T2KK sensitivity as a function of off-axis angle

Updated version, August 23 2006

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2nd T2KK workshop, July 13, 2006

Outline

Motivation

Likelihood analysis:
- Analysis strategy
- Likelihood variables
- Efficiency results
- Future plans

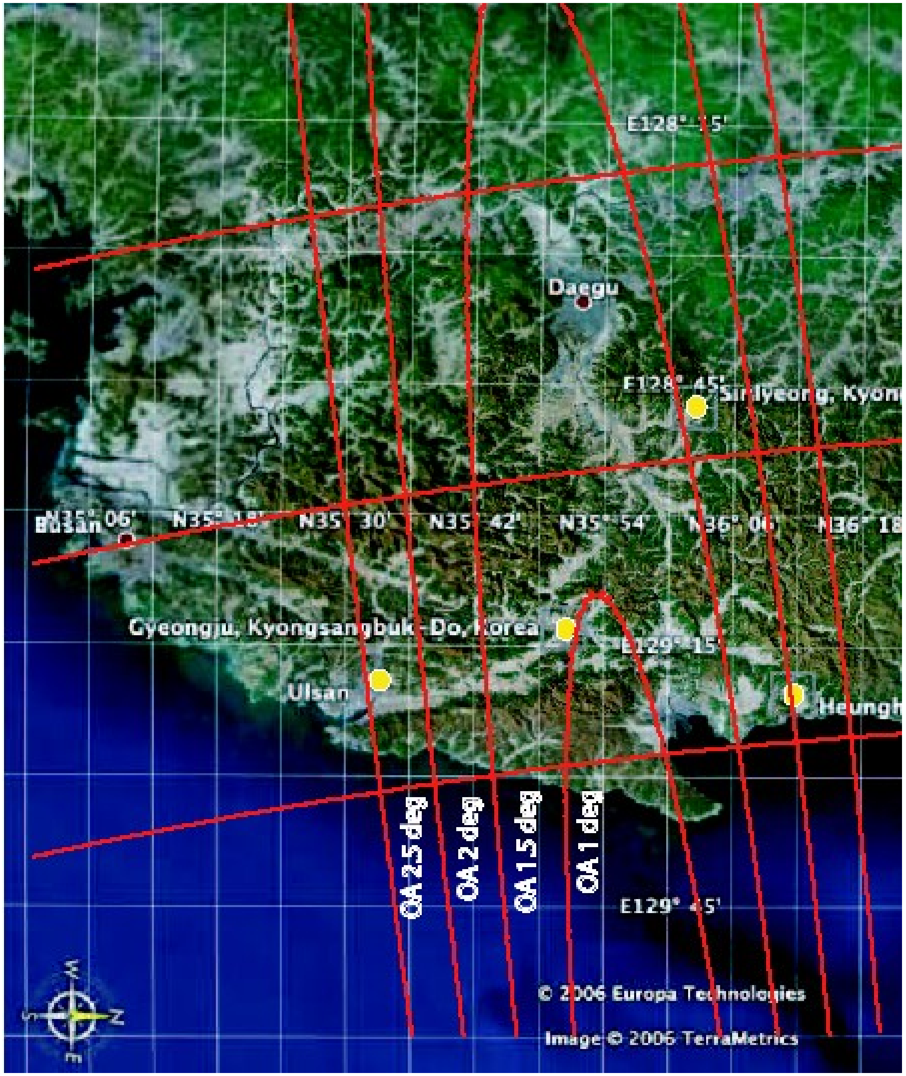
Oscillation analysis
- Introduction
- Spectrum (each off-axis angle)
- χ^2 analysis
- Sensitivity curves
- Conclusions

Overview

Study the sensitivity to CP violation and mass hierarchy as a function of the off-axis angle.

Axis considered:

- 1°Off-Axis (OA)
- 1.5°Off-Axis (OA)
- 2°Off-Axis (OA)
- 2.5°Off-Axis (OA)



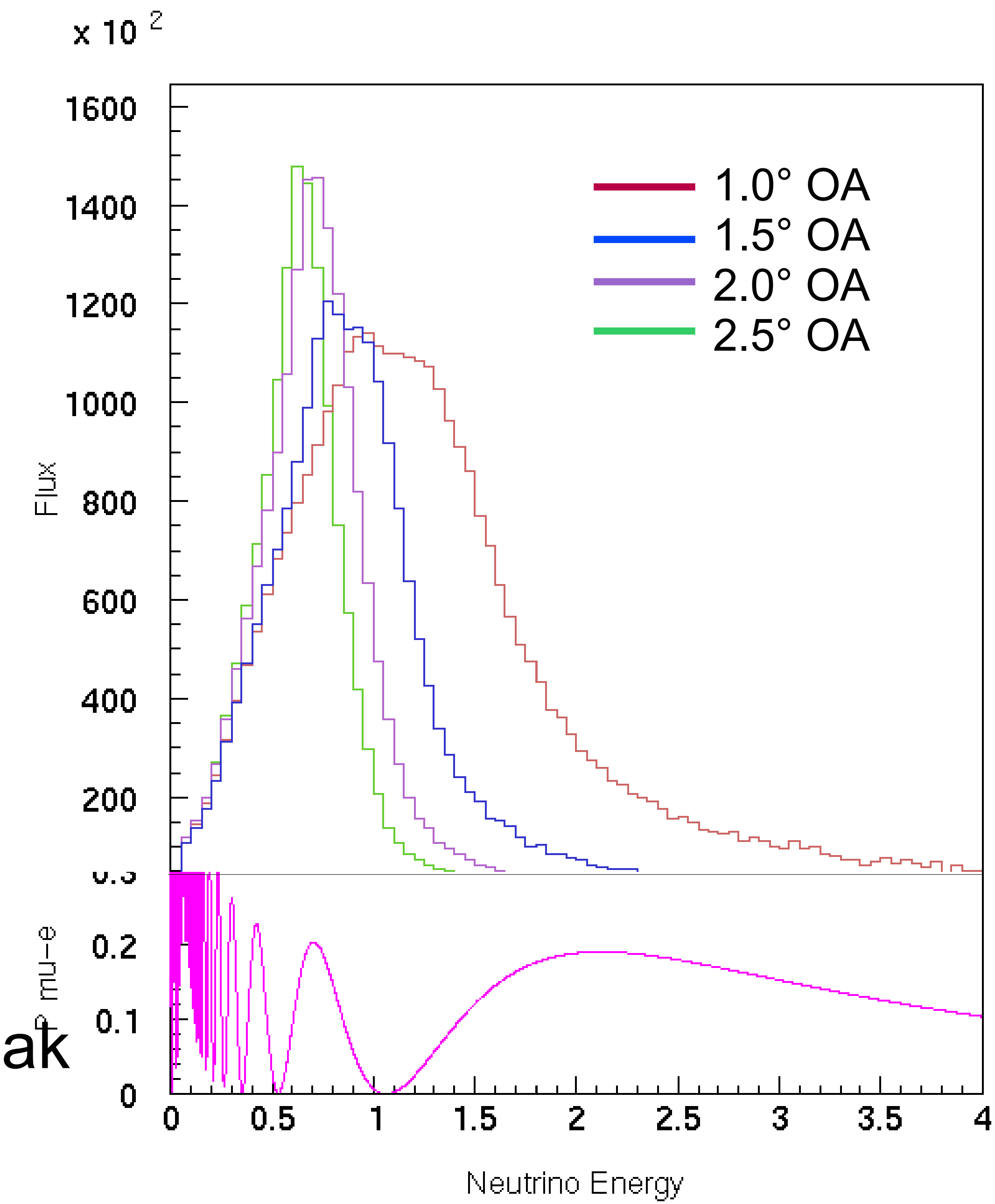
Pros & cons

Small off-axis angle:
(high energy tail)

- ✔ 1^{st} appearance peak
- ✗ more NC background

Big off-axis angle:
(narrow peak)

- ✔ Low background
- ✗ Low statistics at high E
- ✗ Only 2^{nd} appearance peak



Likelihood analysis strategy

Based on the T2K ν_e appearance analysis

- Apply following precuts:
  - FCFV, Evis >100 MeV
  - Single ring
  - e-like
  - no decay electron
- In this study, I used the T2K Monte Carlo.
- Combine Super-K variables into a likelihood to discriminate electrons from π^0.

8 Variables

Standard SK variables:

Ring parameter
PID parameter

New variables, defined for this analysis:

Chi_Xalong
Chi_cos(open)

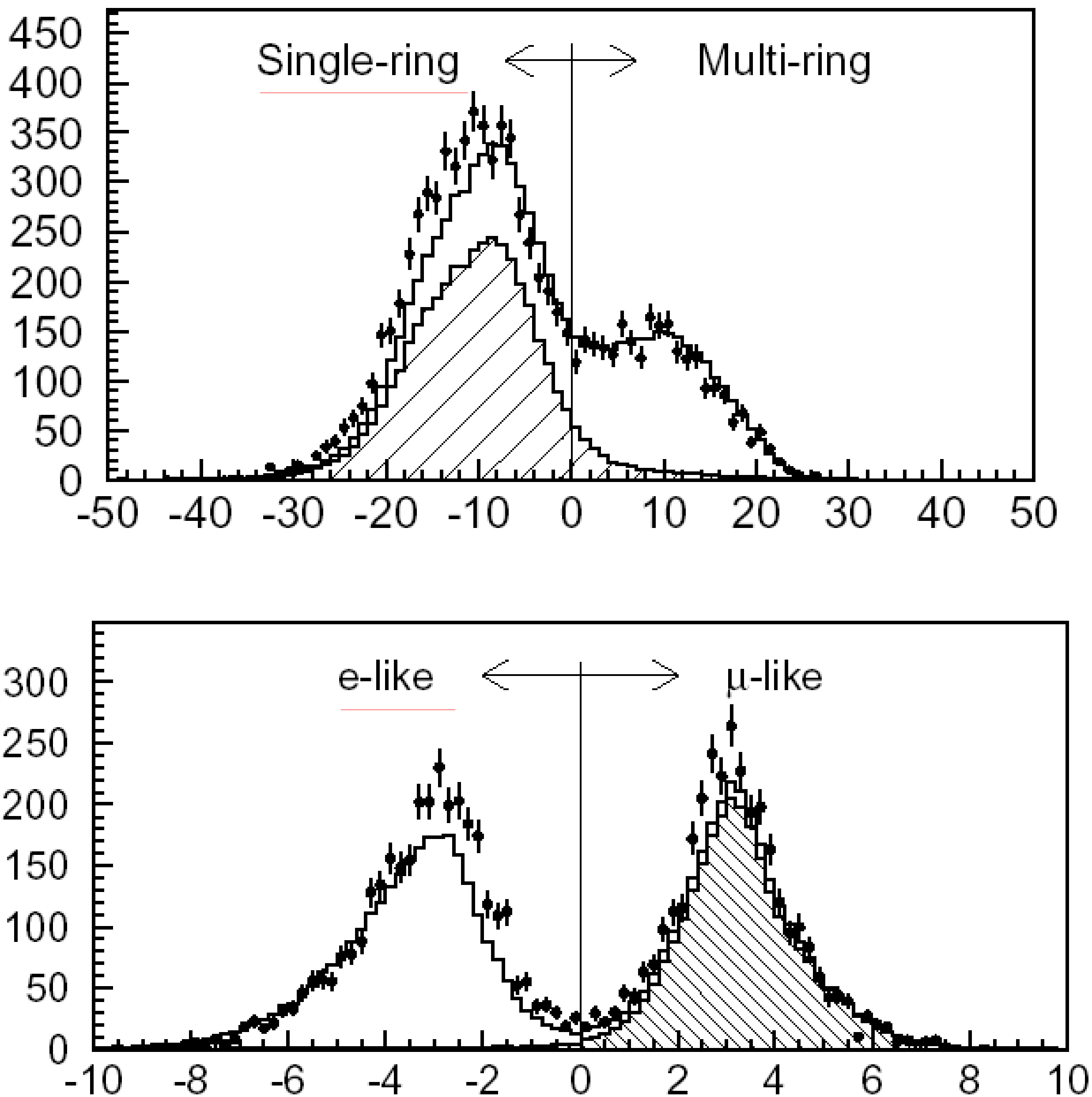
Special π^o fitter variables: (POLfit, Pattern Of Light)

π^o mass
π^o likelihood
Energy fraction of 2nd ring

Beam related variable:

