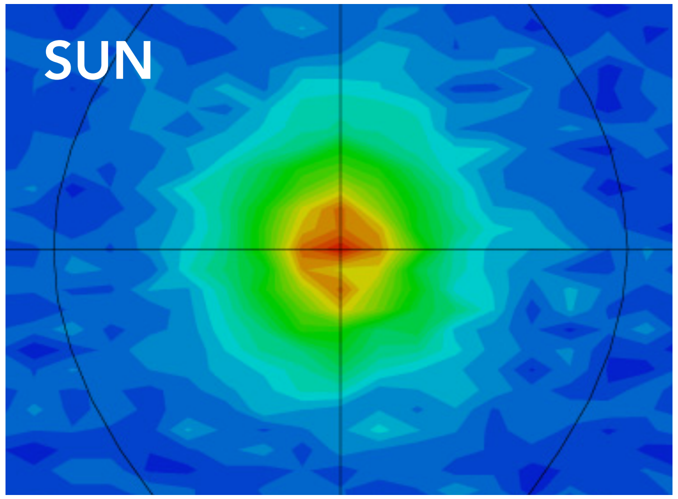
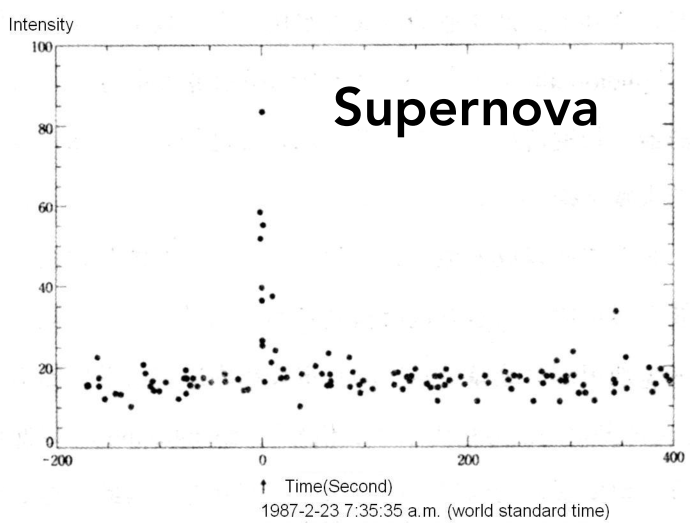
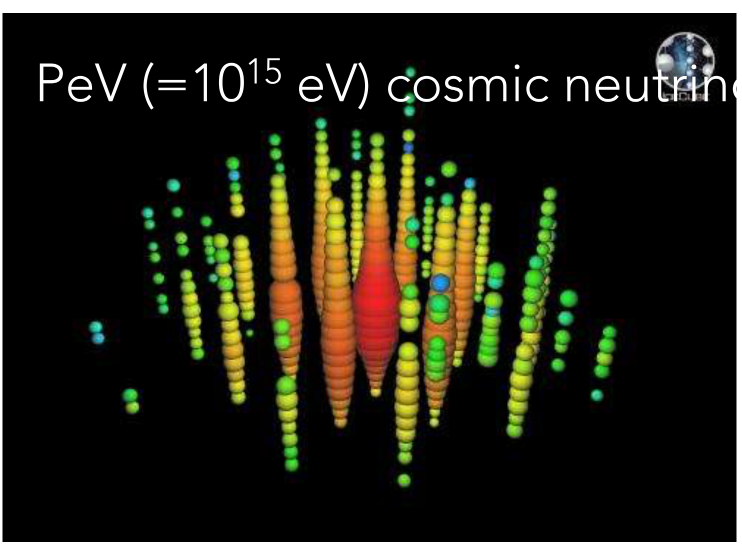
H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF)

RECENT EXPERIMENTAL RESULTS IN NEUTRINO PHYSICS

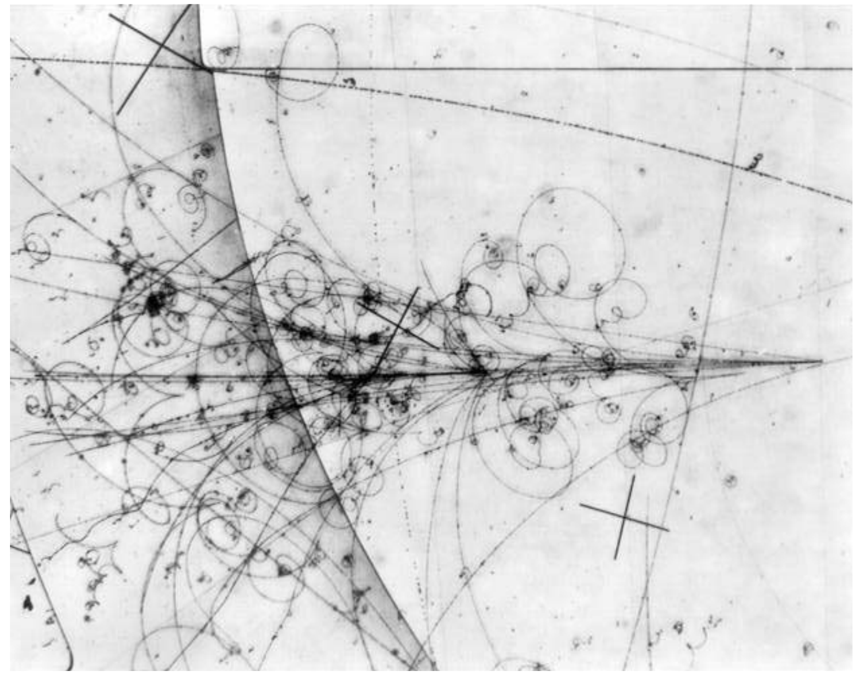
slac summer institute 2017



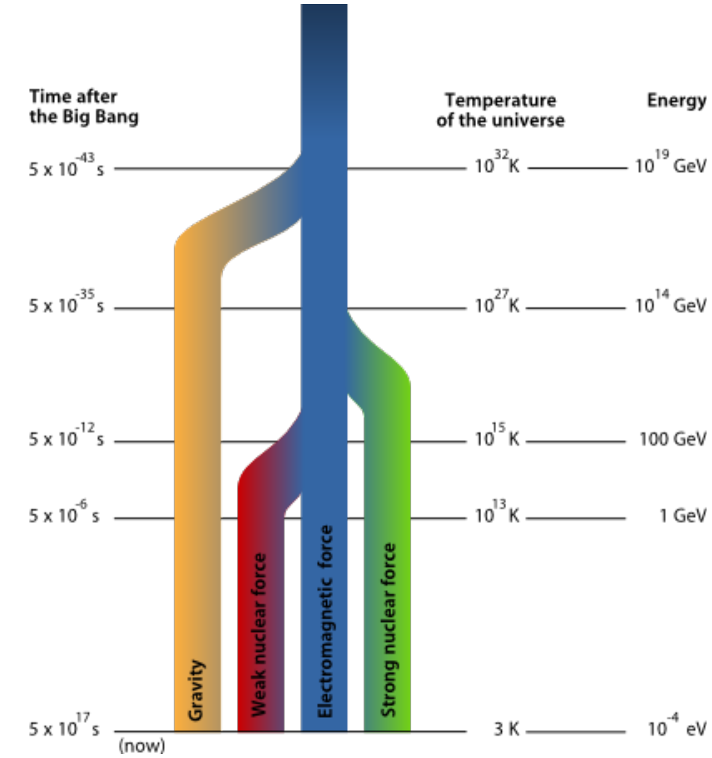




neutrinos as messengers from the cosmos

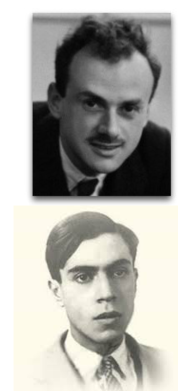


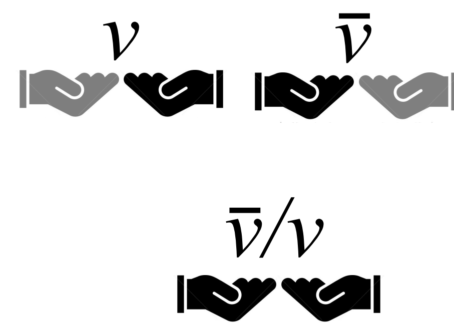
neutrinos as probes of the structure & dynamics of matter

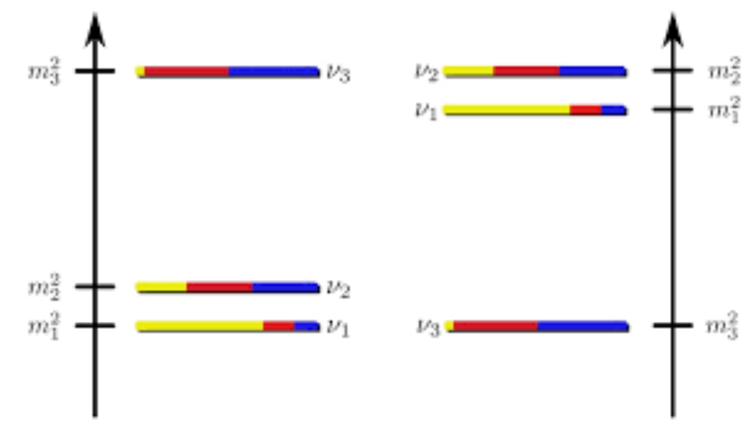


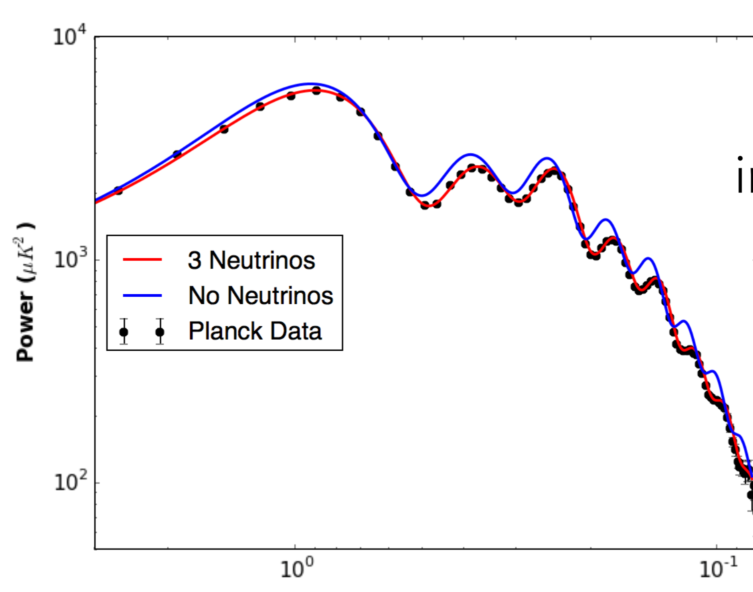
fundamental neutrinos properties and their relation to other particles

ν

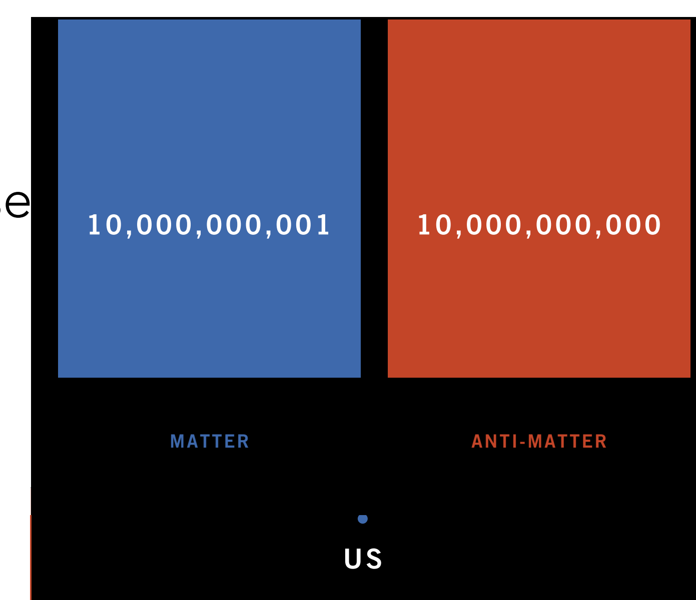








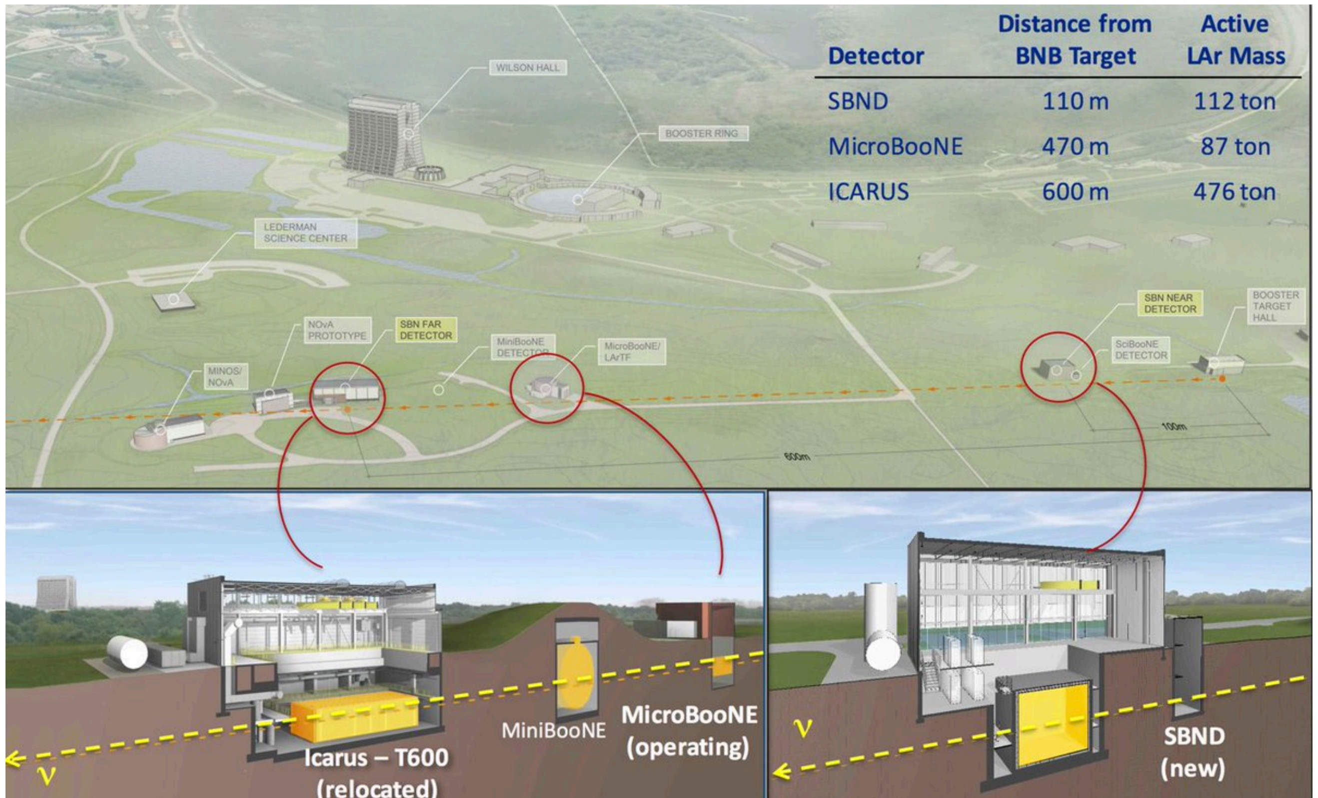
neutrinos and their impact on the universe

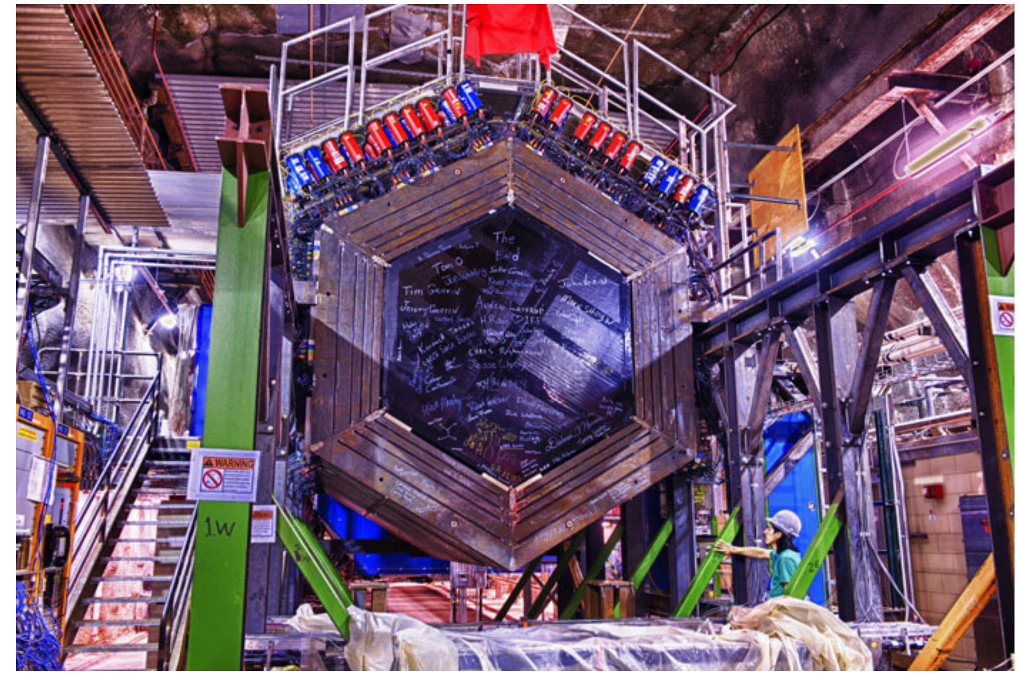


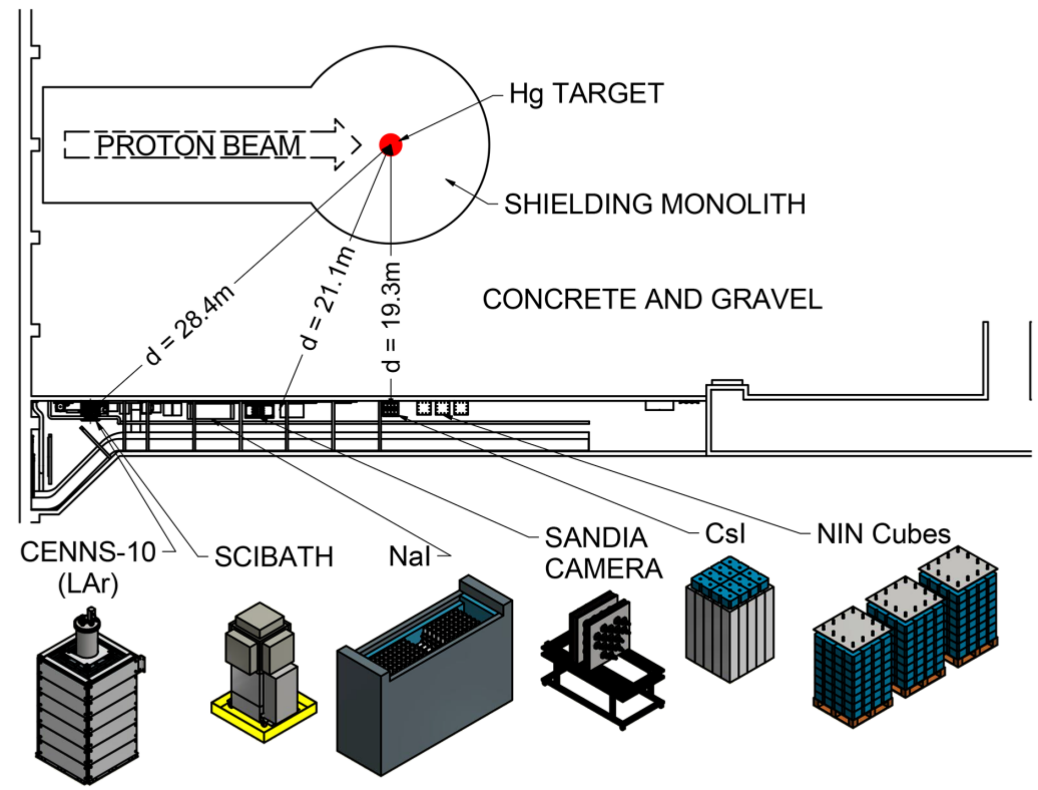
EXCUSES

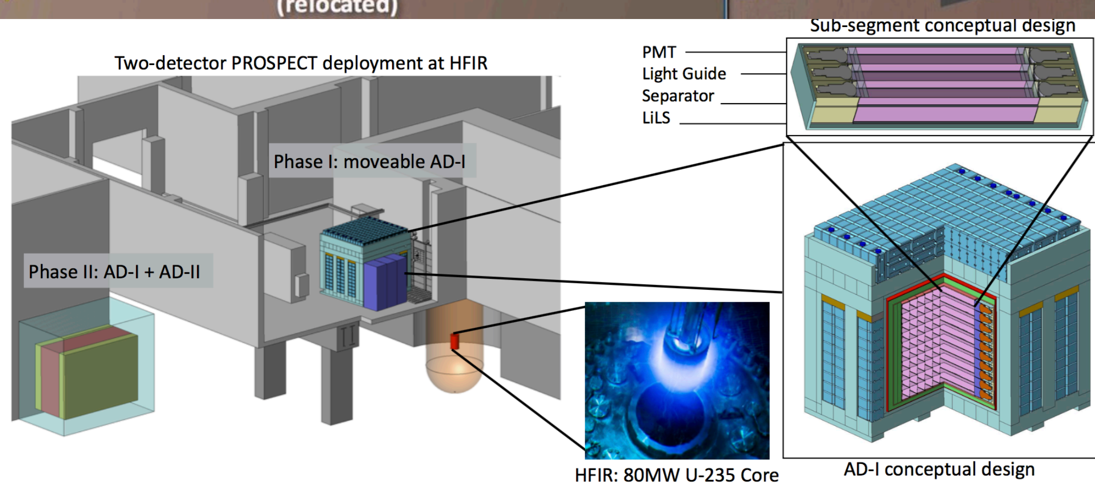
- I am asked to cover "Recent neutrino experimental results"
- I will focus on recent developments in our understanding of fundamental neutrino properties using beams and sources
  - focus on latest results
  - Cosmology (CMB, LSS) covered in detail throughout institute
  - Neutrinoless double beta decay covered by Lisa Kaufman
  - Ice Cube results in the next talk by Spencer Klein
  - A more complete presentation of a future program (DUNE) will be given Wednesday by Ed Blucher
- Still there are many things not covered.
  - omitted areas are exciting and dynamic fields that I cannot do justice to . . . please look elsewhere.
  - my apologies . .. .

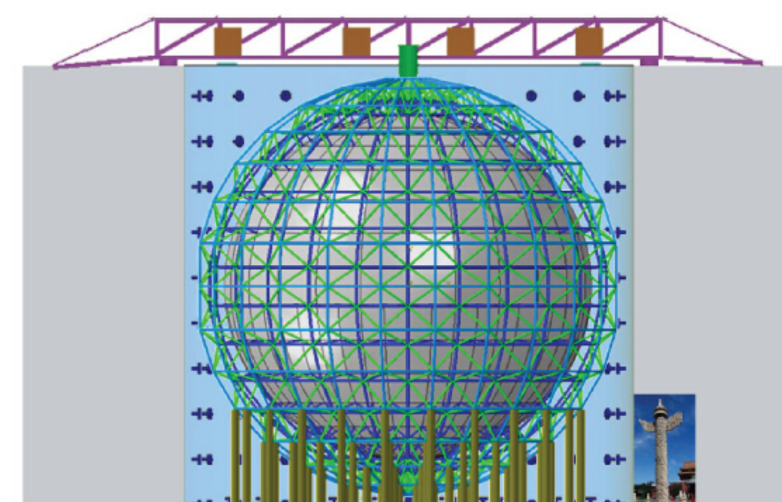
APOLOGIES:


Detector
Distance from BNB Target
Active LAr Mass
SBND
110 m
112 ton
MicroBooNE
470 m
87 ton
ICARUS
600 m
476 ton
WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MINOS/ NOvA
SBN NEAR DETECTOR
BOOSTER TARGET HALL
SciBooNE DETECTOR
MicroBooNE/ LArTF
MiniBooNE
MicroBooNE (operating)
Icarus – T600 (relocated)
SBND (new)
ν




Hg TARGET
PROTON BEAM
SHIELDING MONOLITH
CONCRETE AND GRAVEL
d = 28.4m
d = 21.1m
d = 19.3m
CENNS-10 (LAr)
SCIBATH
NaI
SANDIA CAMERA
CsI
NIN Cubes

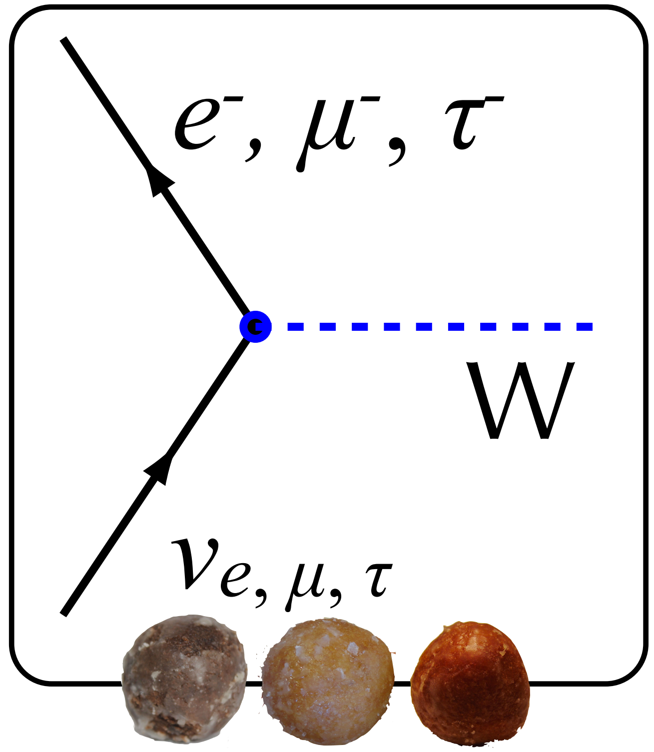

Two-detector PROSPECT deployment at HFIR
Sub-segment conceptual design
PMT
Light Guide
Separator
LiLS
Phase I: moveable AD-I
Phase II: AD-I + AD-II
HFIR: 80MW U-235 Core
AD-I conceptual design



NEUTRINOS

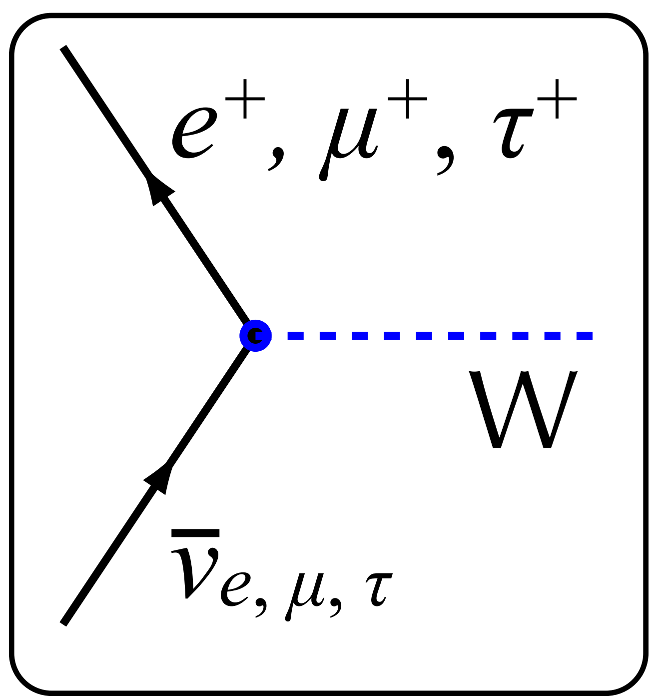
neutrinos and leptons

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-



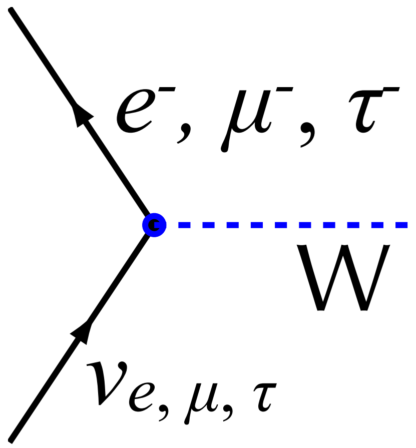
anti-neutrinos and anti-leptons

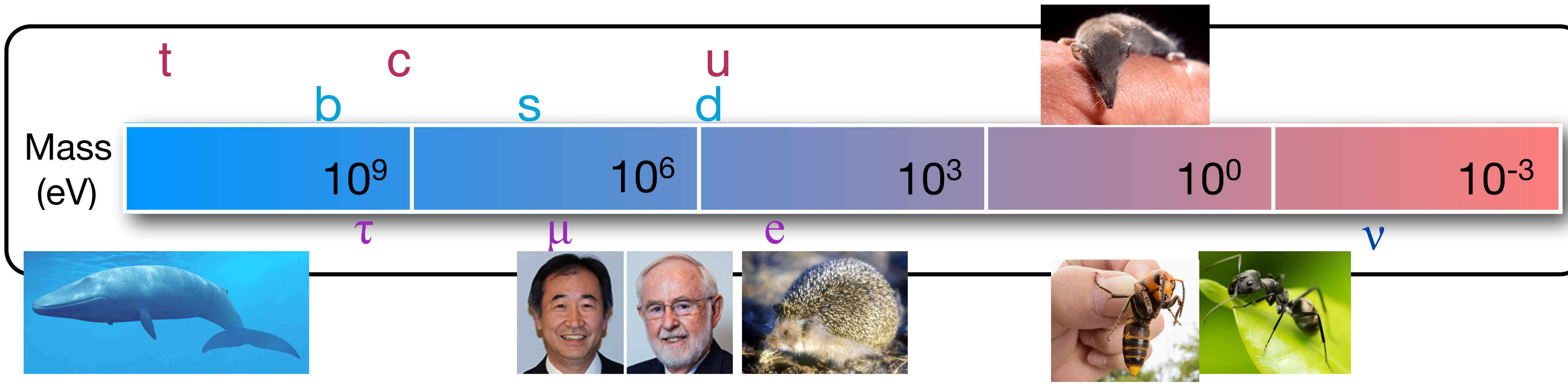
$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
e^+	μ^+	τ^+



- Neutrino "flavor"
  - neutrinos are created along with their corresponding charged anti-lepton
  - neutrinos produce its corresponding charged lepton upon interacting
- "Chiral" nature of weak interaction:
  - weak interaction only engages with "half" of a spin 1/2 fermion
  - "left-handed" neutrinos and "right-handed" antineutrinos interact via the weak interaction

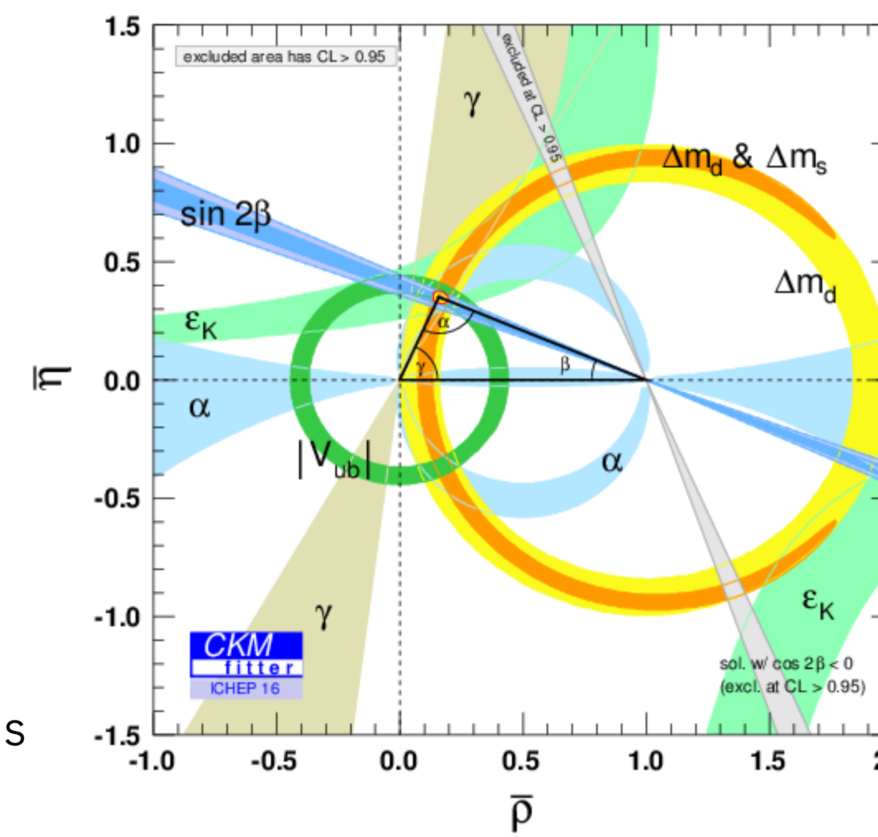
MIXING AND MASS





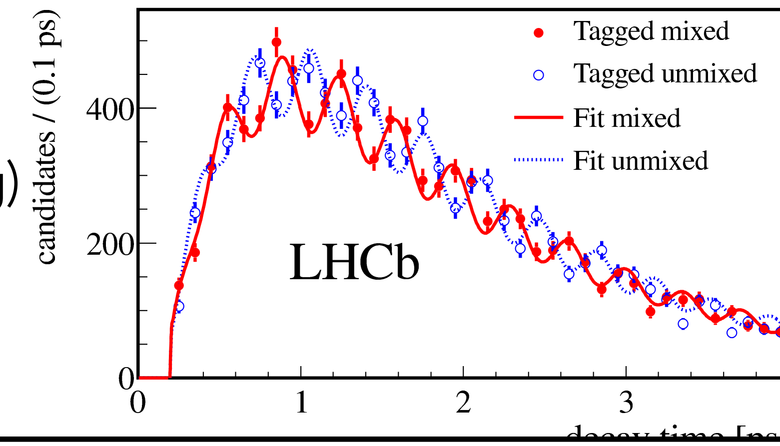
$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \qquad |U_{MNSP}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad |U_{CKM}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$

- Mixing matrix relates flavour and mass states
- We have quite some information about the parameters
- However, relative to neutrinos, for quarks we have
  - many more measurements, allowing consistency tests
  - measured complex phases within the matrix (CP violation)
  - measured the masses
- We know enough to say:
  - the masses of neutrinos is very different from quarks, charged leptons
  - the mixing structure is also very different
- Do neutrino masses and mixing have a different origin?

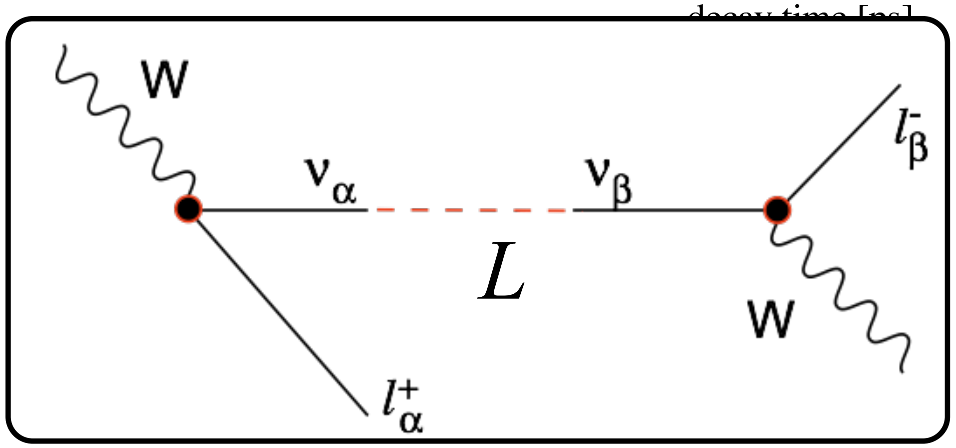


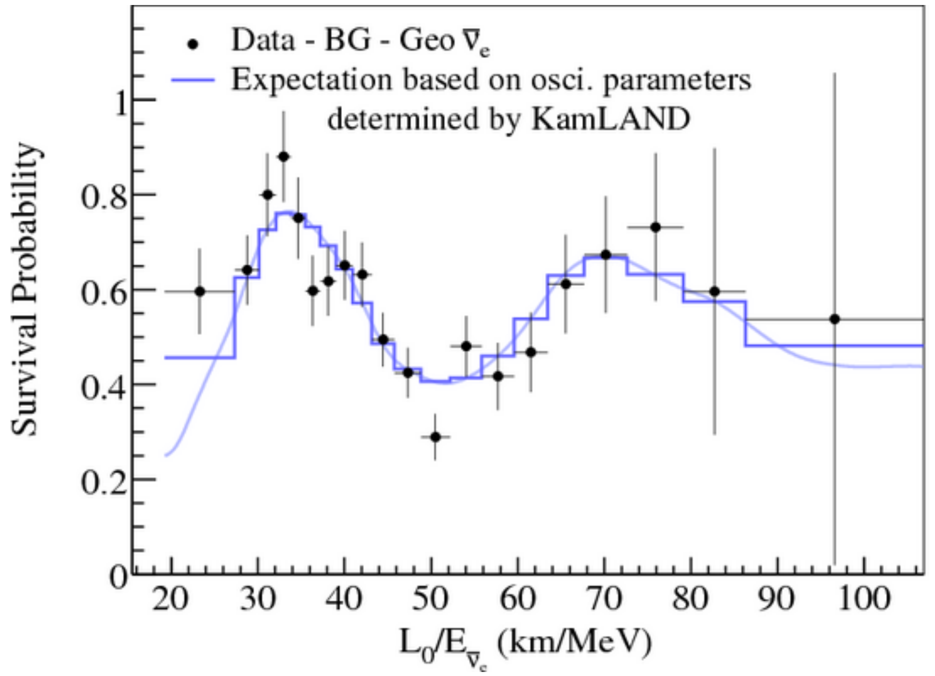
FLAVOR OSCILLATIONS

- Mixing leads to oscillations/precession in time of an observable
  - quarks: neutral mesons oscillating to their anti meson ($B^0 \leftrightarrow \bar{B}^0$ mixing)
  - neutrinos: oscillations of the flavour content of a neutrino



- Neutrino oscillations:
  - neutrinos are produced in a flavour state α $\quad |\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$
    - mass states ν_i evolve differently in time
  - state can acquire a different flavour β, produce a different lepton.
  - **if mass states are non-degenerate and mixing is nontrivial**





in vacuo

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\Sigma_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\Sigma_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin[2.54\Delta m^2_{ij}(L/E)]$$

- Left: "survival probability" = $P(\bar{\nu}_e \to \bar{\nu}_e)$ for reactor neutrinos
  - amplitude of oscillation ↔ mixing matrix elements
  - "frequency" of oscillation in L/E ↔ mass^2 differences

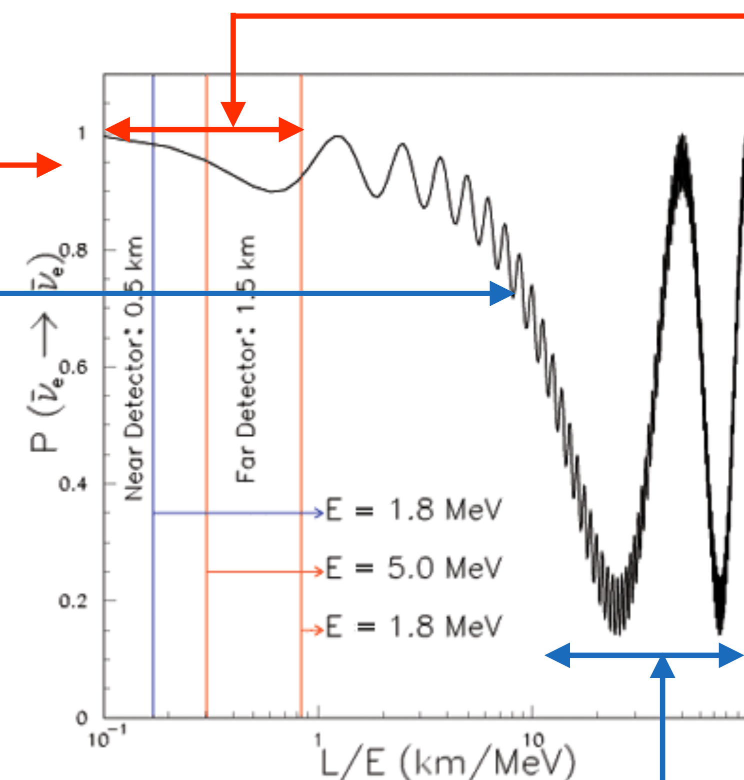
PARAMETRIZING THE MIXING

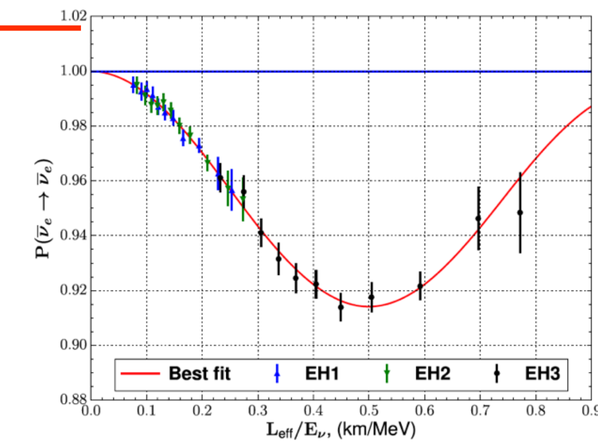
- 3 Mixing angles $\theta_{12,13,23}$ c_{ij}/s_{ij} = cos/sin θ_{ij}
- Dirac phase δ
- Majorana phase $\alpha_{1,2}$ (if Majorana)
- Three masses $m_{1,2,3}$

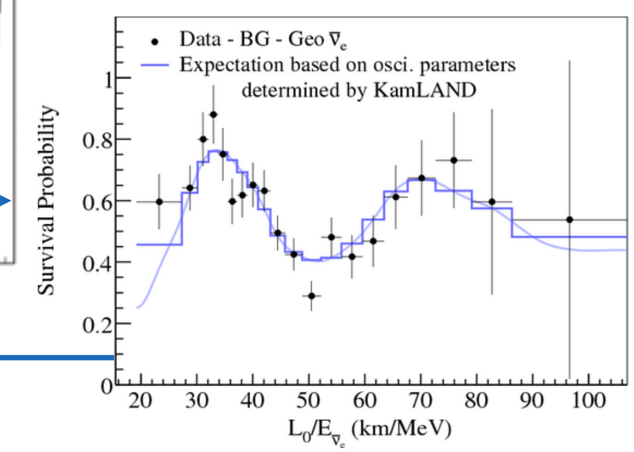
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

$$P(\nu_e \to \nu_e) \sim \quad 1 \quad - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$$

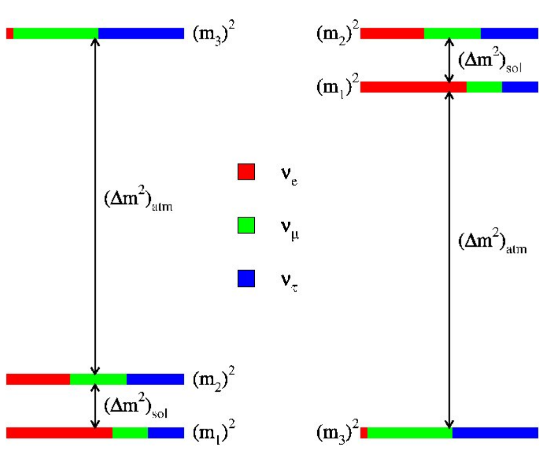
$$- \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

