Long baseline experiment and proton decay searches with Hyper-Kamiokande

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First open meeting for Hyper-Kamiokande project
August 22-23, 2012
Kavli IPMU, Kashiwa

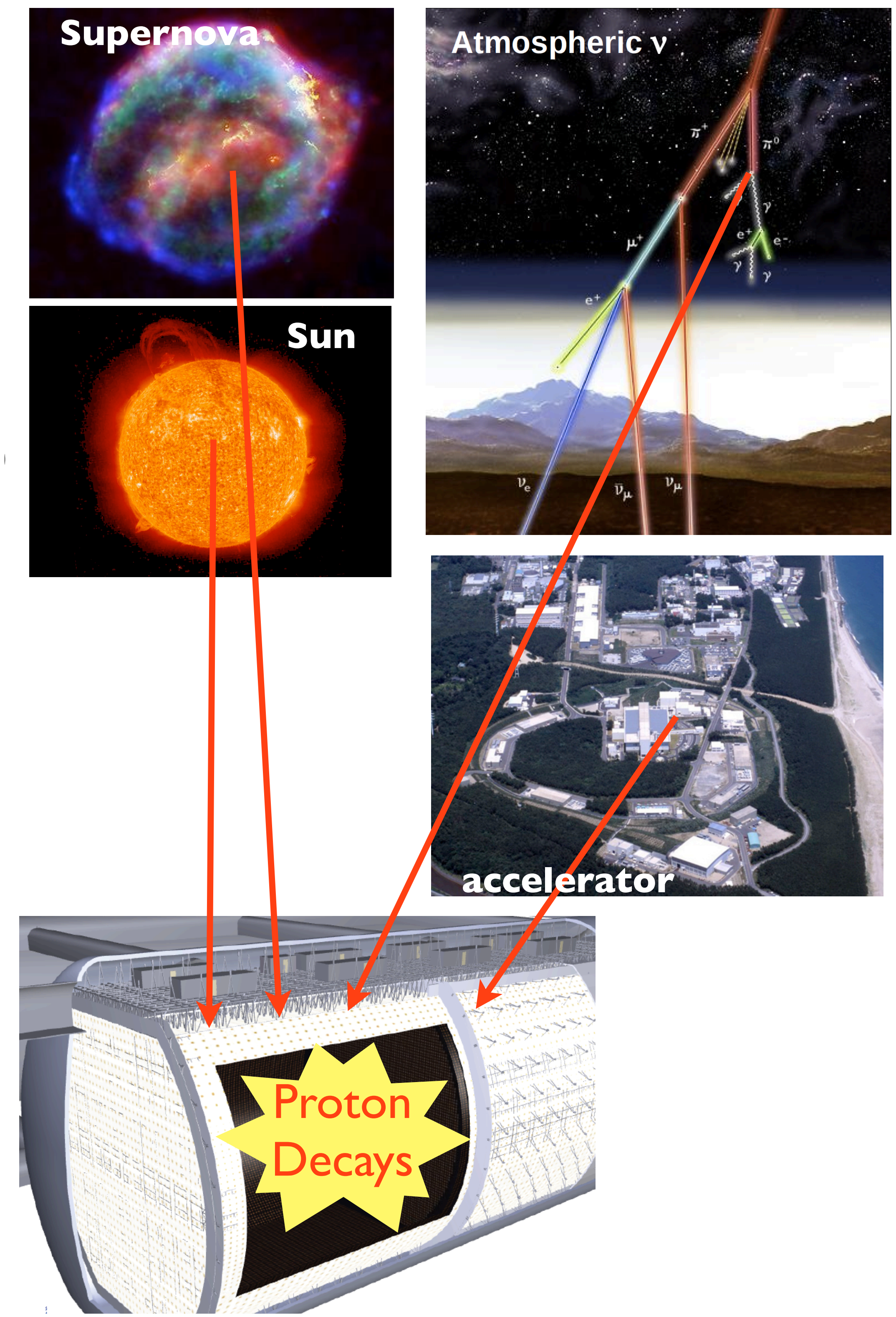
Hyper-K is a multi-purpose detector

"Physics Potential" session

- Overview of accelerator ν + proton decay (MY)
- Systematics for CPV measurements (S.Nakayama/ M.Hartz/K.McFarland)
- Atmospheric ν (R.Wendell)
- Cosmic ray BG estimation (K.Okumura)

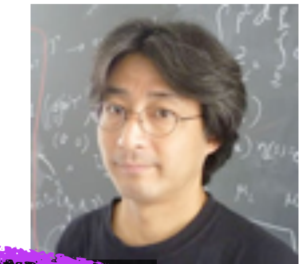
— Break—

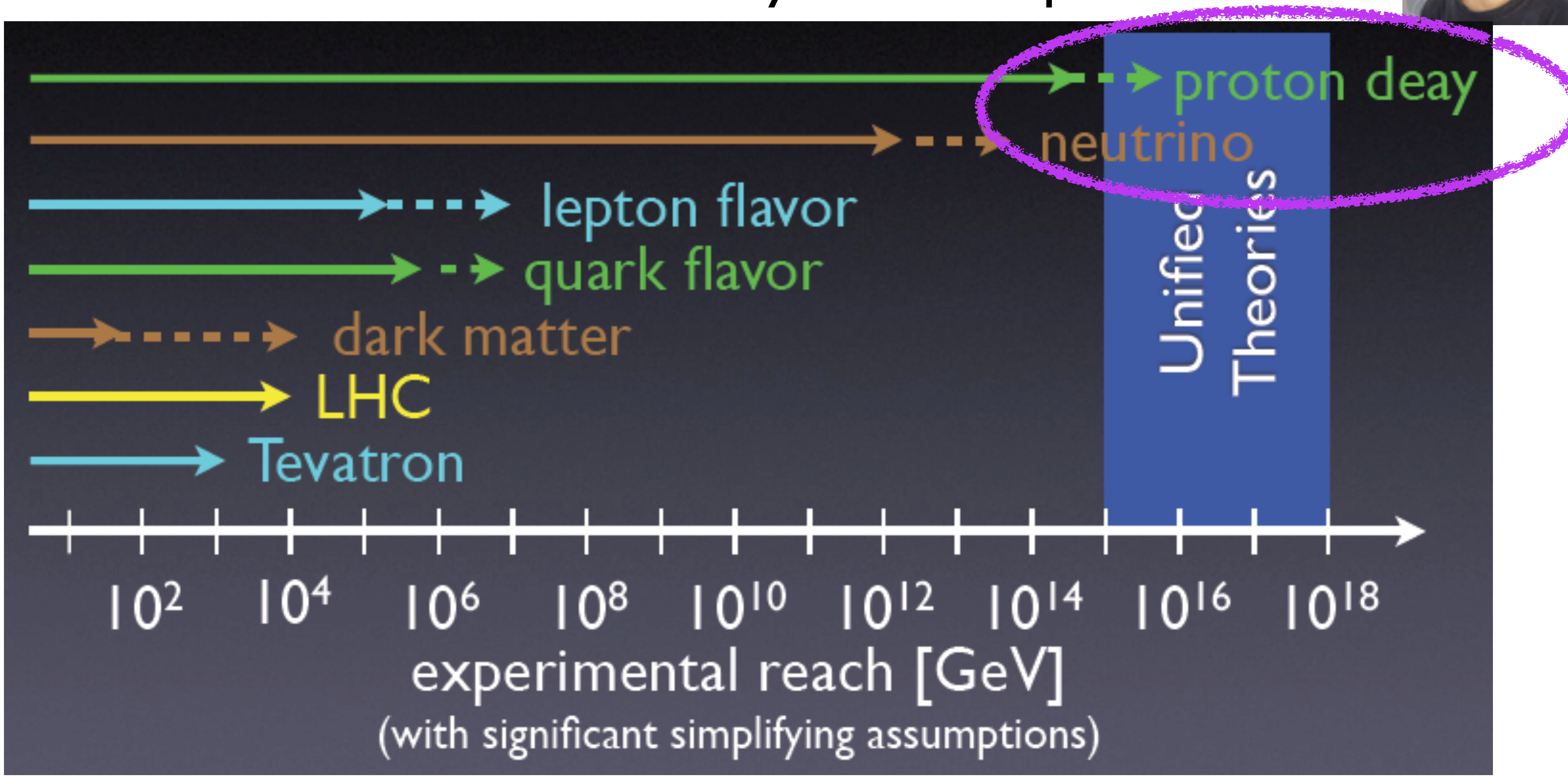
- Solar + SN ν detection (Y.Koshio)
- SN astronomy (S.Horiuchi)
- DM sensitivity (C.Root)



Particle physicists' view

From Murayama-san's presentation

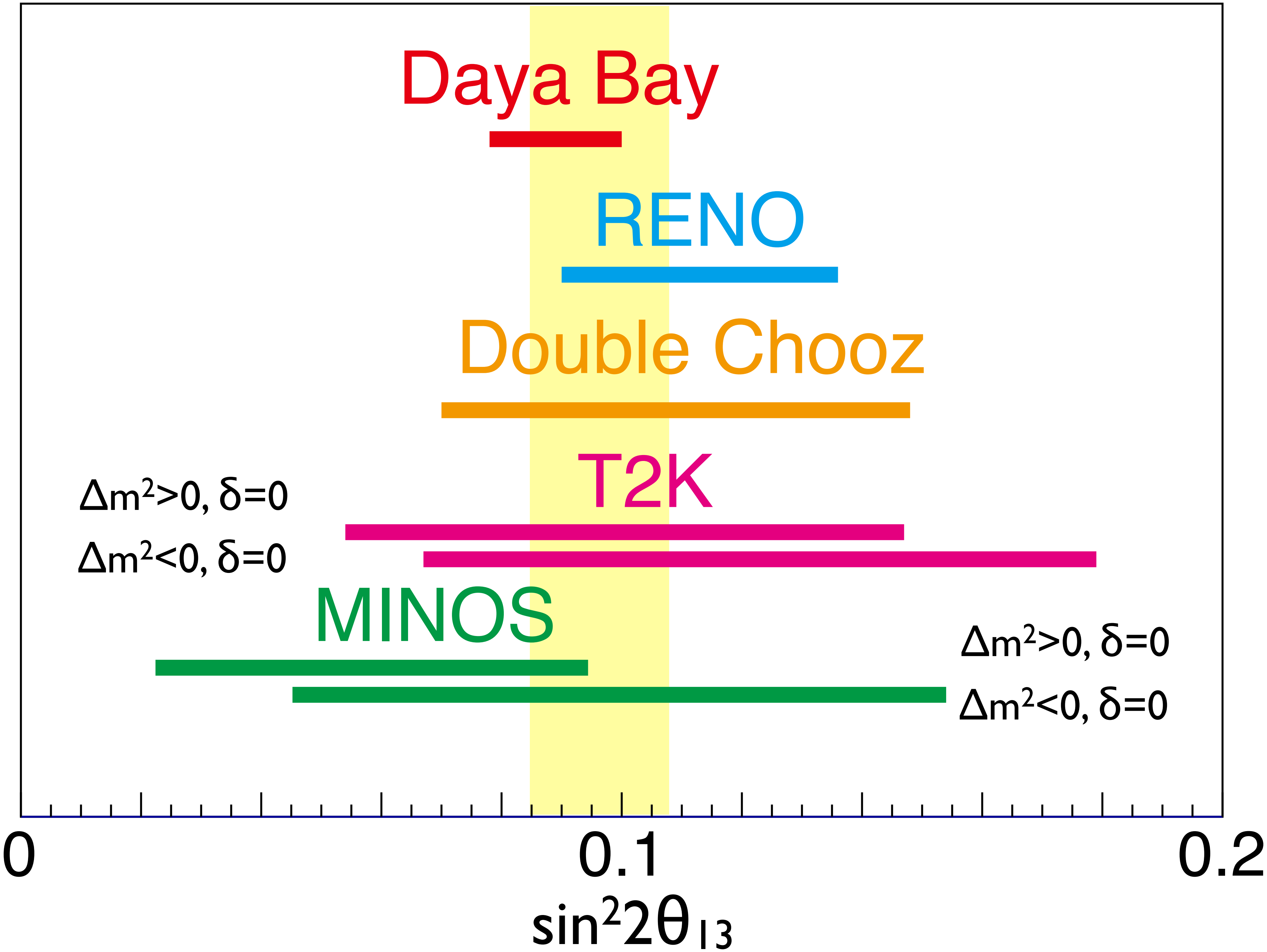




Can probe energy scale far beyond LHC!

Long baseline experiment

$\theta_{13} \neq 0$ established...

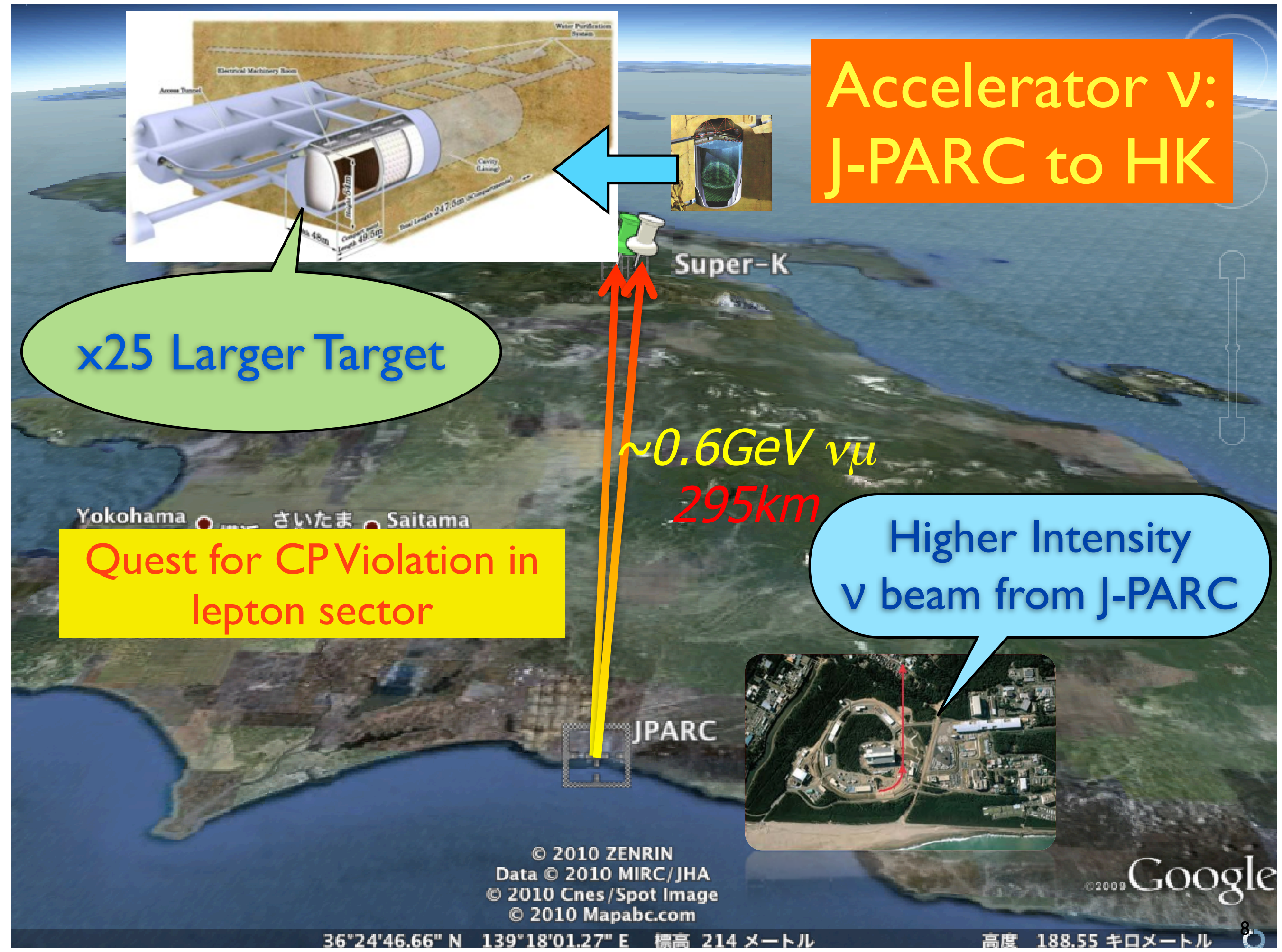


Now is the time to move forward to the next step!

ν oscillation measurements with HK

'Large' value of θ_{13} has opened access to

- ν mass hierarchy
- Octant of θ_{23}
- Leptonic *CP* violation



Hyper-Kamiokande can address
ALL of these
with synergy of accelerator and atm ν

Explore **full picture** of neutrino oscillation!

CP violation in neutrino mixing

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{(m_i^2 - m_j^2)L}{4E_\nu}$$

$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{(m_i^2 - m_j^2)L}{2E_\nu}$$

Rephasing invariant CPV parameter

All mixing angles≠0 for J_{CP}≠0

$$J_{CP} = \mathrm{Im}(U^*_{e3}U_{\mu 3}U_{e2}U^*_{\mu 2}) = \frac{1}{8}\cos\theta_{13}\boxed{\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}}\boxed{\sin\delta}$$

CP violating Dirac phase

Nature kindly prepared

$\sin\theta_{23} \sim 1/\sqrt{2}$

$\sin\theta_{12} \sim 0.55$

$\sin\theta_{13} \sim 0.16$

for us to be able to test CP symmetry in ν oscillation!

$\nu_\mu \rightarrow \nu_e$ probability

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

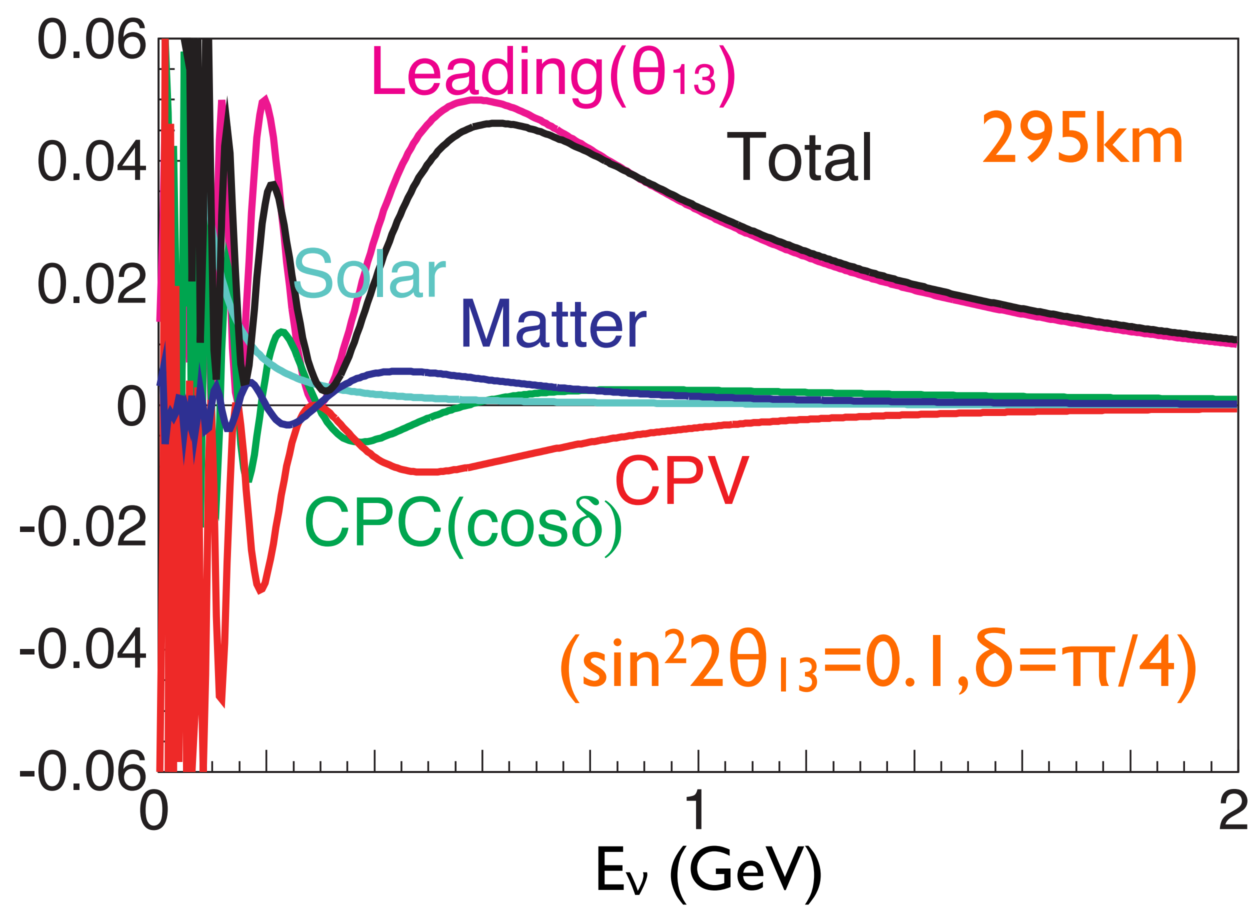
Rich physics (with precise θ_{13} expected from reactor)

Leading term $\propto \sin^2 2\theta_{13}$

CPV term $\propto \sin 2\theta_{13}$

Matter effect $\propto \sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$
signal ↑, CP asymmetry ↓
matter/CP ↑



