T2KK Project
& Likelihood study

Fanny Dufour, Ed Kearns, Boston University

Fermilab Workshop, September 16, 2006

Outline

T2KK project
- Where?
- What kind of beam
- 2 detectors complex
- Spectrum (each off-axis angle)
- χ^2 analysis
- Sensitivity curves

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

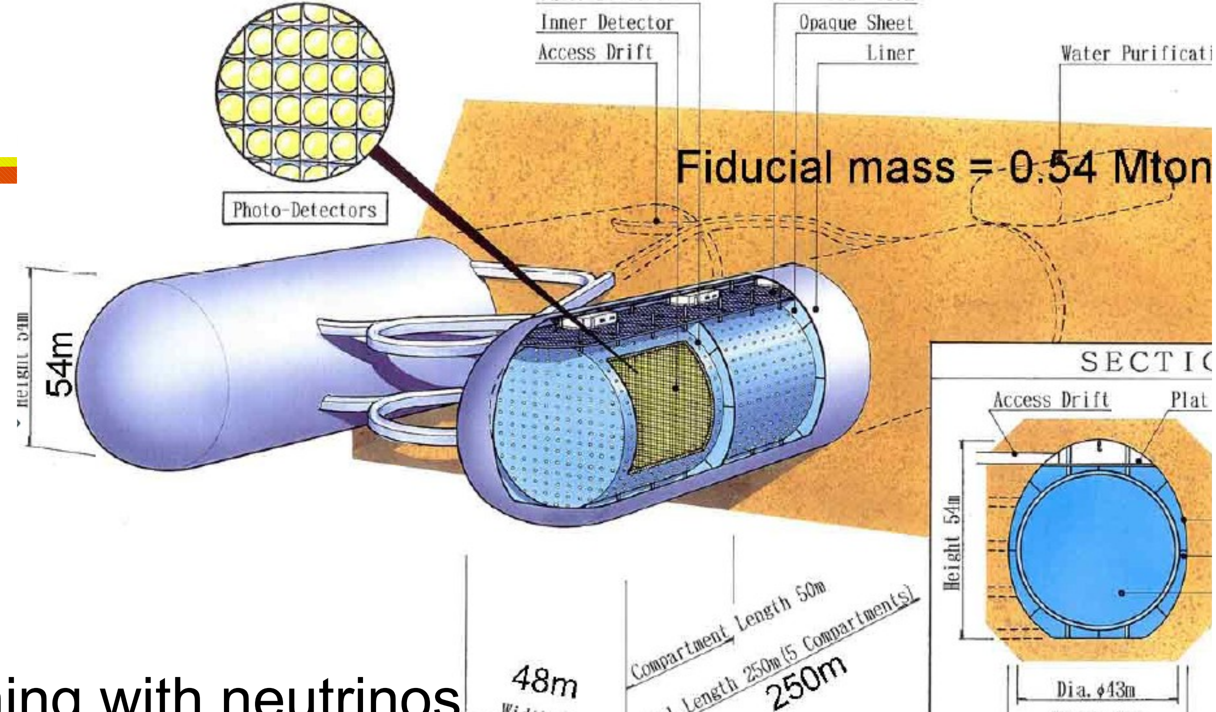
This work was developed for
2[nd] Int'l Workshop on far detector in Korea for the J-Parc neutrino beam
http://t2kk.snu.ac.kr

Working group: T.Kajita, E.Kearns, A. Meregaglia, S. Nakayama, K.Okumura, A.Rubbia, H Minakata et al.

Connection to FNAL -DUSEL study

- Compare the likelihood efficiency → Done
- Use 28GeV, 1MW flux and check sensitivity results with our tools → In progress
- Compare T2KK and FNAL-DUSEL → Next

T2KK



Beam (T2K phase-II)

4MW from JPARC
40 GeV protons
assumed 4 years of running with neutrinos
4 years of running with anti-neutrinos

Off-axis angle =2.5° at Kamioka
simulations range from 1.0° to 2.5° in Korea

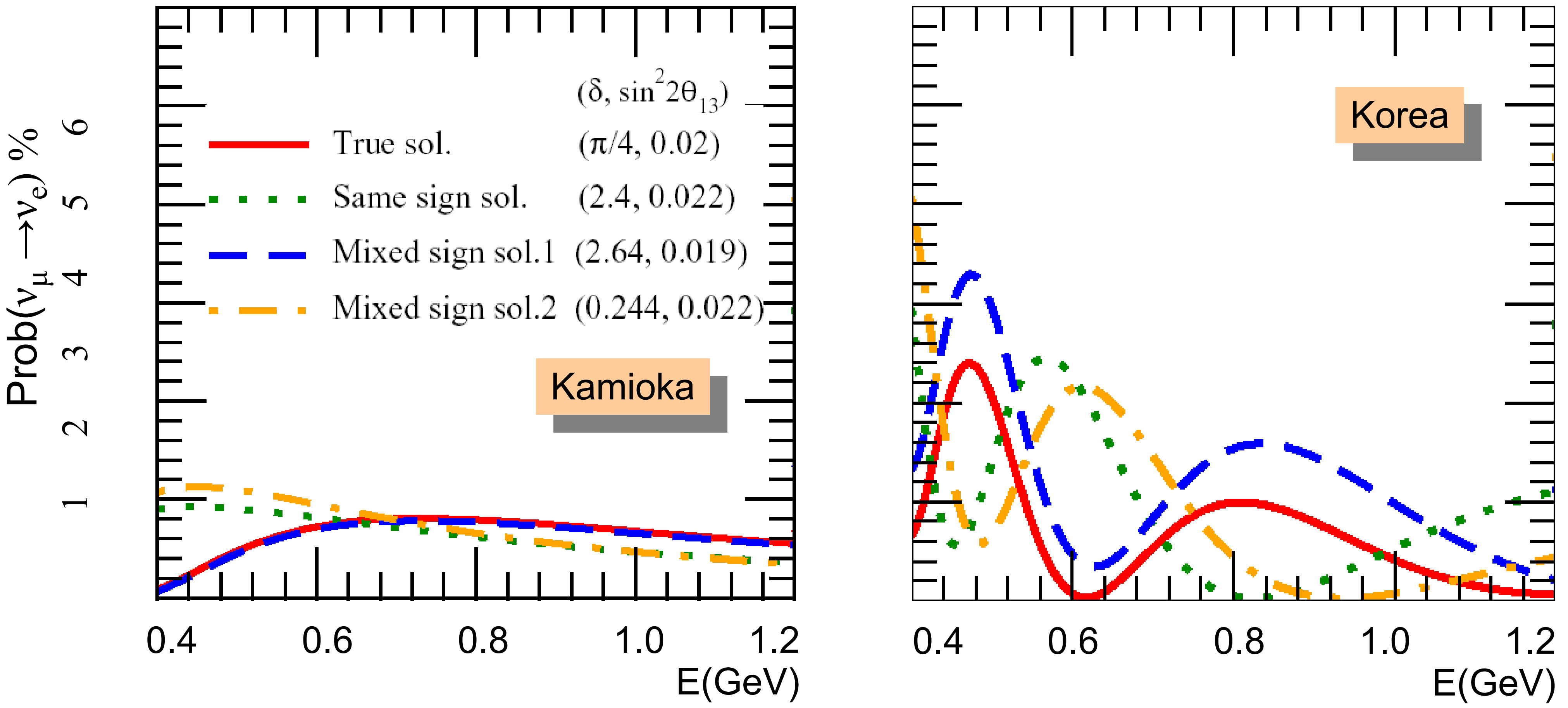
Detectors: (one in Kamioka, one in Korea)

Two 0.5 Mton detectors
with 0.27 Mton fiducial volume each

} **Total volume 1Mton (0.54 FV)**

(NB when testing Kamioka only, FV=0.54Mton)

Oscillation probability

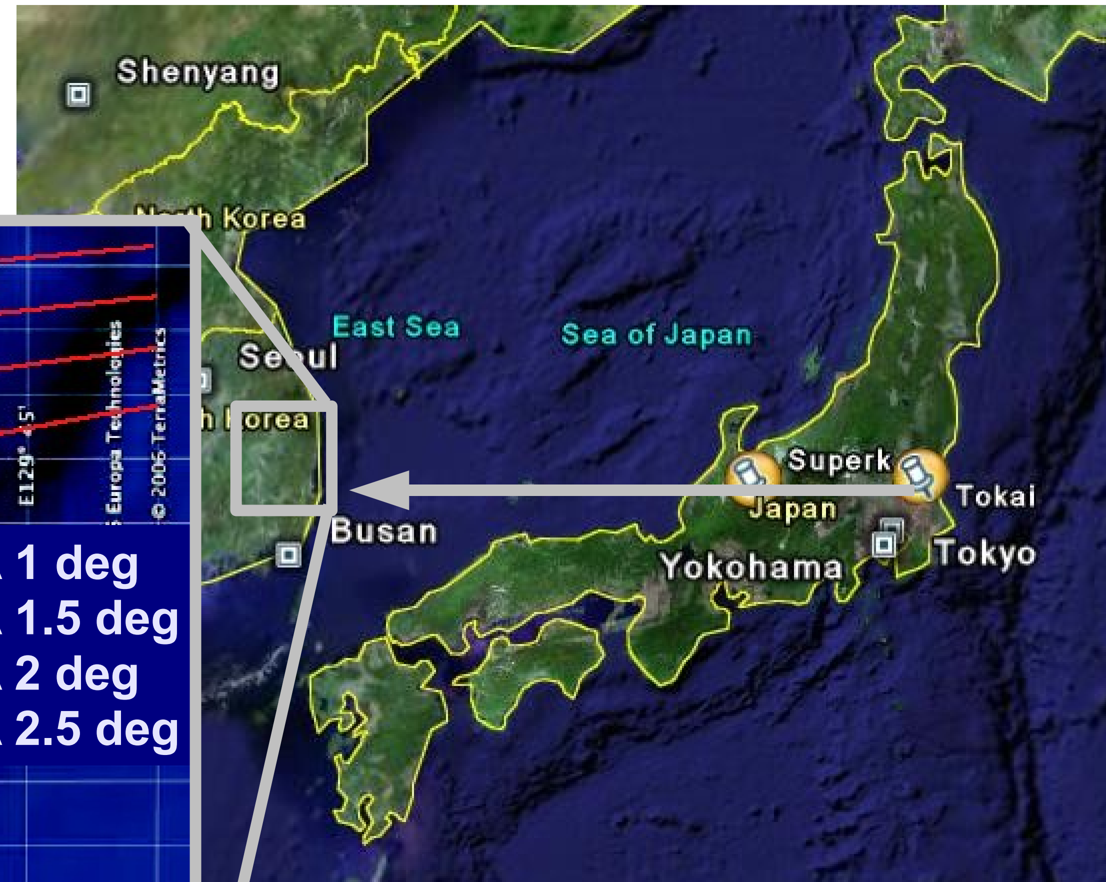


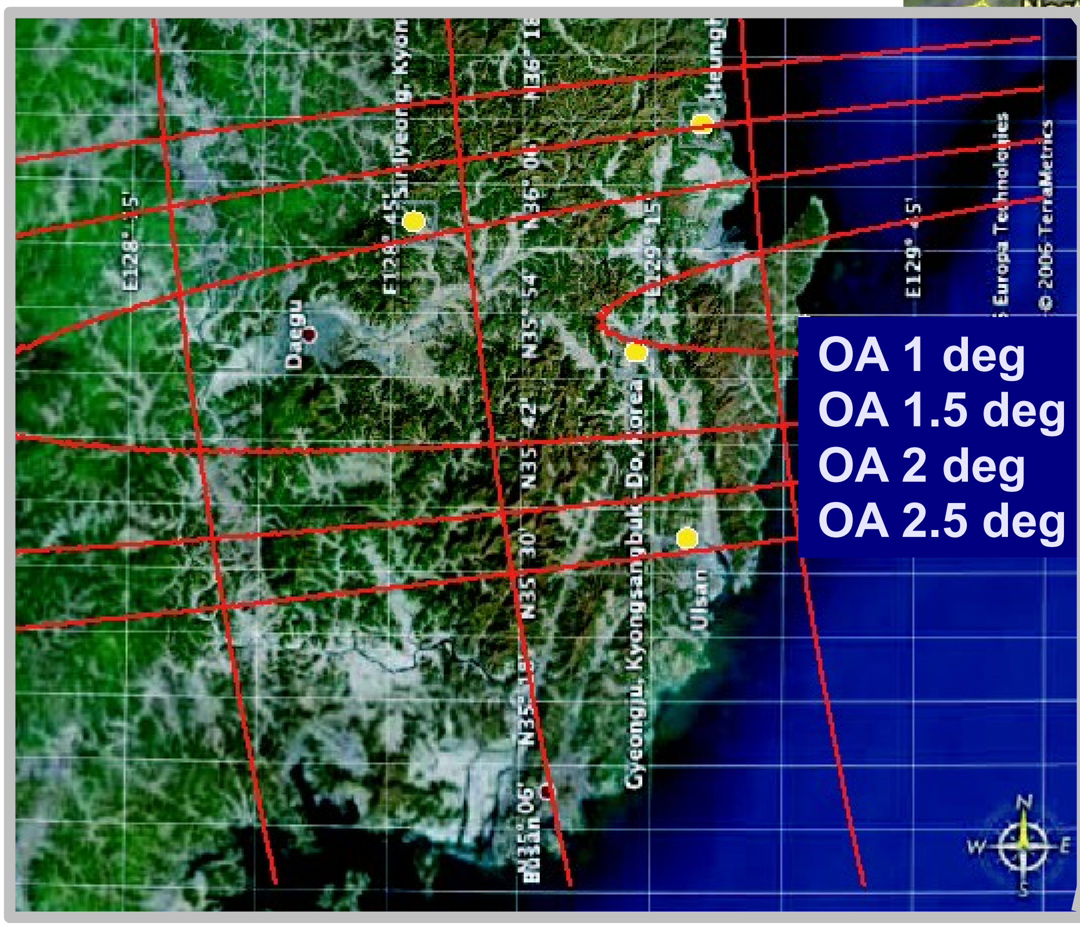
→ Very dynamic in Korea

Ishitsuka et al. PRD72, 033003 (2005)

T2KK (T2K to Korea)

Detecting neutrinos from T2K in Korea → T2KK





Studied OA from 1.0º to 2.5º in Korea (Kamioka fixed at 2.5º)

