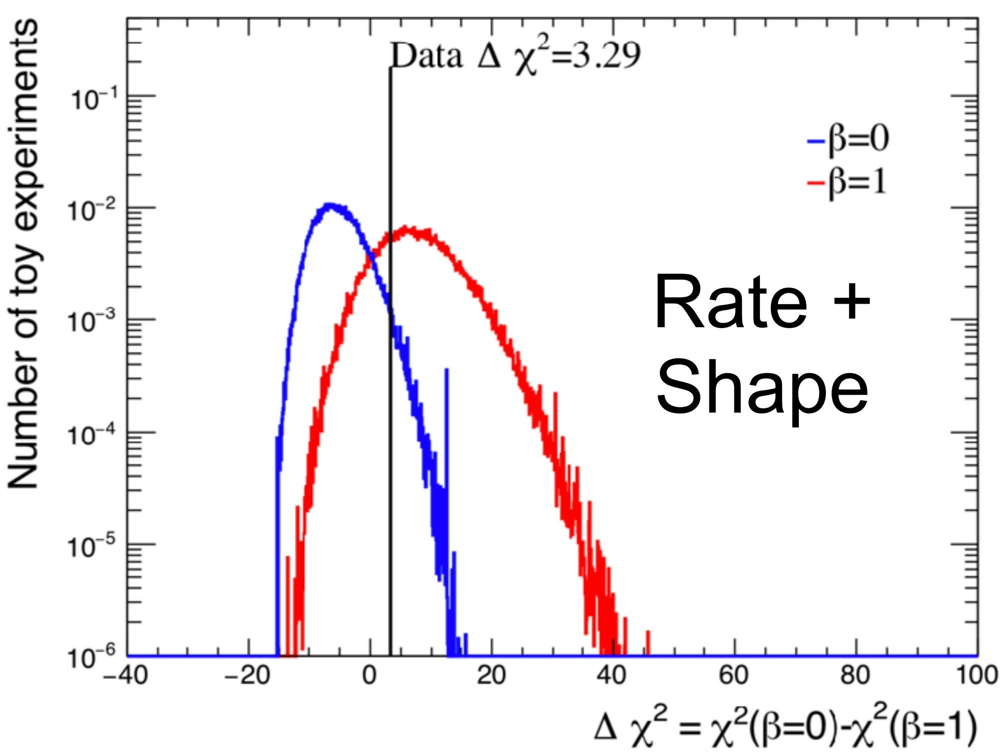
- Best fit: δ_{CP} = -1.885 radian
- 2σ confidence interval NH: [-2.966, -0.628], IH: [-1.799, -0.979]
- CP conservation points (δ_{CP} =0, π) are both outside of 2σ CL

ν_e / $\overline{\nu}_e$ events and δ_{CP}/MO/θ_{23} exp'd



$\bar{\nu}_e$ Appearance Result (New)





- Test with two analysis methods: "Rate-only" and "Rate + Shape"
- Introduce scaled $\bar{\nu}_\mu$->$\bar{\nu}_e$ probability:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

