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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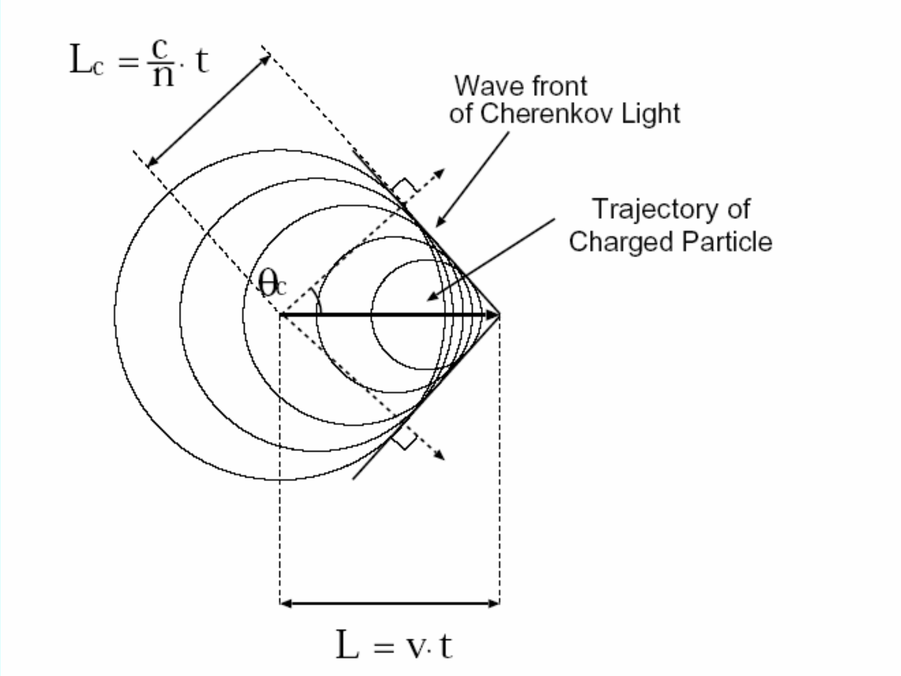
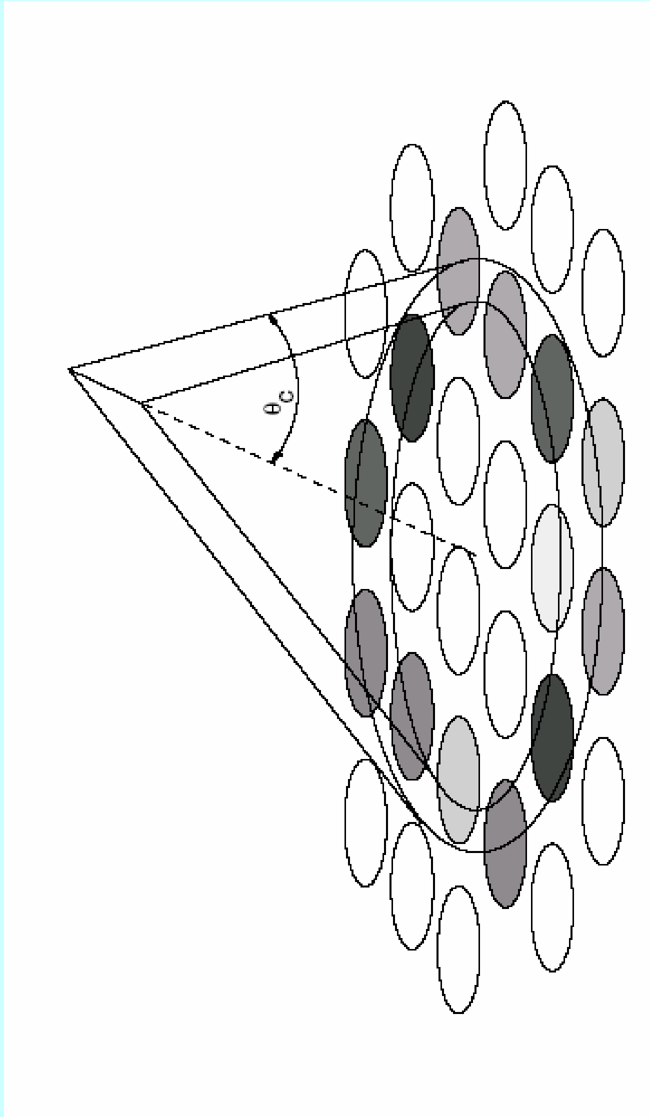
Water Cherenkov Detector a la SK

Cherenkov radiation





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

Threshold p: muon 121 MeV/c
pion 160 MeV/c
proton 1070 MeV/c

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

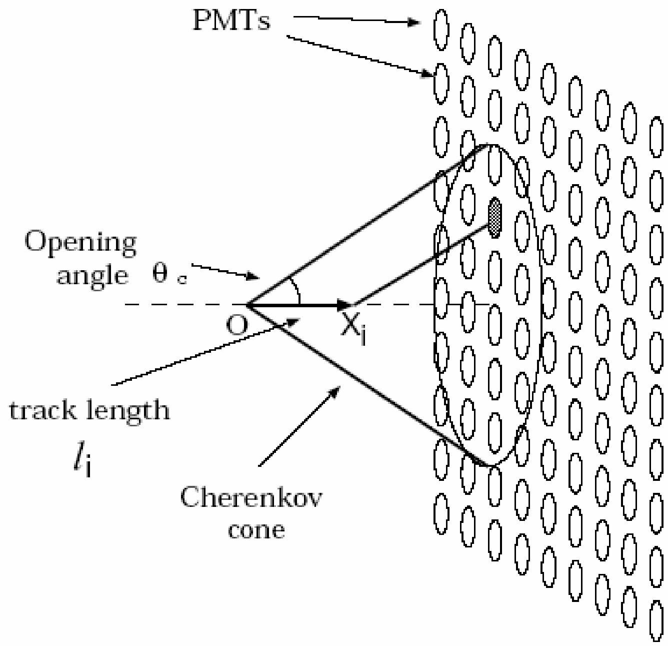
390 photons per 1 cm
(300 nm < λ < 700 nm)

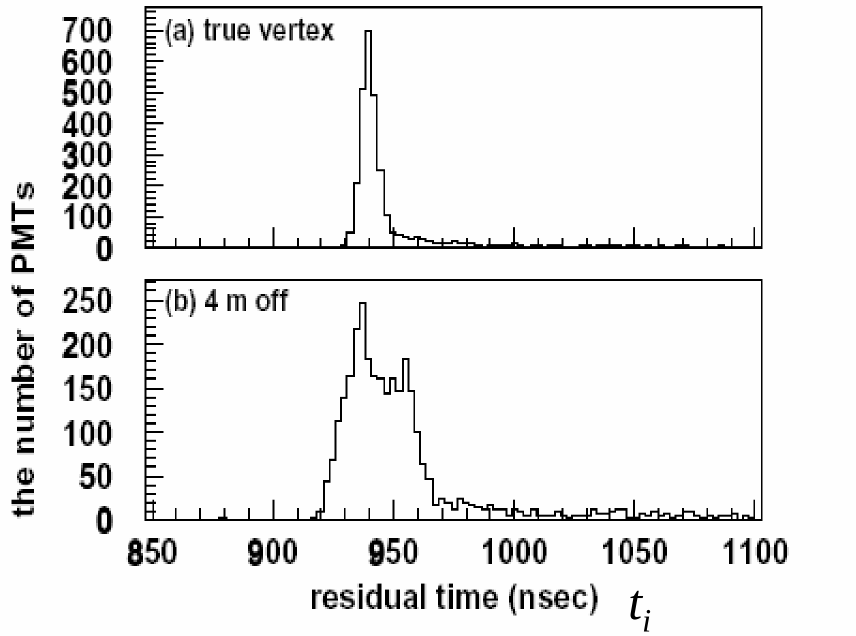
$\lambda =$ wavelength, $n =$ index of refraction

$\beta = v/c, v =$ 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

TOF

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

vertex

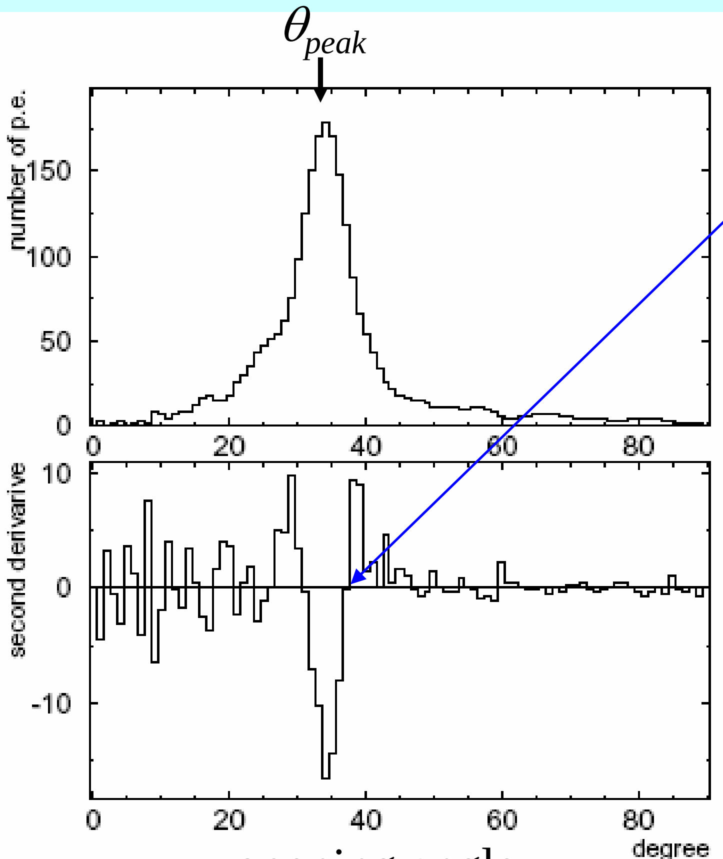
location of PMT i

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:

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

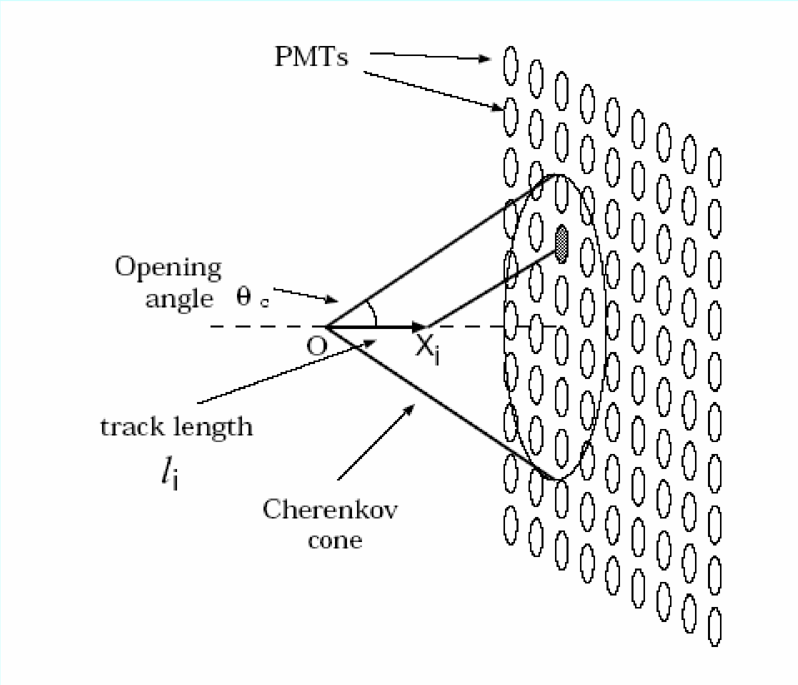
Particle direction:

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

Estimator (maximized by changing $\vec{d}_p$)

$$Q(\theta_{edge}) = \frac{\int_0^{\theta_{edge}} PE(\theta)d\theta}{\sin\theta_{edge}} \cdot \left(\left.\frac{dPE(\theta)}{d\theta}\right|_{\theta_{edge}}\right)^2 \cdot \exp\left[-\frac{(\theta_{edge} - \theta_c)^2}{2\sigma_\theta^2}\right]$$

• 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

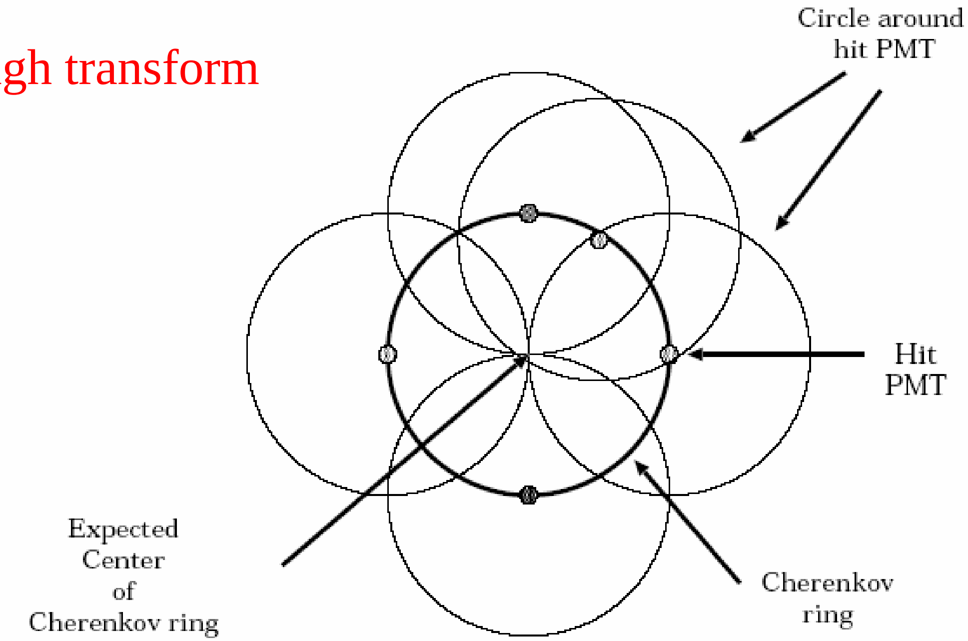
Final estimator to be maximized:

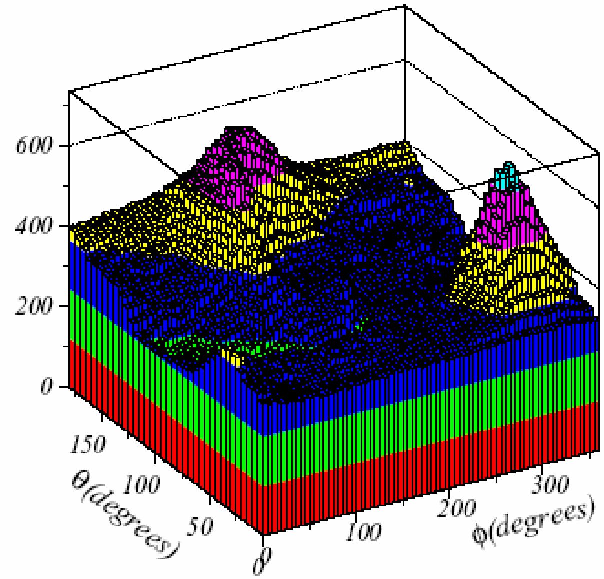
$$G_T = \frac{G_I + G_{O_1} + G_{O_2}}{\sum_i \frac{1}{\sigma_i^2}}$$

by changing vertex position and cone direction

Ring count

Hough transform





Likelihood function for N+1 rings:

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

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

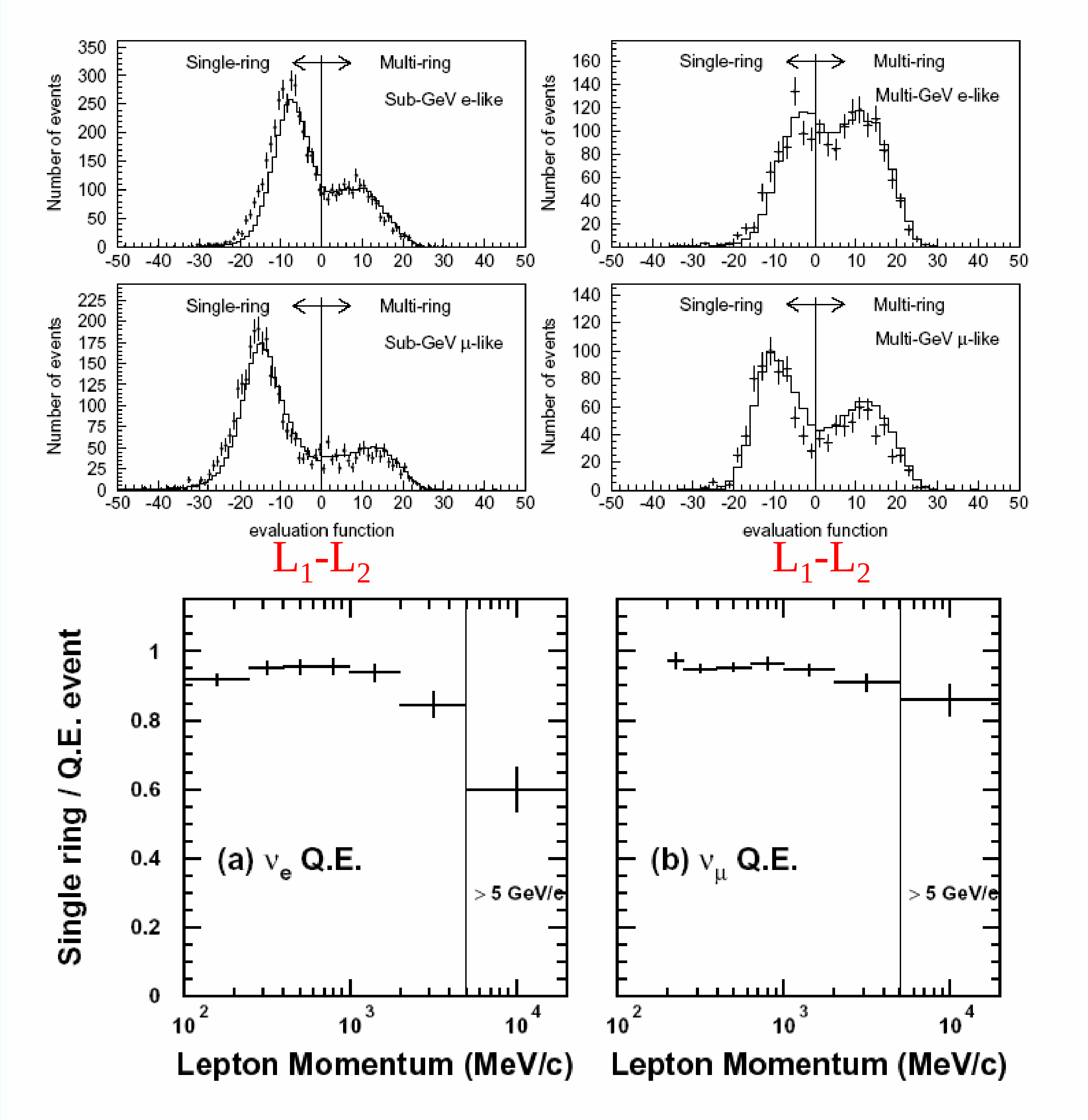
$$= \text{convolution of a single pe} \quad \text{for } q_i^{\exp} < 20 \text{ pe}$$

dist. and a Poisson dist.