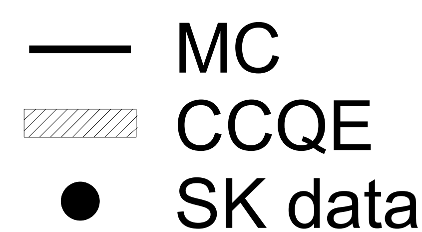
$Cos\theta_{\nu e}$

Ring and PID Parameter:



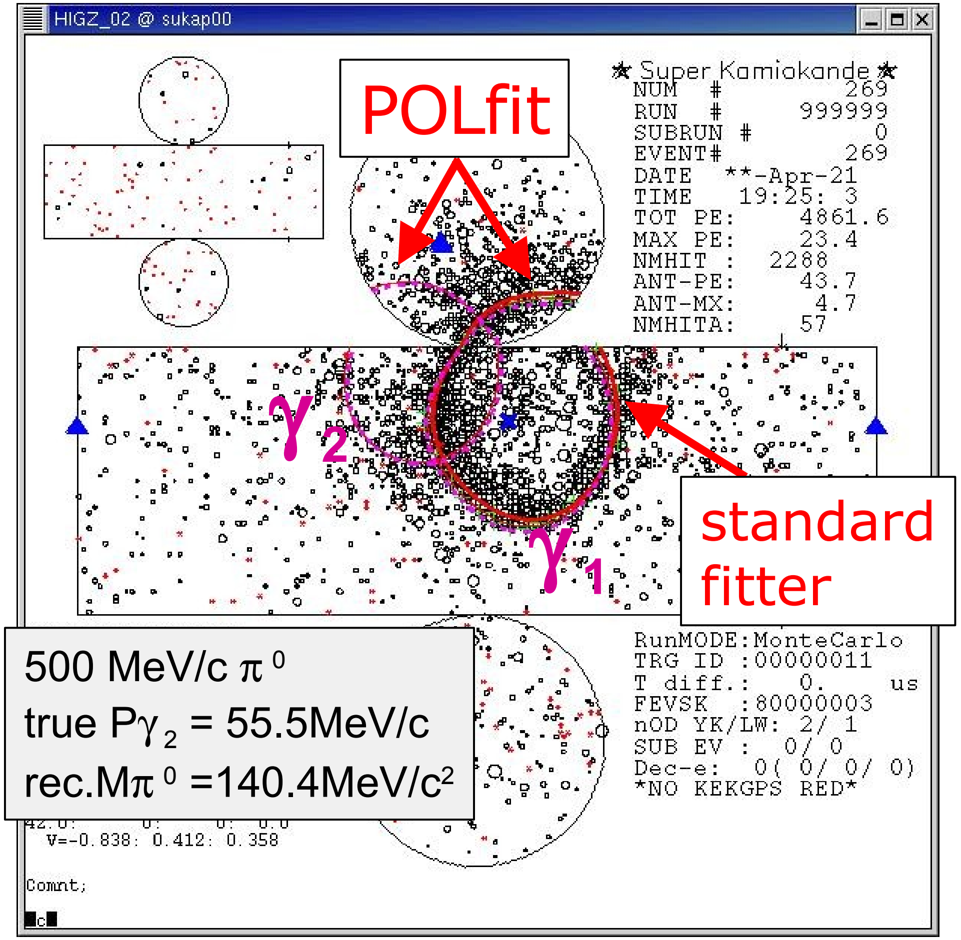
Those variables are not only precuts, (keep single-ring, e-like)

we also use the variables themselves in the likelihood.



POLfit

S.Nakayama's talk
1st T2KK Workshop
November 2005



- Target: FCFV 1R-elike events
- $\Delta L \equiv$ Likelihood(2γ assump.) – Likelihood(electron assump.)

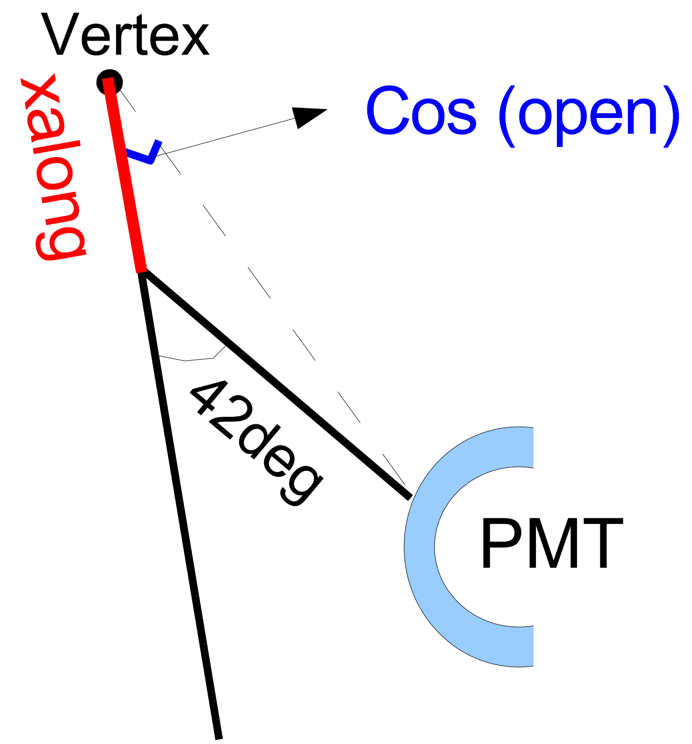
- Try to reconstruct two γ rings
- Input: vertex, visible energy, and the 1st γ direction by the standard fitter
- Compare observed & expected (direct+scatter) charge
- Vary the 2nd γ direction and the energy fraction until the best match found

I use : π^o mass
π^o ΔLikelihood
Energy fraction of 2nd ring

Xalong & Cos(open)

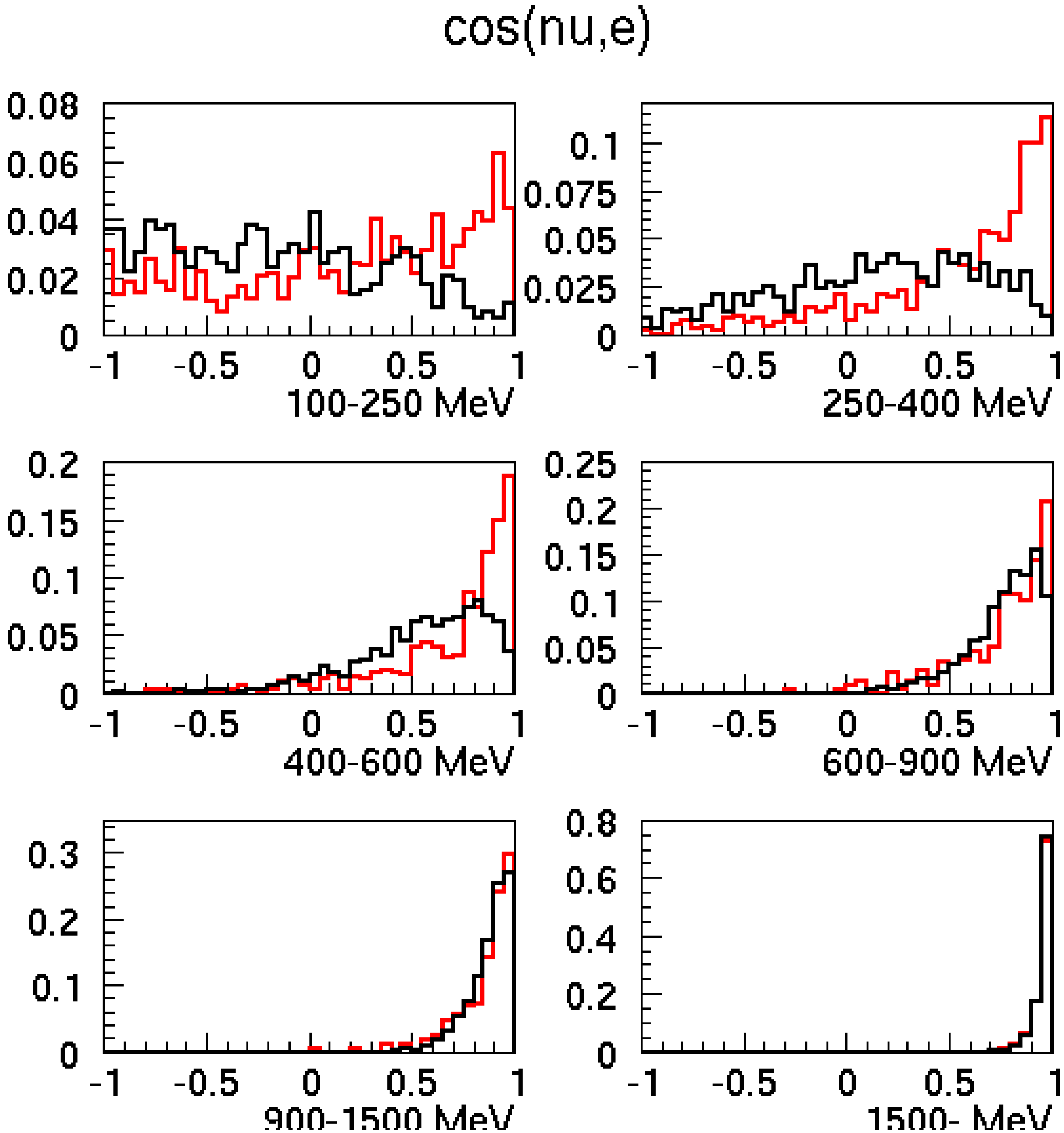
Xalong: Distance between vertex and emitting point of Cherenkov light.

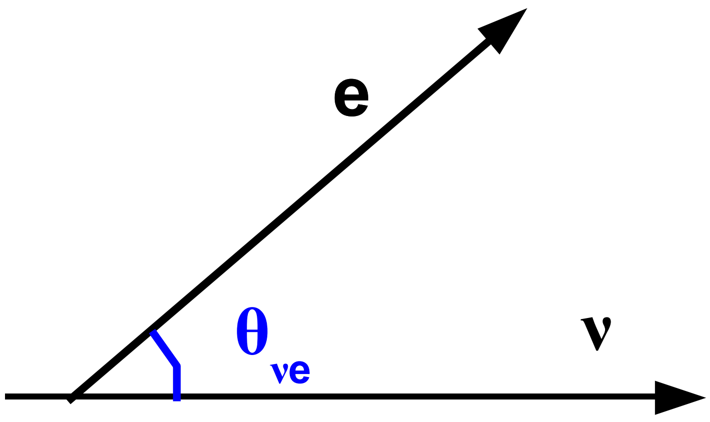
Cos(open): Angle between vertex-pmt vector & direction of particle



- I compute those values for each hit pmt, plot distributions.
- Using part of the MC I create templates of those distributions.
- For each event, I assign a χ^2 value comparing the event against the templates.
- The χ^2 value is added to the likelihood.