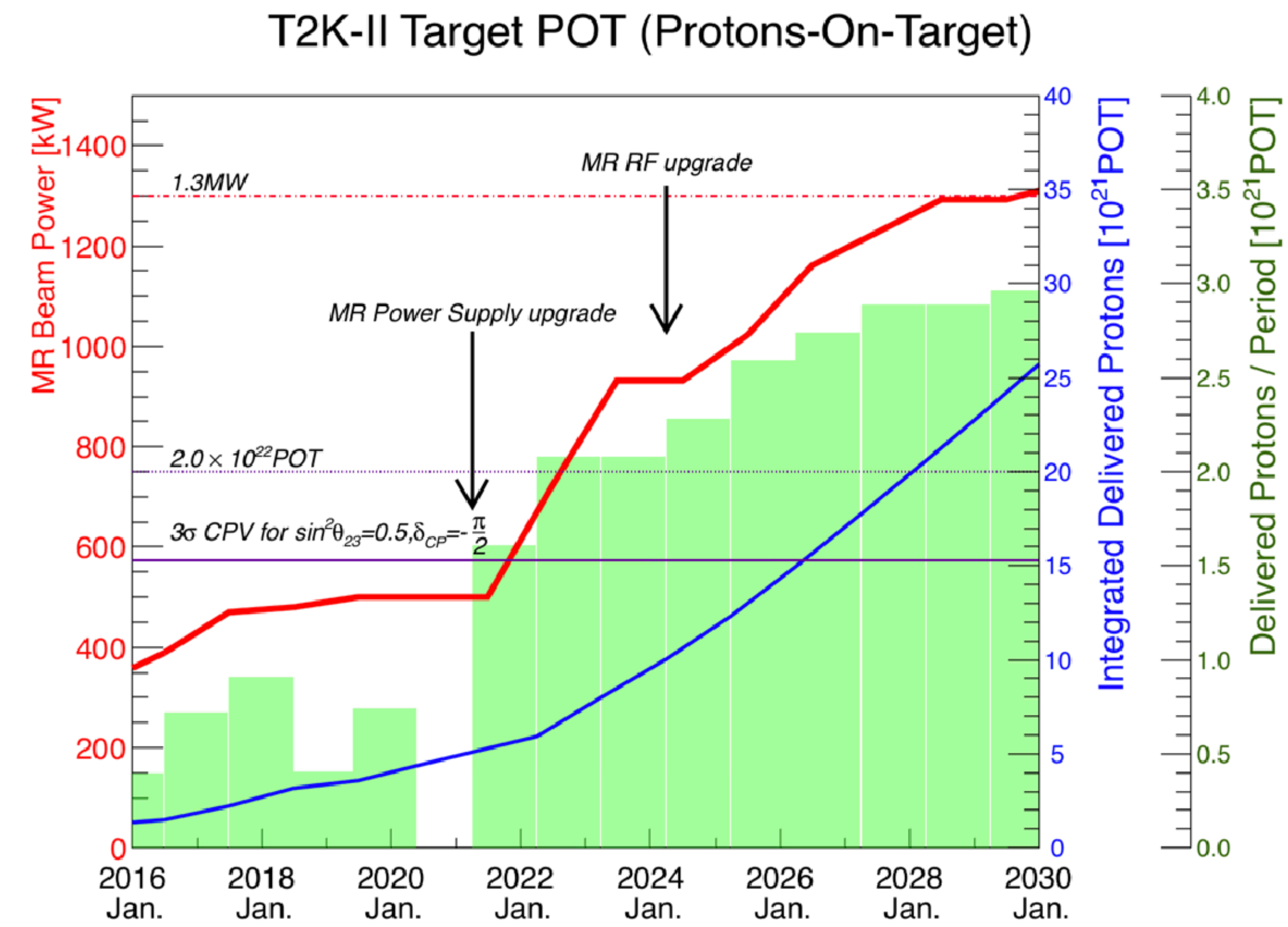
(β: 0=no $\bar{\nu}_e$ appearance, 1=PMNS)

- Rate+shape result excludes no appearance hypothesis by 2σ level though still inconclusive