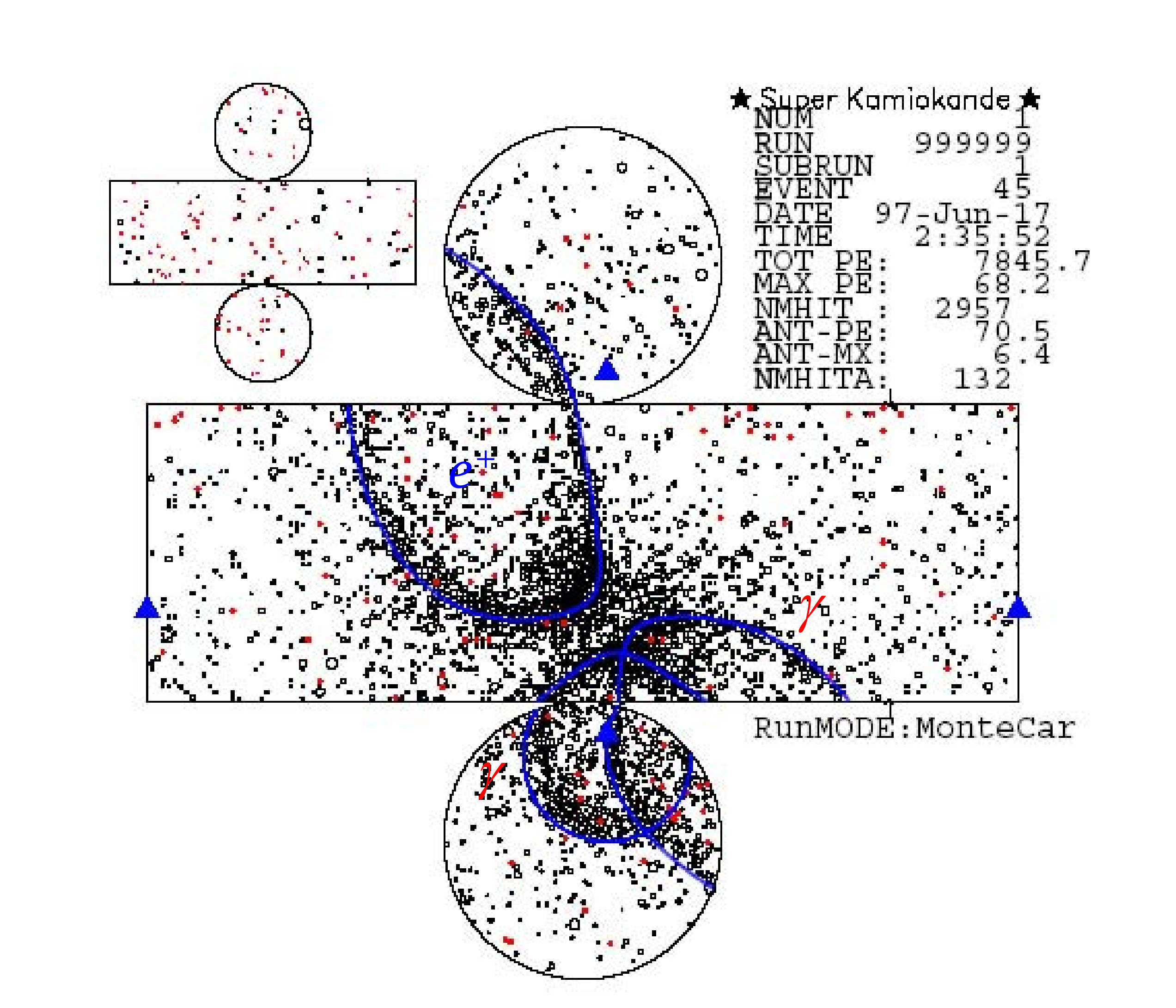
If $L_{N+1} > L_N$, several conditions are checked and a decision is made on how many rings there are

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

- Ring count

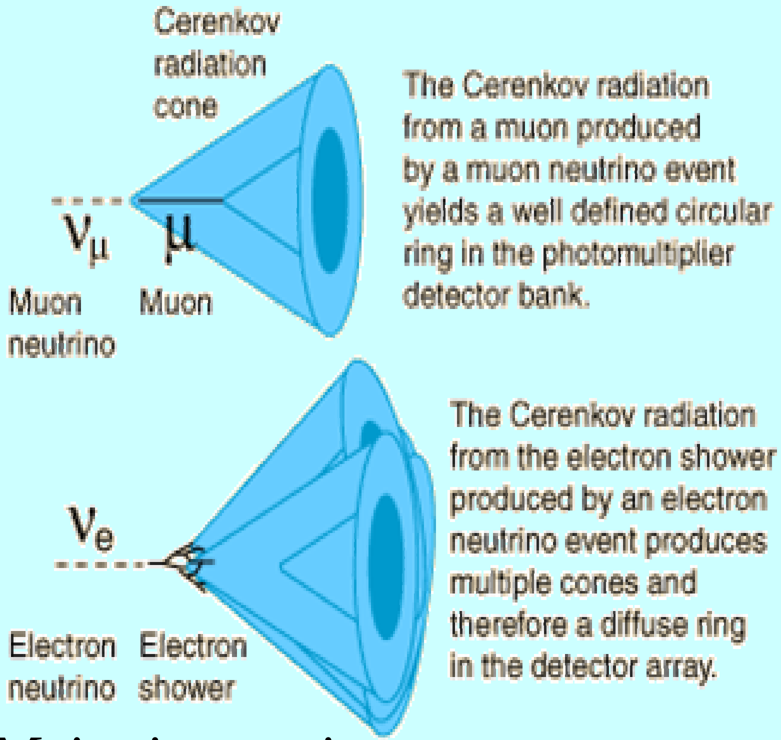


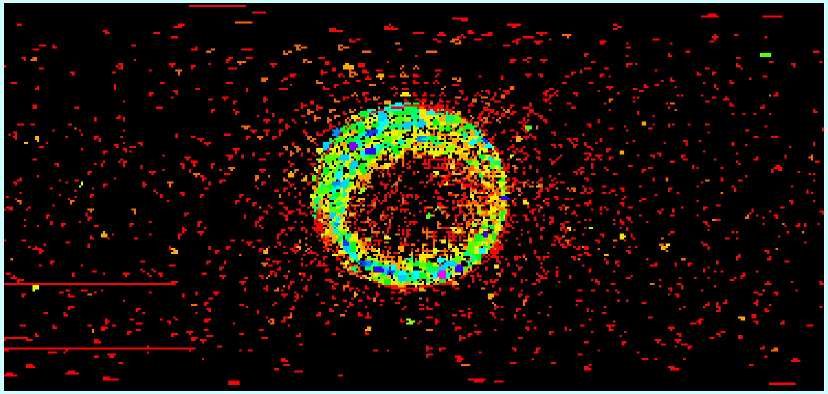
- Ring fitter example $p \to e^+\pi^0(\pi^0 \to \gamma\gamma)$



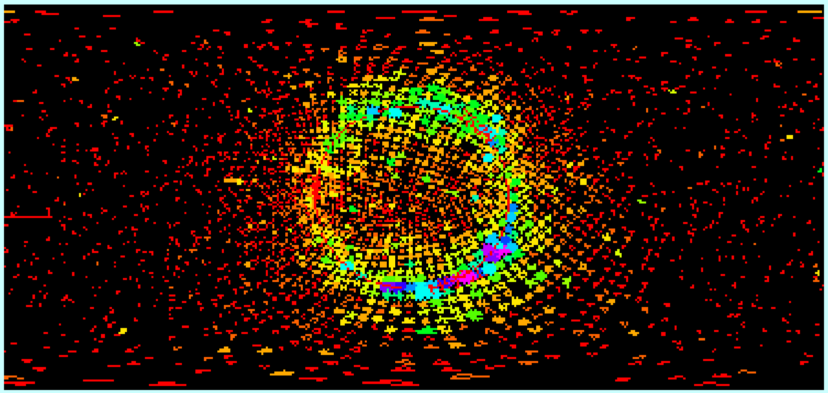
• Particle ID

How do we detect muon and electron neutrinos ?





muon-like ring



electron-like ring

Major interactions:

$\nu_e + n \rightarrow p + e^-$

$\nu_\mu + n \rightarrow p + \mu^-$

Most of time invisible

- Particle ID

Likelihood and probabilities

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

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

→

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

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

Probability

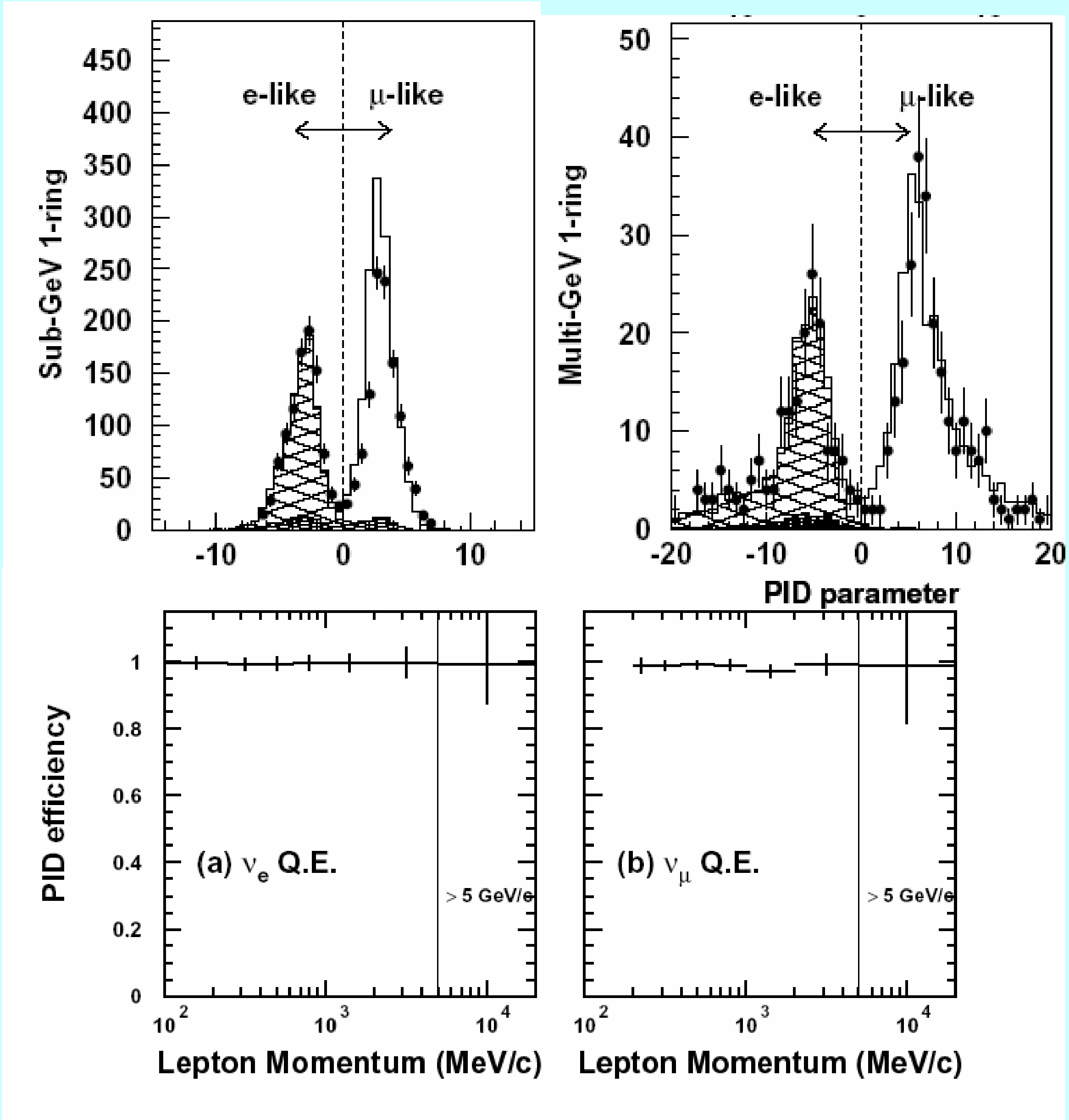
$$P_1(e \text{ or } \mu) = P_1^{pattern}(e \text{ or } \mu) \times P_1^{angle}(e \text{ or } \mu) \quad \text{for a single-ring event}$$

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

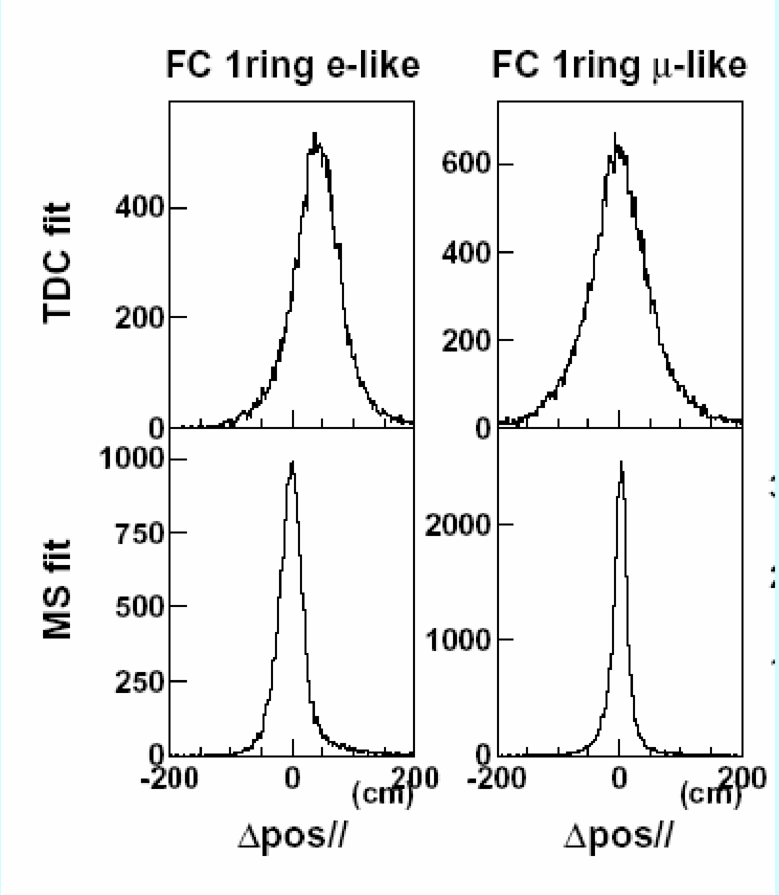
→

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

- Particle ID (μ-like vs. e-like)



