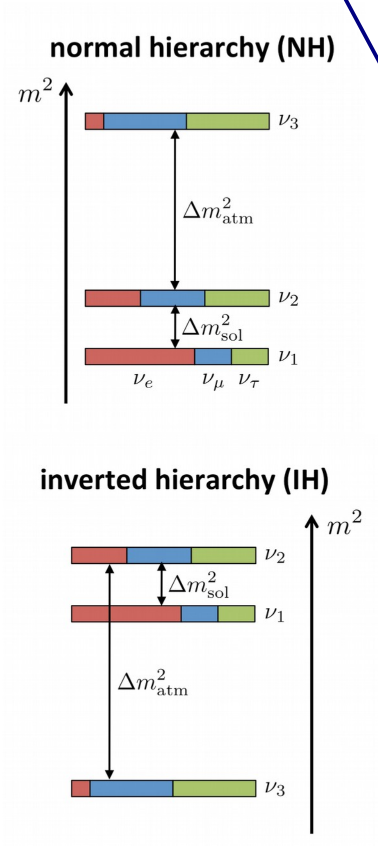
21st International Workshop on Neutrinos from Accelerators – NuFACT 2019

Atmospheric neutrino results from Super-Kamiokande

C. Bronner
Aug. 27th, 2019

Neutrino oscillation
Open questions

Mass hierarchy:
$m_3 > m_2, m_1$?



PDG 2017 summary table

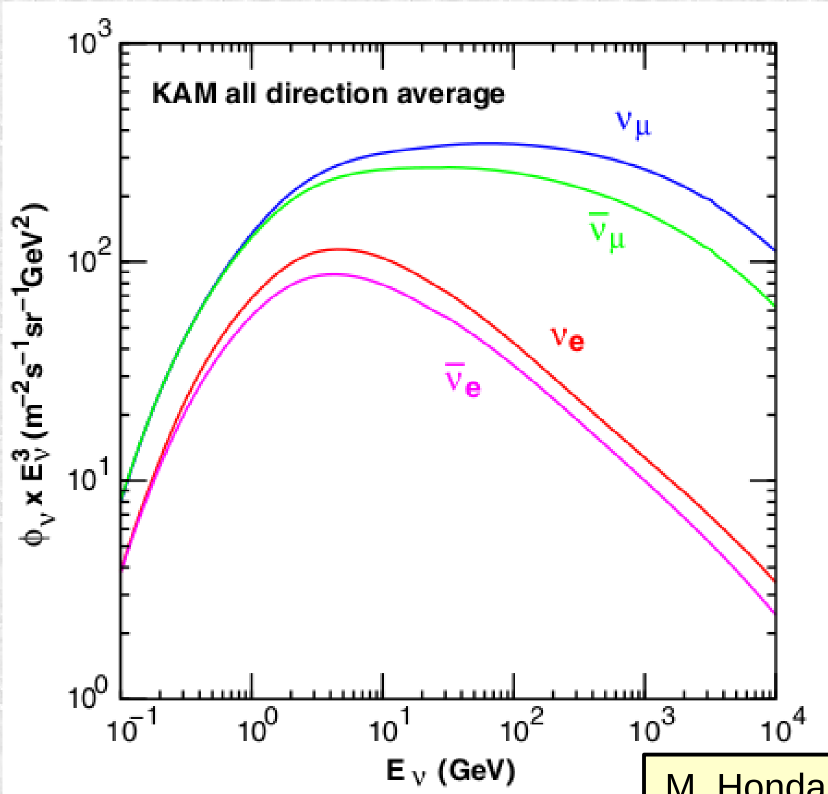
Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Octant of θ_{23}:
$\theta_{23} > \pi/4$?
$\theta_{23} < \pi/4$?

Violation of CP symmetry in neutrino oscillations?

Degeneracies between those 3 questions

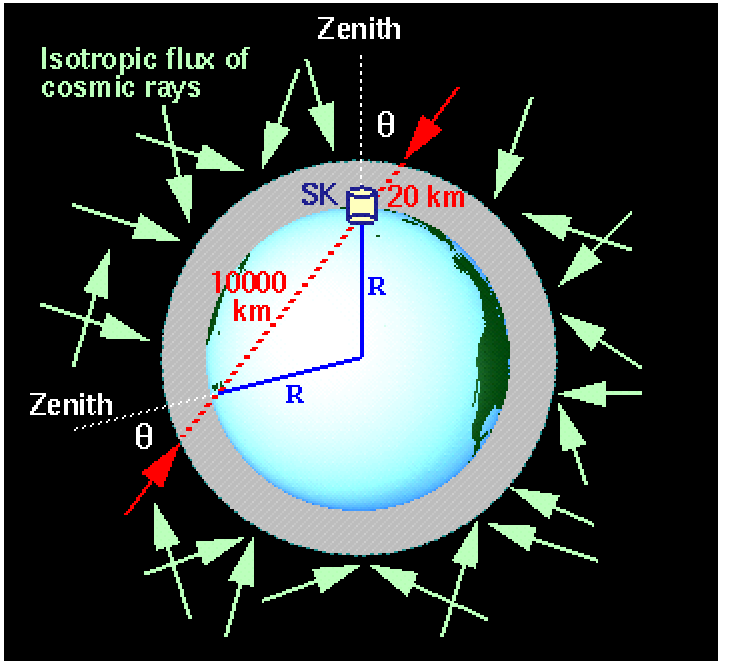
Atmospheric neutrinos
Interest for oscillation measurements



M. Honda

ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ over 5 decades in energy

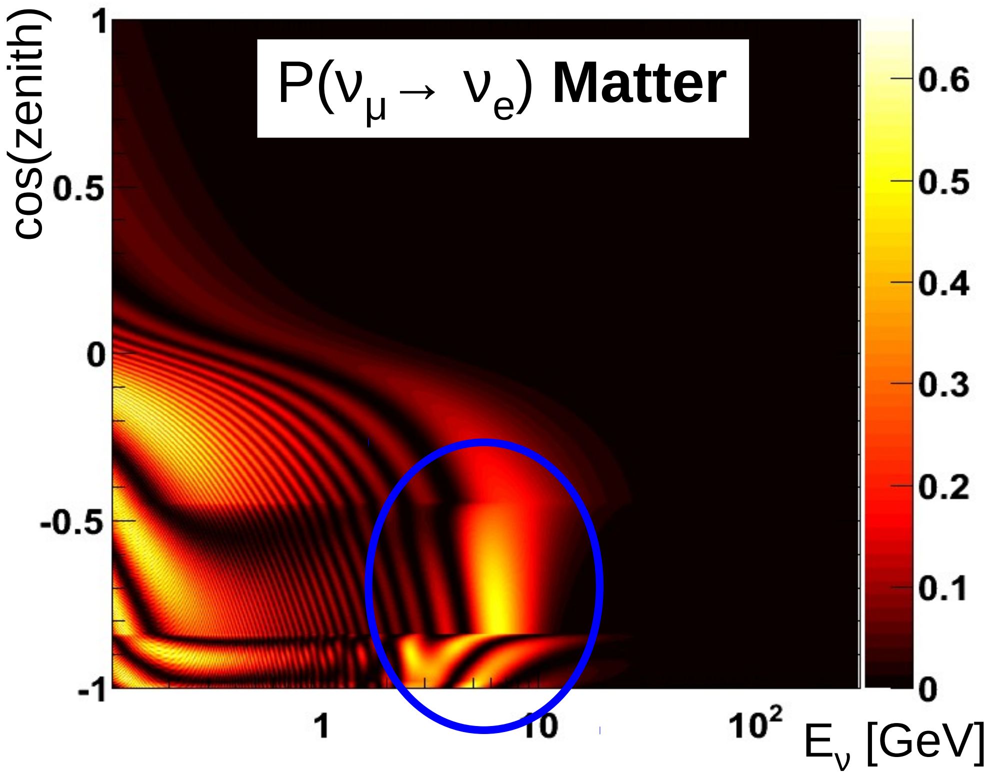
L from 10 to 13000km

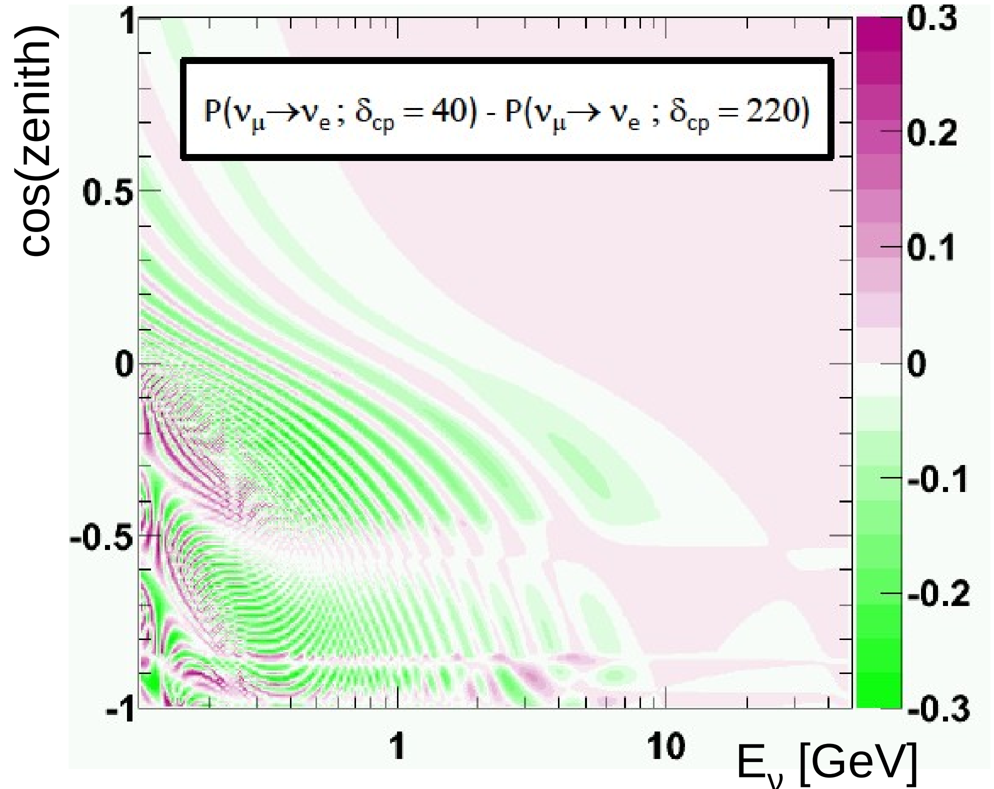


- Large range of neutrino energies and propagation lengths
- Oscillations dominated by $\nu_\mu \rightarrow \nu_\tau$
- Large statistics allow to study sub-dominant effects

