Accelerator Neutrino (2)

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What is the next step?

- $\sin^2 2\theta_{13}$ was determined precisely by reactor experiments.
- ν_e appearance via $\sin^2 2\theta_{13}$ was also observed by an accelerator experiment.

- This is not the end of the story, but actually start of the new story!

ν_e appearance probability Leading term

$$P(\nu_\mu \rightarrow \nu_e) = \boxed{4C_{13}^{\ 2} S_{13}^{\ 2} S_{23}^{\ 2} \sin^2 \Phi_{31}}$$

Leading term

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$$

$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

ν_e appearance probability (exact formula in vacuum)

$$P(\nu_\mu \to \nu_e) = \boxed{4C_{13}^{2} S_{13}^{2} S_{23}^{2} \sin^2 \Phi_{31}}$$

Leading term

$\boxed{\theta_{13}}$

$$+8C_{13}^{2} S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

$\boxed{\text{CPC}}$

$$\boxed{-8C_{13}^{2} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}}$$

$\boxed{\text{CPV}}$

$$+4S_{12}^{2} C_{13}^{2} (C_{12}^{2} C_{23}^{2} + S_{12}^{2} S_{23}^{2} S_{13}^{2} - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$

$\boxed{\text{Solar}}$

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$$

$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

replace δ by −δ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

CP violating term introduced by interference btw. θ_{13} and θ_{12}

ν_e appearance at around oscillation maximum

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2 \Phi_{31} \qquad \boxed{\theta_{13}}$$

$$\cancel{+8C_{13}{}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}} \qquad \boxed{\text{CPC}}$$

$$-8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \qquad \boxed{\text{CPV}}$$

$$+\cancel{4S_{12}{}^2 C_{13}{}^2 (C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}} \qquad \boxed{\text{Solar}}$$

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 - 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{21}$$

Observation

Q. Calculate how much $P(\nu_\mu \rightarrow \nu_e)$ changes between δ=0 and δ=90°

$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 - 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{21}$$

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$\begin{aligned}
\theta_{12} &= 34° \, (\cos\theta_{12} = 0.83, \sin\theta_{12} = 0.56) \\
\theta_{23} &= 45° \\
\theta_{13} &= 9.0° \, (\cos\theta_{13} = 0.99, \sin\theta_{13} = 0.16)
\end{aligned}$$

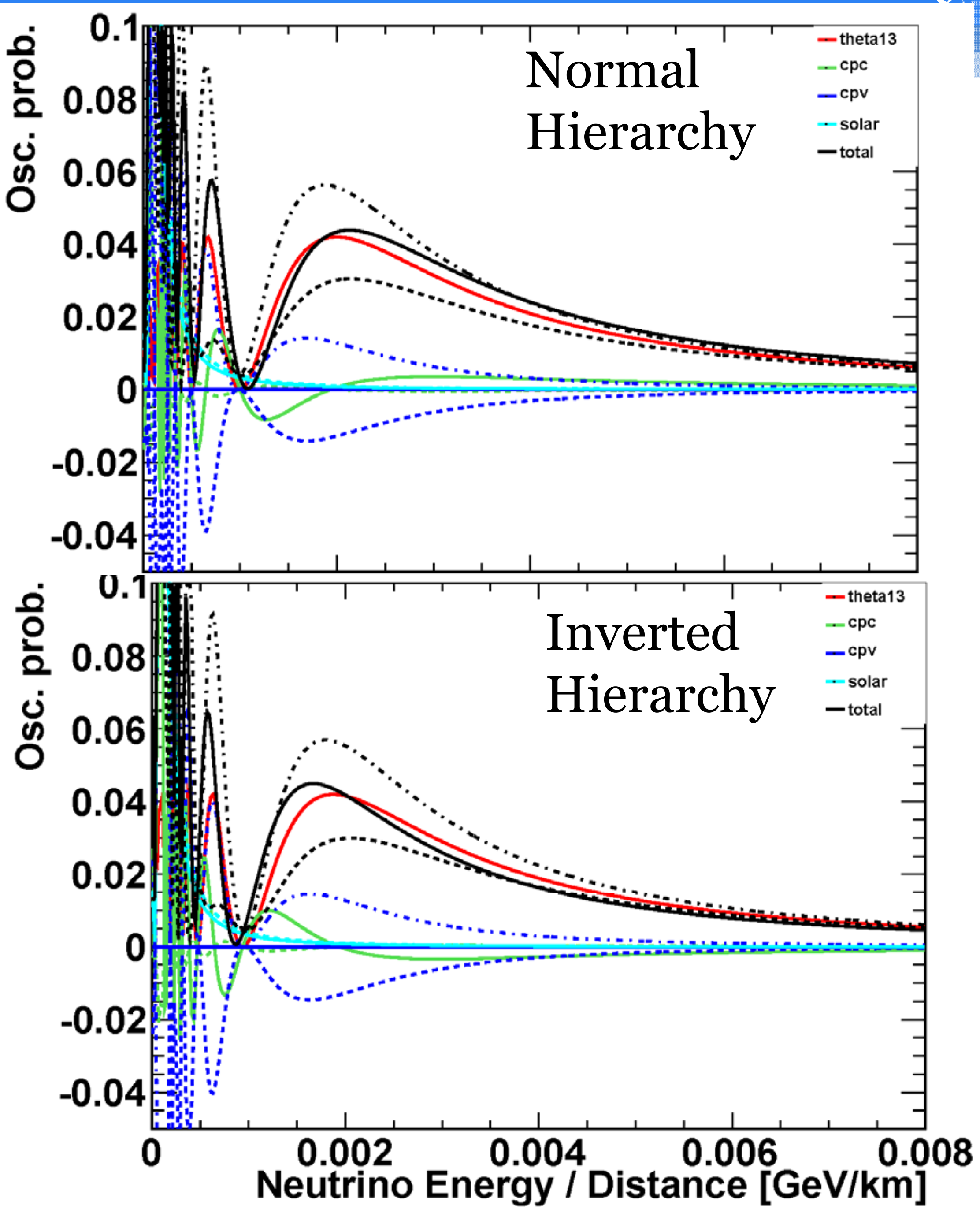
Max. 27% asymmetry (violation) by CP phase

$\nu_\mu \rightarrow \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4\text{e-}3\ \text{eV}^2$
- $\Delta m^2_{12} = 7.59\text{e-}5\ \text{eV}^2$
- $\theta_{12} = 34^\circ$
- $\theta_{23} = 45^\circ$
- $\sin^2 2\theta_{13} = 0.084$
- w/o matter effect

θ_{13}
CPC
CPV
Solar
Total

—— $\delta=0$
– – – $\delta=\pi/2$
—·— $\delta=-\pi/2$



$\nu_\mu \to \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4\text{e-}3\ \mathrm{eV}^2$
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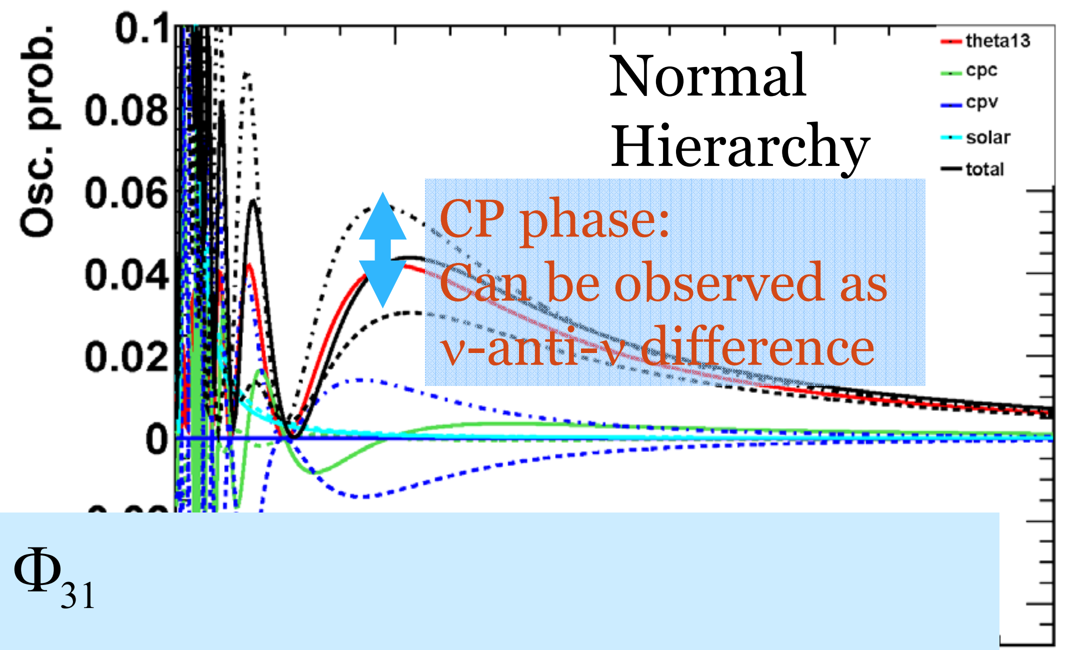


Normal Hierarchy

CP phase:
Can be observed as ν-anti-ν difference

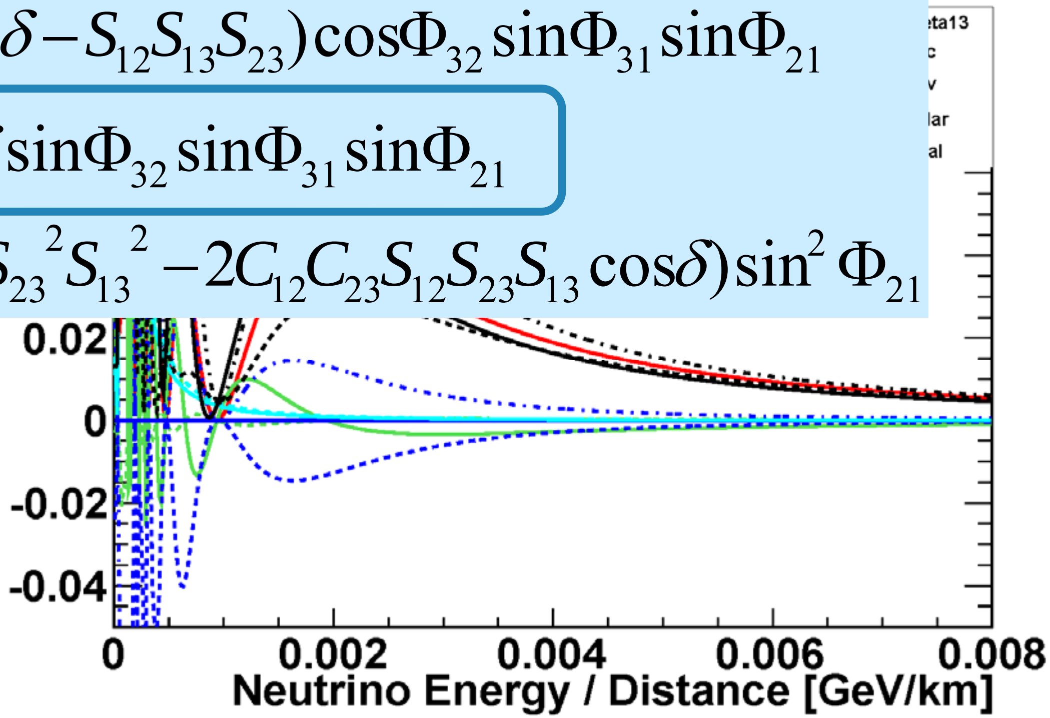
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \\
& \boxed{- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}
\end{aligned}
$$

Total

—— δ=0

- - - δ=π/2

— · — δ=−π/2



$\nu_\mu \rightarrow \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4\text{e-}3\ \mathrm{eV}^2$
- $\Delta m^2_{12} = 7.59\text{e-}5\ \mathrm{eV}^2$
- $\theta_{12} = 34^\circ$
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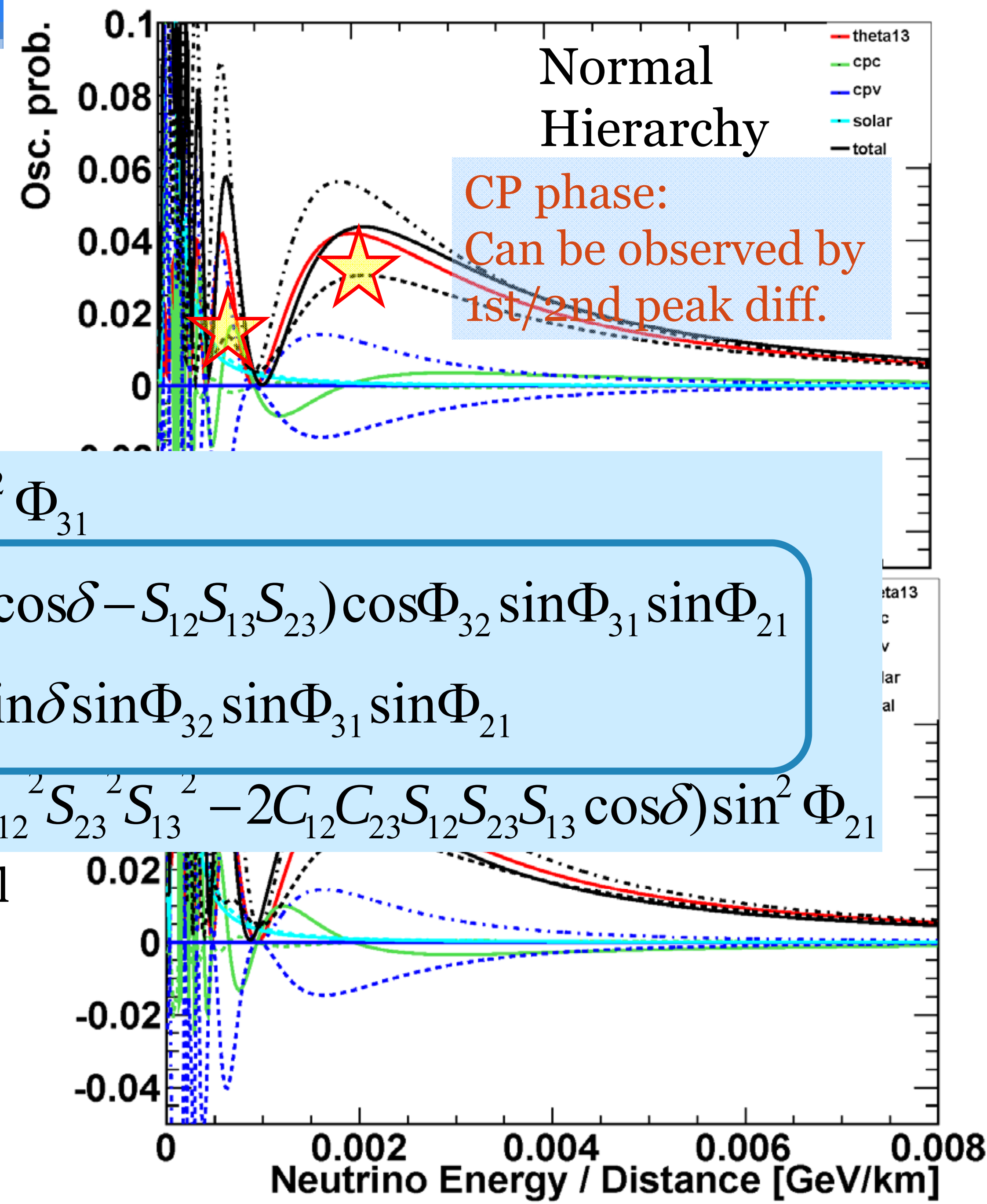


Normal Hierarchy

CP phase:
Can be observed by 1st/2nd peak diff.

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = {} & 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2 \Phi_{31} \\
& \boxed{\begin{aligned} + & 8C_{13}{}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \\ - & 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21} \end{aligned}} \\
& + 4S_{12}{}^2 C_{13}{}^2 (C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}
\end{aligned}
$$

Total

── δ=0

– – – δ=π/2

—·— δ=−π/2

Q. Calculate how much $P(\nu_\mu \rightarrow \nu_e)$changes between δ=0 and δ=90°

$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 - 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{21}$$

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

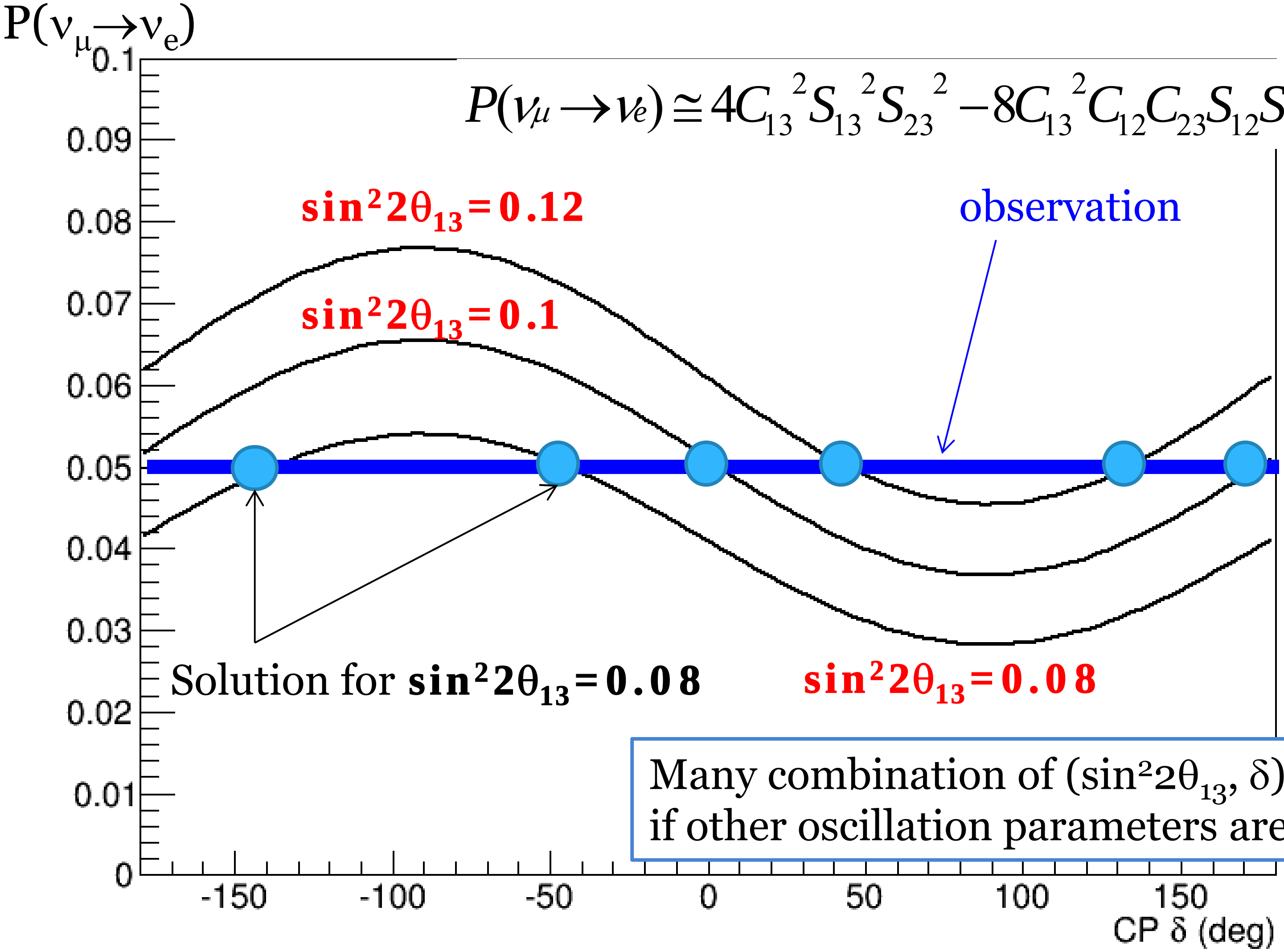
$$\theta_{12} = 34° \, (\cos\theta_{12} = 0.83, \sin\theta_{12} = 0.56)$$
$$\theta_{23} = 45°$$
$$\theta_{13} = 9.0° \, (\cos\theta_{13} = 0.99, \sin\theta_{13} = 0.16)$$

Max. 27% asymmetry (violation) by CP phase

ν_μ to ν_e oscillation probability

at oscillation maximum

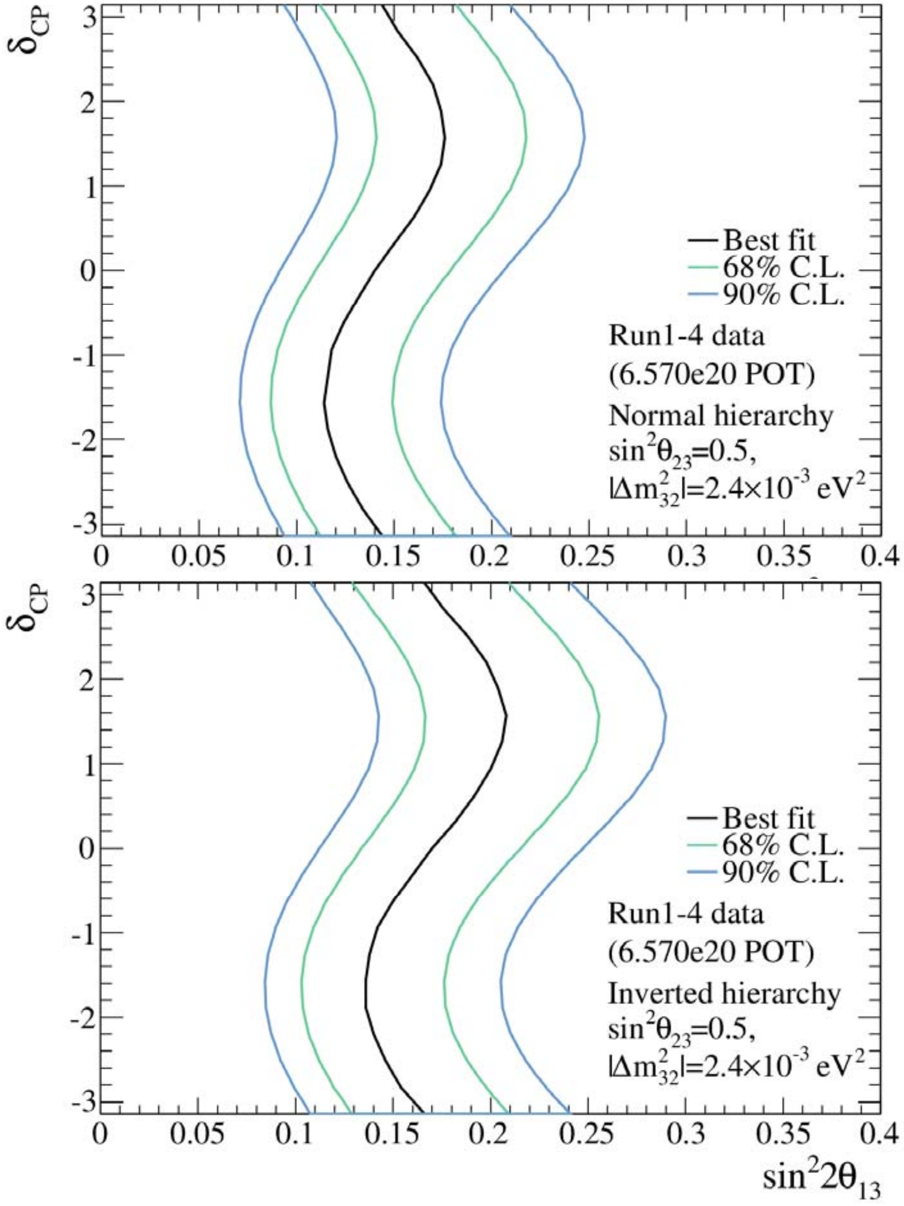
$\sin^2 2\theta_{23}=1$ in vacuum



$$P(\nu_\mu\to\nu_e)\cong 4C_{13}^{2}S_{13}^{2}S_{23}^{2}-8C_{13}^{2}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{21}$$

Many combination of ($\sin^2 2\theta_{13}$, δ) are allowed even if other oscillation parameters are fixed.