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

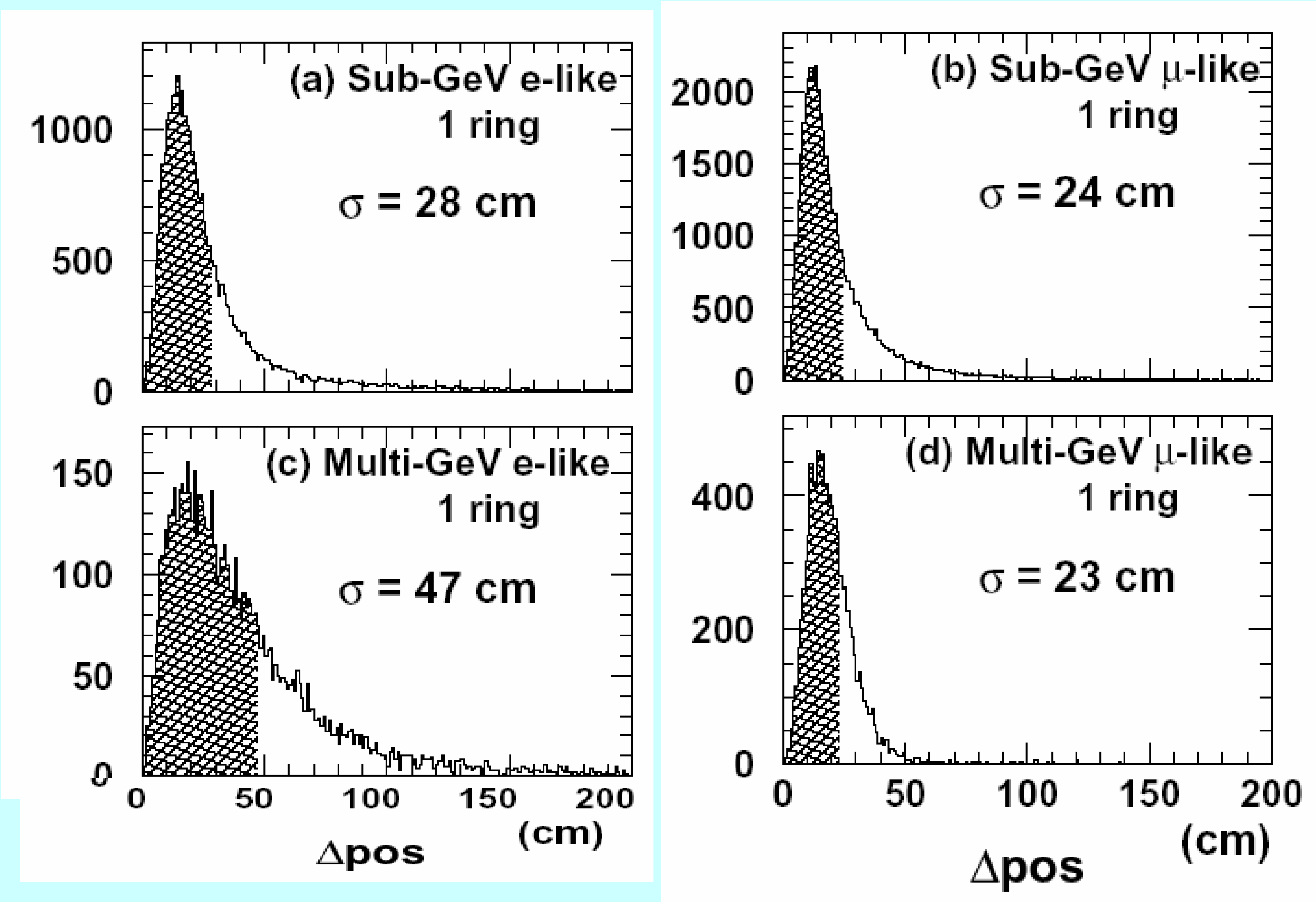


- A vertex shift along a track changes the TOF of each hit by almost equal amount

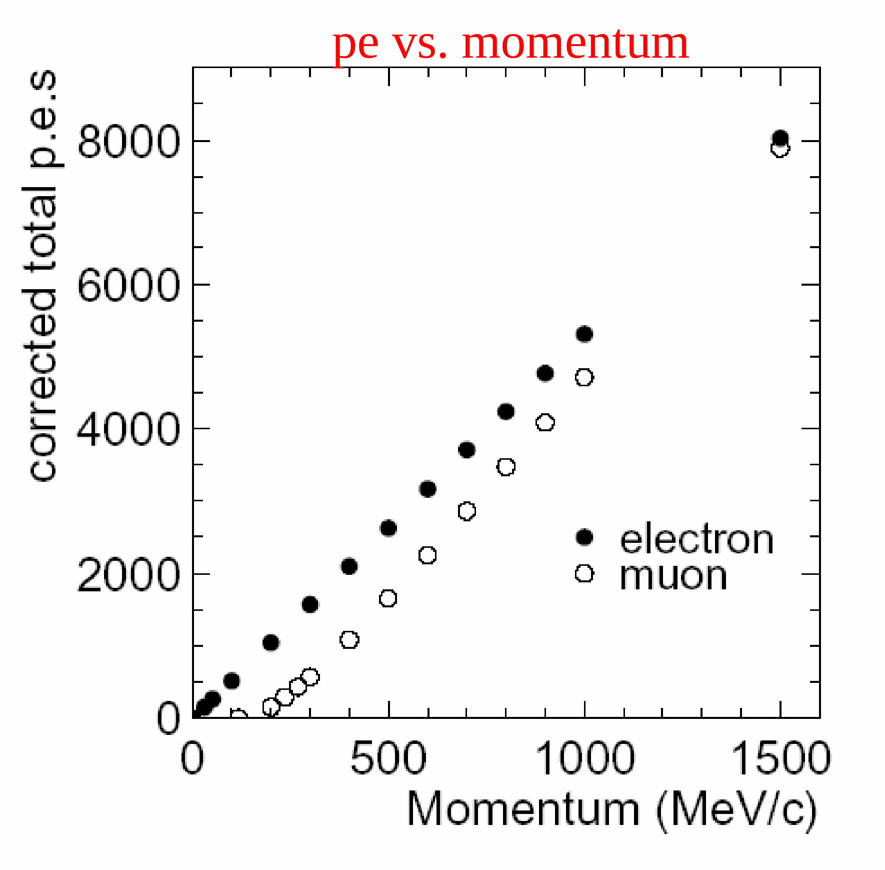
→ Bad vertex resolution along the track

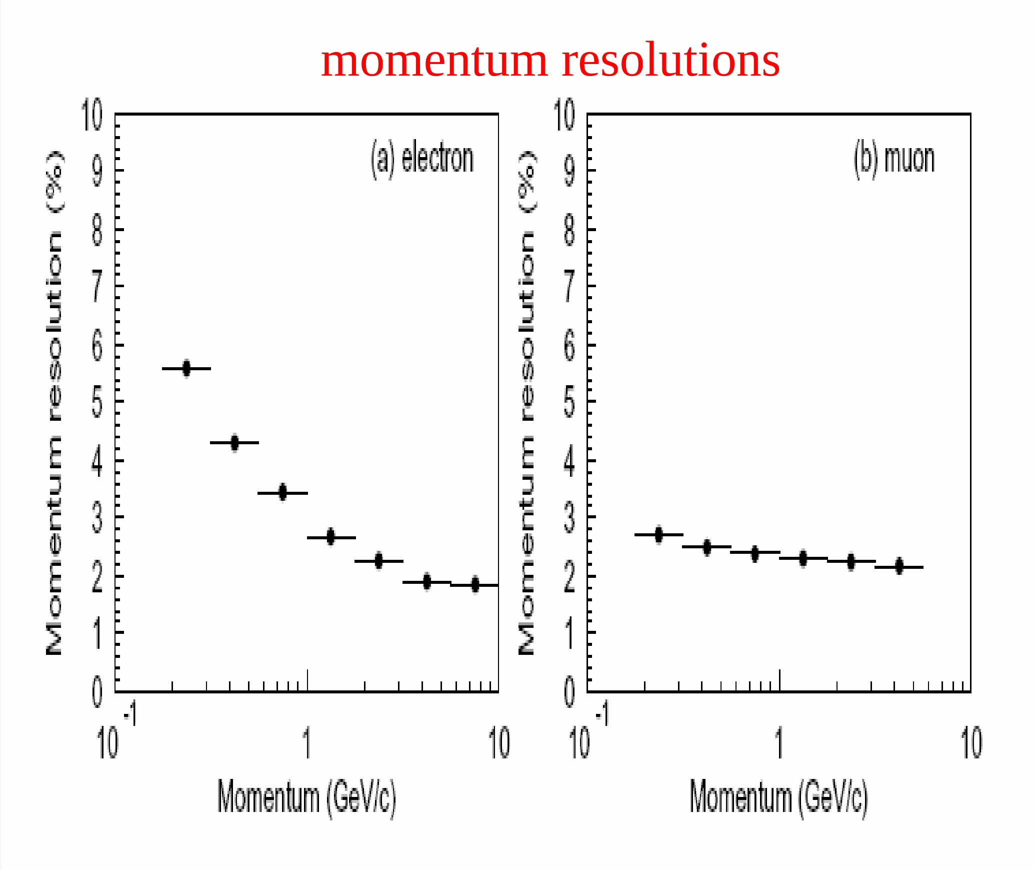
- Ring pattern (charge distribution) gives additional handle to improve vertex resolution along the track

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

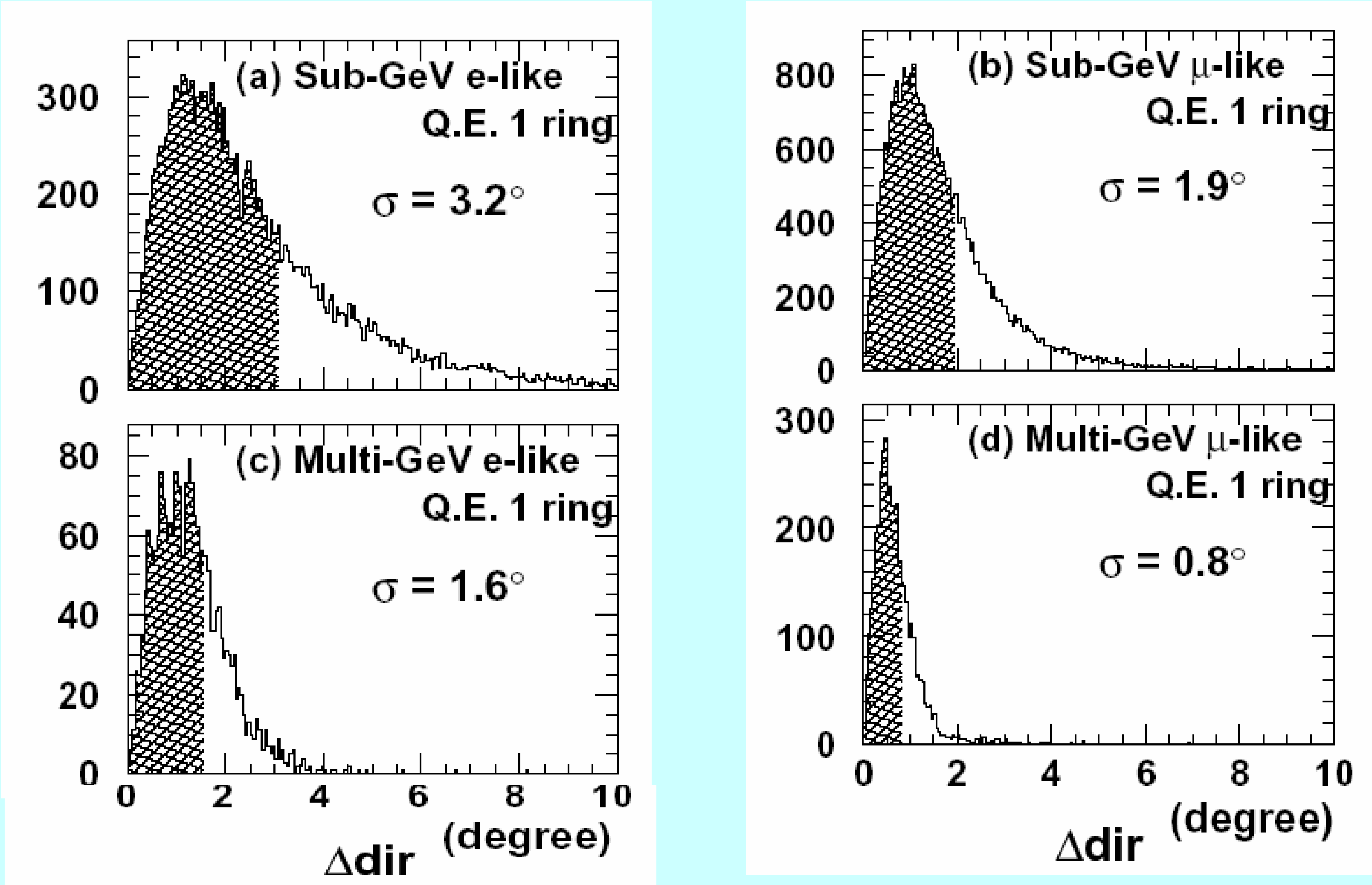


Momentum measurement





- Angular resolutions

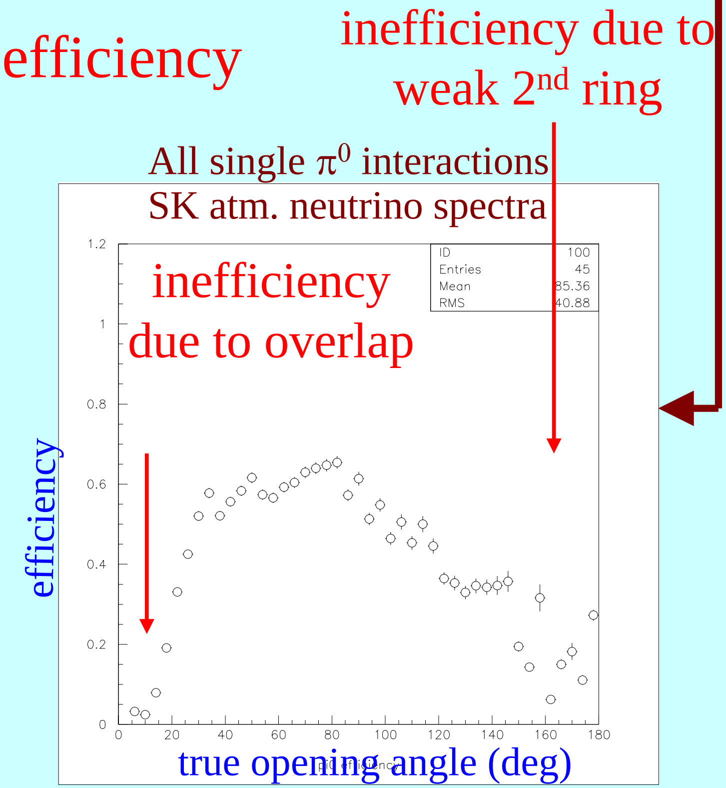


π^0 finder : Motivation and strategy

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

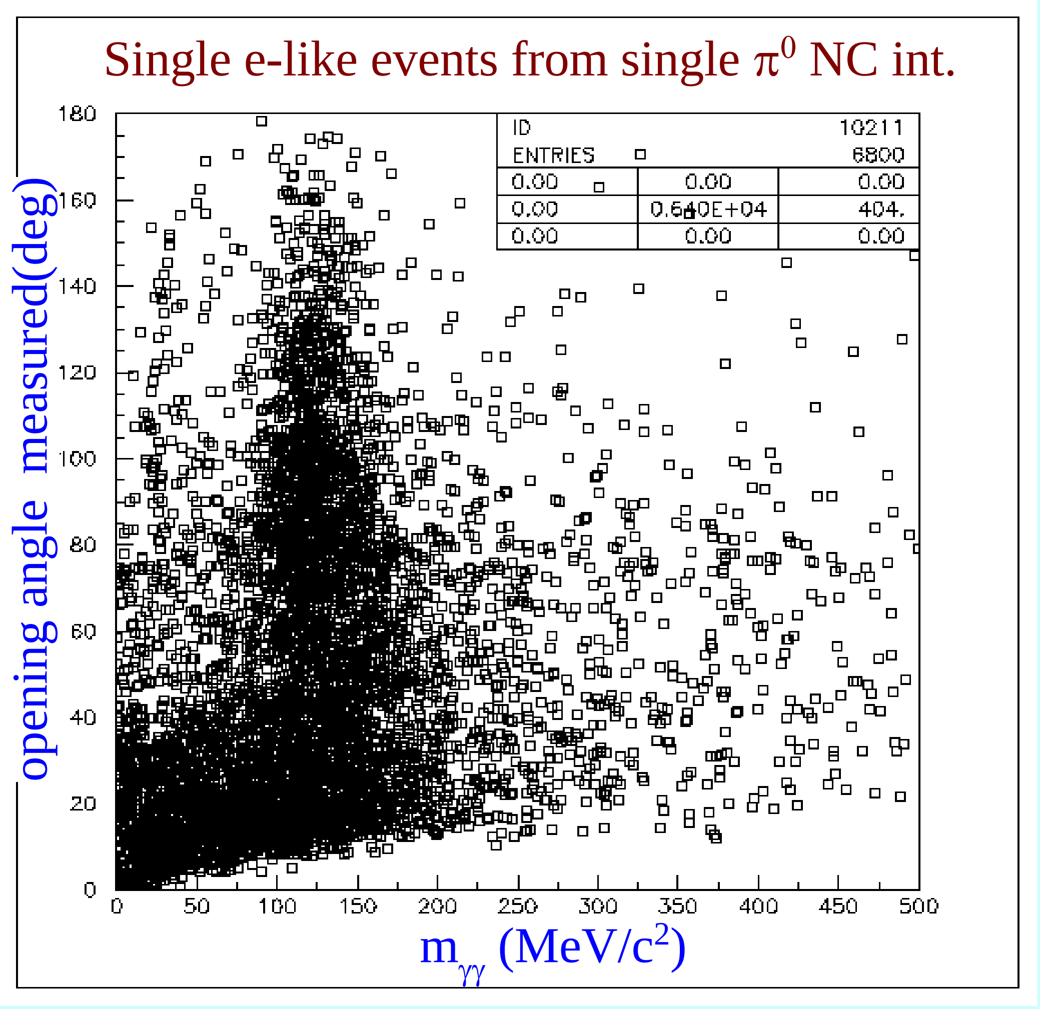
⇒ Needs a smart algorithm to increase efficiency

