Water Cherenkov Detector and Neutrino Oscillation Experiments Using $\nu_\mu \longrightarrow \nu_e$

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Workshop on Very Long Baseline Neutrino Experiments
at Fermilab

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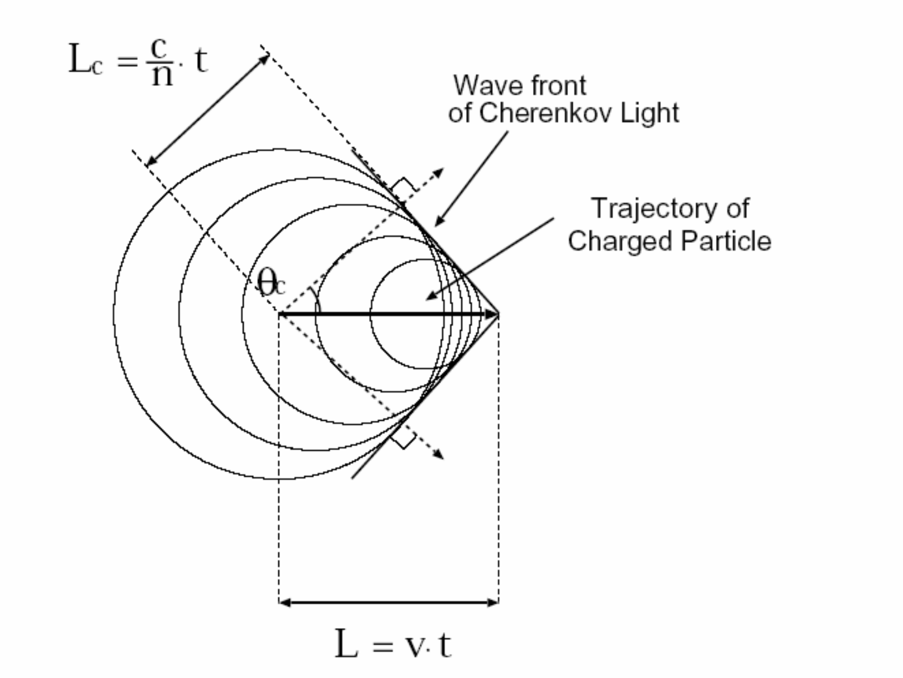
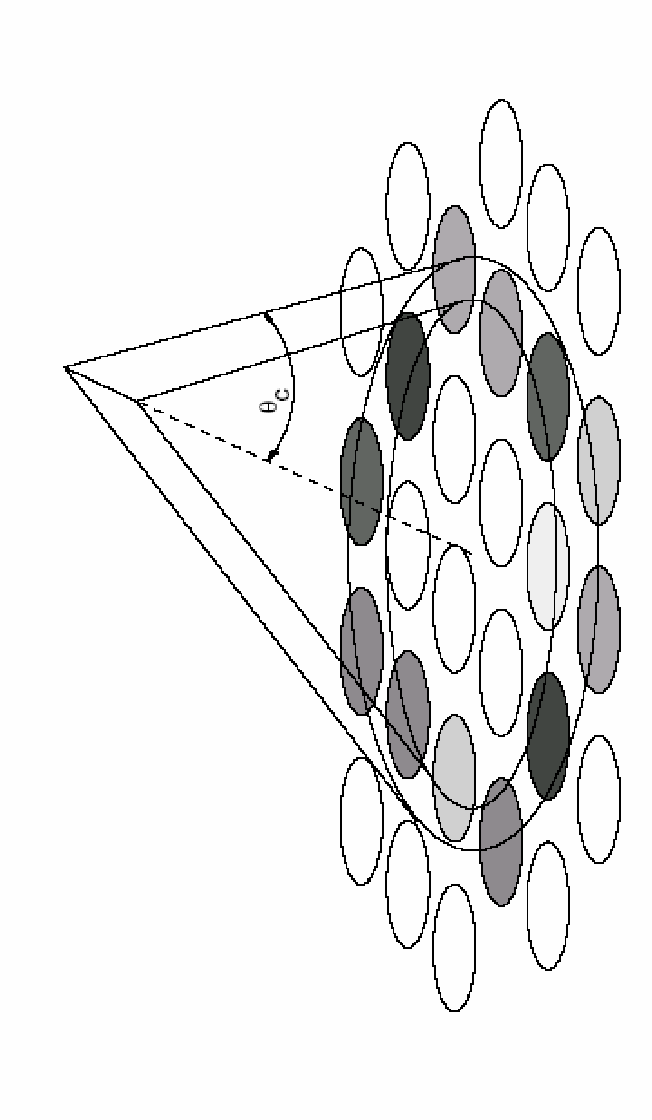
• Water Cherenkov Detector a la SK

Cherenkov radiation





$$\cos\theta_C = \frac{1}{n\beta} \leq 1$$

Threshold p:

muon	121	MeV/c
pion	160	MeV/c
proton	1070	MeV/c

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

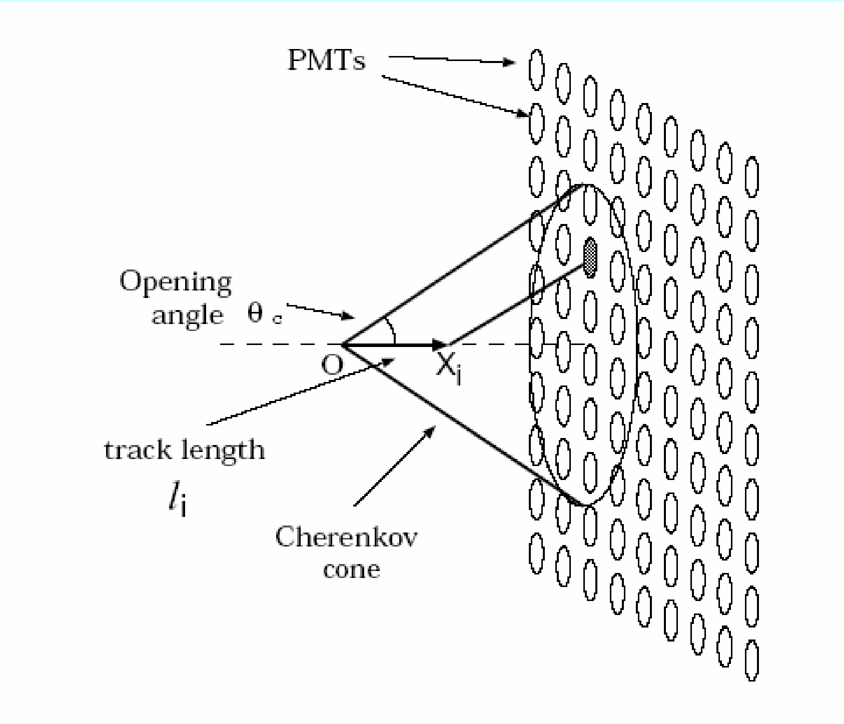
390 photons per 1 cm
(300 nm < λ < 700 nm)

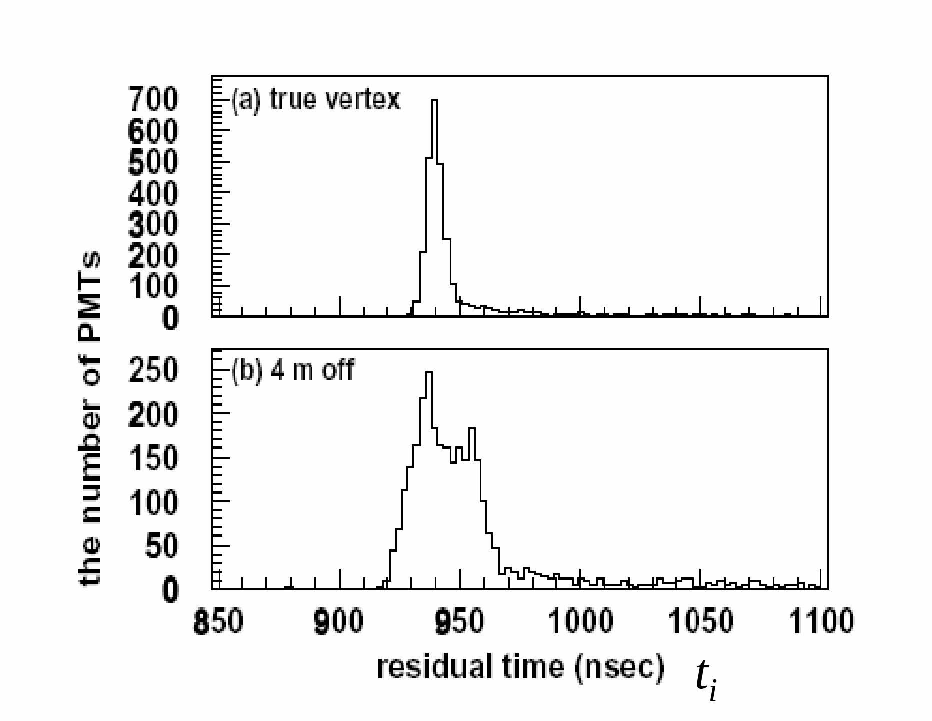
$\lambda =$ wavelength, $n =$ index of refraction

$\beta = v/c, v =$ speed of charged particle

Vertex fit (I) : Point-fit

Good for a point source such as electron ring





Time of photon generation t_i for a photon detected by PMT I at time t^0_i

$$t_i = t_i^0 - \overbrace{\frac{n}{c}\times\left|\vec{P}_i - \vec{O}\right|}^{\text{TOF}}$$

vertex

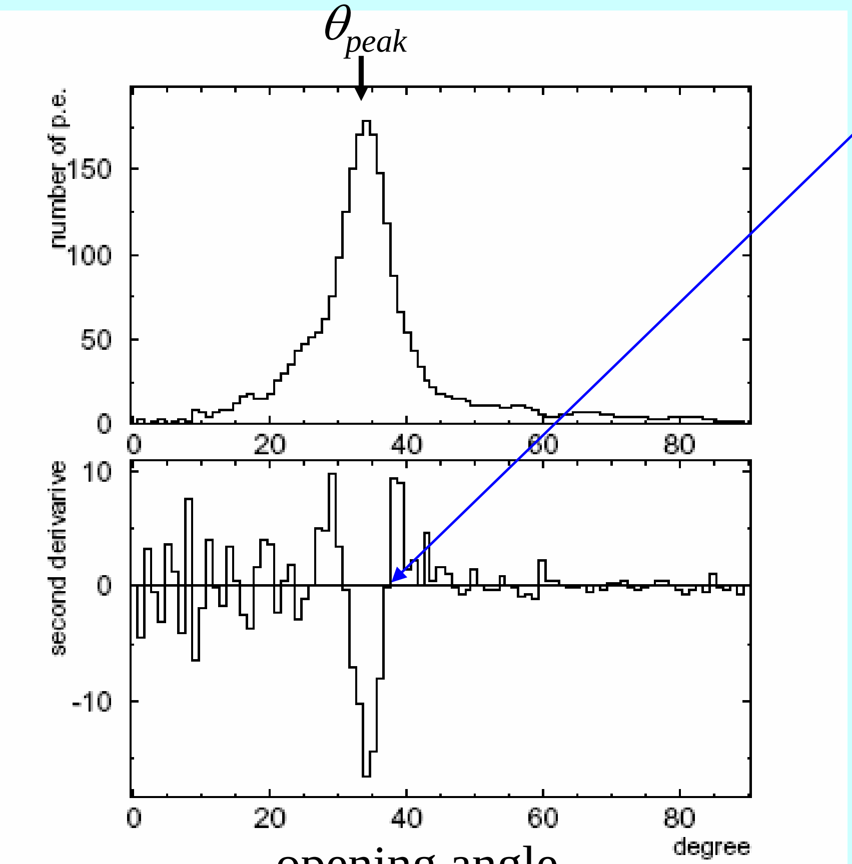
location of PMT i

Estimator to be maximized

$$G_p = \frac{1}{N_{hit}}\sum_i \exp\left[-\frac{1}{2}\left(\frac{t_i - t_0}{1.5\sigma}\right)^2\right], < t_i >= t_0$$

σ~2.5 nsec

Ring edge/ring direction



opening angle
(defined w.r.t. the cone axis)

Ring edge:

$$\theta_{edge} > \theta_{peak} \text{ and } \left.\frac{d^2 PE(\theta)}{d\theta^2}\right|_{\theta_{edge}} = 0$$

Particle direction:

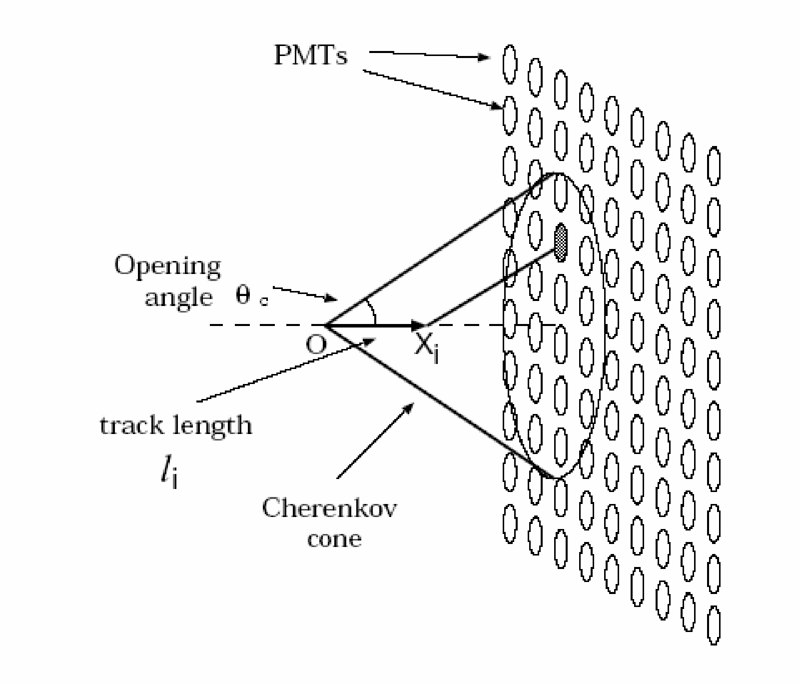
$$\vec{d}_p = \sum_i q_i \frac{\vec{P}_i - \vec{O}_0}{\left|\vec{P}_i - \vec{O}_0\right|}, \; q_i = \text{charge in PMT } i$$

Estimator (maximized by changing $\vec{\mathrm{d}}_\mathrm{p}$)

$$Q(\theta_{edge}) = \frac{\int_0^{\theta_{edge}} PE(\theta)\,d\theta}{\sin\theta_{edge}} \cdot \left(\left.\frac{dPE(\theta)}{d\theta}\right|_{\theta_{edge}} \right)^2 \cdot$$

$$\exp\left[-\frac{(\theta_{edge} - \theta_c)^2}{2\sigma_\theta^2} \right]$$

- Vertex fit (II) : TDC-fit - track length and scattered light effect included



Time residual:

TOF of track TOF of light

$$t_i = t_i^0 - \frac{1}{c}\left|\vec{X}_i - \vec{O}\right| - \frac{n}{c}\left|\vec{P}_i - \vec{O}\right| \text{ for PMTs inside Cherenkov edge}$$

$$= t_i^0 - \frac{1}{c}\left|\vec{X}_i - \vec{O}\right| \qquad \text{for PMTs outside Chernkov edge}$$

Estimators:

$$G_I = \sum_i \frac{1}{\sigma_i^2} \exp\left[-\frac{1}{2}\left(\frac{t_i - t_0}{1.5\sigma}\right)^2 \right] \text{for PMTs inside}$$

$$G_{O_1} = G_{O_1}(t_i) \text{ for PMTs outside and } t_i > t_0$$

$$G_{O_2} = G_{O_2}(t_i) \text{ for PMTs outside and } t_i < t_0$$

scattered light effect

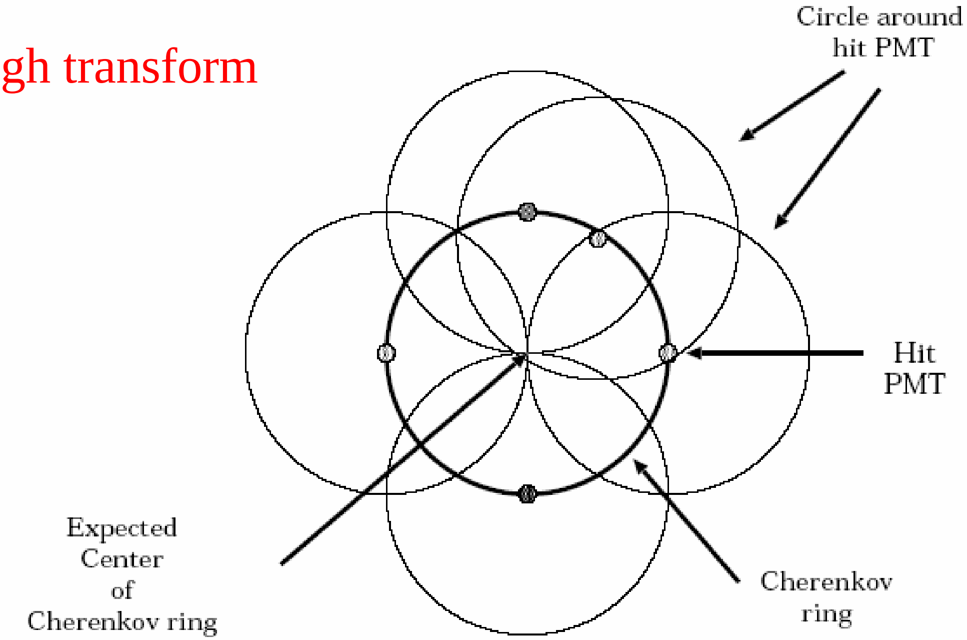
Final estimator to be maximized:

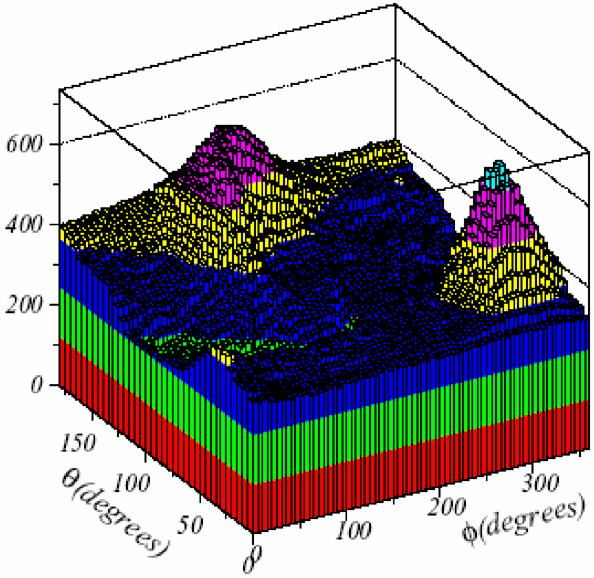
$$G_T = \frac{G_I + G_{O_1} + G_{O_2}}{\sum_i \frac{1}{\sigma_i^2}}$$

by changing vertex position and cone direction

- Ring count

Hough transform





Likelihood function for N+1 rings:

$$L_{N+1} = \sum_i \log\left[prob\left(q_i^{obs}, \sum_n^{N+1} \alpha_n \cdot q_{i,n}^{\exp}\right)\right]$$

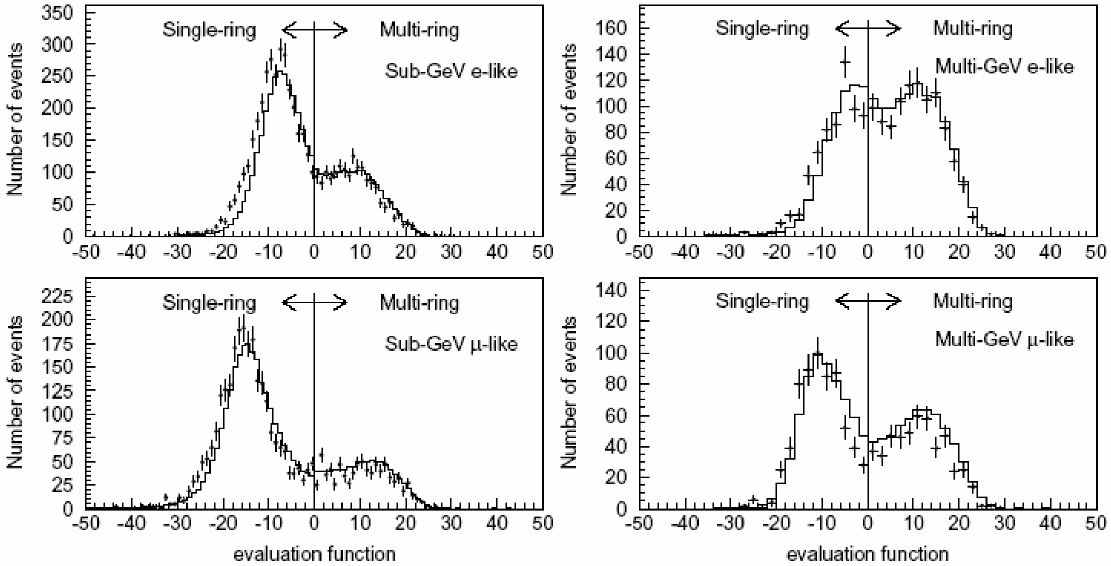
$$prob(q^{obs}, q^{\exp}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\left(q^{obs} - q^{\exp}\right)^2}{2\sigma^2}\right] \text{ for } q_i^{\exp} > 20 \text{ pe}$$

$$= \text{convolution of a single pe dist. and a Poisson dist.} \quad \text{for } q_i^{\exp} < 20 \text{ pe}$$

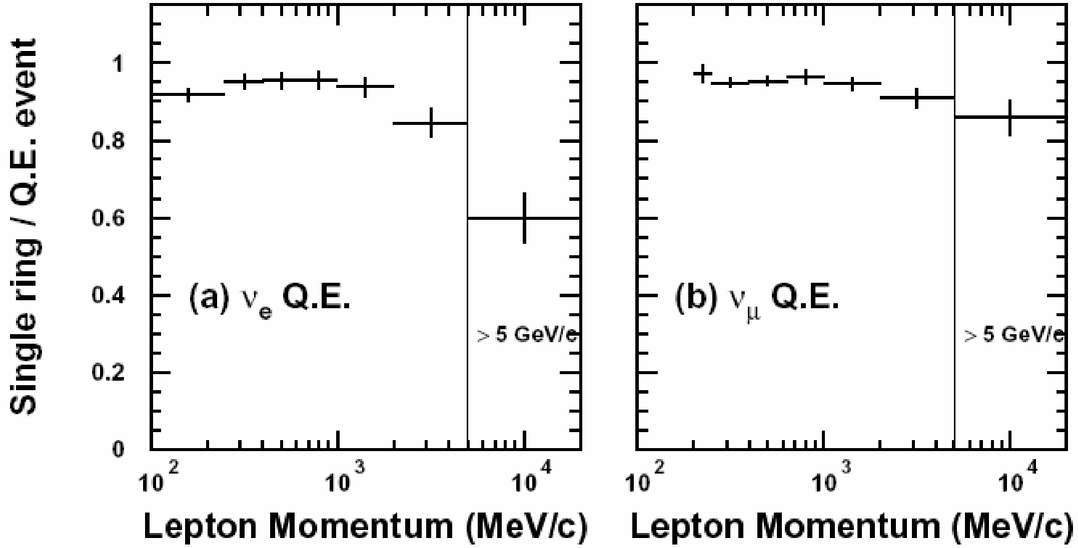
If $L_{N+1} > L_N$, several conditions are checked and a decision is made on how many rings there are

