Neutrino Mass hierarchy and CP-violation

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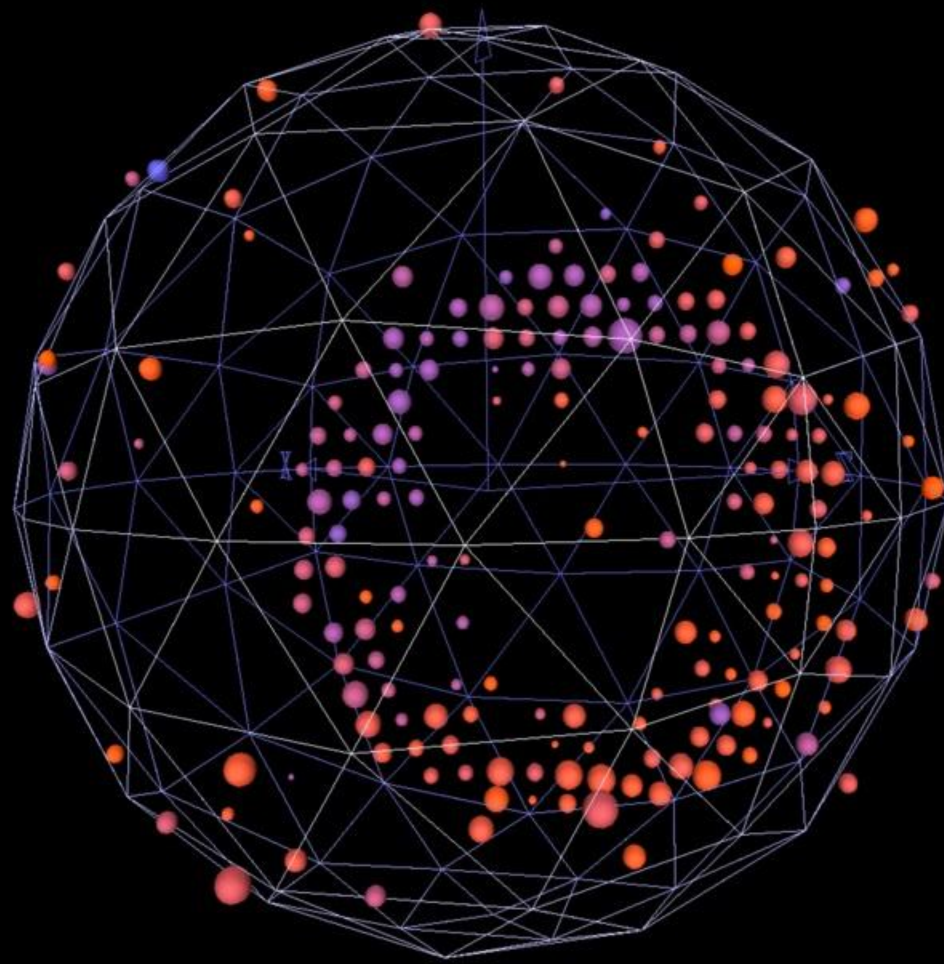
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

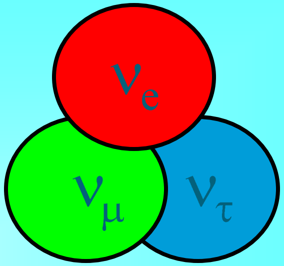
1. Next big
2. Mass hierarchy
3. CP-violation
4. Summary

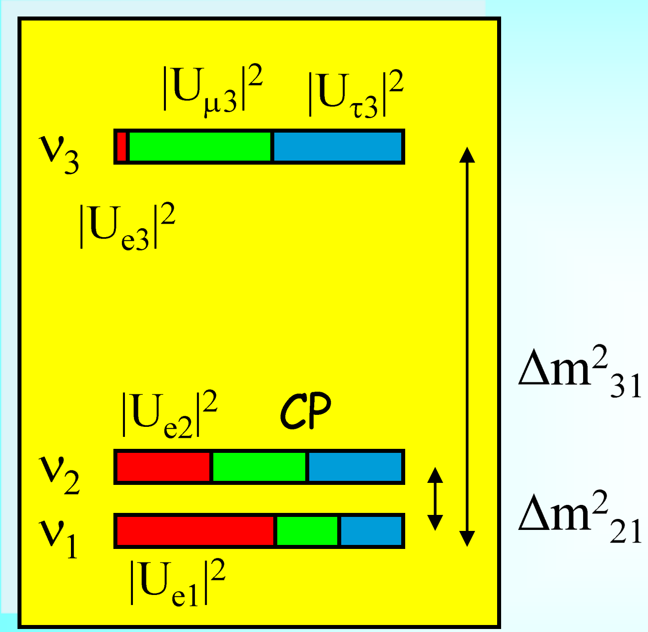
with emphasis on astrophysical/ astroparticle methods

Next Big



Lepton Mixing





FLAVOR

Normal mass hierarchy

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

$\Delta m^2_{32} = 2.5 \times 10^{-3}\ eV^2$

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

Mixing parameters

$\tan^2\theta_{12} = |U_{e2}|^2 / |U_{e1}|^2$ ~ 1/2

$\sin^2\theta_{13} = |U_{e3}|^2$ = 0.022

$\tan^2\theta_{23} = |U_{\mu 3}|^2 / |U_{\tau 3}|^2$ ~ 1.0

TBM, Symmetry?

Mixing matrix:

$\nu_f = U_{PMNS}\, \nu_{mass}$

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

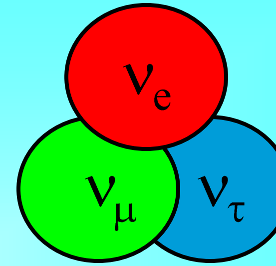
Standard parametrization

$U_{PMNS} = U_{23} I_\delta U_{13} I_{-\delta} U_{12}$

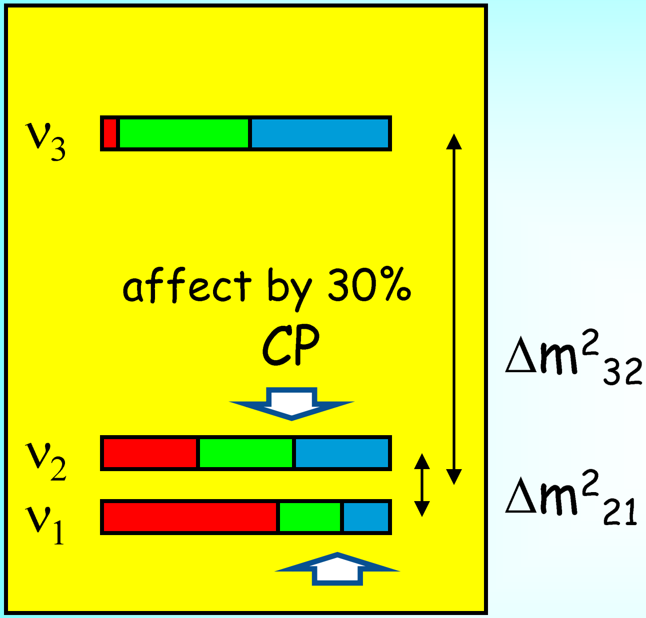
$I_\delta = \mathrm{diag}\,(1, 1, e^{i\delta})$

CP-phase

Ordering and CP violation



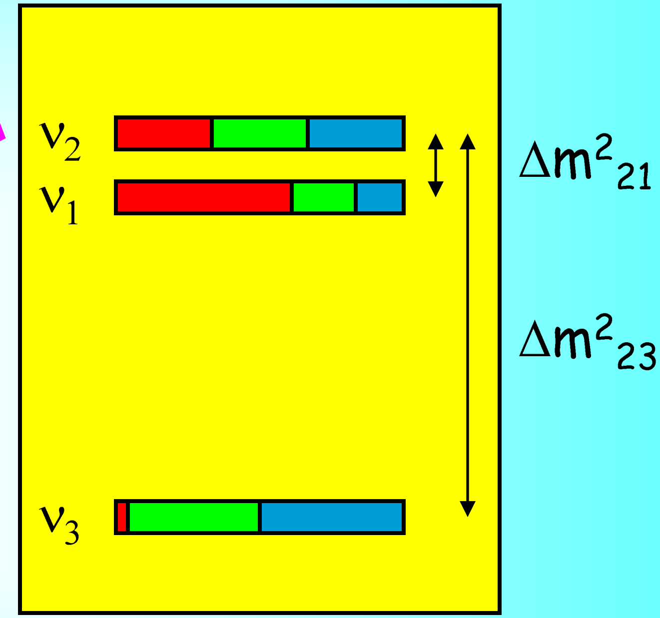
1-2 ordering is fixed by solar neutrinos



Normal mass hierarchy

$\Sigma m > m_h$

$|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$



Inverted mass hierarchy

$\Sigma m > 2\, m_h$

$|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

$|\Delta m^2_{ij}| \Leftrightarrow D_{ij} = 4|U_{ei}|^2|U_{ej}|^2$

mass splittings — oscillation depth

in vacuum

TBM Mixing pattern

P. F. Harrison, D. H. Perkins, W. G. Scott
L. Wolfenstein

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

0.15

0.62-0.64

0.78 - 0.74

$U_{tbm} = U_{23}(\pi/4)\, U_{12}$

$\sin^2\theta_{12} = 1/3$

0.30- 0.31

Not accidental

Accidental, numerology, useful for bookkeeping

Lowest order approximation which corresponds to weakly broken (flavor) symmetry of the Lagrangian

Accidental symmetry (still useful)

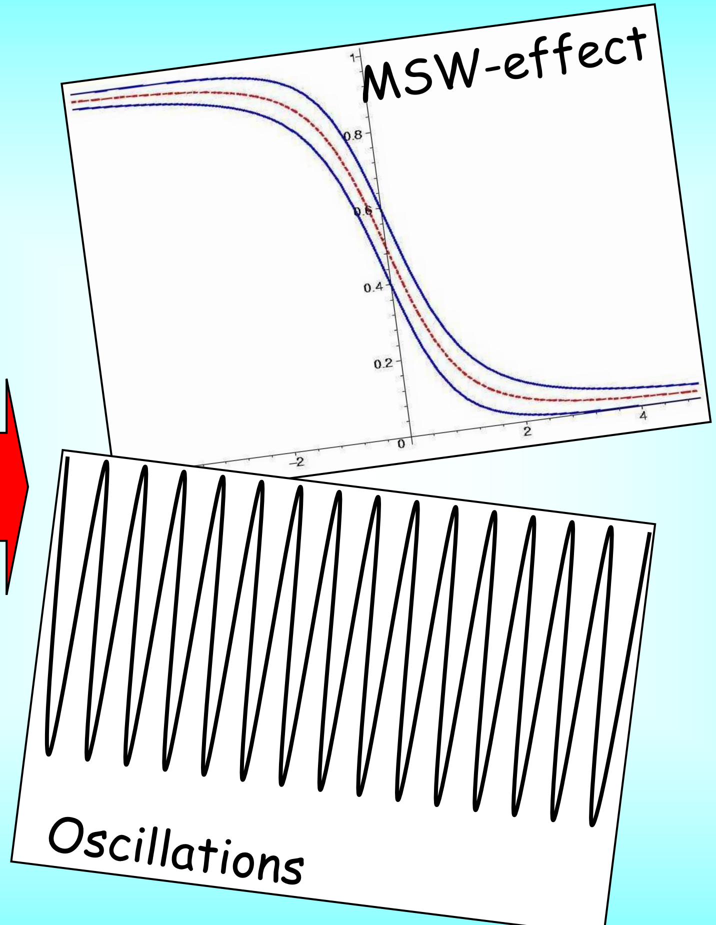
with some other physics and structures associated

There is no relation of mixing with masses (mass ratios); No connection to MO?

TBM: no CP-violation
CPV is related to deviation from TBM

Global oscillation fit

Solar neutrinos
KamLAND
Atmospheric neutrinos
Double Chooz
Daya Bay
MINOS
K2K
RENO
Antares
T2K
DeepCore



Can be resonantly enhanced in matter

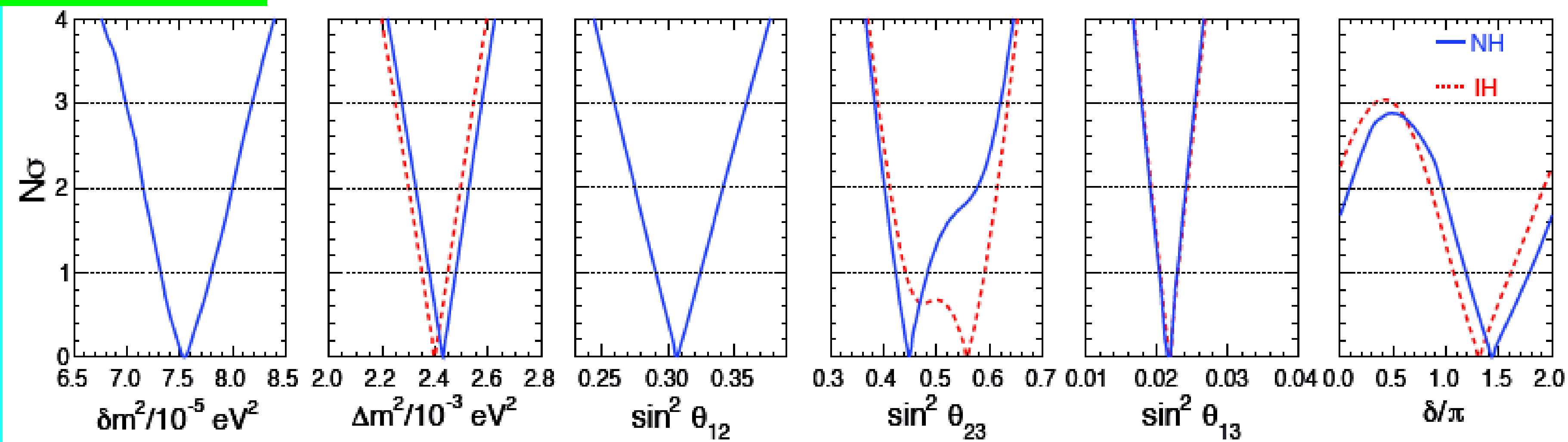
Δm^2

θ

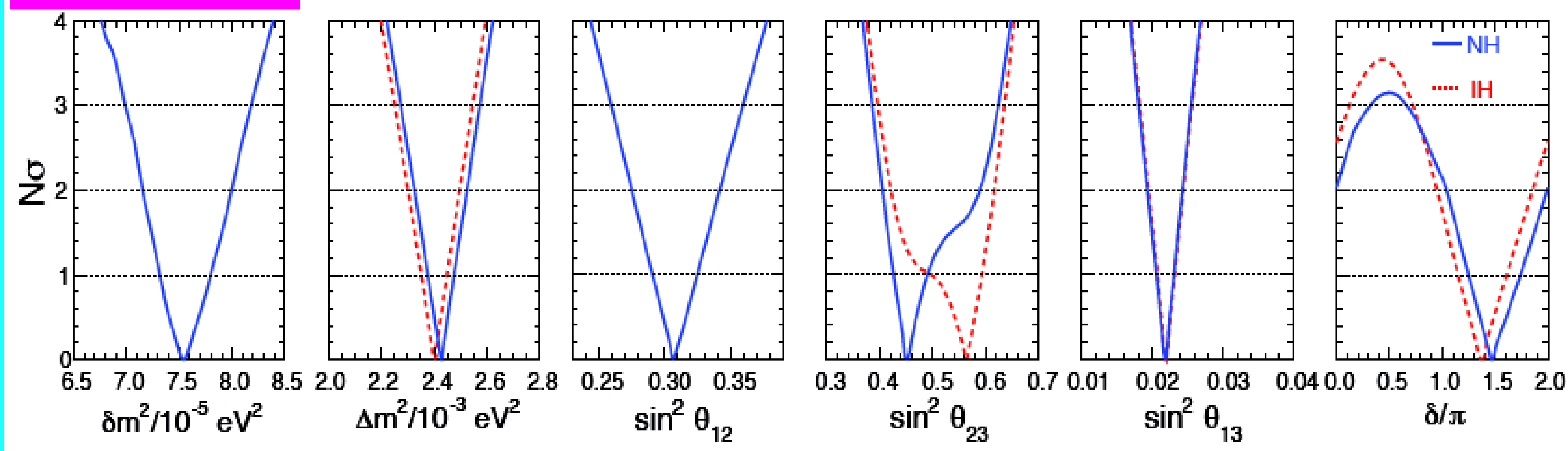
Global 3ν– fit

A. Marrone, TAUP 2015

NOvA - LID



NOvA - LEM



PMNS & CKM

Quark mixing

my prejudice

C. Giunti, M. Tanimoto
H. Minakata, A Y S
Z - Z. Xing
J Harada
S Antusch , S. F. King
Y Farzan, A Y S
M Picariello , … .

$$U_{PMNS} = U_{CKM}^{+} U_{X}$$

where $U_{CKM} \sim V_{CKM}$

has similar hierarchical structure determined by powers of

$\lambda = \sin \theta_C$

From the Dirac matrices of charged leptons and neutrinos

U_X has some special form determined by symmetry

related to mechanism that explains smallness of neutrino mass

$U_X \sim U_{23}(\pi/4)\, U_{12}$

Prediction for the 1-3 mixing

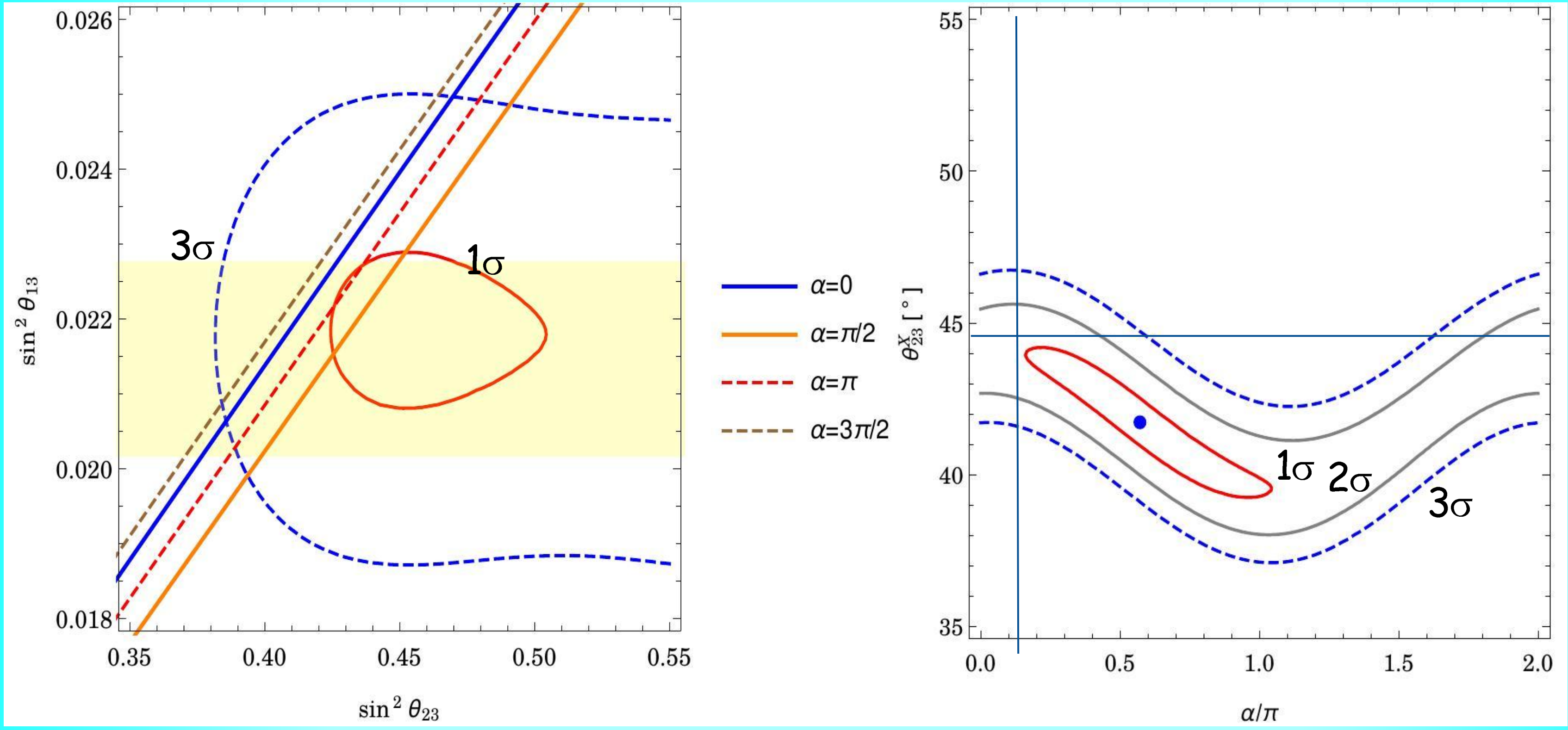
$$\sin^2\theta_{13} = \sin^2\theta_{23} \sin^2\theta_C (1 + O(\lambda^2))$$

$$\sin^2\theta_{13} \sim \tfrac{1}{2} \sin^2\theta_C$$

in a good agreement with measurements

θ_{13} vs. θ_{23}

Normal mass ordering



Dependence of 1-3 mixing on 2-3 mixing for different values of the phase α. Allowed regions are according to the global fit NuFIT

Allowed regions of parameters of U_X

What does this mean?

if not accidental

Quarks and leptons know about each other,
Q L unification, GUT or/and
Common flavor symmetries

Some additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the quark and lepton mixing patterns

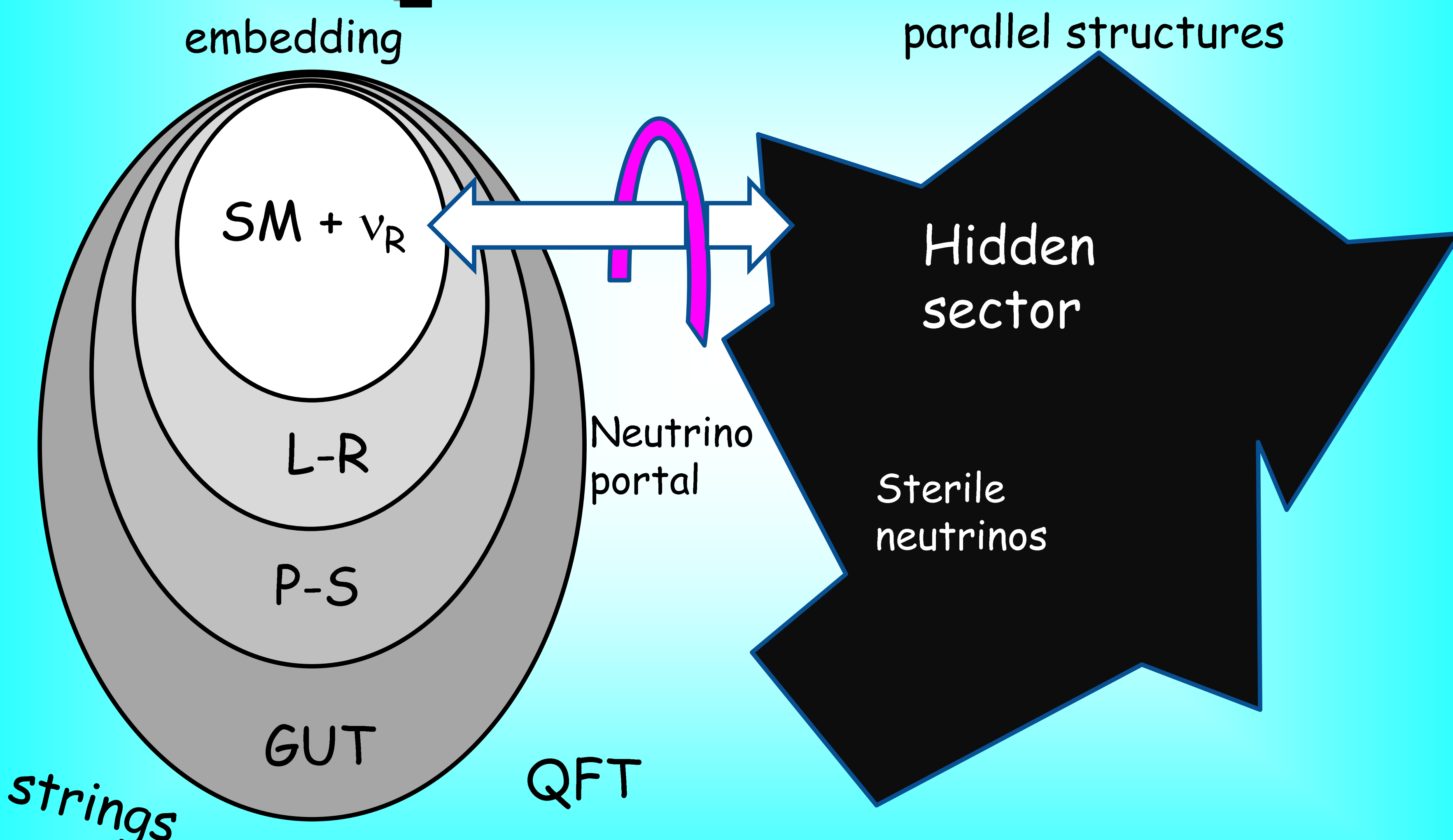
Two types of new physics

CKM

Neutrino new physics

Indicates SO(10): no CKM mixing in the first approximation

Setup



embedding
parallel structures
SM + ν_R
Hidden sector
L-R
Neutrino portal
P-S
Sterile neutrinos
GUT
strings
QFT

Next Big?