- 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



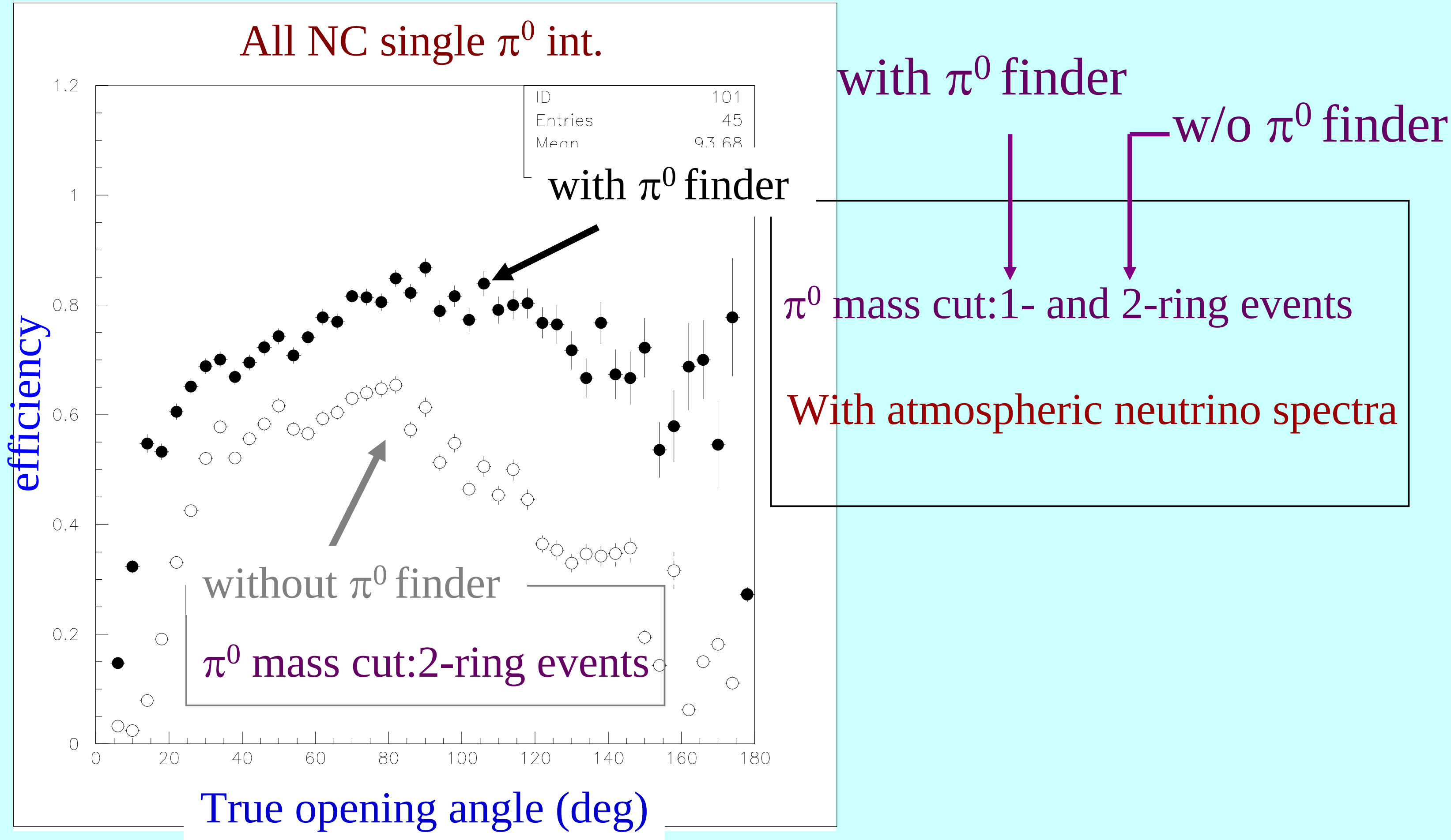
• π^0 finder: Performance

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



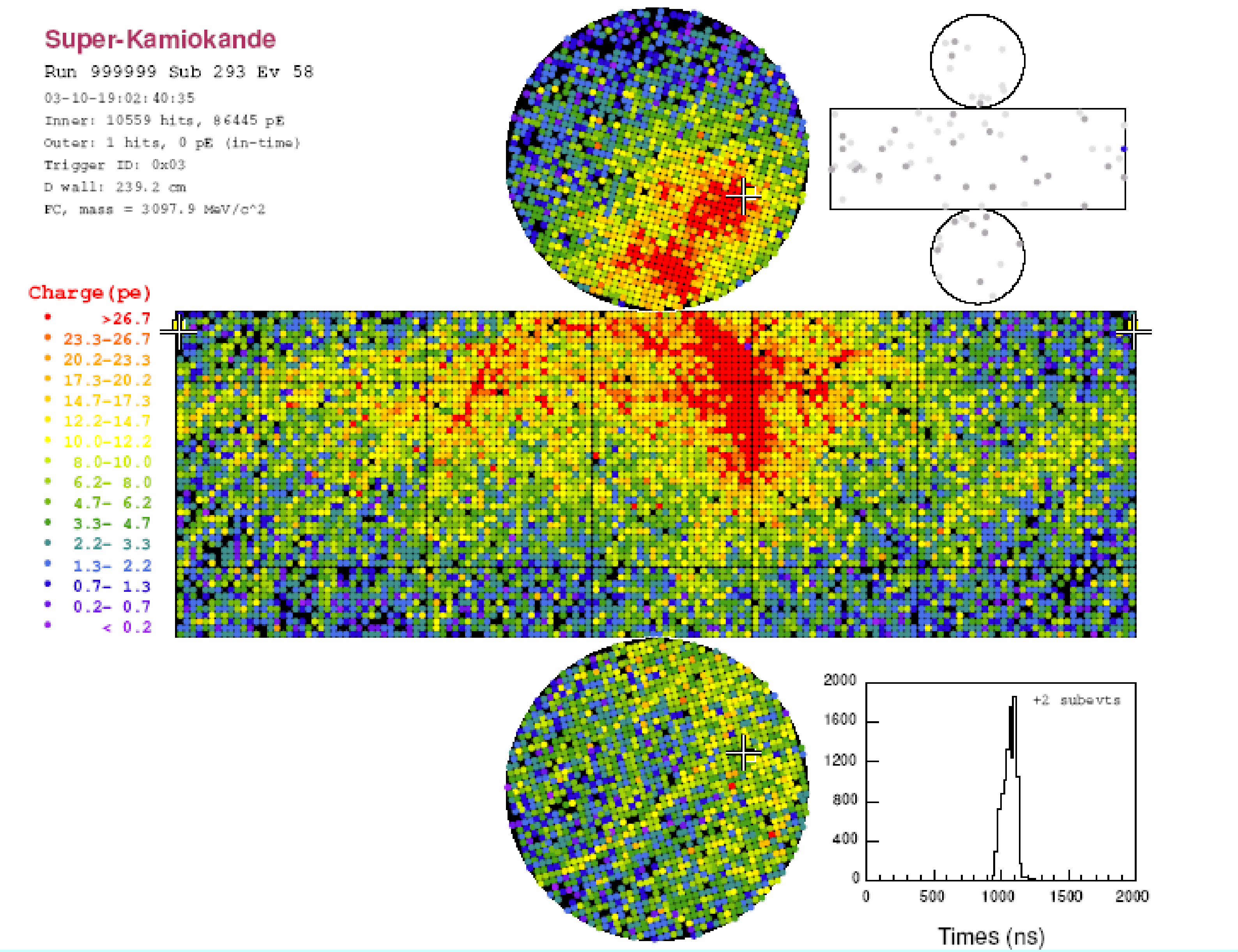
π^0 finder: "Efficiency"

- π^0 "reconstruction efficiency" with standard SK + π^0 finder



- ν_τ event identification (I)

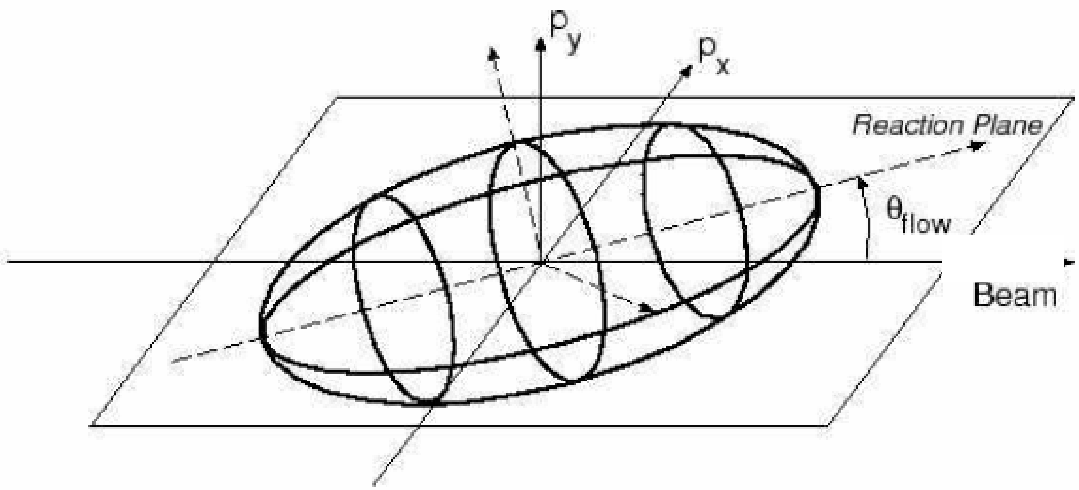
A τ event at SK (simulation)



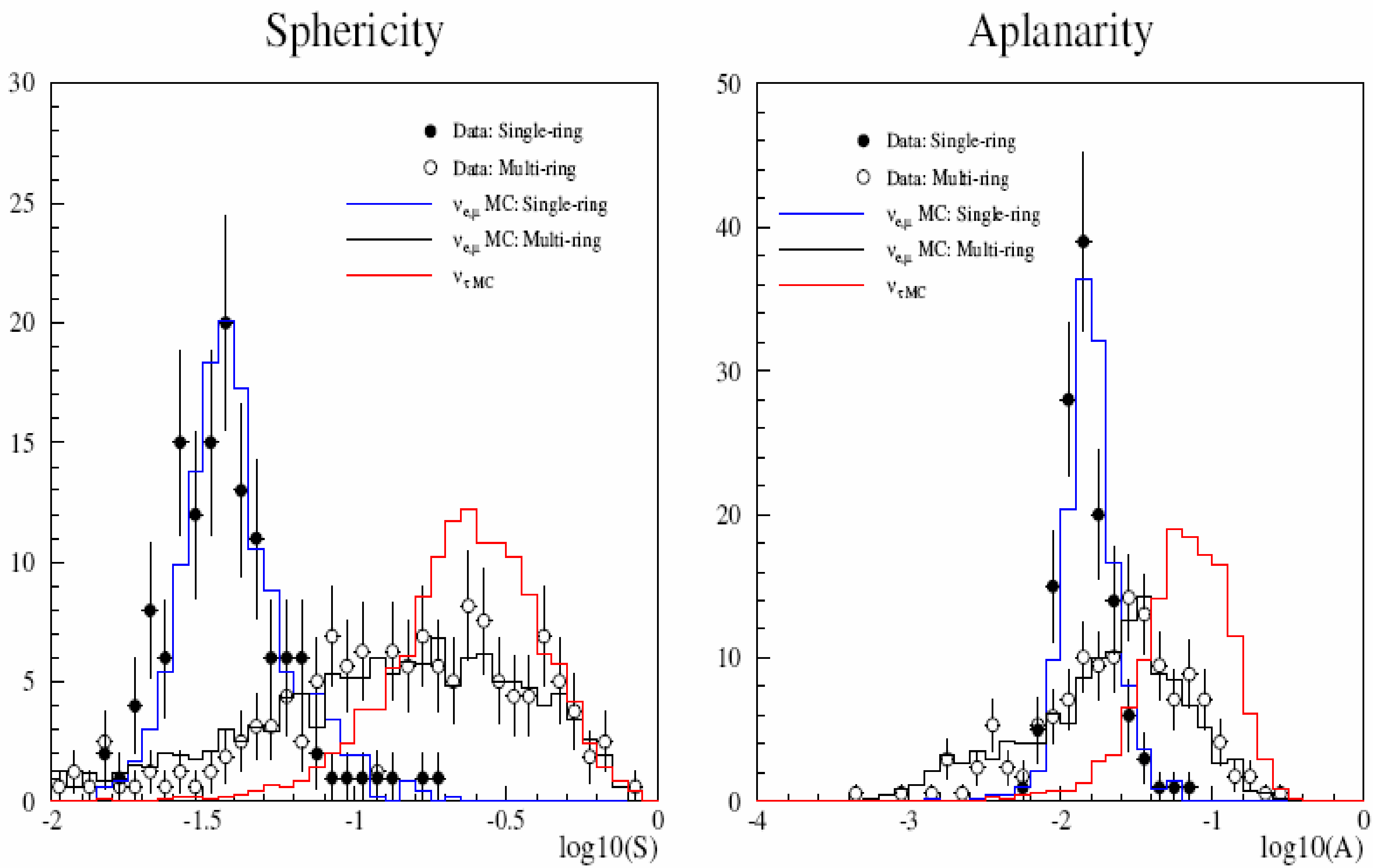
- ν_τ event identification (II)

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

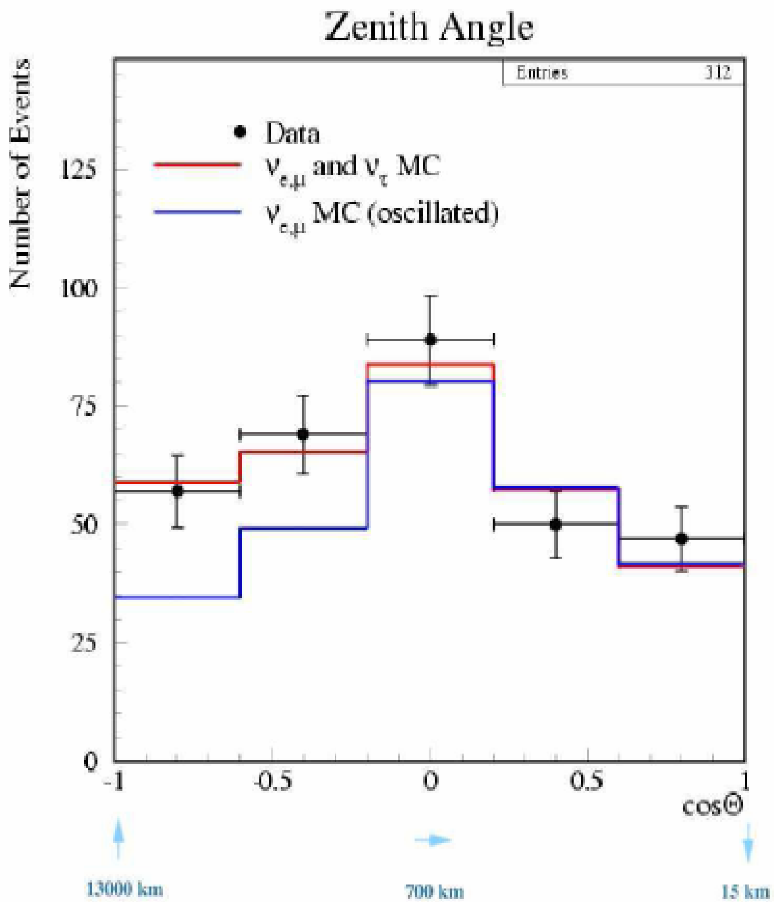
- Sphericity ("roundness")
  $0 < S < 1$: $S = 1$ if the event is spherically symmetric.
- Aplanarity ("flatness")
  $0 < A < 1/2$: $A = 0$ if the event is planar.