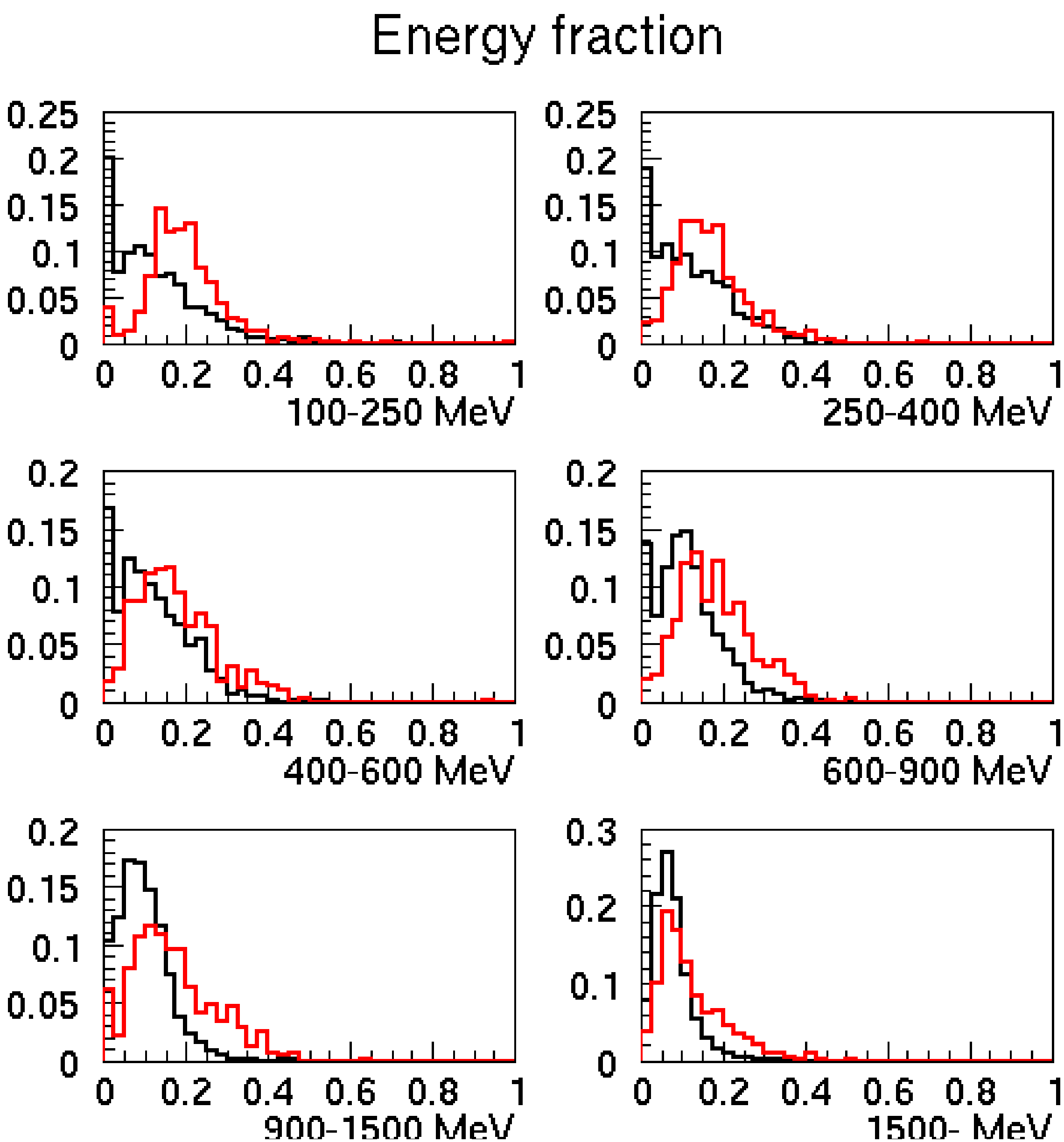
Example of distribution (1)





Bad at high energy

Example of distribution (2)



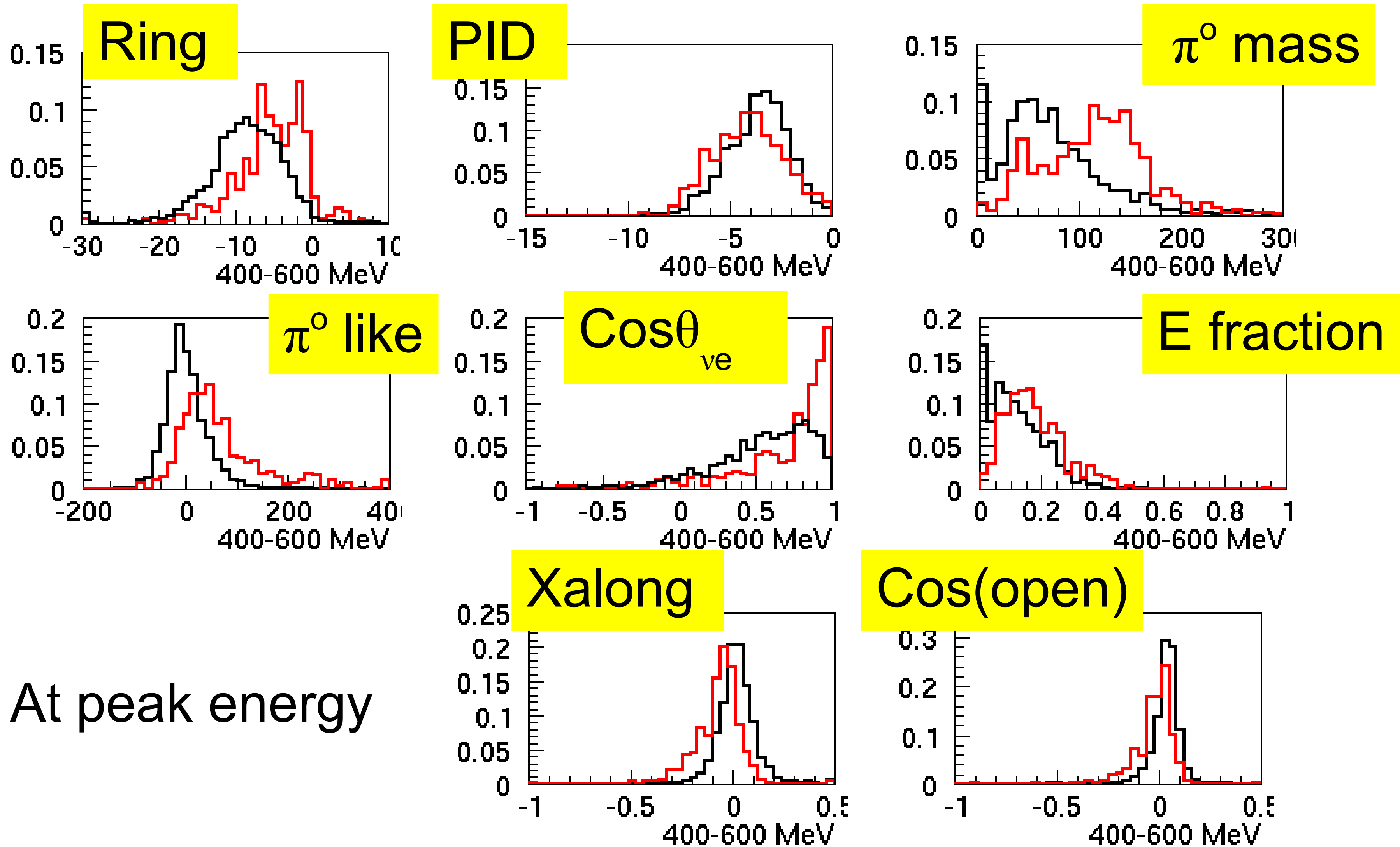
Energy fraction of the 2nd ring.

OK at high energy

Background

Signal

Overview of distributions:

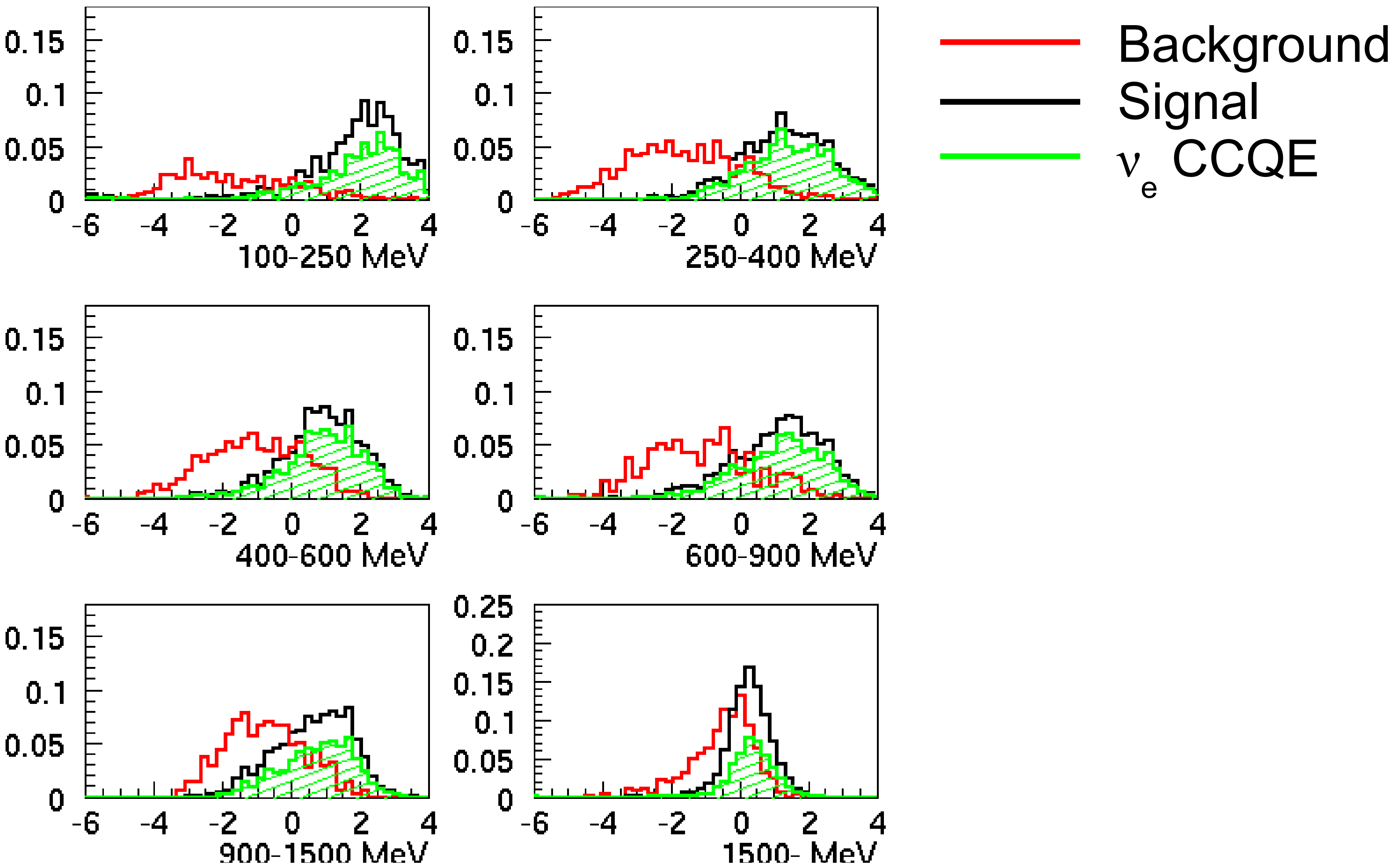


At peak energy

Background

Signal

final likelihood



Final efficiency

E_{rec} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-
ν_μ CC	fcfv	286.9	415.7	370.4	995.0
	1ring	170.2	220.8	146.3	433.6
	e-like	3.6	4.5	5.3	25.4
	nodecay-e	1.4	1.5	1.9	11.9
	likelihood	0.2	0.5	0.6	2.2
	efficiency	14.6%	31.4%	32.0%	18.7%
NC	fcfv	422.0	229.6	86.0	83.6
	1ring	89.0	66.2	26.0	41.1
	e-like	53.4	57.2	24.9	39.6
	nodecay-e	50.4	53.1	20.8	32.6
	likelihood	5.1	10.9	4.0	11.1
	efficiency	10.1%	20.5%	19.5%	34.0%
ν_e	fcfv	12.2	36.7	33.7	73.3
	1ring	5.7	21.6	16.9	37.4
	e-like	5.6	21.3	16.8	37.2
	nodecay-e	4.7	18.9	14.5	30.8
	likelihood	4.0	15.4	11.3	22.1
	efficiency	85.4%	81.8%	78.3%	71.7%