Atmospheric neutrinos
Interest for oscillation measurements

Ability to study the open questions comes mainly from appearance channels $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





Resonance from matter effects

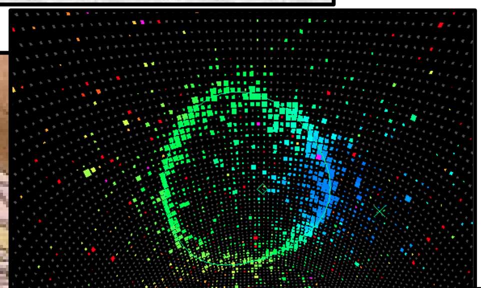
- Only for ν in NH and $\bar{\nu}$ in IH
  → **sensitive to the mass hierarchy**
- Size of the effect depends on $\sin^2(\theta_{23})$
  → **sensitive to θ_{23} octant**

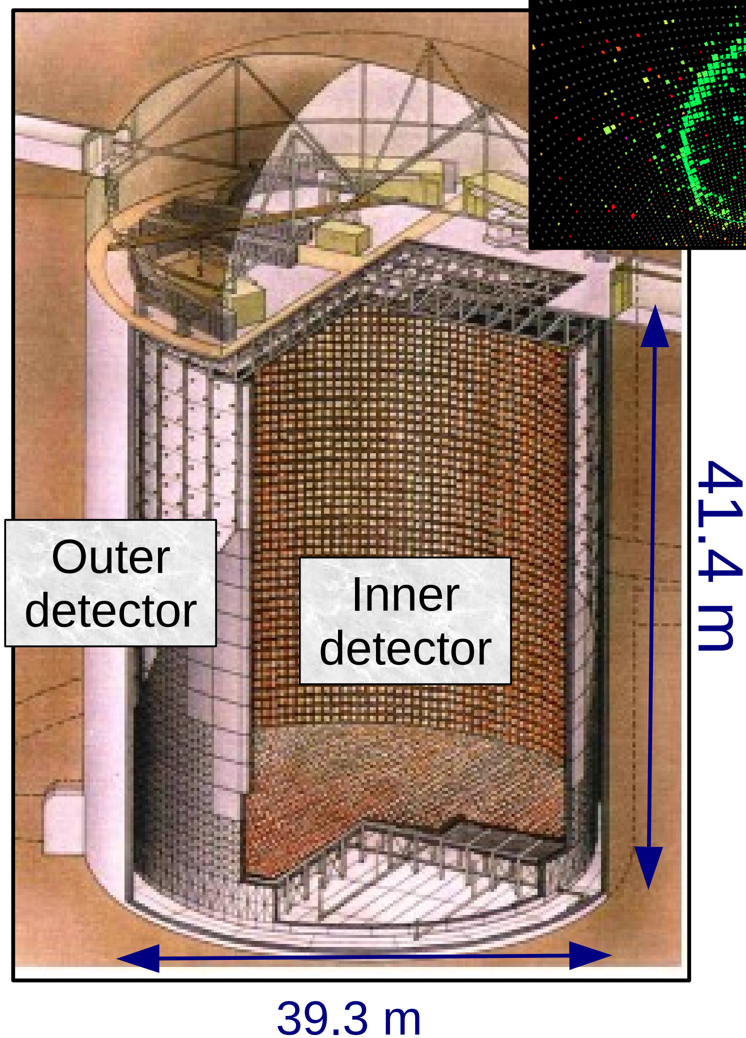
δ_{CP} modifies the oscillation patterns

- Sensitivity from number of sub-GeV ν_e events
- More ν_e appearance events for δ~220-240º, and less for δ~40-45º

Super-Kamiokande experiment

- 50 kt (22.5 kt fiducial) water Cherenkov detector
- 1000m overburden
- Operational since 1996

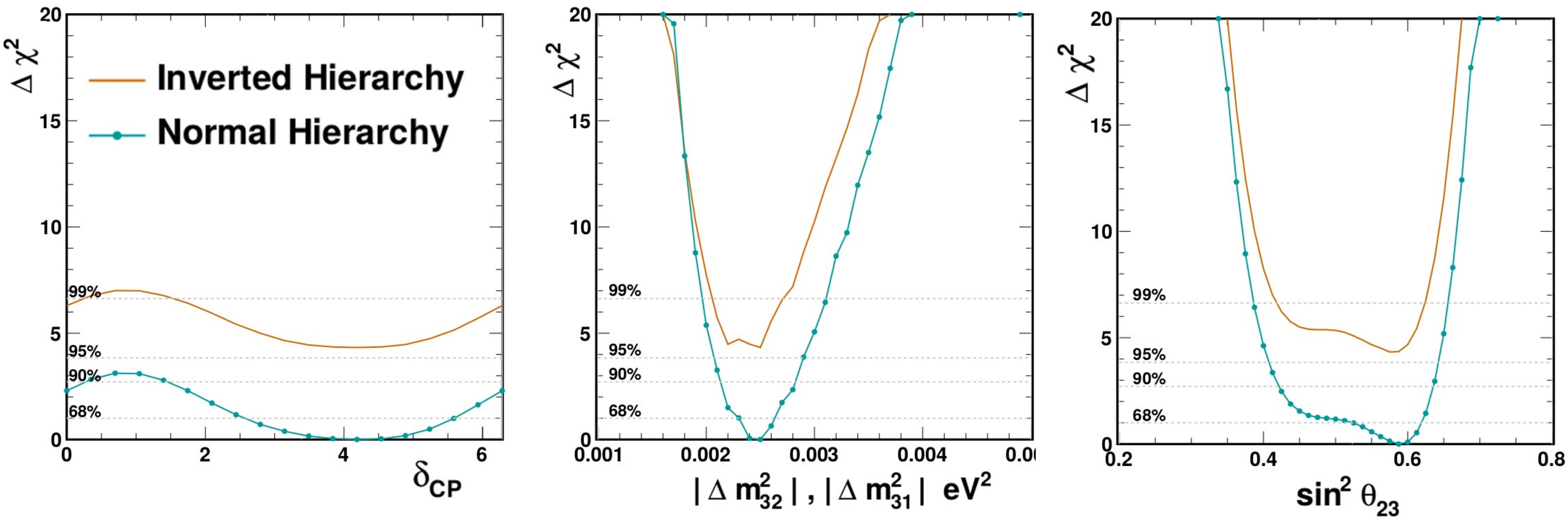




Wide physics program:
- ✓ **Atmospheric neutrinos**
- ✓ Solar neutrinos
- ✓ Supernova neutrinos
- ✓ Proton decay
- ✓ Dark matter indirect detection

- Good separation between $\mu^{\pm}$ and $e^{\pm}$ (**separate ν_{μ} and ν_{e} CC interactions**)
  → Less than 1% mis-PID at 1 GeV
- No magnetic field: **cannot separate ν and $\bar{\nu}$ on an event by event basis**
- **Only detects charged particles above Cerenkov threshold and photons**
  → limitation for energy and directional reconstruction

Current SK I-IV official results
Atmospheric neutrino only

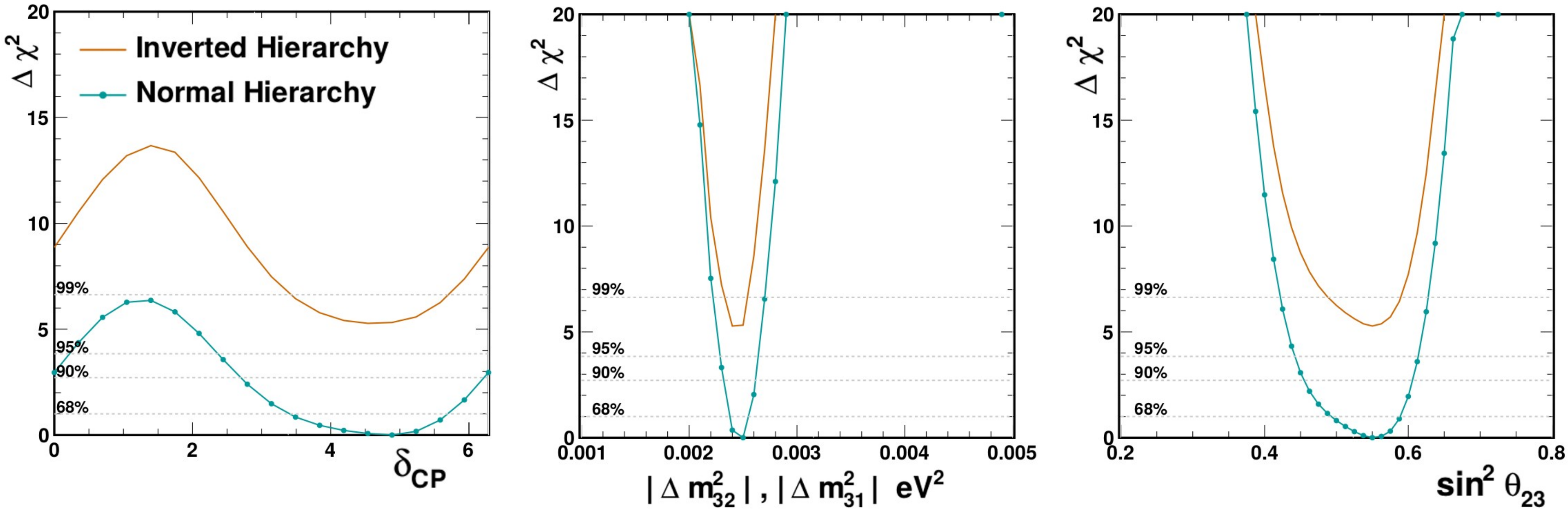


	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	571.33	2.5×10^{-3}	0.5875	4.18
Inverted hierarchy	575.66	2.5×10^{-3}	0.575	4.18

- **Preference for the normal hierarchy: χ^2(NH)-χ^2(IH)=-4.33**
- P-value for this $\Delta\chi^2$ (true values of the parameters corresponding to the NH best fit point) is 0.027 for true IH

PRD 97, 072001 (2018)

Current SK I-IV official results
SK Atmo + reactor + model of T2K



	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	639.43	2.50×10^{-3}	0.550	4.88
Inverted hierarchy	644.70	2.40×10^{-3}	0.550	4.54

- **Slightly stronger preference for the NH: χ^2(NH)-χ^2(IH)=-5.27**
- P-value for this $\Delta\chi^2$ (true values of the parameters corresponding to the NH best fit point) is 0.023 for true IH

