Probing Nonstandard Physics with a long baseline experiment with two identical detectors with different baselines

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Work in progress, in collaboration with
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Plans

- Motivations
- Nonstandard Physics Scenarios
  - Quantum Decoherence (QD) $\leftarrow$ this talk
  - CPT Violation $\leftarrow$ this talk
  - Lorentz Sym. Violation $\leftarrow$ this talk
  - Flavor nonuniversal neutrino interactions with matter (work in progress)
  - Mass Varying Neutrinos (work in progress)
- Summary and Outlook

Motivations

Motivations

- SM: remarkably successful (except for neutrino oscillations and the cold dark matter of the universe)
- Then what else remain to do ?
  - Origin of EWSB (mass) ? $\longrightarrow$ Higgs boson (SM or MSSM, or whatever) anticipated at LHC
  - Nature of CDM's ?
  - Precision measurements of MNS mixings and leptonic CPV (also in the quark sector)
  - Search for new particles and forces (SUSY, Extra dimension,.....) Direct Search of New Physics
  - Search for rare/forbidden processes such as proton decays, LFV decays ($\mu \to e\gamma$, etc.), e/n EDM's, Indirect Search of New Physics

Motivations–Cont'd

Remarkable success of the SM tests not only the validity of

- Principle of local gauge symmetry based on $SU(3)_C \times SU(2)_L \times U(1)_Y$, but also
- Entire theoretical/mathematical framework of quantum field theory (quantum mechanics + special relativity), which is based on the following underlying assumptions
  - 4-dim flat spacetime Lorentz Symmetry
  - Locality
  - Unitarity
- Consequence of Rel. local QFT:
  - Spin-Statistics Theorem
  - CPT theorem

Motivations-Cont'd

What happens if we consider gravity ?

- QFT in the curved spacetime within classical gravity or QFT + Quantum Gravity may violate some conditions for the aforementioned QFT
  $\longrightarrow$ Those theorems could be violated
- For examples,
  - Unitarity may be violated due to balckholes, spacetime foam $\longrightarrow$ Quantum Decoherence (Pure state $\longrightarrow$ Mixed state)
  - CPT violation : either ill-defined, or well-defined but does not commute with the full Hamiltonian
  - Local interaction may not be valid around Planck scale
  - Is Lorentz symmetry exact ?

Motivations-Cont'd

- With precise data in partice physics, we may be able to test some of these effects through quantum decoherence and CPT/Lorentz symmetry violation
- Study Quantum Decoherence, CPT and Lorentz Symmetry Violations using the ν_μ disappearance experiments at T2K(K)
- Complementary to the similar study using $K^0 - \overline{K^0}$ and $B^0 - \overline{B^0}$ oscillations
- We will find that having two detectors and knowing the spectral distributions of the events will be very powerful for such studies, not only for resolving the parameter degeneracies in the neutrino masses and mixings

Quantum Decoherence

What is the quantum decoherence (QD) ?

- In a closed quantum system,
  a pure state $\longrightarrow$ pure state, as the time evolves:

$$\frac{\partial \rho}{\partial t} = L[\rho] = -i[H, \rho]$$

- ρ : neutrino density matrix (operator)
- H : Hamiltonian (hermitian)
- $\rho > 0 \longrightarrow$ Probability Interpretation Possible
- Pure state : Tr $(\rho^2) =$ Tr $\rho = 1$
- Mixed state : Tr $(\rho^2) <$ Tr $\rho = 1$

What is QD ? - II

- In general situation with decoherence, the time evolution is given by the following equation:

$$\frac{\partial \rho}{\partial t} = L[\rho] = -i[H, \rho] + \mathcal{D}[\rho]$$

- dim[$\mathcal{D}$] = Energy $\longrightarrow$ Its inverse defines the coherence length after which the system gets mixed
- The first comprehensive study on this subject by Ellis, Hagelin, Nanopoulos, Srednicki, NPB (1984)
- $K^0 - \overline{K^0}$ and n interferometry: $||\mathcal{D}|| < 10^{-21}$ GeV

What is QD ? : Origin of $\mathcal{D}$ - III

- Quantum gravity :
  - Spacetime foam (Wheeler):
    Ground state of the Quantum gravity might be stochastic media due to singular microscopic fluctuations of metric
  - Blackhole thermodynamics (Hawking):
    Information (phase information) loss when a wavepacket falls into a blackhole
- Naive estimate on the QD from gravity
  $\sim E^3/M_{Pl}^2 \sim 10^{-38}$ for $E \sim 1$ GeV
- But could be enhanced to $\sim E^2/M_{Pl} \sim 10^{-19}$
- Or fundamental scale of gravity may be mower
- Environmental effect : A propagation of quantum system in a dissipative media (including a spacetime foam)

What is QD ? - IV

- In order to specify the form of $\mathcal{D}$, we assume a complete positivity, namely a linear, Markovian, and trace-preserving map $\rho(0) \rightarrow \rho(t)$
- Then, the time evolution is given by the Lindblad form:

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &= L[\rho] = -i[H, \rho] + \mathcal{D}[\rho] \\
\mathcal{D}[\rho] &\equiv \sum_n \{\rho, D_n D_n^\dagger\} - 2 D_n \rho D_n^\dagger
\end{aligned}
$$

- D_n : a result of tracing away the environment dynamics (ν propagation in disspative media, matter with fluctuating density or thermal baths, or spacetime foam in quantum gravity, etc.)

Further simplification

- Assume that the 2nd law of thermodynamics holds for the system: von Neumann entropy

$$S[\rho] \equiv -\mathrm{Tr}(\rho \lg \rho)$$

never decreases in time
This is achieved by enforcing $D_n = D_n^\dagger$
$\longrightarrow \mathcal{D}[\rho] = \sum_n [D_n, [D_n, \rho]]$

- Conservation of the average energy Tr (ρH) requires $[H, D_n] = 0$

- In more general situations (e.g., thermal system with heat bath), the average energy and momenta may not be conserved, and thus not covered by our study

Two flavor case: $\nu_\mu \leftrightarrow \nu_\tau$

Consider two-level system: ν_μ vs. ν_τ

- Survival probability:

$$\begin{aligned} P_{\mu\mu} &= \mathrm{Tr}[\Pi_{\nu_\mu}\rho(t)] \\ &= 1 - \frac{1}{2}\sin^2 2\theta\ \left(1 - e^{-\gamma(E)L}\cos kL\right) \end{aligned}$$

- A significant deviation from the conventional oscillation, if $\gamma L \sim O(1)$
- No well defined theory for calculating $\gamma(E) > 0$
- Three models widely discussed in the literatures: $\gamma = \gamma_0(E/GeV)^n$ with $n = 0, 2, -1$

Models for γ

[Lisi, Marrone, Montanino, PRL (2000) ;
Fogli, Lisi, Marrone, Montanino, PRD (2003)]

- $\gamma = \gamma_0 (E/GeV)^n$ with $n = 0, 2, -1$
  This way, $[\gamma_0]$ =Energy
- $n = 0$ ($\gamma = \gamma_0$ = const.): $\gamma_0 < 3.5 \times 10^{-23}$ GeV
- $n = 2$: even more disfavored, $\gamma_0 < 0.9 \times 10^{-27}$ GeV
- $n = -1$: $\gamma_0 < 2 \times 10^{-21}$ GeV
  NB: For $n = -1$, if $\Delta m^2 = 0$, $s^2_{2\theta} = 1$ and
  $\gamma_0 = 1.2 \times 10^{-21}$ GeV can describe the early SK data on atm ν's

What if we have a far detector in Korea ?

Consider a simple case with two generations:

- Survival probability:

$$
\begin{aligned}
P_{\mu\mu} &= 1 - \frac{1}{2}\sin^2 2\theta\,\left(1 - e^{-\gamma(E)L}\cos\Delta m^2 L/2E\right) \\
&= 1 - P_{\mu\tau}
\end{aligned}
$$

- Probability is still conserved within Lindblad approach
- Scan over 3 parameters: $\Delta m^2, \sin^2 2\theta, \gamma_0$
- Generate the fake data using $\gamma_0 = 0$ and calculate the χ^2 with nonzero γ_0, and generate 90 % and 99 % CL exclusion plots
- At T2KK, we can utilize the full informations on the event spectra at two different L's.

Assumptions on the experimental setup

- 2.5° off-axis T2K 4MW beams
- 4 years ν beam + 4 years $\bar{\nu}$ beam
- Kamioka : 0.27 Mton fid., L = 295 km
  Korea : 0.27 Mton fid., L = 1050 km
- Compare with a single detector at SK with 0.54 Mton fid. (T2K-II)
- Keep only Δm^2_{23} and $\theta_{23} \equiv \theta$ from the standard oscillation formula, and modify it including the possible effects of QD, CPT or Lorentz symmetry violations

Strategies

- Binning
  - $\mu-$like : 20 energy bins (0.2–1.2 GeV)
  - (Kamioka , Korea) x (ν beam , $\bar{\nu}$ beam)
    $\rightarrow$ 20 x 4 = 80 bins in total
- Systematic errors:
  1. spectrum shape : 5 $\%$ (E_ν (GeV) - 0.8) / 0.8
  2. signal detection efficiency : 5 %
  3. QE/non-QE separation : 20
  4. spectrum distortion in Korea : the shape difference between SK and Korea $\rightarrow 1\sigma$

Definition of χ^2

[Fogli et al. PRD66 (2002) 053010; Kajita et al.]

- Define χ^2 as

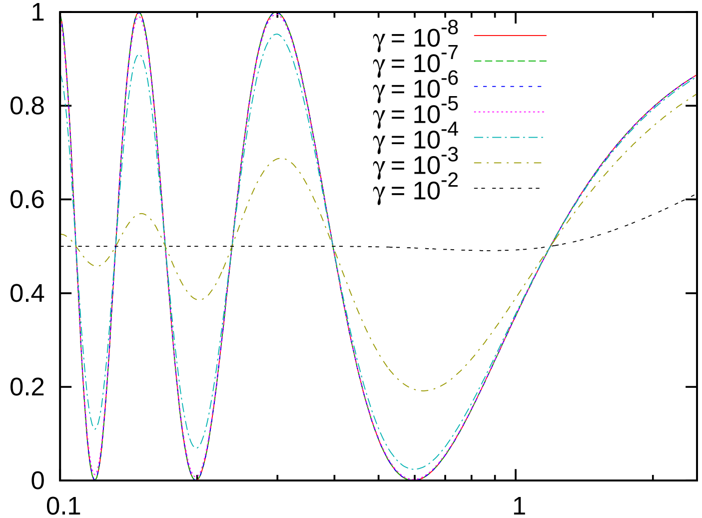
$$\chi^2 = \sum_{k=1}^{4}\sum_{i=1}^{20}\left(\frac{(N_i^{\rm obs}-N_i^{\rm exp})^2}{\sigma_i^2}\right) + \sum_{j=1}^{7}\left(\frac{\epsilon_j}{\tilde{\sigma}_j}\right)^2$$

$$N_i^{\rm exp} = N_i^{\rm BG}(1+\sum_{j=1,3,4} f_j^i \cdot \epsilon_j) + N_i^{\rm Signal}(1+\sum_{j=1,2,4} f_j^i \cdot \epsilon_j)$$

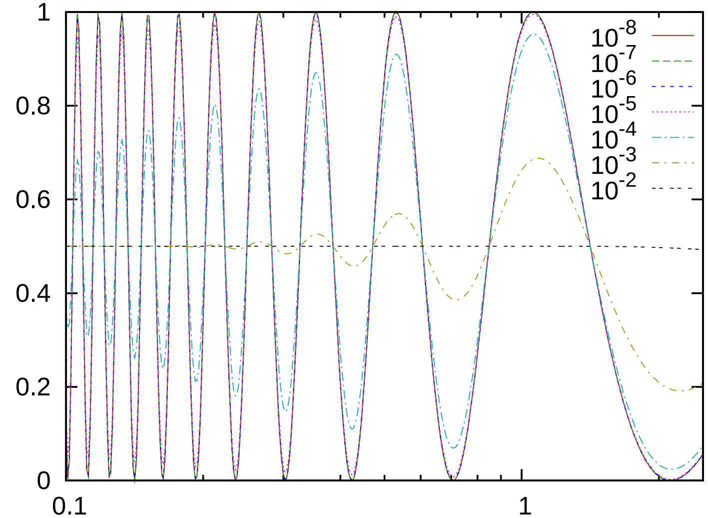
- f_j^i: fractional change in the predicted event rates in the $i-$th bin due to a variation of the paramter ϵ_j
- ϵ_j: systematic error parameters, which are varied to minimize χ^2 for each choice of the oscillation parameters

$$n = -1\text{:}\ \gamma(E) \propto 1/E$$

$P_{\mu\mu}$ vs. E (GeV) for some $\gamma = \beta$



Kamioka

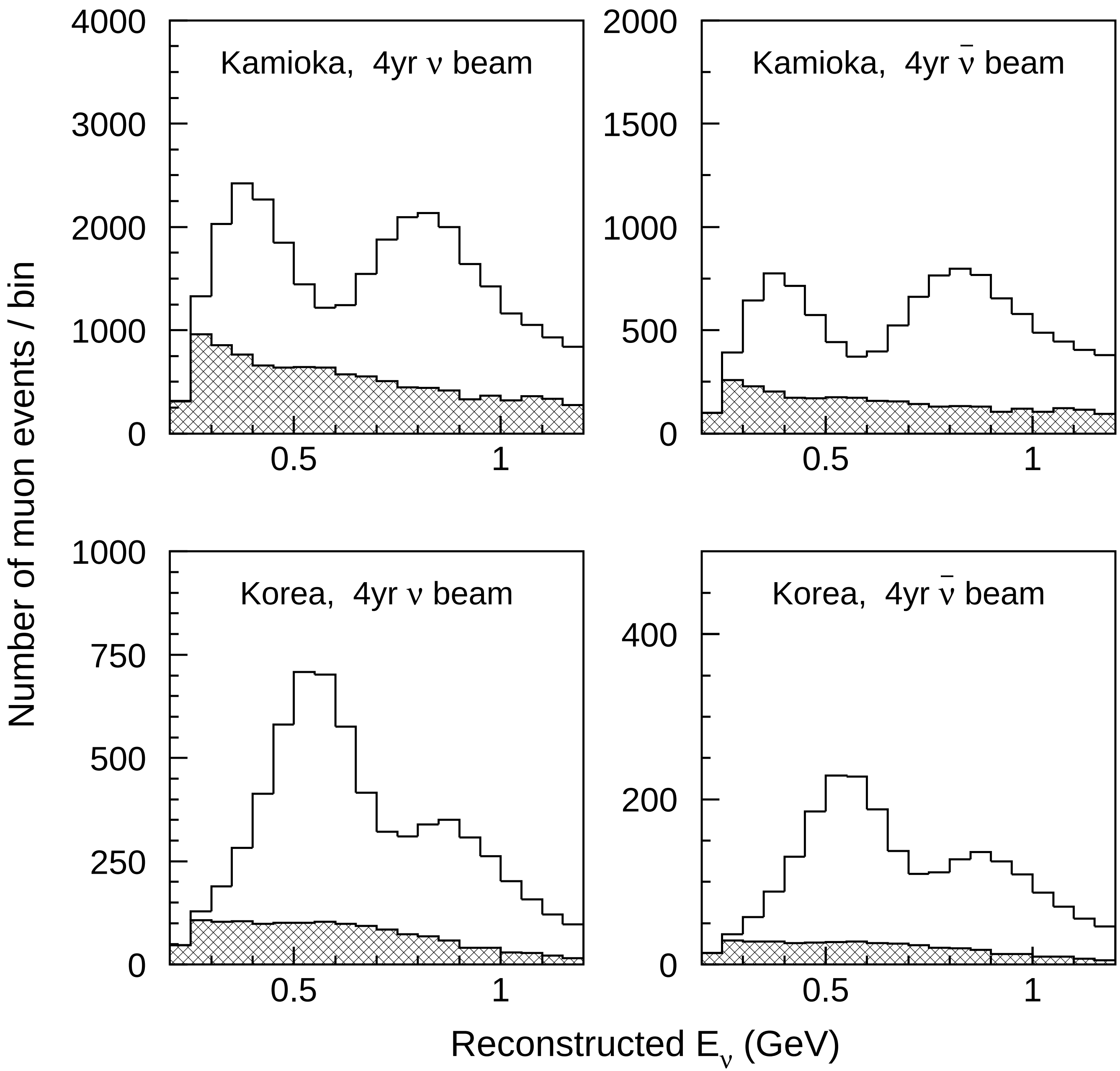


Korea

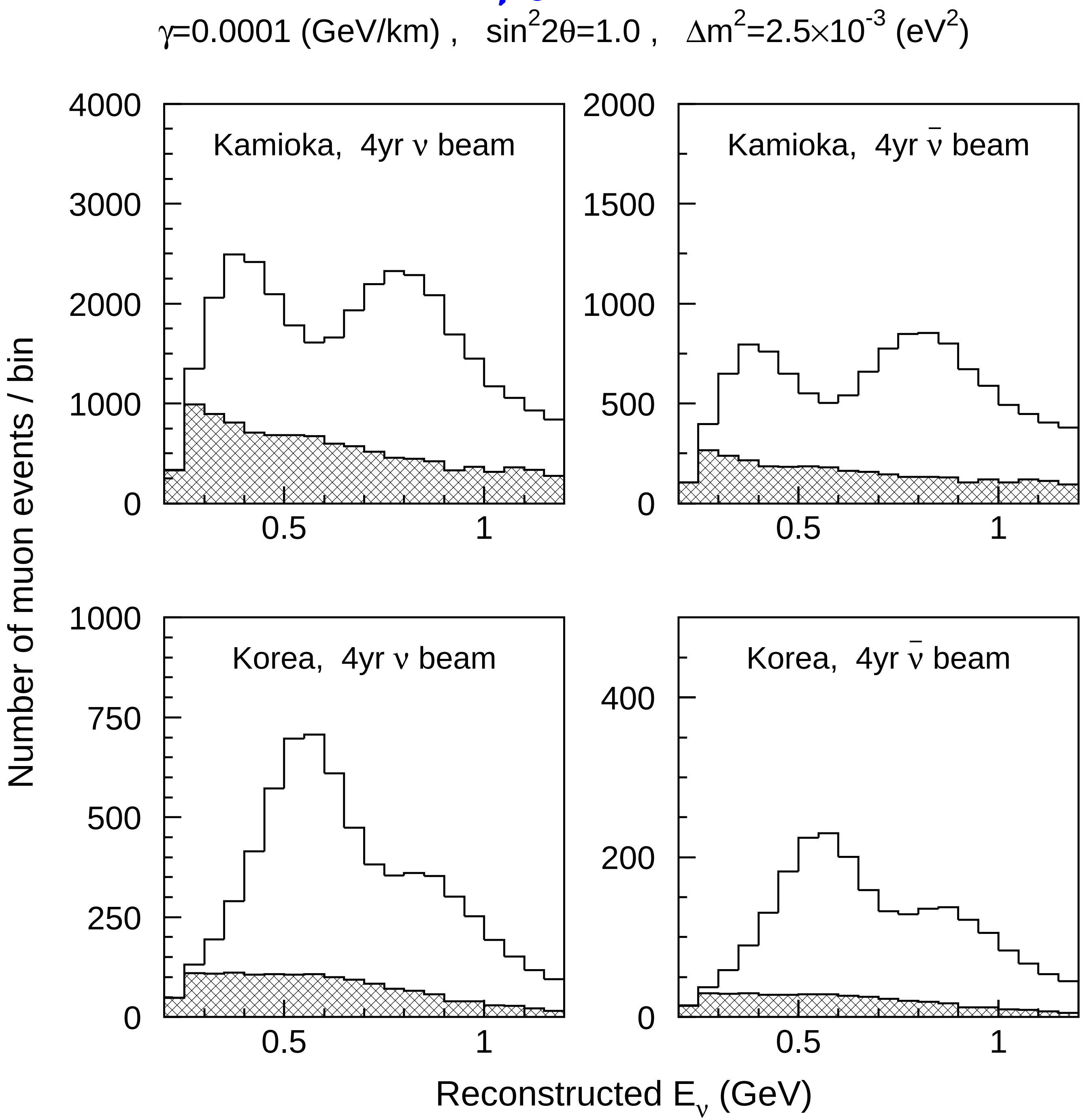
$\gamma = \beta = 10^{-4}$ already shows substantial damping and visible deviation from the conventional oscillations at low E

No Decoherence ($\gamma_0 = 0$)

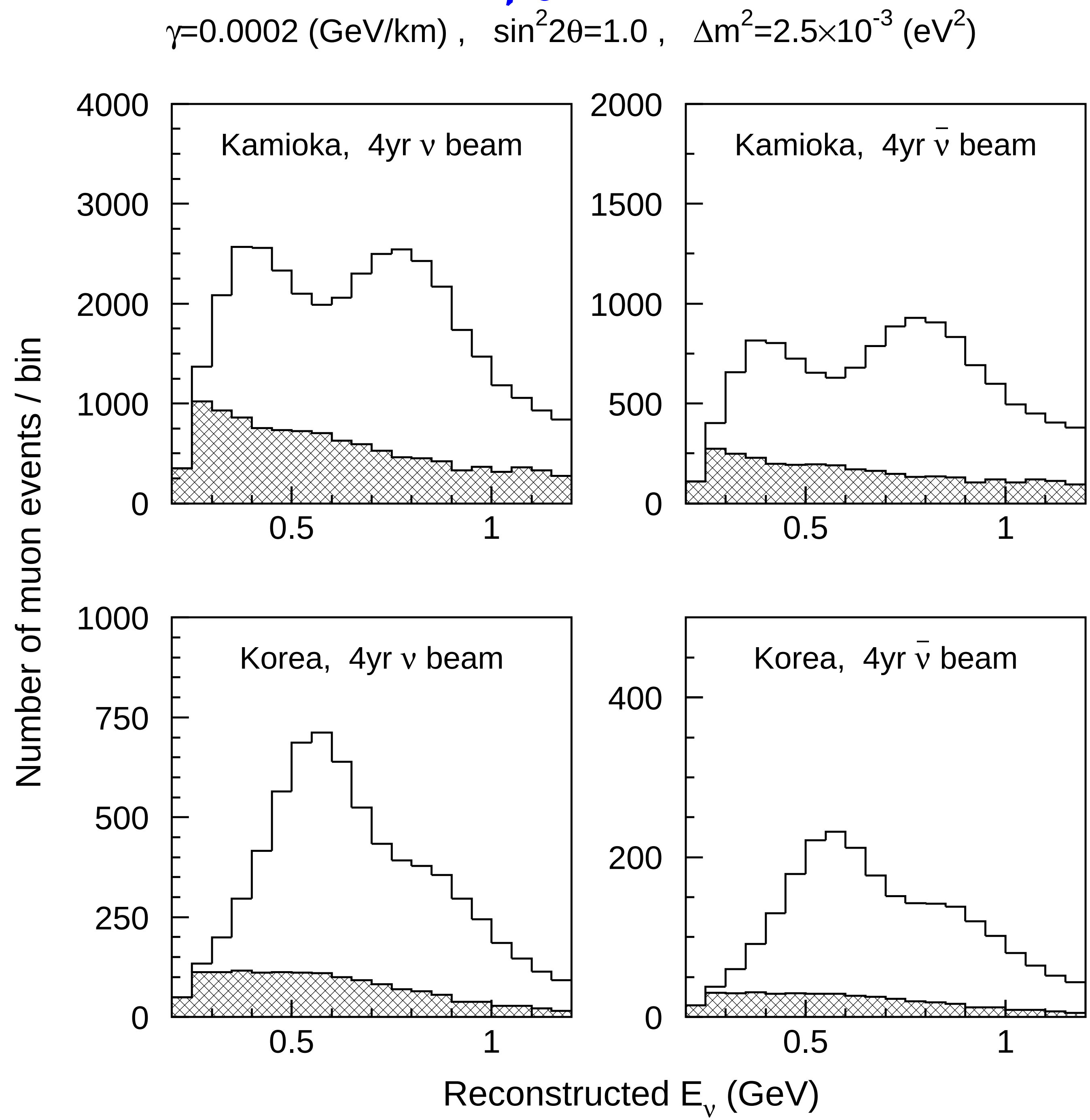
γ=0 (GeV/km) , $\sin^2 2\theta$=1.0 , Δm^2=2.5×10^{-3} (eV^2)