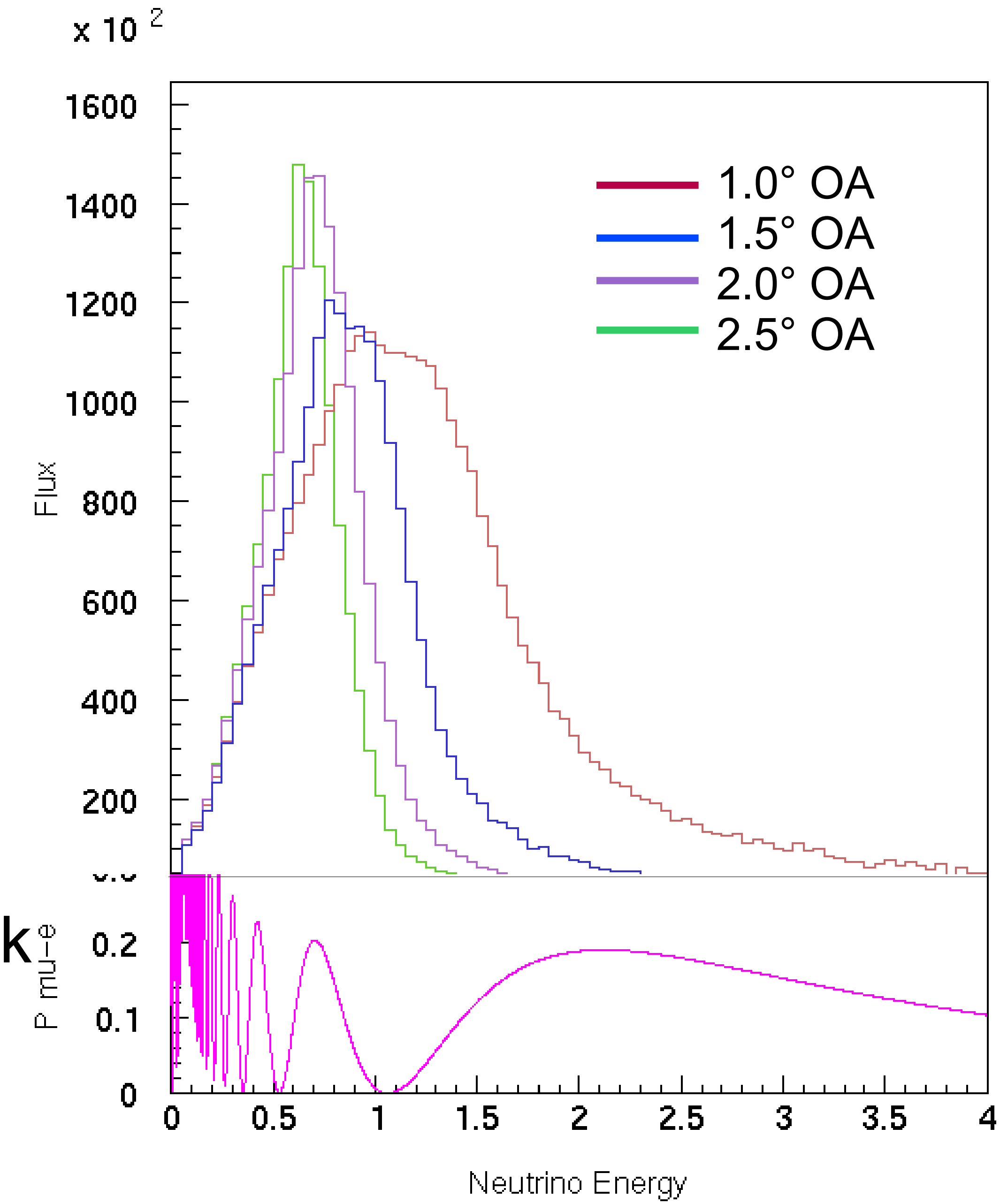
Flux for several off-axis angle

Small off-axis angle:
(high energy tail)

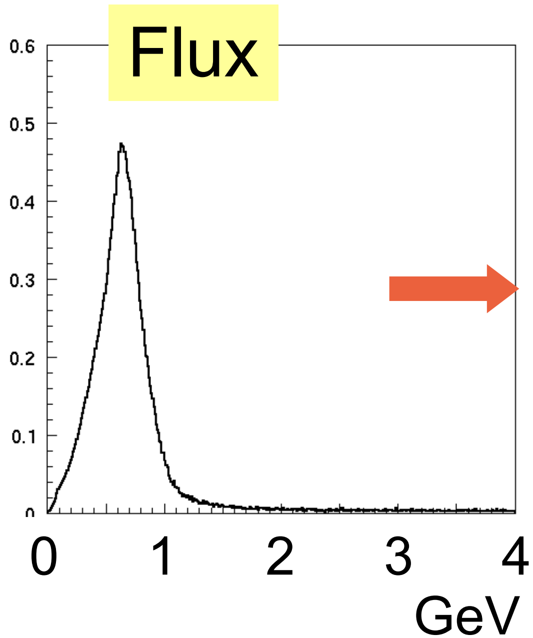
- ✔ 1st appearance peak
- ✗ more NC background

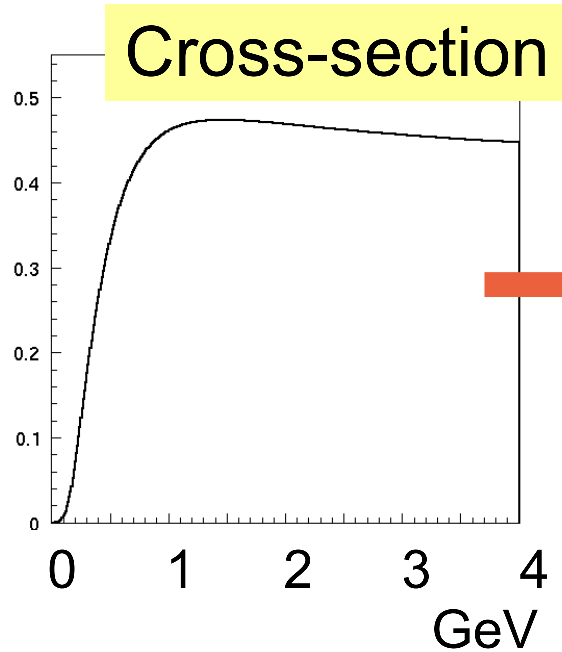
Big off-axis angle:
(narrow peak)

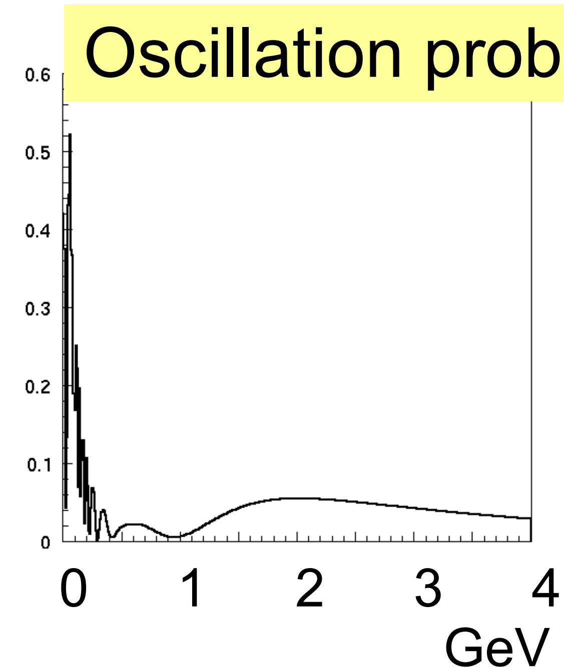
- ✔ Low background
- ✗ Low statistics at high E
- ✗ Only 2nd appearance peak

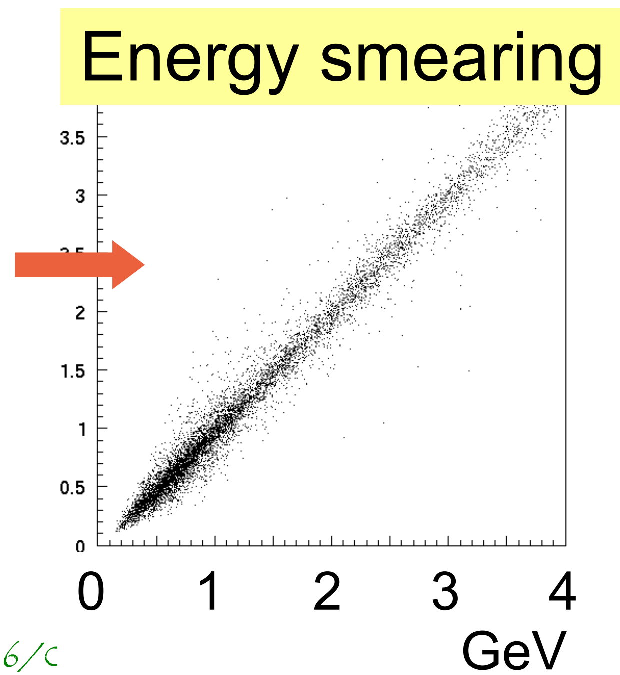


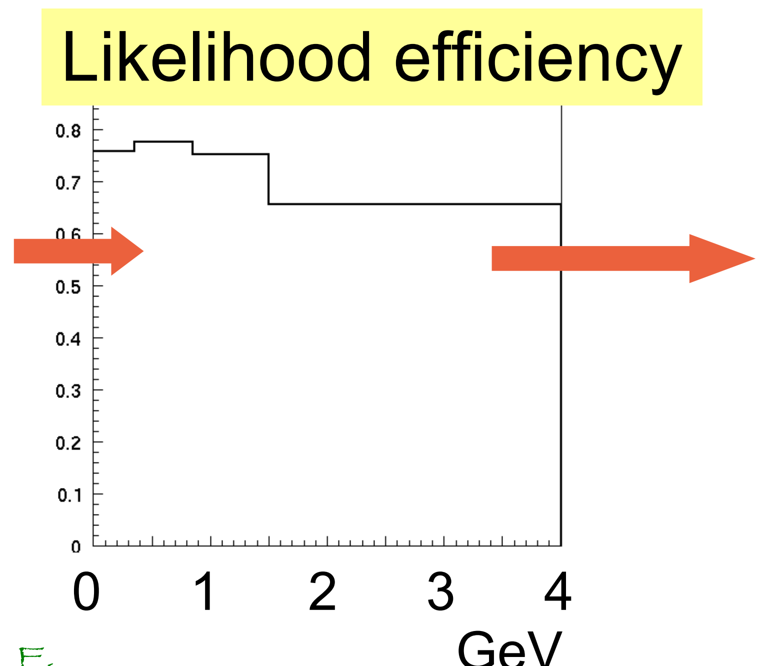
Oscillation analysis











Input signal spectrum for χ^2 analysis

Background spectrum

Use SK atm MC, reweight each event by the T2KK fluxes (for each OA angle)

↓

Apply oscillation for ν_μ

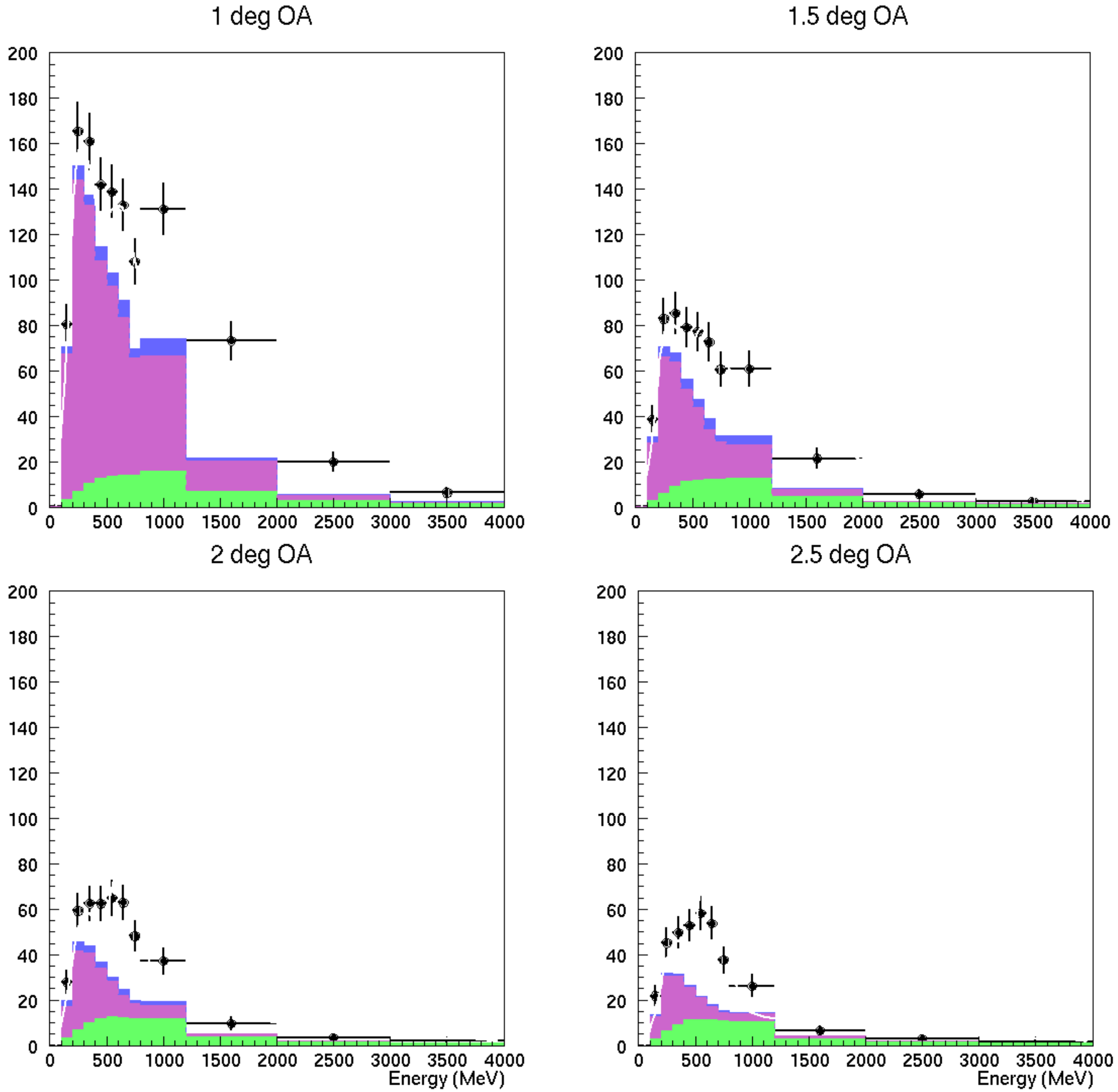
↓

Apply likelihood efficiency

↓

Input background 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:
- 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):