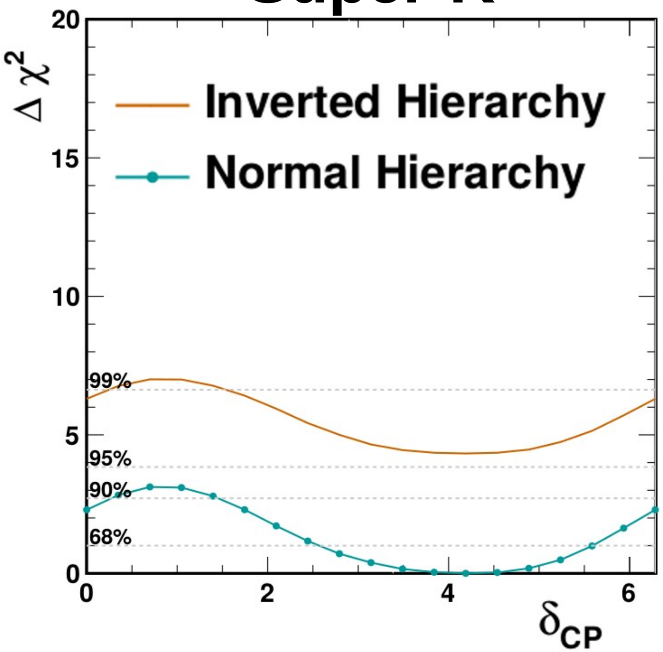
PRD 97, 072001 (2018)

Towards a real T2K and SK joint fit

- Results on previous slides were <u>not</u> a joint analysis between the T2K and SK collaborations
- Used SK tools to build a model of T2K and fit data based on publicly available information (from PRD 91, 072010 (2015), not most recent T2K analysis and data)

The Super-K and T2K collaborations have now formally agreed to pursue a joint analysis of their data sets

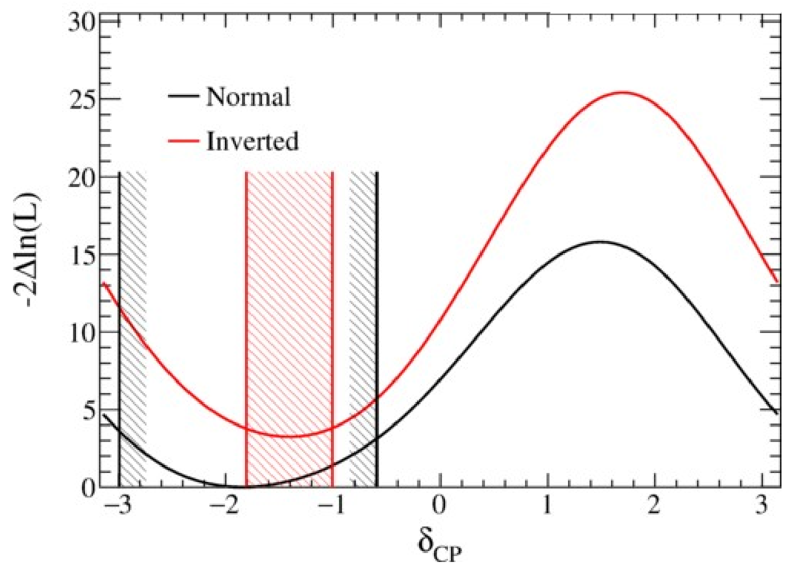
Super-K



PRD 97, 072001 (2018)

+

T2K

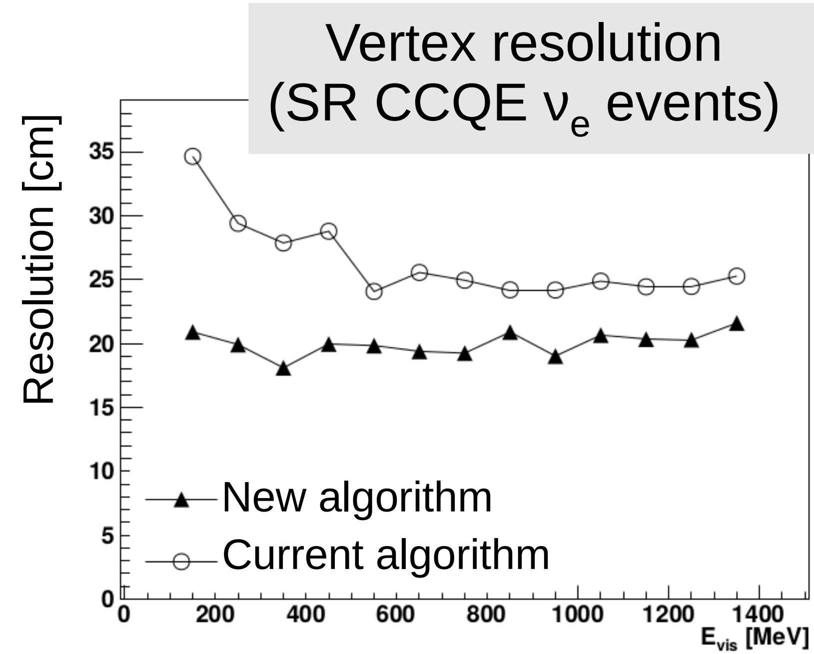


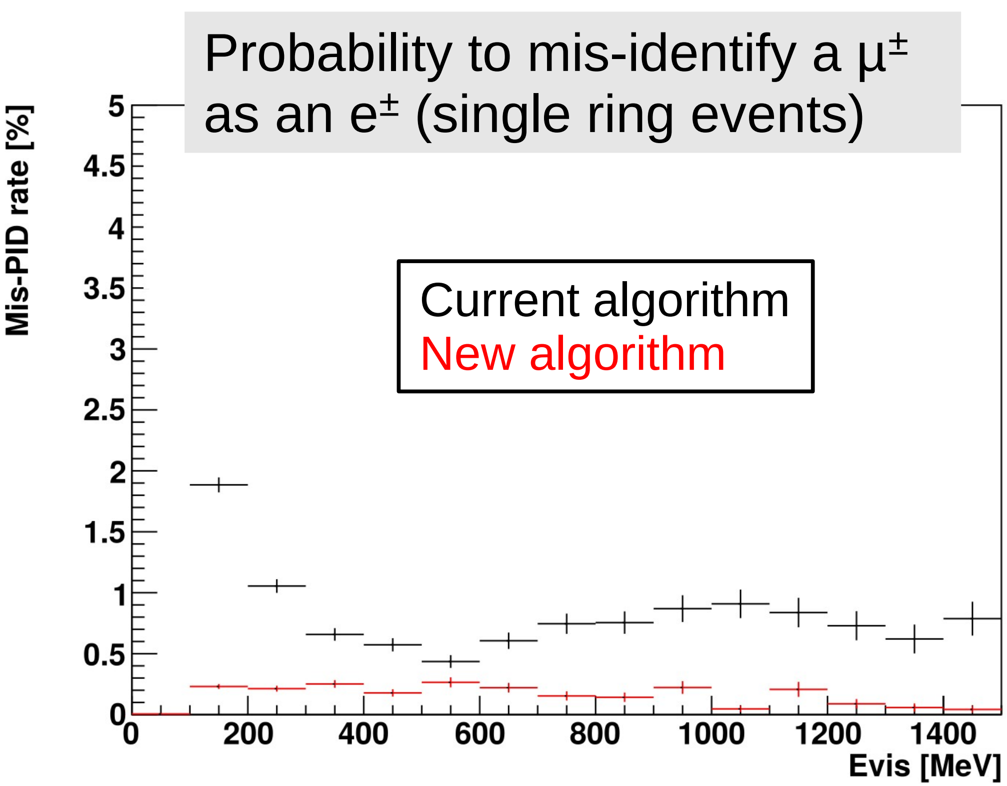
PRL 121, 171802 (2018)

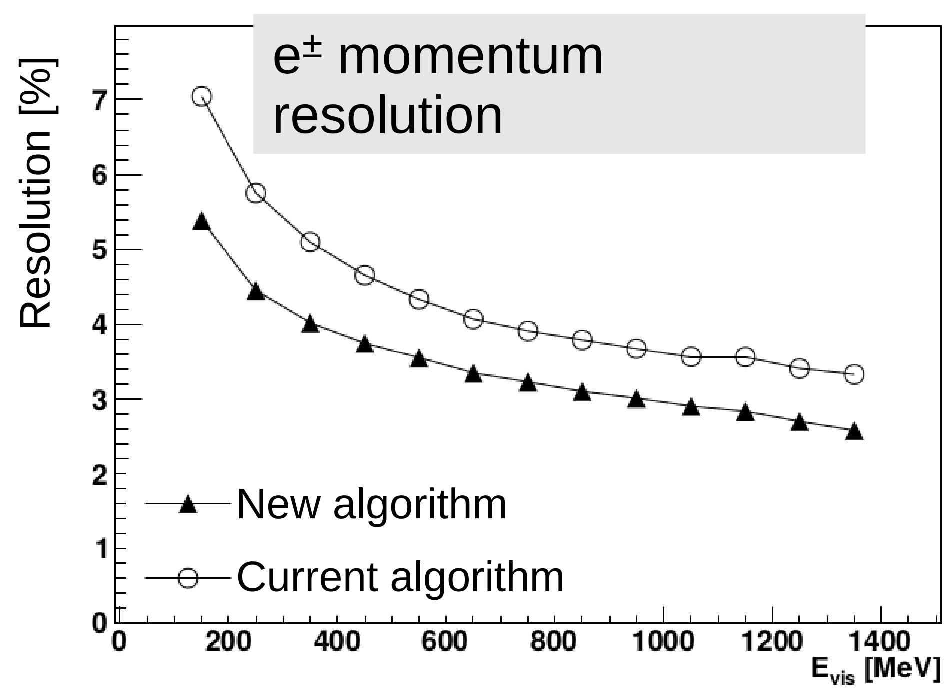
= ?