T2K Run1-4 allowed region of $\sin^2 2\theta_{13}$ for various δ_{CP} values



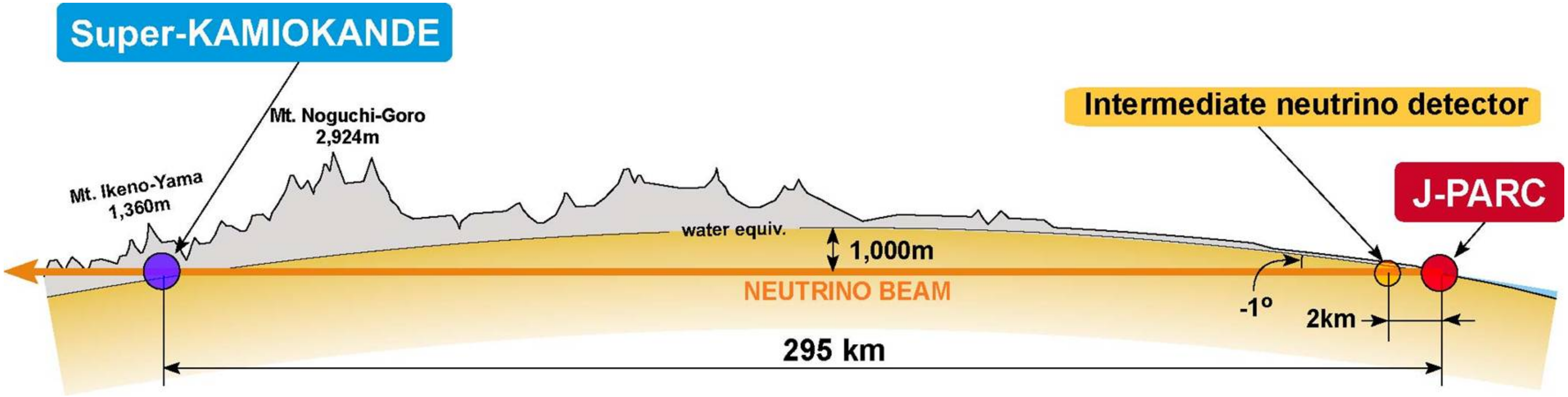
Normal Mass Hierarchy

Inverted Mass Hierarchy

NOTE:
w/o reactor info. on $\sin^2 2\theta_{13}$
$\sin^2 2\theta_{23}$ is fixed 1.

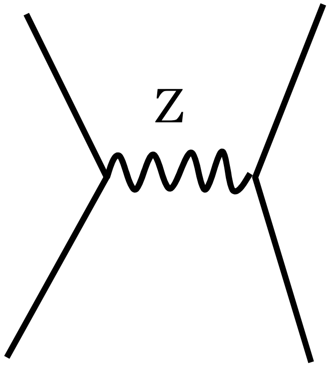
Why allowed region is different for different mass hierarchy?

Earth is not symmetric about flavor nor CP



Interactions not changing final state shift the phase of propagation. (Work as potential)

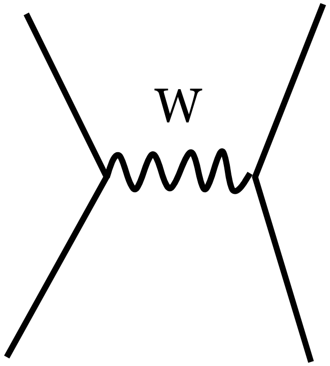
ν_e (or ν_μ, ν_τ) e^- or p or n



ν_e (or ν_μ, ν_τ) e^- or p or n

NC interaction

e^- ν_e ~~(or ν_μ, ν_τ)~~



ν_e ~~(or ν_μ, ν_τ)~~ e^- ~~or p or n~~

CC interaction

Time evolution of wave function $\exp(-iHt)$

Hamiltonian in vacuum

$$-U\begin{pmatrix} p_1 & 0 & 0 \\ 0 & p_2 & 0 \\ 0 & 0 & p_3 \end{pmatrix}U\dagger \simeq -p_1 + \frac{1}{2E}U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}U^\dagger$$

Hamiltonian of the interaction with matter

$$\begin{pmatrix} \sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

n_e: electron density

(Opposite sign for ν and $\bar{\nu}$)

The part which affect the relative phase is,

$$H \approx U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix}U + \begin{pmatrix} \frac{a}{2E} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

This cannot be solved analytically.

$$\boxed{a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}}$$

More complete eq. of ν_e appearance (1st order for matter effect)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^{2}S_{13}^{2}S_{23}^{2}\sin^2\Phi_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2S_{13}^2\right)\right)$$

Leading including matter effect

$$+8C_{13}^{2}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CP conserving

$$-8C_{13}^{2}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CP violating

$$+4S_{12}^{2}C_{13}^{2}(C_{12}^{2}C_{23}^{2}+S_{12}^{2}S_{23}^{2}S_{13}^{2}-2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

Solar

$$-8C_{13}^{2}S_{13}^{2}S_{23}^{2}(1-2S_{13}^{2})\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

Matter effect (This is small)

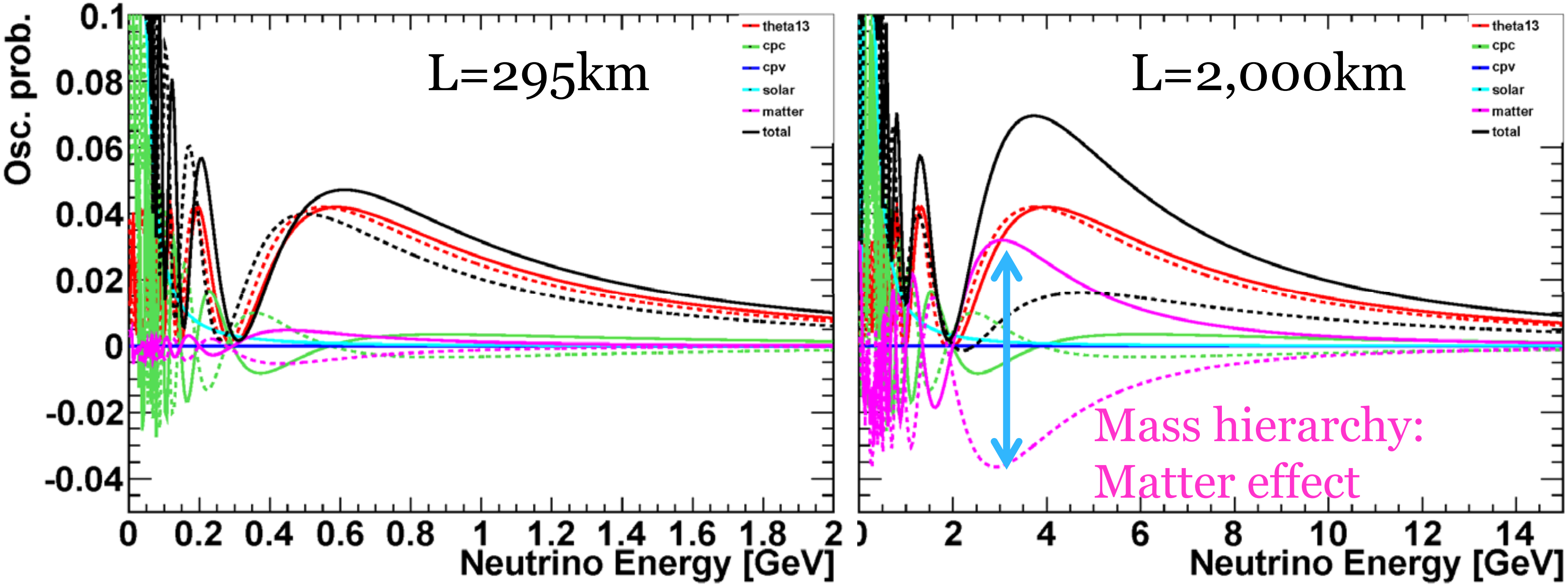
replace δ by −δ and a by $-a$ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

$\nu_\mu \to \nu_e$ oscillation probability

- $\Delta m^2_{23} = 2.4\text{e-}3\ \text{eV}^2$
- $\Delta m^2_{12} = 7.59\text{e-}5\ \text{eV}^2$
- $\theta_{12} = 34^\circ$
- $\theta_{23} = 45^\circ$
- $\sin^2 2\theta_{13} = 0.084$
- w/ matter effect (ρ=2.8 g/cm^3)

θ_{13}
CPC
CPV
Solar
Total

— Normal hierarchy
- - - Inverted hierarchy

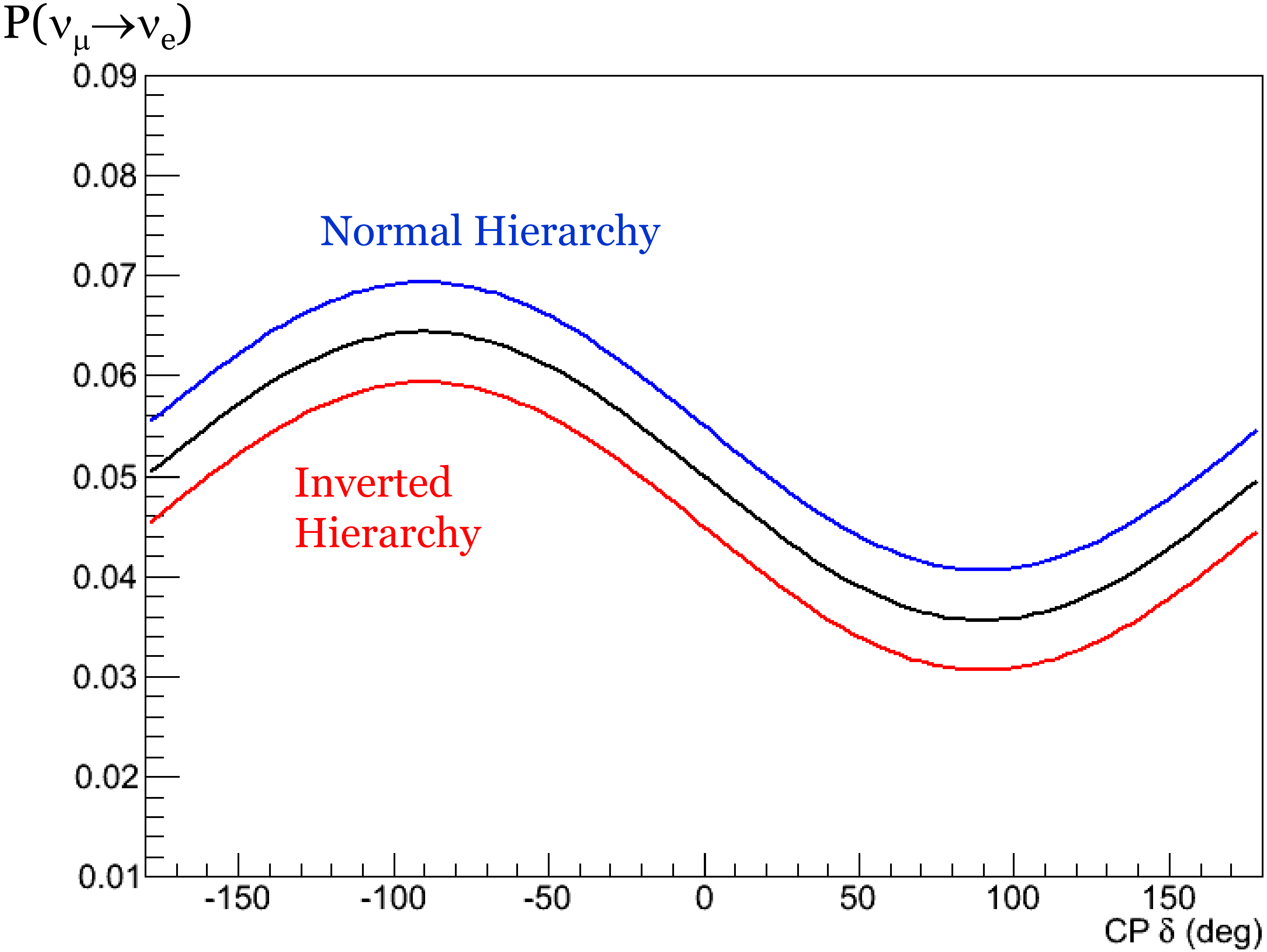


Mass hierarchy:
Matter effect

ν_μ to ν_e oscillation probability

at oscillation maximum

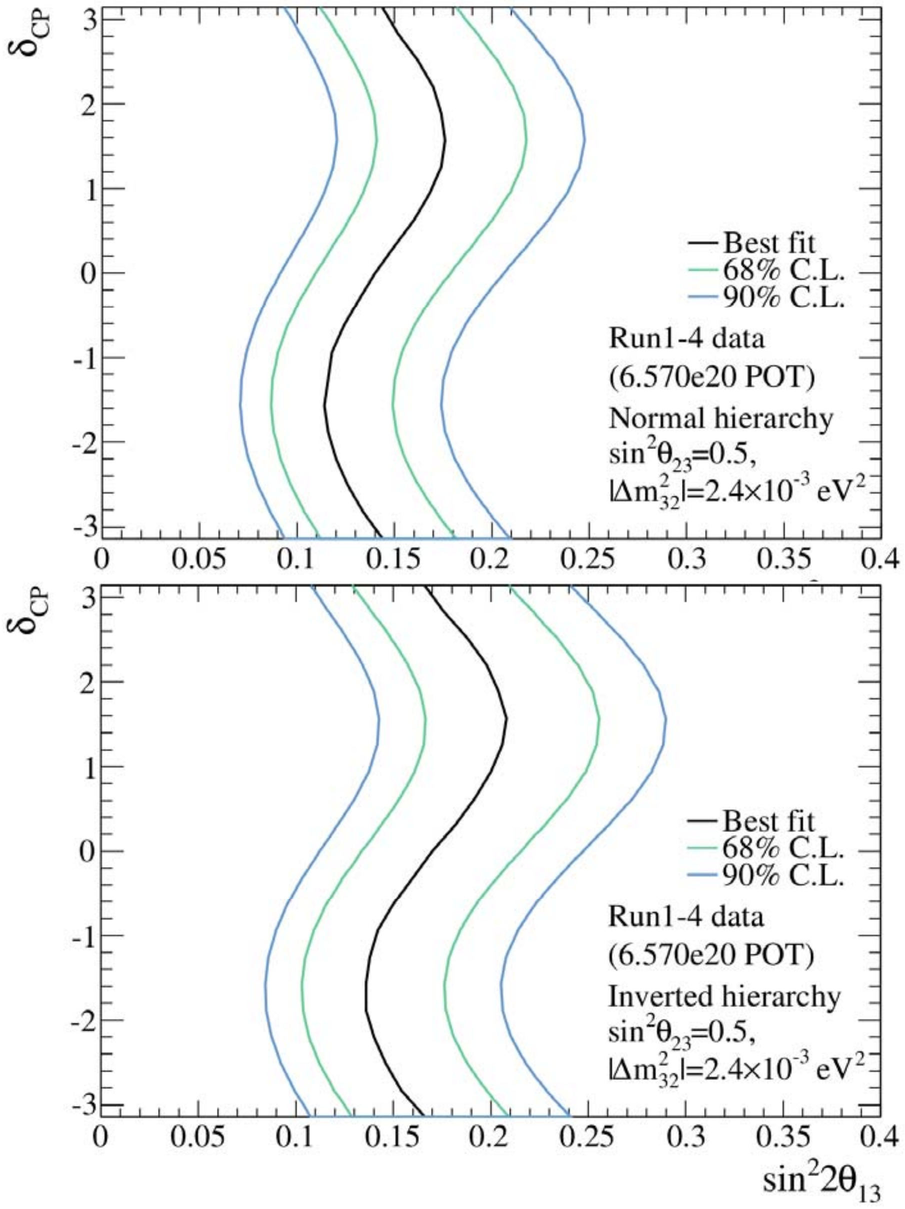
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



T2K Run1-4 allowed region of $\sin^2 2\theta_{13}$ for various δ_{CP} values

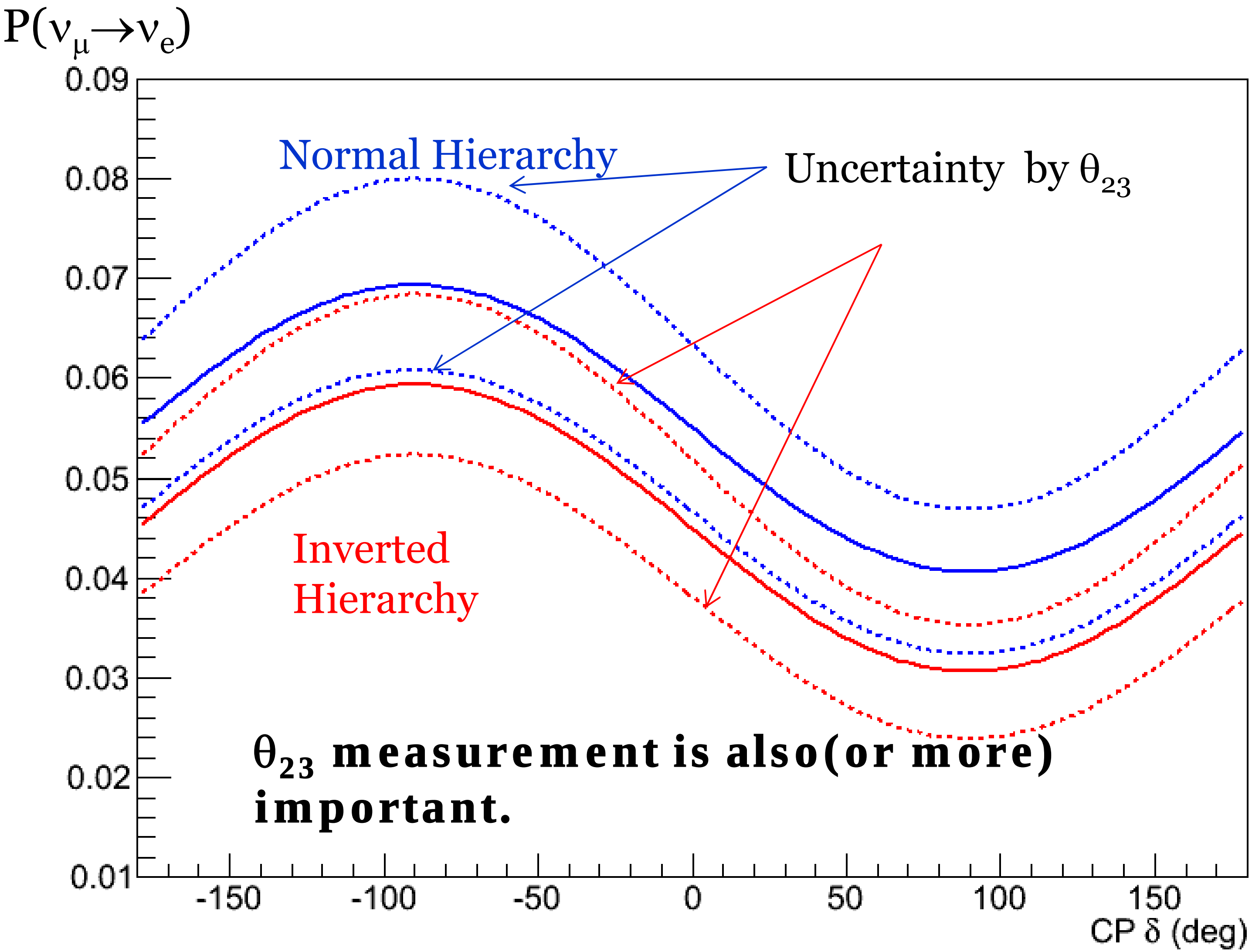
Normal Mass Hierarchy

Inverted Mass Hierarchy



NOTE:
w/o reactor info. on $\sin^2 2\theta_{13}$
$\sin^2 2\theta_{23}$ is fixed 1.