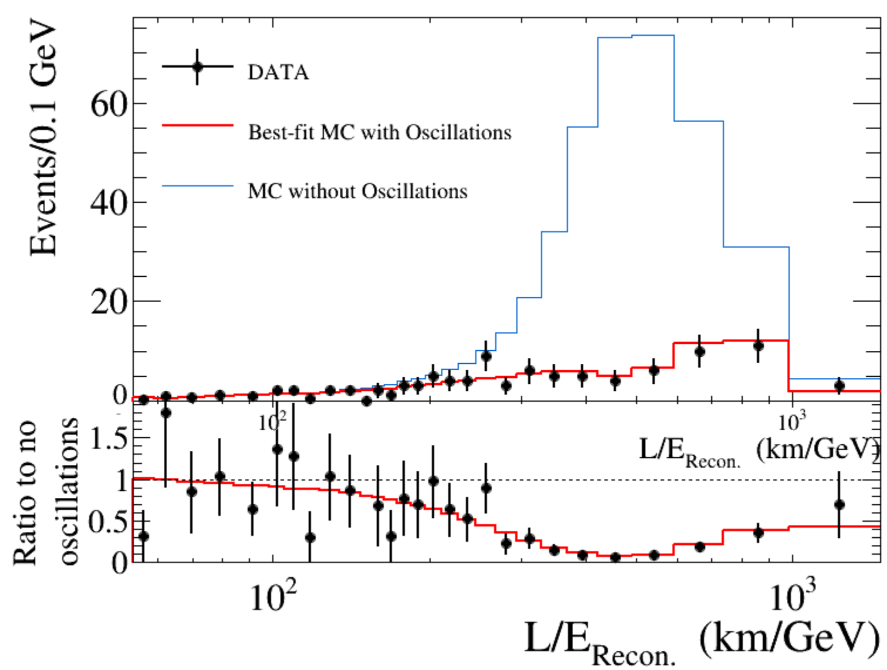






- $\sin^2\theta_{12}$ = 0.307±0.013 (mainly from ☀ SNO, SK)
- Δm^2_{21} = 7.53±0.18 x 10^{-5} eV^2
- $\sin^2\theta_{13}$ = 0.0210±0.0011
- $|\Delta m^2_{32}|$ = 2.45±0.05 x 10^{-3} eV^2

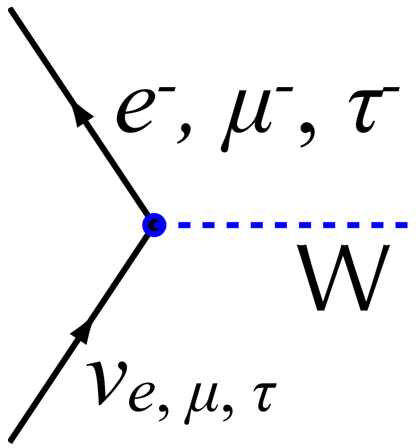


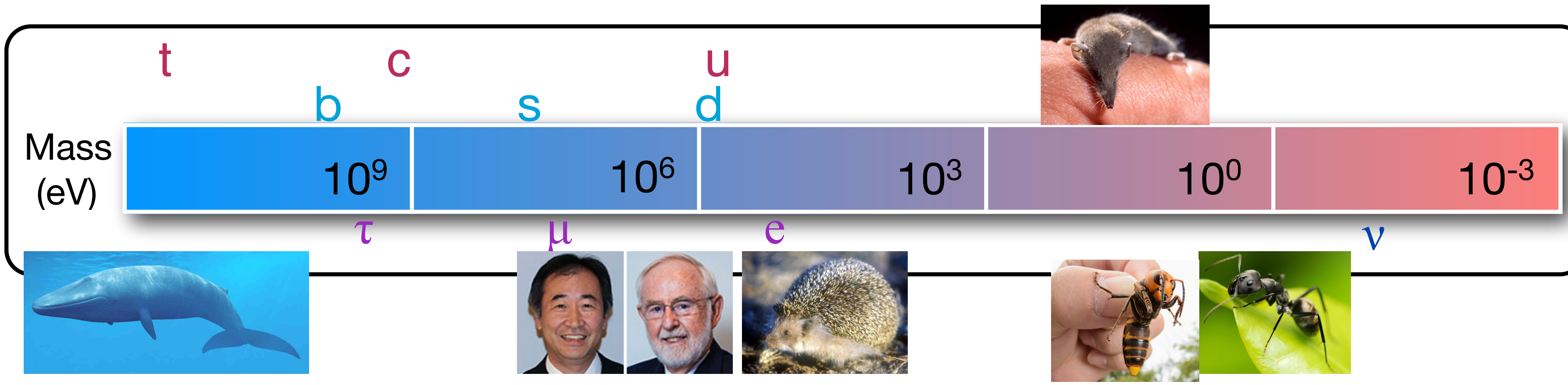


$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{31} L/E)$$

- $\sin^2\theta_{23}$ = 0.51±0.04
- $|\Delta m^2_{32}|$ = 2.45±0.05 x 10^{-3} eV^2

MIXING AND MASS





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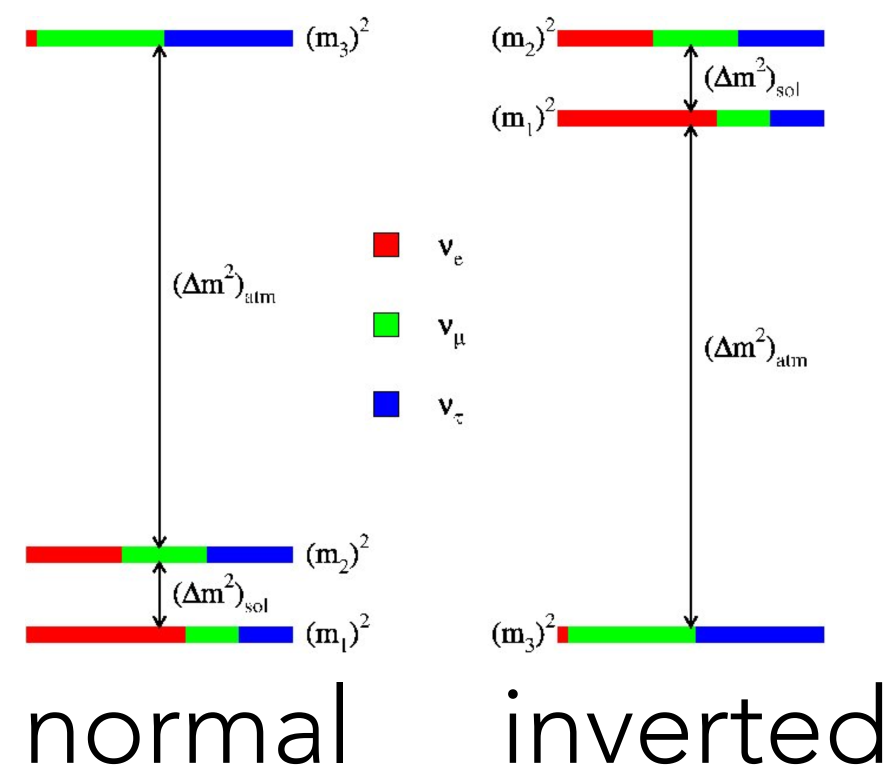
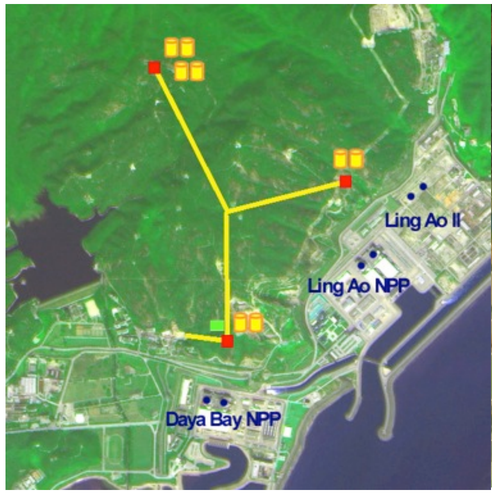
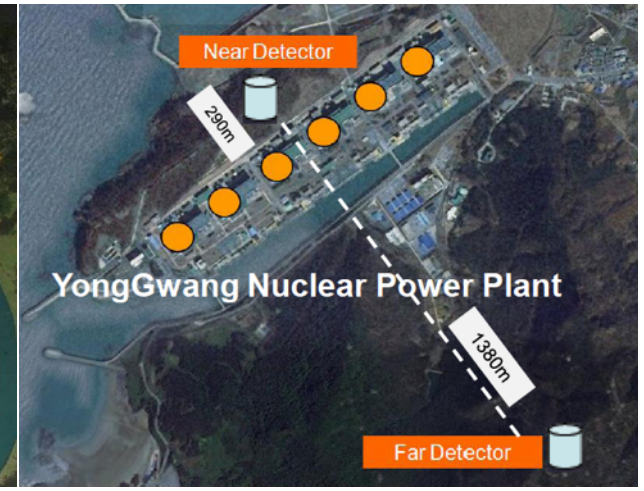
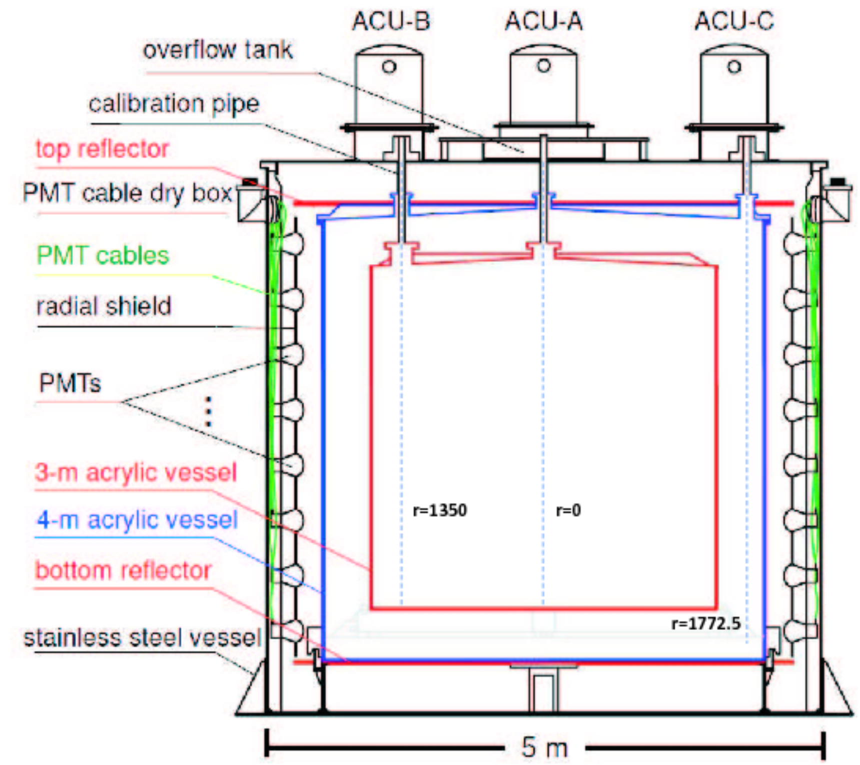
- Questions about the neutrino mixing
  - what is ordering/hierarchy of neutrino masses
  - are there deviations between neutrino and antineutrino oscillations resulting from CP violation?
  - are there any patterns within the mixing?
- All require precision measurements



REACTOR EXPERIMENTS



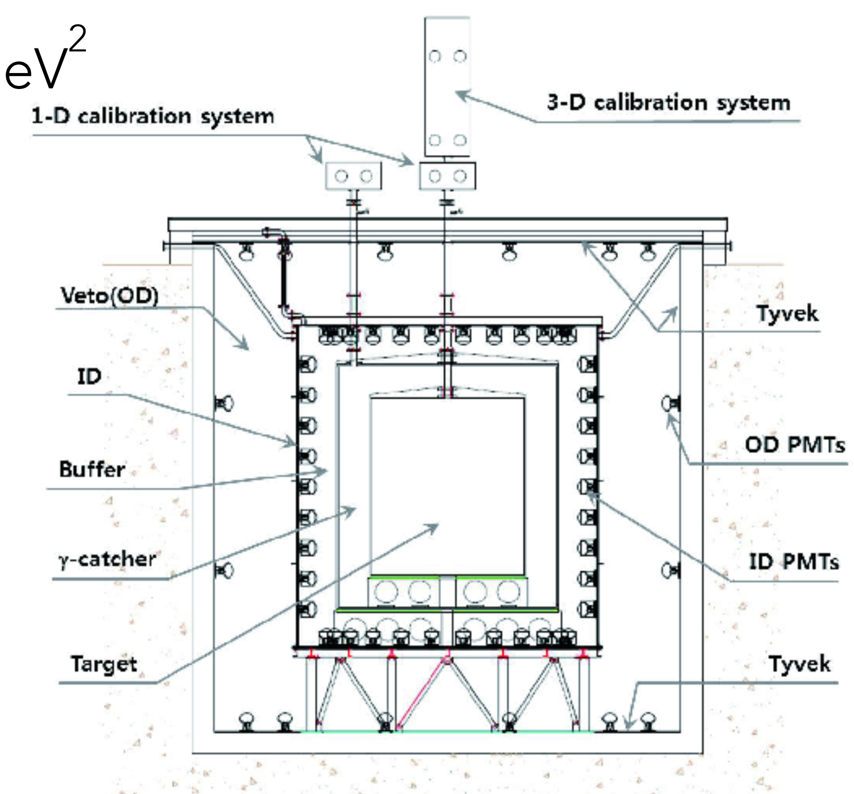


$$P(\nu_e \to \nu_e) \sim \boxed{1 \quad - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)}$$
$$- \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

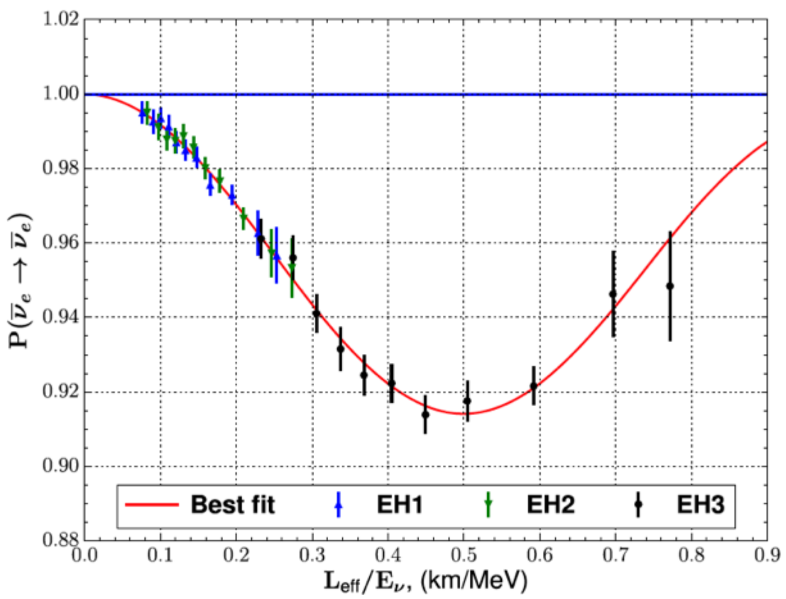
- multi-GW source of of O(MeV) antineutrinos
- detectors ~1-2 km away probe "disappearance" with Δm^2~2-3 x 10^{-3} eV^2
  - near detector to probe rate/spectrum "before" oscillations
- Basic detection principle: inverse beta decay

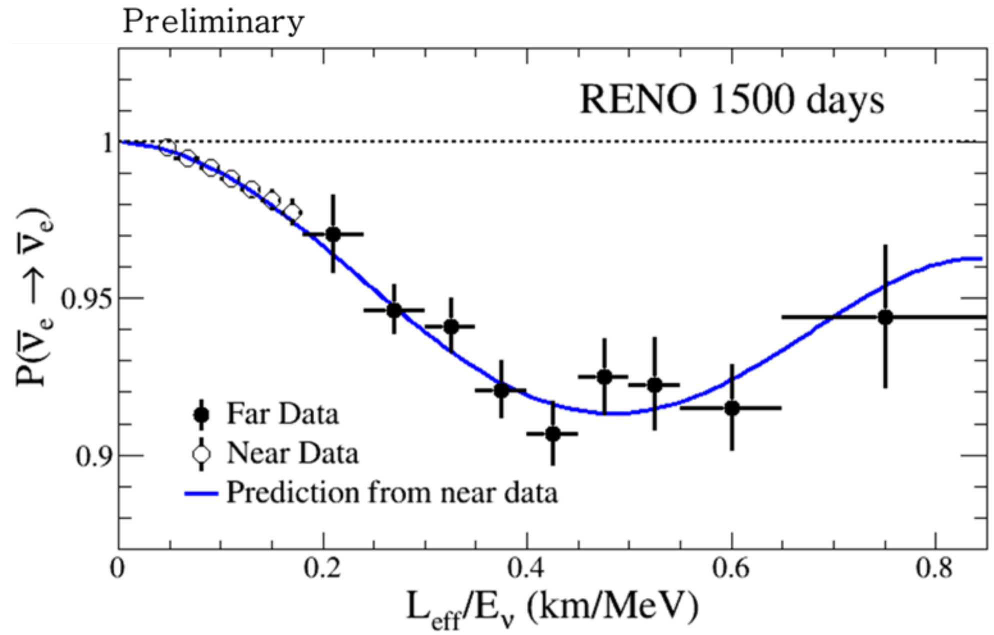
$$\bar{\nu}_e + p \to e^+ + n$$

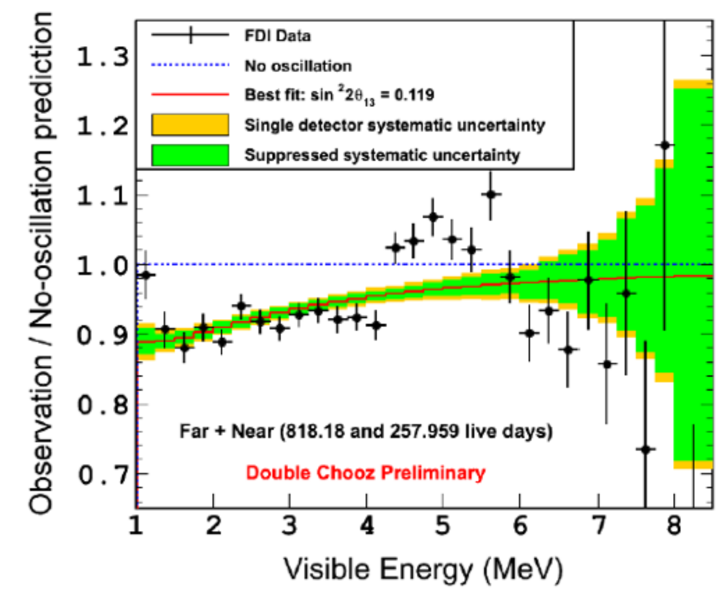
- Liquid scintillator detectors (primarily hydrocarbons)
  - provides free proton targets (hydrogen)
  - Gadolinium doping to aid neutron capture detection
  - "buffer" regions to isolate Gd-loaded region

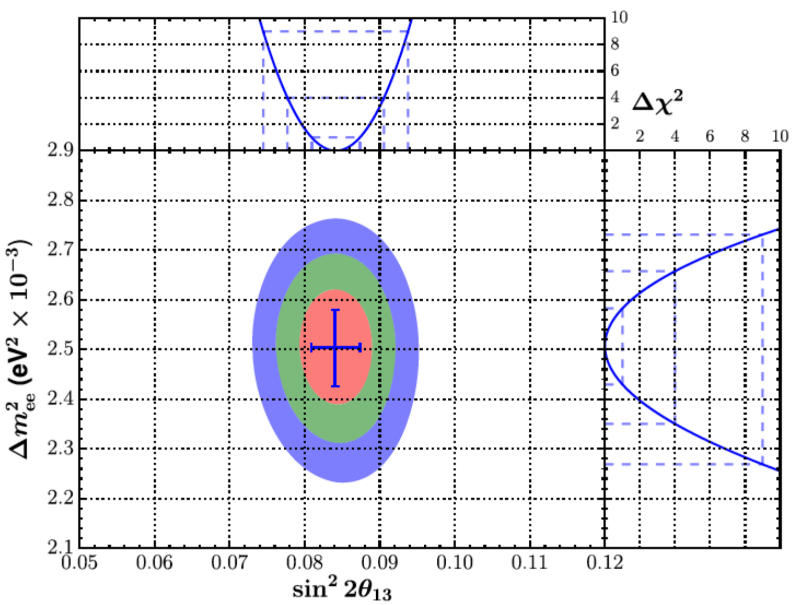


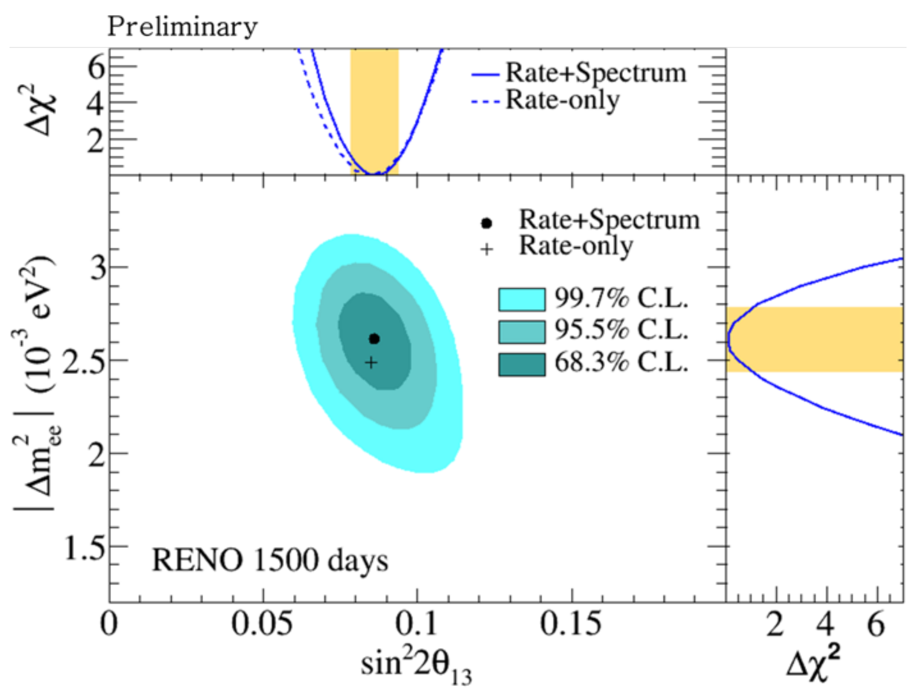
LATEST MEASUREMENTS







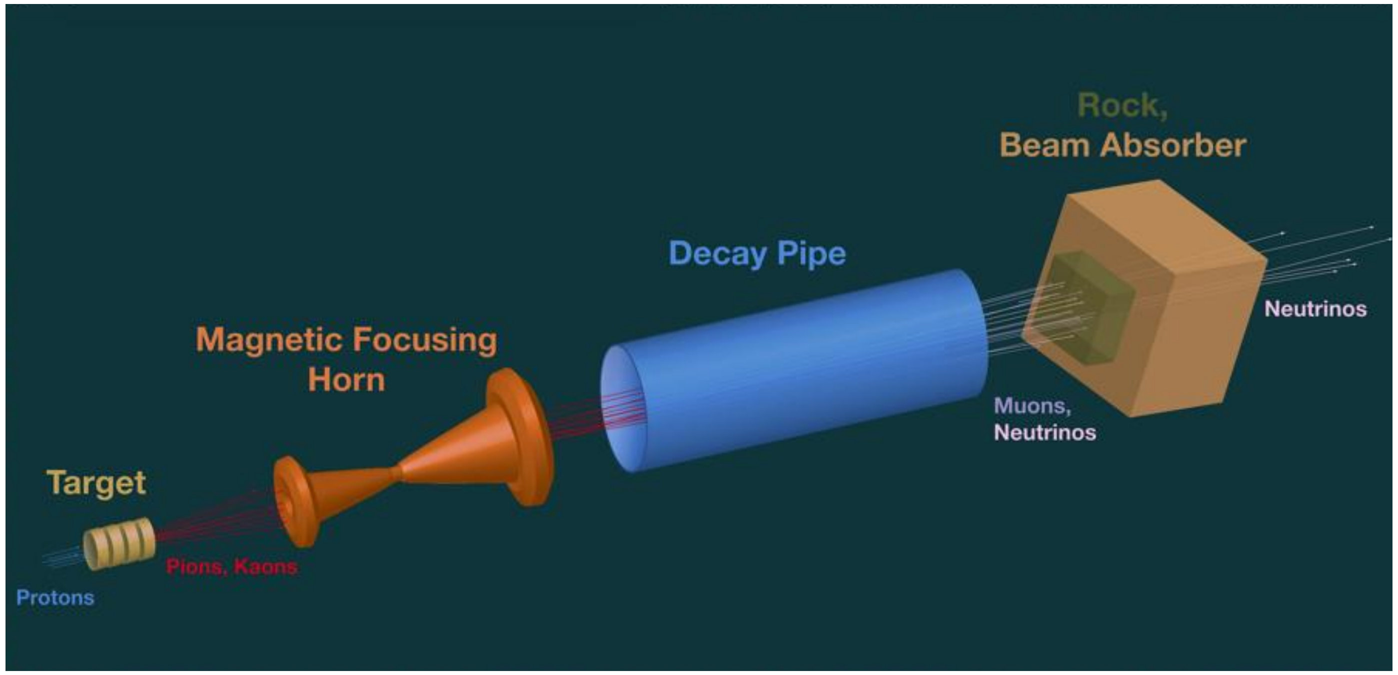




- $|\Delta m^2_{ee}| = \cos^2\theta_{12}\,|\Delta m^2_{31}| + \sin^2\theta_{12}\,|\Delta m^2_{32}|$
  - Daya Bay: $2.50 \pm 0.06 \pm 0.06 \times 10^{-3}$ eV^2
  - RENO: $2.61^{+0.15}_{-0.16} \pm 0.09 \times 10^{-3}$ eV^2

- $\sin^2 2\theta_{13}$
  - Daya Bay
    - $0.0841 \pm 0.0027 \pm 0.0019$
  - RENO:
    - $0.086 \pm 0.006 \pm 0.005$
  - Double Chooz
    - 0.119 ± 0.016
- < 5% precision!

ACCELERATOR-BASED ν BEAM



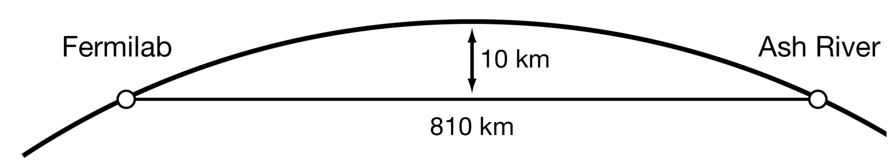
295 km

"Conventional super beam"

- high energy protons impinge on target, induce $\pi^{\pm}$ production
  - (but also $K^{\pm,0}$)
- Magnetic focussing elements:
  - "$\bar{\nu}$-mode": focus positive particles, e.g. π^{+}
  - "ν-mode": focus positive particles, e.g. π^{-}
- decay region
  - "$\bar{\nu}$-mode": $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$
  - "ν-mode": $\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$
- absorber: terminate all particles except neutrinos

810 km

O(GeV) $\nu_{\mu}/\bar{\nu}_{\mu}$-beam with
~1% $\nu_e/\bar{\nu}_e$ contamination



ν OSCILLATIONS IN LBL EXPERIMENTS

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$

- Precision measurement of $2\theta_{23}$.
- CPT tests with antineutrino mode ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)

$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\ & \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & -\alpha \sin\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha \cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\mathcal{O}(\alpha^2) \end{aligned}$$

$$\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

M. Freund, Phys.Rev. D64 (2001) 053003

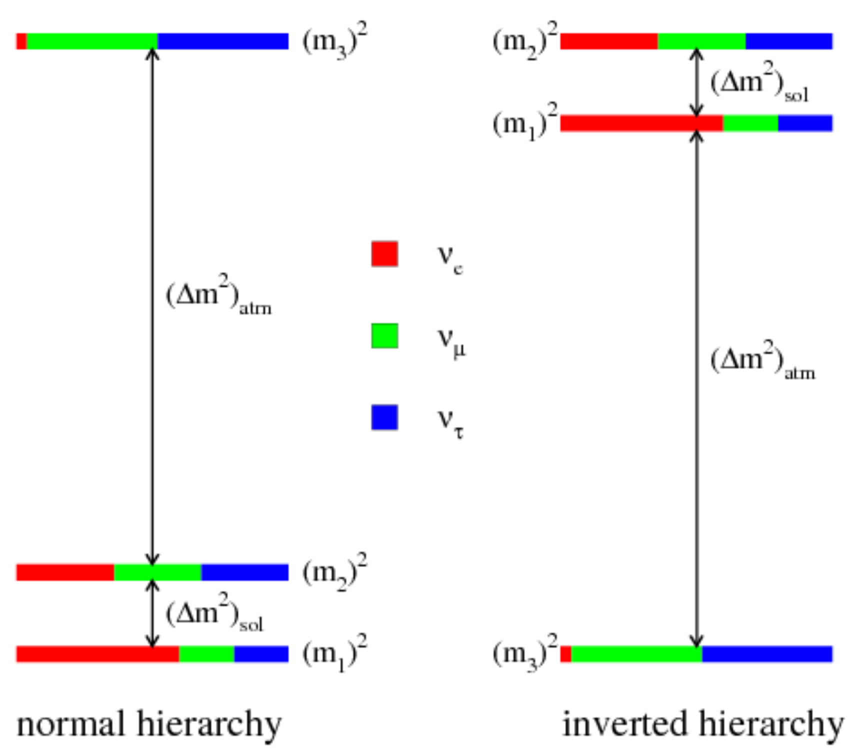
- CP odd phase δ
  - asymmetry of probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ (up to ~30%)
- θ_{23} (as opposed to $2\theta_{23}$) results in "octant" dependence θ_{23}=/>/<45°
- Mass hierarchy sensitivity through x: $\nu_e/\bar{\nu}_e$ enhanced in normal/inverted hierarchy
  - larger in NOvA (~30%) than in T2K (~10%) due to higher E, longer L

Interdependence on common parameters leads to joint analysis

QUICK SUMMARY FOR $\nu_\mu \rightarrow \nu_e$

- increase $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$
  - enhance both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- CP violating parameter δ
  - δ =0,π: no CP violation: vacuum oscillation probabilities equal
  - δ ~-π/2 : enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - δ ~+π/2: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

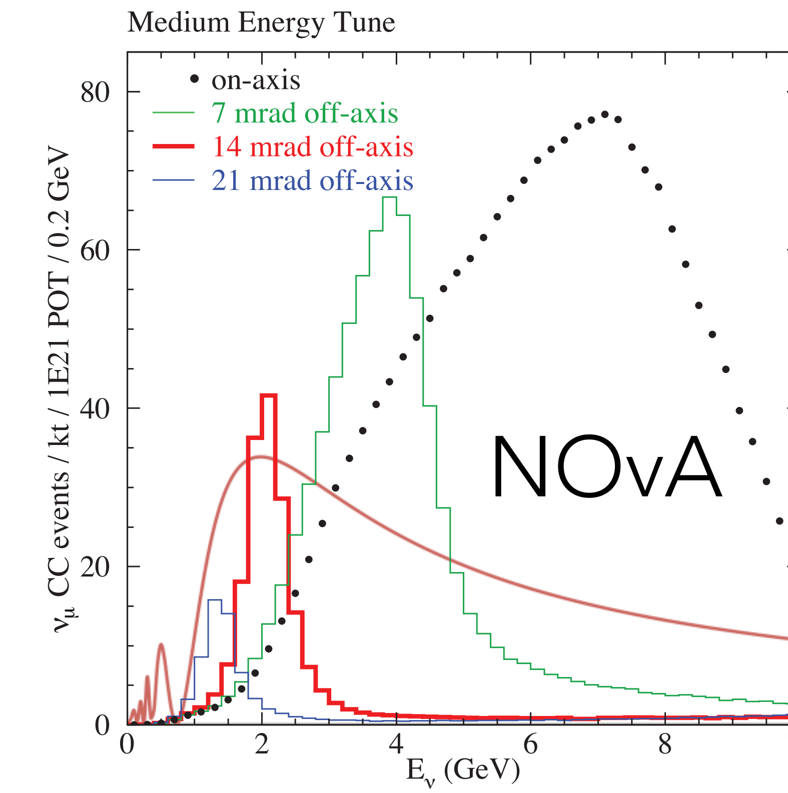
- "normal" hierarchy:
  - enhance $\nu_\mu \rightarrow \nu_e$
  - suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

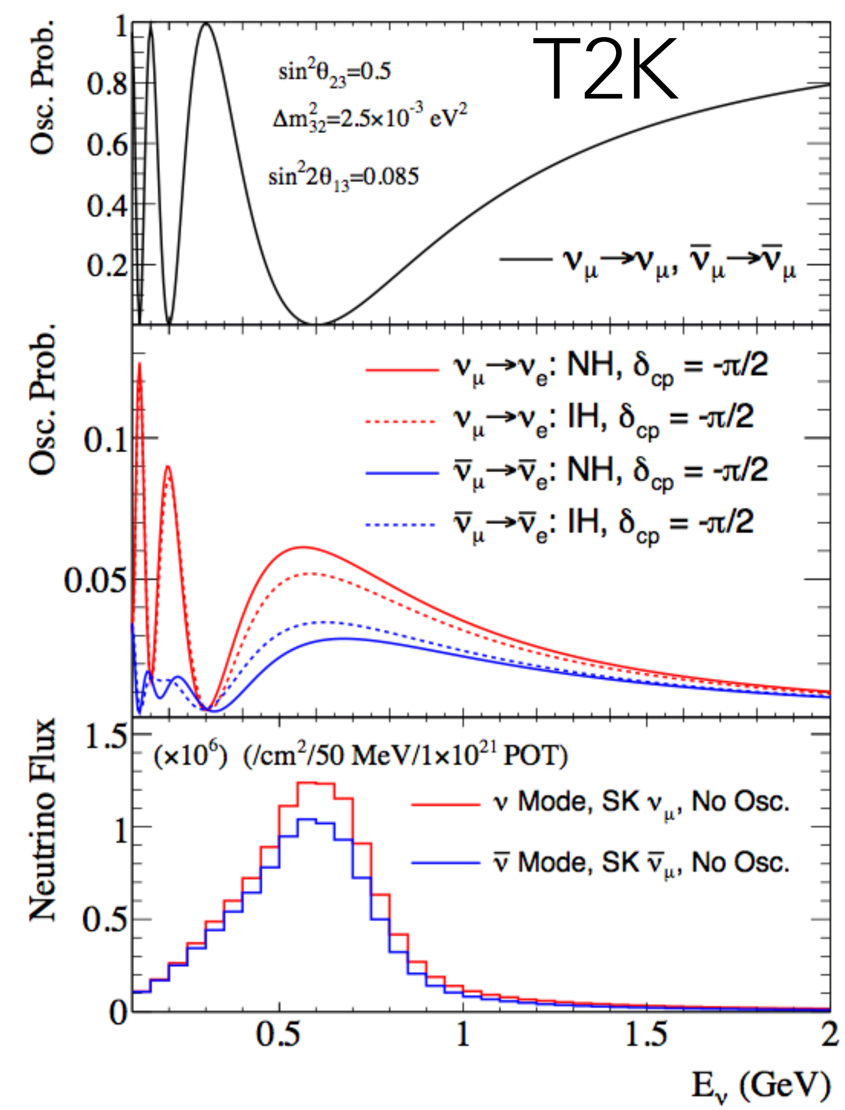


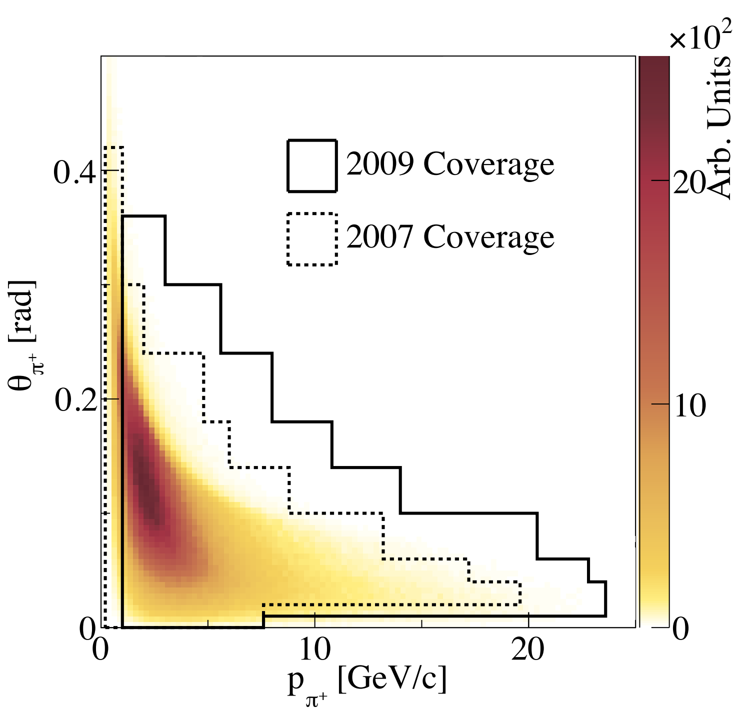
- "inverted" hierarchy:
  - suppress $\nu_\mu \rightarrow \nu_e$
  - enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

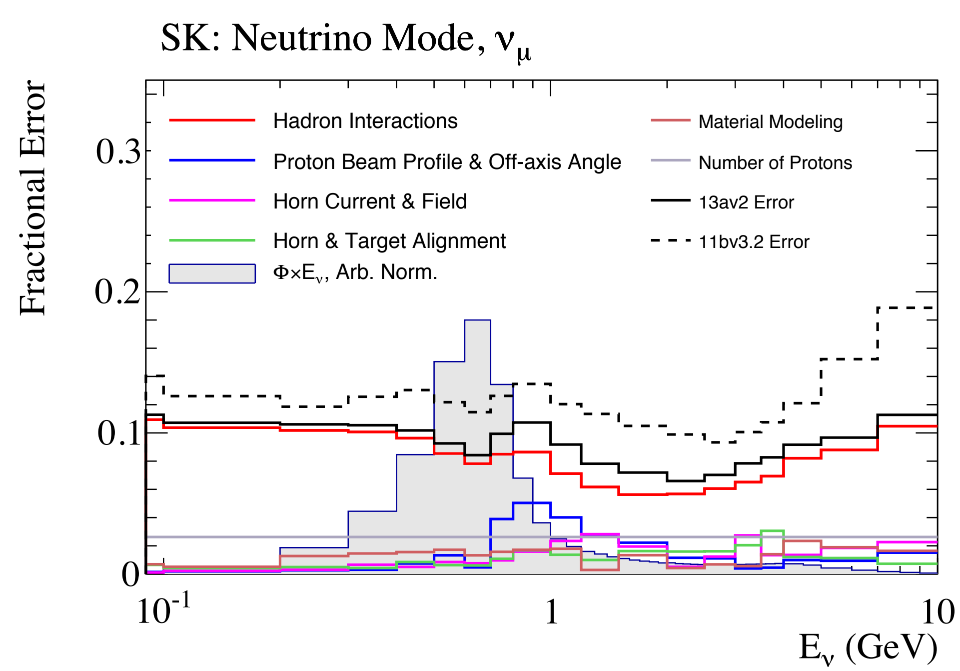
NEUTRINO FLUX

- Both NOvA and T2K use "off-axis" configuration
  - neutrino beam is directed slightly away from the far detector
    - lower and narrower energy spectrum
  - tune this to coincide with maximum neutrino oscillation probability based on known Δm^2 (and baseline L)
- Neutrino flux predictions based on detailed simulations
  - *ex situ* hadron production measurements (e.g. NA61/SHINE)
  - *in situ* beam monitor (e.g. proton beam optics)