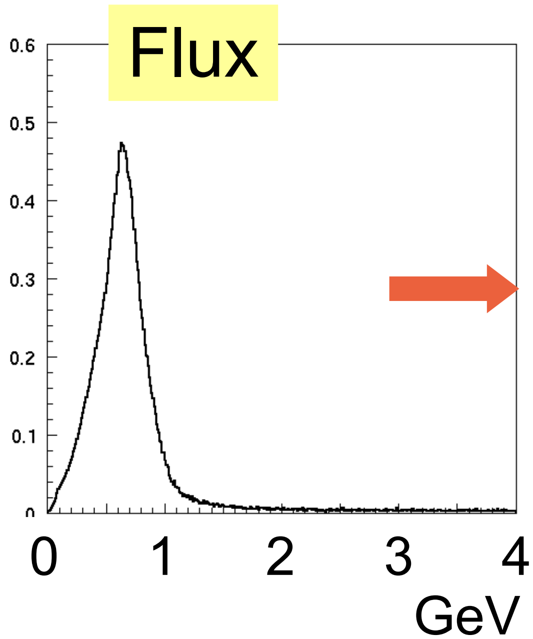
NB: arbitrary numbers

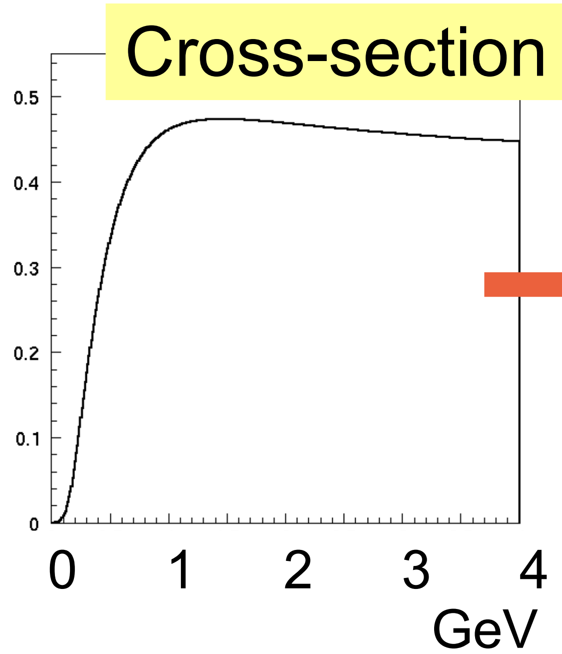
Likelihood future

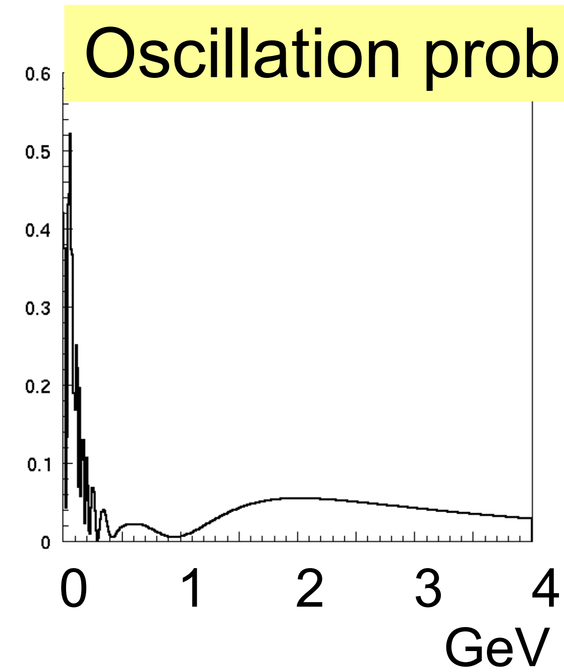
There is room for improvement:

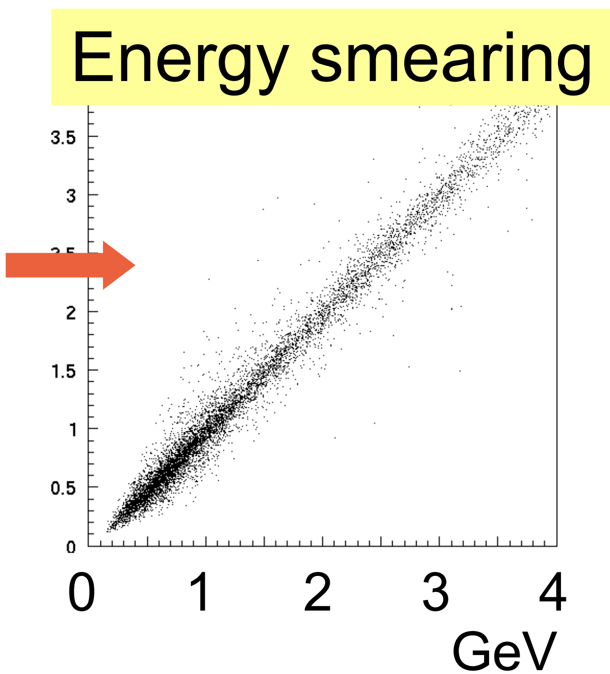
- Add new variables (Total pe charge/Evis, SK-II software variables, etc)
- Use different set of variables for different energies
- Extend analysis to higher energy bins
- Test Neural Network analysis
- Compare with atmospheric data
  $\rightarrow$ Check how well the variables are reproduced by MC.

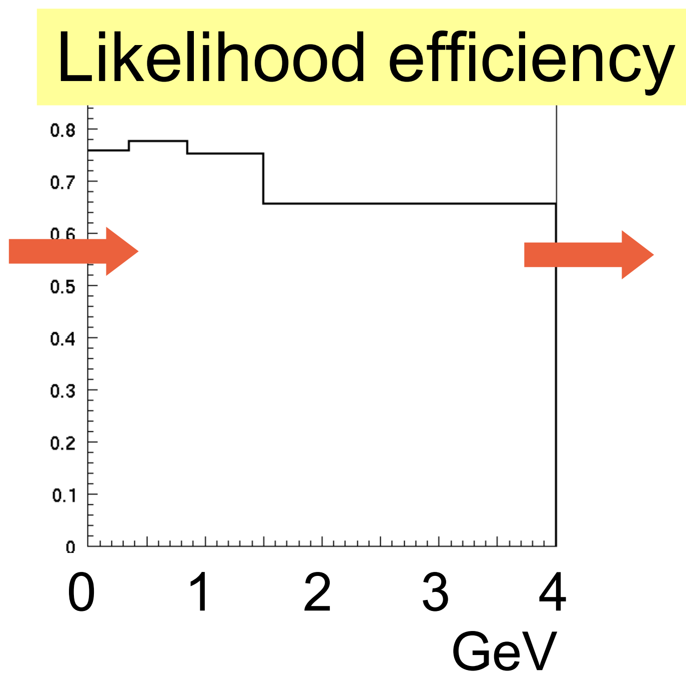
Oscillation analysis





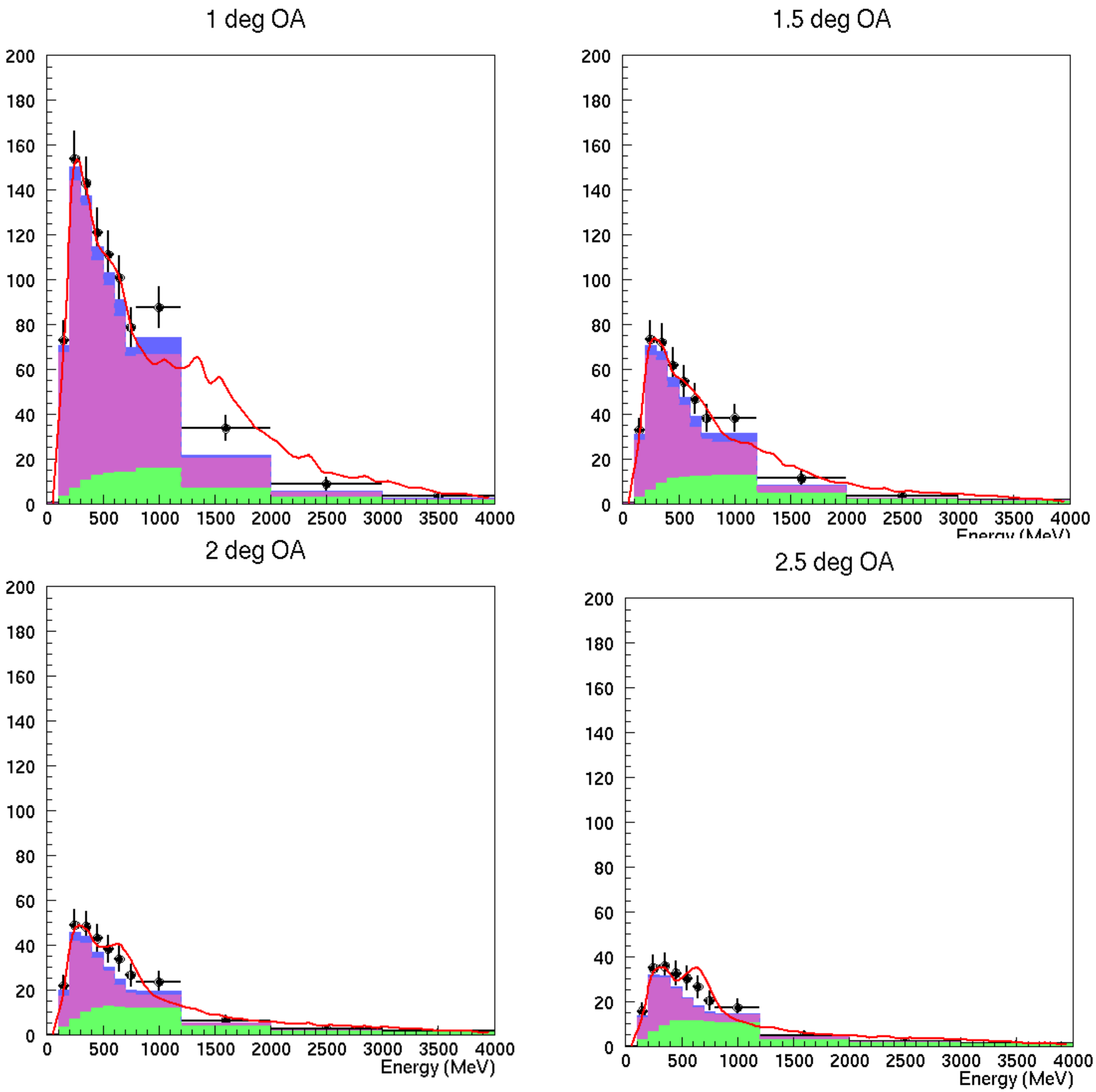






Input spectrum
for χ^2 analysis

Spectrum for each OA



0.27 Mton (FV)
4 yr ν run
4MW
$\sin^2 2\theta_{13}=0.1$
$\delta = \pi/2$

Background:
- beam ν_e
- NC
- ν_μ mis-ID

Signal+Background:
- Without detector effect
- With detector effect

χ^2 Definition

The oscillation analysis was done for: 4MW beam

k=1,4

- 0.27Mton at Kamioka or 0.54Mton in Kamioka *When Kamioka only*
- 0.27Mton in Korea
- 4 years running of neutrino
- 4 years running of antineutrino

With the following energy bins (MeV):

i=1,7

- 400-500, 500-600, 600-700, 700-800,
- 800-1200, 1200-2000, 2000-3000

$$\chi^2 = \sum_{k=1}^{4} \left(\sum_{i=1}^{7} \frac{\left(N(e)_i^{\rm obs} - N(e)_i^{\rm exp}\right)^2}{\sigma_i^2} \right) + \sum_{j=1}^{3} \left(\frac{\epsilon_j}{\tilde{\sigma}_j} \right)^2$$

$$N(e)_i^{\rm exp} = N_i^{\rm BG} \cdot (1 + \sum_{j=1}^{2} f_j^i \cdot \epsilon_j) + N_i^{\rm signal} \cdot (1 + f_3^i \cdot \epsilon_3) \quad .$$

hep-ph 0604026 eq 3) and 4)

One bug was fixed...