Mass ordering

Leptonic CP violation

Dirac phase δ_{CP}

correlate in determination

Theoretically related?

Should be in complete theory

can affect...

Type of spectrum (hierarchical vs. quasi-degenerate)

absolute values of masses

Nature of neutrino mass: (Majorana vs. Dirac)

Majorana phases

Deviation of 2-3 mixing from maximal

Octant

ν_s Sterile neutrinos

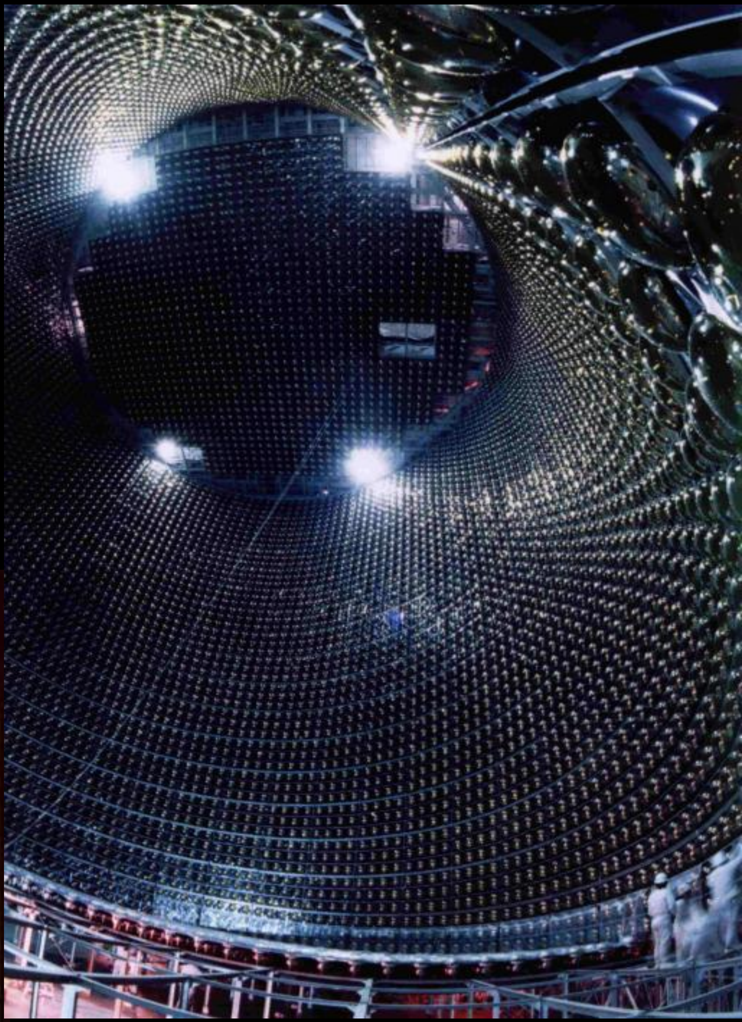
1 eV mass scale - not a small perturbation of the 3ν picture

May help to establish hierarchy

More CP-phases 2 more Dirac phases

A. Palazzo, *R. Gandhi et al,*

Mass hierarchy



Mass hierarchy

Further advance

Step to discover CP

important by itself

Theoretical implications

Phenomenology

Supernova neutrinos

Atmospheric neutrinos

bb0n decay

LBL

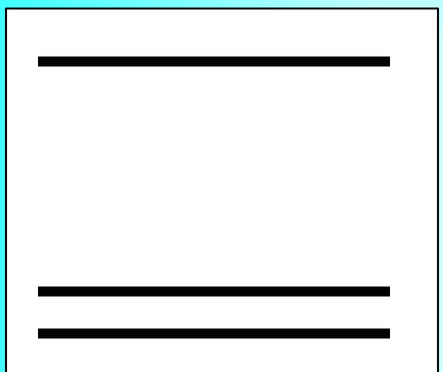
Solar neutrinos

Cosmology

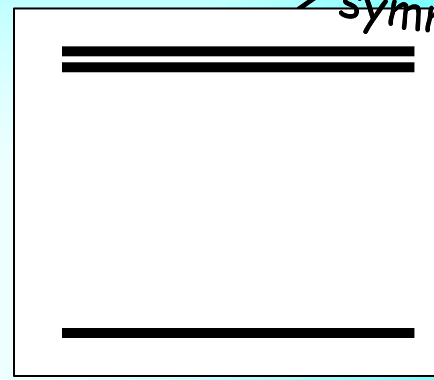
Theoretical implications

generically

Quasi-degenerate
→ symmetry



Normal vs. special



$$\frac{m_2}{m_3} \sim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}} = 0.18$$

$$\theta \sim \sqrt{\frac{m_2}{m_3}}$$

the weakest
hierarchy

Similar to quark spectrum

rescaling

See-saw

Quark-lepton
symmetry

Unification

$$\frac{\Delta m}{m} \sim \frac{\Delta m_{21}^2}{2\,\Delta m_{32}^2} = 1.6\ 10^{-2}$$

but 1-2 mixing strongly
deviates from maximal

Pseudo-Dirac + 1 Majorana

Flavor symmetries

Broken $L_e - L_\mu - L_\tau$ symmetry

Race for mass hierarchy

Matter effect on 1-3 mixing

Oscillations, conversion

Precise measurements of Δm^2 at reactors

JUNO, RENO-50

Cosmology Σm

Atmospheric neutrinos

PINGU

ORCA

INO

LBL experiments

NOvA

LBNF – DUNE

JPARC-HK

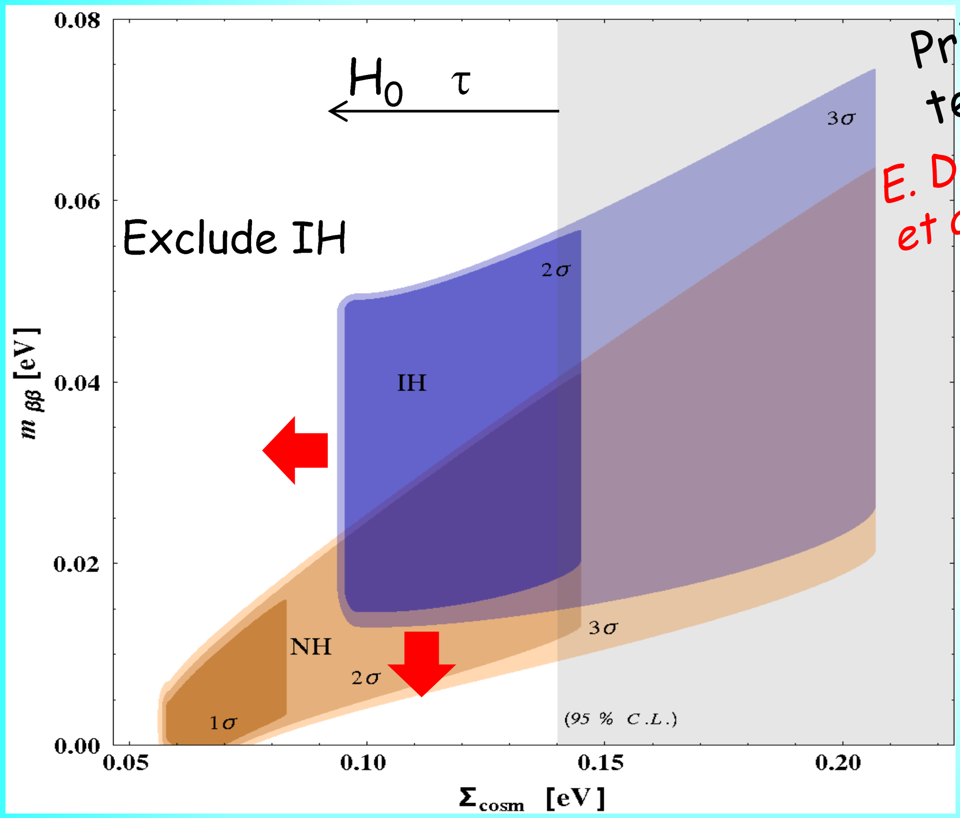
Supernova neutrinos

Earth matter effects, energy spectra

Double beta decay m_{ee}

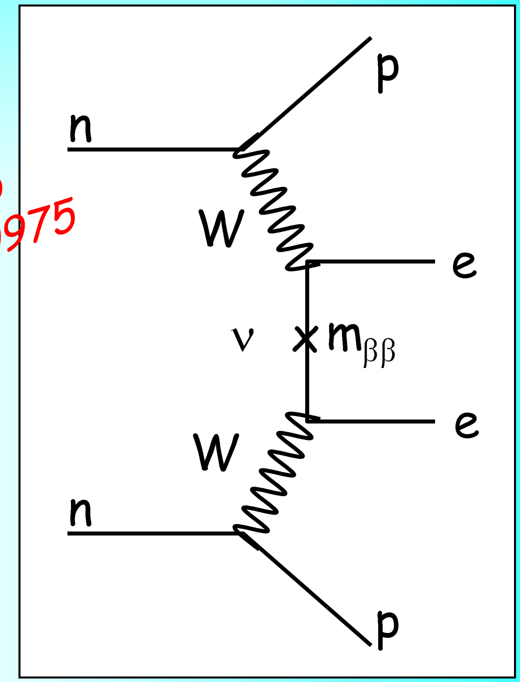
Cosmology and Double beta decay

$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{\iota\alpha} + U_{e3}^2 m_3 e^{\iota\phi}$



Priors and tensions

E. Di Valentino et al., 1511.00975



S. Dell'Oro, et al, 1505.02722 [hep-ph]

τ - reionization optical depth

Constraints from cosmological surveys and from oscillations.
The 1σ region for the IH case is not present at this confidence level.
The grey - the 95% C.L. excluded region coming from Cosmology

JUNO

Also RENO-50

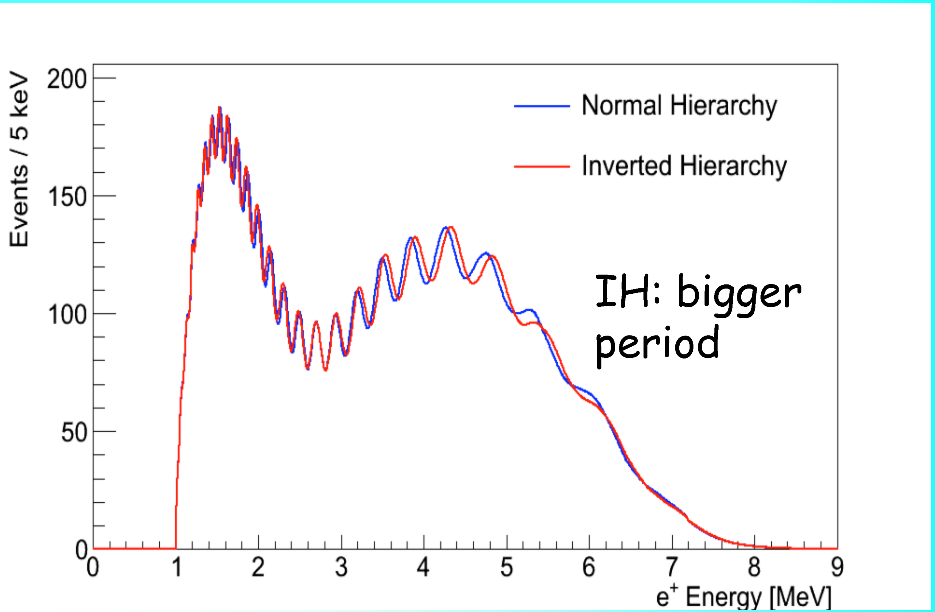
Jiangmen Underground Neutrino Observatory

d = 700 m, L = 53 km, P = 36 GW

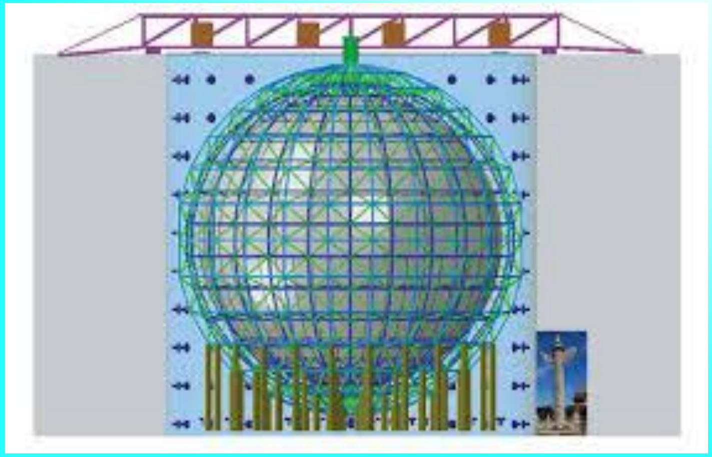
20 kt LAB scintillator

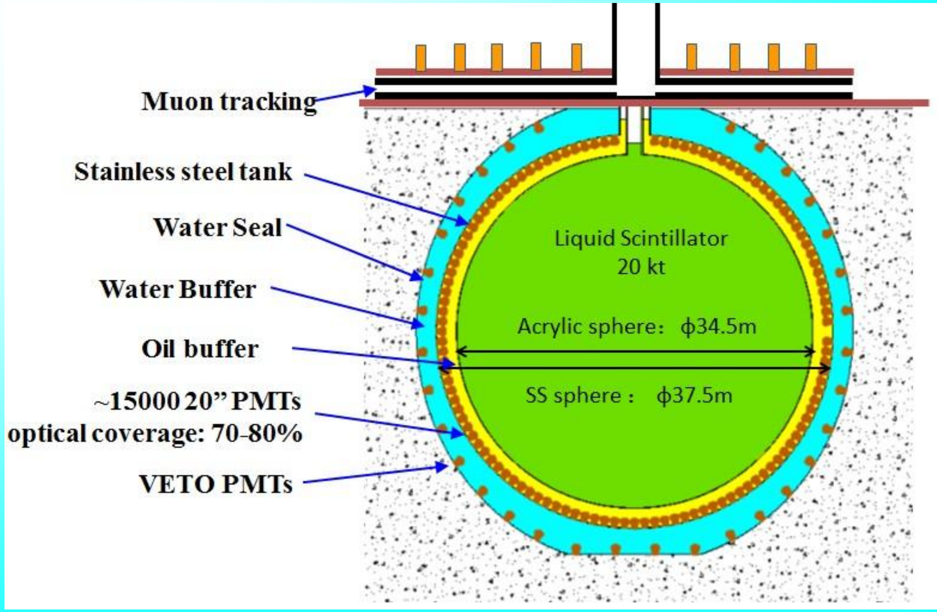
$n + p \rightarrow d + \gamma$

Key requirement:
energy resolution 3% at 1 MeV



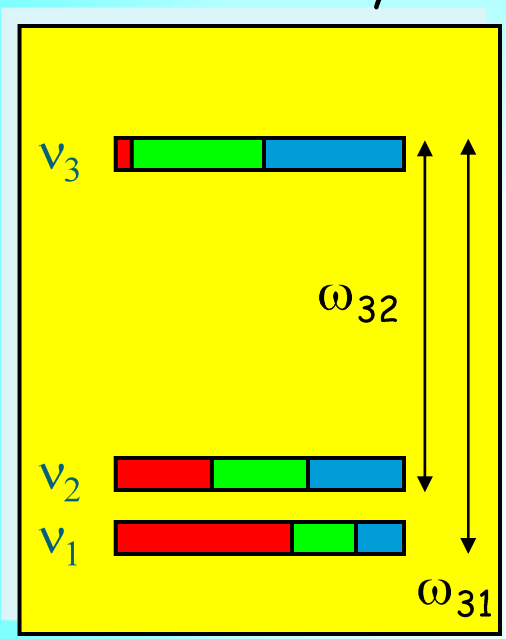
Operation in 2020
(3 - 4)σ in 6 years





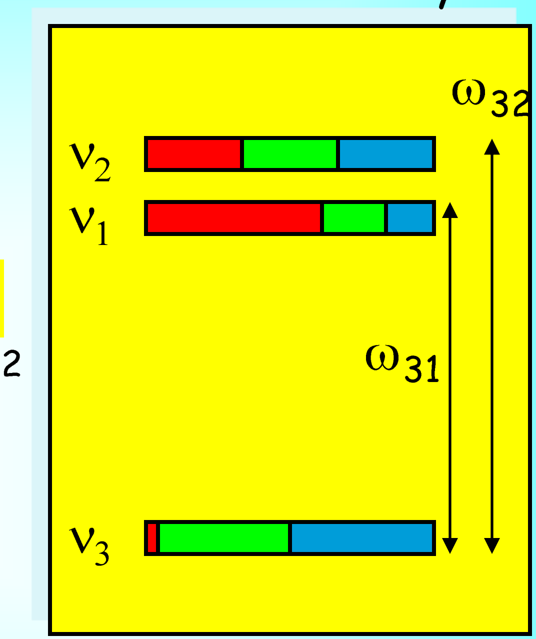
Mass ordering with reactors

Normal hierarchy



$\omega_{31} > \omega_{32}$

Inverted hierarchy



$\omega_{31} < \omega_{32}$

Oscillation frequency

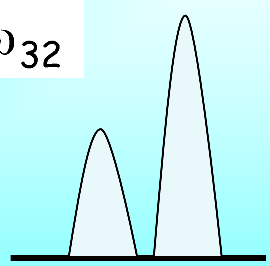
$\omega_{ij} = \Delta m^2_{ij} / 2E$

Oscillation depth:

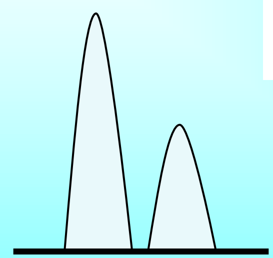
$D_{31} = 4|U_{e1}|^2|U_{e3}|^2$

$D_{31} \sim 2D_{32}$

Fourier analysis



Higher frequency - larger depth



Higher frequency – smaller depth

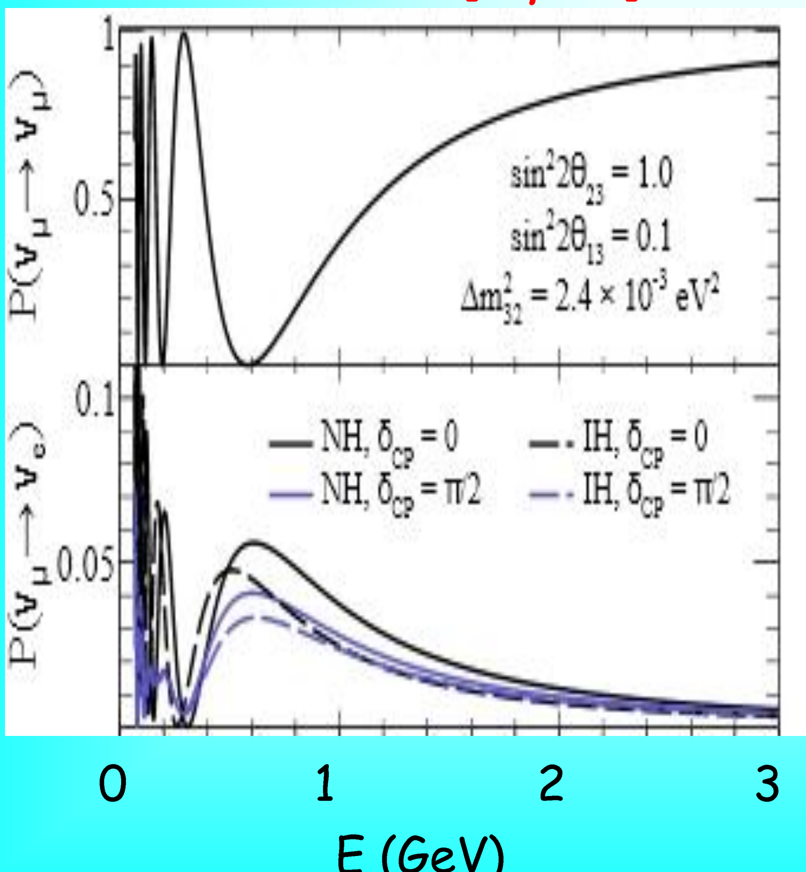
$D_{32} = 4|U_{e2}|^2|U_{e3}|^2$

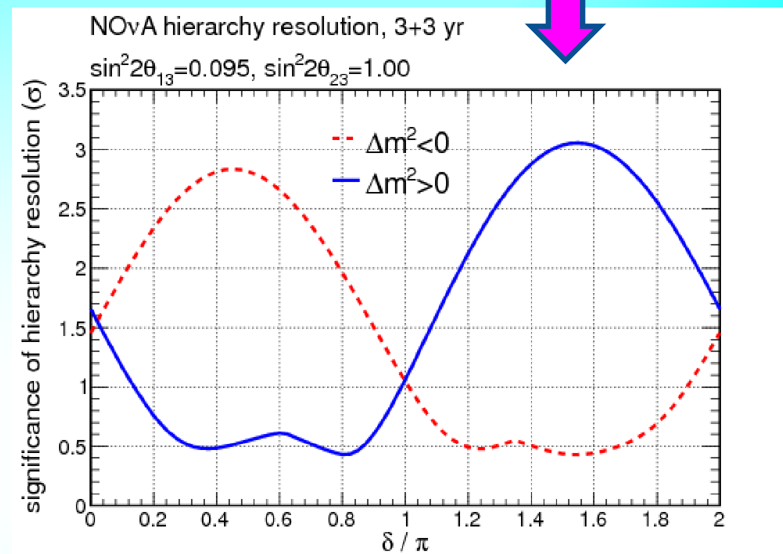
S. Petcov
M. Piai

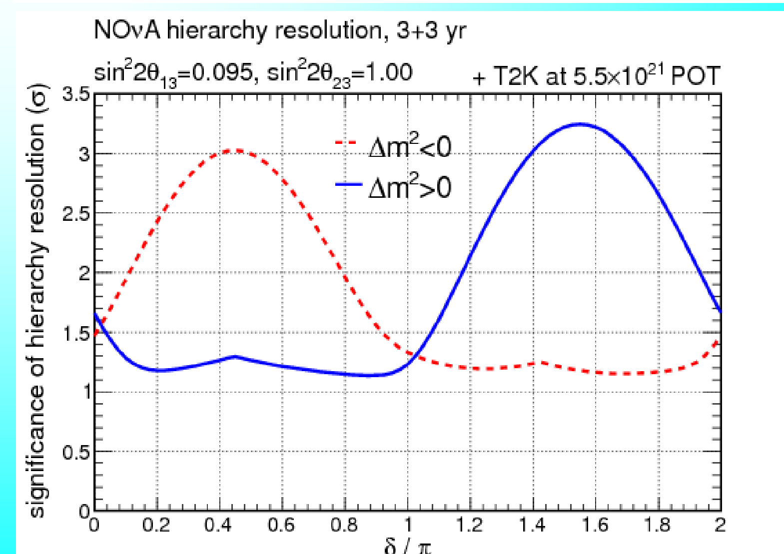
NOvA and T2K sensitivity

now 90%

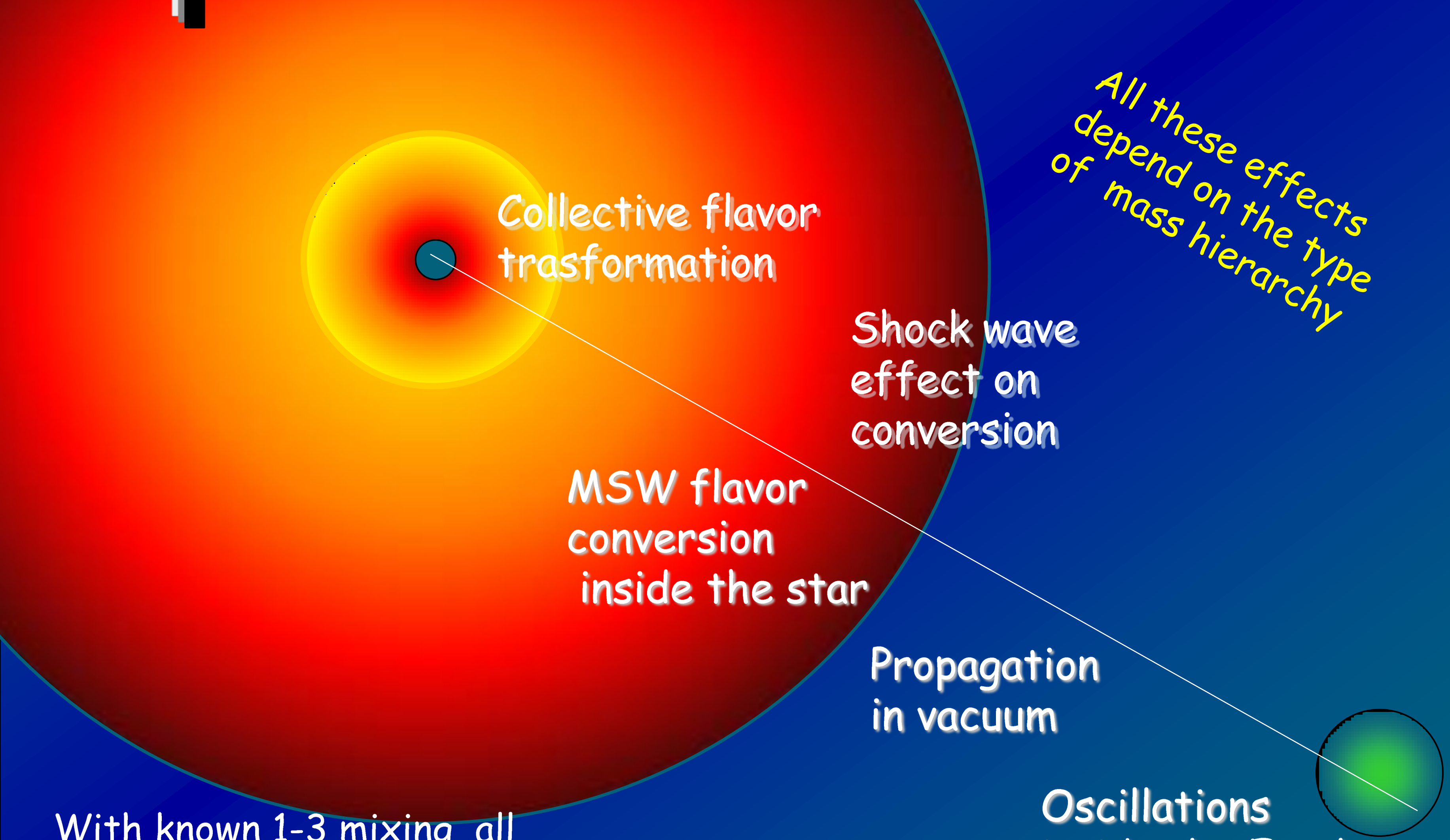
T2K Collaboration (K. Abe et al.).
Phys.Rev. D91 (2015) 7, 072010
arXiv:1502.01550 [hep-ex]







Supernova neutrinos



With known 1-3 mixing all MSW transitions are adiabatic

Hierarchy affects

Time rise of the anti-ν_e burst initial phase: fast → IH *P. Serpico et al*

Strong suppression of the ν_e peak → NH

$\nu_e \rightarrow \nu_3$

Permutation of the electron and non-electron neutrino spectra

A. Dighe, A. S.
C. Lunardini

Earth matter effects

in the antineutrino channel only → NH

in the neutrino channel only → IH

If the earth matter effect is observed for antineutrinos NH is established!

Shock wave effect

in neutrino channels → NH
in antineutrino → IH
G. Fuller, et al
R. Tomas et al

Neutrino collective effects

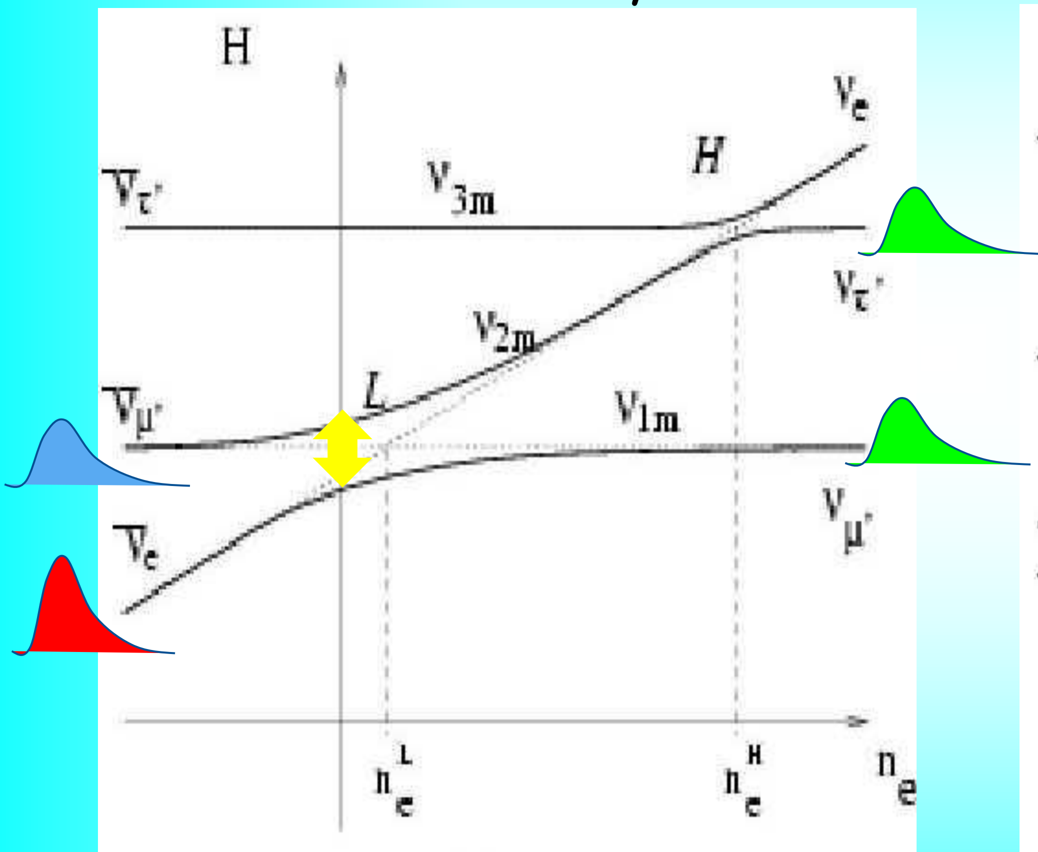
Different for IH and NH cases; spectral splits at high energies → IH
G. Fuller, et al
B. Dasgupta ,et al

Earth matter effect and hierarchy

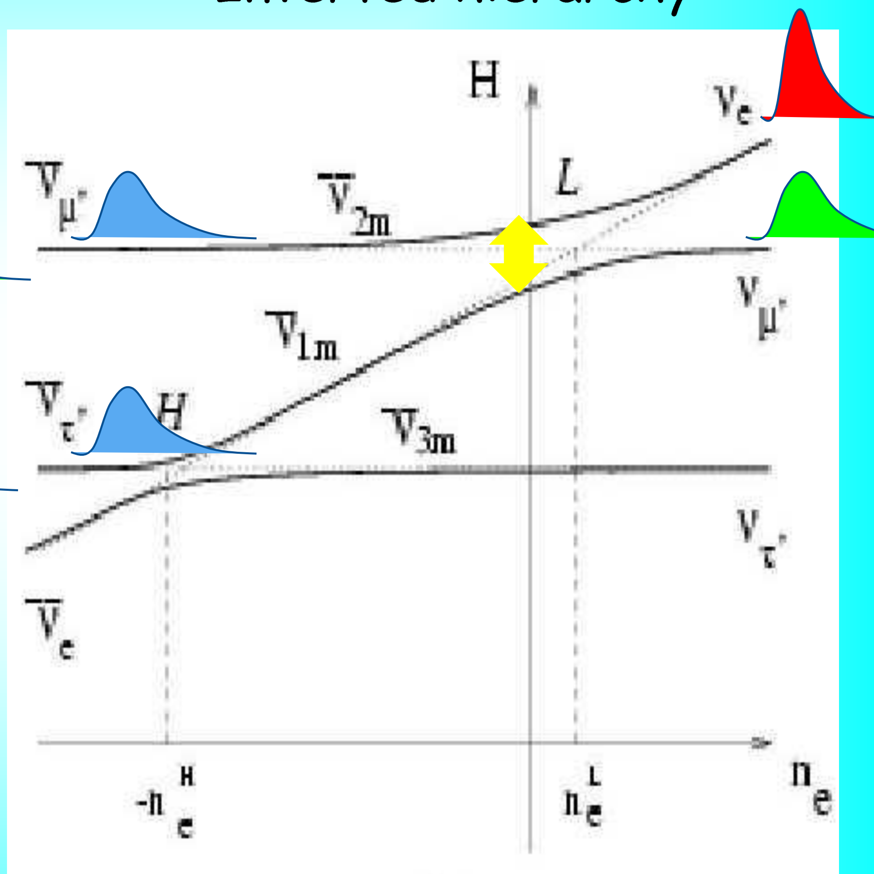
Adiabatic evolution

Level crossings

Normal hierarchy



Inverted hierarchy

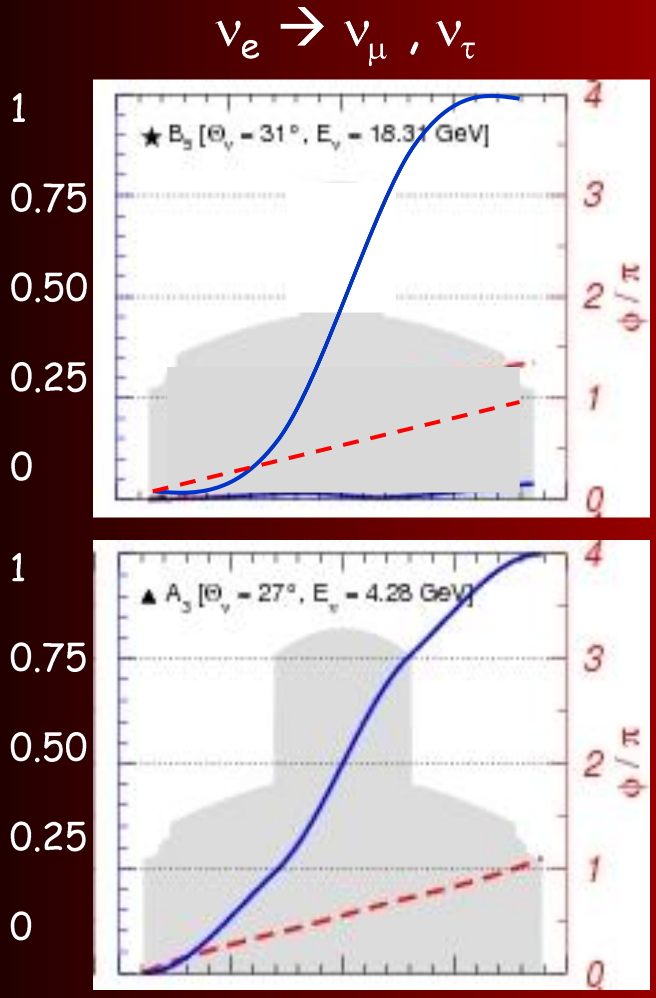


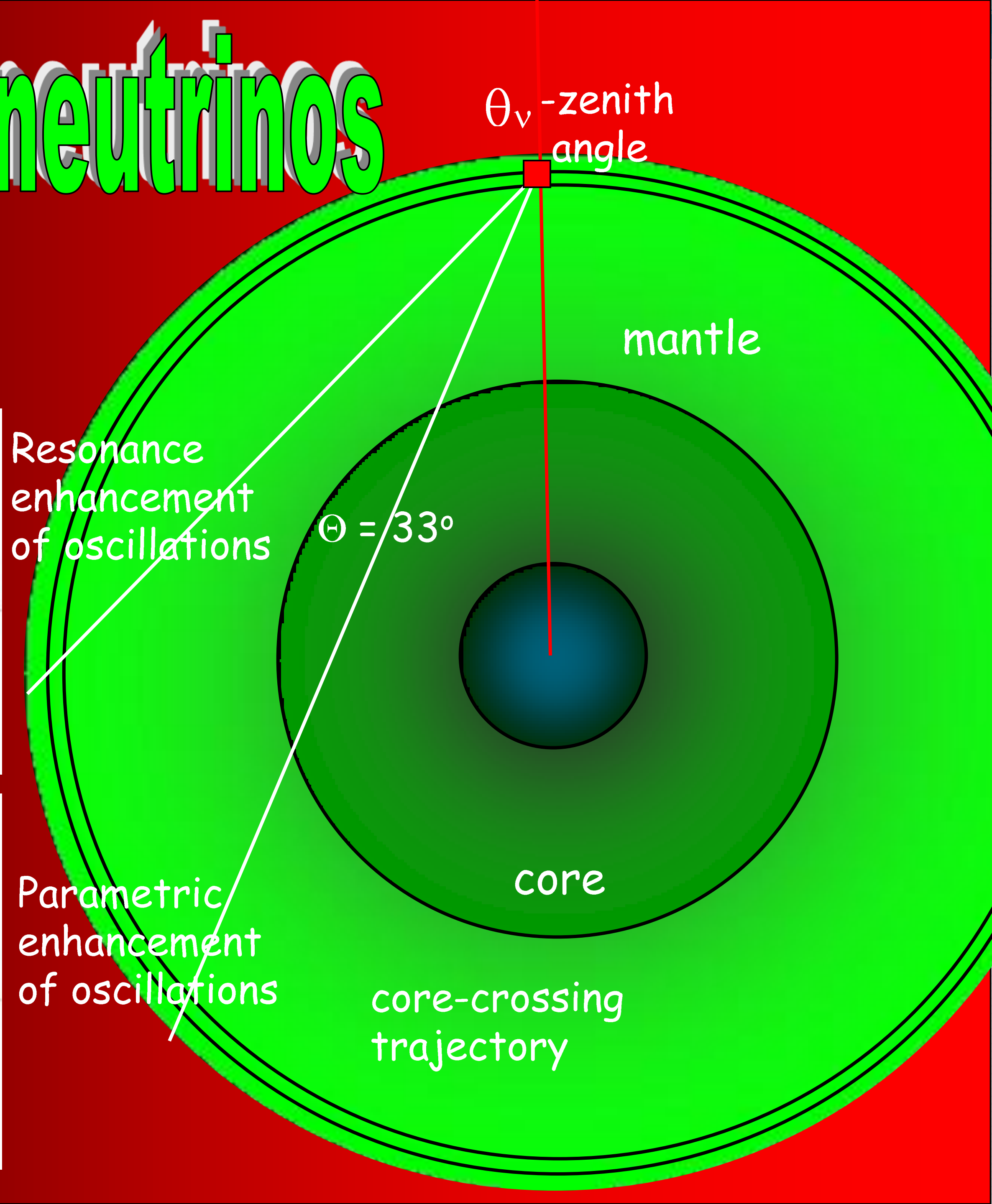
No Earth matter effect provided that initial fluxes of ν_μ' and ν_τ' are identical

Collective effects and shock waves may change this.

Atmospheric neutrinos

Oscillations in the Earth



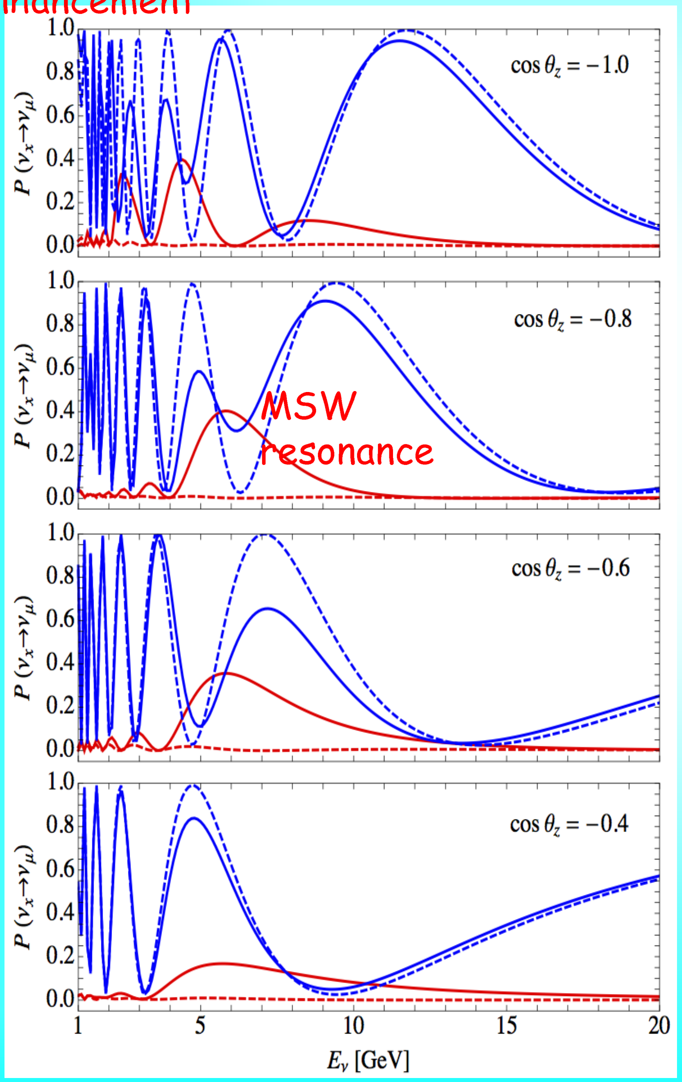


Probabilities

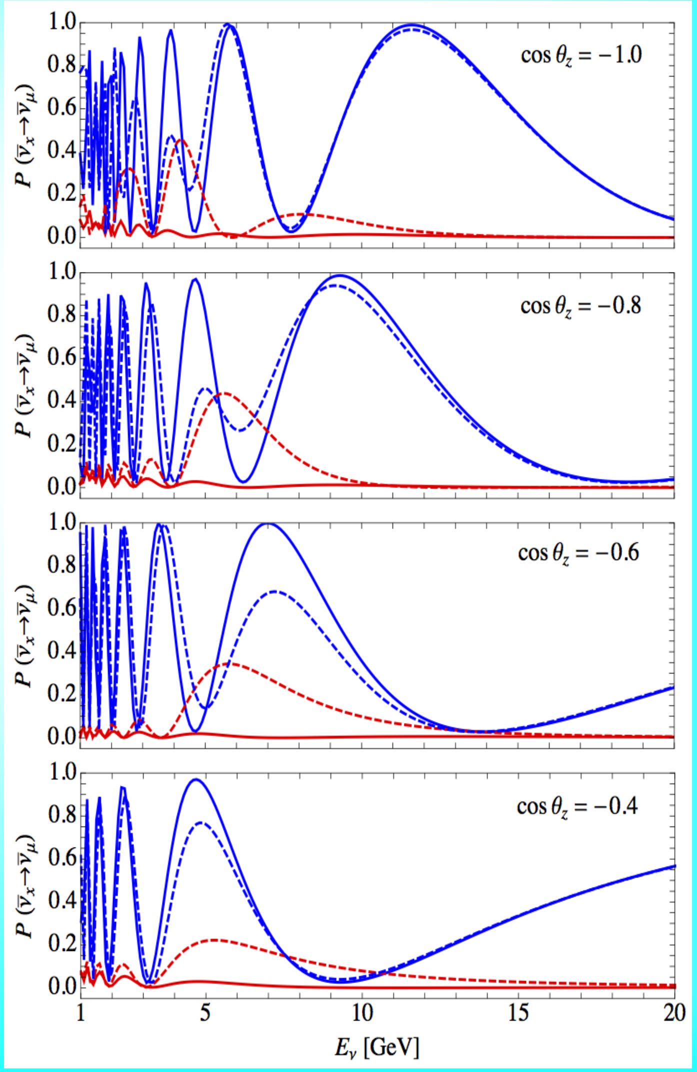
NH – solid, IH – dashed
$x = \mu$ - blue, $x = e$ - red