CP measurement strategy with Hyper-K

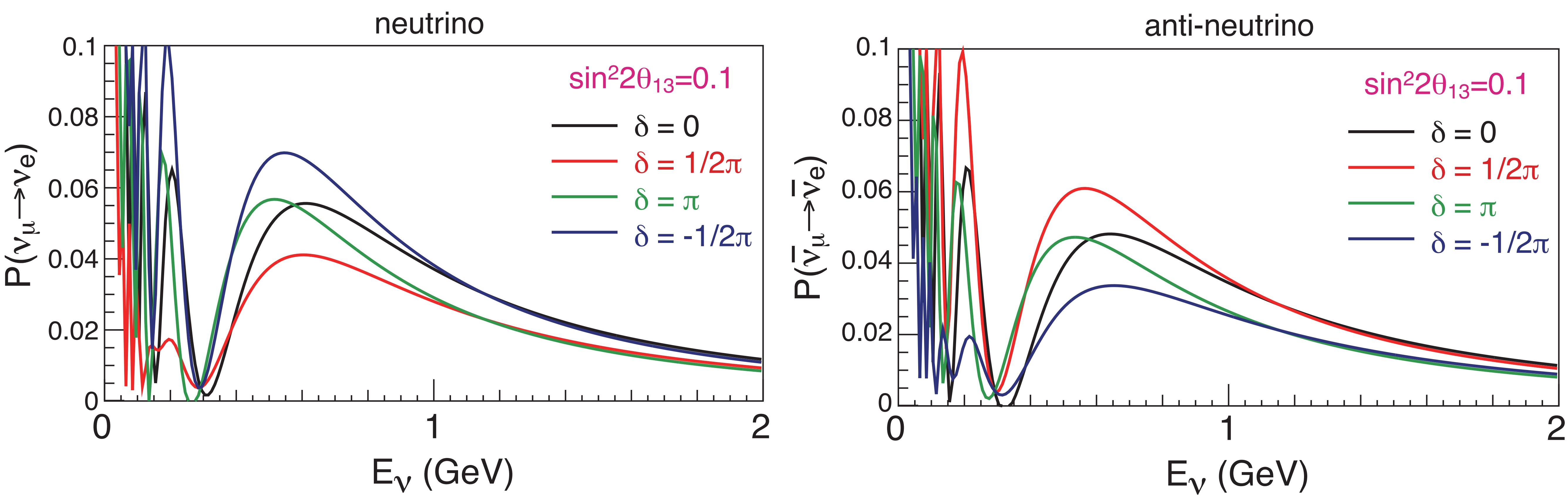
- Strength of water Cherenkov detector
  - Huge mass – statistics is always critical
  - Excellent reconstruction/PID performance especially in sub-GeV region (quasielastic→single ring)
- Best matched with low energy, narrow band beam
  - Off-axis beam with relatively short baseline
    - Less matter effect
    - Complementary to >1000km baseline experiments planned in EU/US

J-PARC ν beam + Hyper-K will be an excellent option in Japan

(natural extension of technique proved by T2K)

$\nu_\mu \rightarrow \nu_e$ probability with L=295km

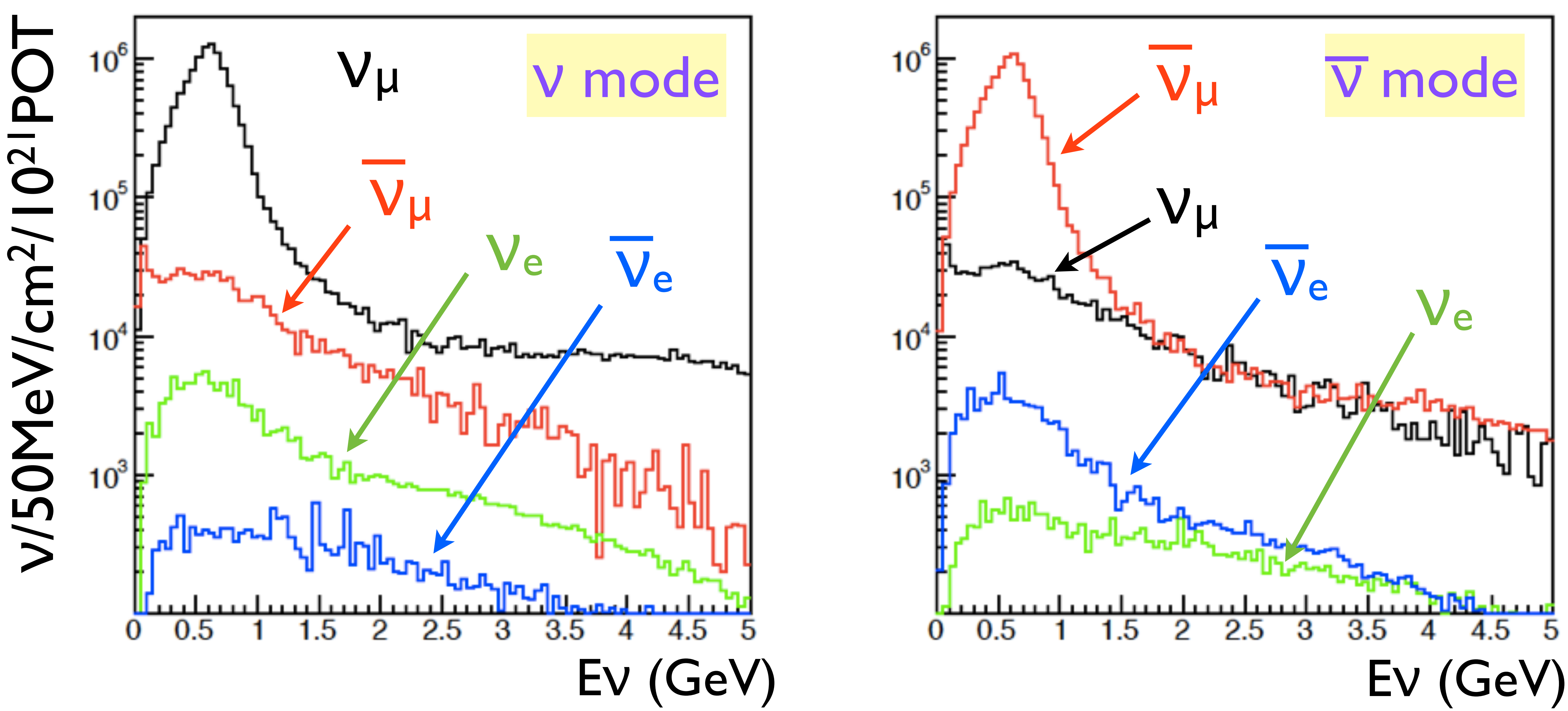
Normal mass hierarchy



- CPV search by comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Sensitive to exotic (non-MNS) CPV

The ν beam

Expected neutrino flux at Hyper-K (unoscillated)



2.5° off-axis beam from J-APRC
Peaked at oscillation maximum
Suppress BG from high energy component (ν_τ negligible)

Simulation of HK events

- Based on FULL simulation and reconstruction utilizing SK/T2K tools
  - Number of PMT reduced for 20% coverage
  - Also for proton decay, atm ν
  - (Simulation session tomorrow)
- ν_e event selection the same as T2K
  - Well established and understood

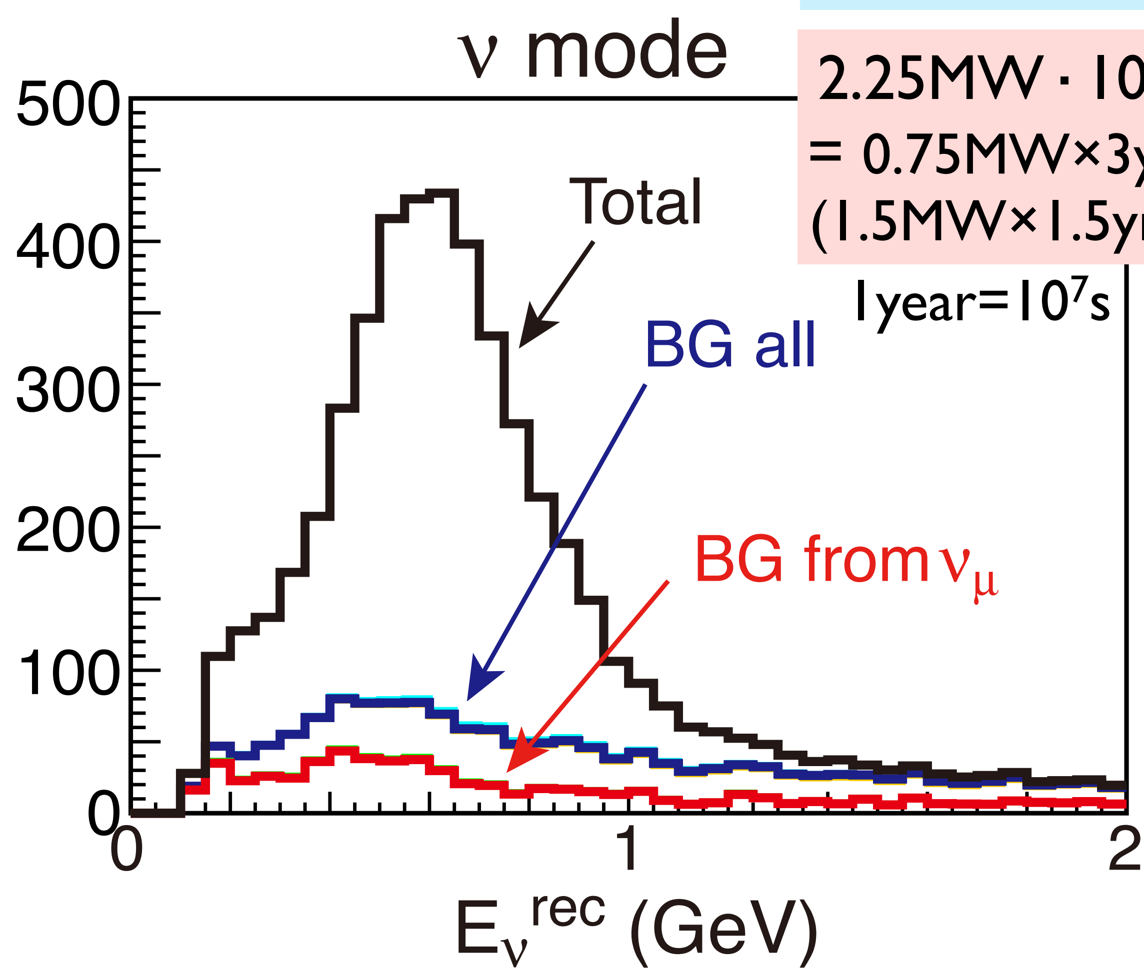
Signal efficiency	64%
ν_μ CC BG rejection	>99.9%
NC π^0 BG rejection	95%

(for E_ν^{rec}<1.25GeV)

Reliable prediction of event observables

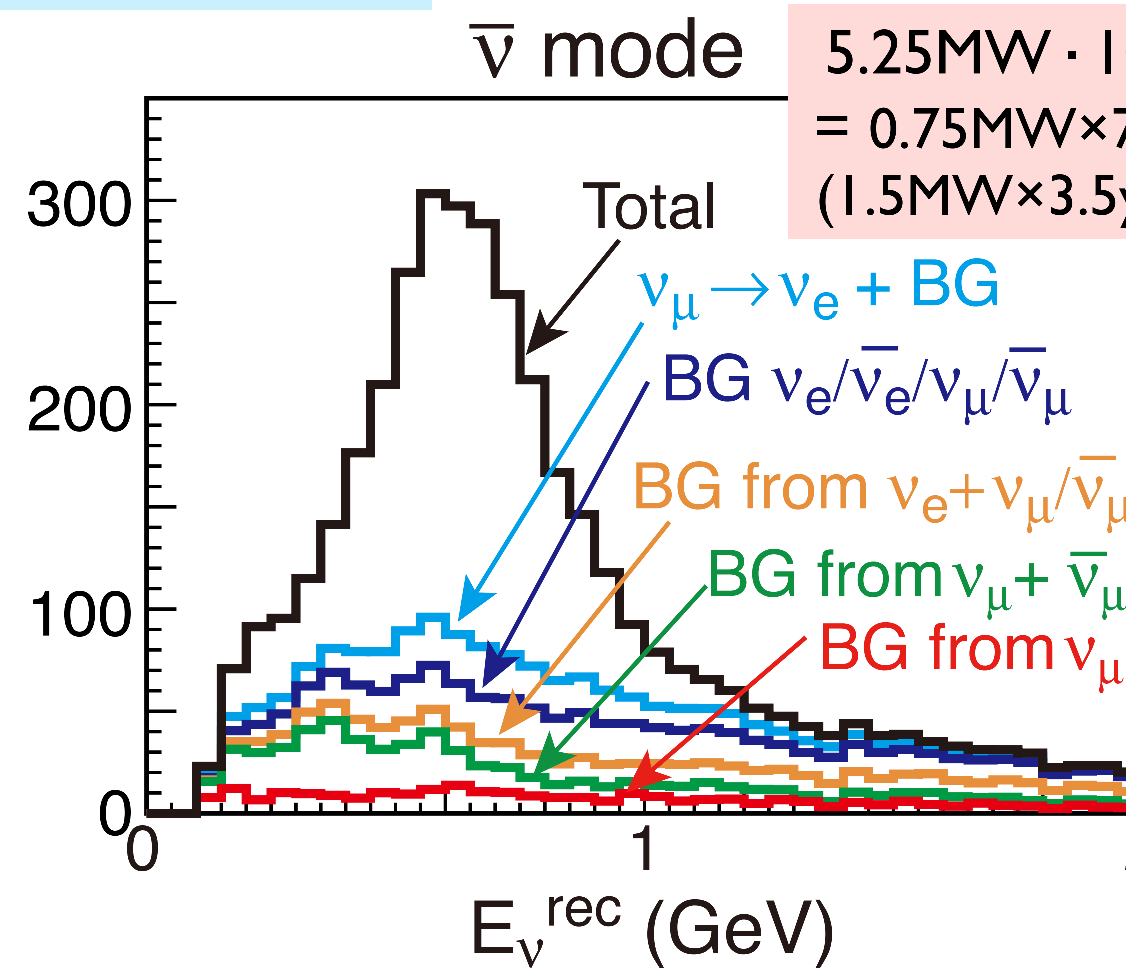
ν_e candidates after selection

$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH



2.25MW · 10^7s
= 0.75MW×3yrs
(1.5MW×1.5yrs)

1year=10^7s



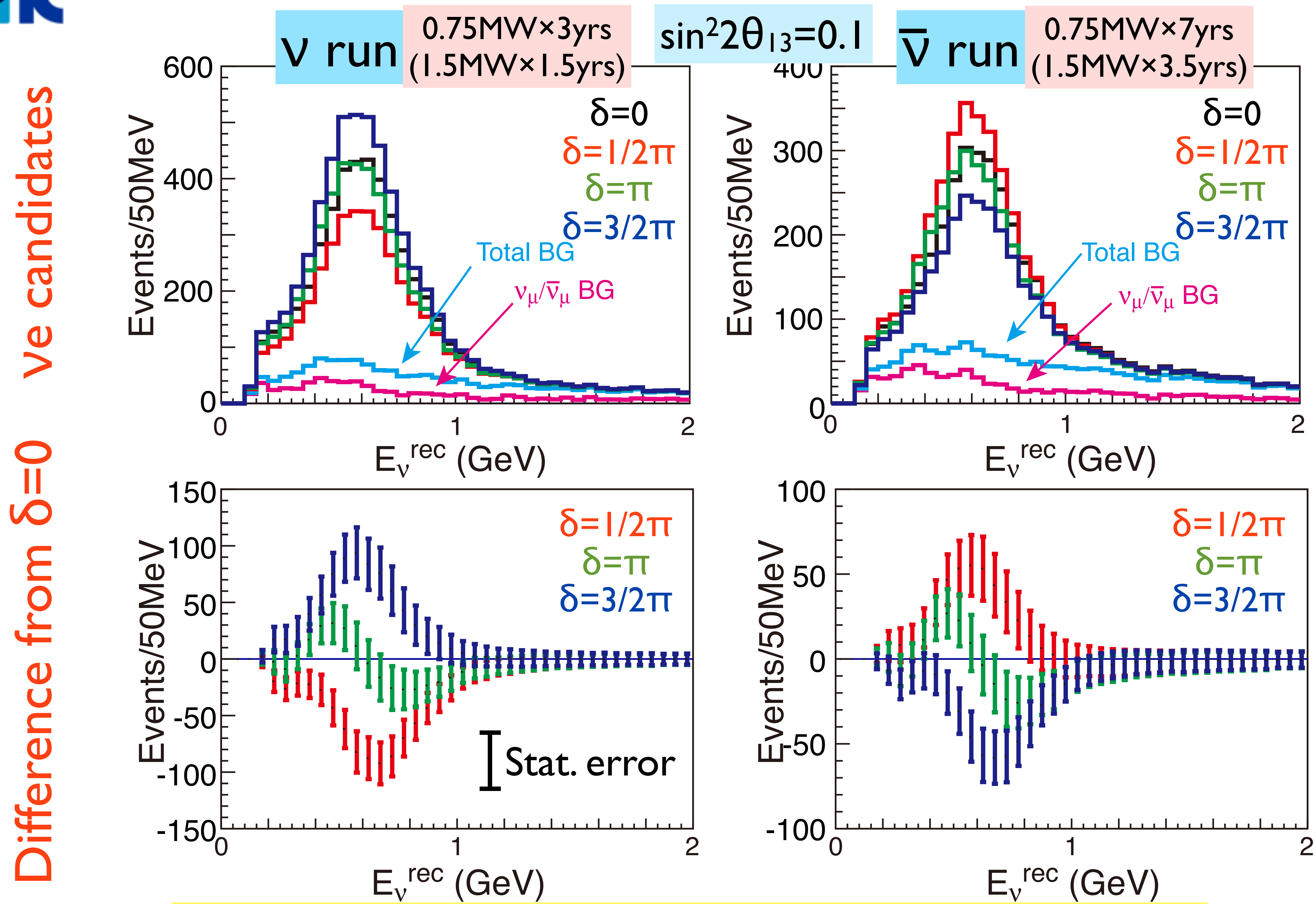
5.25MW · 10^7s
= 0.75MW×7yrs
(1.5MW×3.5yrs)

	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

2000-3000 signal events expected for each of ν and $\bar{\nu}$

Effect of δ

1year=10^7sec

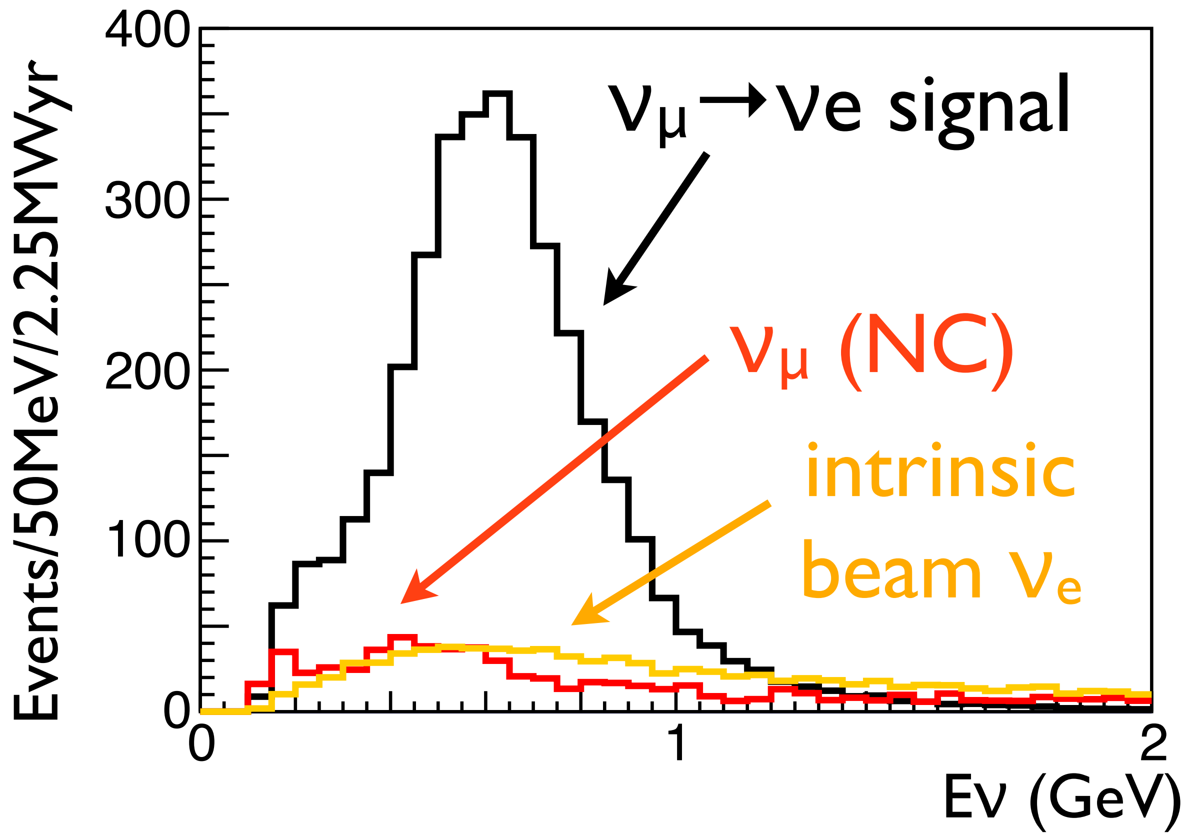


Number + shape: sensitive to all values of δ

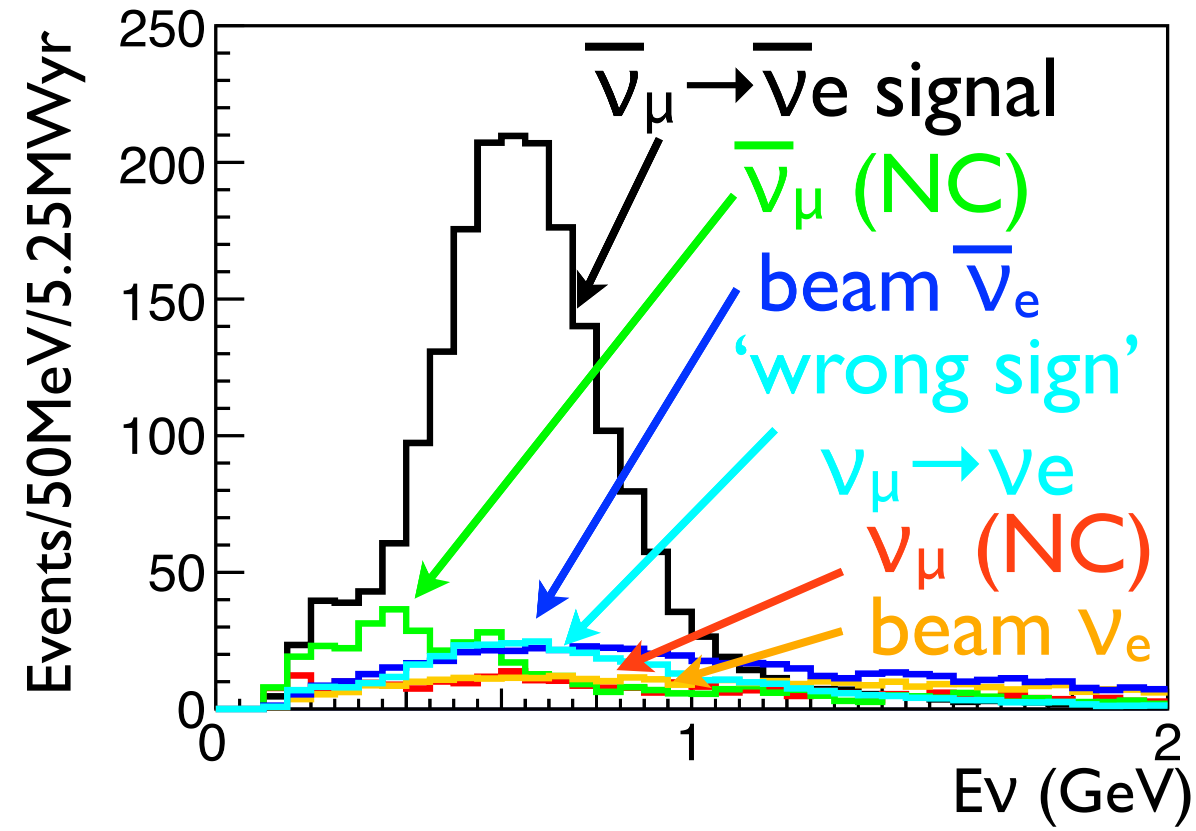
Background sources

$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH

ν run



$\bar{\nu}$ run



ν_μ originate background (mostly neutral current π^0) and intrinsic beam ν_e are dominant background.