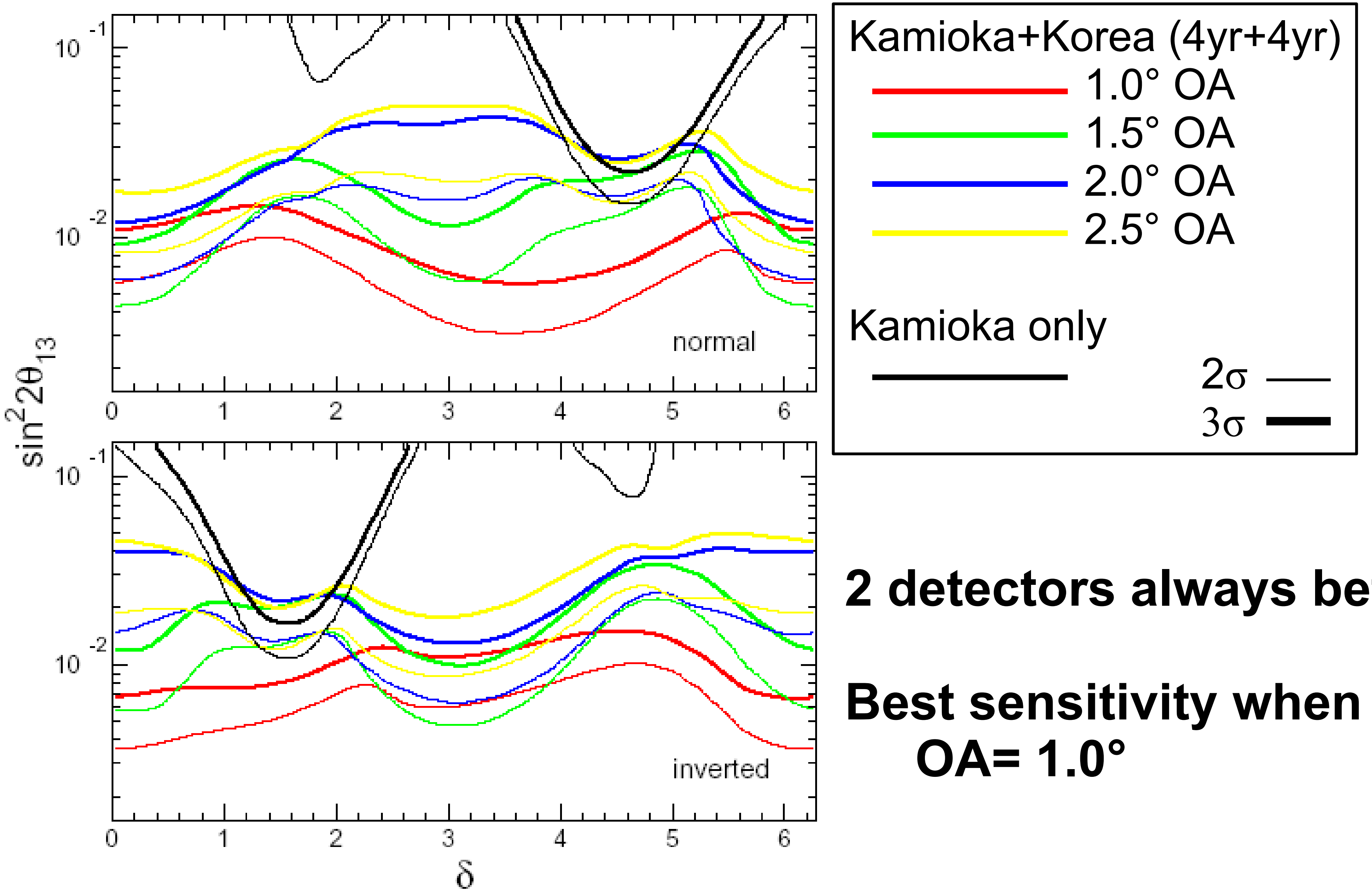
So the next set of slide always have and old and a new slide.

The bug was:
In the case of the 2 detector setup (Kamioka+Korea) I was assigning the background according to the off-axis angle for both Kamioka and Korea, which is wrong.

I should have kept the background setup to 2.5OA for Kamioka and change only the background for Korea.

Sorry for the confusion.

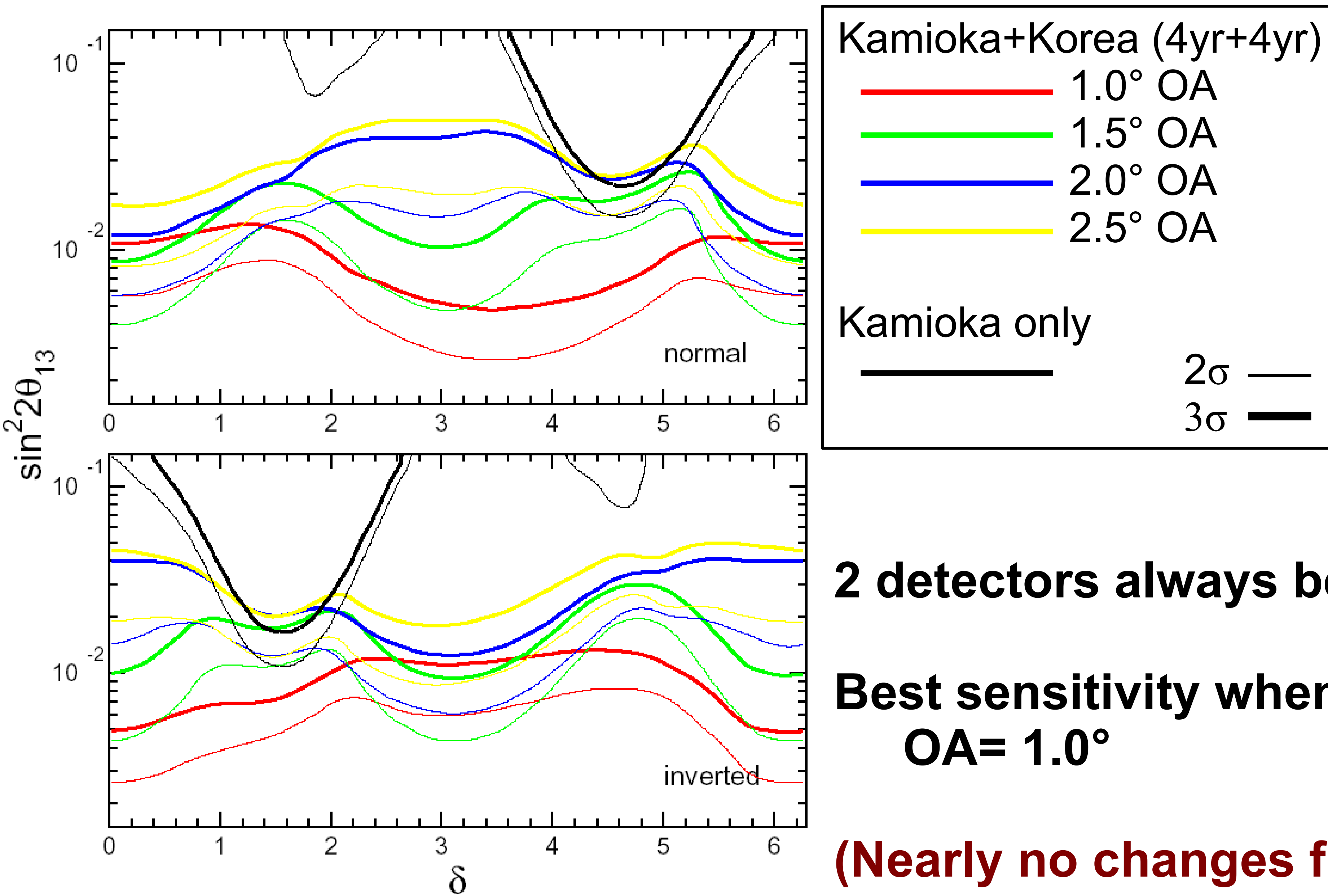
Sensitivity mass hierarchy (old)



2 detectors always better

Best sensitivity when OA= 1.0°

Sensitivity mass hierarchy (new)

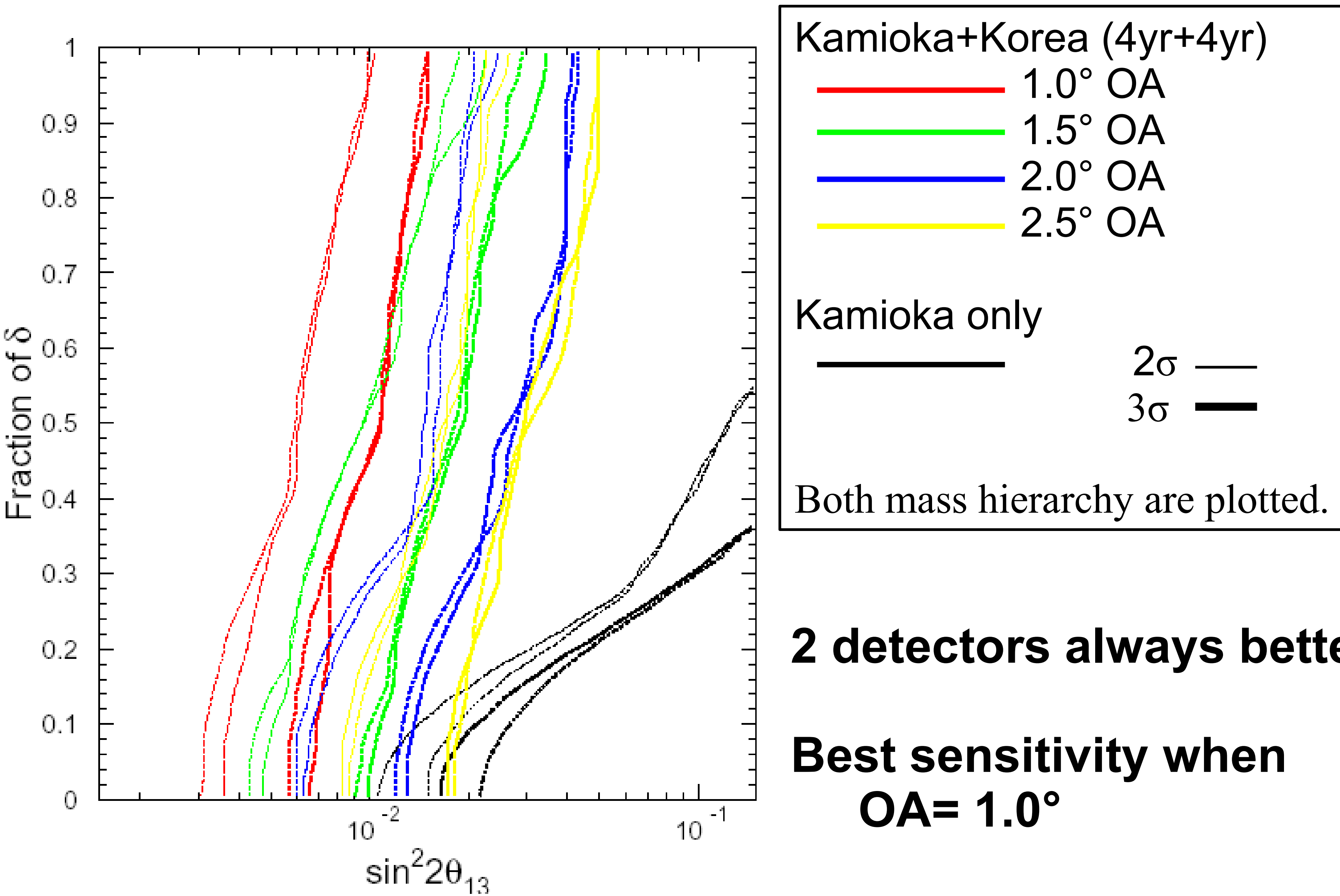


2 detectors always better

Best sensitivity when OA= 1.0°

(Nearly no changes from the old slide)

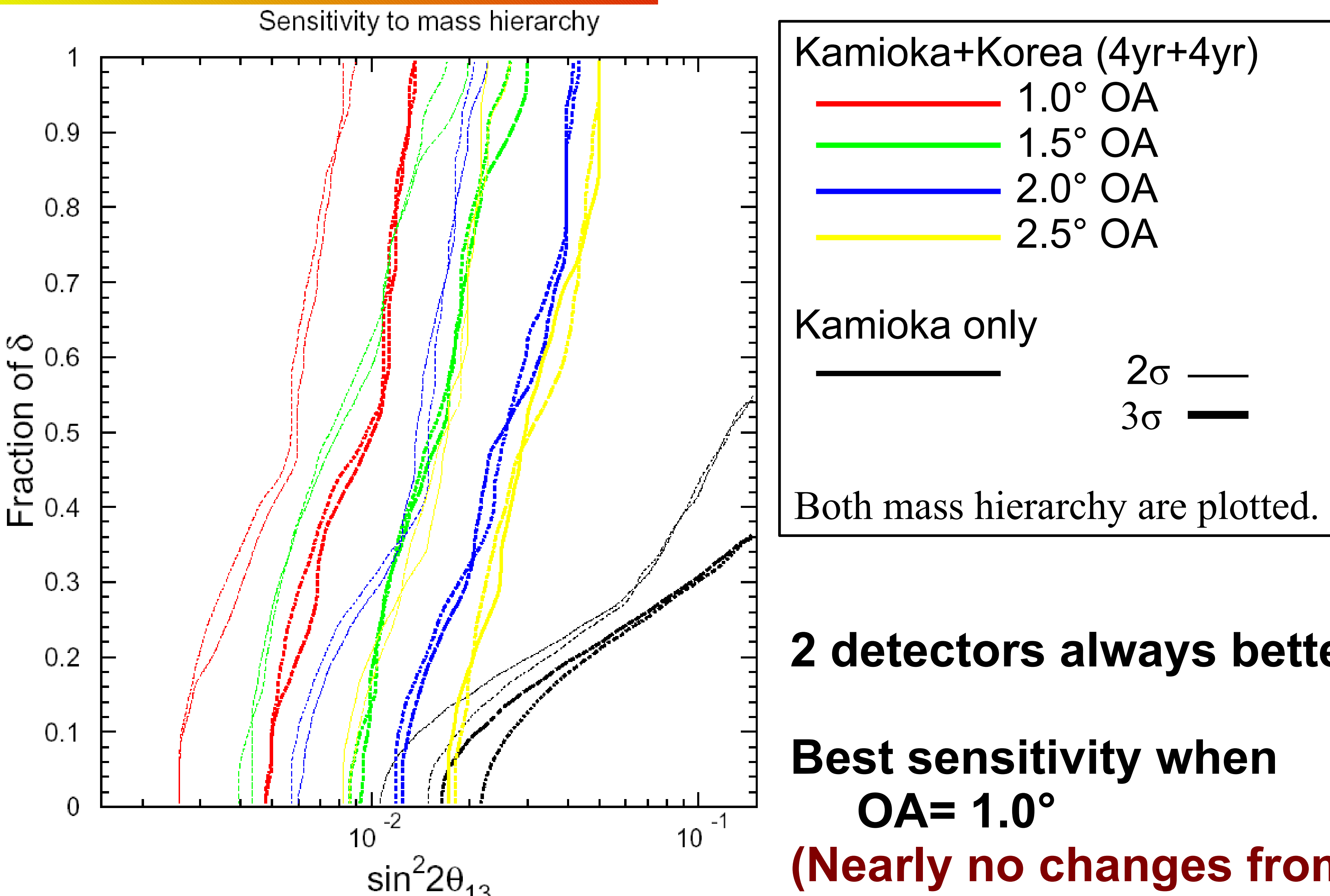
Sensitivity mass hierarchy (old)