Paramentric enhancement

neutrinos



antineutrinos



Method

Measurement of $E - \theta$ distributions of different type of events.
Compare events for the normal and inverted orderings

"tracks"

$\nu_\mu + N \rightarrow \mu + h$

$\nu_\tau + N \rightarrow \tau + h$
$\rightarrow \mu + \nu + \nu$

muon track
+ cascade

Measurements

$E_\mu \quad \theta_\mu \quad E_h$ — inelasticity

$E_\nu = E_\mu + E_h$
$E_h \; E_\mu \; \theta_\mu \rightarrow \theta_\nu$ — reconstruction

"cascades"

$\nu_e + N \rightarrow e + h$

$\nu_\alpha + N \rightarrow \nu_\alpha + h$

$\nu_\tau + N \rightarrow \tau + h$
$\rightarrow h + \nu$
$\rightarrow e + \nu + \nu$

cascades

$E_\nu \quad \theta_\nu$ — reconstruction

H-asymmetry and distinguishability

Quick estimator (metric) of discovery potential

E. Kh. Akhmedov,
S. Razzaque, A. Y. S.
arXiv: 1205.7071

For each ij- bin
Hierarchy asymmetry
H-asymmetry

$$S_{ij} = \frac{[\,N_{ij}^{IH} - N_{ij}^{NH}]}{\sqrt{N_{ij}^{NH}}}$$

``Distinguishability''

If NH is true hierarchy → N_{ij}^{NH} ``experimental'' number of events
→ N_{ij}^{IH} ``fit'' number of events

$|S_{ij}|$ statistical significance of establishing true hierarchy

Uncorrelated systematic error

$N_{ij}^{NH} \rightarrow \sigma_{ij}^2 = N_{ij}^{NH} + (f\, N_{ij}^{NH})^2$ in denominator

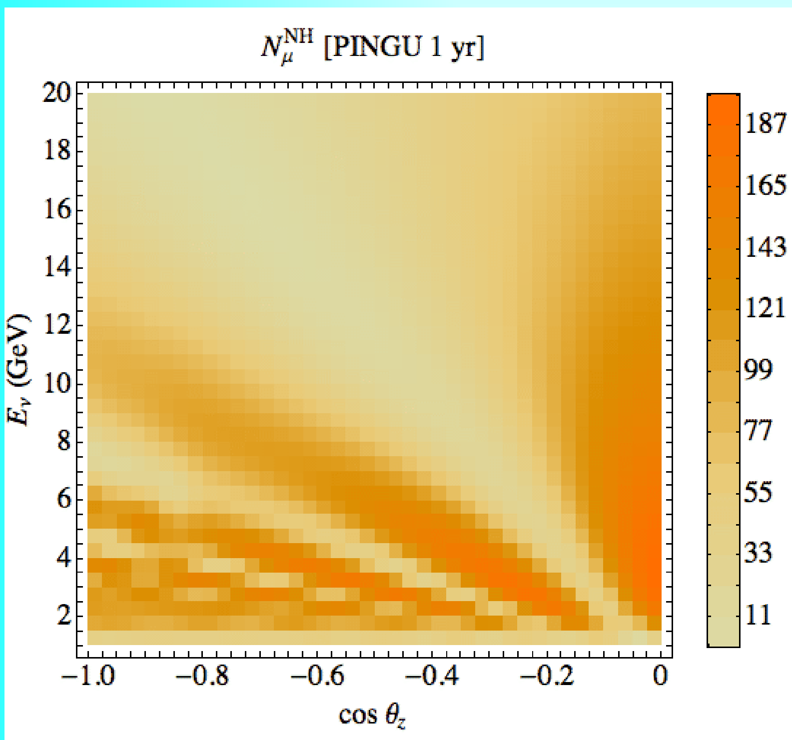
Total distinguishability

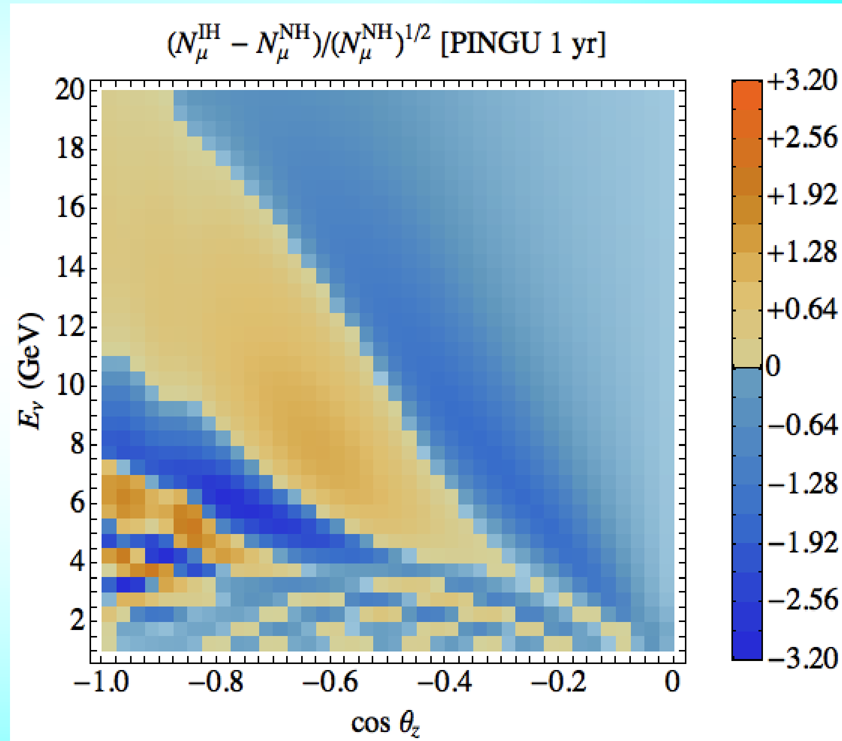
$S^{tot} = [\Sigma_{ij}\, S_{ij}^2\,]^{1/2}$

Track events

~ 10^5 events/year

``Distinguishability"





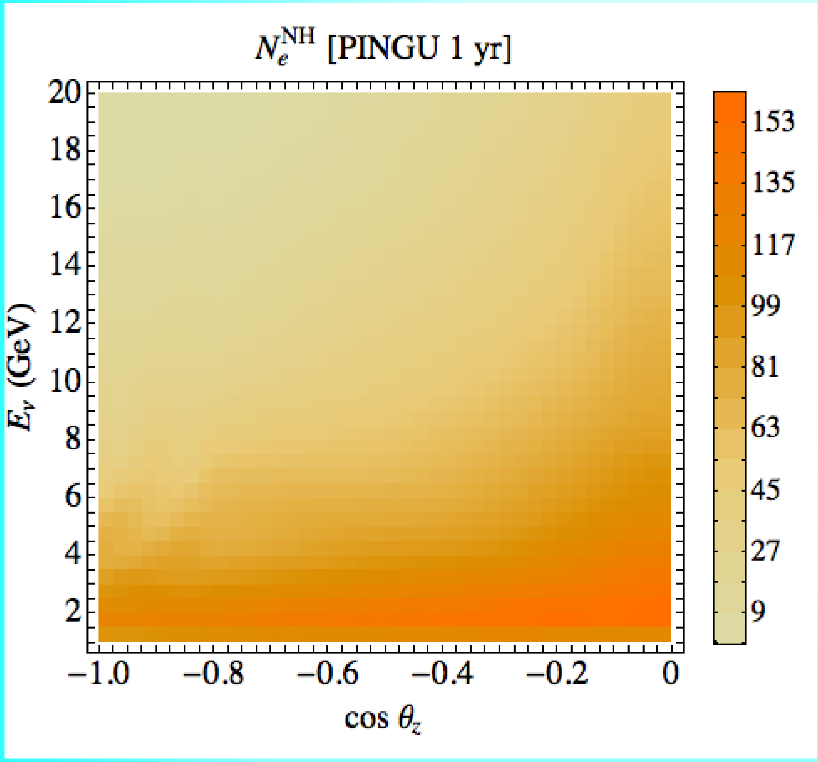
Estimator of sensitivity

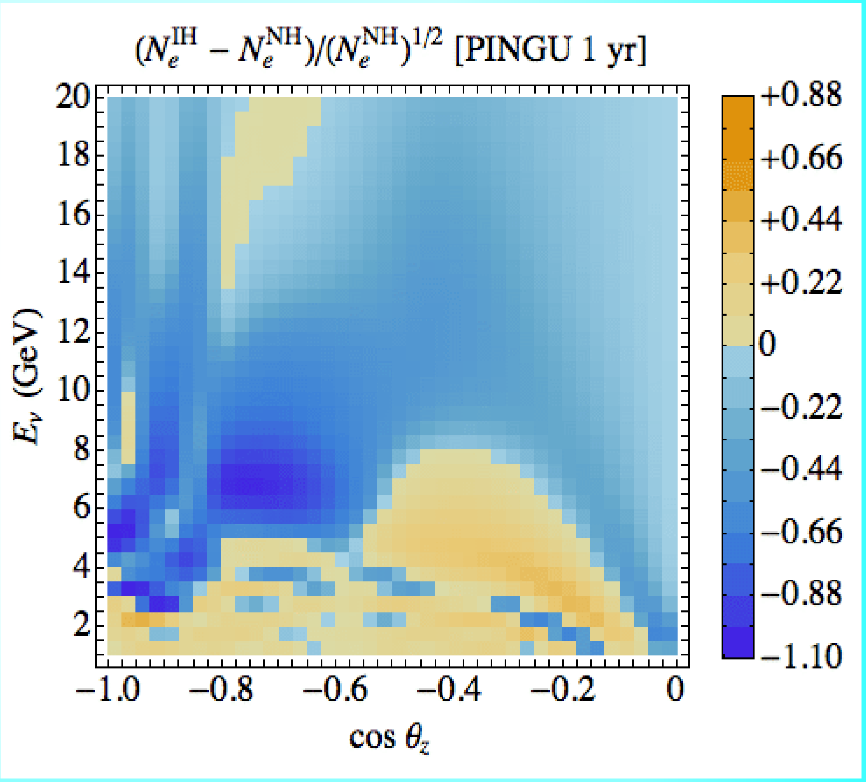
S – asymmetry

|S| - significance

Cascade events

``Distinguishability"





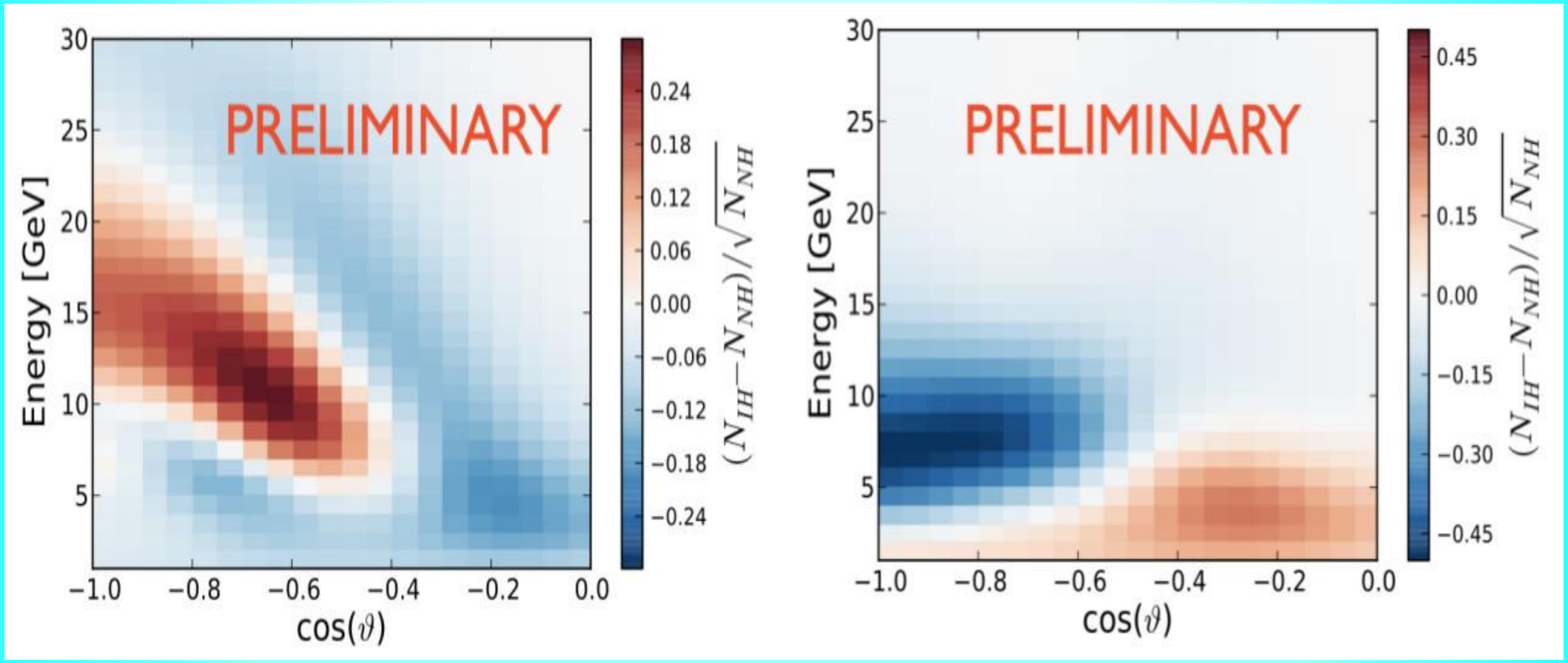
Statistical significance

Smeared distributions

Ken Clark

Over energy and angle resolution functions

PINGU



tracks

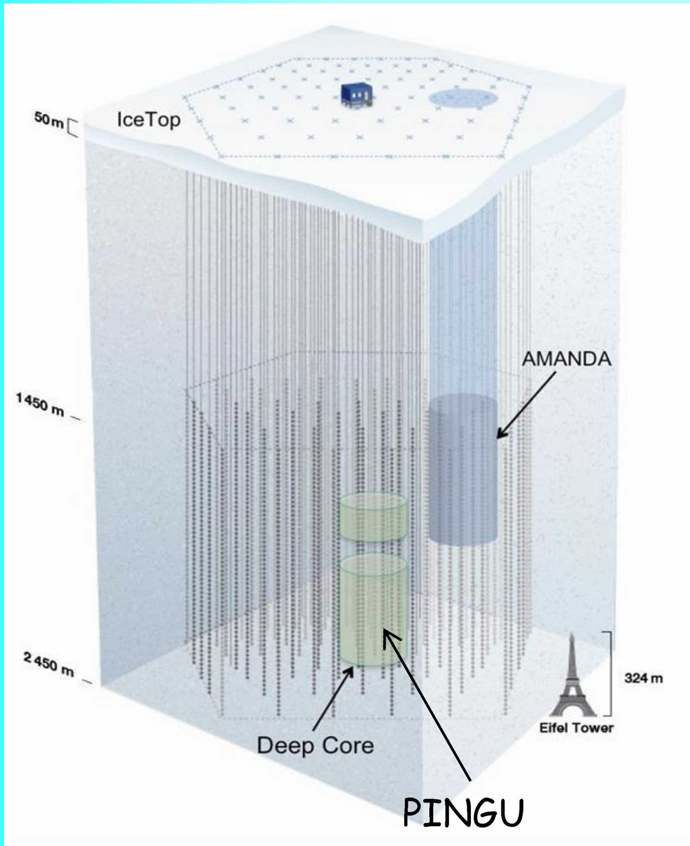
cascades

distinguishability

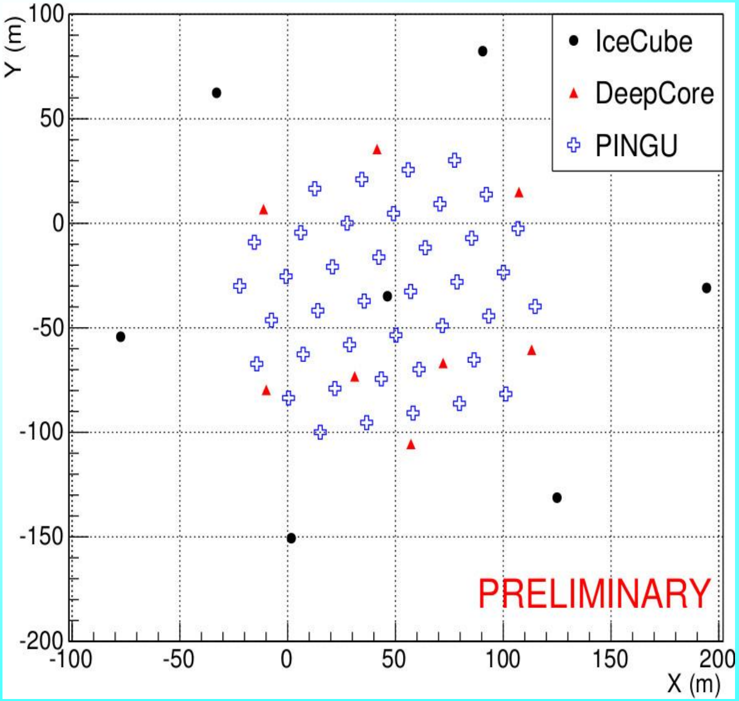
PINGU

Precision IceCube
Next Generation
Upgrade

K. Clark



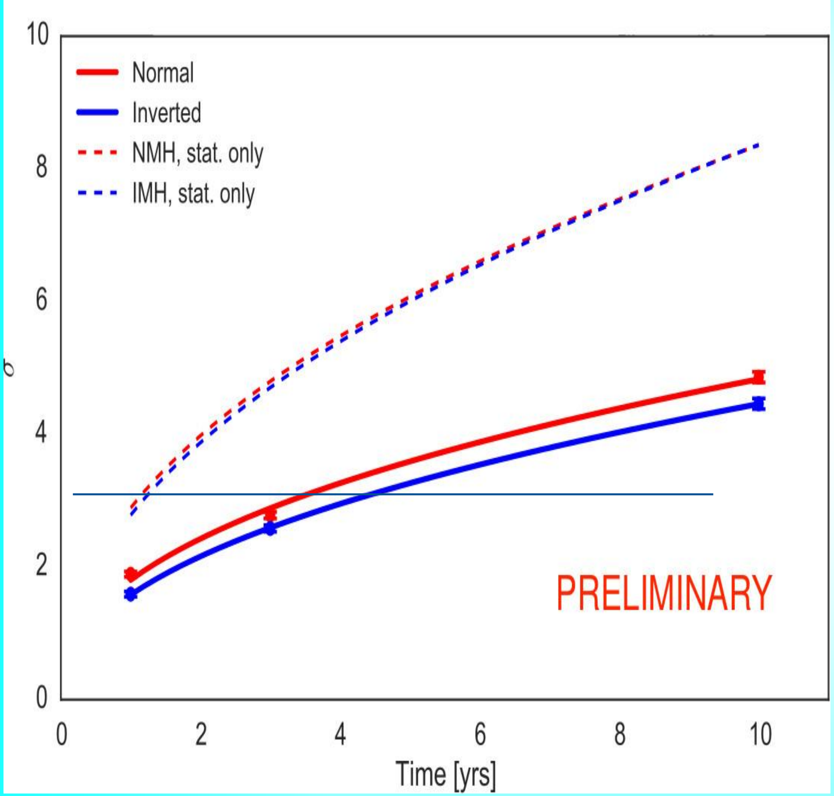
40 strings
96 DOM's per string



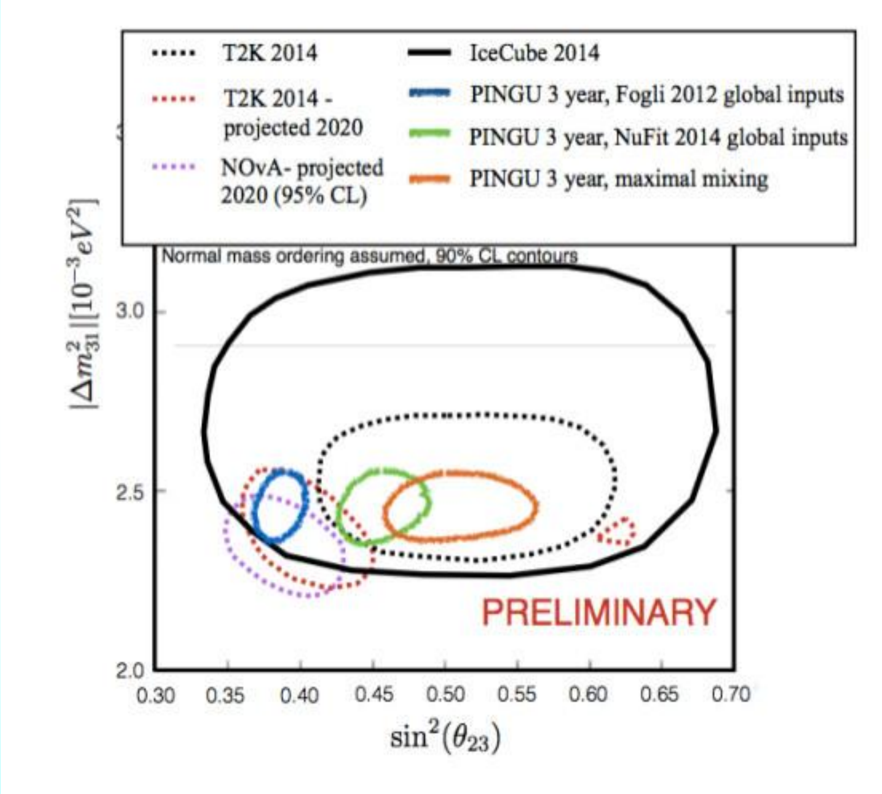
Sensitivity

K. Clark

Mass hierarchy



Parameters of the 2-3 sector



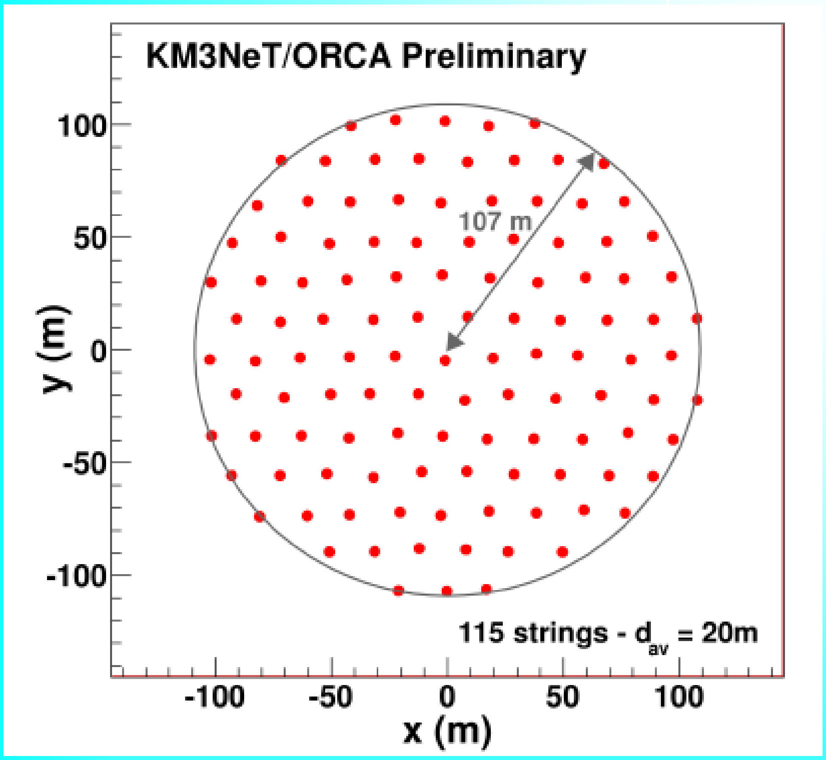
Deviation from maximal: symmetry or no symmetry, Octant