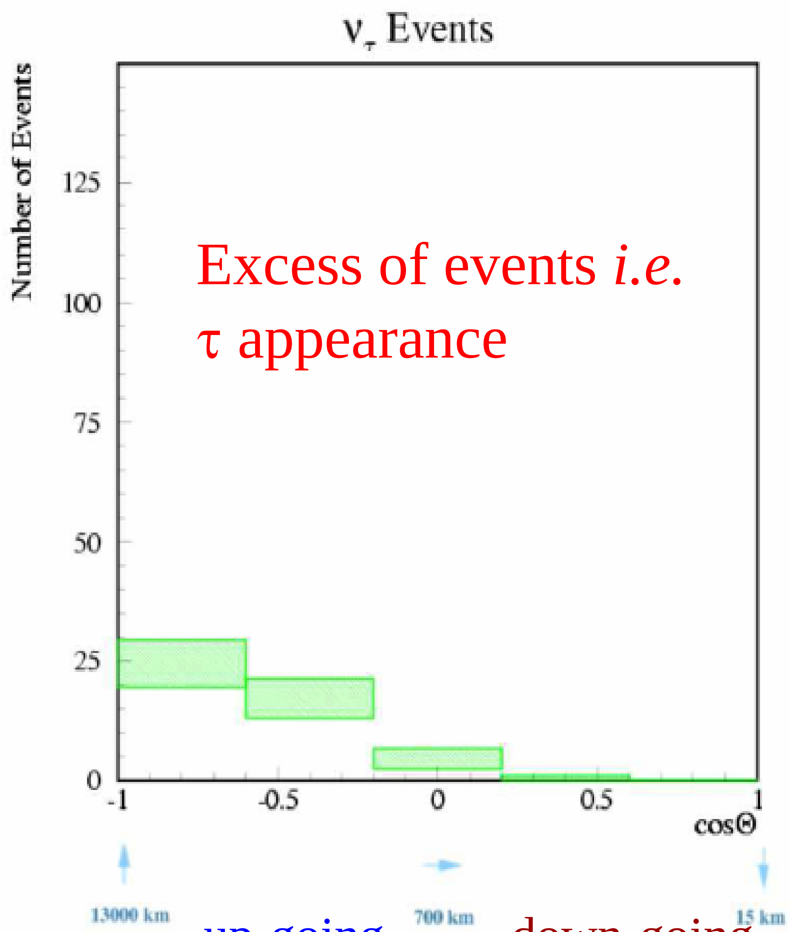


• ν_τ event identification (III)



• ν_τ event identification(VI) After some cuts plus a cut on likelihood





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 $\nu_\mu \rightarrow \nu_e$

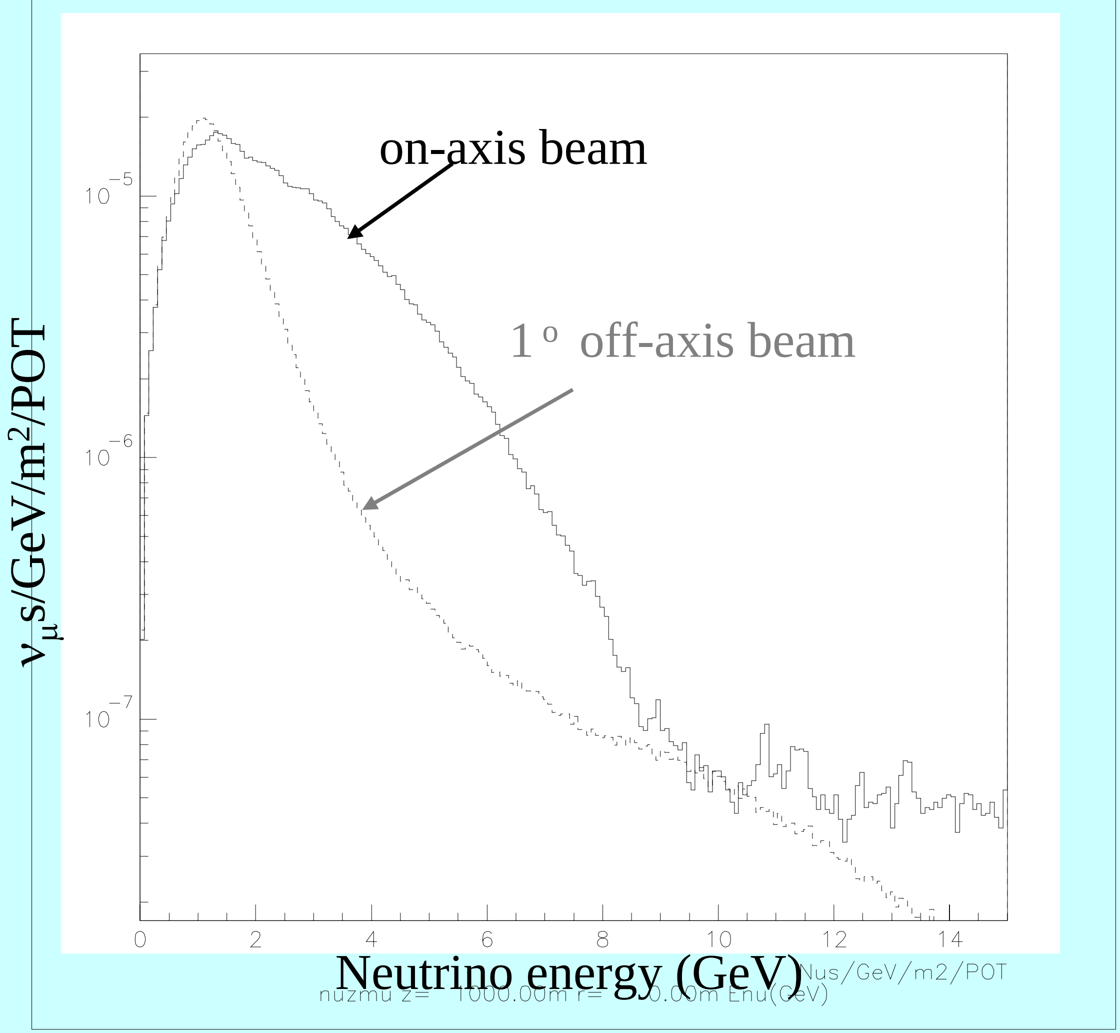
See, for example, PRD68 (2003) 12002 by BNL group for physics argument.

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
    - $\nu_{\mu,\tau,e} + N \rightarrow \nu_{\mu,\tau,e} + N' + \pi^0$ + (invisible n $\pi^\pm$s, $n \geq 0$), with $\pi^0 \rightarrow \gamma\ (\gamma)$
    - 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



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^o**

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

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

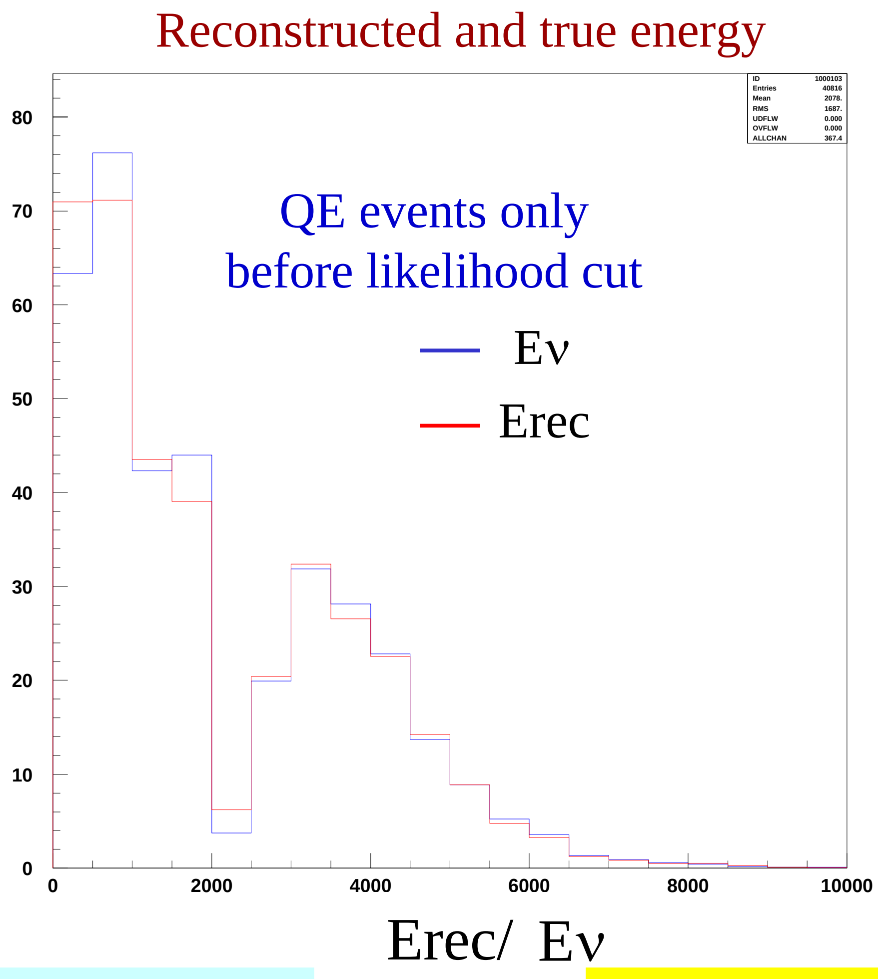
To reduce events with invisible charged pions

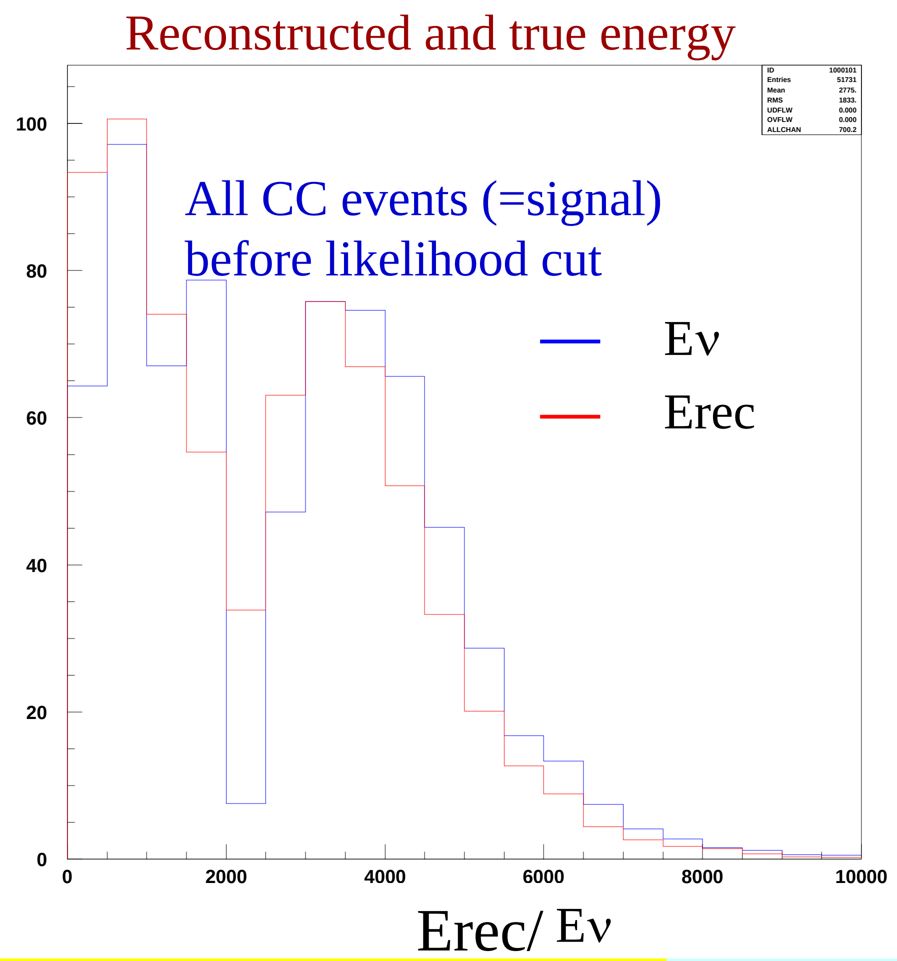
- Likelihood analysis using the following 9 variables: With π^0 finder
  - π^0 mass (pi0mass)
  - energy fraction (efrac)
  - costh
  - π^0-likelihood (pi0-like)
  - e-likelihood (e-like)
  - Δ log π^0-likelihood (Δlog pi0like)
  - single ring-ness (dlfct)
  - total charge/electron energy (poa)
  - Cherenkov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