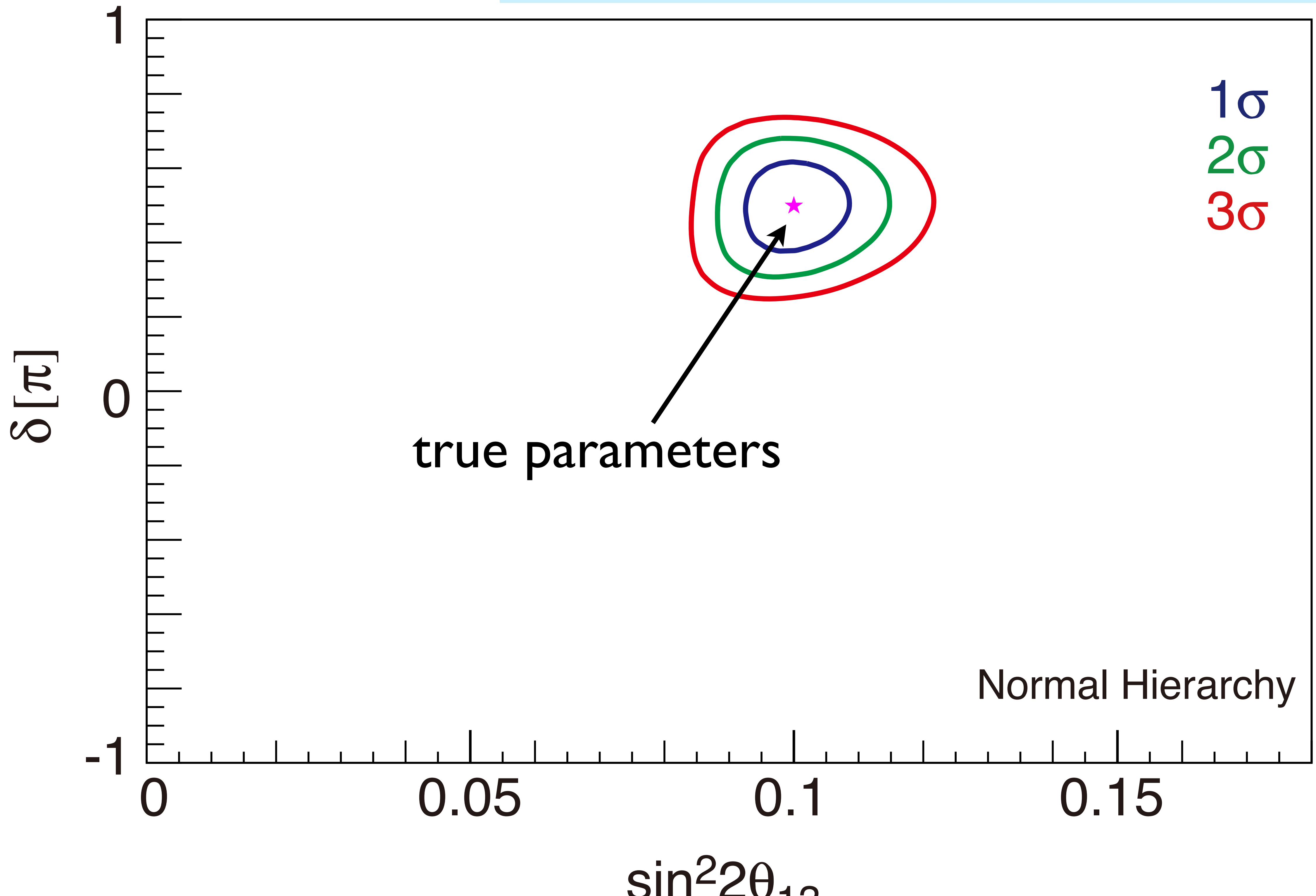
For anti-neutrino running, 'wrong sign' (ν) BG ~ anti-ν because of cross section difference.
In addition, 'wrong sign' appearance significant (~20%)

Reconstructed energy spectrum of BG is rather flat.

Expected allowed region: example

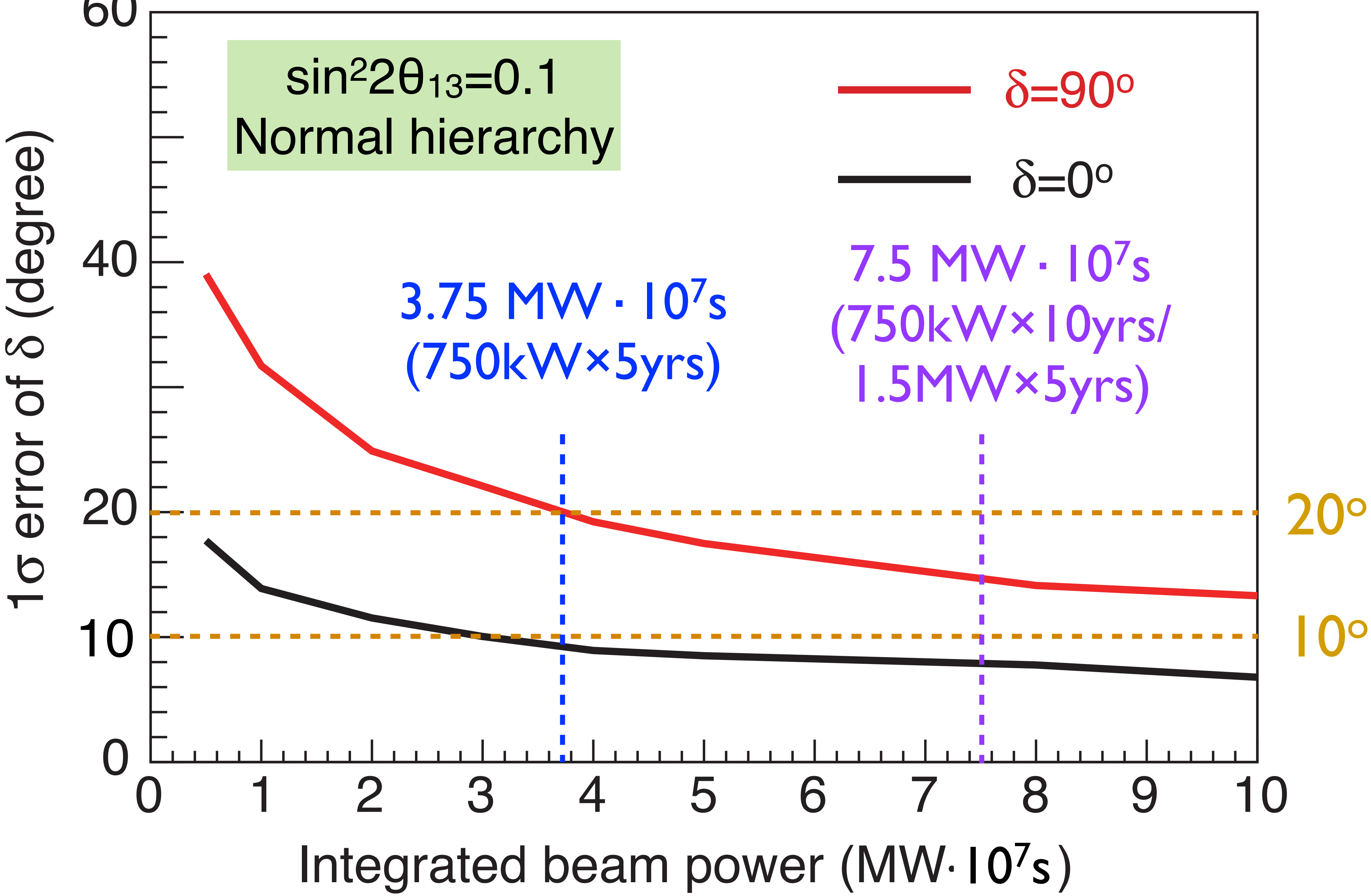
0.75MW×10yrs

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



Measurement of δ (1σ)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

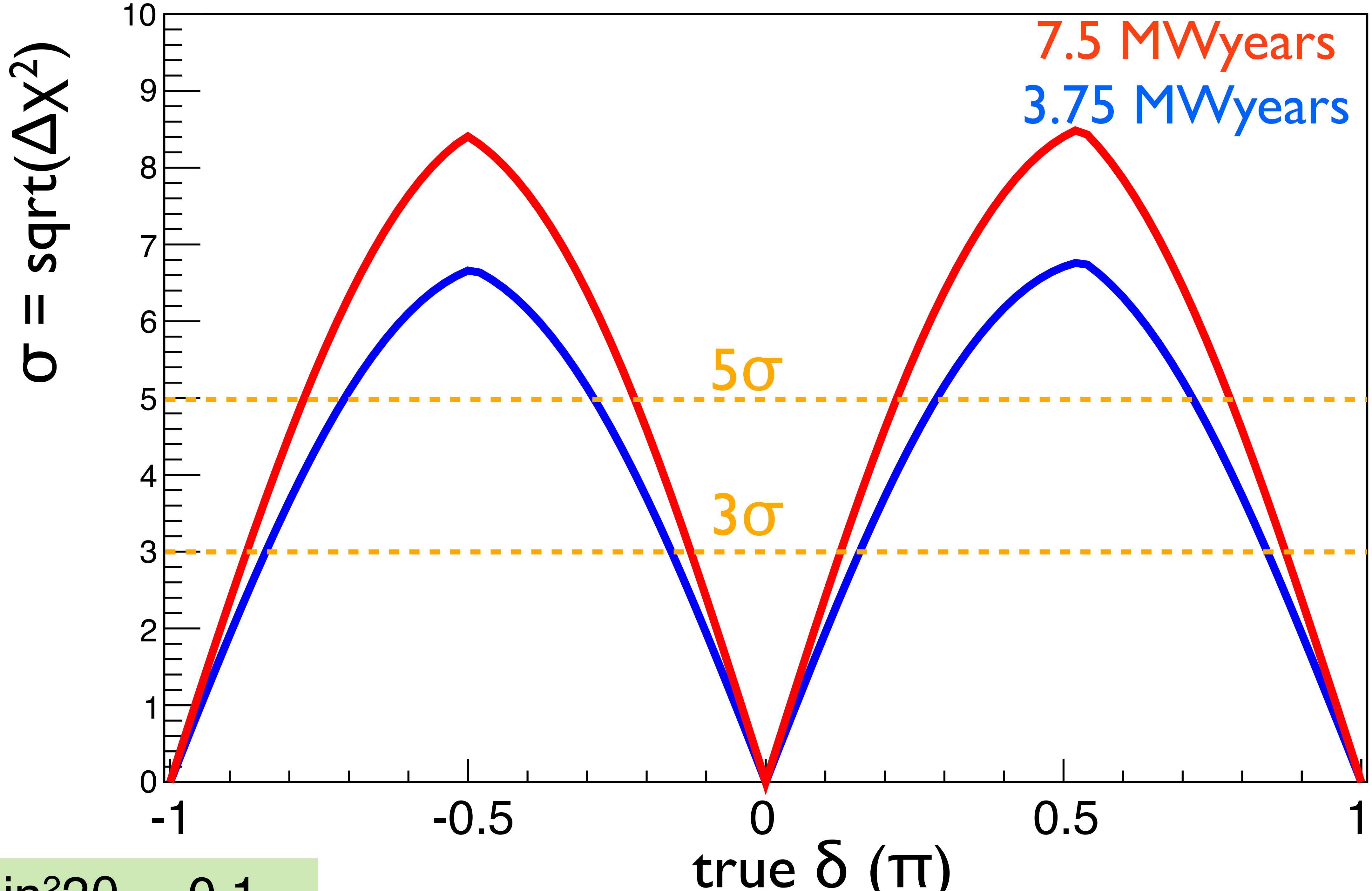


<20° for δ=90°, <10° for δ=0

Hyper-K CPV sensitivity

(Exclusion of δ=0,π)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



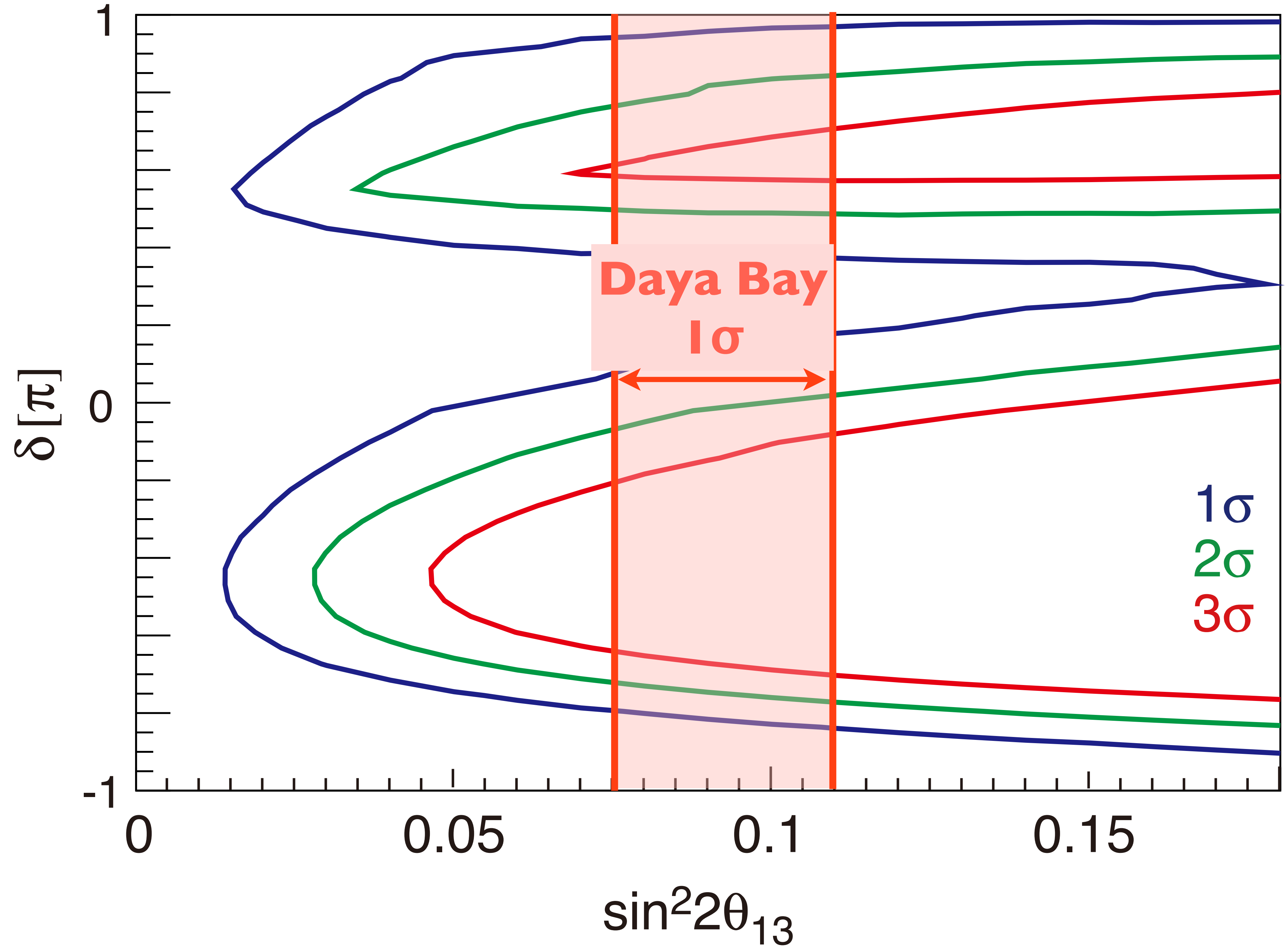
$\sin^2 2\theta_{13}=0.1$
Normal hierarchy

For 74(55)% of δ, >3(5)σ with 7.5MWyrs

Mass hierarchy

0.75MW×10yrs

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



Chance to determine MH! See also later talk (atm ν)

Ongoing study: effect of systematics

- Check effect of systematics with updated χ^2 definition
- Assuming that normalization will be given by ND
  - For ν_μ in ν run, $\bar{\nu}_\mu$ and ν_μ in $\bar{\nu}$ run
- Systematic parameters (total 11)
  - Normalization $f^{\nu}_{\rm norm}, f^{\bar{\nu}}_{\rm norm}, f^{\bar{\nu}}_{\rm WS}$
  - CCnon-QE/CCQE $f^{\nu}_{nQE}, f^{\bar{\nu}}_{nQE}$
  - ν_μ (~NC) $f^{\nu}_{\nu\mu}, f^{\bar{\nu}}_{\nu\mu}, f^{\bar{\nu}}_{\bar{\nu}_\mu}$
  - Intrinsic νe $f^{\nu}_{\nu e}, f^{\bar{\nu}}_{\nu e}, f^{\bar{\nu}}_{\bar{\nu}_e}$
- No energy dependence (yet)

χ^2 used for systematics study

ν run

$$\chi^2 = \sum_i^{for\,\nu} \Big[N^i - (1+f^{\nu}_{\mathrm{norm}}) \Big\{ n^i_{\nu_\mu\to\nu_e,QE} + (1+f^{\nu}_{nQE}) n^i_{\nu_\mu\to\nu_e,nQE} + n^i_{\bar{\nu}_\mu\to\bar{\nu}_e} + (1+f^{\nu}_{\nu_\mu})(n^i_{\nu_\mu} + n^i_{\bar{\nu}_\mu}) + (1+f^{\nu}_{\nu_e})(n^i_{\nu_e} + n^i_{\bar{\nu}_e}) \Big\} \Big]^2 / N^i$$

antiν run

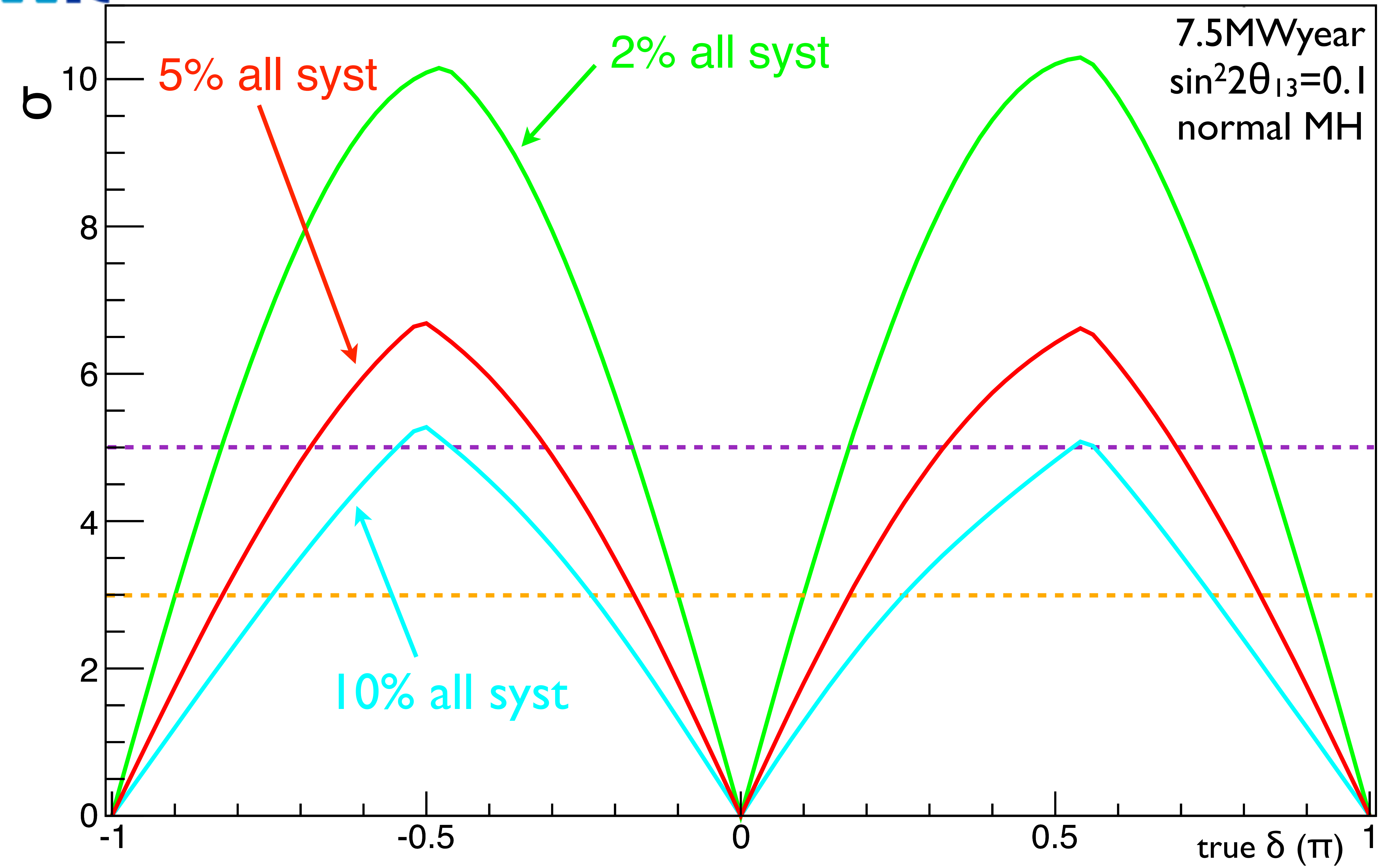
wrong sign

$$+ \sum_i^{for\,\bar{\nu}} \Big[N^i - (1+f^{\bar{\nu}}_{\mathrm{norm}}) \Big\{ n^i_{\bar{\nu}_\mu\to\bar{\nu}_e,QE} + (1+f^{\bar{\nu}}_{nQE}) n^i_{\bar{\nu}_\mu\to\bar{\nu}_e,nQE} + (1+f^{\bar{\nu}}_{\bar{\nu}_\mu}) n^i_{\bar{\nu}_\mu} + (1+f^{\bar{\nu}}_{\bar{\nu}_e}) n^i_{\bar{\nu}_e} \Big\} + (1+f^{\bar{\nu}}_{\mathrm{WS}}) \Big\{ n^i_{\nu_\mu\to\nu_e,QE} + (1+f^{\nu}_{nQE}) n^i_{\nu_\mu\to\nu_e,nQE} + (1+f^{\bar{\nu}}_{\nu_\mu}) n^i_{\nu_\mu} + (1+f^{\bar{\nu}}_{\nu_e}) n^i_{\nu_e} \Big\} \Big]^2 / N^i$$