ORCA

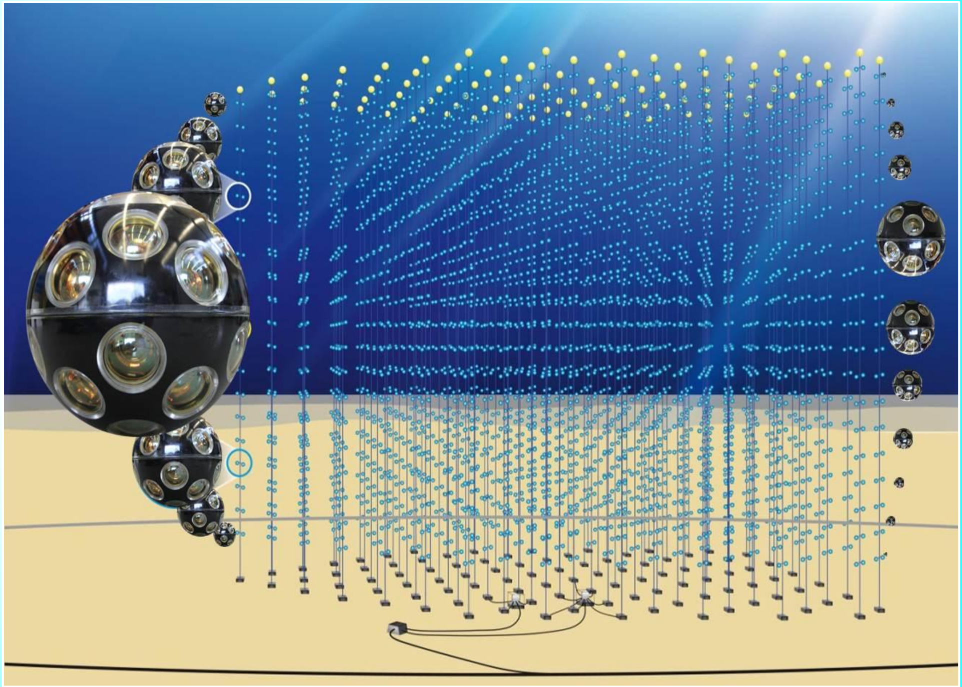
Oscillation Research with
Cosmics in the Abyss

J. Brunner , C. James

115 lines, 20m spaced,
18 DOMs/line, 6m spaced
Instrumented volume ~3.8 Mt,
2070 OM



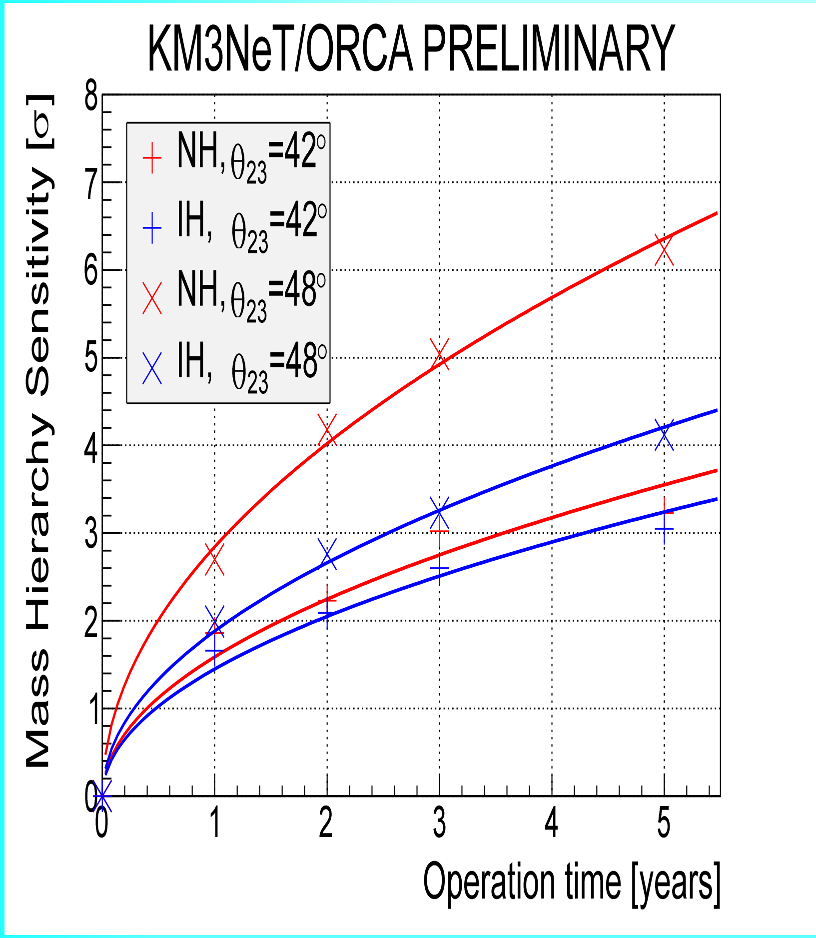
Ronald Bruijn, ICRC 2015



- 31 3" PMTs
- Digital photon counting
- Directional information
- Wide angle view

Sensitivity to MH

J. Brunner



Dependence of sensitivity on time for fixed θ_{23} values and δ_{CP} fixed to zero

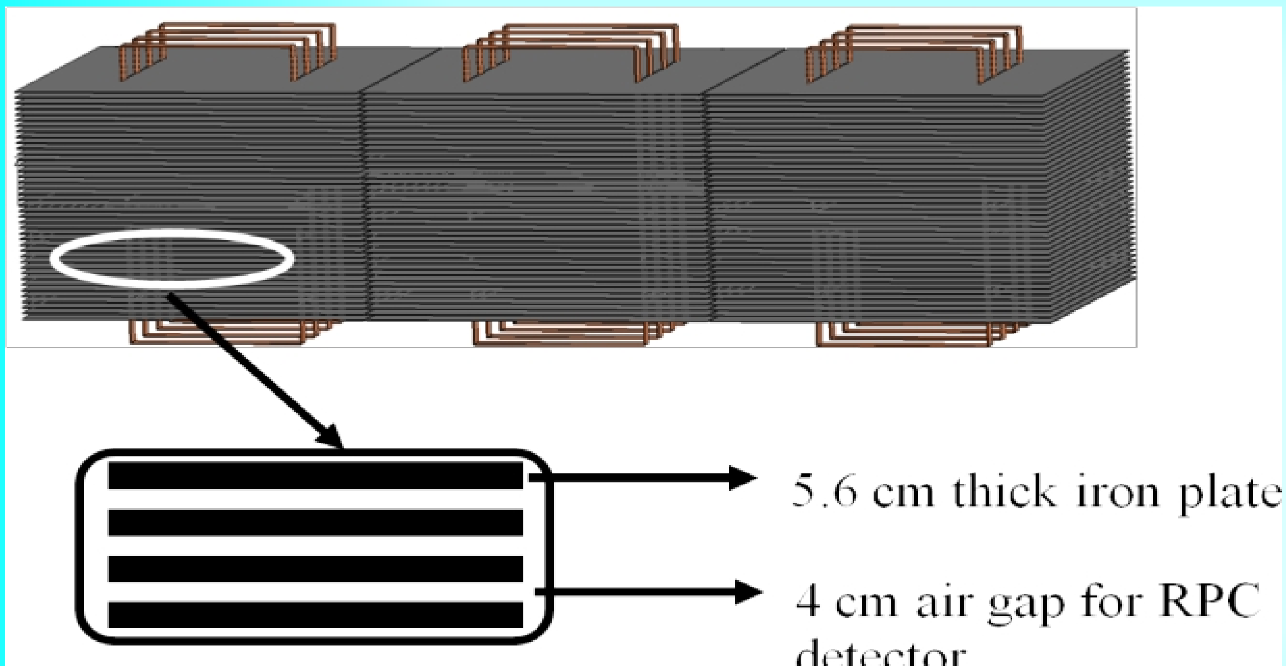
- Track vs shower event classification
- Full MC detector response matrices including misidentified and NC events
- Atmospheric muon contamination
- Neutral current event contamination
- Various Systematic uncertainties

Martijn Jongen, ICRC 2015

INO-ICAL

ICAL Collaboration (Ahmed Shakeel et al.)
arXiv:1505.07380 [physics.ins-det]

The 50 kt magnetized iron calorimeter (ICAL) detector at the India-based Neutrino Observatory (INO)



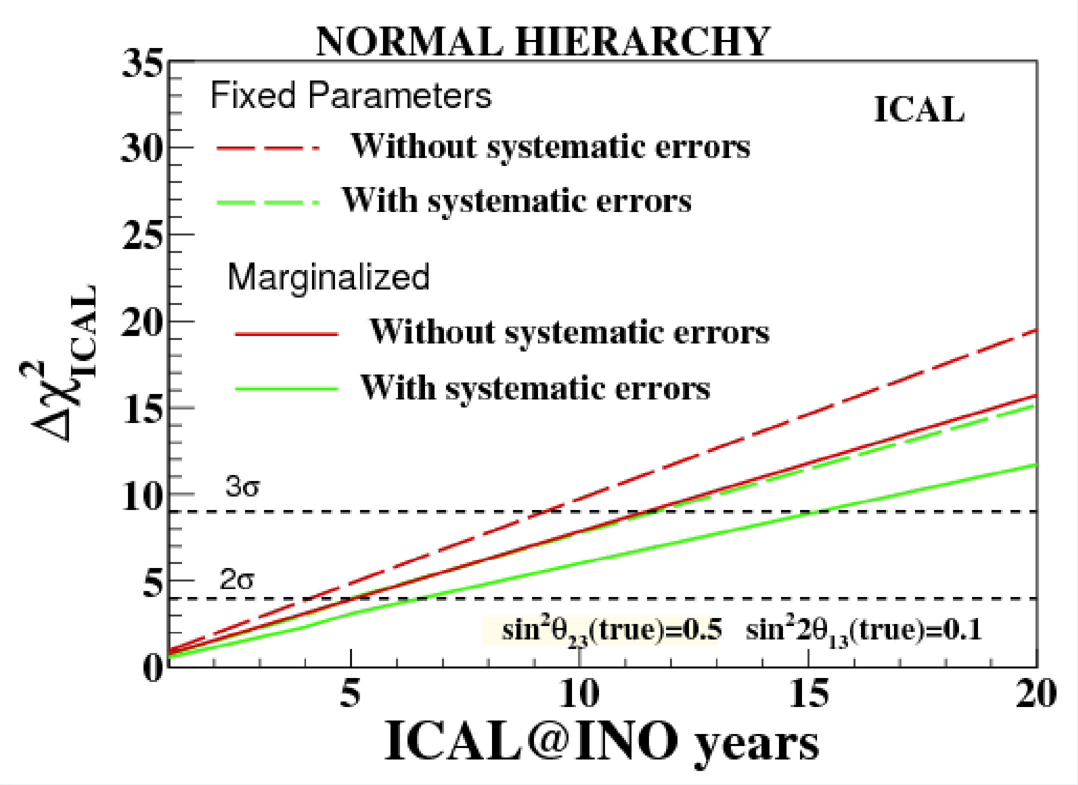
Resistive plate chambers

Energy and direction of the muons; energy of multi-GeV hadrons; charge of muon

The energy and zenith angle dependence of the atmospheric neutrinos in the multi-GeV range.

Sensitivity to hierarchy

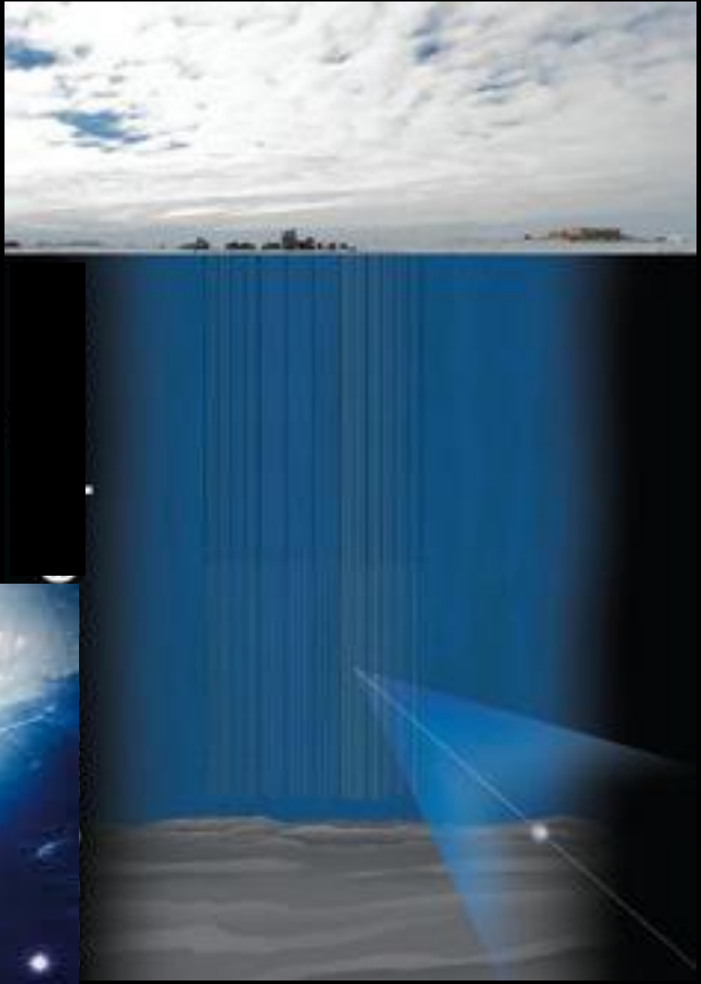
ICAL Collaboration
(Ahmed Shakeel et al.)
arXiv:1505.07380 [physics.ins-det]

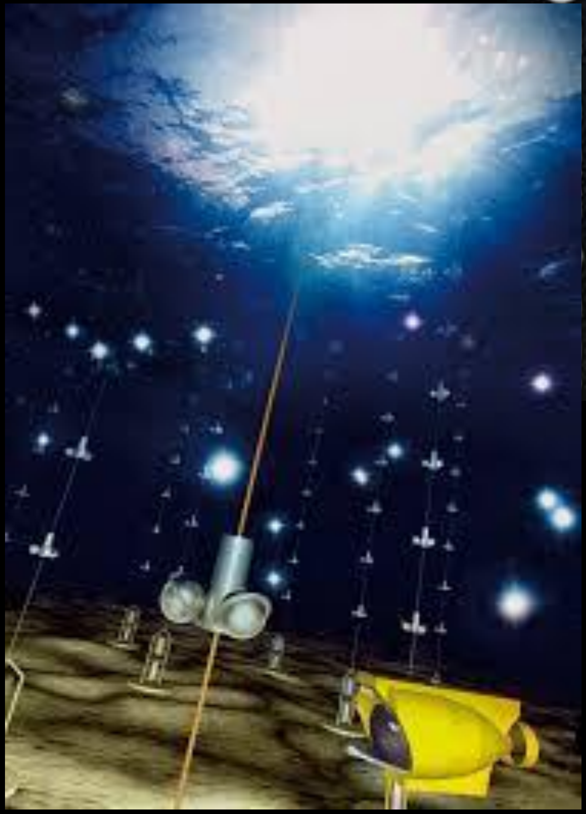


10 -15 years

The impact of systematic uncertainties on mass hierarchy sensitivity.
The red (green) lines – without (with) systematic uncertainties
Long-dashed lines are for fixed values of parameters (1-3 mixing, 2-3 mixing, mass splitting), solid -marginalized

CP-violation





Leptonic CP-phase

phenomenology

Theory

probe of the underlying physics, enters various test equalities

Predicting CP-phase?

In quark sector?
Special values of

Cosmic neutrinos

Long Baseline Neutrino beams

The only possible way to measure the phase
bln $, after 20??

Atmospheric neutrinos

0nbb- decay

insensitive to CPV in standard 3nu scenario

Solar neutrinos

Supernova neutrinos

Cosmology

Leptogenesis

Lepton asymmetry, oscillations in the Early Universe

CP-phase and the framework

B. Dasgupta, A. Y. S. ,
Nucl.Phys. B884 (2014) 357
1404.0272 [hep-ph]

$U_{PMNS} \sim V_{CKM}^{+} U_X$

If the only source of CP violation → V_{CKM}^{+}

No CPV → U_X

$\Rightarrow$ $\sin\theta_{13} \sin\delta_{CP} = (-\cos\theta_{23}) \sin\theta_{13}^{q} \sin\delta_q$

$\sin\theta_{13} \sim \lambda$, $\sin\theta_{13}^{q} \sim \lambda^3$

$\delta_q = 1.2 +/- 0.08$ rad

$\sin\delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2 \sim 0.046$

$\delta_{CP} \sim -\delta$ or $\pi + \delta$

where $\delta = (s_{13}^{q}/s_{13})\, c_{23} \sin\delta_q$

Implications

If the phase δ_{CP} deviates substantially from 0 or π, new sources of CPV beyond CKM

New sources may have specific symmetries which lead to particular values of δ_{CP} e.g. $-\pi/2$

In general

neglecting terms of the order $\sim \lambda^3$

$$\sin \delta_{CP} = s_{13}^{-1} [\sin(\alpha_\mu + \delta_X) V_{ud} |X_{e3}| - \sin \alpha_e \, |V_{cd}| X_{\mu 3}\,]$$

here α_μ , δ_X and α_e are parameters of U_X

Some special values of δ_{CP} can be obtained under certain assumptions

if $X_{e3} = 0$ we have $\sin \delta_{CP} \sim -\sin \alpha_e$

if $\alpha_e = \pi/2$ $\delta_{CP} \sim 3\pi/2$

One can find structure of the RH sector which lead to these conditions

Generalized CP-symmetry

Combine CP with flavor symmetries to predict CP phase

$\nu_\mu - \nu_\tau{}^C$ reflection symmetry of the mass matrix

$\nu_\mu \rightarrow \nu_\tau{}^C$ $\nu_\tau \rightarrow \nu_\mu{}^C$

$\sin\theta_{13}\cos\delta = 0$ ⇒ $\delta = +/- 90^0$

P.F. Harrison, W. G. Scott PLB547, 219 (2002)

W. Grimus, L Lavoura, PL579, 113 (2004)

Y. Farzan, A.S. hep-ph/0610337

Generalized reflection symmetry

$\nu_\alpha \rightarrow X_{\alpha\beta}\,\nu_\beta{}^C$ X is a unitary matrix

Invariance $X^T m_\nu X = m_\nu{}^*$

Generalization of the residual symmetry approach

Flavor and CP symmetry

$G_f \rtimes H_{CP}$

Flavons

Residual symmetries
of the mass matrices

$G_l \rtimes H^l_{CP}$ $\quad$ $G_\nu \rtimes H^\nu_{CP}$

M_l $\quad$ M_ν

A_4 $\quad$ S_4 $\quad$ T' $\quad$ $\Delta(96)$ $\quad$ $\Delta(48)$ $\quad$ $\Delta(27)$

R. Mohapatra, C C Nishi,
F. Feruglio, C. Hagedorn,
R. Ziegler, E Ma, G-J. Ding,
S.F. King, C. Luhn,
A. J. Stuart, Y-L. Zhou,
... Talk by T. Neder

$G_\nu = Z_2 \times Z_2$ → no CP violation $\delta = 0$

$G_\nu = Z_2$ → usually $\delta = 0, +/- \pi/2, \pi$ *C. Hagedorn, et al*

δ may depend on free parameter and take any value *Y. Farzan, A.S.*

Measuring CP-phase

Global fit

T2K + NOvA + reactors

J-PARC- SK

750 kw upgrade

at 2- 3 σ

$3\pi/2$ from 0

Dedicated experiments

J-PARC- HK

DUNE LBNF

ESS European spalation Source (Lund)

~ 5 - 7 σ

result in 2030 - 2035

~ 2 bln US$

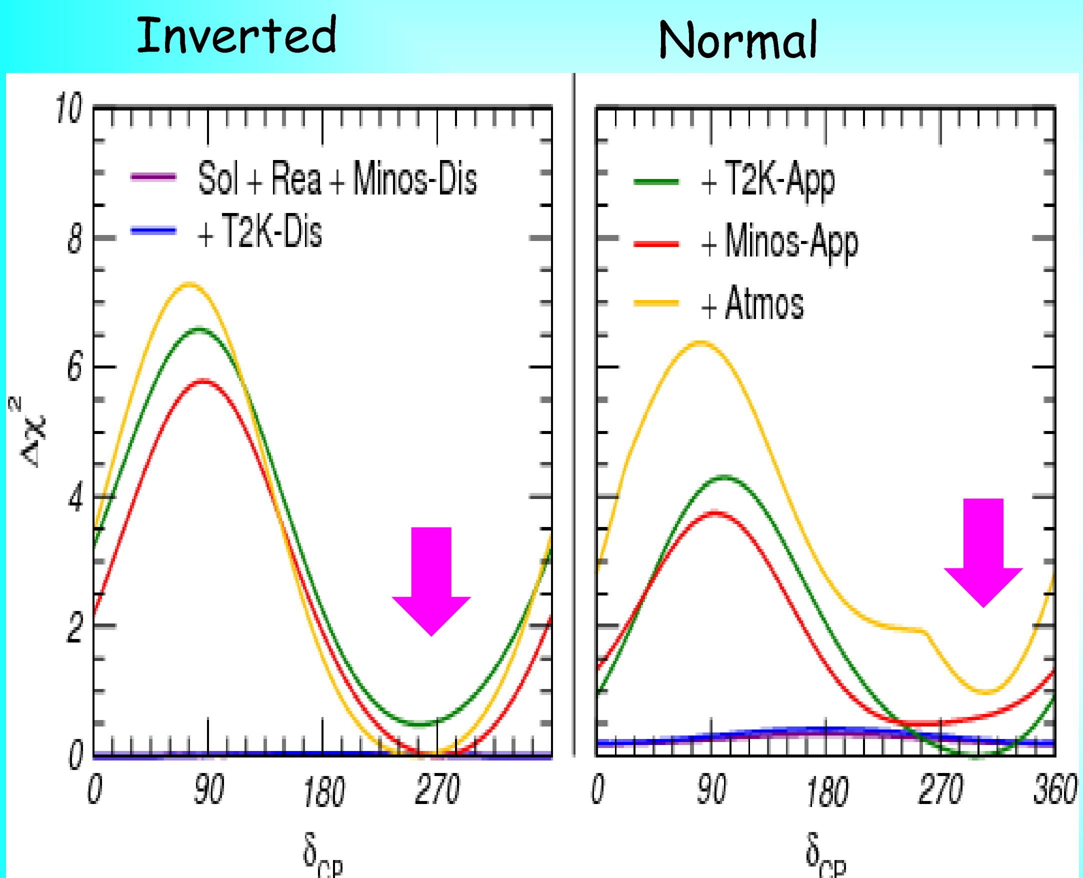
Long term and expensive commitment

Alternative?