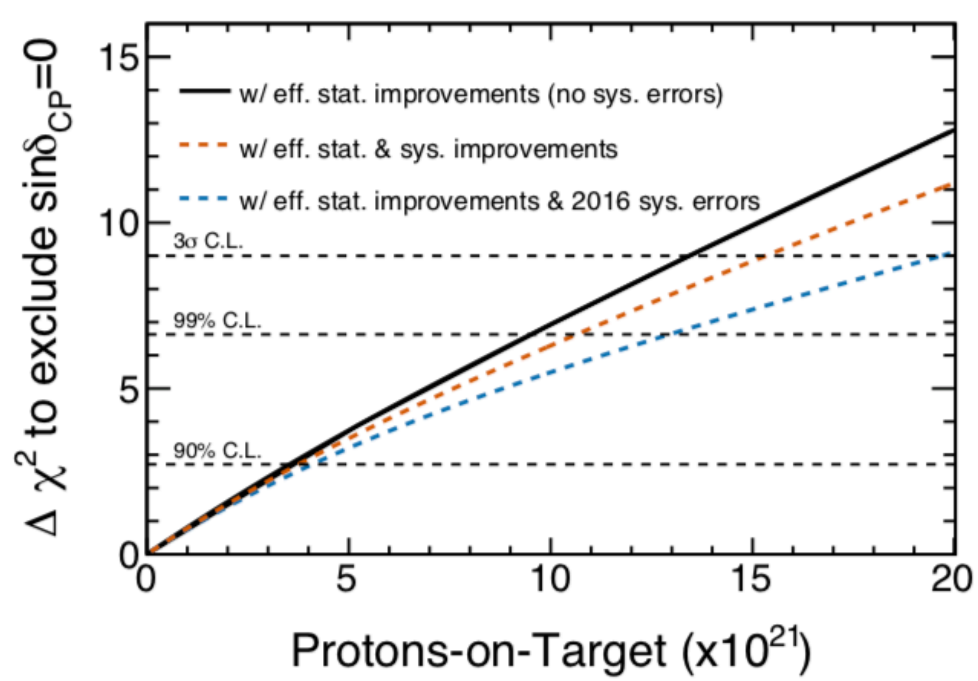
	Rate-only	Rate+Shape
No app. (β=0)	0.0686 (1.82σ)	0.0244 (2.25σ)
PMNS (β=1)	0.246 (1.16σ)	0.261(1.12σ)