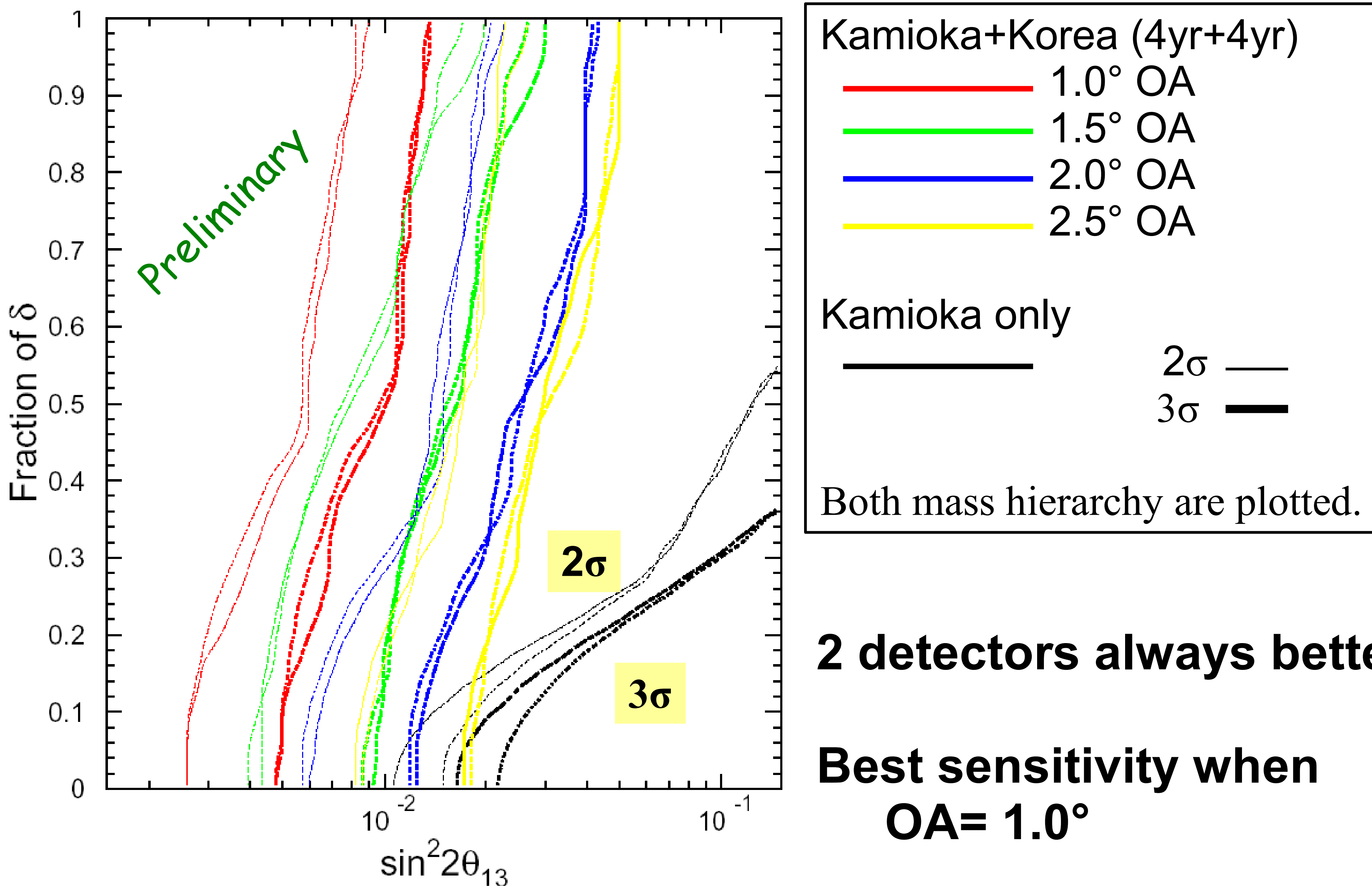
i=1,7
- 400-500, 500-600, 600-700, 700-800,
- 800-1200, 1200-2000, 2000-3000

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

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

hep-ph 0604026 eq 3) and 4)

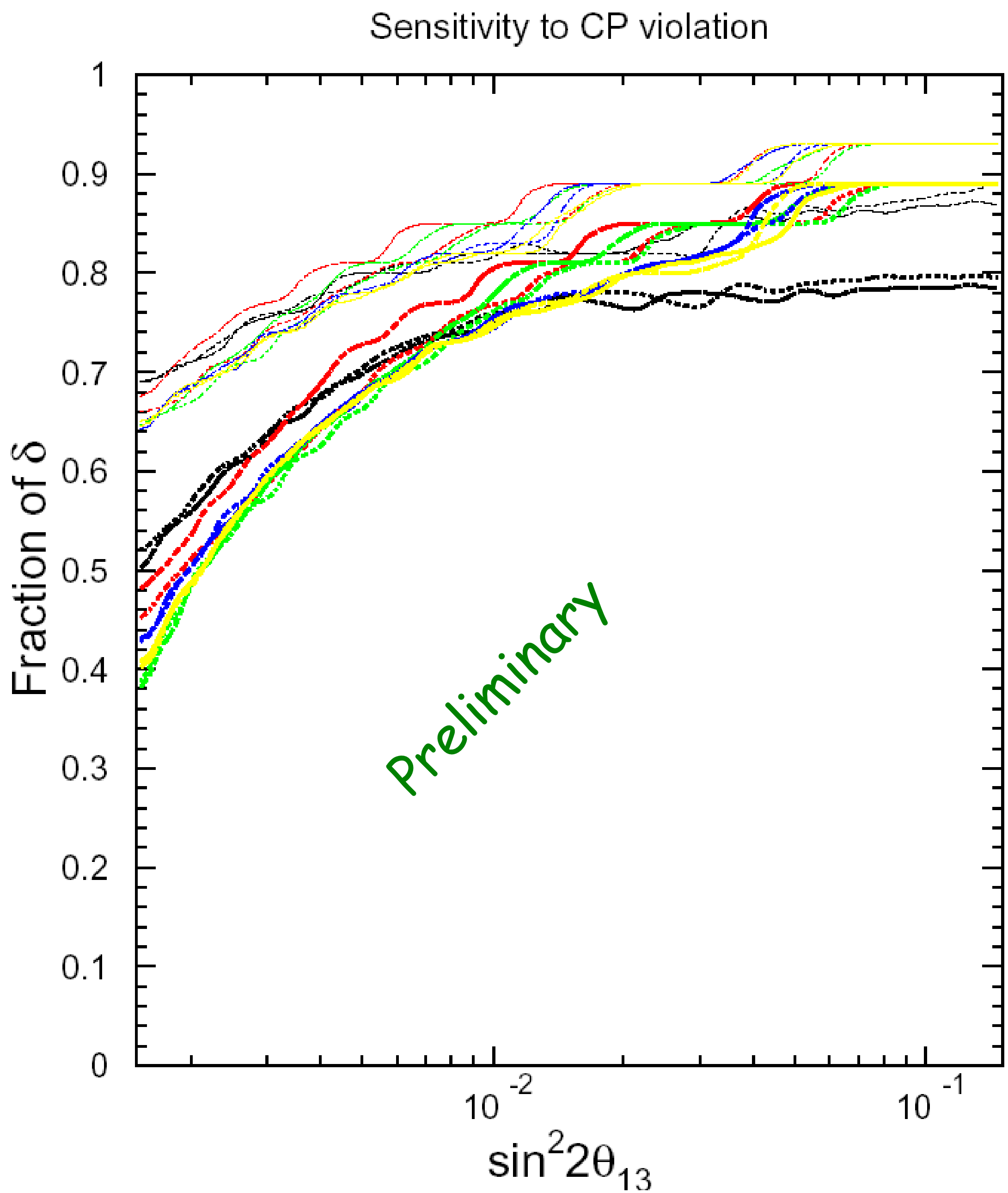
Sensitivity to mass hierarchy



2 detectors always better

Best sensitivity when OA= 1.0°

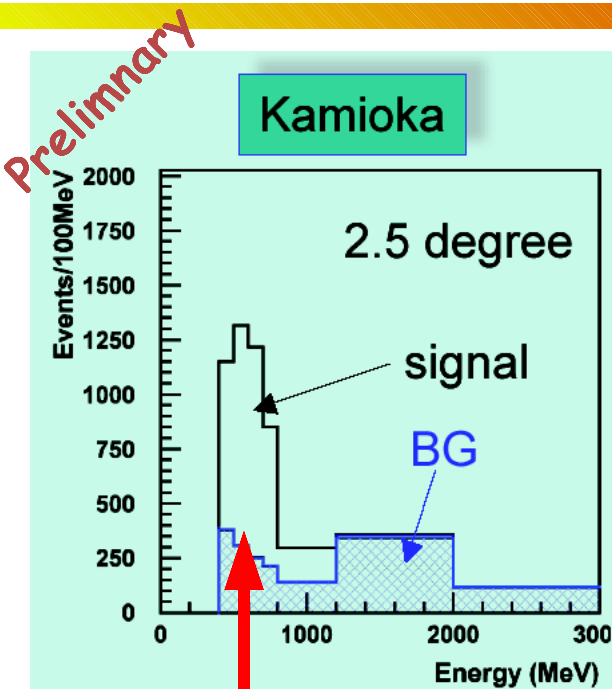
Sensitivity to CP violation



In general there is not much difference between different off-axis angle

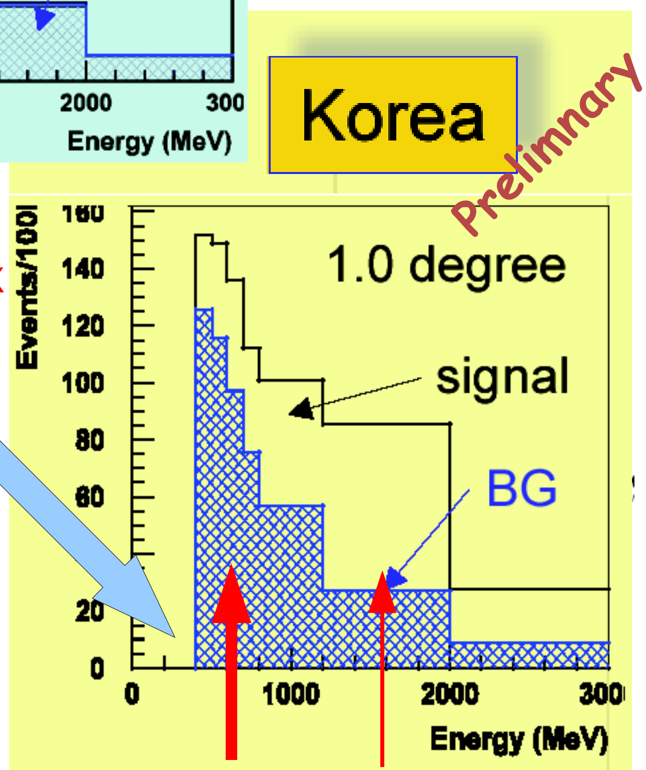
In the case where θ_{13} is very small then 1.0° OA is the best of the 2 detector setup (ie Kamioka+ Korea), but Kamioka only would be slightly better.

T2KK FNAL comparison

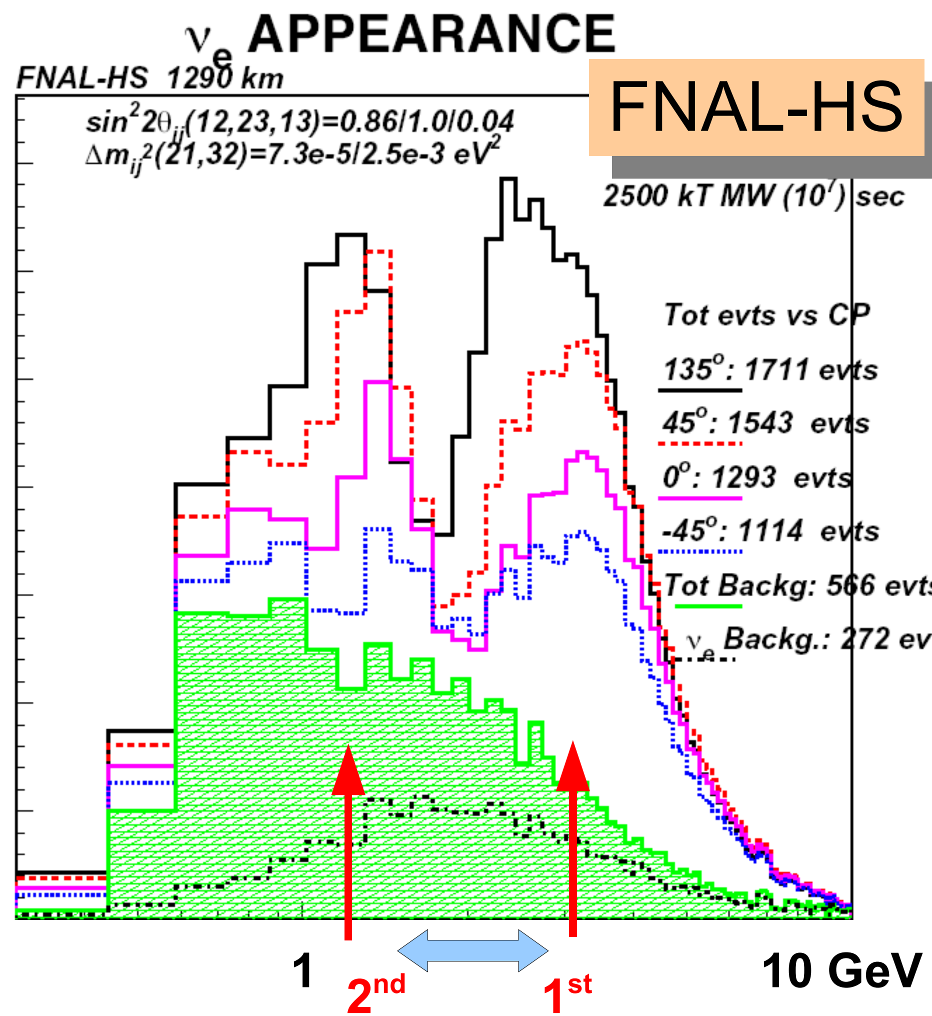


0.27 Mton
4 yr ν run
4MW
$\sin^2 2\theta_{13}=0.1$
$\delta = \pi/2$

1[st] osc max



2[nd] 1[st]



http://www.hep.net/nusag_pub/May2006talks.html
Milind Diwan's talk

Likelihood study

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

Beam related variable:

$\cos\theta_{\nu e}$

Standard SK variables:

Ring parameter
PID parameter

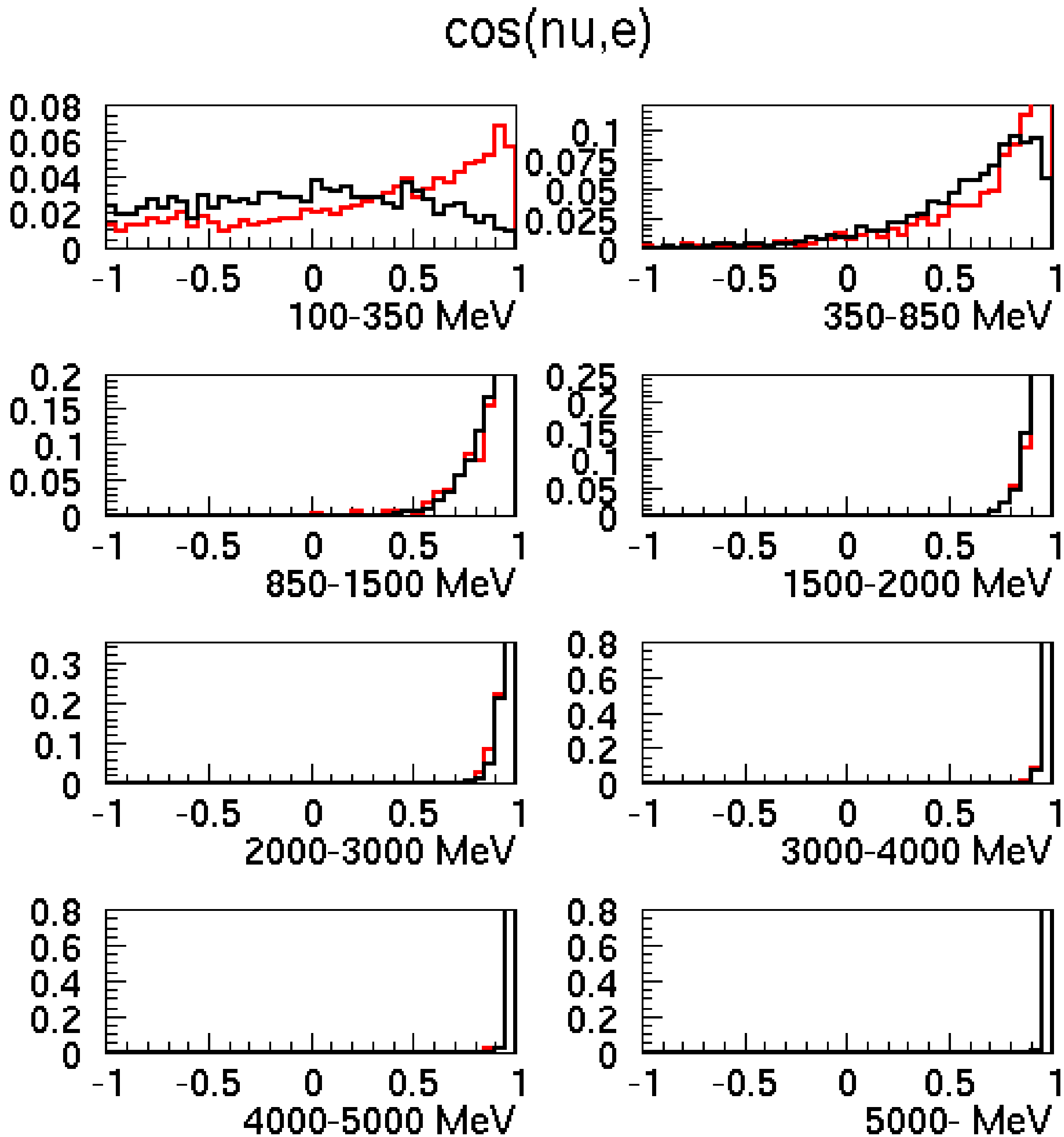
Special π^o fitter variables: (POLfit, Pattern Of Light)

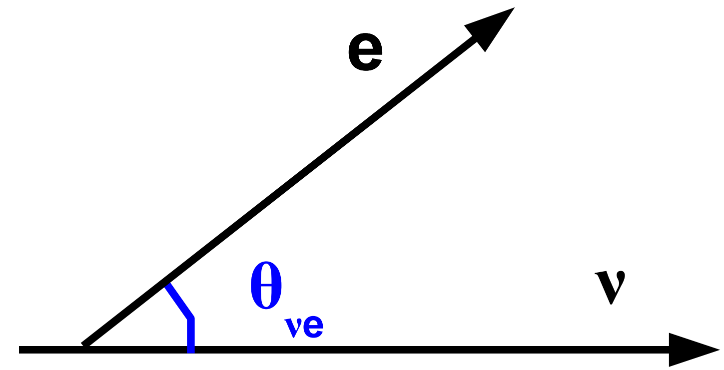
π^o mass
π^o likelihood
Energy fraction of 2^{nd} ring

New variables, defined for this analysis:

Chi_Xalong
Chi_cos(open)

$\cos\theta_{\nu e}$



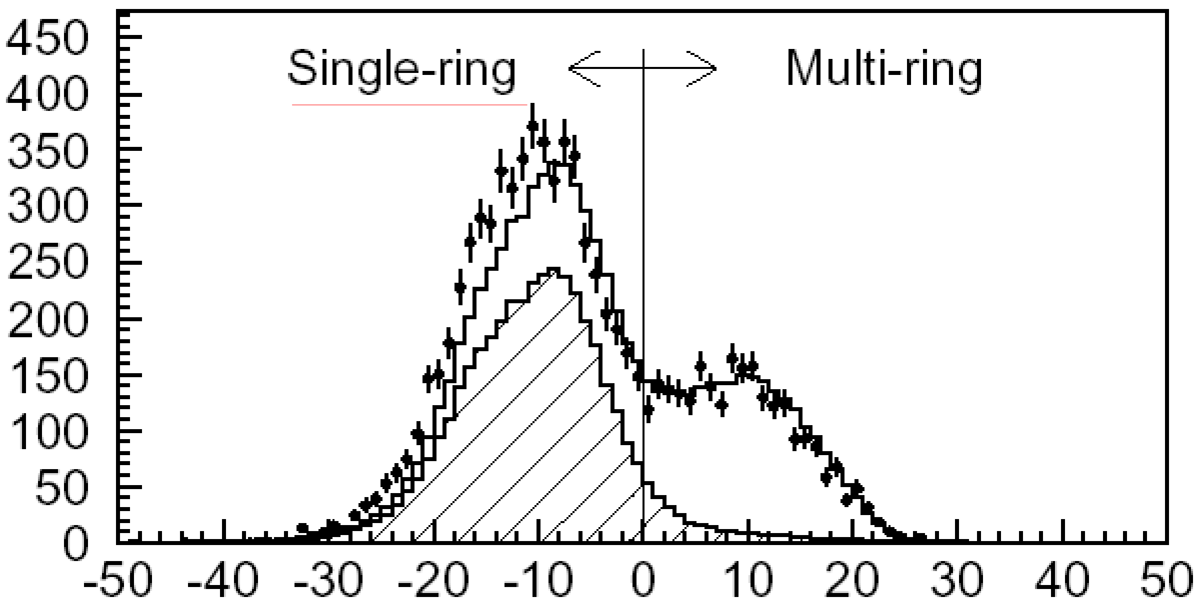


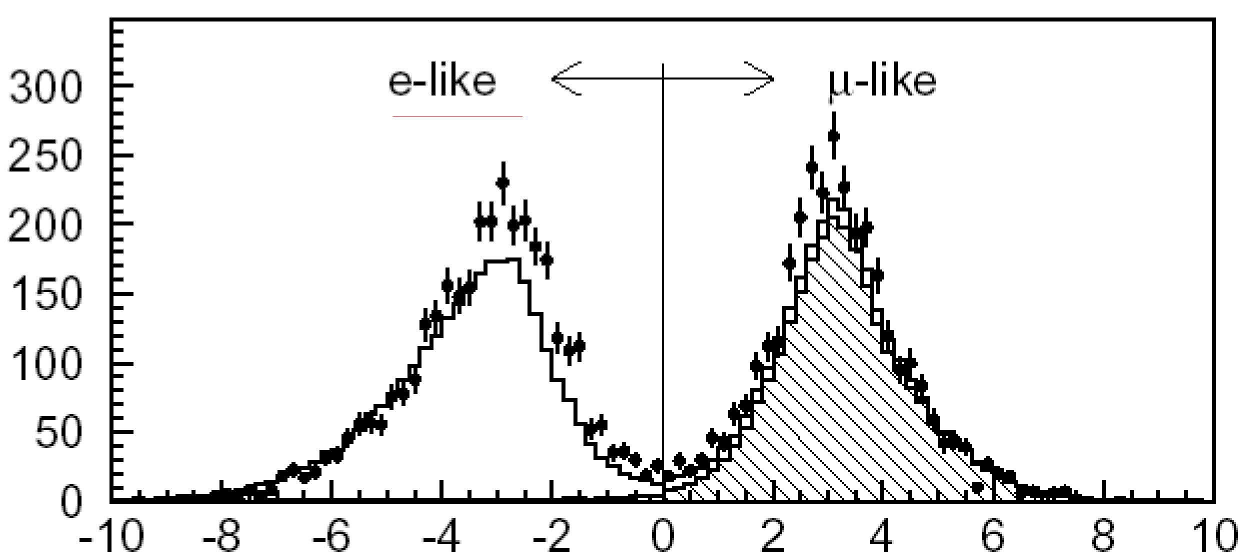
Bad at high energy

Background

Signal

Ring and PID Parameter:



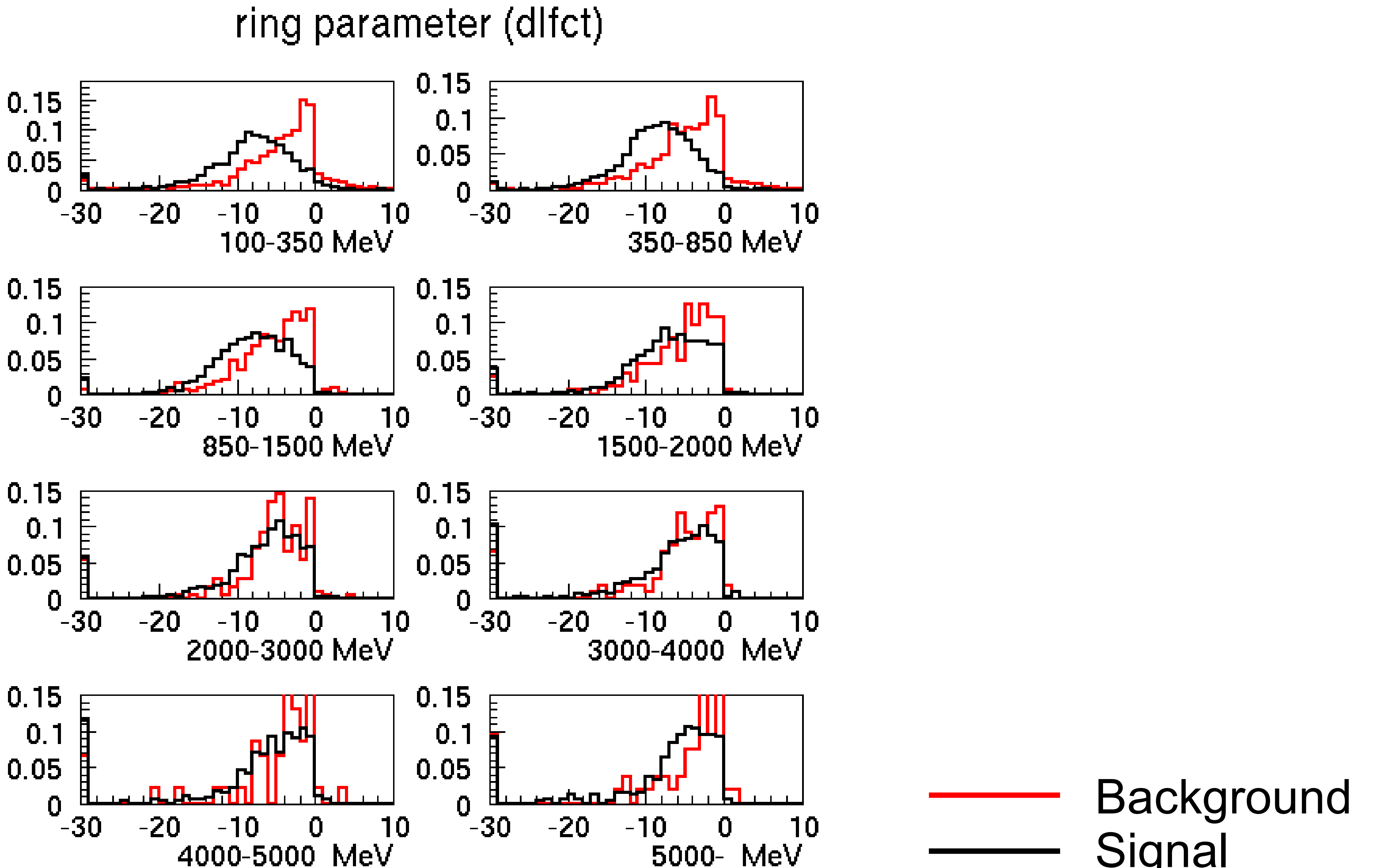


Those variables are not only precuts, (keep single-ring, e-like)