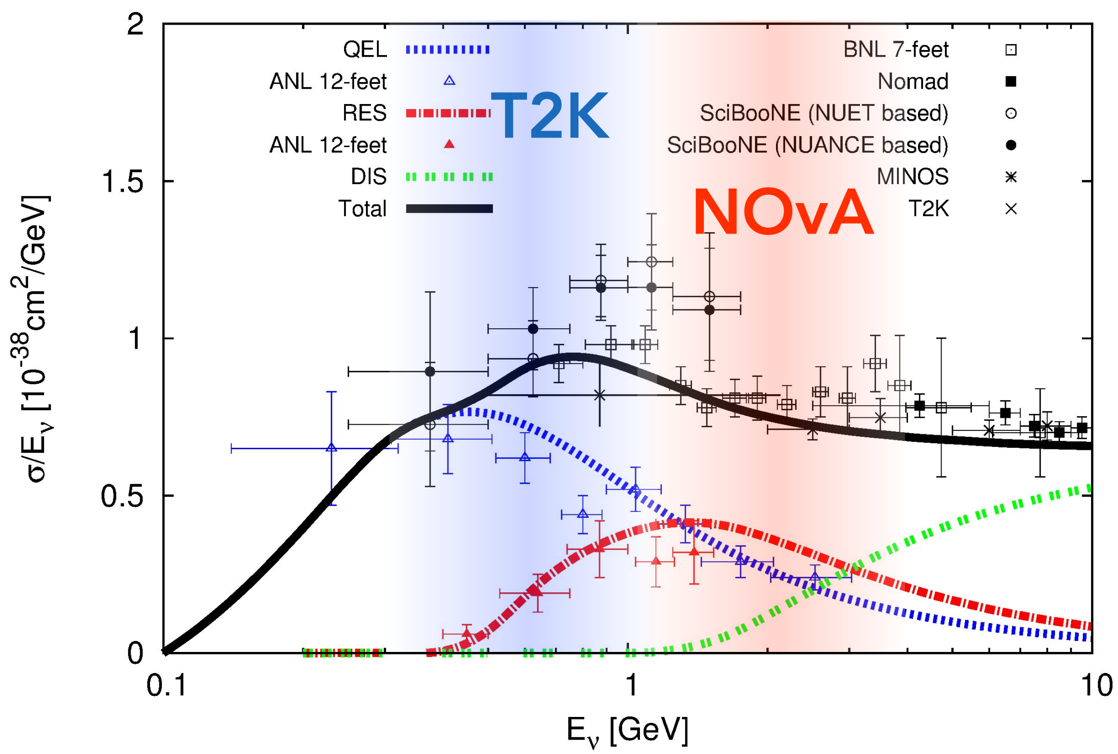


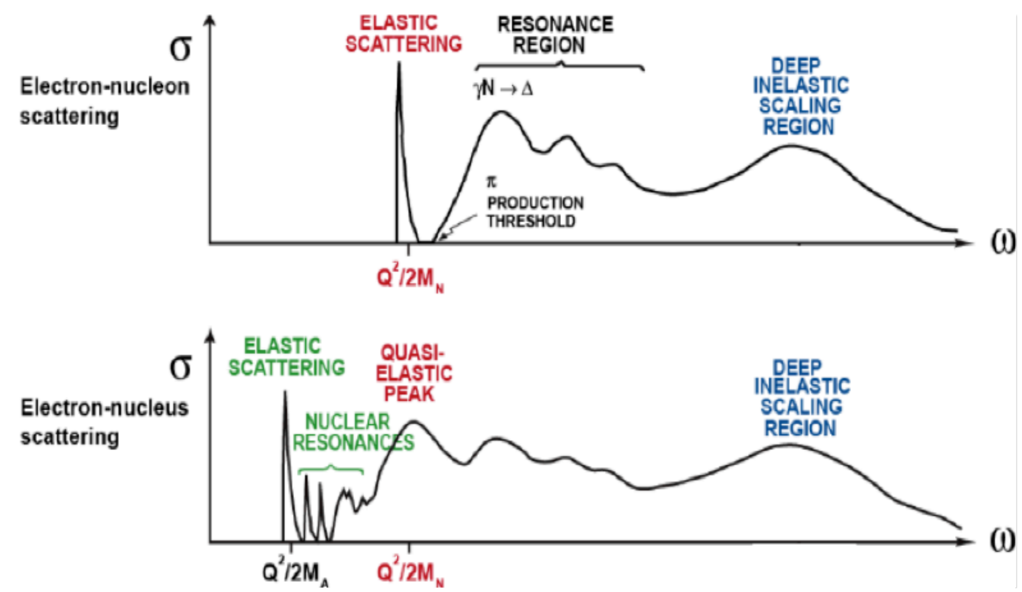


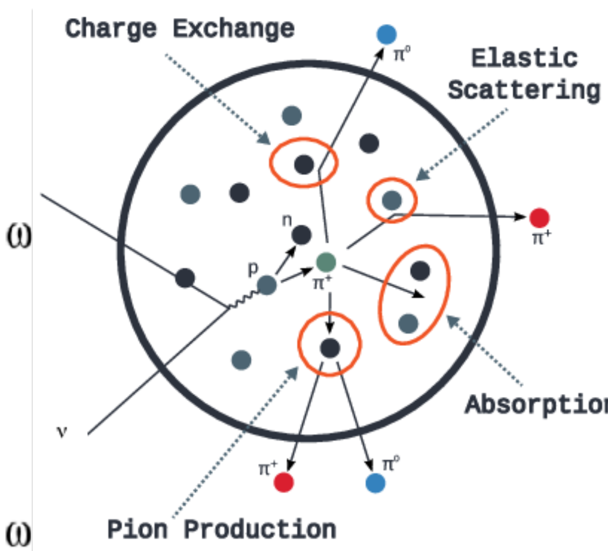




NEUTRINO INTERACTIONS



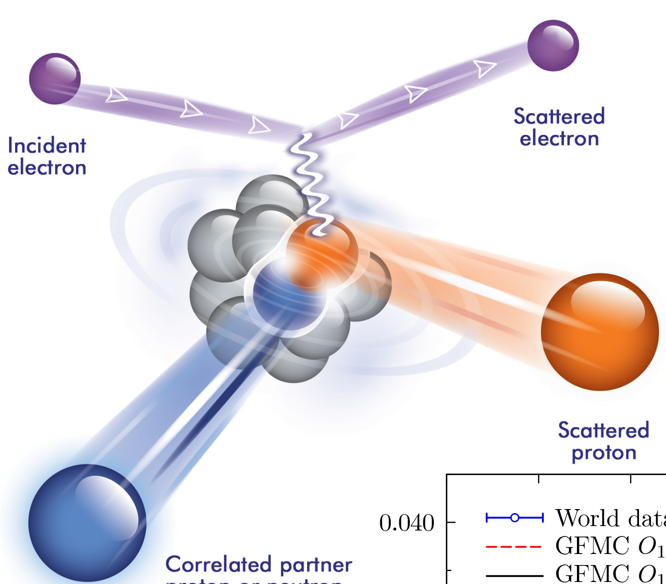


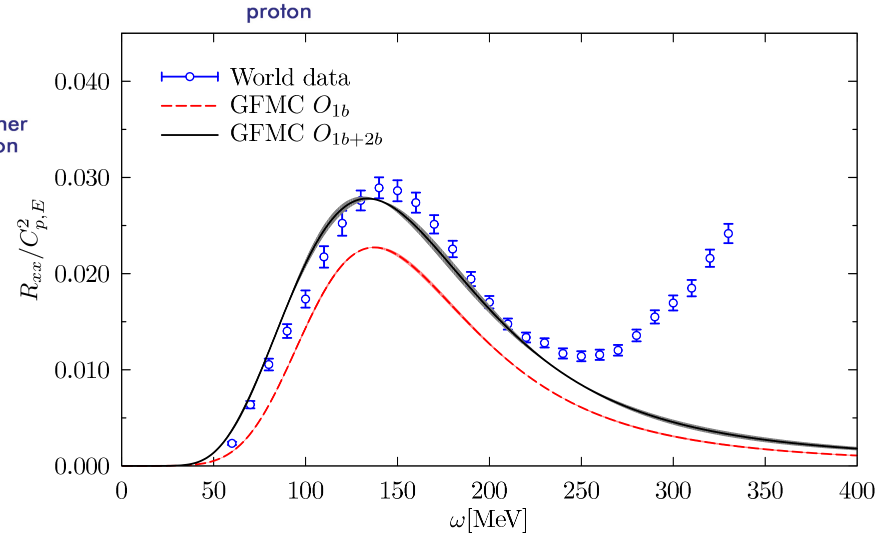


$$\nu_\ell + n \rightarrow \ell + p$$

$$\nu_\ell + p \rightarrow \ell + \Delta^{++}$$

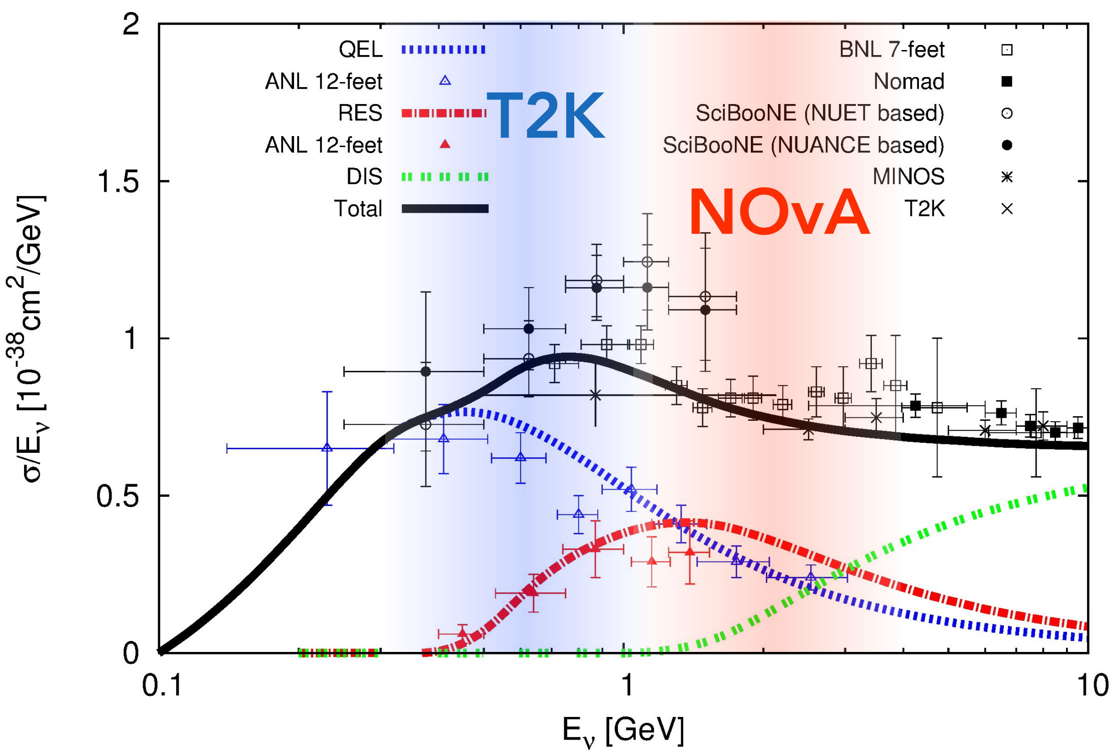
$$\nu_\ell + q \rightarrow \ell + X$$

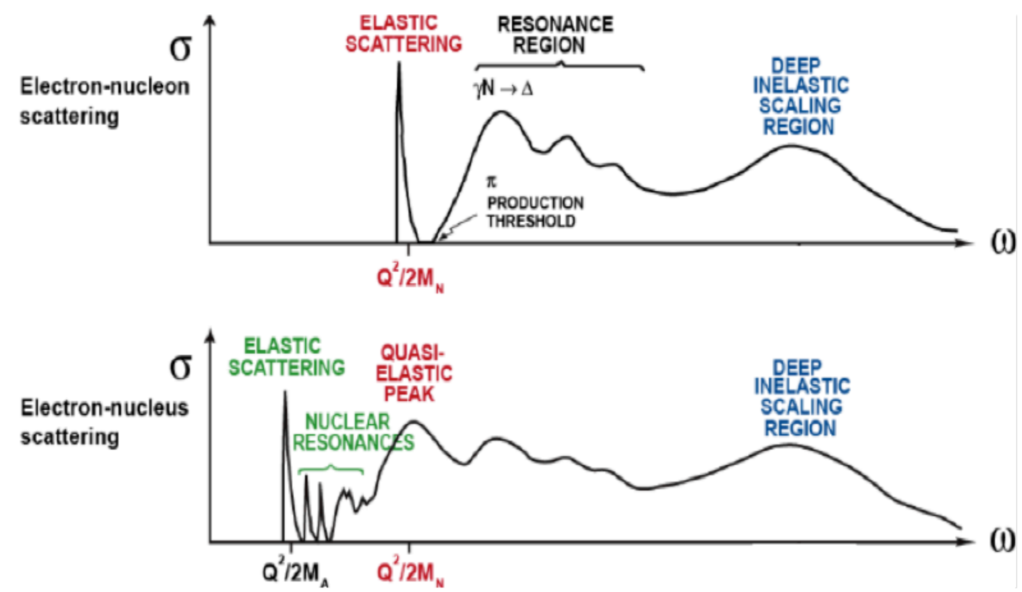


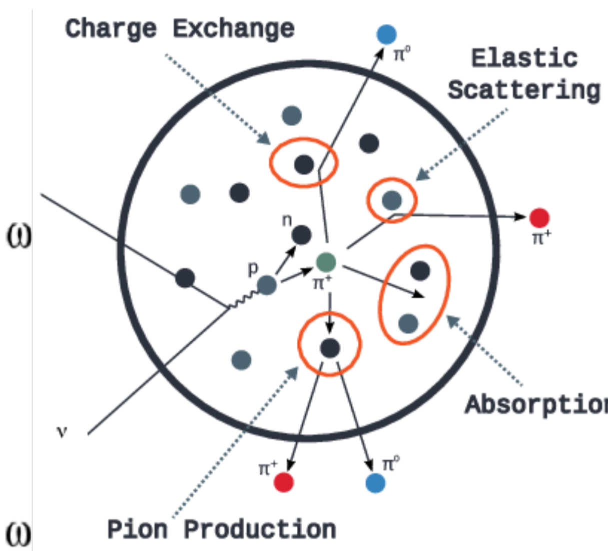


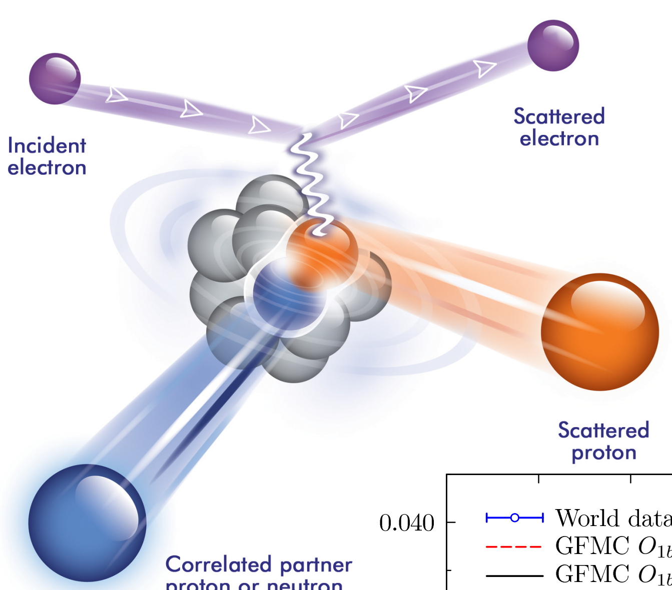
- ν interactions mainly on ^{12}C (NOvA), ^{16}O (T2K)
- Wide range of mechanisms and topologies
  - quasi-elastic → resonance → deep inelastic
  - models built primarily from "underlying" nucleon-level interactions, accounting for nuclear effects
    - initial state "Fermi" momentum/binding
    - propagation of hadrons through the target nucleus.
- Recent highlight on multi-body effects
  - still coming to grips with this . . . . .

NEUTRINO INTERACTIONS





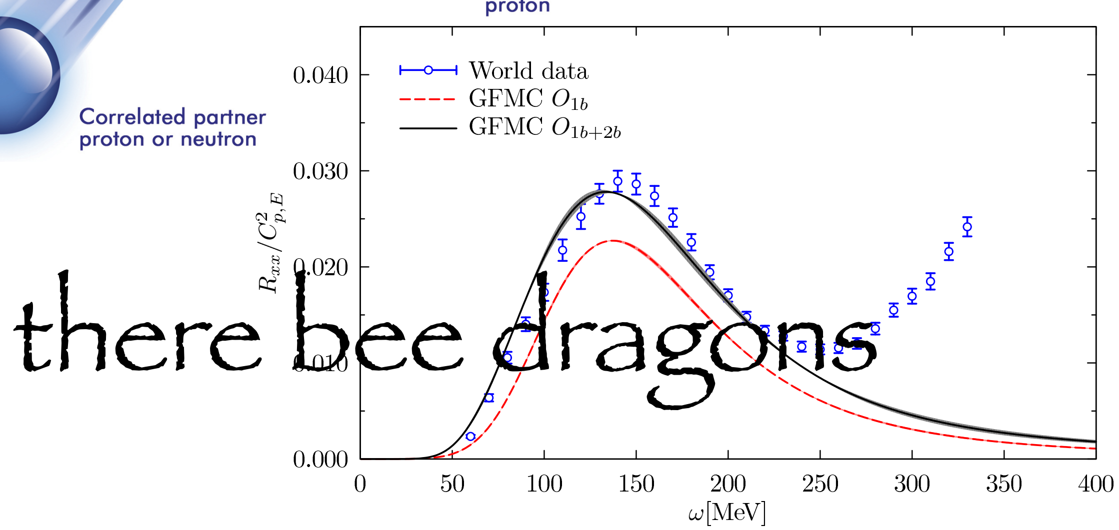




$$\nu_\ell + n \to \ell + p$$

$$\nu_\ell + p \to \ell + \Delta^{++}$$

$$\nu_\ell + q \to \ell + X$$



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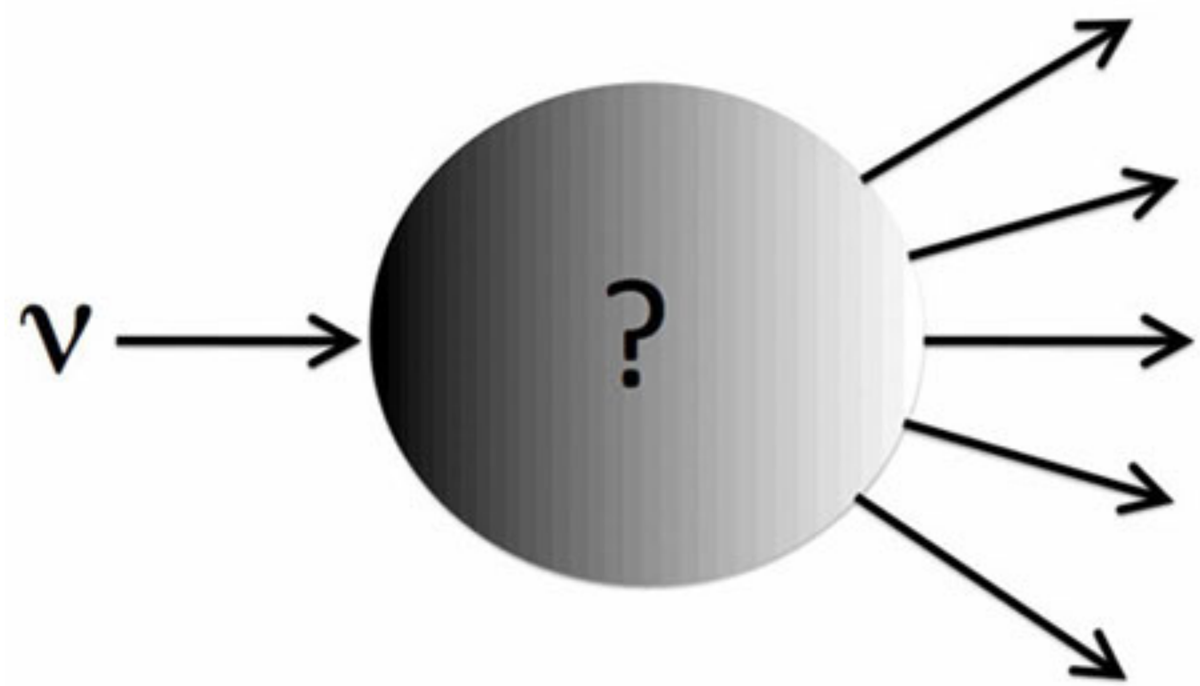
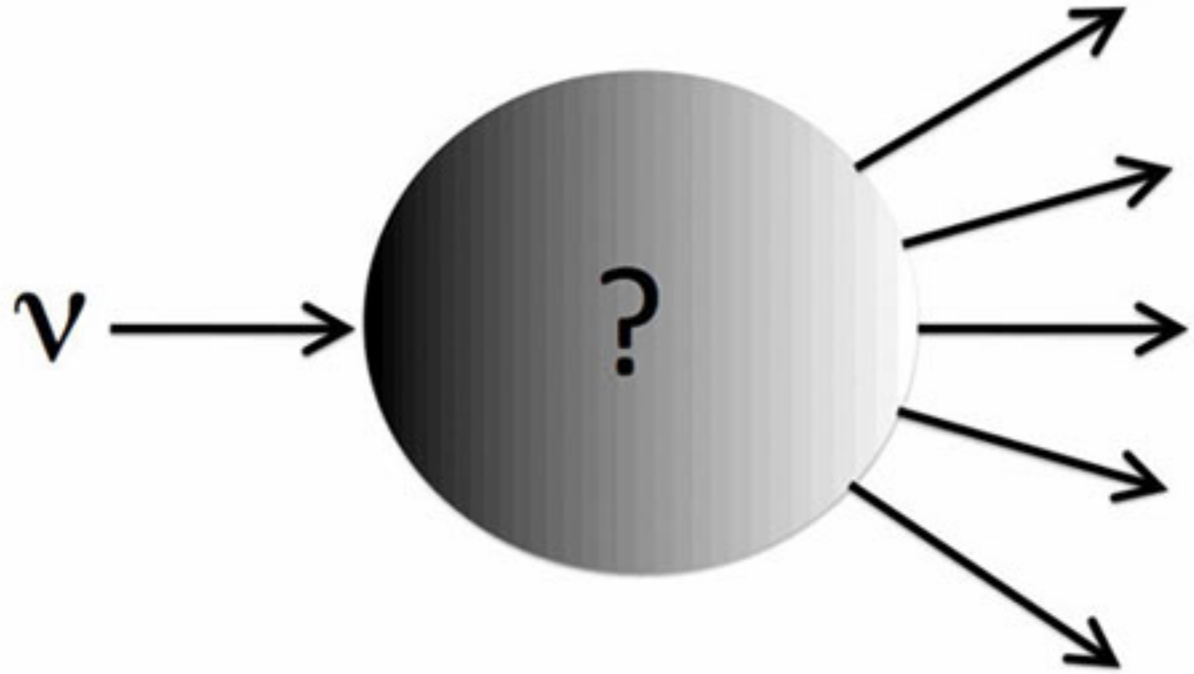
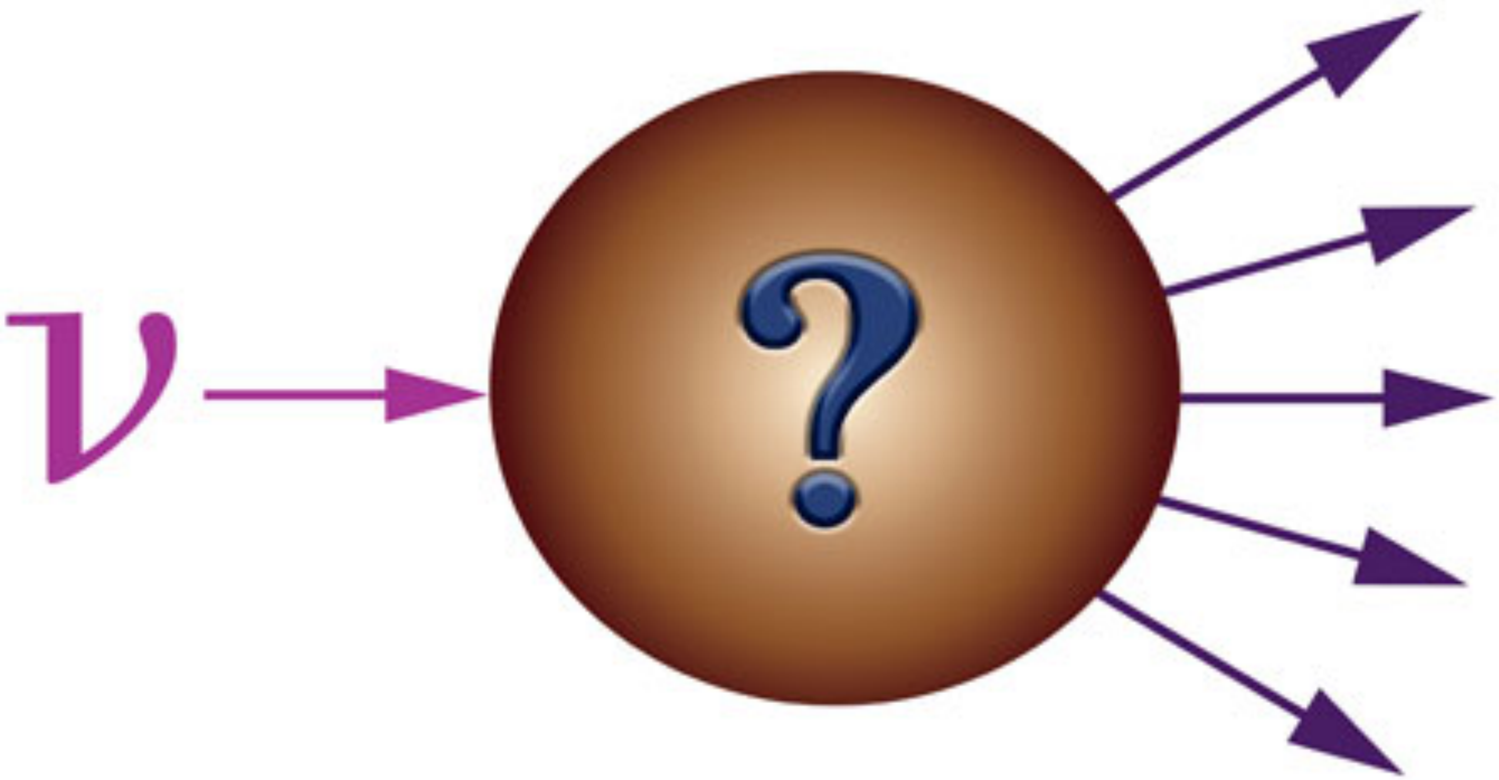
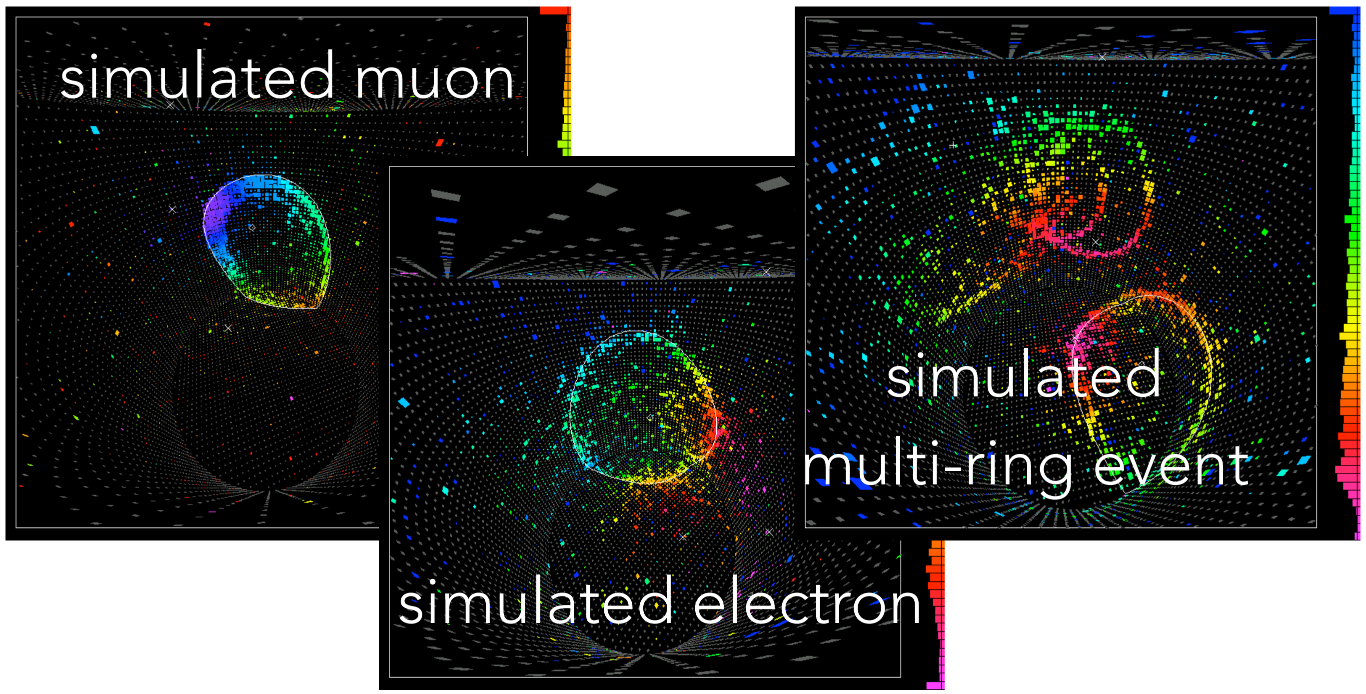

ν
?

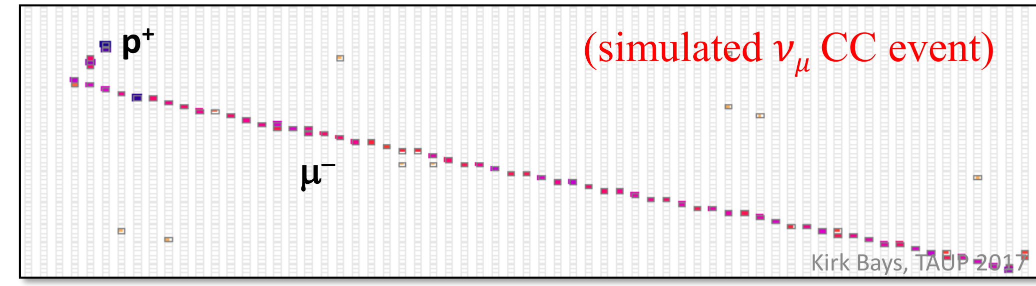

ν
?

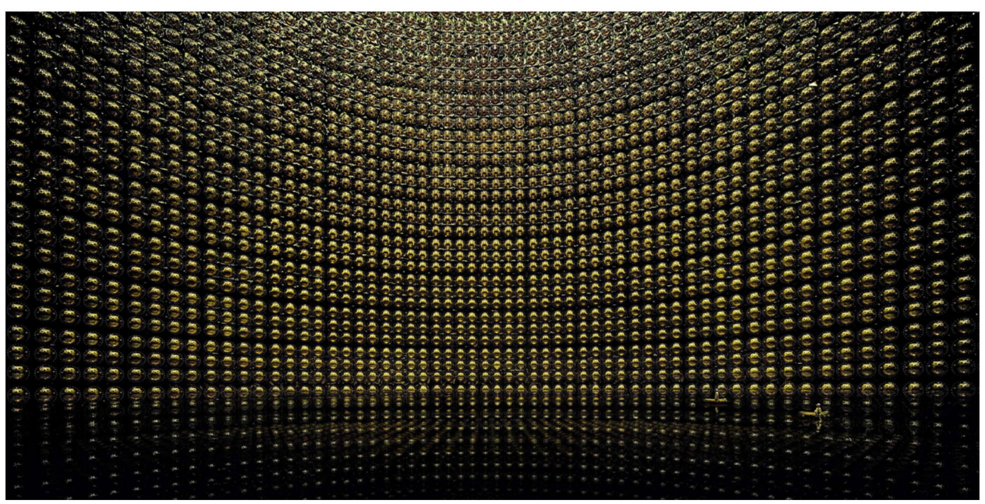

ν
?

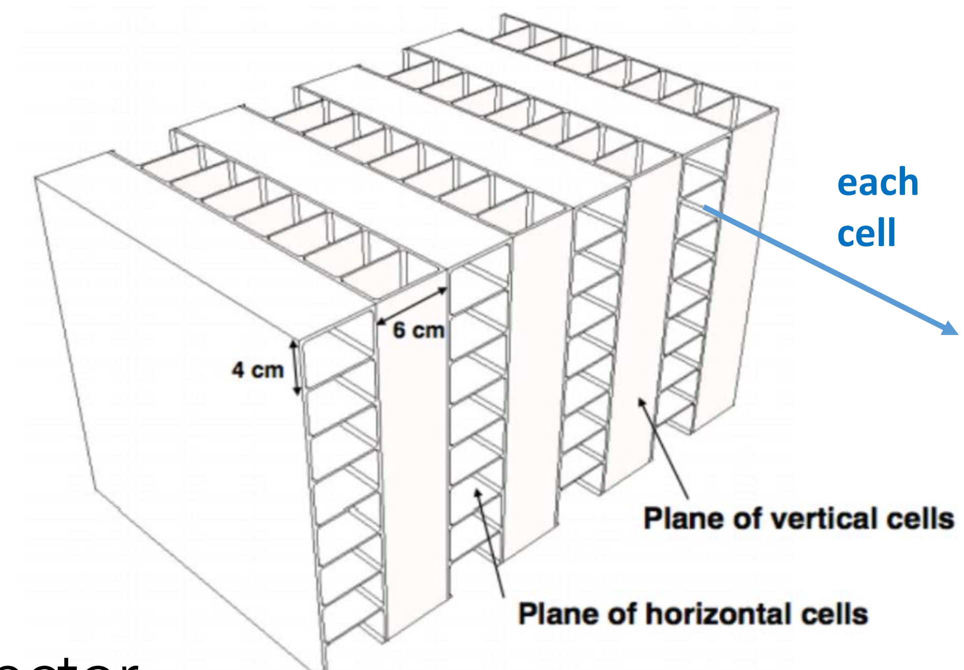

FINAL STATE NUCLEONS FOR NEUTRINO-NUCLEUS INTERACTIONS
This 2-day workshop will discuss the problems of extracting neutrino-nucleon information from neutrino-nucleus reactions and to further the efforts to addressing this complicated issue. The workshop also aims to further develop the synergy between the electron and neutrino scattering communities.
ν
?
TOPICS:
• Neutrino Cross-sections
• Final State Interactions
• Event Generators
• Initial State Interactions
ORGANIZING COMMITTEE:
E. Christy (Hampton Univ.)
D. Higinbotham (JLab)
N. Kalantarians (Hampton Univ.)
C. Mariani (VA Tech)
R. Schiavilla (ODU/JLab)
WWW.JLAB.ORG/CONFERENCES/FUNFACT/INDEX.HTML

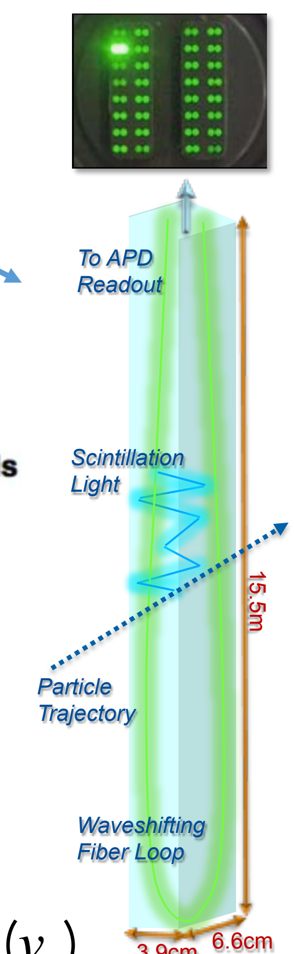
EVENTS IN "FAR DETECTOR"











- Left: Super-Kamiokande water Cherenkov detector
  - select events with single showering "electron-like" ring (ν_e) or "muon-like" ring (ν_μ)
- Right: NOvA tracking detector
  - select events with electromagnetic shower (ν_e) or long minimum ionizing muon track (ν_μ)

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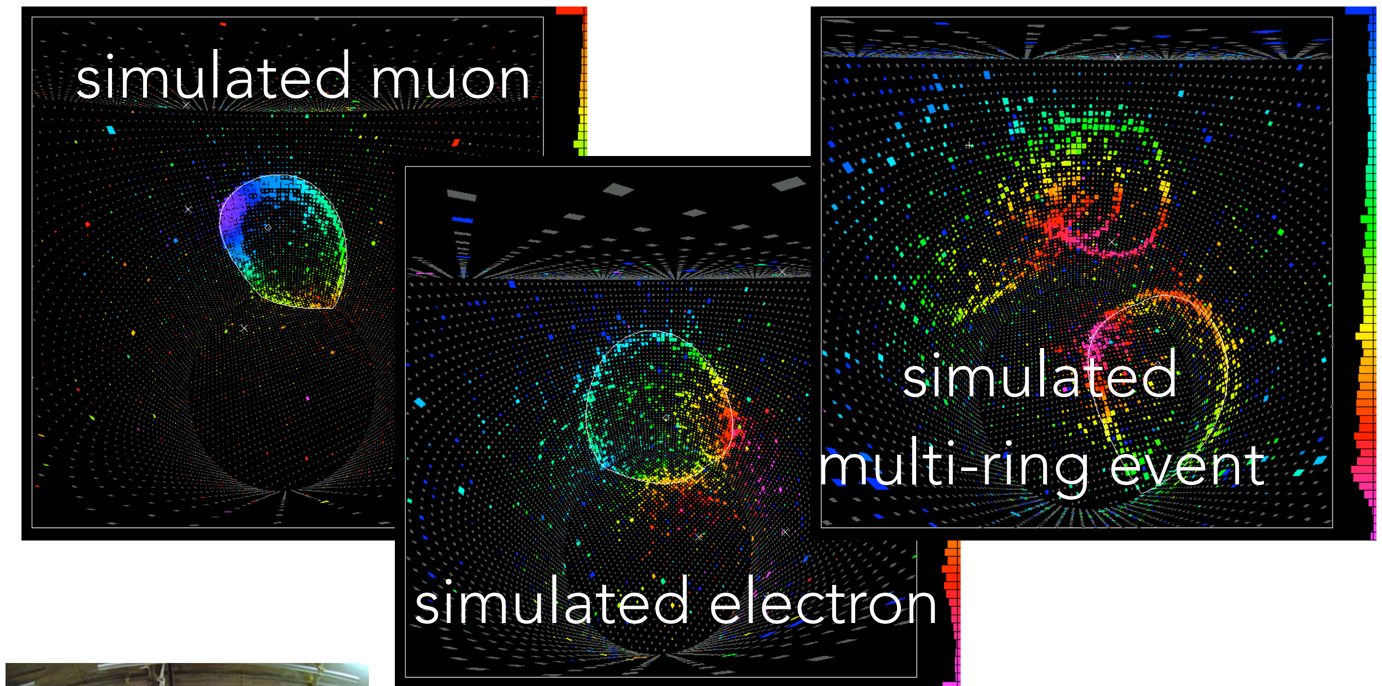

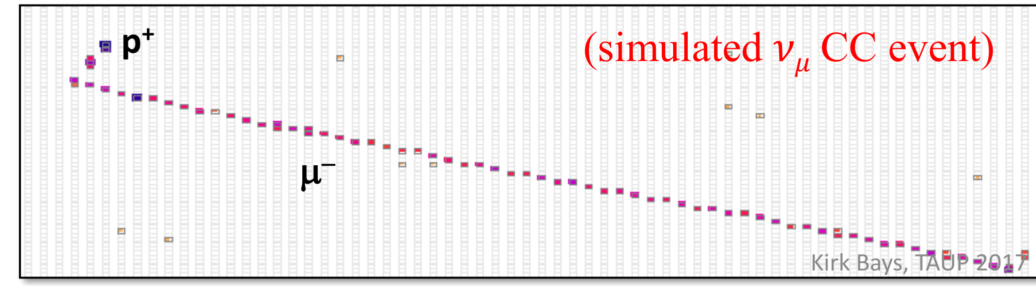

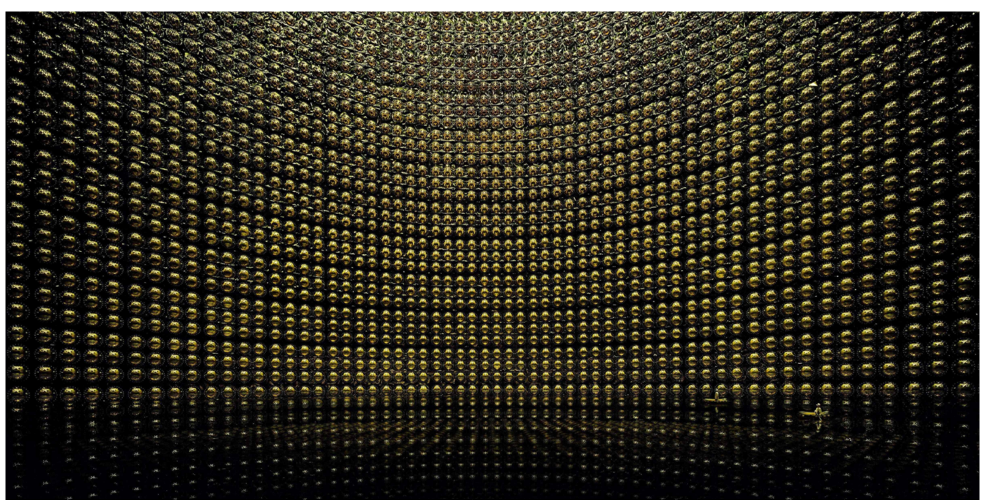

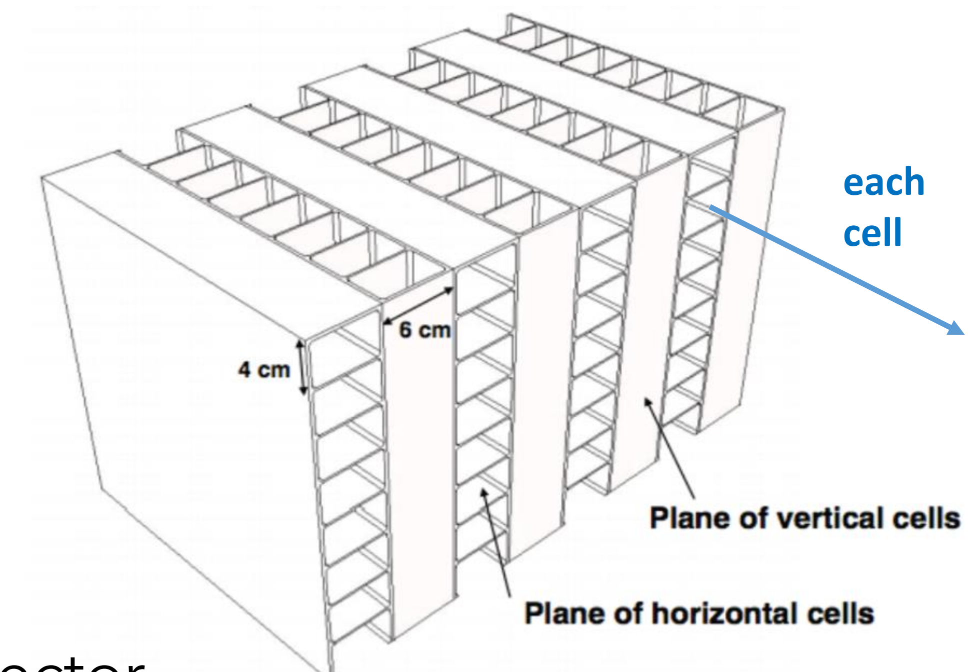

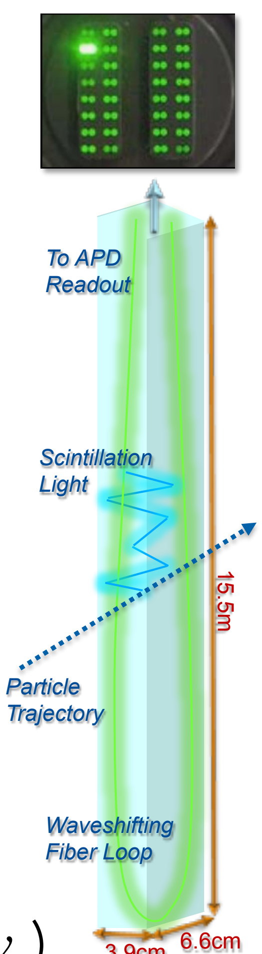

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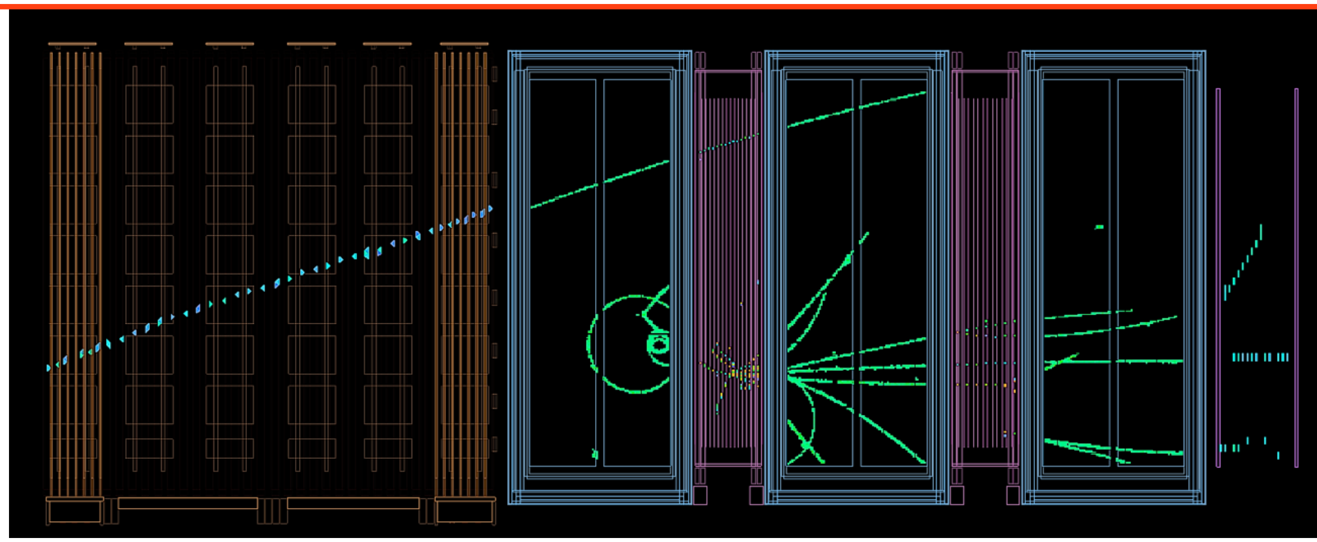
ANALYSIS STRATEGY

Combine ν_μ/ν_e channels to incorporate information from both (antineutrino mode as well)



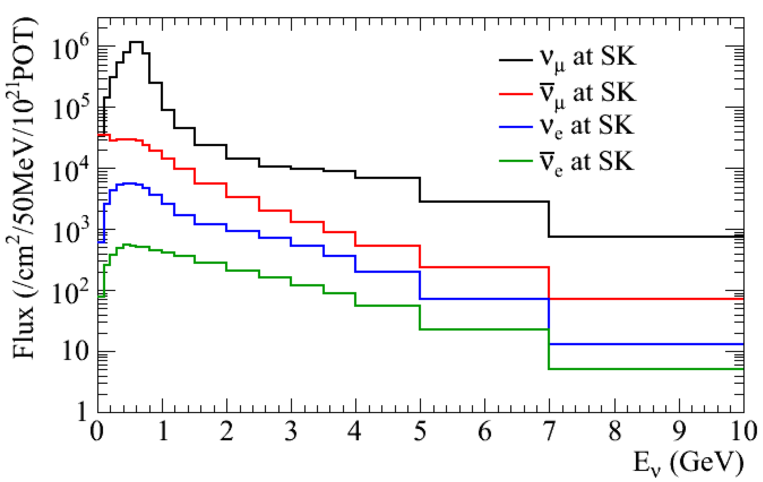
Near detectors observe the neutrinos prior to oscillations