Future Prospects

Beam Plan and Expected Sensitivity

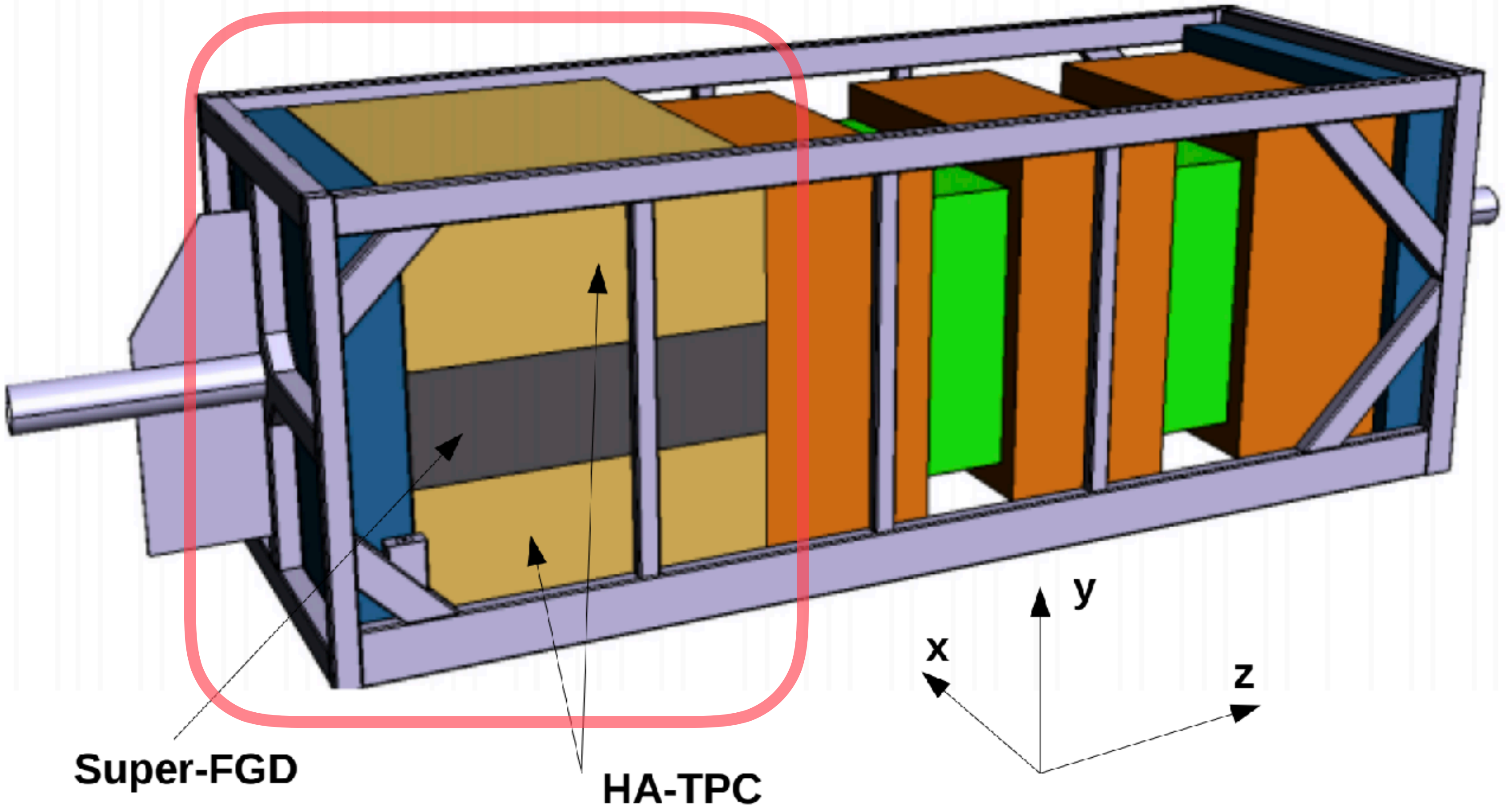


- MR PS upgrade in 2020
- Upgrade to 1.3 MW beam by
  - repetition rate (2.48 → 1.16 sec)
  - increase proton / pulse (+28%)
- Associated improvement in neutrino beam line
- 20 x 10^{21} POT by 2028



- Reducing systematic error is necessary
  - ~9% (current) → 4% (goal)

Near Detector Upgrade



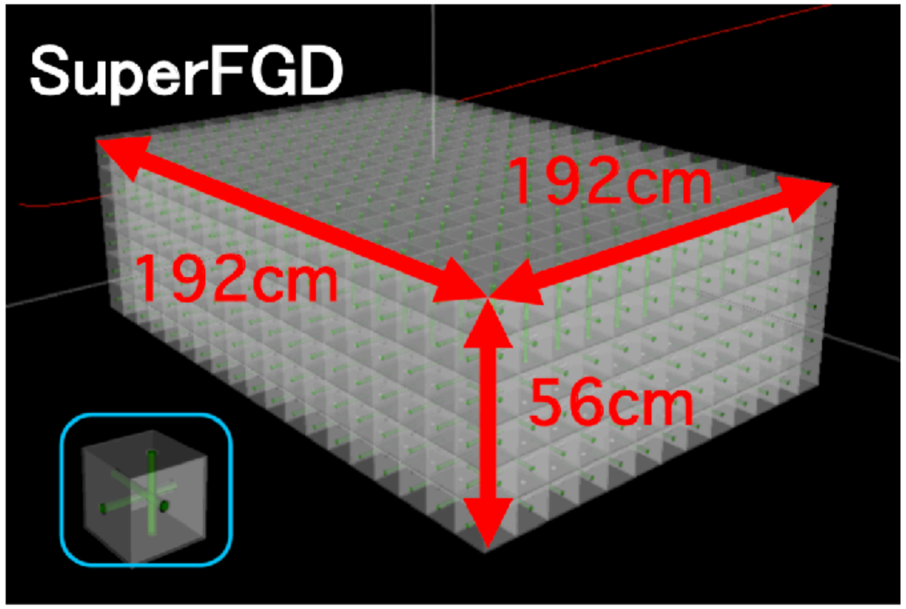
- Upgrade for 4% systematic error and 3σ exclusion of CP conservation