$$+ \sum_{\mathrm{syst.\,par}} \frac{f^2}{\sigma^2}$$

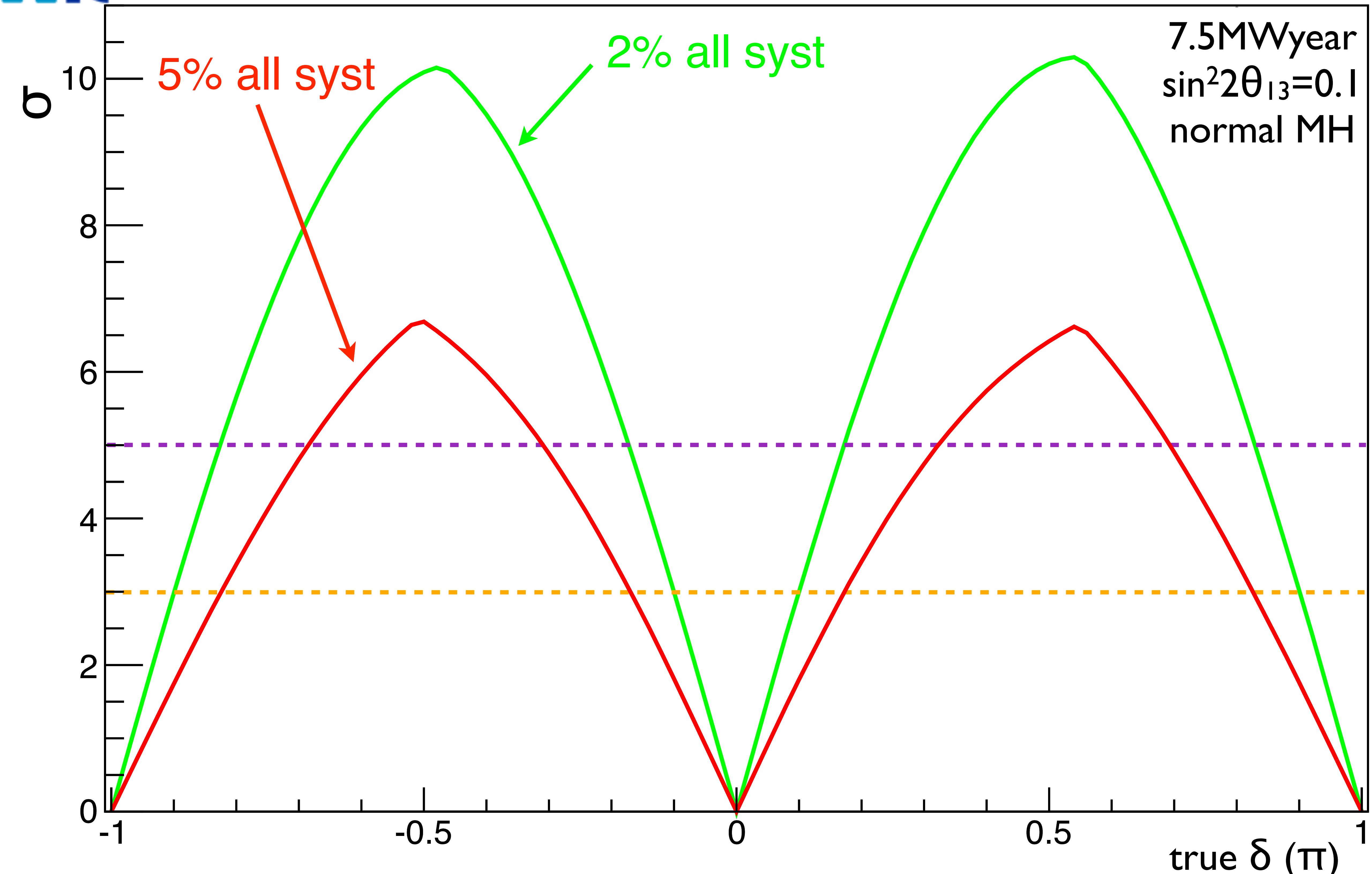
(Used E_ν^{rec}<1.2GeV)

Effect of systematics



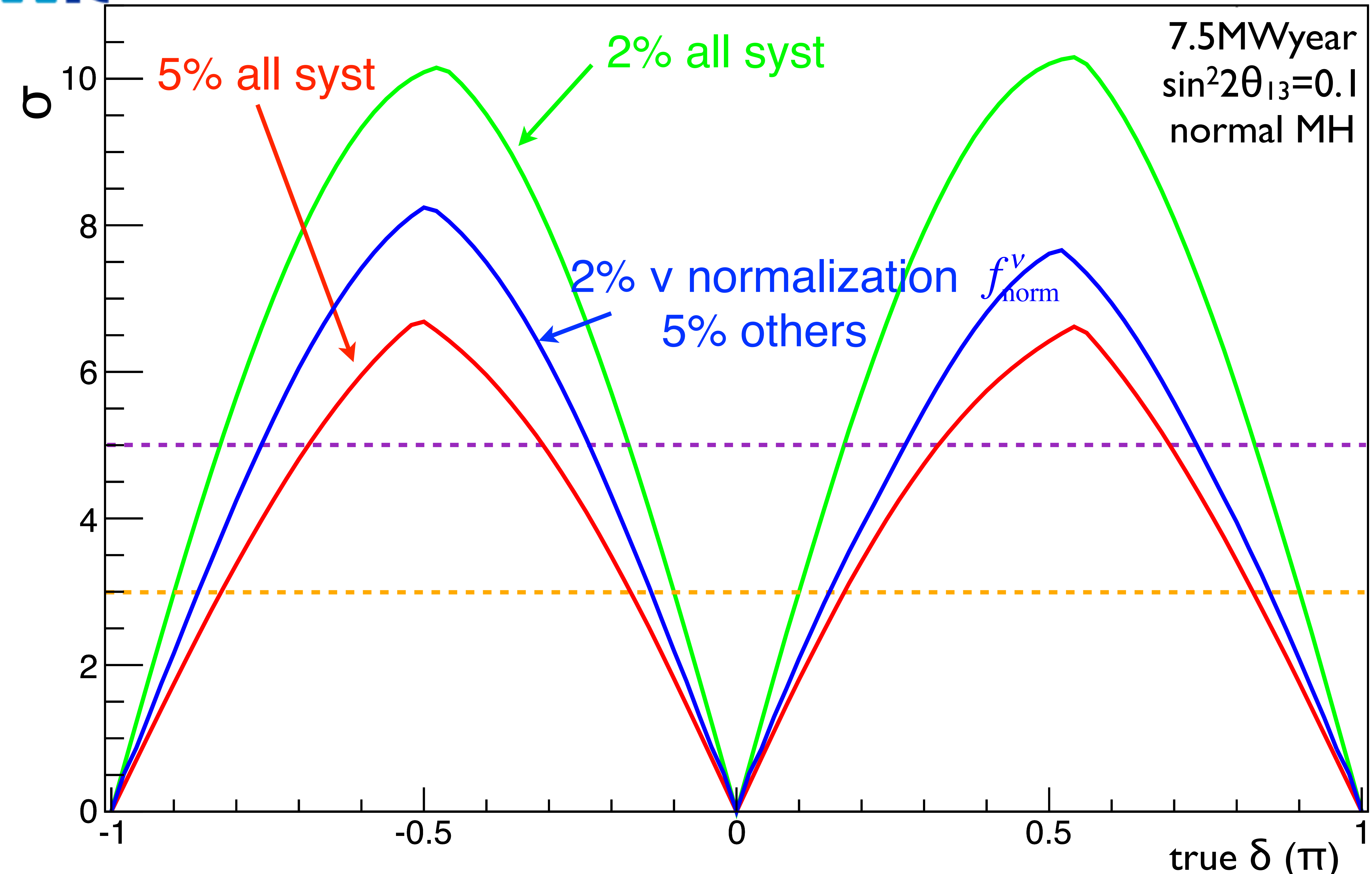
Effect of systematics is significant, but even with 10%, >3σ possible

Effect of normalization



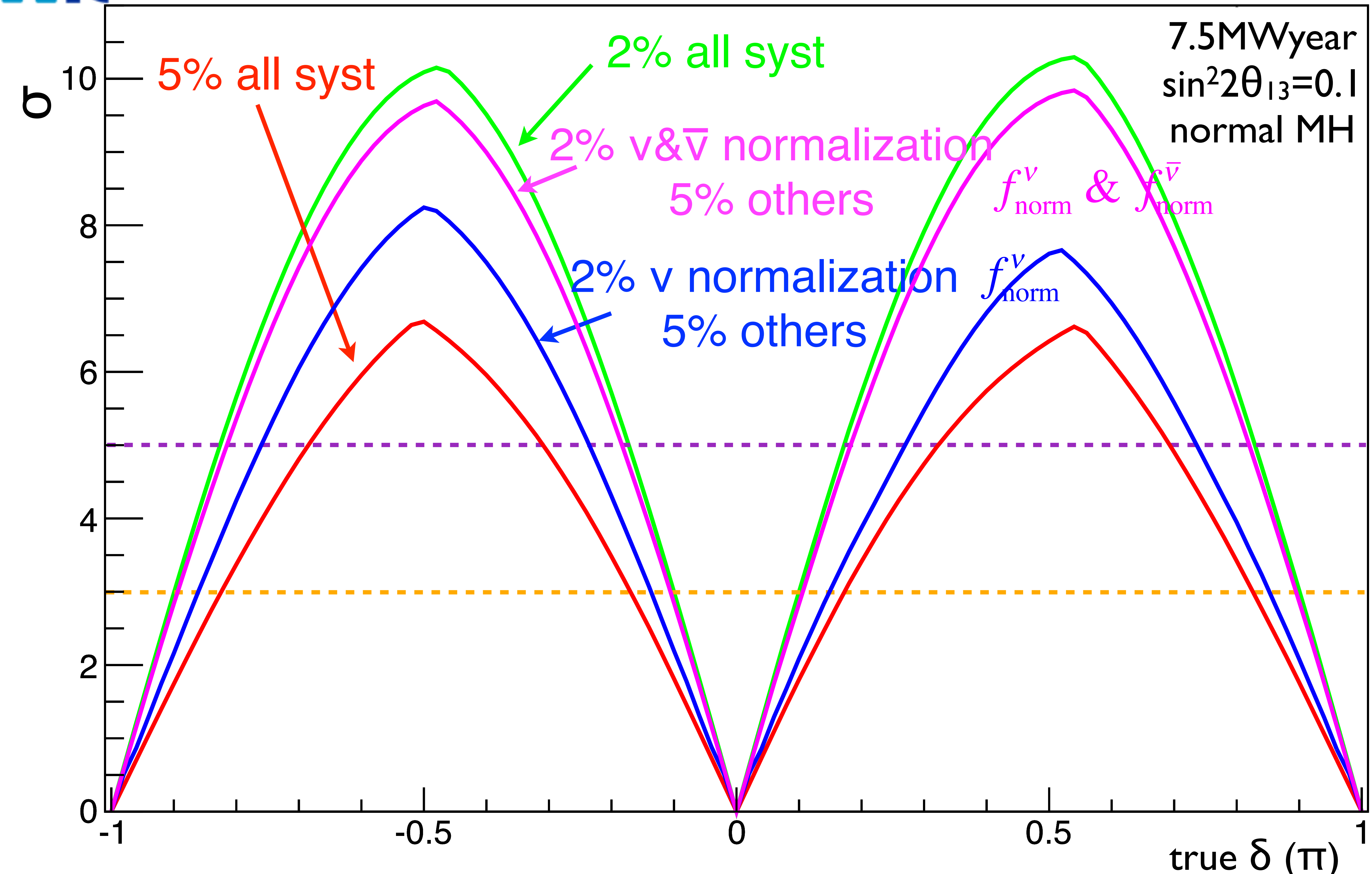
Normalization has largest effect

Effect of normalization



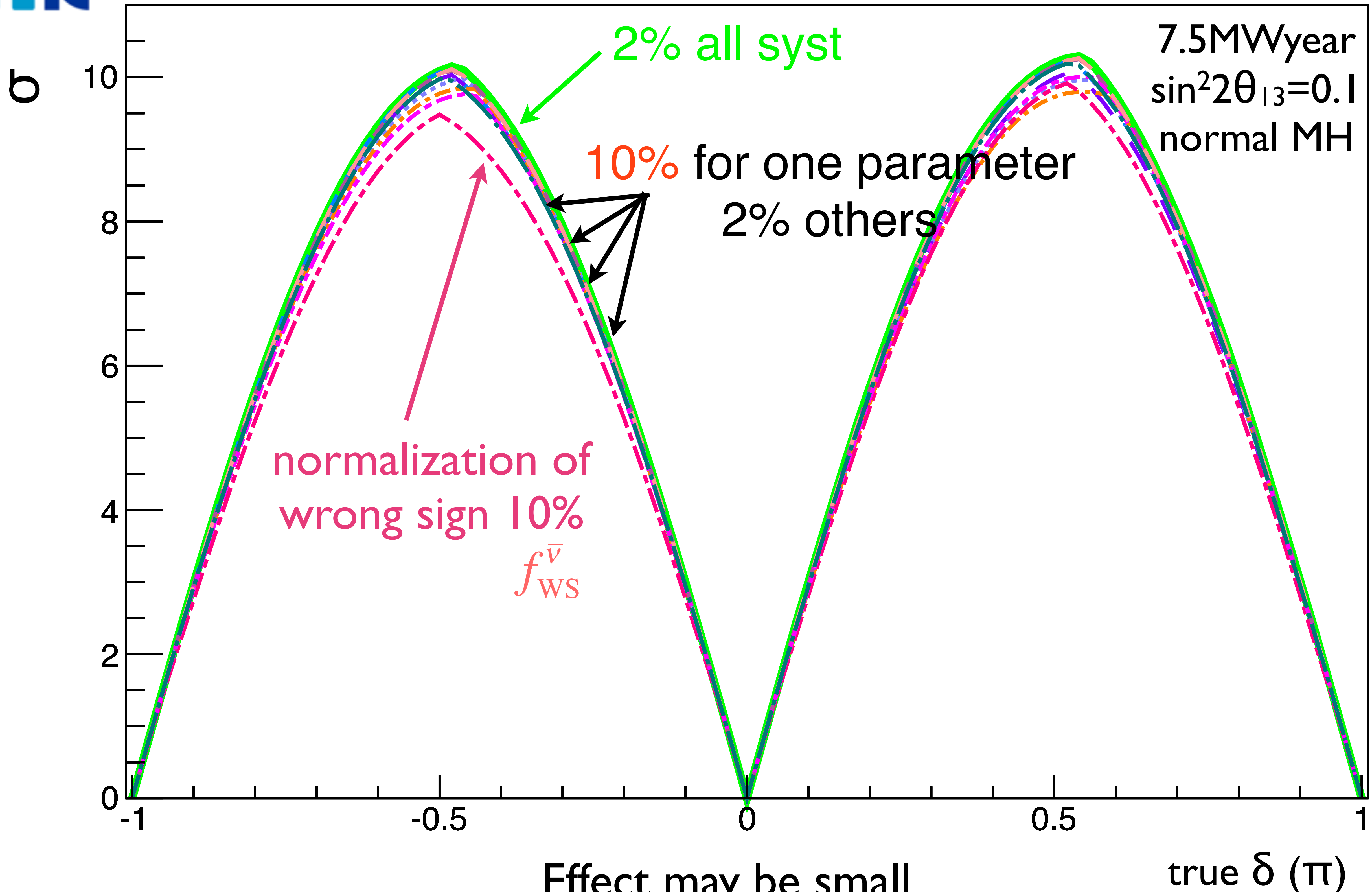
Normalization has largest effect

Effect of normalization



Normalization has largest effect

Other systematics



Effect may be small

Note: preliminary study with simple parametrization, study ongoing

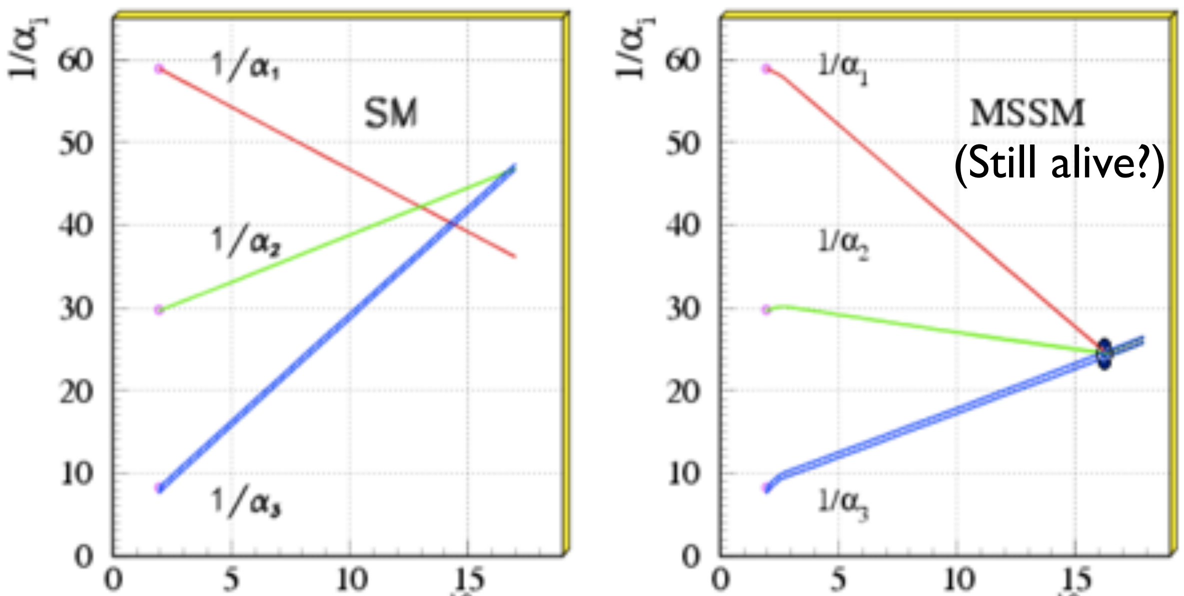
Summary of first part (LBL)

- J-PARC + Hyper-K LBL experiment has potential to reveal full picture of neutrino oscillation.
  - CPV >3σ(5σ) for 74(55)% of δ.
  - Synergy with atmospheric ν → Roger's talk
- Systematic uncertainties are important for study of sub-leading CPV effect.
  - Ongoing work:
    quantifying near detector requirements and make conceptual design
    - Improve (upgrade) ND280 ?
    - Other detector at J-PARC?
    - Intermediate detector @~2km ?
  - Will be discussed in following talks and tomorrow

Search for nucleon decays

Nucleon decays

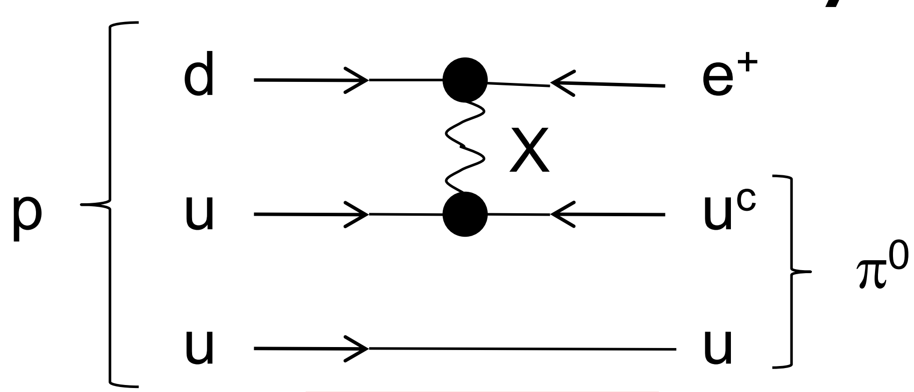
- Only direct probe of Grand Unified Theory



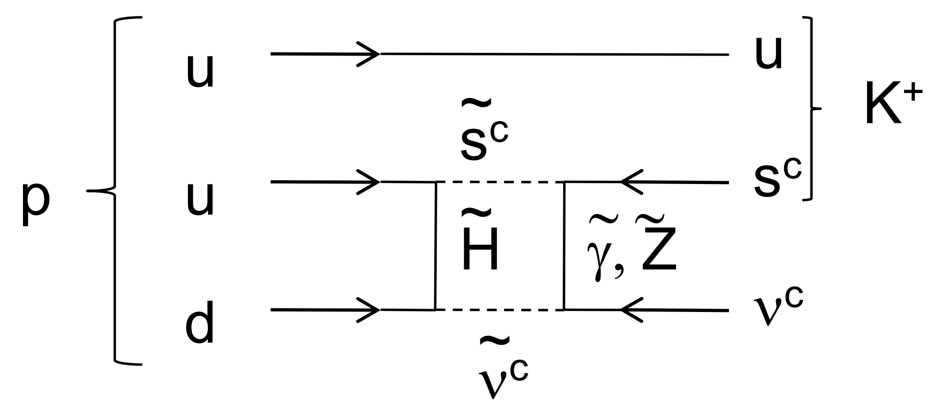
PDG2012

Many GUT models predict decays of protons and bound neutrons with $\tau = O(10^{34\text{-}35})$ years

- Two modes favored by many models:



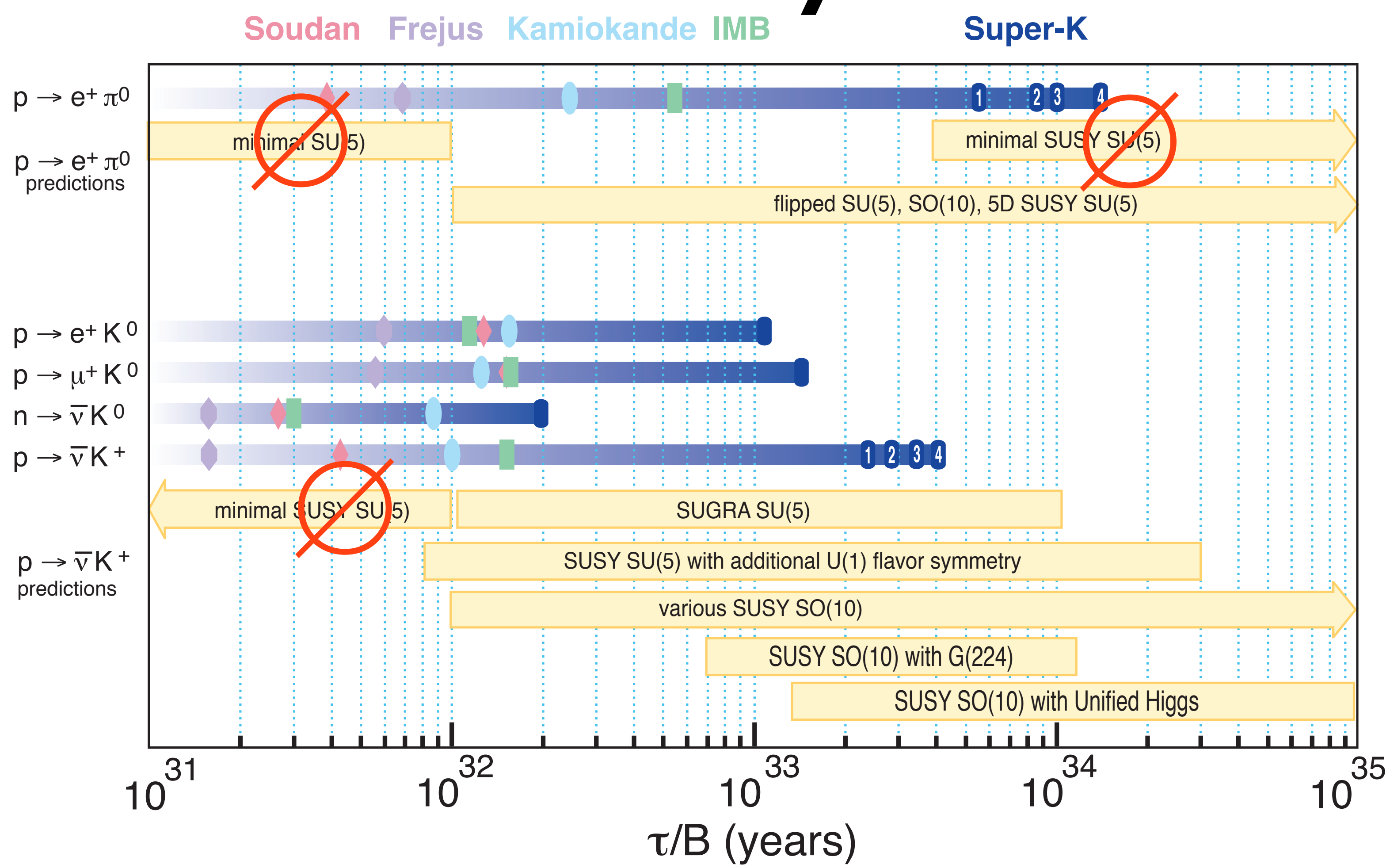
$p \rightarrow e^+\pi^0$



$p \rightarrow \nu K^+$

Other modes are also important (we don't know correct model!)