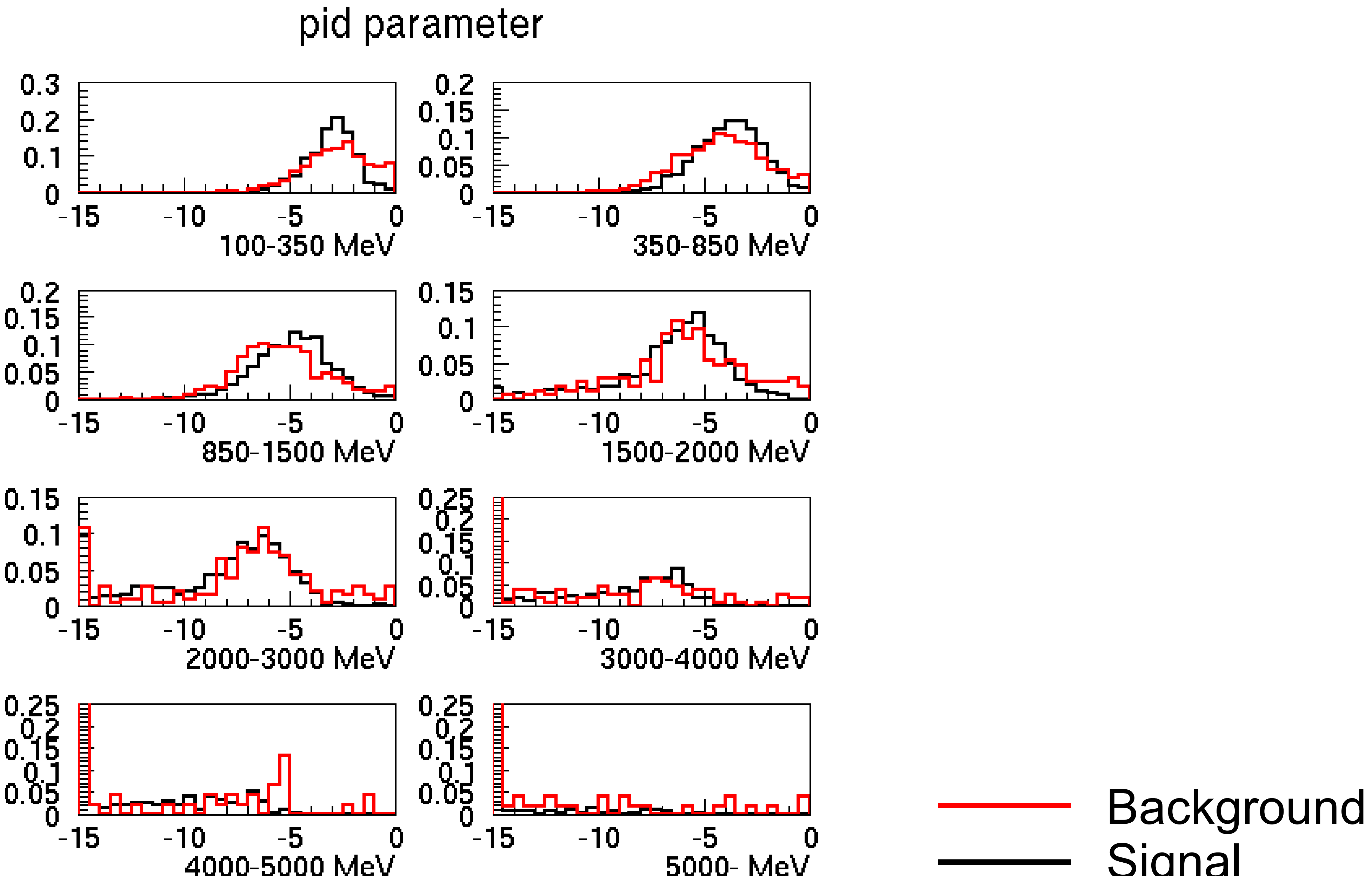
we also use the variables themselves in the likelihood.

MC
CCQE
SK data

Ring counting parameter

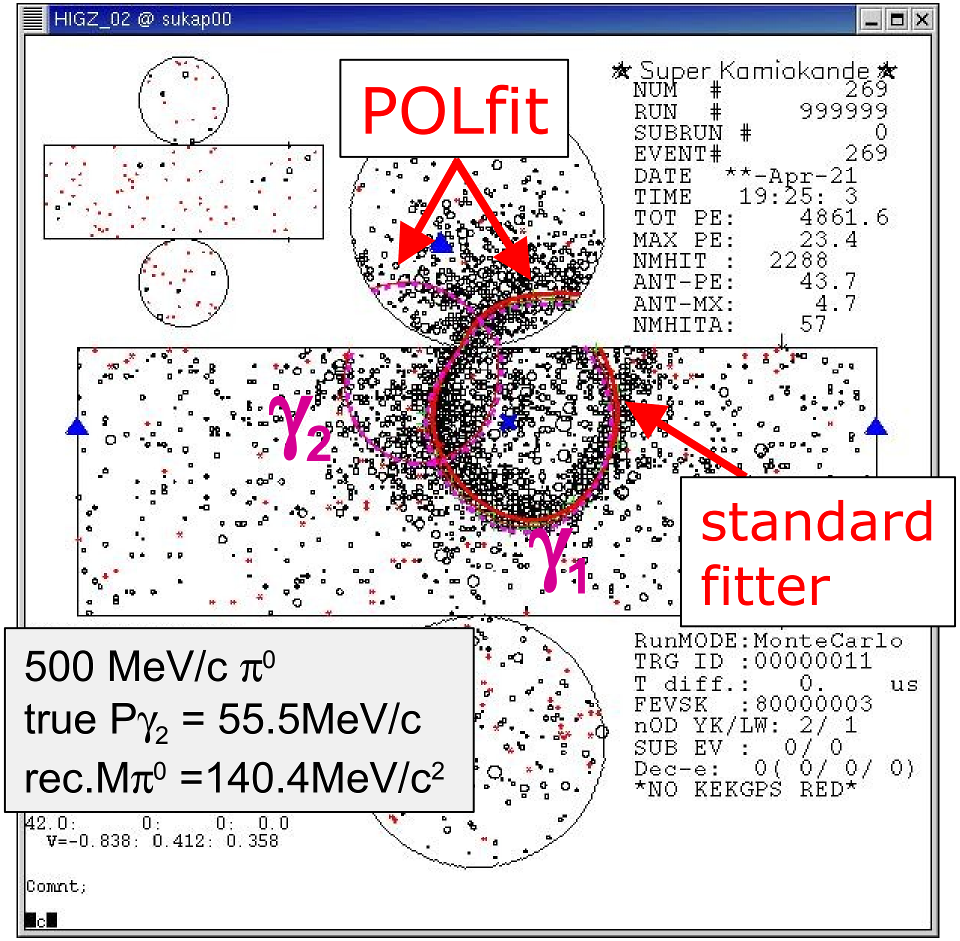


PID parameter



POLfit

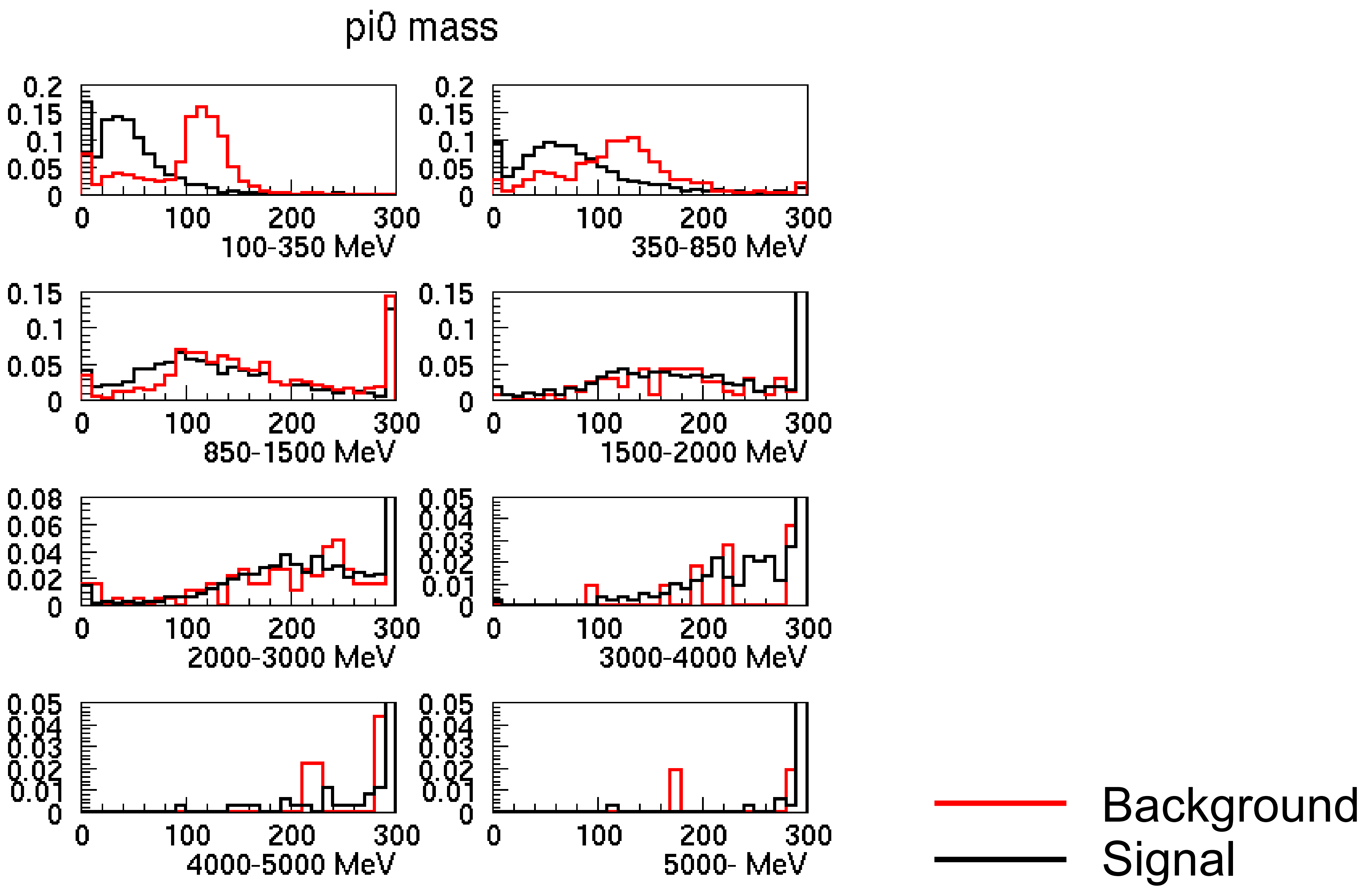
S.Nakayama's talk
1^{st} T2KK Workshop
November 2005



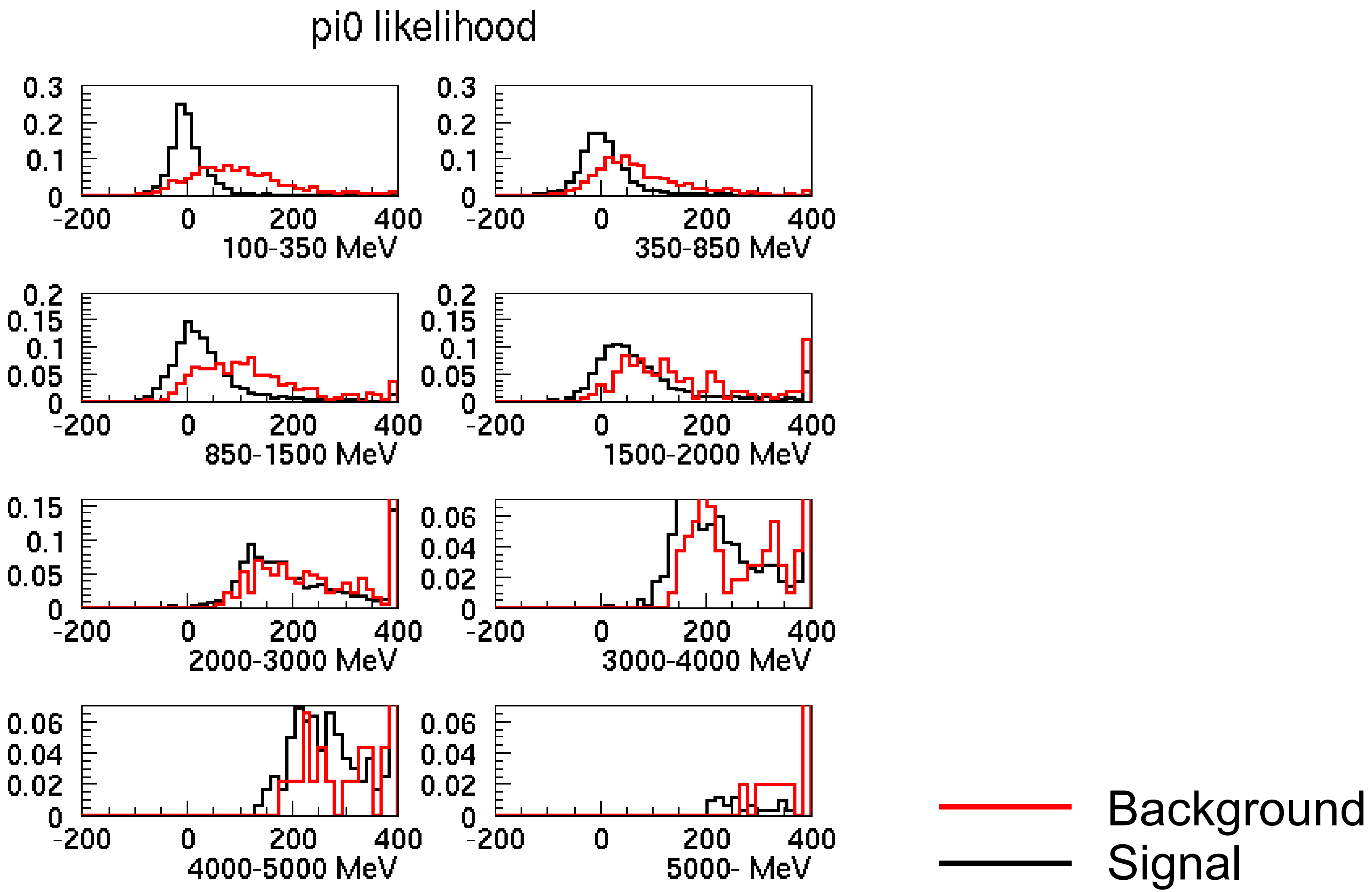
- Target: FCFV 1R-elike events
- $\Delta L \equiv$ Likelihood(2γ assump.) – Likelihood(electron assump.)
- Try to reconstruct two γ rings
- Input: vertex, visible energy, and the 1^{st} γ direction by the standard fitter
- Compare observed & expected (direct+scatter) charge
- Vary the 2^{nd} γ direction and the energy fraction until the best match found