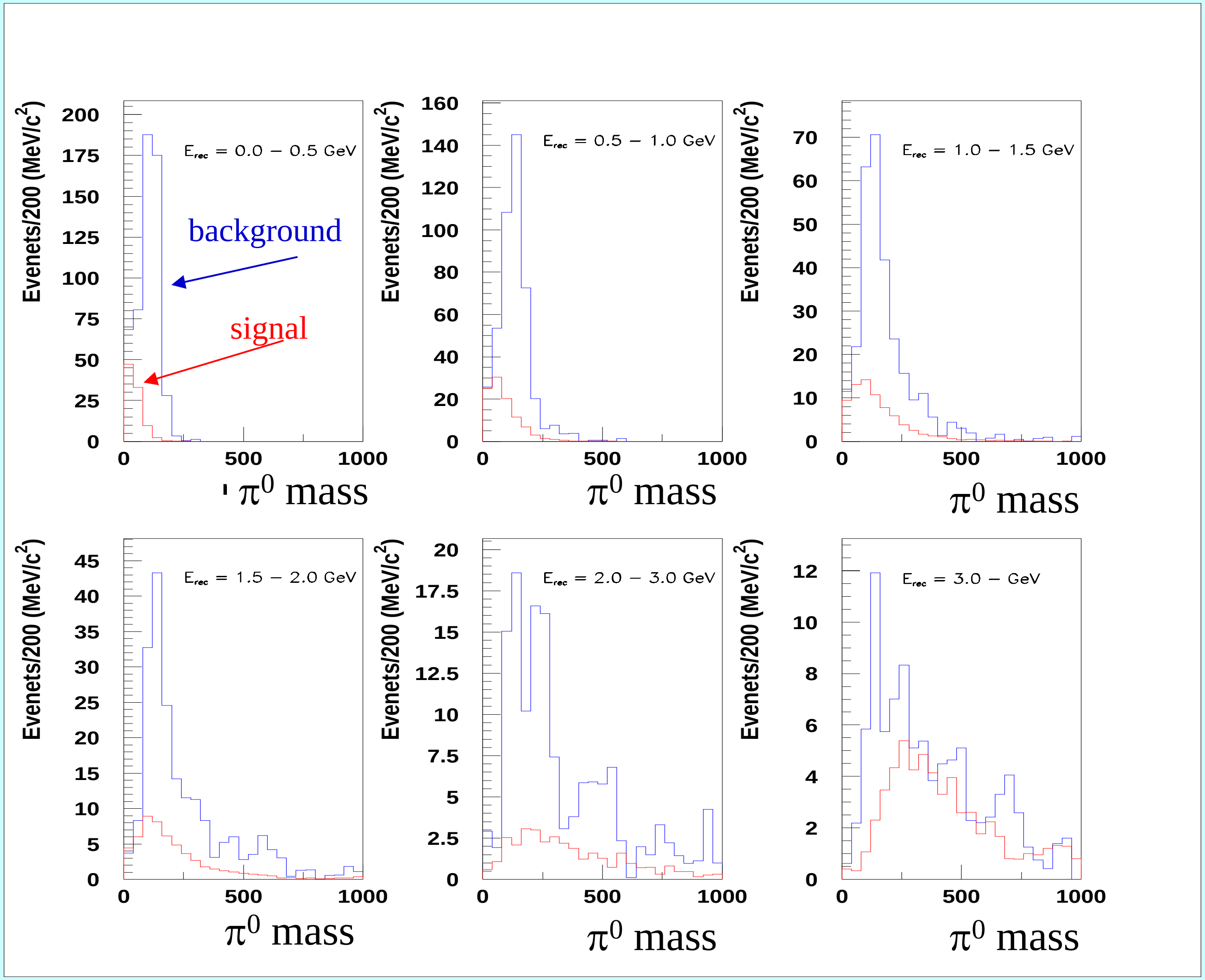


All CC events that survive the initial cuts are signals

• Useful Variables to form likelihood function

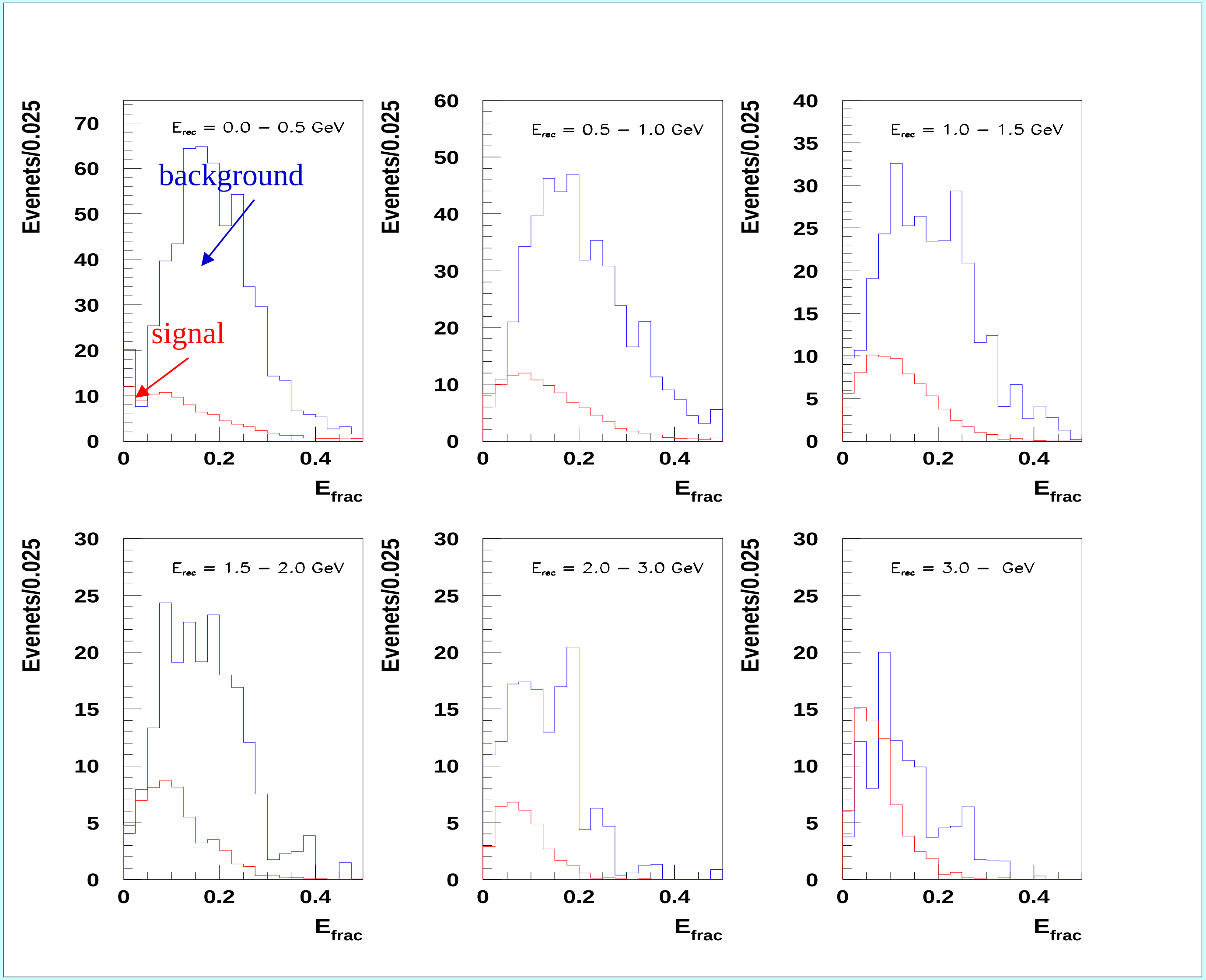
• π^0 mass

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



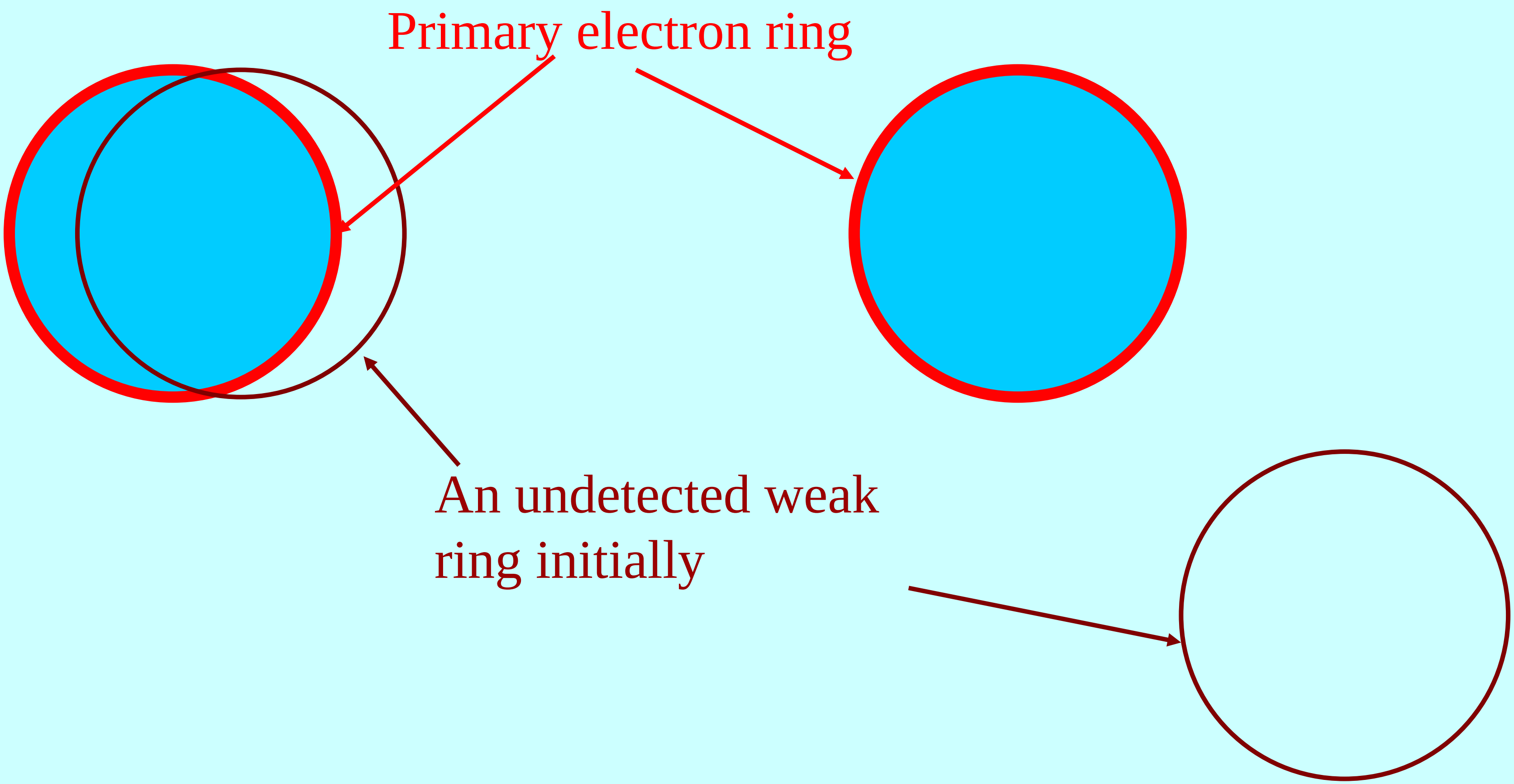
- Difference between log of two π^0-likelihoods (wide vs. forward) from POLfit

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

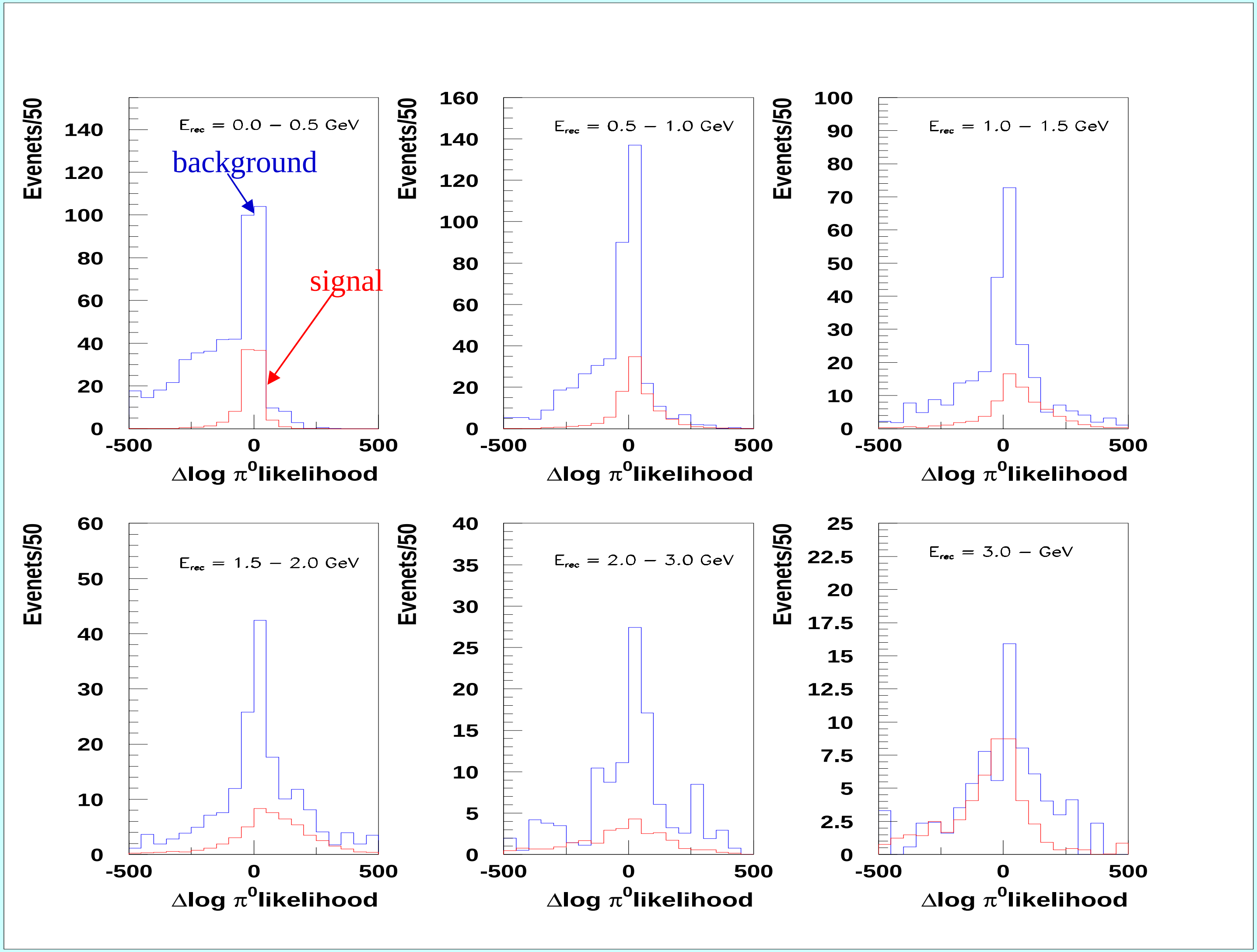
  This algorithm practically gives likelihood how likely the event is single e-like

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

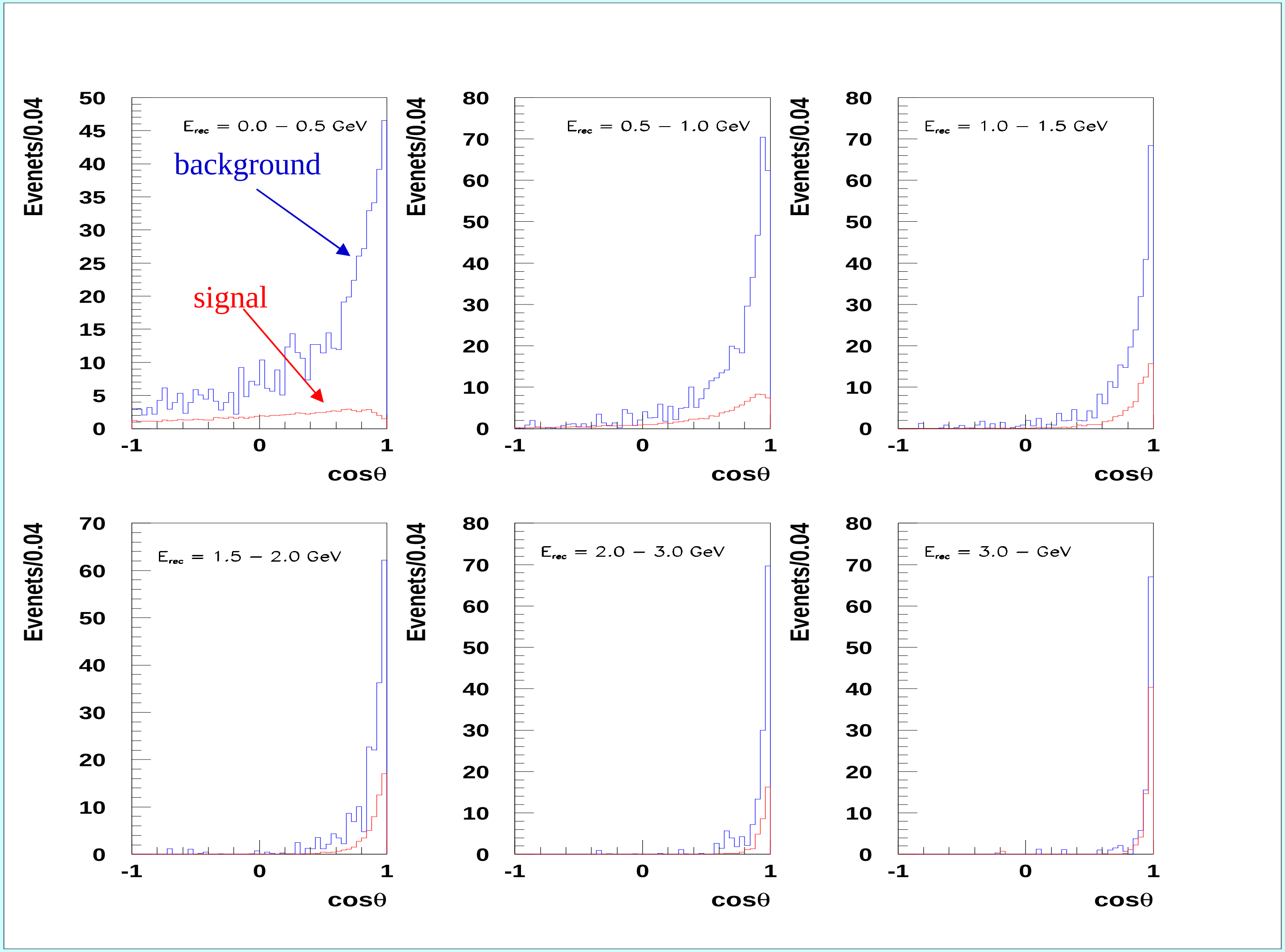
  - See the difference log π^0-likelihood (forward) - log π^0- likelihood (wide)



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

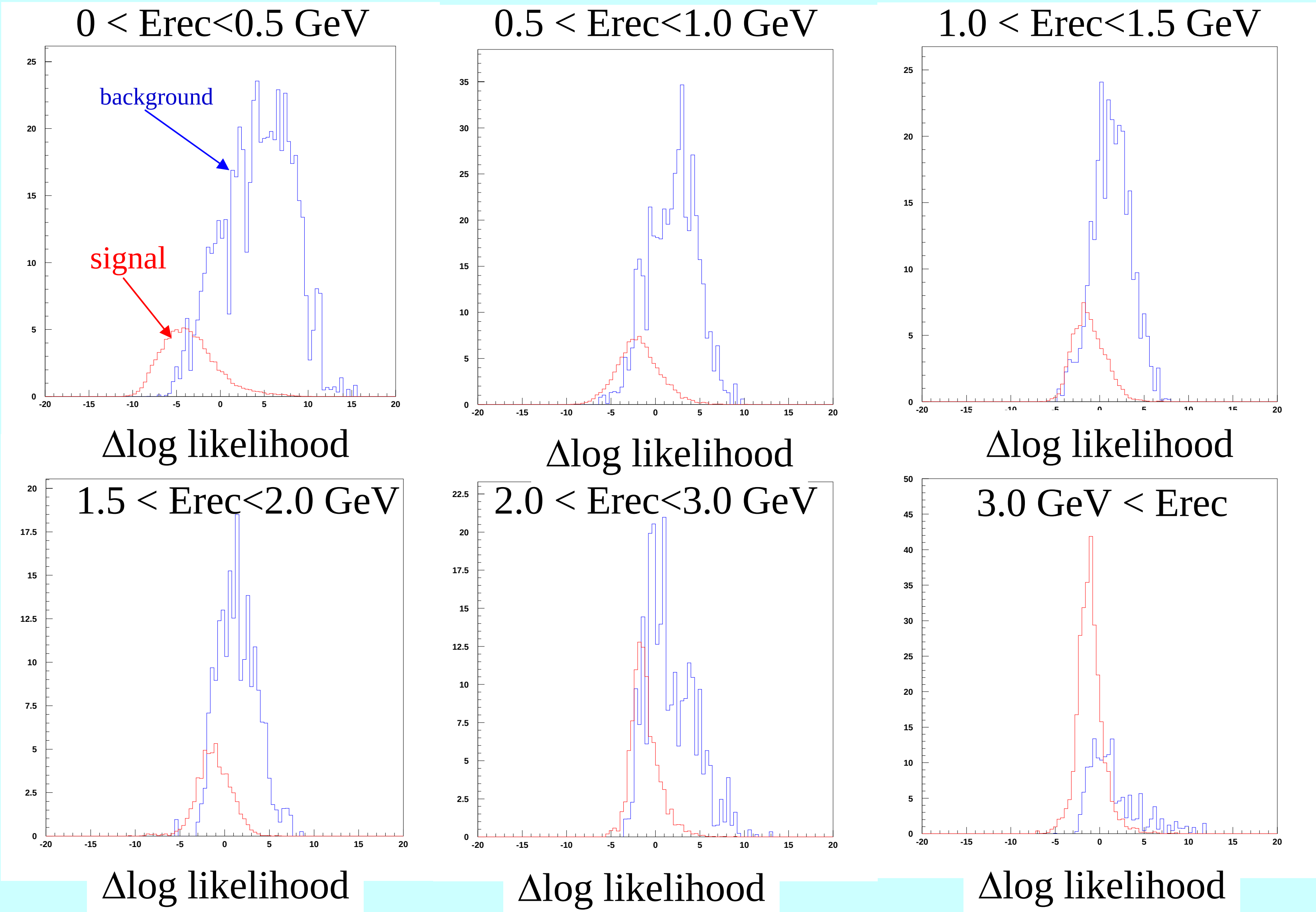


- $\text{costh} = \cos\theta_e$



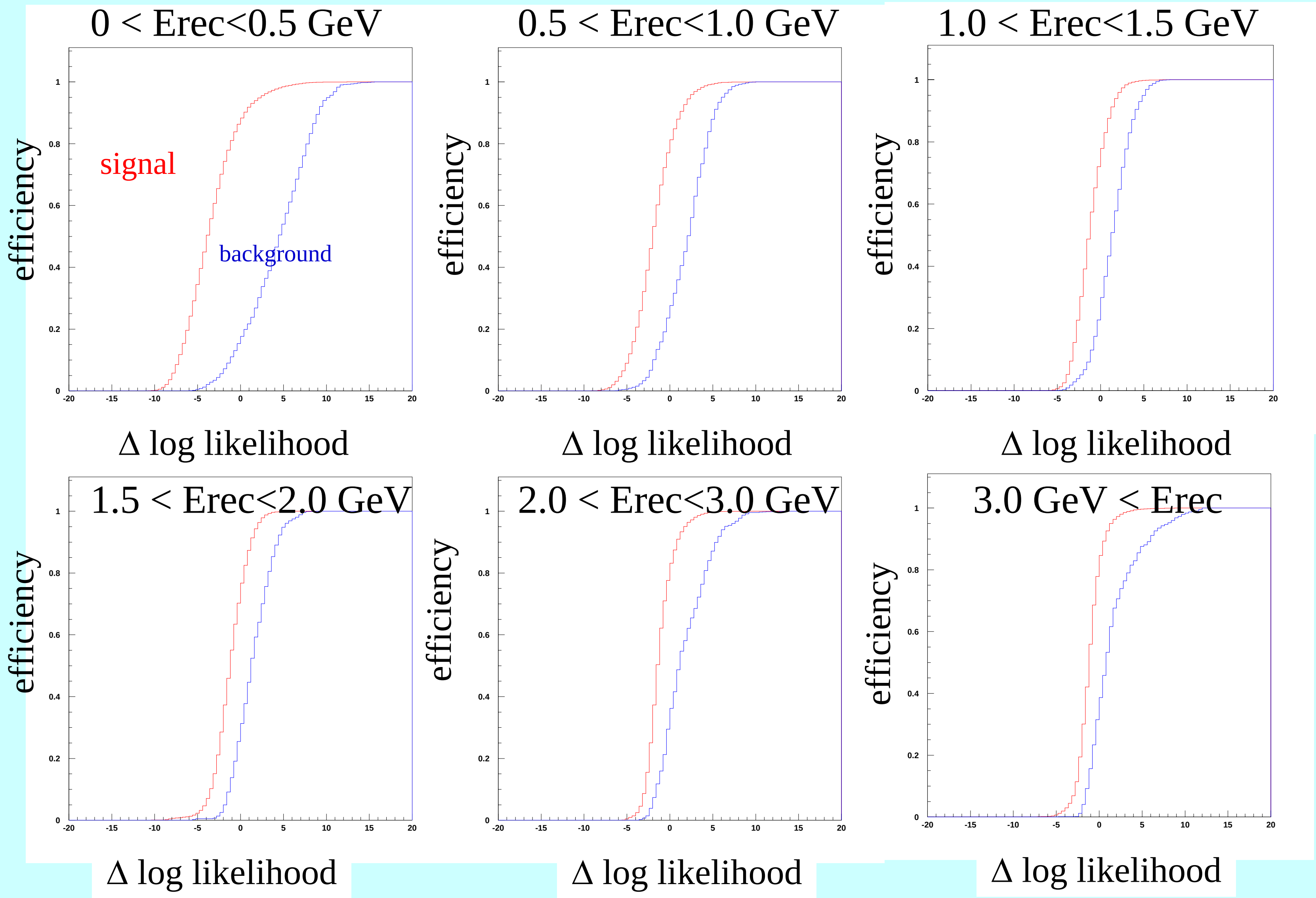
Trained with ν_e CC events for signal, ν_μ CC/NC & $\nu_{e,\tau}$ NC for bkg