Proton decay searches



Best limits have been set by Water Cherenkov detectors

After >15 years of Super-K (220kt · yrs),

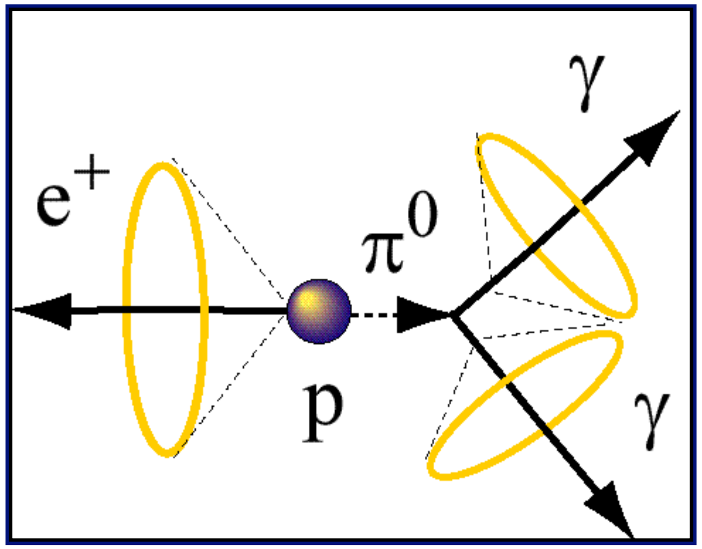
$\tau(p\to e^+\pi^0) > 1.3\times10^{34}$ years

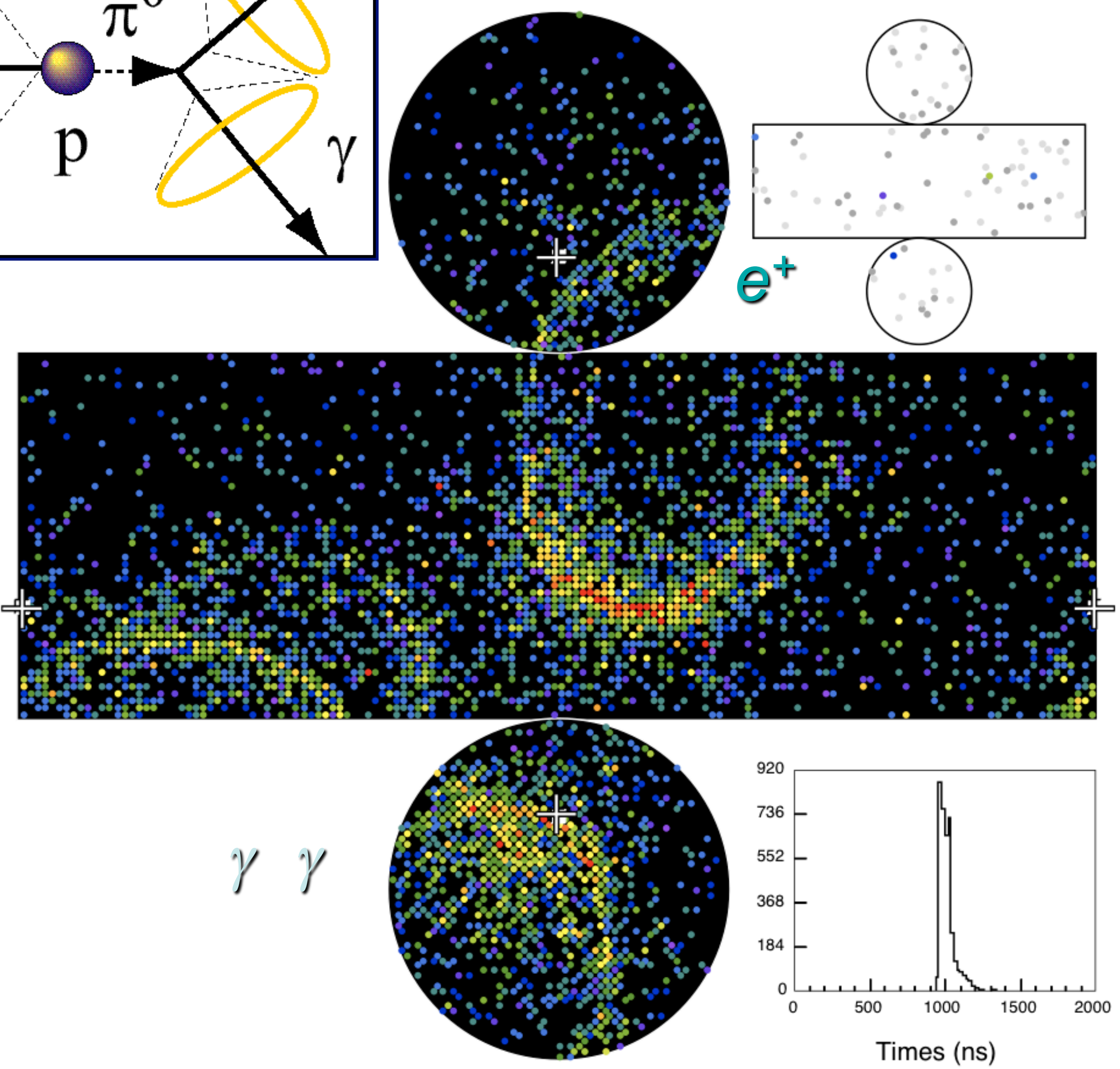
$\tau(p\to\nu K^+) > 4.0\times10^{33}$ years

@90%CL

Order of magnitude improvement necessary to be significant!

$p \rightarrow e^+\pi^0$ search





$e^+\pi^0$ selection

Invariant mass of p
Momentum balance

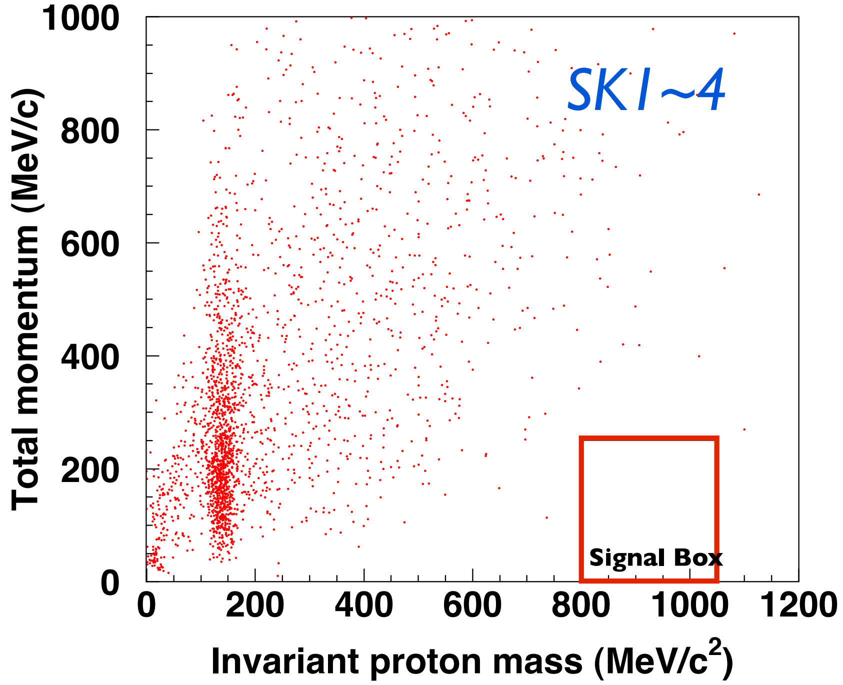
- 2 or 3 e-like rings
- No decay-e
- $85 < M_{\pi^0} < 185$ MeV/c^2 (3ring)
- $800 < M_p < 1050$ MeV/c^2
- $p_{tot} < 250$MeV/c

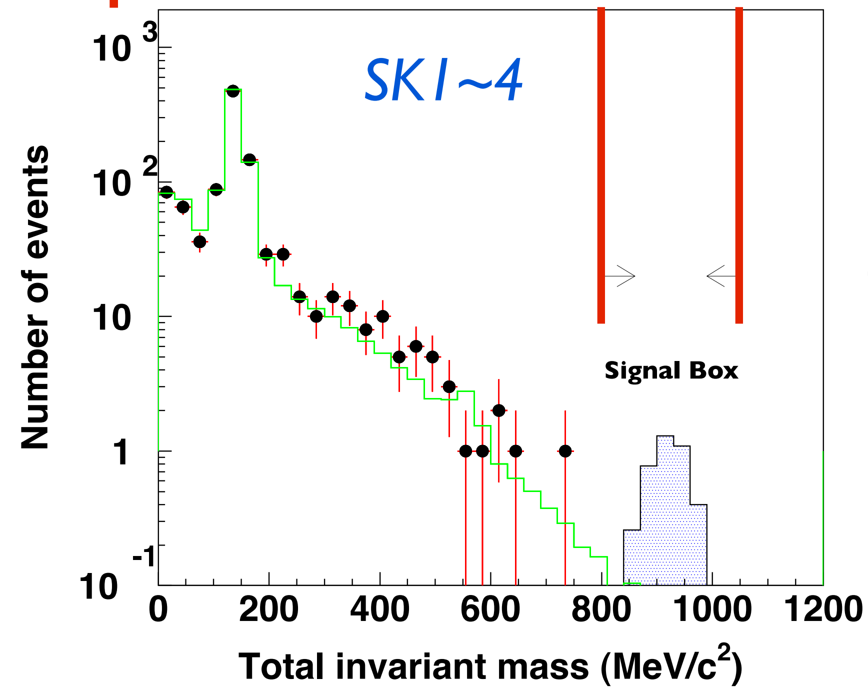
Efficiency 45%
(π interaction in nucleus)

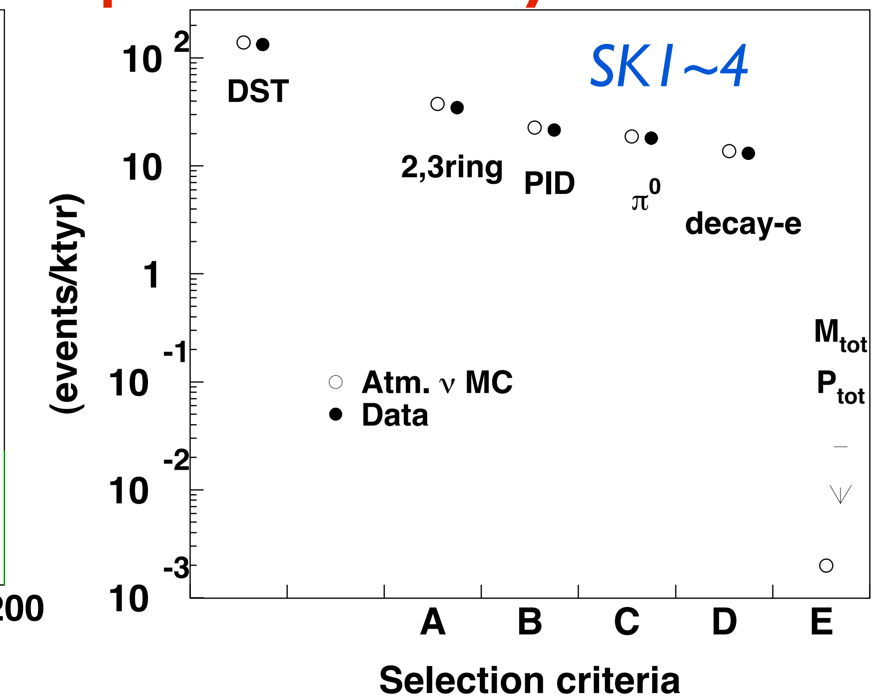
2/10 free protons in H_2O

$p \rightarrow e^+\pi^0$ search: BG (atm ν)

Super-K data are well reproduced by BG MC.

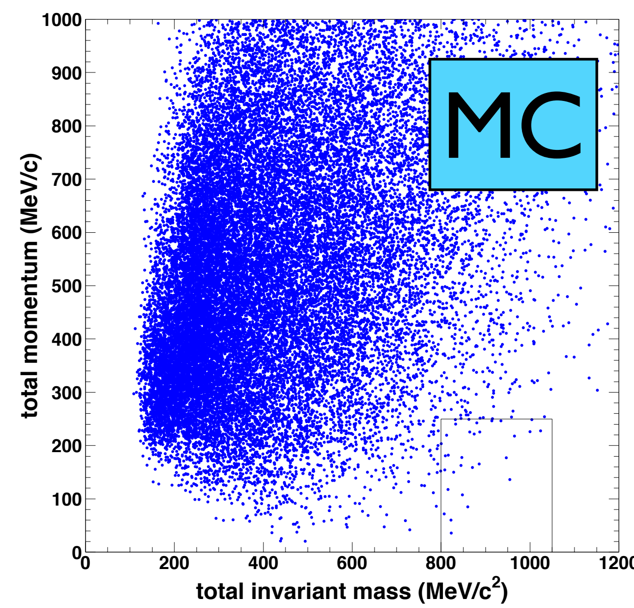


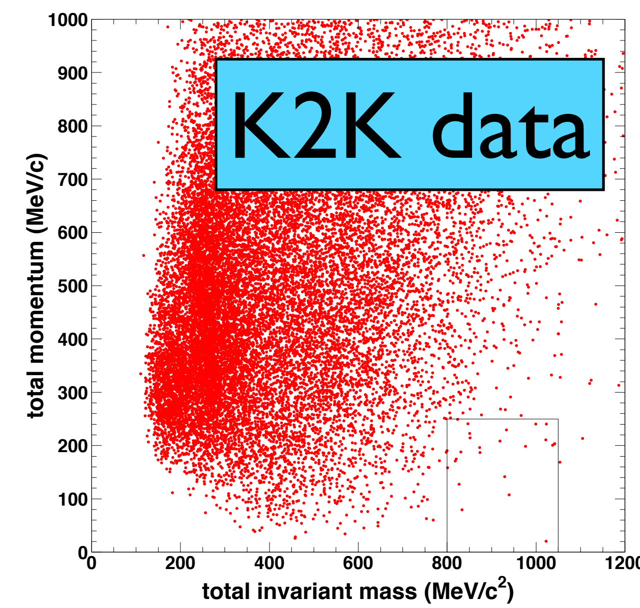




BG prediction confirmed with high statistics K2K 1kton near detector measurement

PRD 77, 032003(2008)





$$1.63^{+0.42}_{-0.33}(stat.)^{+0.45}_{-0.51}(syst.)[\mathrm{Mt} \times \mathrm{years}]^{-1}(E_\nu < 3GeV)$$

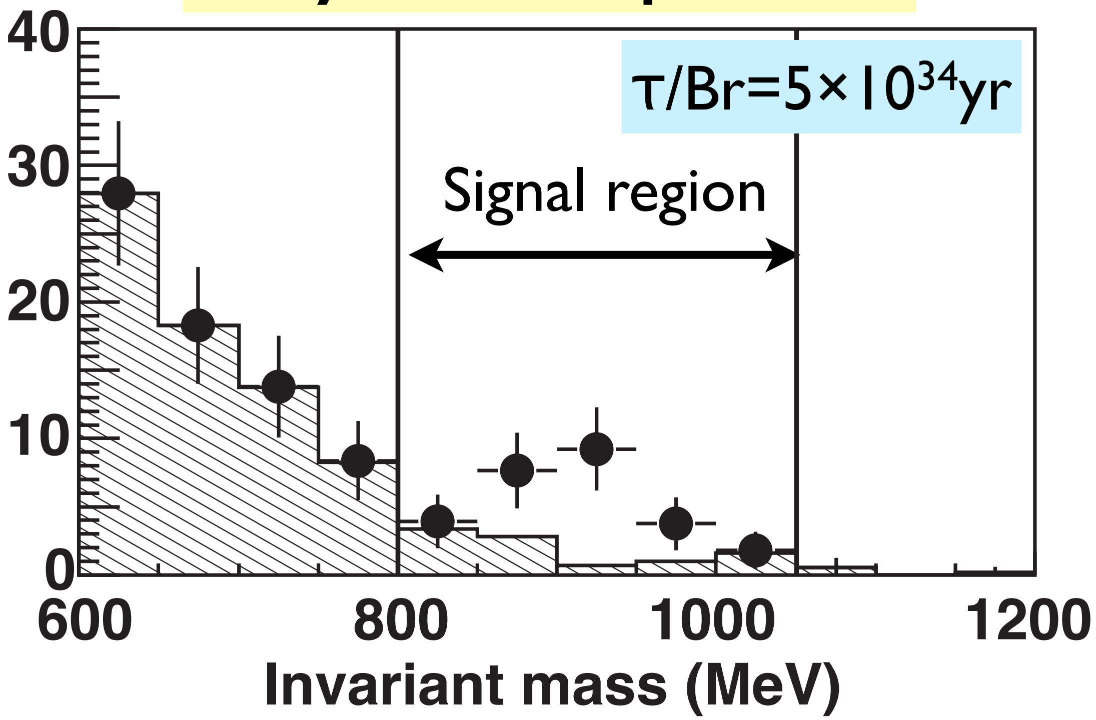
Consistent w/ simulation 1.8±0.3(stat.)