$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{NEAR}$

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ (θ_{23}, θ_{13}, δ_{CP})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})
ν_μ, ν_e backgrounds

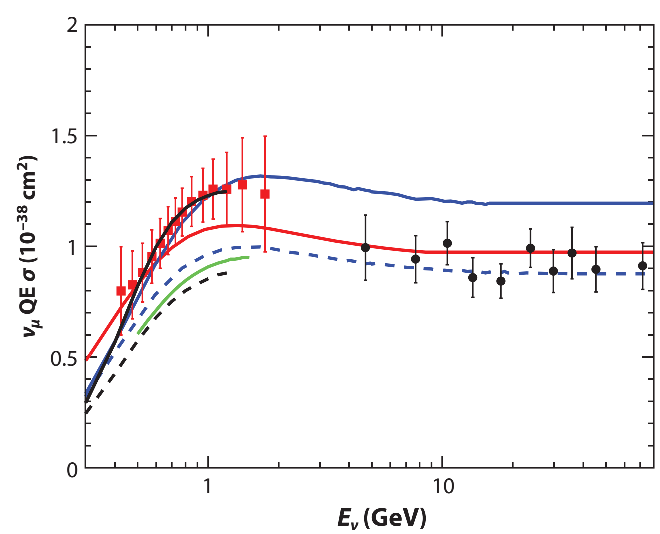
$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

φ_ν



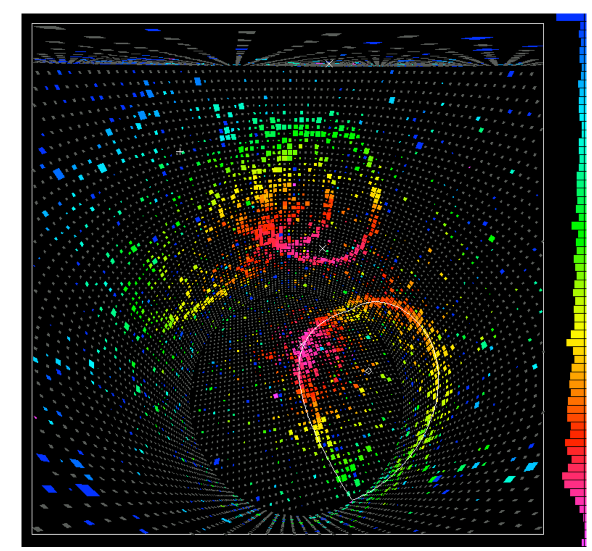
MC simulation of neutrino beamline tuned with external data + operational parameters

σ_ν



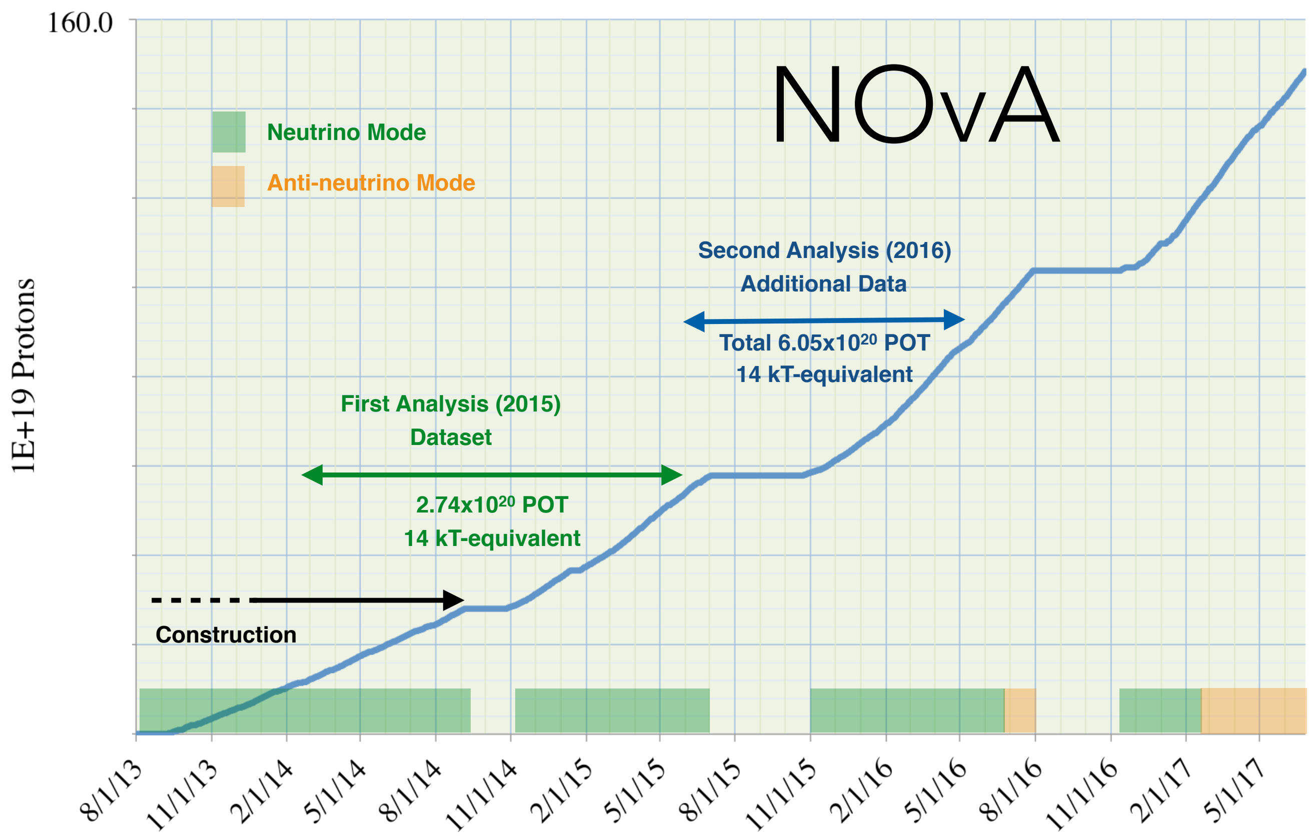
Neutrino cross section and interaction model tuned to external measurements

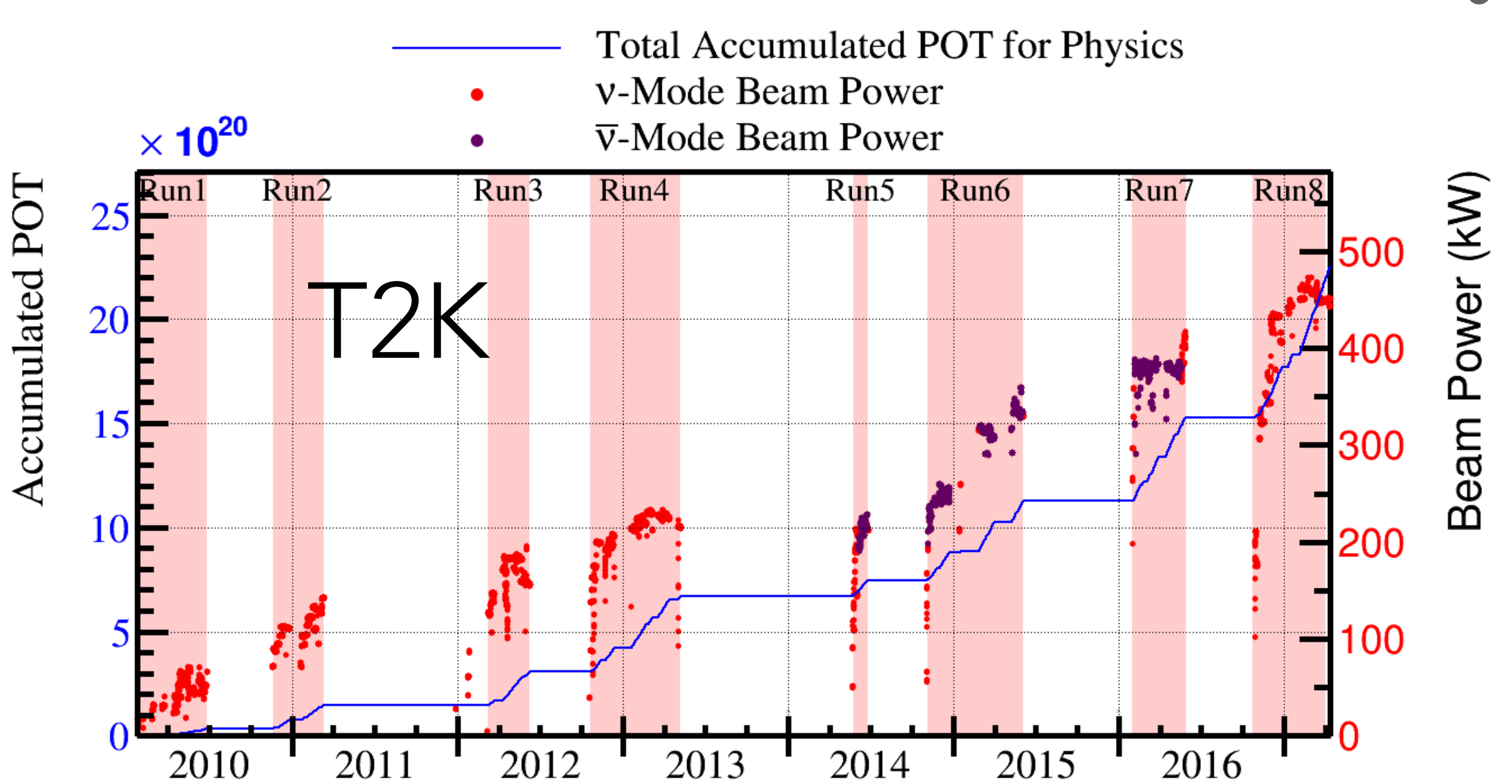
ε_{FAR}



Detector simulation to determine efficiencies/ backgrounds

DATA TAKING

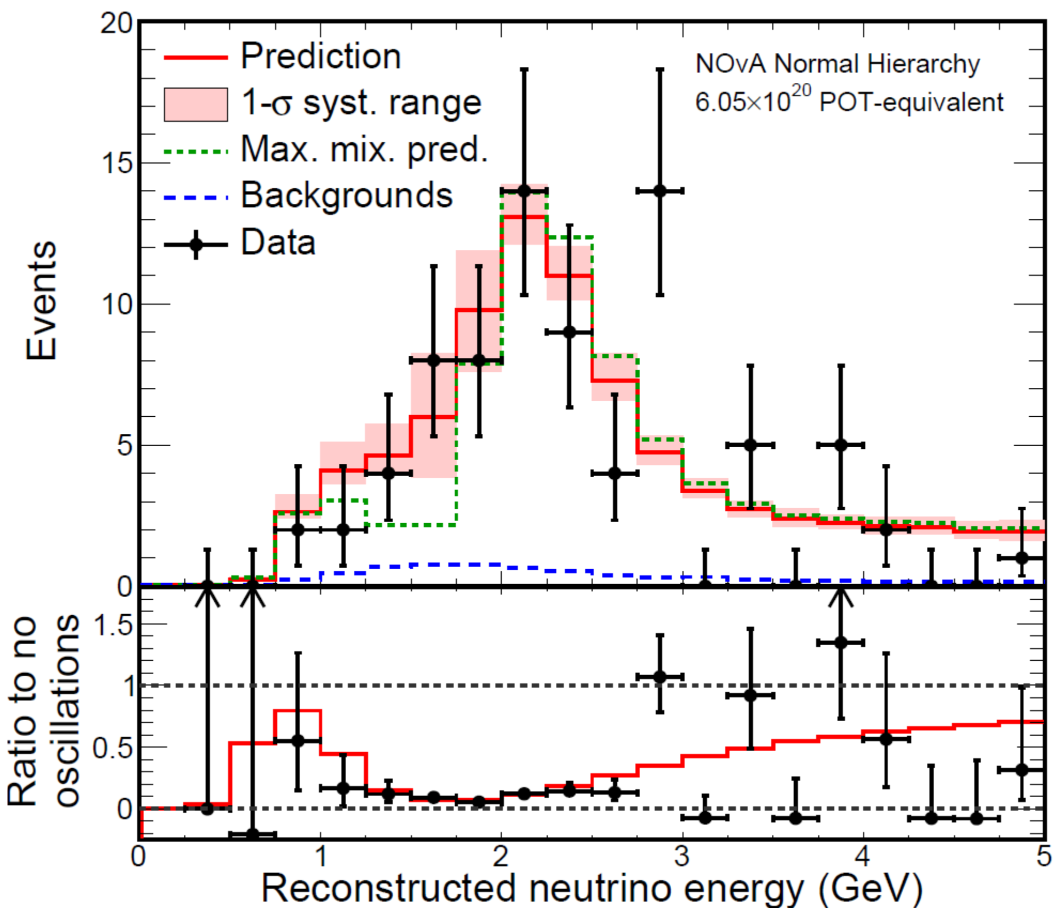


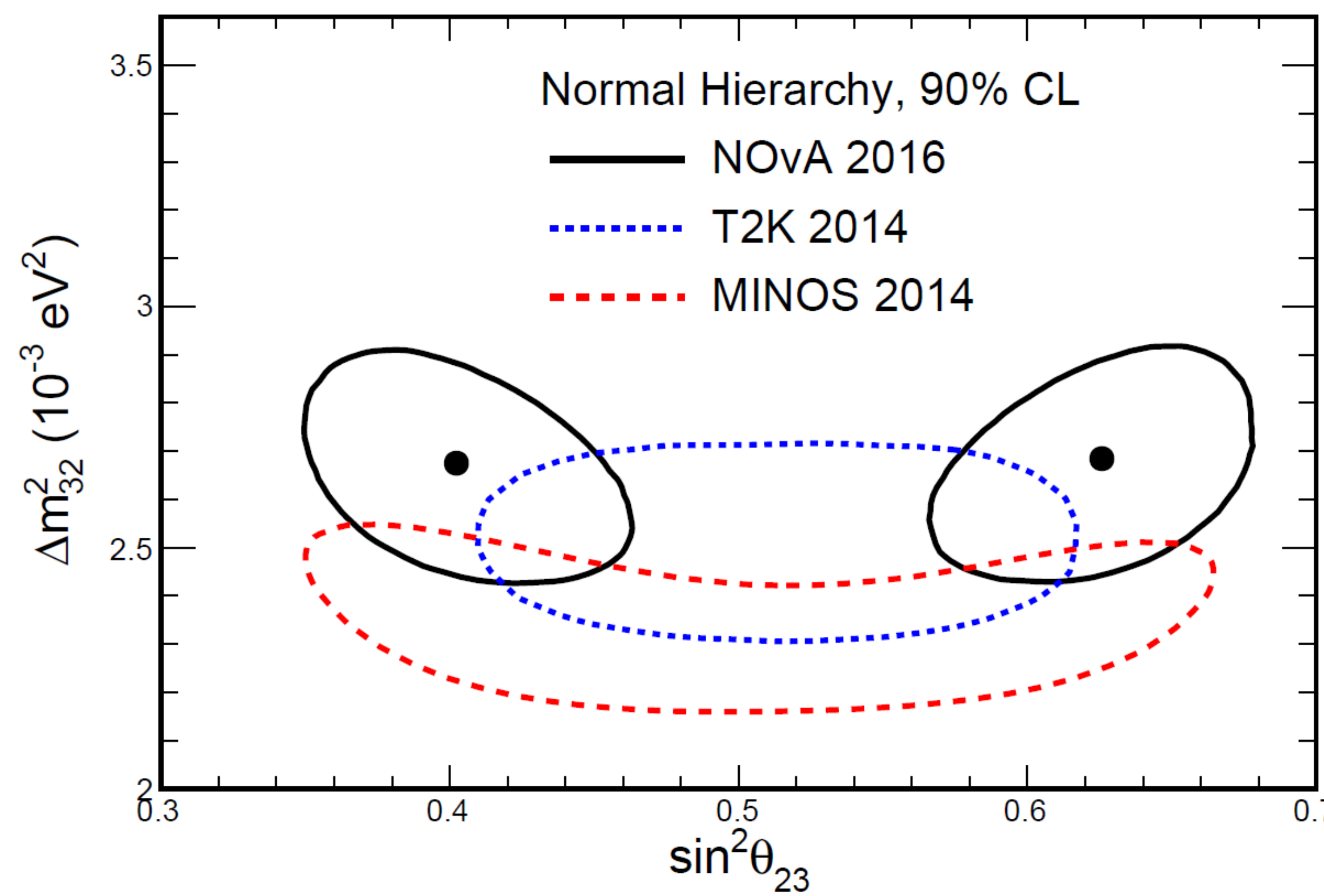


- Both experiments accumulating data at a rapid clip
- NOvA:
  - beam power at ~650 kW regularly
  - antineutrino mode data-taking started
  - (analysis is with neutrino data)
- T2K:
  - beam power reaching 475 kW
  - recently doubled neutrino-mode data
  - combined analysis of neutrino and anti-neutrino mode data

NOvA ν_μ EVENTS

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m^2_{31} \frac{L}{4E}$$





- Large disappearance effect observed
  - 78 ν_μ events vs. 473 in absence of oscillations
- "Maximal" mixing disfavored (2.6 σ)

$$\sin^2\theta_{23} = \begin{array}{l} 0.404^{+0.030}_{-0.022} \\ 0.624^{+0.022}_{-0.030} \end{array}$$

$$\Delta m^2_{32} = 2.67 \pm 0.11 \times 10^{-3} \mathrm{eV}^2$$

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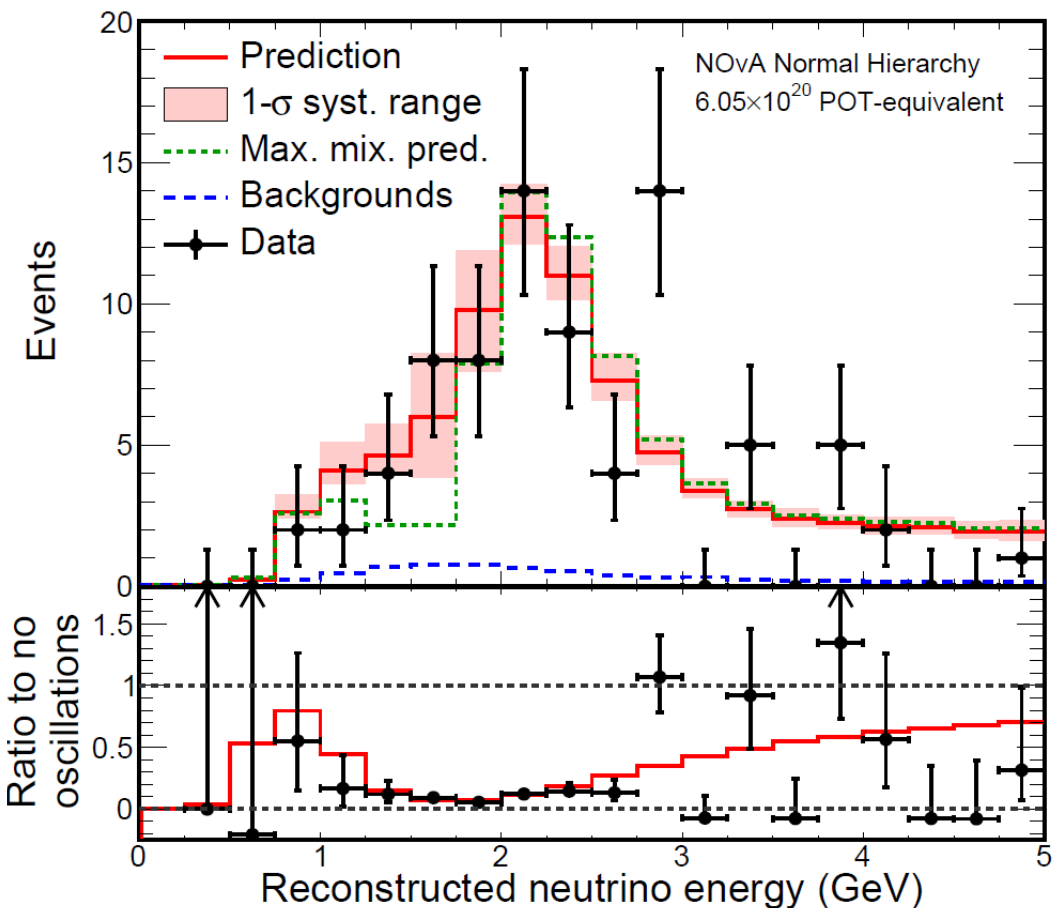

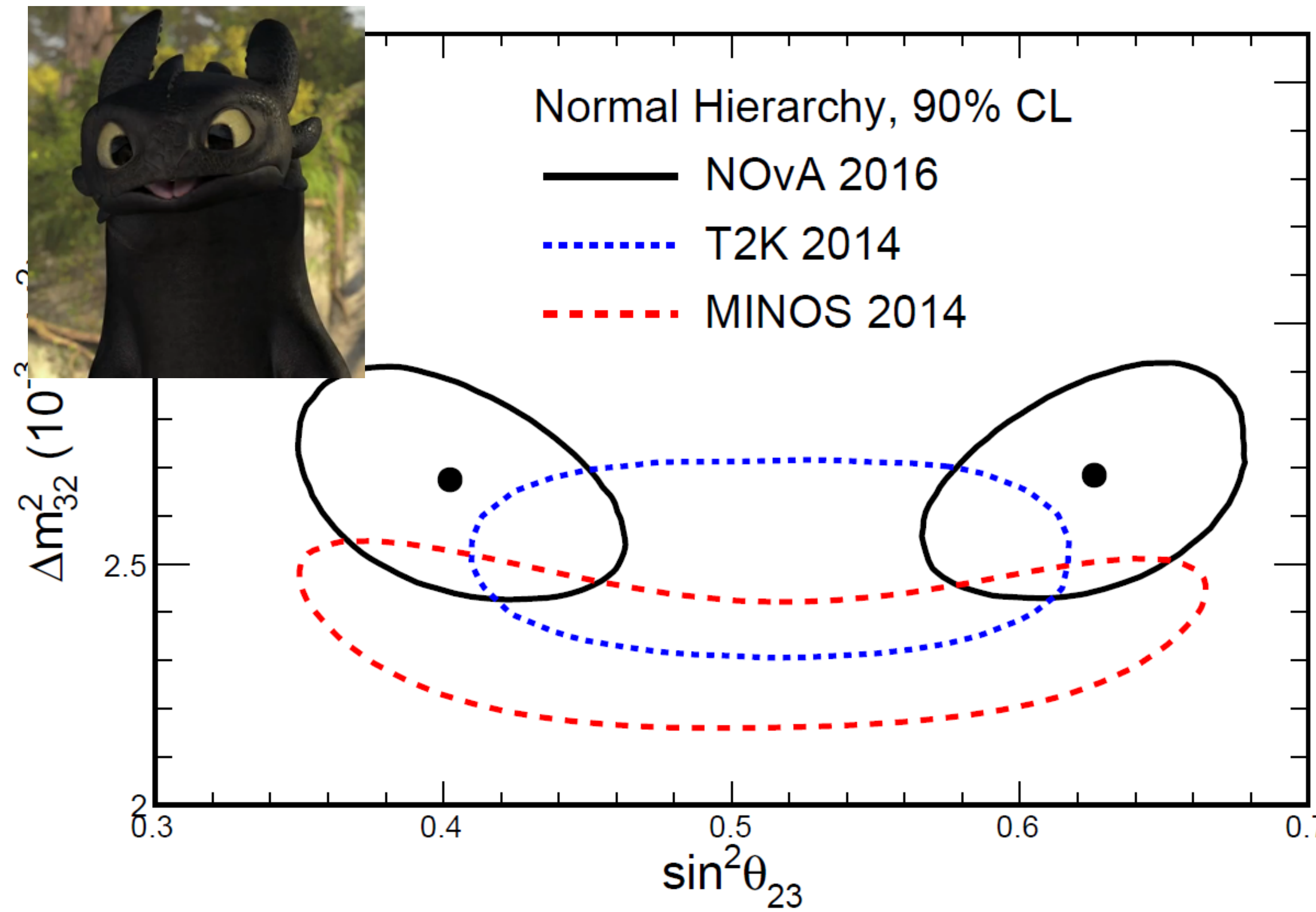

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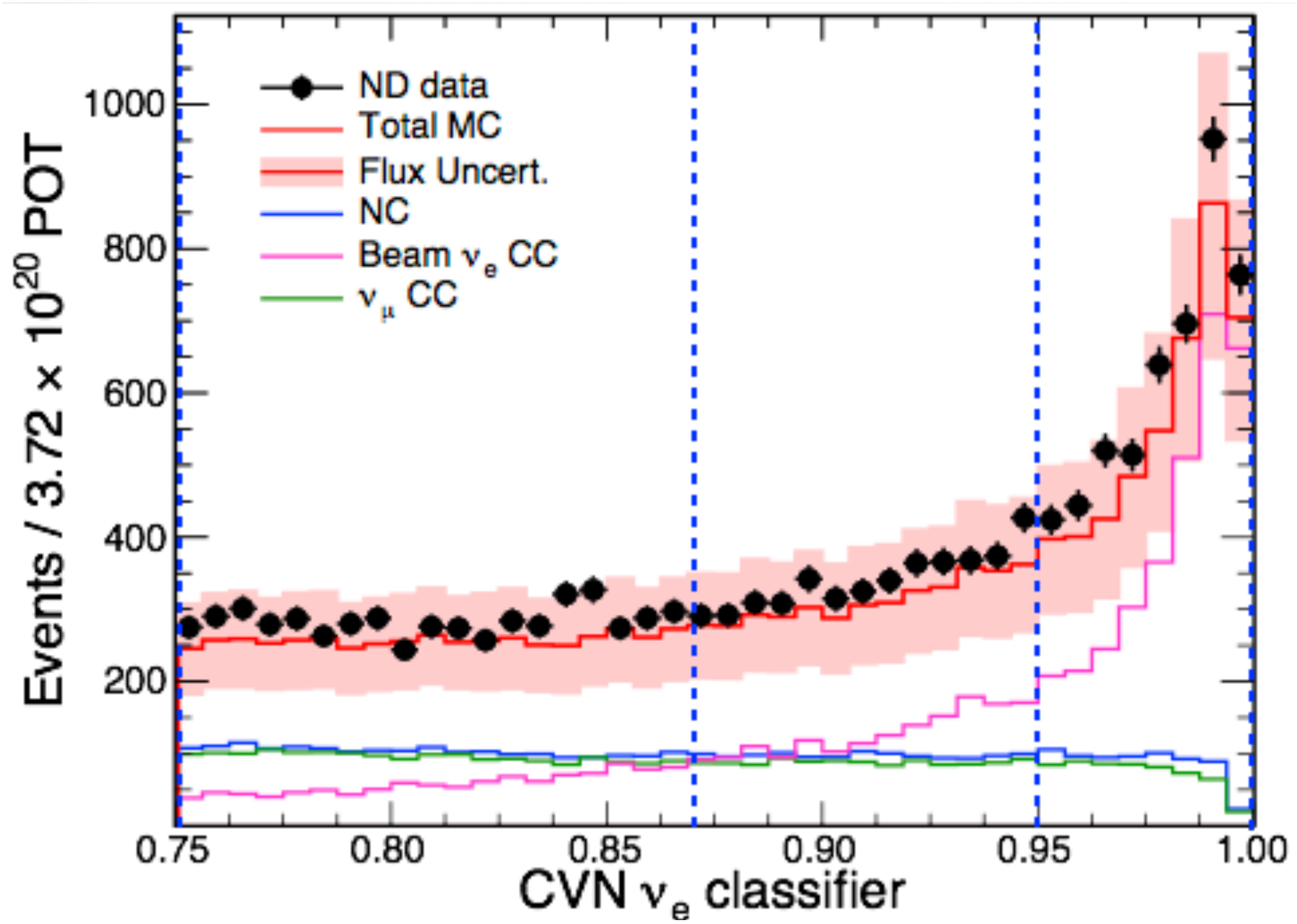
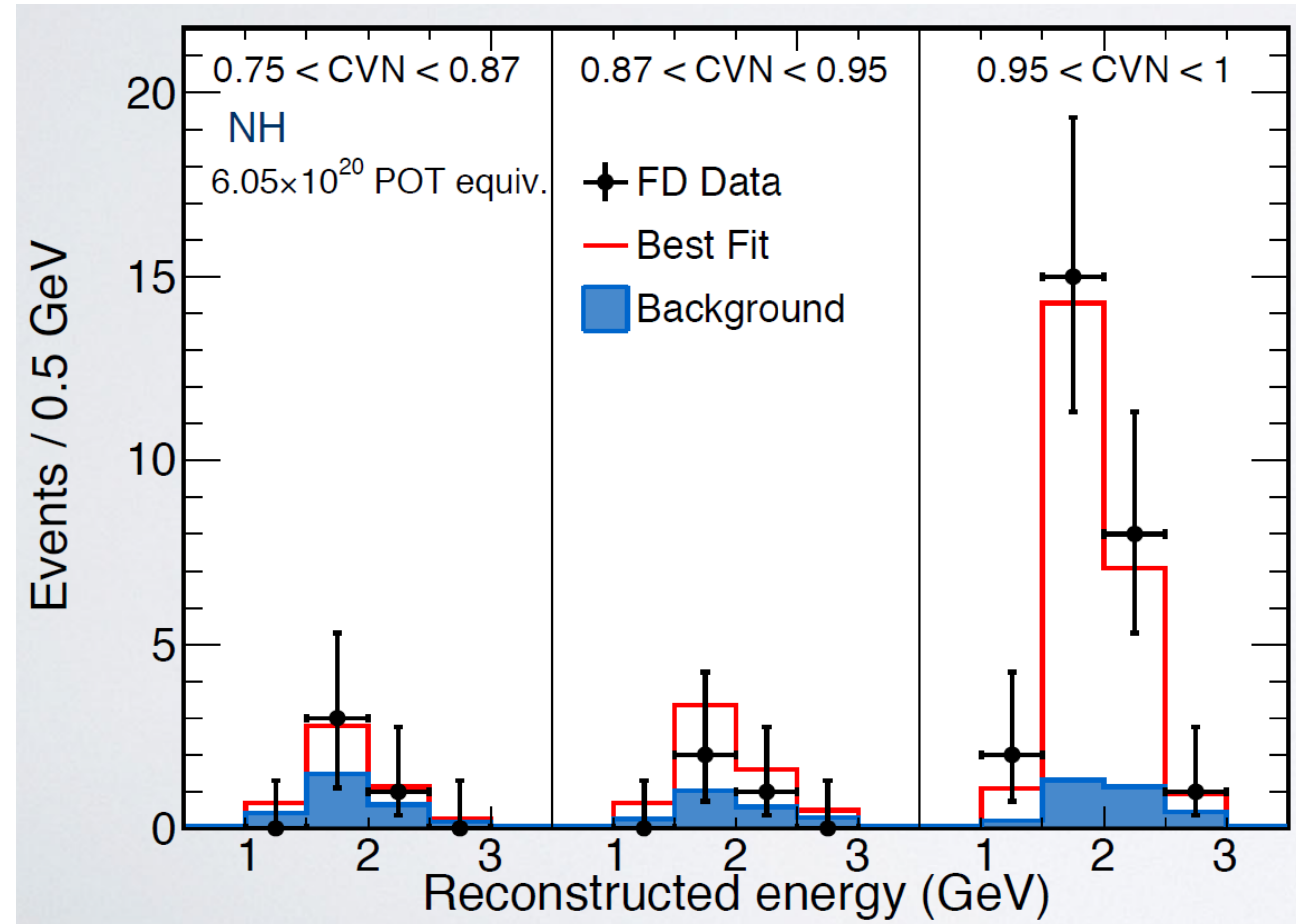
NOvA ν_e EVENTS

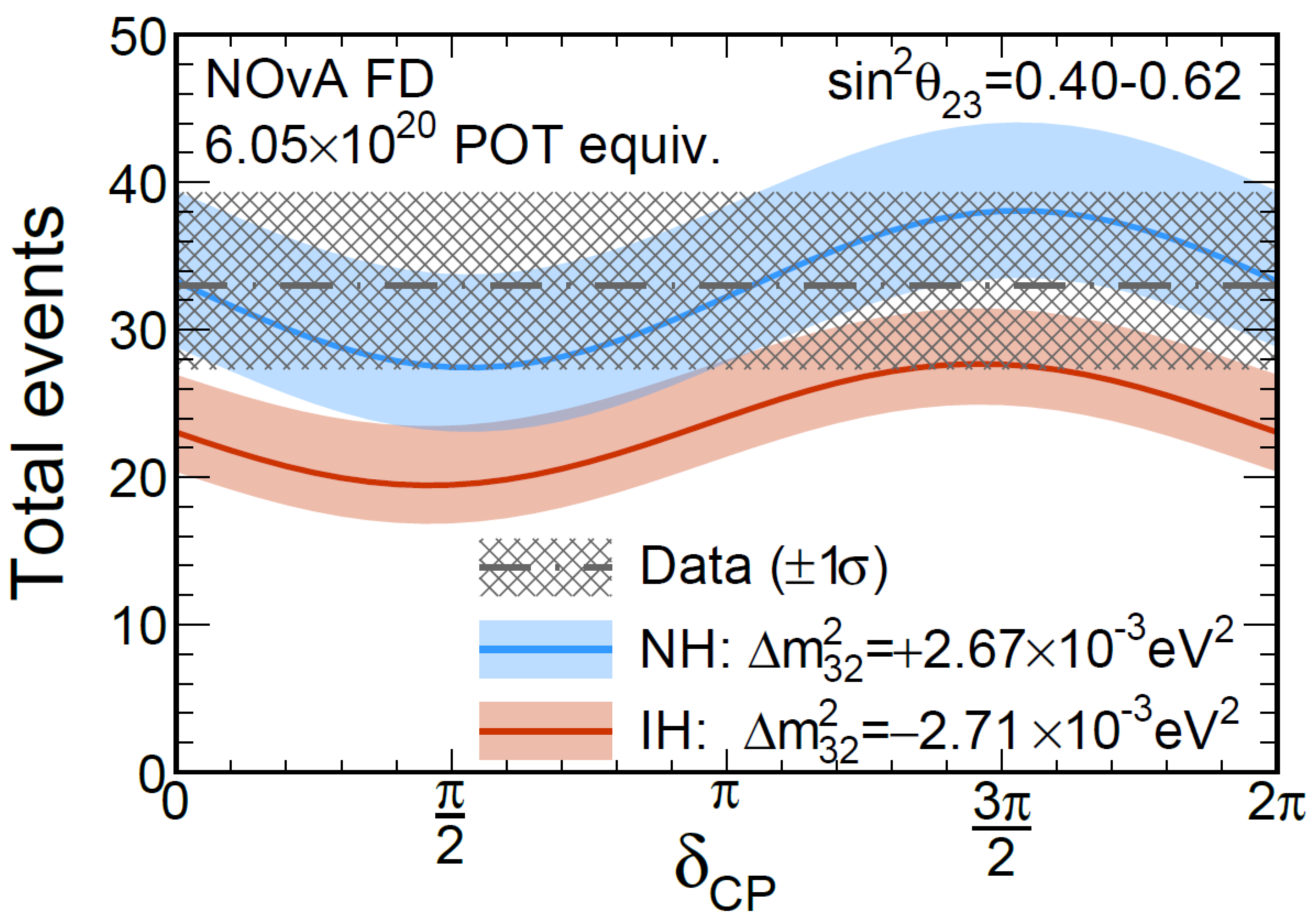


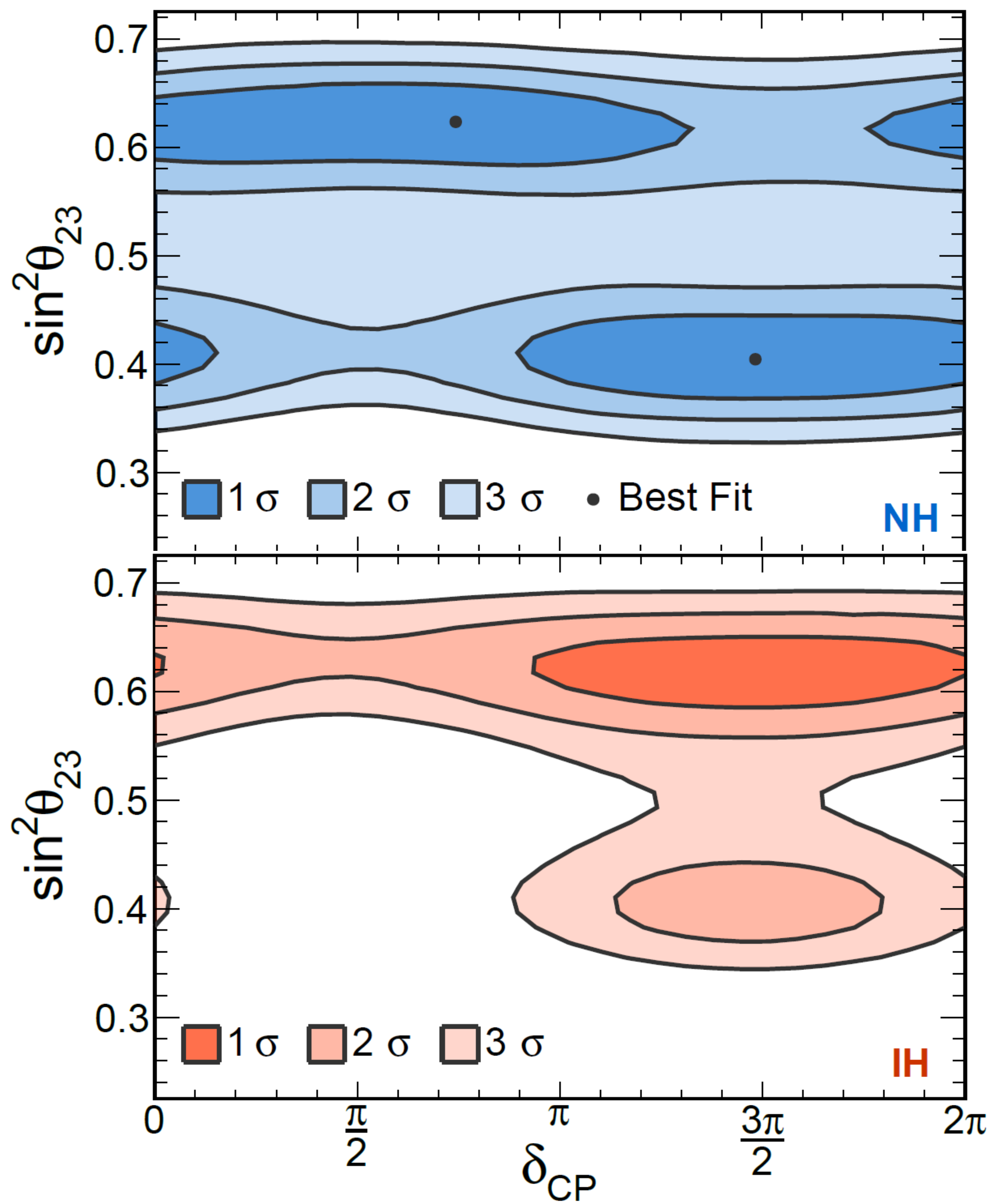


- Convolutional neural network used to select ν_e events
  - ~30% improvement in efficiency relative to previous methods
  - verified with ν_e events in near detector (left)
- 33 events observed with background of 8.2±0.8
  - binned analysis in CVN classifier and energy

RESULTS

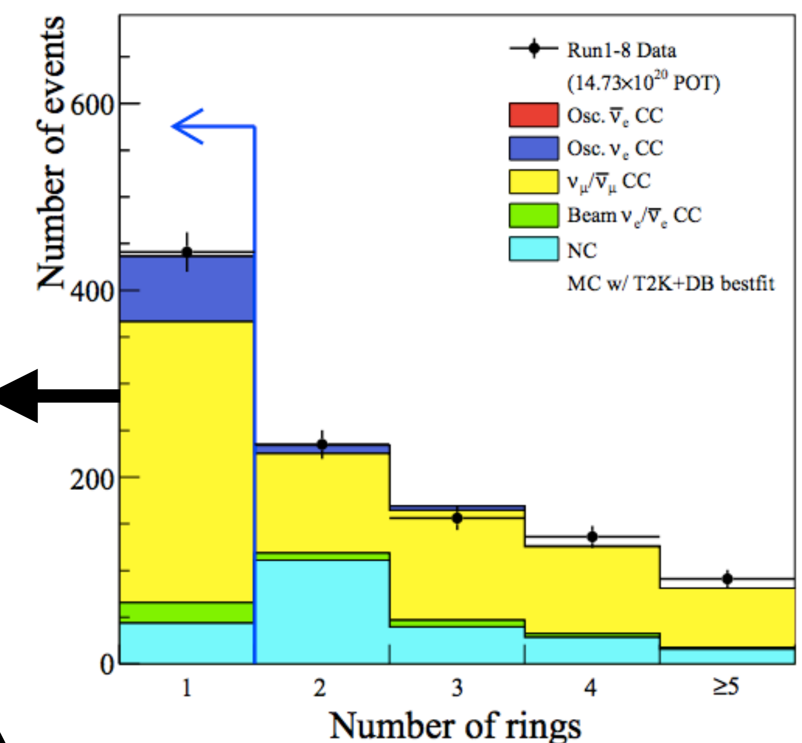
- Lower octant ($\sin^2\theta_{23} = 0.4$)
  - $\delta_{CP} = +3\pi/2$ ($-\pi/2$) preferred
- Upper octant ($\sin^2\theta_{23} = 0.6$)
  - $\delta_{CP} = +\pi/2$ preferred
- Large regions of IH disfavoured (except near $\delta_{CP} = +3\pi/2$ ($-\pi/2$))



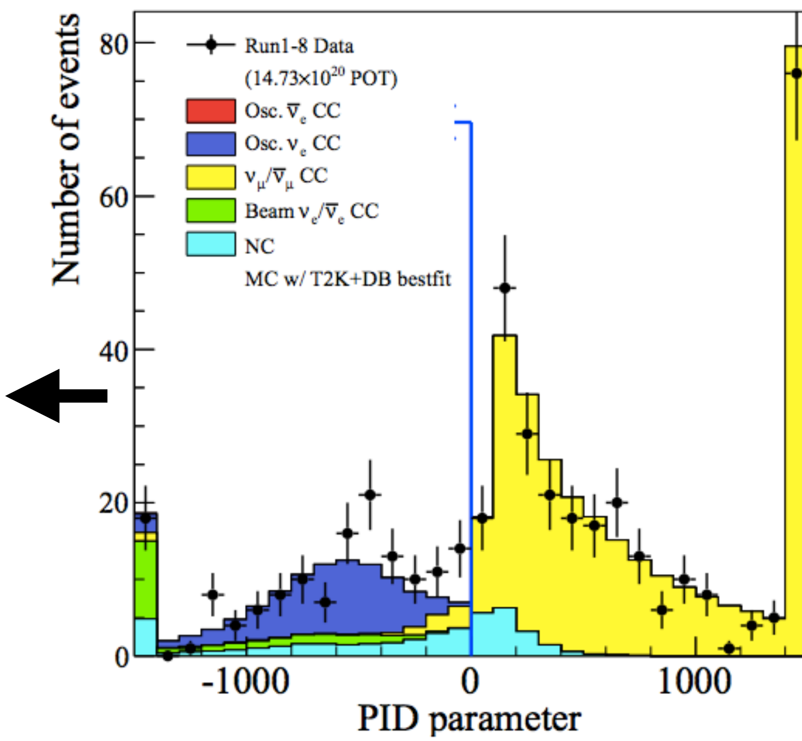


T2K SELECTION SCHEME (SIMPLIFIED)