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

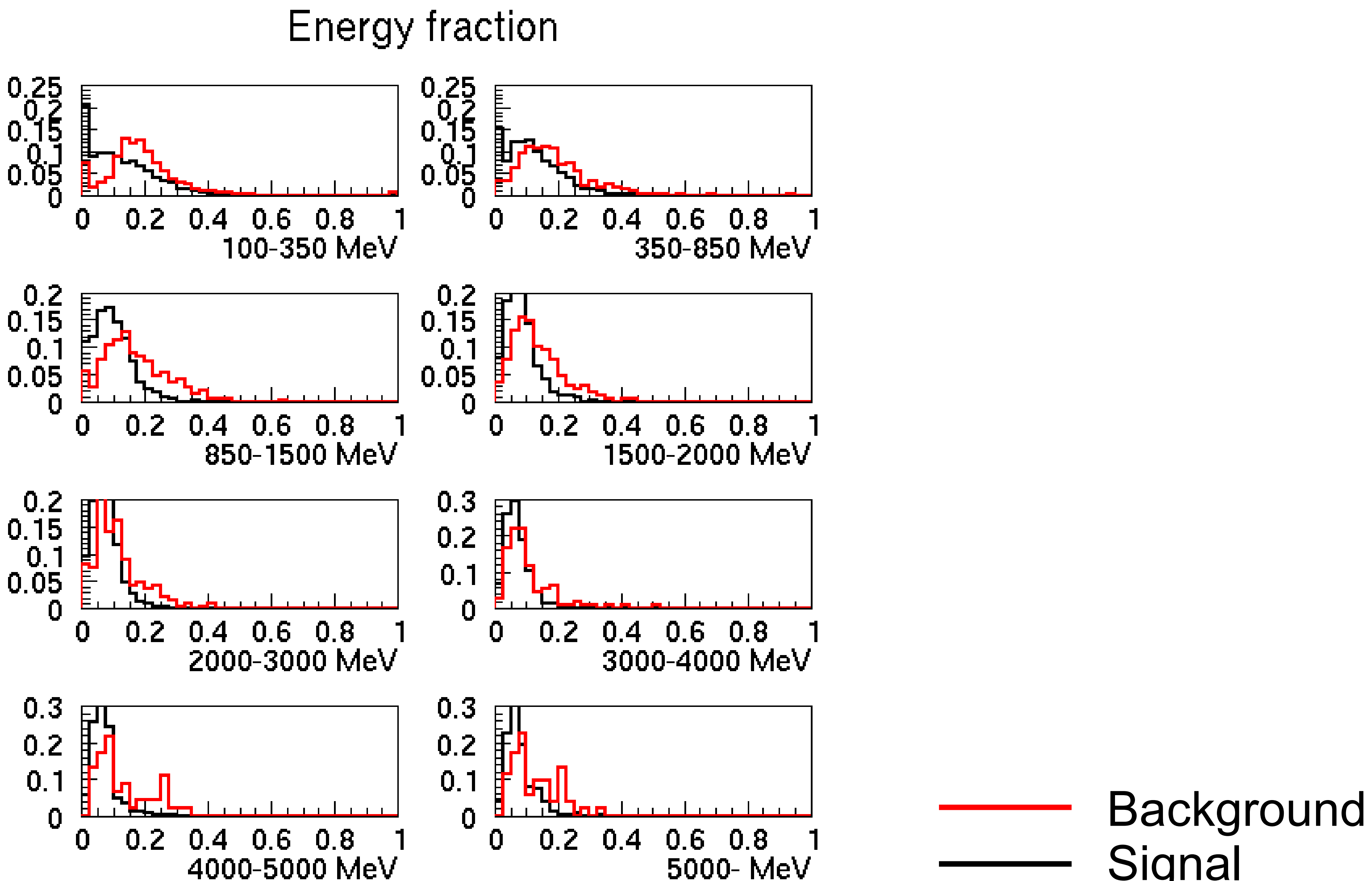
POLfit variables – π^o mass



POLfit variables – π^o Likelihood:



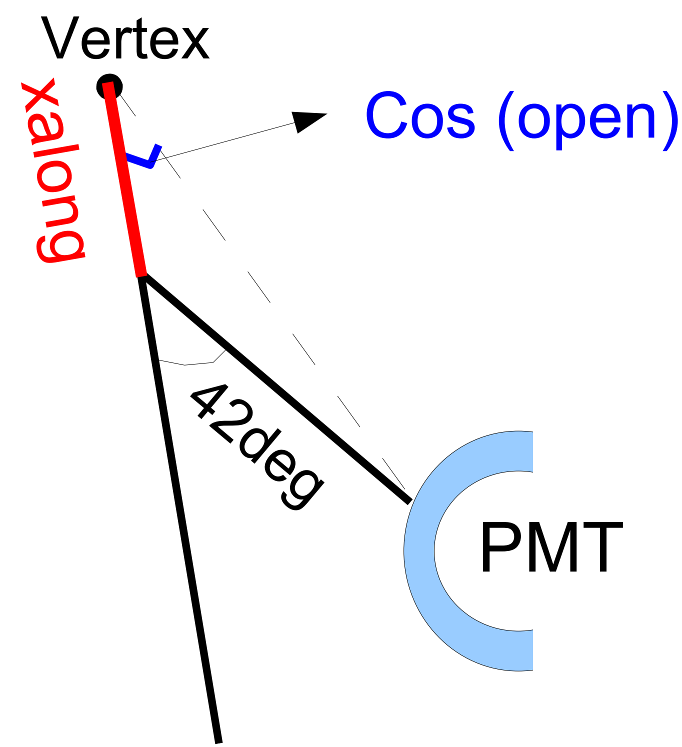
POLfit variables – Energy fraction



Xalong & Cos(open)

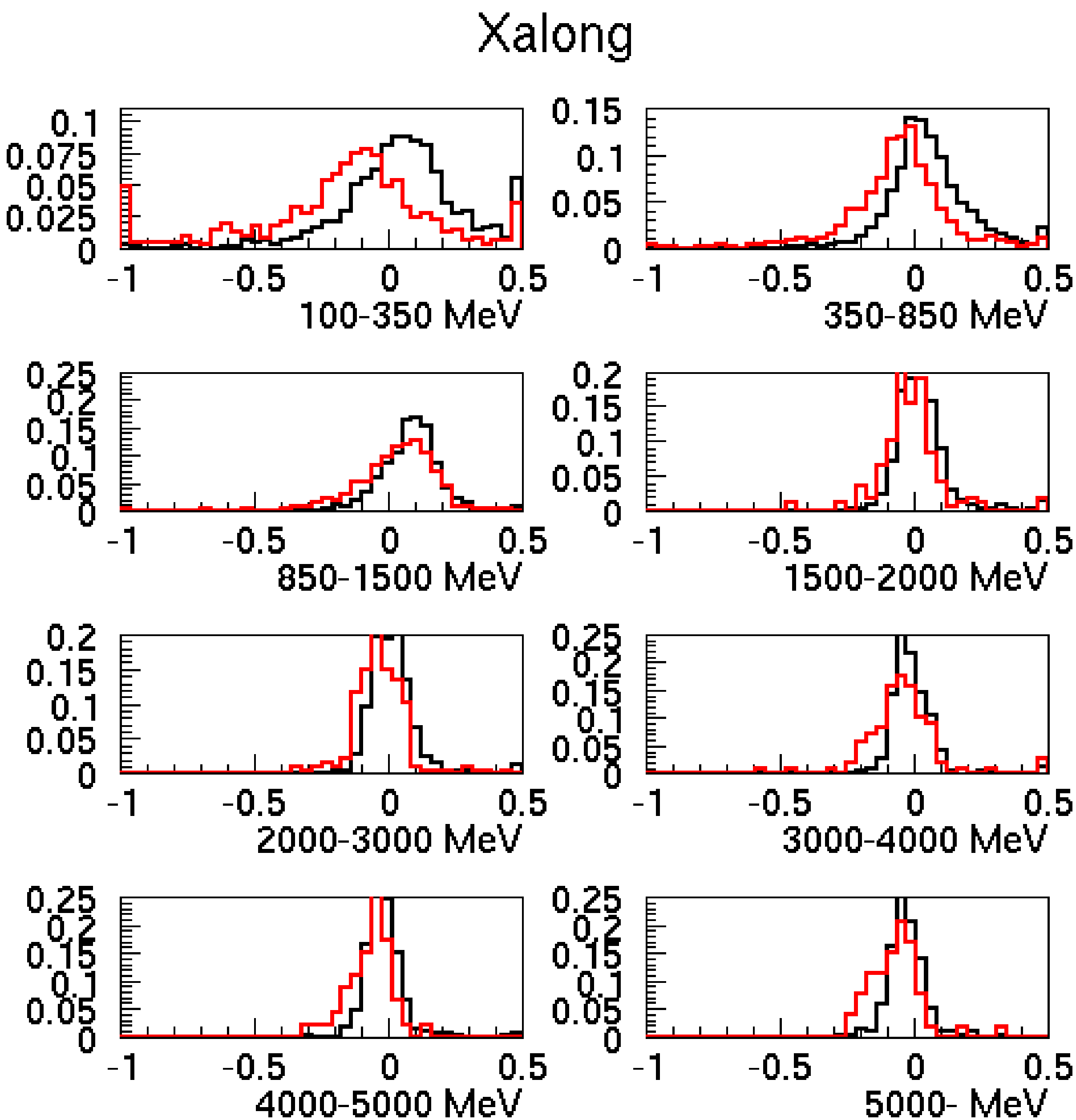
Xalong: Distance between vertex and emitting point of Cherenkov light.

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

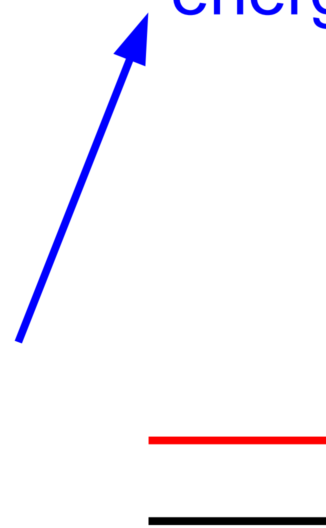


- I compute those values for each hit pmt, plot distributions.
- Using part of the MC I create templates of those distributions.
- For each event, I assign a χ^2 value comparing the event against the templates.
- The χ^2 value is added to the likelihood.

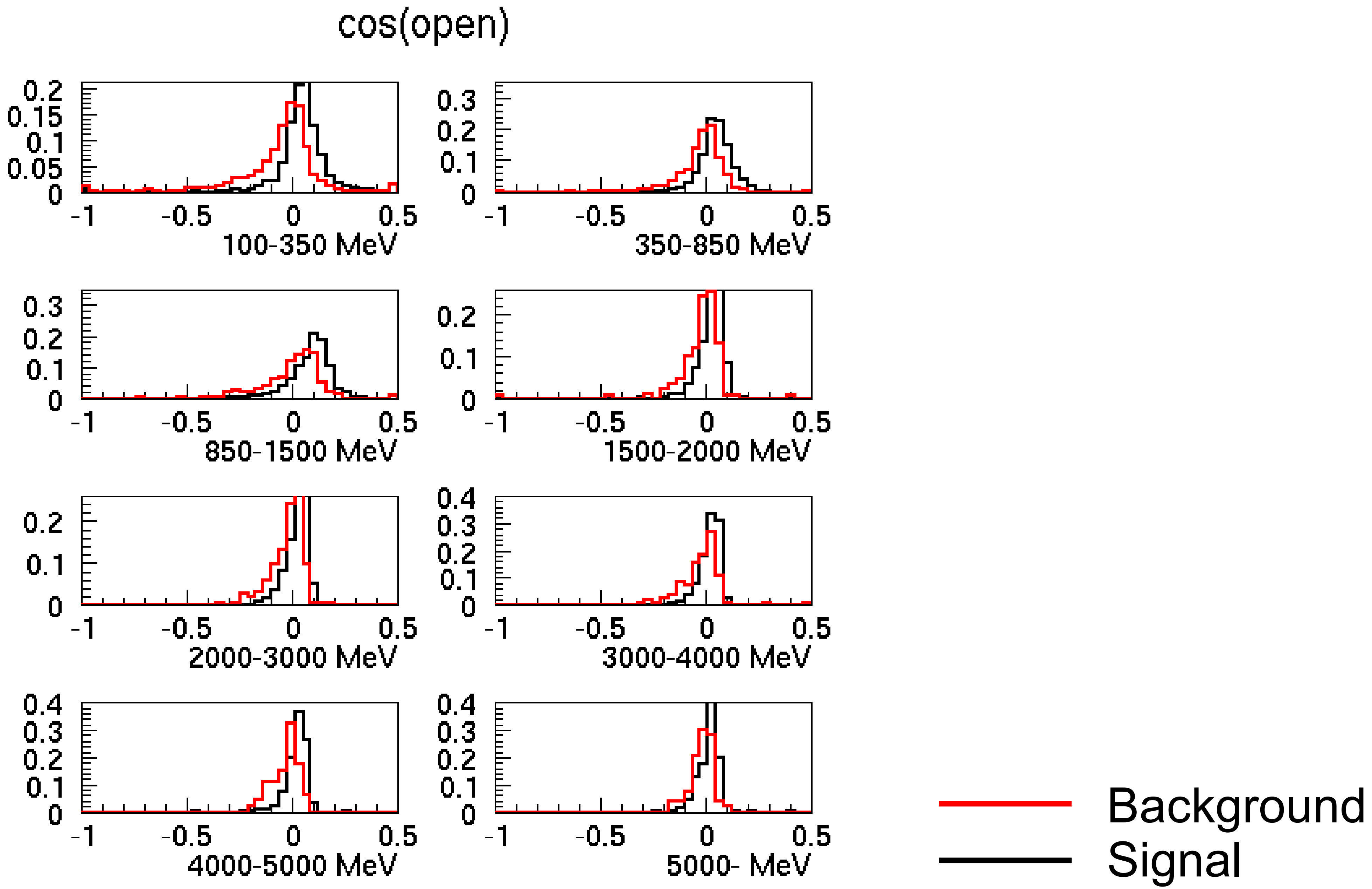
Xalong



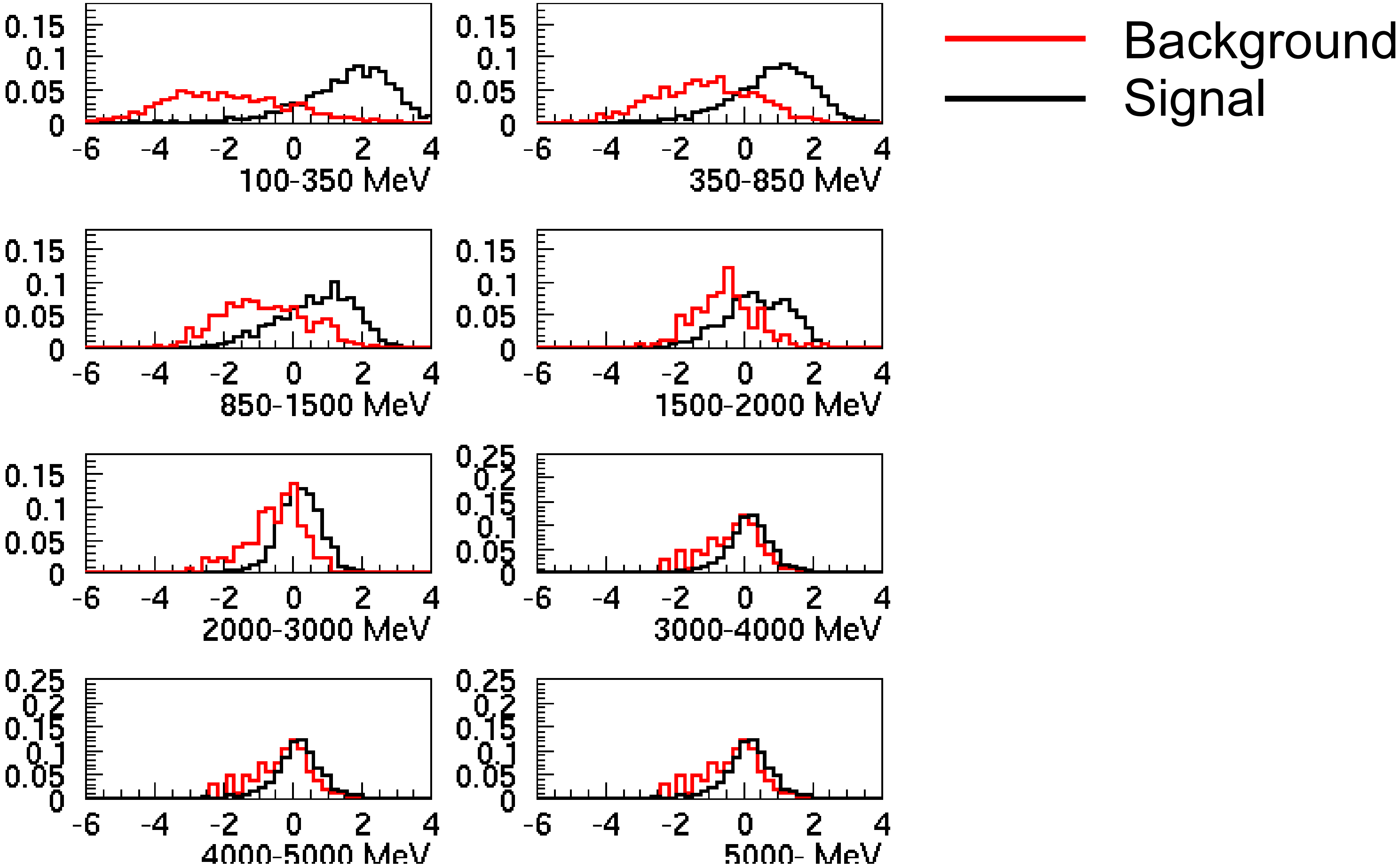
Still useful at high energies



Cos (open)