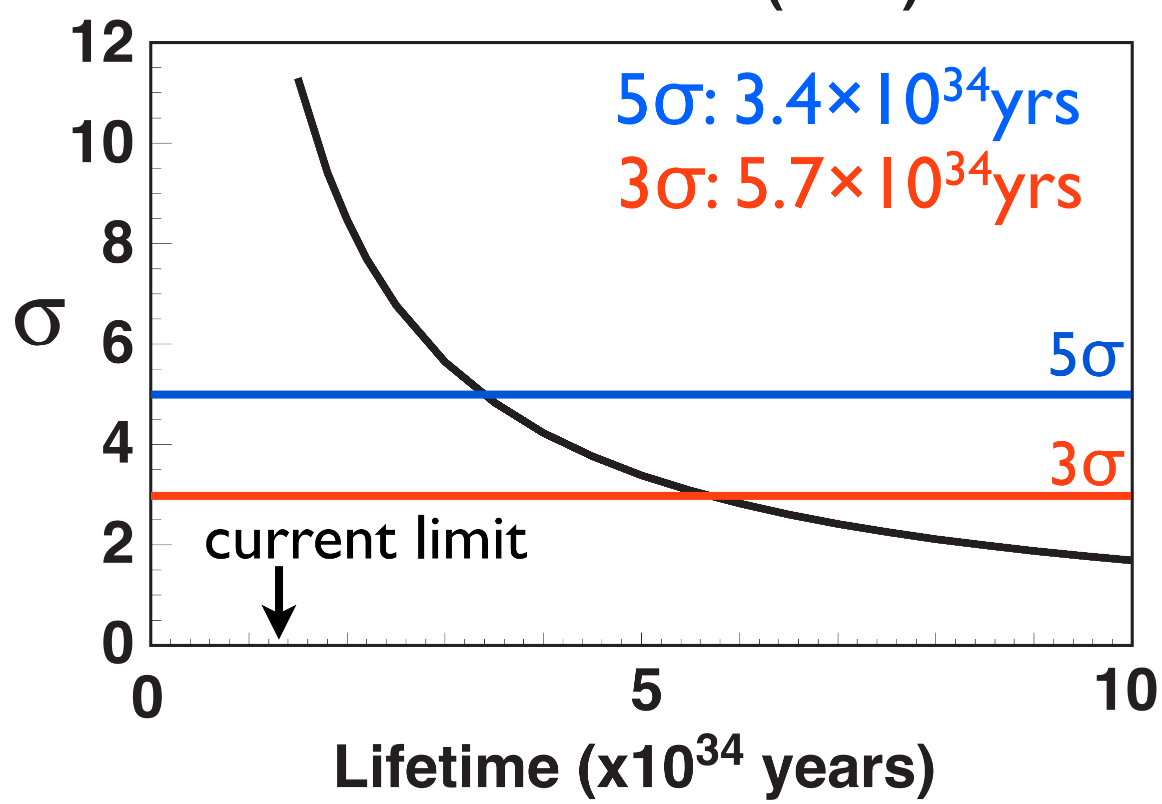
Reliable prediction of next generation experiment

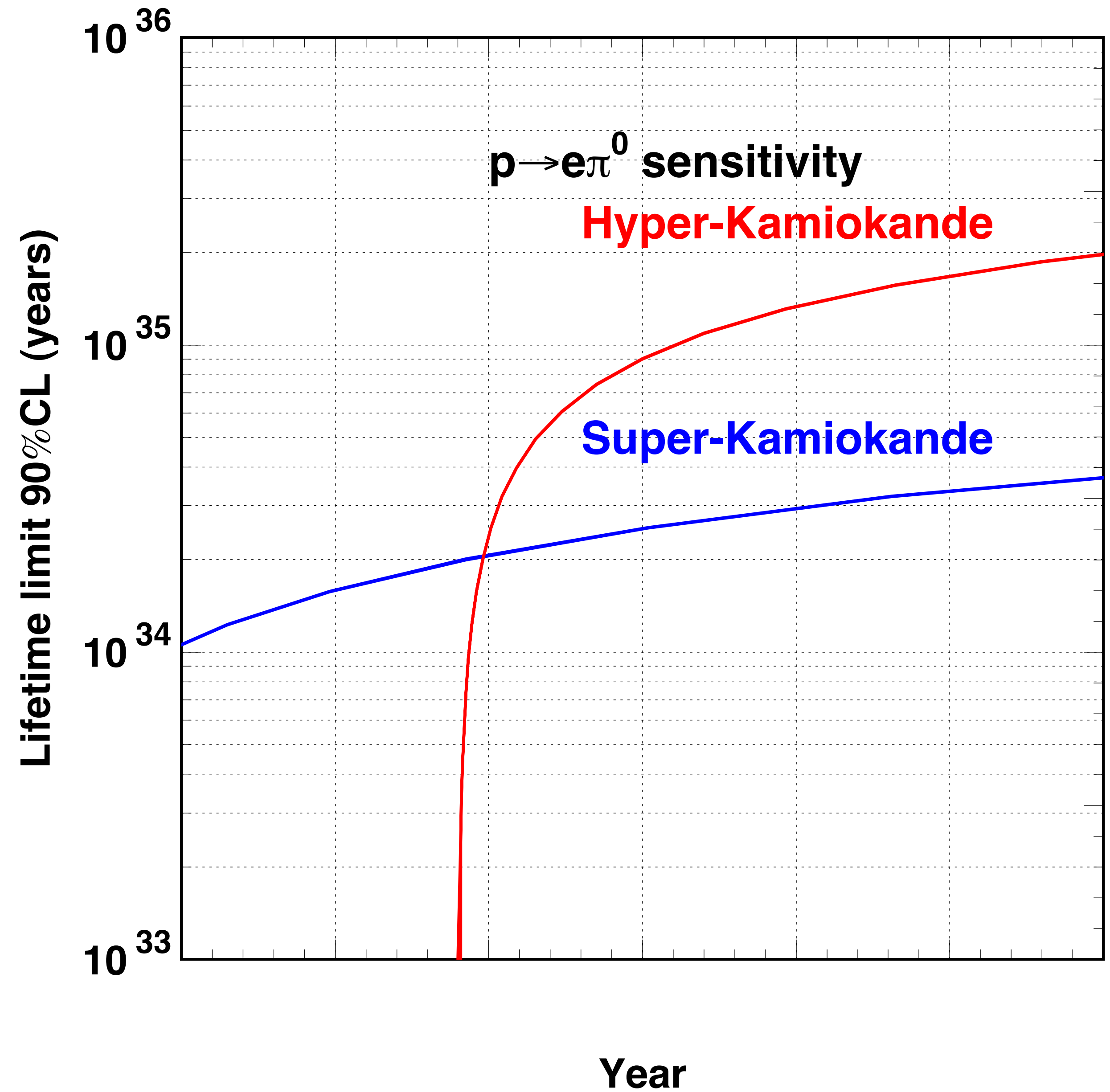
Hyper-K $p \to e^+\pi^0$ sensitivity

(Using only number of events)

10 years exposure





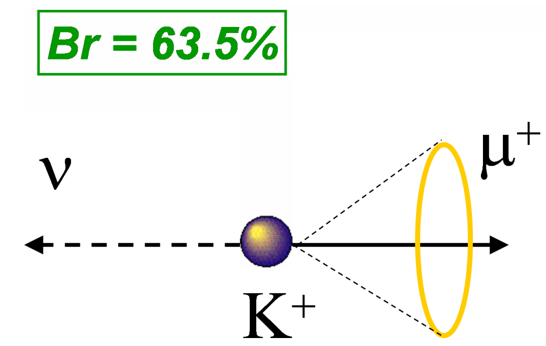


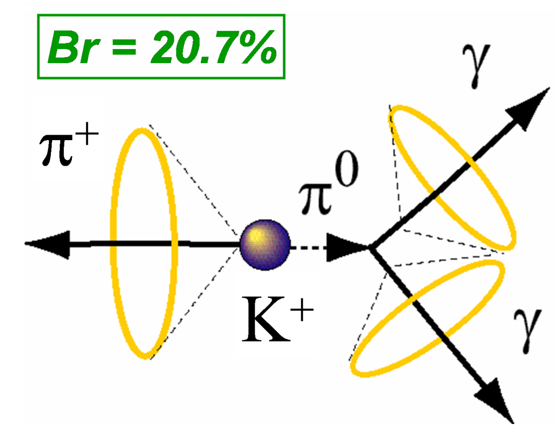
Will surpass SK limit in ~1 year.

90% limit with 10 years: 1.3×10^{35}yrs

$p \rightarrow \nu K^+$ search

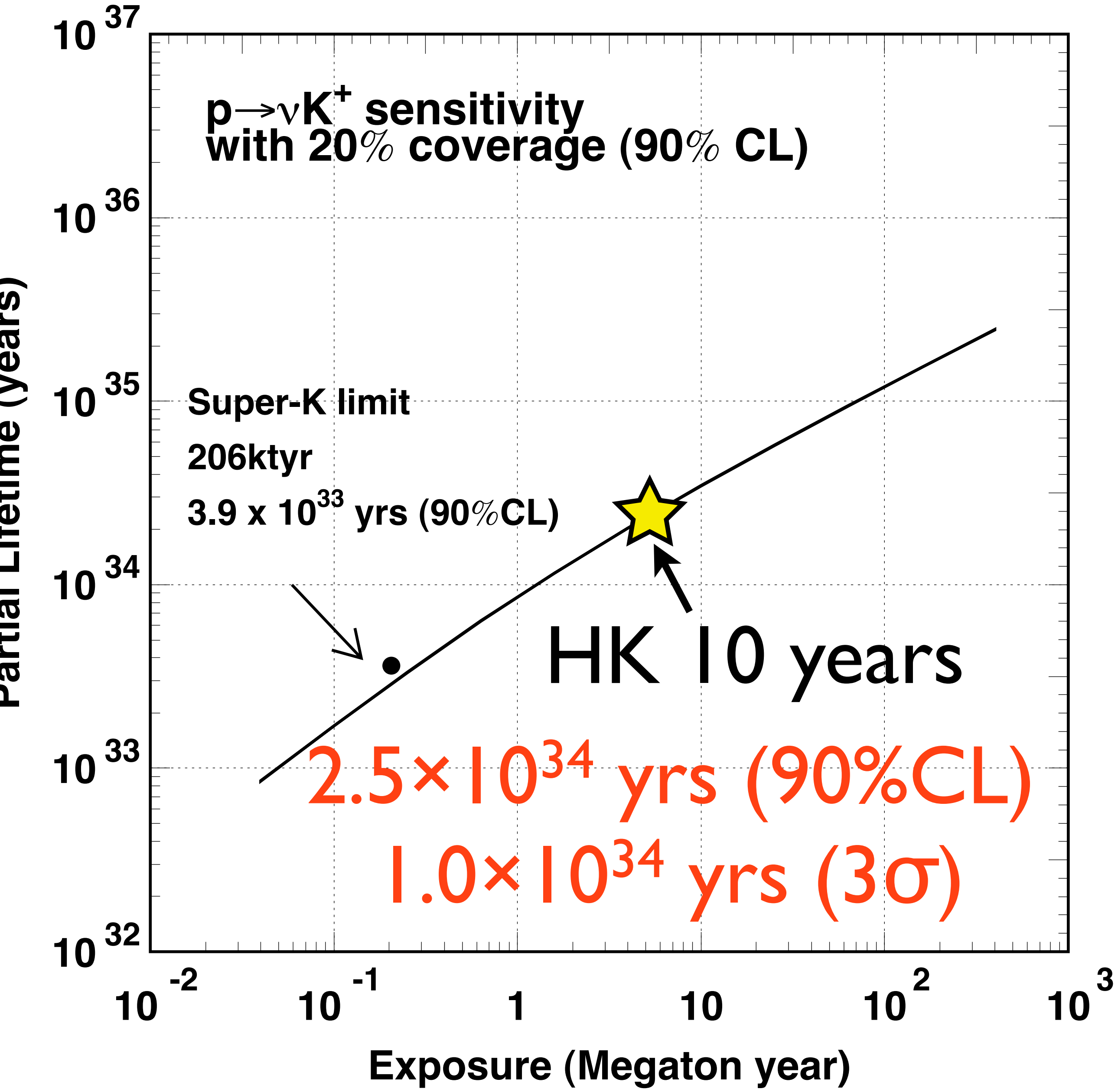
- K^+ invisible (below Cherenkov threshold)
- $K^+ \rightarrow \mu\nu$ (Br: 63.5%)
  - Method 1: Tag with nuclear de-excitation γ
    - Measurement of de-excitation γ: nucl-ex/0604006
  - Method 2: Search excess in P_μ distribution
- $K^+ \rightarrow \pi^+\pi^0$ (Br: 20.7%)
  - 205 MeV/c π^0 + activity in opposite direction (π^+ just above threshold)

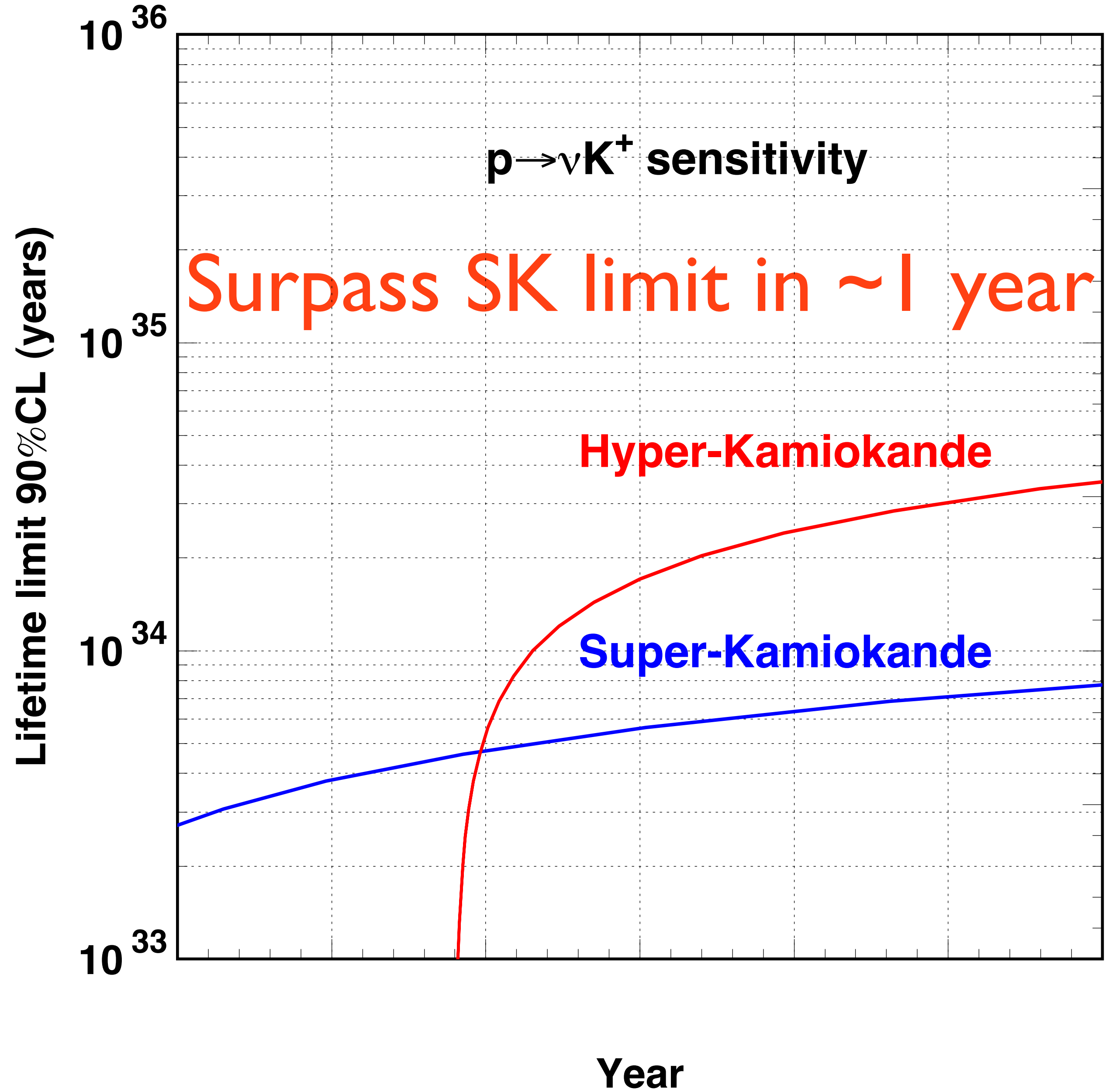




	Efficiency (%)	BG (/Mtyr)
$K \rightarrow \mu\nu$+nucl. γ	7.1	1.6
$K \rightarrow \nu\mu$	43	1940
$K \rightarrow \pi\pi$	6.7	6.7

Hyper-K $p\to\nu K^+$ sensitivity

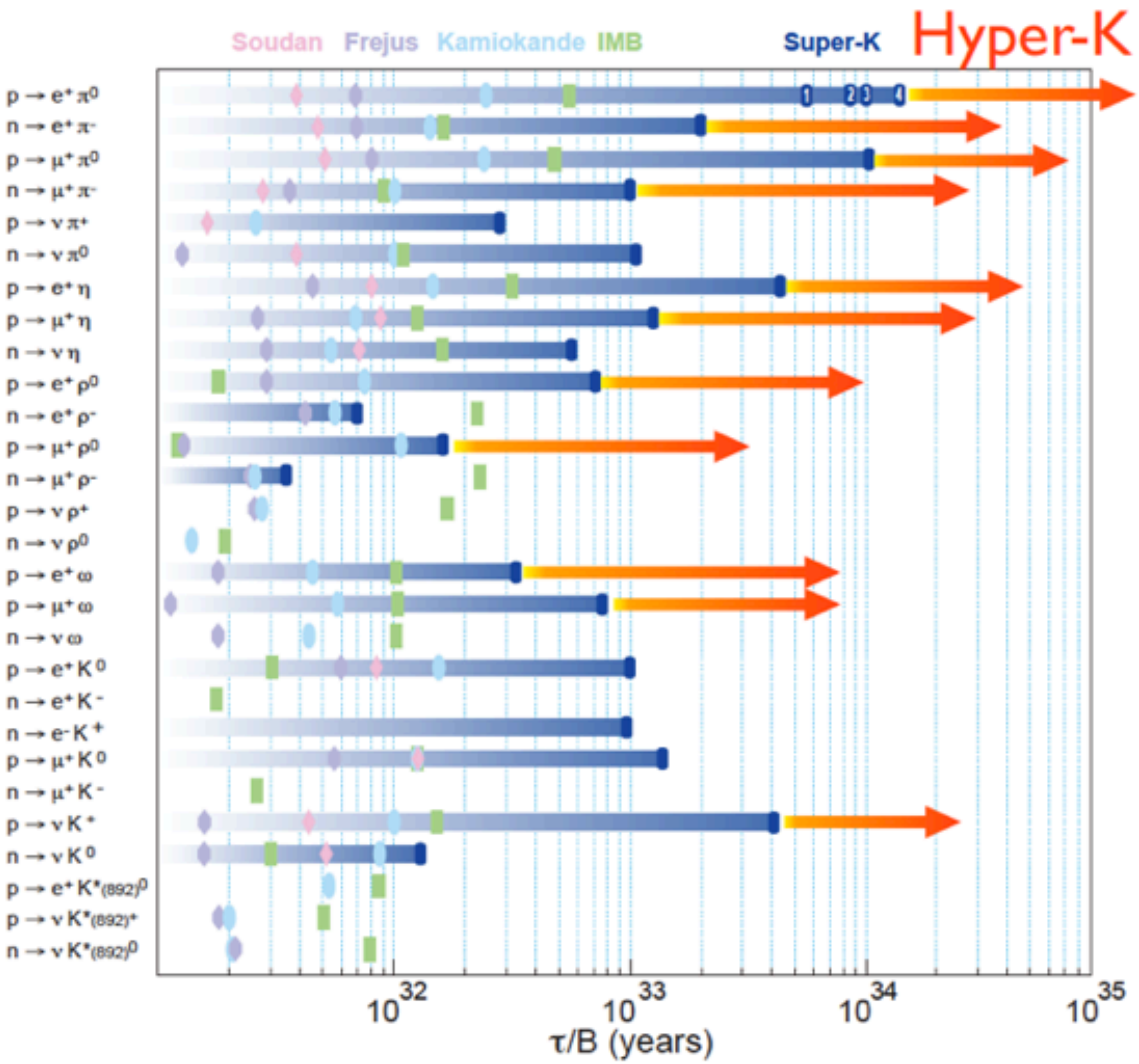




(cf. 2×10^{34} @90% w/ 20kt LAr 10yr)

Nucleon decay searches with HK

~10 times better sensitivity than current Super-K limits



- $p \rightarrow e^+\pi^0$:
  - 1.3×10^{35}yrs (90%CL)
  - 5.7×10^{34}yrs (3σ)
- $p \rightarrow \nu K^+$:
  - 2.5×10^{34}yrs (90%CL)
  - 1.0×10^{34}yrs (3σ)

- Many other modes:
  - (p,n)→(e,μ)+(π, ρ, ω, η)
  - K^0 modes
  - $\nu\pi^0$, $\nu\pi^+$
  - n-nbar oscillation
  - dinucleon decays

>3σ possible for lifetime above current SK limits

Conclusions

Hyper-K has excellent potential for fundamental physics.

- Long baseline neutrino experiment
  - Test of *CP* symmetry in lepton sector
    - CPV >3σ(5σ) for 74(55)% of δ
  - Full picture of neutrino oscillation (together with atm ν)
  - Systematics important to exploit full capability (see following talks)
- Search for proton (nucleon) decays
  - Direct probe of GUT
  - HK sensitivity ~×10 of current limits by SK
  - Good chance to observe signals
    - >3σ: 5.7×10^{34} for $e^+\pi^0$, 1.0×10^{34} for νK^+ with 10 yrs

Backup

Japan's Strategy for Future Projects

The Final Report of the Subcommittee on Future Projects of High Energy Physics (Chair: T. Mori)

- **Should the neutrino mixing angle θ_{13} be confirmed as large, Japan should aim to realize a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.** This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

- Large θ_{13} confirmed!
- Large scale ν detector for
  - Studies on CP symmetry (with accelerator reinforcement)
  - Search for proton decays
- With international cooperation

Recognized as Japanese HEP community Strategy
(as well as international neutrino community)

χ^2 definition used in LoI

Fake data → N^i

Oscillated MC w/ syst. error

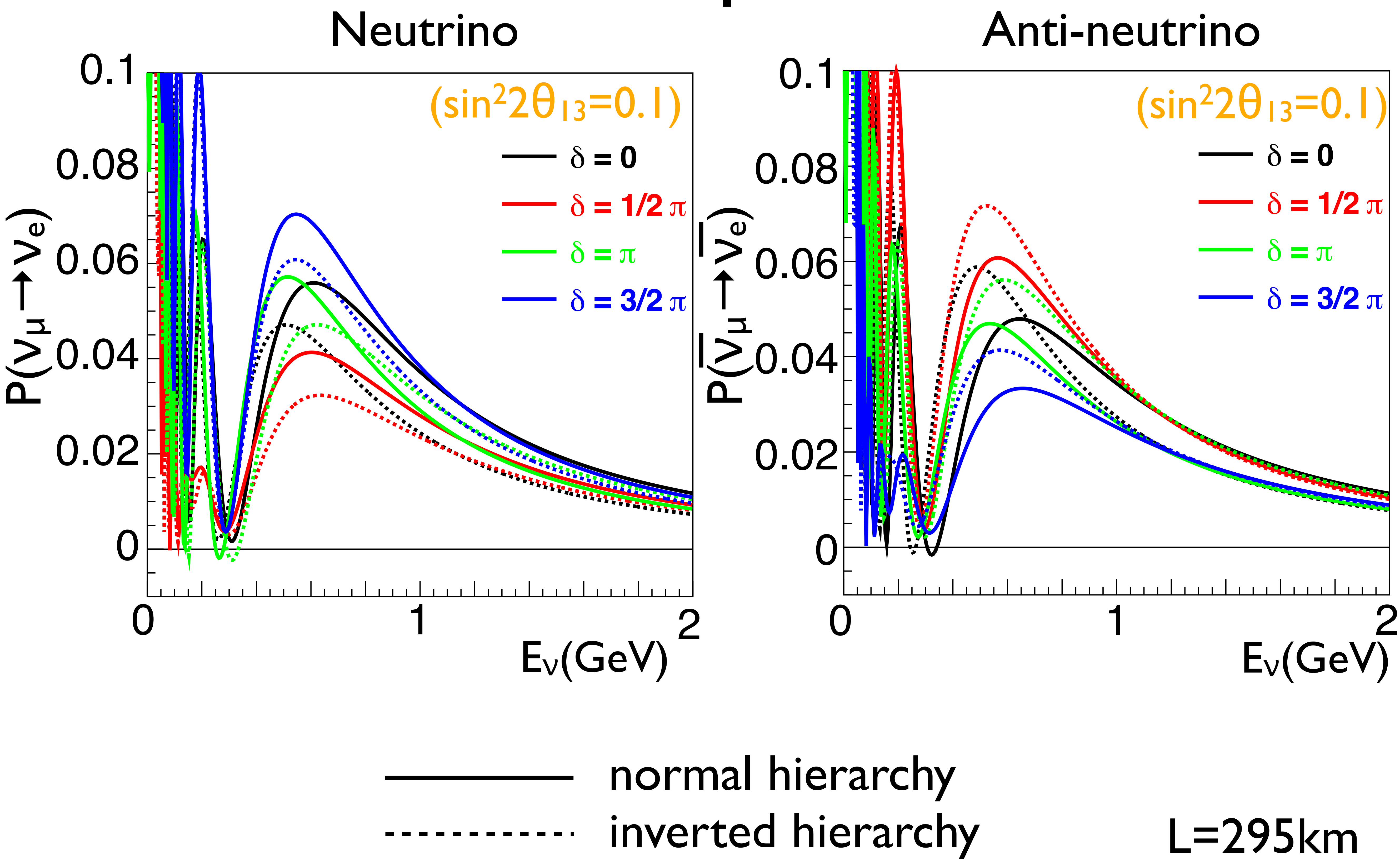
$$\chi^2 = \sum_{\nu,\overline{\nu}} \sum_i \left[N^i - \left\{ 1 \pm \frac{1}{2} f_{\nu/\overline{\nu}} \right\} \cdot \left((1 + f_{\rm sig}) \cdot n^i_{\rm sig} + (1 + f_{\nu_\mu}) \cdot n^i_{\nu_\mu} + (1 + f_{\nu_e}) \cdot n^i_{\nu_e} \right) \right]^2 / N^i$$

$$+ \frac{{f_{\rm sig}}^2}{{\sigma_{\rm sig}}^2} + \frac{{f_{\nu_\mu}}^2}{{\sigma_{\nu_\mu}}^2} + \frac{{f_{\nu_e}}^2}{{\sigma_{\nu_e}}^2} + \frac{{f_{\overline{\nu}/\nu}}^2}{{\sigma_{\nu/\overline{\nu}}}^2},$$

assumed syst. errors (all 5%)