START

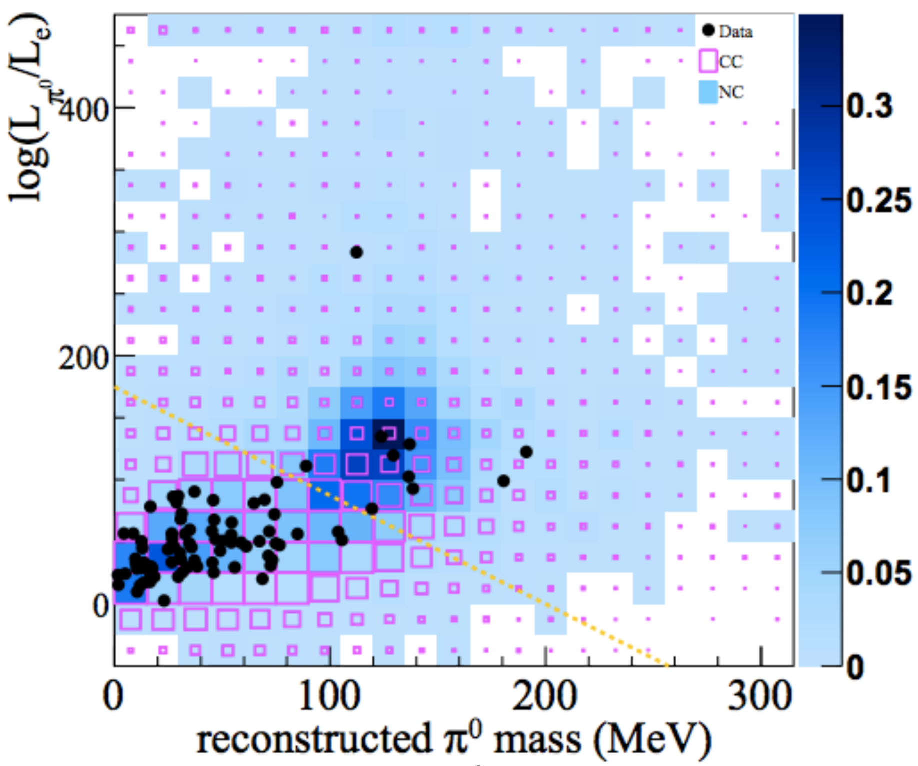


select 1 ring events

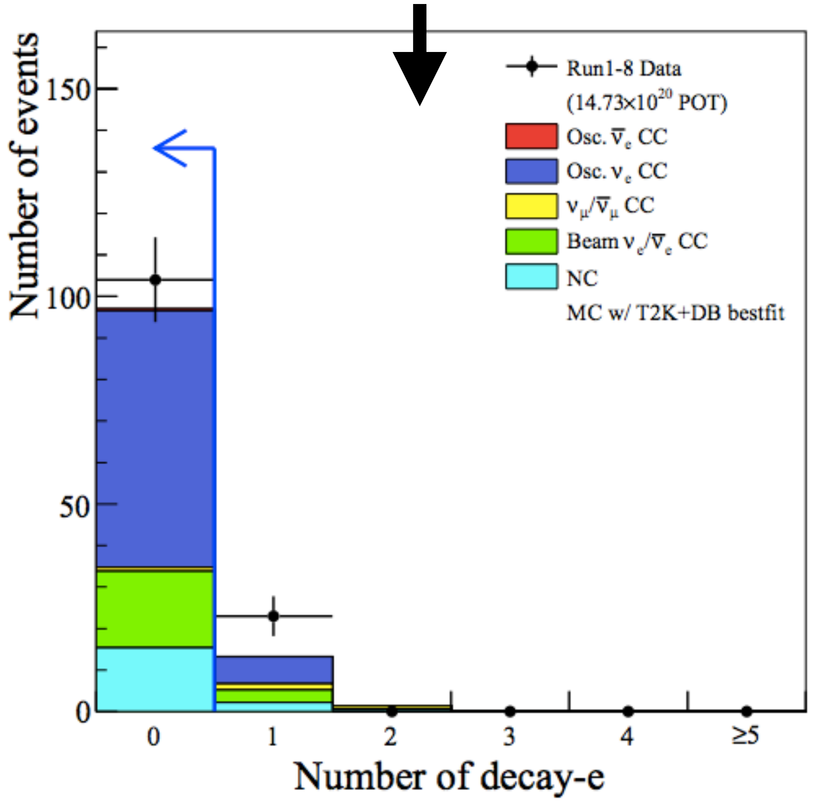


separate e/μ-like events

"1Rμ" events



suppress π^0 background



- ν-mode
  - Separate 0 and 1 decay electron ($\pi^+ \to \mu^+ \to e^+$)
- $\bar{\nu}$-mode
  - only 0 decay electron

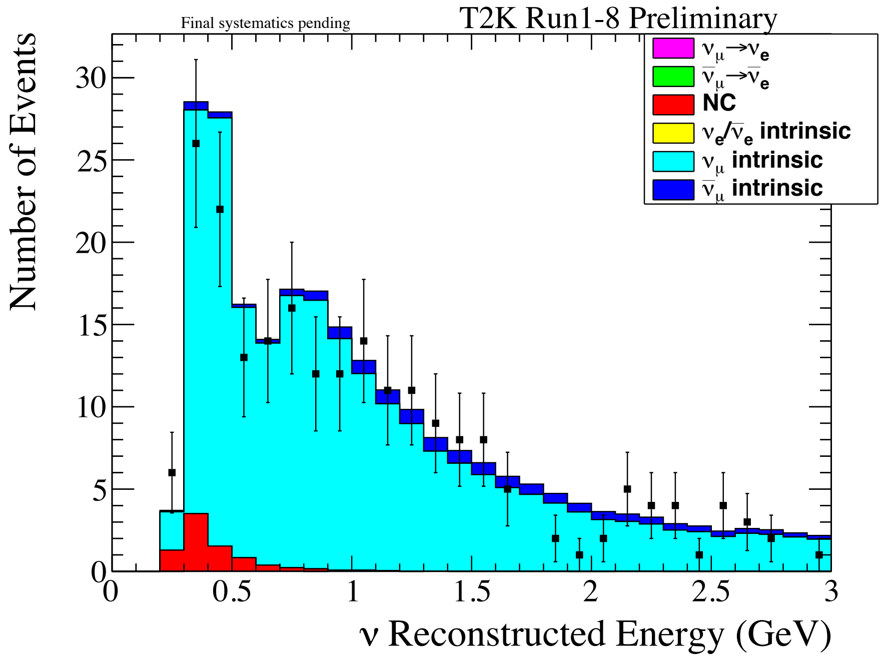
$$\nu_\ell + n \to \ell + p$$

$$\nu_\ell + p \to \ell + \Delta^{++}$$

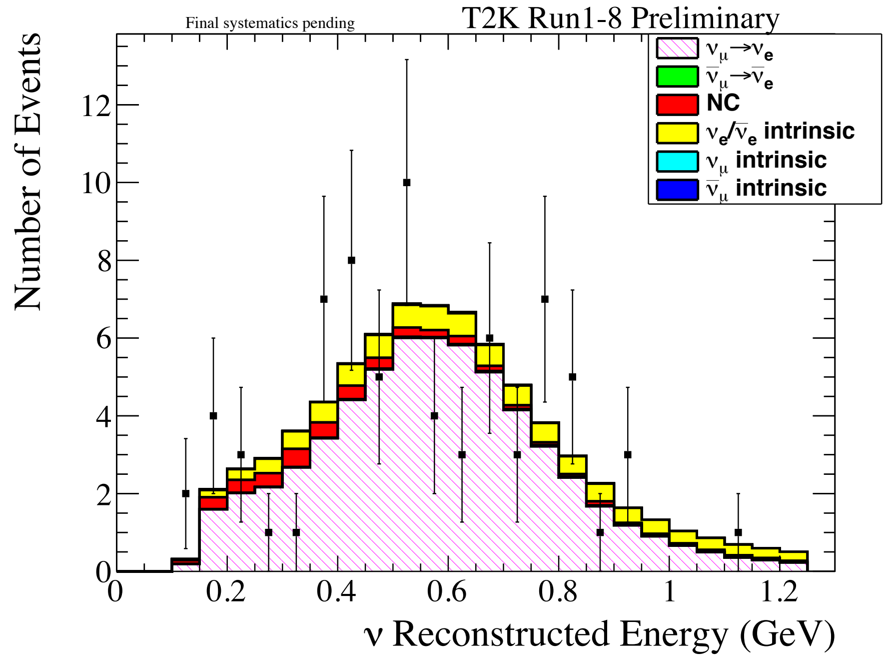
- Five samples:
  - ν-mode
    - 1Rμ
    - 1Re 0 d.e., 1Re 1 d.e.
  - $\bar{\nu}$-mode
    - 1Rμ
    - 1Re 0 decay electron

T2K EVENTS

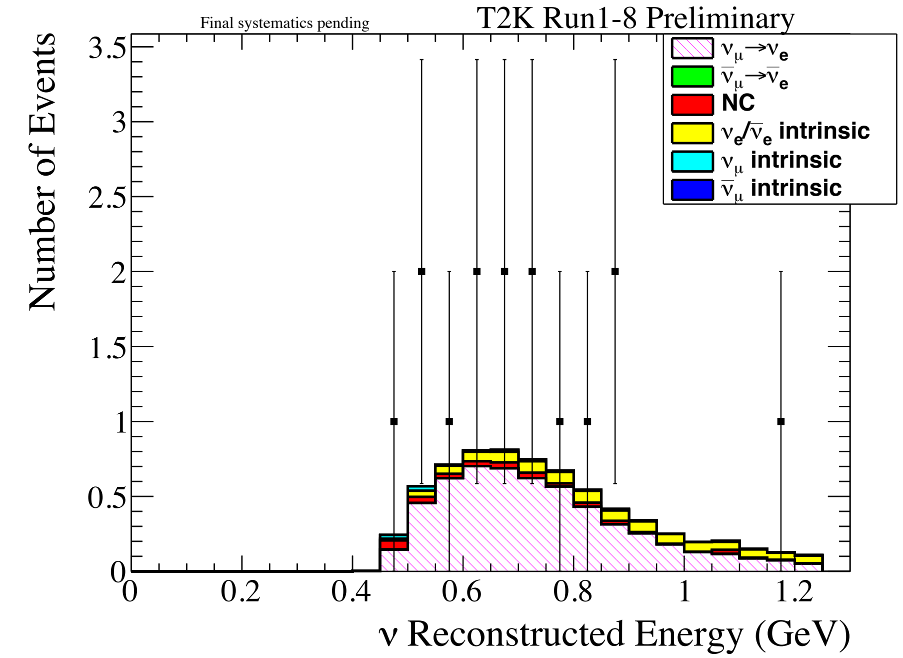
ν-mode 1Rμ



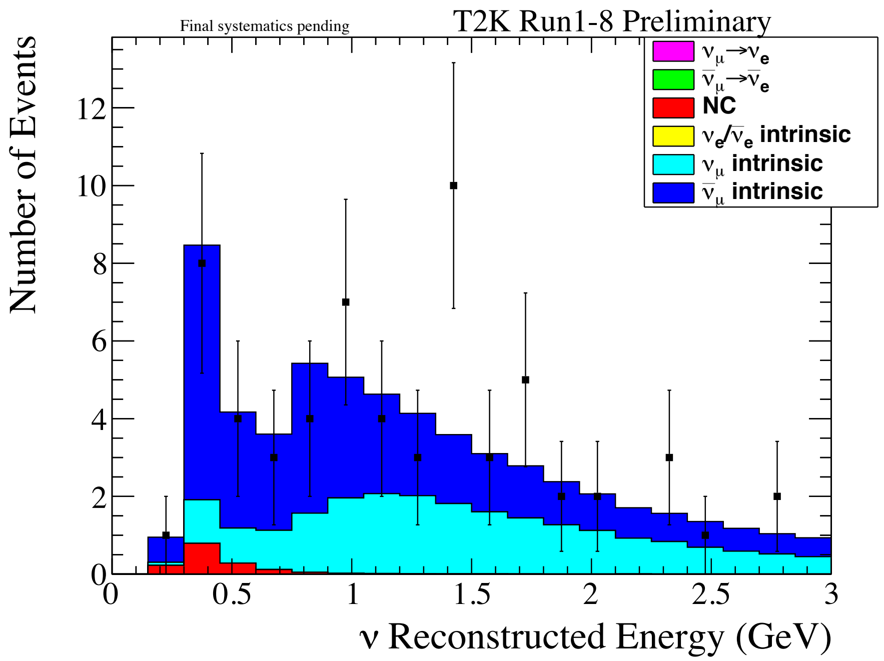
ν-mode 1Re, 0 d.e.



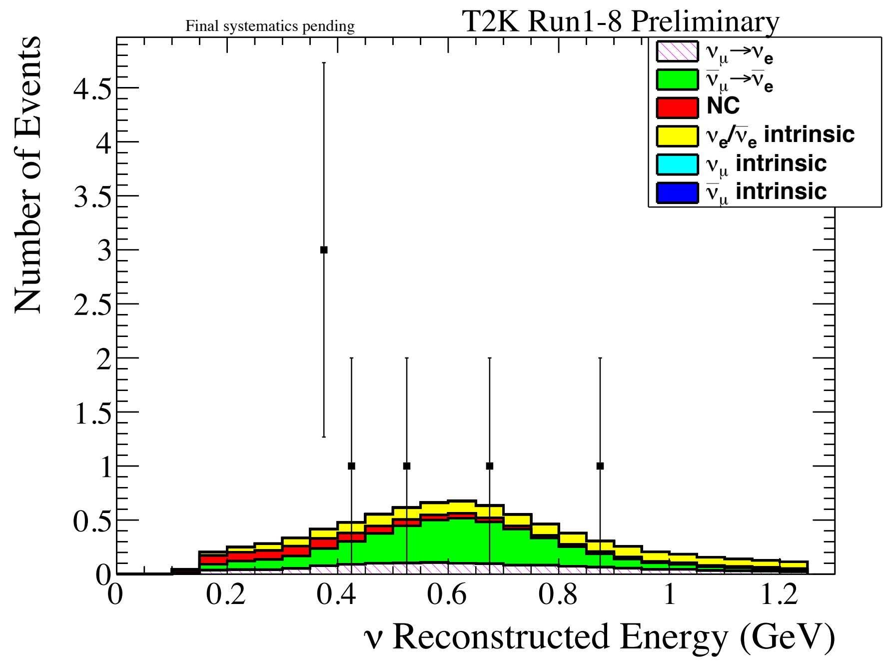
ν-mode 1Re, 1 d.e.



$\bar{\nu}$-mode 1Rμ



$\bar{\nu}$-mode 1Re, 0 d.e.



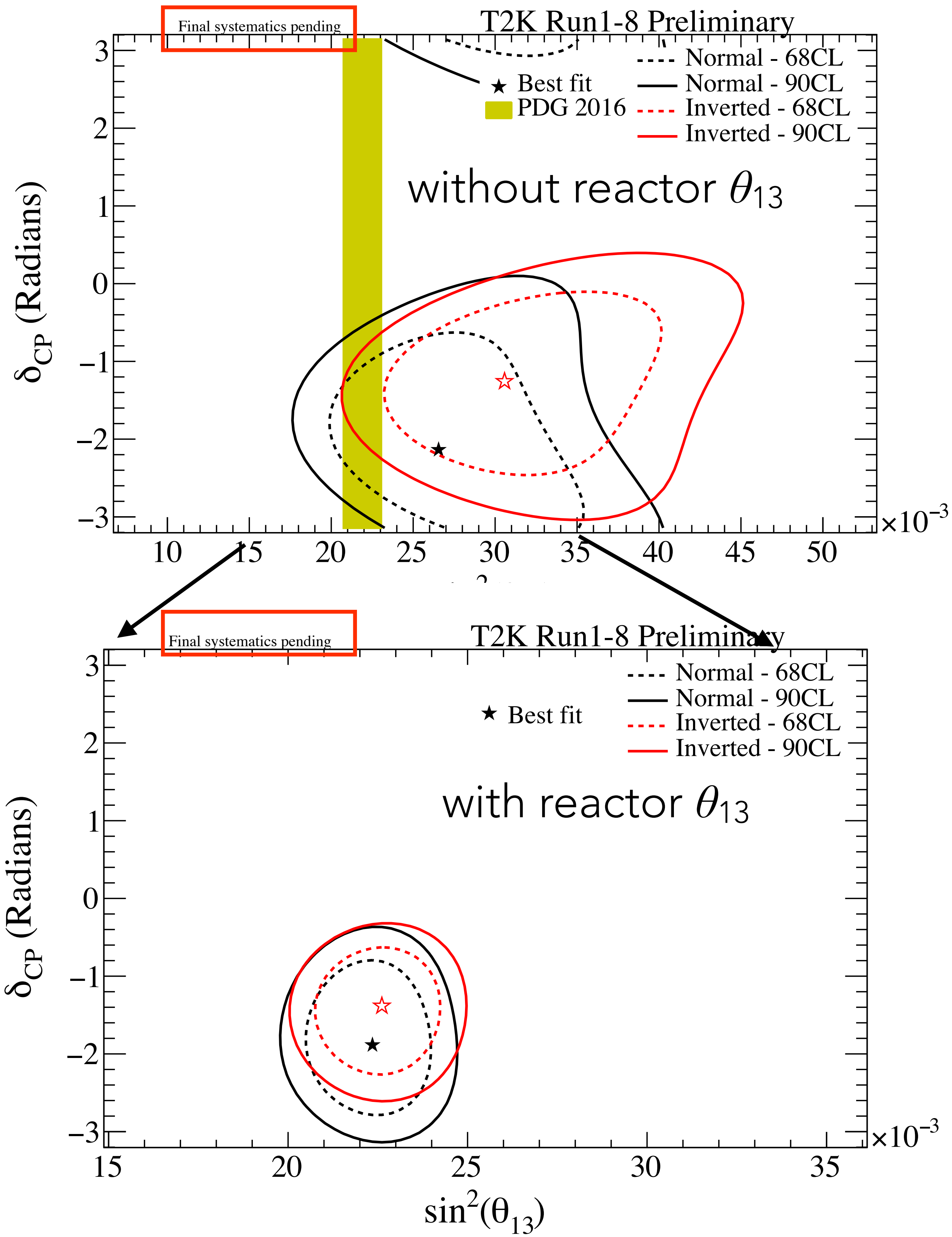
- New ML-based algorithm fully in use
- 20-30% increase in effective efficiency for selection ν_e events

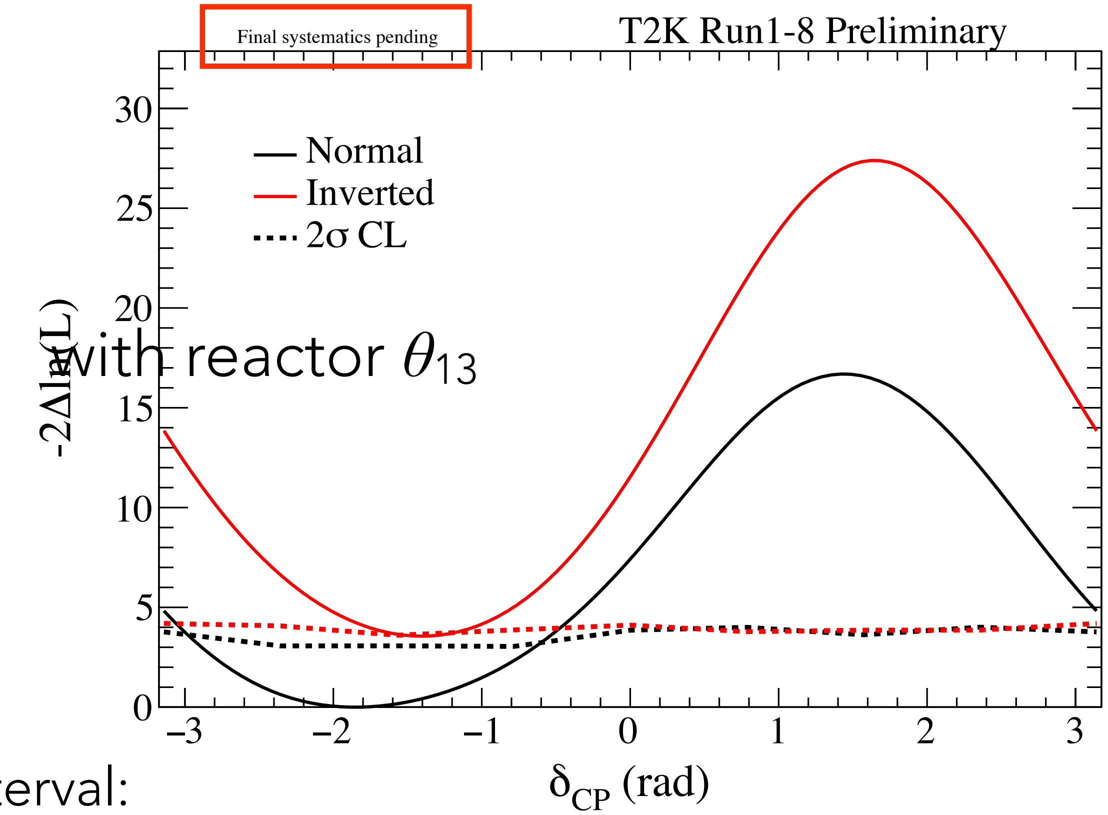
EVENT RATES

		$-\pi/2$	0	$+\pi/2$	π	**OBS**
ν mode	1Re 0 d.e.	**73.5**	61.4	49.9	61.9	**74**
	1Re 1 d.e.	**6.9**	6.0	4.9	5.8	**15**
$\bar{\nu}$ mode	1Re 0 d.e.	**7.9**	9.0	10.0	8.9	**7**
ν mode	1Rμ	**267.8**	267.4	267.7	268.2	**240**
$\bar{\nu}$ mode	1Rμ	**63.1**	62.9	63.1	63.1	**68**

- ν_μ candidate prefer maximal disappearance
  - $\sin^2\theta_{23}$ ~0.5
- ν_e candidates favor large appearance in $\nu_\mu \rightarrow \nu_e$
  - normal hierarchy, δ_{CP} ~$-\pi/2$ ($+3\pi/2$)

T2K RESULTS



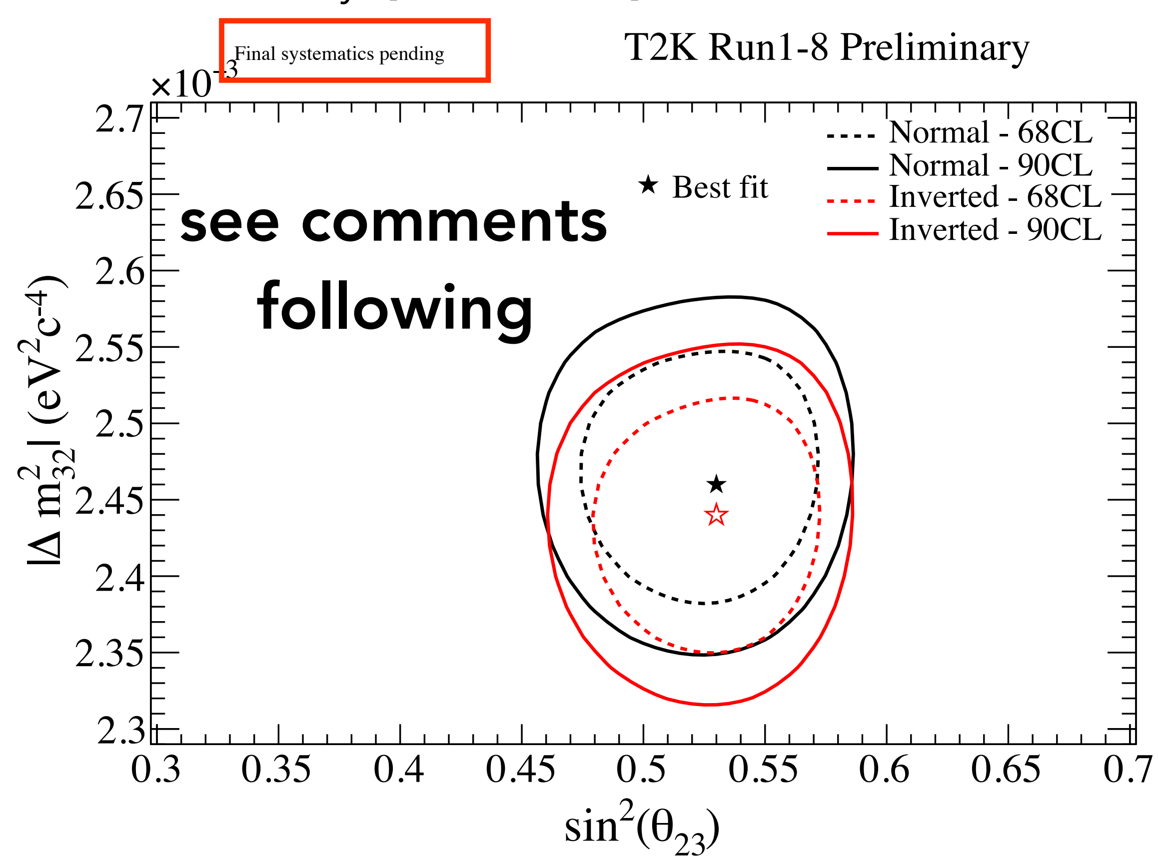


1 σ δ_{CP} interval:

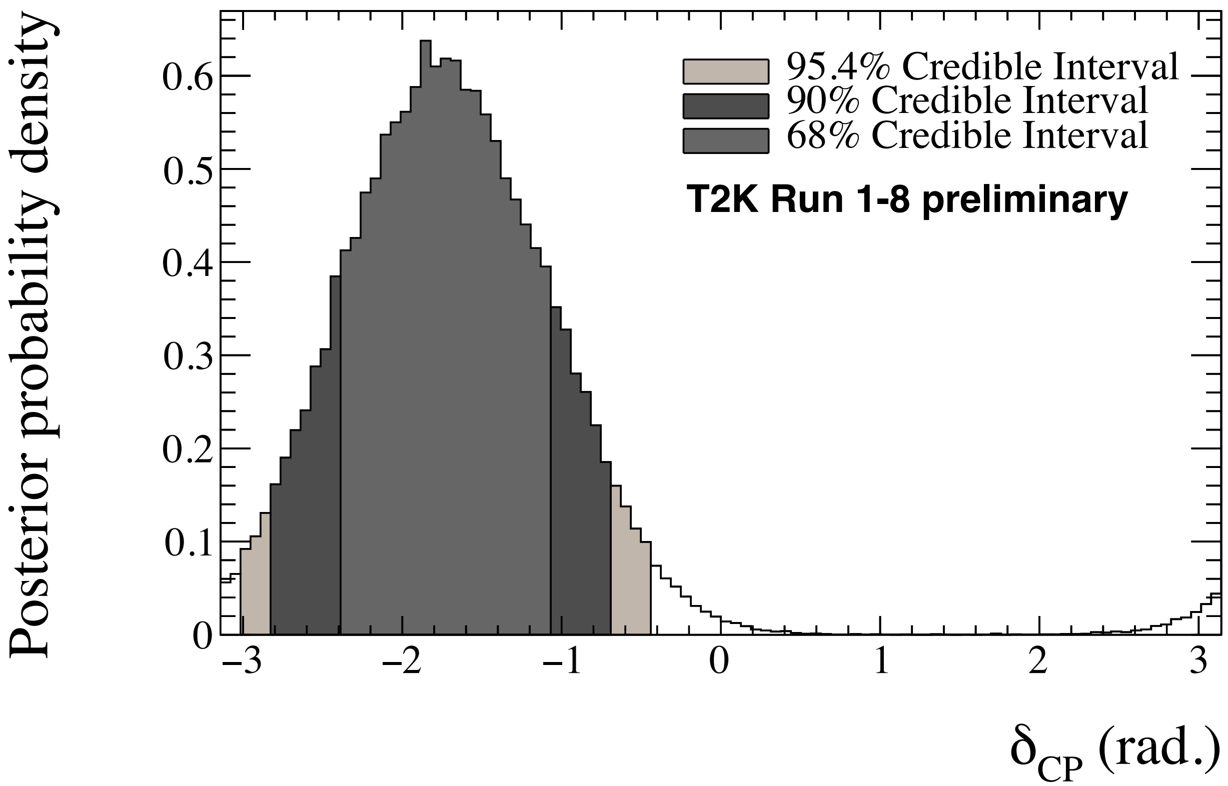
- Normal hierarchy: [-2.49, -1.23] radians

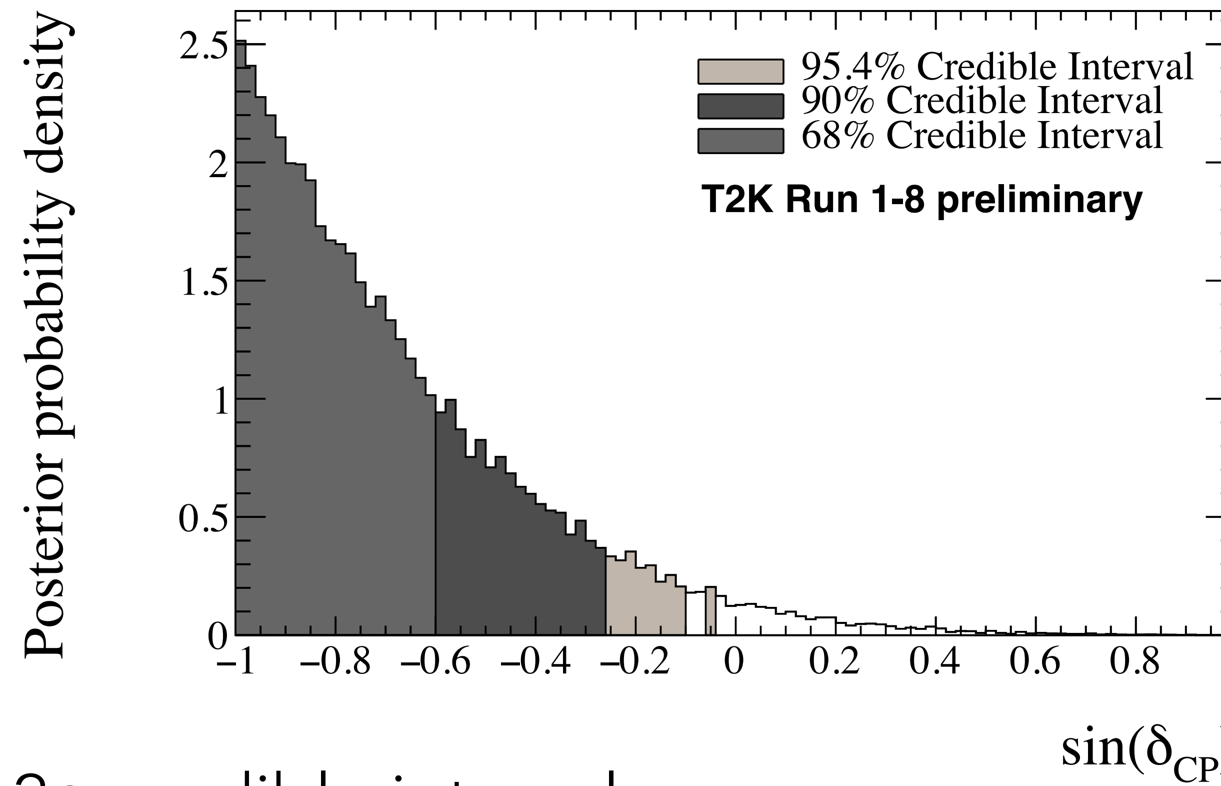
2 σ δ_{CP} intervals:

- Normal hierarchy: [-2.98, -0.60] radians
- Inverted hierarchy: [-1.53, -1.18] radians



T2K BAYESIAN ANALYSIS





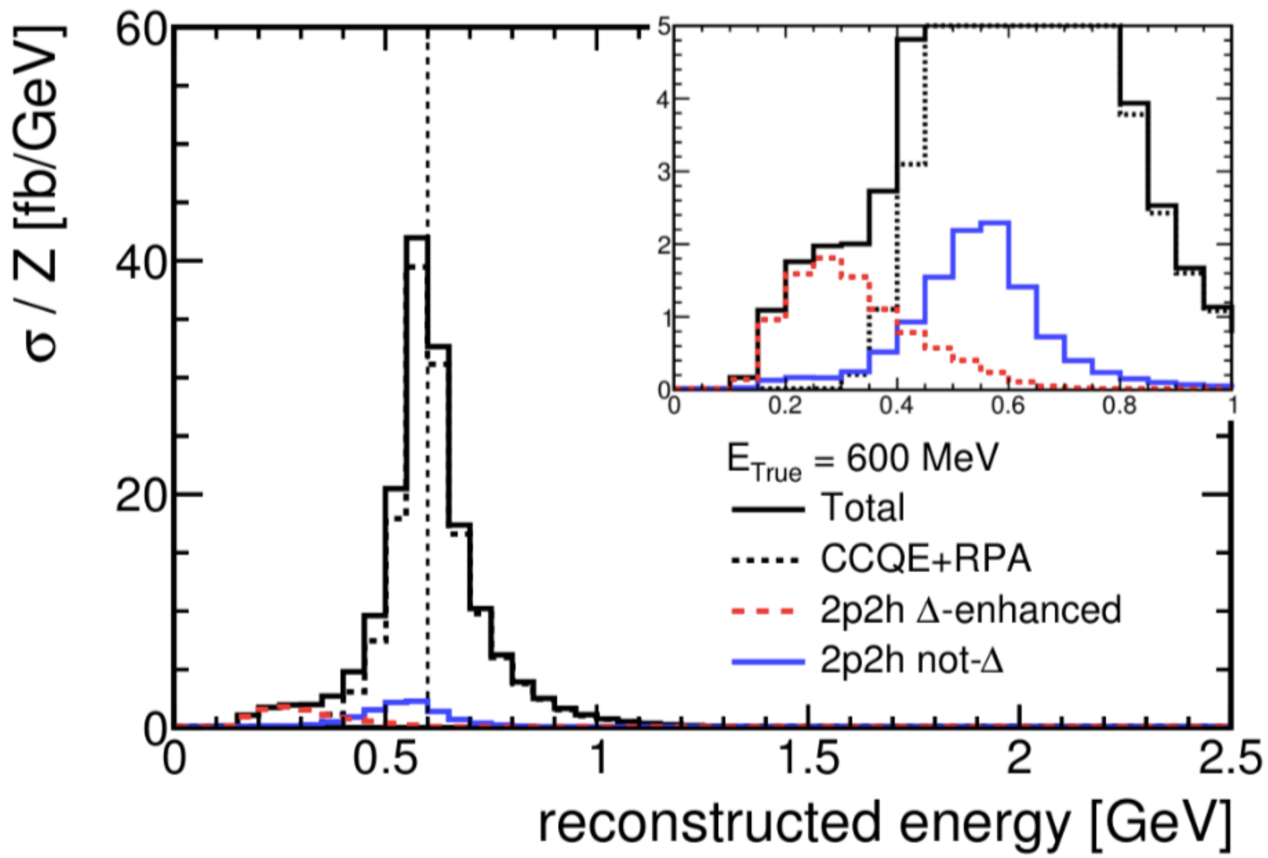
- Posterior probabilities based on Markov chain Monte Carlo
- δ_{CP}: two priors:
  - flat in δ_{CP}
  - flat in sin δ_{CP} (amplitude of CP asymmetry)
- Weak preference for normal hierarchy and upper octant ($\sin^2\theta_{23}$ >0.5)

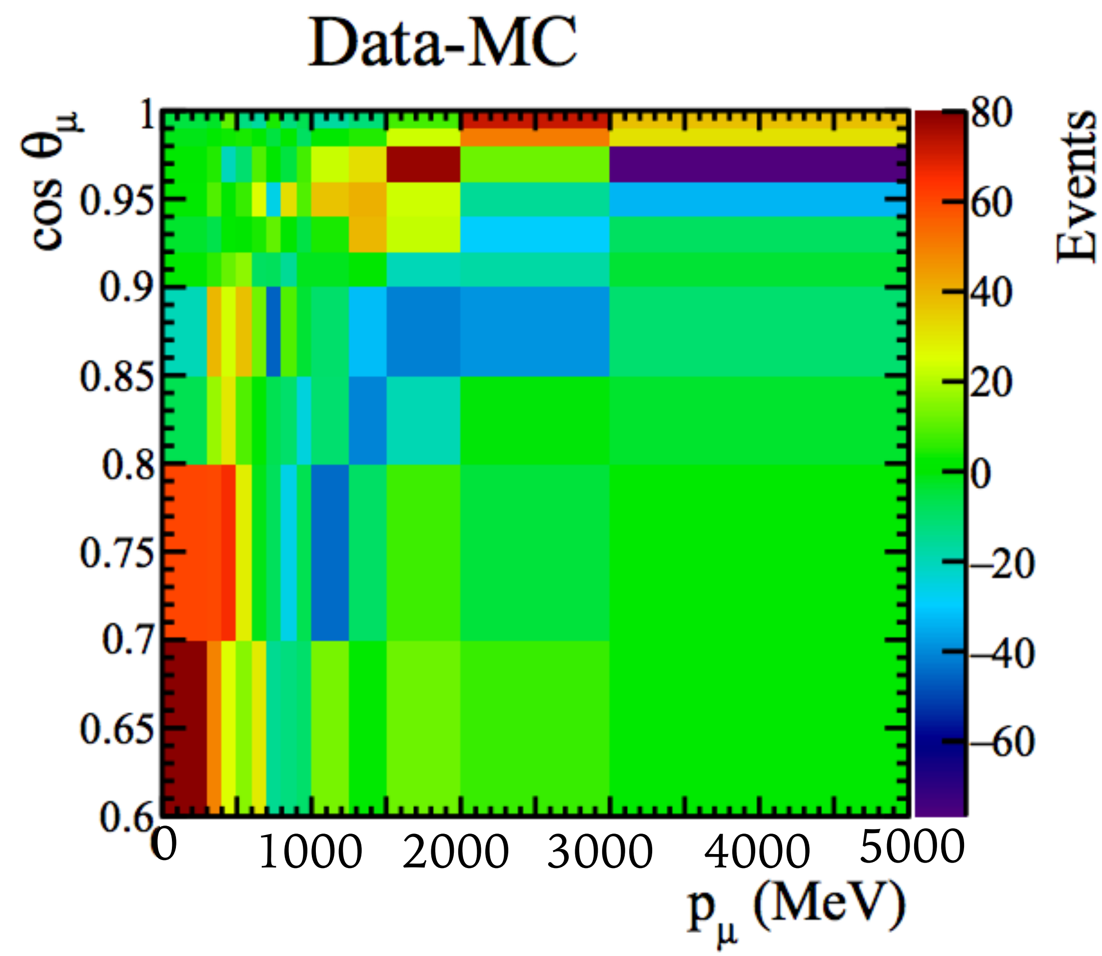
2σ credible intervals

- Flat prior on δ_{CP}: [-3.02, -0.44] rad.
- Flat prior on sin δ_{CP}: [-3.04, -0.10] rad.