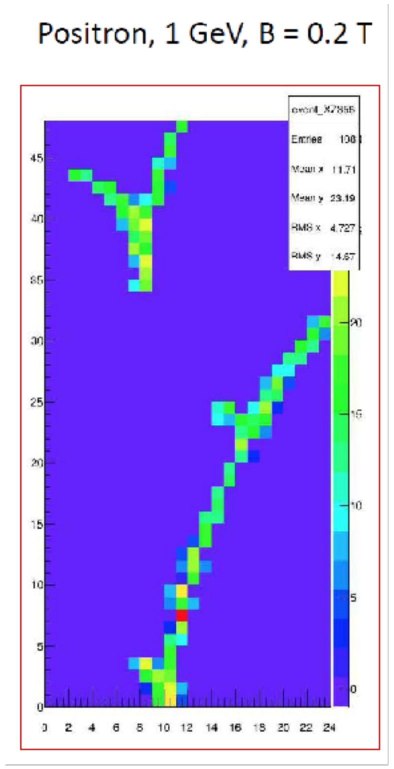
- Increase acceptance of large angle scattering and low energy particles

- Highly granular scintillator: detector (Super-FDG)

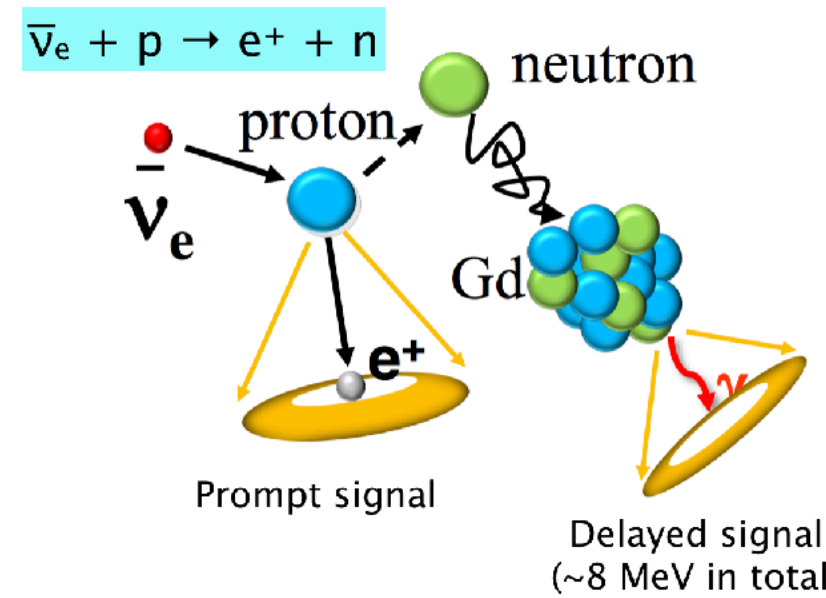
- High angle TPC (x2) + TOF

- TDR under review





Super-K refurbishment and SK-Gd

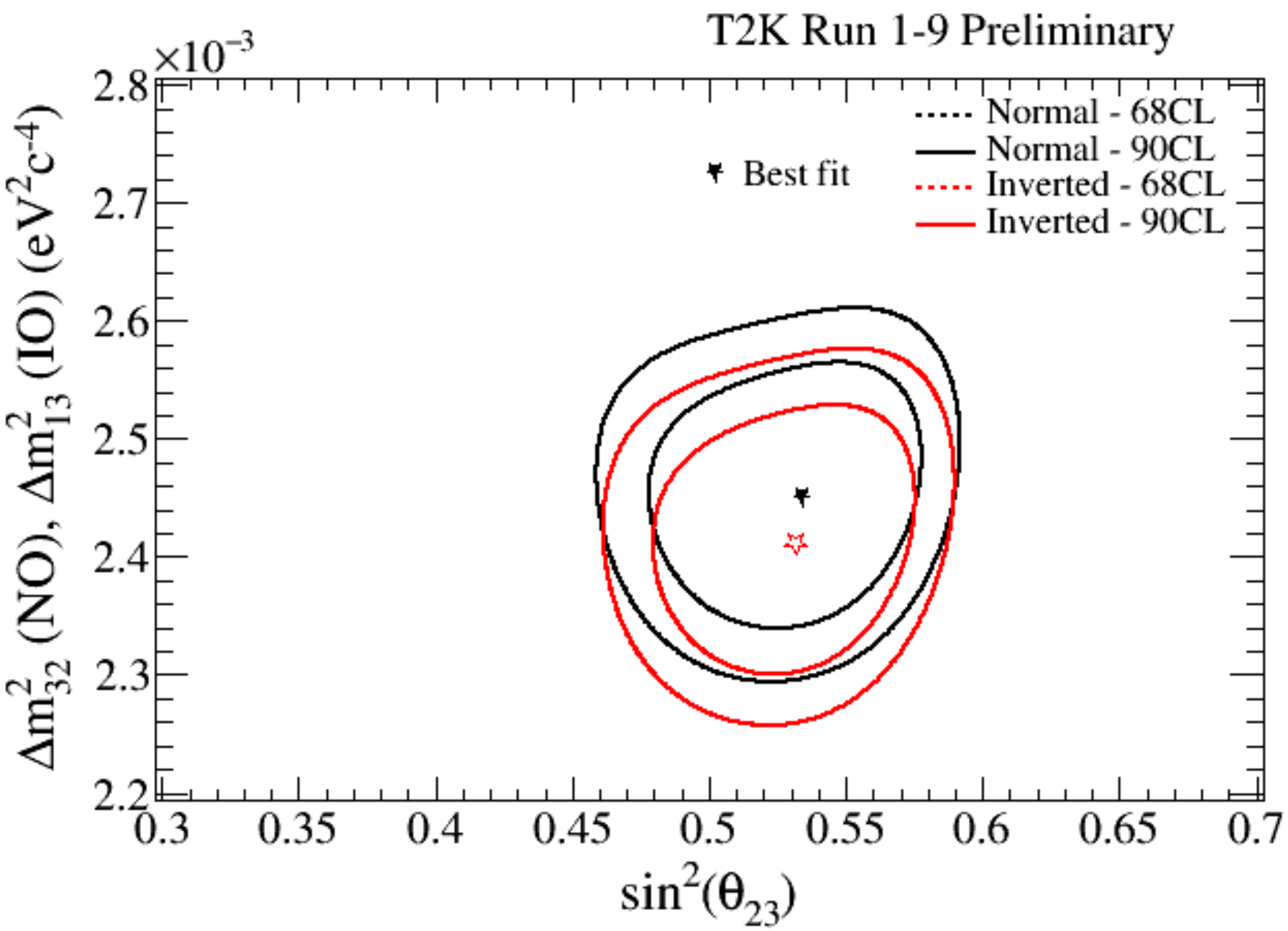


- Refurbishment work is on-going from summer 2018 for SK-Gd
- Water filling almost completed and will resume from next month
- Gd loading schedule with consideration of J-PARC schedule
- Start from 0.01% Gd
  → 0.1% Gd

Summary

- T2K collaboration has released updated oscillation results with increased anti-neutrino data up to May 2018
- CP conservation values (δ_{CP} =0, π) are not within 2σ CL intervals
  - Strong motivation for further beam data taking for 3σ exclusion
- New result of $\overline{\nu}_e$ appearance with 2σ CL level
- Many upgrade plans (Beam, Near detector, SK-Gd) are on-going