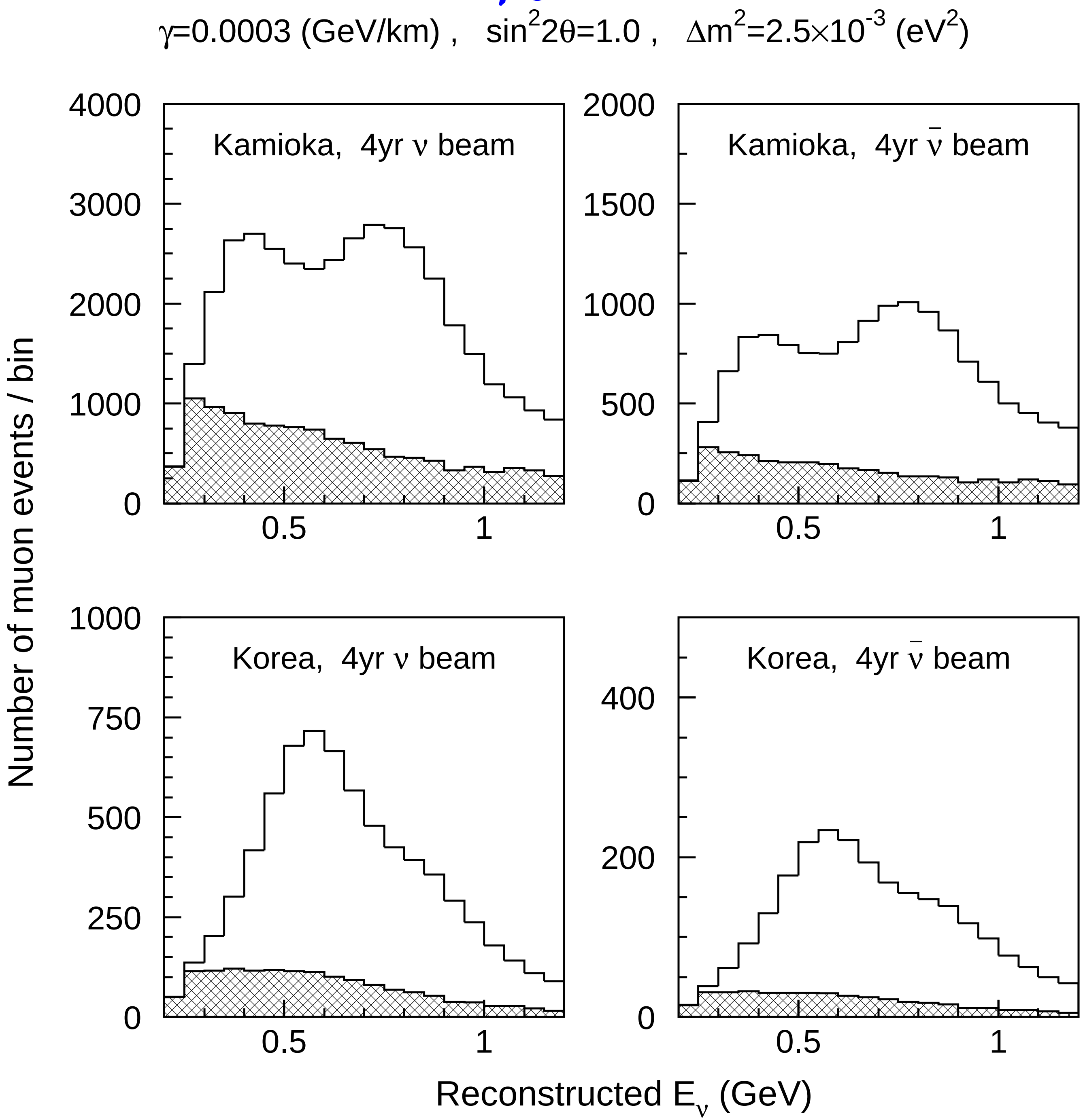
Decoherence with $\gamma_0 = 1 \times 10^{-4}$ GeV/km



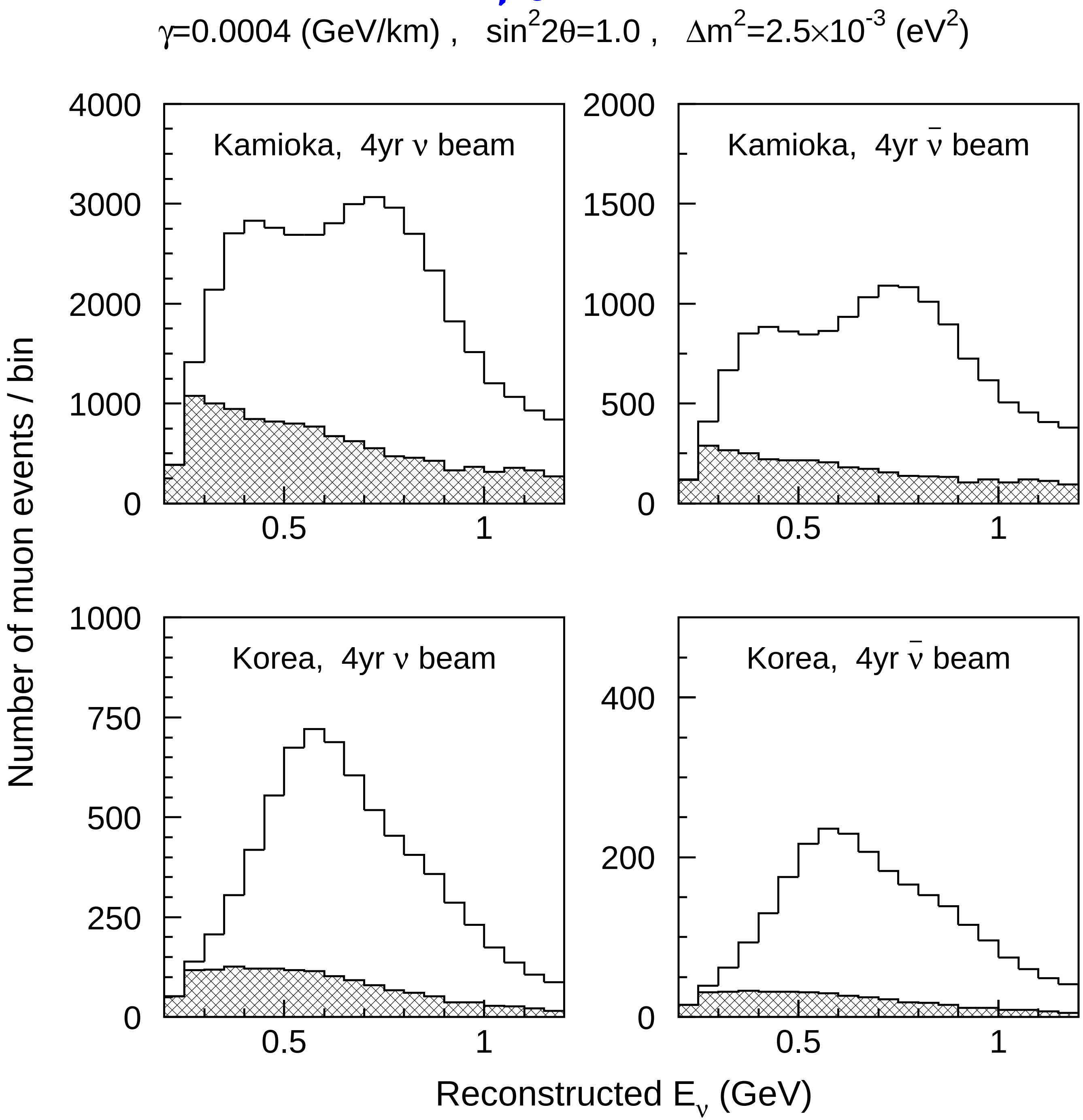
Decoherence with $\gamma_0 = 2 \times 10^{-4}$ GeV/km



Decoherence with $\gamma_0 = 3 \times 10^{-4}$ GeV/km



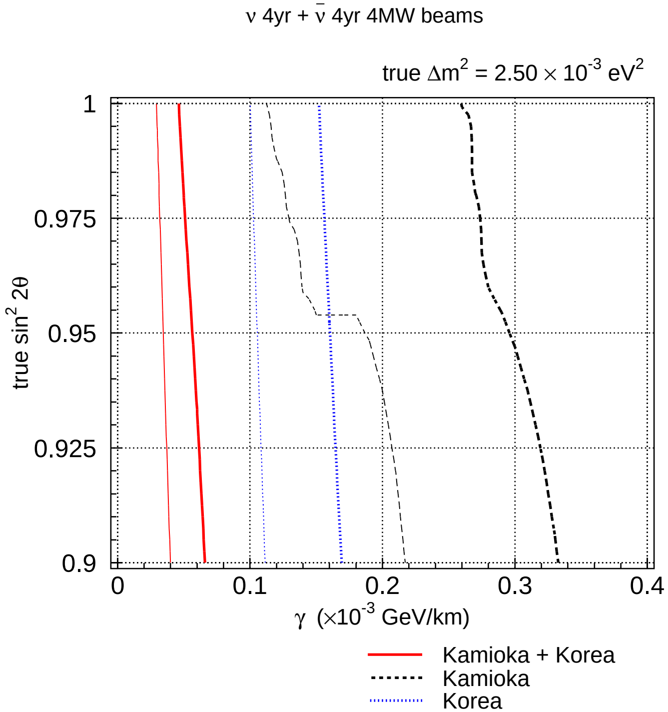
Decoherence with $\gamma_0 = 4 \times 10^{-4}$ GeV/km

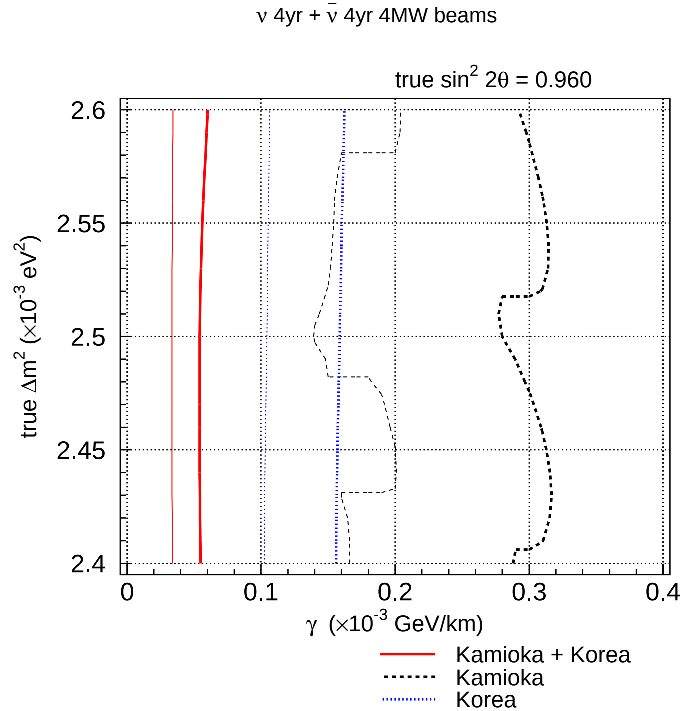


What if we have a far detector in Korea ?

- Qualitatively, we observe both the spectral distortion and the exponential suppressions in the number of events, if there is quantum decoherence, in addition to the conventional neutrino oscillations
- To say more quantitatively the sensitivity on the decoherence parameter β from T2KK experiments, we need to do χ^2 analysis
- More complete analysis including the uncertainties in Δm^2, θ is under way, and we will see the importance of having a detector in Korea in order to probe decoherence effects

Exclusion Plots

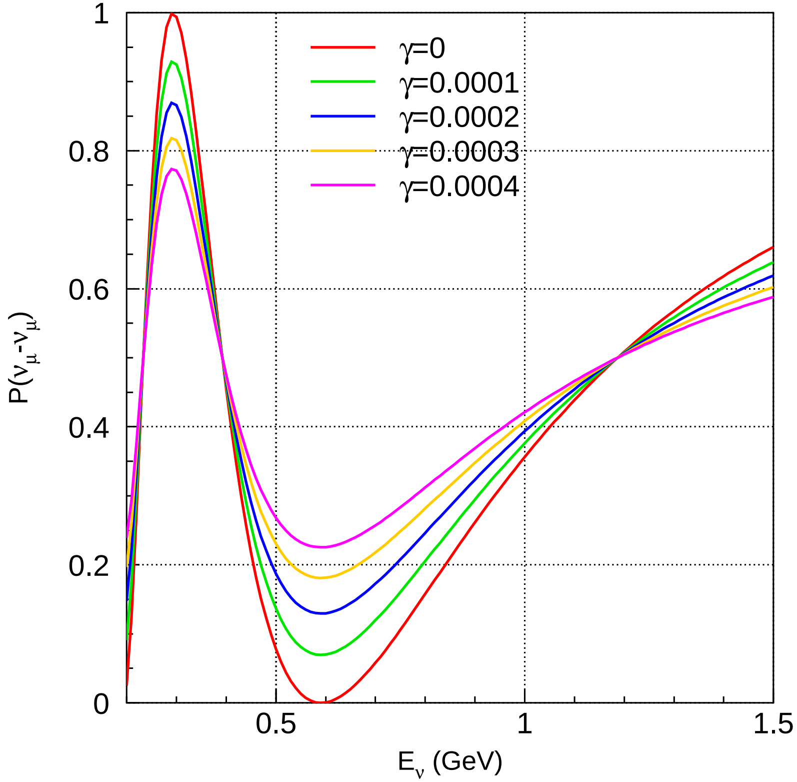




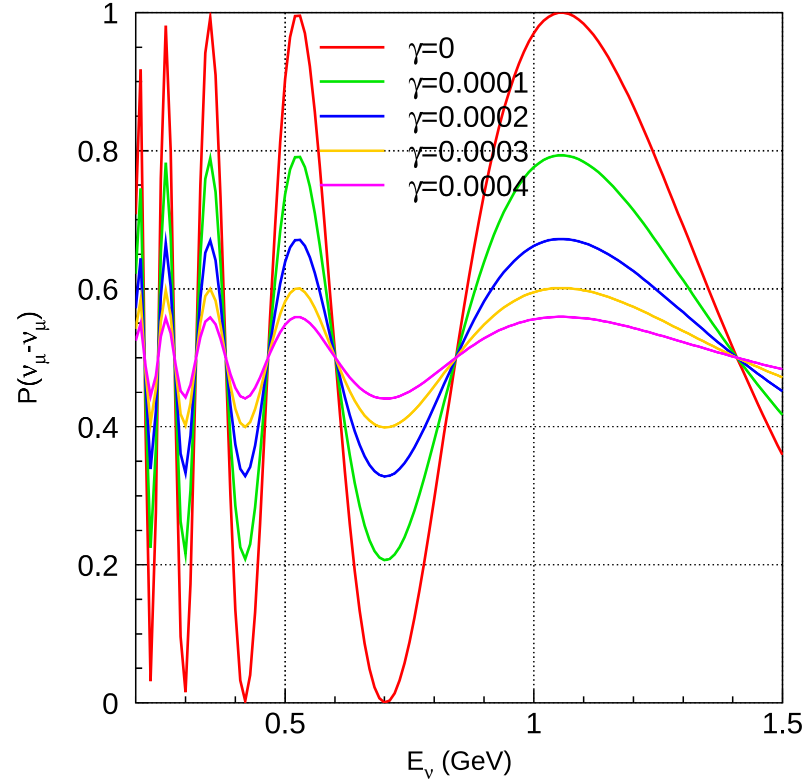
- Thin curve : 90 % CL ,   thick curve : 99 % CL
- $\gamma \lesssim 0.4(0.6) \times 10^{-4}$ GeV / km at T2KK,
  compared with $\gamma < 1.4(1.8) \times 10^{-4}$ GeV/km at T2K–II
  cf. Current bound: $\lesssim 1 \times 10^{-2}$ GeV/km
- T2KK is more powerful than T2K–II for $\gamma \sim 1/E$

$n = 0$**:** $\gamma(E) =$ **Constant**

$P_{\mu\mu}$ vs. E (GeV) for some γ_0 for $n = 0$



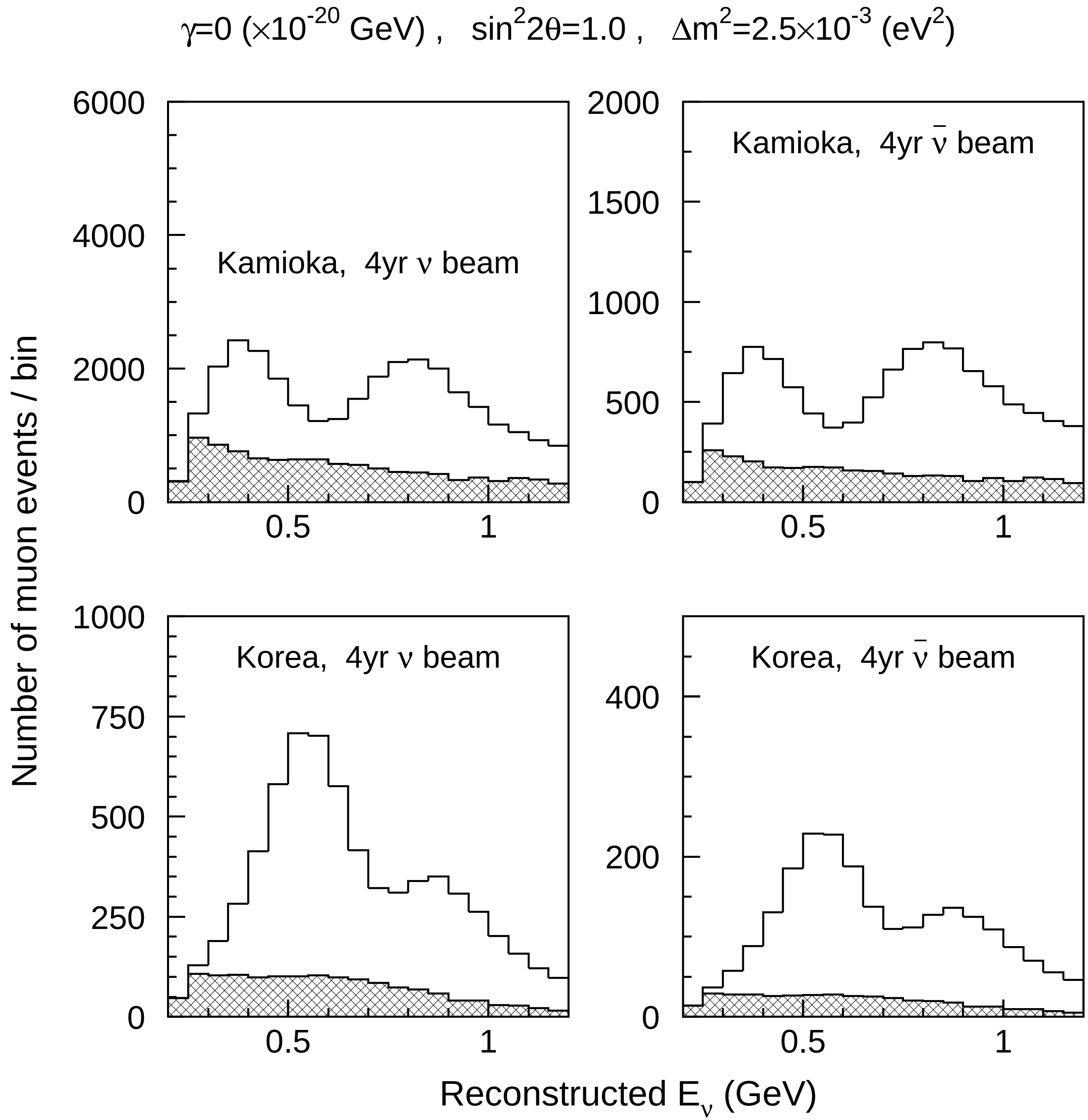
Kamioka



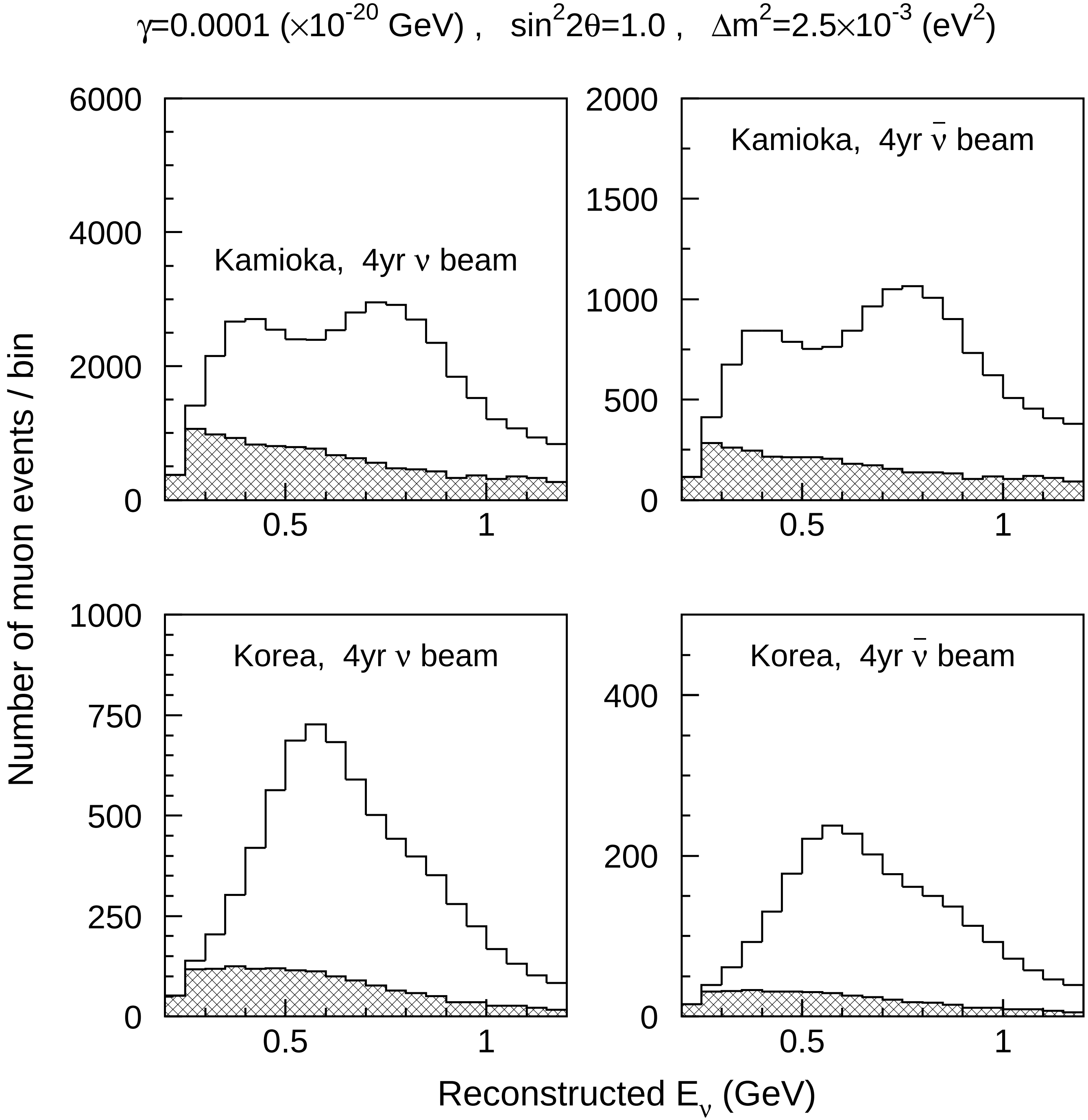
Korea

We assumed $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, and $\sin^2 2\theta = 1$

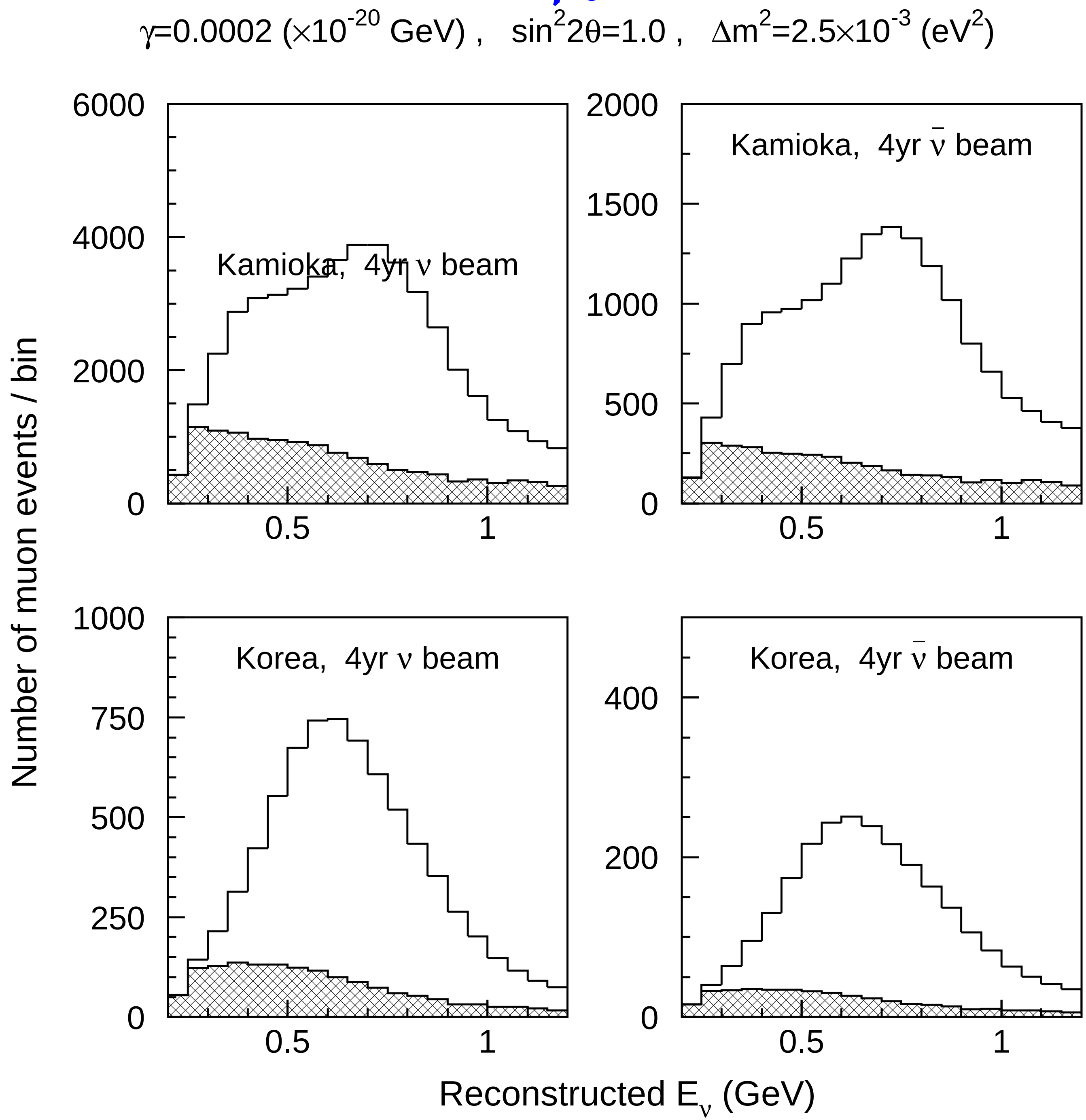
No Decoherence ($\gamma_0 = 0$)