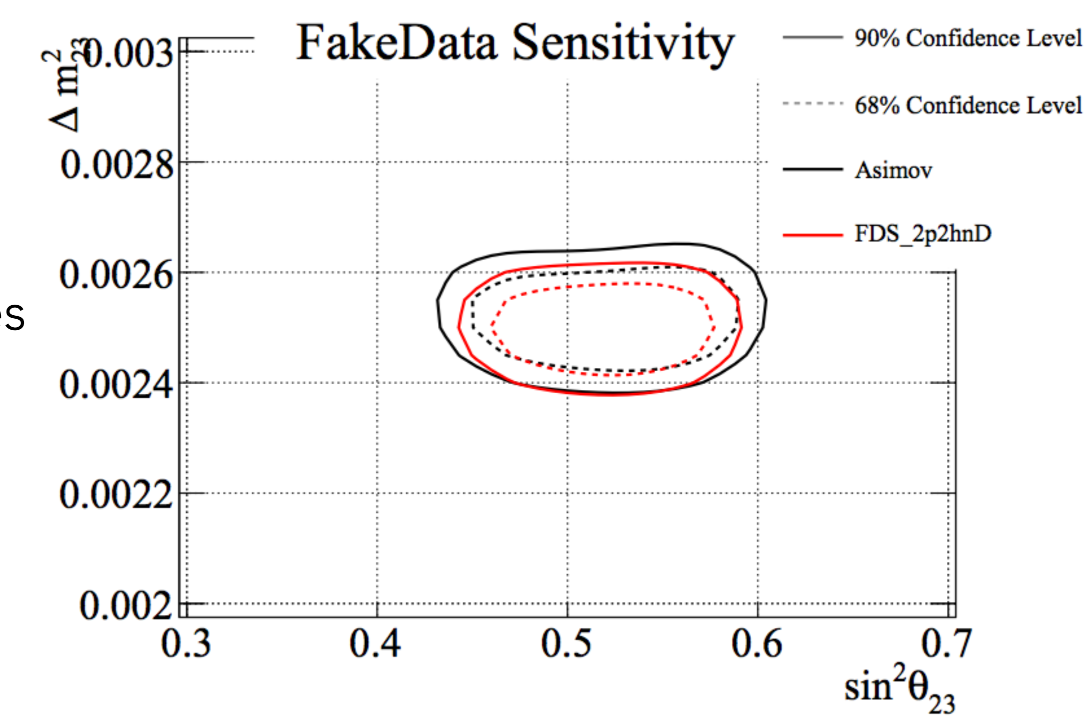
	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.214	0.022	0.236
$\sin^2\theta_{23} > 0.5$	0.668	0.096	0.764
SUM	0.882	0.118	1.000

T2K MODEL SENSITIVITY





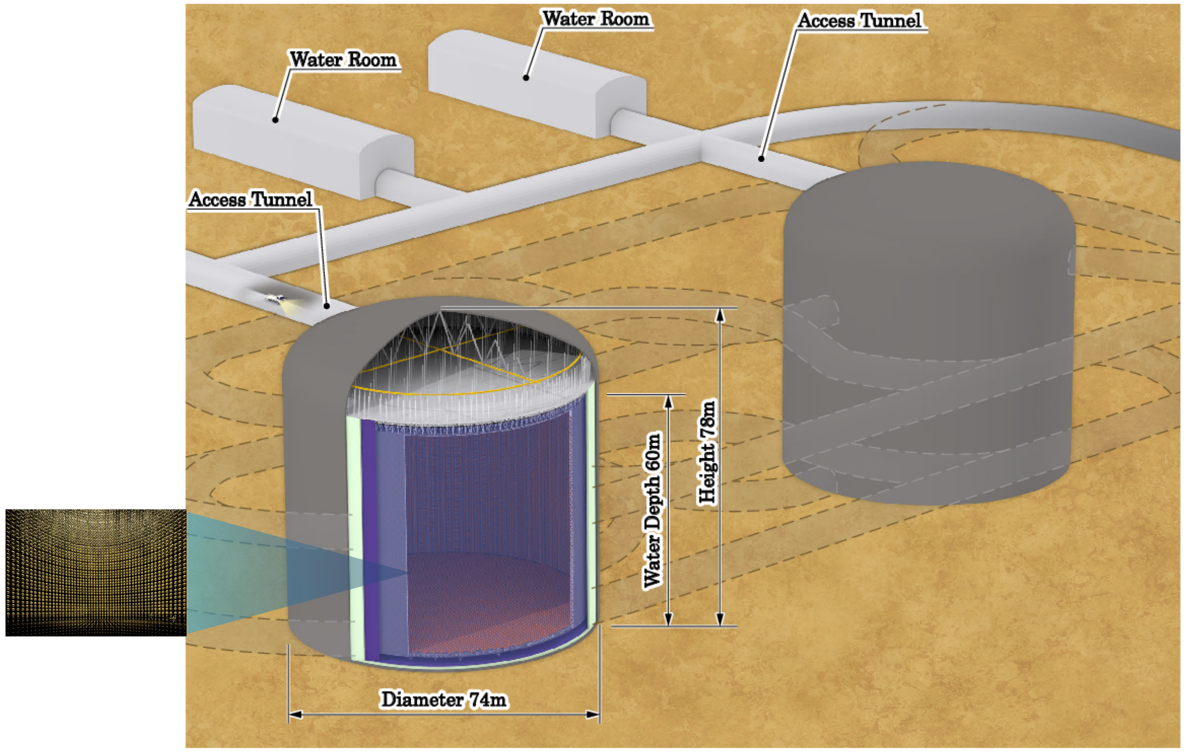
- Significant “2p2h” interactions with multi-body dynamics
- Two modes with differing kinematics:
  - “Δ-enhanced” region
  - “not-Δ” enhanced region
- “Fake data” to study impact of data/MC near detector differences put into one or the other mode and re-performing full analysis
- Impact on $\sin^2\theta_{23}/\Delta m^2_{32}$ contours
  - these may be revised in the future
- Negligible impact on δ_{CP}

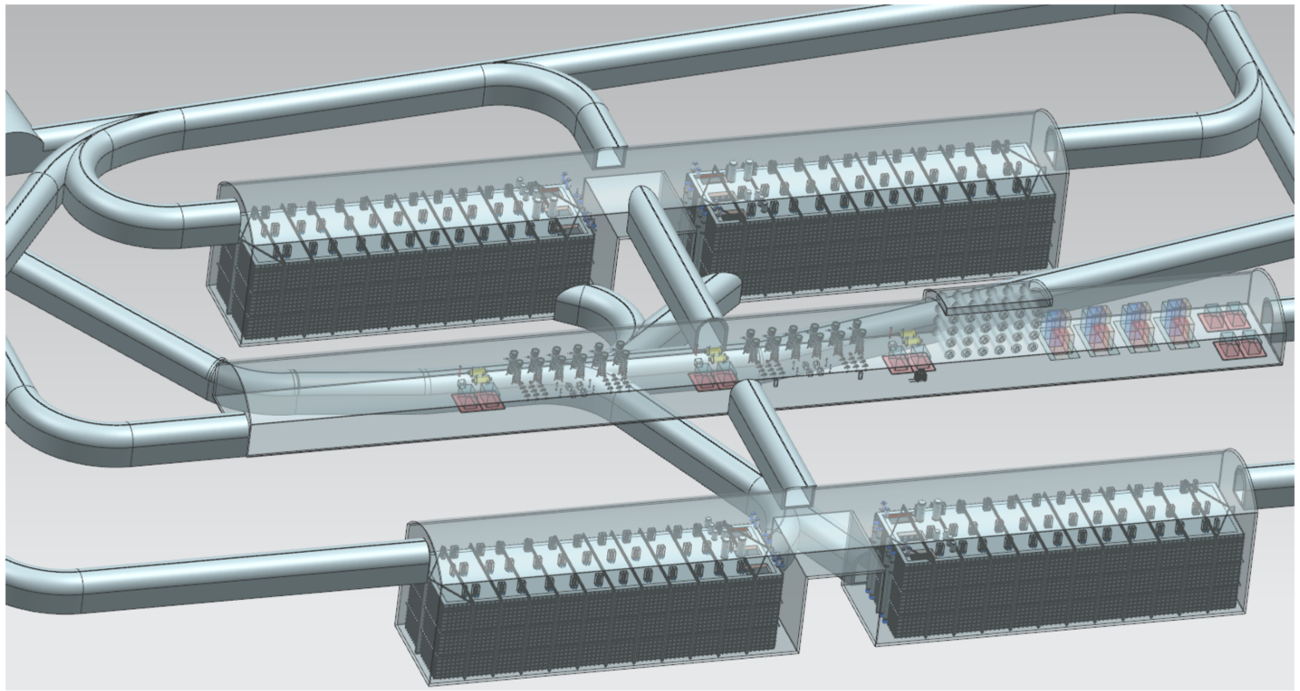


FUTURE PROSPECTS

$$N \propto \Phi_\nu \times V \times \rho \times \epsilon \times \sigma_\nu$$

systematics

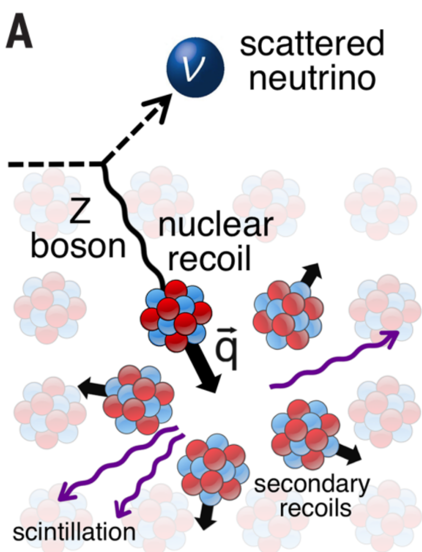


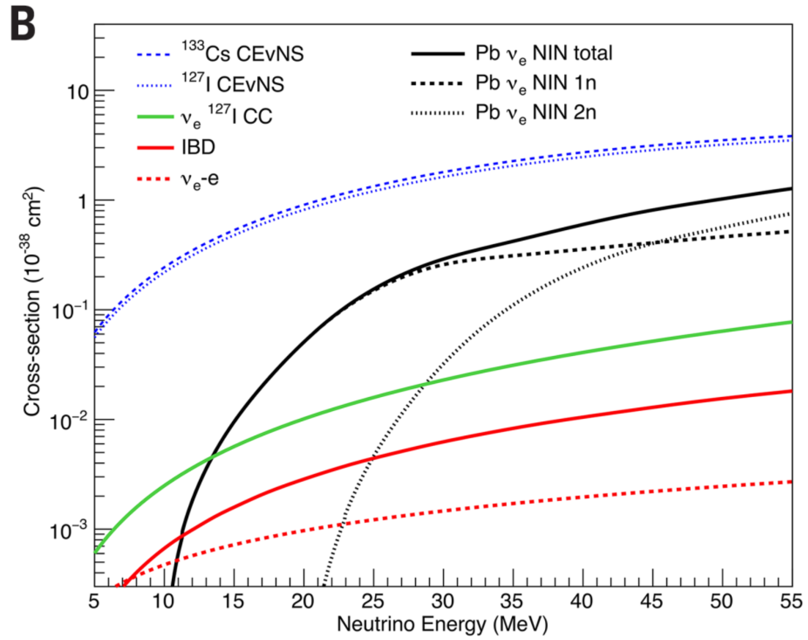


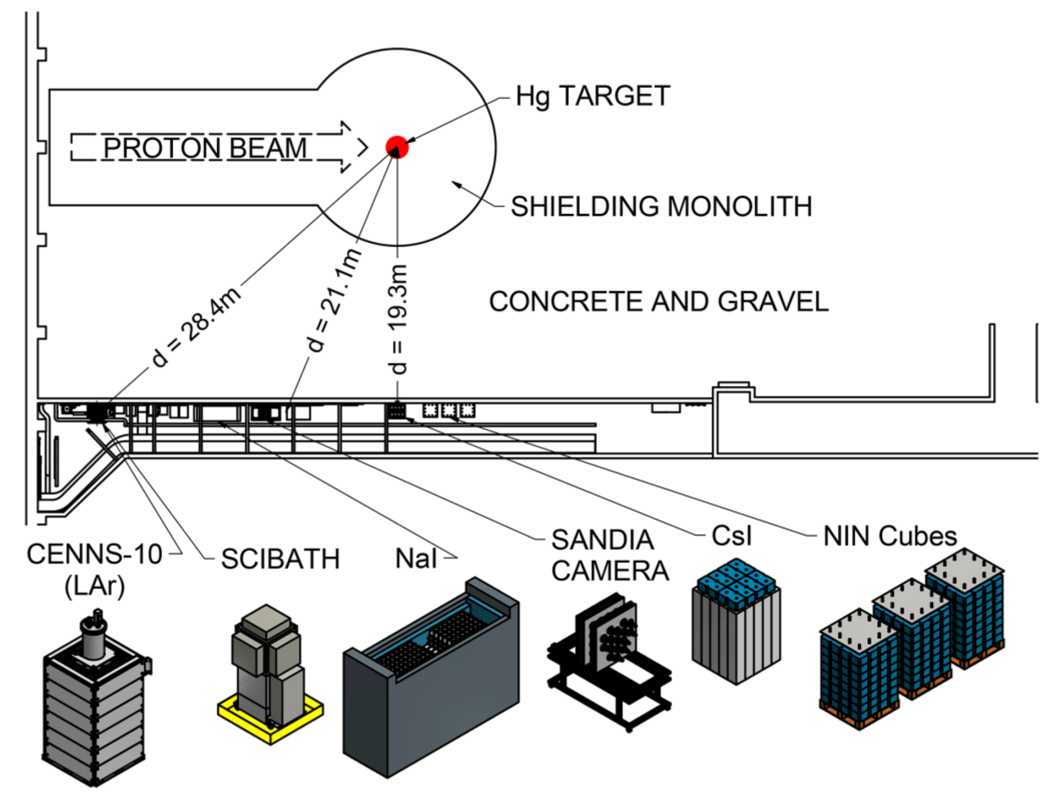
CONCLUSIONS:

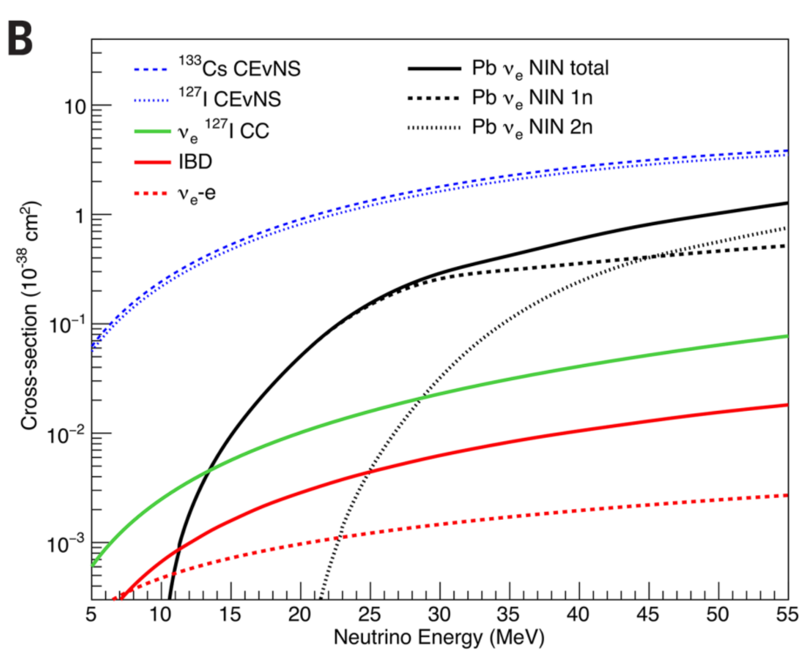
- The study of neutrino mixing is advancing rapidly!
  - NOvA, T2K: increasing sensitivity to CP violation and mass ordering
  - NOvA, T2K, reactor experiment: high precision on mixing parameters
  - tensions?
- Increasing beam intensity, extended run times on the horizon but still a ways to go . . . .
  - data will continue to accumulate rapidly
    - exciting advancements in analysis methods accelerating progress
  - systematic uncertainties requirements will become increasingly stringent
    - Better understanding of ν flux, ν-A interactions, efficiencies, resolutions, backgrounds . . . .
- Next generation (JUNO, DUNE, Hyper-Kamiokande) preparing to roll out in 2020-2025
  - More from Ed Blucher
  - significant progress needed/expected to keep program going and to prepare for the future
- Many interesting topics not covered here:
  - recent observation of coherent scattering
  - reactor neutrino flux anomalies (spectrum, etc.)
  - neutrino-nucleus interaction studies
  - . . . . . .

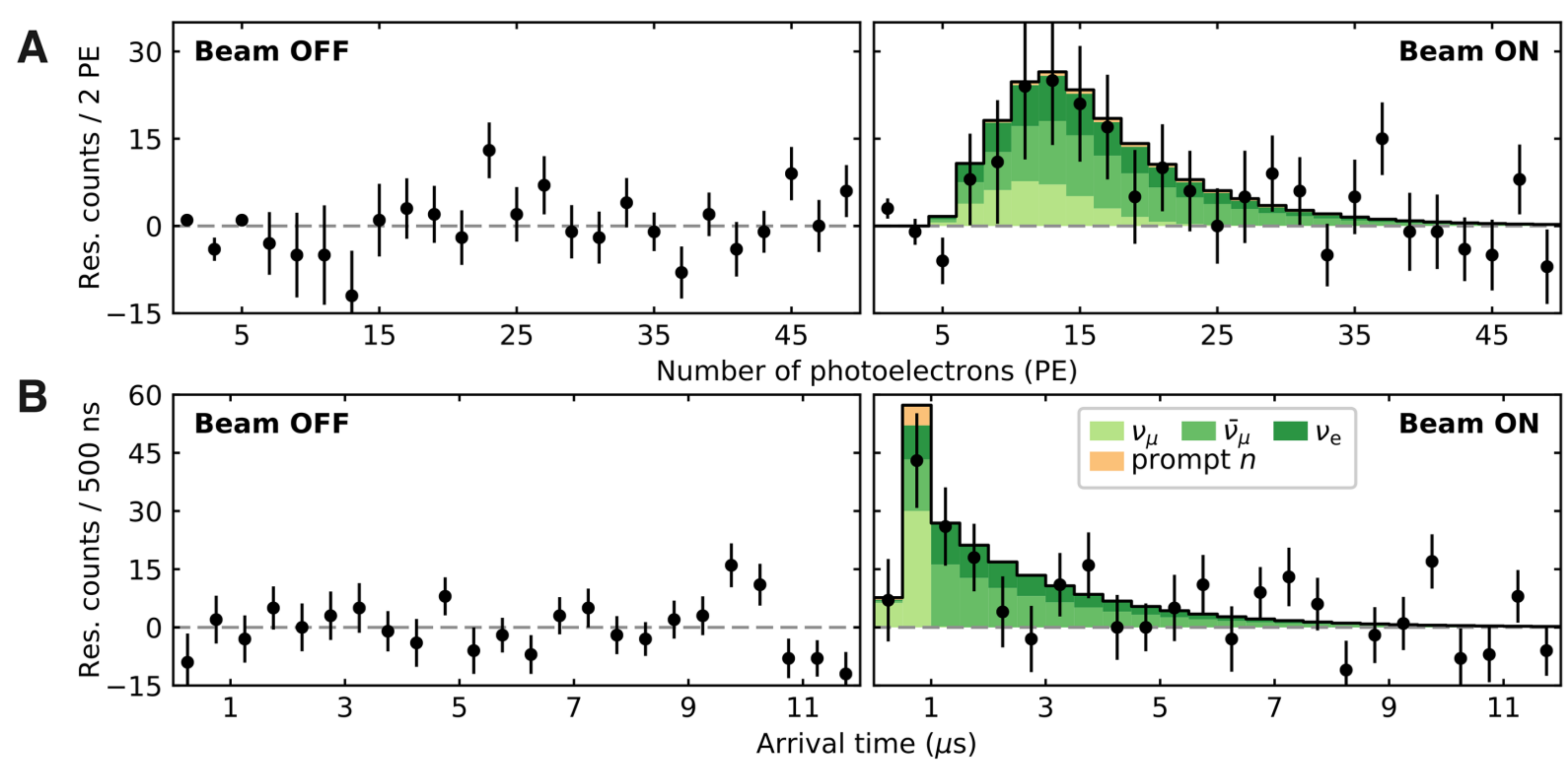
COHERENT NEUTRINO SCATTERING











SYSTEMATIC ERRORS

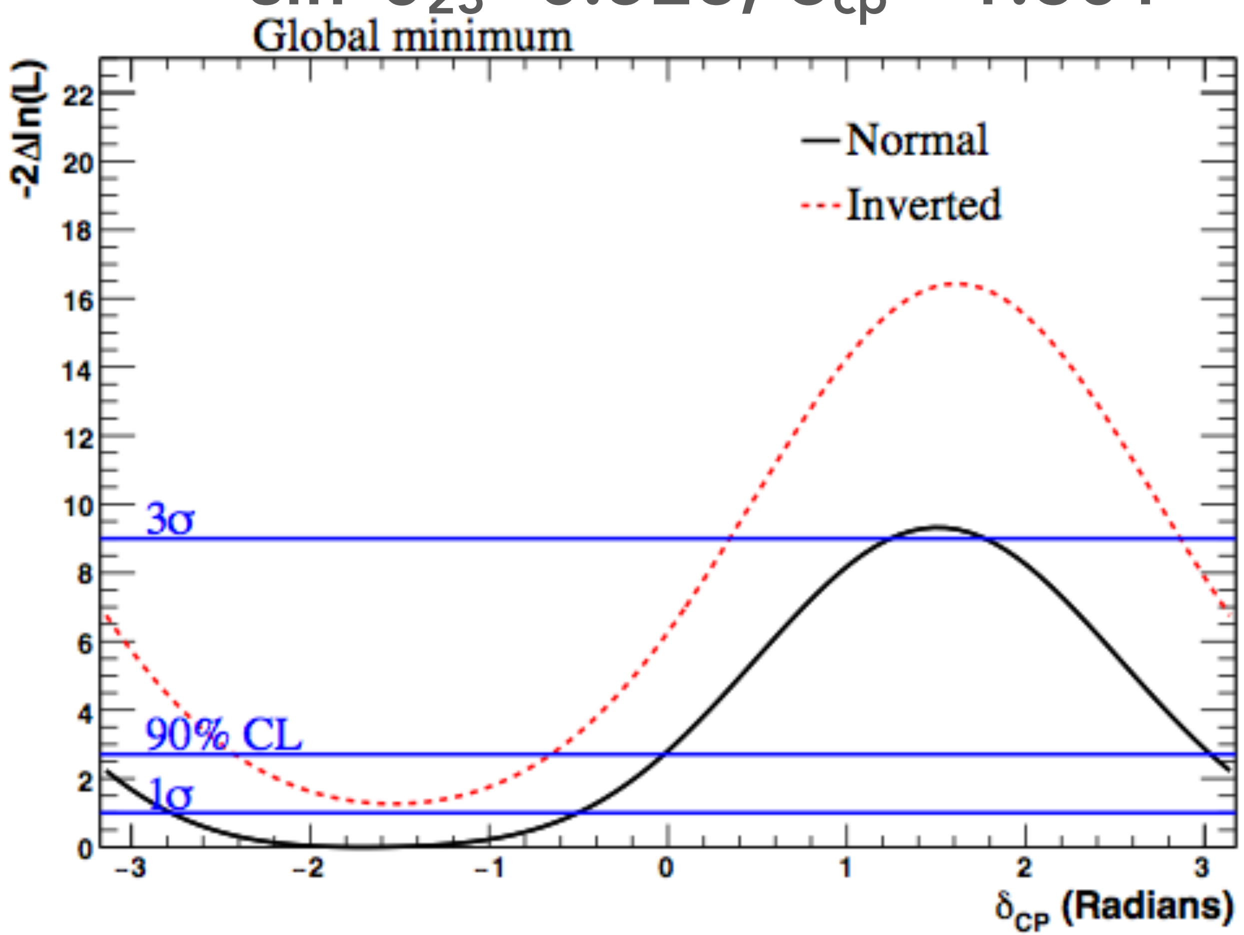
	% Errors on Predicted Event Rates, Osc. Parameter Set A					
	1R μ-Like		1R e-Like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	**4.40**	**3.76**	**6.10**	**6.51**	**20.94**	**4.77**

Parameter	Set A value	Set B value
$\sin^2\theta_{12}$	0.304	0.304
$\sin^2\theta_{23}$	0.528	0.45
$\sin^2\theta_{13}$	0.0217	0.0217
Δm^2_{21}	7.53×10^{-5} eV^2	7.53×10^{-5} eV^2
Δm^2_{32}	2.509×10^{-3} eV^2	2.509×10^{-3} eV^2
δ_{CP}	-1.601	0

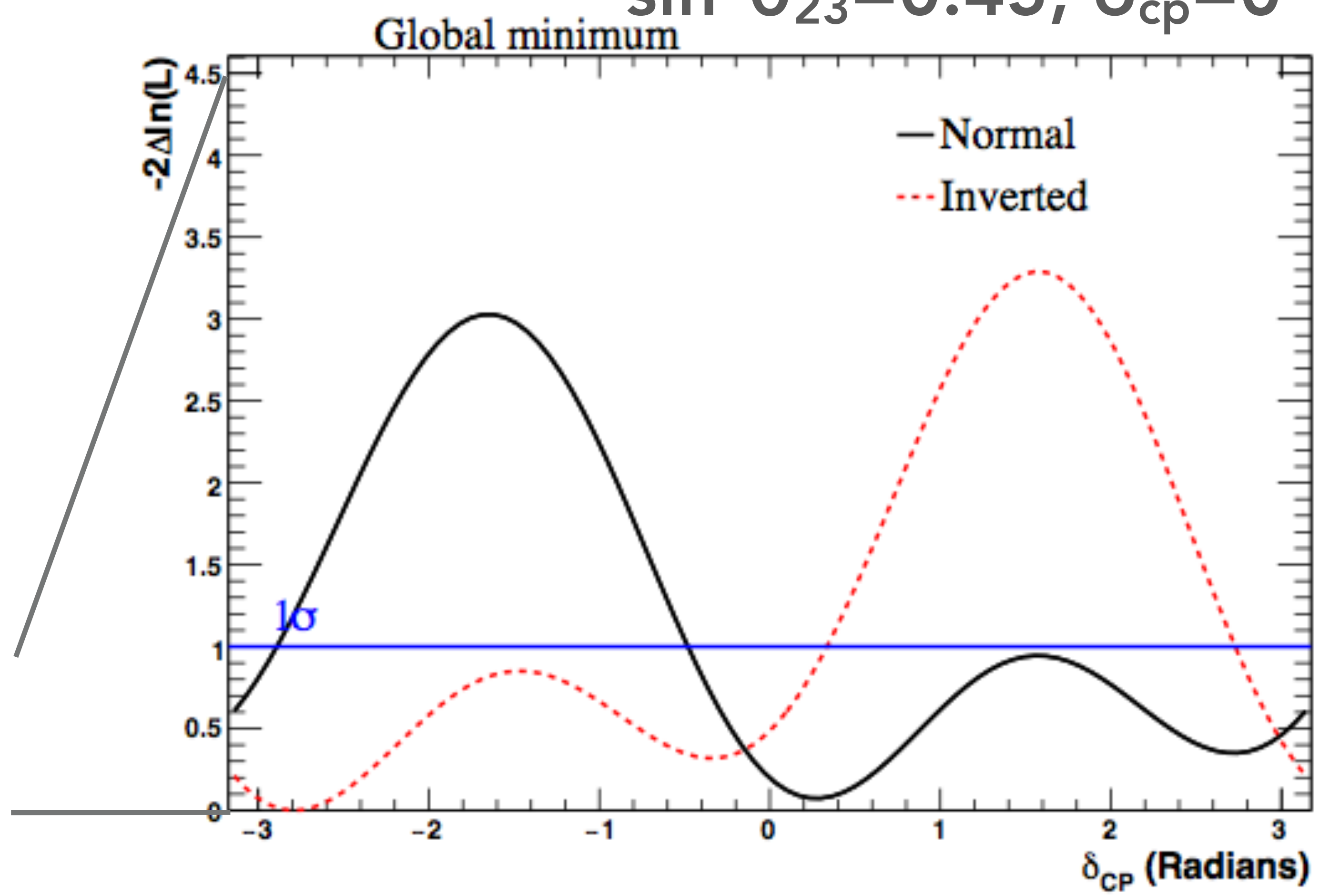
Near-maximal in A, non-maximal in B

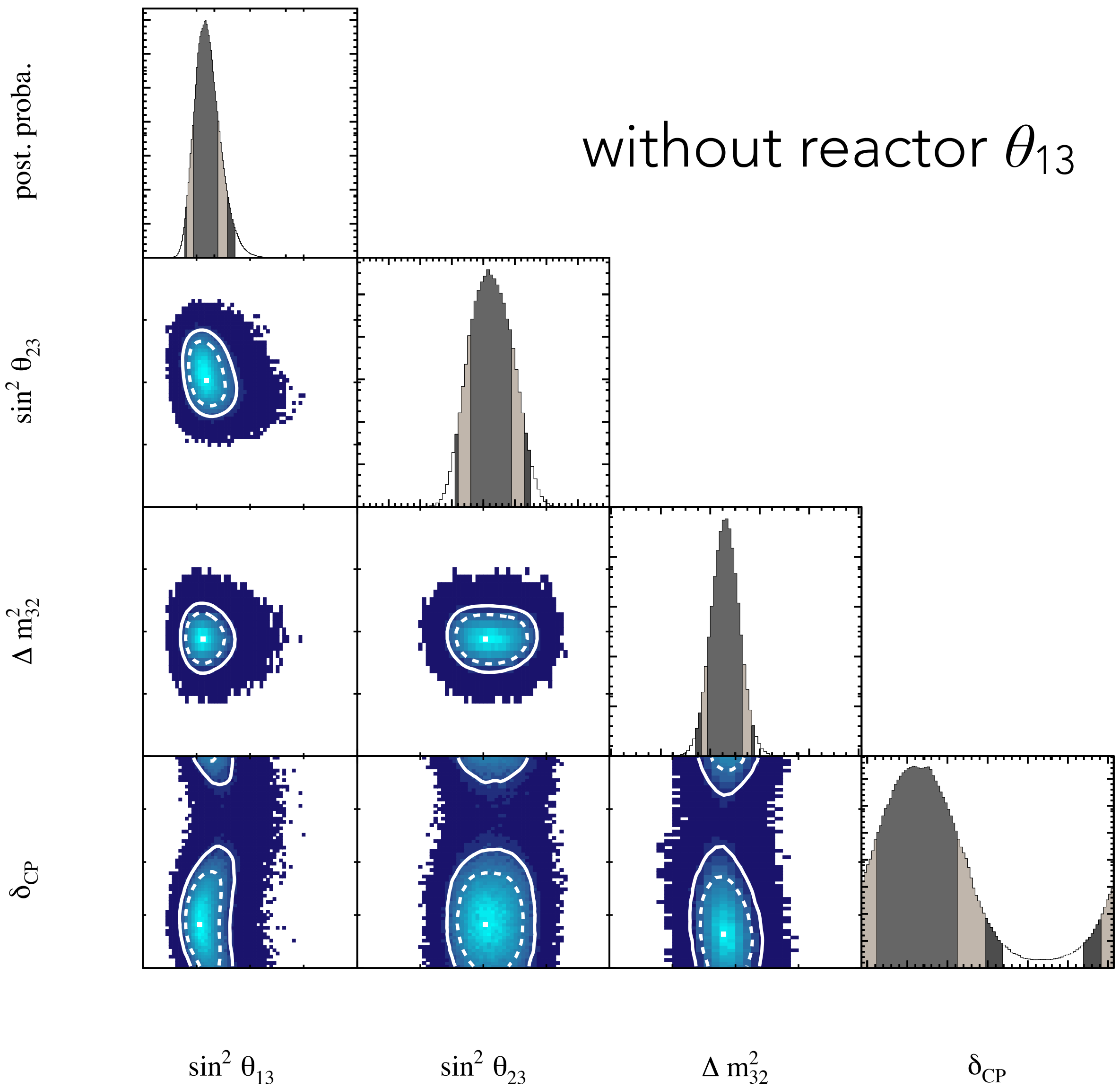
CP violation in A, CP conservation in B

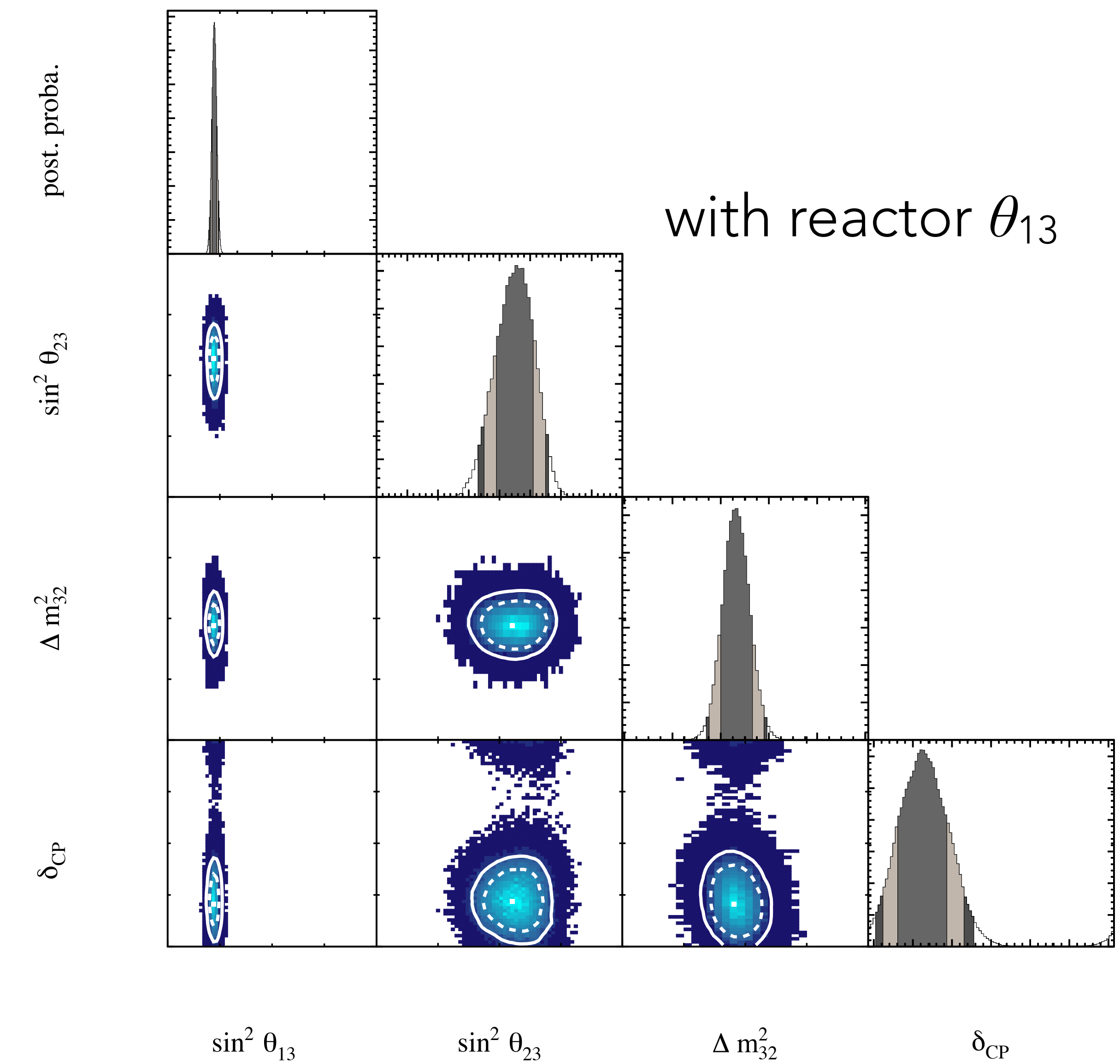
$\sin^2\theta_{23}$=0.528, δ_{cp}=-1.601

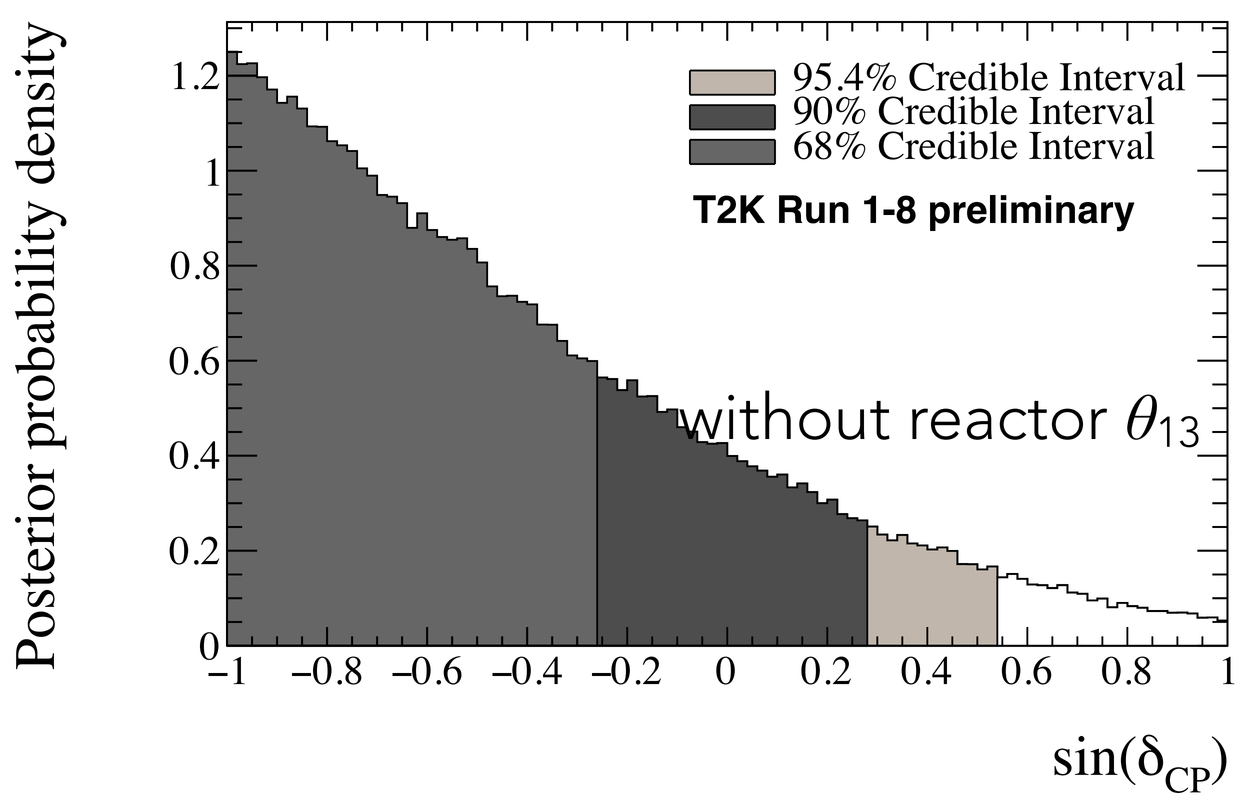


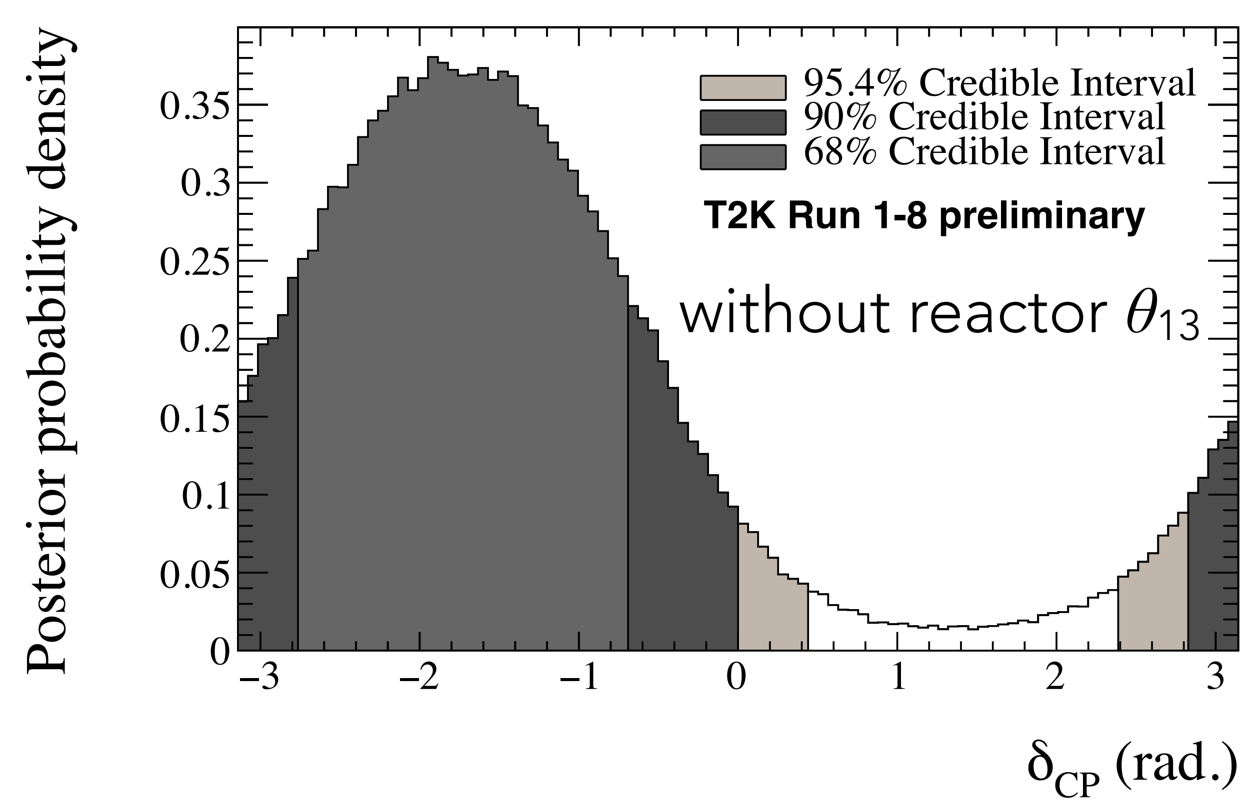
$\sin^2\theta_{23}$=0.45, δ_{cp}=0

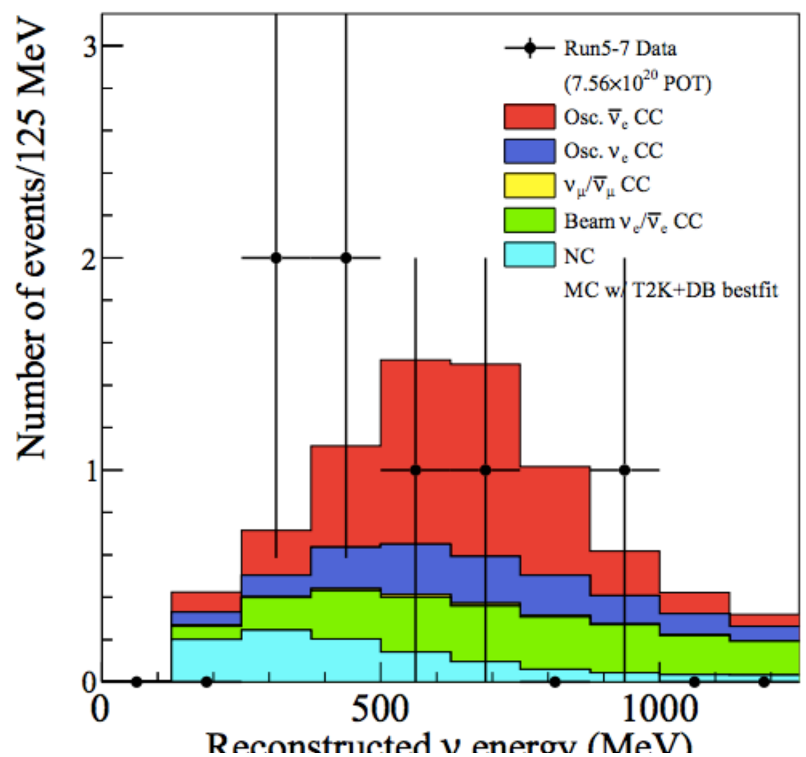


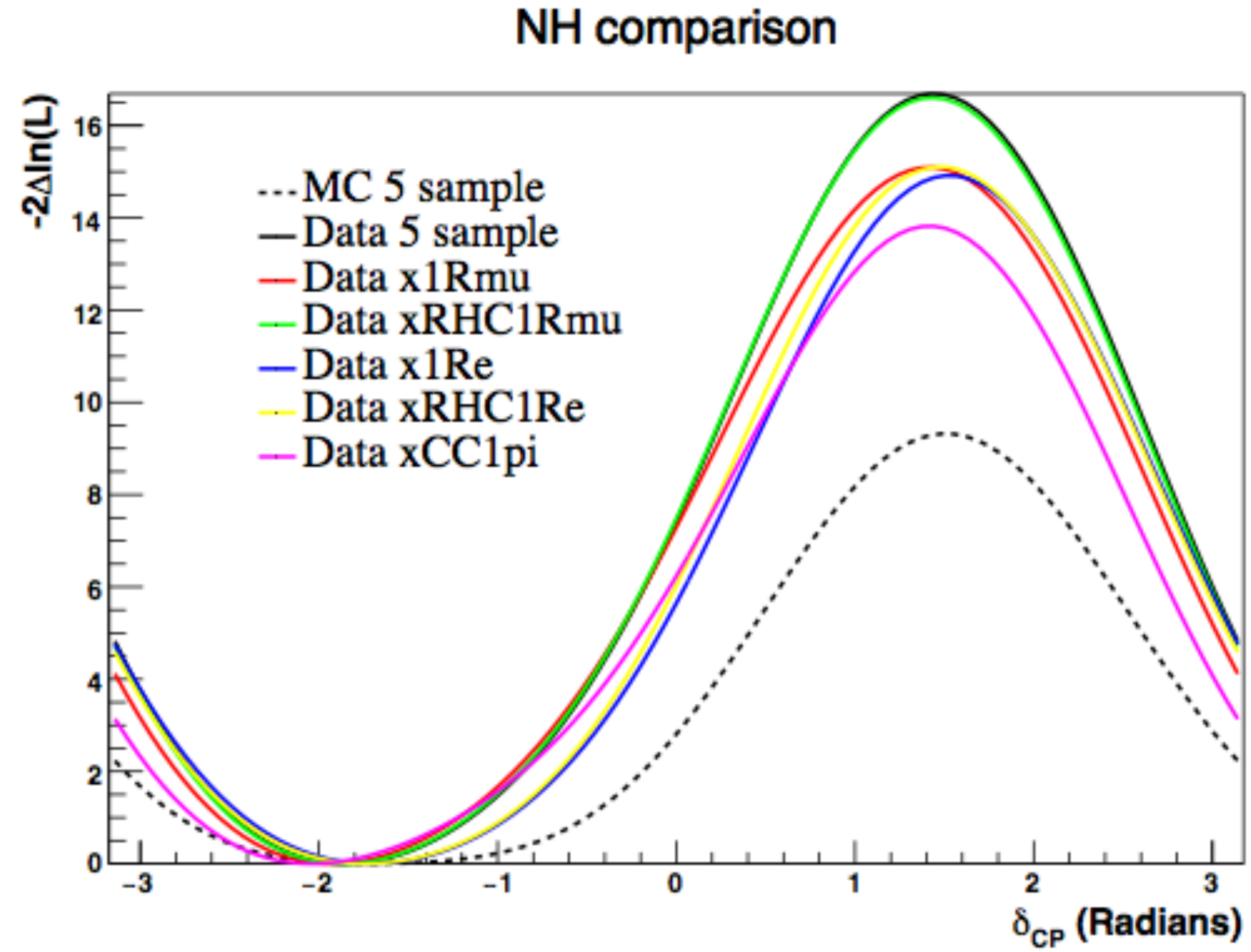

without reactor θ_{13}
post. proba.
$\sin^2\theta_{23}$
Δm^2_{32}
δ_{CP}
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
Δm^2_{32}
δ_{CP}

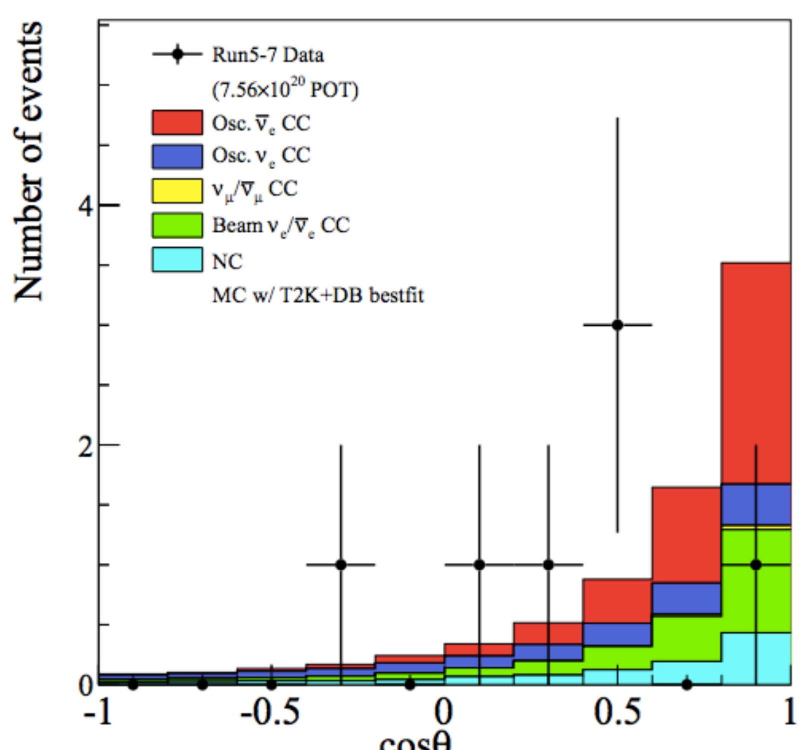

with reactor θ_{13}
post. proba.
$\sin^2\theta_{23}$
Δm^2_{32}
δ_{CP}
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
Δm^2_{32}
δ_{CP}