New reconstructrion algorithm in SK

- New reconstruction algorithm developed for Super-K events “fiTQun”
- Provides improved performance for vertex and momentum resolution, as well as PID
- Used for T2K oscillation analysis since 2017 but not in Super-K analysis shown in previous slides







New reconstructrion algorithm in SK
Separation of ν_e and $\bar{\nu}_e$ events

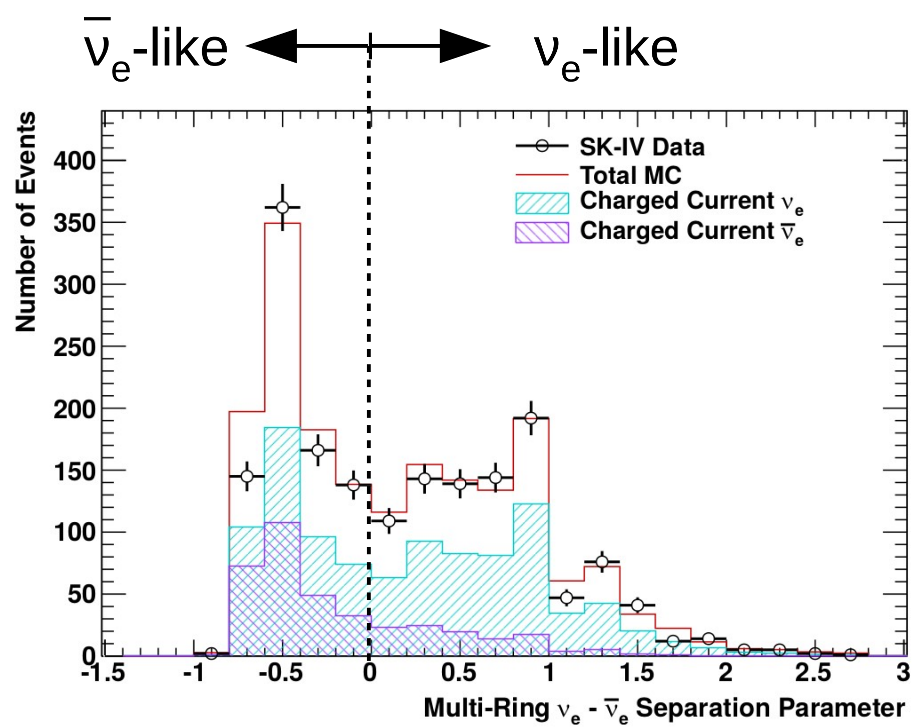
- To improve MH sensitivity, statistical separation of Multi-GeV Multi-Ring ν_e and $\bar{\nu}_e$ events
- Two steps using likelihoods:
  - separate ν_e+ $\bar{\nu}_e$ from other
  - separate ν_e from $\bar{\nu}_e$
- Both steps improved with the new reconstruction algorithm

Separate ν_e+ $\bar{\nu}_e$ from other

	New algorithm	Old algorithm
Efficiency	**75.7%**	69.7%
Purity	**77.8%**	69.5%

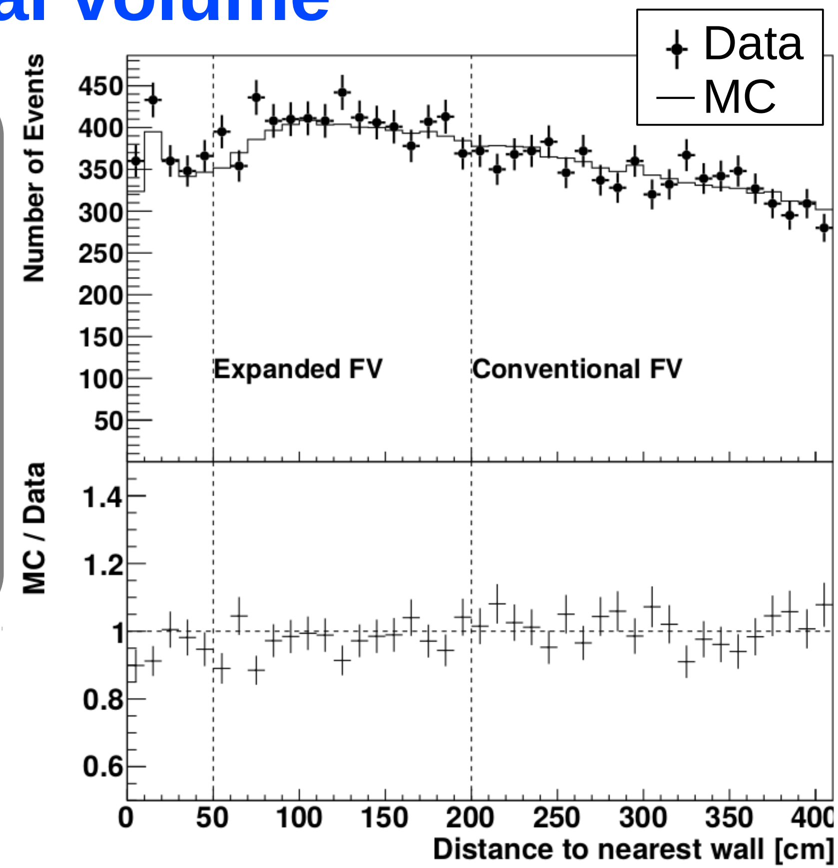
Separate ν_e from $\bar{\nu}_e$

		New algorithm	Old algorithm
True CC $\boldsymbol{\nu_e}$	Efficiency	**56.8%**	53.6%
	Purity	**58.8%**	52.6%
True CC $\boldsymbol{\bar{\nu}_e}$	Efficiency	**68.4%**	70.9%
	Purity	**30%**	25.9%

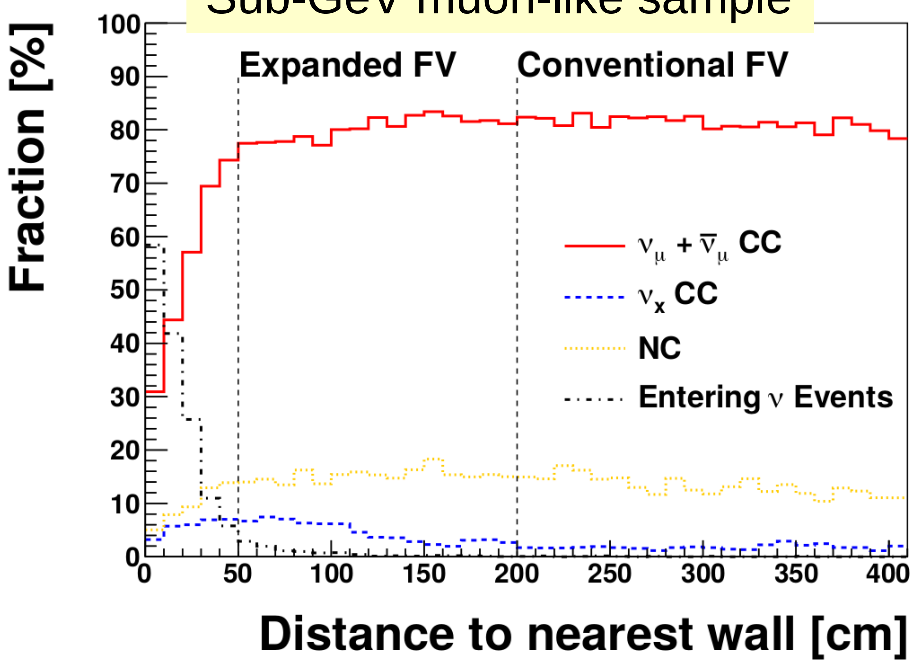


New reconstructrion algorithm in SK
Extension of fiducial volume

- Analysis for the mass hierarchy is limited by statistics
- Previous results use a fiducial volume cut 2m away from the walls: 30% of the target mass of the inner detector is lost
- Improved performance of new algorithm allow to extend FV to 50 cm from the walls
- T2K uses optimized FV cut since 2017, includes some events from this '0.5-2m from wall' region



Sub-GeV muon-like sample



Possible issues when increasing FV:
- Reconstruction performance near the wall
- Entering background

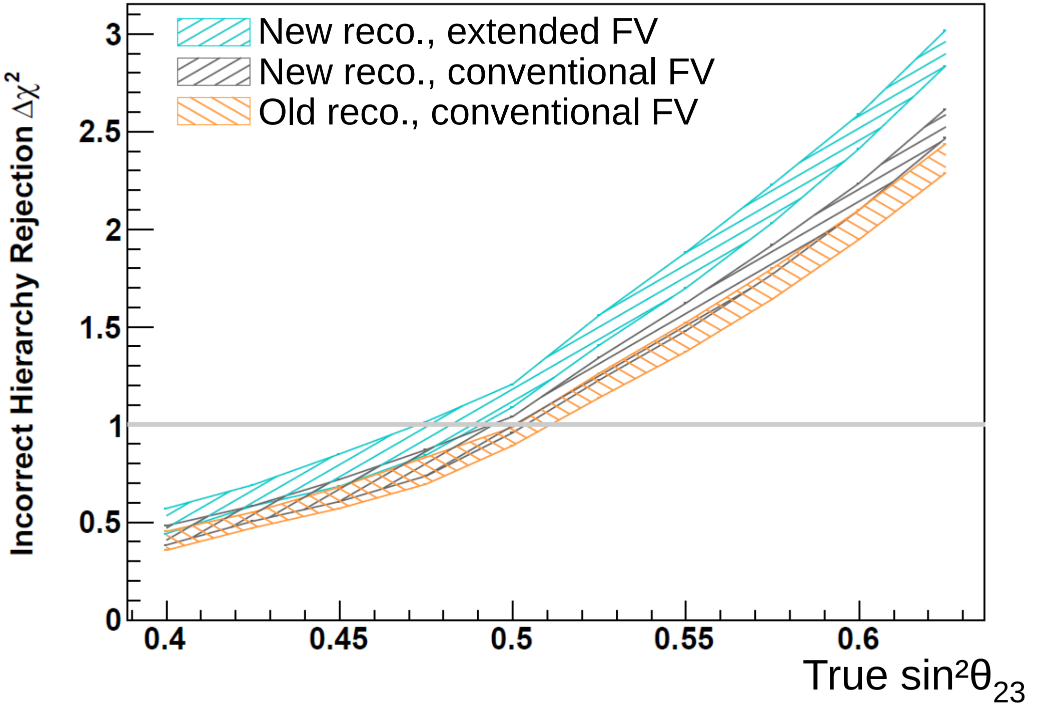
FV cut 2m → 0.5m:
+32% target mass

New reconstructrion algorithm in SK
Sensitivity improvement

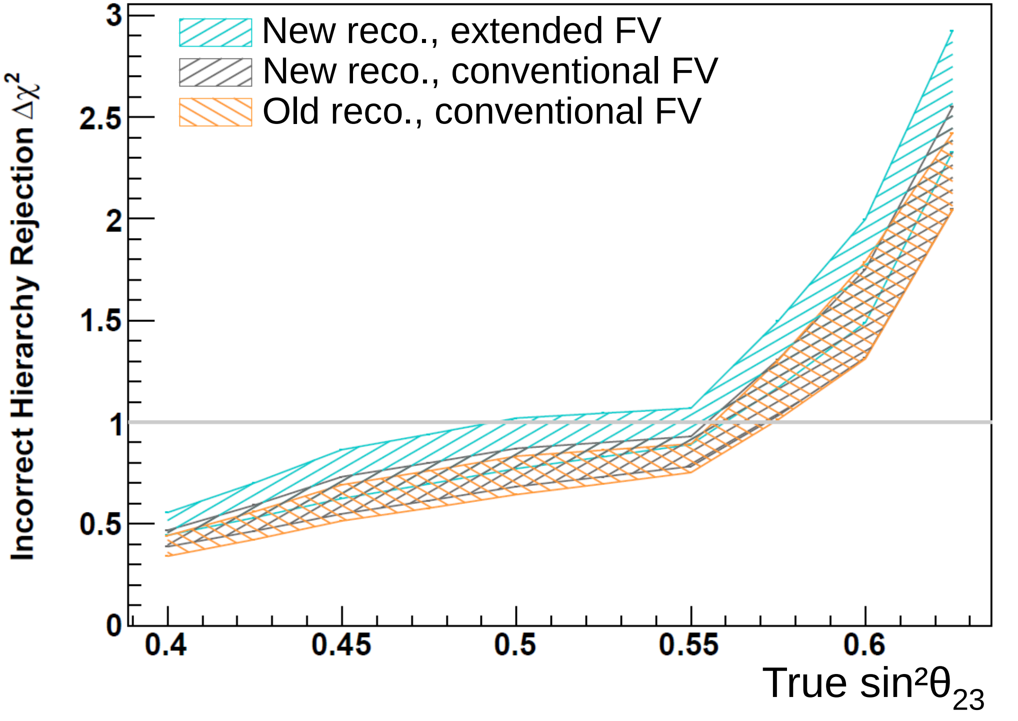
This leads to an increased sensitivity to the mass hierarchy