Sub-GeV : Evis<1.33 GeV, Multi-GeV: Evis>1.33 GeV

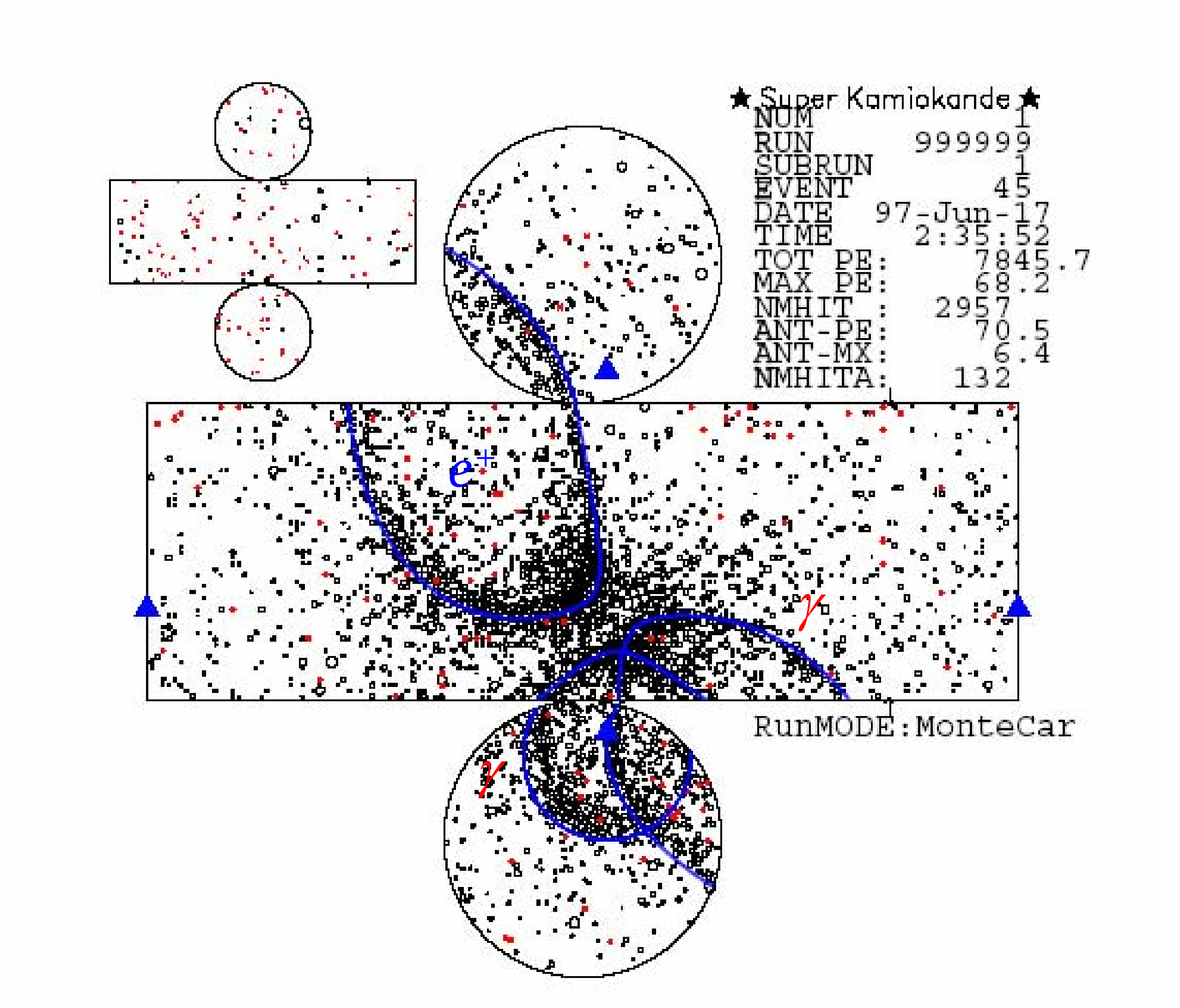
- Ring count



L_1-L_2 L_1-L_2



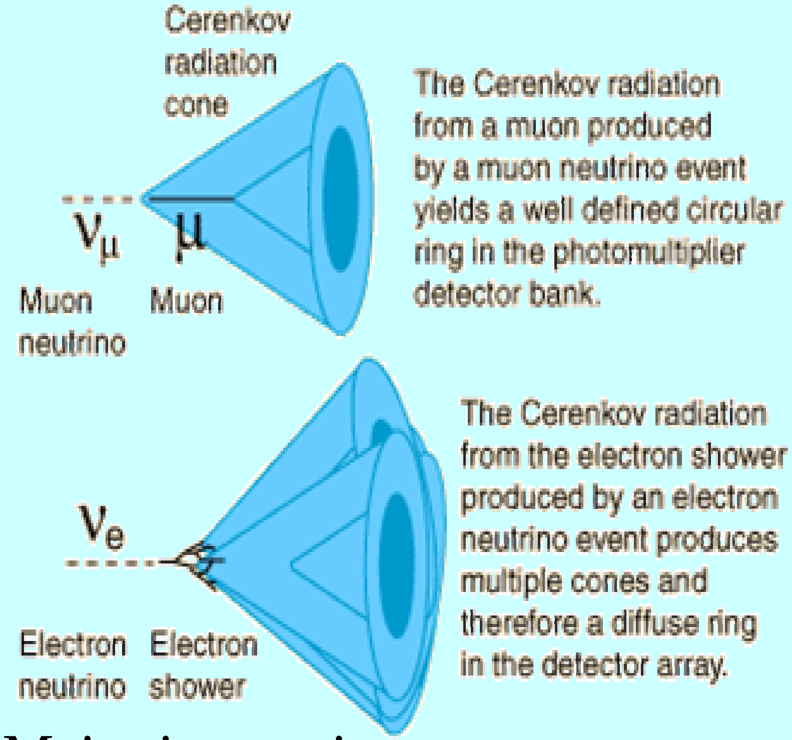
Ring fitter example $p \rightarrow e^{+}\pi^{0}(\pi^{0} \rightarrow \gamma\gamma)$



```
NUM            1
RUN       999999
SUBRUN         1
EVENT         45
DATE   97-Jun-17
TIME     2:35:52
TOT PE:     7845.7
MAX PE:       68.2
NMHIT :   2957
ANT-PE:       70.5
ANT-MX:        6.4
NMHITA:    132
RunMODE:MonteCar
```

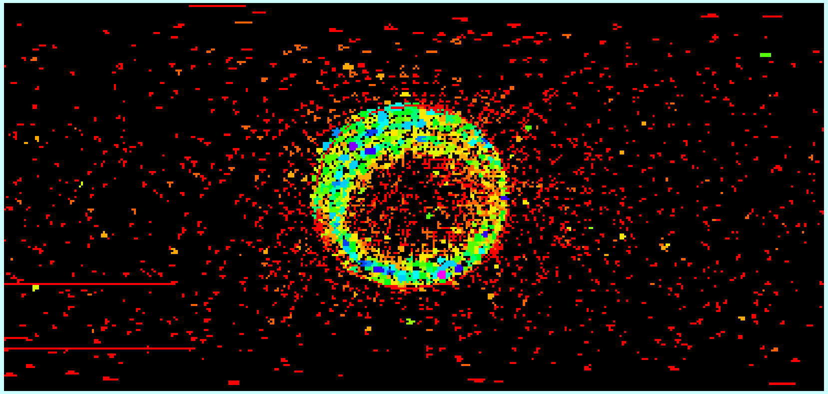
- Particle ID

How do we detect muon and electron neutrinos ?

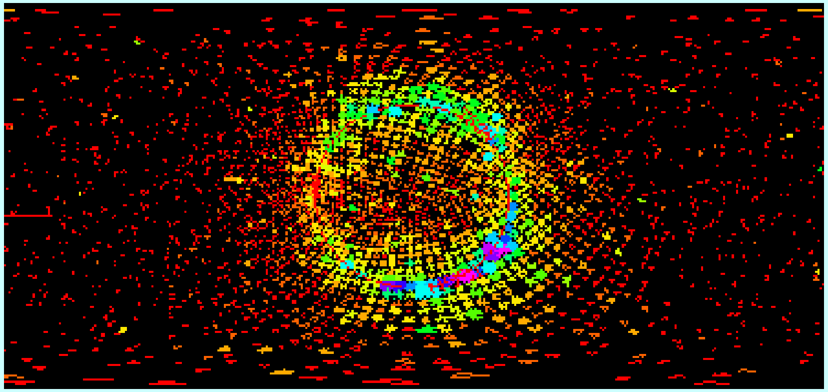


The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.



muon-like ring



electron-like ring

Major interactions:

$$\nu_e + n \rightarrow \boxed{p} + \boxed{e^-}$$

$$\nu_\mu + n \rightarrow \boxed{p} + \boxed{\mu^-}$$

Most of time invisible

- Particle ID

Likelihood and probabilities

$$L_n(e\text{ or }\mu) = \prod_{\theta_i < 1.5\theta_c} prob\left(q_i^{obs}, q_{i,n}^{\exp}(e\text{ or }\mu) + \sum\nolimits_{n' \neq n} q_{i,n'}^{\exp}\right)$$

$$\chi_n^2(e\text{ or }\mu) = -2\log L_n(e\text{ or }\mu) + const$$

$$P_n^{pattern}(e\text{ or }\mu) = \exp\left[-\frac{(\chi_n^2(e\text{ or }\mu) - \min(\chi_n^2(e), \chi_n^2(\mu)))^2}{2\sigma_{\chi_n^2}^2}\right]$$

$$P_n^{angle}(e\text{ or }\mu) = \exp\left[-\frac{(\theta_n^{obs} - \theta_n^{\exp}(e\text{ or }\mu))^2}{2\sigma_\theta^2}\right]$$

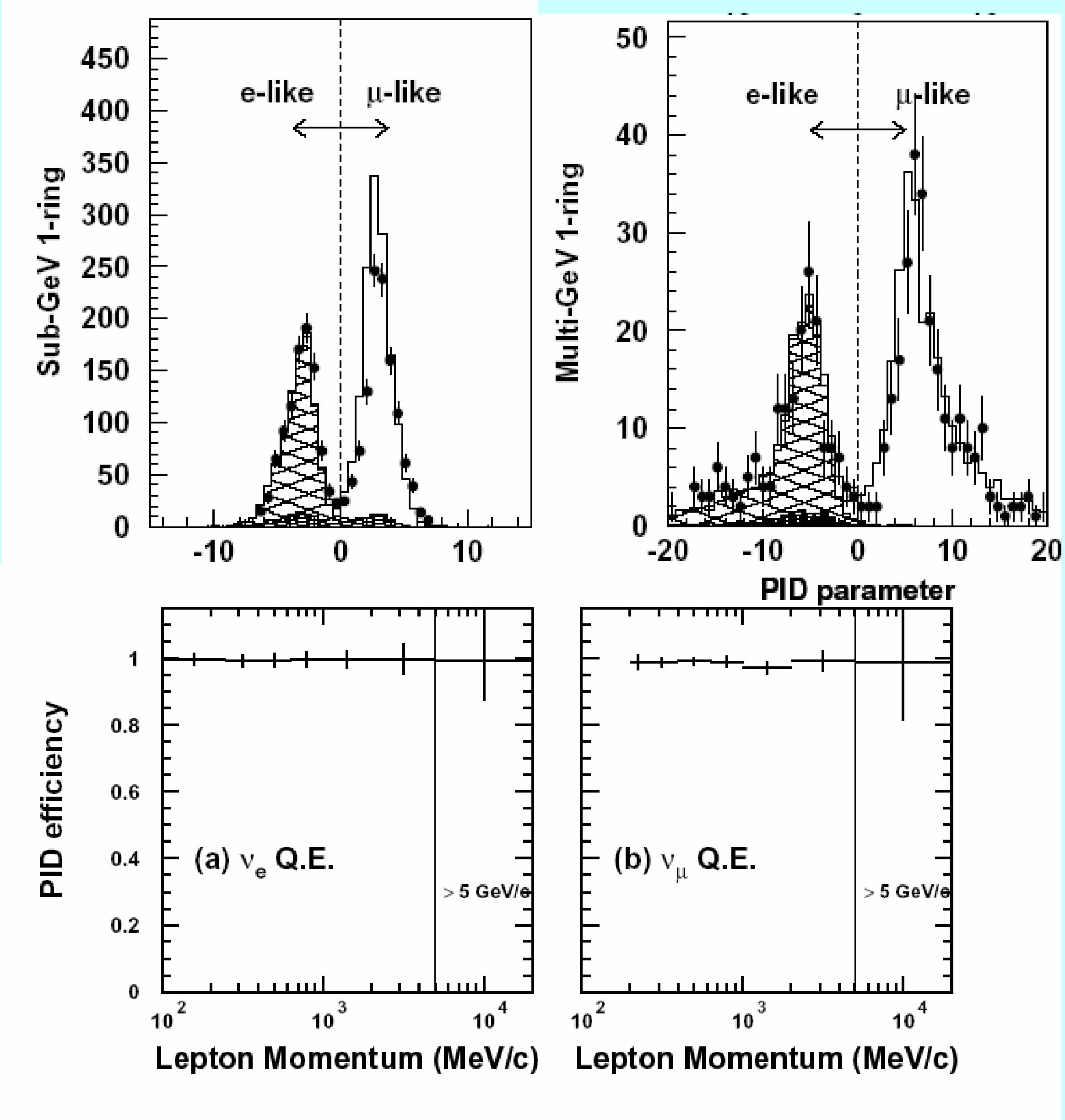
Probability

$$P_1(e\text{ or }\mu) = P_1^{pattern}(e\text{ or }\mu) \times P_1^{angle}(e\text{ or }\mu) \quad \text{for a single-ring event}$$

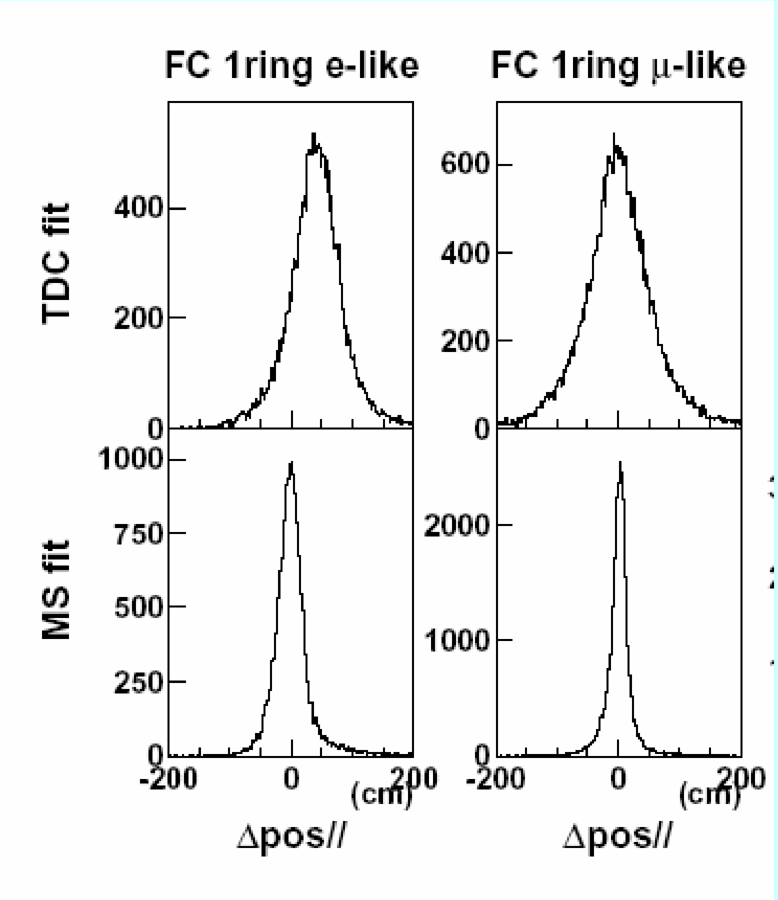
$$P_n(e\text{ or }\mu) = P_n^{pattern}(e\text{ or }\mu) \quad \text{for a multi-ring event}$$

$$P \equiv \sqrt{-\log P(\mu)} - \sqrt{-\log P(e)}$$

- Particle ID (μ-like vs. e-like)



• Vertex fit (III) : MS-fit – Timing and charge info used for a single ring event



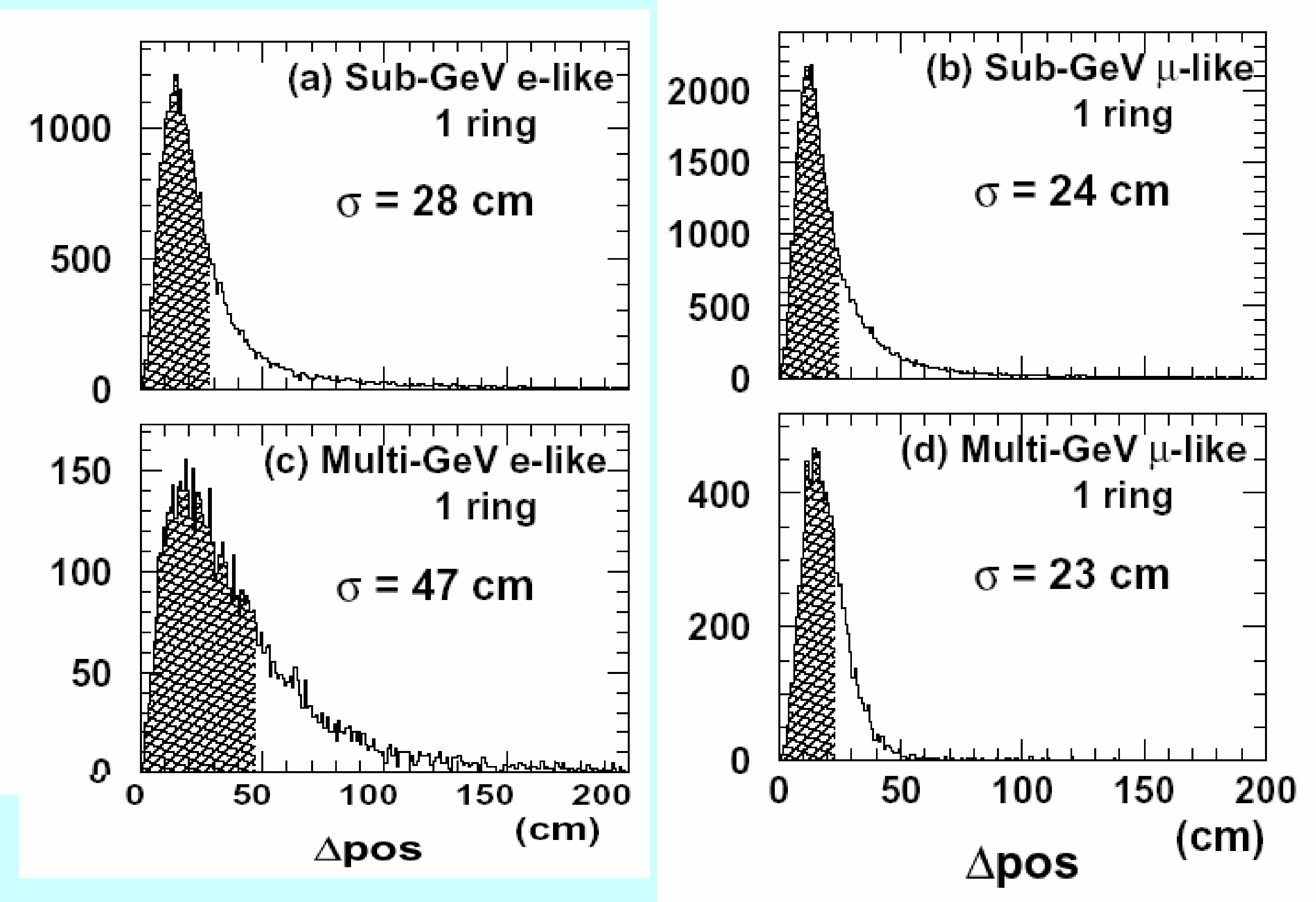
- A vertex shift along a track changes the TOF of each hit by almost equal amount

→

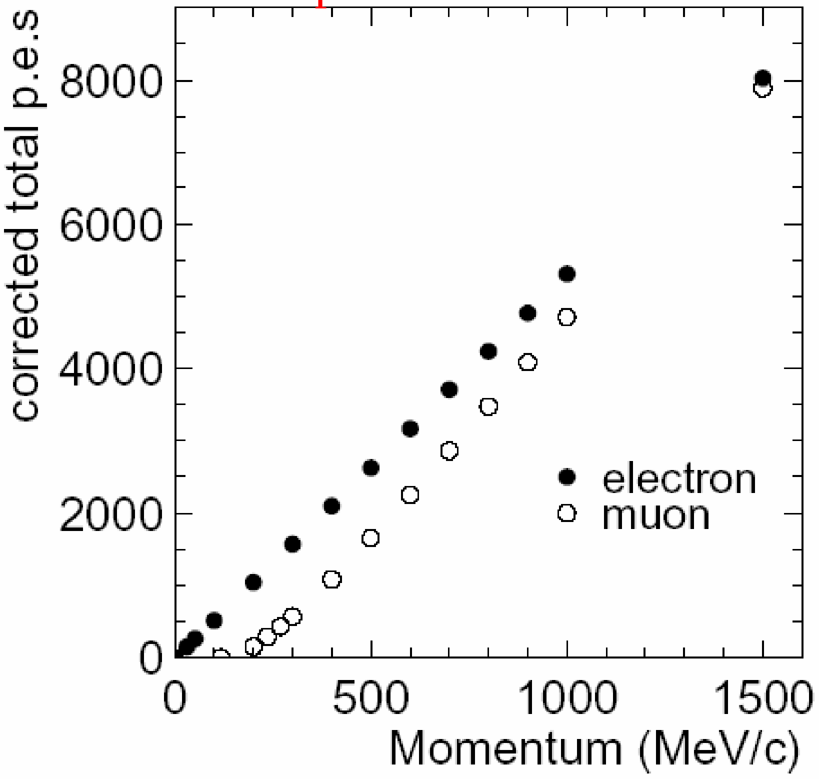
Bad vertex resolution along the track

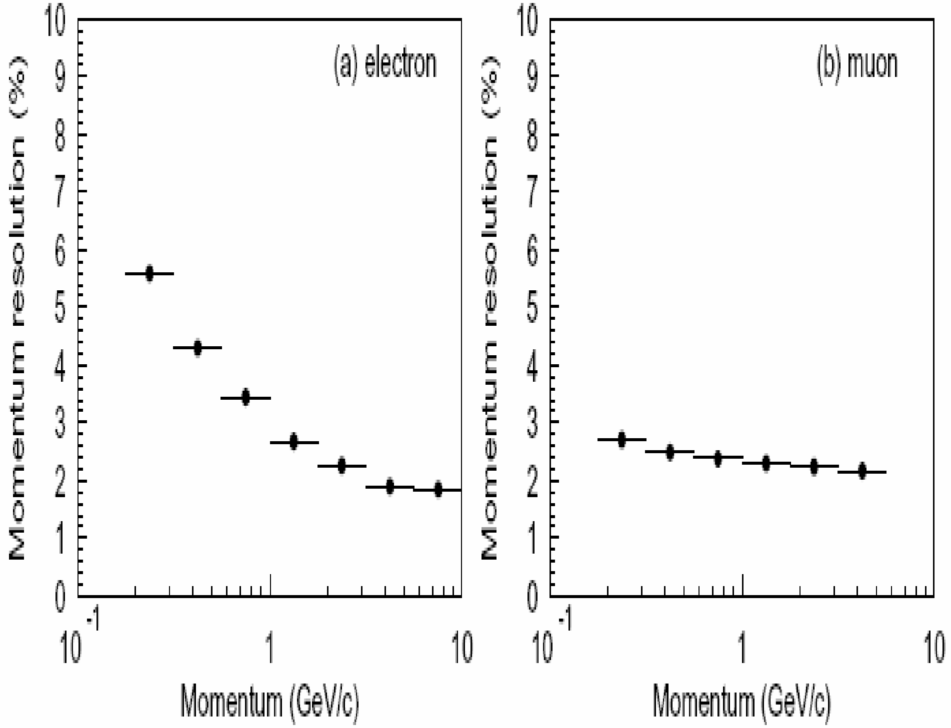
- Ring pattern (charge distribution) gives additional handle to improve vertex resolution along the track

- Vertex fit (III) : MS-fit – Timing and charge info used for a single ring event