Atmospheric parameter: Δm^2_{32} and θ_{23}



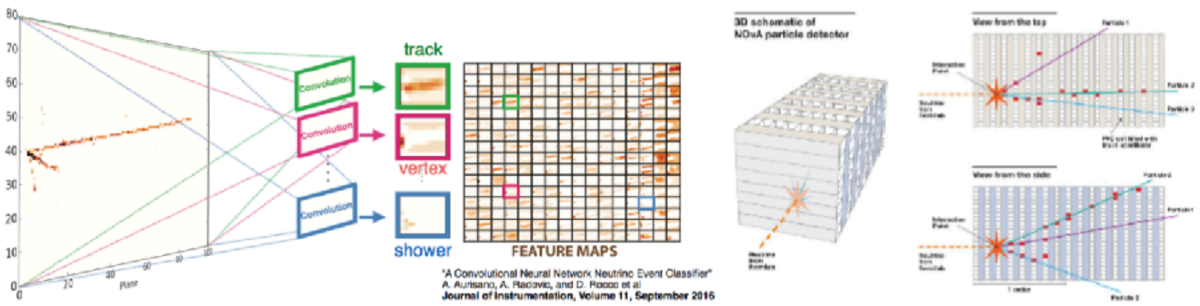
- With reactor constraint
- Best fit lies in 2nd octant ($\sin^2\theta_{23}$=0.532)
- Consistent with maximal mixing

Best-fit and 1σ conf. interval

	NH	IH
$\lvert\Delta m^2_{32}\rvert$ (eV^2)	2.452 [2.382, 2.523]	2.432 [2.361, 2.501]
$\sin^2\theta_{23}$	0.532 [0.495, 0.562]	0.532 [0.497, 0.561]

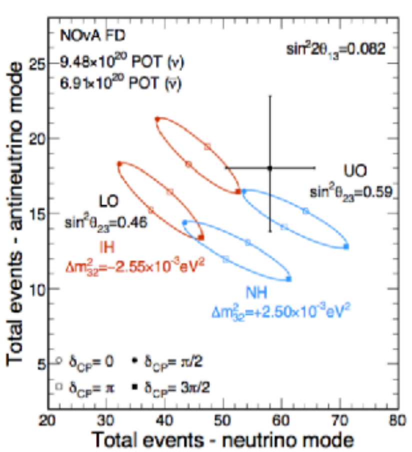
NOvA Experiment

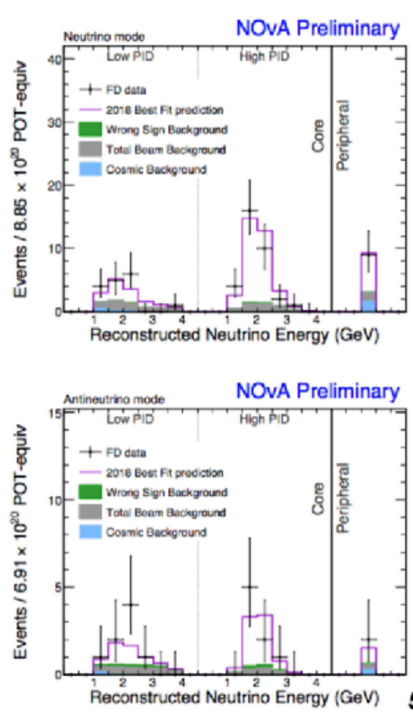
- US long-baseline neutrino oscillation experiment
  - Fermilab neutrino beam to Sudan mine ⇒ 810 km baseline length
  - Off-axis neutrino beam
  - > 700 kW beam achieved
  - Functionally identical near/far detectors
    - Segmented liquid scintillator bars
    - 14 kton total mass (65% active mass)
  - Data analysis
    - Event classification with Convolutional Neural Network



New Results from NOvA

- NOvA Updated results for Neutrino2018 (June 4, 2018) M. Sanchez @ Neutrino2018
  - First antineutrino results with 6.9×10^{20} POT (in addition to neutrino-mode 8.85×10^{20} POT data)
    - 18 antineutrino events ⇔ 5.3 events BG
    - 58 neutrino events ⇔ 15 events BG
  - "> 4σ evidence of $\bar{\nu}_e$ appearance"





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    - 18 antineutrino events ⇔ 5.3 events BG
    - 58 neutrino events ⇔ 15 events BG
  - Prefer non-maximal θ_{23} with 1.8σ and exclude lower octant at similar level
  - Prefer NH by 1.8σ and exclude π/2 in IH at >3σ
- Competition is severe, therefore stable and powerful beam delivery to T2K is the key