- New reconstruction algorithm produce e-like samples with improved purity
- Larger increase of sensitivity from the extension of FV, as the analysis is statistically limited

True Normal Hierarchy



True Inverted Hierarchy



Sensitivity for SK-IV 3118.5 days of livetime

Reactor constraint: $\sin^2(\theta_{13})=0.0210 \pm 0.0011$

Other analysis improvements

New analysis of SK IV data using this new reconstruction and extended fiducial volume, as well as a number of additional improvements

Update of interaction model

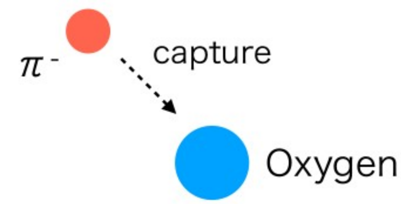
- Moved to NEUT 5.4.0
- CCQE: changed from Relativistic Fermi Gas (RFG) to Local Fermi Gas (LFG) model by Nieves et al.
- DIS: many updates, including:
  - include CKM matrix elements
  - update of low Q^2 corrections by Bodek and Yang
- Updated values of parameters describing pions Final State Interactions

Update of systematic uncertainties

- CCQE: updated for LFG
- DIS: updated for NEUT 5.4.0 + add uncertainty from pion multiplicities
- Final state interactions
- Solar flux uncertainties updated for additional data

Neutron production from pion capture implemented in simultation

- OLD
  - single proton emission



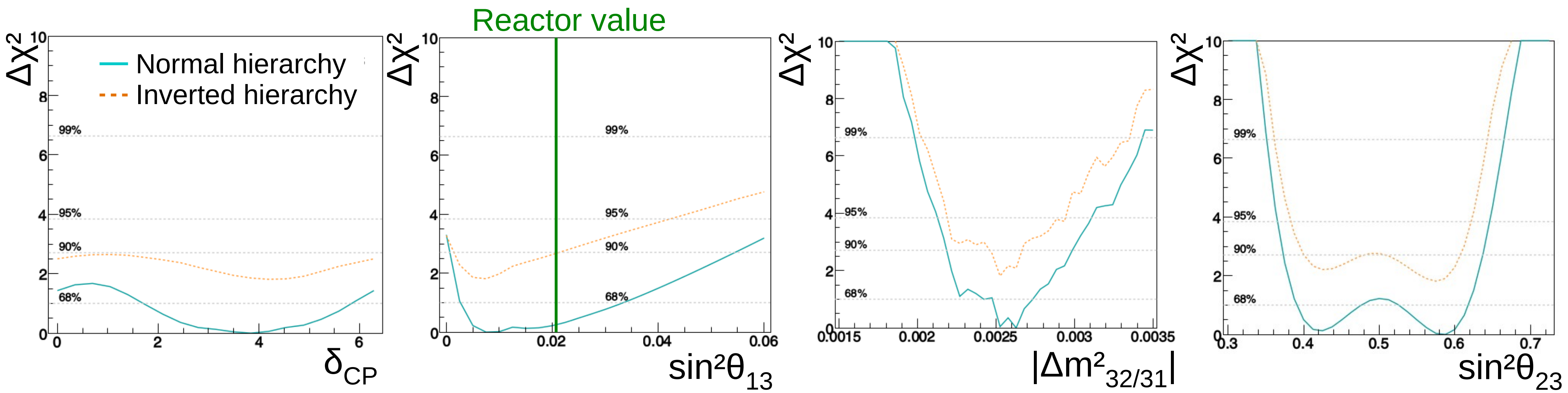
- NEW

  3 pattern of pi- capture
  - 98% : π^-np -> nn : two neutron emission ・・・①
  - 2% : π^-A_Z -> n(n)γ $(A-1)_{Z-1}$: radiative pion capture
    - E_γ > 100MeV : π^-A_Z -> nγ $(A-1)_{Z-1}$ ・・・②
    - E_γ < 100MeV : π^-A_Z -> n nγ $(A-1)_{Z-1}$ ・・・③

Additional SK-IV data

Livetime: 2519 → 3118.5 days (+23.7%)

Analysis with new reconstruction and FV
SK atmospheric only



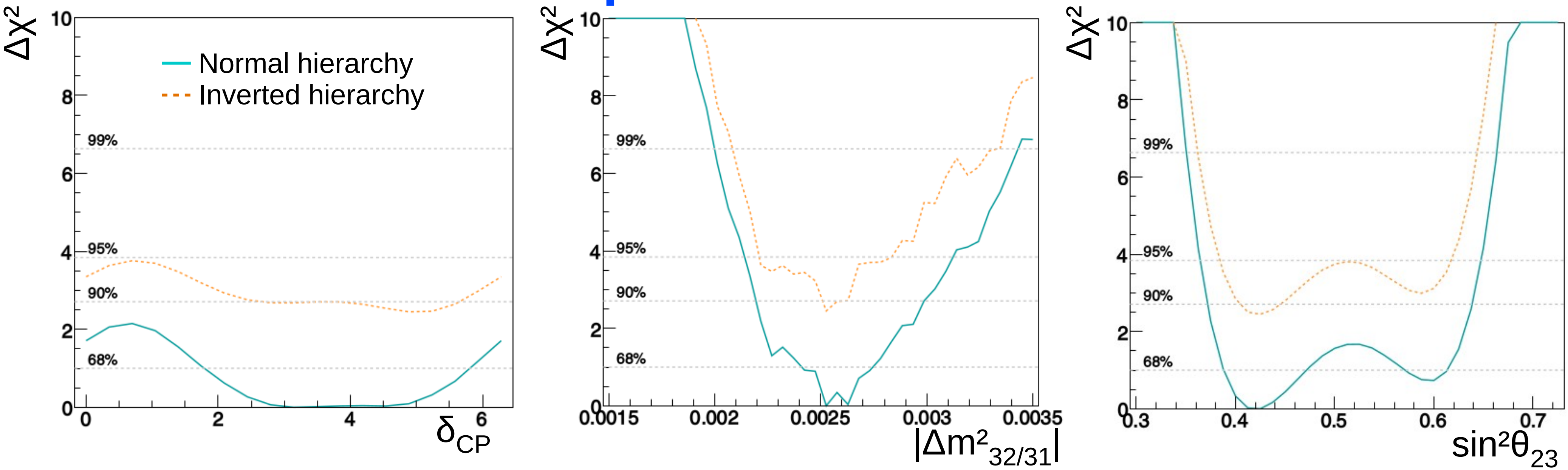
	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}	$\sin^2(\theta_{13})$
NH	576.3	2.63×10^{-3}	0.588	3.84	0.008
IH	578.1	2.53×10^{-3}	0.575	4.19	0.008

Preference for the normal hierarchy, $\Delta\chi^2$=-1.81

SK-IV only, 3118.5 days of livetime

Prog. Theor. Exp. Phys. 2019, 053F01

Analysis with new reconstruction and FV
SK atmospheric + reactor results



	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
NH	576.5	2.53×10^{-3}	0.425	3.14
IH	579	2.53×10^{-3}	0.425	4.89

Preference for NH
$\Delta\chi^2=-2.45$

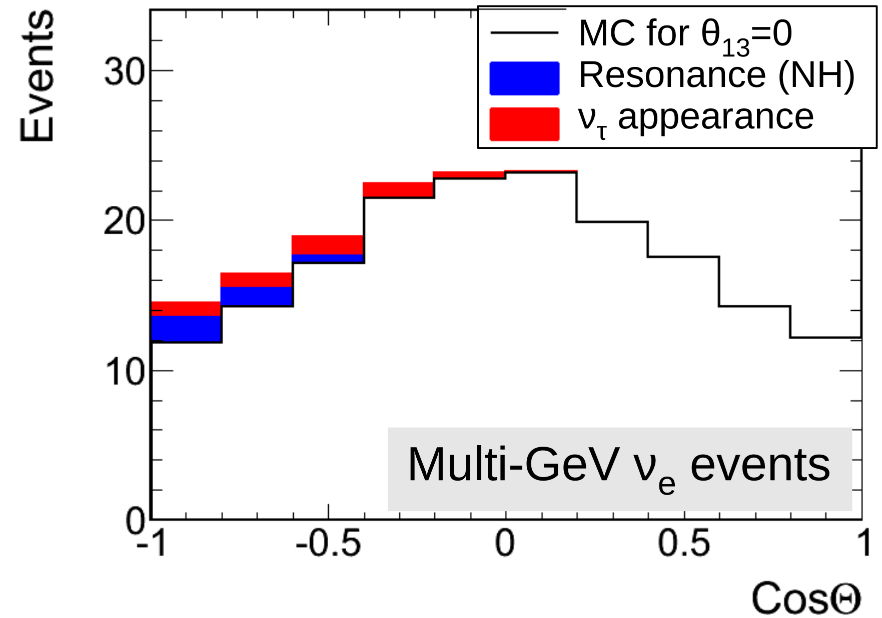
True $\sin^2\theta_{23}$	0.4	0.425	0.5	0.6
p_0(IH)	0.025	0.033	0.065	0.072
$\mathrm{CL}_s^{\mathrm{H}}$	0.308	0.260	0.229	0.143

SK-IV only, 3118.5 days of livetime
Reactor constraint: $\sin^2(\theta_{13})=0.0210 \pm 0.0011$