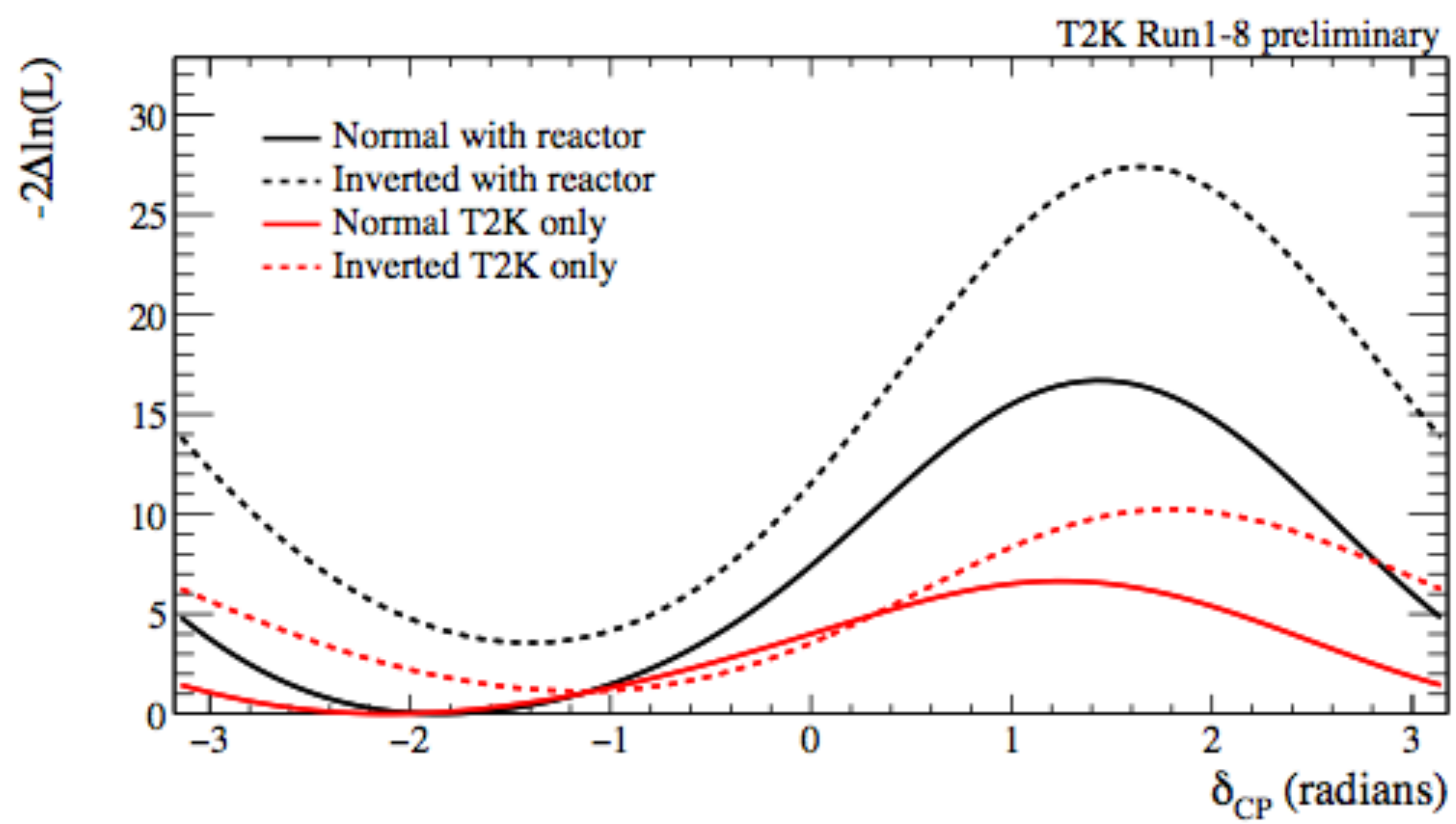

95.4% Credible Interval
90% Credible Interval
68% Credible Interval
T2K Run 1-8 preliminary
without reactor θ_{13}
Posterior probability density
$\sin(\delta_{CP})$

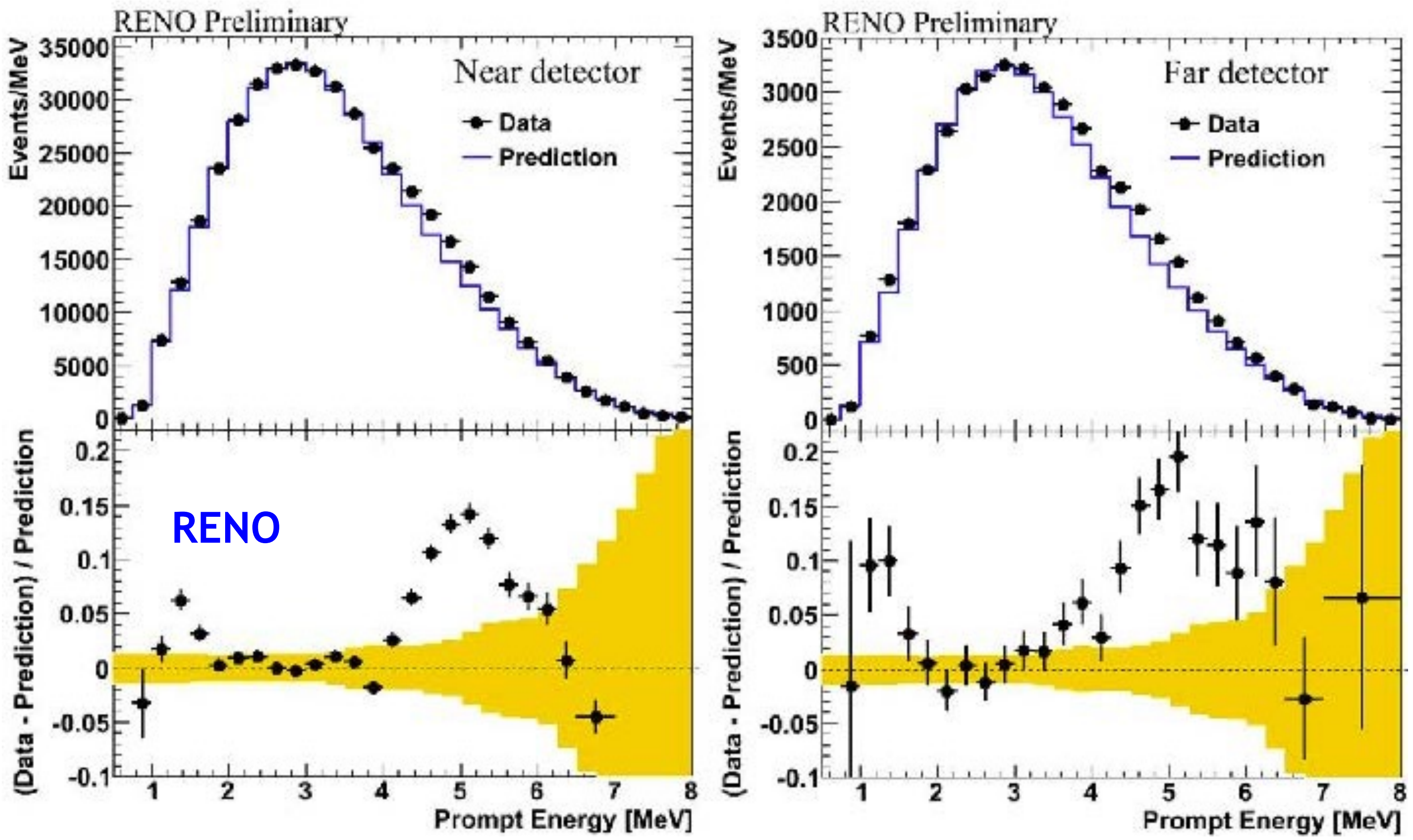

95.4% Credible Interval
90% Credible Interval
68% Credible Interval
T2K Run 1-8 preliminary
without reactor θ_{13}
Posterior probability density
δ_{CP} (rad.)

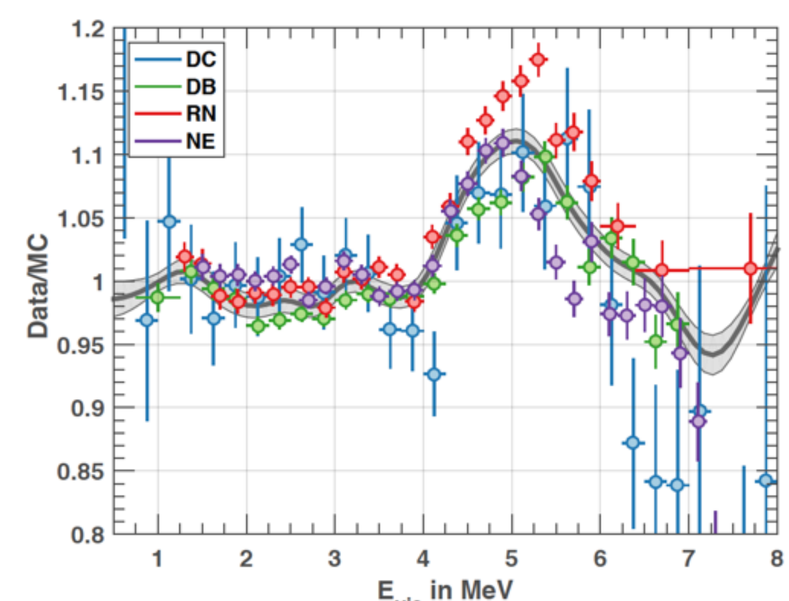

Run5-7 Data
(7.56×10^20 POT)
Osc. ν̄e CC
Osc. νe CC
νμ/ν̄μ CC
Beam νe/ν̄e CC
NC
MC w/ T2K+DB bestfit
Number of events/125 MeV
Reconstructed ν energy (MeV)


NH comparison
MC 5 sample
Data 5 sample
Data x1Rmu
Data xRHC1Rmu
Data x1Re
Data xRHC1Re
Data xCC1pi
-2Δln(L)
δCP (Radians)


Run5-7 Data
(7.56×10^20 POT)
Osc. ν̄e CC
Osc. νe CC
νμ/ν̄μ CC
Beam νe/ν̄e CC
NC
MC w/ T2K+DB bestfit
Number of events
cosθbeam

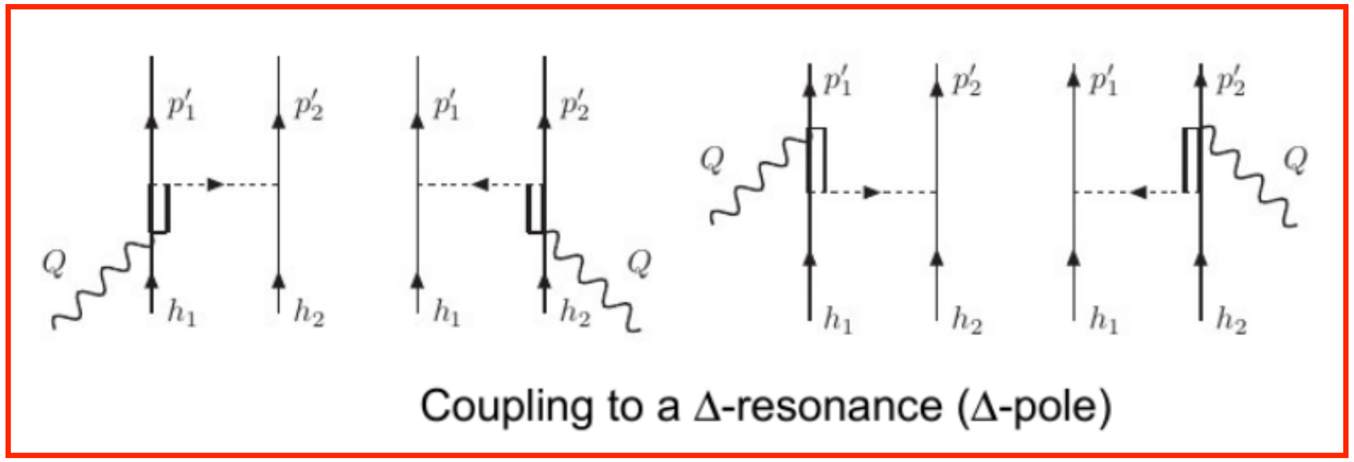

T2K Run1-8 preliminary
Normal with reactor
Inverted with reactor
Normal T2K only
Inverted T2K only
-2Δln(L)
δCP (radians)

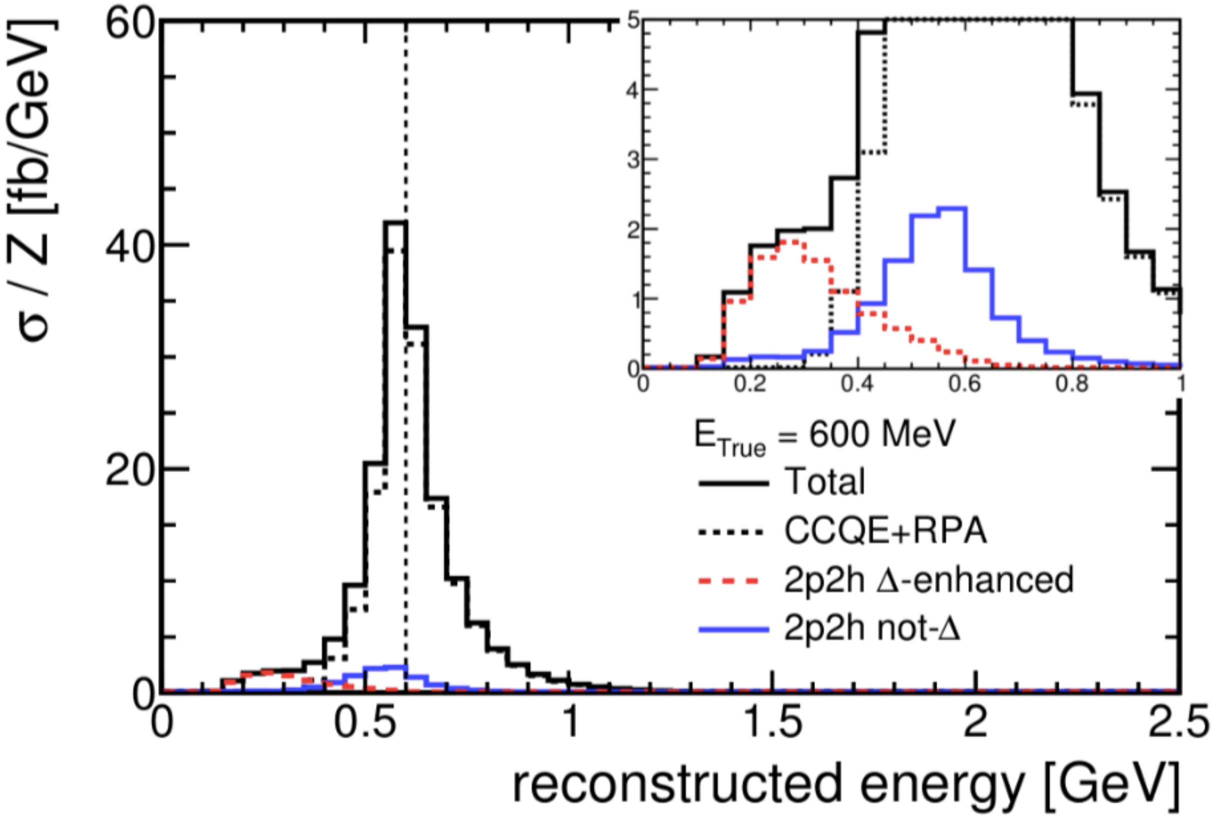

RENO Preliminary
Near detector
Data
Prediction
Events/MeV
(Data - Prediction) / Prediction
Prompt Energy [MeV]
RENO
RENO Preliminary
Far detector
Data
Prediction
Events/MeV
(Data - Prediction) / Prediction
Prompt Energy [MeV]


DC
DB
RN
NE
Data/MC

MULTINUCLEON MODELING ERROR

- The 2p-2h processes produce events with lower reconstructed energy
  - Energy mis-reconstruction largest in processes involving coupling to a **Δ resonance**
- Model the energy reconstruction error: allow strength of the 2p-2h cross-section to vary between all Δ-enhanced and all not-Δ-enhanced
- Also allow normalization for 2p-2h to vary separately for neutrinos and antineutrinos





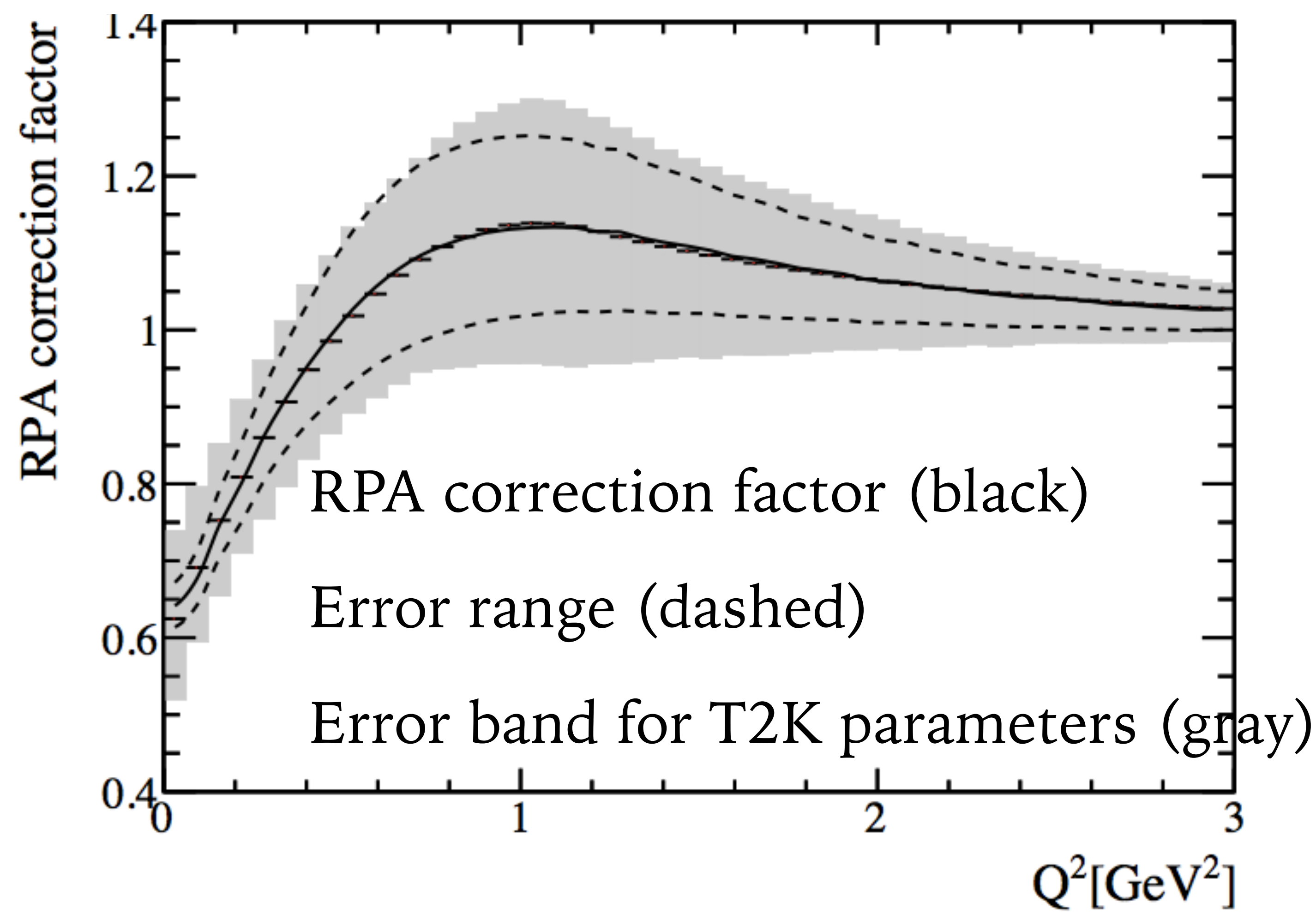
RPA CORRECTION UNCERTAINTY

- Correction for long-range correlations in the nucleus modifies Q^2 dependence of CCQE cross section
- Introduce a parametrization of this correction:

$$f(x) = \begin{cases} A(1-x')^3 + 3B(1-x')^2x' + 3p_1(1-x')x'^2 + Cx'^3, & x < U \\ 1 + p_2\exp(-D(x-U)), & x > U \end{cases}$$

$x = Q^2$

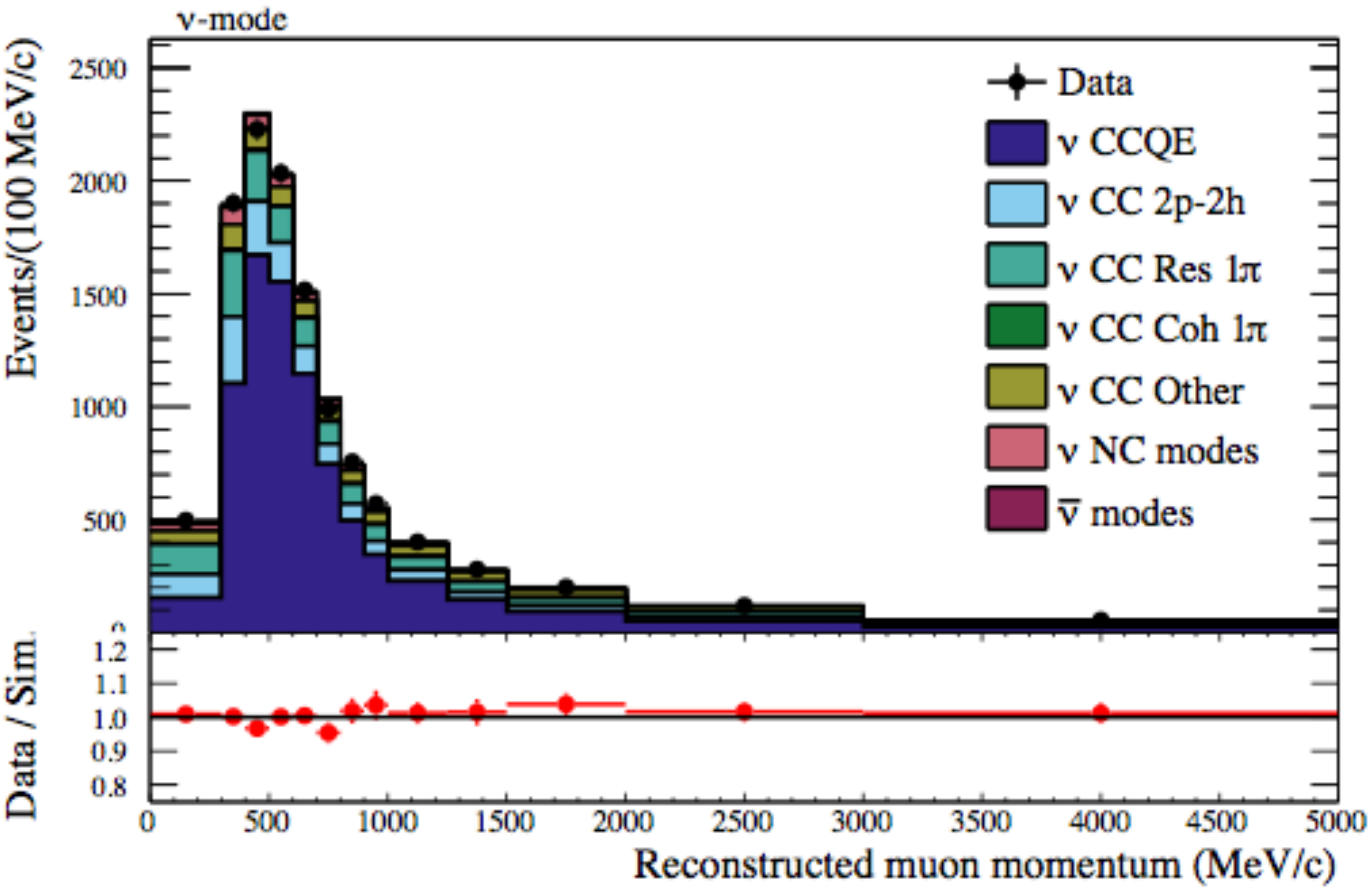
- Uncertainties on the parameters cover the theoretical uncertainty on the RPA correction factor



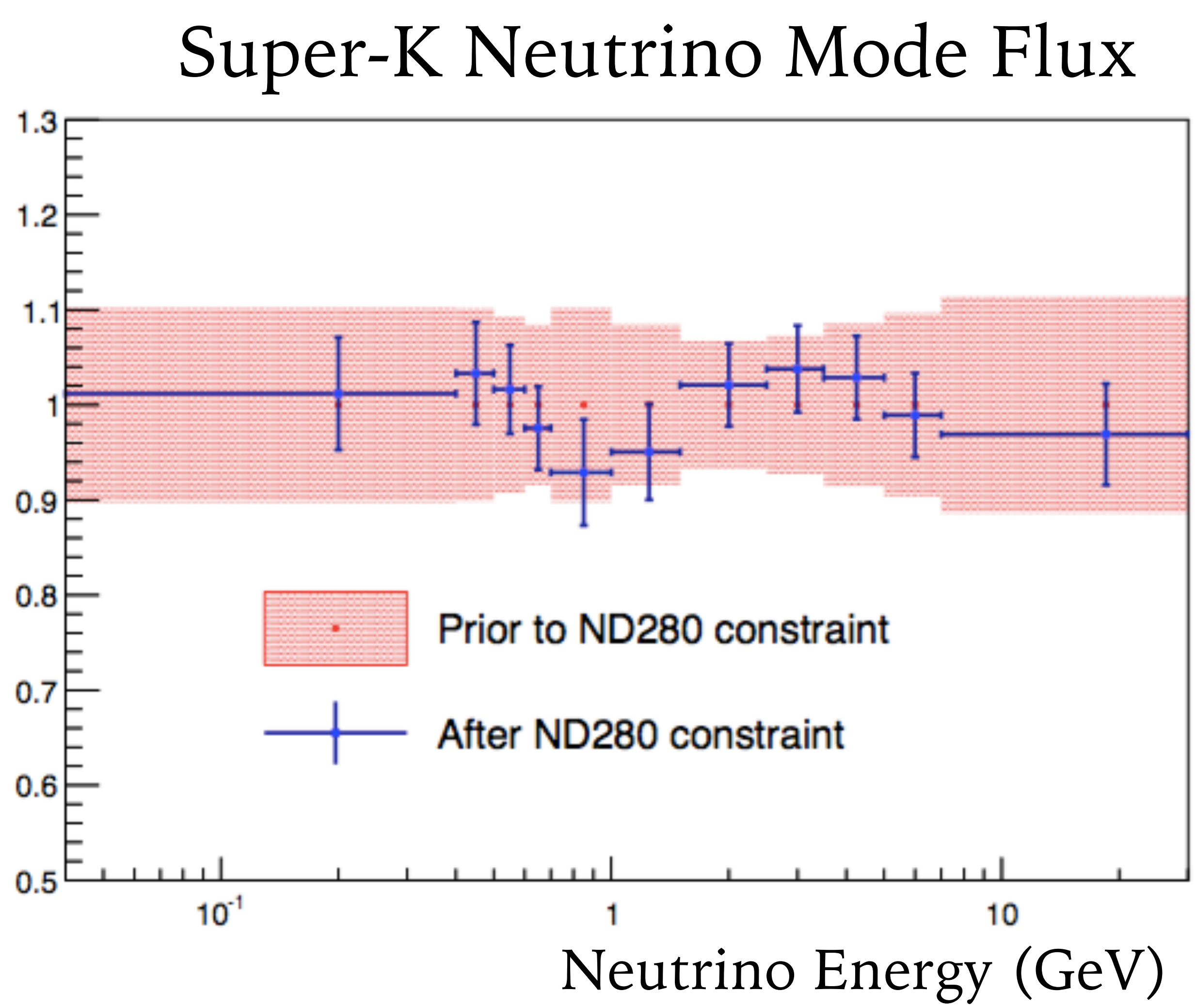
FITTING ND280 DATA

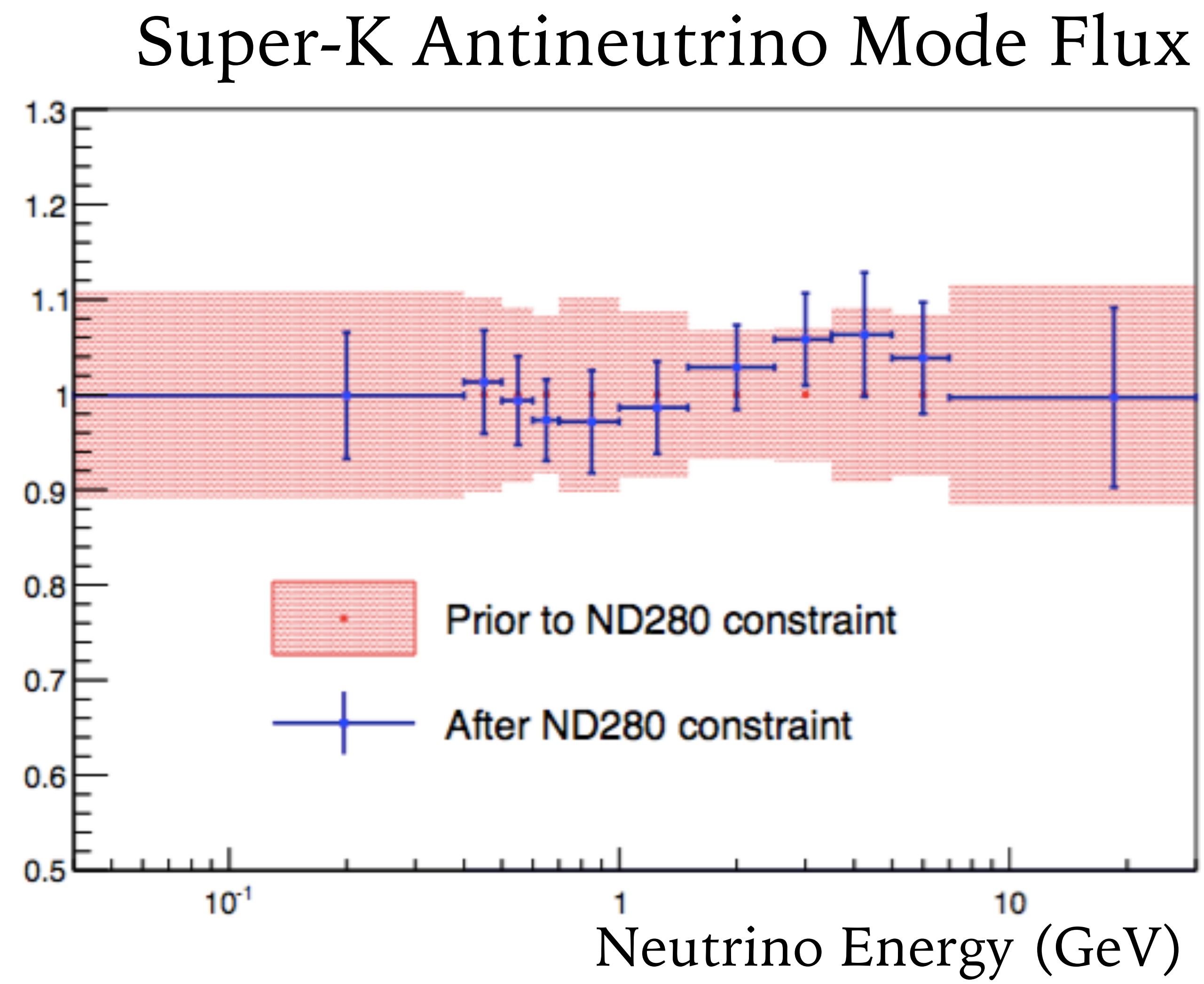
- Since 2016, include FGD2 (water targets) to extract interactions on H_2O
  - Separate data sets in FGD1 and FGD2
- Neutrino mode separated by number of charged pions: **CC-0π, CC-1π, CC-Other**
- Antineutrino mode separate by number of TPC tracks: **CC-1Track, CC-NTrack**
  - In antineutrino mode, separate samples for μ^+ and μ^- candidates

- Example fitted FGD2 CC-0π muon momentum (right)
- The fit reproduces the data well with a p-value of 0.47



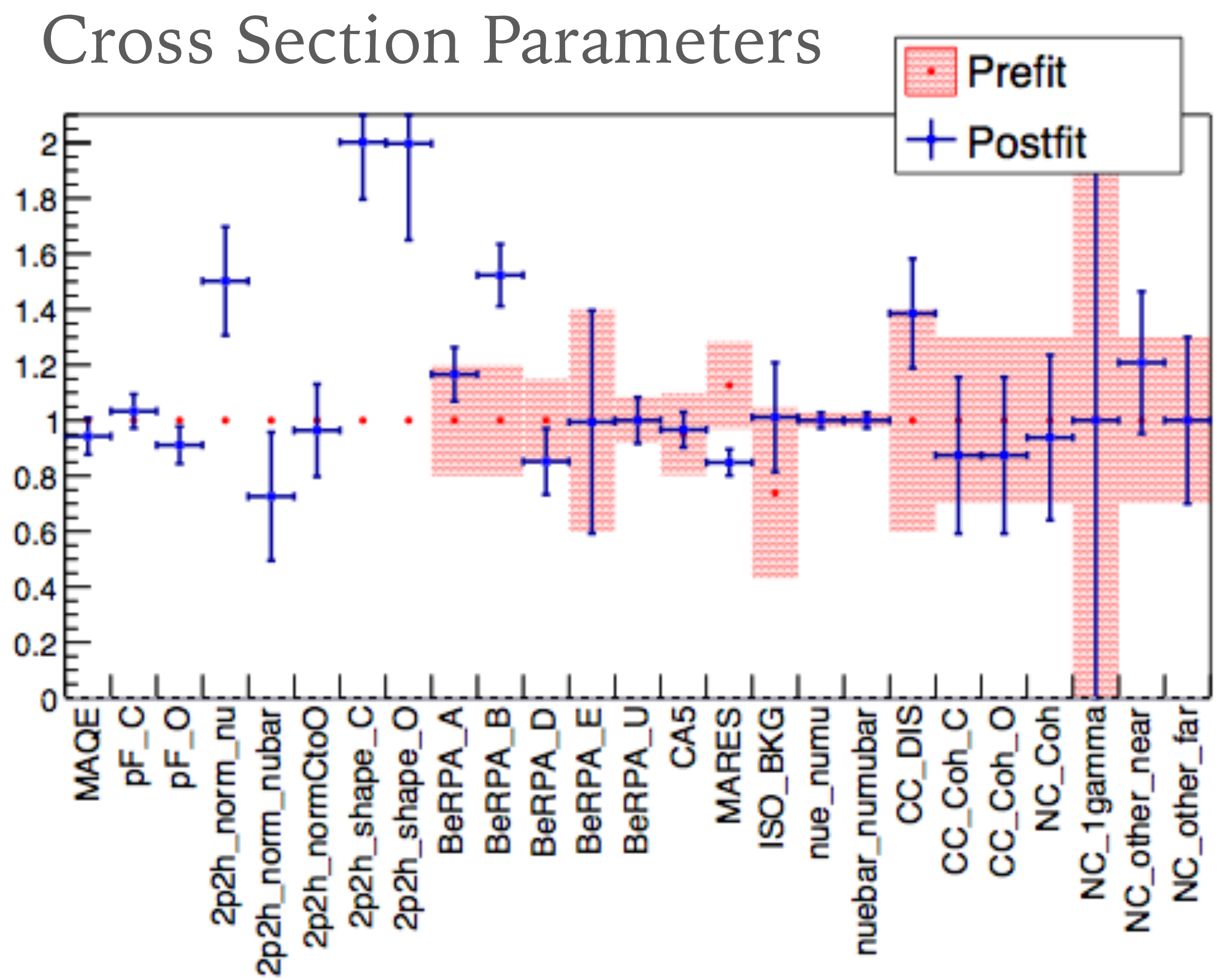
FITTED FLUX PARAMETERS



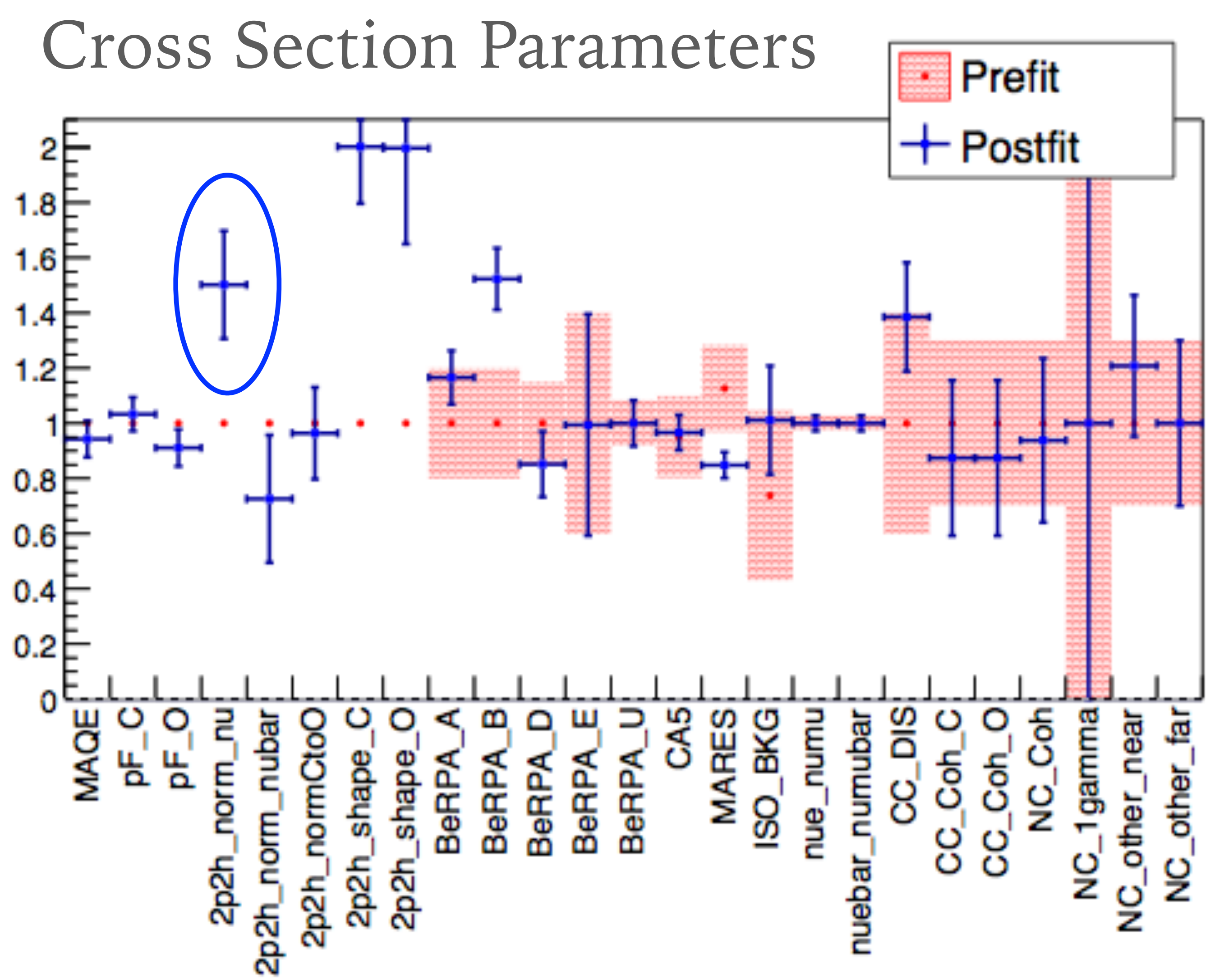


- Fitted flux parameters are generally near their nominal value of 1.0
- Most of the fitted flux parameters fall within their assigned 1 sigma prior uncertainty