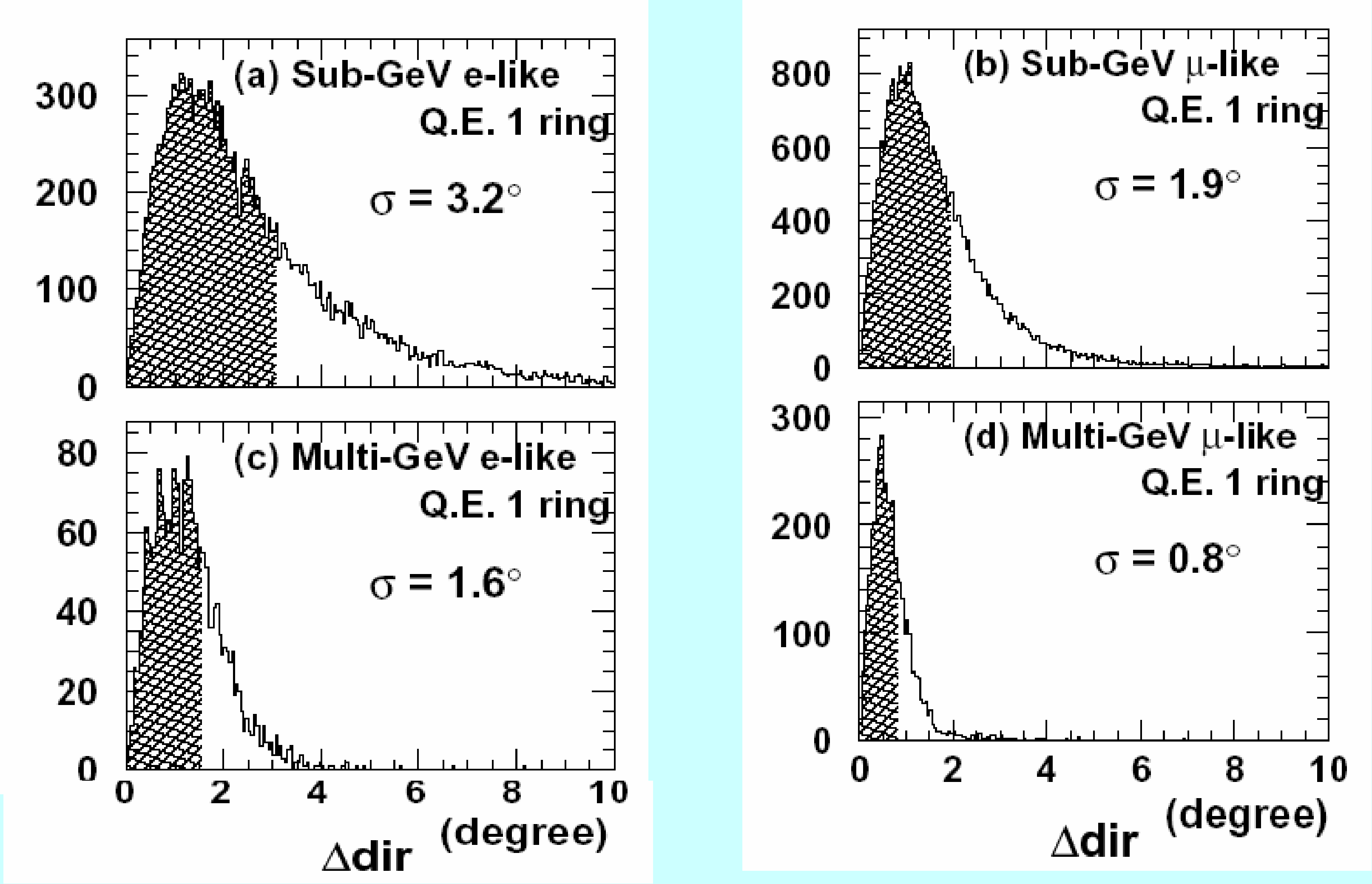


Momentum measurement


pe vs. momentum


momentum resolutions

- Angular resolutions

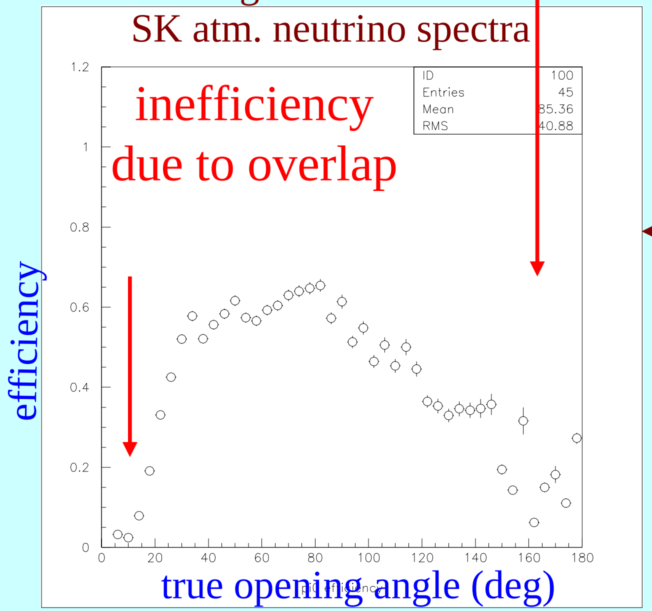


π^0 finder : Motivation and strategy

- π^0 reconstruction efficiency with standard SK software
  - Inefficiency due to overlap
  - Inefficiency due to a week 2^{nd} ring
  - Inefficiency in between

Needs a smart algorithm to increase efficiency

- POLfit (Pattern Of Light fit)
  - Always looks for an extra ring in a single e-like ring event
  - Observed light pattern is compared with templates
  - Scattered light due to processes such as Mie scattering taken into account
  - Outputs: Likelihoods in addition to information of the extra-photon are provided



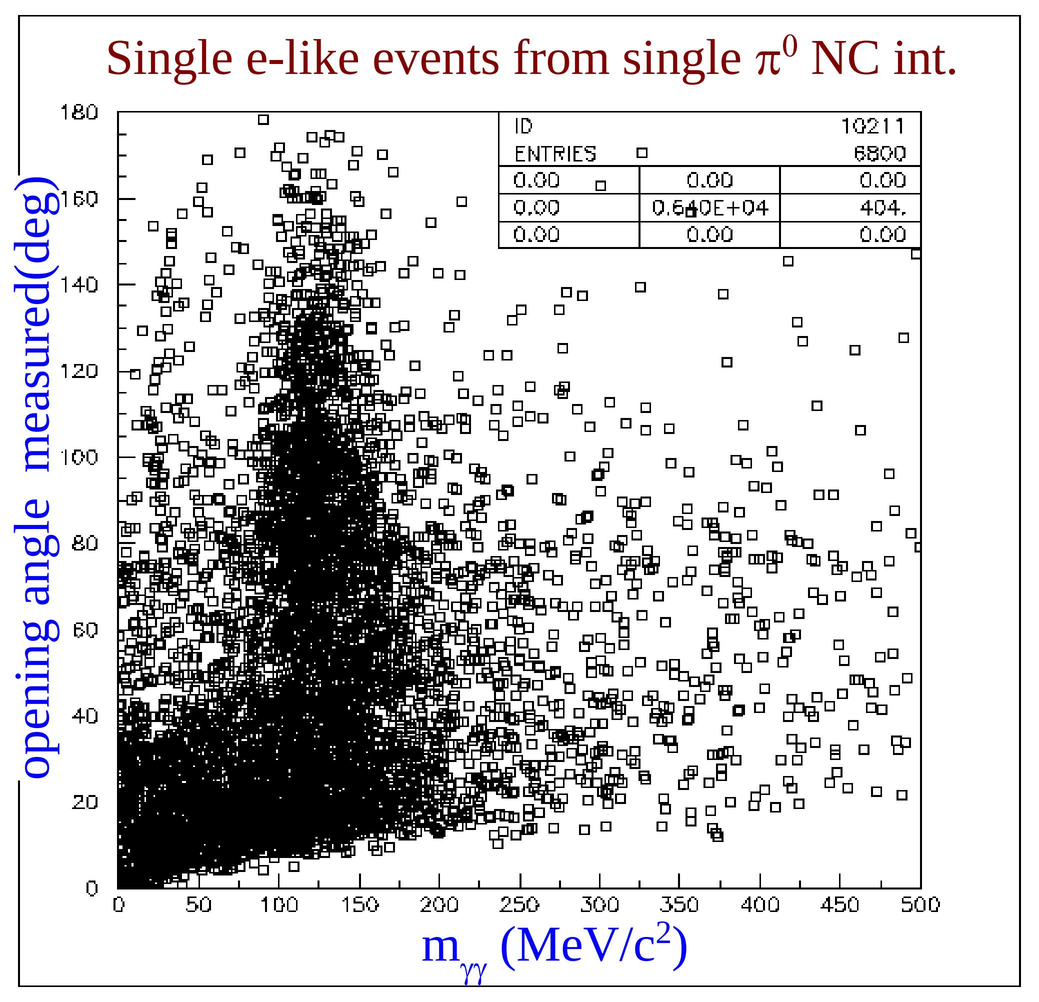
inefficiency due to weak 2^{nd} ring

All single π^0 interactions
SK atm. neutrino spectra

inefficiency due to overlap

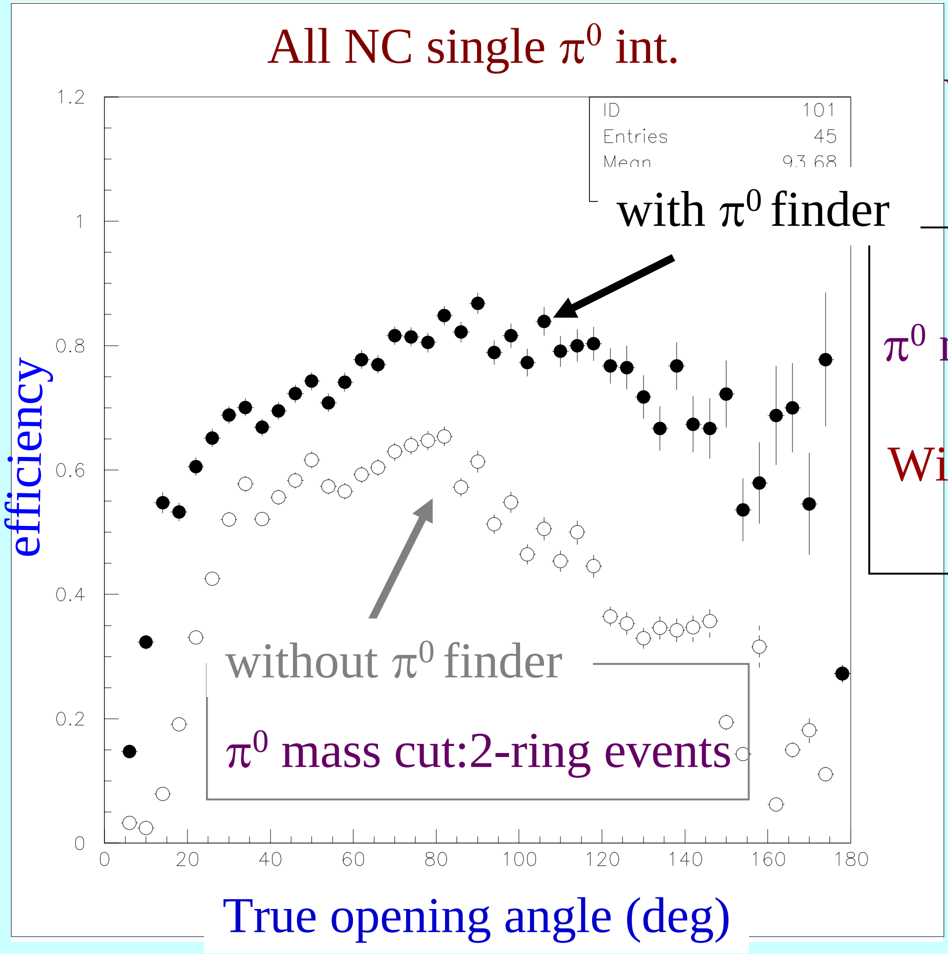
π^0 finder: Performance

- Measured opening angle vs. π^0 mass using π^0 finder



π^0 finder: “Efficiency”

- π^0 “reconstruction efficiency” with standard SK + π^0 finder



with π^0 finder

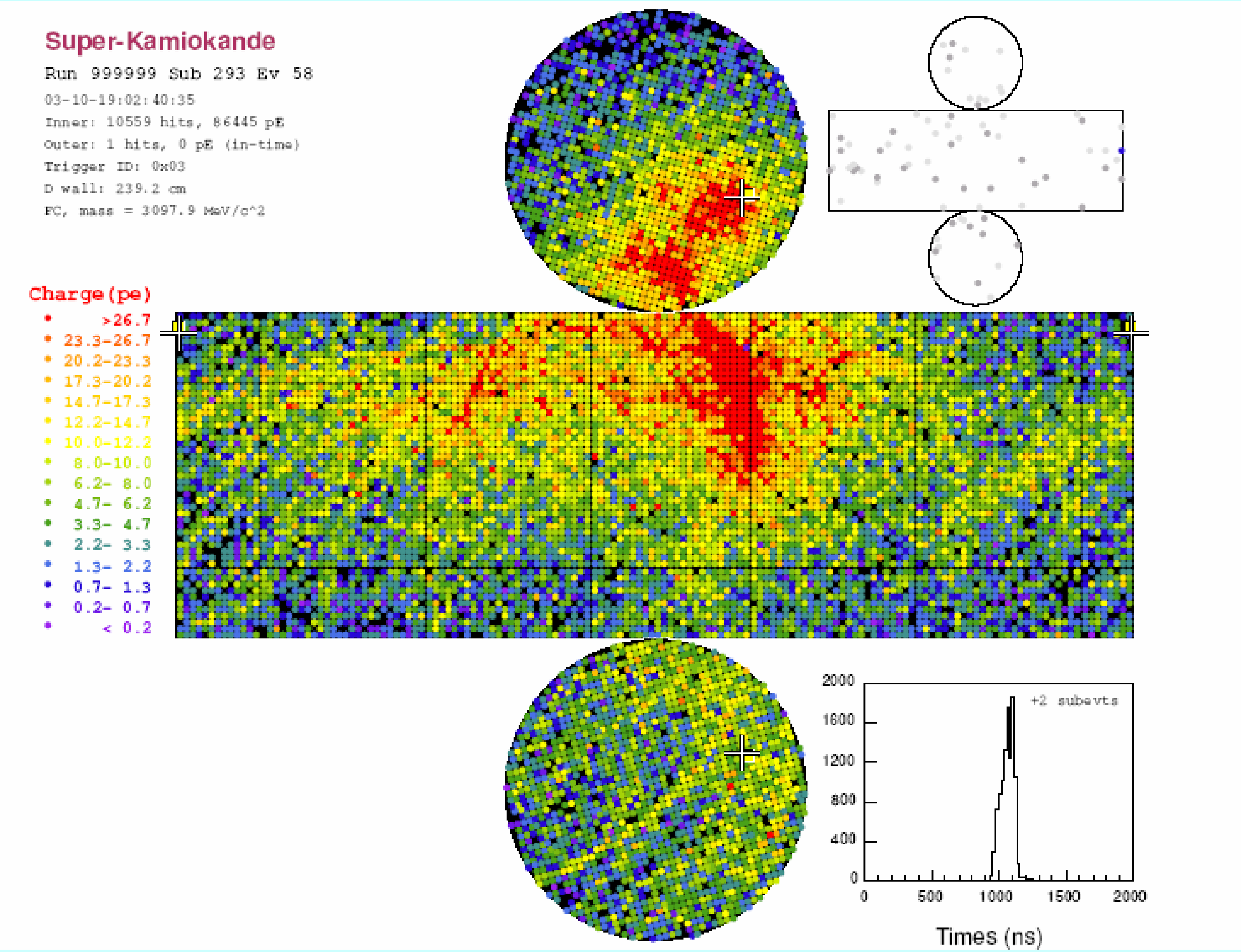
w/o π^0 finder

π^0 mass cut:1- and 2-ring events

With atmospheric neutrino spectra

- ν_τ event identification (I)

A τ event at SK (simulation)



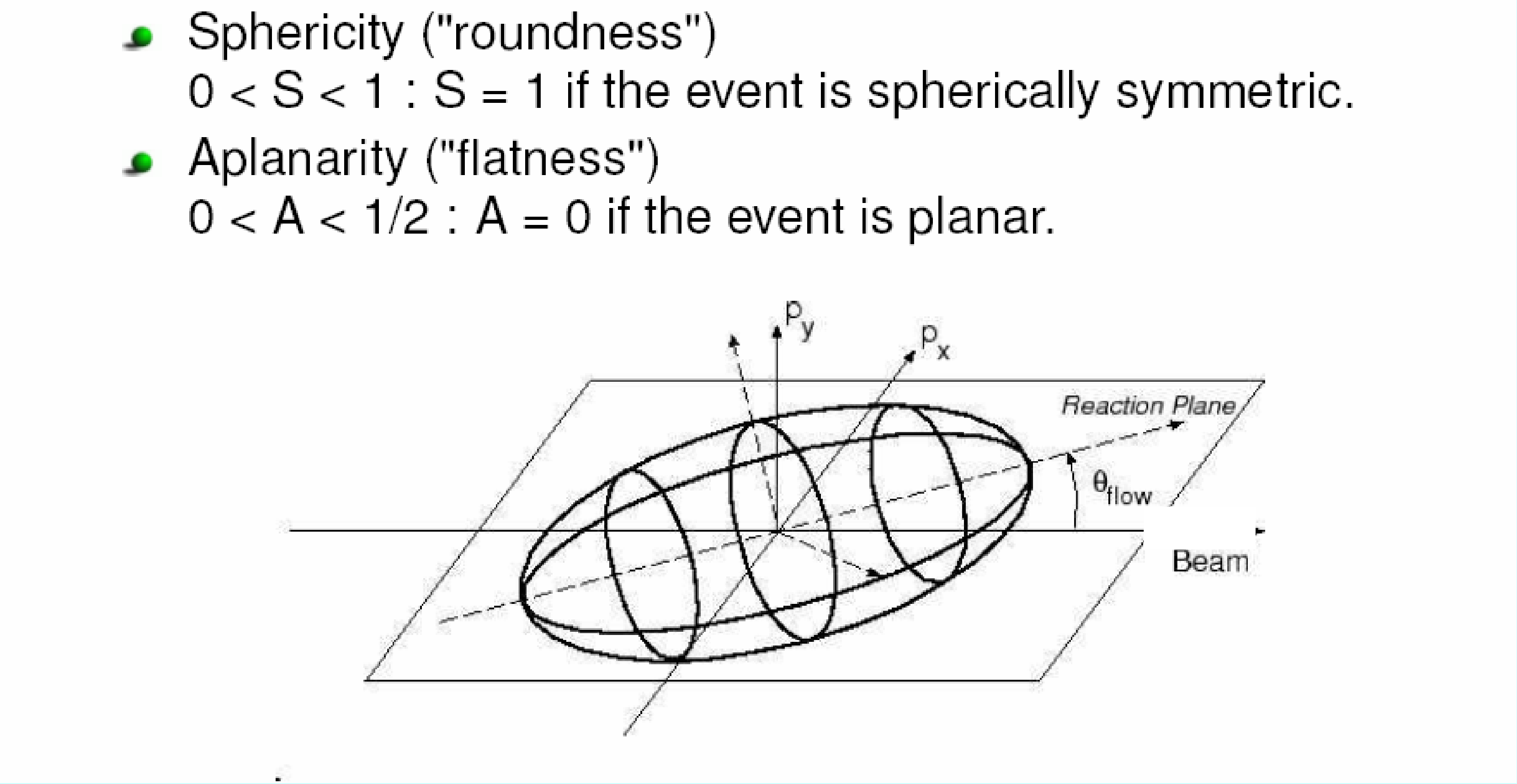
Super-Kamiokande
Run 999999 Sub 293 Ev 58
03-10-19:02:40:35
Inner: 10559 hits, 86445 pE
Outer: 1 hits, 0 pE (in-time)
Trigger ID: 0x03
D wall: 239.2 cm
FC, mass = 3097.9 MeV/c^2

Charge(pe)

●	>26.7
●	23.3-26.7
●	20.2-23.3
●	17.3-20.2
●	14.7-17.3
●	12.2-14.7
●	10.0-12.2
●	8.0-10.0
●	6.2- 8.0
●	4.7- 6.2
●	3.3- 4.7
●	2.2- 3.3
●	1.3- 2.2
●	0.7- 1.3
●	0.2- 0.7
●	< 0.2

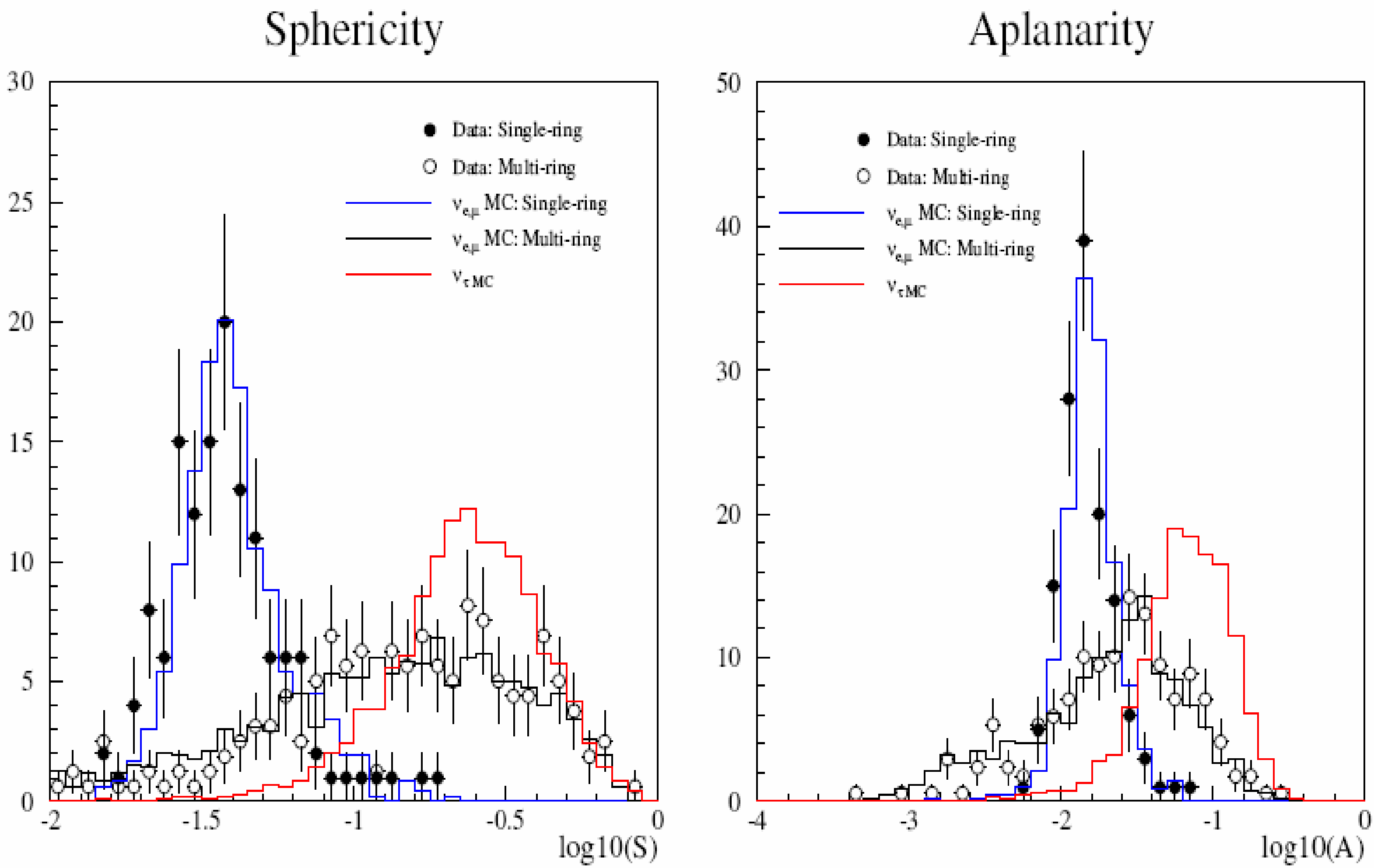
ν_τ event identification (II)

In addition to traditional SK variables, new variables such as sphericity and aplanarity that describe topology of events are also used to define a likelihood to distinguish τ events from others



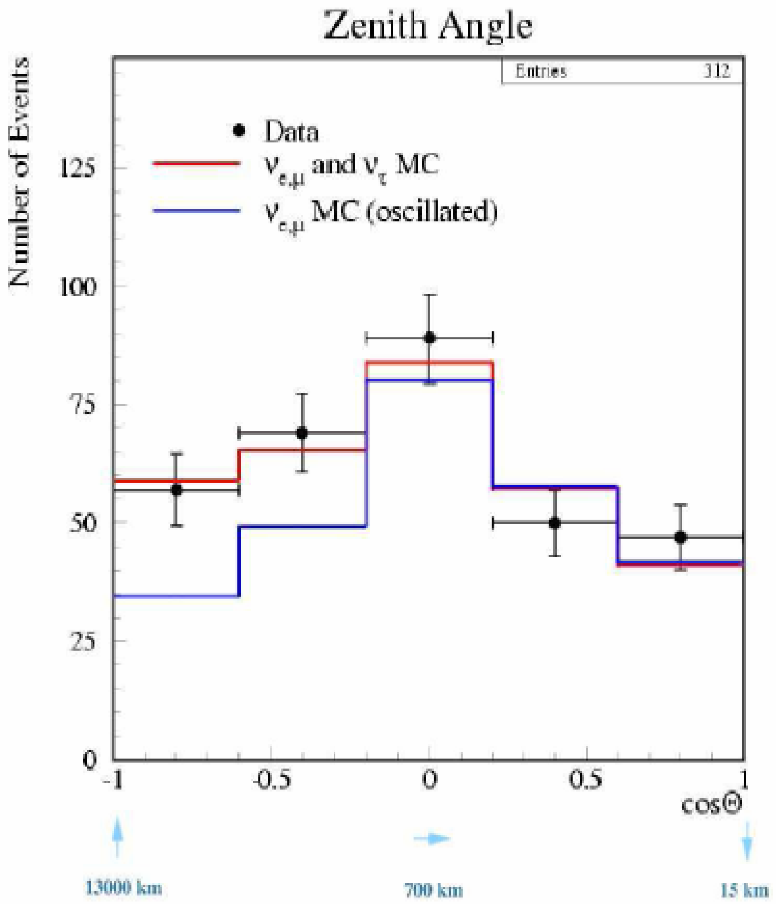
- Sphericity ("roundness")
  $0 < S < 1$: $S = 1$ if the event is spherically symmetric.
- Aplanarity ("flatness")
  $0 < A < 1/2$: $A = 0$ if the event is planar.