- 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)

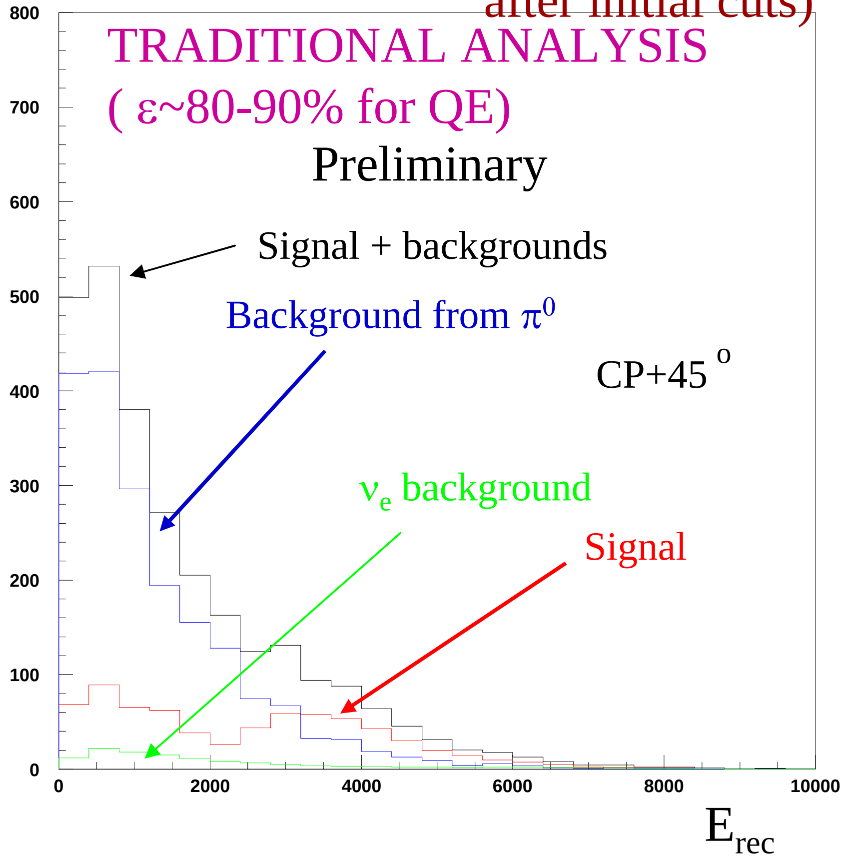


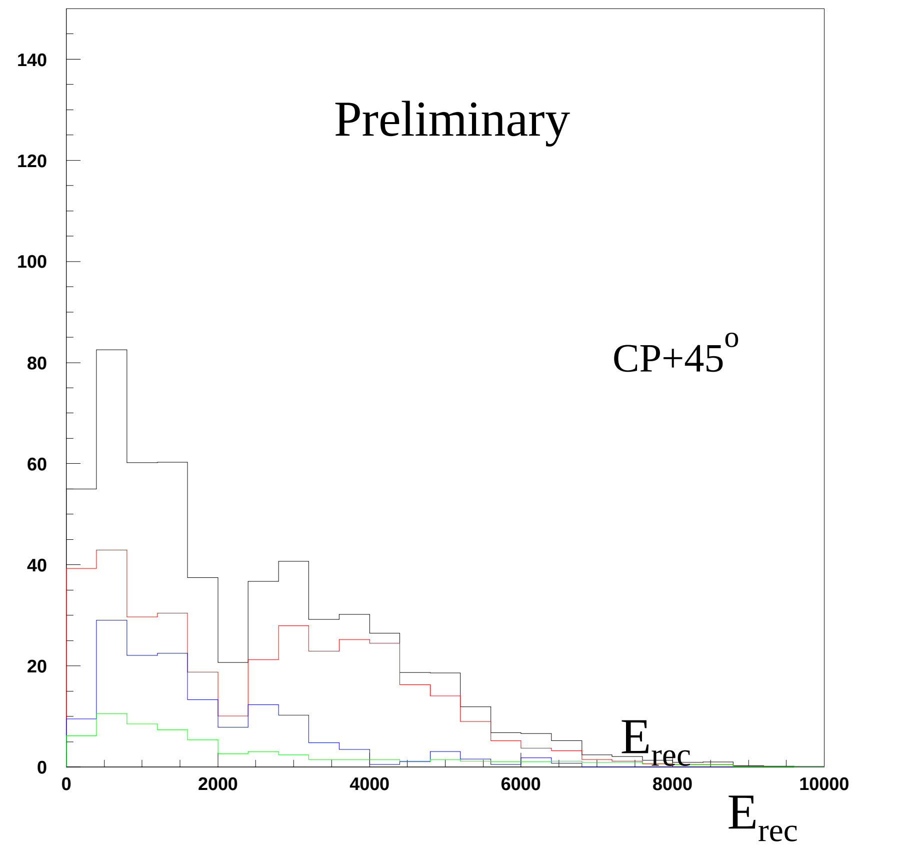
BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

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

Δ log likelihood cut (~50% signal retained) After initial cuts





Signal 700 ev Bkgs 2004
(1877 from π^0+others)
(127 from ν_e)

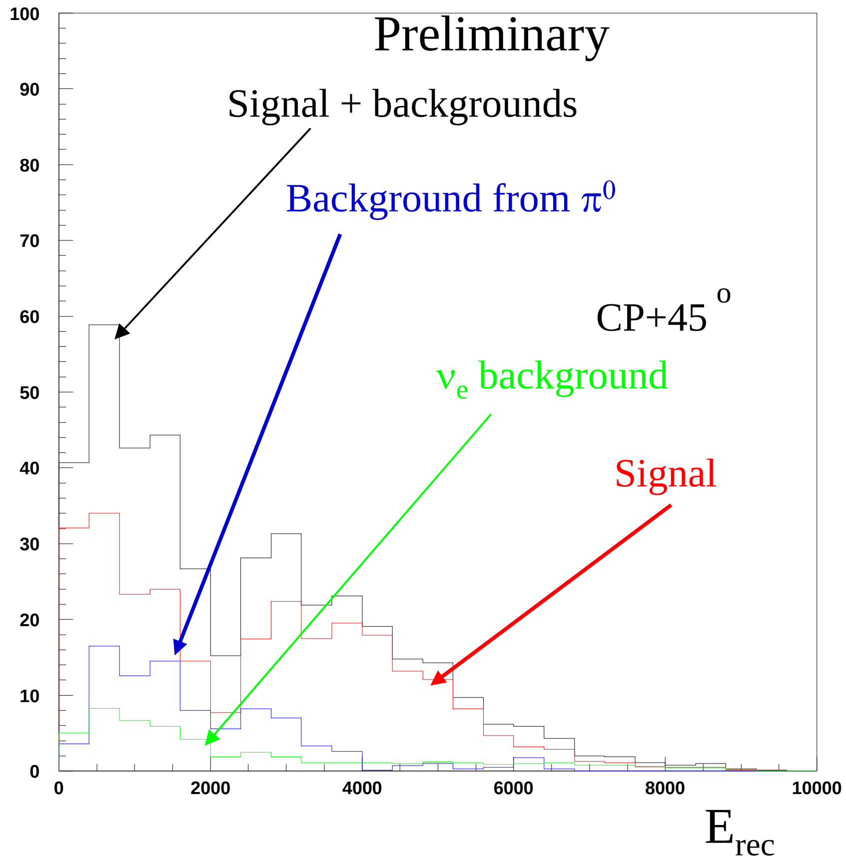
Signal 350 ev Bkgs 169
(147 from π^0+others)
(61 from ν_e)

BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

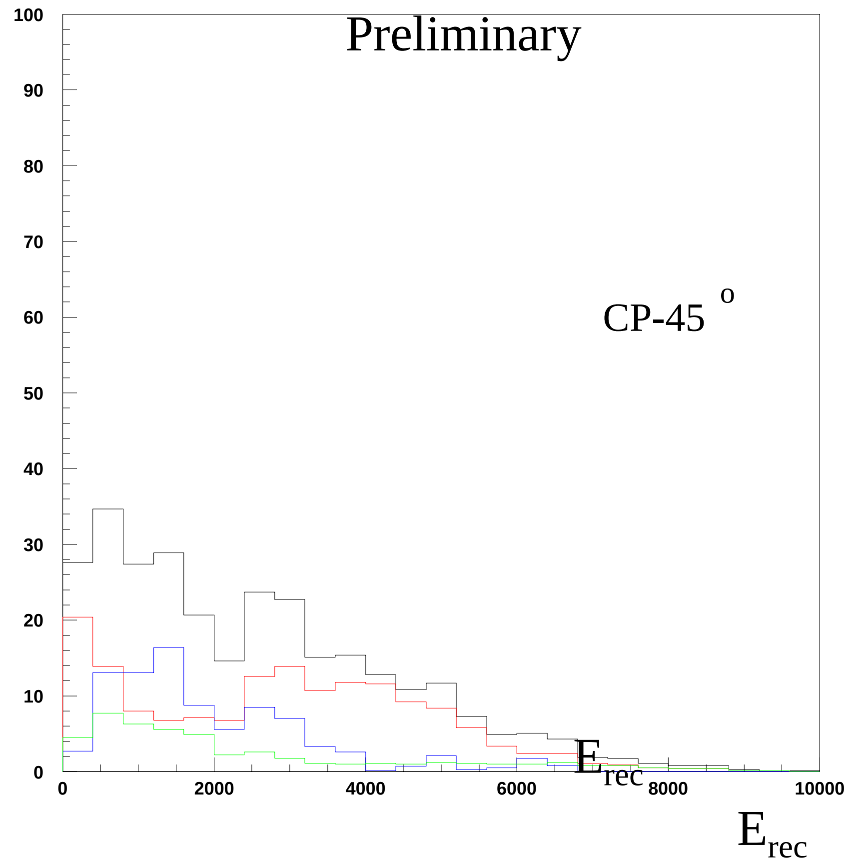
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

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)



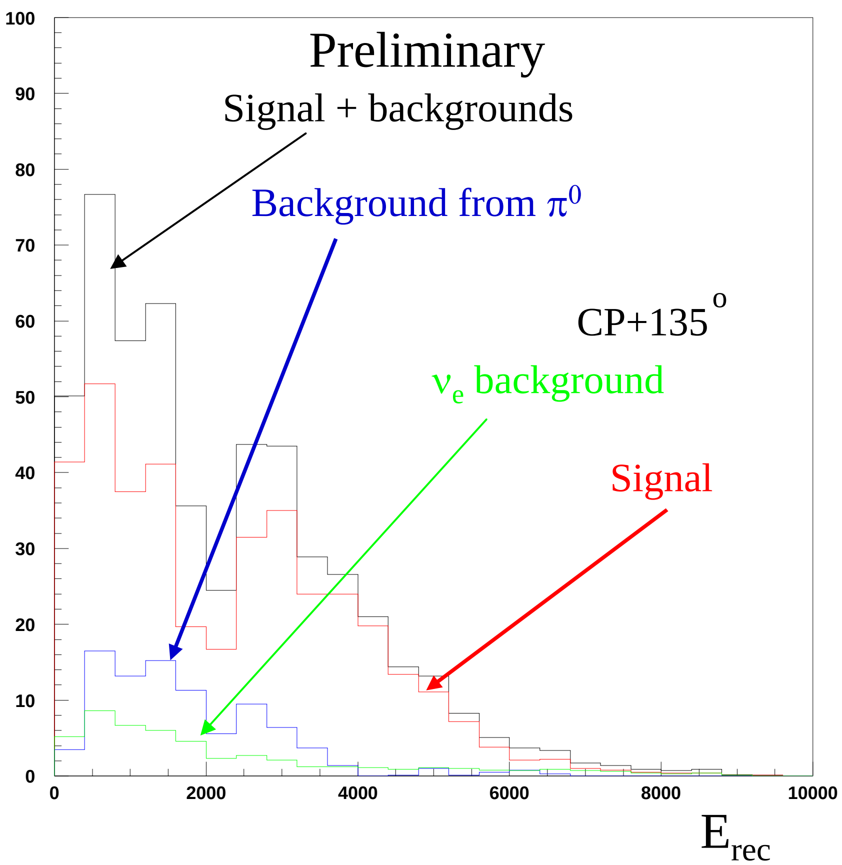
Signal 158 ev   Bkgs 135
(87 from π^0+others)
(48 from ν_e)

BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

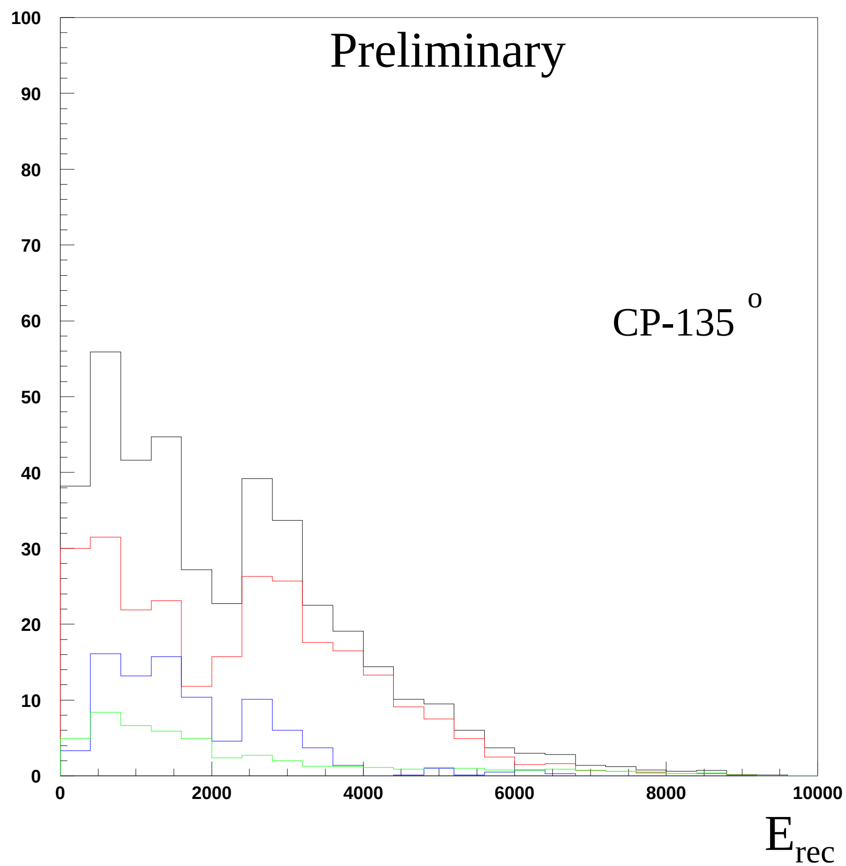
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

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)