Decoherence with $\gamma_0 = 1 \times 10^{-24}$ GeV

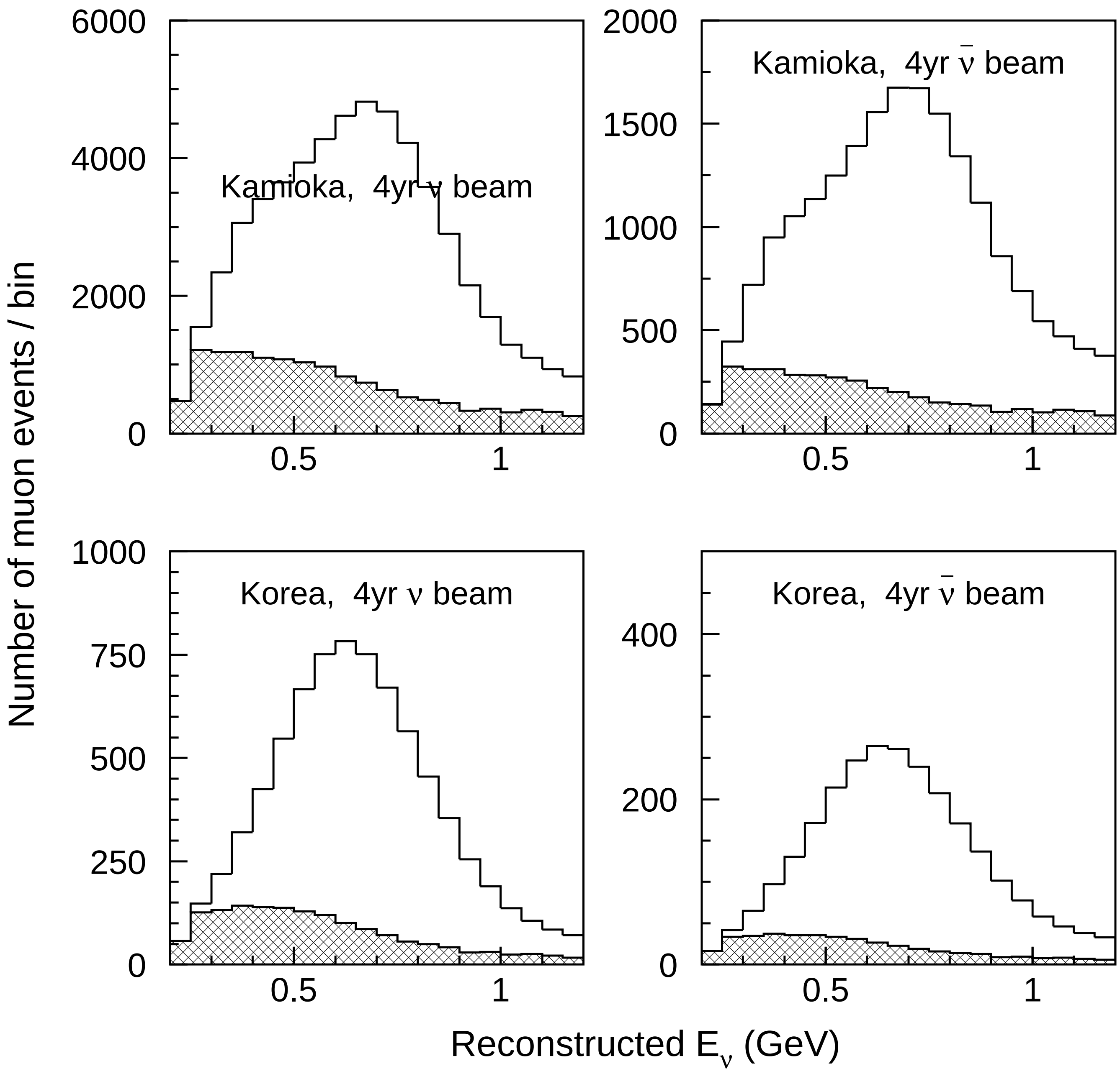


Decoherence with $\gamma_0 = 2 \times 10^{-24}$ GeV

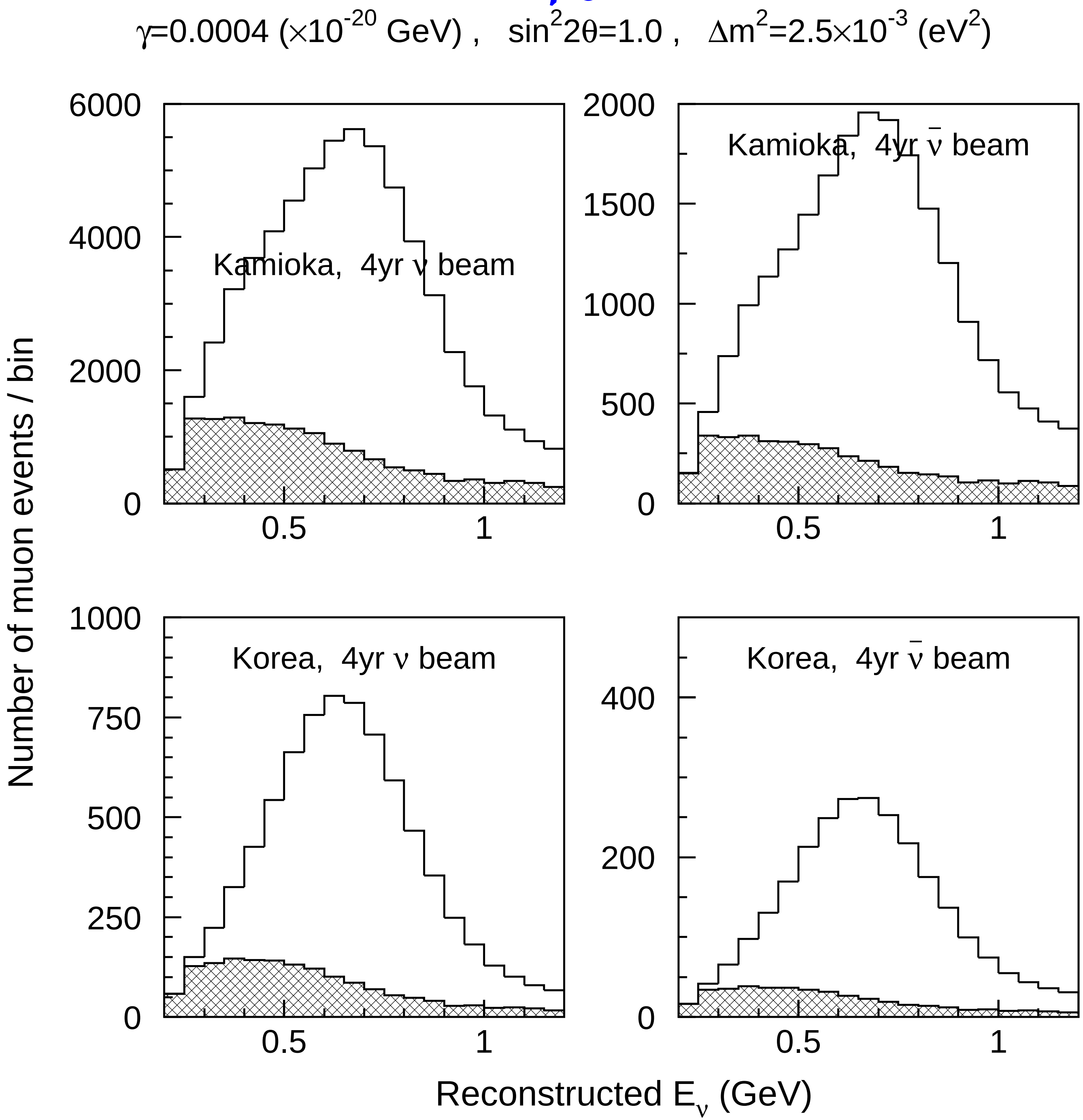


Decoherence with $\gamma_0 = 3 \times 10^{-24}$ GeV

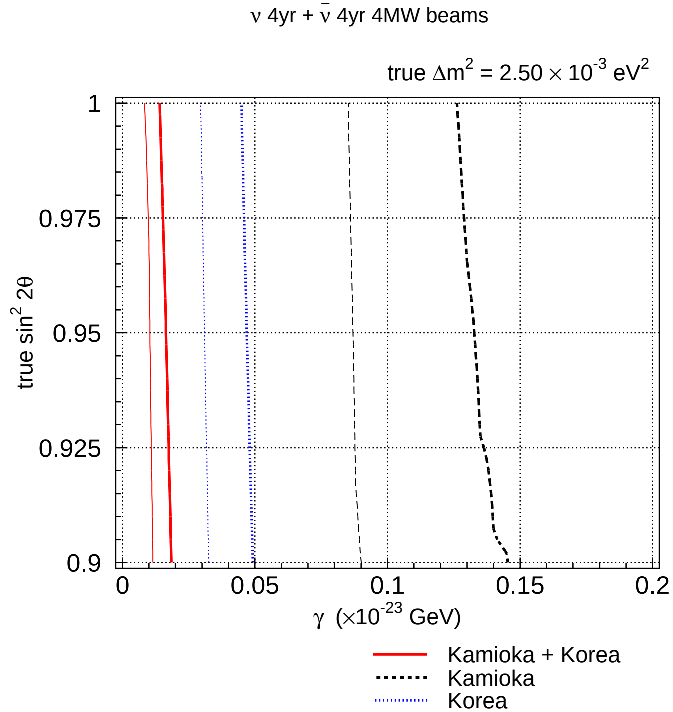
γ=0.0003 ($\times 10^{-20}$ GeV) , $\sin^2 2\theta$=1.0 , $\Delta m^2 = 2.5 \times 10^{-3}$ (eV^2)

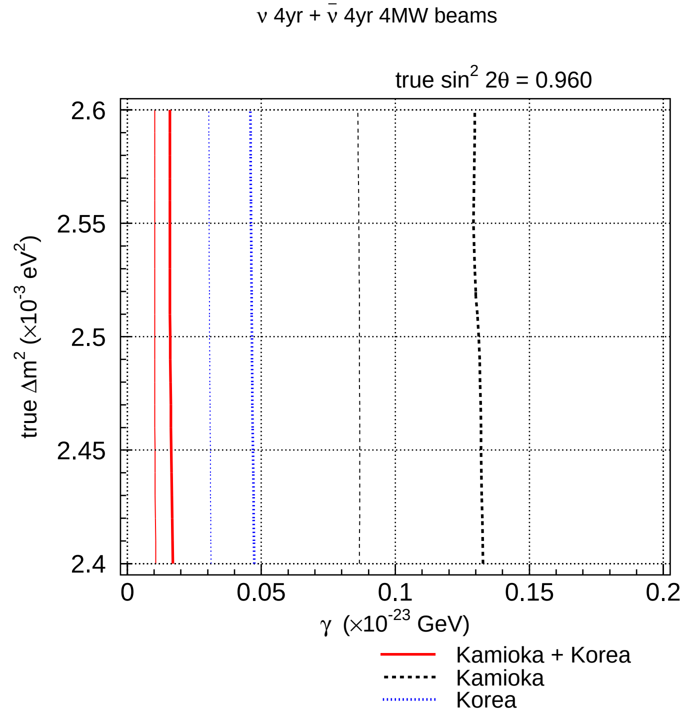


Decoherence with $\gamma_0 = 4 \times 10^{-24}$ GeV



Exclusion Plots





- $\gamma \lesssim 0.1(0.2) \times 10^{-24}$ GeV at T2KK, compared with $\gamma < 0.9(1.6) \times 10^{-24}$ GeV at T2K–II, due to longer L
  Current bound 3.5×10^{-23} GeV
- T2KK is more powerful than T2K–II alone for $\gamma =$Constant

$$n = \mathbf{2}\text{:}\ \gamma(E) \propto E^2$$

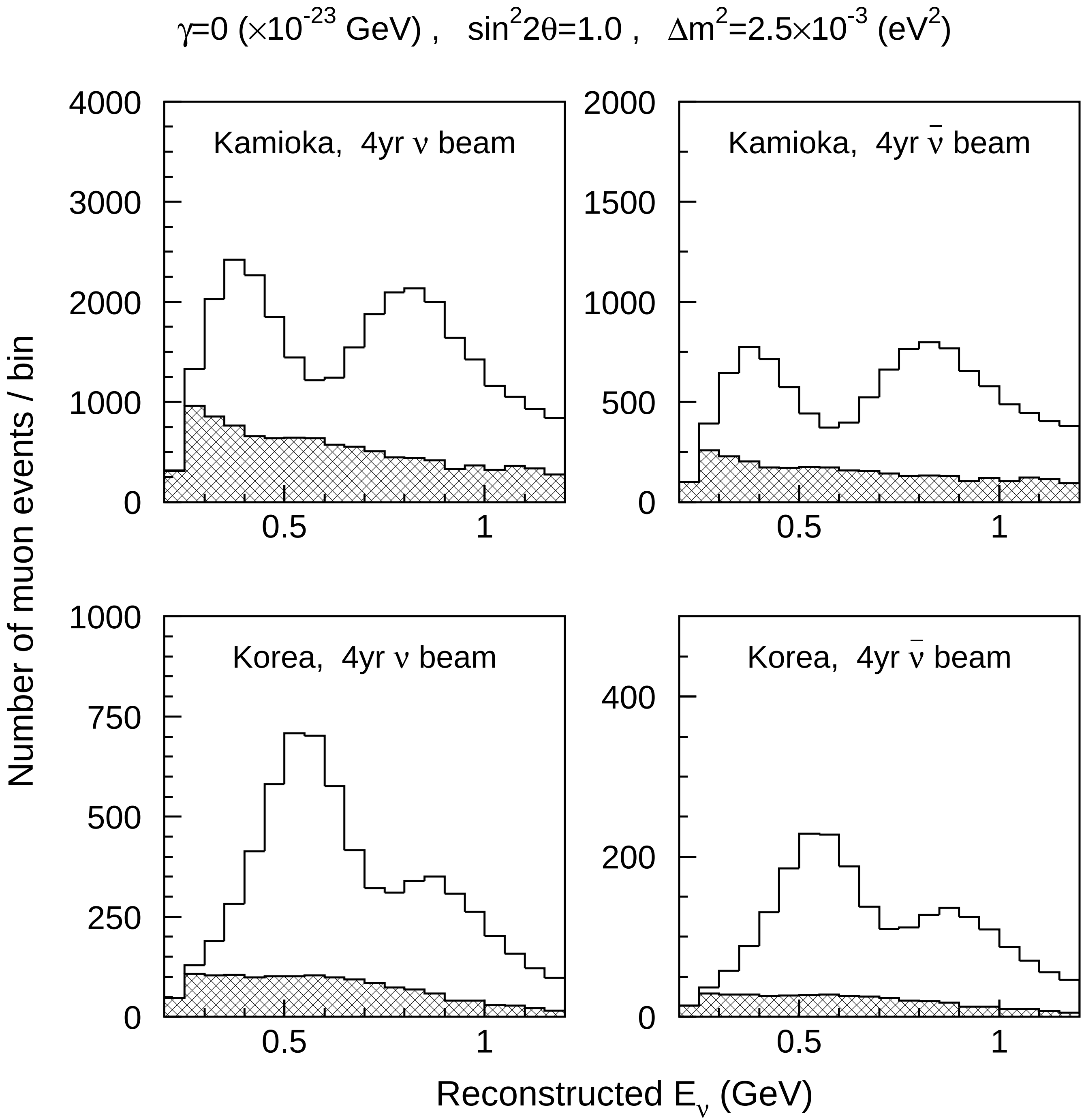
$P_{\mu\mu}$ vs. E (GeV) for some γ_0 for $n = 2$

- Not so competetive with SK, since Energy E and length L at T2K(K) are smaller than SK ($E \lesssim 10^3$ GeV, and $L \lesssim 10^5$ km)

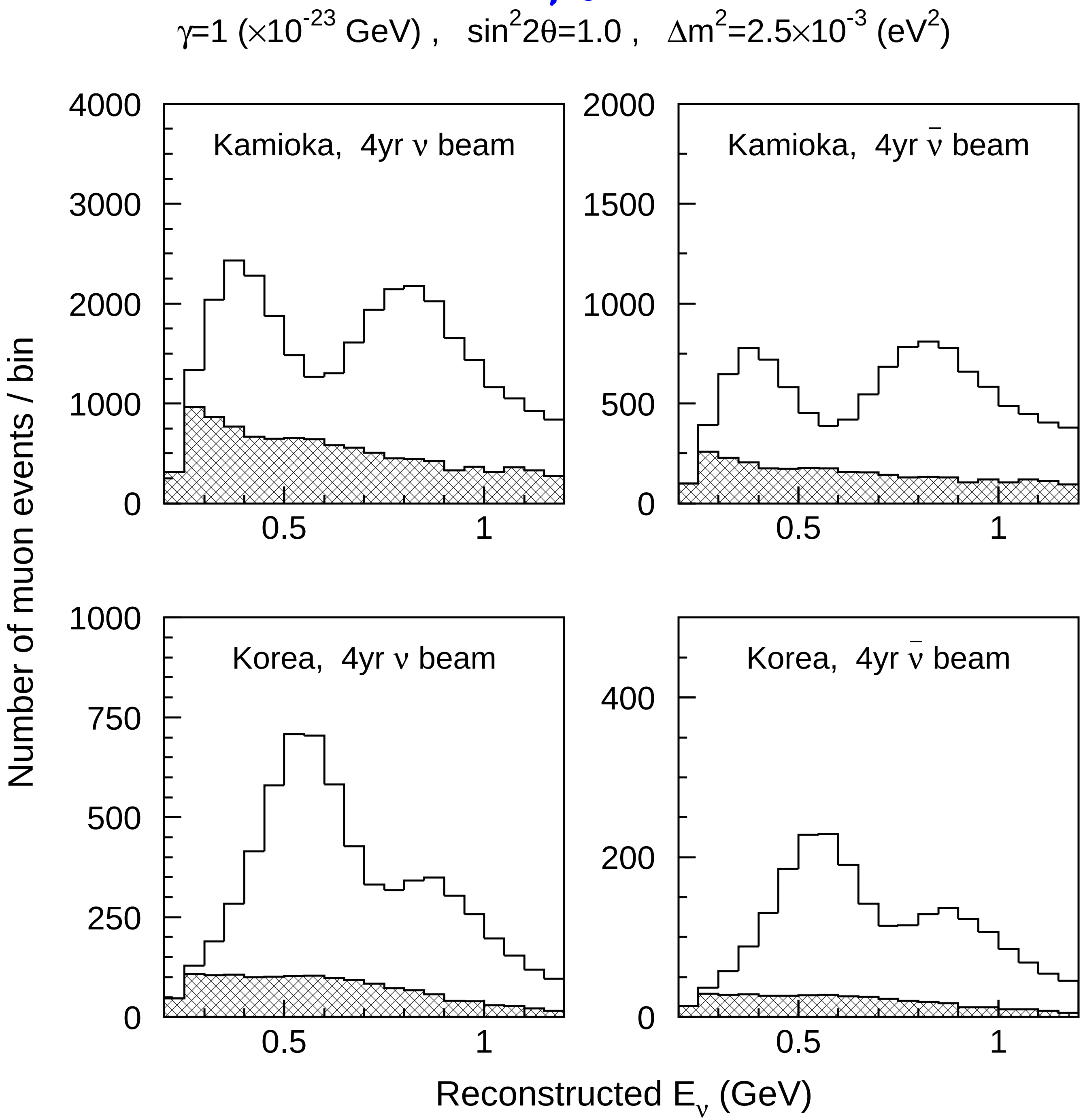
  cf.) Remember the damping factor is $\sim e^{-\gamma_0 E^2 L}$

  - T2KK : $E \lesssim 1$ GeV and $L \sim 300 - 1000$ km
  - SK : E upto $\sim$ 1 TeV and $L \sim 10^4$ km
- Therefore, more dampling at SK than at T2KK, and SK is more sensitive to $\gamma \sim E^2$

No Decoherence ($\gamma_0 = 0$)

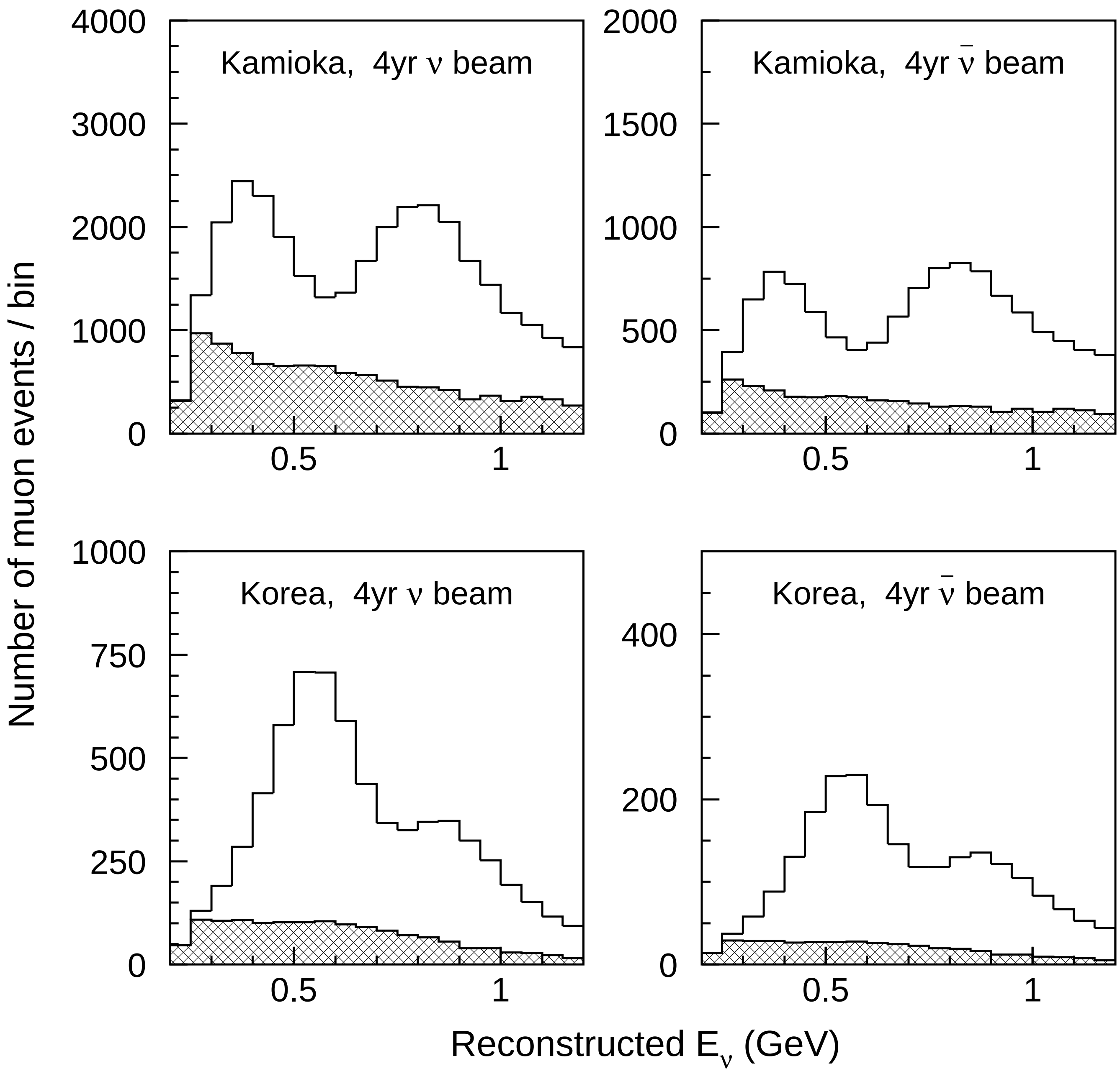


Decoherence with $\gamma_0 = 1 \times 10^{-24}$ GeV



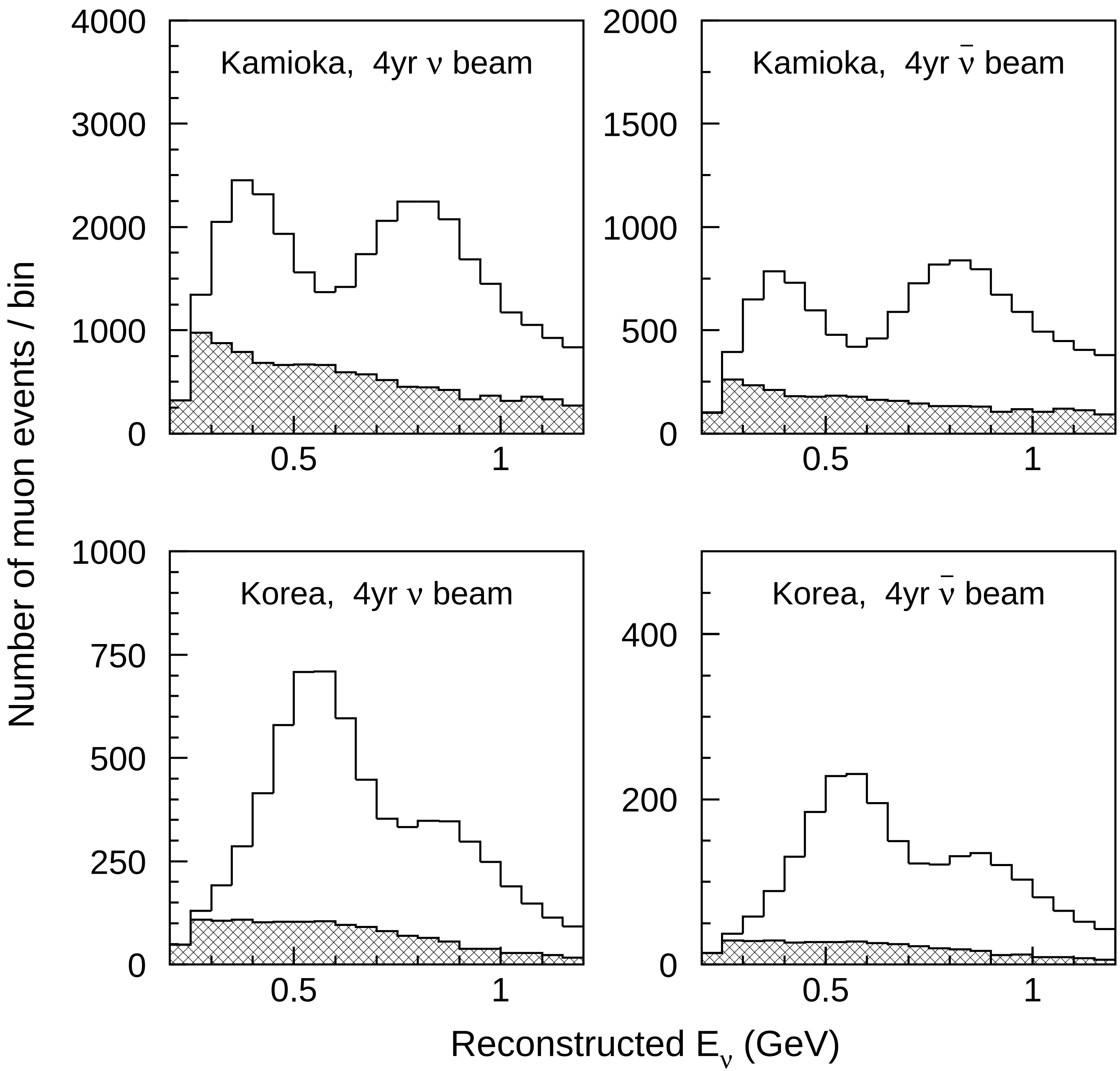
Decoherence with $\gamma_0 = 2 \times 10^{-24}$ GeV