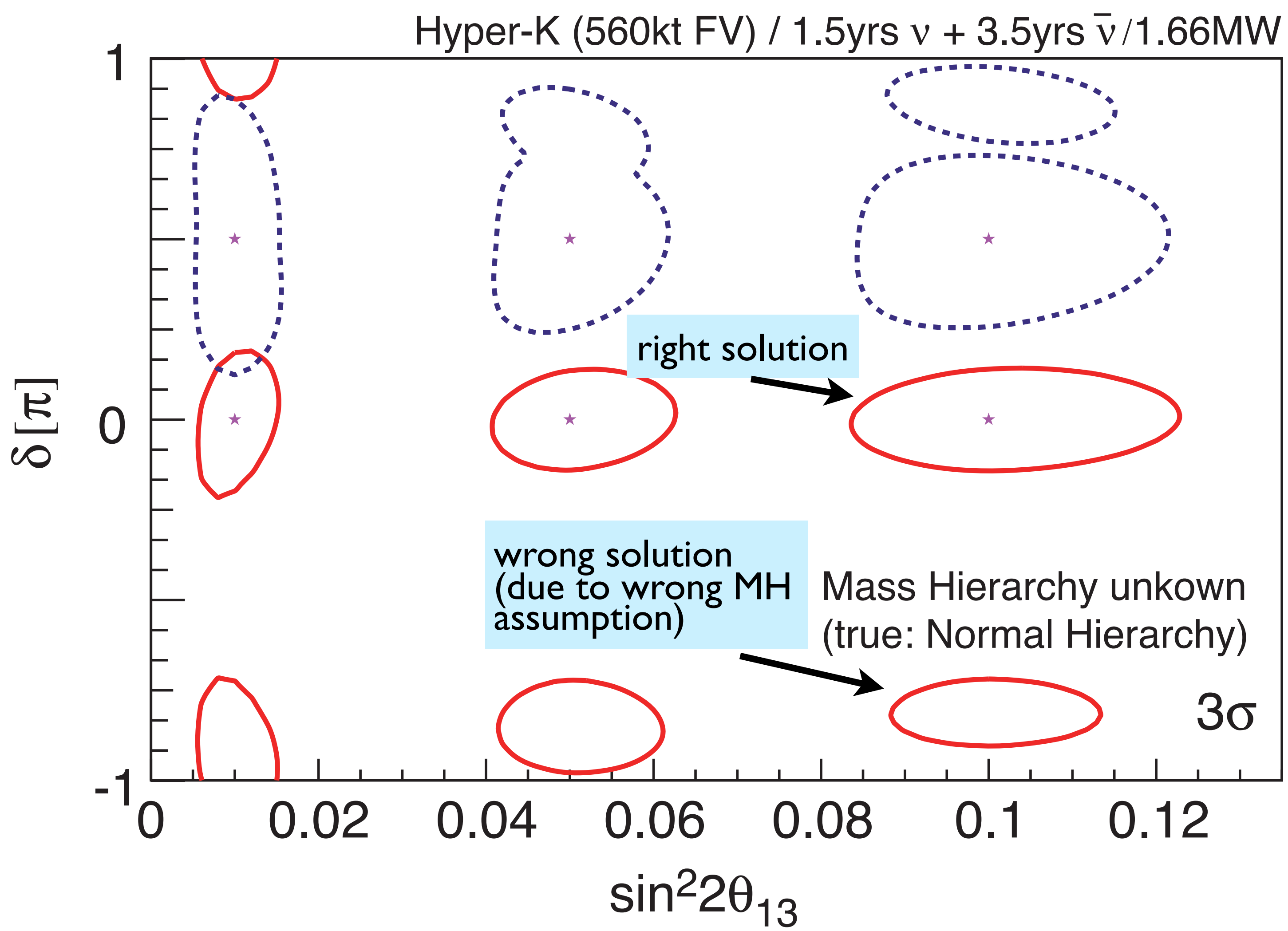
signal eff., ν_μBG, ν_eBG, ν/anti-ν ratio

Oscillation probability



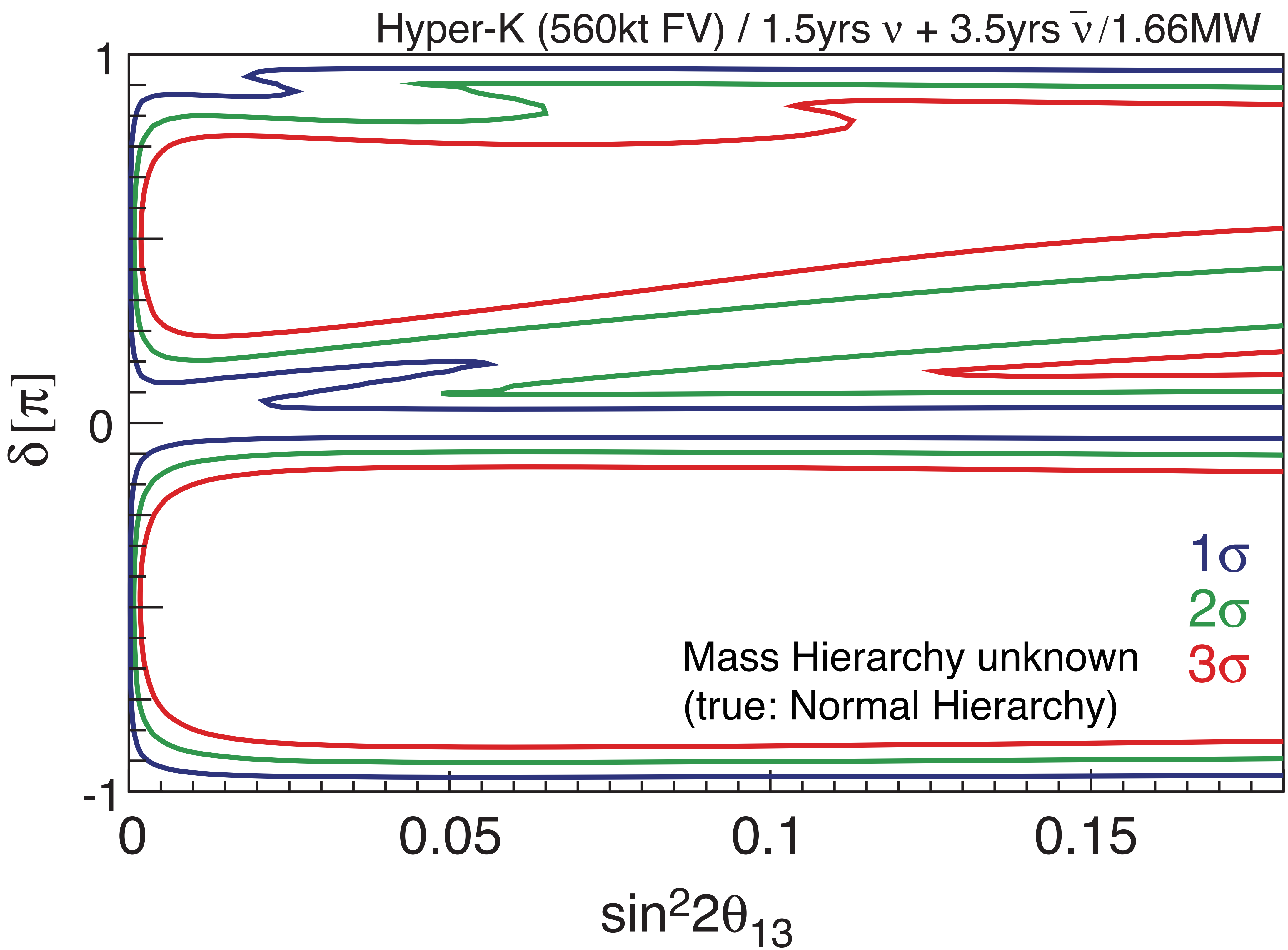
If mass hierarchy is unknown

Normal mass hierarchy (unknown)



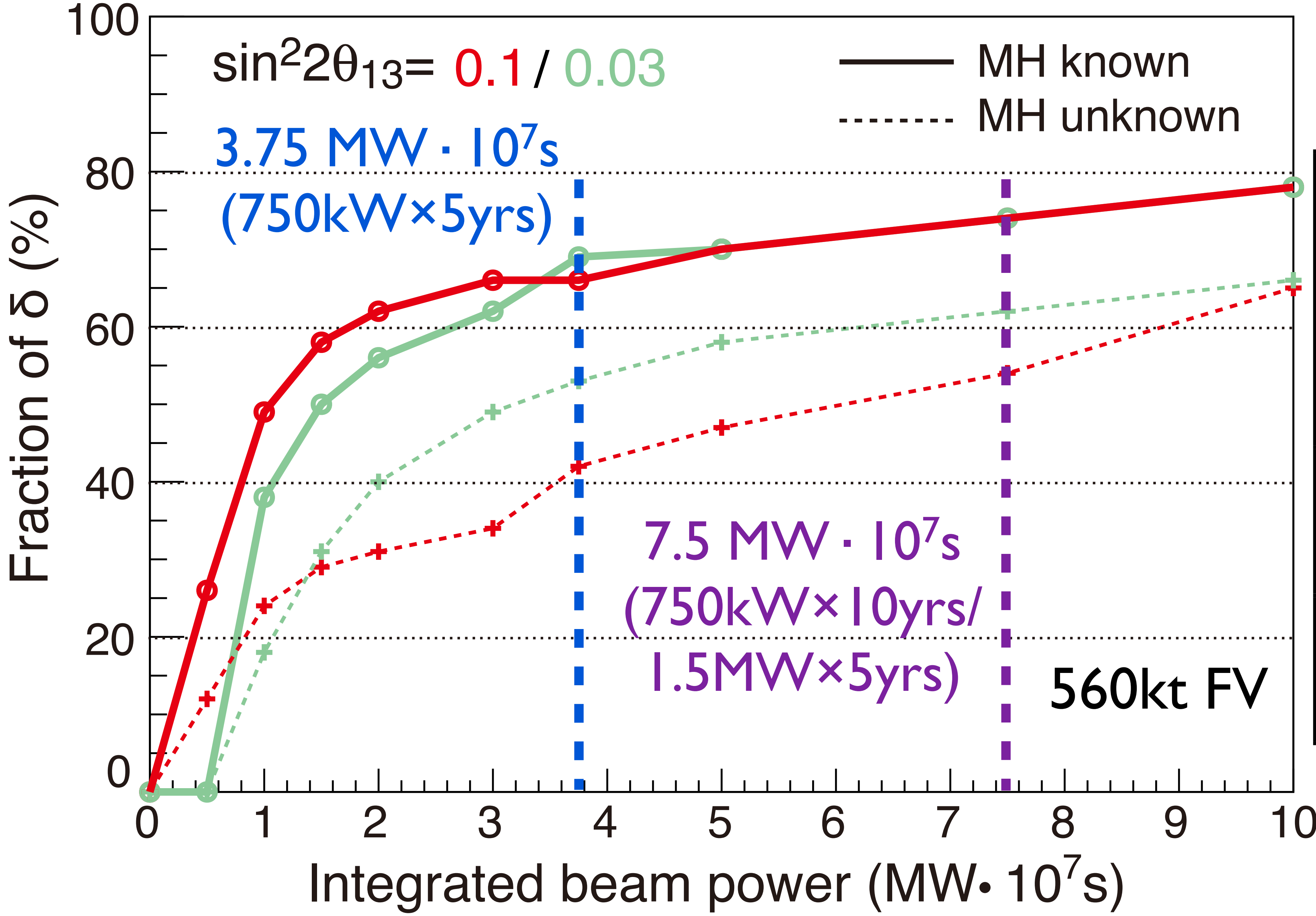
- multiple solutions, wider allowed region due to wrong MH assumption.
- Input (mass hierarchy) from other experiments may become important.
  - from Noνa? or ν-less DB? or...
- One possibility is to determine MH by atm. ν study (discuss later)

Mass hierarchy unknown case



Sensitivity to *CP* violation

Fraction of true δ possible to observe CPV with >3σ



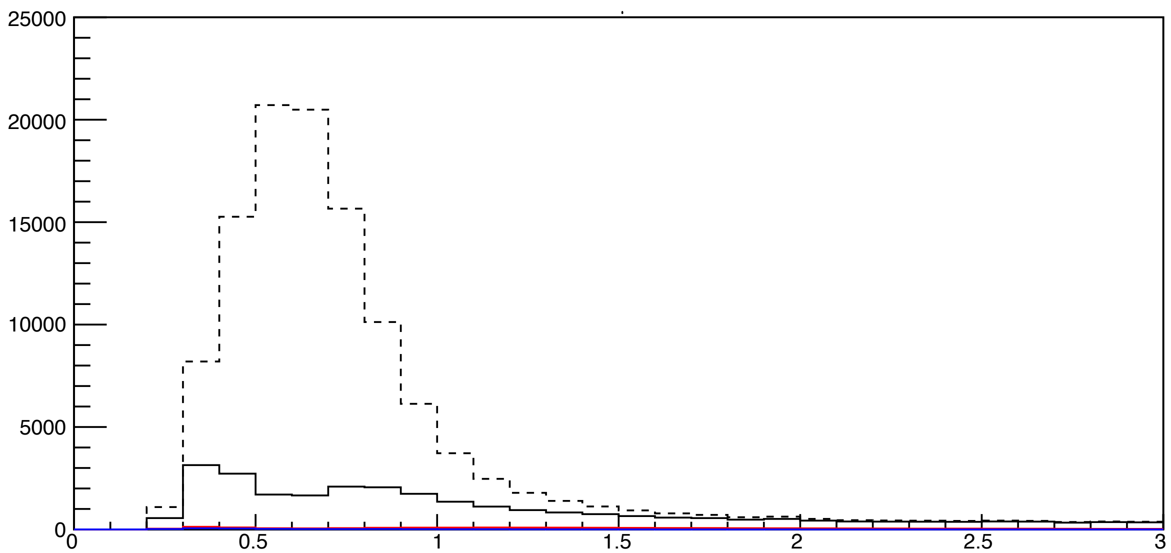
$\sin^2 2\theta_{13}=0.1$

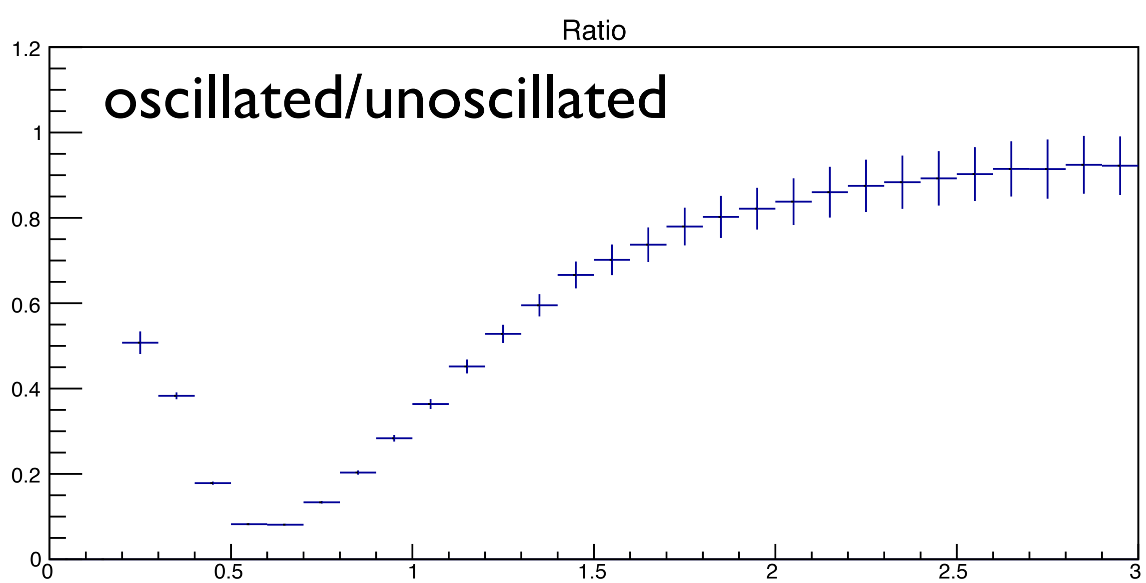
Integ. power (MW× 10^7s)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

- With known mass hierarchy (atm ν, other expt's), CP violation can be observed (3σ) for ~70% of δ