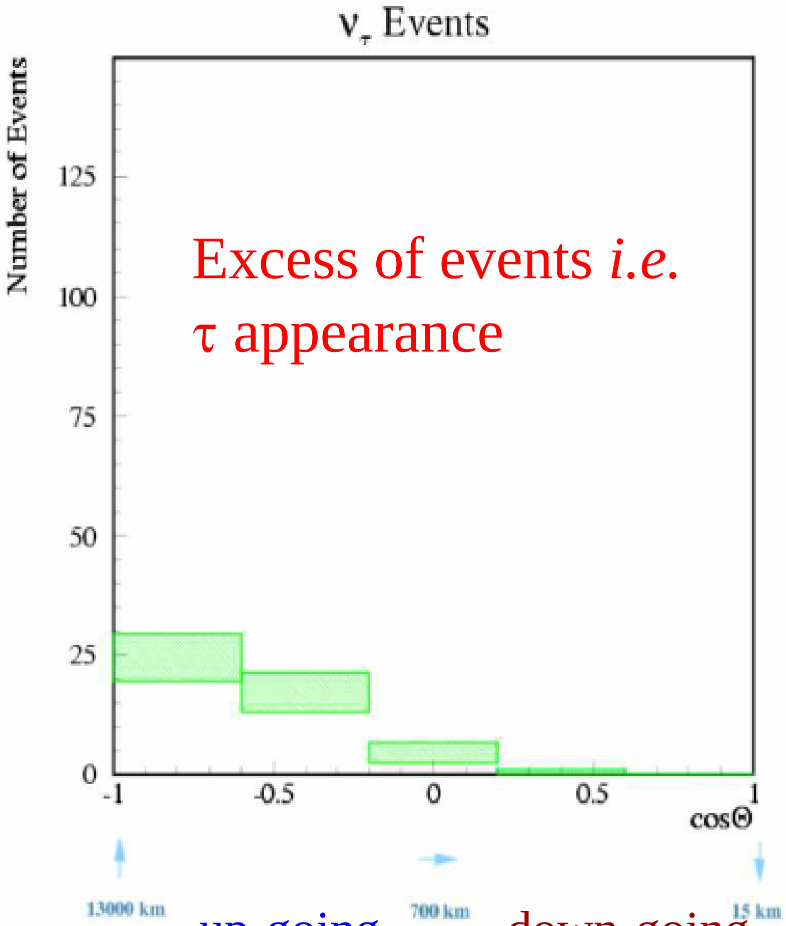
- ν_τ event identification (III)



- ν_τ event identification(VI)

After some cuts plus a cut on likelihood





Excess of events *i.e.*
τ appearance

up-going down-going

up-going down-going

• Very Long Baseline Neutrino Oscillation Experiment

Setting the stage

- ~ a half megaton F.V. water Cherenkov detector, for example UNO at 2,540 (BNL-HS) km and 1,480 km (Fermilab-Henderson) from the beam source
- BNL very long baseline wide band neutrino beam
- VLB neutrino oscillation experiment $\nu_\mu \rightarrow \nu_e$

See, for example, PRD68 (2003) 12002 by BNL group for physics argument.

But it is based on 4-vector level MC and on very optimistic assumptions

How do we find the signal for $\nu_\mu \rightarrow \nu_e$

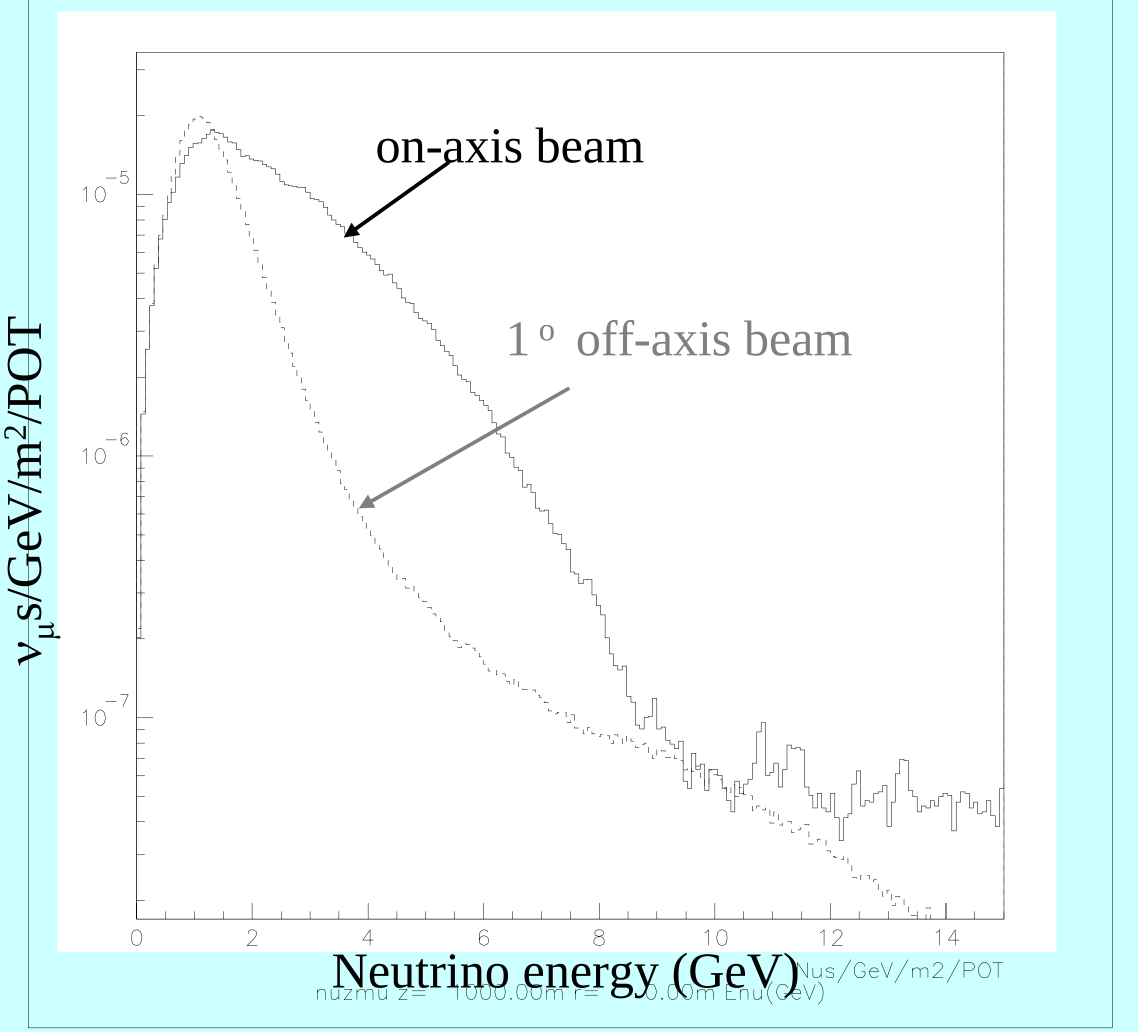
- $\nu_\mu \rightarrow \nu_e$ and $\nu_e + N \rightarrow e$ + invisible N' + (invisible n $\pi^\pm$s, $n \geq 0$)
- Look for single electron events
- Major background

$\gamma\ (\gamma)$

  - $\nu_{\mu,\tau,e} + N \rightarrow \nu_{\mu,\tau,e} + N' + \pi^0$ + (invisible n $\pi^\pm$s, $n \geq 0$)
  - ν_e contamination in beam (typically 0.7%)

- Neutrino spectra of on- and off-axis BNL Superbeams

PRD68 (2003) 12002; private communication w/ M.Diwan



on-axis beam

1^{o} off-axis beam

ν_μs/GeV/m^2/POT

Neutrino energy (GeV)

- How is analysis done ?
  - Use of SK atmospheric neutrino MC
    - Standard SK analysis package + special π^0 finder
    - Flatten SK atm. ν spectra and reweight with BNL beam spectra
    - Normalize with QE events: 12,000 events for ν_μ , 84 events for beam ν_e for 0.5 Mt F.V. with 5 years of running, 2,540 (1,480) km baseline

2500 kt• MW•10^7 sec
BNL 30 GeV AGS

distance from BNL to Homestake
(distance from Fermilab to Henderson)

    - Reweight with oscillation probabilities for ν_μ and for ν_e
  - Oscillation parameters used:
    - **Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x 10^{-3}eV^2**
    - **$\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=0,+45,+135,-45,-135°**

Probability tables from Brett Viren of BNL

Selection criteria used to improve

- Initial cuts: Traditional SK cuts only
  - One and only one electron-like ring with energy and reconstructed neutrino energy more than 100 MeV without any decay electron

$$E_\nu^{rec} = \frac{m_N E_e}{m_N - (1-\cos\theta_e)E_e}$$

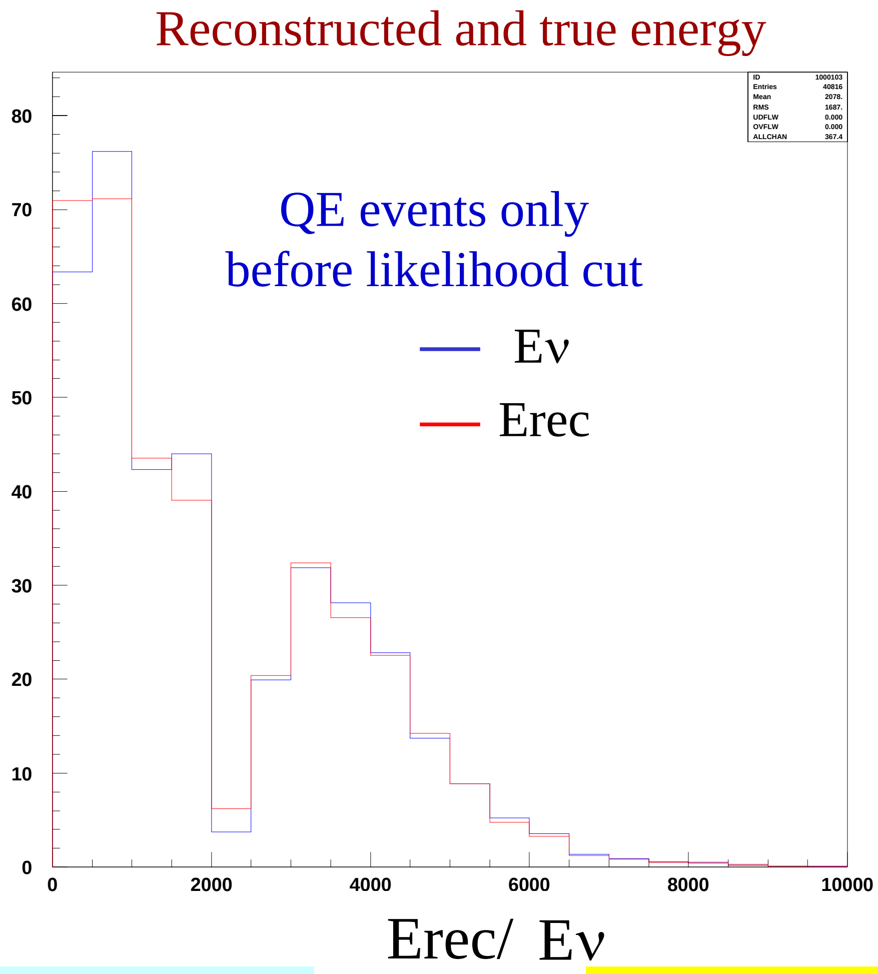
To reduce events with invisible charged pions

- Likelihood analysis using the following 9 variables: With π^0 finder
  - π^0 mass (pi0mass)
  - energy fraction (efrac)
  - costh
  - π^0-likelihood (pi0-like)
  - e-likelihood (e-like)
  - Δ log π^0-likelihood (Δlog pi0like)
  - single ring-ness (dlfct)
  - total charge/electron energy (poa)
  - Cherenkov angle (ange)

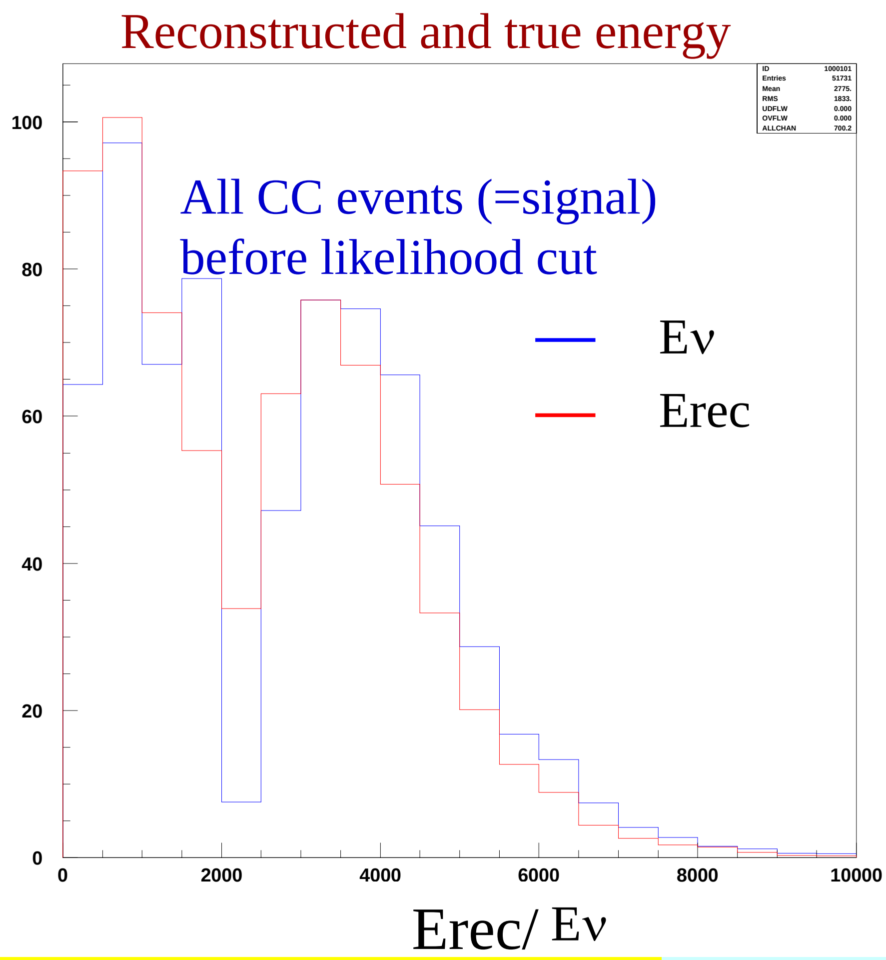
- How well can we measure neutrino energy ?

From now on only single e-like events after initial cuts will be used

Oscillation effect on with CPV+45^o at 2,540 km


Reconstructed and true energy

QE events only
before likelihood cut


Reconstructed and true energy

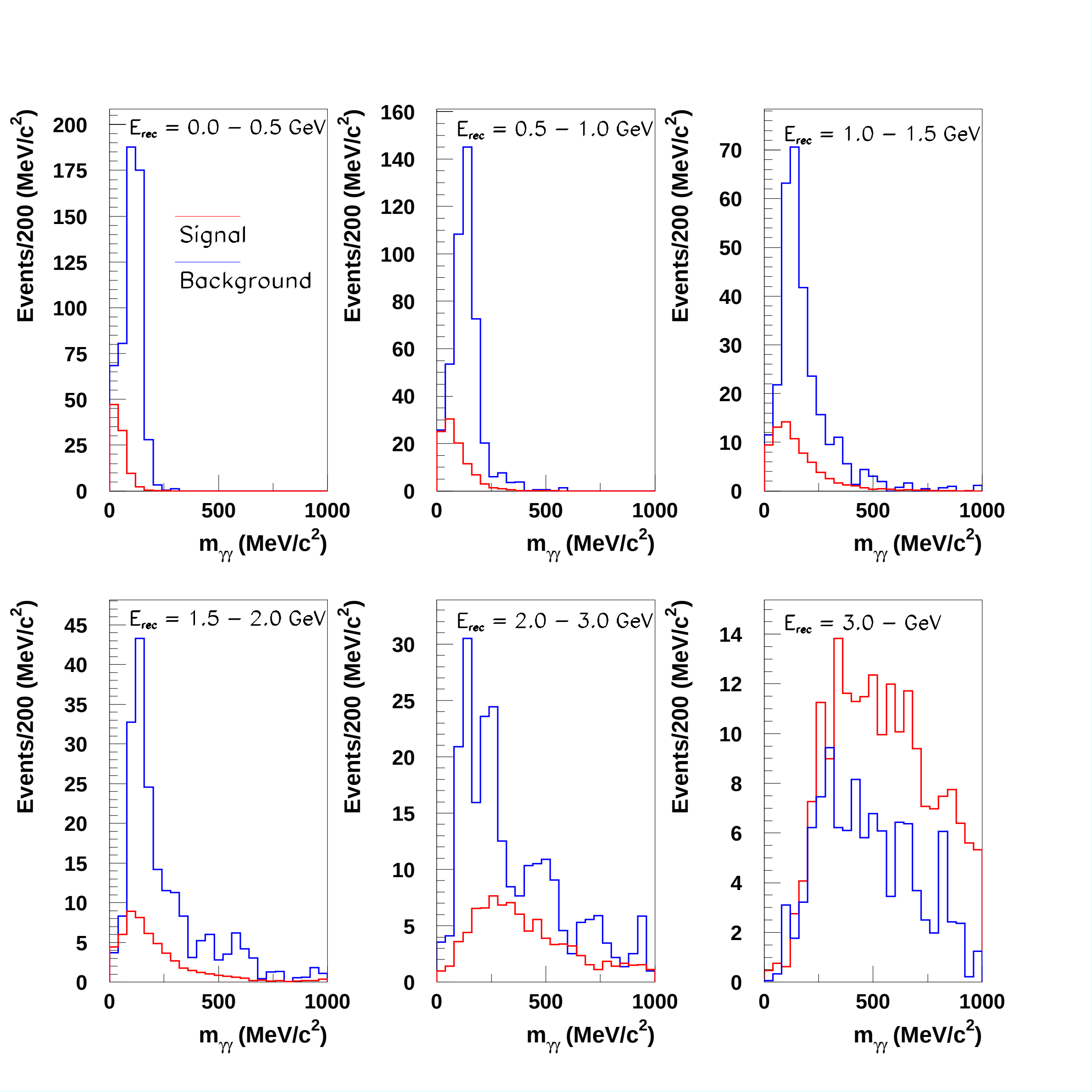
All CC events (=signal)
before likelihood cut

All CC events that survive the initial cuts are signals

• Useful Variables to form likelihood function

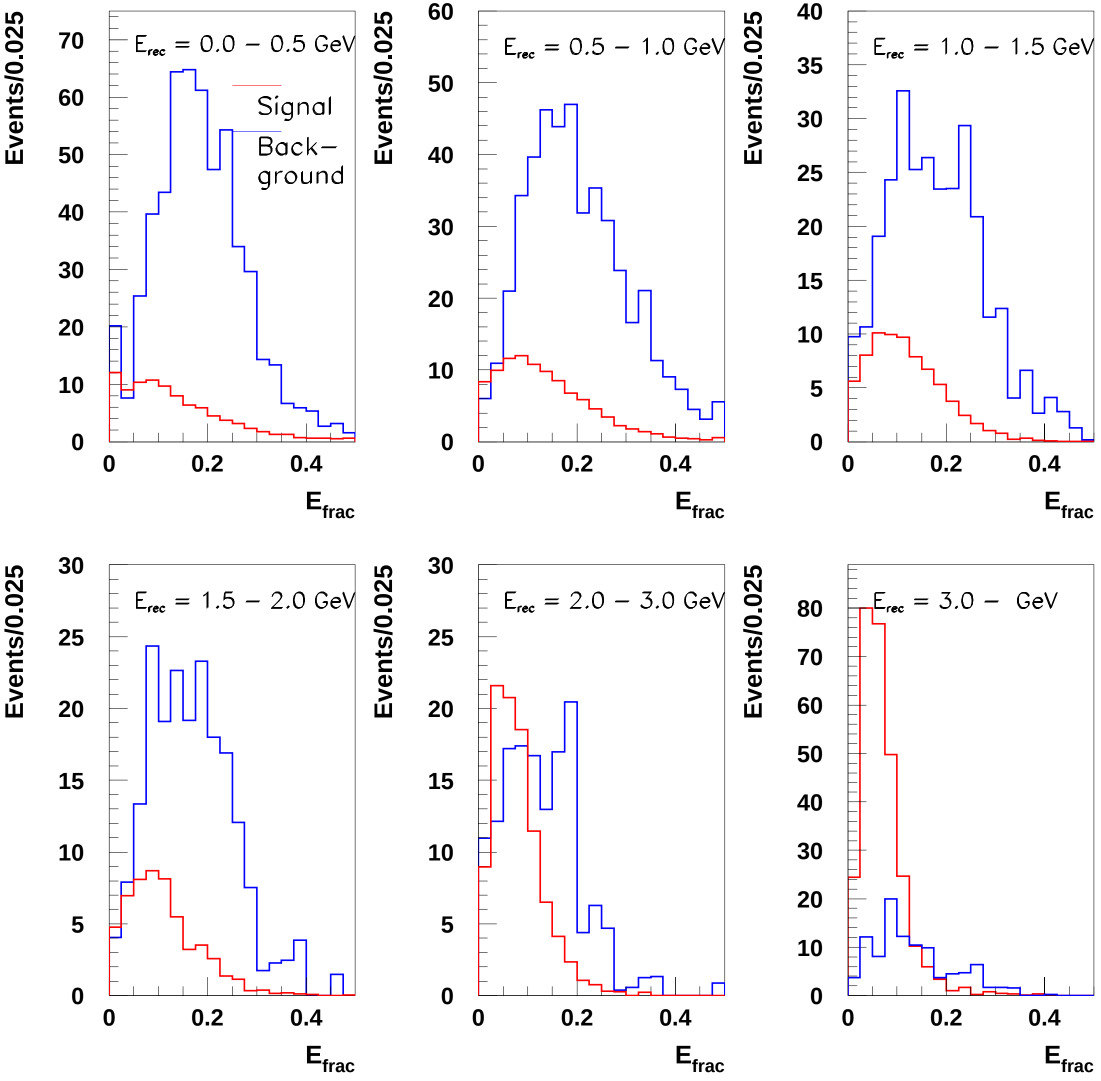
- π^0 mass

All the distributions of useful variables are obtained with neutrino oscillation “on” with CPV phase angle $+45^0$