All possible alternatives must be explored and scenarios of developments in the next 20 years should be considered

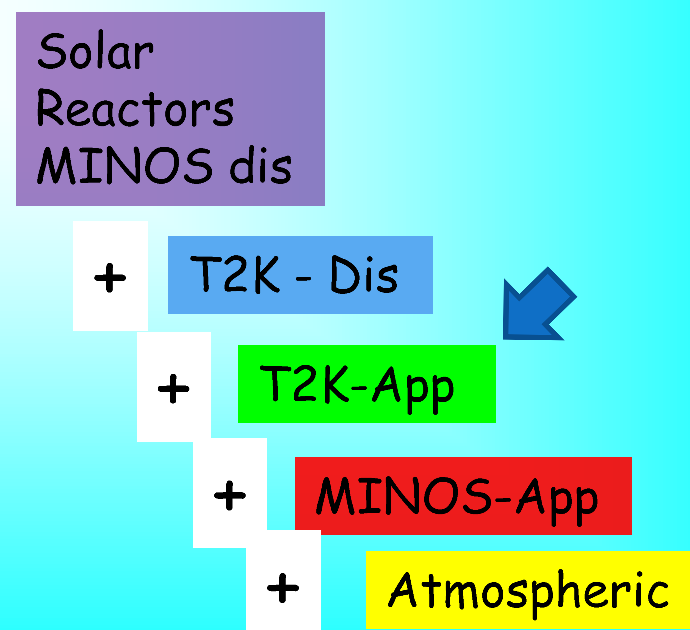
CP-phase from global fit

M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, JHEP 1411 (2014) 052, 1409.5439 [hep-ph]



Contribution of different sets of experimental results to the determination of the CP violating phase.

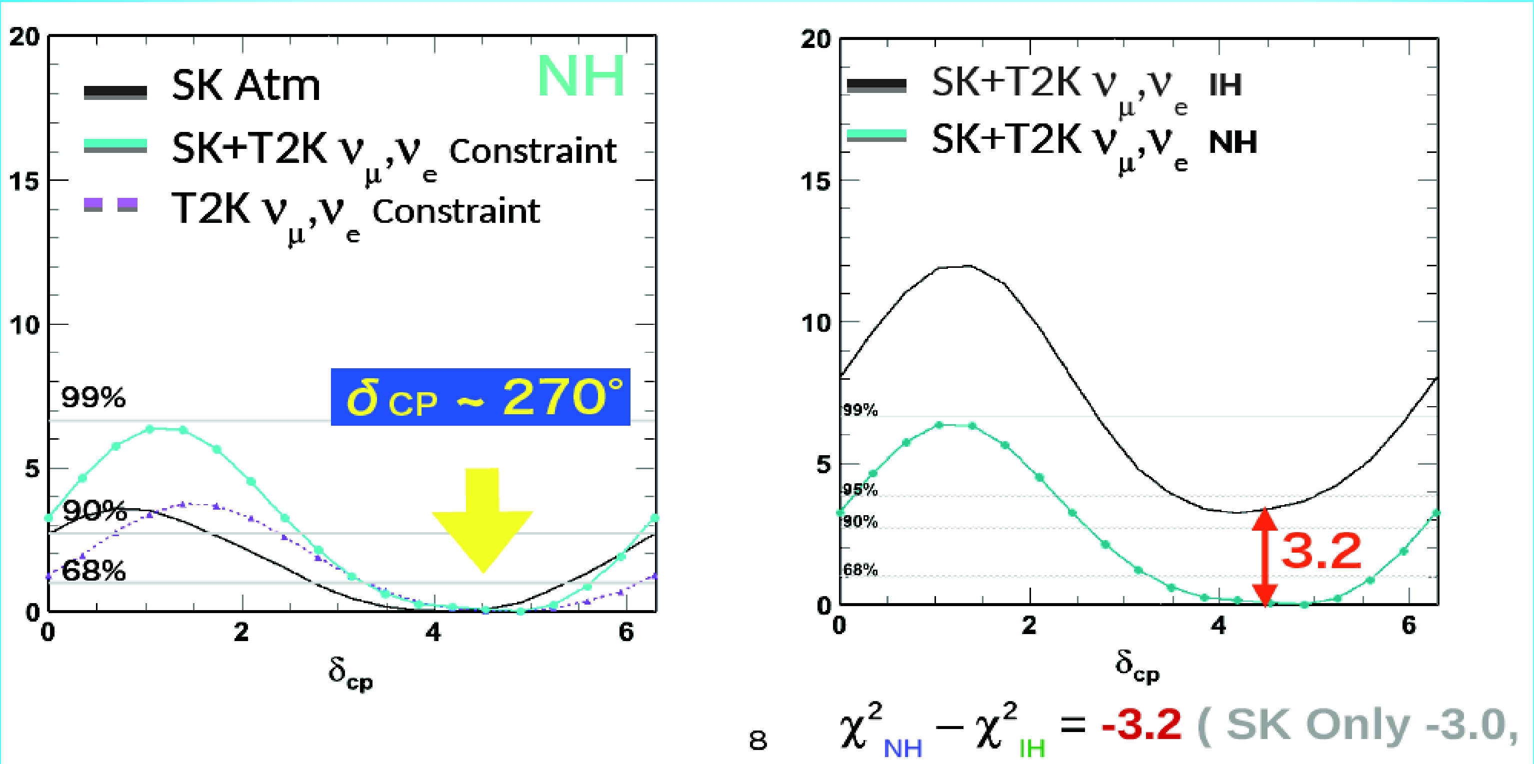
Genesis of determination



Atm nu contribution: excess of sub GeV nue events

SK + T2K

T. Nakaya, Workshop for Neutrino facilities in Japan August 2015



CPV: 90 % CL

NH: 95% CL Atm. give the main contribution

First glimpses of CPV and Hierarchy

NOvA

NuMI Off-Axis ν_e Appearance

FNAL – Ash River
L = 810 km, 14 kton
Liquid scintillator
off axis 3.3° E = 1 - 3 GeV

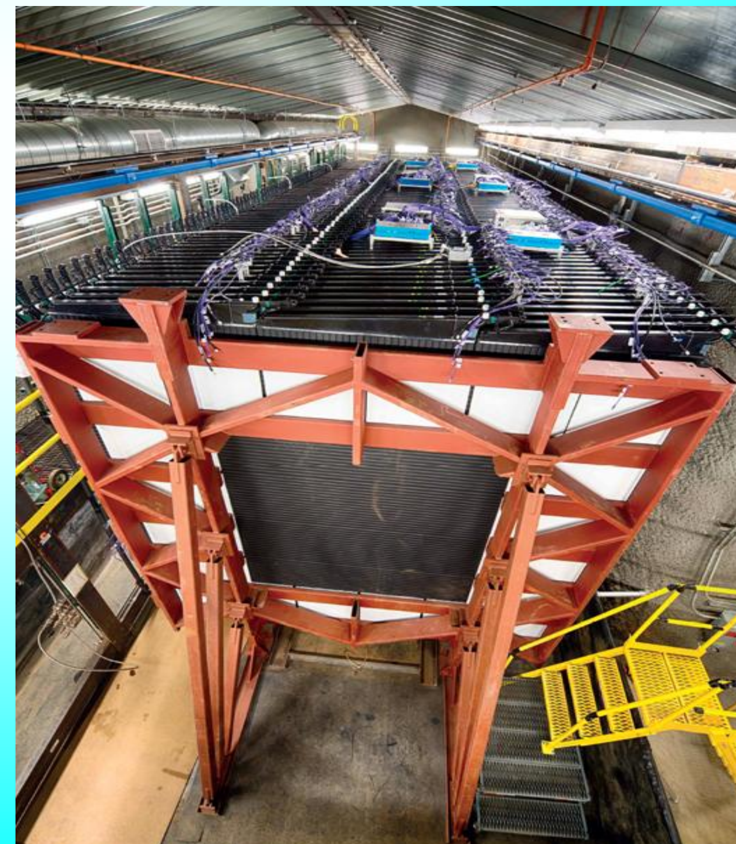
$\nu_\mu - \nu_e$ oscillations in matter

ν_e - appearance

after 7.6% of expected exposure

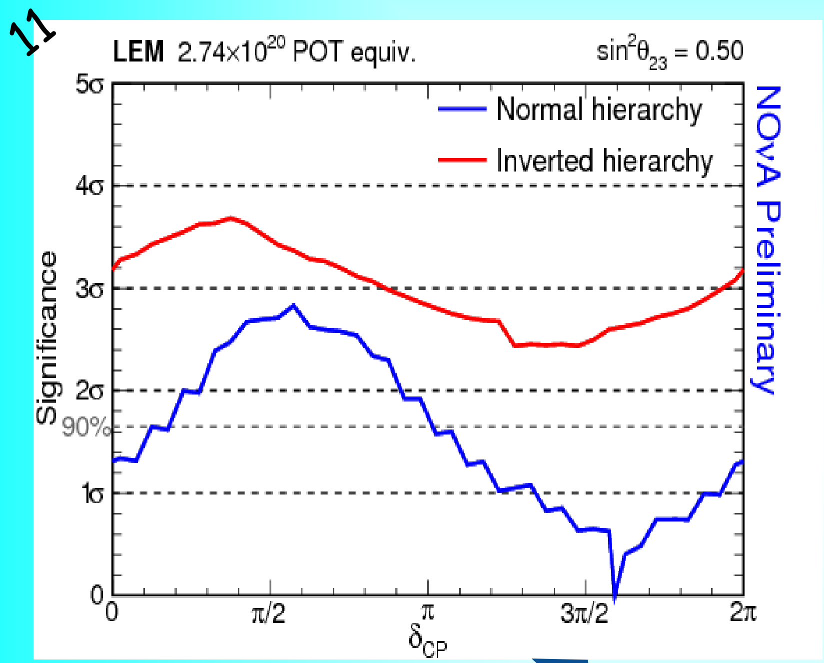
2 methods of events selection:

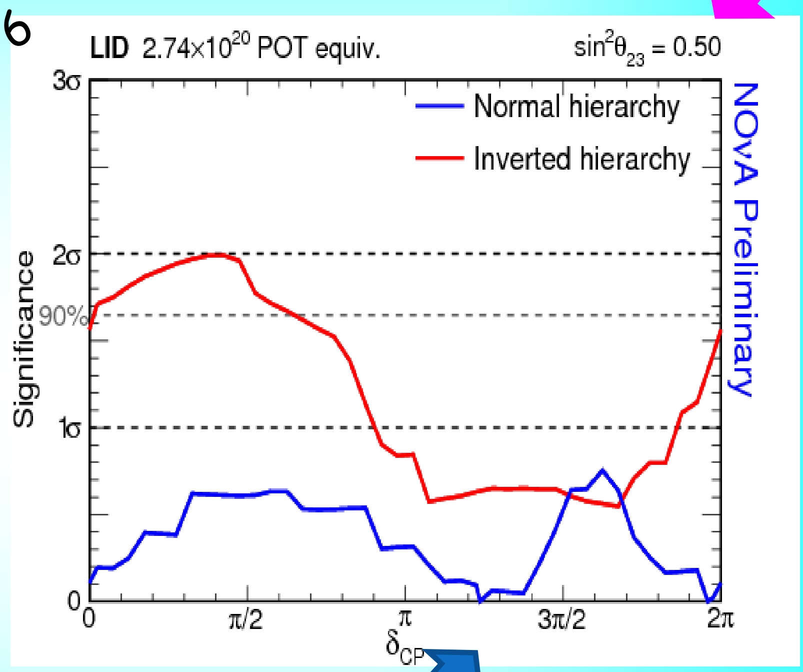
LID (Likelihood Identification): 6 events
LEM (Library event matching): 11 events



NOvA results

J. Bian, (for NOvA Coll.)
1510.05708 [hep-ex]





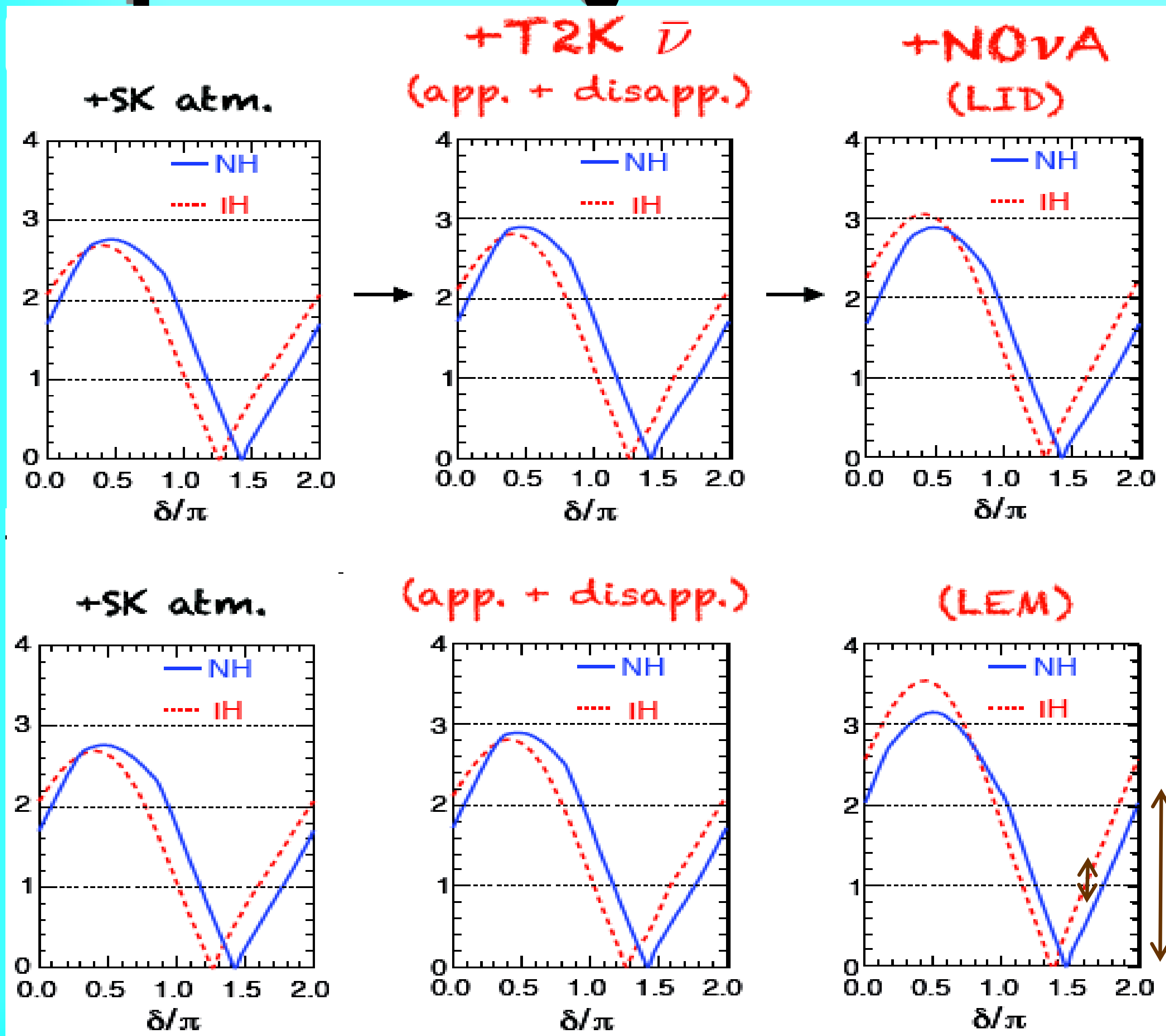
$\delta_{CP} = 3\pi/2$ is preferred in agreement with T2K result

NH is preferred in all range of δ

IH is disfavored at 2.2σ

CP-phase from global fit

A. Marrone
TAUP 2015



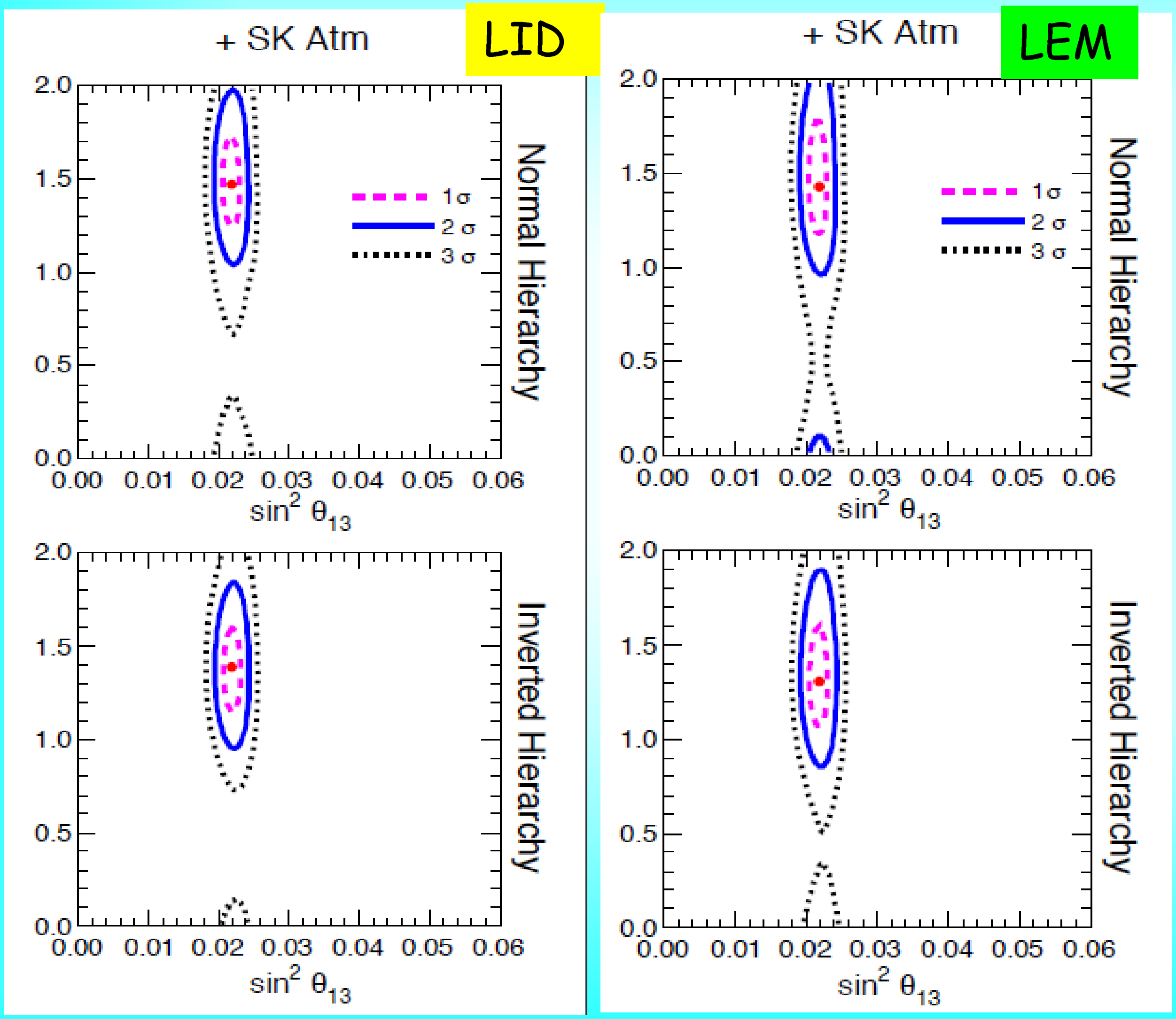
with NOvA the case of CP violation is a bit stronger