Actually, **w/ θ_{23} uncertainty**

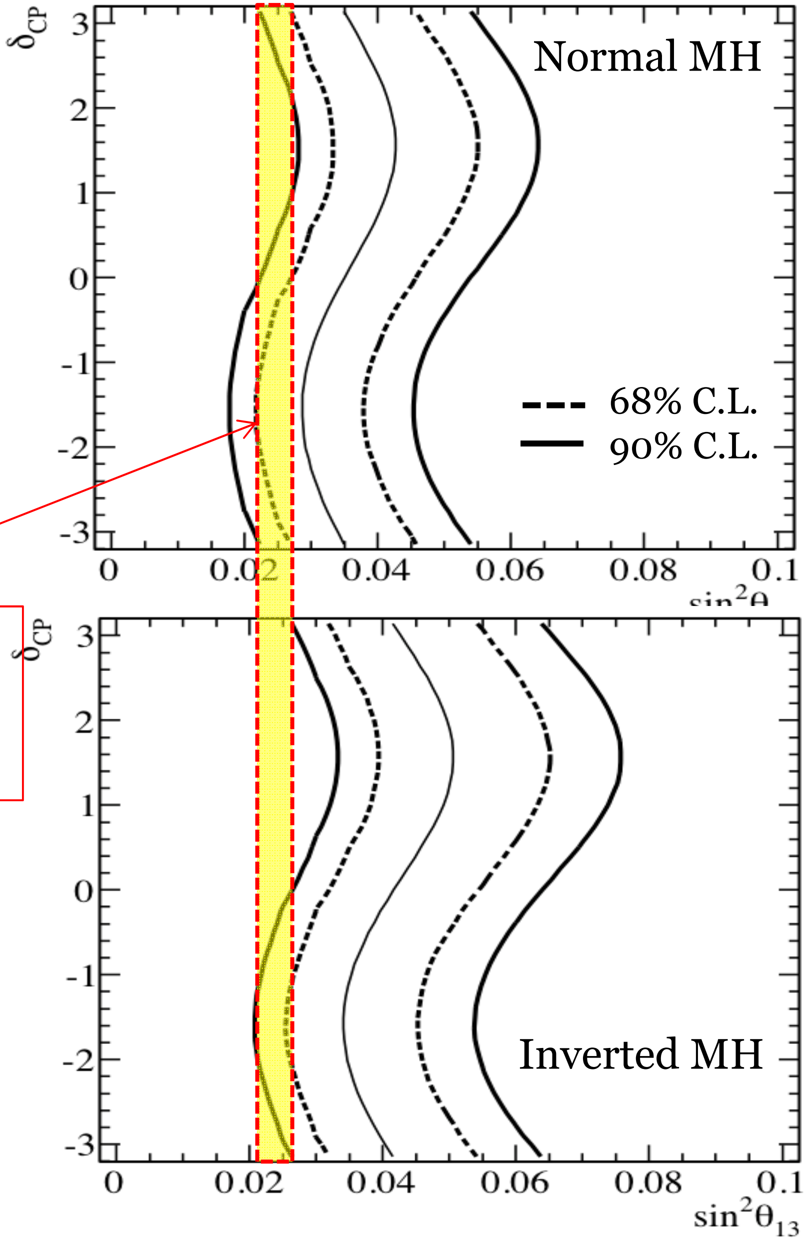


θ_{23} measurement is also(or more) important.

T2K Run1-4 data
(data till 2013)
Preliminary

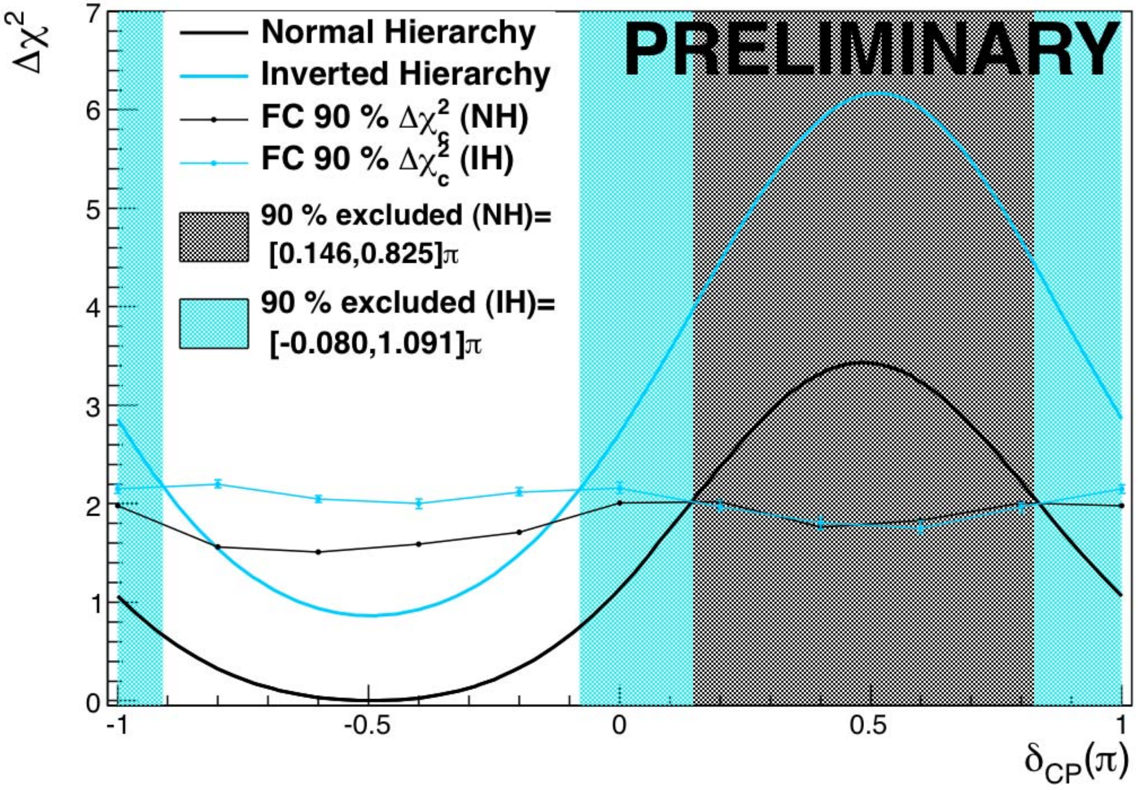
Fit ν_μ sample and ν_e sample simultaneously by $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ and Δm^2

Now uncertainty of $\sin 2\theta_{23}$ is included.



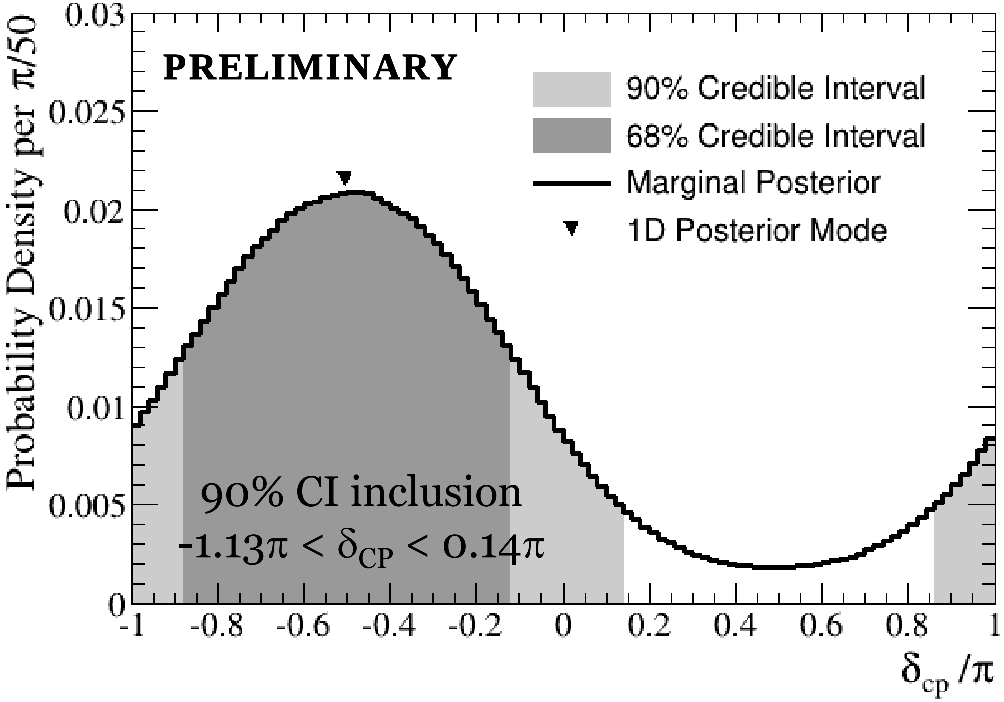
68% allowed region from reactor measurement (PDG2013)

Get allowed region for δ by combining T2K data and reactor data



Another way of expressing result
Bayesian posterior probability

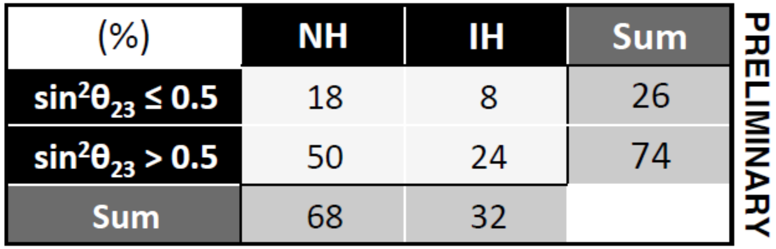
Assume $P(NH) = P(IH) = 0.5$



90% CI inclusion

$-1.13\pi < \delta_{CP} < 0.14\pi$

posterior probability for θ_{23} octants and mass hierarchies



(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26
$\sin^2\theta_{23} > 0.5$	50	24	74
Sum	68	32	

From now on,
T2K & NOvA

T2K full stat(7.8E21 POT) sensitivity

(7.8E21 POT=750kW x 5e7sec @ 30GeV)

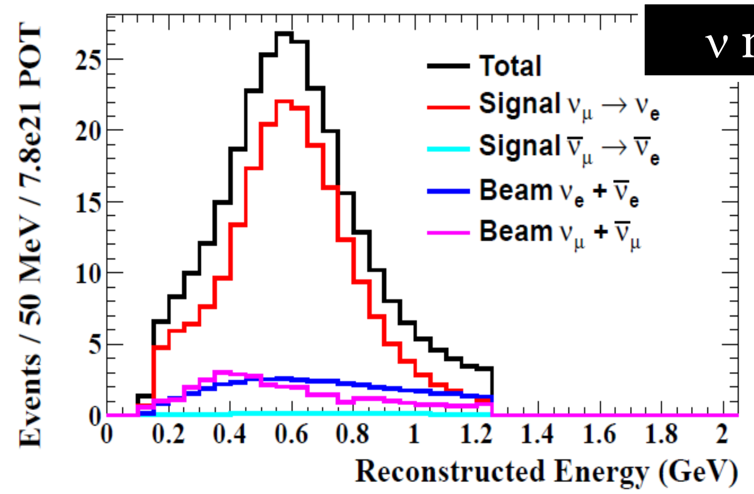
- ✓ Combined 3 Flavor Appearance and Disappearance Fit
- ✓ w/ and w/o reactor results
  - ▫ $\sin^2 2\theta_{13}=0.1\pm0.005$: marginalize by error(=Daya Bay reactor sys. error)
- ✓ w/ and w/o current systematic error
  - ▫ Assume same error for anti-ν mode. +10% overall normalization error.
- ✓ ν-mode:anti-ν mode running ratio =50%:50% for case study

Reconstructed Energy Spectra

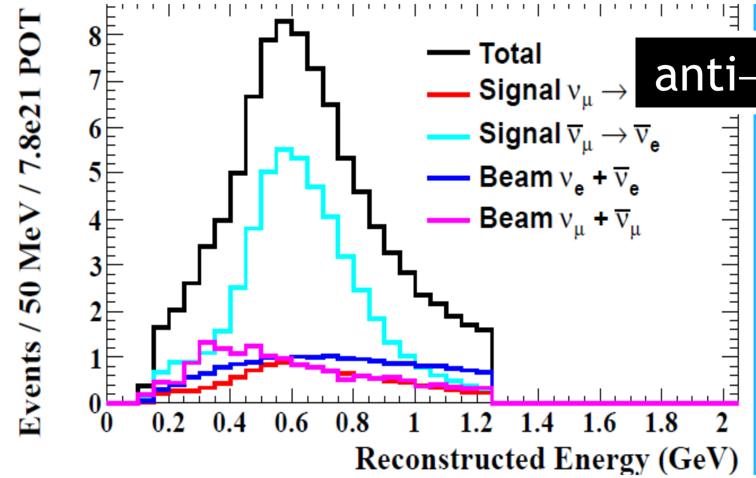
$\delta=0$, $\sin^2 2\theta_{23}=1$
$\Delta m^2=2.4\text{x}10^{-7}$ eV^2

ν_e appearance sample

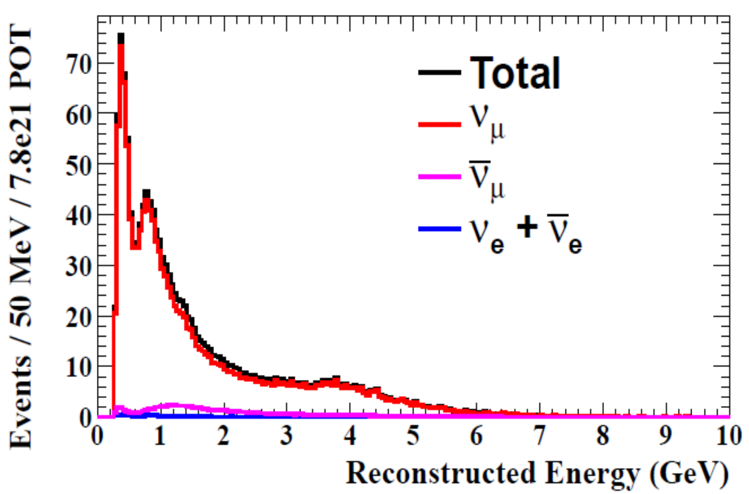
ν mode

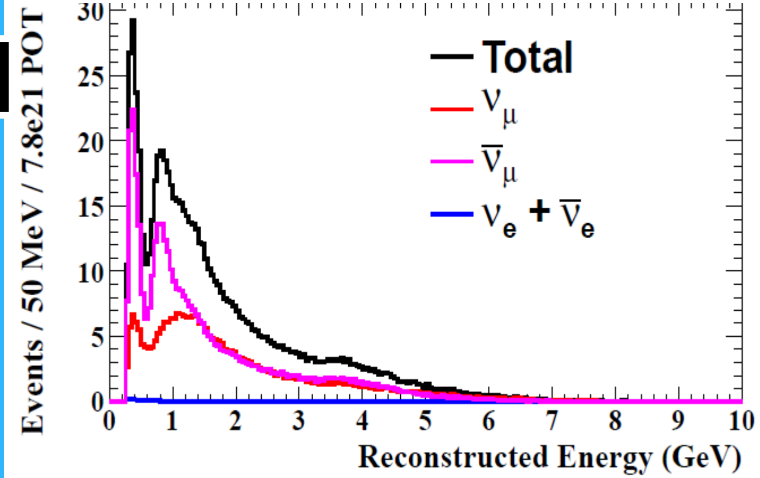


anti–ν mode



ν_μ disappearance sample





ν:anti-ν=50%:50% case
ν mode 106 signal events, 39 bkg. events
anti-ν mode 24 signal events, 22 bkg events (5.6 from $\nu_\mu \to \nu_e$)

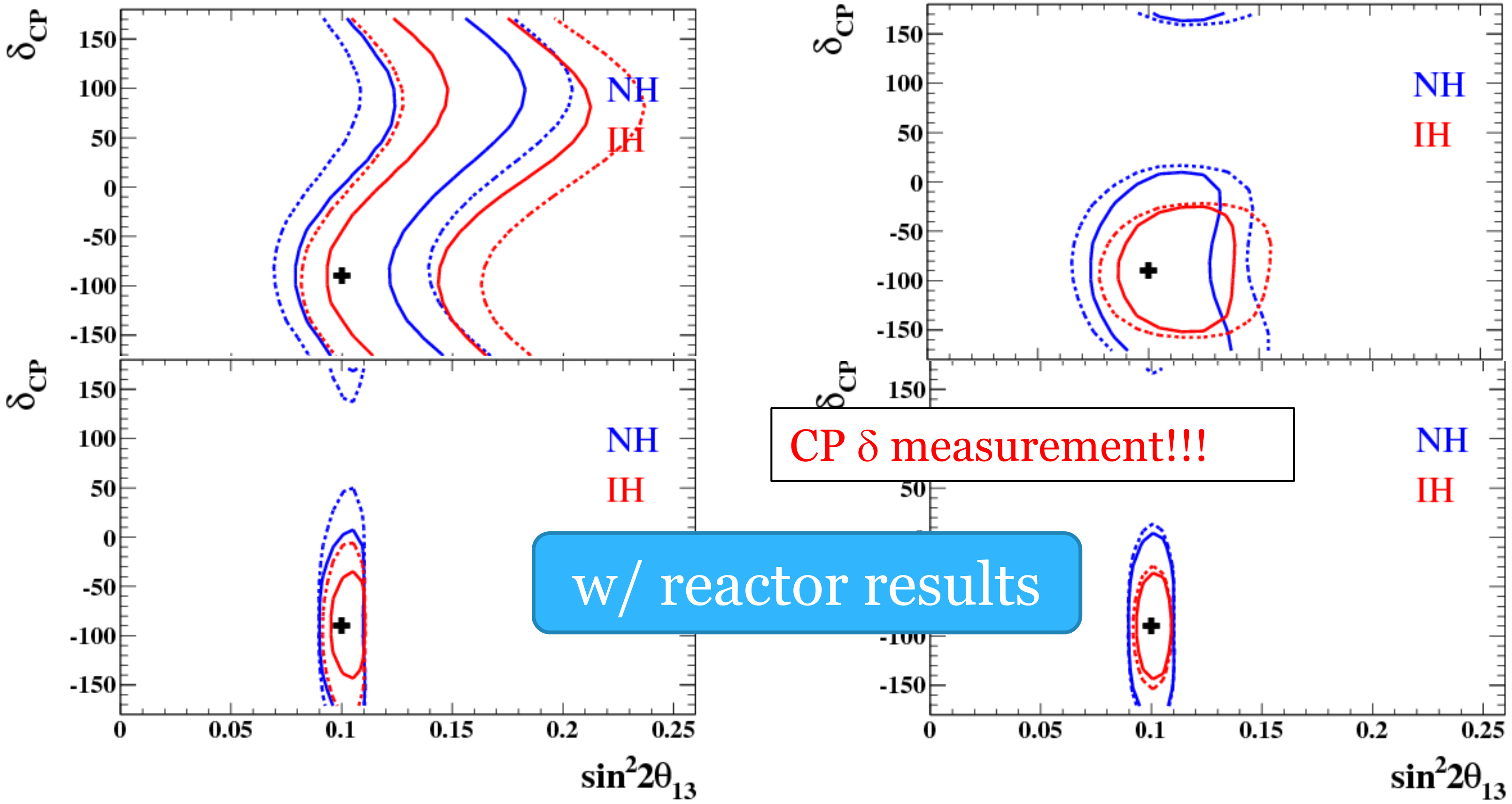
T2K full sensitivity
Expected 90% C.L. allowed region

δ_{CP}=-90, $\sin^2 2\theta_{23}$=1.0
Normal Hierarchy

Allowed region assuming NH or IH
Solid : w/o systematic error
Dashed : w/ 2012 systematic error

Running fraction

ν mode:anti-ν mode = 100%:0% 50%:50%



CP δ measurement!!!

w/ reactor results

Allowed region assuming NH or IH
Solid : w/ 2012 systematic error
Dashed : w/o systematic error

Expected 90% C.L. allowed region.

θ_{23} octant degeneracy, $\sin^2\theta_{23}=0.4$ case

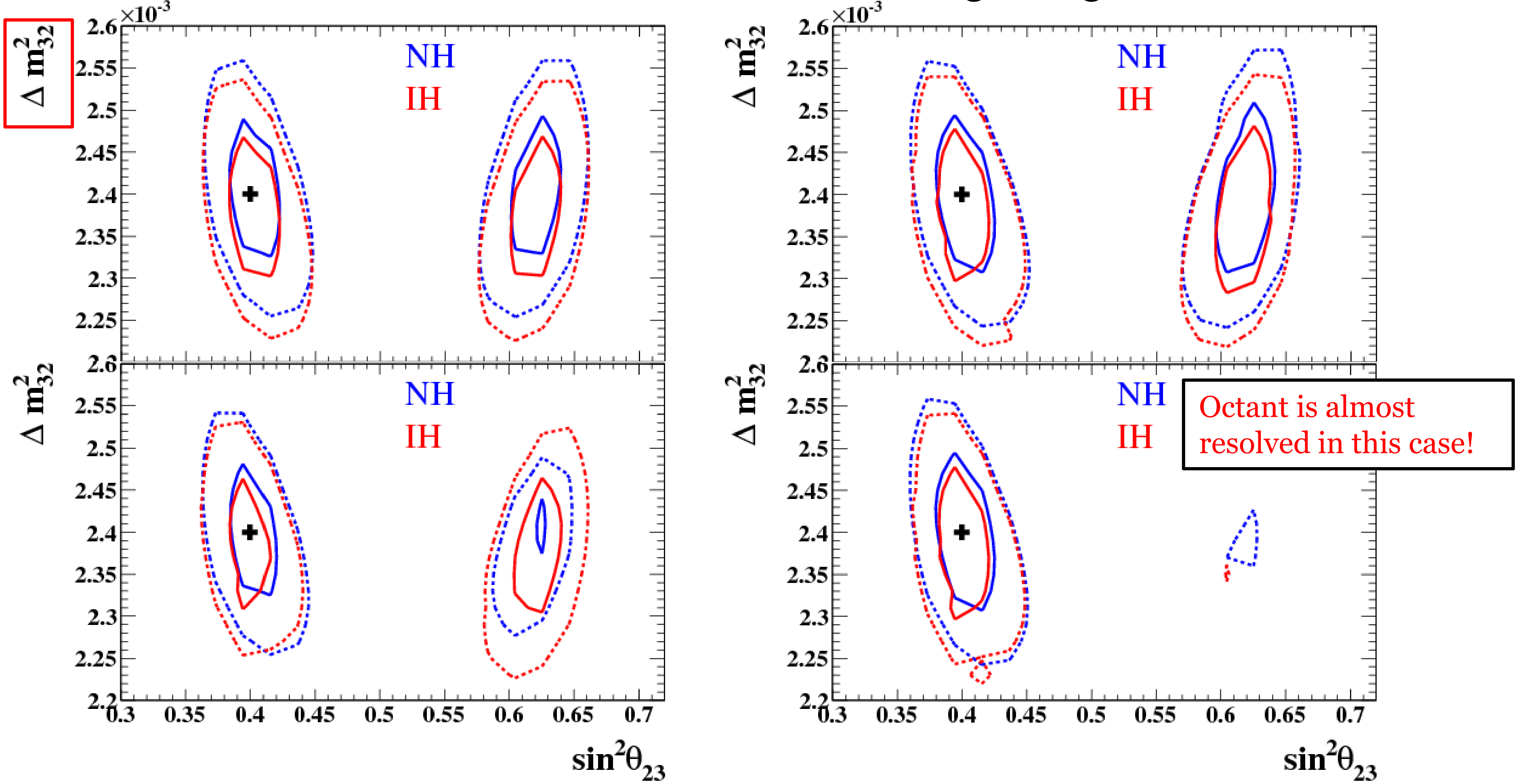
True δ=0

* current 90% limit corresponds to $\sin^2\theta_{23}=0.39$.