- Energy fraction of 2nd ring

Fake ring has less energy than real one



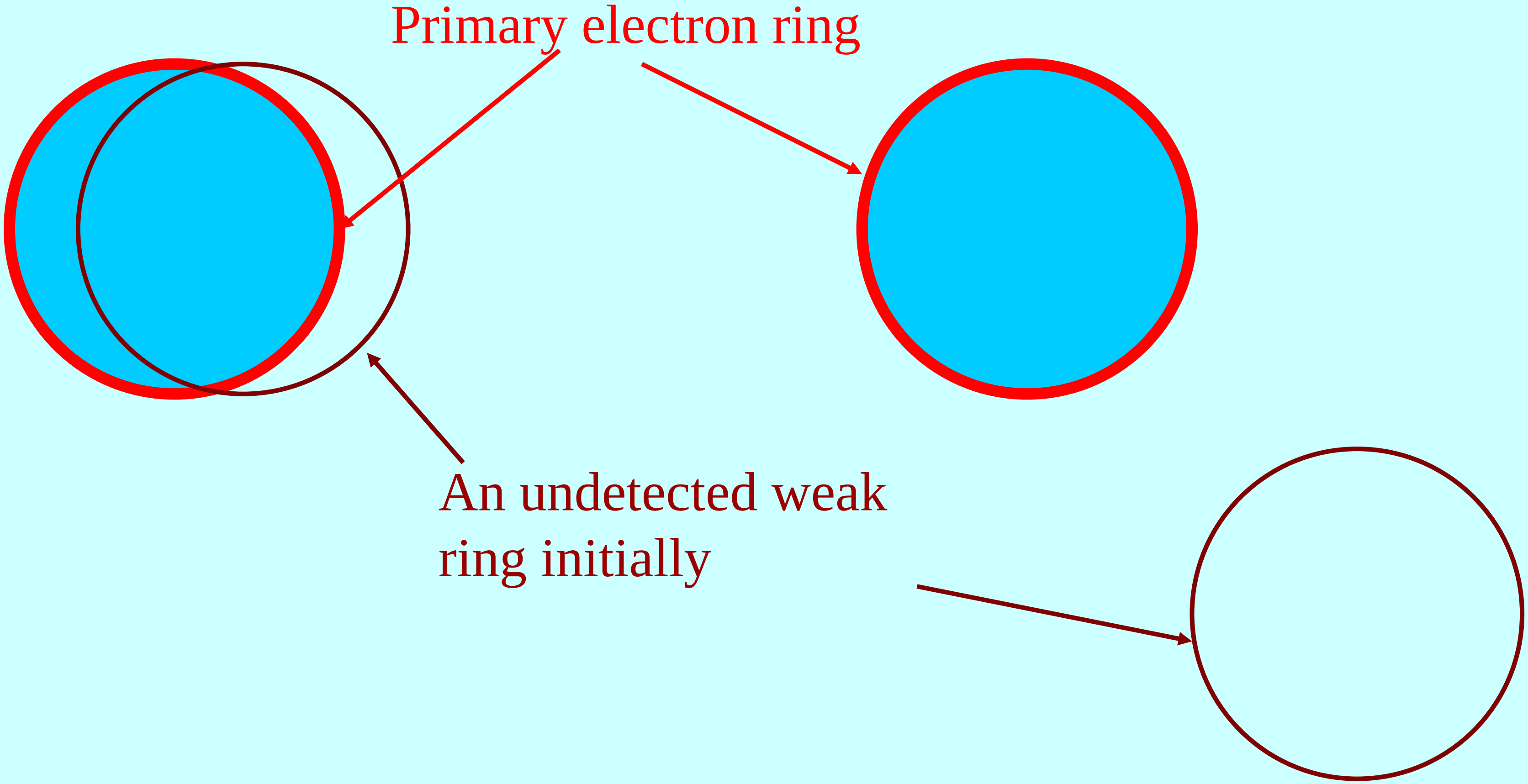
- Difference between log of two π^0-likelihoods (wide vs. forward) from POLfit

  -One algorithm optimized to find an extra ring near the primary ring (forward region)

  This algorithm practically gives likelihood how likely the event is single e-like

  - Another algorithm optimized to find an extra ring in wider space (wide region)

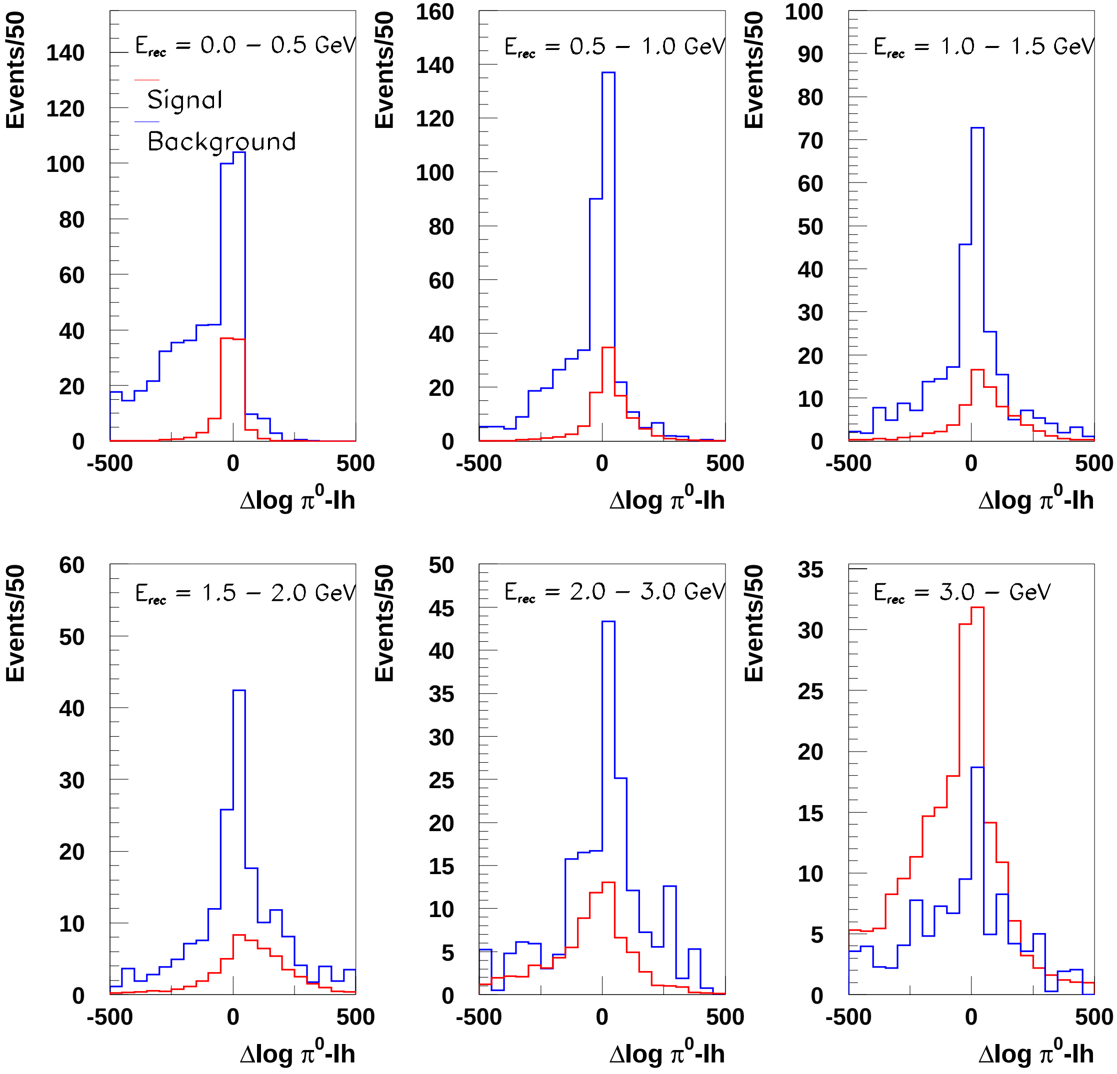
  - See the difference log π^0-likelihood (forward) - log π^0- likelihood (wide)



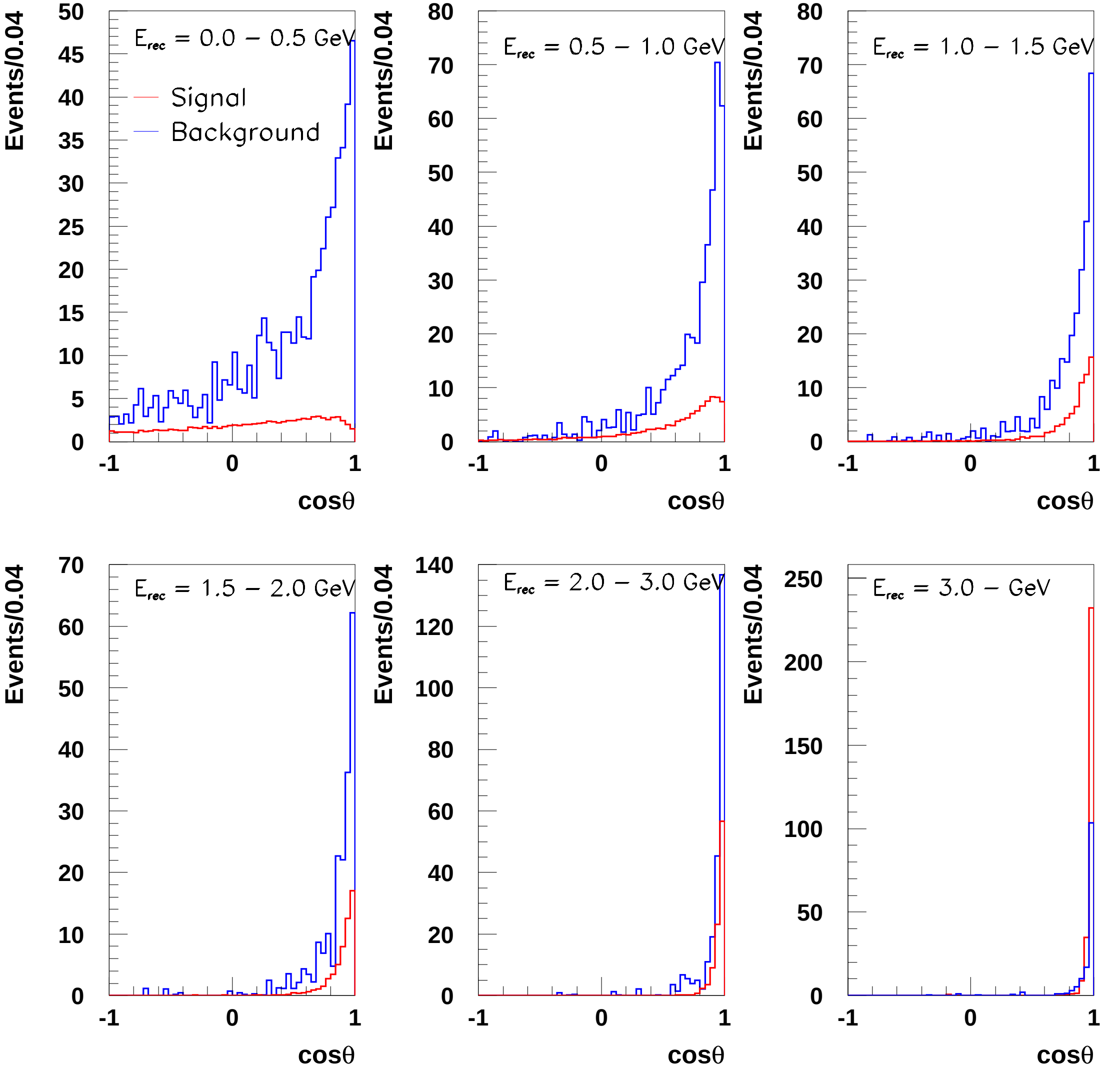
Primary electron ring

An undetected weak ring initially

- Difference between log of two π^0-likelihood (wide vs. forward) from POLfit



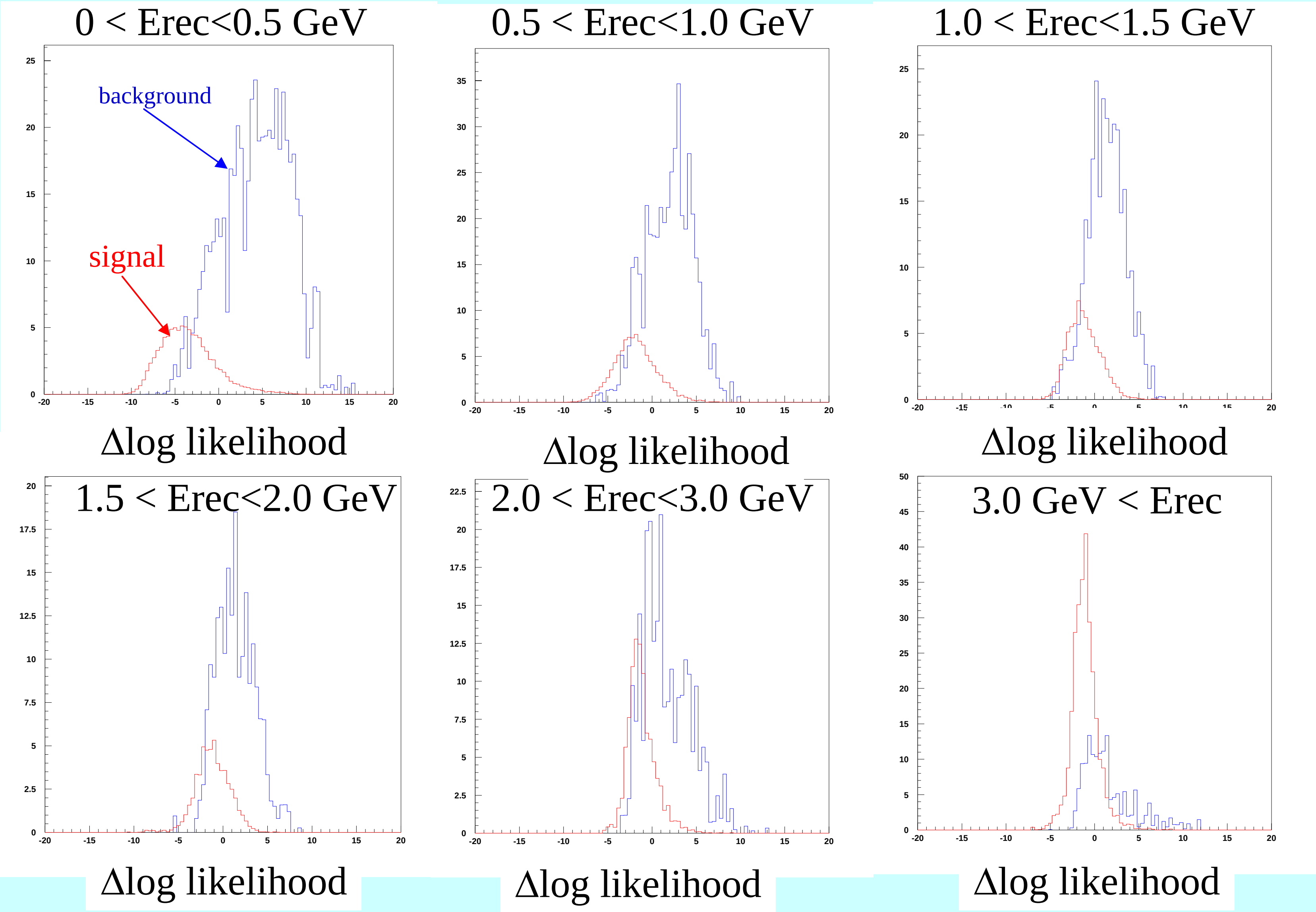
- costh = cos θ_e



Trained with ν_e CC events for signal, ν_μ CC/NC & $\nu_{e,\tau}$ NC for bkg

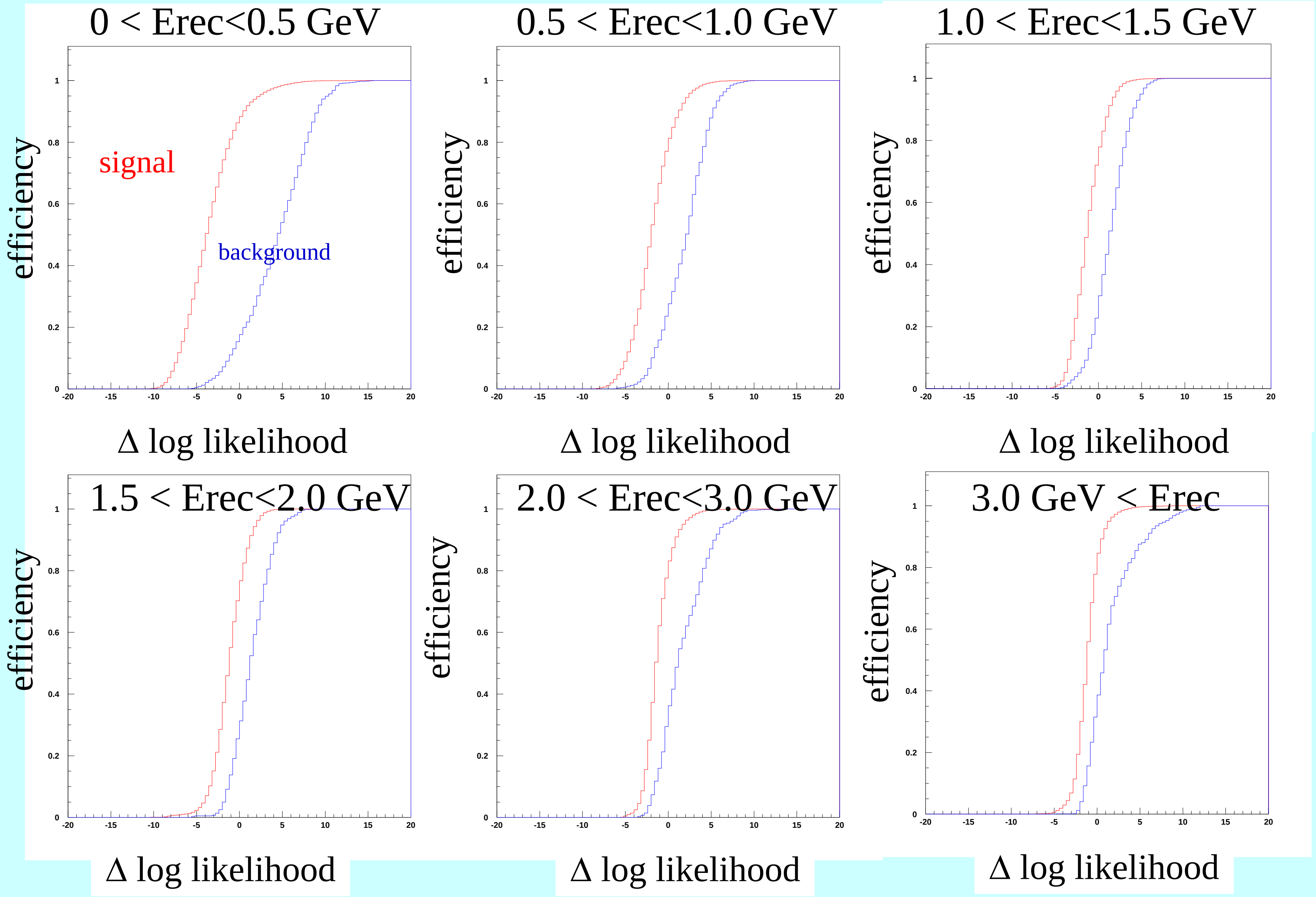
- Δ log likelihood distributions

log likelihood ratio (signal vs. background)



Trained with ν_e CC events for signal, ν_μ CC/NC & $\nu_{e,\tau}$ NC for bkg

Efficiency of a cut on Δ log likelihood (signal vs background)



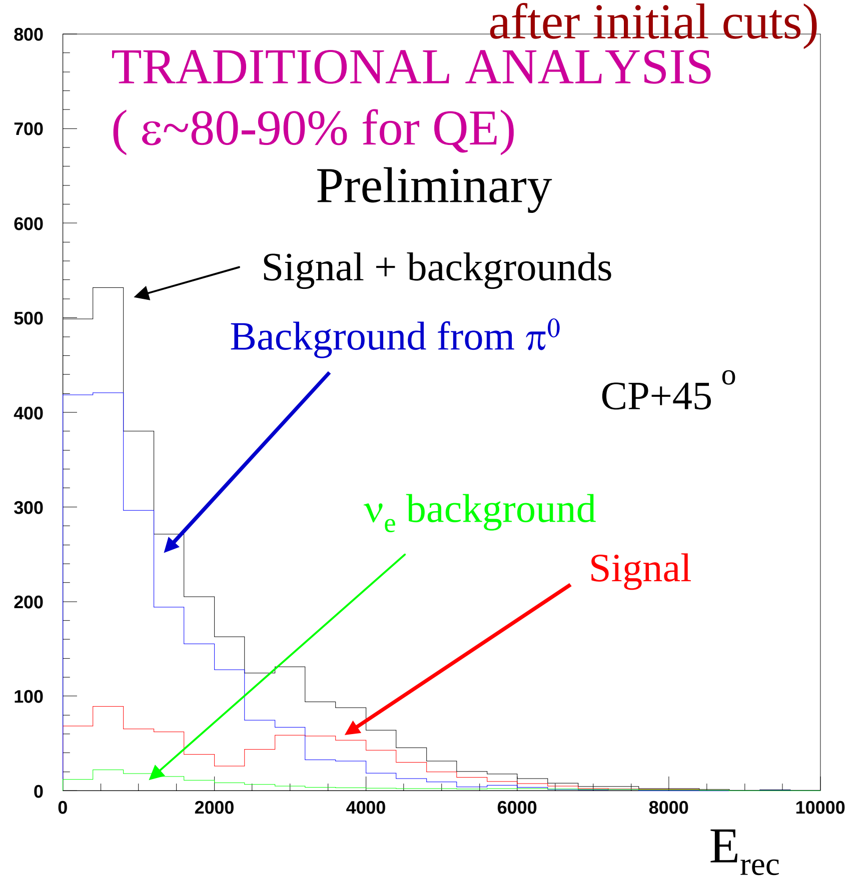
BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

After initial cuts

No Δ log likelihood cut (100% signal retained after initial cuts)

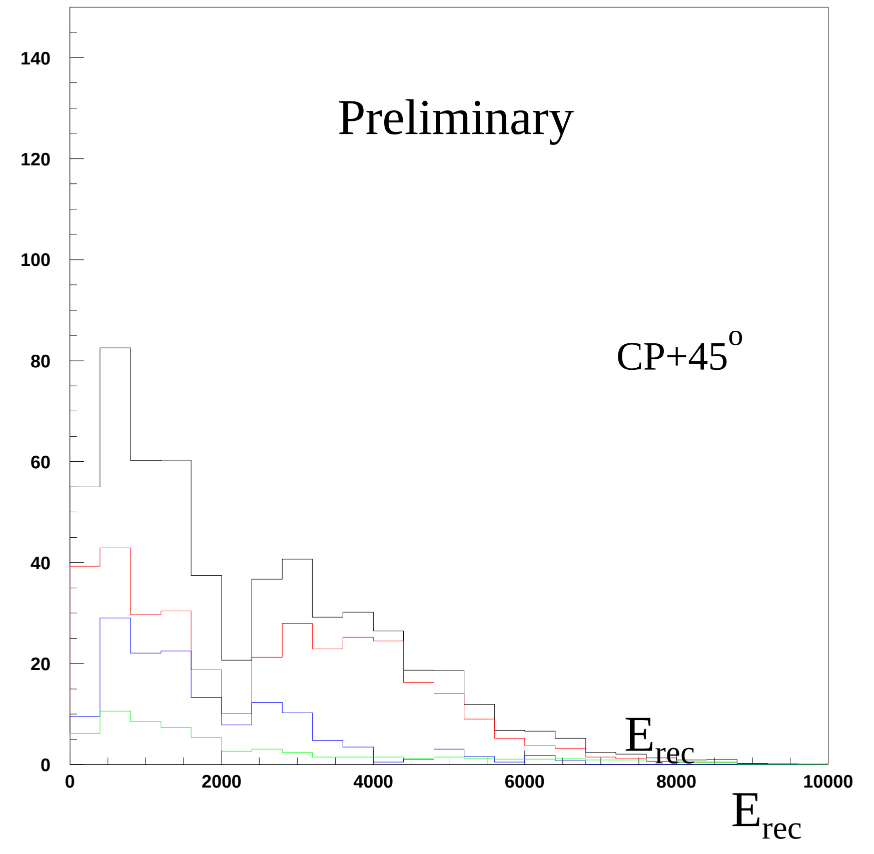


Signal 700 ev Bkgs 2004

(1877 from π^0+others)

(127 from ν_e)

Δ log likelihood cut (~50% signal retained)



Signal 350 ev Bkgs 169

(147 from π^0+others)

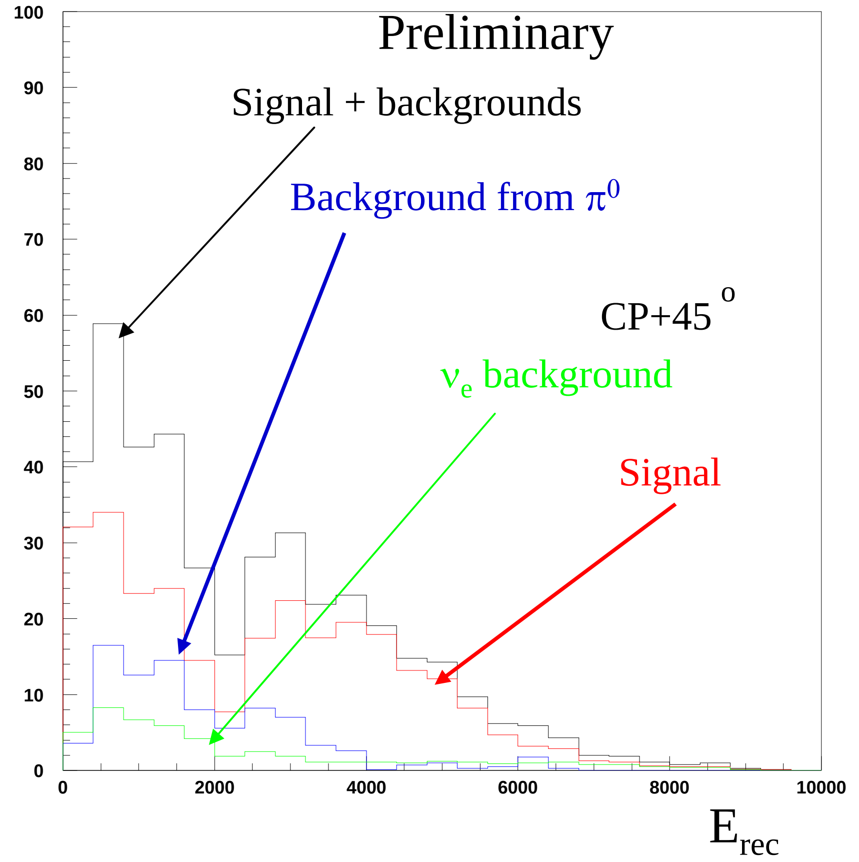
(61 from ν_e)

BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log likelihood cut (40% signal retained)

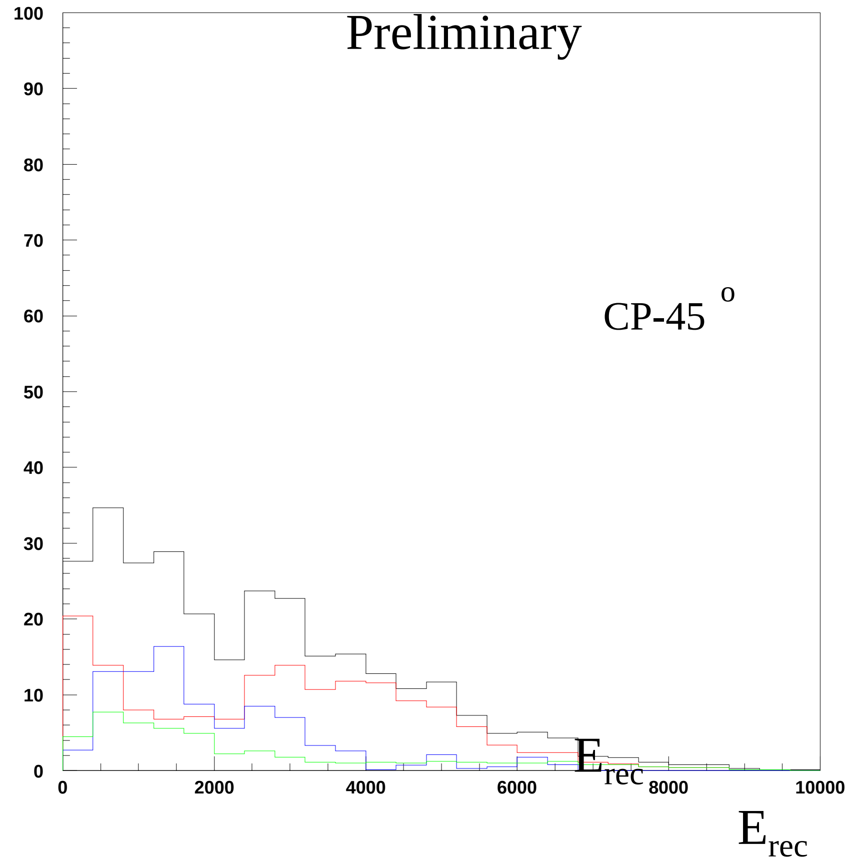


Signal 280 ev Bkgs 136

(87 from π^0+others)

(49 from ν_e)

Δ log likelihood cut (~40% signal retained)



Signal 158 ev Bkgs 135

(87 from π^0+others)

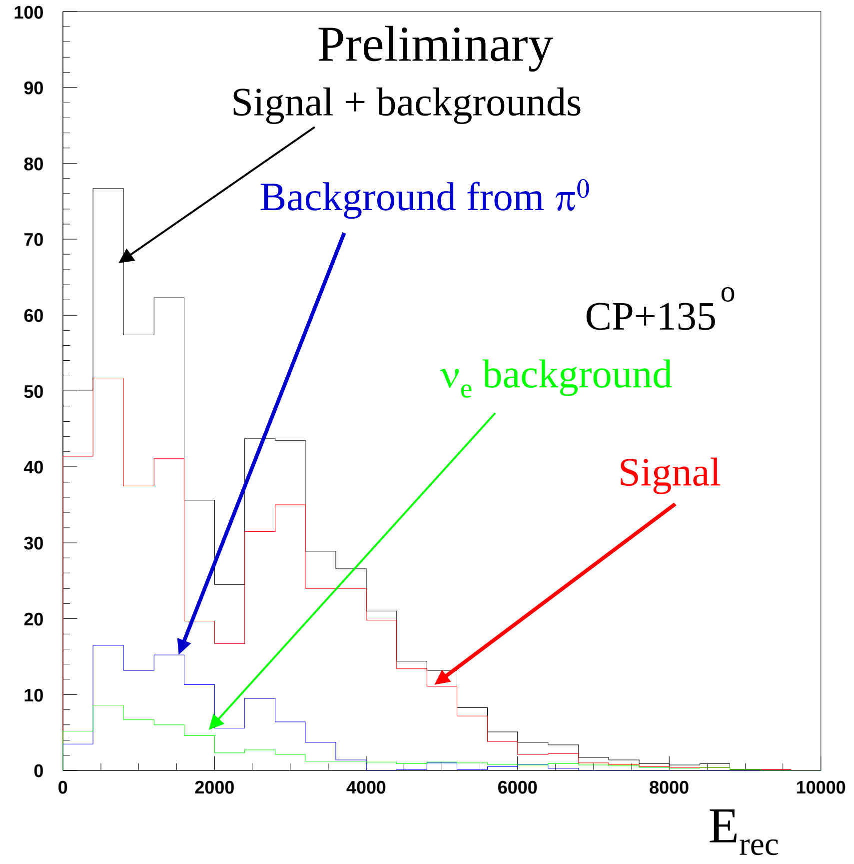
(48 from ν_e)

BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

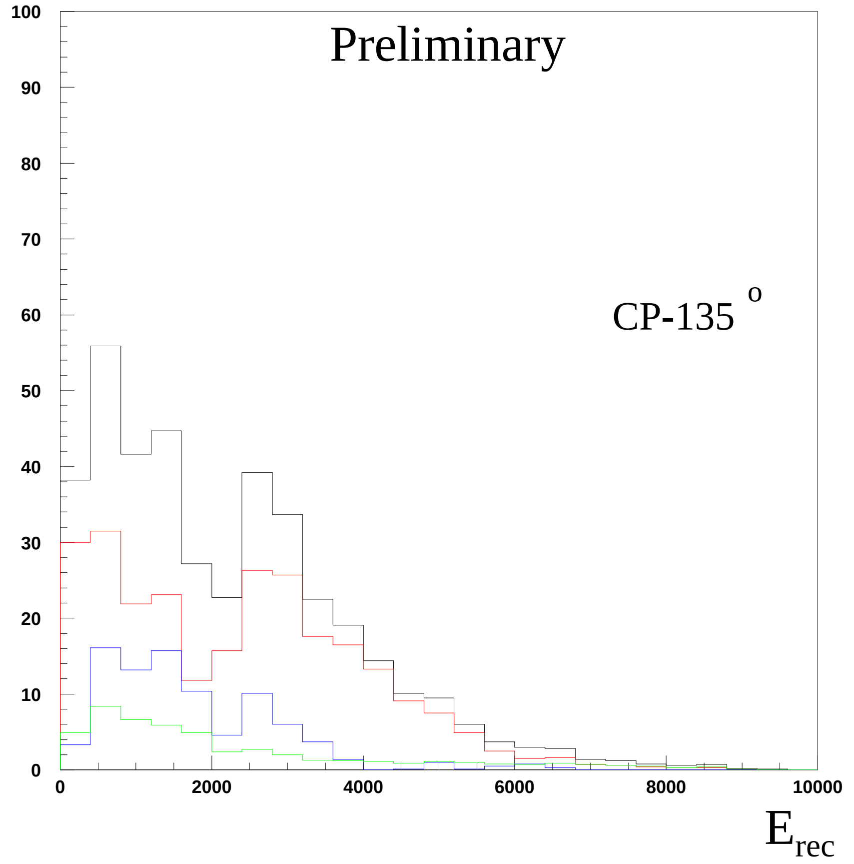
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam
for backgrounds

Δ log likelihood cut (40% signal retained)



Signal 386 ev Bkgs 136
(89 from π^0+others)
(50 from ν_e)

Δ log likelihood cut (~40% signal retained)



Signal 263 ev Bkgs 136
(87 from π^0+others)
(49 from ν_e)

BNL-Homestake (2540 km)

- Effectiveness of variables

Neutrino oscillation was on to define template distributions. For analysis with CPV=+45°

Variable removed	Signal	Bkg	Effic	Signal	Bkg π^0	Beam ν_e	$S/B(\pi^0)$
None	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	280	87	49	3.22
Δpi0lh	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	281	102	50	2.75
poa	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	281	94	49	2.98
pi0-lh	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	278	94	51	2.95
e-lh	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	277	94	46	2.96
efrac	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	281	98	49	2.85
pi0mass	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	280	105	50	2.66
costh	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	279	101	49	2.76
ange	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	280	98	49	2.86
dlfct	ν_e CC	ν_μ all, ν_e,ν_τ NC	40%	277	95	49	2.93

BNL-Homestake (2540 km)

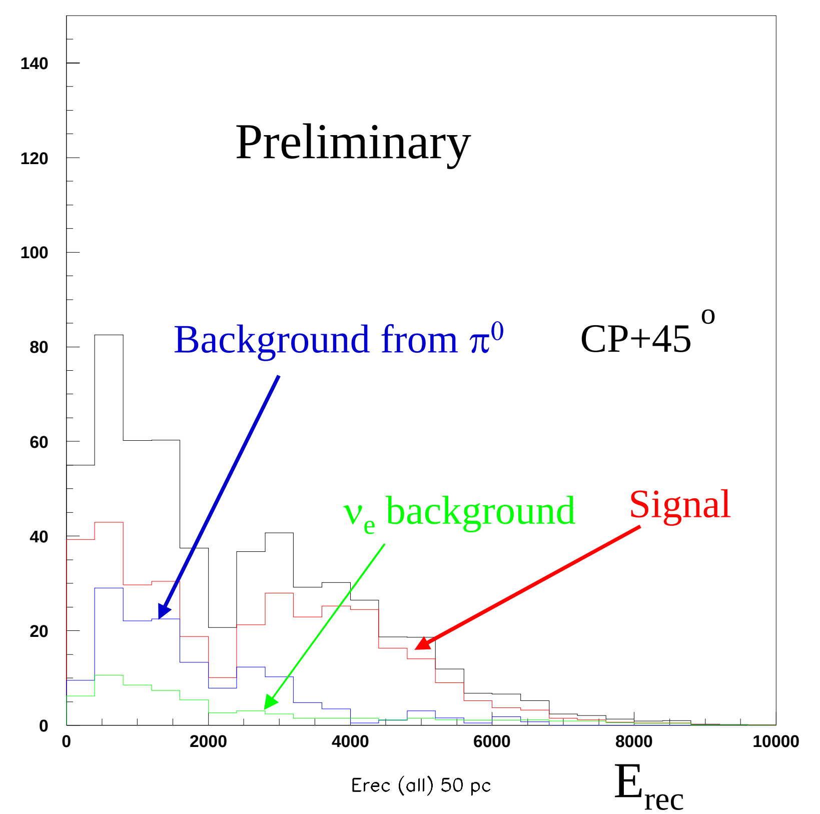
• Breakdown of interaction mode

Interaction mode	$0<E_{rec}<1$ GeV		$1<E_{rec}<2$ GeV		$2<E_{rec}<3$ GeV		3 GeV $<E_{rec}$	
	Sig	Bkg π^0	Sig	Bkg π^0	Sig	Bkg π^0	Sig	Bkg π^0
CC QE	82%	7%	69%	1%	28%	0%	50%	0%
$1\ \pi^0$	3%	3%	5%	8%	11%	0%	8%	0%
$1\ \pi^{+-}$	14%	7%	22%	1%	45%	0%	30%	0%
DIS	1%	0%	3%	1%	15%	18%	13%	0%
NC $1\ \pi^0$	0%	39%	0%	68%	0%	23%	0%	25%
$1\ \pi^{+-}$	0%	29%	0%	3%	0%	0%	0%	0%
DIS	0%	11%	0%	9%	0%	59%	0%	75%
Others	0%	3%	1%	10%	3%	0%	0%	0%

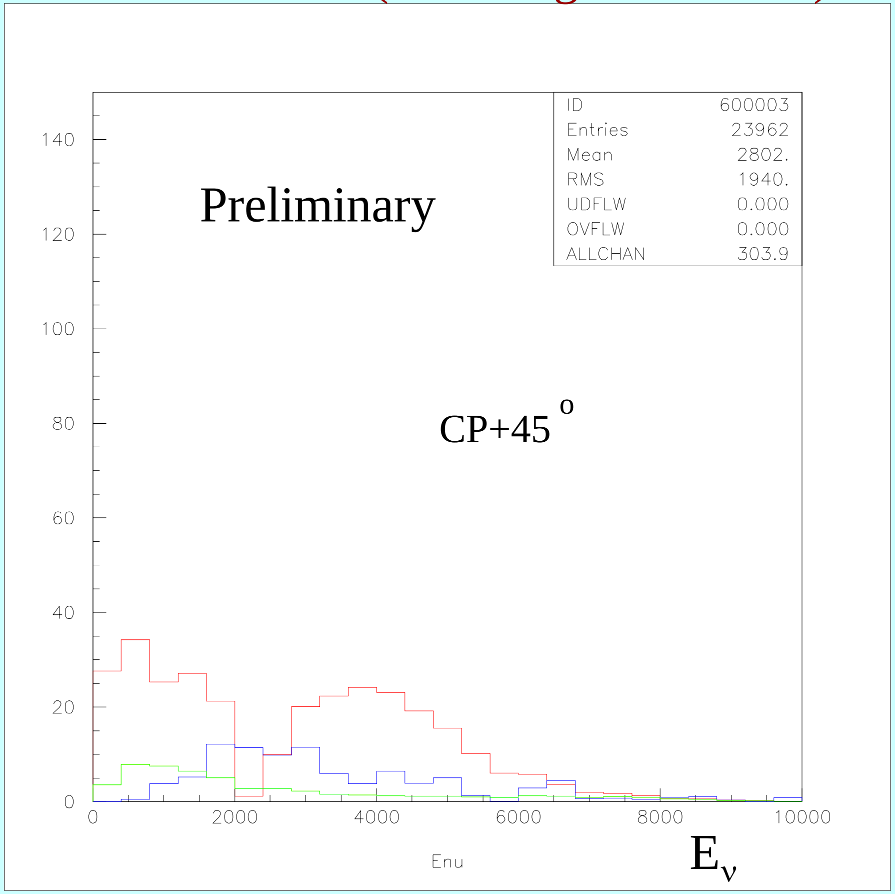
BNL-Homestake (2540 km)

- E_{rec} vs. E_ν

Δlikelihood cut (~40% signal retained)



Δlikelihood cut (~40% signal retained)

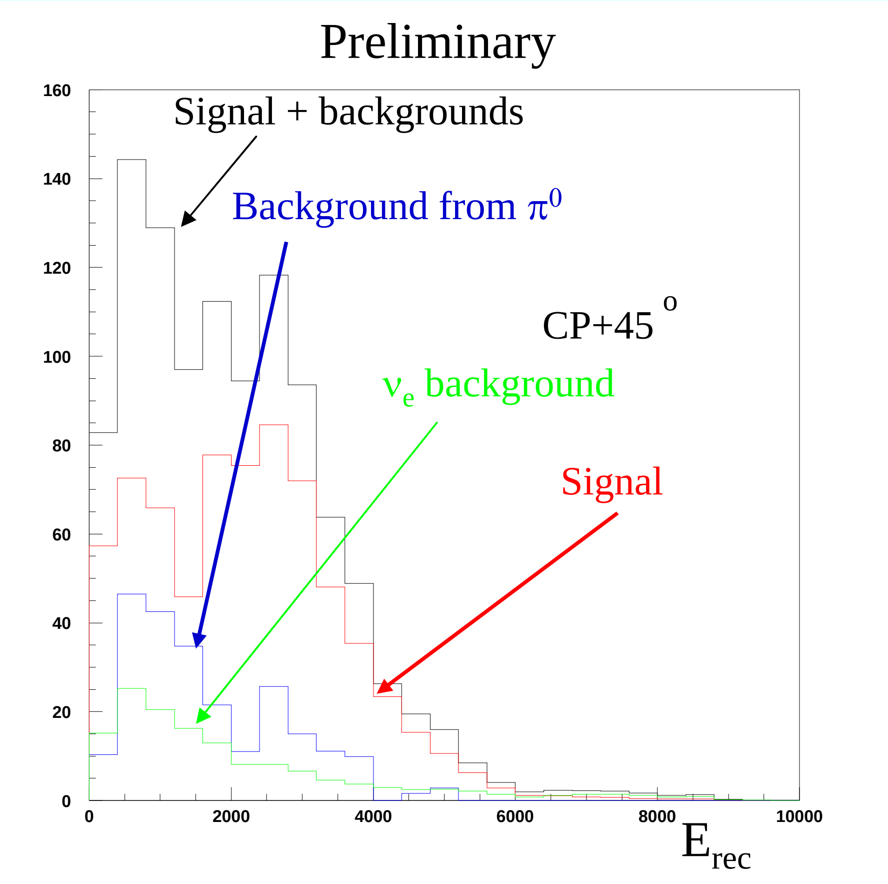


Fermilab-Henderson (1480 km)

- Effect of cut on Δ log likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log likelihood cut (40% signal retained)

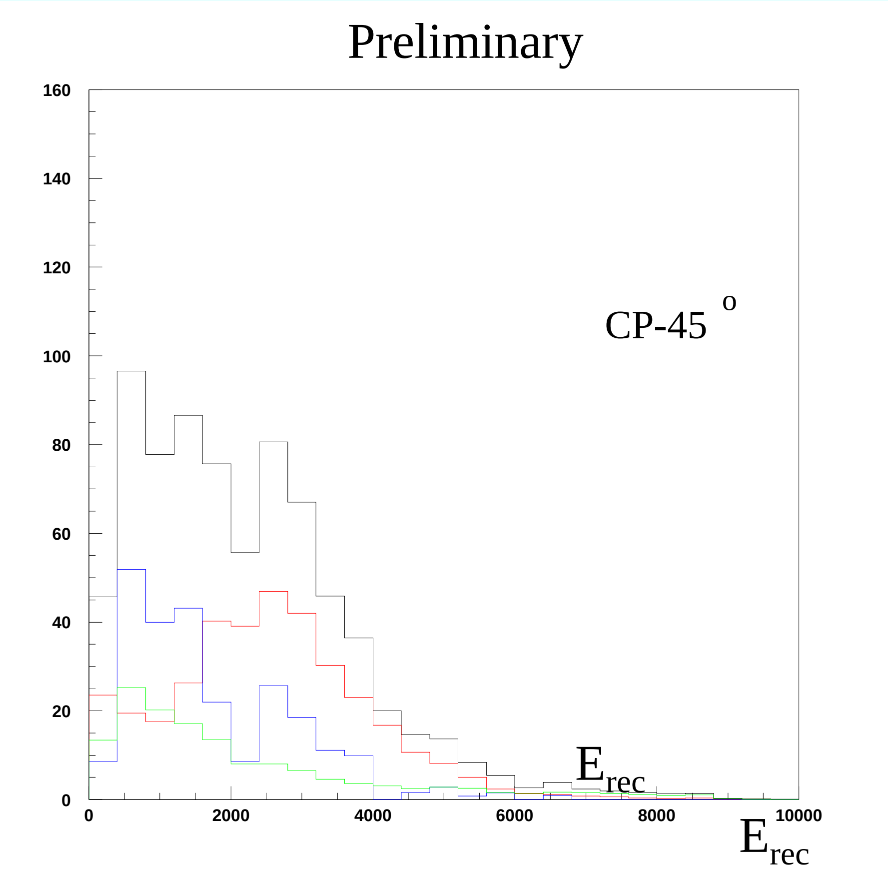


Signal 699 ev Bkgs 373

(233 from π^0+others)

(141 from ν_e)

Δ log likelihood cut (~40% signal retained)



Signal 357 ev Bkgs 389

(247 from π^0+others)

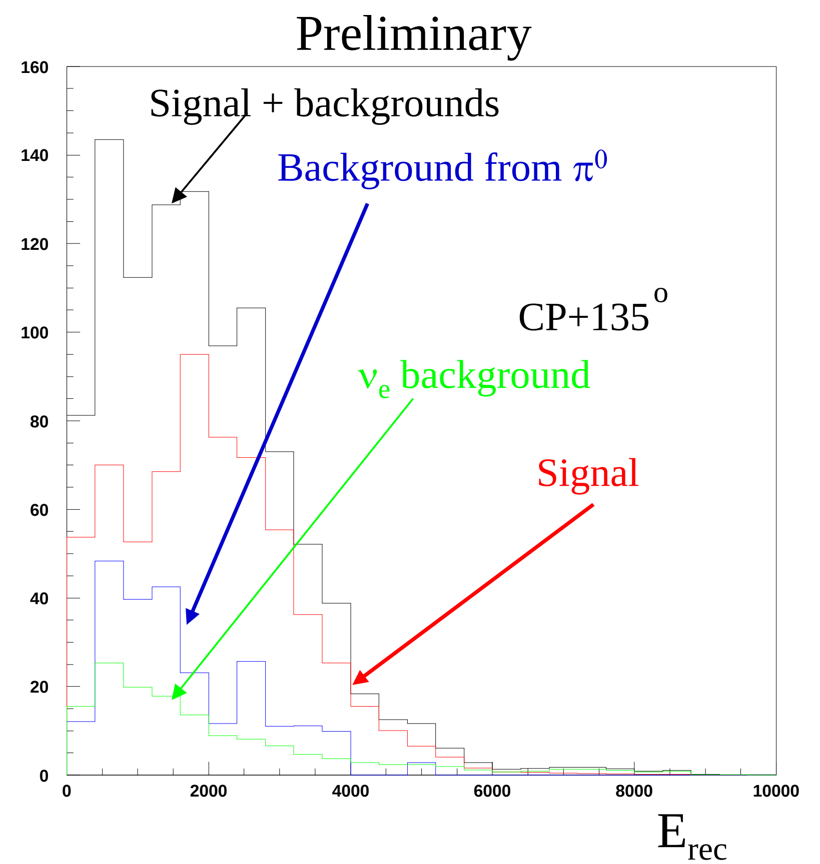
(142 from ν_e)

Fermilab-Henderson (1480 km)

- Effect of cut on Δ ln likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log likelihood cut (~40% signal retained)

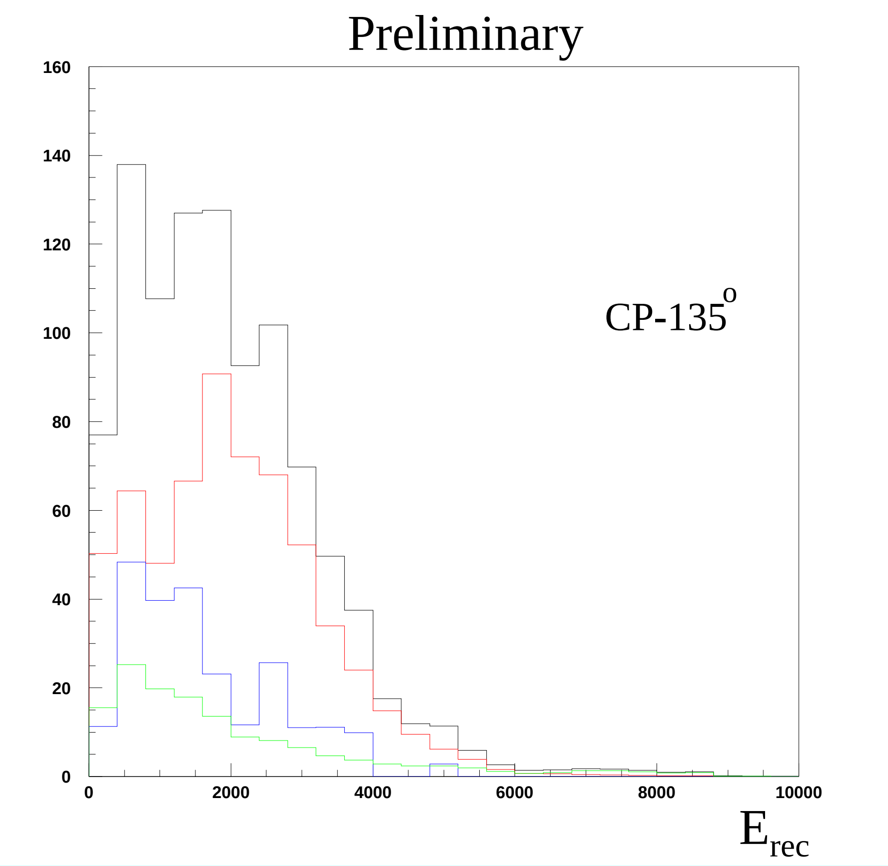


Signal 645 ev Bkgs 379

(237 from π^0+others)