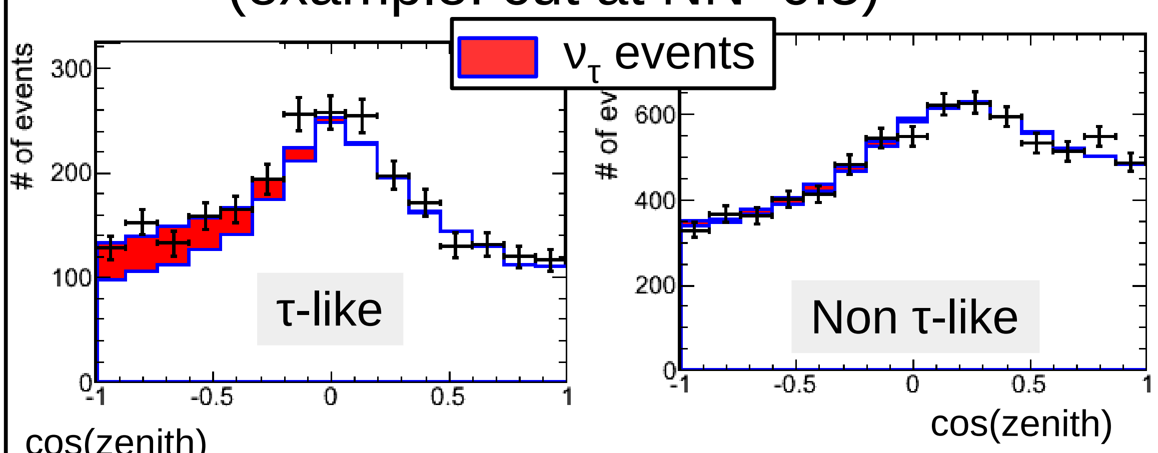
Prog. Theor. Exp. Phys. 2019, 053F01

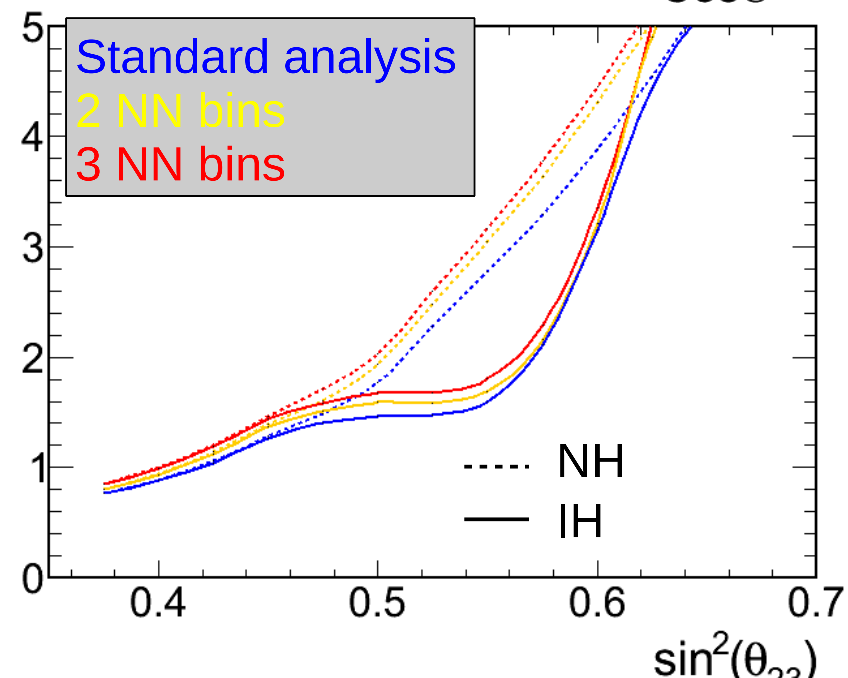
Future improvements
Use tau NN for oscillation analysis

- Up/down asymmetric group of events with normalization uncertainties are major backgrounds for mass hierarchy
- CC ν_τ cross-section has 25% uncertainty
- Can use NN output variable as an additional PDF variable for samples sensitive to the mass hierarchy



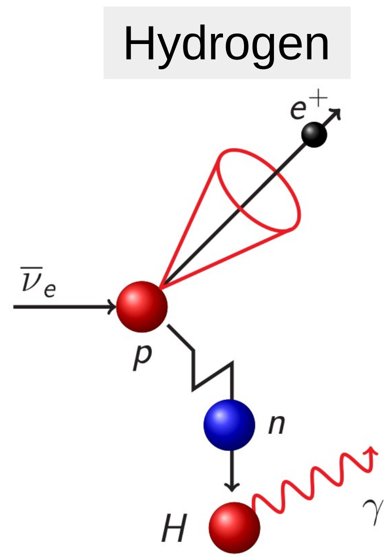
NN ouput can be used to isolate ν_τ events
(example: cut at NN=0.5)



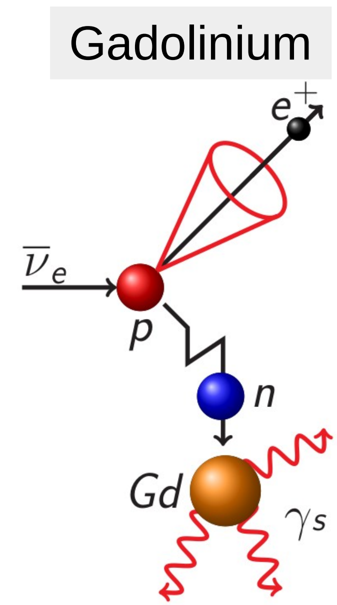


Future
Neutron tagging

- Neutrons cannot be directly seen in Super-K
- Can be detected from gammas emitted during their capture
- **SK IV-V**: can use capture on hydrogen **efficiency~20%**
- Future **SK-Gd**: capture on Gd **efficiency~80%** at 0.1% Gd loading



Single 2.2 MeV γ



8 MeV γ cascade

<u>Possible benefits:</u>

- ✓ statistical $\nu_e/\overline{\nu}_e$ separation in Sub-GeV samples for δ
- ✓ Improve statistical $\nu_e/\overline{\nu}_e$ separation in Multi-GeV samples for MH
- ✓ Correct for missing (invisible) energy to improve energy resolution

<u>Challenges</u>

- ✗ uncertainties on neutron production for high energy ν on nuclear targets
- ✗ uncertainties on re-interactions in nuclear material and water
- ✗ No measurement currently available

Preparation for SK-Gd

- Tank refurbished in preparation for Gd dissolution in water
- Main goal was to fix water leak
- Work complete, SK data taking re-started in January 2019 (“SK V”)
- Preparing to dissolve Gd in water early 2020

- ✓ Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- ✓ This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment.

Summary

- Super-K is sensitive to the mass hierarchy through a matter induced resonance in the muon to electron flavor oscillation probability and to the value of δ_{CP} through the Sub-GeV electron like events

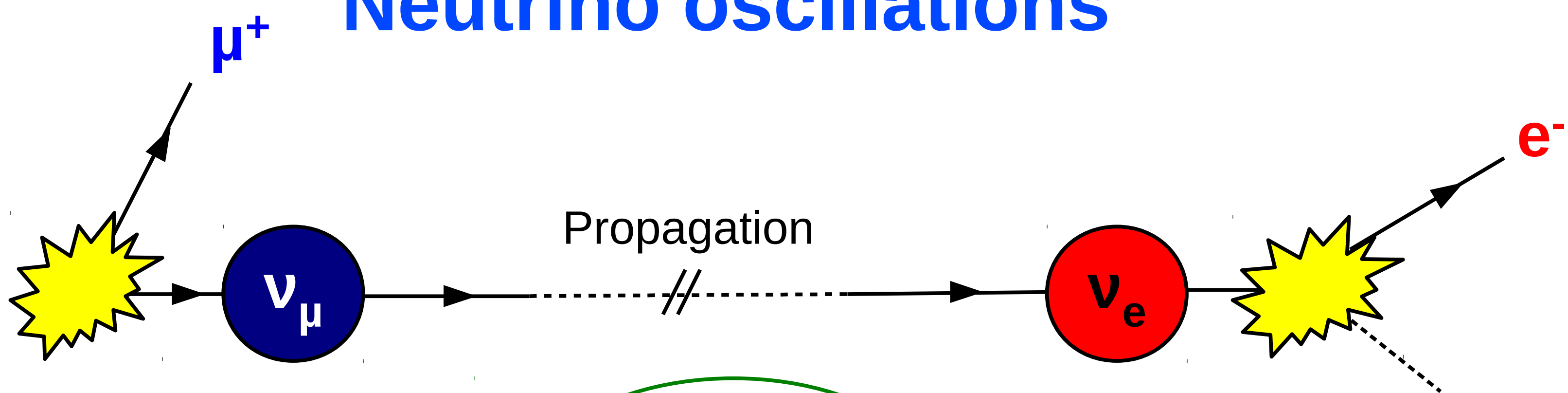
- Use of a new reconstruction algorithm increases the sensitivity of the experiment to the mass hierarchy, through more pure samples and the use of an expanded fiducial volume

- A new analysis of the SK-IV data was performed using this new reconstruction and additional improvement. Finds a preference for the normal hierarchy, which is favored by between 70% and 85% depending on the true value of the oscillation parameters assumed

- The T2K and Super-K collaboration have started working on a joint analysis of their data to study neutrino oscillations

Additional slides

Neutrino oscillations



Flavor eigenstates
(interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
(propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

$P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino

- Amplitude of oscillations depends on the mixing matrix U
- Phase of the oscillation depends on energy and difference of mass squared: $\mathbf{\Delta m^2_{ij} L/E}$

$(\Delta m^2_{ij} = m^2_i - m^2_j)$

Neutrino oscillations Parameters

In practice, for neutrino oscillations:

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

"Atmospheric" "Reactor" "Solar"