Running fraction

ν mode:anti-ν mode = 100%:0%

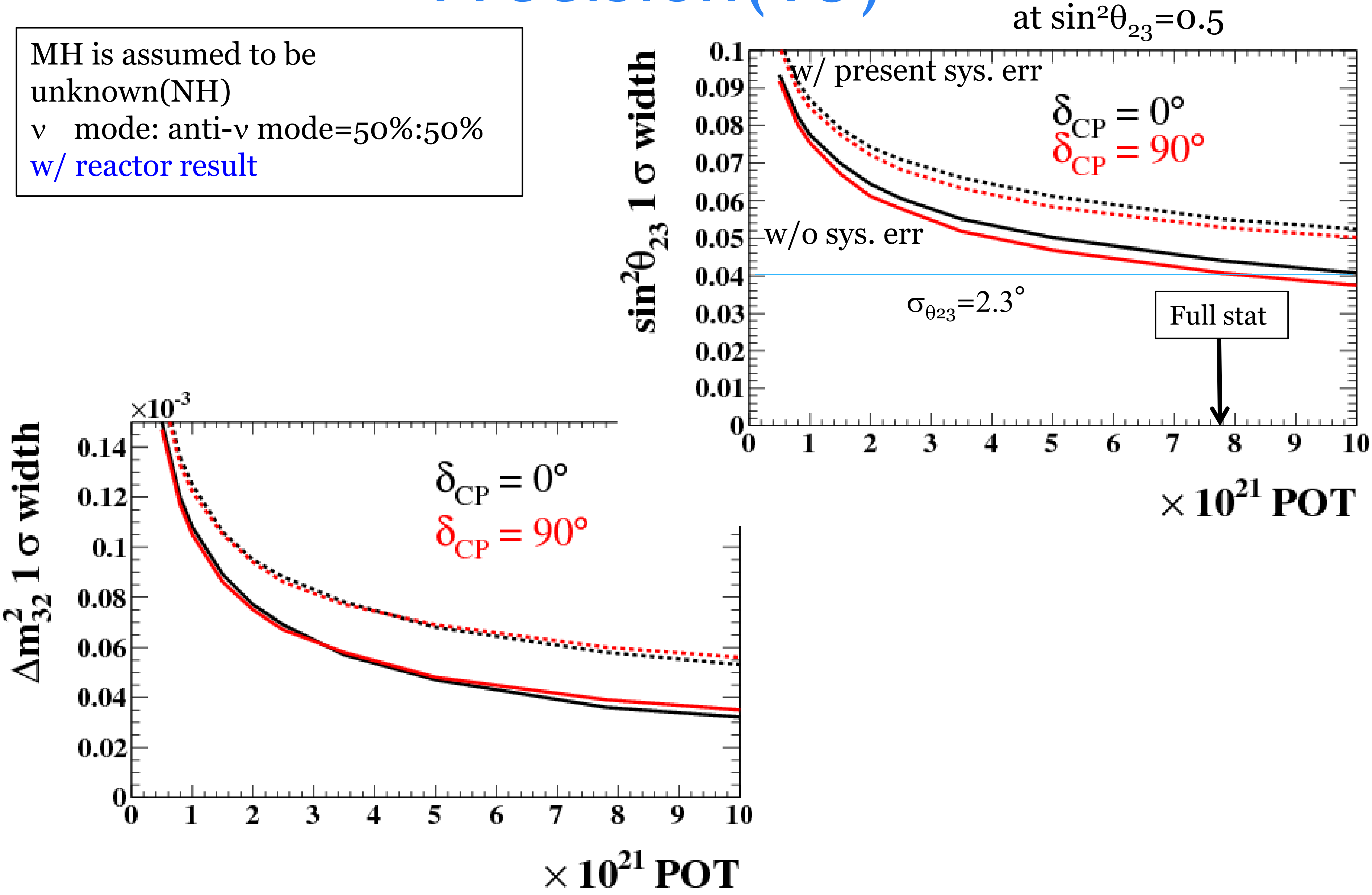
50%:50%



Octant is almost resolved in this case!

Precision(1σ)

MH is assumed to be unknown(NH)
ν mode: anti-ν mode=50%:50%
w/ reactor result



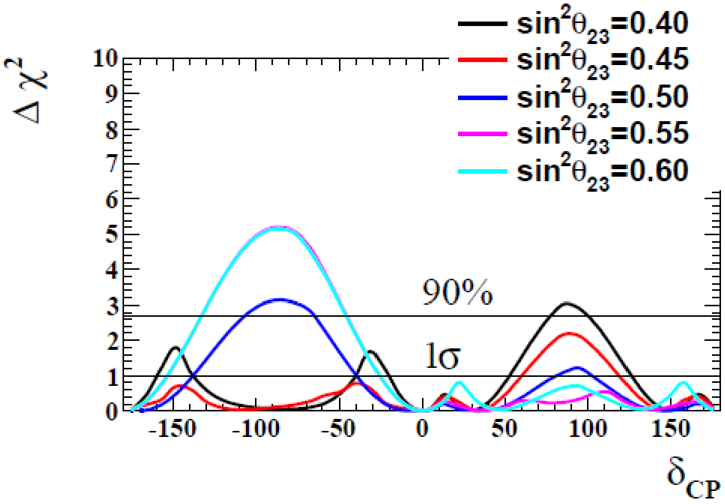
CP violation (sinδ≠0) sensitivity

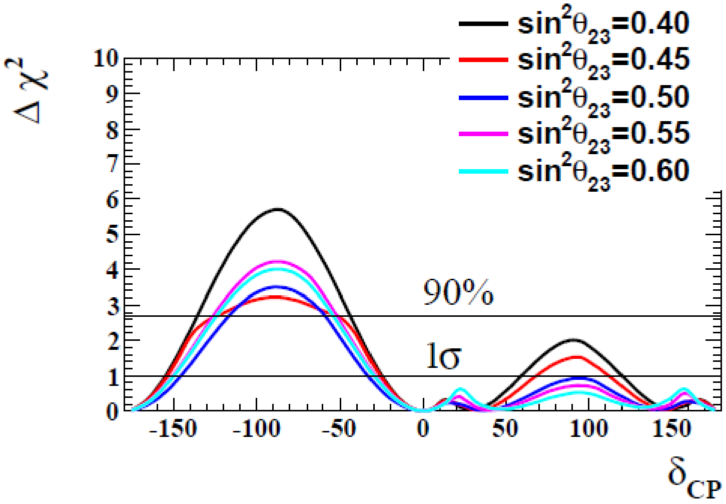
100% ν-mode

50%:50% ν-mode: $\bar{\nu}$:mode

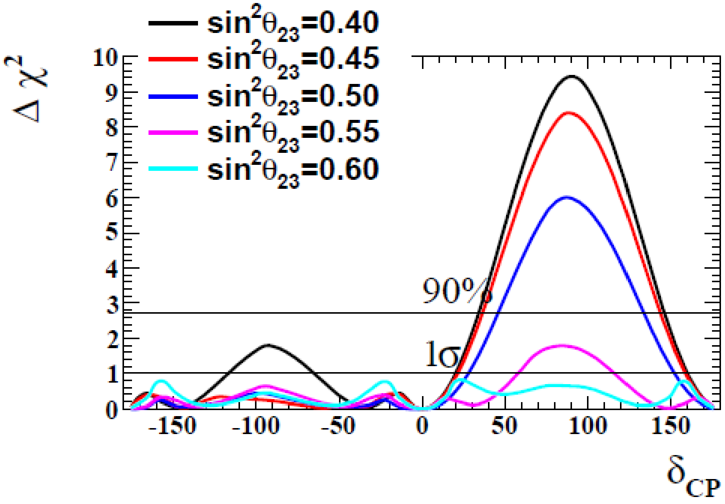
NH

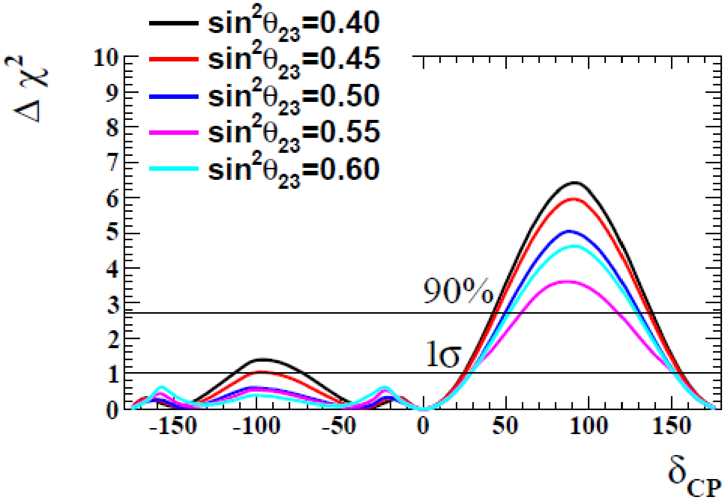
NH





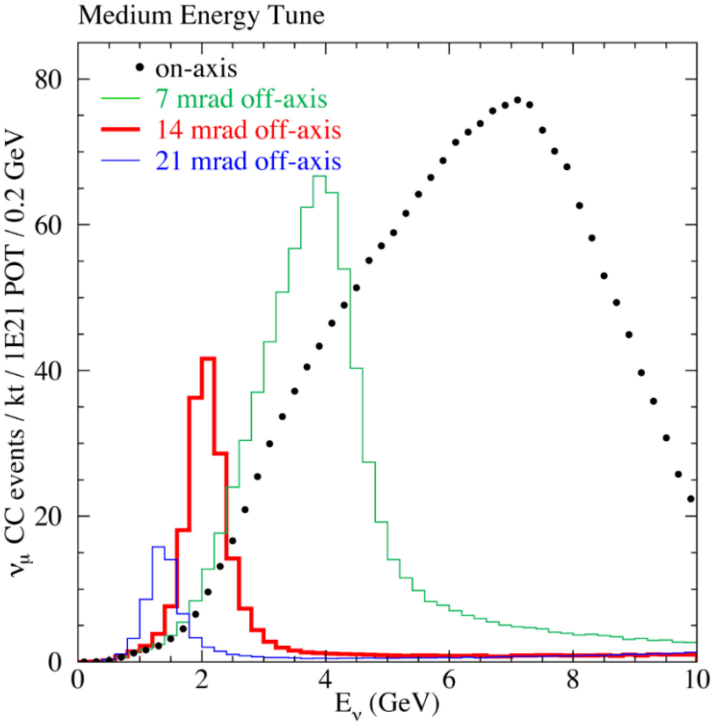
IH

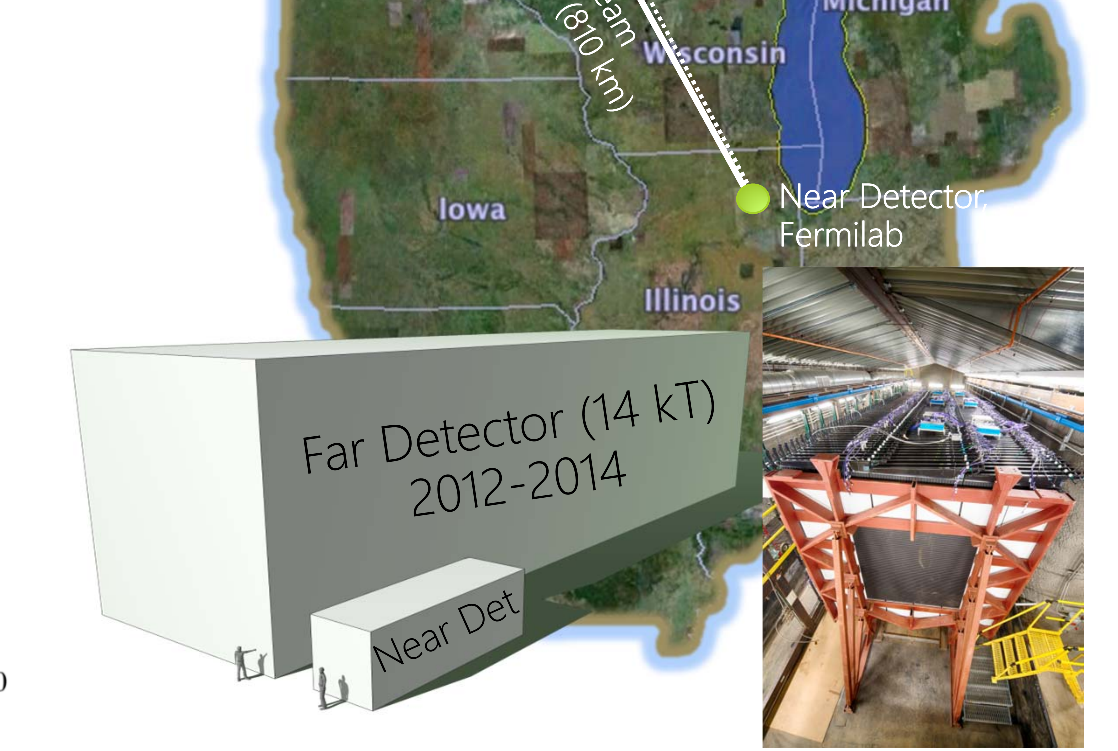




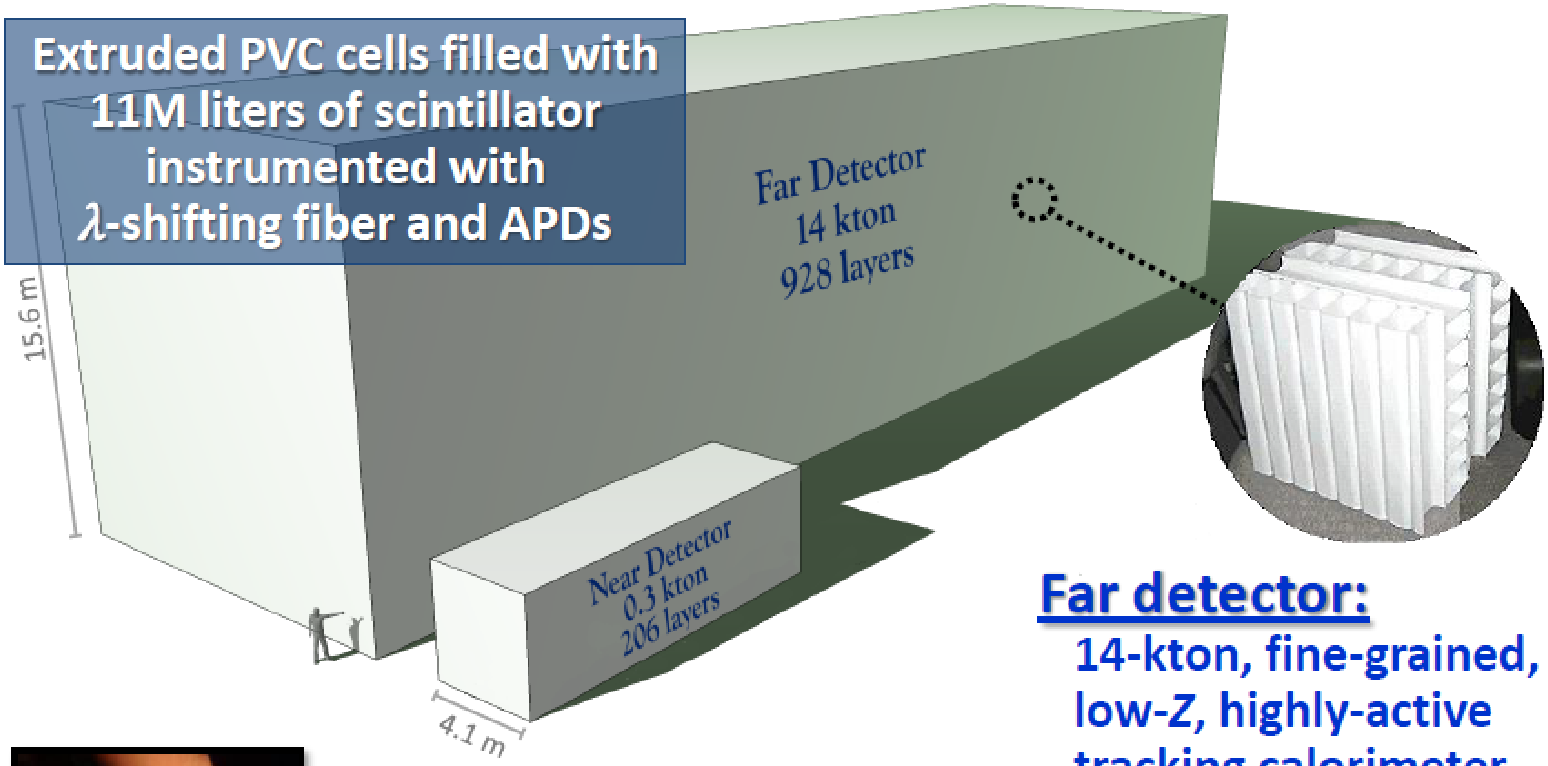
NOvA

Baseline length 810km
FNAL NuMI off-axis beam
400kW → 700kW


Medium Energy Tune

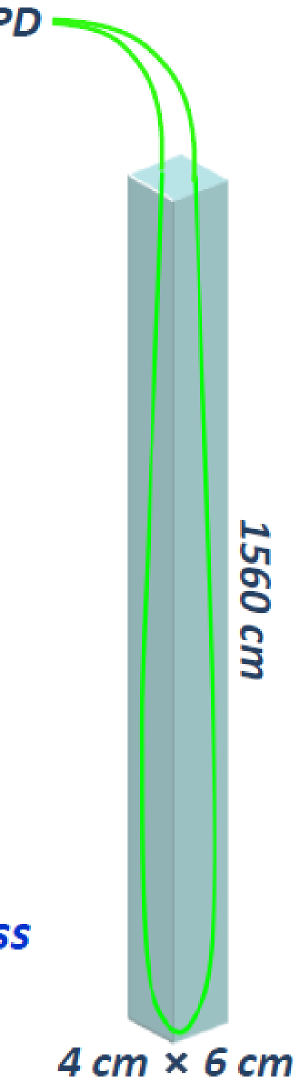


NOνA Detectors



Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

A NOνA cell



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter

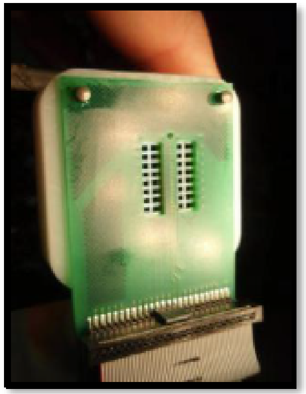
→ *360,000 channels*

→ *77% active by mass*

Near detector:

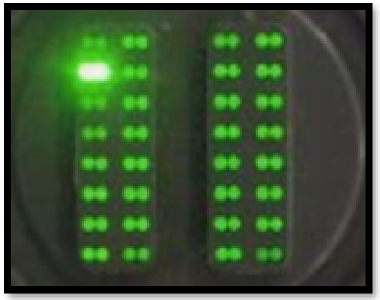
0.3-kton version of the same

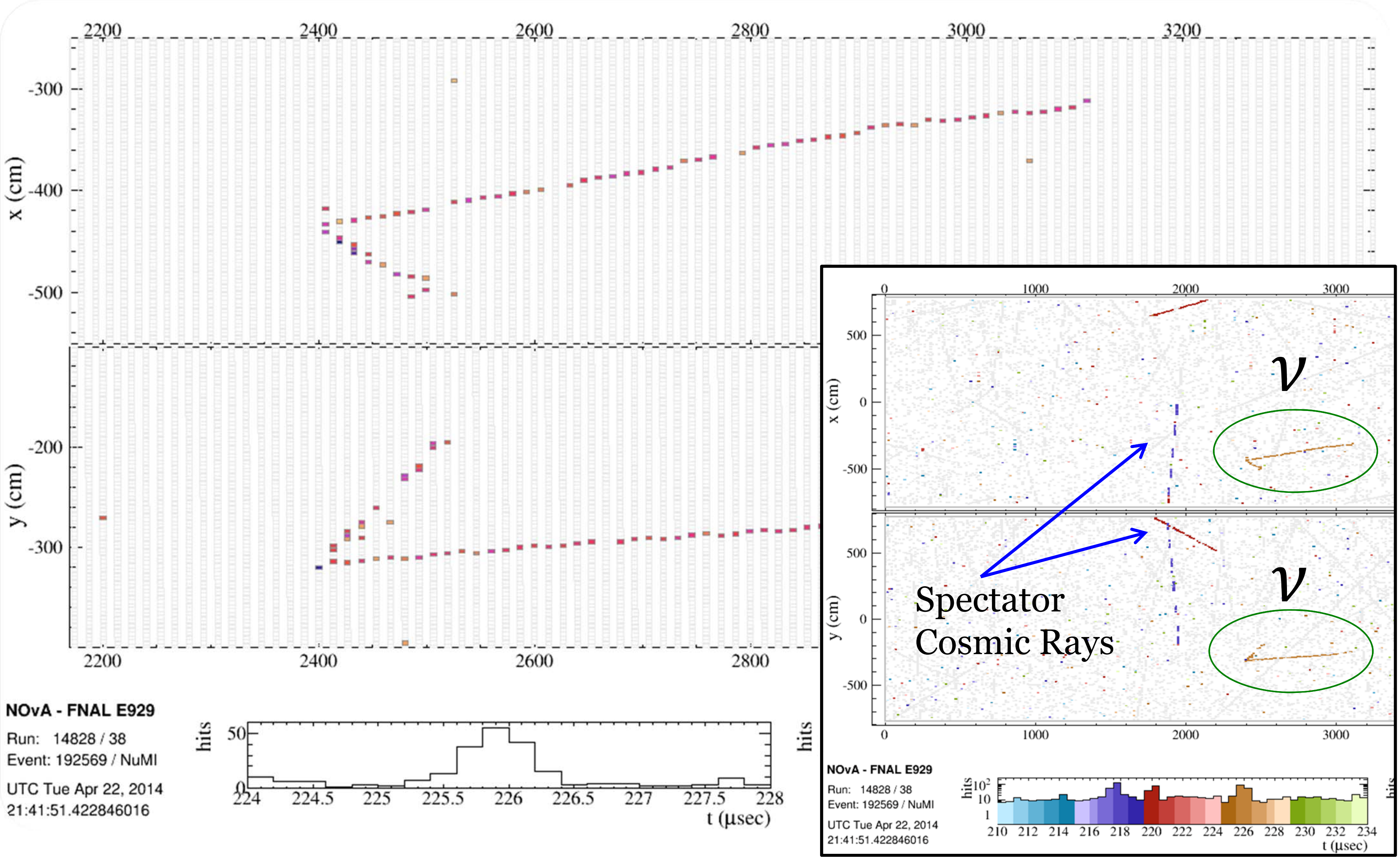
→ *18,000 channels*



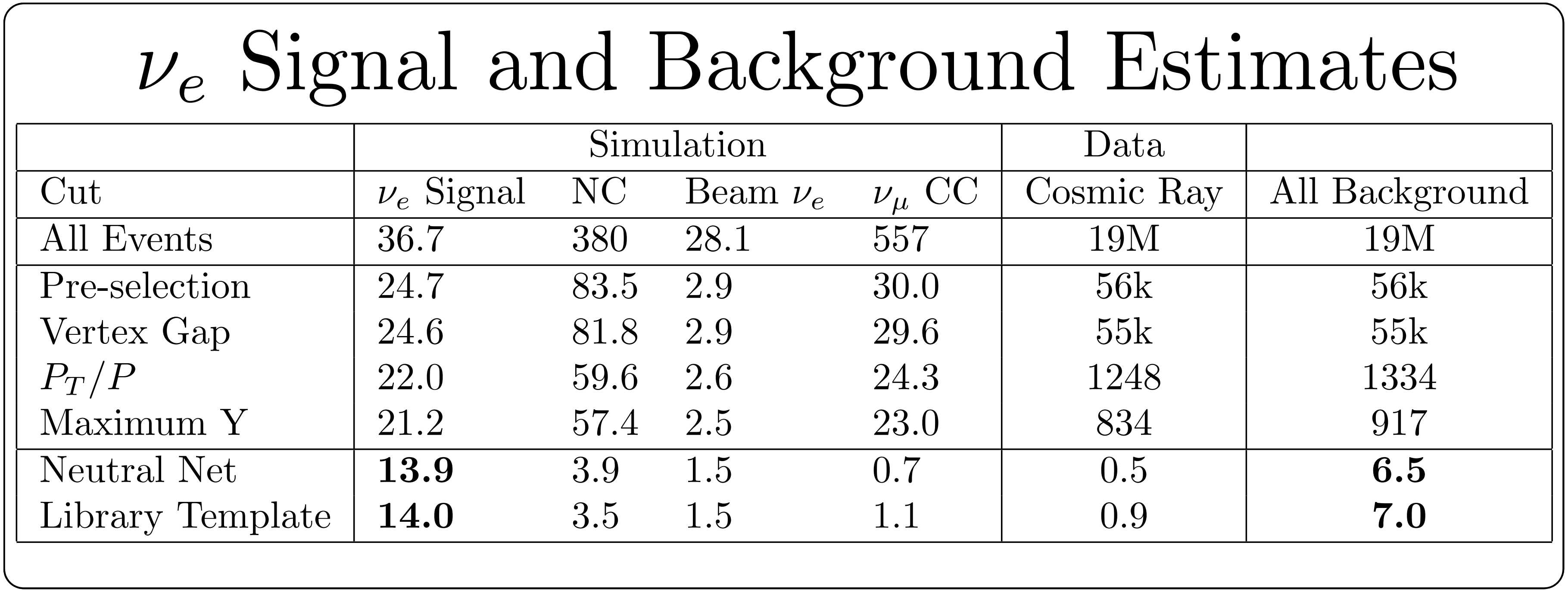
32-pixel APD ←

Fiber pairs from 32 cells →





Spectator
Cosmic Rays



ν_e Signal and Background Estimates

	Simulation				Data	
Cut	ν_e Signal	NC	Beam ν_e	ν_μ CC	Cosmic Ray	All Background
All Events	36.7	380	28.1	557	19M	19M
Pre-selection	24.7	83.5	2.9	30.0	56k	56k
Vertex Gap	24.6	81.8	2.9	29.6	55k	55k
P_T/P	22.0	59.6	2.6	24.3	1248	1334
Maximum Y	21.2	57.4	2.5	23.0	834	917
Neutral Net	**13.9**	3.9	1.5	0.7	0.5	**6.5**
Library Template	**14.0**	3.5	1.5	1.1	0.9	**7.0**