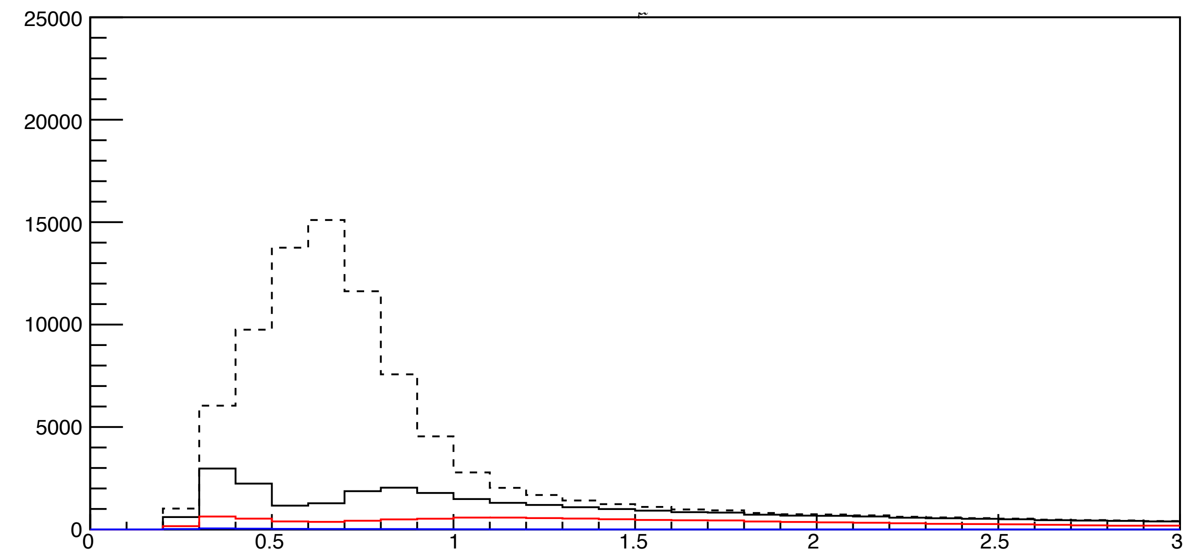
1ring μ like events

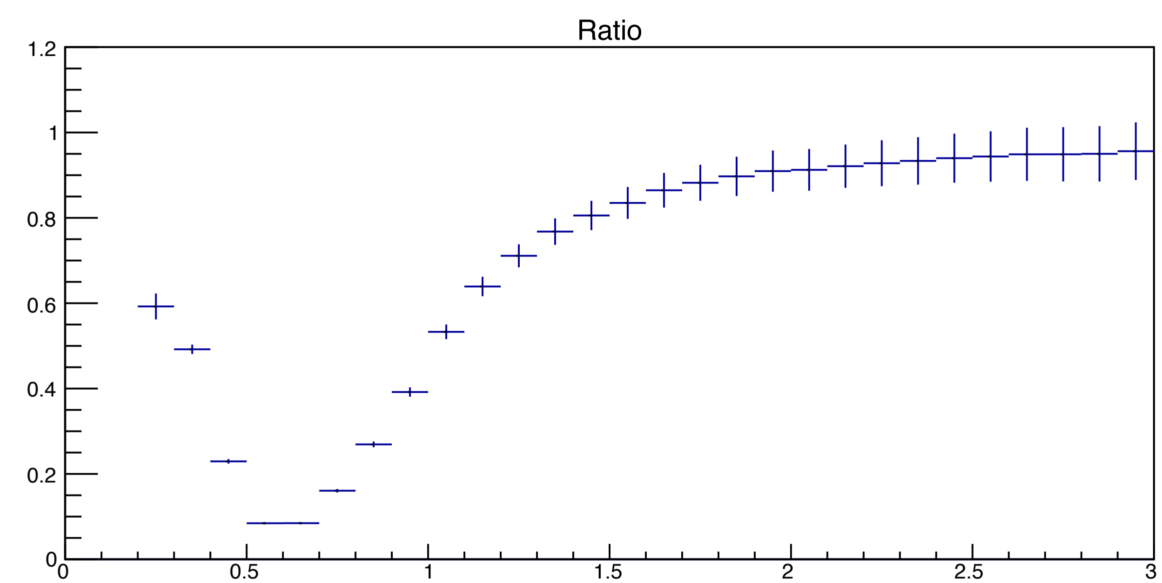
ν





ν-bar

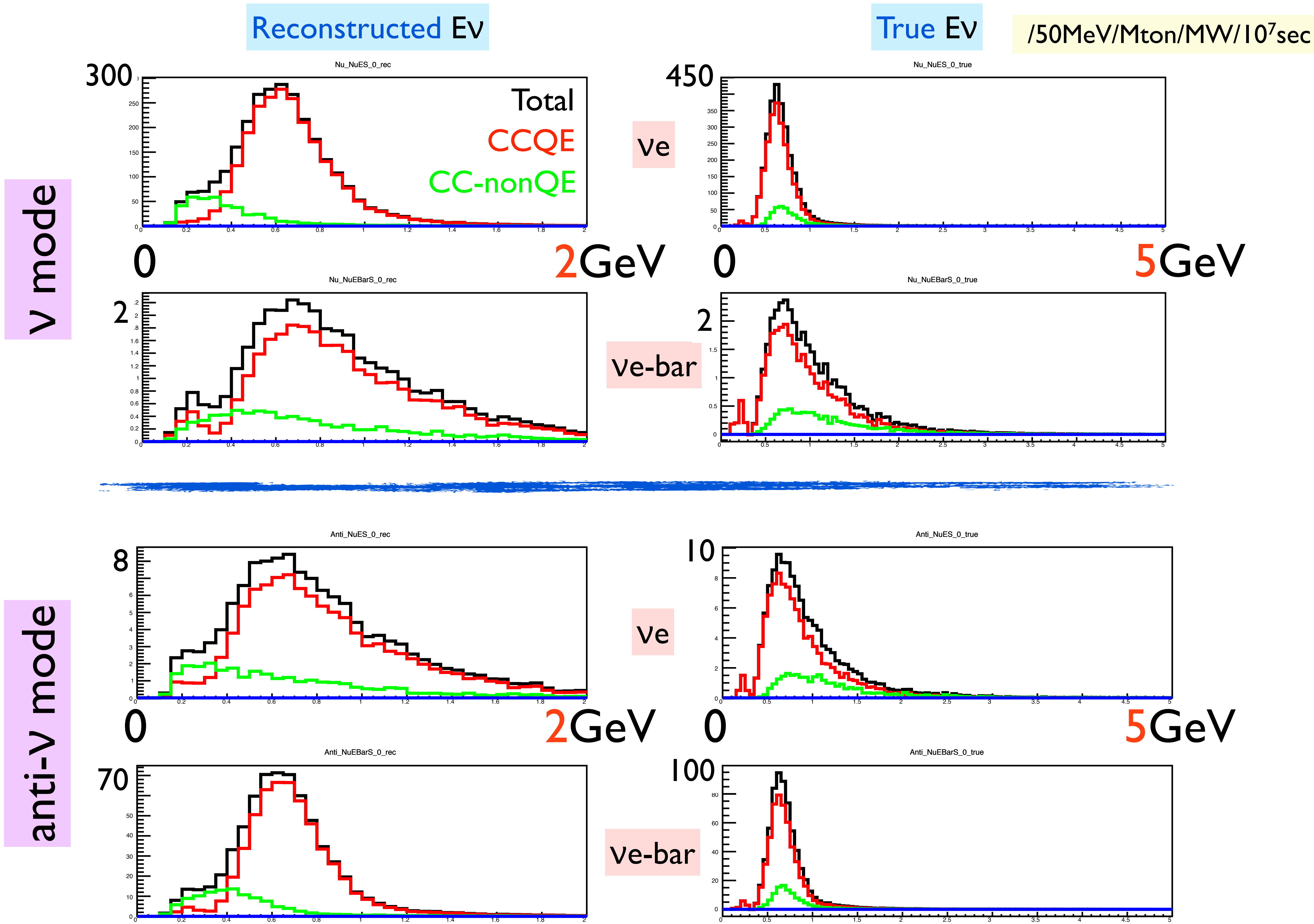




Appearance νe

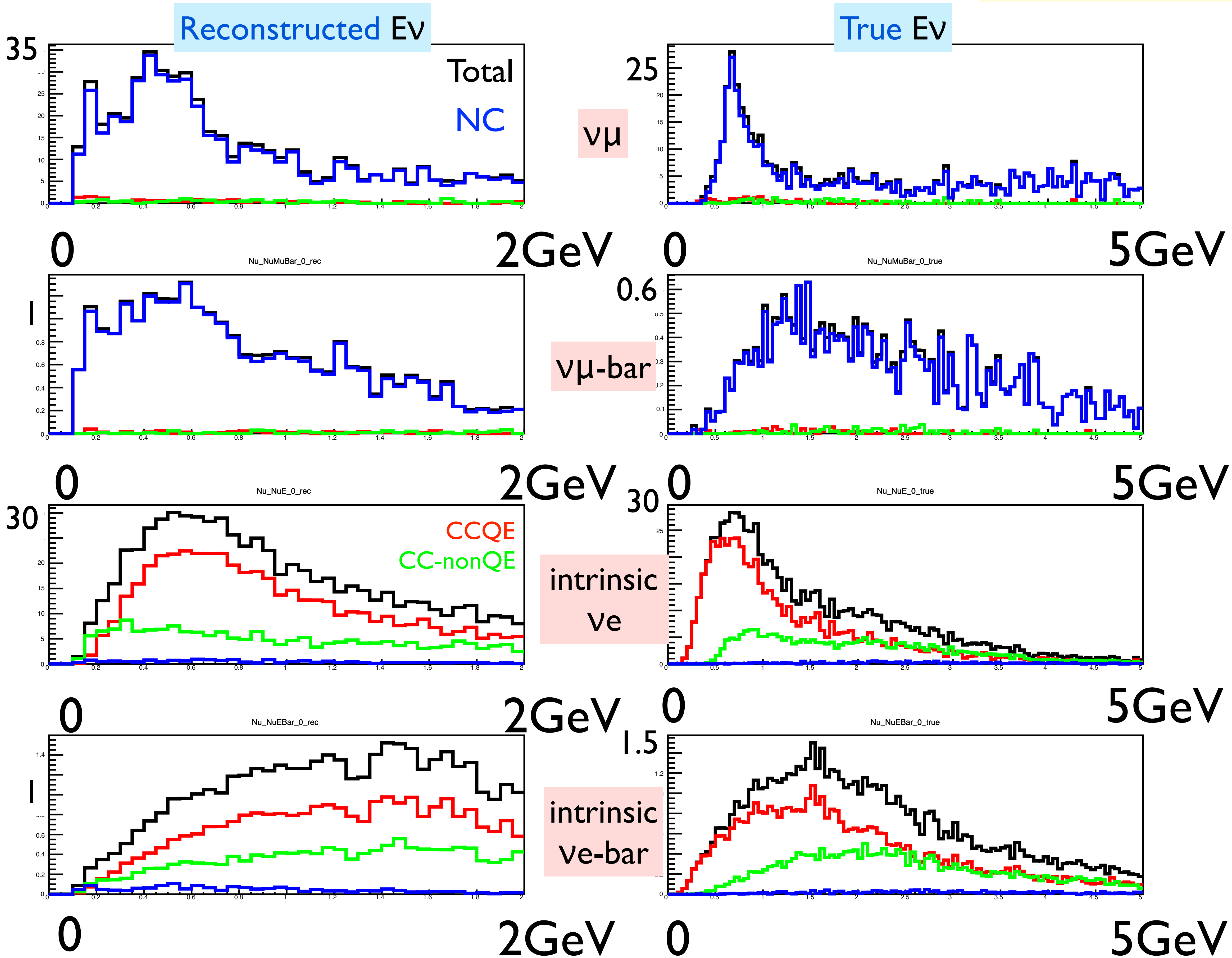
Plots overlaid (not stacked)

/50MeV/Mton/MW/10^7sec



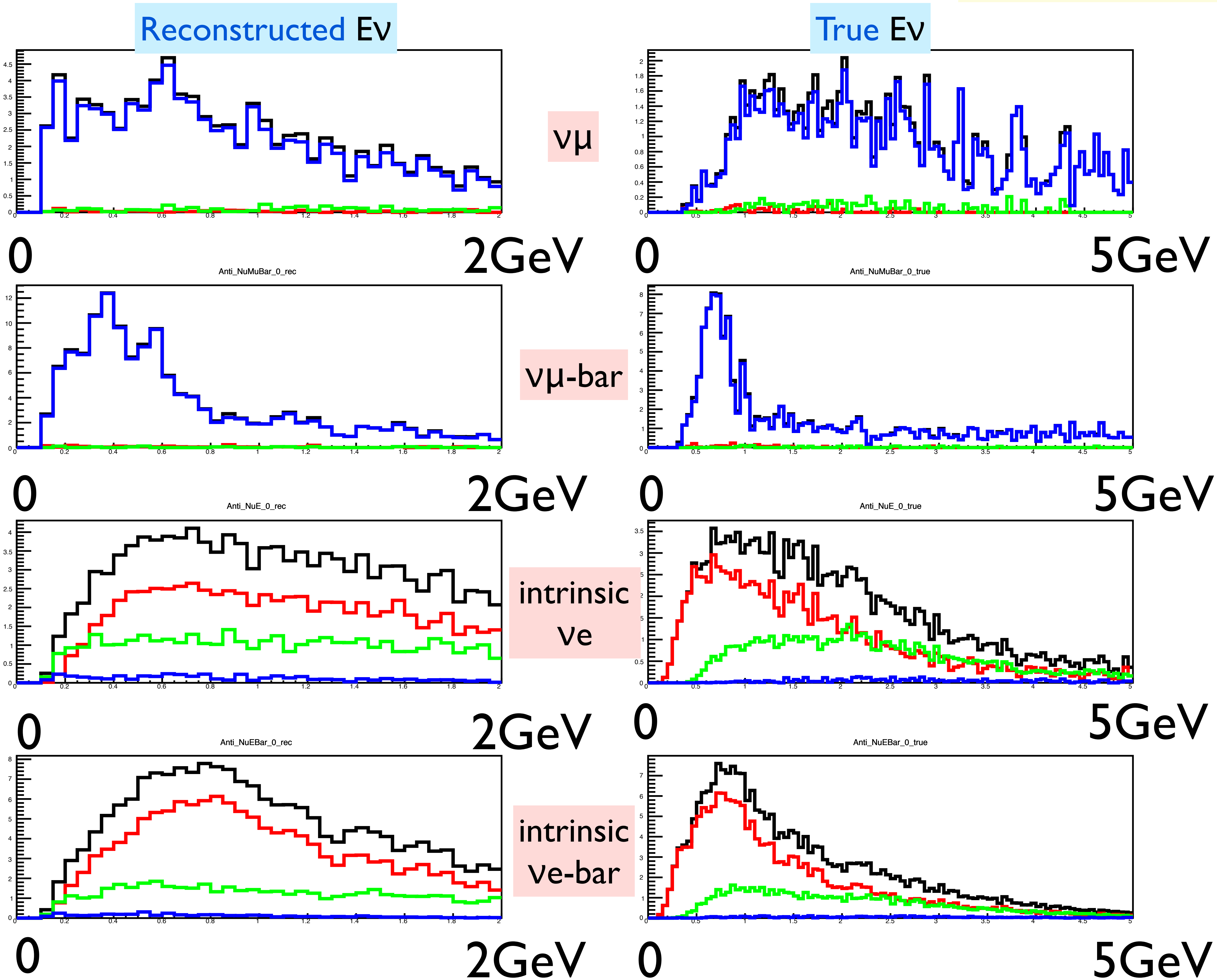
BG in nu run

/50MeV/Mton/MW/10^7sec



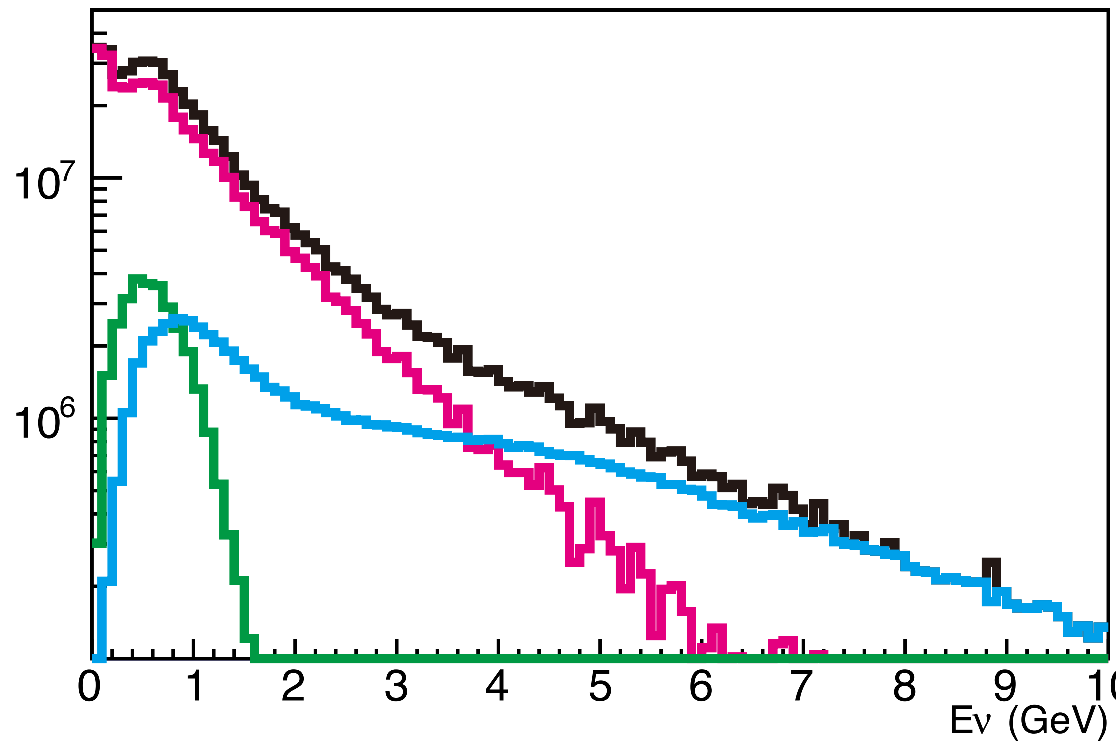
BG in anti-nu run

/50MeV/Mton/MW/10^7sec

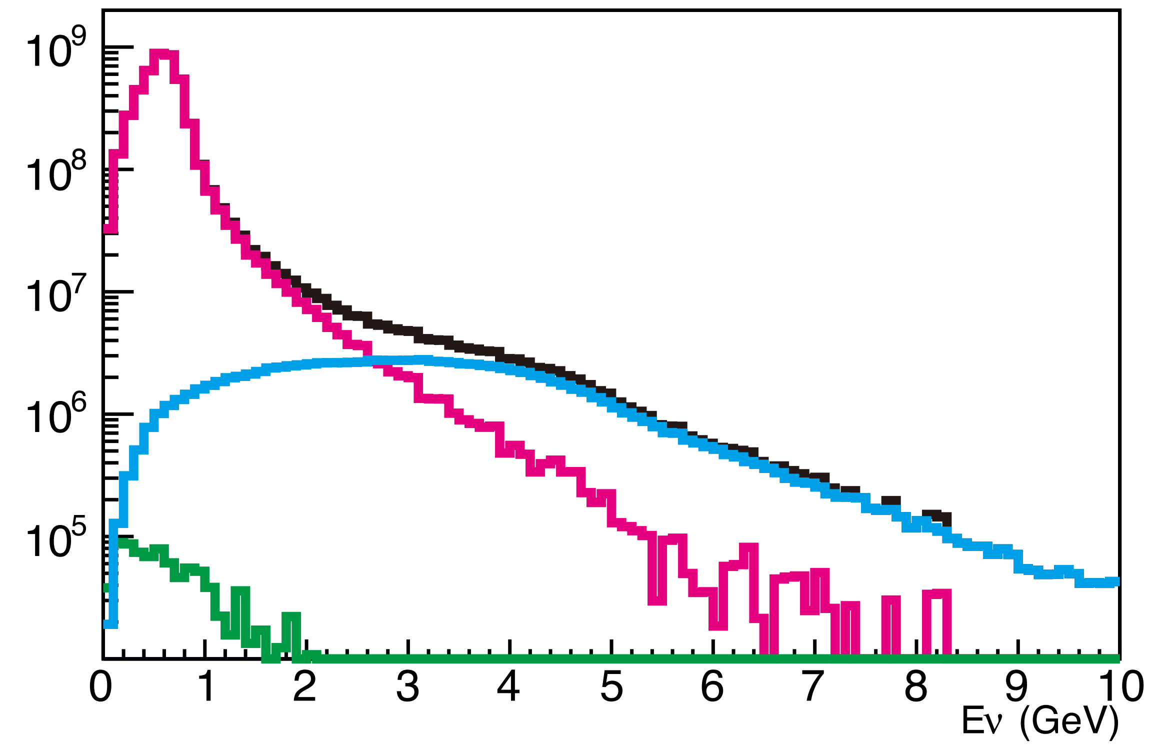


Flux by parents (anti-ν run) π,K,μ

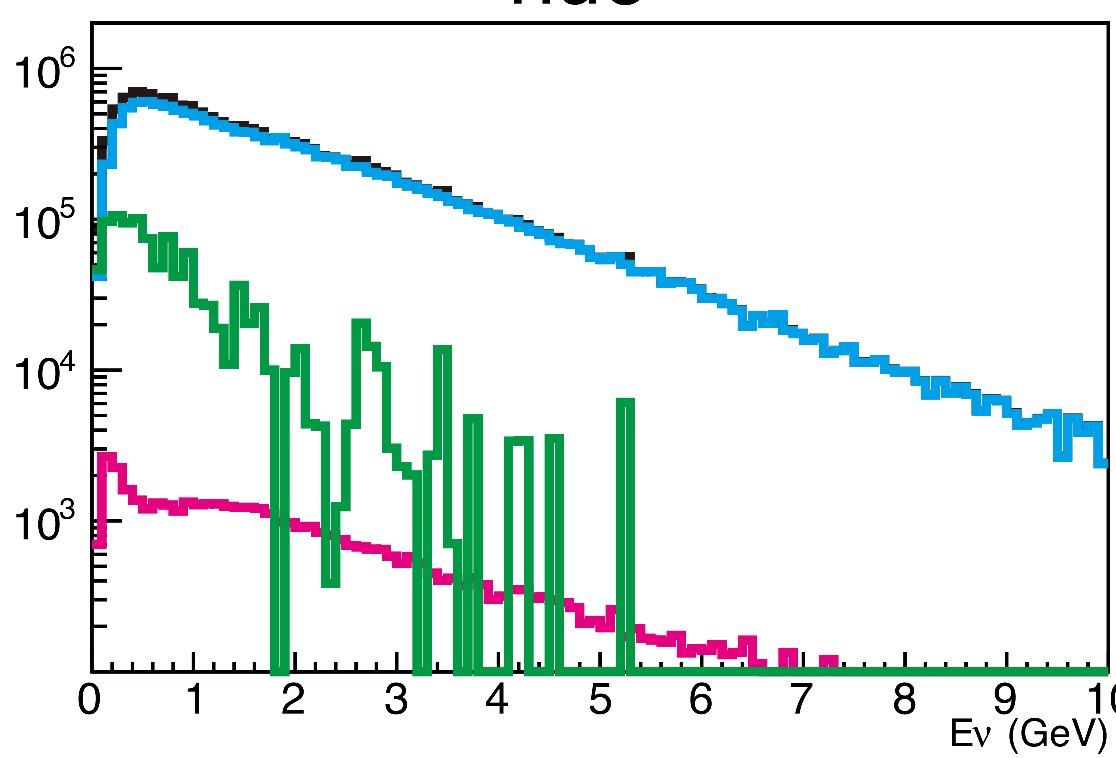
numu



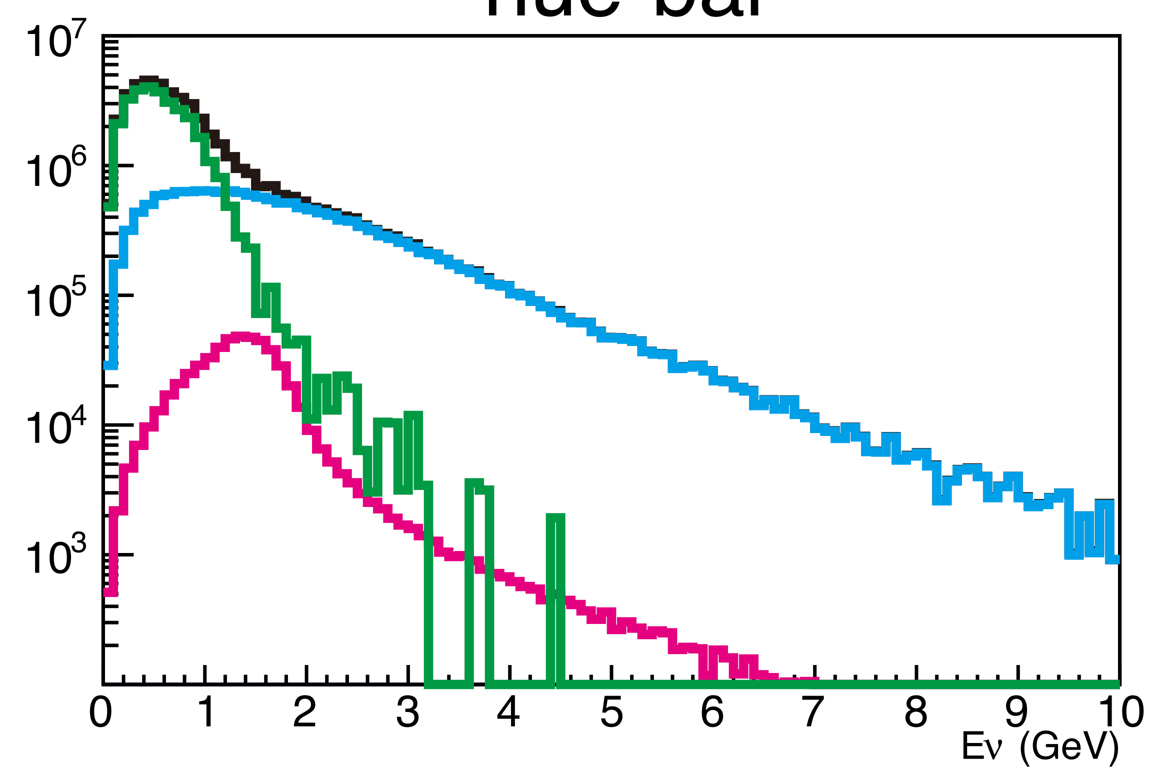
numu-bar



nue



nue-bar



Sensitivity to *CP* violation

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$