γ=2 ($\times 10^{-23}$ GeV) , $\sin^2 2\theta$=1.0 , Δm^2=2.5$\times 10^{-3}$ (eV^2)

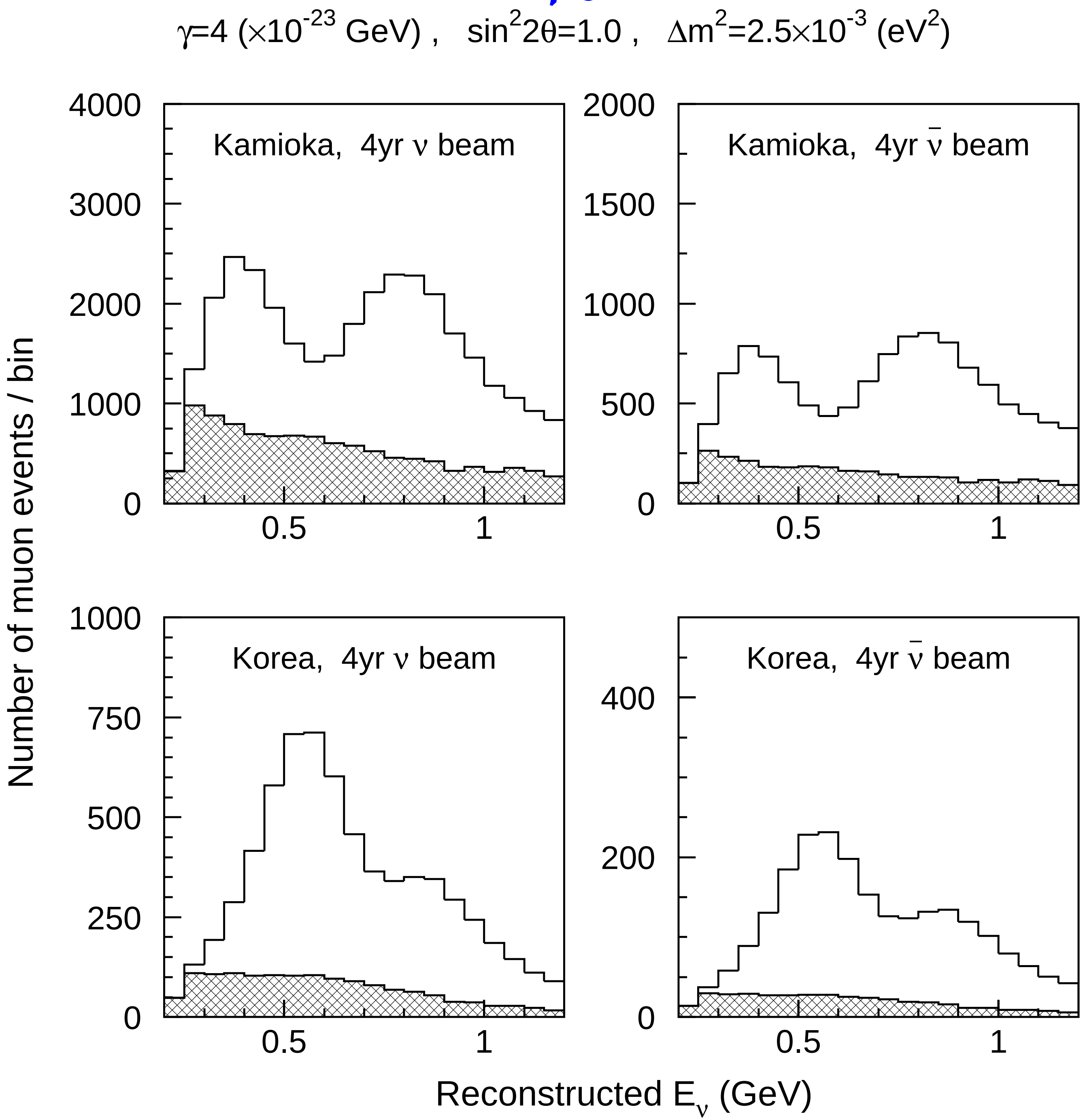


Decoherence with $\gamma_0 = 3 \times 10^{-24}$ GeV

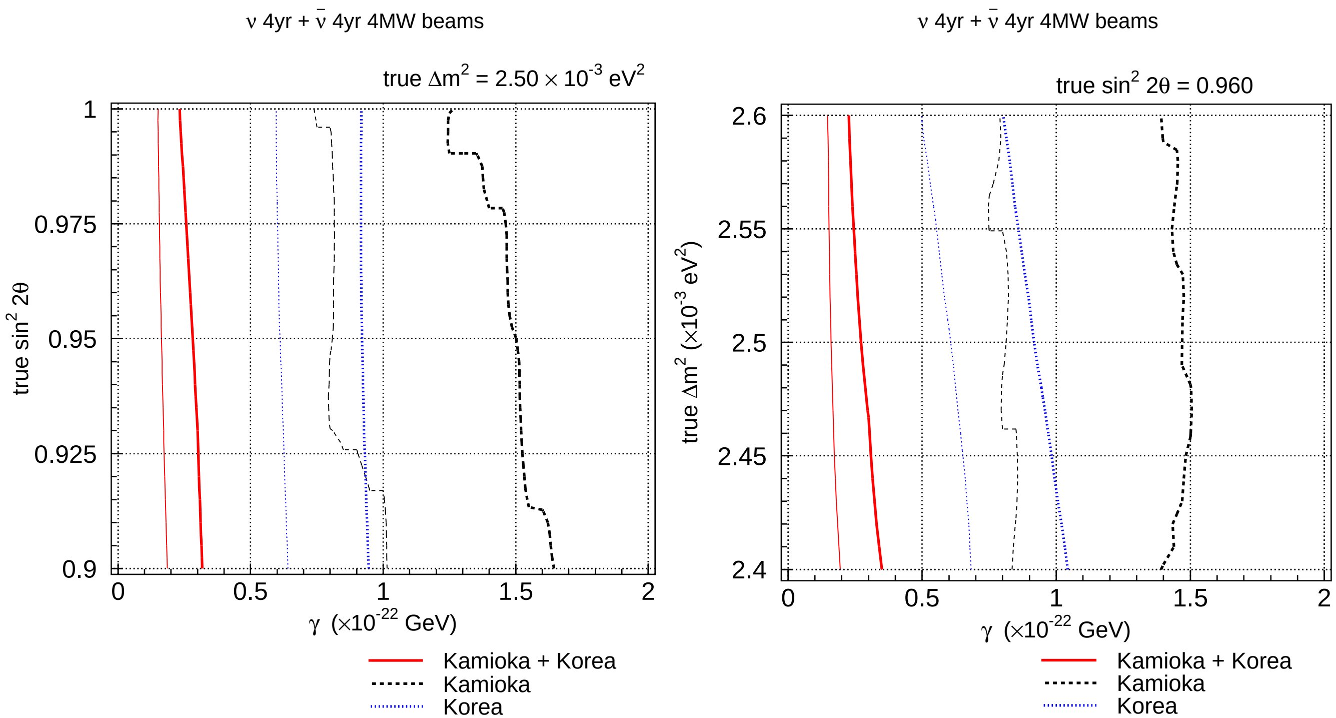
γ=3 ($\times 10^{-23}$ GeV) , $\sin^2 2\theta$=1.0 , Δm^2=2.5$\times 10^{-3}$ (eV^2)



Decoherence with $\gamma_0 = 4 \times 10^{-24}$ GeV



Exclusion Plots



- Roughly $\gamma < 2(3) \times 10^{-23}$ GeV at T2KK
  Current bound : $< 0.9 \times 10^{-27}$ GeV
- T2KK is more powerful than T2K–II alone for $\gamma \sim E^2$
- Less powerful than SK, due to the limited $E_\nu \lesssim 1$ GeV, whereas $E_\nu \lesssim 1$ TeV at SK and $L \lesssim 10^4$ km

$$\gamma(E) = \gamma_0 / L$$

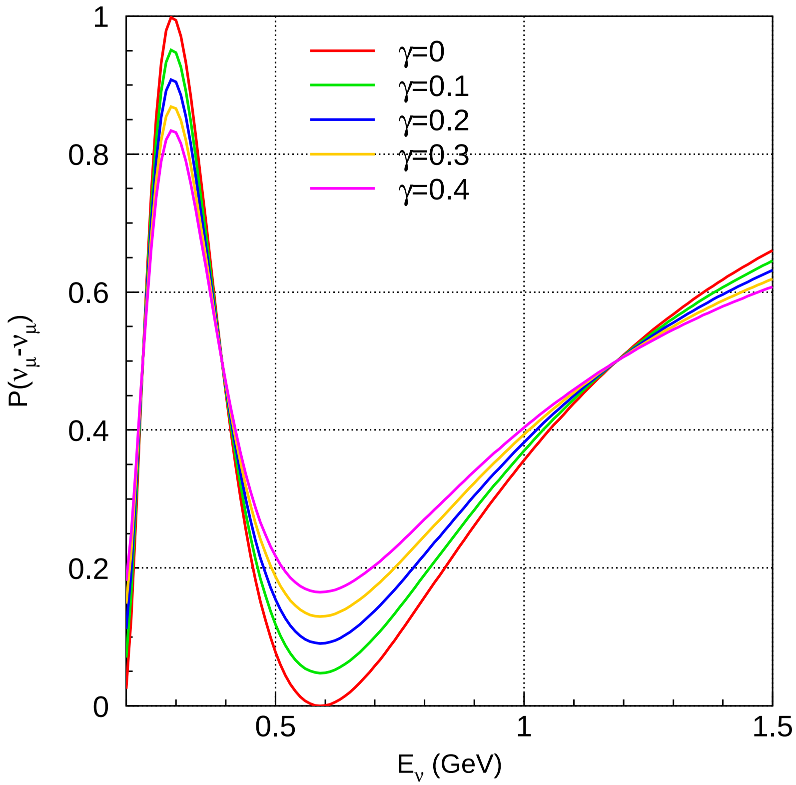
$\gamma \sim 1/L$ (?)

- Barenboim et al. showed that all the ν data, including the LSND, the spectral distribution of KAMLAND and SK, can be fit, if

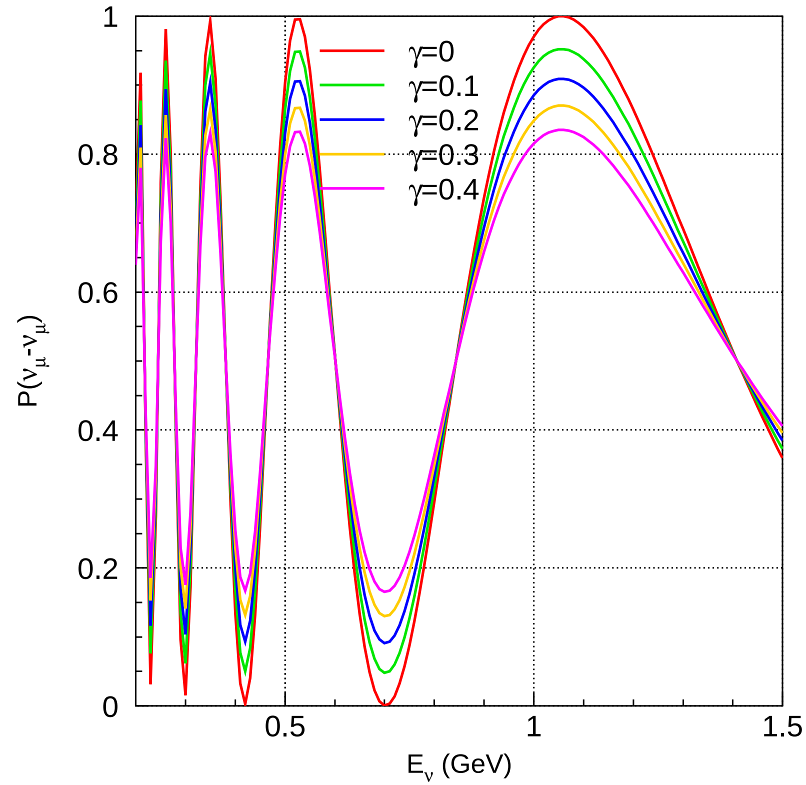
$$\gamma \sim 1.2 \times 10^{-2}/L(\mathrm{km})$$

  in some channels (not all the channels)
- Exponential suppression independent of oscillation length
- They argue it is too large to be quantum gravity effects
- Still worthwhile to think about this scenario, and try to test this at another ν experiments

$P_{\mu\mu}$ vs. E (GeV) for some γ_0



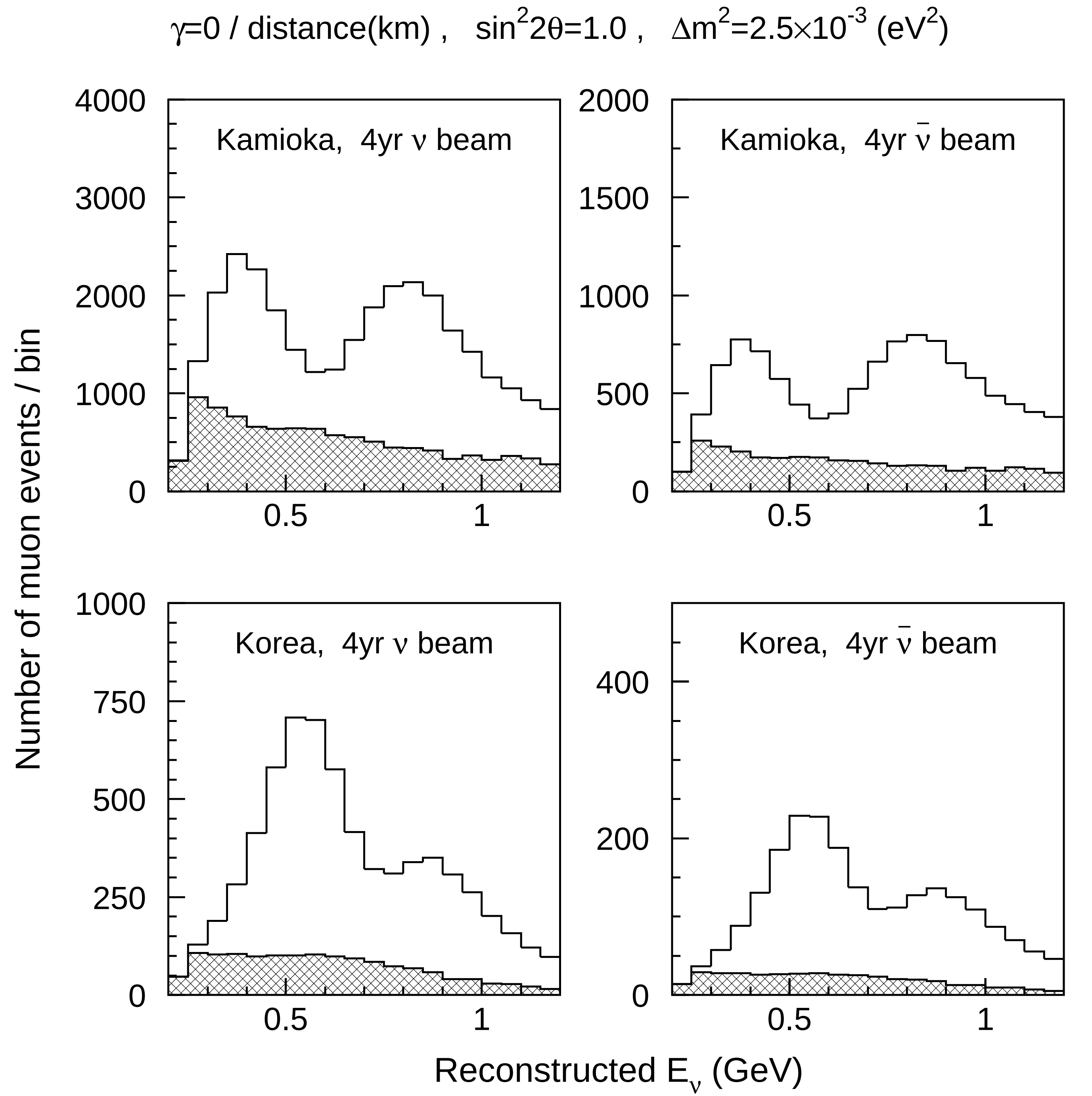
Kamioka



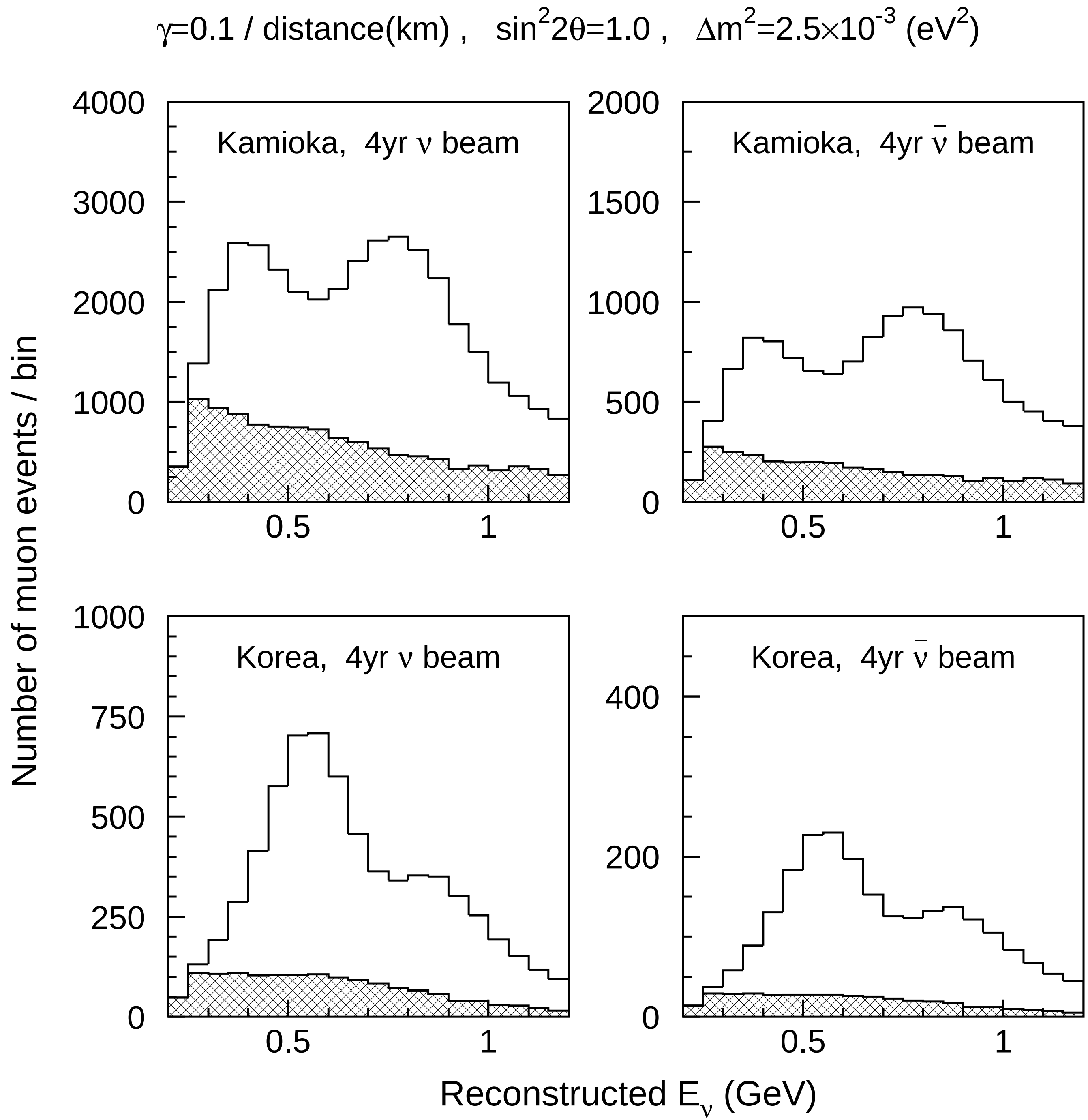
Korea

We assumed $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, and $\sin^2 2\theta = 1$