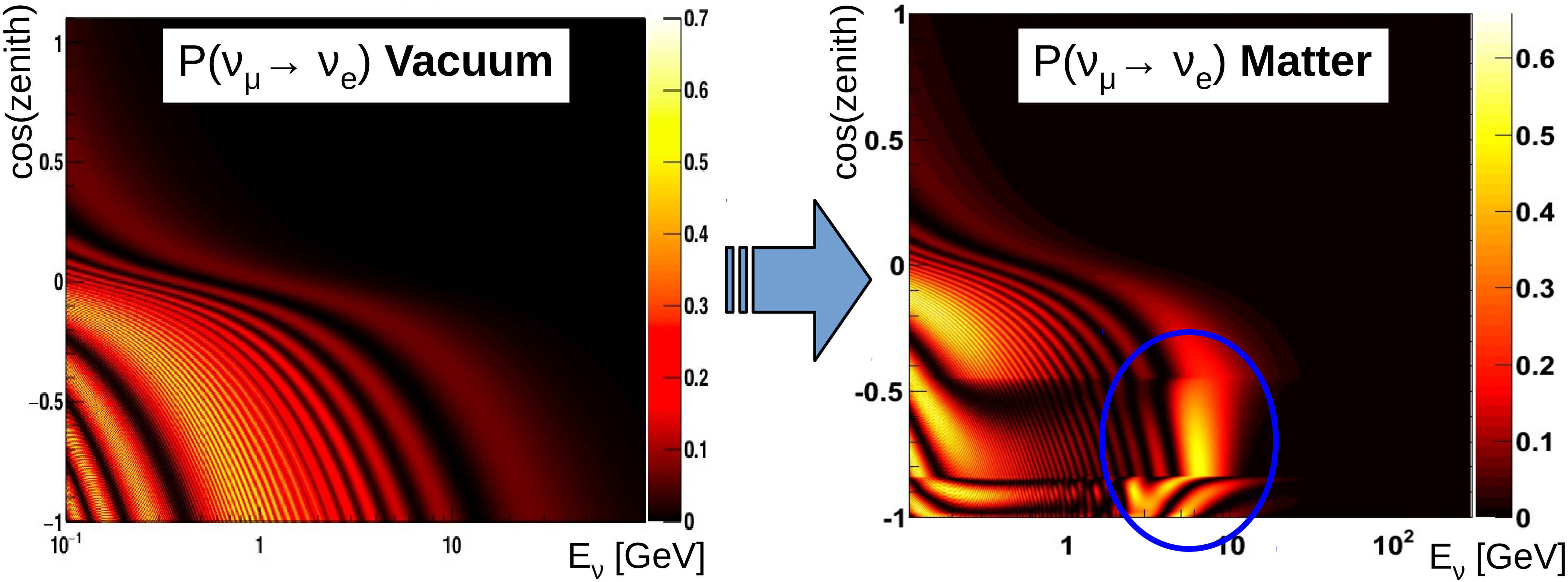
($c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$)

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on **6 parameters**:

- 3 mixing angles $\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}}$
- 2 independent mass splittings $\boldsymbol{\Delta m^2_{ij}}$
- 1 complex phase, the CP phase $\boldsymbol{\delta}$

- Observed both disappearance and appearance of neutrino flavors
- All mass splittings (Δm^2_{ij}) and mixing angles (θ_{ij}) measured to be non-zero
- Only δ still unknown (not well constrained by data)
- Sign of $\Delta m^2_{32/31}$ unknown

Atmospheric neutrino oscillations
Matter effects

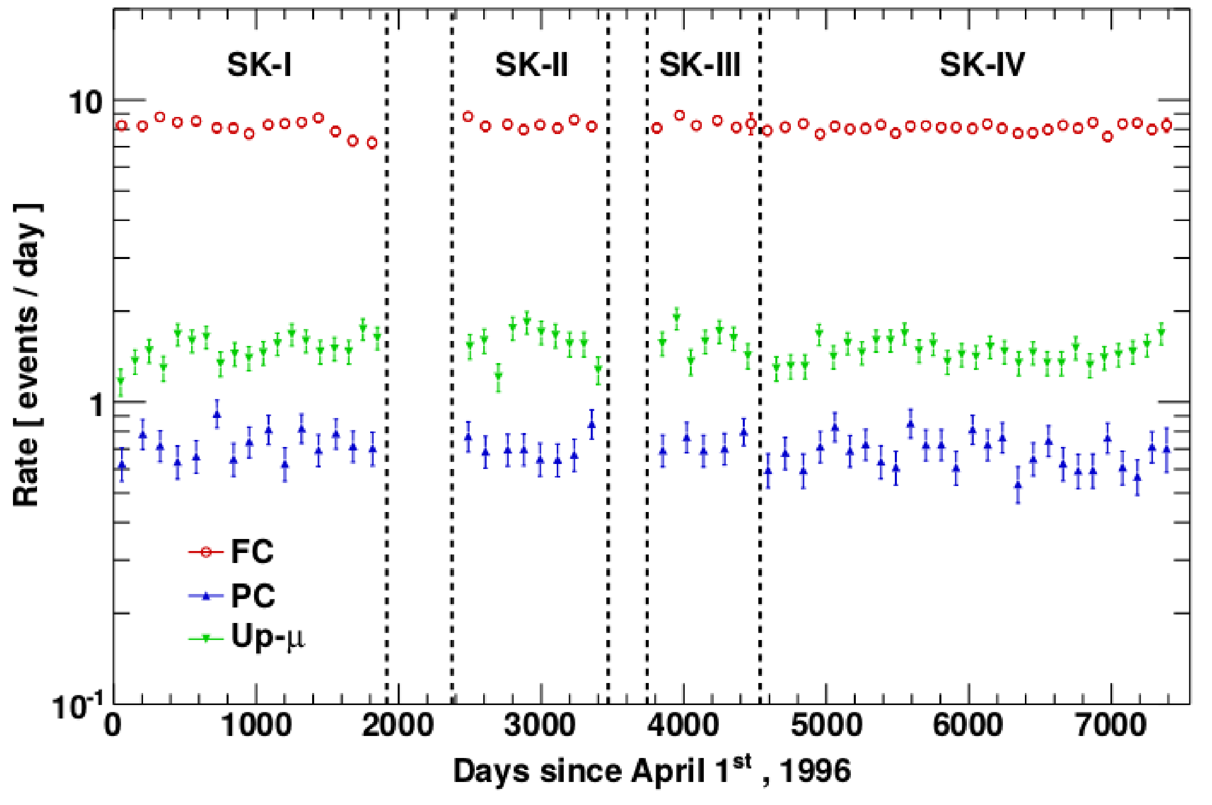


Presence of a resonance driven by θ_{13} induced matter effects between 2 and 10 GeV

- Only for ν in NH and $\bar{\nu}$ in IH → sensitivity to the mass hierarchy
- Size of the effect depends on $\sin^2(\theta_{23})$ → sensitive to θ_{23} octant
- MH sensitivity increases with larger statistics, improved ability to separate interactions of ν and $\bar{\nu}$ and constraint on $\sin^2(\theta_{23})$

Dataset for SK I-IV results

- 4 SK periods with different detector conditions over 20 years
- Total livetime: 5326 days (328 kton-year)
- 27505 muon-like and 20949 electron-like events



Stable event rates for the different topologies

Dataset for SK I-IV analysis (PRD 97, 072001 (2018)), not new SK IV analysis with new reconstruction and extended fiducial volume

Oscillation analysis

- Maximum likelihood method
- Minimize χ^2 with respect to systematics for a grid of values of parameters to fit
- Minimization uses iterative matrix inversion method
- Binned χ^2 assuming Poisson statistics in each bin

<u>Oscillation parameters</u>

- $\sin^2(\theta_{13})$= 0.0219 ± 0.0012 (reactor)
- $\sin^2(\theta_{12})$= 0.304 ± 0.014 (solar+Kamland)
- Δm^2_{21}=(7.53 ± 0.18) × 10^{-5} eV^2/c^4 (solar+Kamland)
- $\sin^2(\theta_{23})$, $\Delta m^2_{32/31}$ and δ free

Expected nb evts in bin n

Observed nb of evts in bin n

Pull for syst. i

$$\chi^2 = 2\sum_n \left(E_n - \mathcal{O}_n + \mathcal{O}_n \ln \frac{\mathcal{O}_n}{E_n} \right) + \sum_i \left(\frac{\epsilon_i}{\sigma_i} \right)^2$$

$$E_n = \sum_j E_{n,j} \left(1 + \sum_i f^i_{n,j} \epsilon_i \right)$$

Effect of a 1σ variation of syst. i on nb of evts in bin n for SK period j

Predictions calculated separately for each SK period

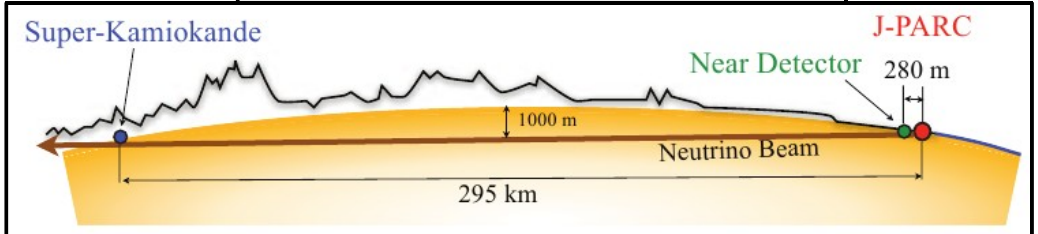
- different detector configurations, water quality and performance → different MC simulations
- Some systematic uncertainties depend of the SK period
- Expectation from each period summed to compute χ^2

Analysis with external constraints

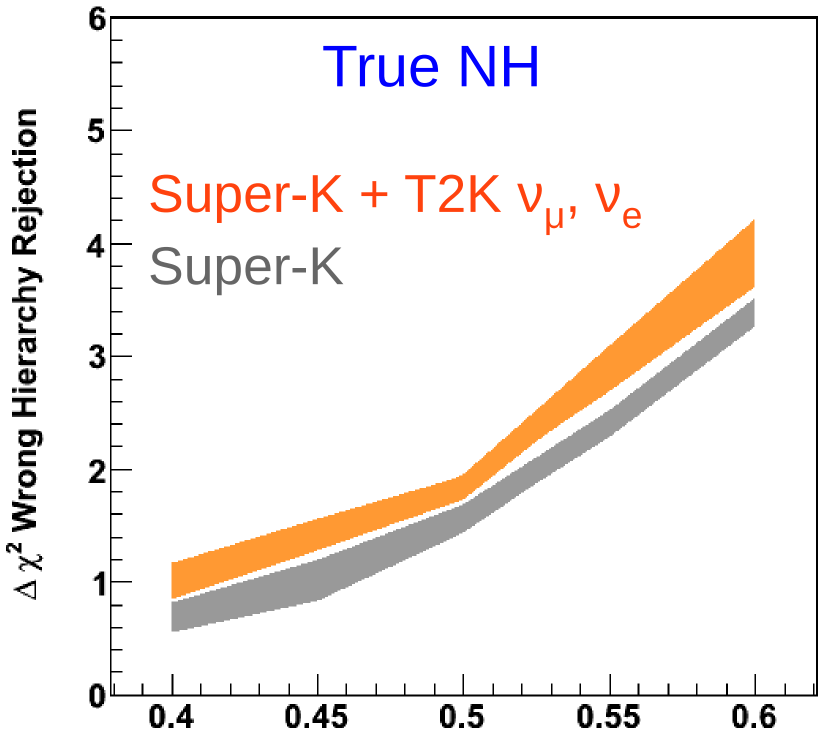
Motivations

- Uncertainty on value of $\sin^2(\theta_{23})$
  → uncertainty for MH determination
- Precise measurements of $\sin^2(\theta_{23})$ and $|\Delta m^2_{32}|$ by LBL experiments
- Both experiments have sensitivity to δ
- Combination can also break degeneracies in certain cases