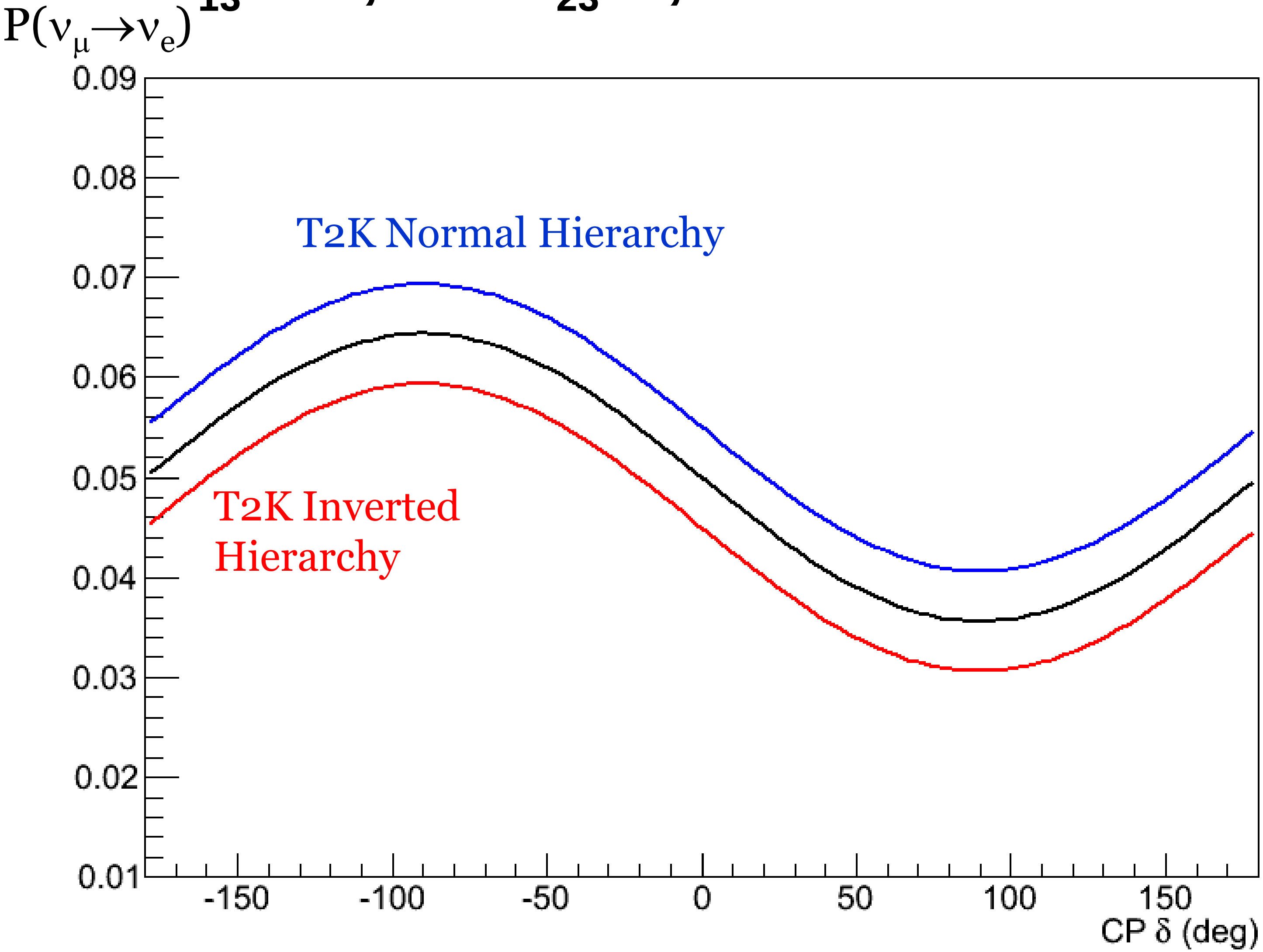
- Exposure 6×10^{20} POT
- 1 yr at design mass/beam power
- 14 kt total detector mass

- Signal estimates are leading order
- Simple oscillation w/o matter effect
- Averaged over hierarchy and δ_{CP}

ν_μ to ν_e oscillation probability

at oscillation maximum

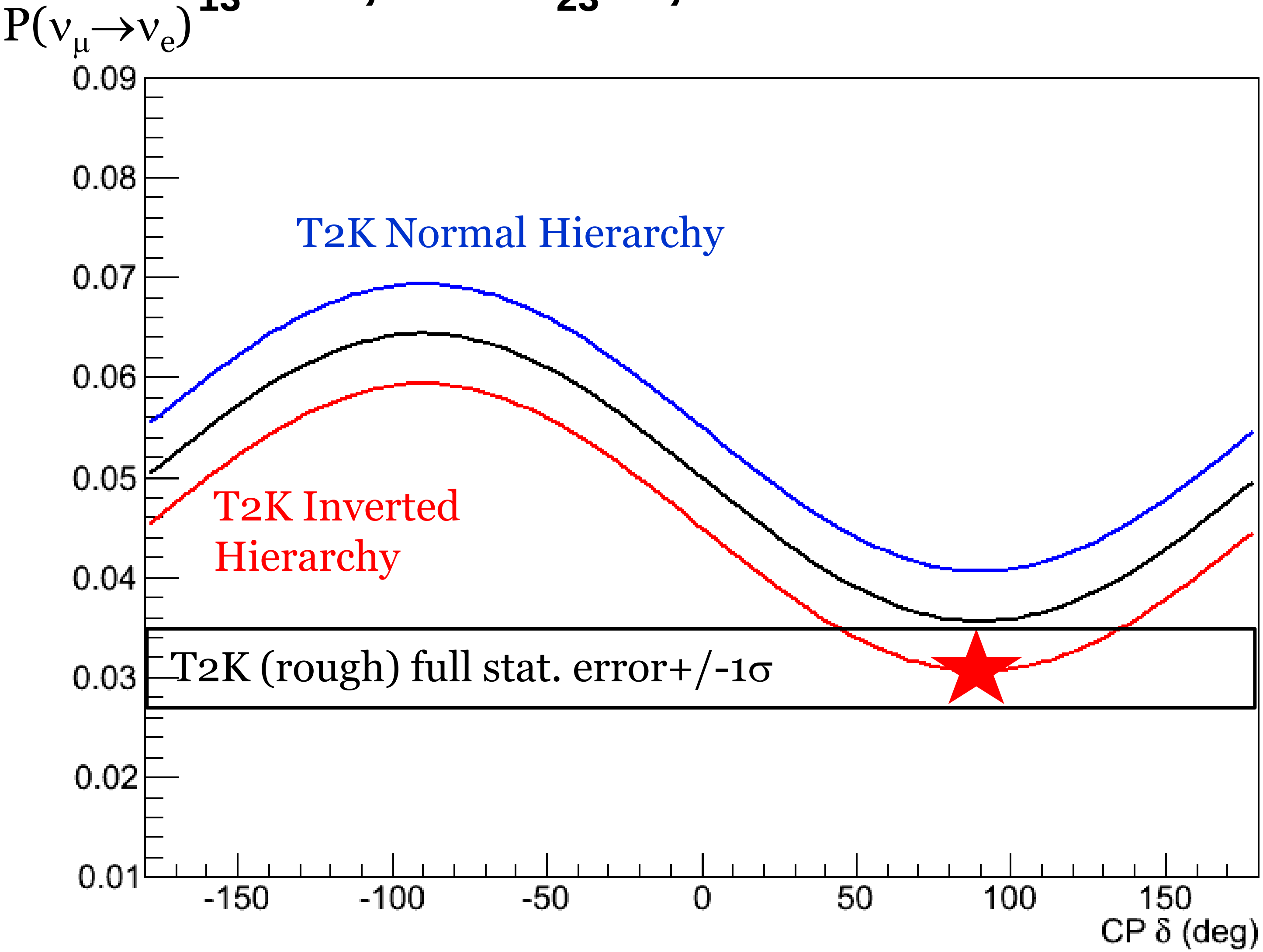
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

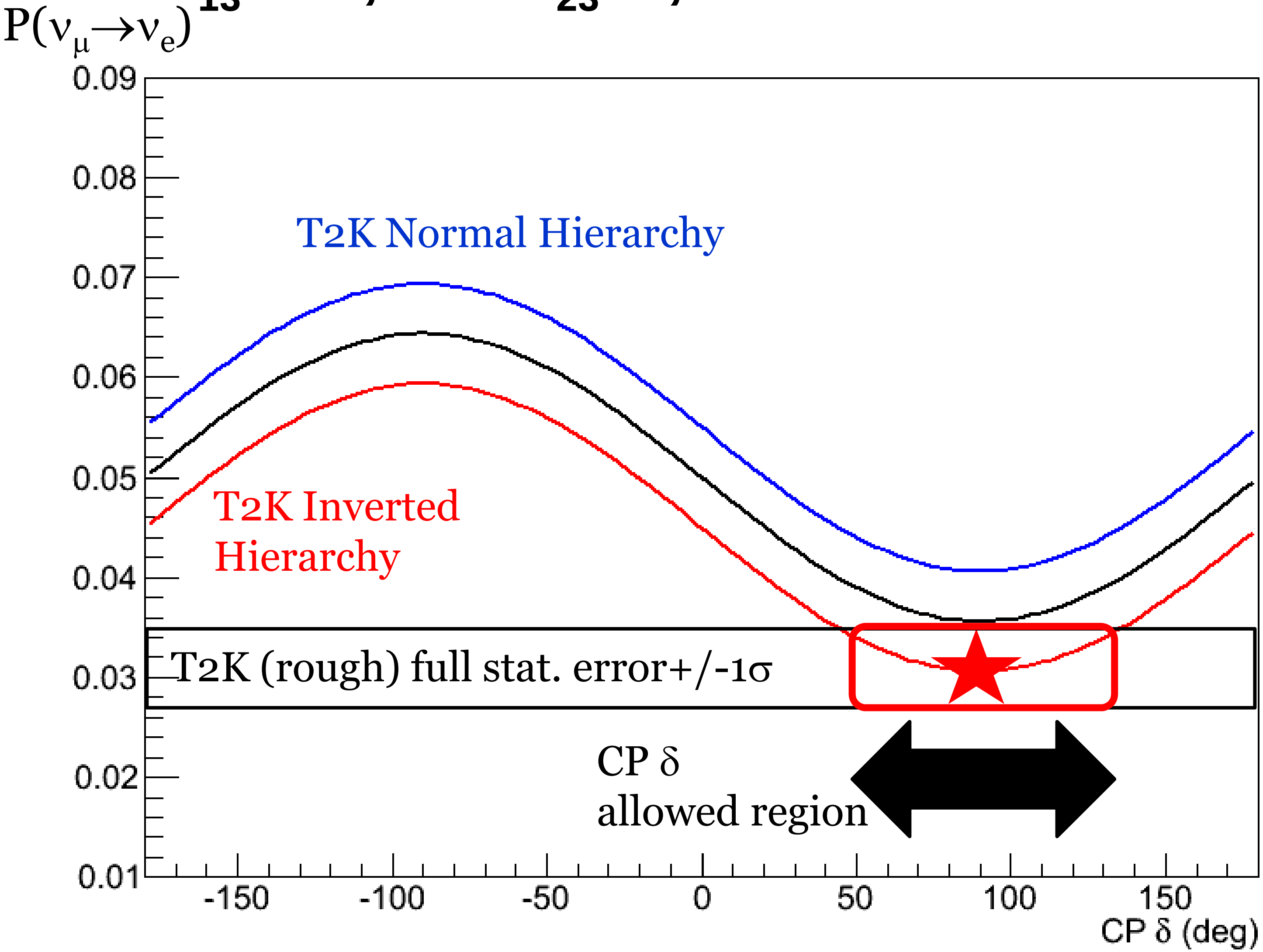
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

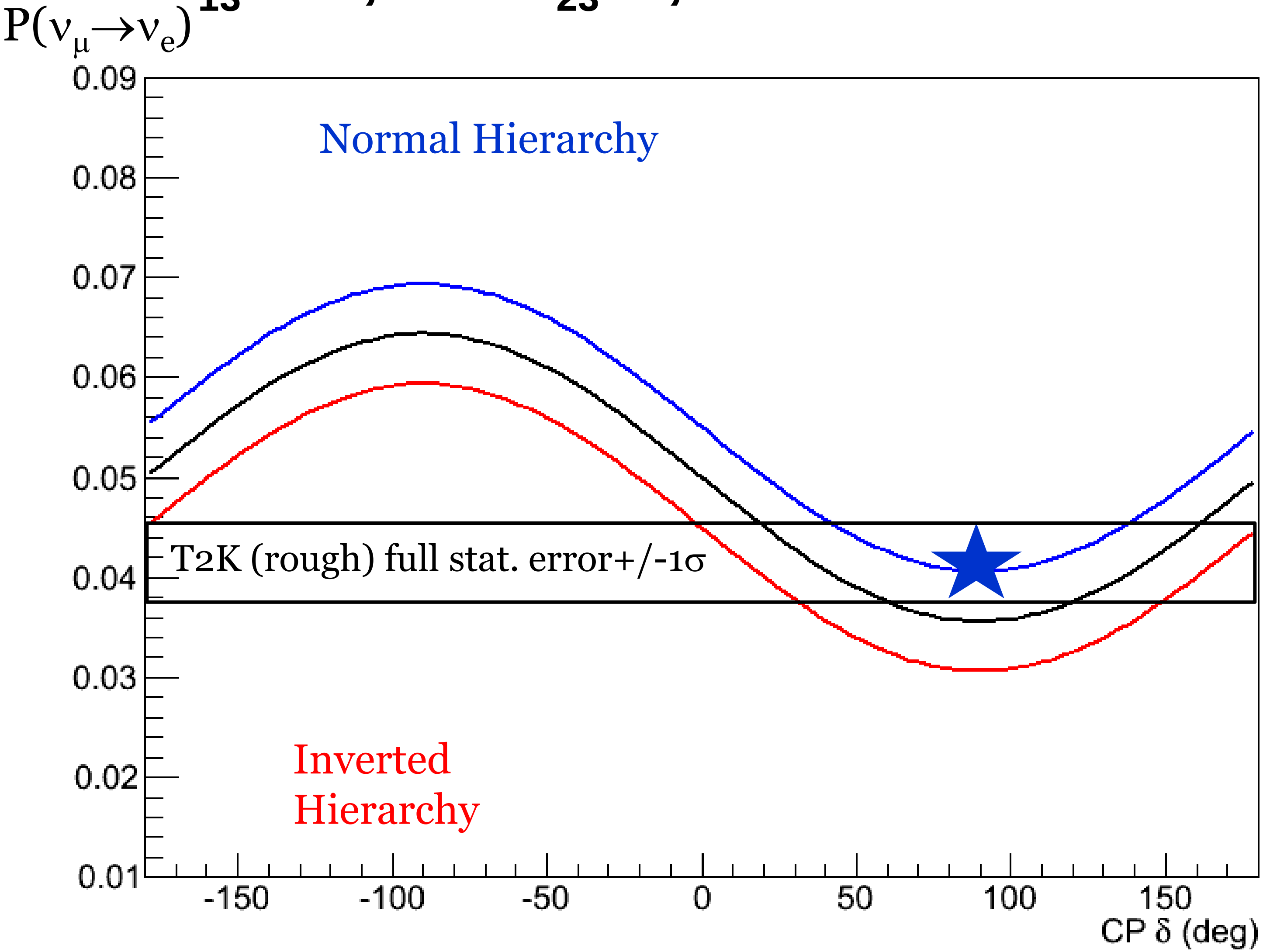
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

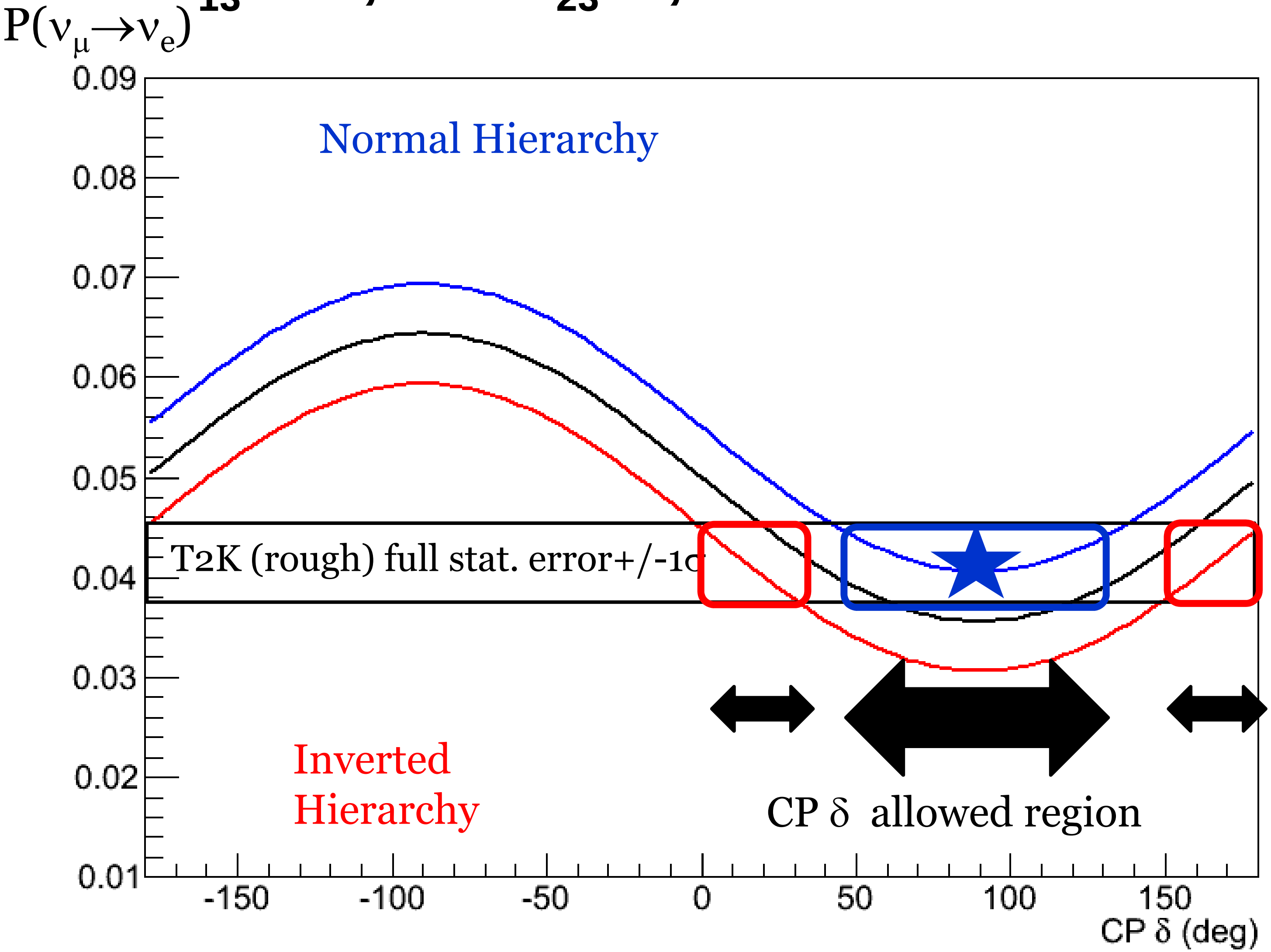
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