(142 from ν_e)

Δ log likelihood cut (~40% signal retained)



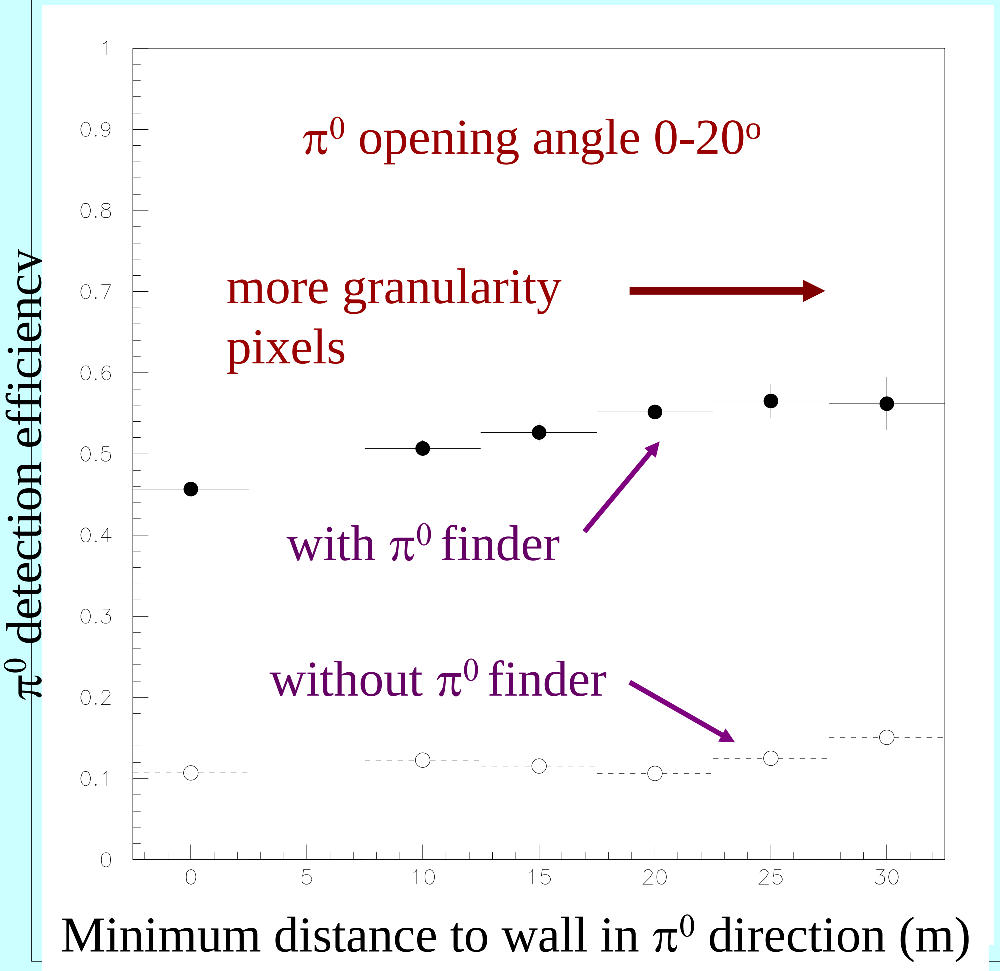
Signal 609 ev Bkgs 379

(237 from π^0+others)

(142 from ν_e)

• Granularity and π^0 efficiency for same PMT coverage

Expected improvement with UNO?



Compared with a smaller detector

- π^0 efficiency improves when min. distance increases (up to 20%)
- For smaller π^0 opening angle finer granularity is needed.
- See the power of the π^0 finder
- What PMT coverage needed? 10,20,40% (SK-I has 40% coverage)

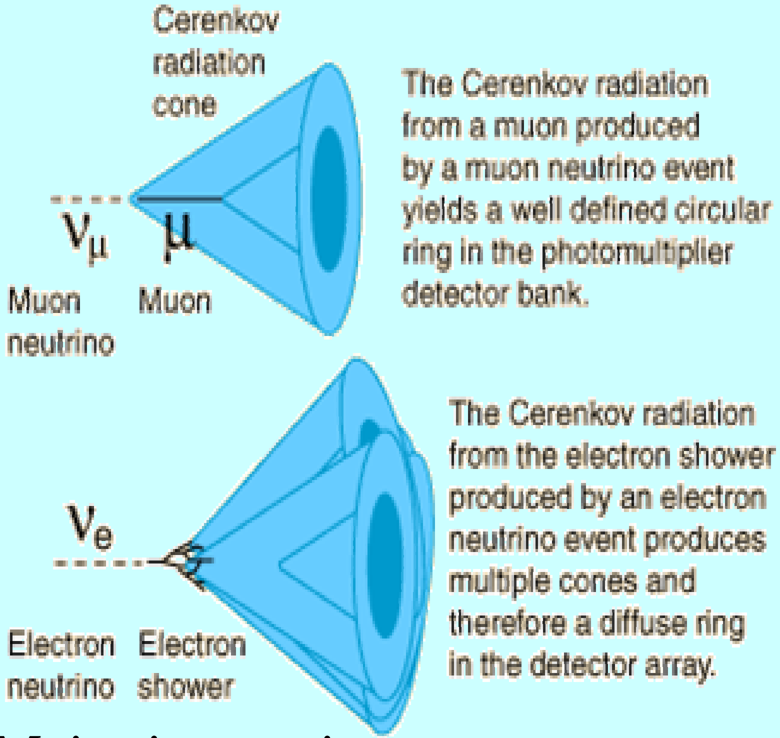
• Conclusions

- Realistic MC simulation studies have been performed for the BNL very long baseline scenario with a water Cherenkov detector. It was found that BNL wideband ν_μ beam combined with a UNO type detector DO A GREAT JOB whether the baseline is 2,540 km or 1,480 km.
  – Very exciting news ! But always do proper MC simulations!
- It was demonstrated that there is room to greatly improve S/B ratio beyond the standard water Cherenkov detector reconstruction codes even with currently available codes.
  - We may need further improvement of algorithm/software, which is quite doable.
  - Detailed studies on sensitivity on oscillation parameters needed with different neutrino spectrum to optimize the beam spectrum.
  - A larger detector such as UNO has an advantage over a smaller detector such as SK (we learned a lesson from 1kt at K2K): Both PMT coverage AND granularity are important
- In collaboration with BNL and Fermilab, proper simulations of a next generation water Cherenkov detector, its optimized design with reasonable ν_μ beam will produce sweet fruits for exciting physics

Backup Slides

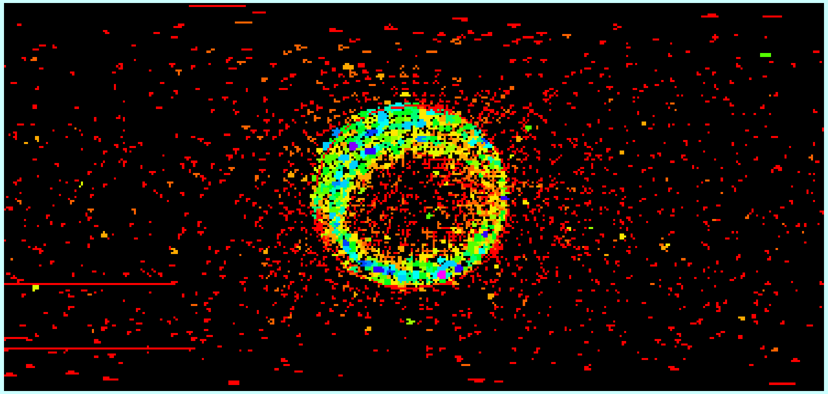
Electron-like vs. muon-like ring

How do we detect muon and electron neutrinos ?

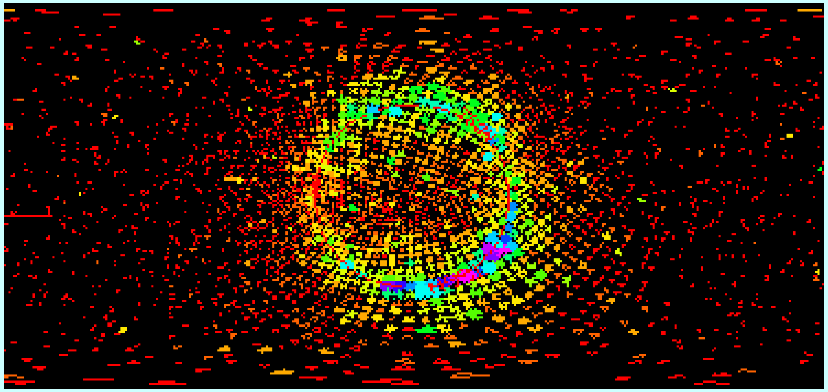


The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.



muon-like ring



electron-like ring

Major interactions:

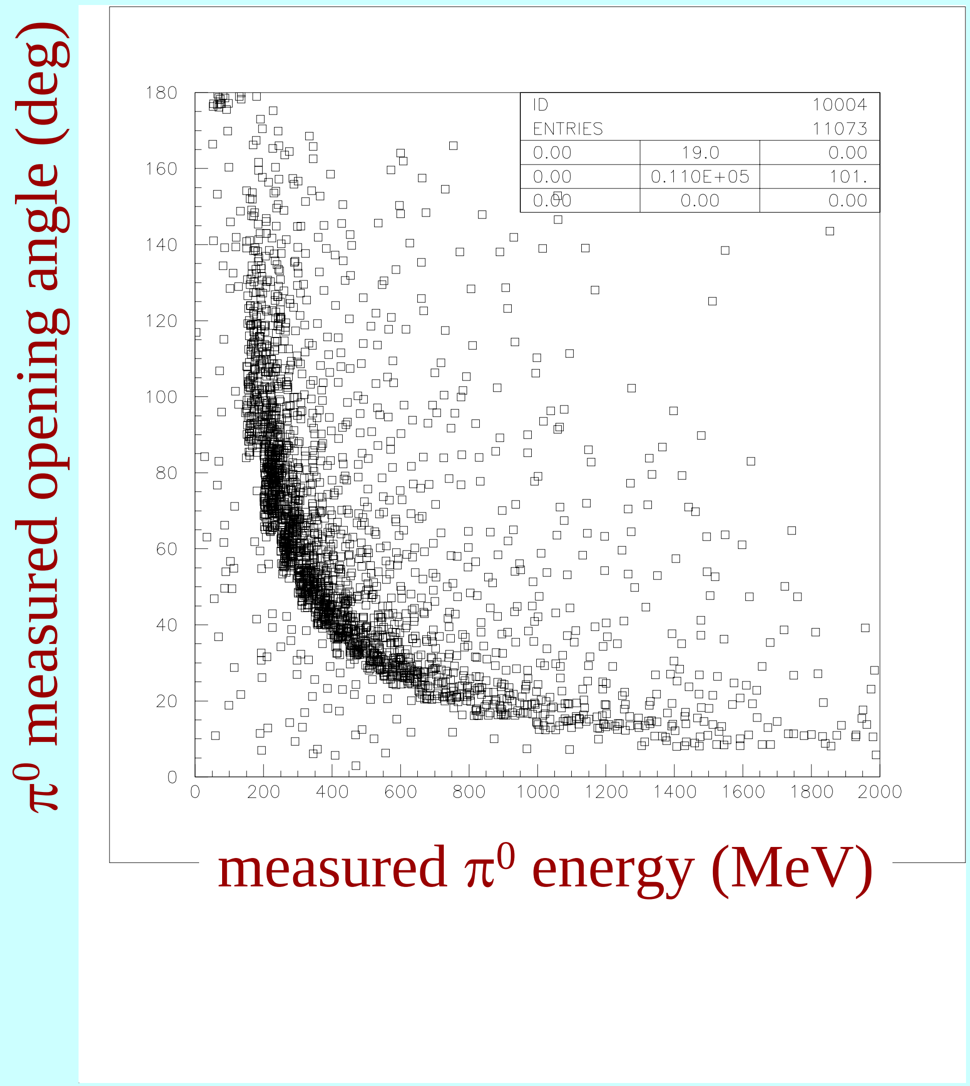
$\nu_e \ + n -> \boxed{p} + \boxed{e^-}$

$\nu_\mu \ + n -> \boxed{p} + \boxed{\mu^-}$

Most of time invisible

π^0 efficiency

- **π^0 opening angle vs. measure π^0 energy**



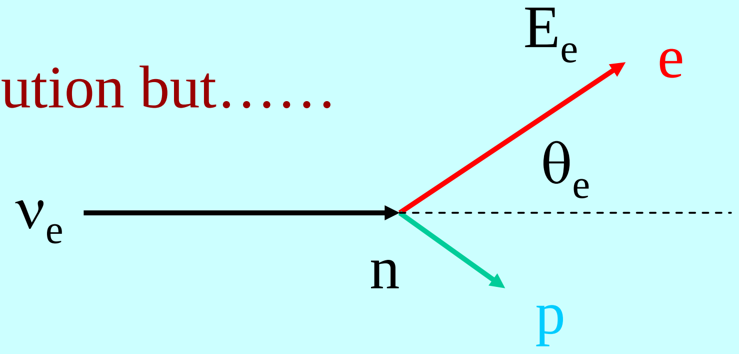
Note: The energy spectrum of π^0 is that of SK atm. ν interactions

- What are sources of the signal?

  - **Neutrino energy reconstruction**

    QE events give the best energy resolution but……

$$E_\nu^{rec} = \frac{m_N E_e}{m_N - (1 - \cos\theta_e) E_e}$$



E_e

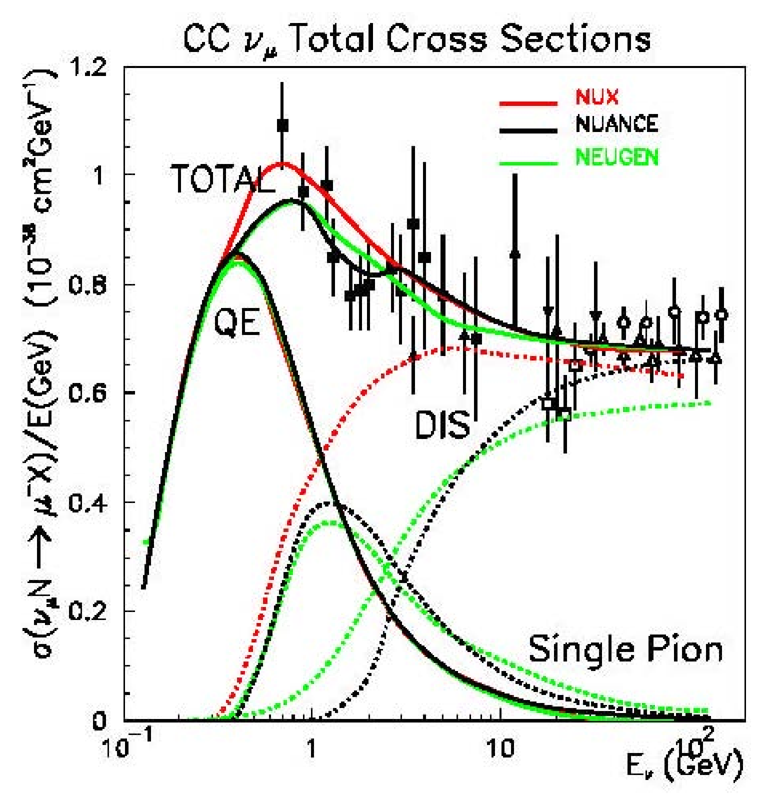
e

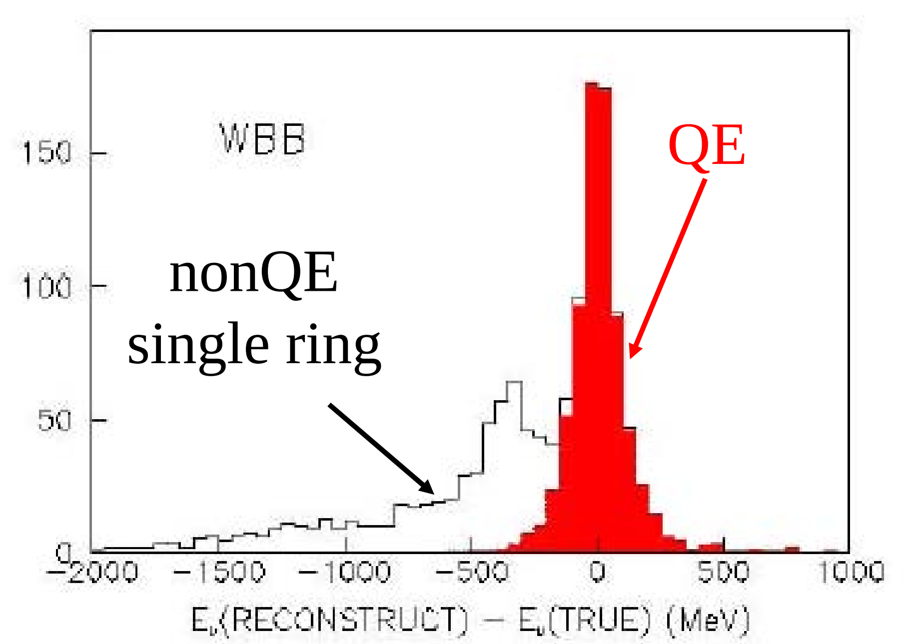
θ_e

ν_e

n

p



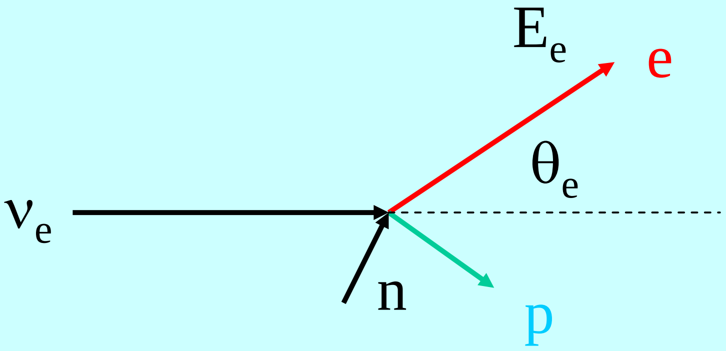


QE

nonQE
single ring

- costh = cos θ_e

$$E_\nu^{rec} = \frac{m_N E_e}{m_N - (1 - \cos\theta_e) E_e}$$

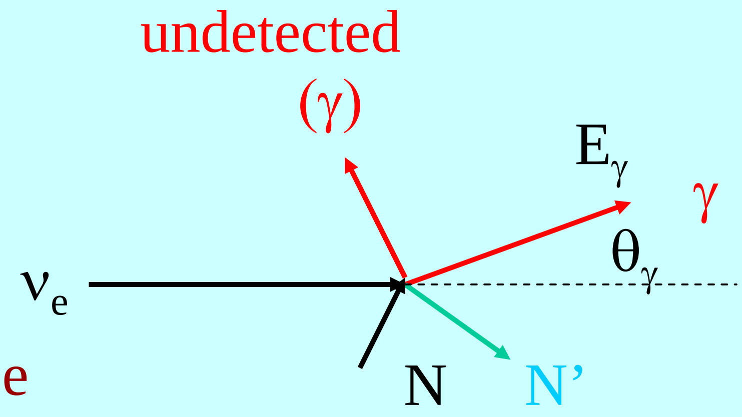


It is not clear why the distributions of costh behave as shown in the following.

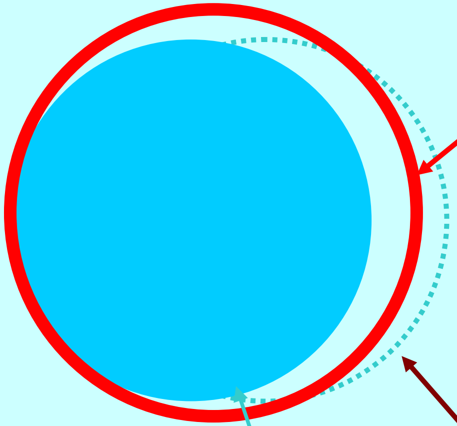
My speculation:

1) The signal events from QE scattering have larger θ_e due to the Fermi motion of the target neutron in oxygen in the low energy region.

2) For lower energy background events, the minimum opening angle is larger. In those events accepted as signal, π^0 decay is very asymmetric and the primary γ carries most of the energy.



- e-likelihood



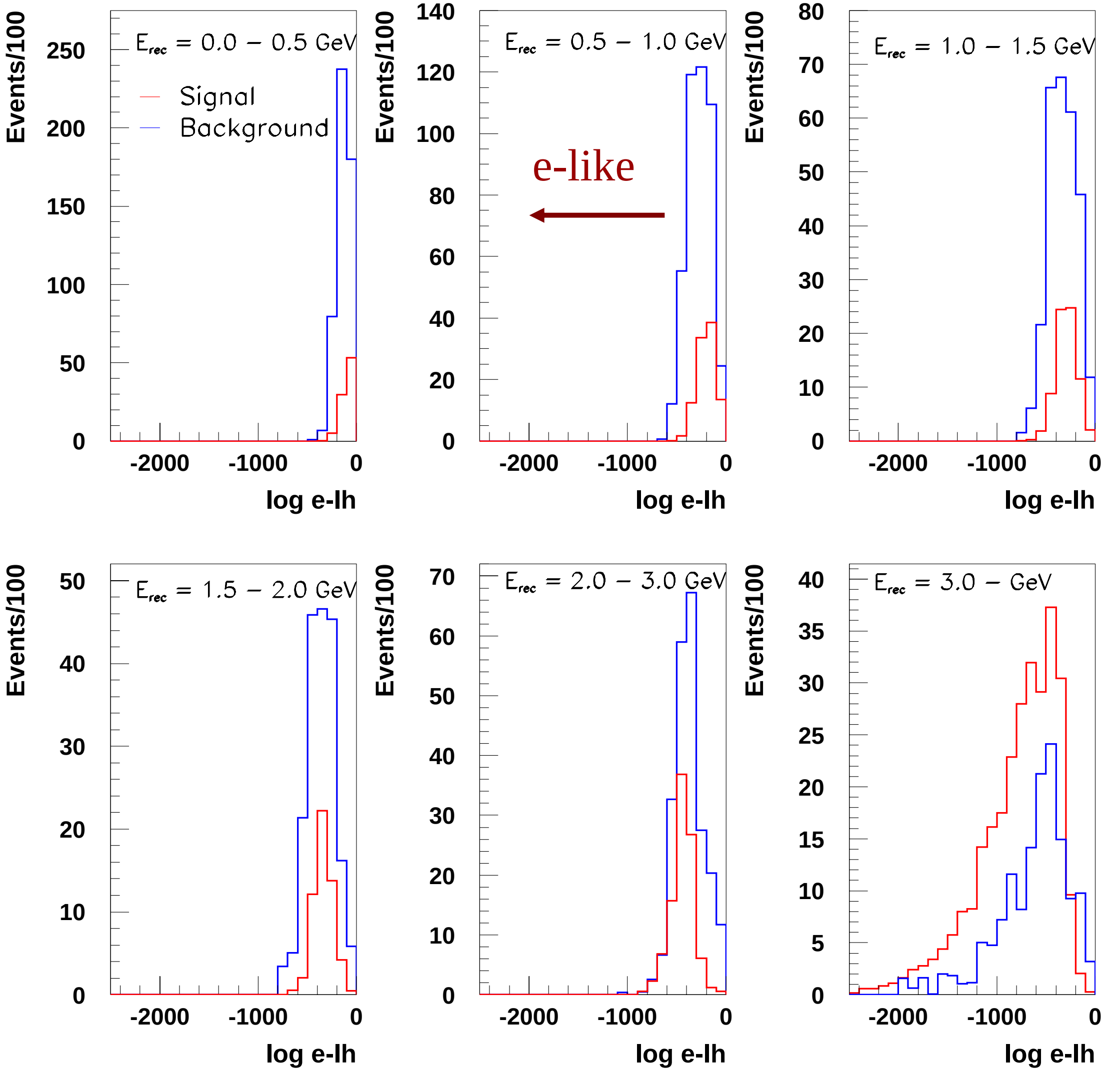
Found as an electron

- Two overlapped e-like rings identified as an e-like ring look like a fuzzier electron than an electron at lower energy
- At higher energy multiple particles go into a similar direction and identified as an e-like ring – could look less fuzzy than an electron