cos(open)
100-350 MeV
350-850 MeV
850-1500 MeV
1500-2000 MeV
2000-3000 MeV
3000-4000 MeV
4000-5000 MeV
5000- MeV
Background
Signal

Final likelihood



Final efficiency

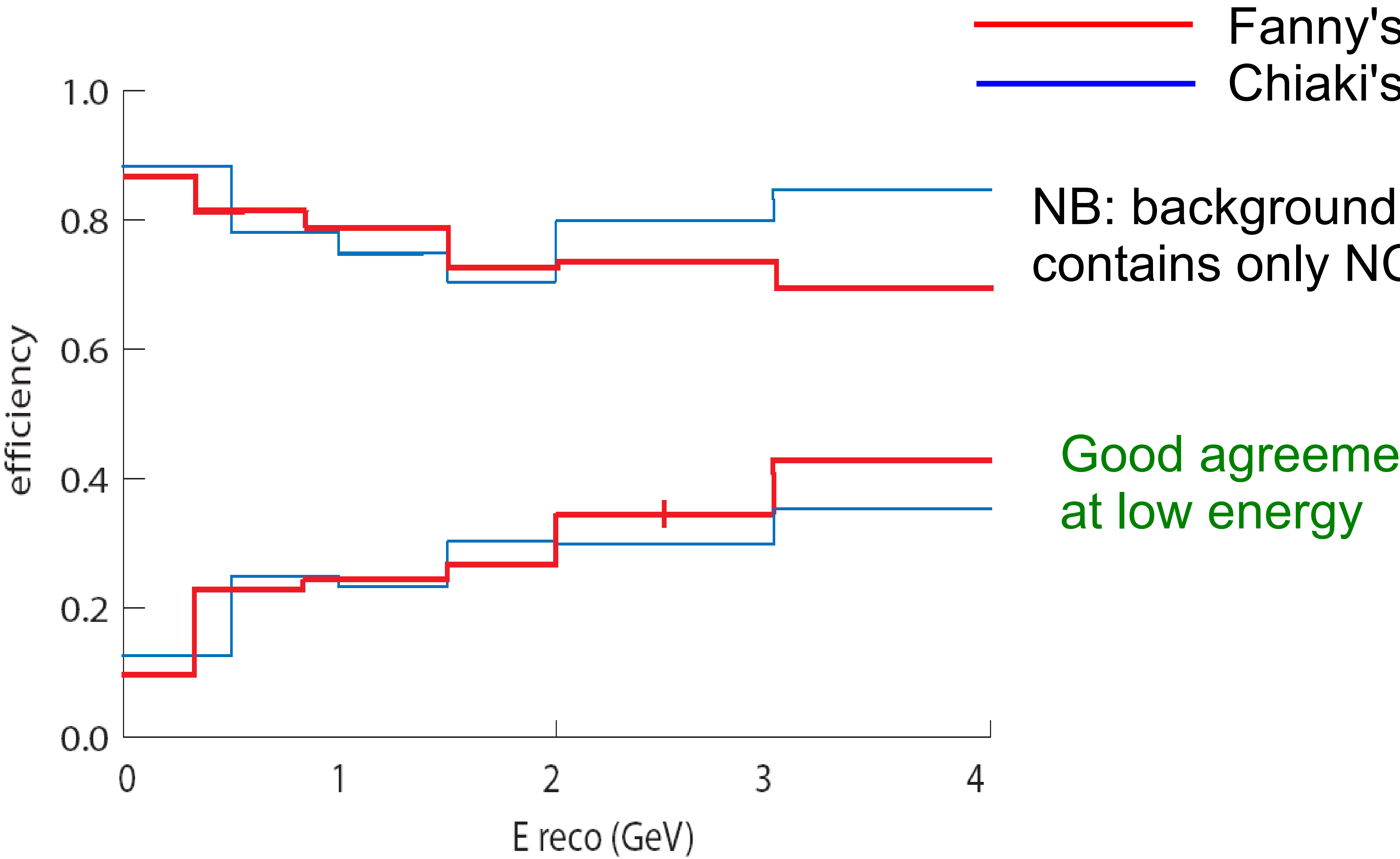
Precuts efficiency:

E_{true} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC	Precuts eff:	nan	0.5%	0.6%	0.8%	0.9%
NC	Precuts eff:	20%	26%	26%	22%	18%
ν_e	Precuts eff:	94%	80%	61%	46%	36%

Likelihood efficiency:

E_{rec} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC	Likelihood eff:	10.4%	25.2%	25.6%	11.1%	14.6%
NC	Likelihood eff:	10.9%	22.1%	23.4%	24.6%	34.9%
ν_e	Likelihood eff:	87.1%	80.8%	78.6%	72.6%	73.2%

Comparison with Chiaki's efficiency



NB: background contains only NC.

Good agreement at low energy

Likelihood future

There is room for improvement:

- Study new variables
- Use different set of variables for different energies
- Test Neural Network analysis
- Compare with SK atmospheric data
  → Check how well the variables are reproduced by MC.

Conclusions

Likelihood analysis:

Likelihood efficiency ranges from:

87.1% to **73.2%** for signal

10.9% to **34.9 %** for NC background

My likelihood results are in good agreement with Chiaki's at low energies.

Oscillation analysis conclusions:

For mass hierarchy study:

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

For CP violation study:

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

Backups:

Final likelihood efficiency

E_{rec} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC	precuts	154.0	107.0	39.0	27.0	48.0
	likelihood	16.0	27.0	10.0	3.0	7.0
	efficiency	**10.4%**	**25.2%**	**25.6%**	**11.1%**	**14.6%**
NC	precuts	798.0	913.0	410.0	191.0	186.0
	likelihood	87.0	202.0	96.0	47.0	65.0
	efficiency	**10.9%**	**22.1%**	**23.4%**	**24.6%**	**34.9%**
ν_e	precuts	712.0	2855.0	2192.0	1088.0	1691.0
	likelihood	620.0	2307.0	1723.0	790.0	1238.0
	efficiency	**87.1%**	**80.8%**	**78.6%**	**72.6%**	**73.2%**

NB:
raw number of events

Final efficiency

E_{true} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC	*fcfv*	*14.0*	*36839.0*	*10843.0*	*3261.0*	*4629.0*
	1ring	*12.0*	*34040.0*	*8386.0*	*1867.0*	*2098.0*
	e-like	*0.0*	*509.0*	*96.0*	*62.0*	*82.0*
	nodecay-e	*0.0*	*204.0*	*72.0*	*27.0*	*40.0*
	Precuts eff:	**nan**	**0.5%**	**0.6%**	**0.8%**	**0.9%**
NC	*fcfv*	*10.0*	*2390.0*	*1536.0*	*895.0*	*1892.0*
	1ring	*2.0*	*733.0*	*528.0*	*311.0*	*591.0*
	e-like	*2.0*	*646.0*	*419.0*	*221.0*	*414.0*
	nodecay-e	*2.0*	*644.0*	*398.0*	*196.0*	*357.0*
	Precuts eff:	**20%**	**26%**	**26%**	**22%**	**18%**
ν_e	*fcfv*	*279.0*	*3051.0*	*3941.0*	*2177.0*	*4939.0*
	1ring	*264.0*	*2693.0*	*2829.0*	*1234.0*	*2268.0*
	e-like	*262.0*	*2661.0*	*2807.0*	*1224.0*	*2258.0*
	nodecay-e	*262.0*	*2471.0*	*2430.0*	*1002.0*	*1857.0*
	Precuts eff:	**94%**	**80%**	**61%**	**46%**	**36%**

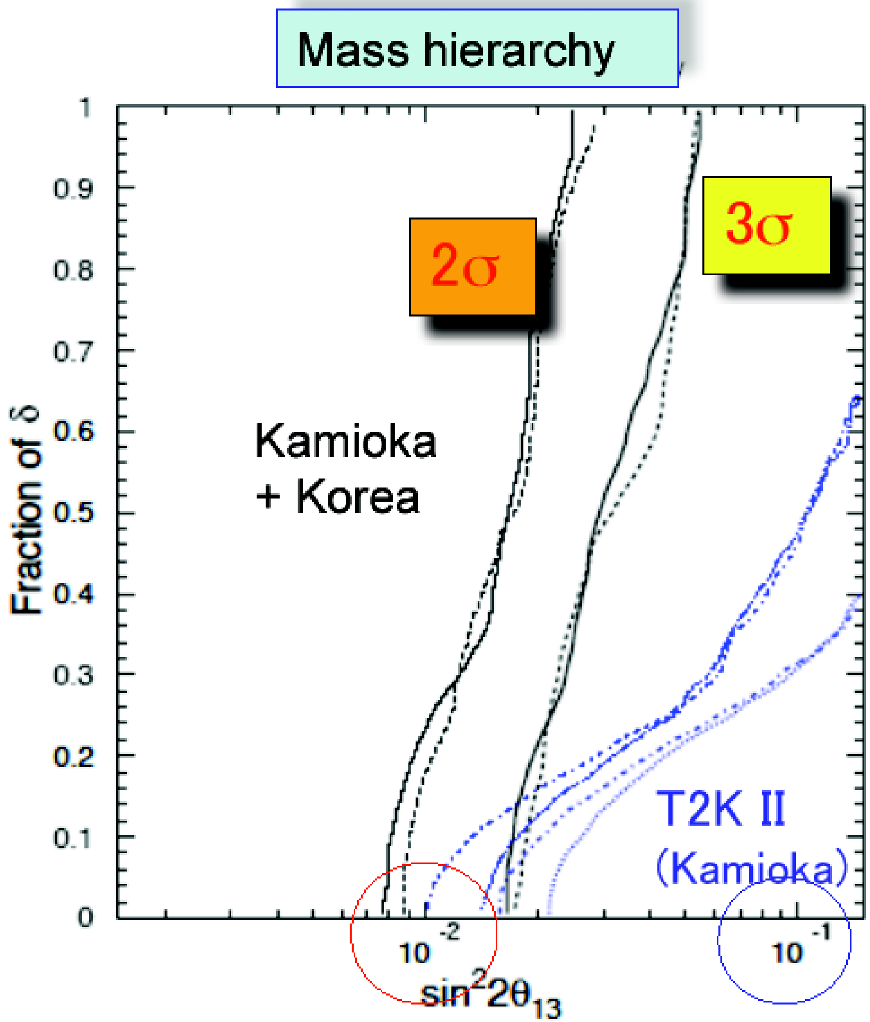
E_{rec} (GeV)		0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC	**Likelihood effi**	**10.4%**	**25.2%**	**25.6%**	**11.1%**	**14.6%**
NC	**Likelihood eff**	**10.9%**	**22.1%**	**23.4%**	**24.6%**	**34.9%**
ν_e	**Likelihood eff**	**87.1%**	**80.8%**	**78.6%**	**72.6%**	**73.2%**

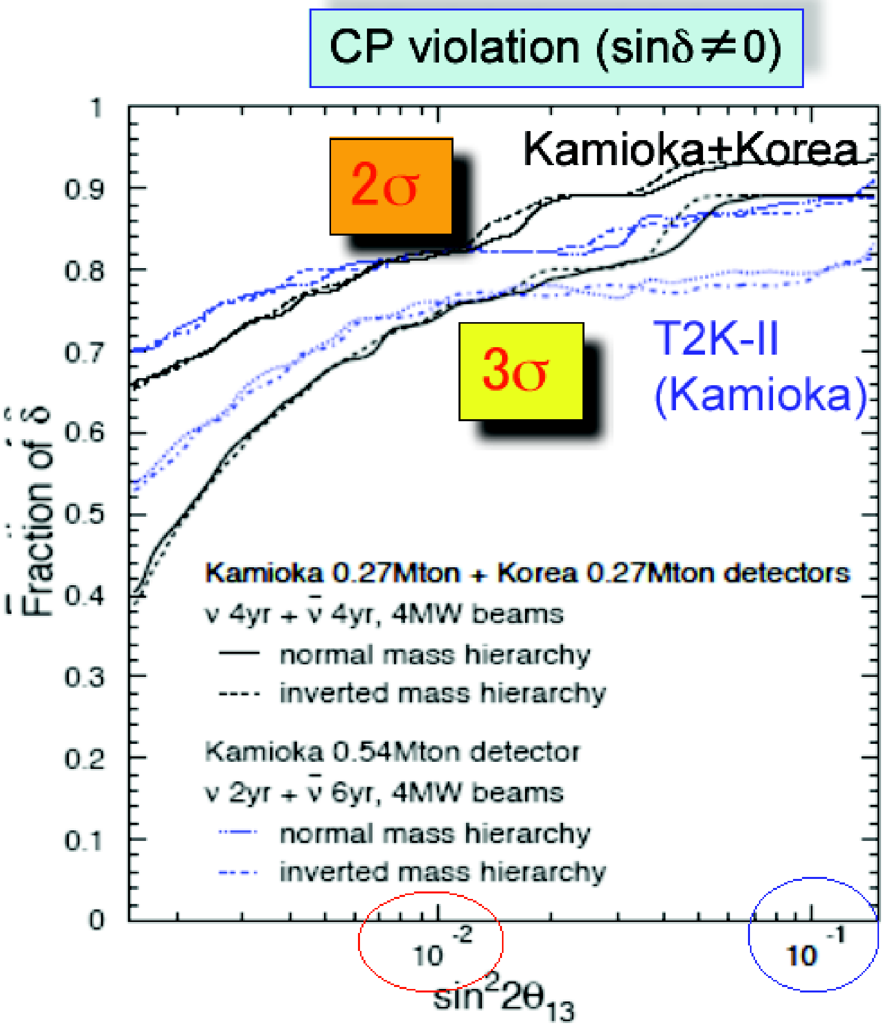
Slide taken from T. Kajita, NOW 2006

Expected sensitivity (2)

hep-ph/0504026

Total mass of the detectors = 0.54 Mton fid. mass
4 years neutrino beam + 4 years anti-neutrino beam