2 detectors always better

Best sensitivity when OA= 1.0°

Sensitivity mass hierarchy (new)

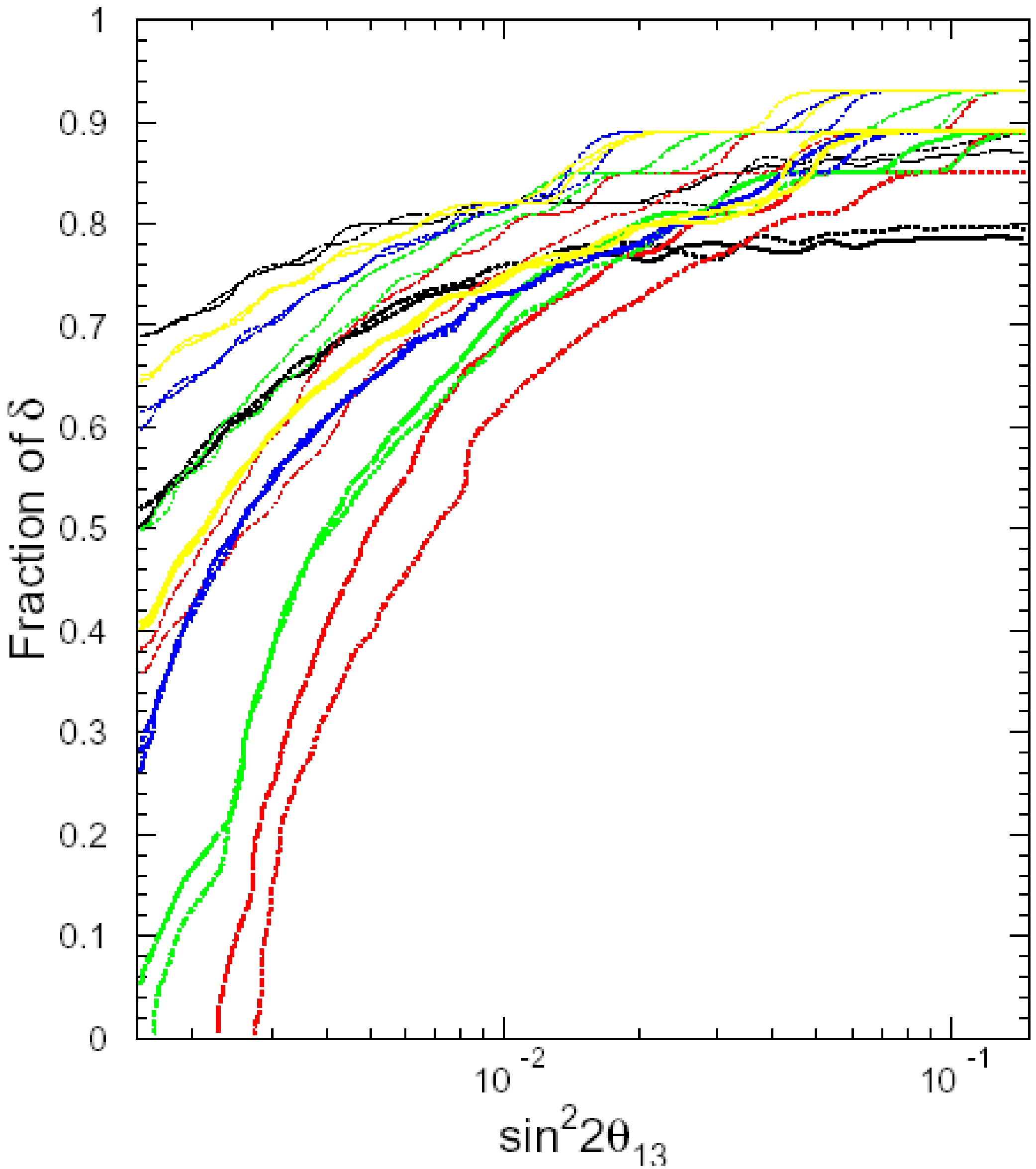


2 detectors always better

Best sensitivity when OA= 1.0°

(Nearly no changes from the old slide)

Sensitivity CP violation (old)



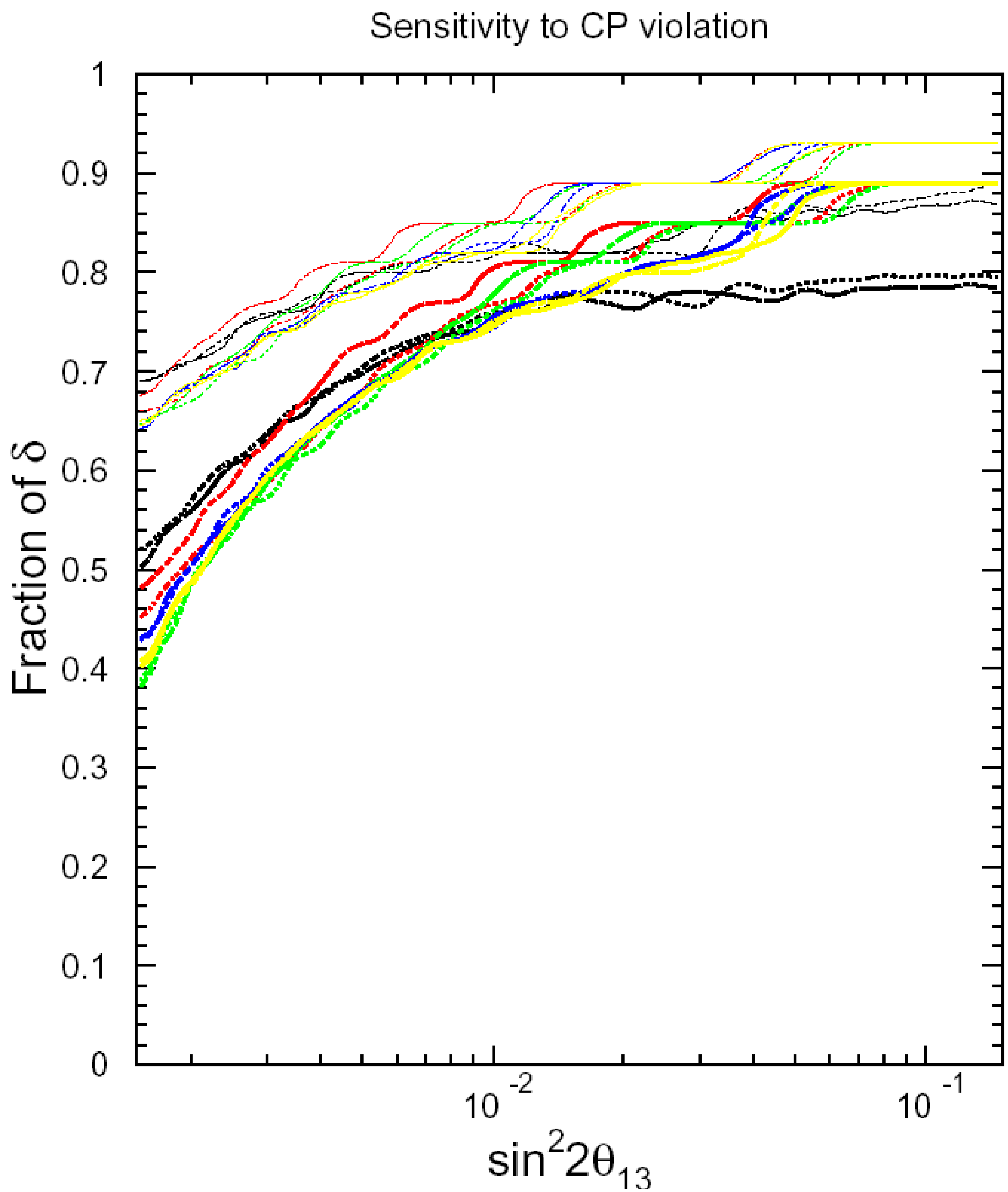
If $\sin^2 2\theta_{13}$ is big:

Best sensitivity with 2 detectors (& big OA)

If $\sin^2 2\theta_{13}$ is small:

Best sensitivity with Kamioka only

Sensitivity CP violation (new)



MAJOR CHANGES

In general there is not much difference between OA angle.

In the case where θ_{13} is very small then 1.0° OA is the best of the 2 detector setup (ie Kamioka+ Korea), but Kamioka only would even be better.

Conclusions (old)

Likelihood analysis developed for ν_e appearance:

ε = 82% / BG = 21% → ε = 72% / BG = 34%

Oscillation analysis conclusions:

For mass hierarchy:

Best set up is when OA is small (= 1.0°)

1^{st} osc maximum → matter effect

For CP violation study:

Best set up is Kamioka only (for small $\sin^2 2\theta_{13}$)

or OA big (= 2.5°) if 2 detectors (for big $\sin^2 2\theta_{13}$)

2^{nd} osc maximum → bigger CP effect

Future plan: Extend analysis to higher energies (especially for 1° OA)

Conclusions (new)

Likelihood analysis developed for ν_e appearance:

ε = 82% / BG = 21% → ε = 72% / BG = 34%

Oscillation analysis conclusions:

For mass hierarchy:

Best set up is when OA is small (= 1.0°)