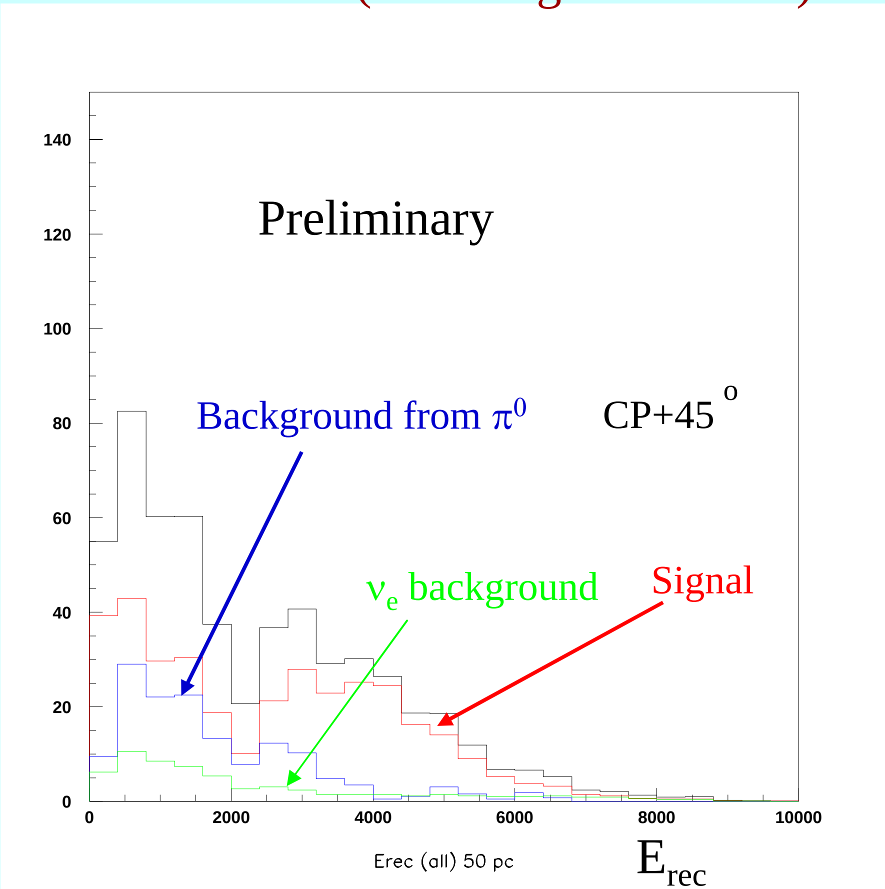
• Breakdown of interaction mode

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%

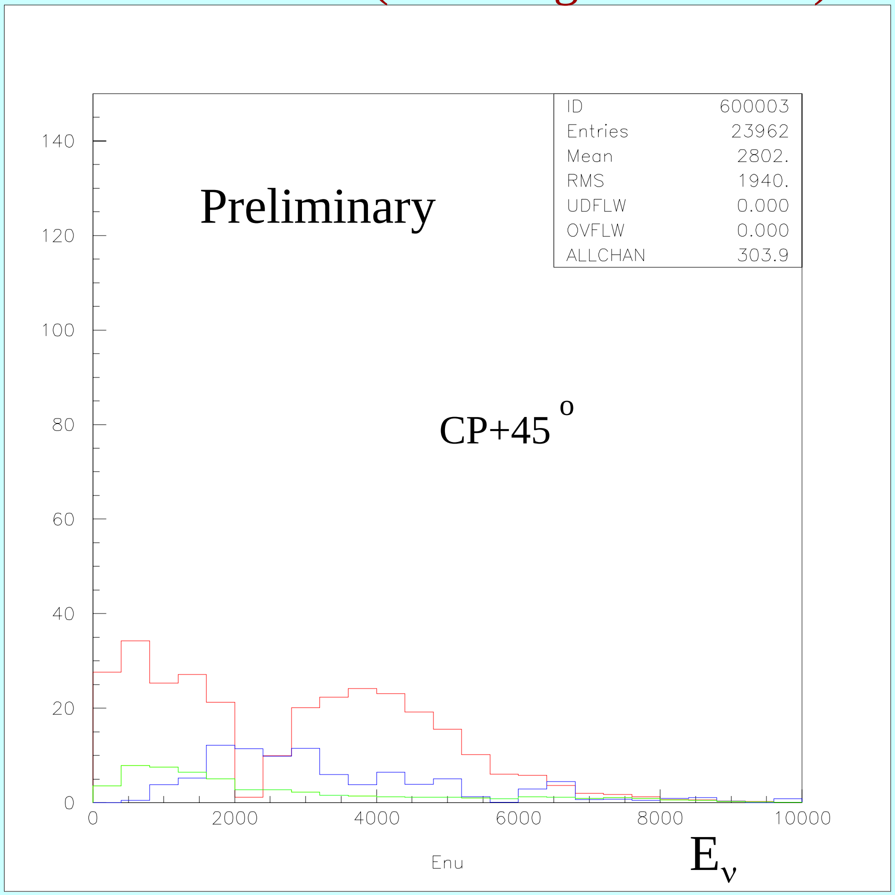
BNL-Homestake (2540 km)

- E_{rec} vs. E_ν

Δlikelihood cut (~40% signal retained)



Δlikelihood cut (~40% signal retained)

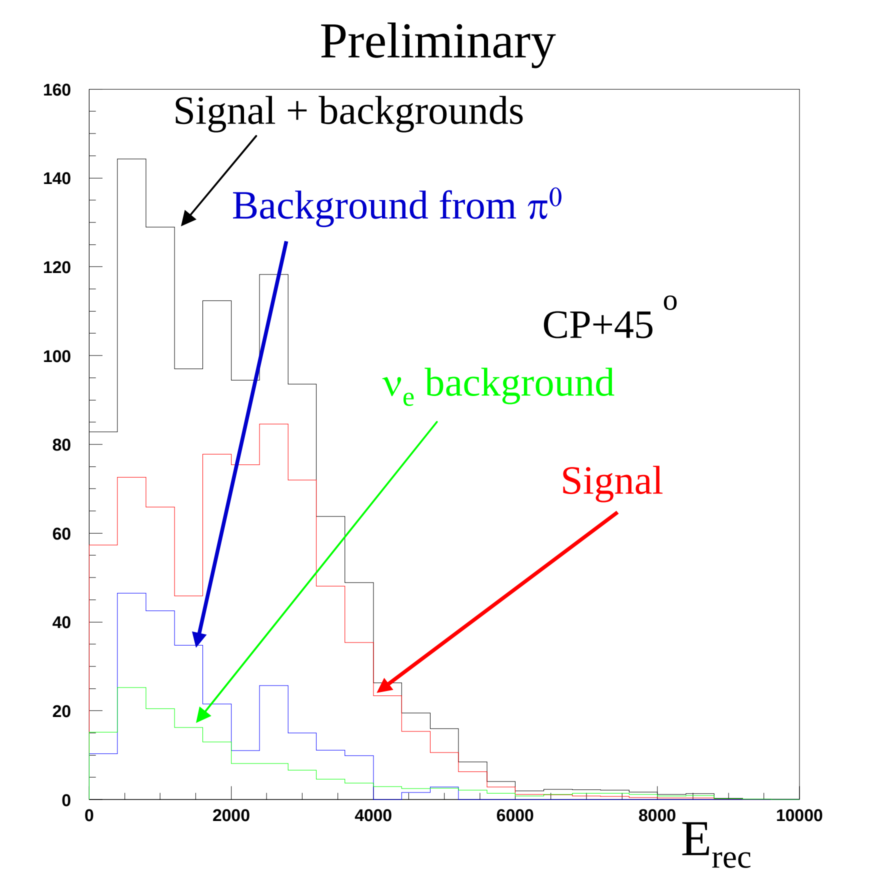


Fermilab-Henderson (1480 km)

- Effect of cut on Δ log likelihood

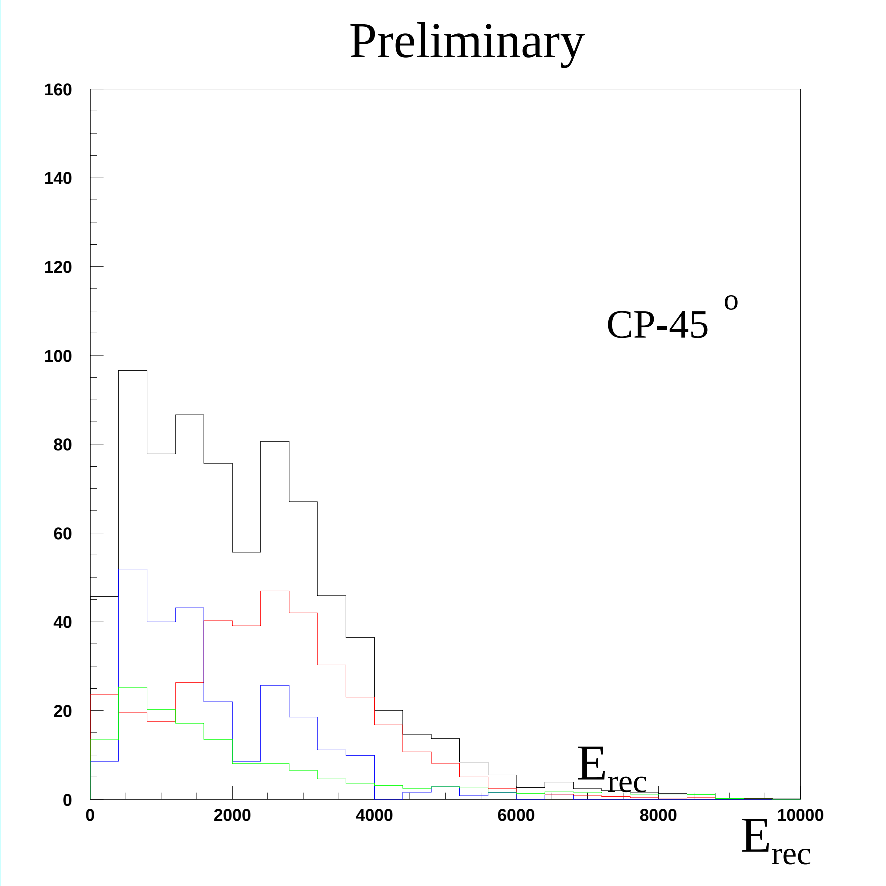
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

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)



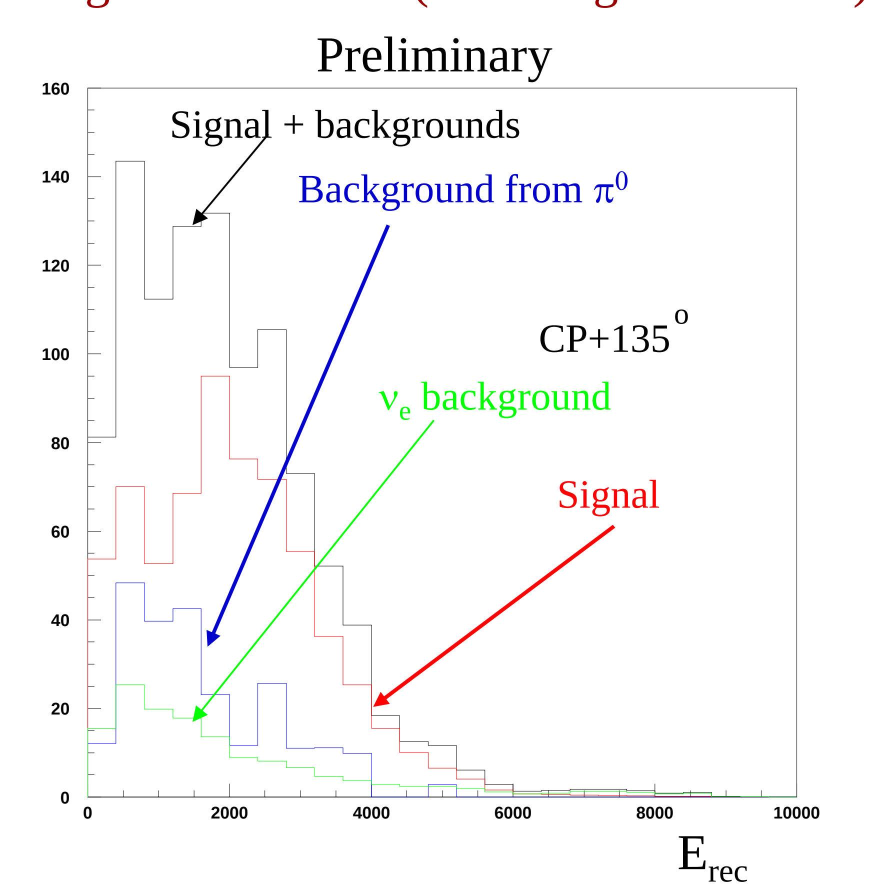
Signal 357 ev Bkgs 389
(247 from π^0+others)
(142 from ν_e)

Fermilab-Henderson (1480 km)

- Effect of cut on Δ ln likelihood

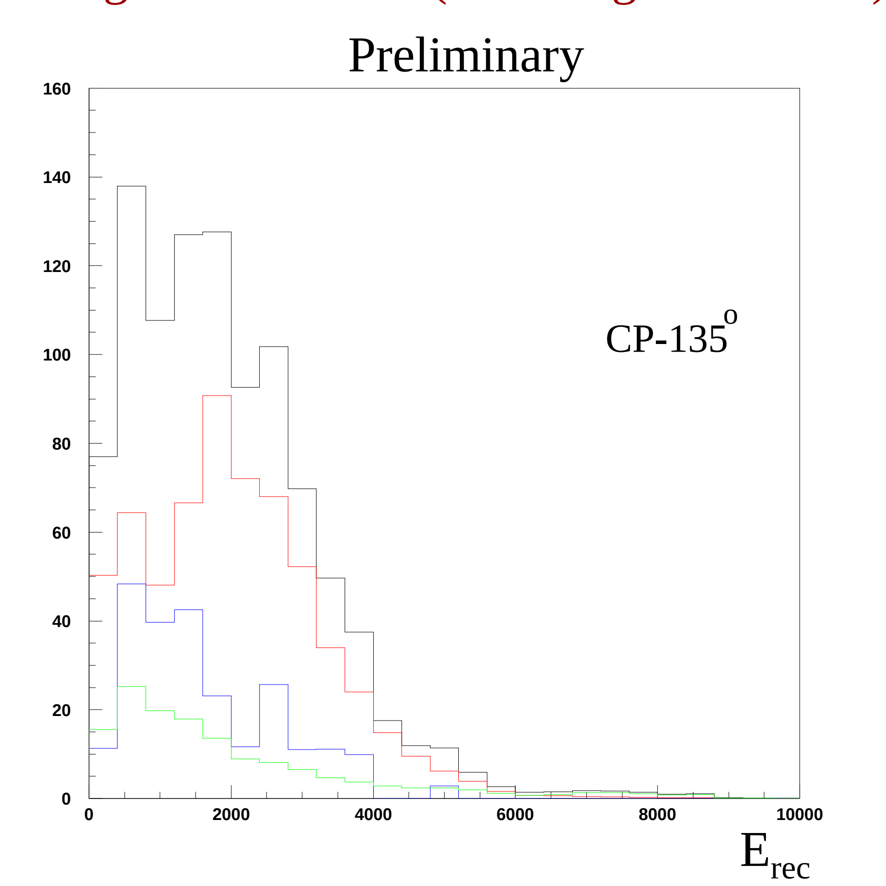
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log likelihood cut (~40% signal retained)



Signal 645 ev Bkgs 379
(237 from π^0+others)
(142 from ν_e)

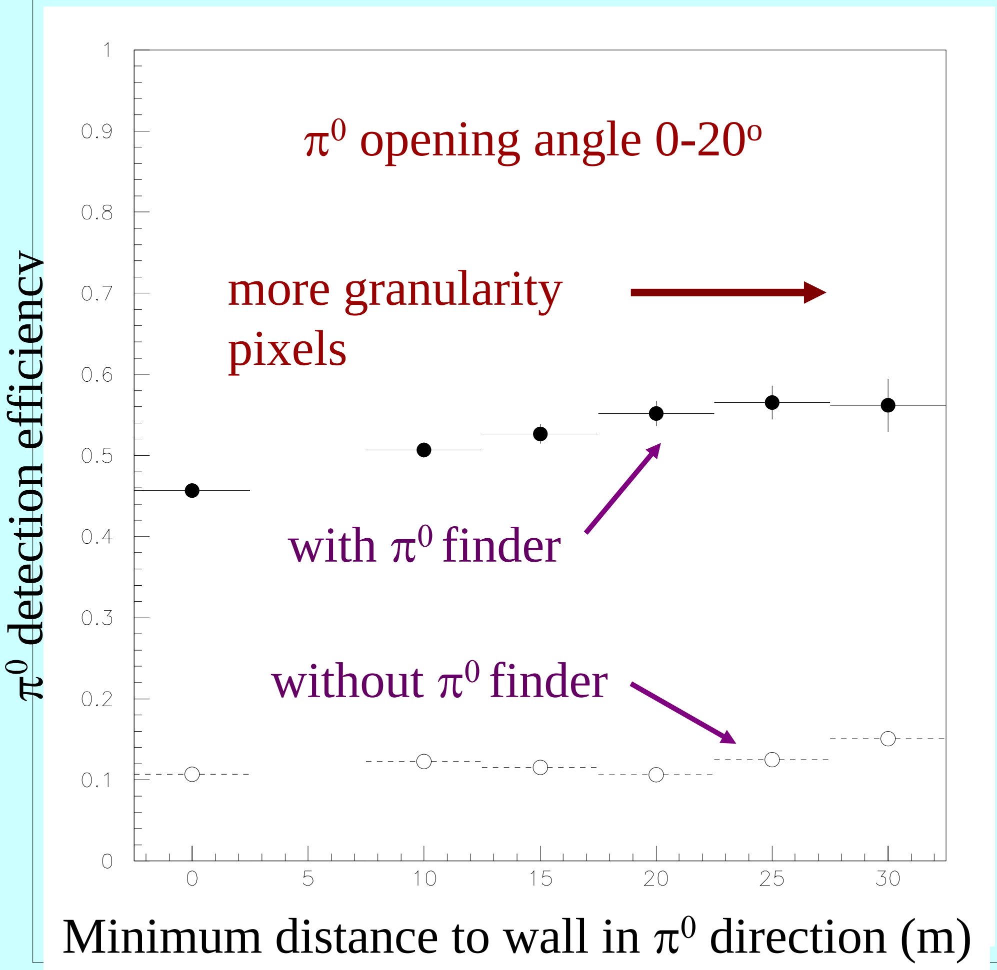
Δ log likelihood cut (~40% signal retained)



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