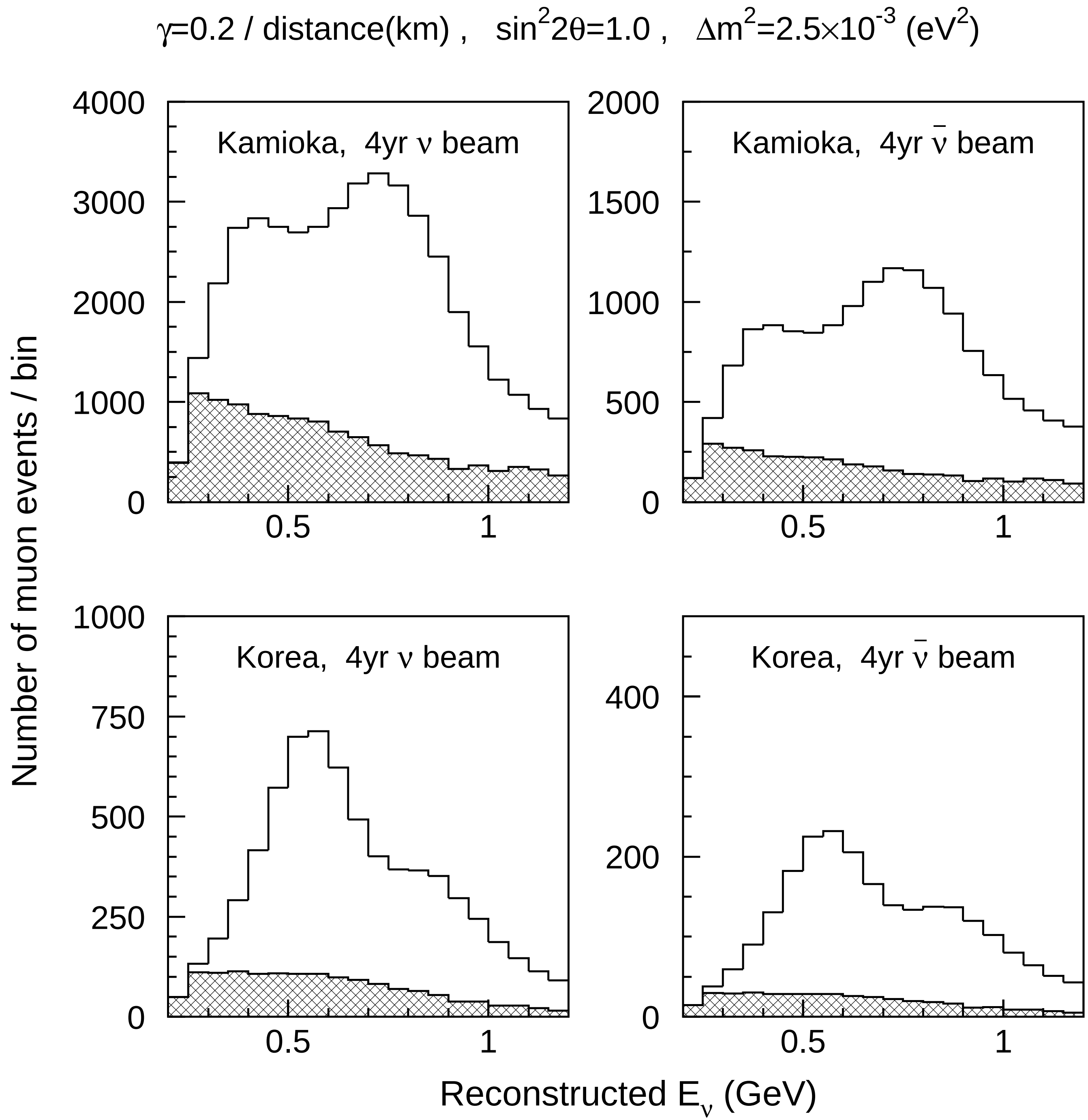
No Decoherence ($\gamma = 0$)



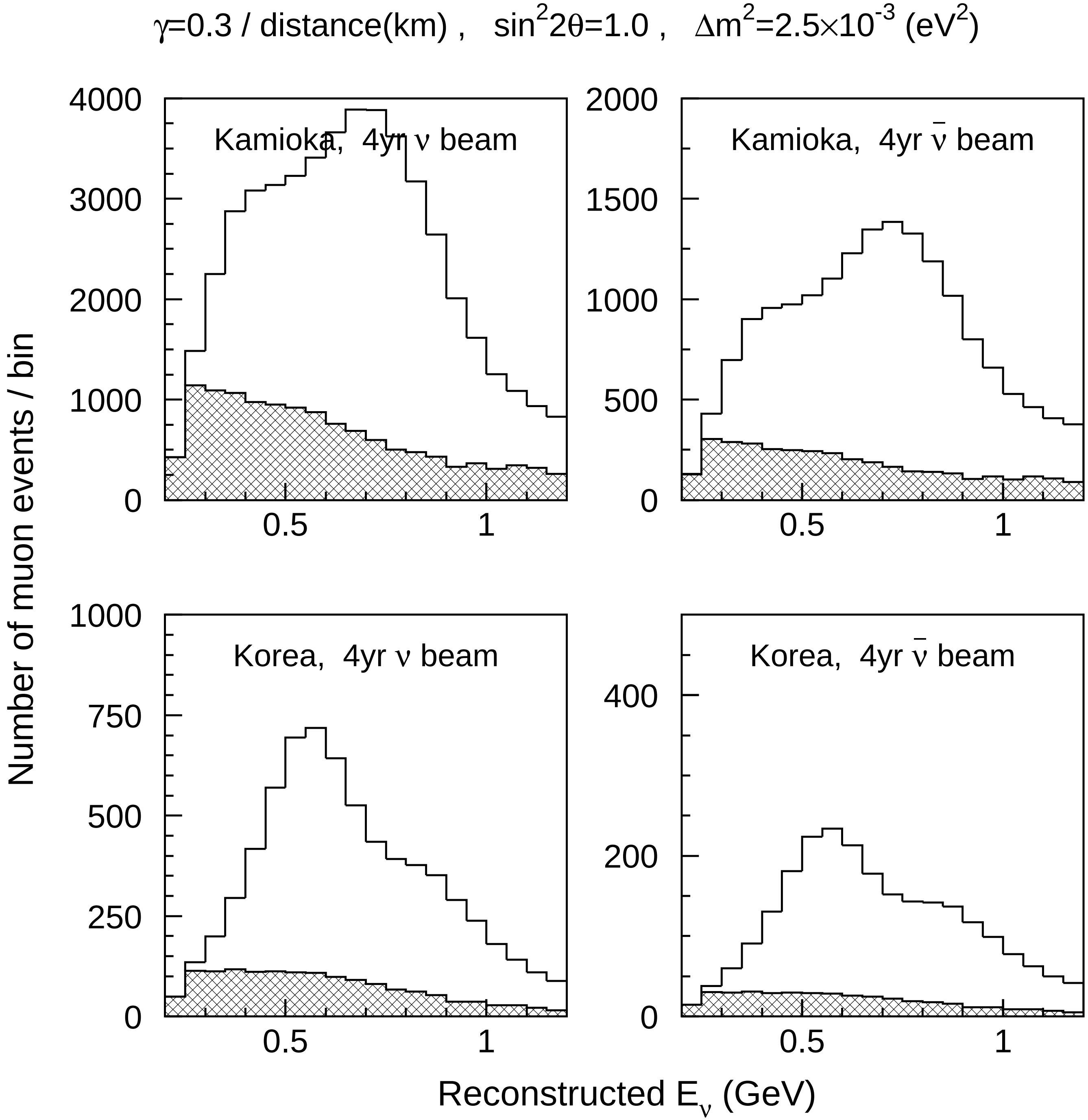
Decoherence with $\gamma = 0.1/L$ (km)



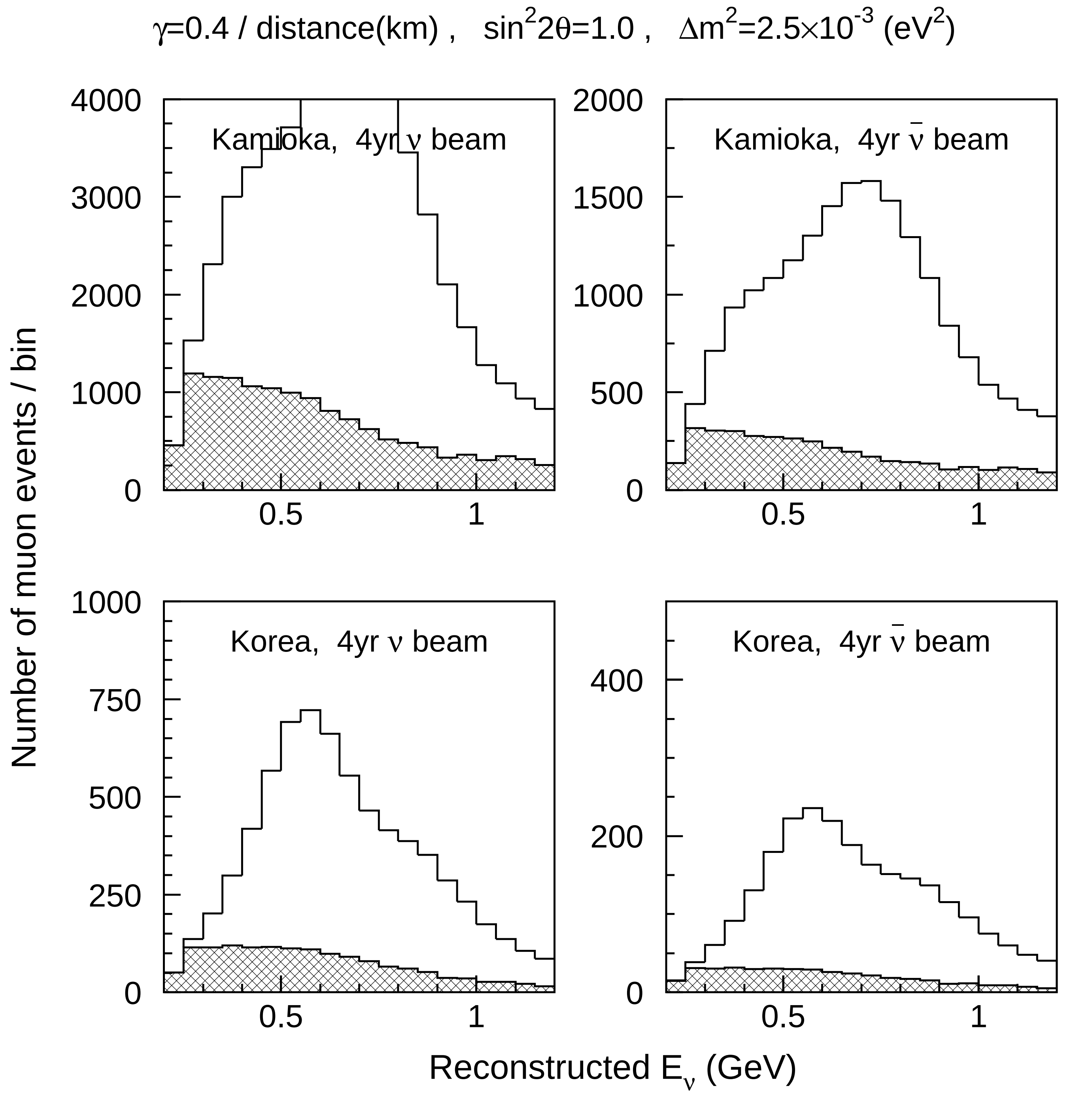
Decoherence with $\gamma = 0.2/L$ (km)



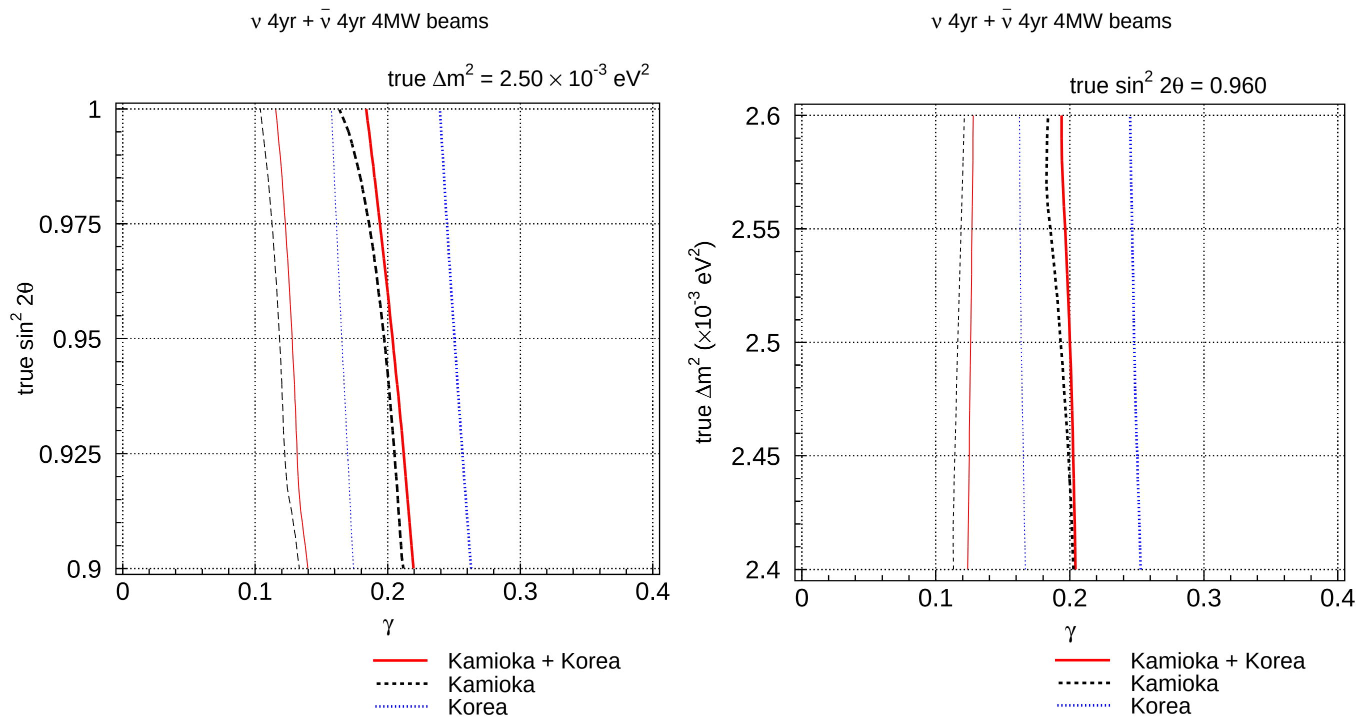
Decoherence with $\gamma = 0.3 / L$ (km)



Decoherence with $\gamma = 0.4 / L$ (km)



Exclusion Plots



- $\gamma \lesssim 0.12$ at T2KK
- T2KK $\sim$ T2K–II alone for $\gamma \sim 1/L$
- Cannot probe down to $\gamma_0 \sim 1.2 \times 10^{-2}$
- How can we test this scenario ???

Summary Table for QD

Models	Curent bound	T2K-II	T2KK
$\gamma =$ (const.)	$< 3.5 \times 10^{-23}$	0.9×10^{-24}	0.1×10^{-24}
$\gamma \sim 1/E$	$< 2.0 \times 10^{-21}$	2.8×10^{-23}	0.8×10^{-23}
$\gamma \sim E^2$	$< 0.9 \times 10^{-27}$	8×10^{-23}	2×10^{-23}
$\gamma \sim 1/L$	$\approx 1.2 \times 10^{-2}$	$\lesssim 0.1$	$\lesssim 0.12$

Table 1: Present 90 % CL upper bounds on γ_0's, as well as the bounds from T2K-II and T2KK for various forms of the QD parameter γ_0's

cf. Higuchi-san's talk : $\gamma_0 < 1.4 \times 10^{-22}$ GeV from SK L/E data

Test of CPT violation

Recall the usual QFT

Assumptions

- 4-dim flat spacetime with Lorentz symmetry
- Locality: local interactions
- Unitarity: Existence of unitary S matrix

Consequences

- Spin-Statistic Theorem
- CPT Symmetry: $m_n = m_{\bar{n}}$, $\tau_n = \tau_{\bar{n}}$
  cf) Partial decay widths for n and $\bar{n}$ may differ
  $\longrightarrow$ Signatures of CP violation

Possible Violation of CPT

- Classical/quantum gravity can lead to CPT violation
- $m_n \neq m_{\bar{n}}, \quad \tau_n \neq \tau_{\bar{n}}$
- Implications in the neutrino physics :
  - $\Delta m^2_\nu \neq \Delta m^2_{\bar{\nu}}$ and $\theta \neq \overline{\theta}$
  - A possible resolution of the LSND within 3 light neutrino flavors (Barenboim and Lykken, ...)
- Survival Probability

$$P_{\mu\mu} = 1 - \sin^2 2\theta \; \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- For $\bar{\nu}$, replace by $\Delta\overline{m}^2$ and $\bar{\theta}$
- We can test this scenario at T2K(K)
  (Sorry, plots are not ready yet)

Lorentz Symmetry Violation

Possible violation of Lorentz symmetry

- Within the QFT, one can study spontaneous violation of Lorentz symmetry due to nonvanishing VEV's of some vector or tensor fields
- Most notably by Coleman and Glashow, and in a series of works by Kostelecky and collborators
- CPT could be either conserved or violated in this scheme
- For example, a violates both CPT and Lorentz sym., whereras c terms violate only Lorentz symmetry

$$\mathcal{L} = a_{\mu AB}\overline{L}_A\gamma^\mu L_B + \frac{i}{2} c_{\mu\nu AB}\left[\overline{L}_A\gamma^\mu D_\nu L_B - (D_\nu\overline{L}_A)\gamma^\mu L_B\right]$$

- Assume rotational symmetry : two possibilities with $A = B = 0$

Modified Neutrino Oscillations

- Modified $E - p$ dispersion relation:

$$\frac{m^2(=mm^\dagger)}{2p} \longrightarrow cp + \frac{m^2}{2p} + b$$

c: CPT conerving maximal v (3×3 hermitian)
b: CPT violating interaction (3×3 hermitian)

- Consider 2 generation case
(Coleman & Glashow; Barger et al.; Kostelecky,....)

$$\begin{aligned} P_{\mu\mu} &= 1 - \sin^2 2\Theta \ \sin^2(\Delta L/4) \\ \Delta \sin 2\Theta &= |\frac{\Delta m^2}{E} \sin 2\theta_m + 2\delta b e^{i\eta} \sin 2\theta_b + 2\delta c e^{i\eta'} E \sin 2\theta \\ \Delta \cos 2\Theta &= \frac{\Delta m^2}{E} \cos 2\theta_m + 2\delta b \cos 2\theta_b + 2\delta c E \cos 2\theta_c \end{aligned}$$

Special Case of Foot, Leung, Yoshida

- Consider $\theta_m = \theta_b = \theta_c = \theta, \quad \eta = \eta^{'} = 0$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \ \sin^2 \left[L \left(\frac{\Delta m^2}{4E} + \frac{\delta b}{2} + \frac{\delta c E}{2} \right) \right]$$

- A simple and interesting modification of conventional neutrino oscillations due to tiny violation of Lorentz symmetry parametrized by δb and δc
- For antineutrino ($\bar{\nu}$) beam,
  $(\delta b, \delta c) \to (-\delta b, \delta c)$
- We consider $\delta c = 0$ and $\delta b = 0$ separately
- Scan over Δm^2, $\sin^2 \theta$ and δb (or δc)

$\delta b = 0$ and $\delta c \neq 0$

- $\delta b = 0$: No CPT violating interactions
- Both mass from Δm^2 and velocity mixings from δc
- Current bounds on δc (Coleman & Glashow) :

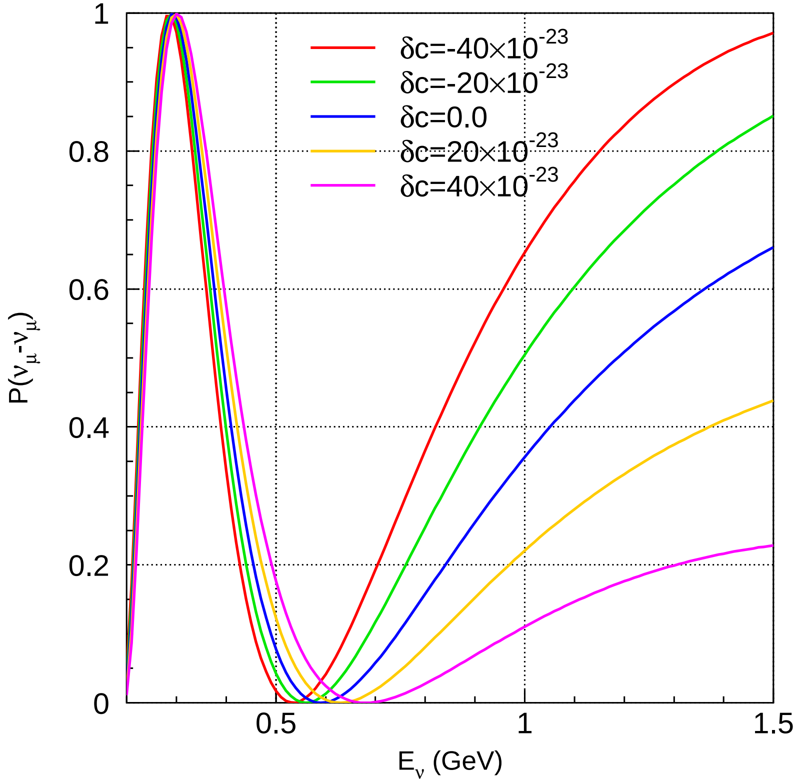
$$\delta c_{e\mu} < 4 \times 10^{-21}, \quad |\delta c_{\nu_e \nu_\mu}| < 6 \times 10^{-22}$$

- ν (and $\overline{\nu_\mu}$) survival probability:

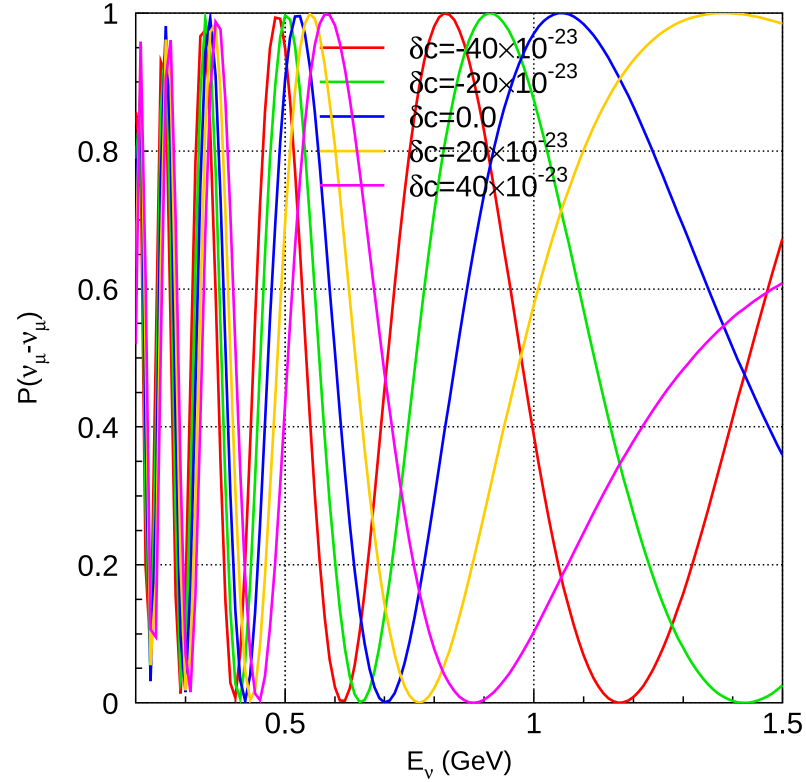
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \ \sin^2 \left[L \left(\frac{\Delta m^2}{4E} + \frac{\delta c E}{2} \right) \right]$$