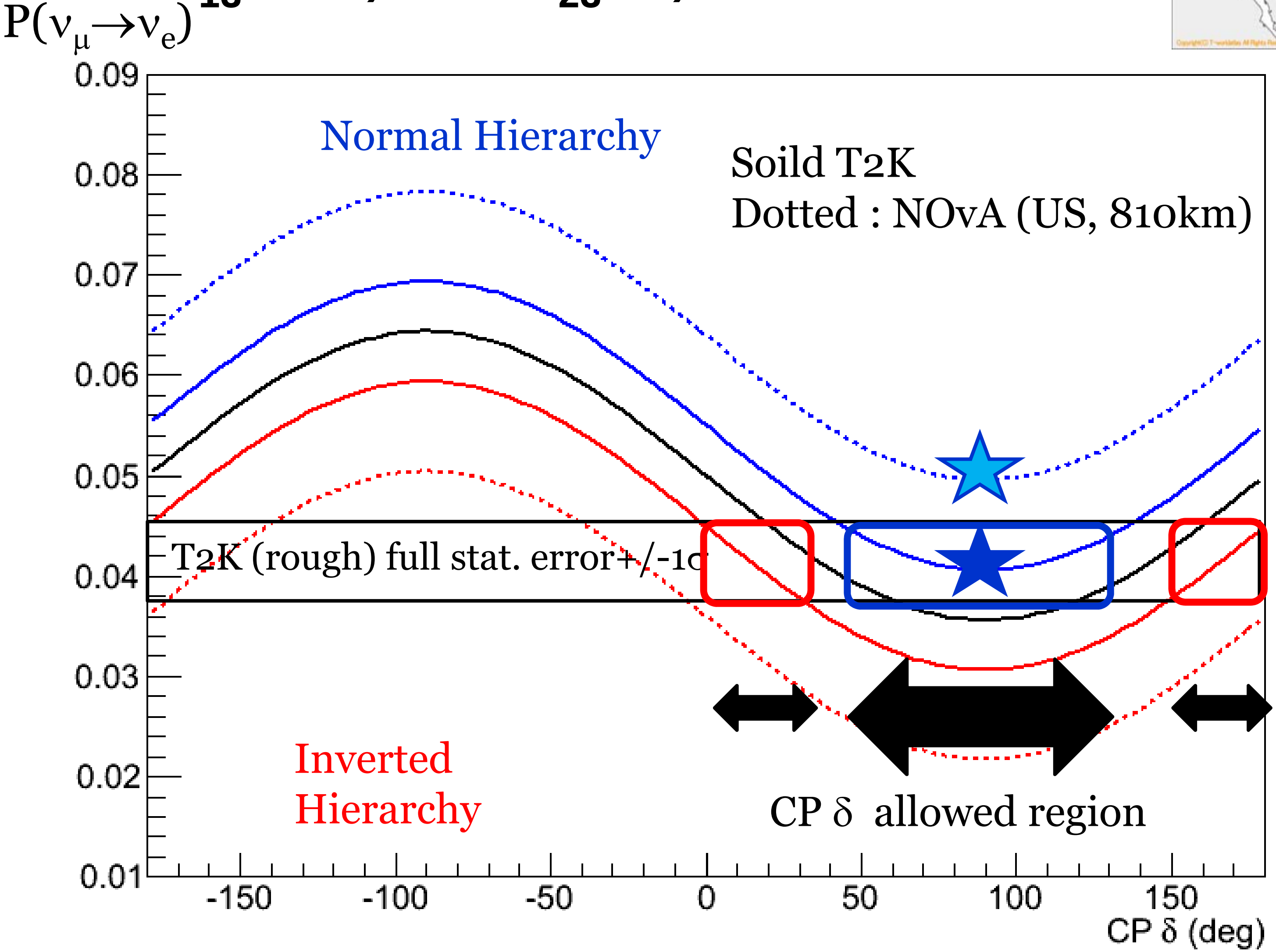
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probabil

at oscillation maximum

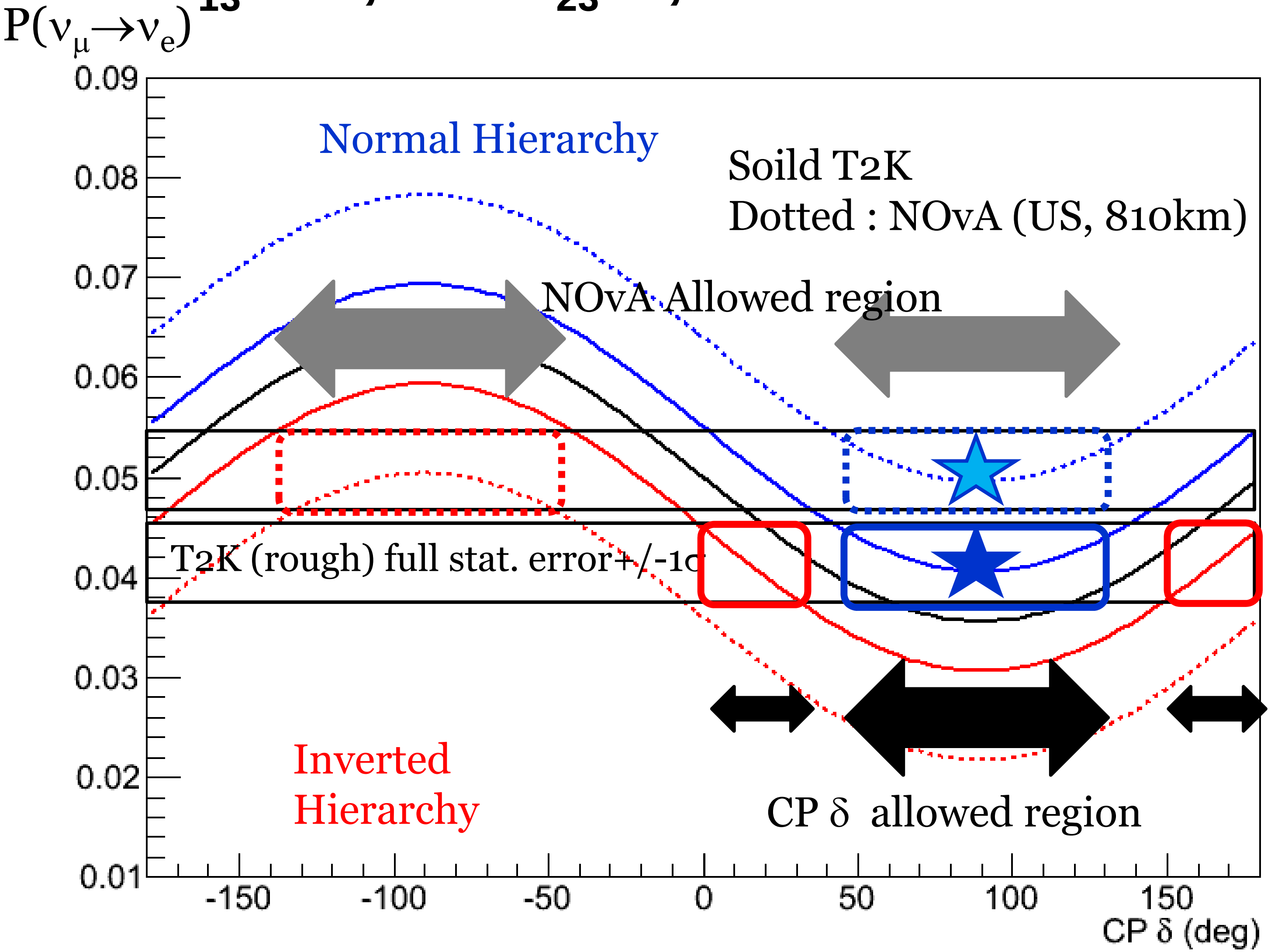
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

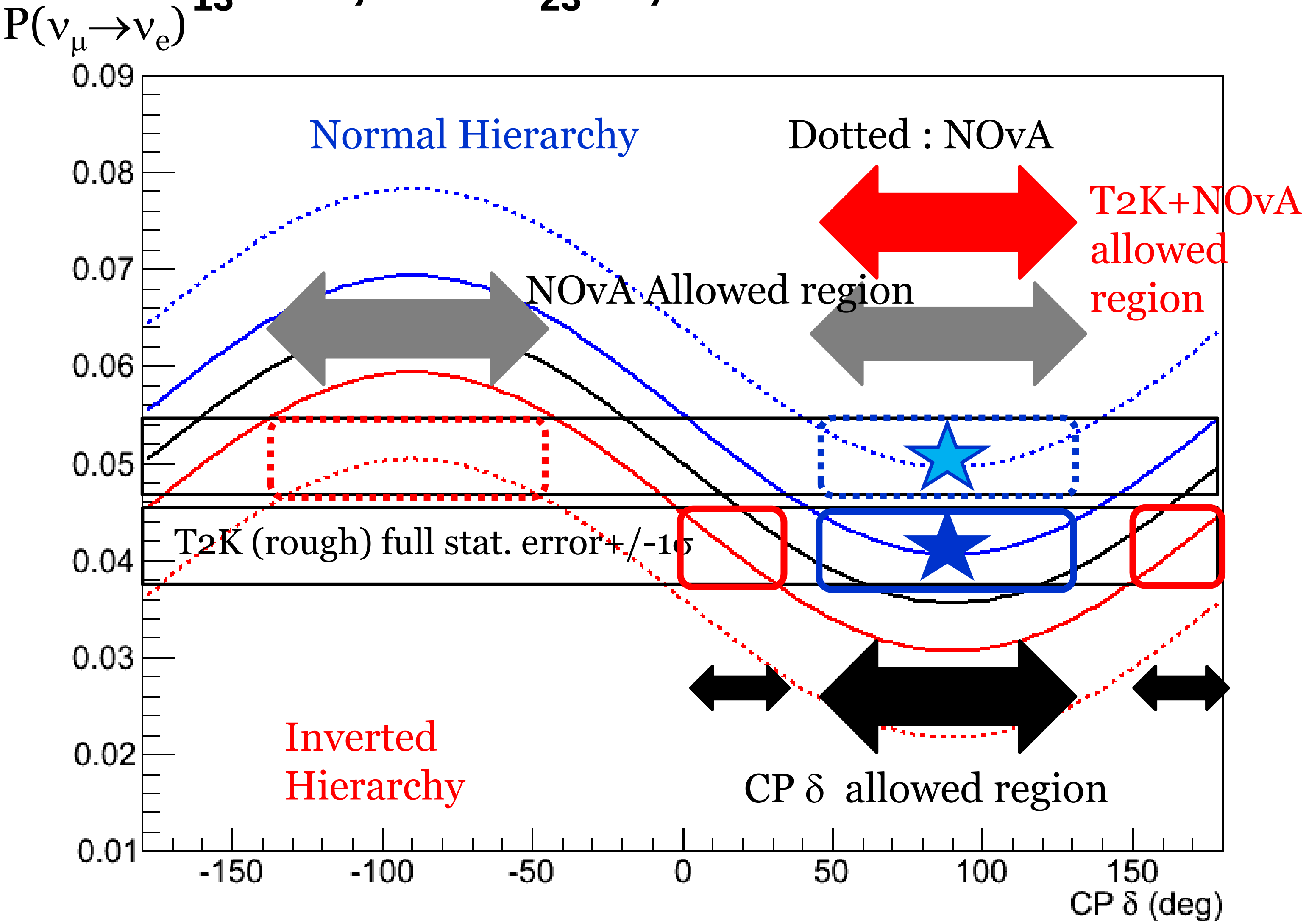
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

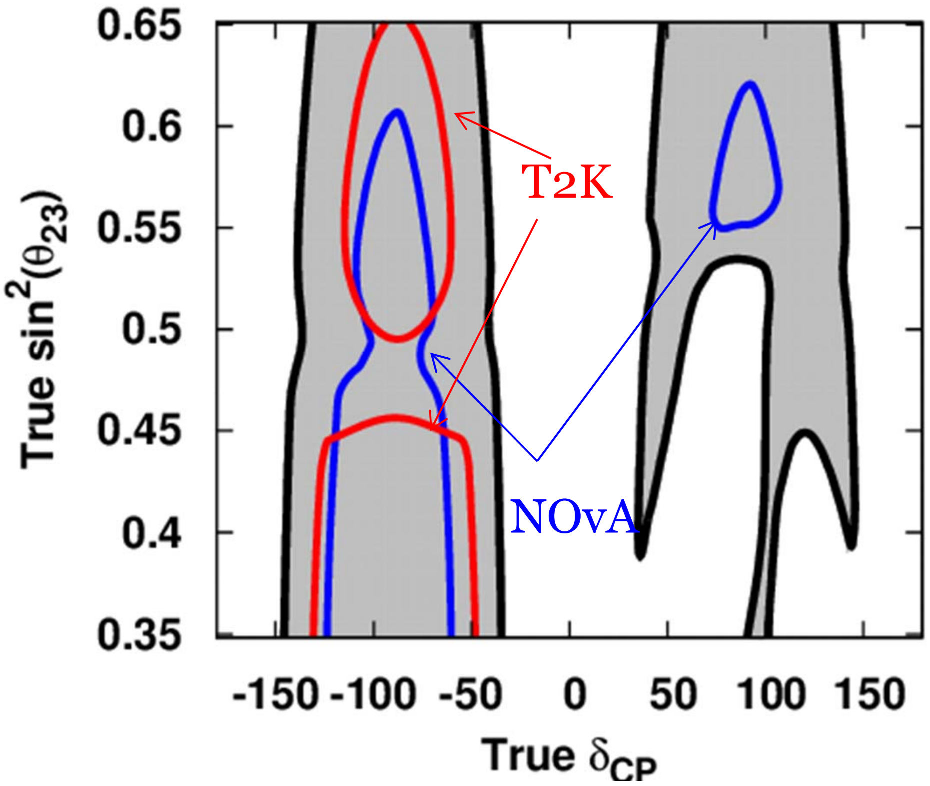
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect

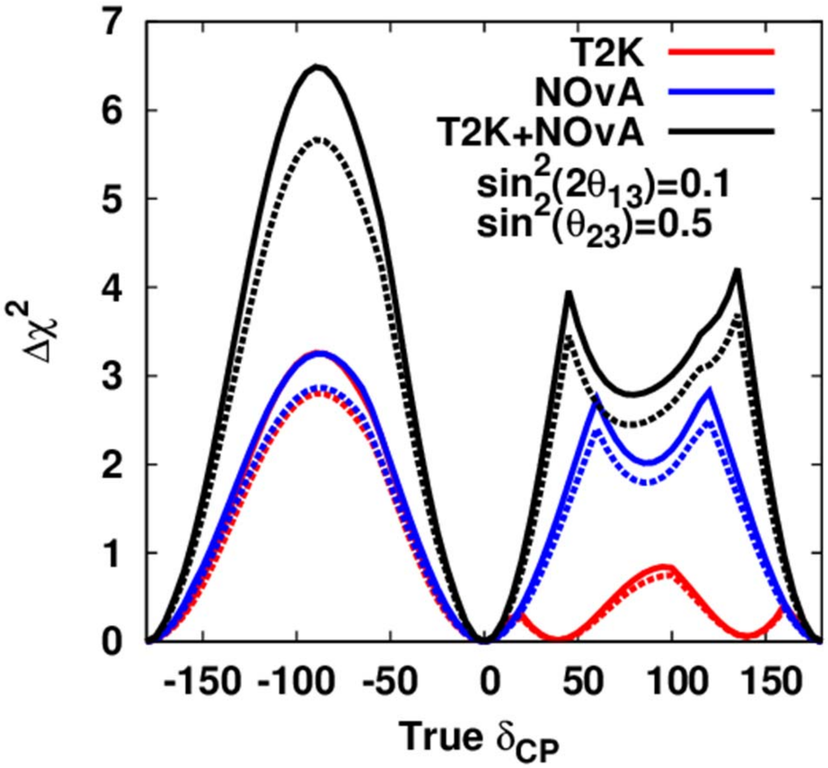


T2K+NOvA CP violation sensitivity

- Assuming both experiments run 50% ν-mode, 50% anti-ν mode.
- with 5% normalization uncertainty on signal and 10% normalization uncertainty on background.
- Shown is NH case.

solid : w/o sys. error
dash: w/ sys. error



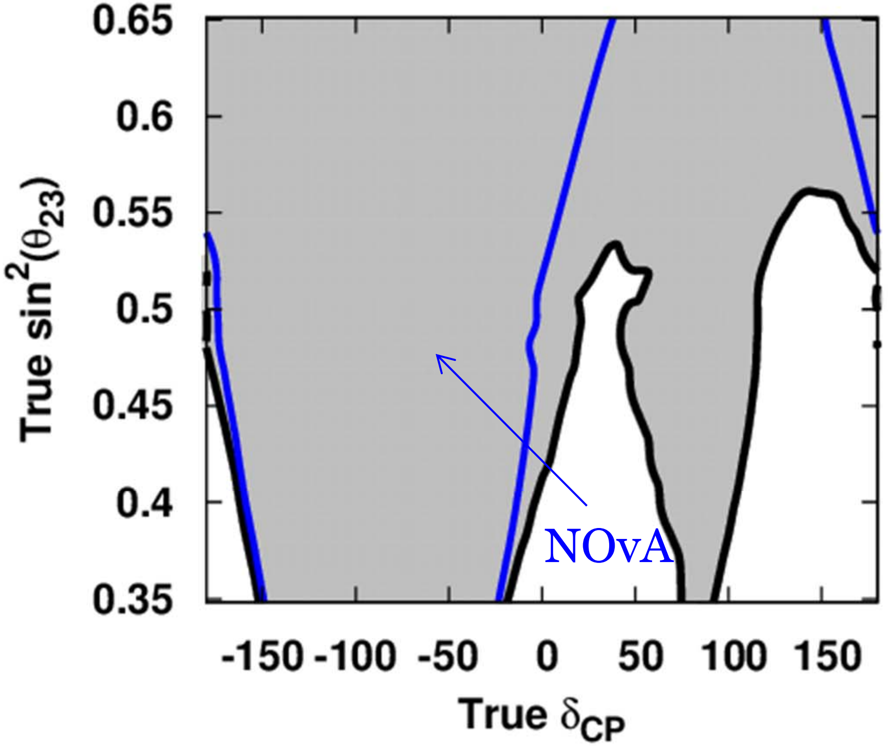


Region where $\sin\delta = 0$ (CP conservation) can be excluded by 90% C.L.

sensitivity to non-zero CP-violating term

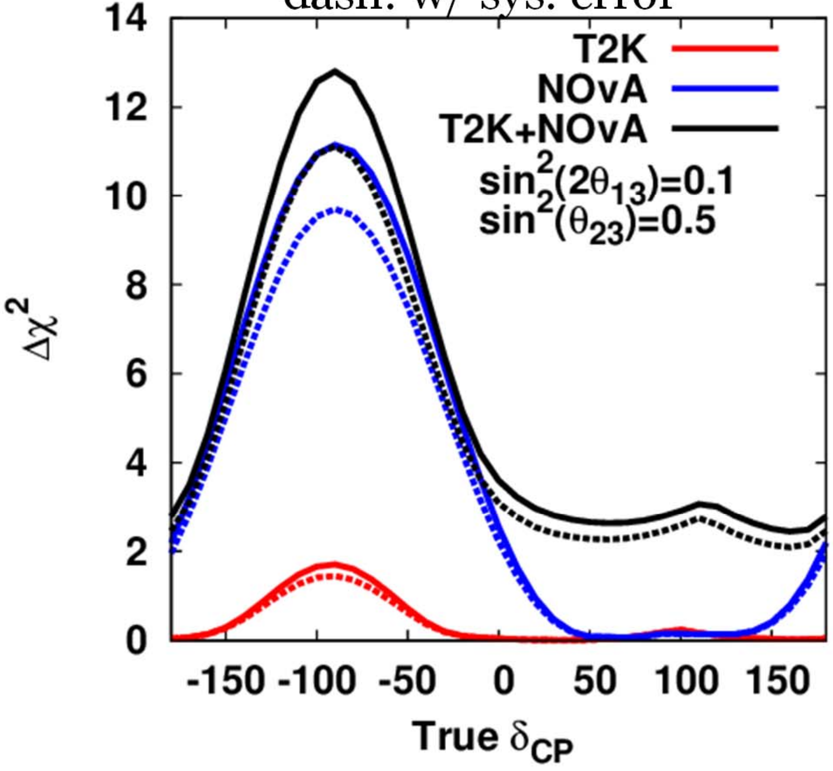
T2K+NOvA CP violation sensitivity

- Assuming both experiments run 50% ν-mode, 50% anti-ν mode.
- with 5% normalization uncertainty on signal and 10% normalization uncertainty on background.
- Shown is NH case.