1st osc maximum → matter effect

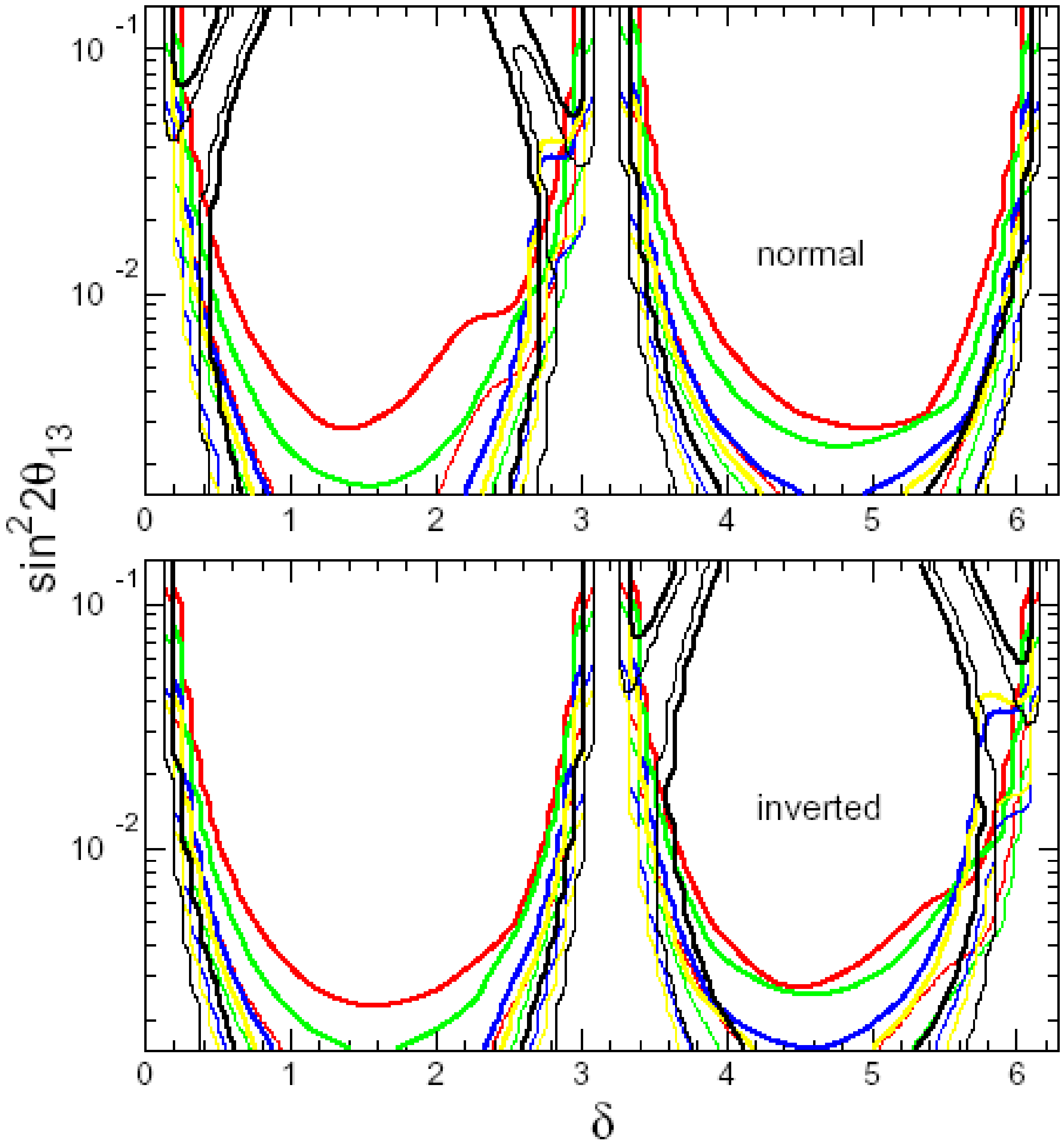
For CP violation study:

Not many difference for different OA angle unless θ_{13} is very small and in that case 1.0° OA is the best of 2 detector setup, but Kamioka only would even be better.

Future plan: Extend analysis to higher energies (especially for 1° OA)

Backups:

Sensitivity CP violation



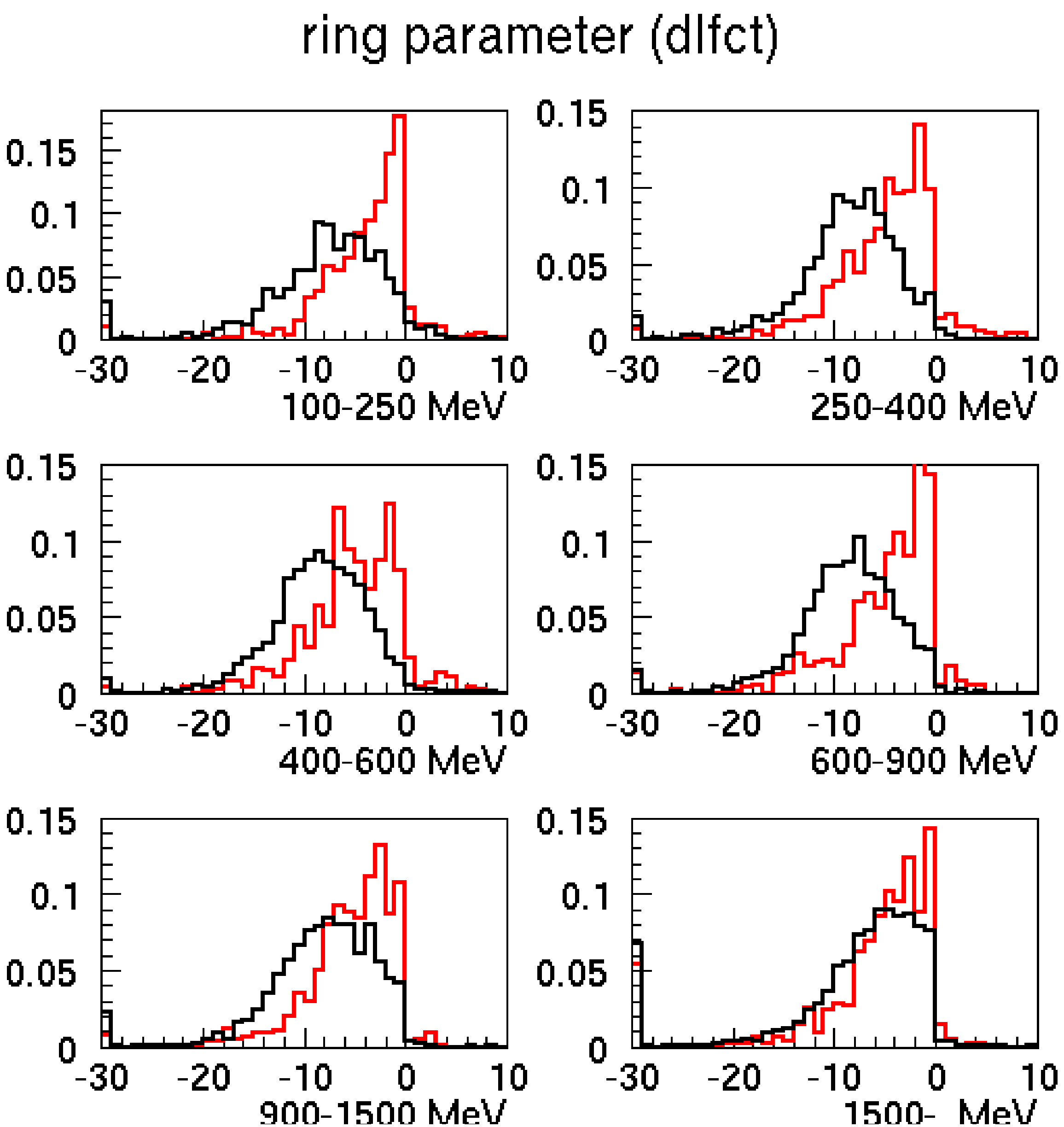
If $\sin^2 2\theta_{13}$ is big:

Best sensitivity with 2 detectors (big OA)

If $\sin^2 2\theta_{13}$ is small:

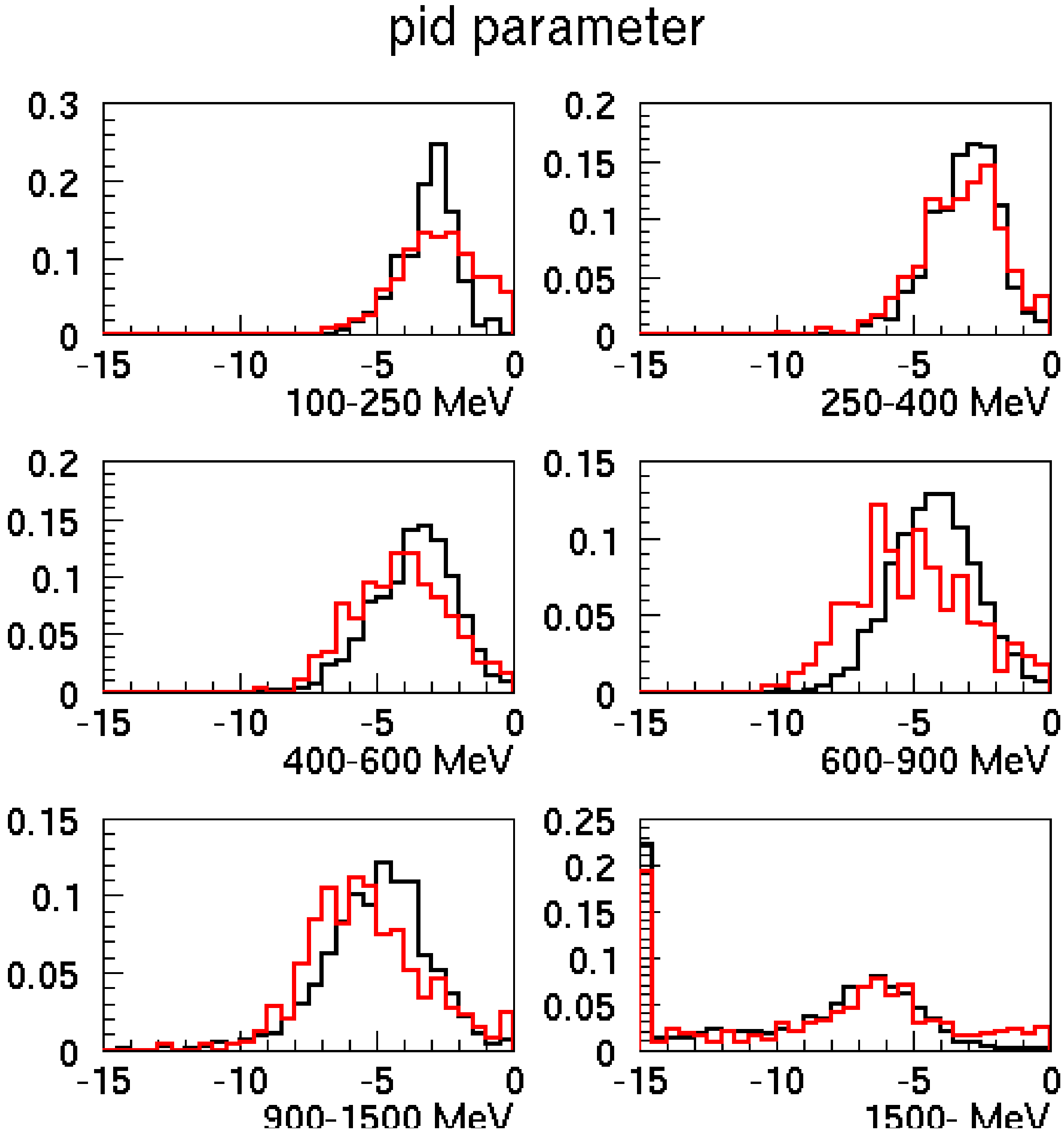
Best sensitivity with Kamioka only

ring param

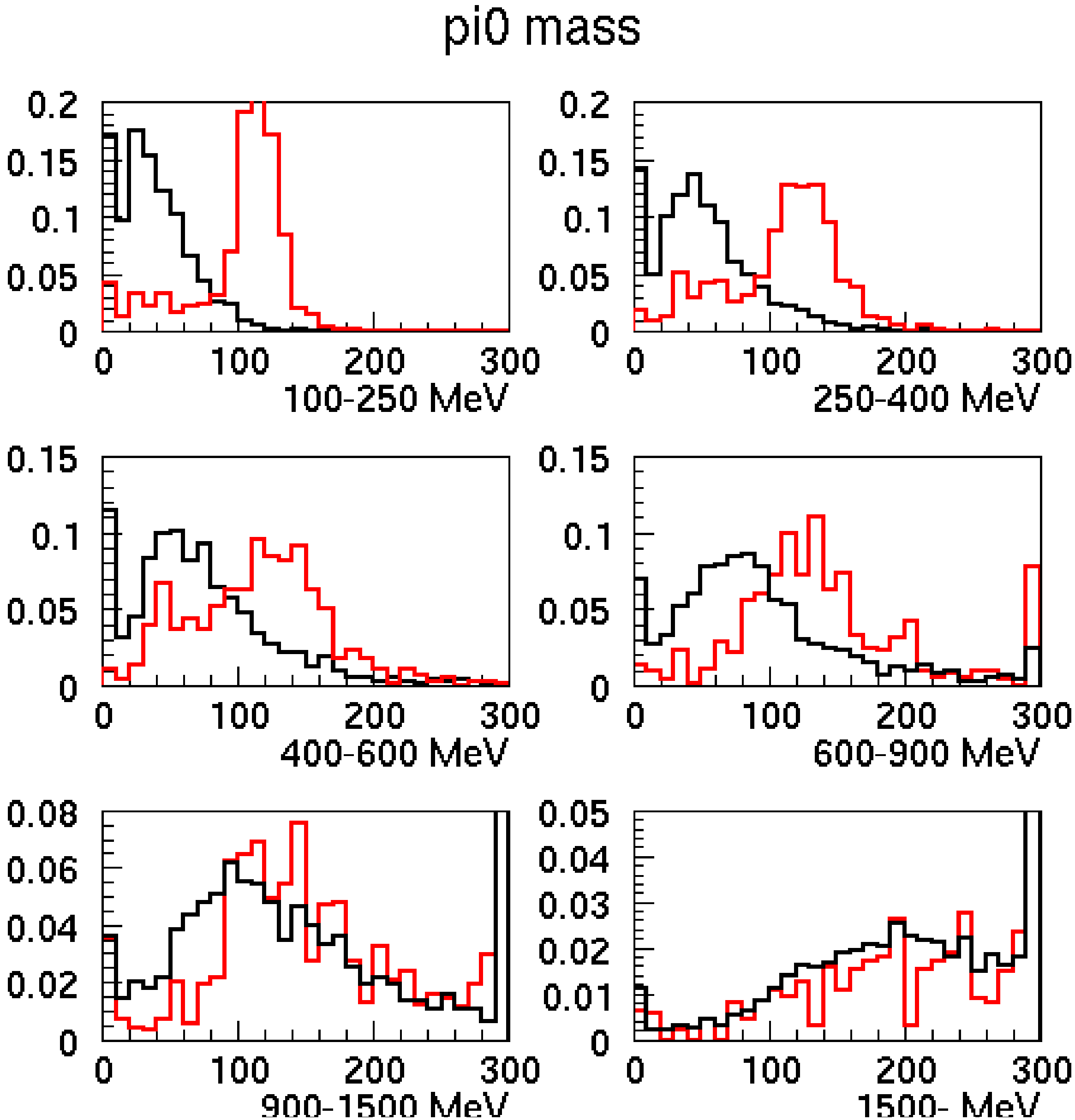


ring parameter (dlfct)
0.15
0.1
0.05
0
-30
-20
-10
0
10
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV

pid

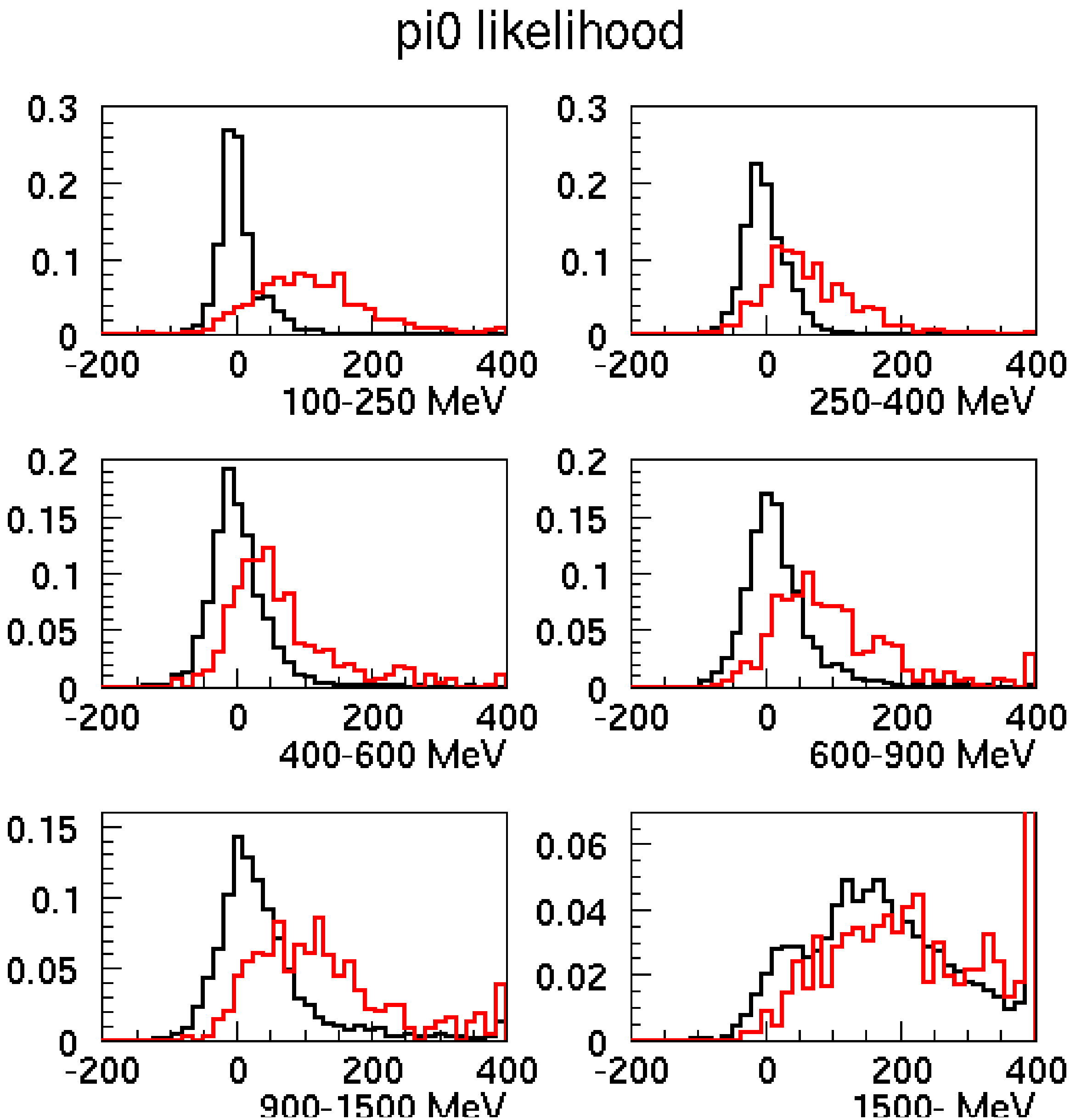

pid parameter
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV

pi0mass

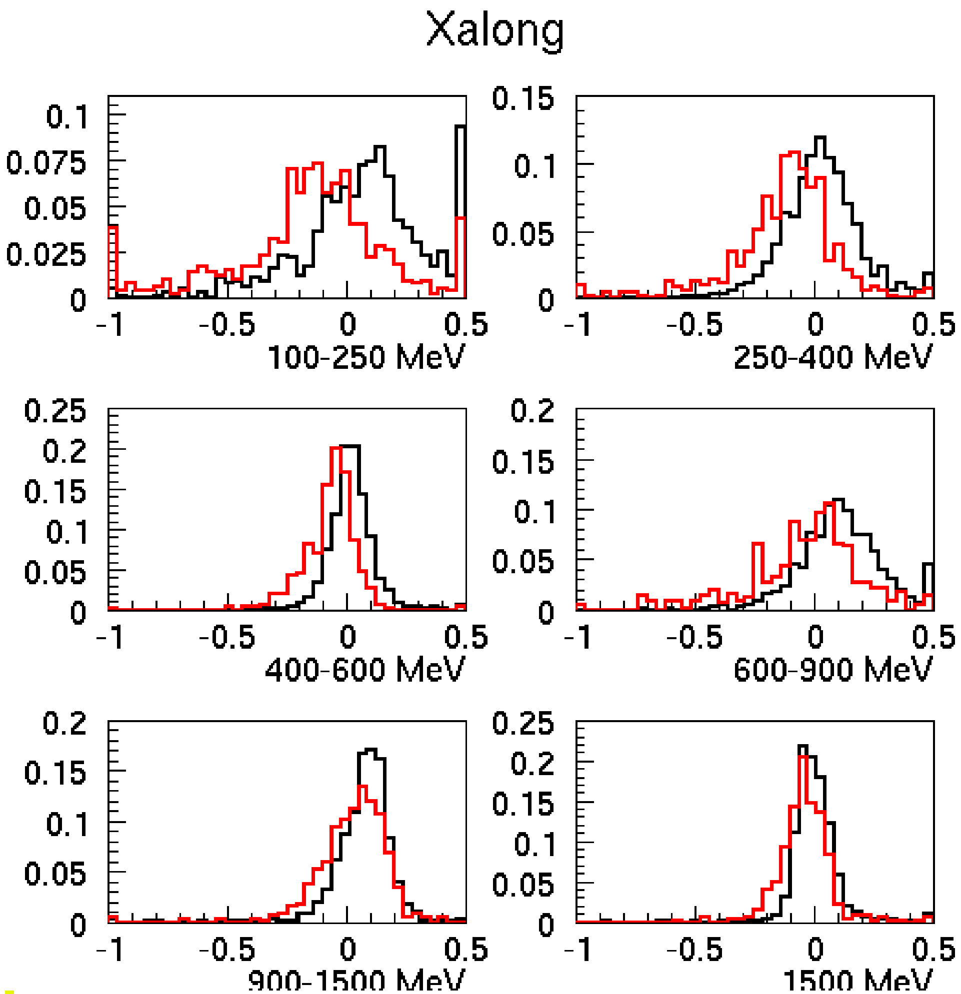


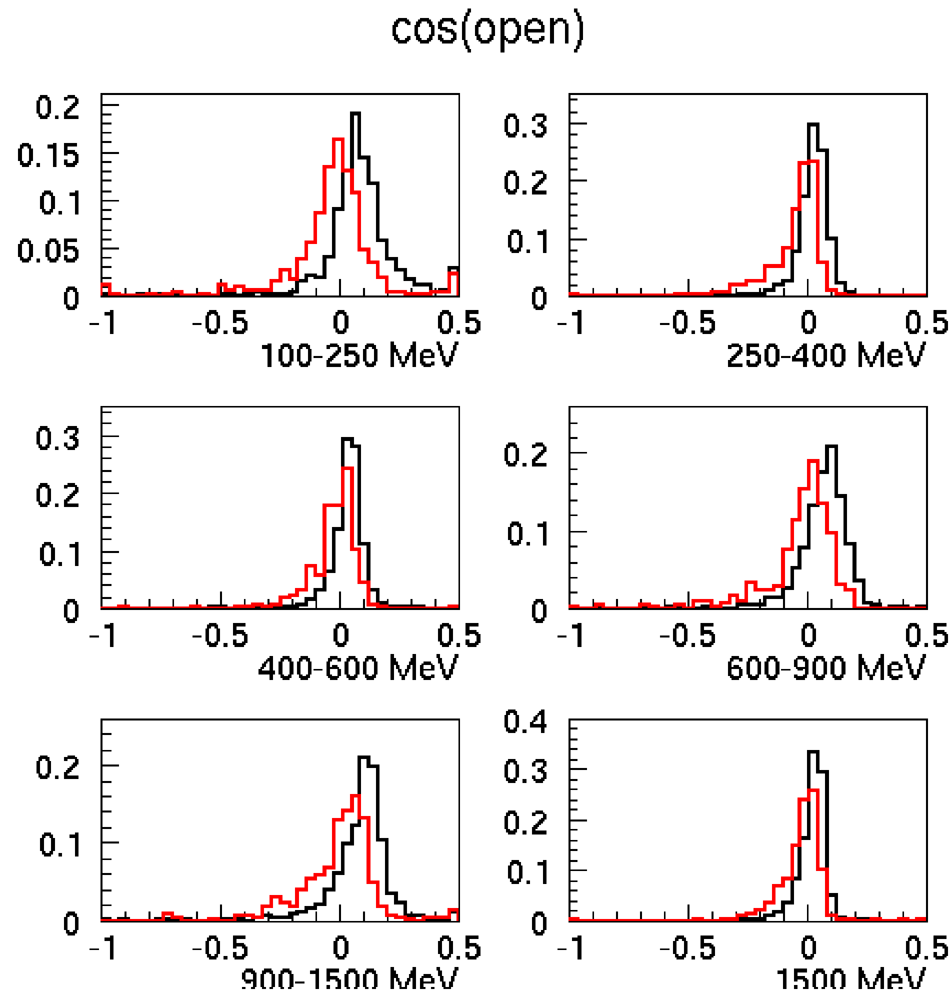
pi0 mass
0.2
0.15
0.1
0.05
0
0
100
200
300
100-250 MeV
250-400 MeV
400-600 MeV
600-900 MeV
900-1500 MeV
1500- MeV
0.08
0.06
0.04
0.02
0.05
0.04
0.03
0.02
0.01

pi0like


pi0 likelihood
0.3
0.2
0.1
0
-200
0
200
400
100-250 MeV
250-400 MeV
0.15
0.05
400-600 MeV
600-900 MeV
900-1500 MeV
0.06
0.04
0.02
1500- MeV

xalong cosopen (distribution)





usefulness of variables

add/remove variables
eff tables