- Scan over $(\Delta m^2, \sin^2 2\theta, \delta c)$

Survival Prob. for some δc's

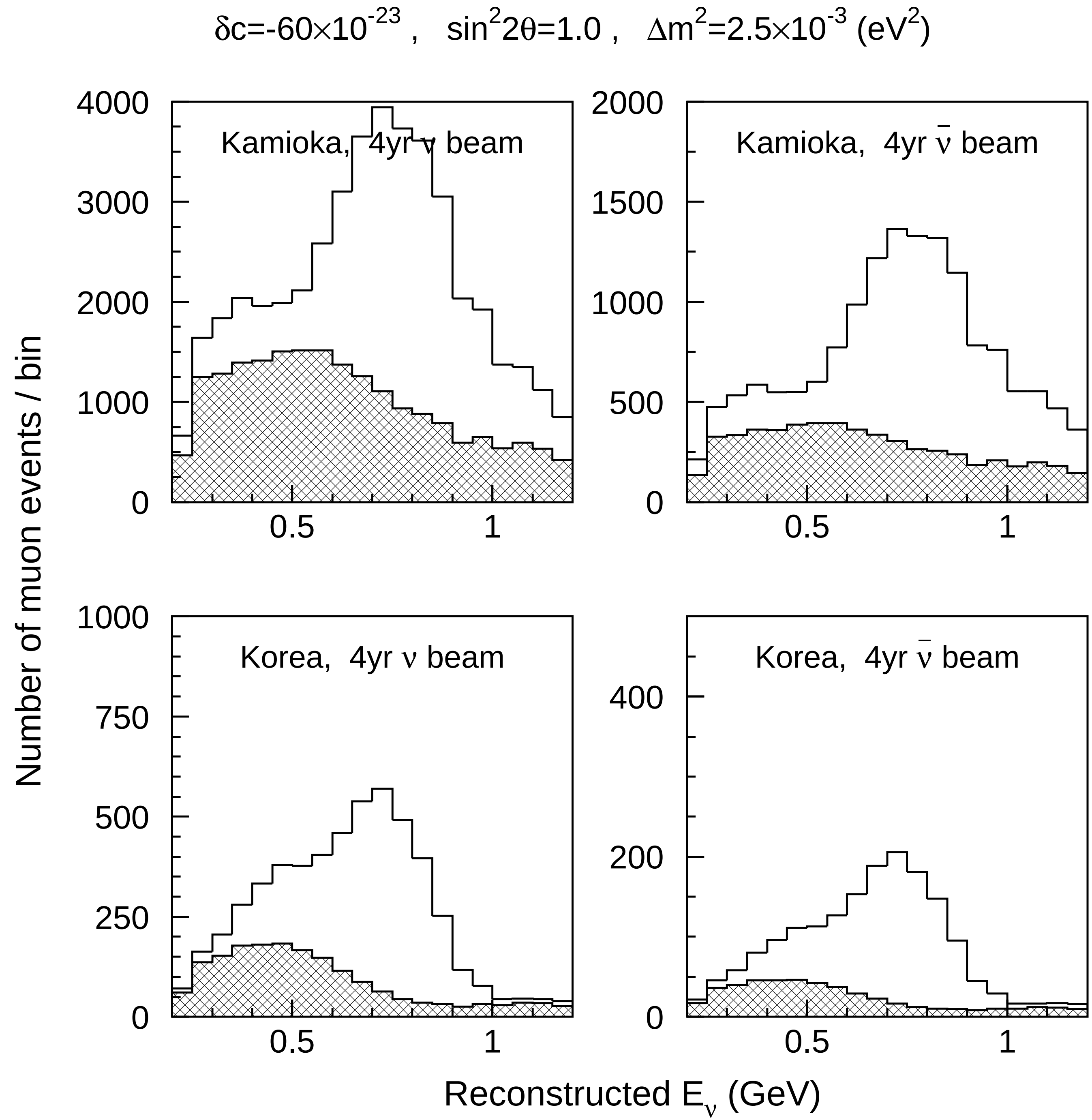


Kamioka



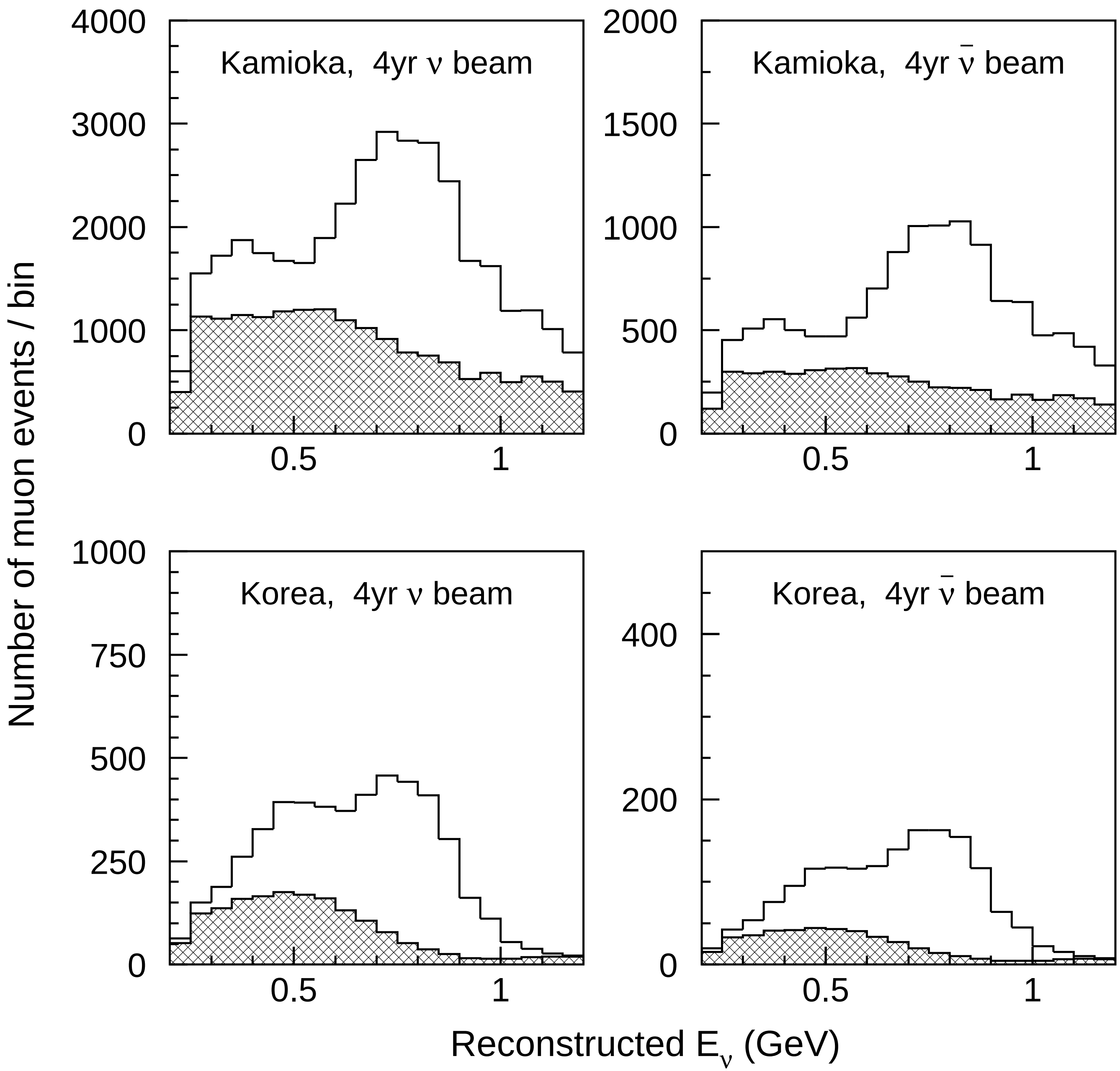
Korea

$\delta c = -60 \times 10^{-23}$

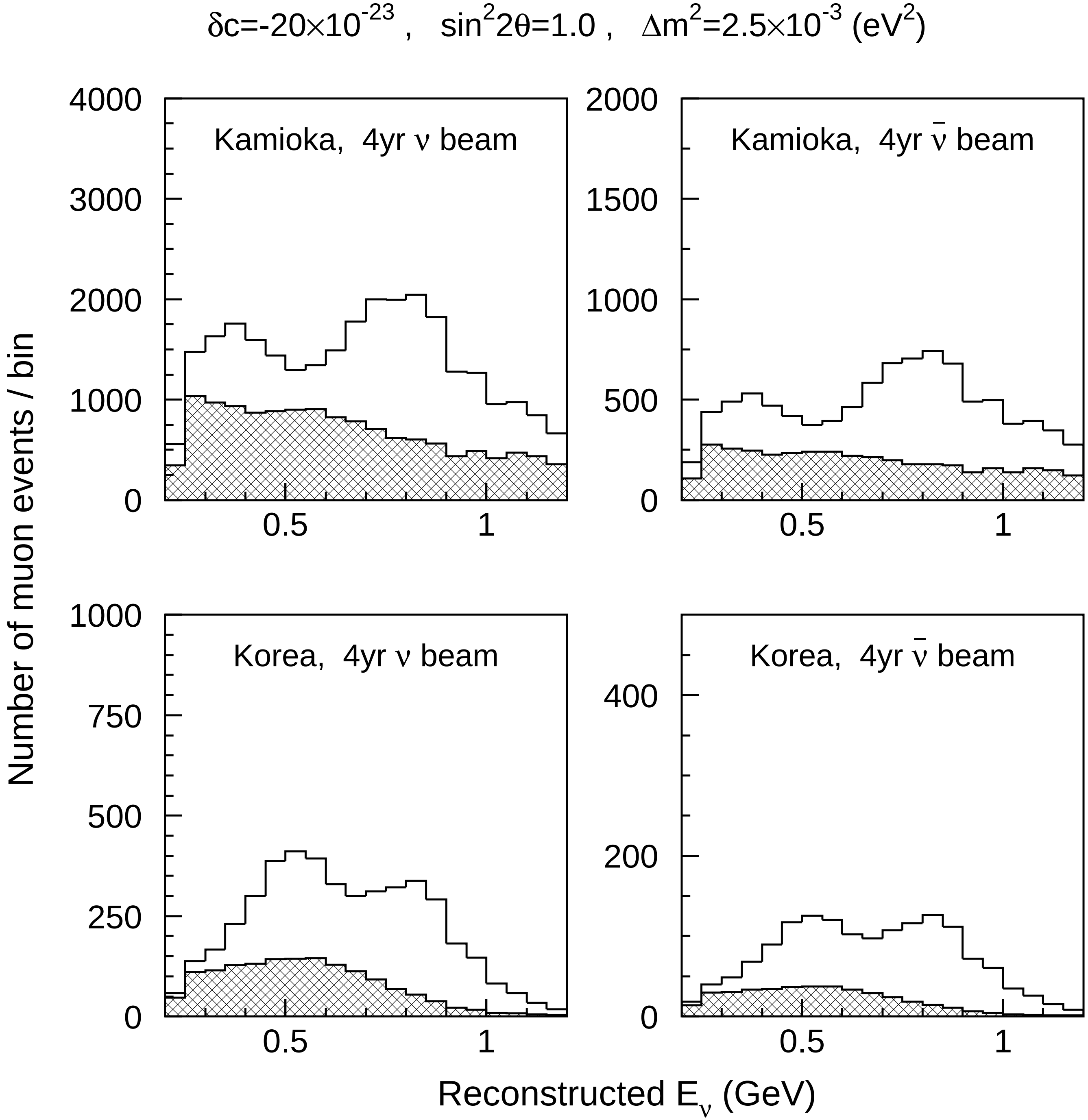


$\delta c = -40 \times 10^{-23}$

$\delta c = -40 \times 10^{-23}$, $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.5 \times 10^{-3}$ (eV^2)

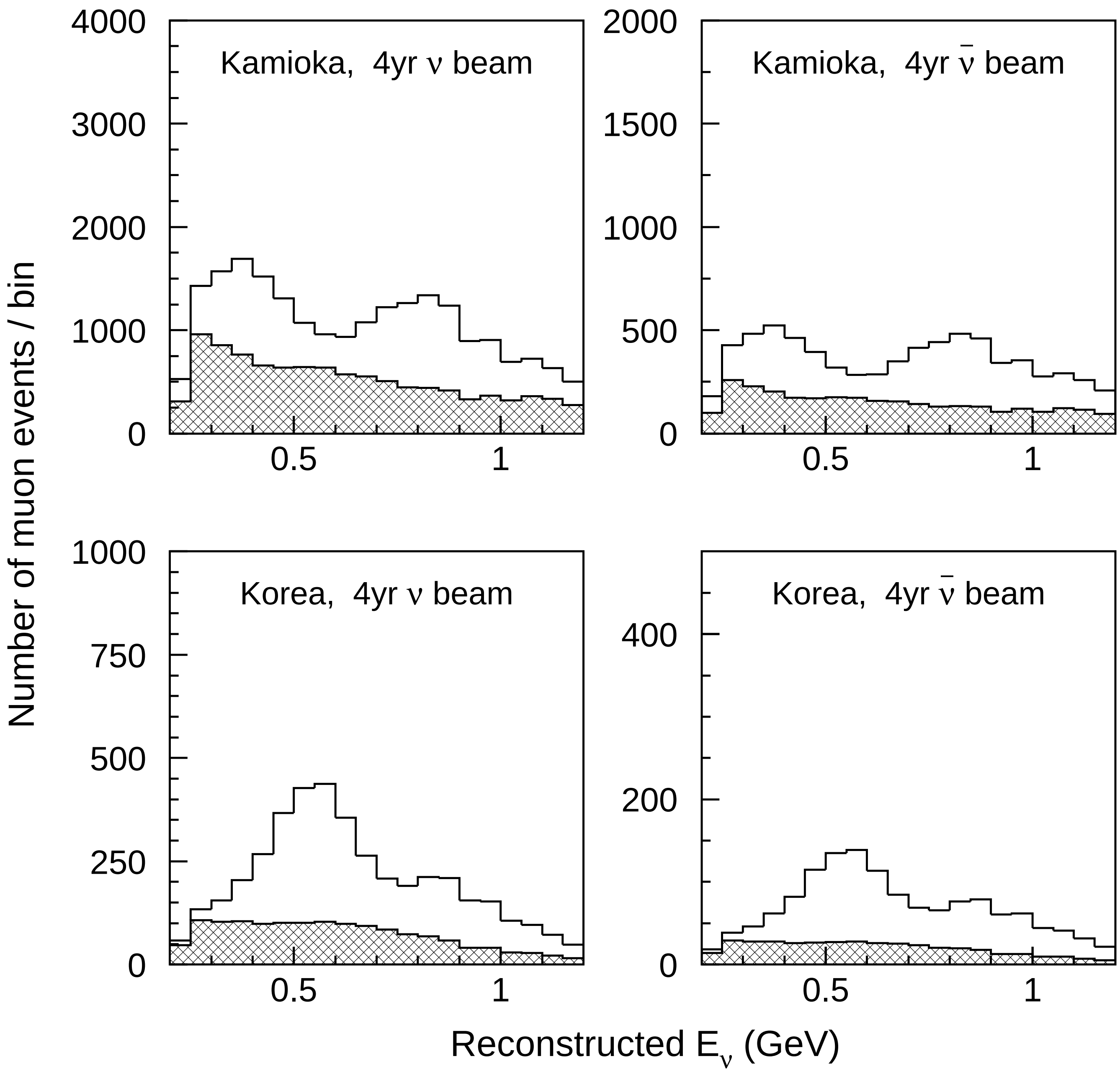


$\delta c = -20 \times 10^{-23}$

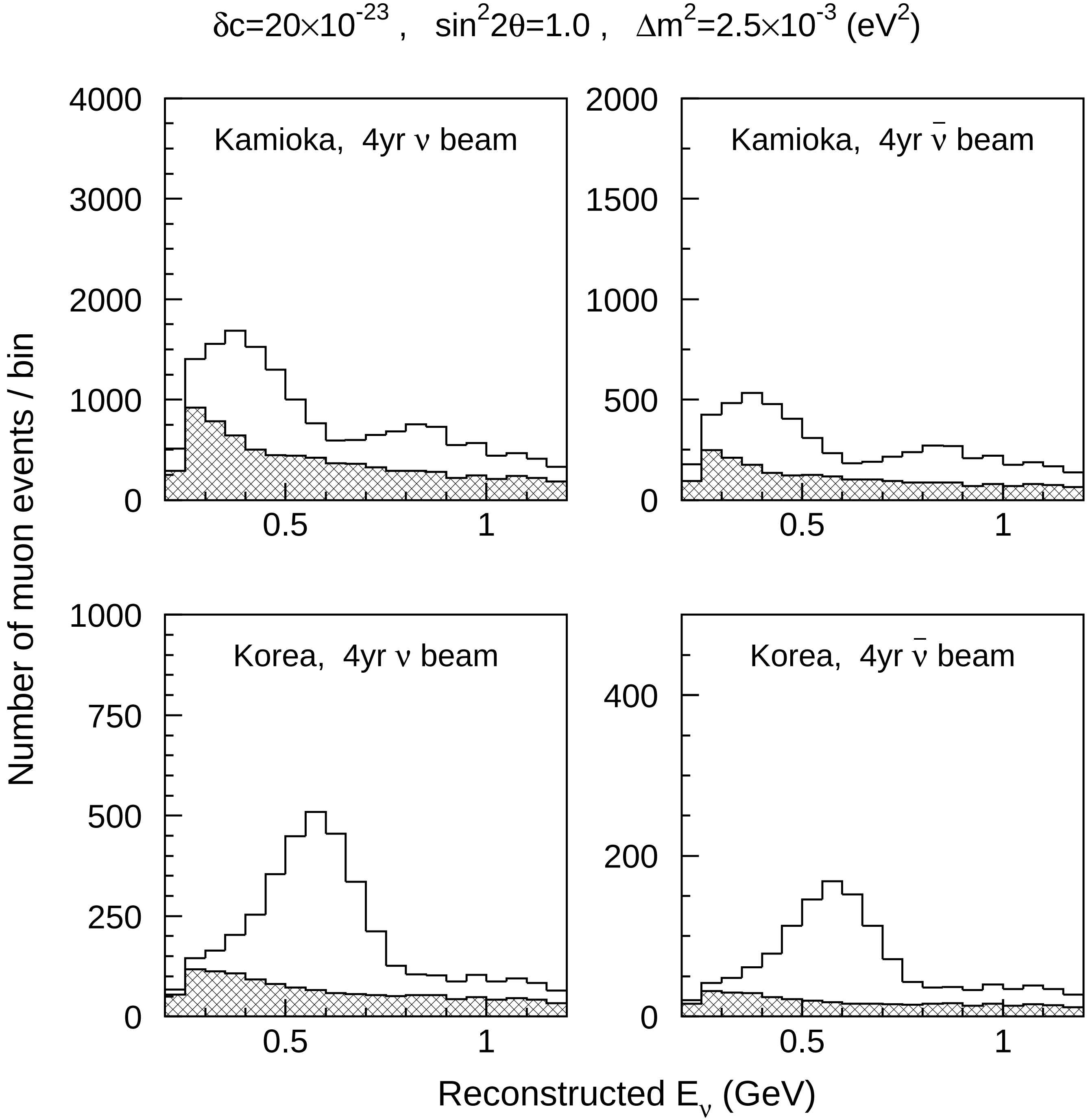


$\delta c = 0$

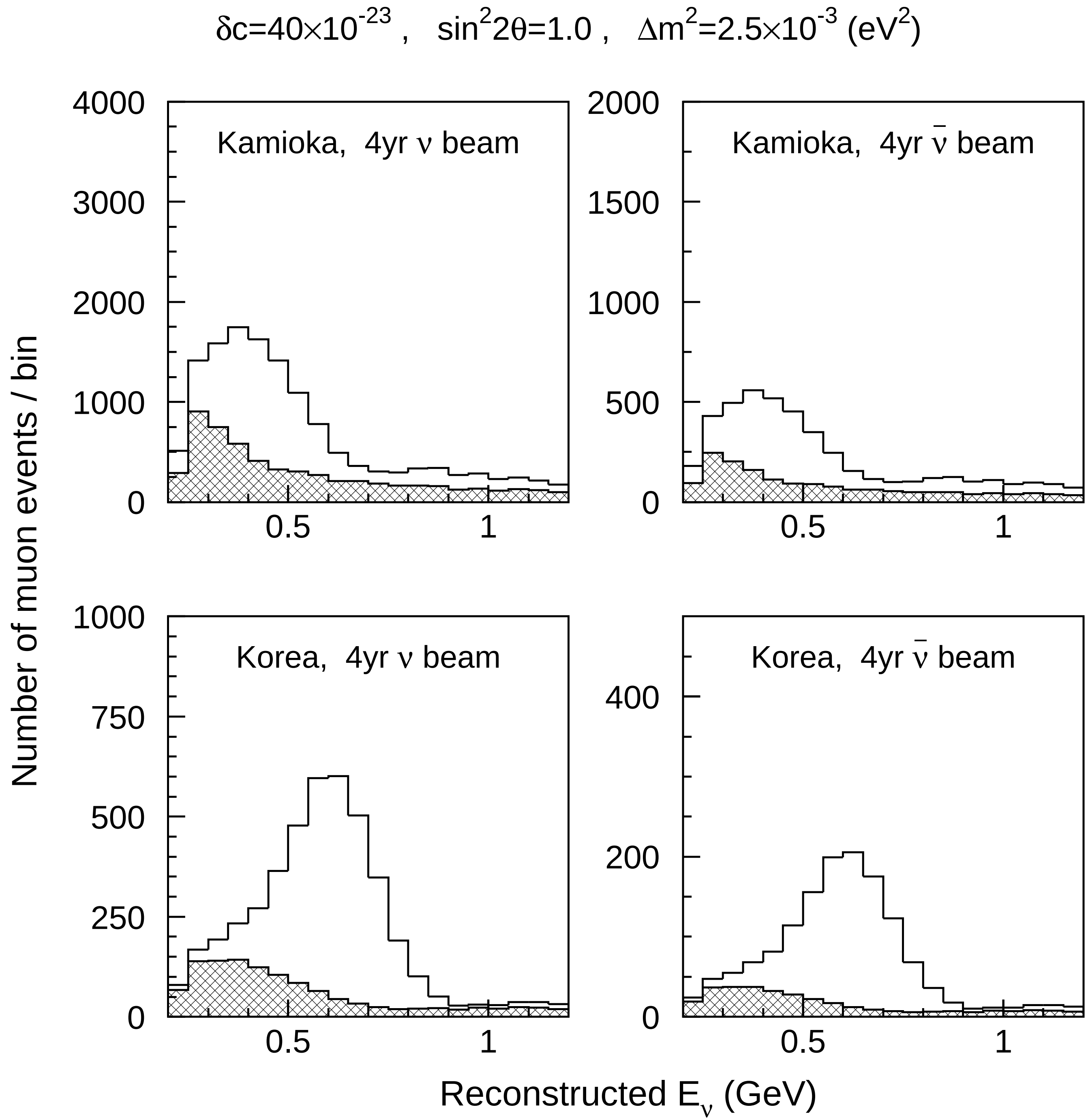
$\delta c = 0 \times 10^{-23}$, $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.5 \times 10^{-3}$ (eV^2)