$\delta_{CP} = \pi/2$ is disfavores a bit stronger

CP phase effect is stronger than hierarchy

CP-phase

Correlations with 1-3 mixing



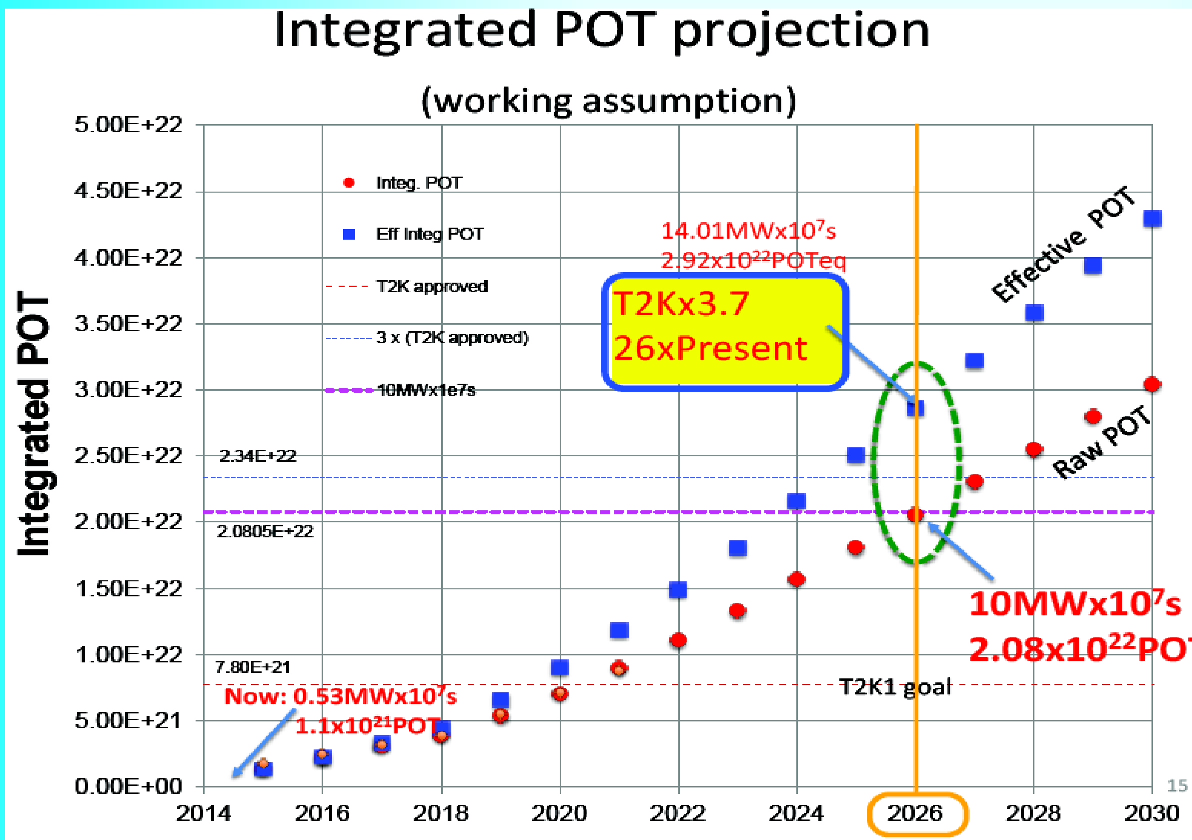
$\delta_{CP} = 3\pi/2$ is preferred in agreement with T2K result

JPARC upgrade

T. Kobayashi, August 2015

2018 – 2019 : 0 .75 MW
2020: 1.0 MW
Before 2026: 1.3 MW ➡ 2.1 x 10^{22} p.o.t.

existing results:
0.11 x 10^{22} p.o.t



JPARC- HK alone establishing CPV with C.L. > 3 σ before HK, DUNE…

Ice Cube

100 GeV

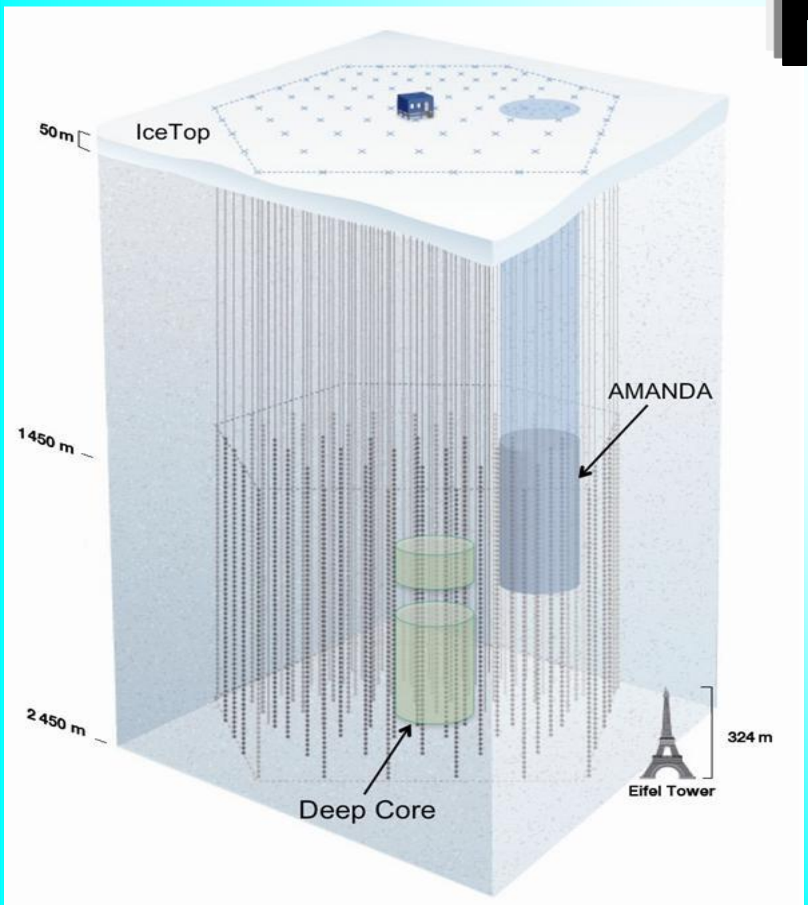
Deep Core

10 - 15 GeV

PINGU
ORCA

Mass hierarchy

3 GeV



Super-PINGU -ORCA

3 times denser array than PINGU

0.5 – 1 GeV

Few Mtons in sub-GeVrange

S. Razzaque, A.Y.S. 1406.1407 hep-ph

Megaton-scale
Ice
Cherenkov
Array

MICA

0.01 GeV

Interference

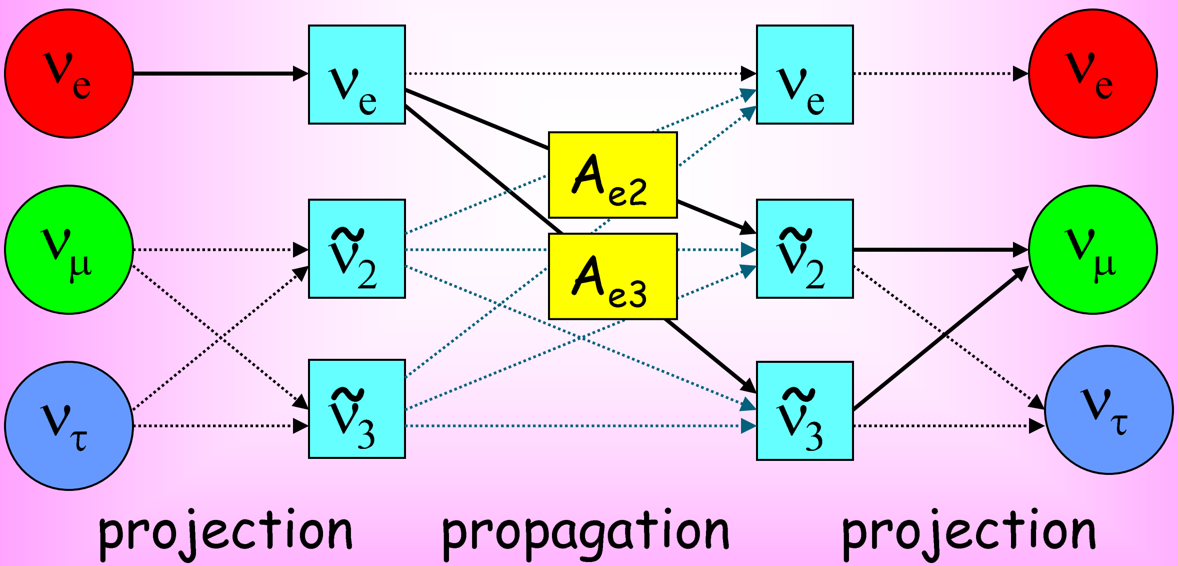
For $E > 0.1$ GeV

Propagation basis

$\nu_f = U_{23} I_\delta \tilde{\nu}$

$I_\delta = \mathrm{diag}\,(1, 1, e^{i\delta})$

CP-violation and 2-3 mixing are excluded from dynamics of propagation



A_{22} A_{33} A_{23}

CP appears in projection only

For instance: $A(\nu_e \to \nu_\mu) = \cos\theta_{23} A_{e2} e^{i\delta} + \sin\theta_{23} A_{e3}$

"Magic lines"

V. Barger, D. Marfatia,
K Whisnant
P. Huber, W. Winter,
A.S.

$$P(\nu_e \rightarrow \nu_\mu) = |\cos\theta_{23} A_{e2} e^{i\delta} + \sin\theta_{23} A_{e3}|^2$$

$$P_{int} = 2 s_{23} c_{23} |A_{e2}||A_{e3}| \cos(\phi + \delta)$$

$\phi = \arg(A_S A_A^*)$

Dependence on δ disappears, interference term is zero if

$P_{int} = 0$

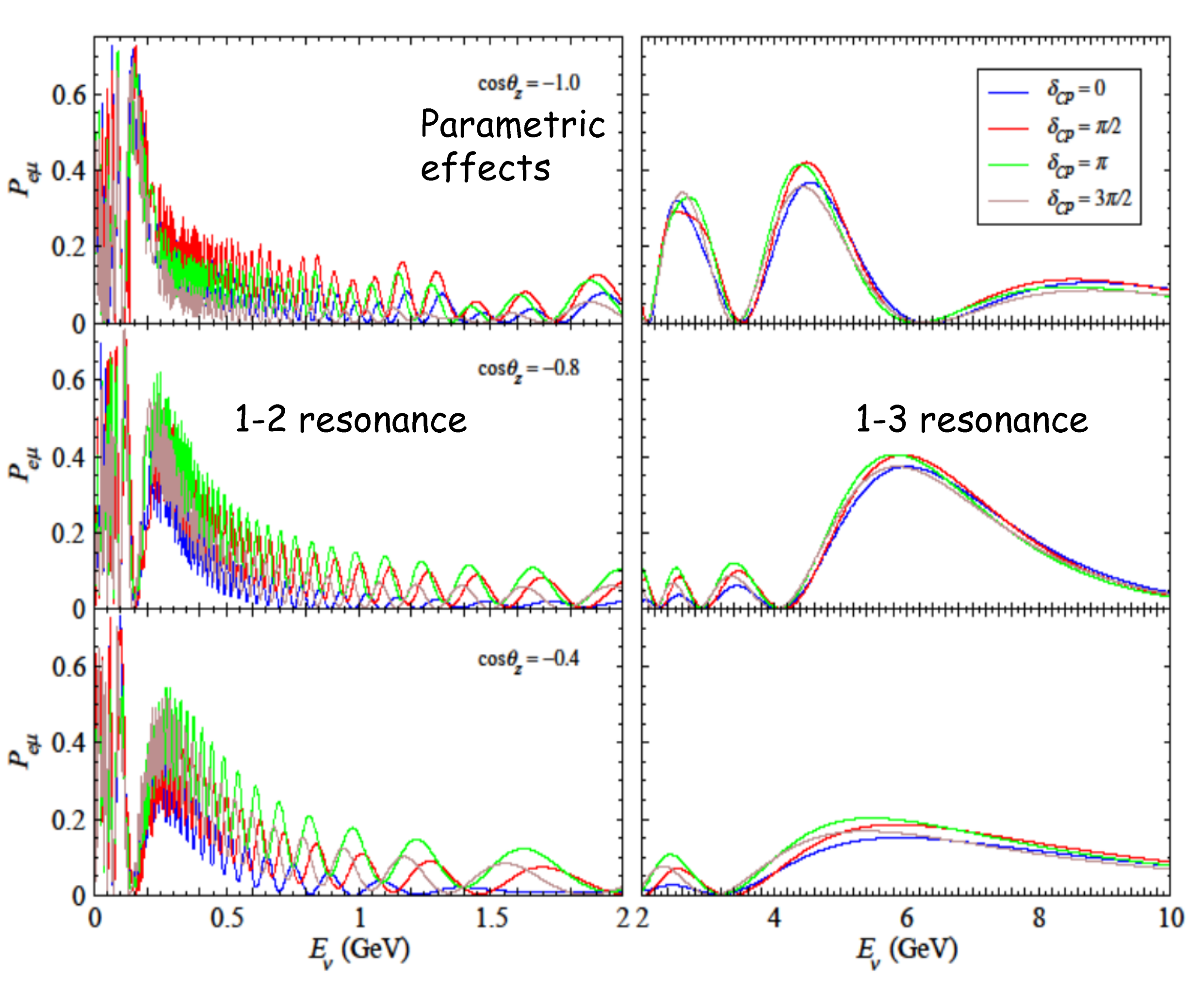
- $A_{e2} = 0$ - solar magic lines
- $A_{e3} = 0$ - atmospheric magic lines
- $(\phi + \delta) = \pi/2 + 2\pi k$ - interference phase condition

$\phi(E, L) = -\delta + \pi/2 + \pi k$ depends on δ

Probabilities

S. Razzaque, A.Y.S.
arXiv: 1406.1407 hep-ph

$\nu_e \rightarrow \nu_\mu$ NH



Large (10%) effect at E ~ (0.5 – 1.5) GeV

The key: with change of the phase

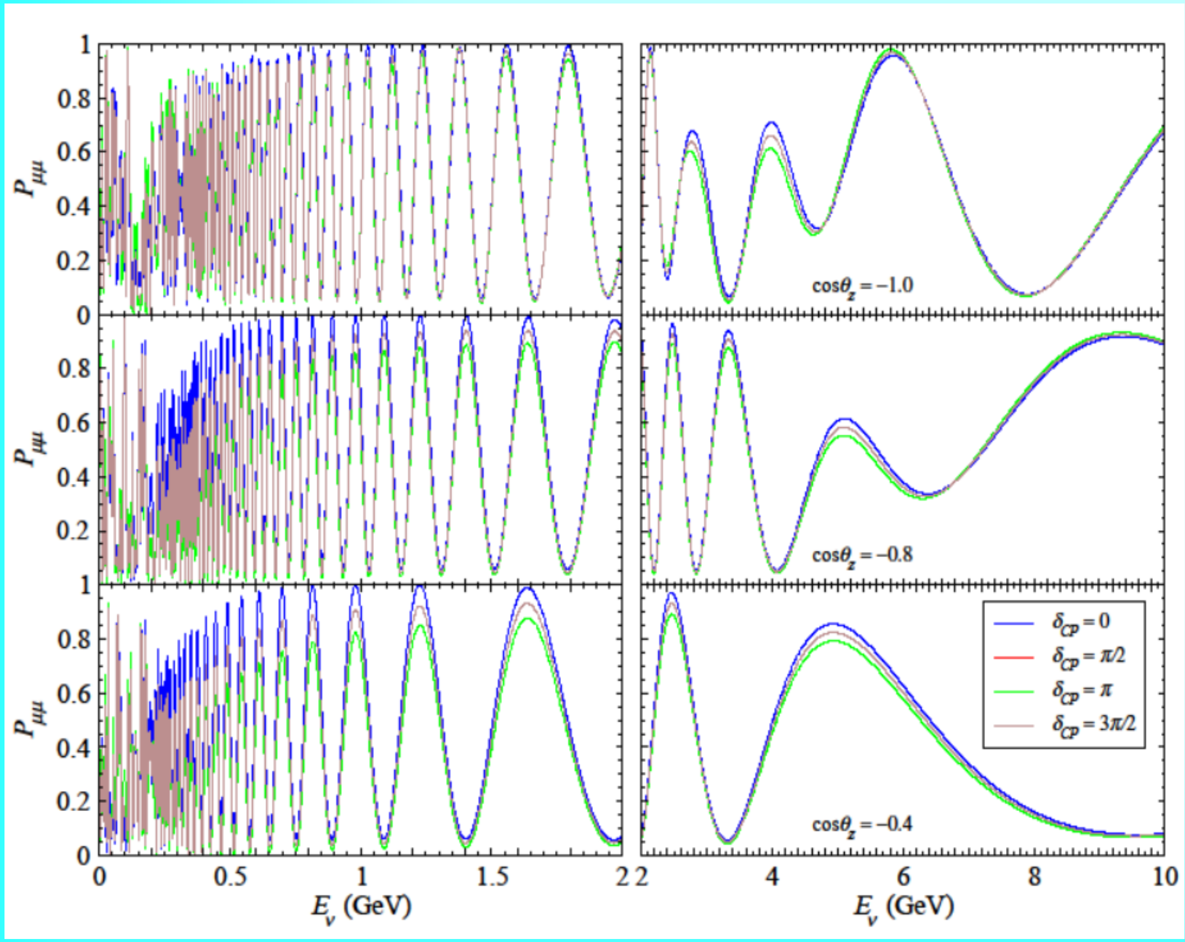
systematic shift of curves, the same for all zenith angles in mantle

Averaging over fast oscillations and integration over zenith angle does not wash out CP phase effect

Probabilities

S. Razzaque A Y S

$\nu_\mu \rightarrow \nu_\mu$



No phase shift

Effect is opposite to $\nu_e \rightarrow \nu_\mu$ with change of δ

Flavor suppression of effects for ν_μ events

Flavor identification is crucial

Distinguishability for CP

Quick estimator (metric) of discovery potential

For each energy-zenith angle bin ij relative CP-difference

$$S_{ij} = \frac{N_{ij}^{\delta} - N_{ij}^{\delta=0}}{\sqrt{N_{ij}^{\delta=0}}}$$

no fluctuations

If is true value → N_{ij}^{δ} corresponds to ``true'' value of events
→ $N_{ij}^{\delta=0}$ ``measured'' number of events

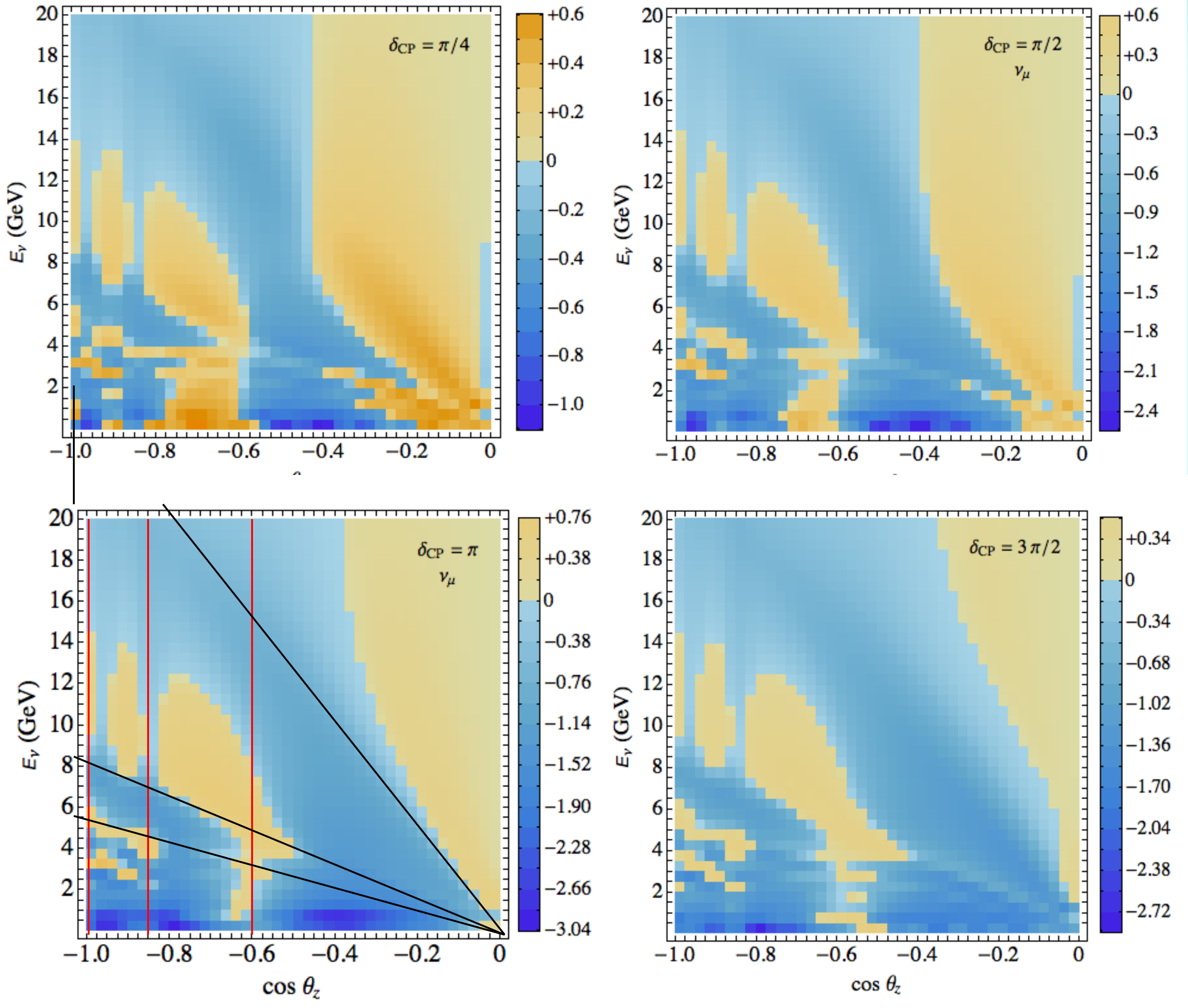
$|S_{ij}|$ - distinguishability of different values of CP-phase