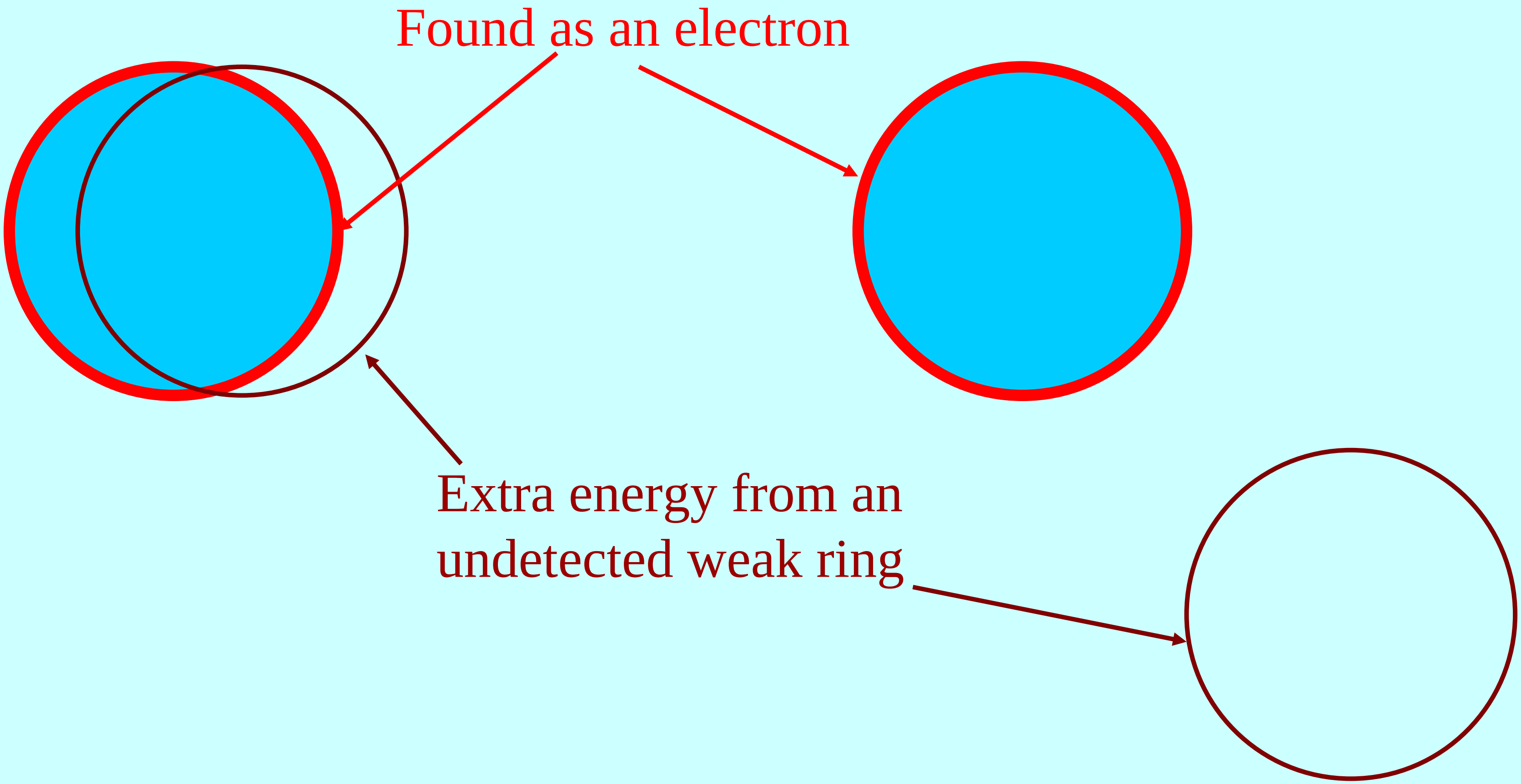
Extra energy from an undetected weak ring

primary ring

e-likelihood


e-like

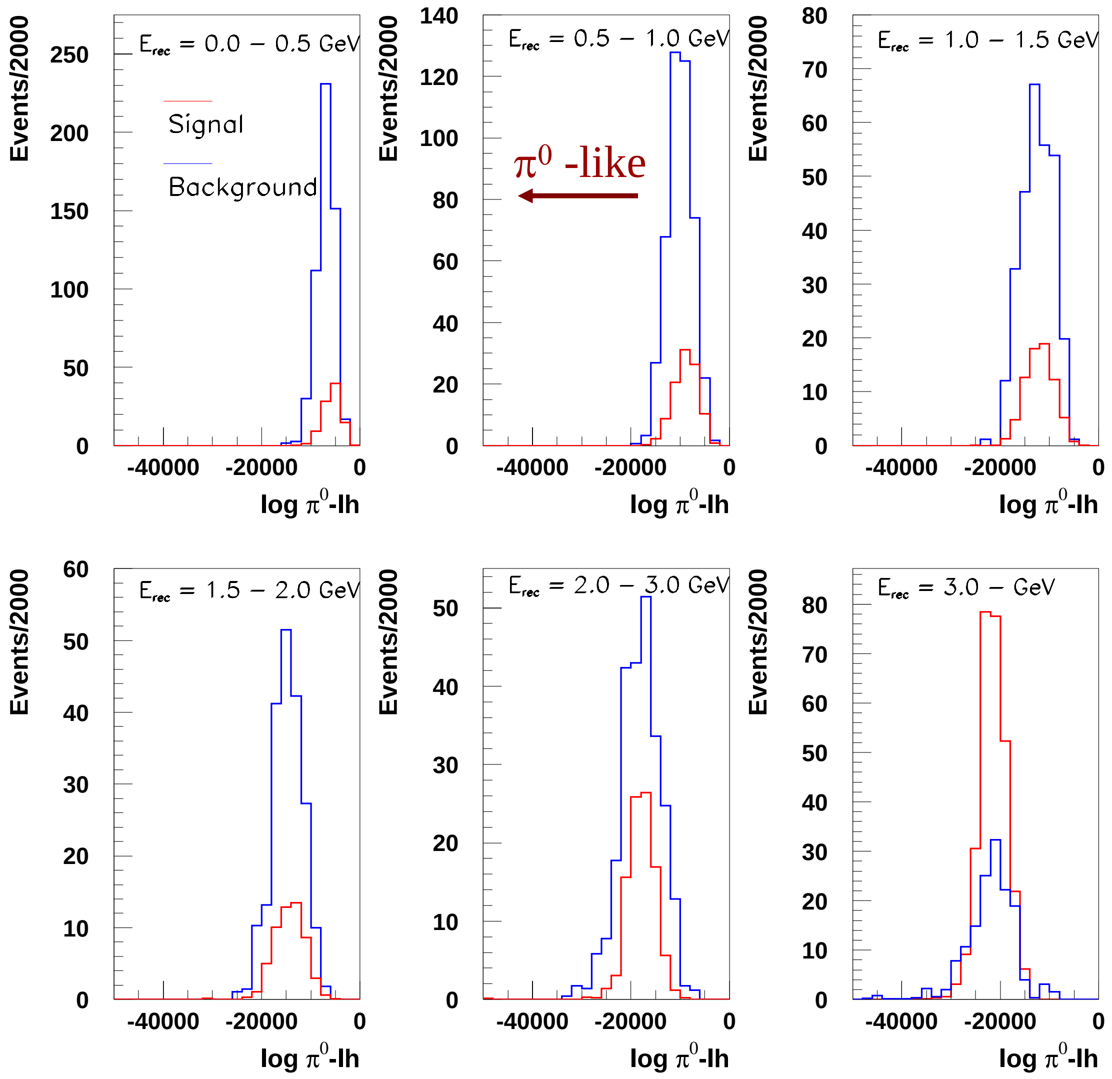
- **π^0 likelihood** tells whether an event is consistent with a single π^0 event



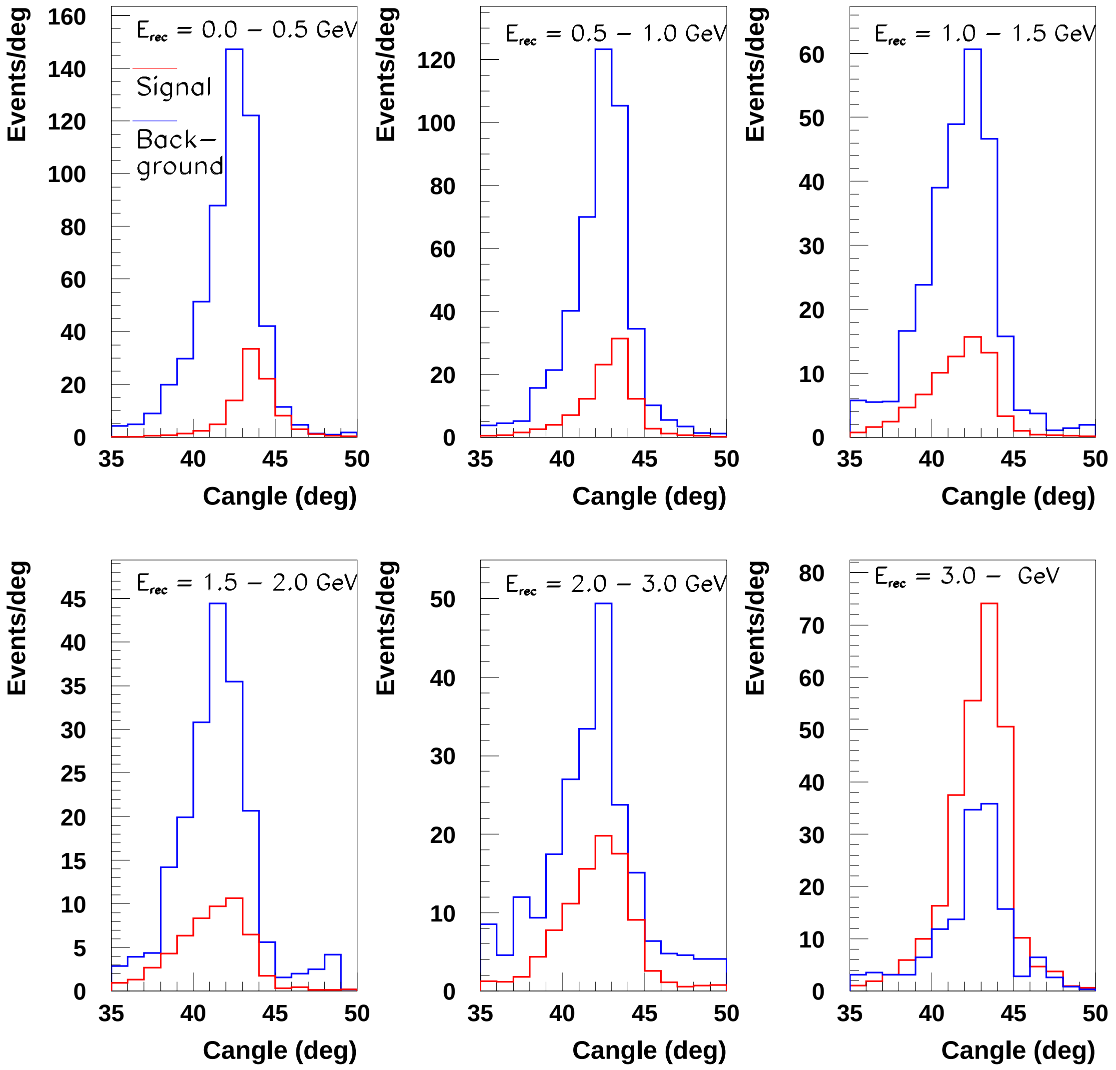
Found as an electron

Extra energy from an undetected weak ring

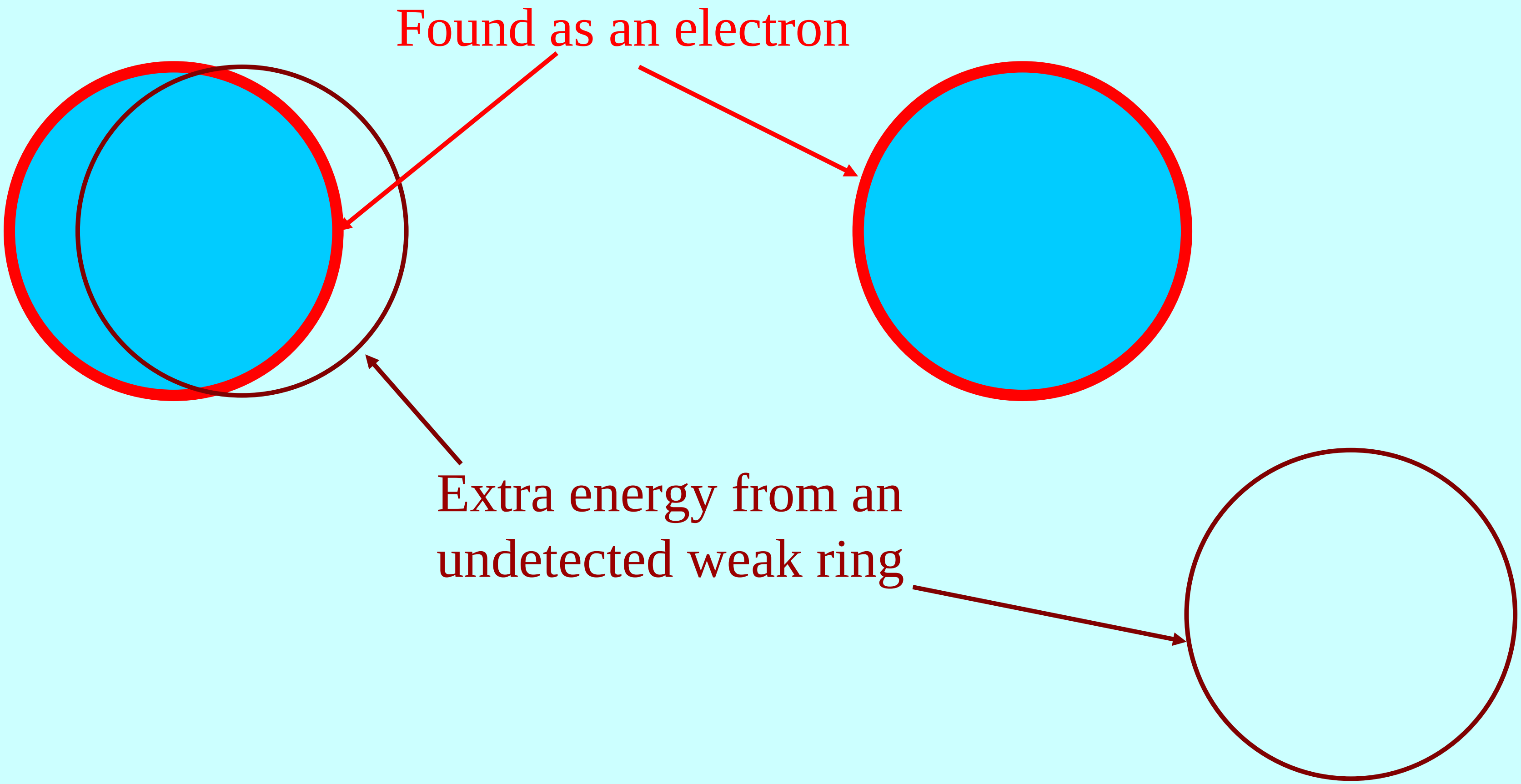
π^0 likelihood



- Cherenkov angle (ange)



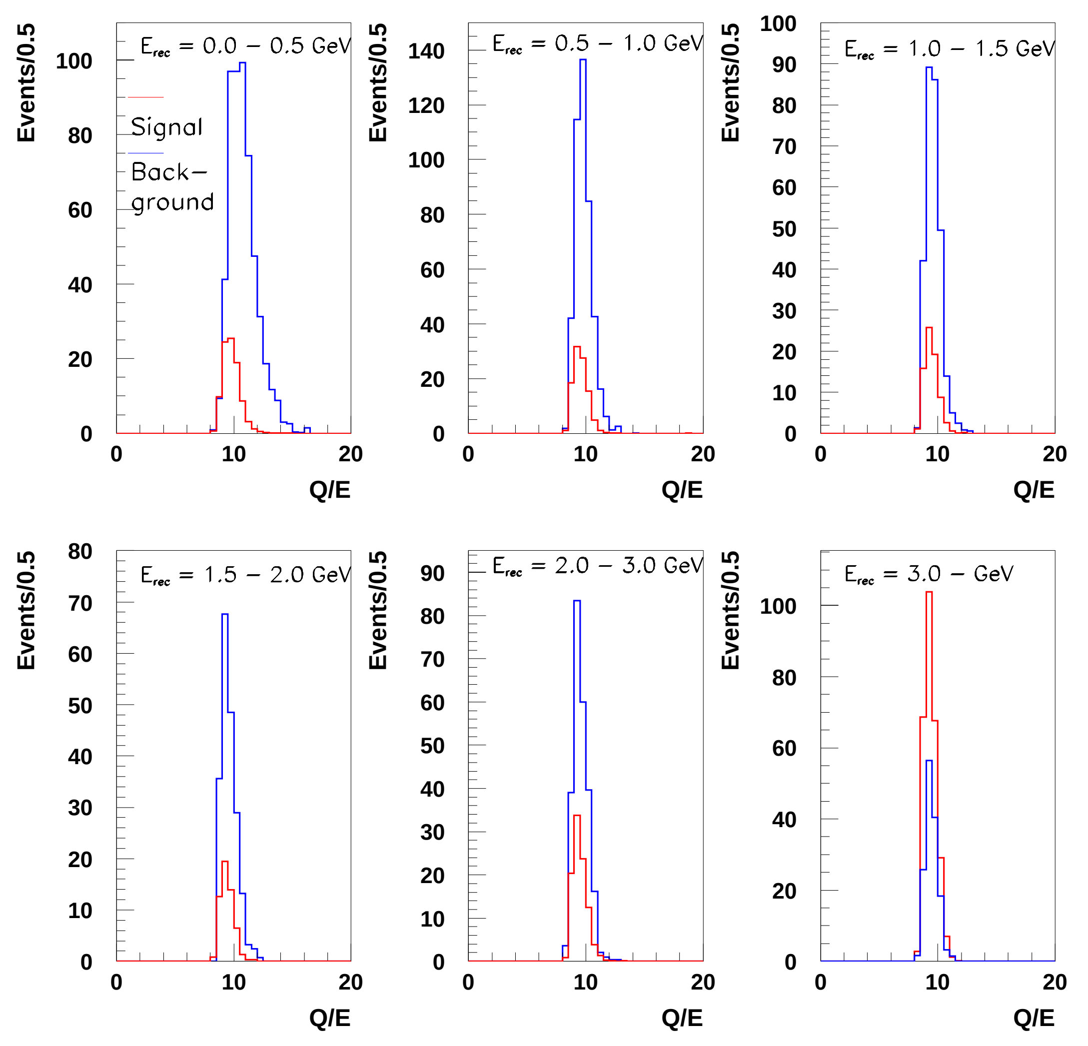
- Total charge/primary ring energy (poa)



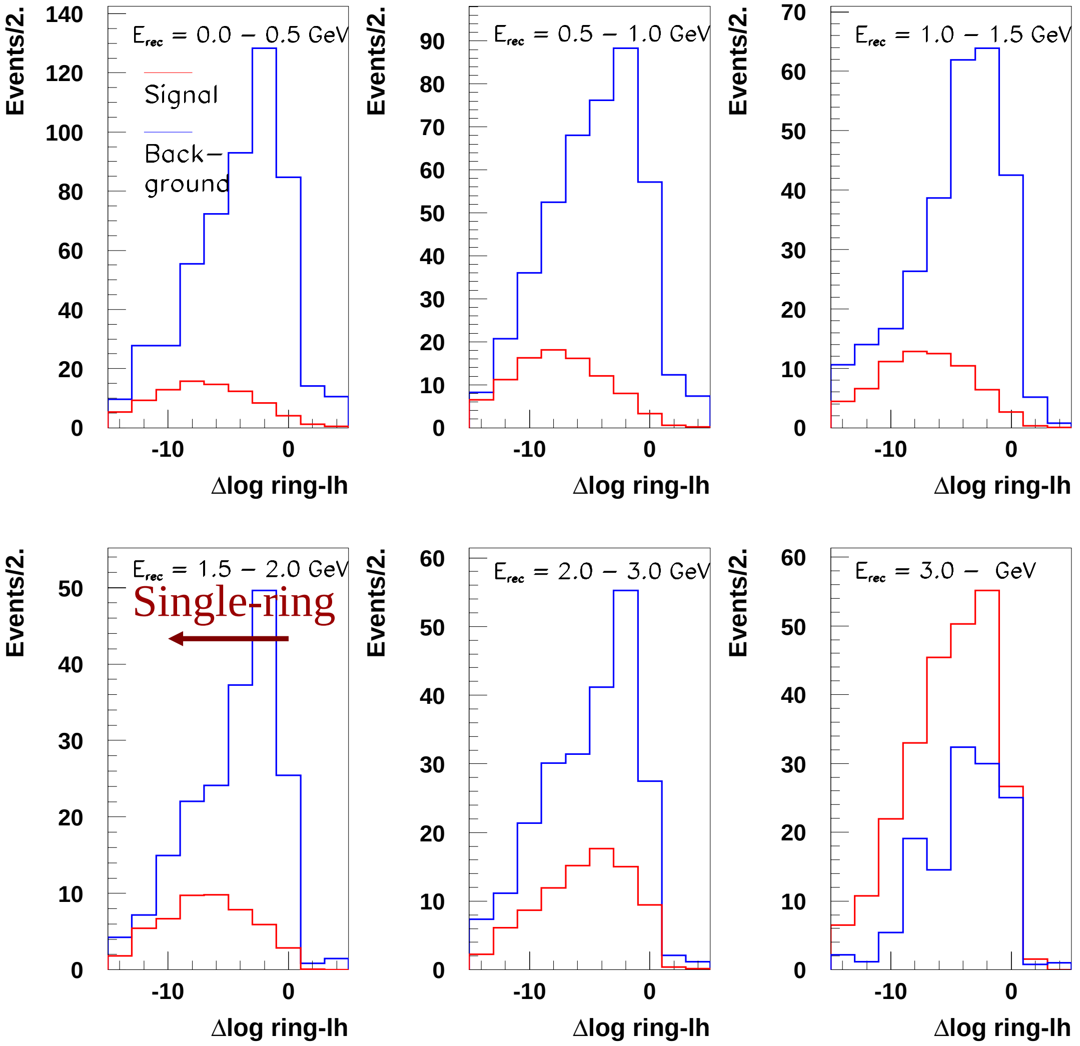
Found as an electron

Extra energy from an undetected weak ring

- Total charge/primary ring energy (poa)



- Single-ring-ness (dlfct)



Single-ring

- S/B

2540 km

Summary of analysis of BNL superbeam@HS

CP phase	Signal	Bkg	Effic	Signal	Bkg	Beam ν_e
0^o	ν_e CC	ν_μ all, ν_e NC	~40%	197	90	48
-135^o	ν_e CC	ν_μ all, ν_e NC	~40%	263	87	49
$+135^o$	ν_e CC	ν_μ all, ν_e NC	~40%	386	89	50
-45^o	ν_e CC	ν_μ all, ν_e NC	~40%	159	87	48
$+45^o$	ν_e CC	ν_μ all, ν_e NC	100%	700	1878	127
			~50%	349	145	62
			~40%	279	87	49

with traditional water Cherenkov cuts

- S/B

1480 km

Summary of analysis of Fermilab superbeam@HN

CP phase	Signal	Bkg	Effic	Signal	Bkg	Beam ν_e
0^o	ν_e CC	ν_μ all, ν_e NC	~40%	498	230	140
-135^o	ν_e CC	ν_μ all, ν_e NC	~40%	609	237	142
$+135^o$	ν_e CC	ν_μ all, ν_e NC	~40%	646	238	142
-45^o	ν_e CC	ν_μ all, ν_e NC	~40%	357	247	142
$+45^o$	ν_e CC	ν_μ all, ν_e NC	100%	1754	5395	374
			~50%	877	415	177
			~40%	699	233	141

with traditional water Cherenkov cuts

• Future prospect/plans

- All the variables used to define the likelihood seem useful : any more?
- Some variables associated with some pattern recognition such as π^0-likelihood and e-likelihood seem quite useful

  More sophisticated pattern recognition algorithm is desirable and possible
- ν_τ CC interactions in water need to be simulated

  My first guess is that the contribution from these interactions is not large because τ is mostly produced by DIS and in general there are many particles in the event (not a single ring event).
- This kind of analysis can give an insight to optimize neutrino beam spectrum

  Studies on sensitivities to oscillation parameters should be done

  Careful study of the source of background and the associated neutrino energy is needed

  What granularity UNO needs to have?