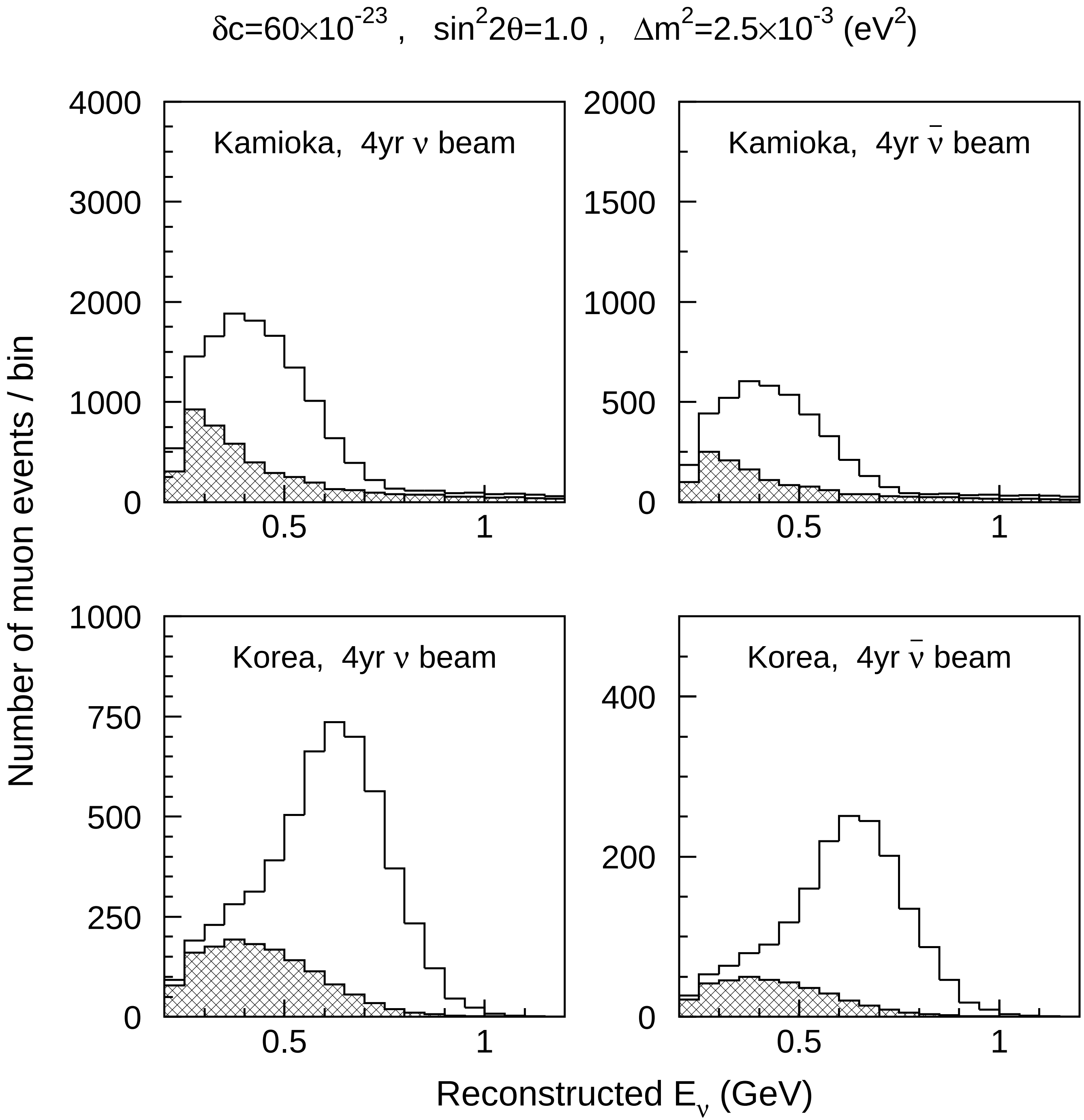
$\delta c = 20 \times 10^{-23}$



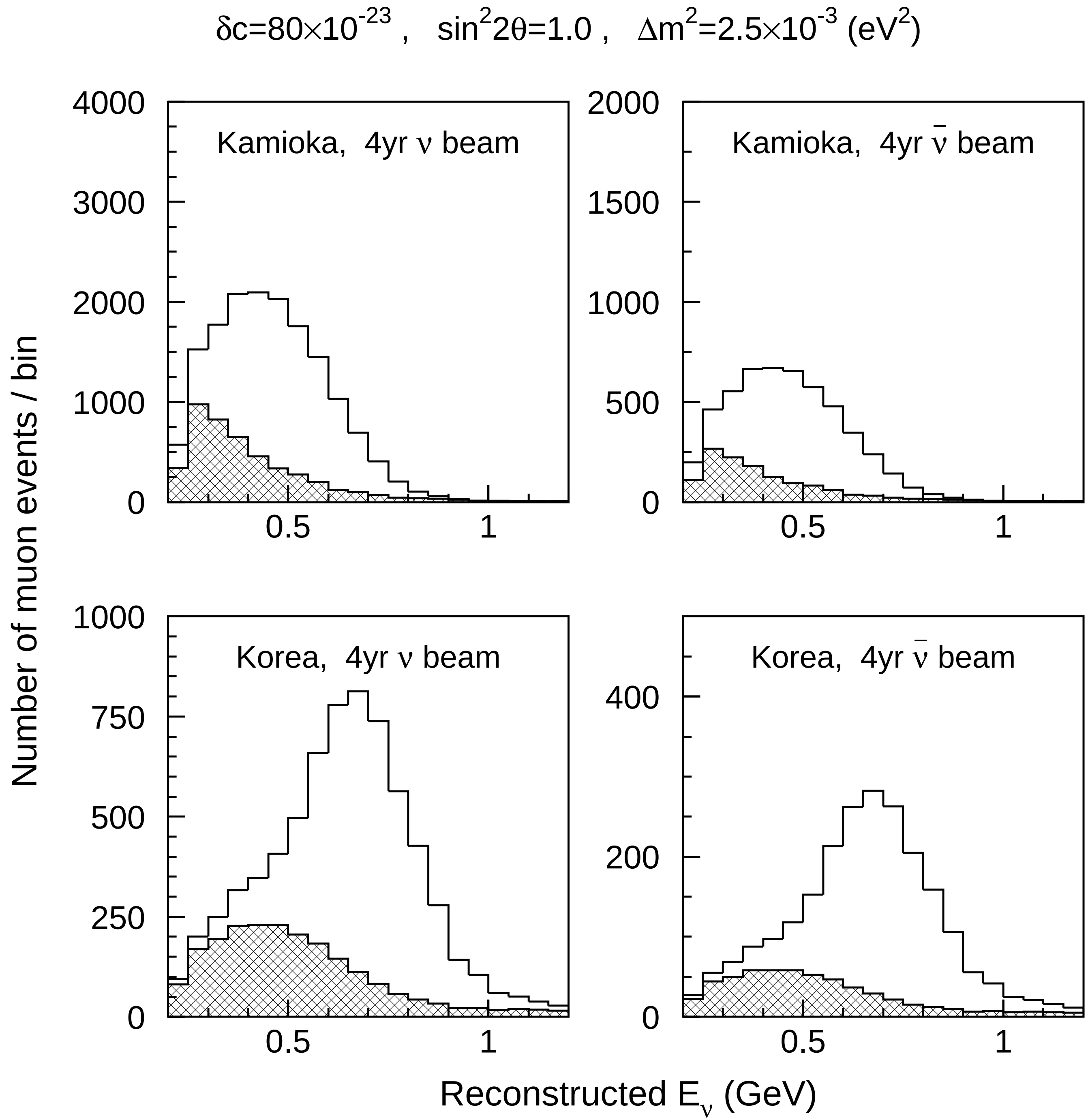
$$\delta c = 40 \times 10^{-23}$$



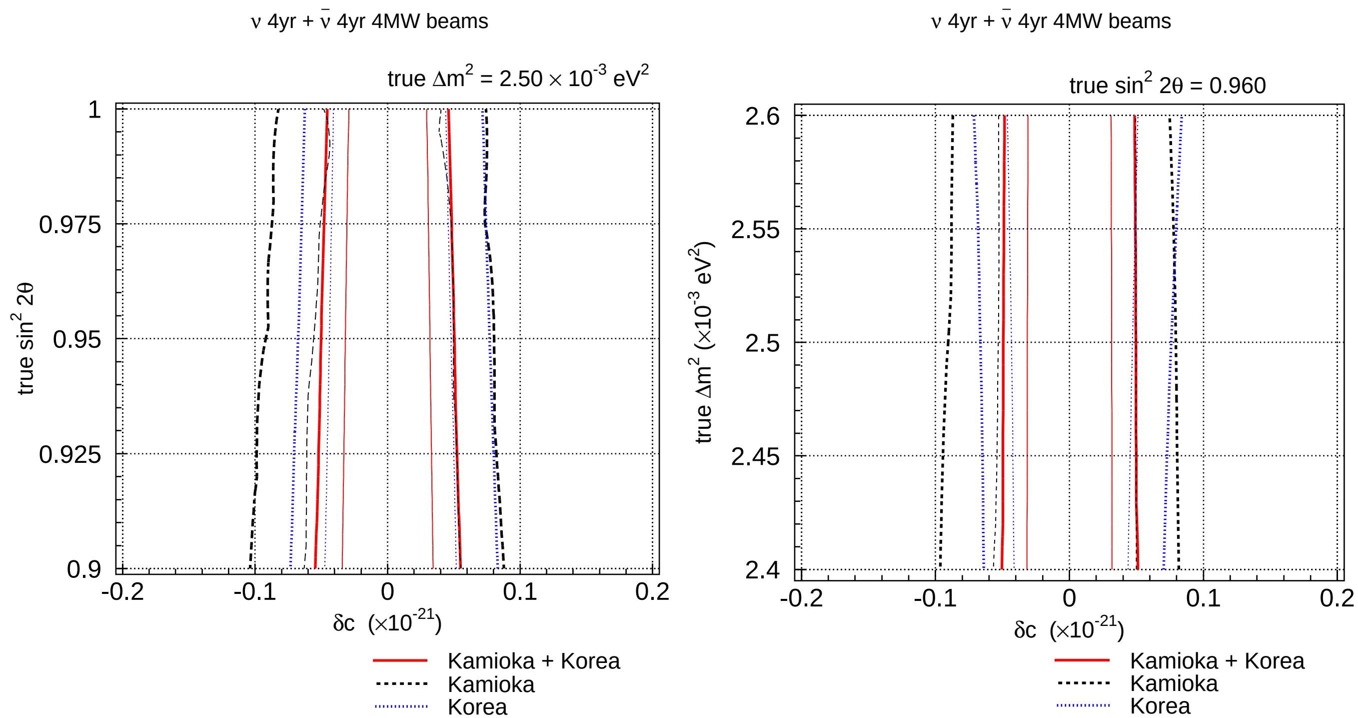
$\delta c = 60 \times 10^{-23}$



$\delta c = 80 \times 10^{-23}$



Exclusion Plots



- $|\delta c| \lesssim 0.3(0.5) \times 10^{-22}$ at T2KK,
  compared with $\delta c \lesssim 0.5(0.8) \times 10^{-22}$ at T2K–II
- T2KK is more powerful than SK alone for δc
- More stringent bound on δc than the charged lepton case $|\delta c_{e\mu}| < 4 \times 10^{-21}$ and $|\delta c_{\nu_e \nu_\mu}| < 6 \times 10^{-22}$

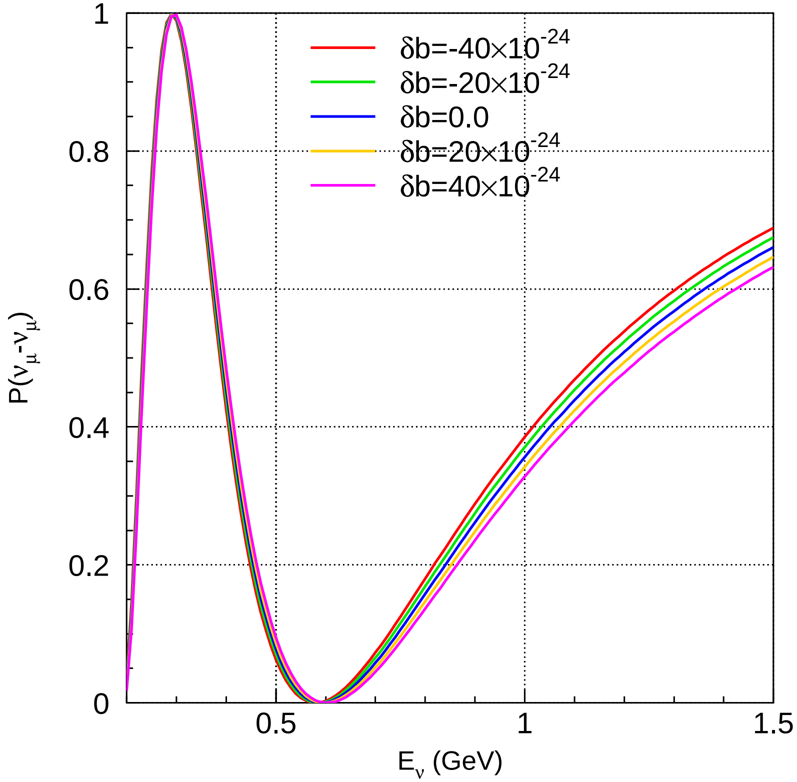
$\delta c = 0$ and $\delta b \neq 0$

- $\delta c = 0$: No velocity mixing
- $\delta b \neq 0$: CPT violting interaction
- Survival probabilities for (anti)muon ν's:

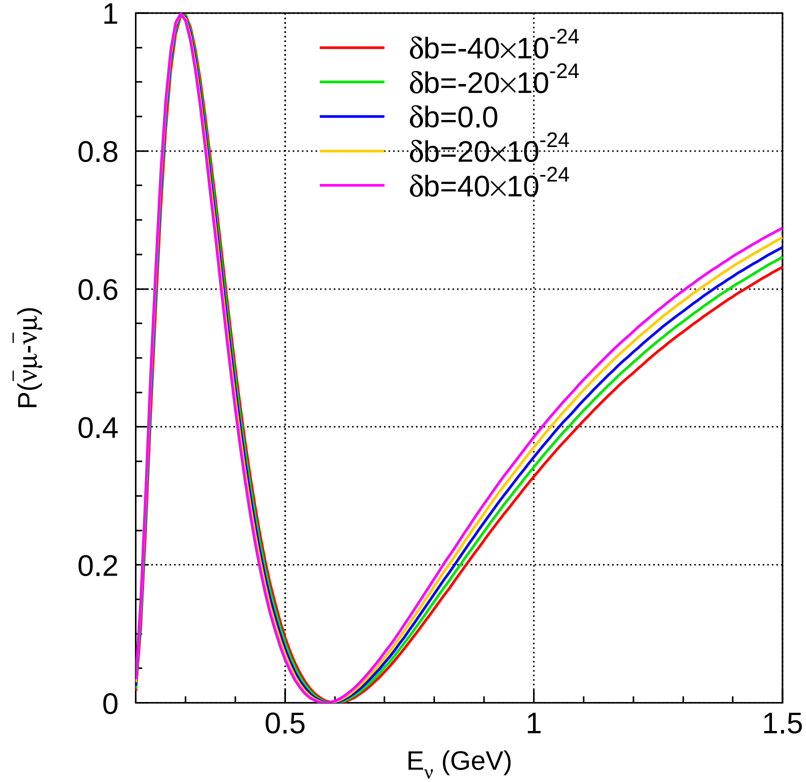
$$P_{\mu\mu(\bar{\mu}\bar{\mu})} = 1 - \sin^2 2\theta \ \sin^2 \left[\left(\frac{\Delta m^2}{4E} \pm \frac{\delta b}{2} \right) L \right]$$

- This form is similar to the CPT test in the previous slide, but not quite the same (different E dependence)
- Barger et al. studied this case with $\theta_b = \theta_m$, and argued that one can probe $\delta b < 3 \times 10^{-23}$ GeV at neutrino factories with 10^{19} stored muons with 20 GeV energy and 10 kton detector
- $\delta b_{\mu\tau} < 3 \times 10^{-20}$ GeV from atm. neutrino data