Region where MH can be distinguished by 90% C.L.

solid : w/o sys. error
dash: w/ sys. error



sensitivity to resolve MH

Target of neutrino oscillation experiments

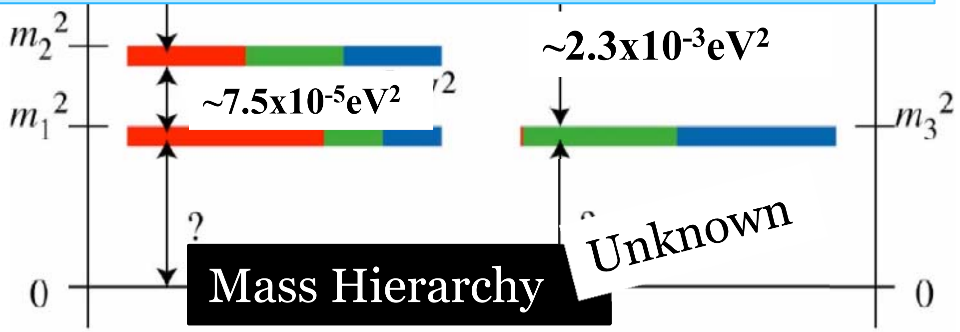
CP phase
KEY to understand the origin of matter dominant universe

Unknown

Mixing matrix for

Combination of results from reactor experiments, T2K and NOvA
Will enhance the sensitivity For these physics

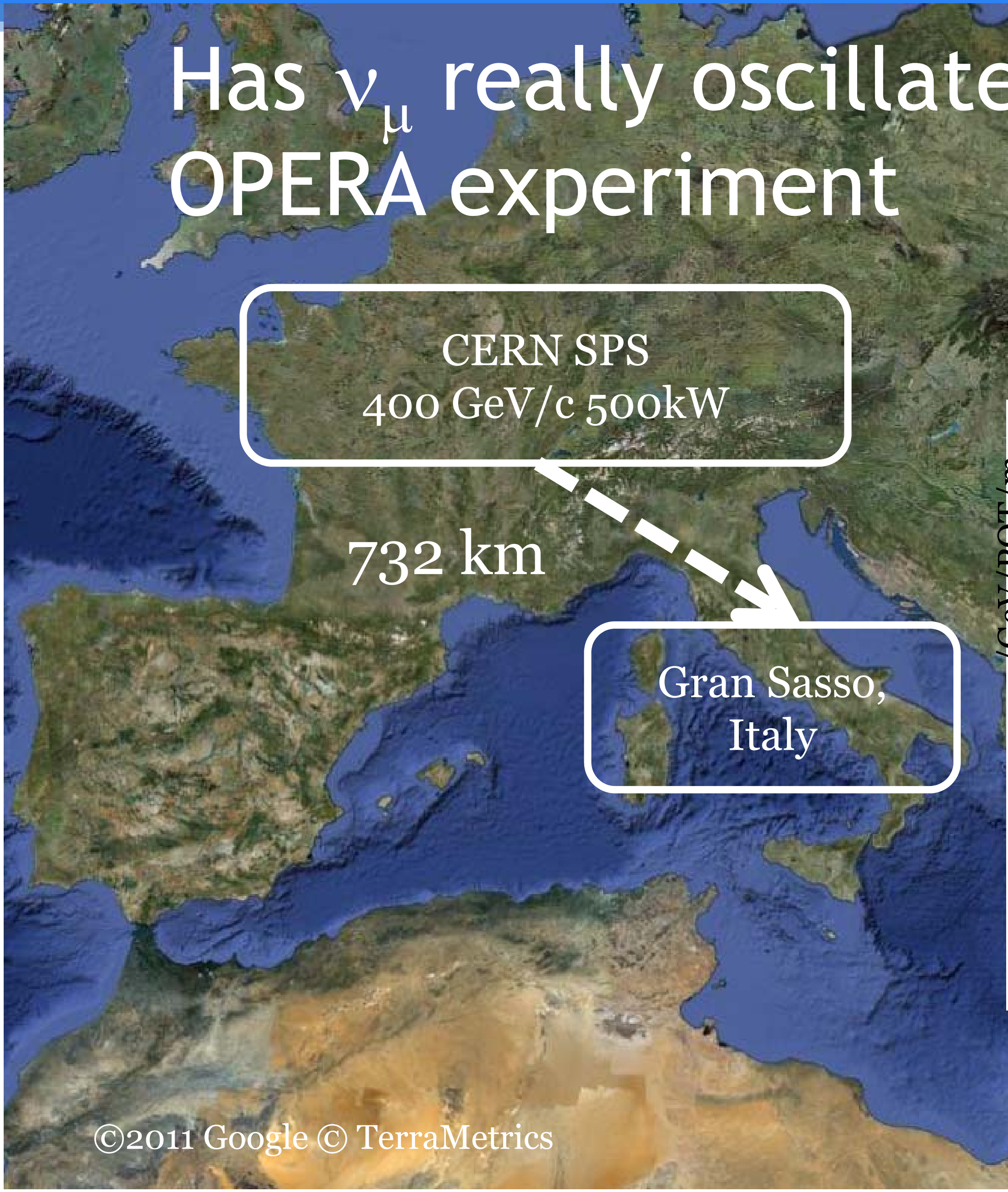
Big Impact
on 0ν double-β decay search
(hence on Majorana ν confirmation)



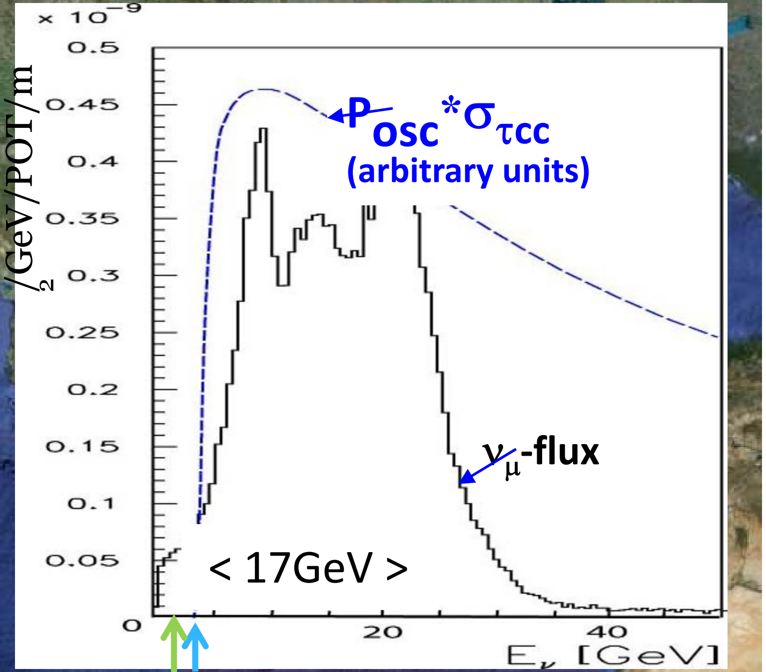
Mass Hierarchy

Unknown

Has ν_μ really oscillate to ν_τ? OPERA experiment



©2011 Google © TerraMetrics



< 17GeV >

τ production threshold (~3.5 GeV)

Oscillation maximum (~1.4 GeV)

ν_τ – Appearance Experiment

Difficulty

- ✓ Tau lifetime: 2.9x10^{-13}s

→c*lifetime*γ: ~1mm

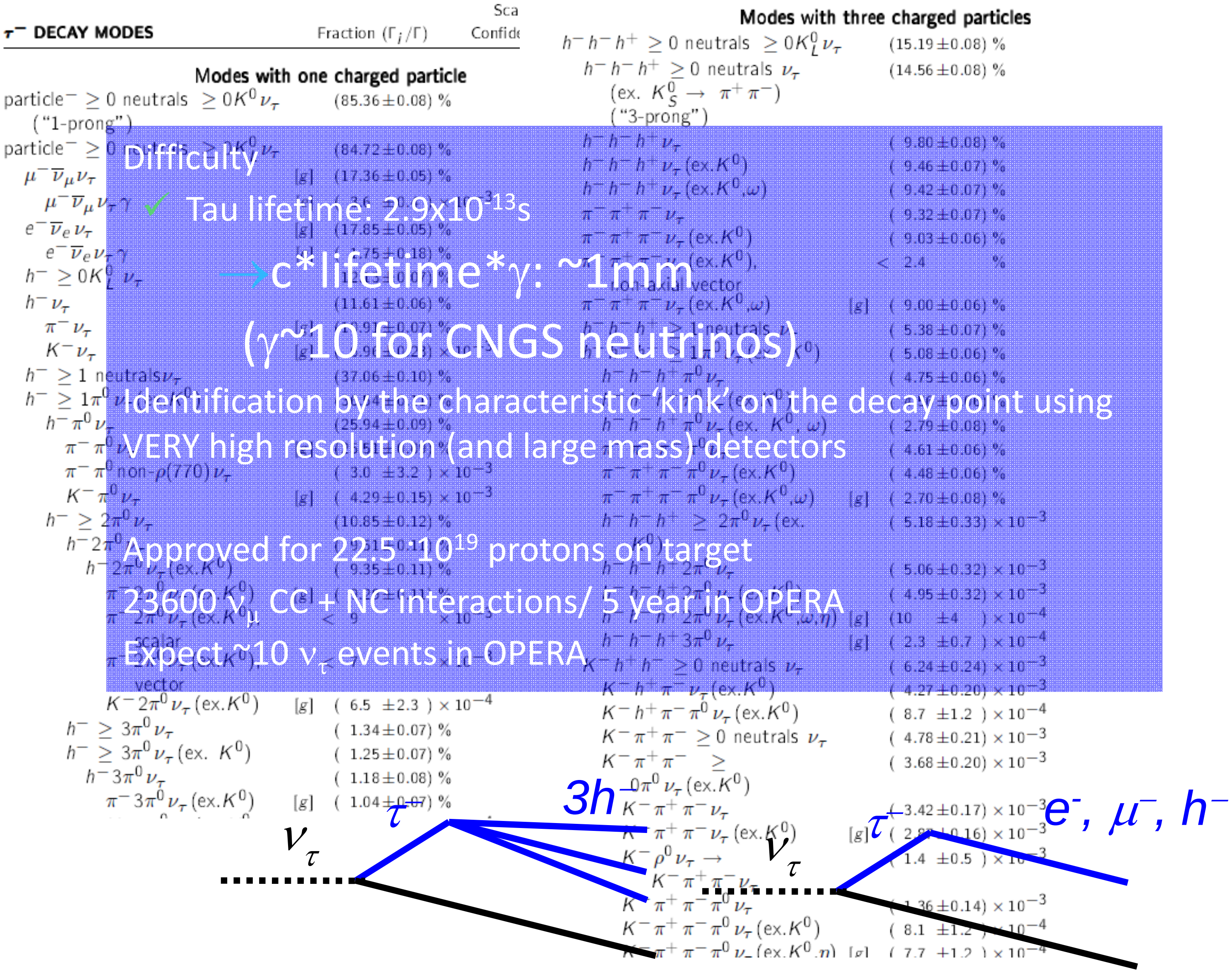
(γ~10 for CNGS neutrinos)

Identification by the characteristic ‘kink’ on the decay point using VERY high resolution (and large mass) detectors

Approved for 22.5·10^{19} protons on target

23600 ν_μ CC + NC interactions/ 5 year in OPERA

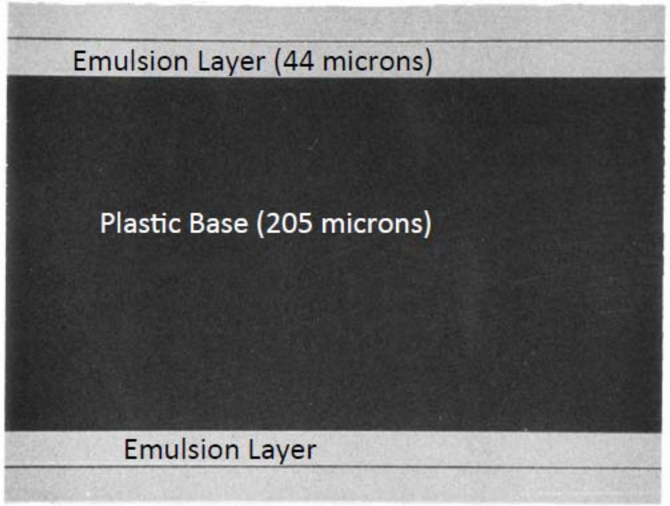
Expect ~10 ν_τ events in OPERA

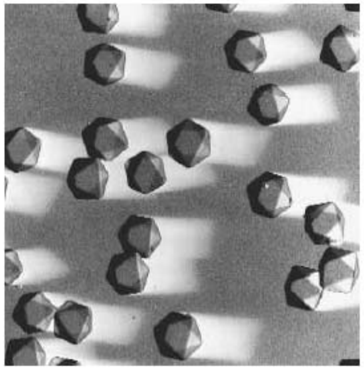


τ^- DECAY MODES		Fraction (Γ_i/Γ)	Sca Confid
Modes with one charged particle			
particle$^-$ ≥ 0 neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.36 ± 0.08) %	
particle$^-$ ≥ 0 [illegible] $\geq 0K^0\nu_\tau$		(84.72 ± 0.08) %	
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g]	(17.36 ± 0.05) %	
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[illegible]	[illegible]	
$e^-\overline{\nu}_e\nu_\tau$	[g]	(17.85 ± 0.05) %	
$e^-\overline{\nu}_e\nu_\tau\gamma$	[illegible]	(1.75 ± 0.18) %	
$h^- \geq 0K^0_L\,\nu_\tau$		[illegible]	
$h^-\nu_\tau$		(11.61 ± 0.06) %	
$\pi^-\nu_\tau$	[g]	([illegible].91±0.07) %	
$K^-\nu_\tau$	[g]	([illegible].96±0.[illegible]) × 10^{-3}	
$h^- \geq 1$ neutrals ν_τ		(37.06 ± 0.10) %	
$h^- \geq 1\pi^0\nu_\tau$(ex.K^0)		[illegible]	
$h^-\pi^0\nu_\tau$		(25.94 ± 0.09) %	
$\pi^-\pi^0\nu_\tau$	[g]	[illegible]	
$\pi^-\pi^0$ non-$\rho(770)\,\nu_\tau$		$(3.0\pm3.2) \times 10^{-3}$	
$K^-\pi^0\nu_\tau$	[g]	$(4.29\pm0.15) \times 10^{-3}$	
$h^- \geq 2\pi^0\nu_\tau$		(10.85 ± 0.12) %	
$h^-2\pi^0\nu_\tau$		(9.51 ± 0.11) %	
$h^-2\pi^0\nu_\tau$(ex.K^0)		(9.35 ± 0.11) %	
$\pi^-2\pi^0\nu_\tau$(ex.K^0)	[g]	(9.2[illegible]±0.11) %	
$\pi^-2\pi^0\nu_\tau$(ex.K^0), scalar		$< 9 \times 10^{-3}$	
$\pi^-2\pi^0\nu_\tau$(ex.K^0), vector		[illegible]	
$K^-2\pi^0\nu_\tau$(ex.K^0)	[g]	$(6.5\pm2.3) \times 10^{-4}$	
$h^- \geq 3\pi^0\nu_\tau$		(1.34 ± 0.07) %	
$h^- \geq 3\pi^0\nu_\tau$(ex. K^0)		(1.25 ± 0.07) %	
$h^-3\pi^0\nu_\tau$		(1.18 ± 0.08) %	
$\pi^-3\pi^0\nu_\tau$(ex.K^0)	[g]	(1.04 ± 0.07) %	
Modes with three charged particles			
$h^-h^-h^+ \geq 0$ neutrals $\geq 0K^0_L\nu_\tau$		(15.19 ± 0.08) %	
$h^-h^-h^+ \geq 0$ neutrals ν_τ (ex. $K^0_S \to \pi^+\pi^-$) ("3-prong")		(14.56 ± 0.08) %	
$h^-h^-h^+\nu_\tau$		(9.80 ± 0.08) %	
$h^-h^-h^+\nu_\tau$(ex.K^0)		(9.46 ± 0.07) %	
$h^-h^-h^+\nu_\tau$(ex.K^0,ω)		(9.42 ± 0.07) %	
$\pi^-\pi^+\pi^-\nu_\tau$		(9.32 ± 0.07) %	
$\pi^-\pi^+\pi^-\nu_\tau$(ex.K^0)		(9.03 ± 0.06) %	
$\pi^-\pi^+\pi^-\nu_\tau$(ex.K^0), non-axial vector		< 2.4 %	
$\pi^-\pi^+\pi^-\nu_\tau$(ex.K^0,ω)	[g]	(9.00 ± 0.06) %	
$h^-h^-h^+ \geq 1$ neutrals ν_τ		(5.38 ± 0.07) %	
$h^-h^-h^+ \geq 1\pi^0\nu_\tau$(ex. K^0)		(5.08 ± 0.06) %	
$h^-h^-h^+\pi^0\nu_\tau$		(4.75 ± 0.06) %	
$h^-h^-h^+\pi^0\nu_\tau$(ex.K^0)		[illegible]	
$h^-h^-h^+\pi^0\nu_\tau$(ex. K^0, ω)		(2.79 ± 0.08) %	
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$		(4.61 ± 0.06) %	
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$(ex.$K^0$)		(4.48 ± 0.06) %	
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$(ex.$K^0$,$\omega$)	[g]	(2.70 ± 0.08) %	
$h^-h^-h^+ \geq 2\pi^0\nu_\tau$(ex. K^0)		$(5.18\pm0.33) \times 10^{-3}$	
$h^-h^-h^+2\pi^0\nu_\tau$		$(5.06\pm0.32) \times 10^{-3}$	
$h^-h^-h^+2\pi^0\nu_\tau$(ex.K^0)		$(4.95\pm0.32) \times 10^{-3}$	
$h^-h^-h^+2\pi^0\nu_\tau$(ex.K^0,ω,η)	[g]	$(10\pm4) \times 10^{-4}$	
$h^-h^-h^+3\pi^0\nu_\tau$	[g]	$(2.3\pm0.7) \times 10^{-4}$	
$K^-h^+h^- \geq 0$ neutrals ν_τ		$(6.24\pm0.24) \times 10^{-3}$	
$K^-h^+\pi^-\nu_\tau$(ex.K^0)		$(4.27\pm0.20) \times 10^{-3}$	
$K^-h^+\pi^-\pi^0\nu_\tau$(ex.K^0)		$(8.7\pm1.2) \times 10^{-4}$	
$K^-\pi^+\pi^- \geq 0$ neutrals ν_τ		$(4.78\pm0.21) \times 10^{-3}$	
$K^-\pi^+\pi^- \geq 0\pi^0\nu_\tau$(ex.$K^0$)		$(3.68\pm0.20) \times 10^{-3}$	
$K^-\pi^+\pi^-\nu_\tau$		$(3.42\pm0.17) \times 10^{-3}$	
$K^-\pi^+\pi^-\nu_\tau$(ex.K^0)	[g]	(2.8[illegible]±0.16) × 10^{-3}	
$K^-\rho^0\nu_\tau \to K^-\pi^+\pi^-\nu_\tau$		$(1.4\pm0.5) \times 10^{-3}$	
$K^-\pi^+\pi^-\pi^0\nu_\tau$		$(1.36\pm0.14) \times 10^{-3}$	
$K^-\pi^+\pi^-\pi^0\nu_\tau$(ex.$K^0$)		$(8.1\pm1.2) \times 10^{-4}$	
$K^-\pi^+\pi^-\pi^0\nu_\tau$(ex.$K^0$,$\eta$)	[g]	$(7.7\pm1.2) \times 10^{-4}$	

OPERA using Nuclear emulsion

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*



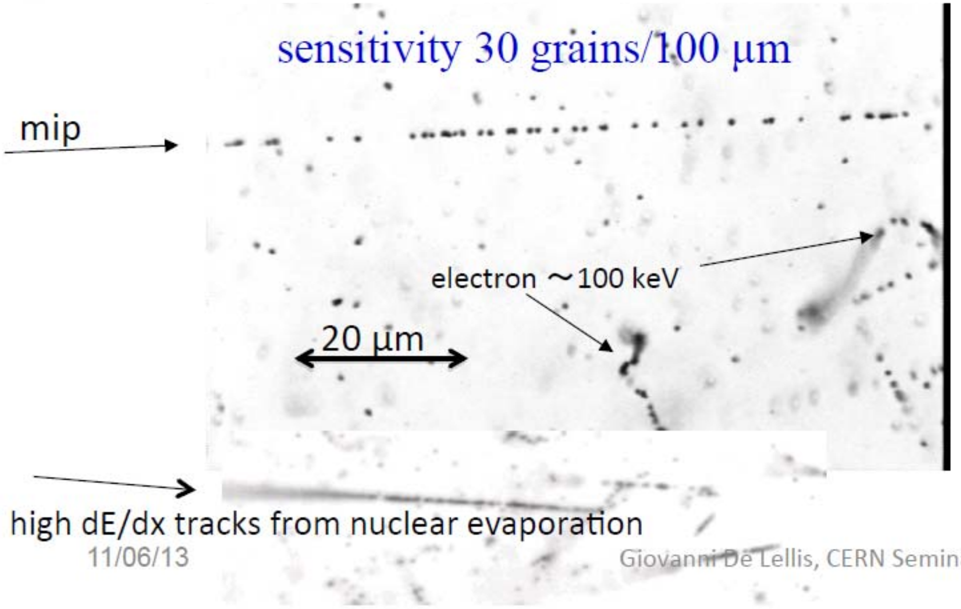


basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

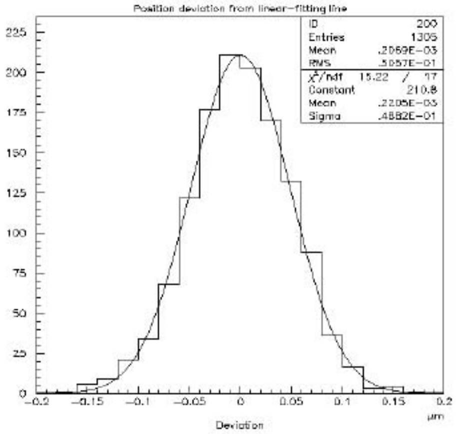


sensitivity 30 grains/100 μm

high dE/dx tracks from nuclear evaporation

intrinsic resolution: 50 nm

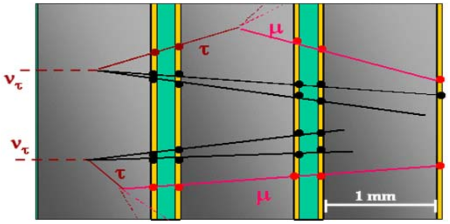
deviation from linear-fit line. (2D)

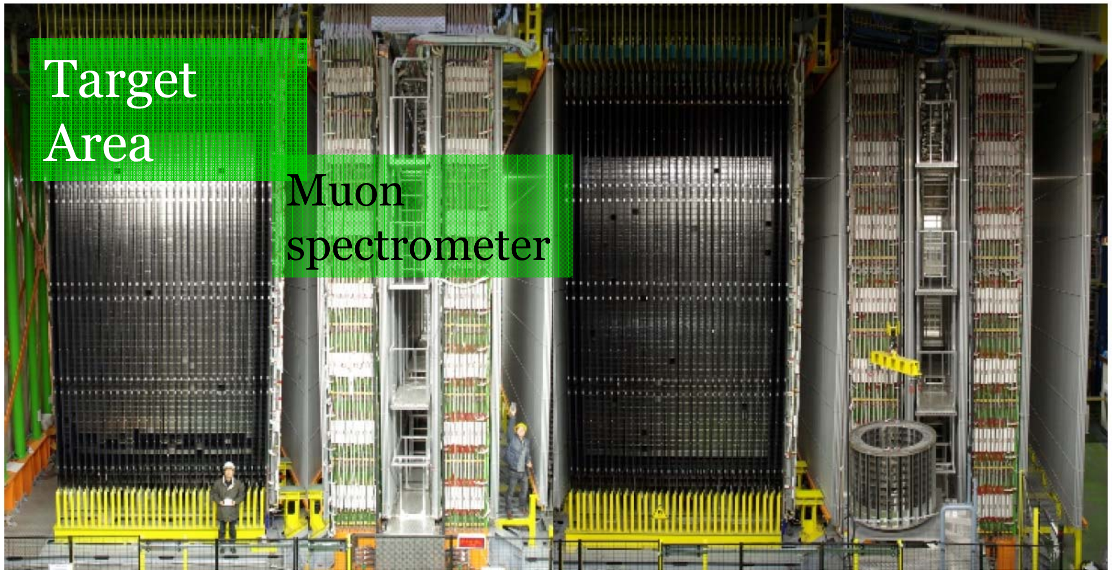


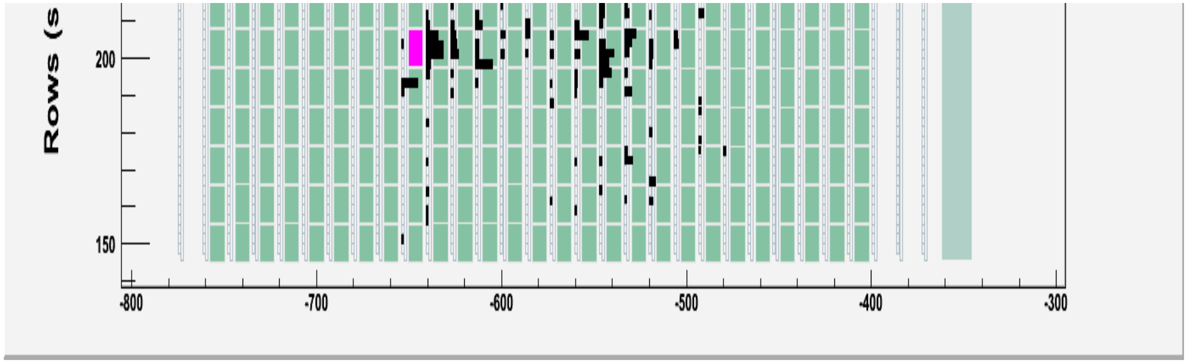
OPERA, 1.2kton emulsion detector, since 2008