Total distinguishability $S^{tot} = [\Sigma_{ij} S_{ij}^2]^{1/2}$

CP-domains

S-distributions for different values of δ

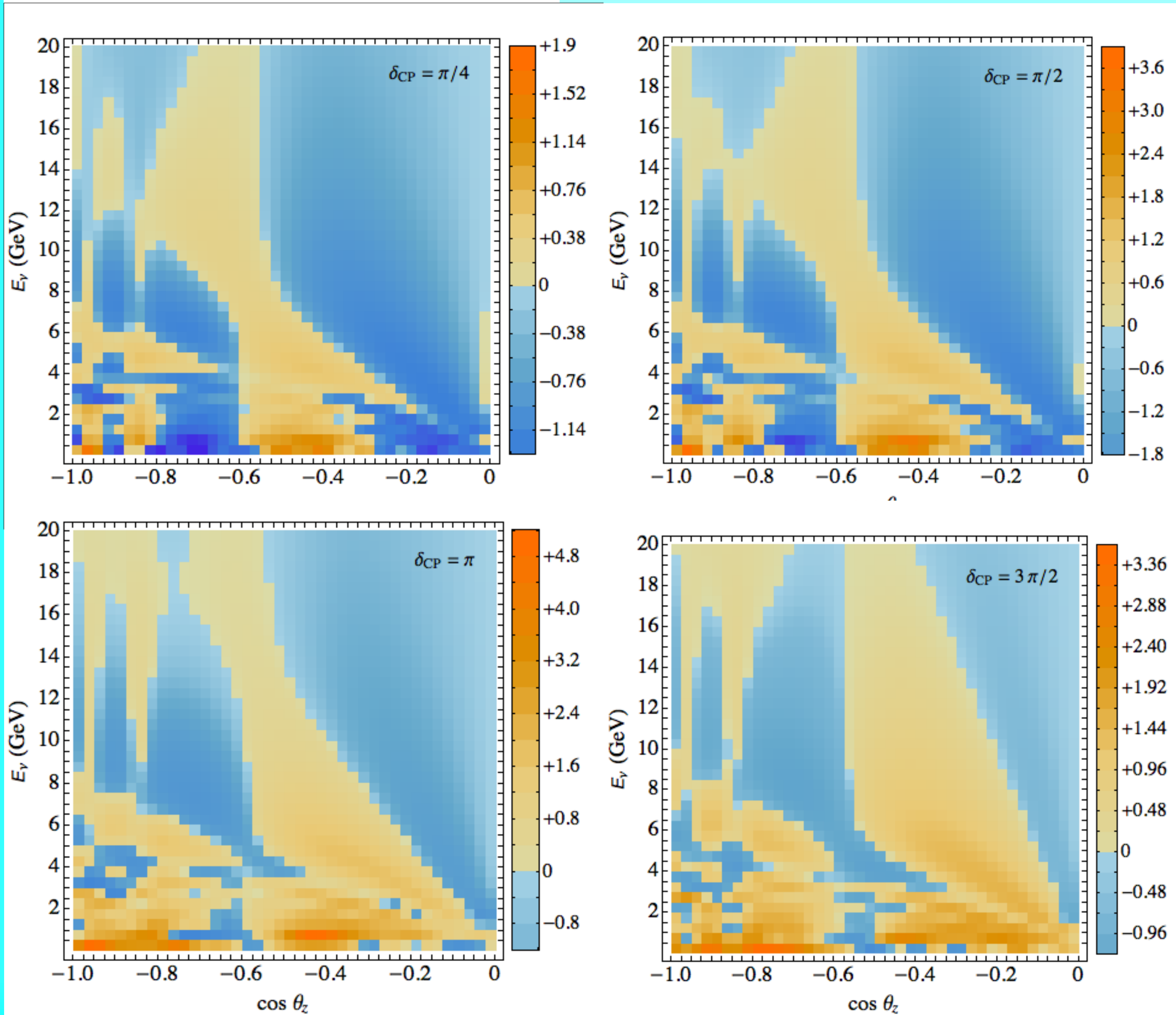
ν_μ-events (track + cascade)



CP-effect:
2 - 5 %
ΔN = 2 – 10 events in each small bin

CP-domains

Cascades (ν_e - events)



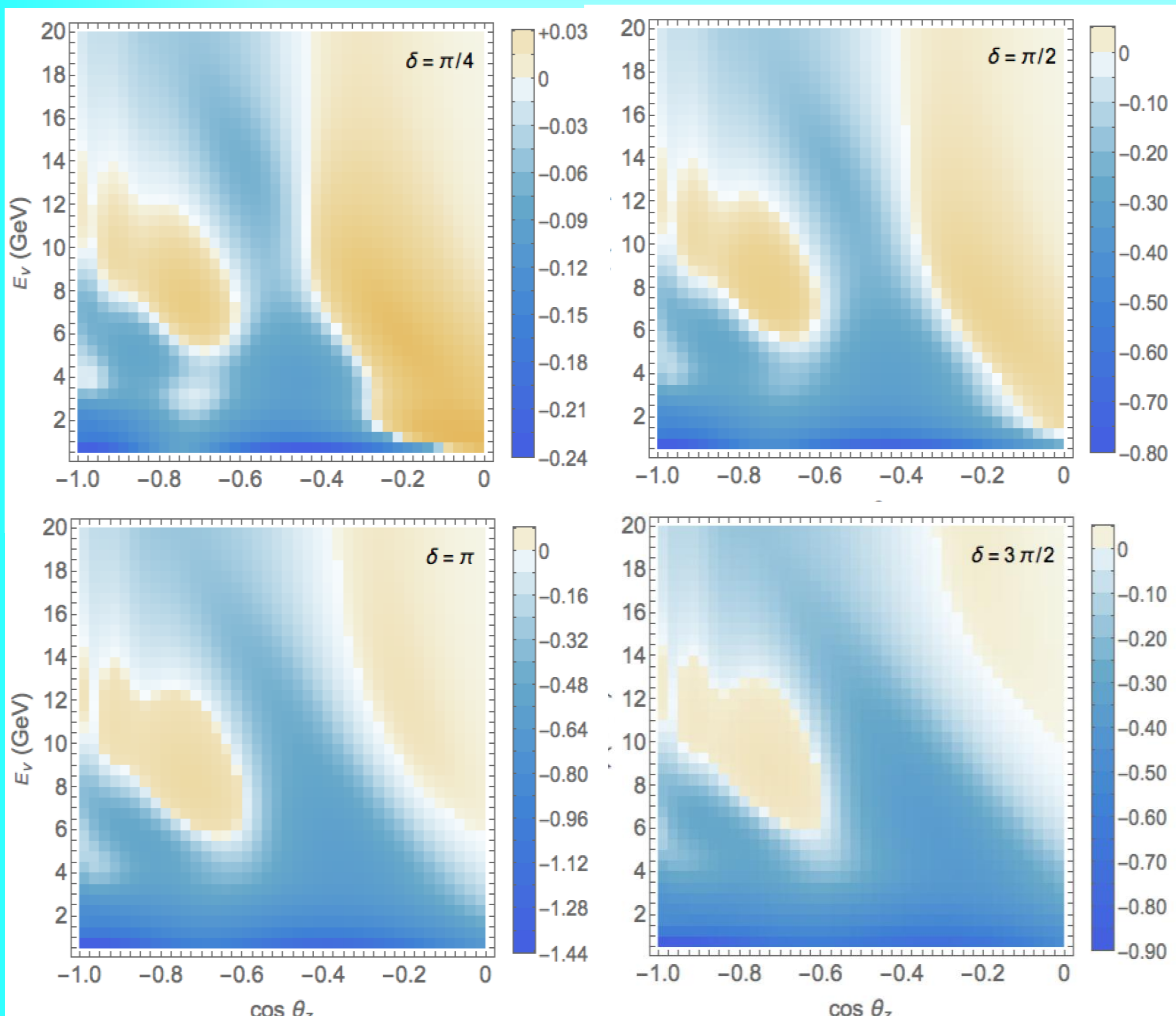
S-distributions for different values of δ

Strong asymmetry of CP differences

Have opposite sign at low energies with respect to ν_μ-events

Smeared distributions

For different values of CP phase



ν_μ- CC events (track + cascade)

S-distributions for different values of δ

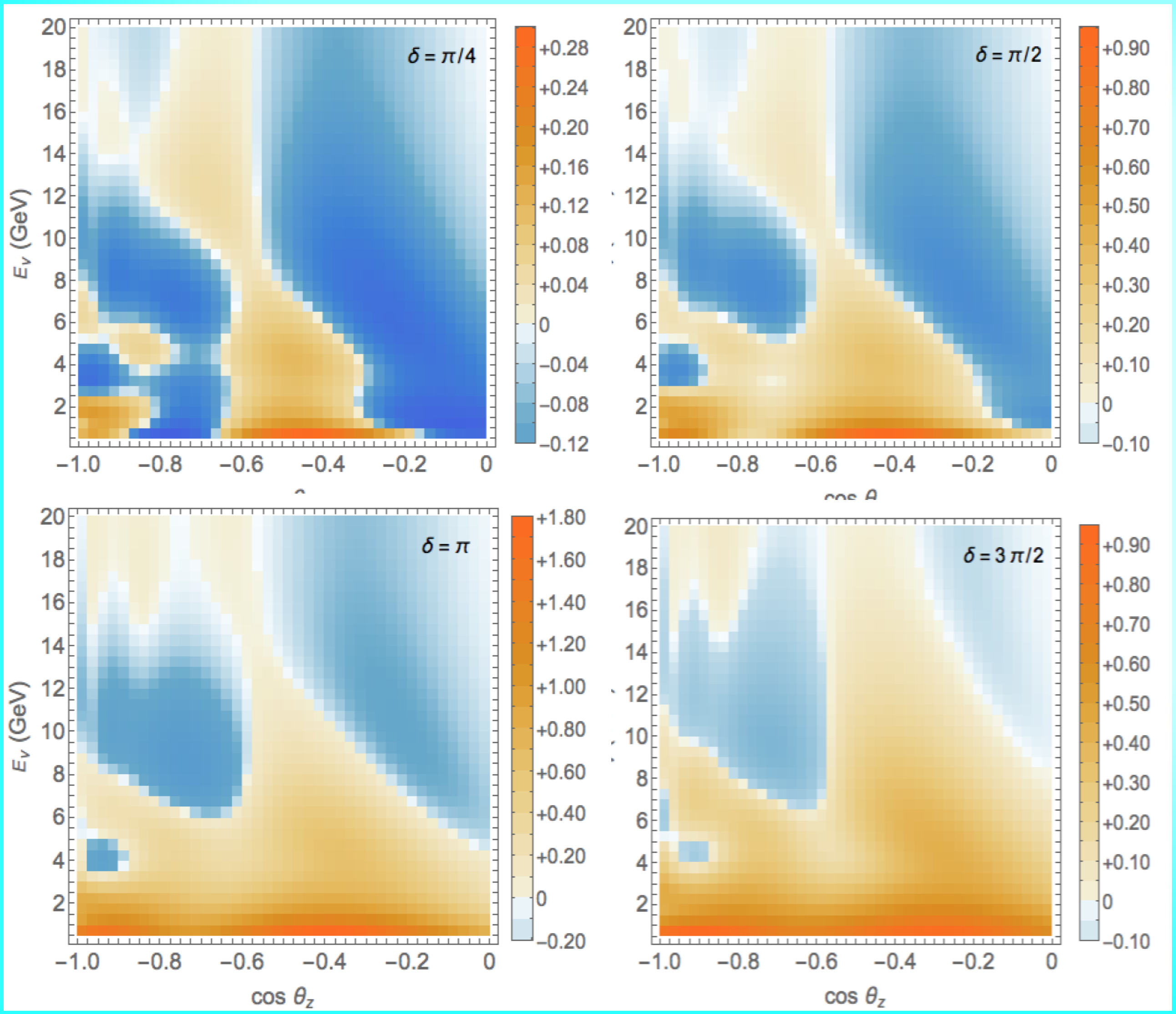
Super PINGU 1 year

After smearing over neutrino energy and direction

S distributions

S. Razzaque, A.Y.S. arXiv: 1406.1407 v2 hep-ph

Smeared distributions



ν_e - CC events (cascades)

S-distributions for different values of δ

Super PINGU
1 year

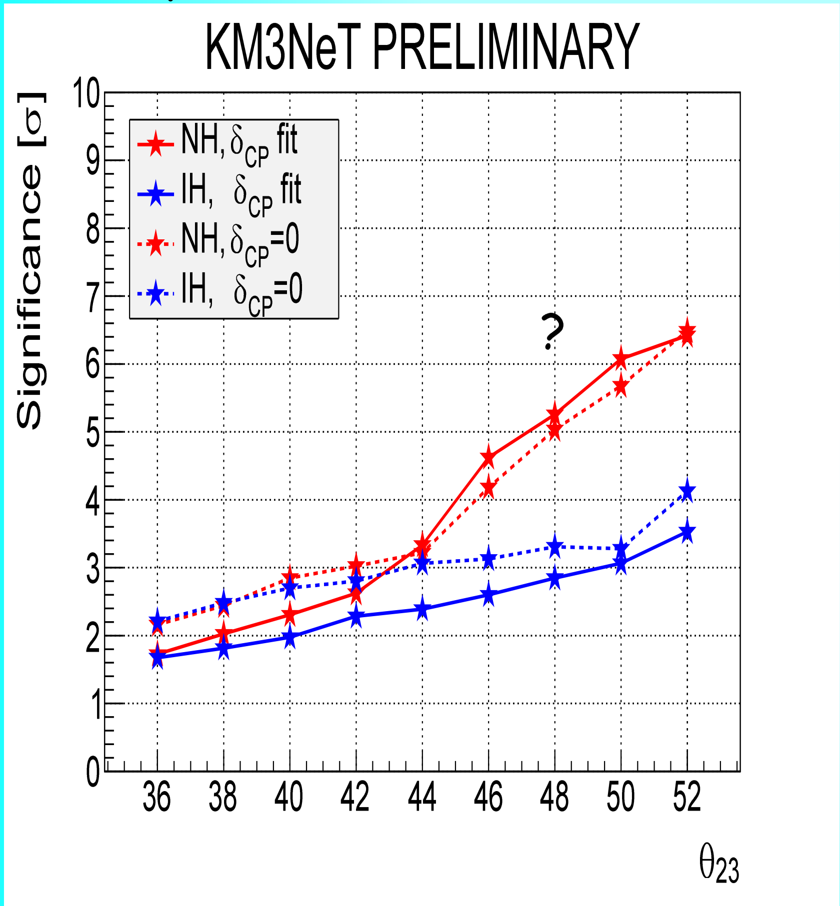
After smearing over neutrino energy and direction

S. Razzaque, A.Y.S.
arXiv: 1406.1407 v2 hep-ph

Can we measure this?

Effect of CP phase

3 years



J. Brunner

Dependence of sensitivity on θ_{23} .
Higher for NH than IH.

Second octant easier than first octant.

When fixing δ_{CP} to zero sensitivity increases by ~0.5σ

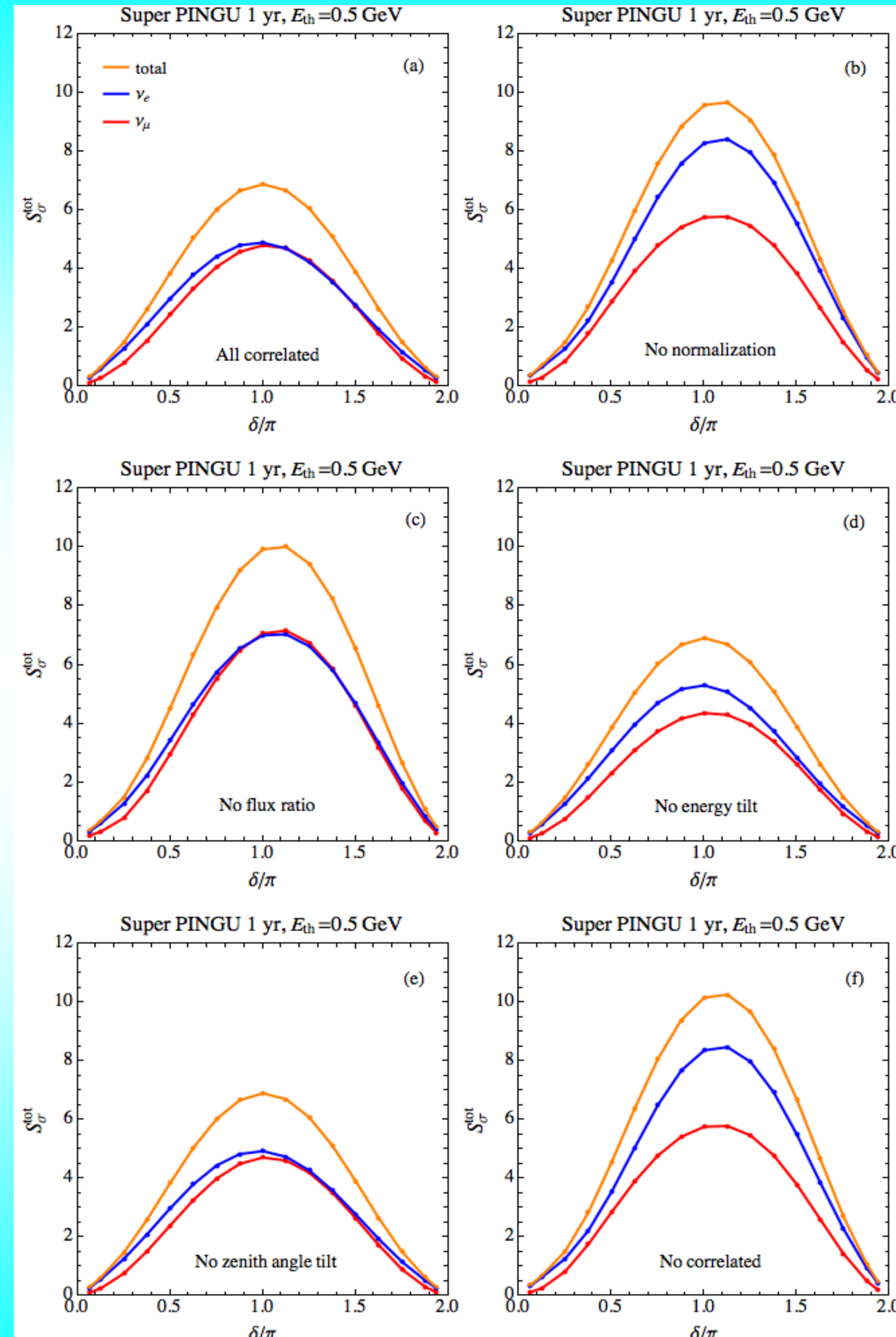
Martijn JONGEN
ICRC 2015,

Sensitivity of SuperPINGU

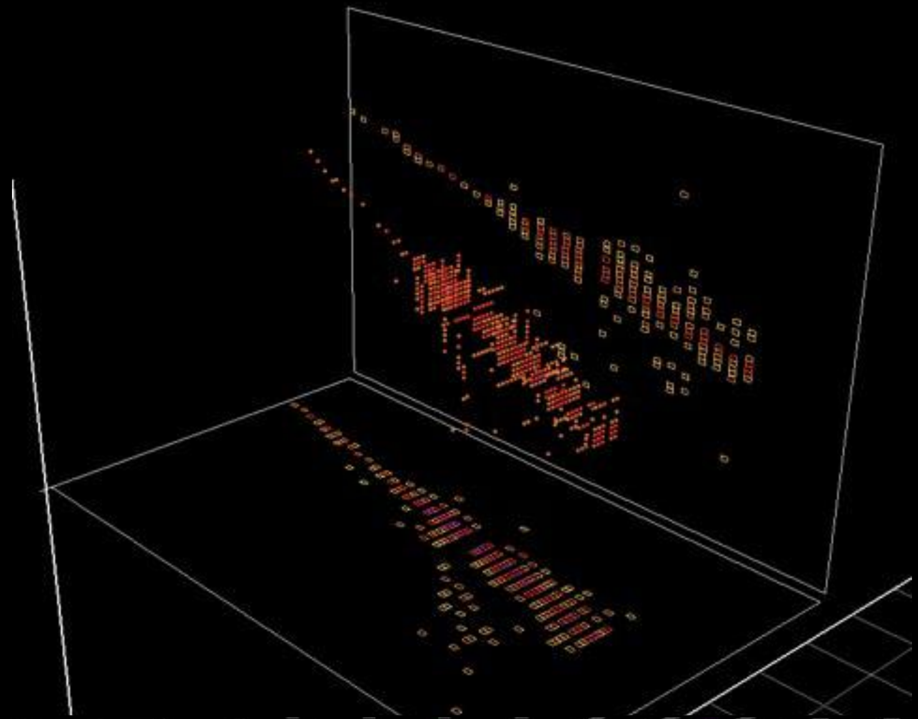
Effect of correlated systematic errors

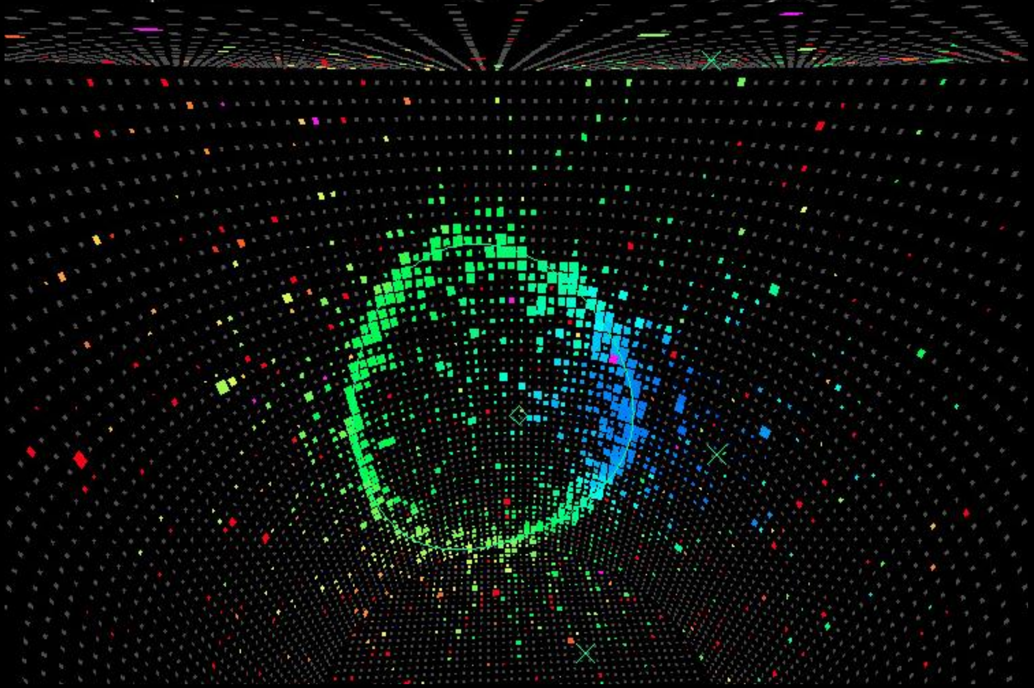
Flavor misidentification can further reduce distinguishability by factor 1.5 - 2

Still S_σ ~ 3-4 for $\delta = \pi$ after 4 years of exposure



Conclusion





First glimpses of CPV and mass hierarchy
Maximal CP and NH are favored at about 2σ level
With present facilities (maybe their upgrades) that it can increase up to 3σ

CP can be first?

Race for the mass hierarchy with about the same time scale and significance:

PINGU – updated proposal is expected this year
ORCA – start to build detector (several strings in 2016)

JUNO – beginning of construction, capacity – still open questions

About 30 SN neutrino bursts approaching the earth

CP-violation: change of strategy? With existing facilities can reach more than 3σ. Question about accuracy will be the issue

Super- PINGU, ORCA detectors to measure CP, eventually MICA

CP-violation: new proposals: e.g. Neutrinos from muon decay
And Ga-uploaded SK type detector.