Survival Prob. at Kamioka for some δb's

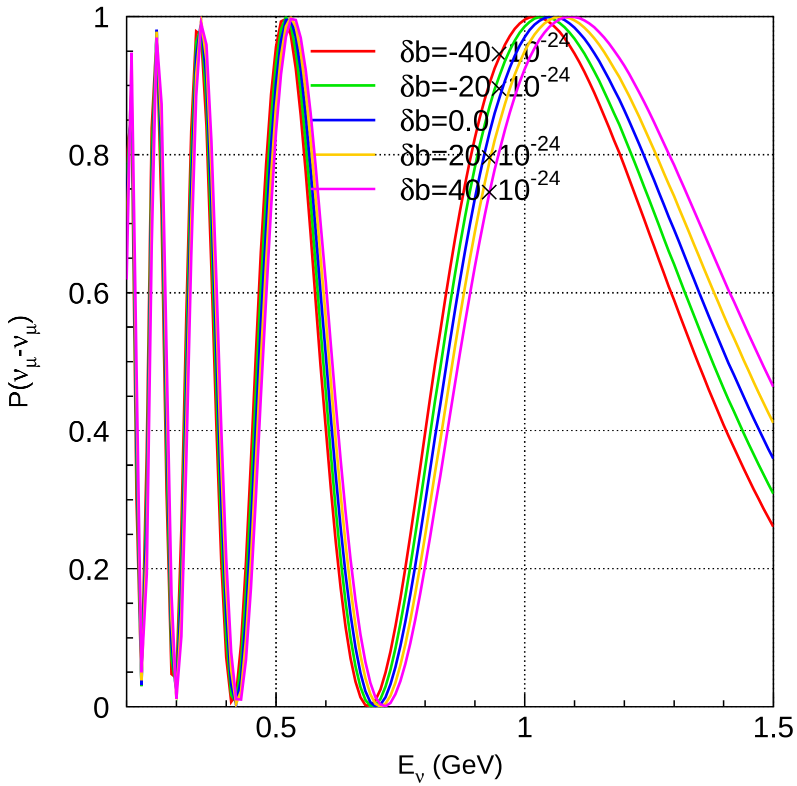


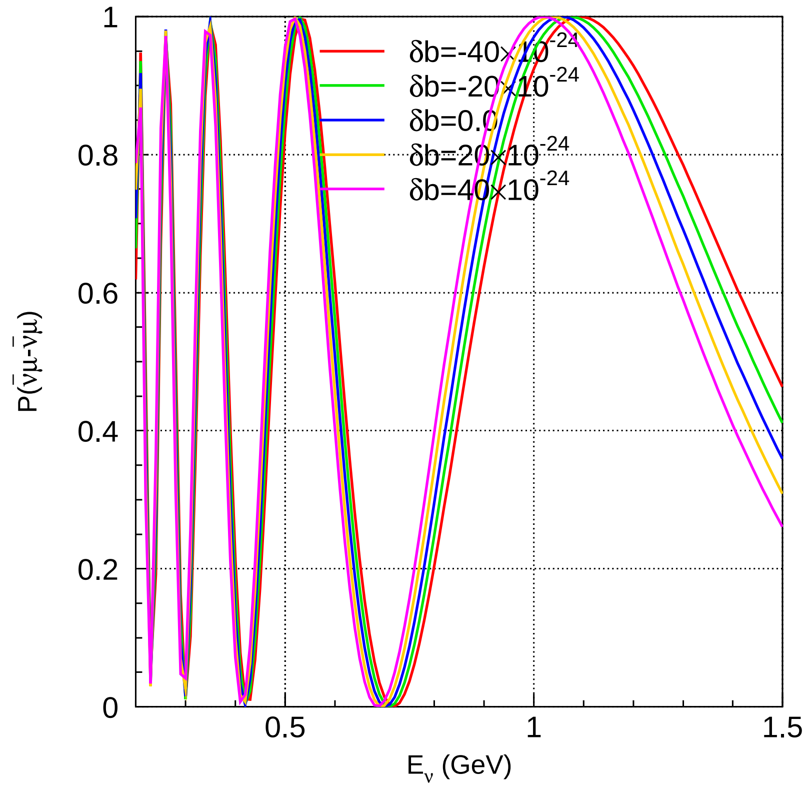
ν Beam



$\overline{\nu}$ Beam

Survival Prob. at Korea for some δb's

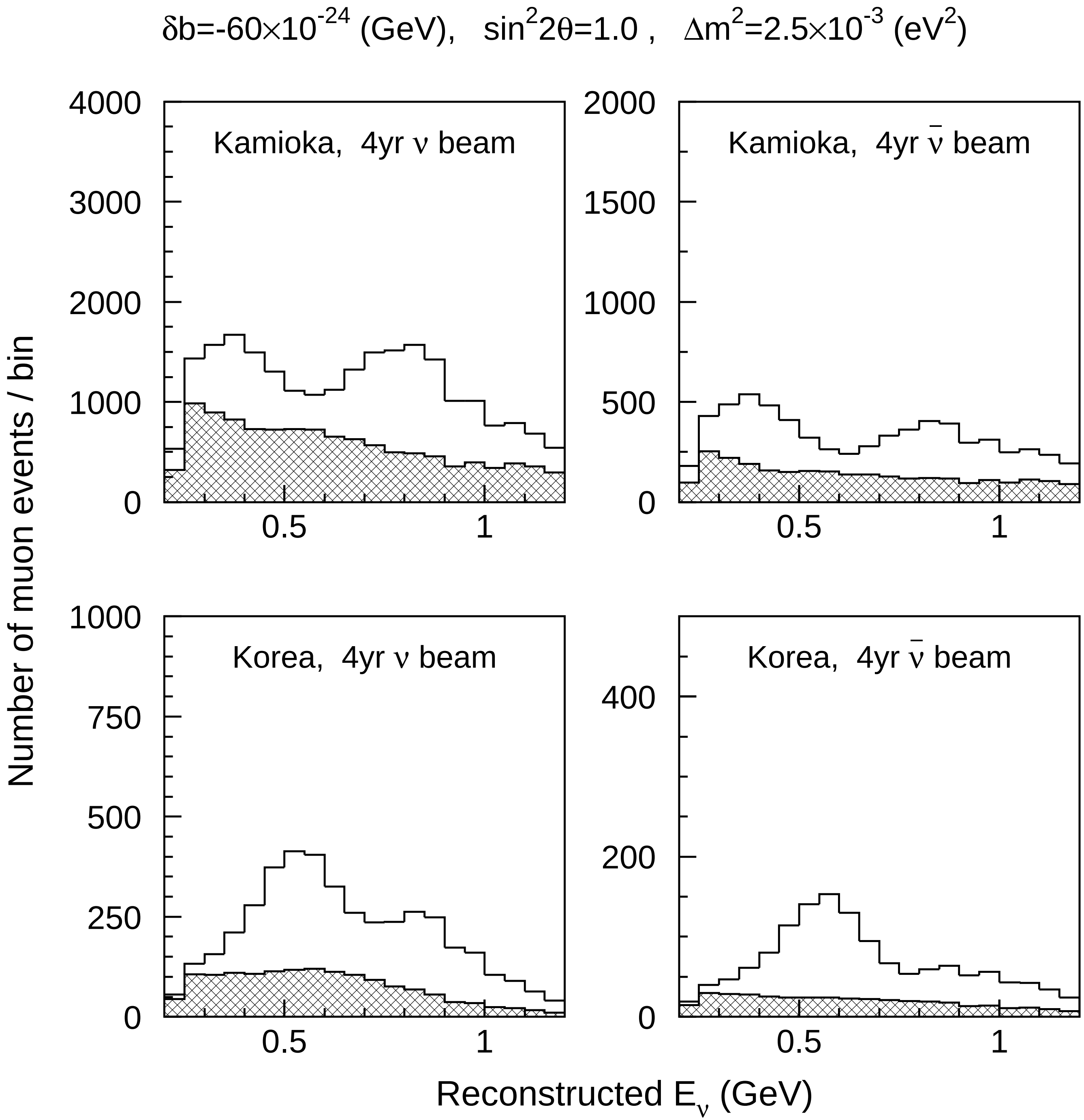




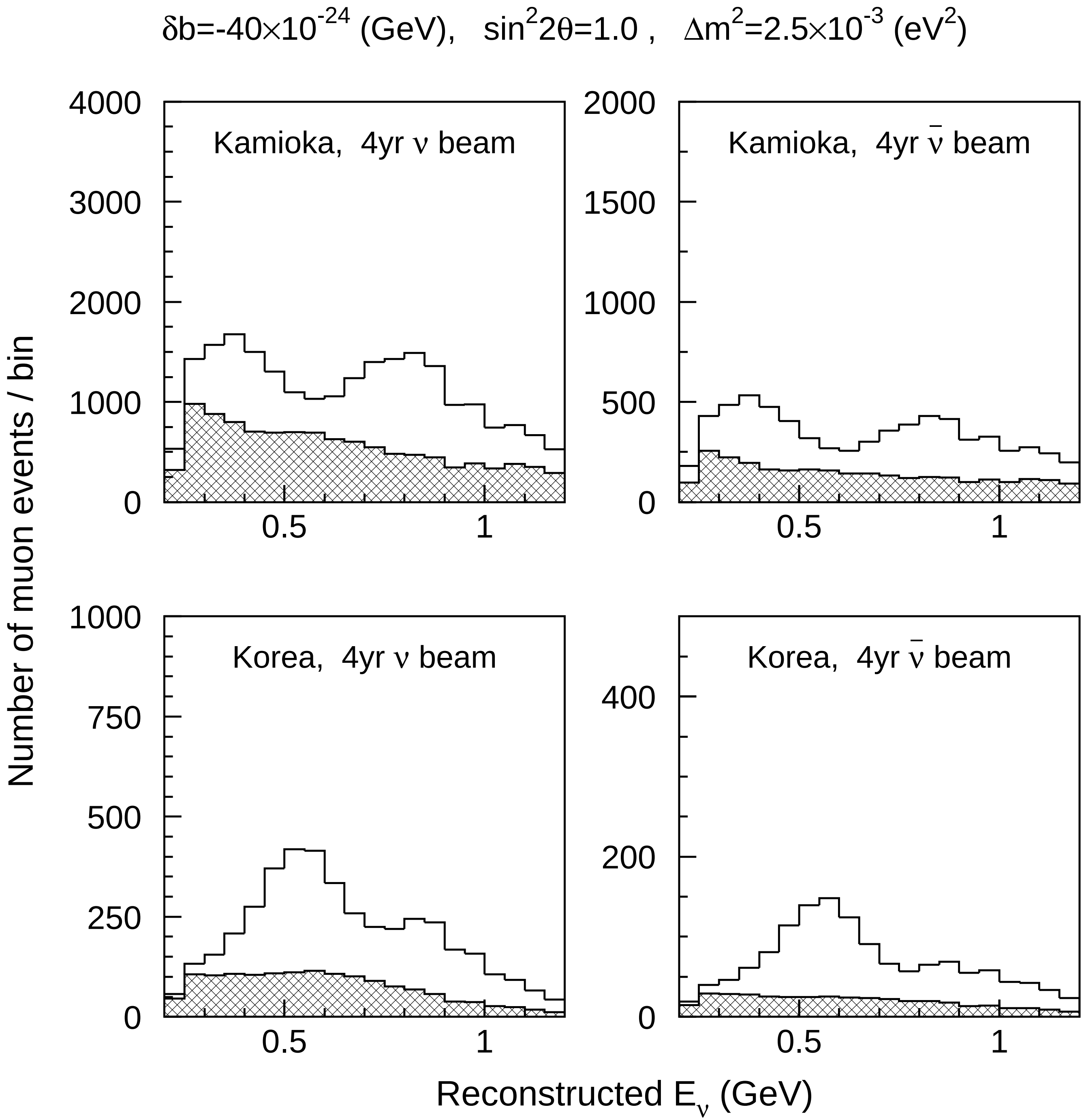
ν Beam

$\overline{\nu}$ Beam

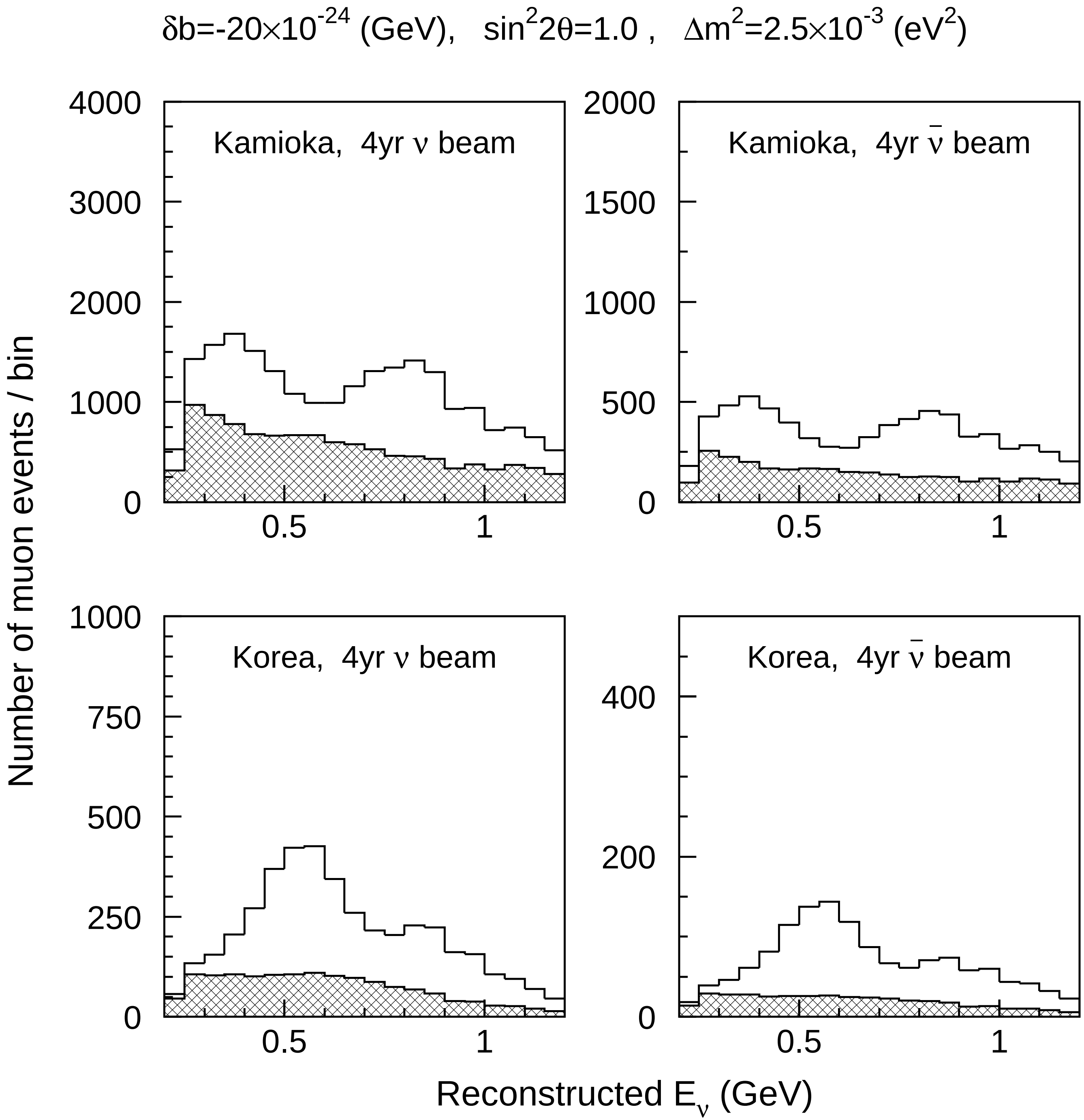
$\delta b = -60 \times 10^{-24}$ GeV



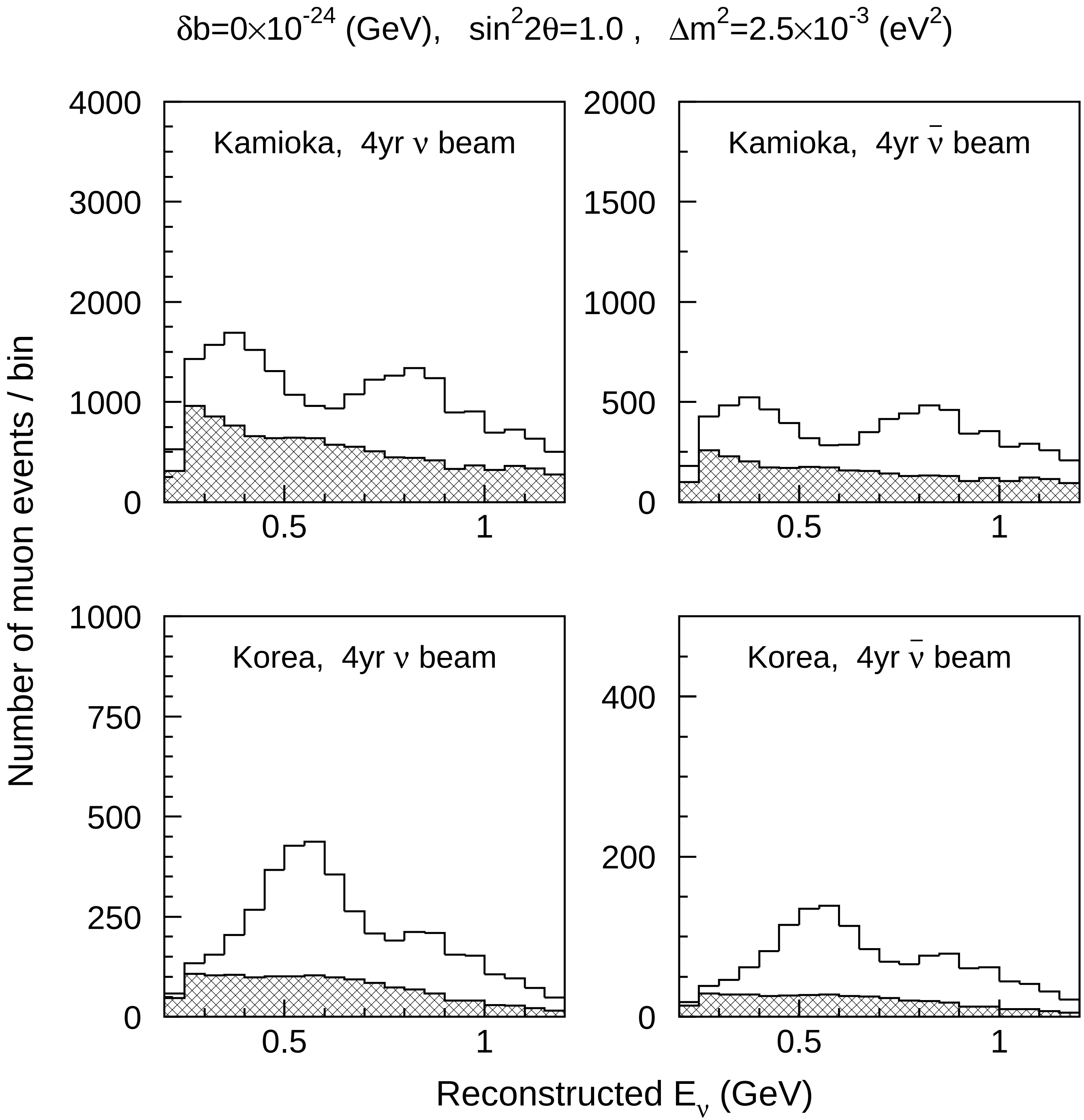
$$\delta b = -40 \times 10^{-24}\ \mathbf{GeV}$$



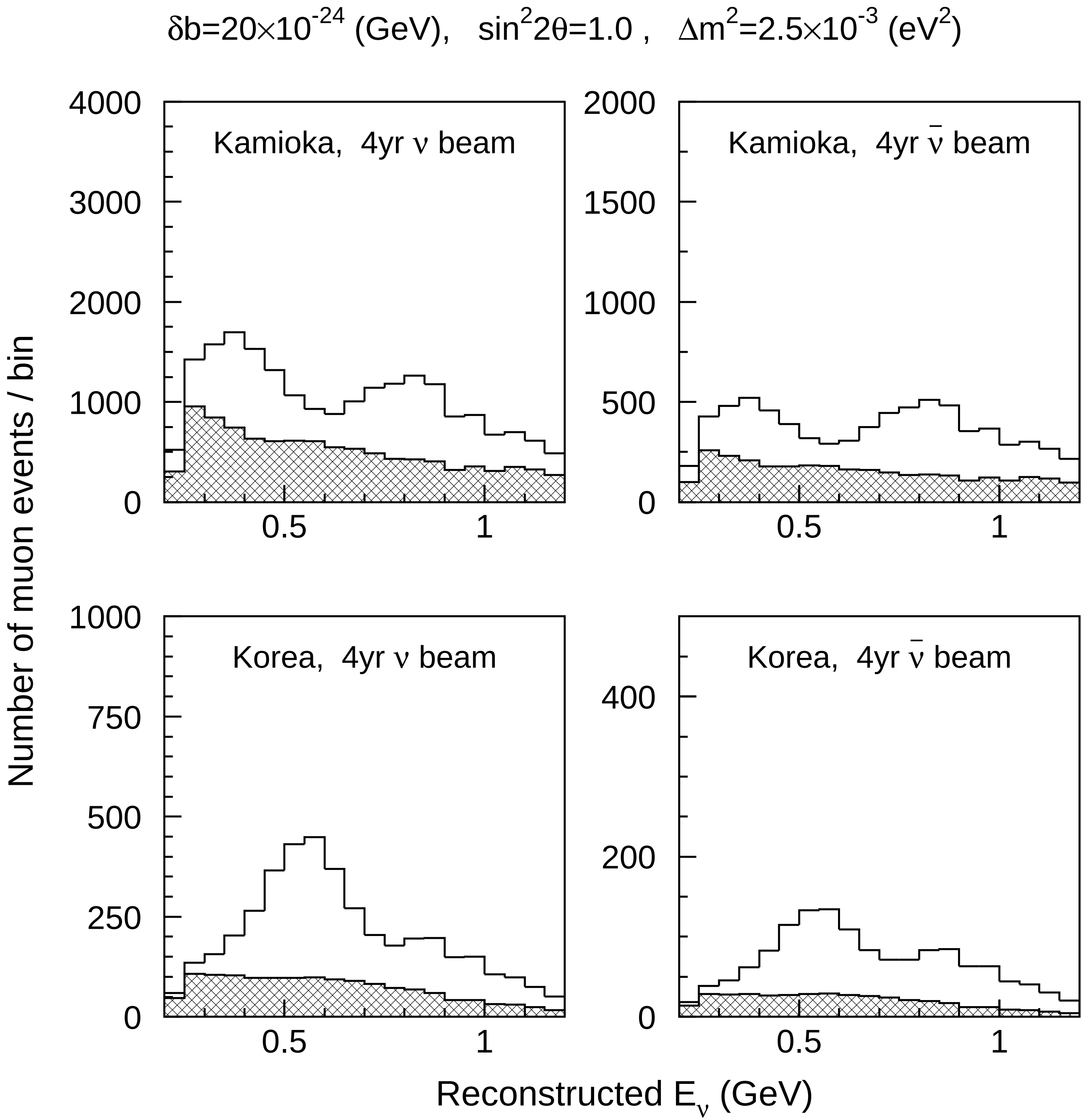
$\delta b = -20 \times 10^{-24}$ GeV



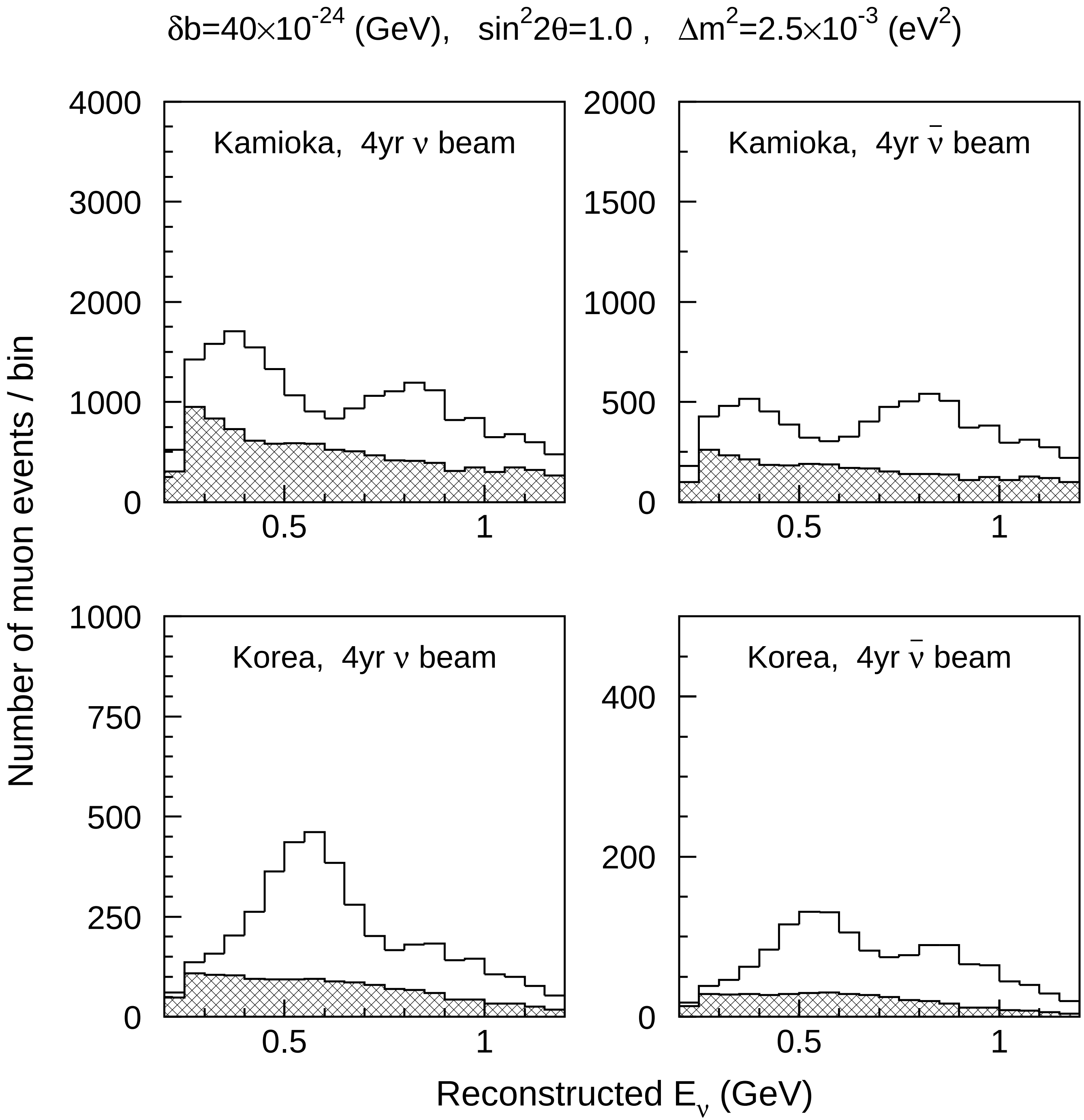
$\delta b = 0 \times 10^{-24}$ **GeV**



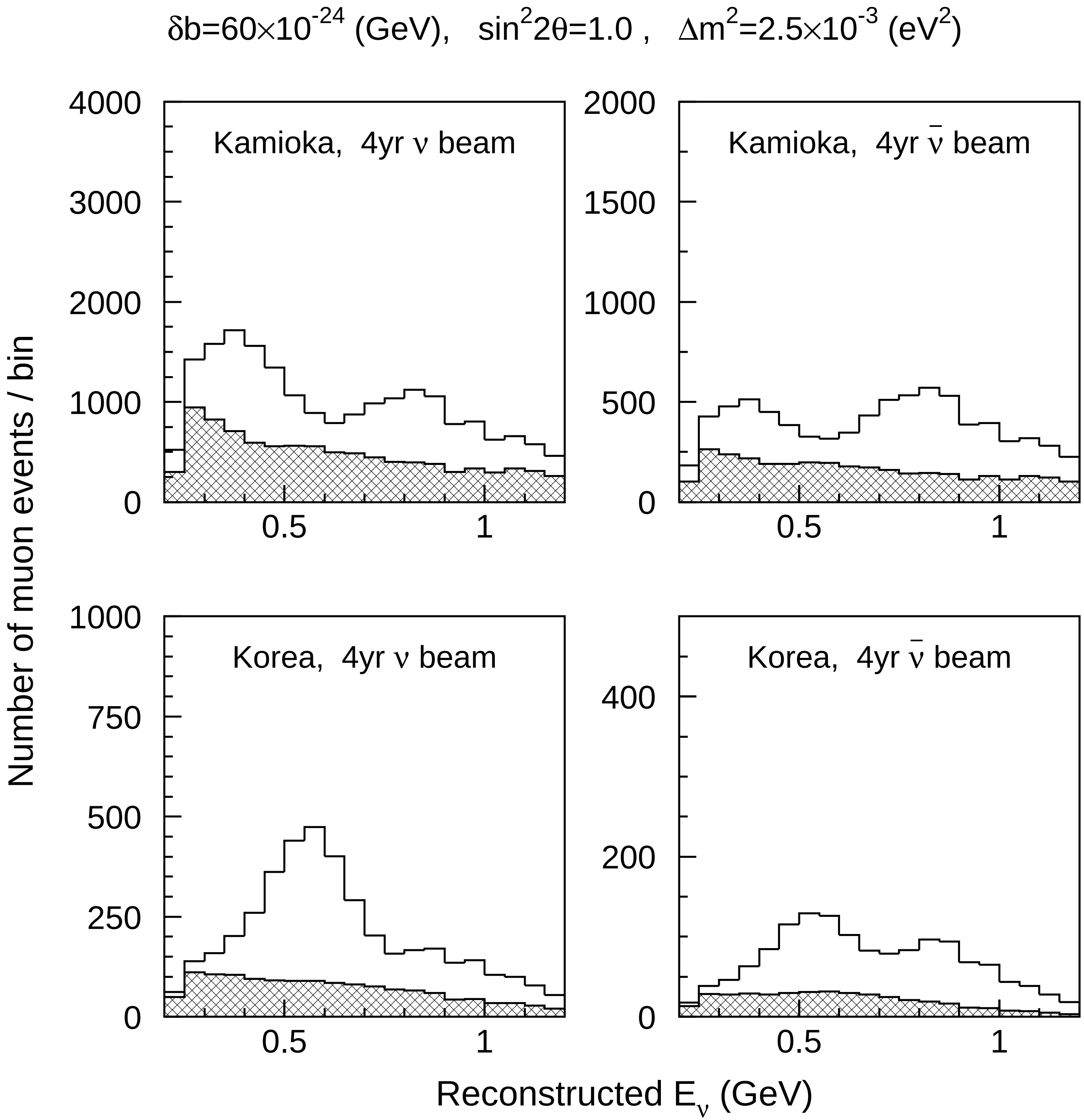
$\delta b = 20 \times 10^{-24}$ GeV



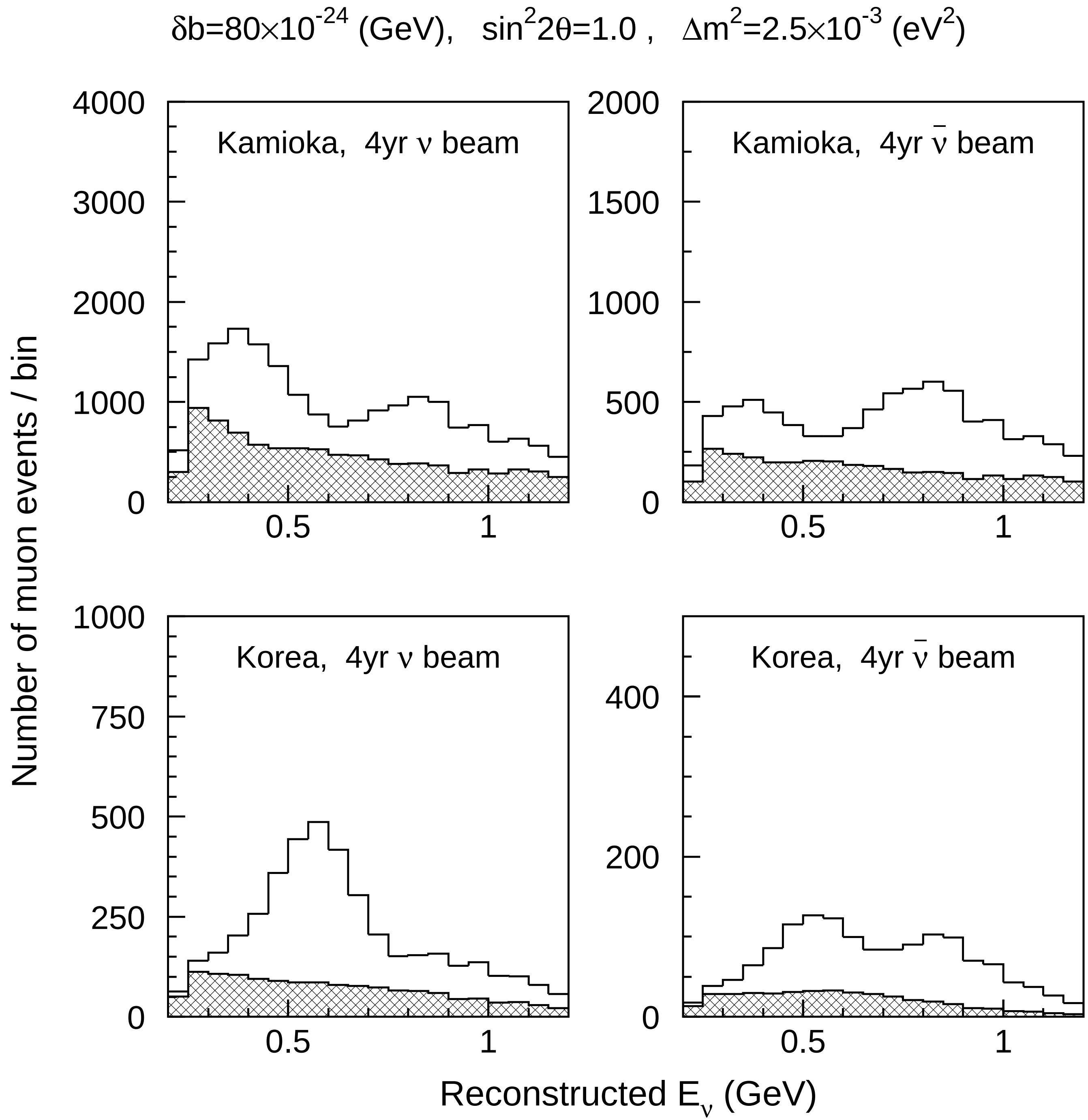
$\delta b = 40 \times 10^{-24}$ GeV



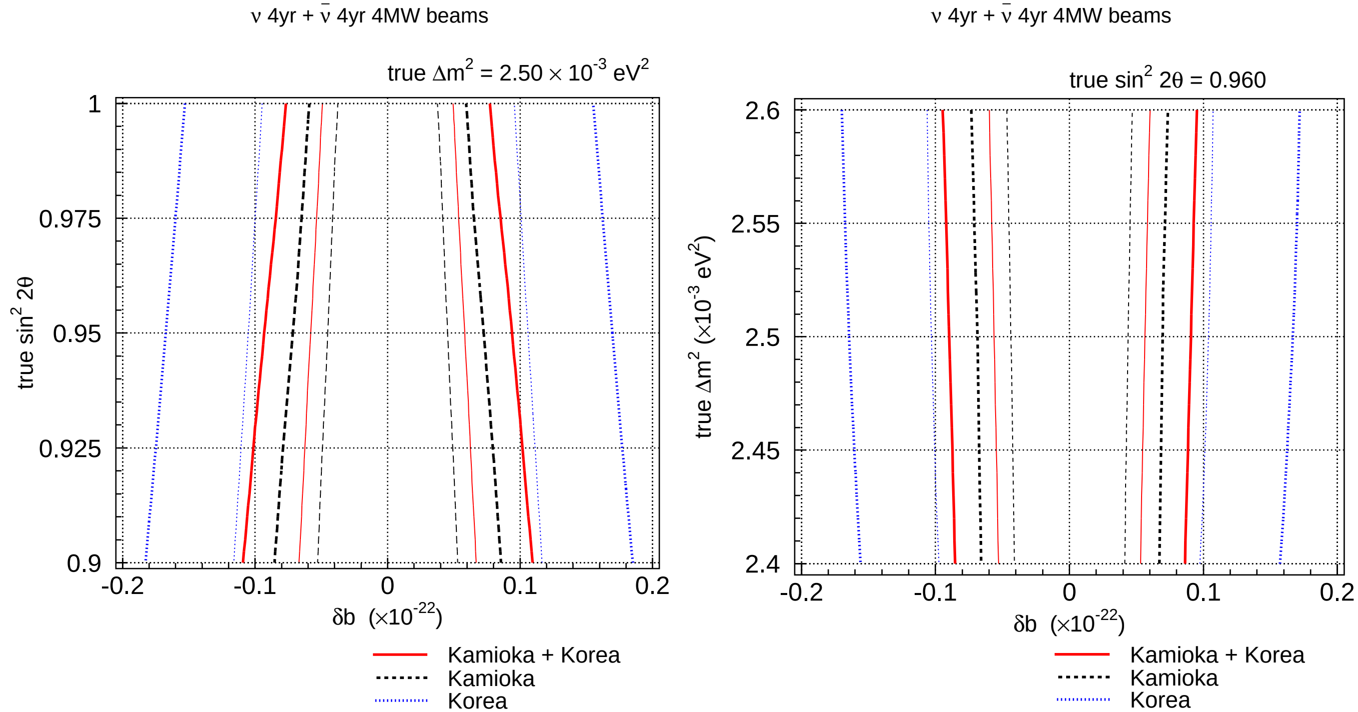
$\delta b = 60 \times 10^{-24}$ GeV



$\delta b = 80 \times 10^{-24}$ GeV



Exclusion Plots



- $\delta b \lesssim 0.5(0.8) \times 10^{-23}$ GeV at T2KK, compared with $\delta b \lesssim 0.4(0.6) \times 10^{-23}$ GeV at T2K–II
- T2KK is less powerful than T2K-II δb
- Still better than $\delta b < 3 \times 10^{-23}$ GeV at ν factories, and current bound 3×10^{-20} GeV

Summary Table for Lorentz/CPT Violation

Models	Curent bound	T2K-II	T2KK
δc	$< 40 \times 10^{-22}$	0.5×10^{-22}	0.3×10^{-22}
δb (GeV)	$< 3.0 \times 10^{-20}$	0.4×10^{-23}	0.5×10^{-23}

Table 2: Present 90 % CL upper bounds

- T2KK can improve the bounds on the Lorentz/CPT violation far better than the current bounds, and can compete with ν factories
  cf. ν factory down to 3×10^{-23} GeV (Barger et al.)
- Current SK data may provide another interesting bounds on δb and δc (remember $\gamma \sim E^2$)

Summary and Outlook

Summary and Outlook

- QFT theory in curved spacetime and Quantum Gravity may induce some nonstandard physics effects due to
  - Quantum decoherence
  - Violation of CPT
  - Violation of Lorentz symmetry
- T2KK type experiments can improve the bounds on such nonstandard physics related with neutrinos
- In most cases, better to have T2KK rather than T2K, because more informations on the energy spectrum available, which is a nice addition to its main role to lift parameter degenracies in the neutrino sector
- See our paper in prepartion for other scenarios such as mass varying neutrinos and flavor nonuniversal neutrino interactions with matter