146621 bricks, each 8.3kg

- 56 (1mm) Pb sheets
- 57 (300μm) emulsion layers
- 2 (300μm) changeable sheets (CS)

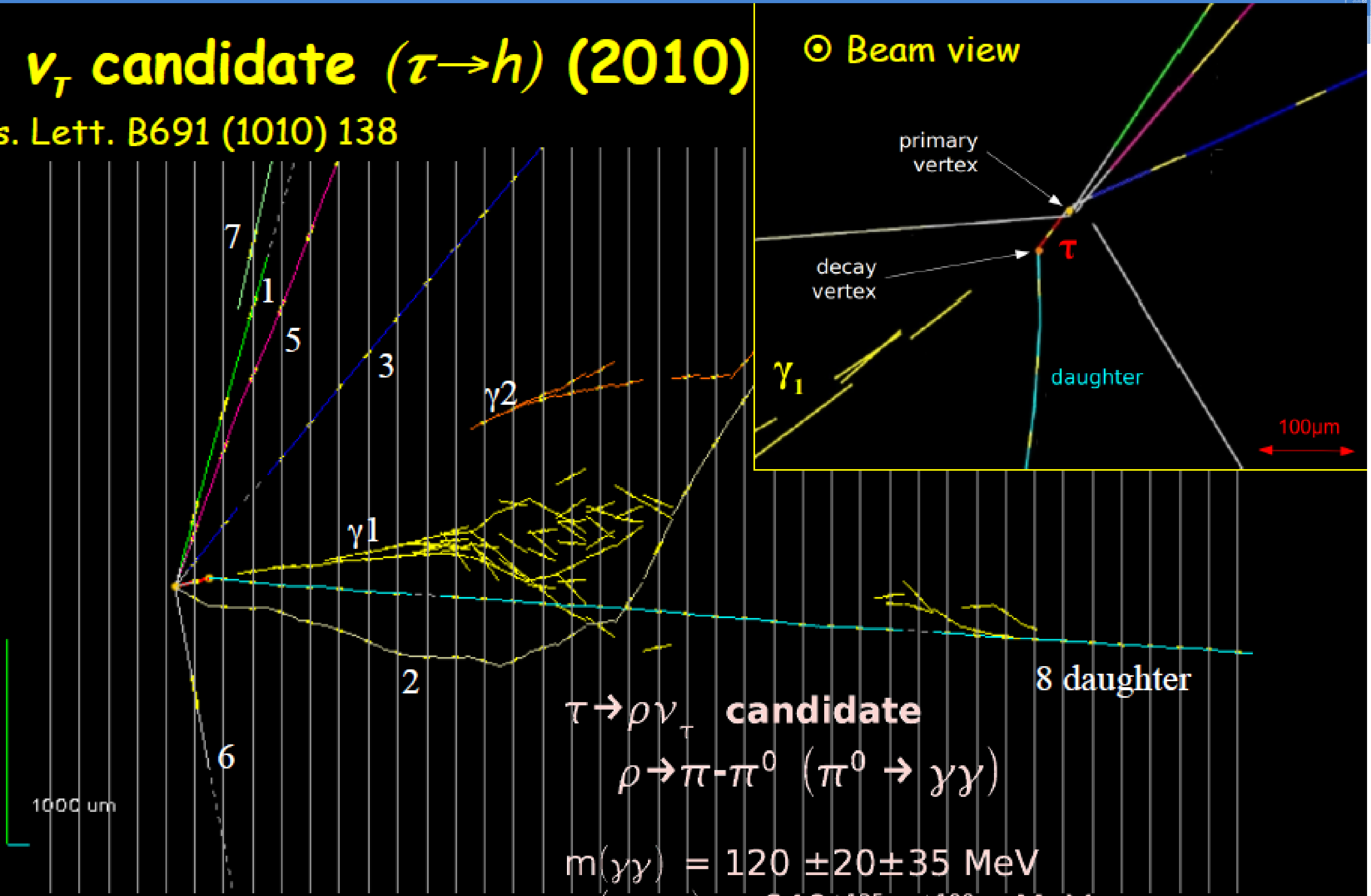






1st ν_τ candidate ($\tau \rightarrow h$) (2010)

Phys. Lett. B691 (1010) 138



$\tau \rightarrow \rho \nu_\tau$ **candidate**

$\rho \rightarrow \pi^- \pi^0$ ($\pi^0 \rightarrow \gamma\gamma$)

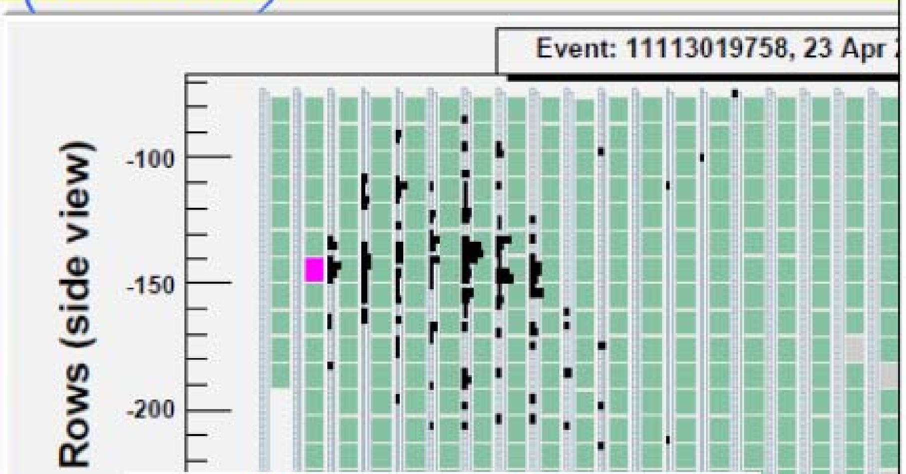
$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV

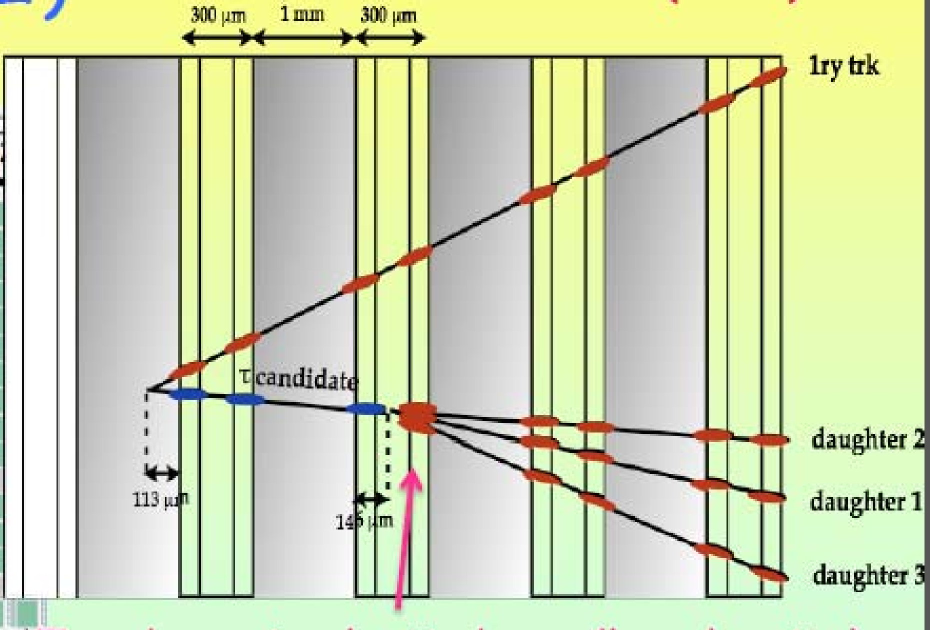
$m(\pi^-\gamma\gamma) = 640^{+125}_{-80}{}^{+100}_{-90}$ MeV

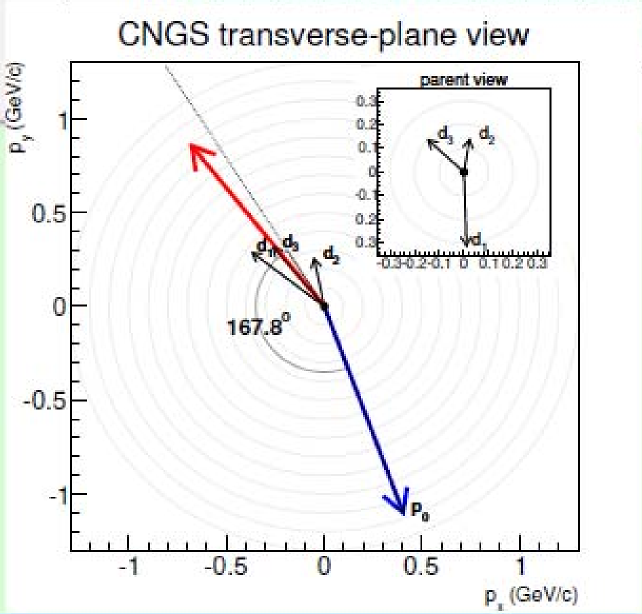
$Br(\tau \rightarrow \rho \nu_\tau) \sim 25\%$

2^{nd} ν_τ candidate (2012) ($\tau \rightarrow 3h$)

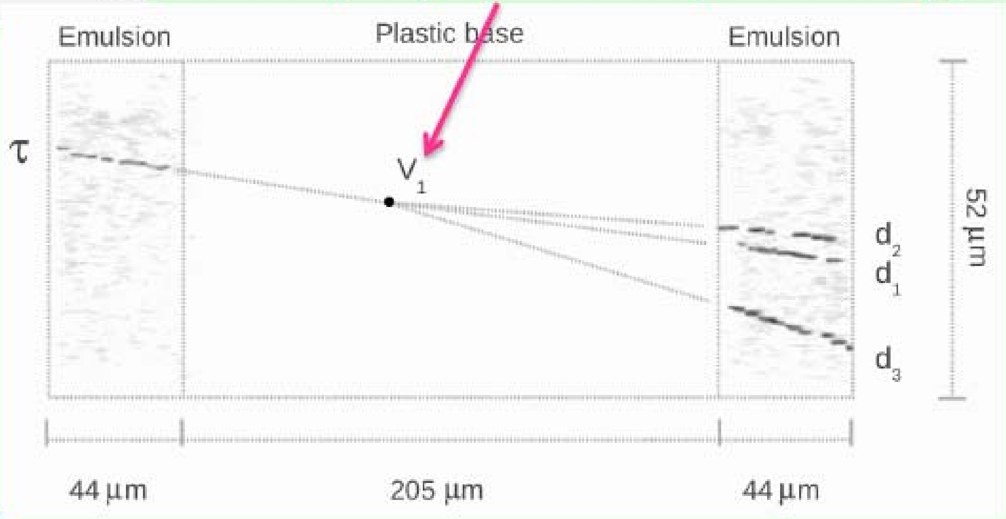
JHEP 11 (2013) 036





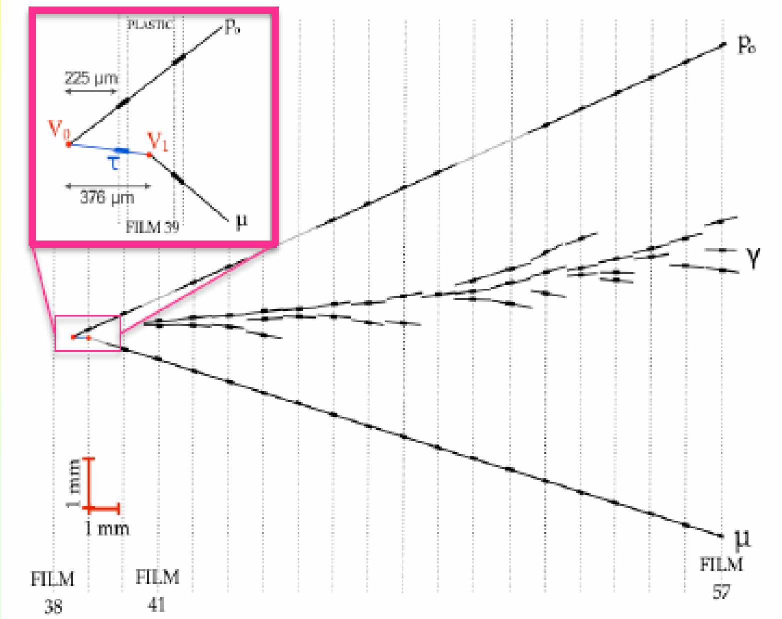


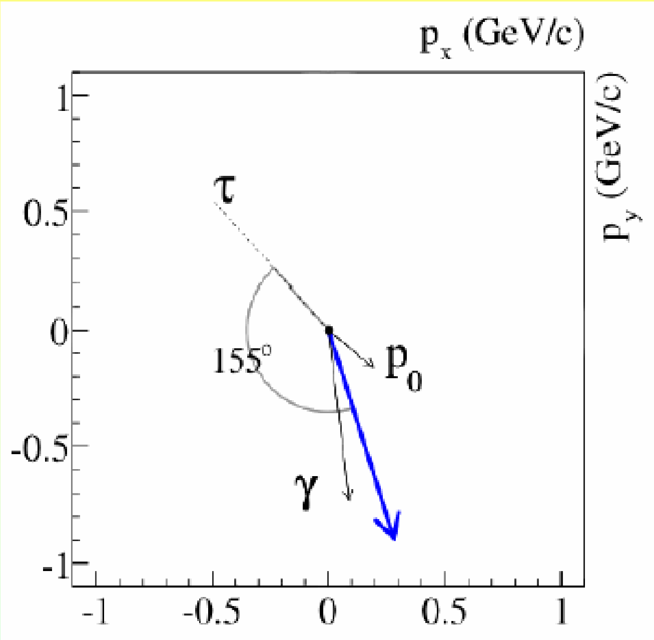
Tau decay in plastic base (low density)

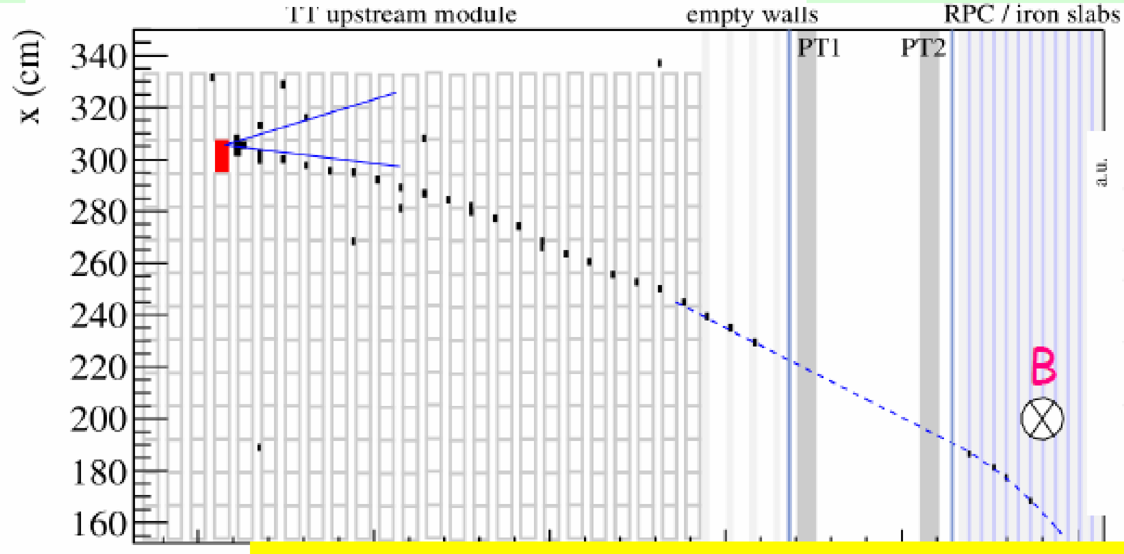


3rd ν_τ candidate ($\tau \rightarrow \mu$) (2013)

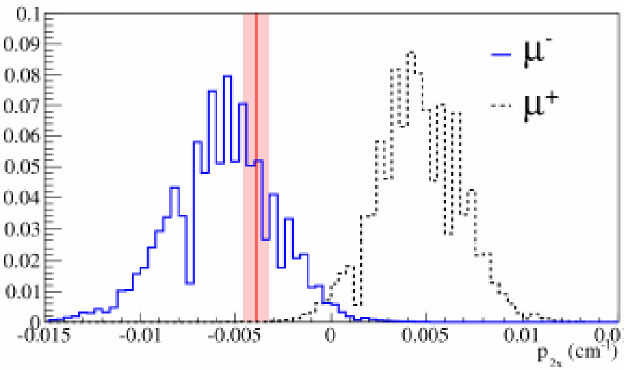
PHYSICAL REVIEW D 89 (2014) 051102(R)





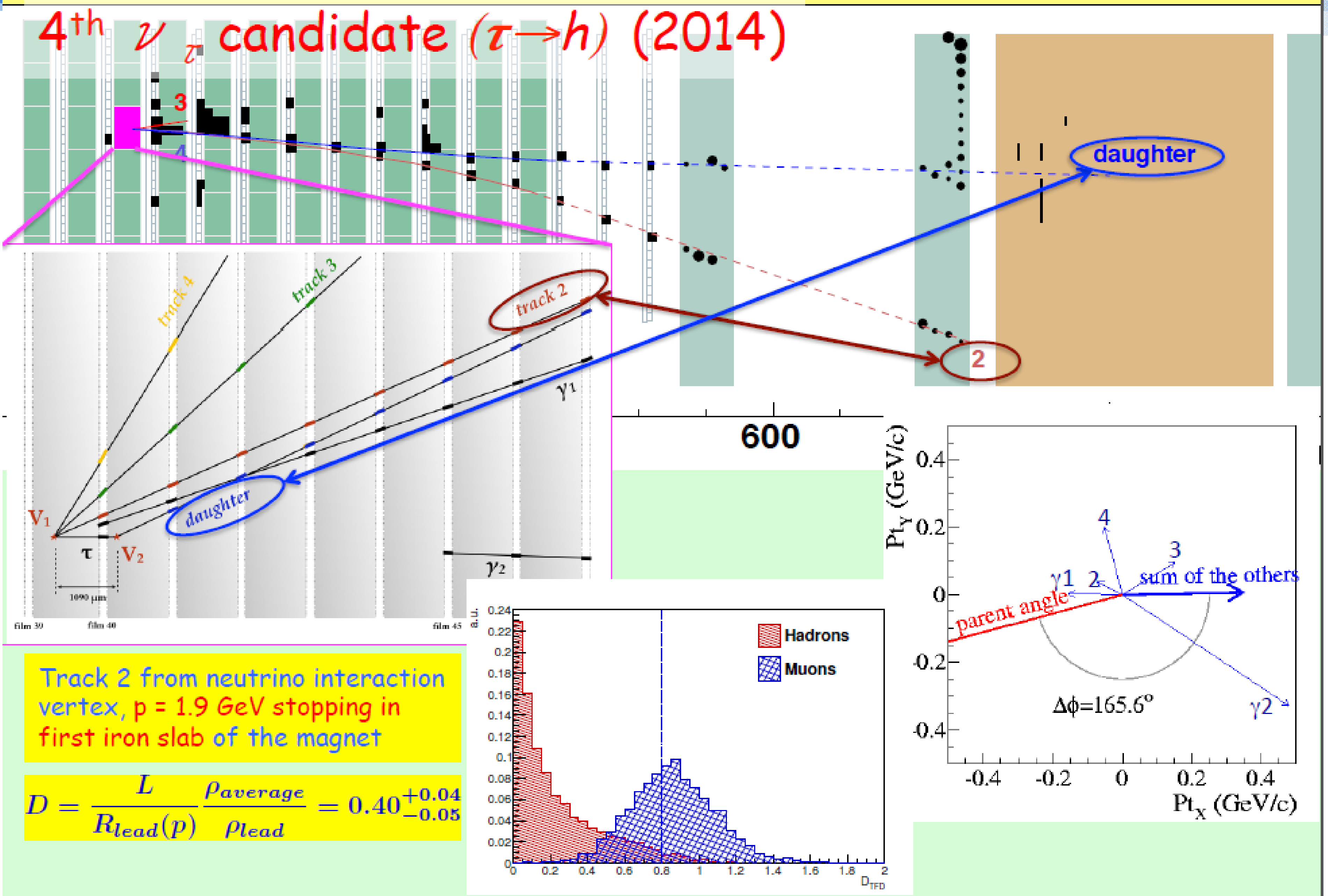


Negative muon measured in the muon spectrometer



First measurement of the lepton charge in appearance mode

4th ν_τ candidate ($\tau \rightarrow h$) (2014)



Track 2 from neutrino interaction vertex, p = 1.9 GeV stopping in first iron slab of the magnet

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.40^{+0.04}_{-0.05}$$

Data sample:

2008/09 : 398 (0μ events) + 1553 (1μ events)

2010/11/12 : 582 (0μ events) + 2153 (1μ events)

The expected signal and background is normalized to the number of located events

$$n^{0\mu}(\nu_\tau^{CC}) = \frac{\langle\sigma(\nu_\tau^{CC})\rangle}{\langle\sigma(\nu_\mu^{CC})\rangle}\,\frac{\langle\epsilon^{0\mu}(\nu_\tau^{CC})\rangle}{\langle\epsilon^{0\mu}(\nu_\tau^{CC})\rangle + \alpha\,\langle\epsilon^{0\mu}(\nu_\tau^{NC})\rangle}\, n^{0\mu} \qquad \alpha = \frac{NC}{CC}$$

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ \mathrm{meV}^2$	Total background	Observed
τ→h	0.4 ± 0.08	0.033 ± 0.006	2
τ→3h	0.57 ± 0.11	0.155 ± 0.03	1
τ→μ	0.52 ± 0.1	0.018 ± 0.007	1
τ→e	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4

Two statistical method :

- Fisher combination of single channel p-value
- Likelihood ratio

p-value = 1.03×10^{-5} of no oscillation

no oscillation excluded at 4.2 σ CL