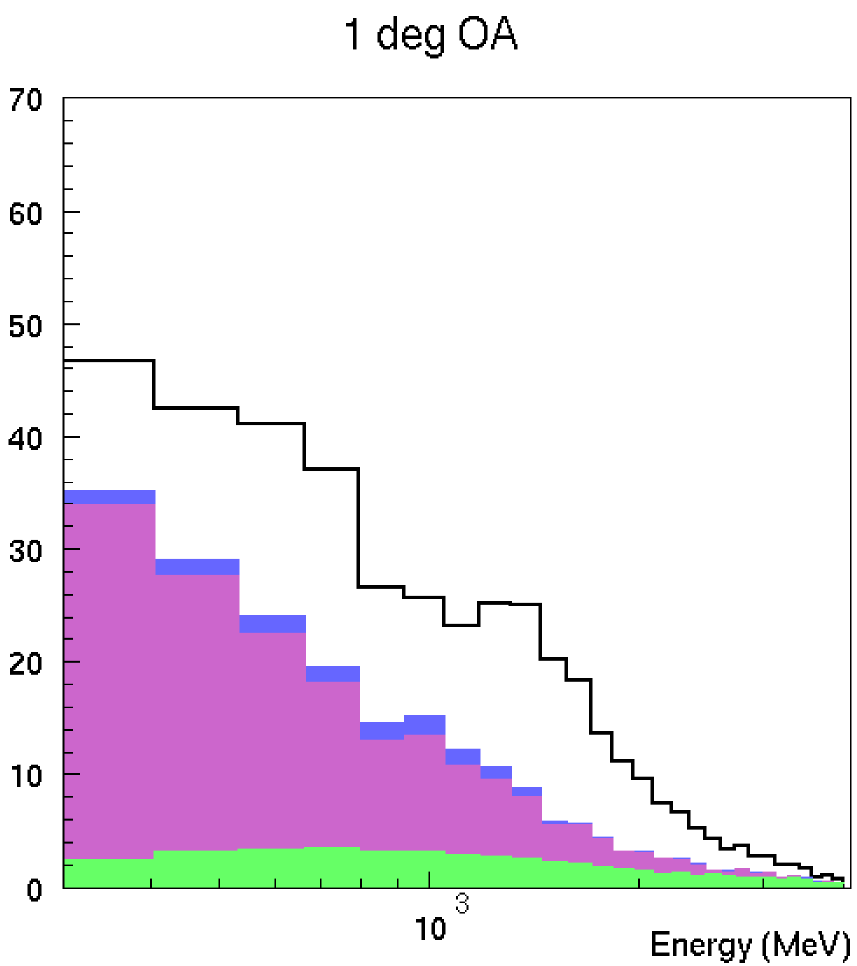


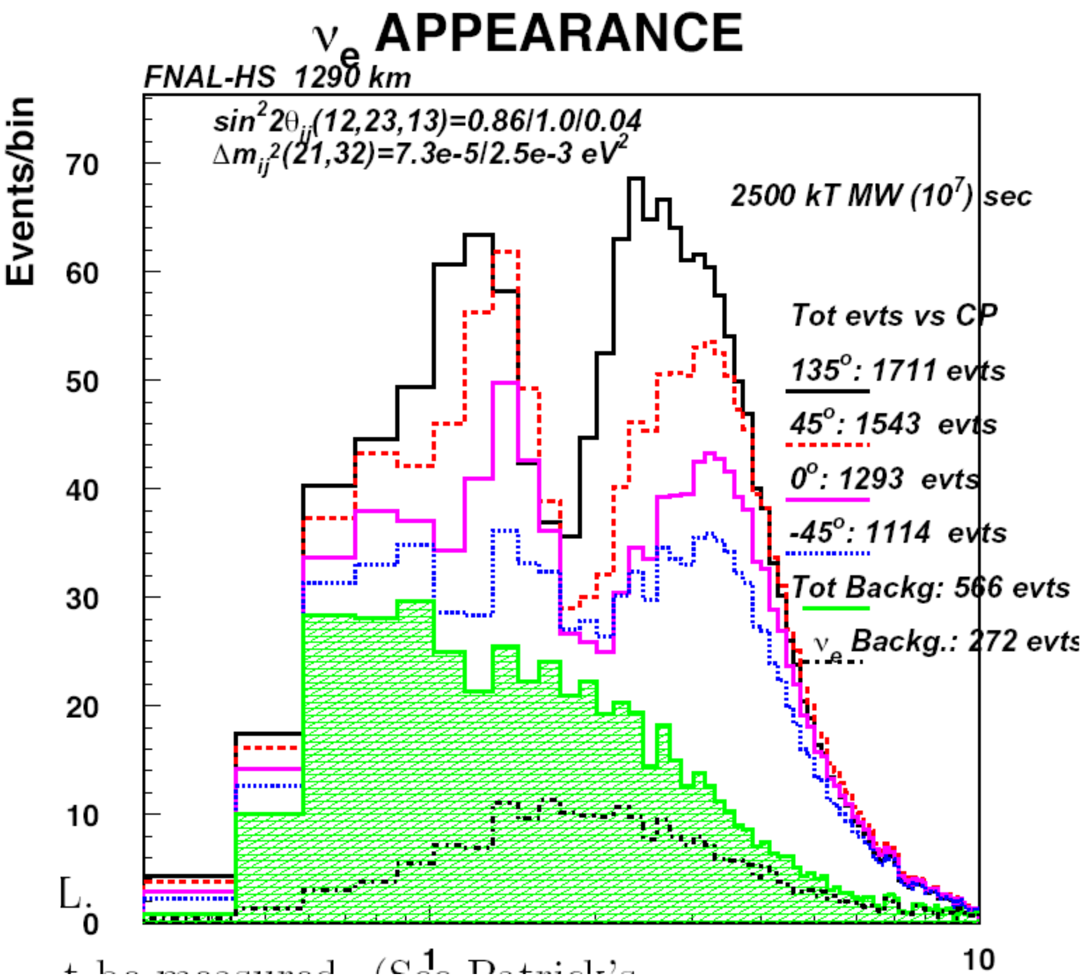
Final efficiency (2.0-10.0 Gev)

NB: arbitrary numbers

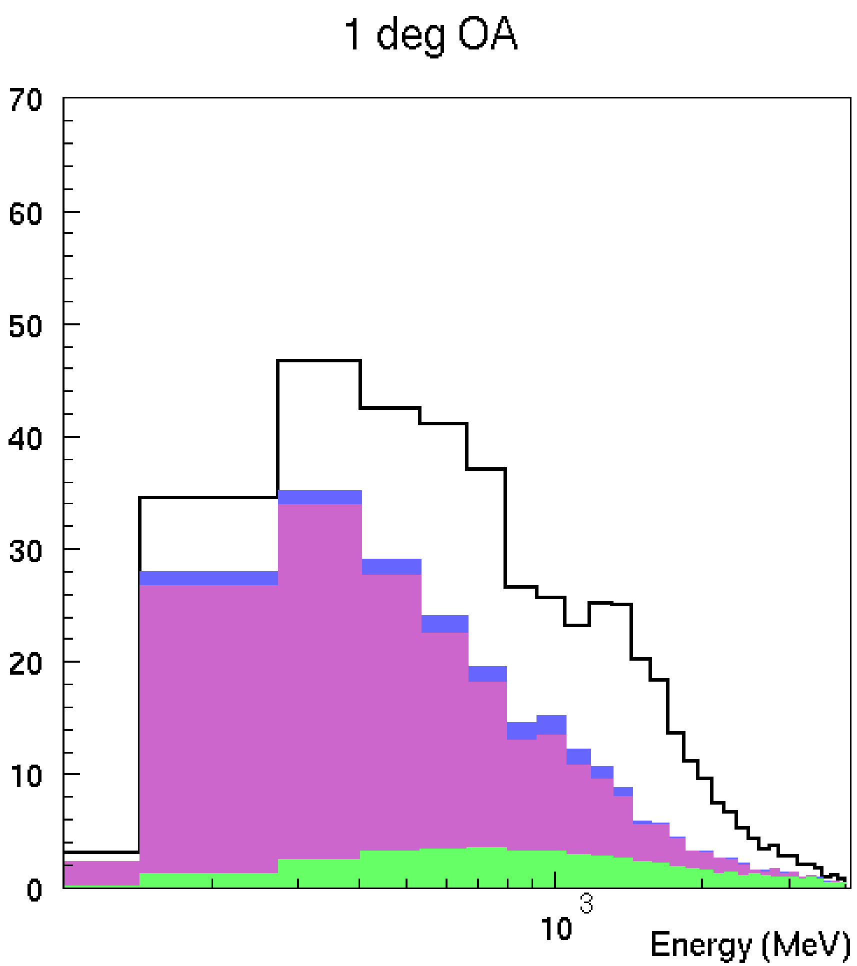
E_{rec} (GeV)		2.0-3.0	3.0-4.0	4.0-5.0	5.0-
ν_μ CC	fcfv	4547.0	2910.0	1751.0	1673.0
	1ring	1703.0	1308.0	971.0	1099.0
	e-like	91.0	83.0	48.0	76.0
	nodecay-e	48.0	40.0	17.0	36.0
	likelihood	7.0	8.0	9.0	8.0
	efficiency	14.6%	20.0%	52.9%	22.2%
NC	fcfv	499.0	215.0	86.0	65.0
	1ring	237.0	128.0	60.0	46.0
	e-like	230.0	124.0	59.0	46.0
	nodecay-e	186.0	98.0	43.0	37.0
	likelihood	65.0	41.0	15.0	19.0
	efficiency	34.9%	41.8%	34.9%	51.4%
ν_e	fcfv	4098.0	2132.0	1027.0	935.0
	1ring	2022.0	1156.0	578.0	609.0
	e-like	2013.0	1153.0	576.0	603.0
	nodecay-e	1691.0	970.0	446.0	466.0
	likelihood	1238.0	675.0	351.0	390.0
	efficiency	73.2%	69.6%	78.7%	83.7%

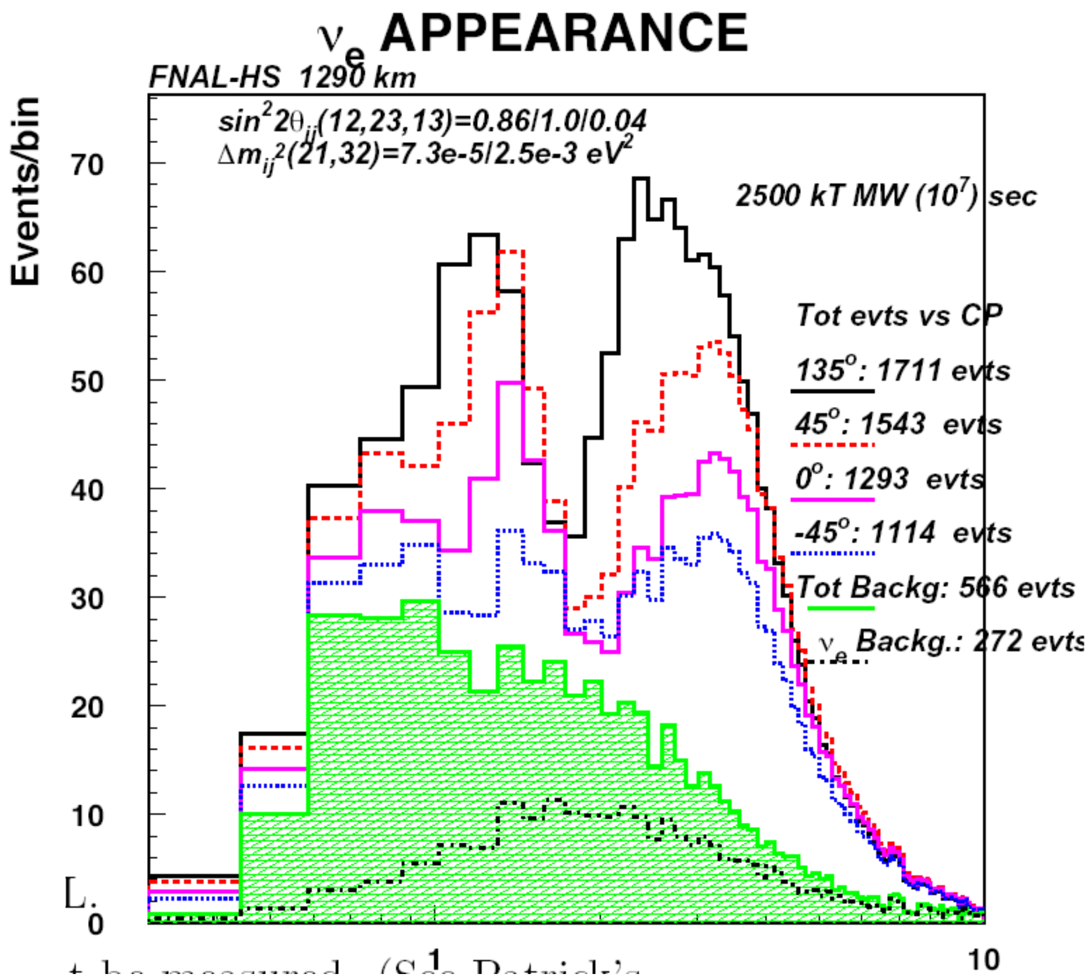
T2KK FNAL comparison





T2KK FNAL comparison





Conclusions

Likelihood analysis developed for ν_e appearance:

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

Oscillation analysis conclusions:

For mass hierarchy study:

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 be slightly better.