FITTED INTERACTION MODEL PARAMETERS

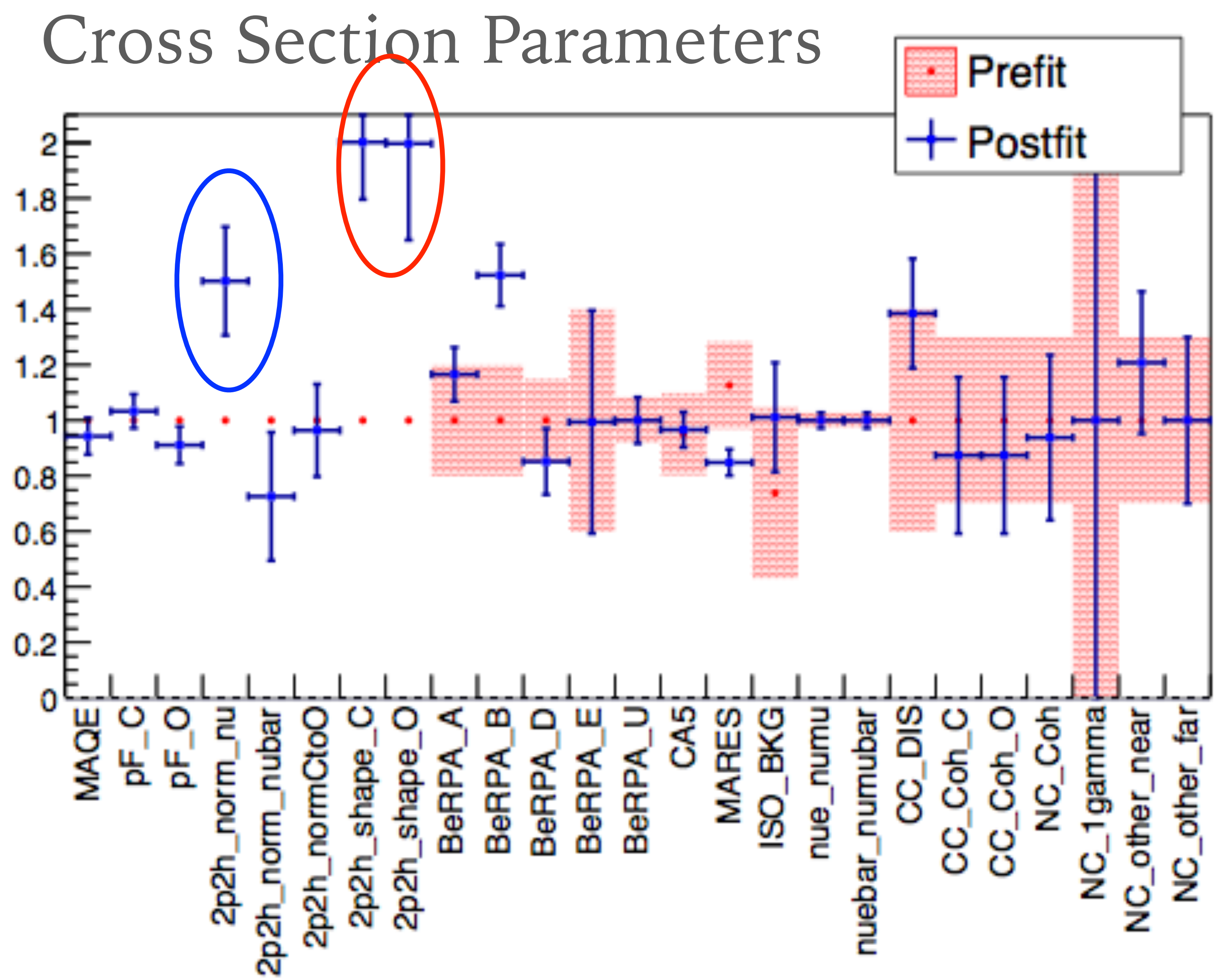


FITTED INTERACTION MODEL PARAMETERS



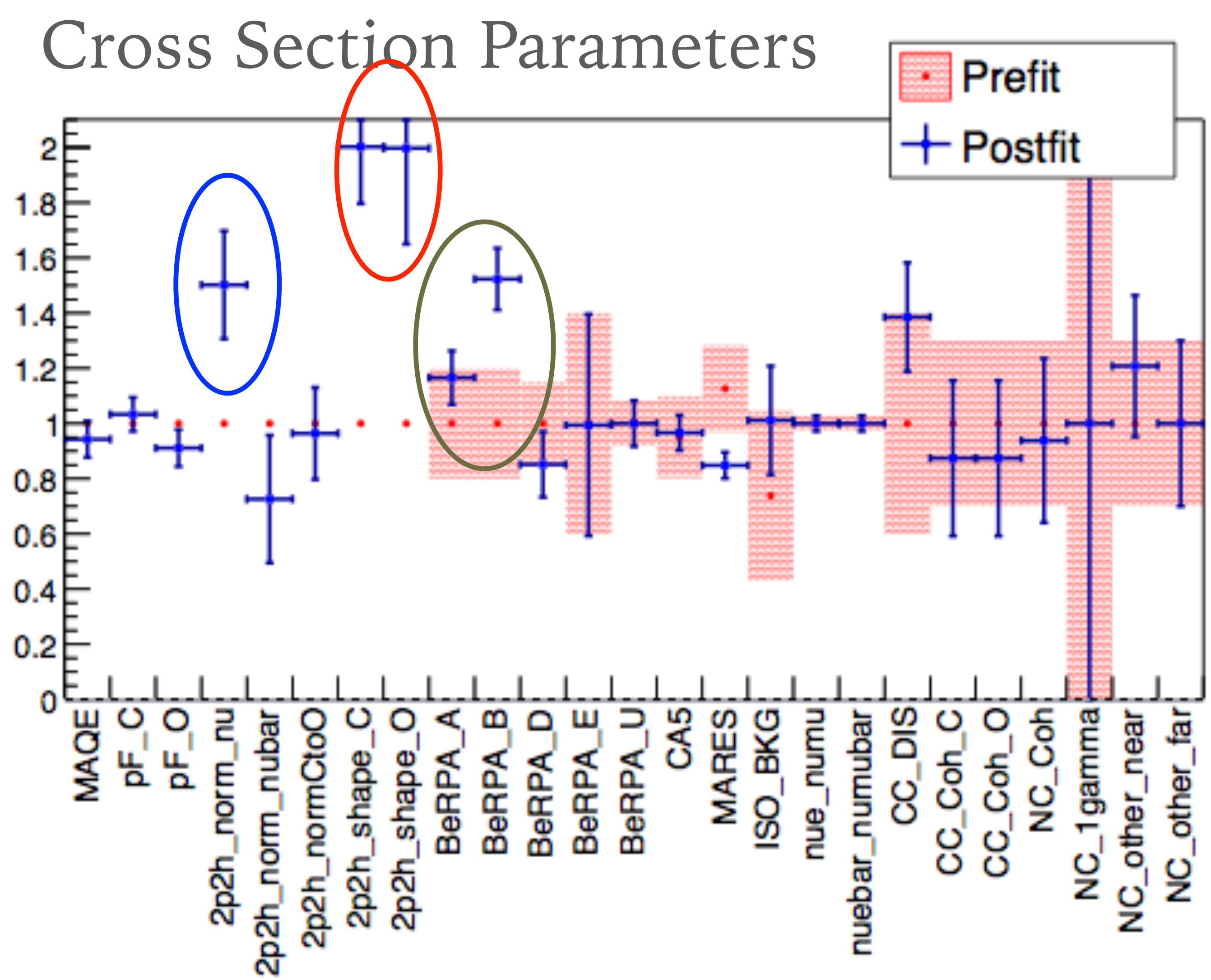
- The 2p-2h for neutrinos is enhanced by 50%

FITTED INTERACTION MODEL PARAMETERS



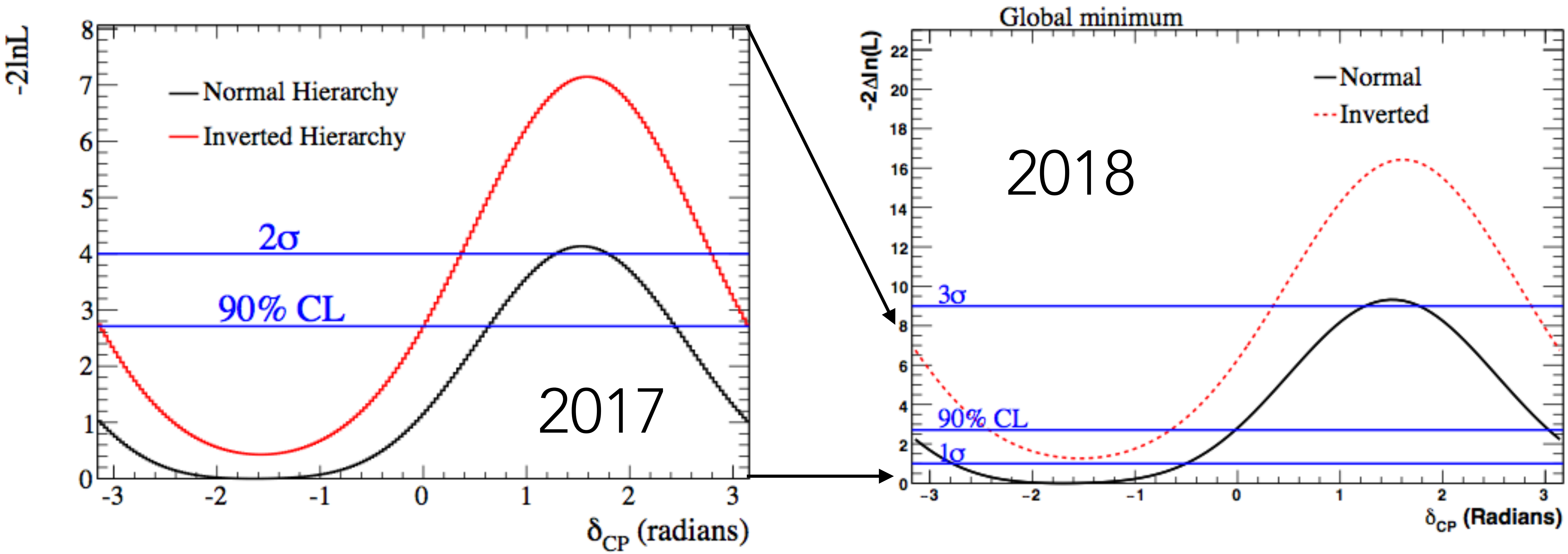
- The 2p-2h for neutrinos is enhanced by 50%
- The 2p-2h shape is shifted so that the Δ-enhanced component of the cross section is increased to maximum

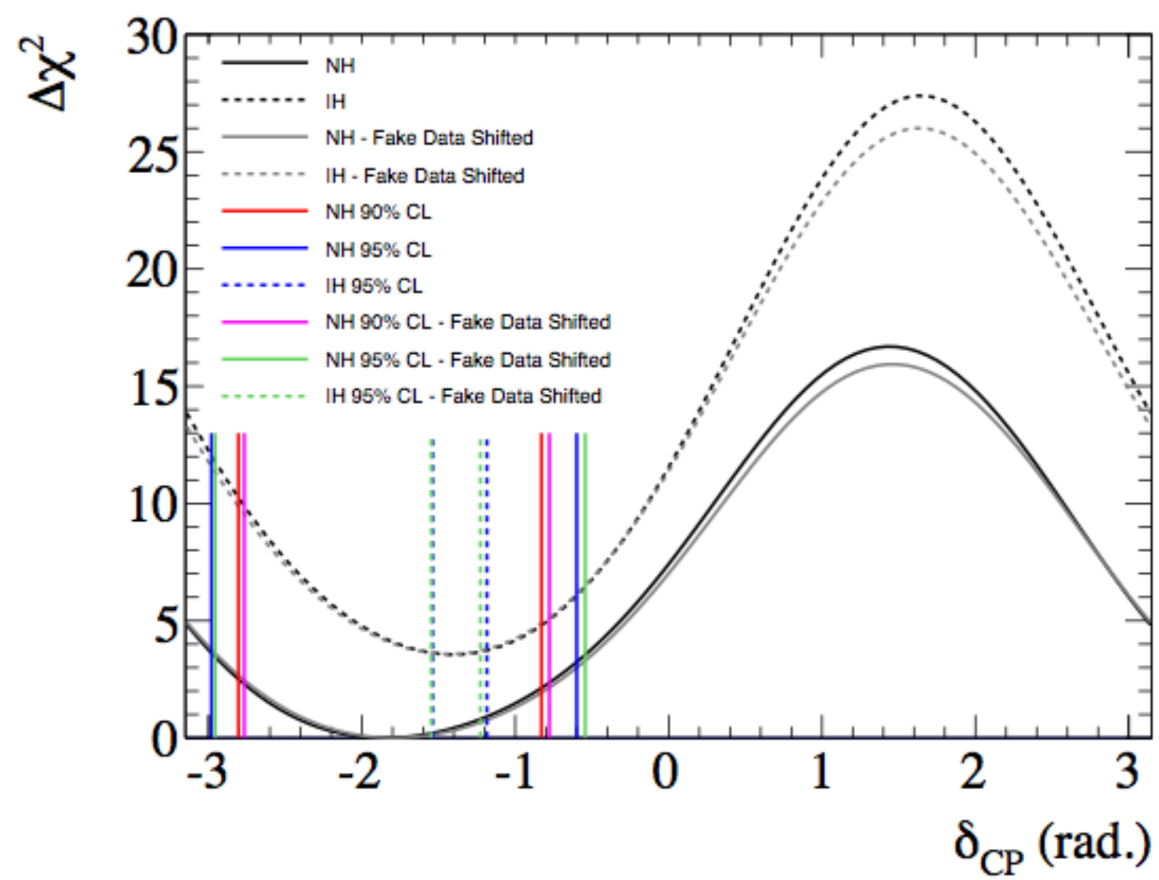
FITTED INTERACTION MODEL PARAMETERS



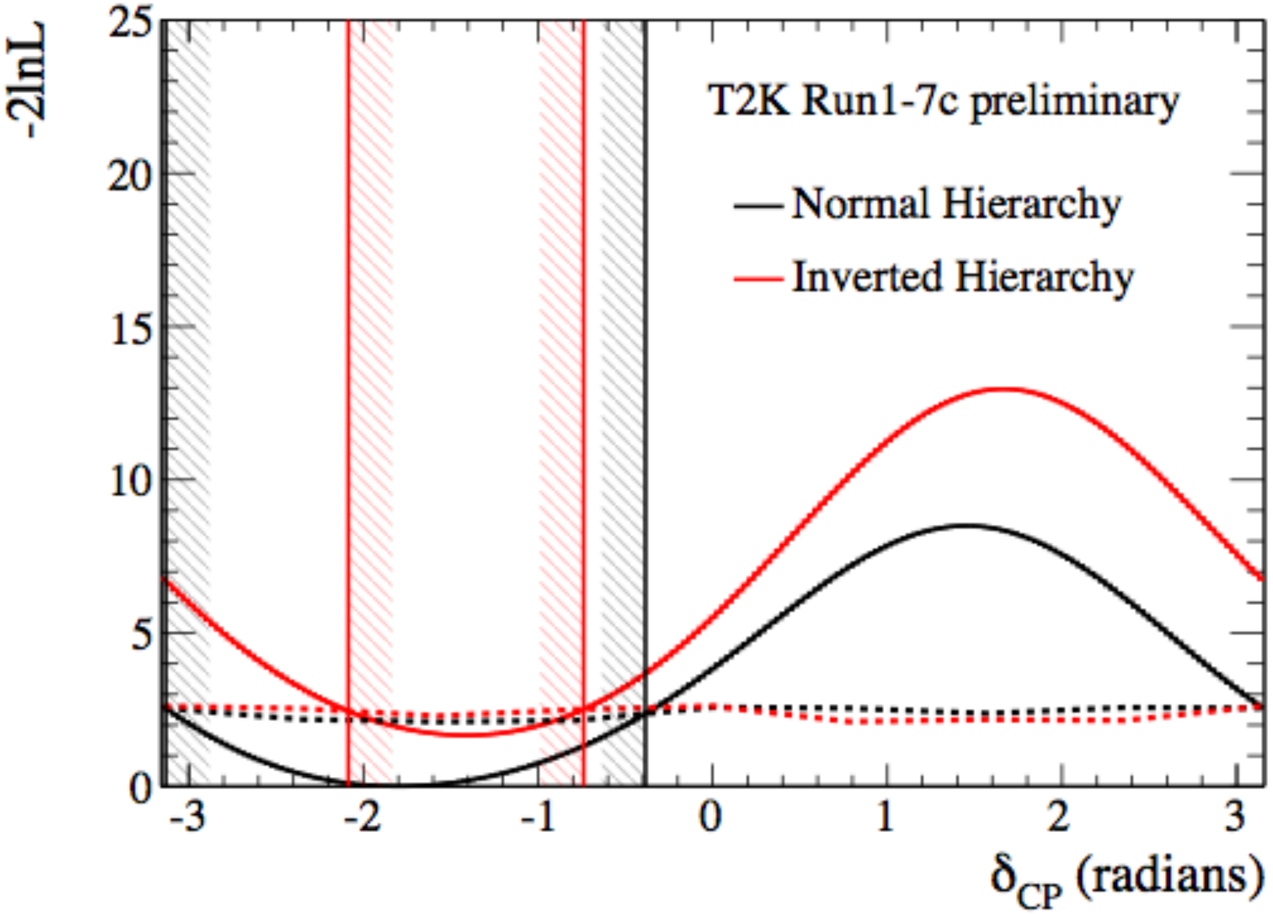
- The 2p-2h for neutrinos is enhanced by 50%
- The 2p-2h shape is shifted so that the Δ-enhanced component of the cross section is increased to maximum
- The RPA parameters for Q^2 below 1 GeV^2 are increased, enhancing the cross section in that region

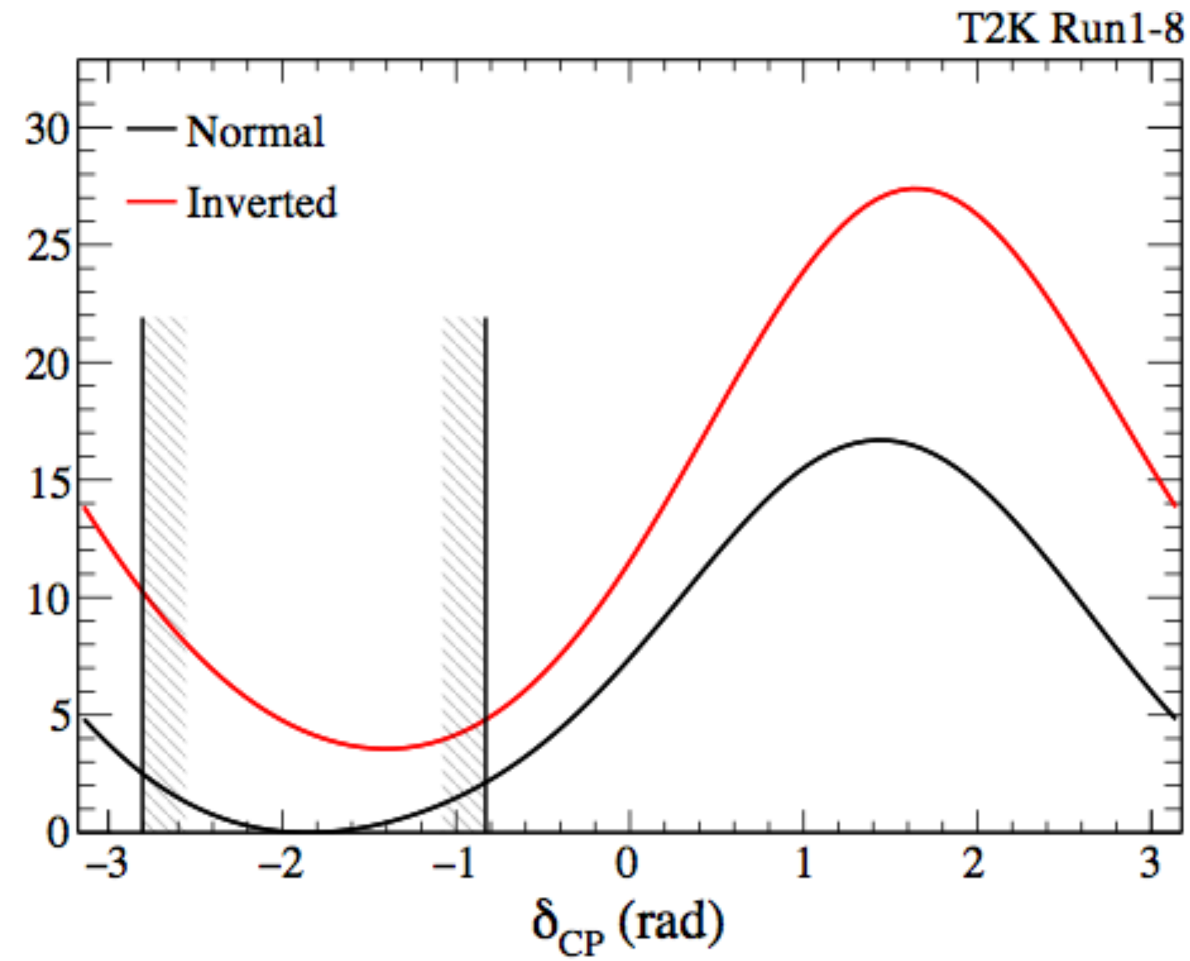
2017 vs 2018 SENSITIVITY




$\Delta\chi^2$
NH
IH
NH - Fake Data Shifted
IH - Fake Data Shifted
NH 90% CL
NH 95% CL
IH 95% CL
NH 90% CL - Fake Data Shifted
NH 95% CL - Fake Data Shifted
IH 95% CL - Fake Data Shifted
δ_{CP} (rad.)

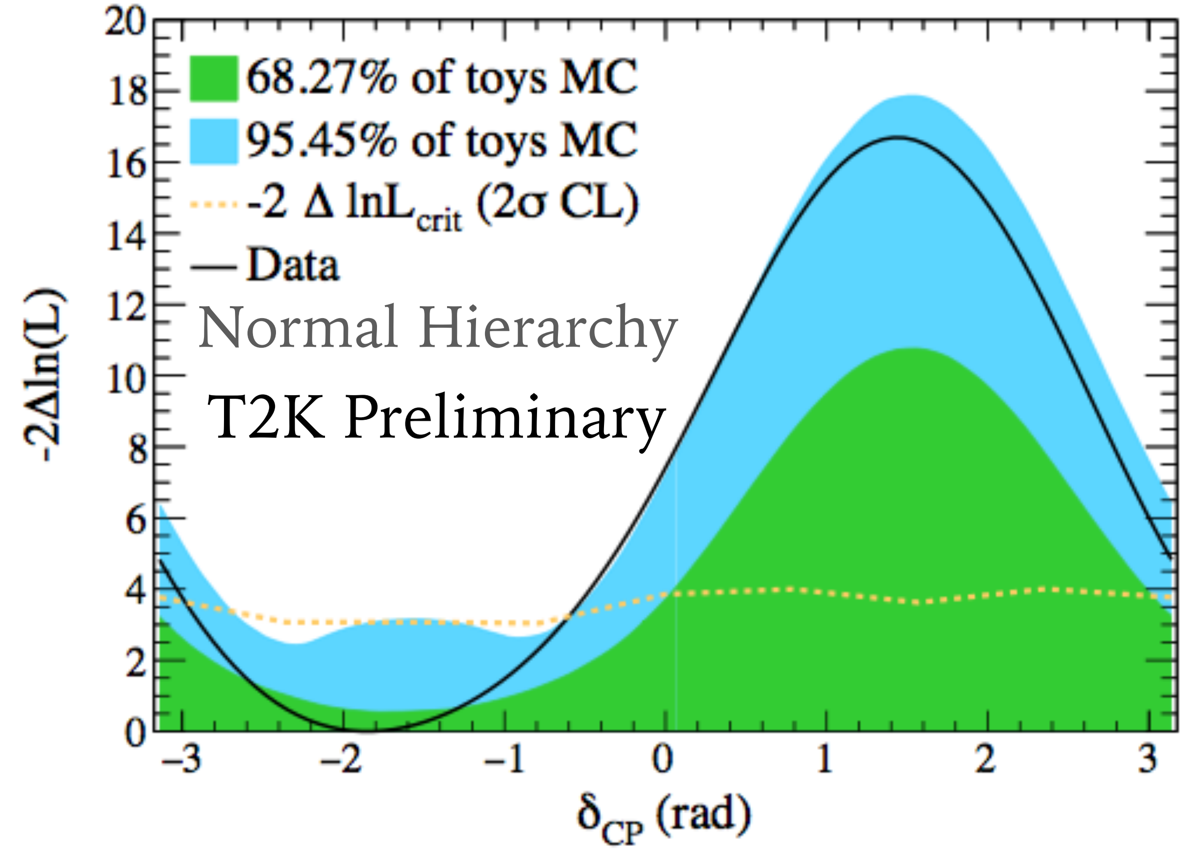
2016 VS. 2017

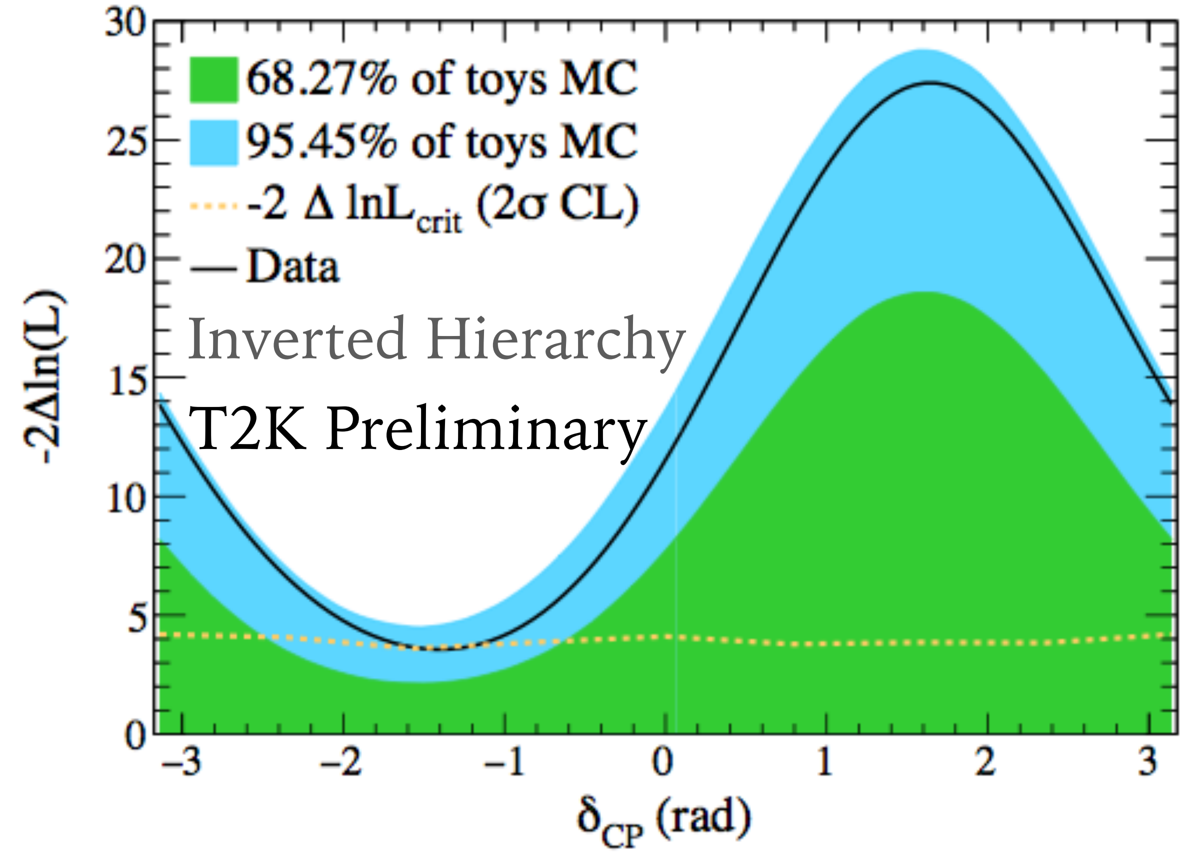


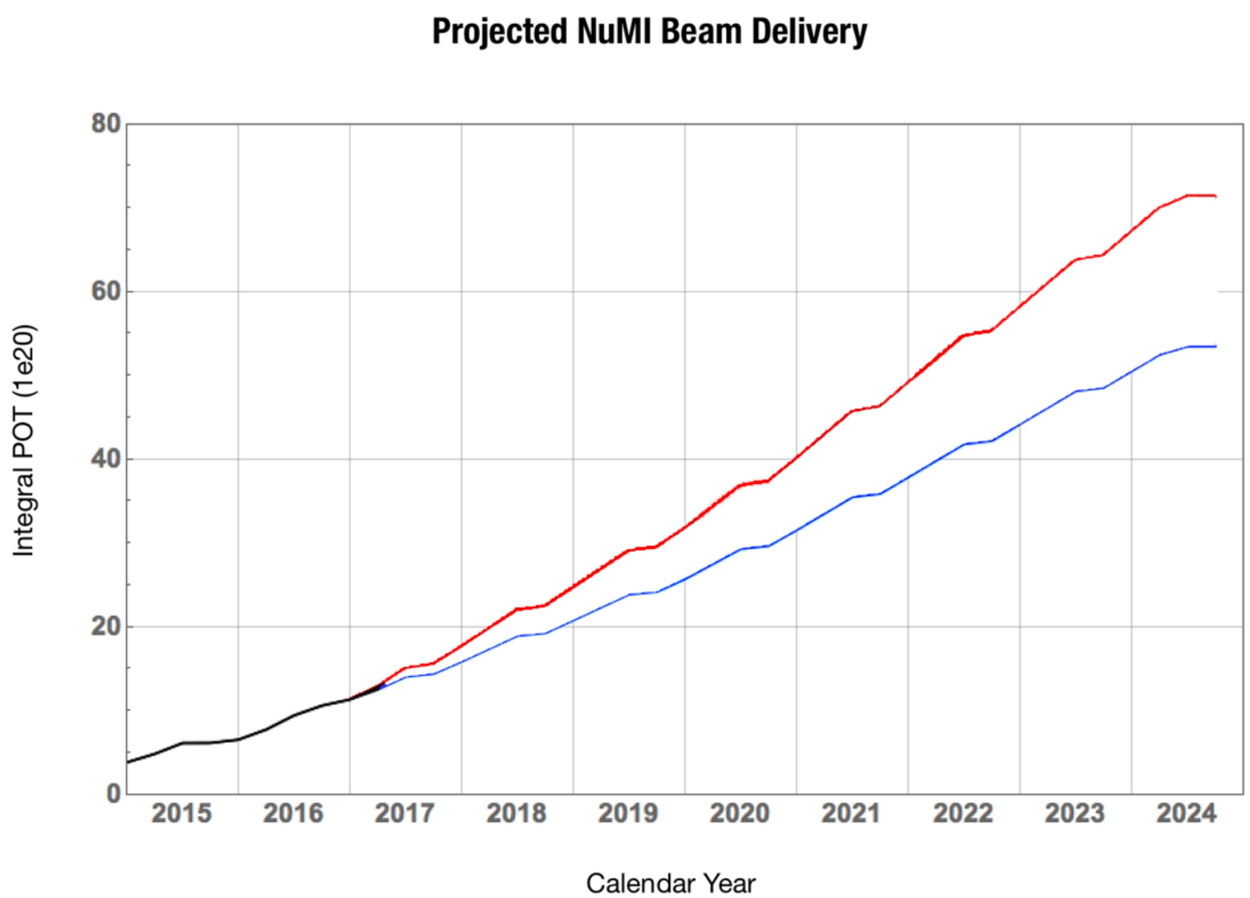


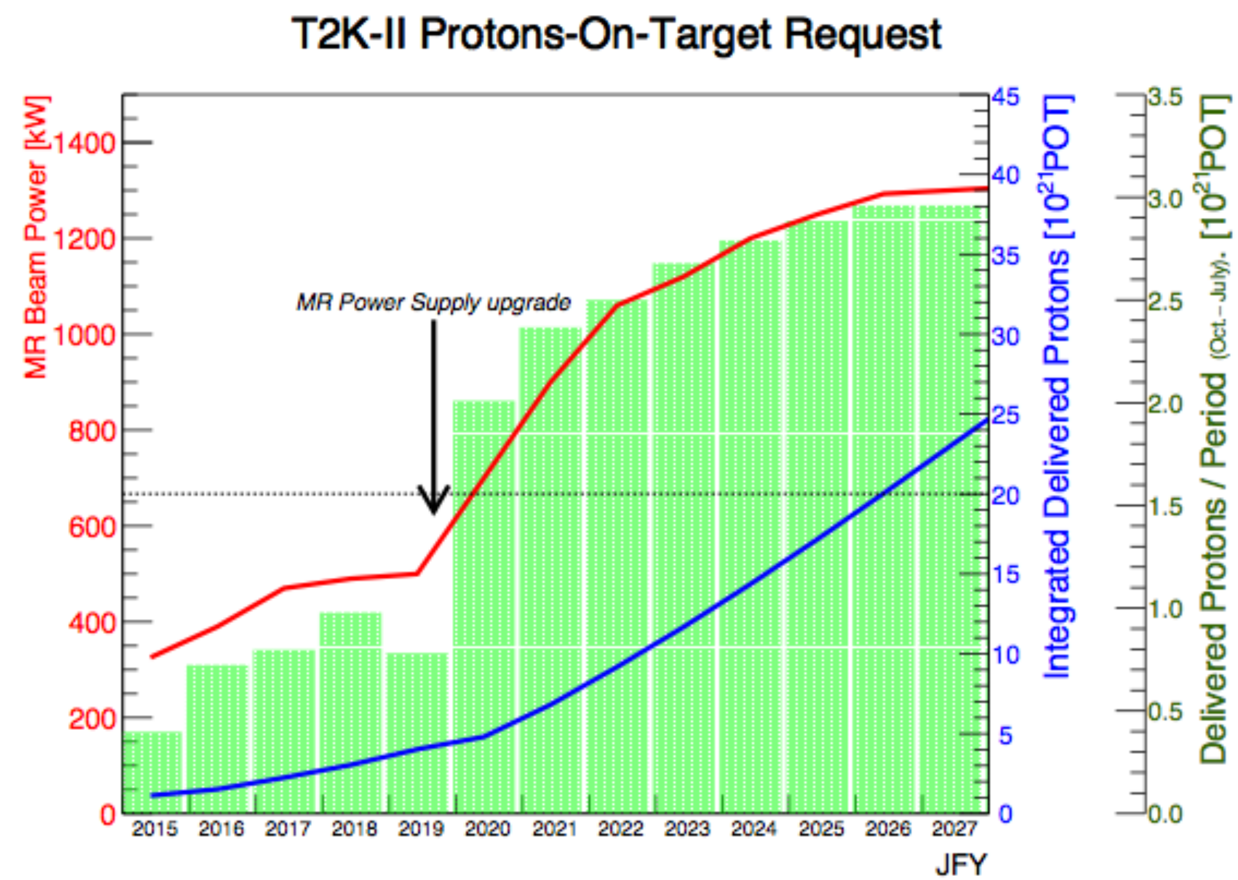
- Run 1-7c 90% CL intervals
  - Normal hierarchy: [-3.13, -0.39] radians
  - Inverted hierarchy: [-2.09, -0.74] radians
- Run 1-8:
  - Normal hierarchy: [-2.80, -0.83] radians

SENSITIVITY VS> RESULT

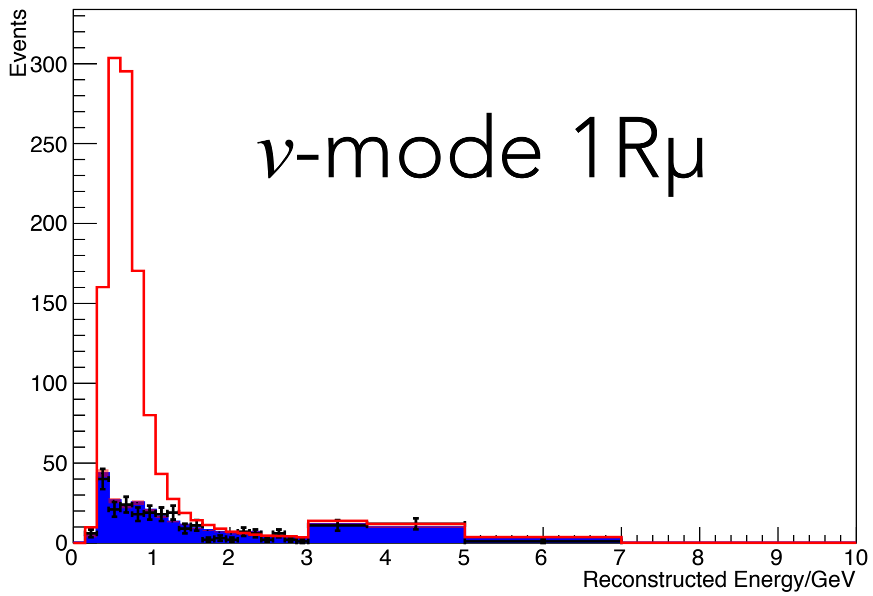


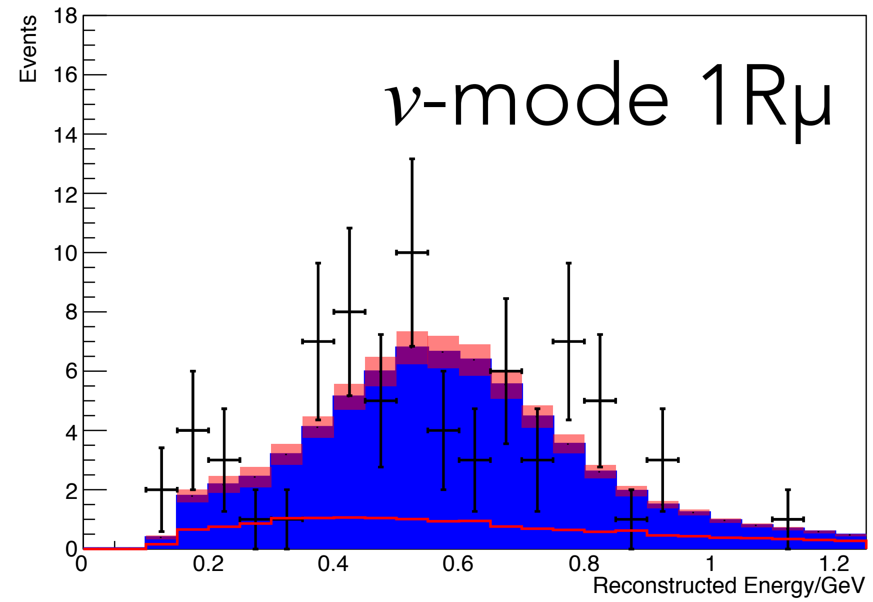


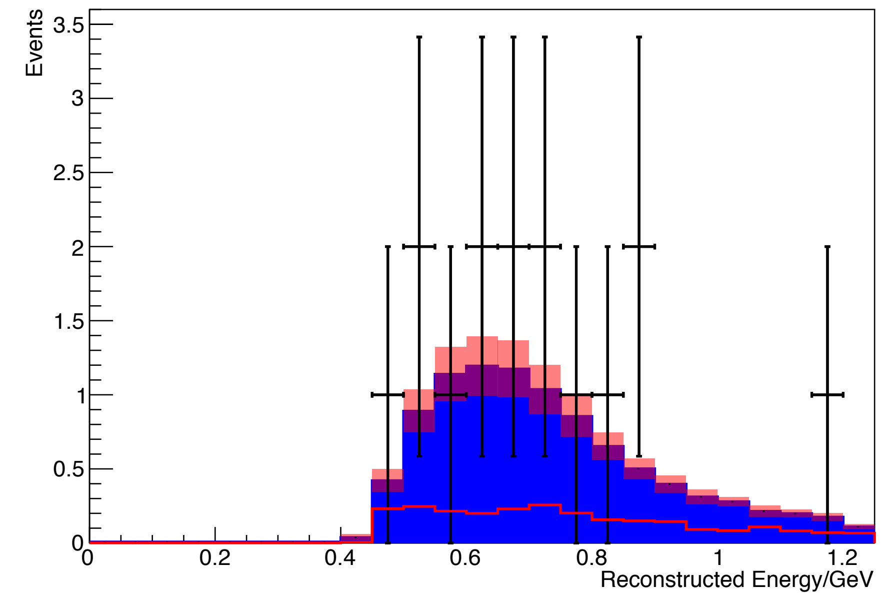

Projected NuMI Beam Delivery
Integral POT (1e20)
0
20
40
60
80
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
Calendar Year

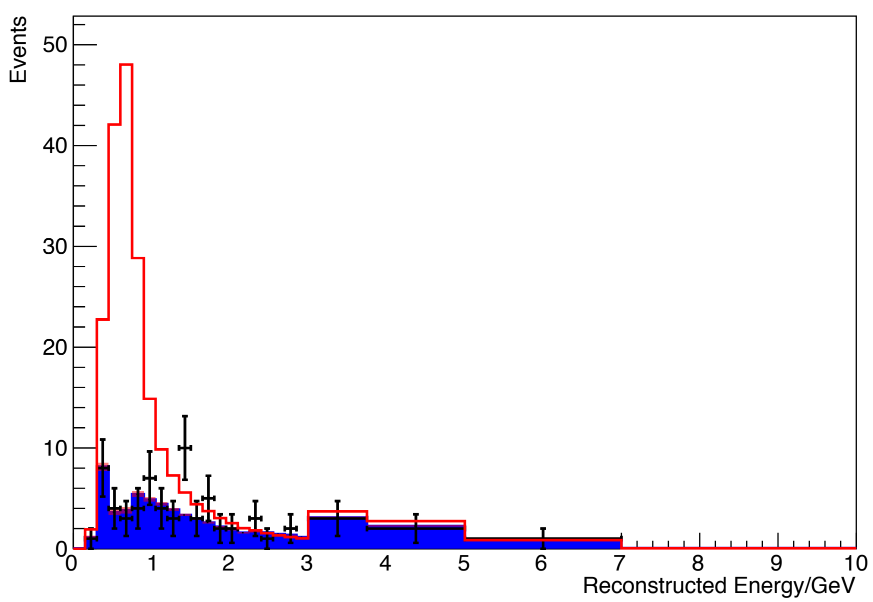

T2K-II Protons-On-Target Request
MR Beam Power [kW]
Integrated Delivered Protons [10^21POT]
Delivered Protons / Period (Oct.–July), [10^21POT]
MR Power Supply upgrade
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25
30
35
40
45
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
JFY

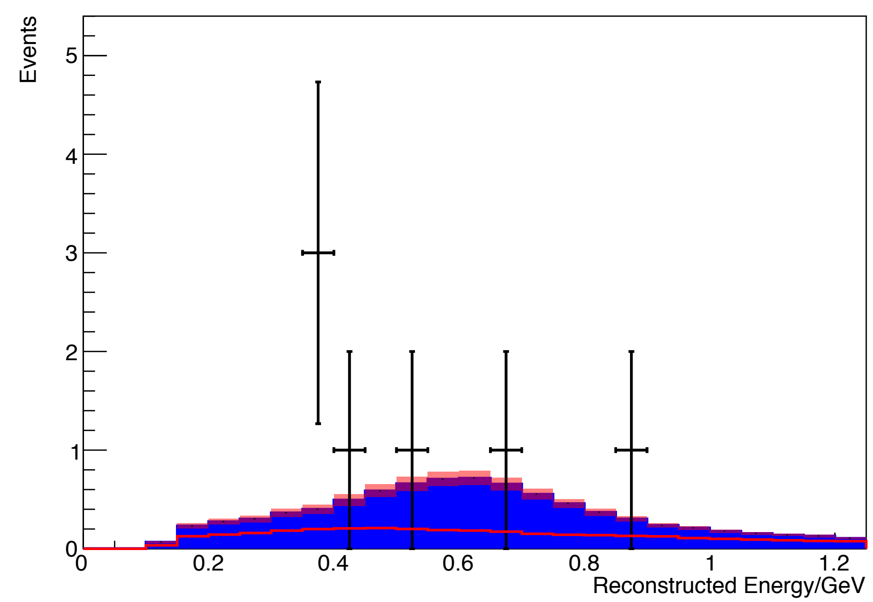
t2K EVENTs

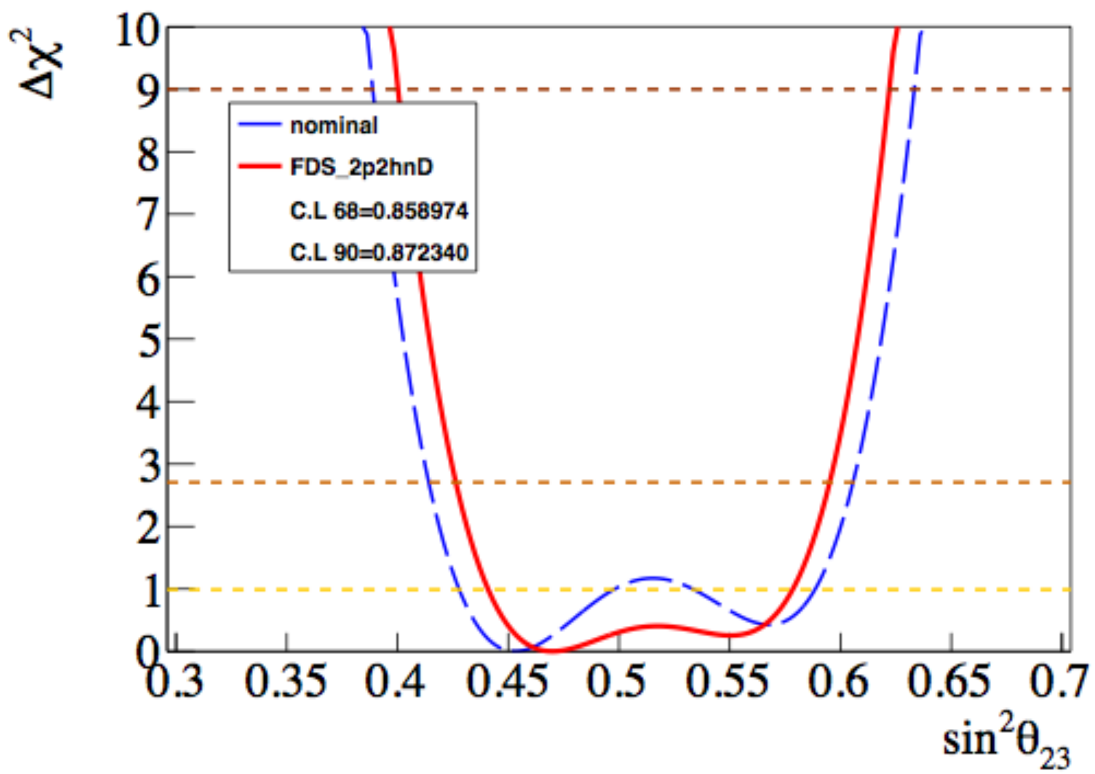

ν-mode 1Rμ
Events
Reconstructed Energy/GeV


ν-mode 1Rμ
Events
Reconstructed Energy/GeV


Events
Reconstructed Energy/GeV


Events
Reconstructed Energy/GeV


Events
Reconstructed Energy/GeV



$\Delta\chi^2$
nominal
FDS_2p2hnD
C.L 68=0.858974
C.L 90=0.872340
$\sin^2\theta_{23}$