Tokai To Kamioka (T2K)



- Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam
- L=295 km from J-PARC to Super-K
- Near detector complex to constrain systematic uncertainties

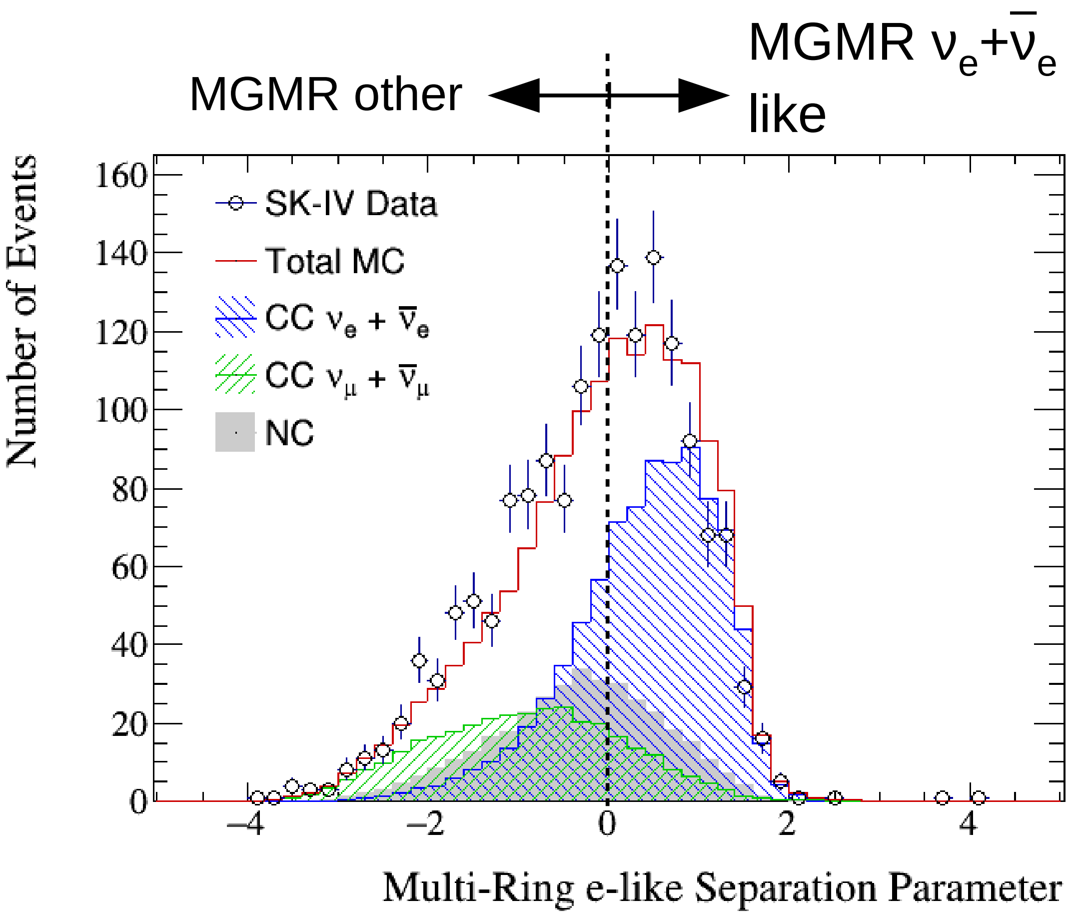


Error bands: uncertainty due to unknown δ value

- **NOT** a joint analysis between the 2 collaborations.
- Use SK tools to build a model of T2K and fit data based on publicly available information
- Uses T2K data and analysis from PRD 91, 072010 (2015) – not latest results (6.57e20 POT in ν-mode, no $\bar{\nu}$-mode data, no appearance CC1π sample, not using new reconstruction and fiducial volume)

Event selection
FVFC multi-ring multi-GeV events - 1

First likelihood aims at removing NC and $\nu_\mu/\bar{\nu}_\mu$ events which ended up in the MR e-like sample due to reduced PID performance for multi-ring events



<u>4 variables:</u>

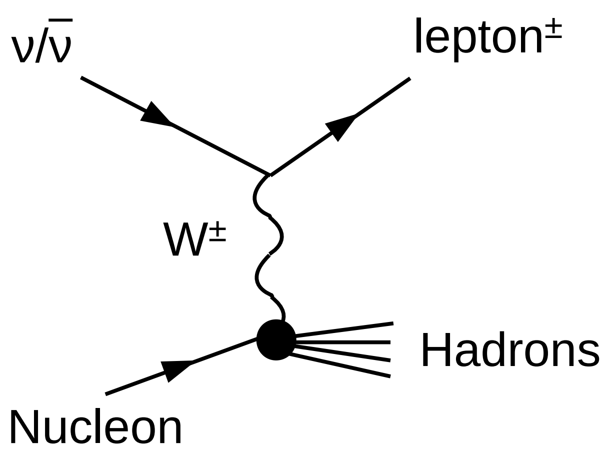
- PID of most energetic ring
- Momentum fraction of m.e.r
- Nb of Michel electrons
- Largest distance between a Michel electron vertex and primary vertex

Plot from SK I-IV analysis (PRD 97, 072001 (2018)), not new SK IV analysis with new reconstruction and extended fiducial volume

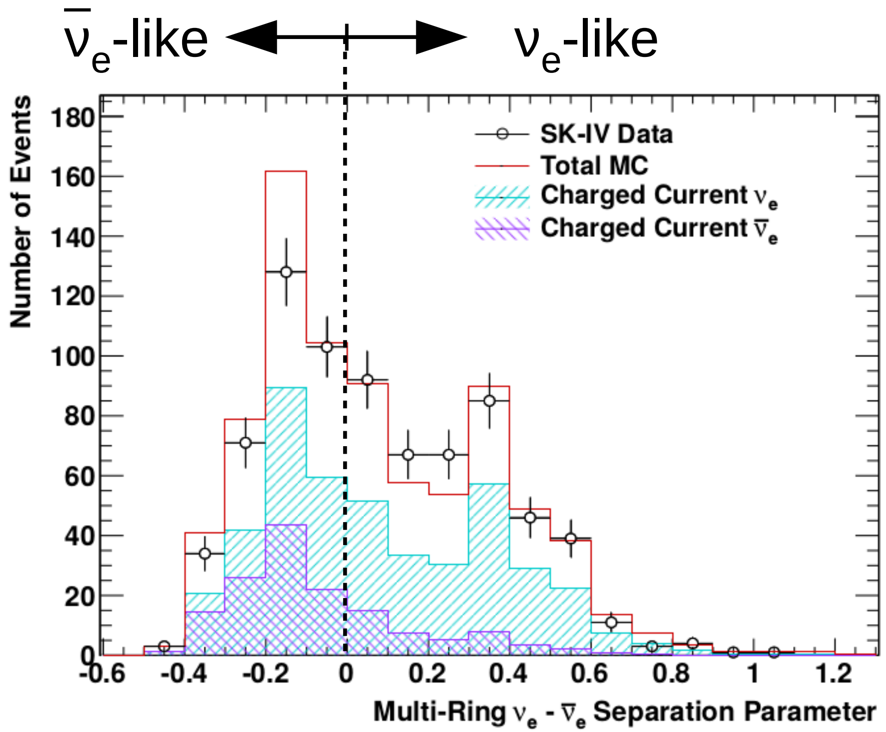
Event selection
FVFC multi-ring multi-GeV events - 2

Second likelihood is the real statistical separation between ν_e and $\bar{\nu}_e$ events

Dominant interaction is CC DIS



Larger transferred energy fraction (Bjorken y) for ν than $\bar{\nu}$



	Neutrino	Anti-neutrino
Nb of rings	More	Less
Nb of Michel e-	More	Less
Transverse momentum	Larger	smaller

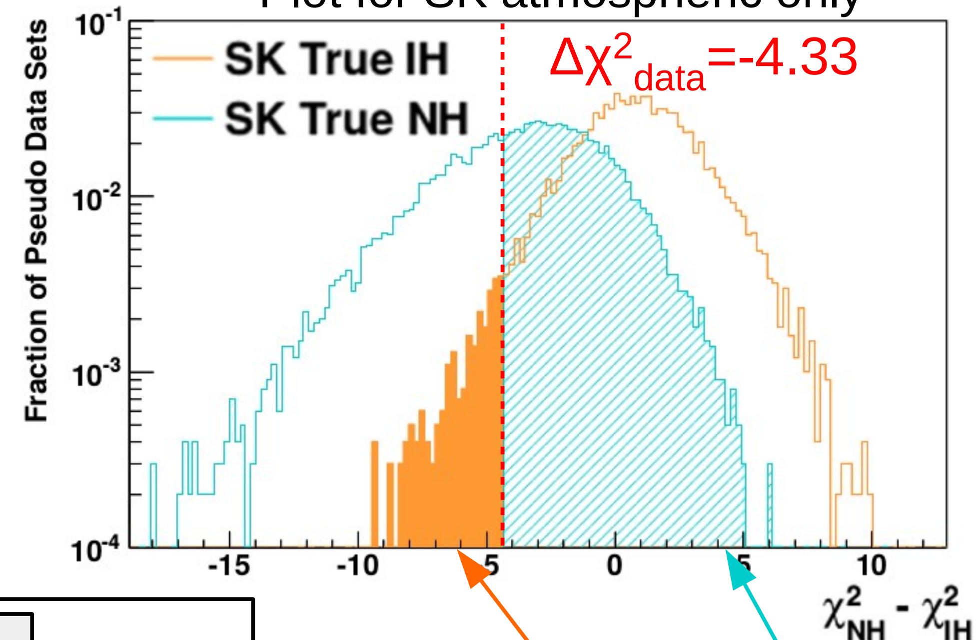
Plot from SK I-IV analysis (PRD 97, 072001 (2018)), not new SK IV analysis with new reconstruction and extended fiducial volume

Result from SK I-IV analysis (PRD 97, 072001 (2018)), not new SK IV analysis with new reconstruction and extended fiducial volume

Mass hierarchy Significance

- MH significance does not go as √(χ2)
  → compute p-values using toy MC
- Limited sensitivity at current statistics
  → Also compute CLs values
- Significance depend on true values of θ_{23} and δ
  → Compute for different true values

Plot for SK atmospheric only



P-values and CLs for IH exclusion

P-values	Lower	Best fit	Upper
SK only	0.012	0.027	0.020
SK+T2K model	0.004	0.023	0.024

CLs	Lower	Best fit	Upper
SK only	0.181	0.070	0.033
SK+T2K model	0.081	0.075	0.056

$$CL_s = \frac{p_0(IH)}{1 - p_0(NH)}$$

Lower/upper edges of the 90% CL intervals for $\sin^2(\theta_{23})$ and δ