Feasibility Study on ν_e Appearance Experiment Using BNL VLB Neutrino Beam with UNO

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Introduction

Setting the stage

- **UNO, ~ a half megaton F.V. water Cherenkov detector**
- **BNL very long baseline neutrino beam idea**

→

- **VLB neutrino oscillation experiment**

See, for example, PRD68 (2003) 12002 for physics argument

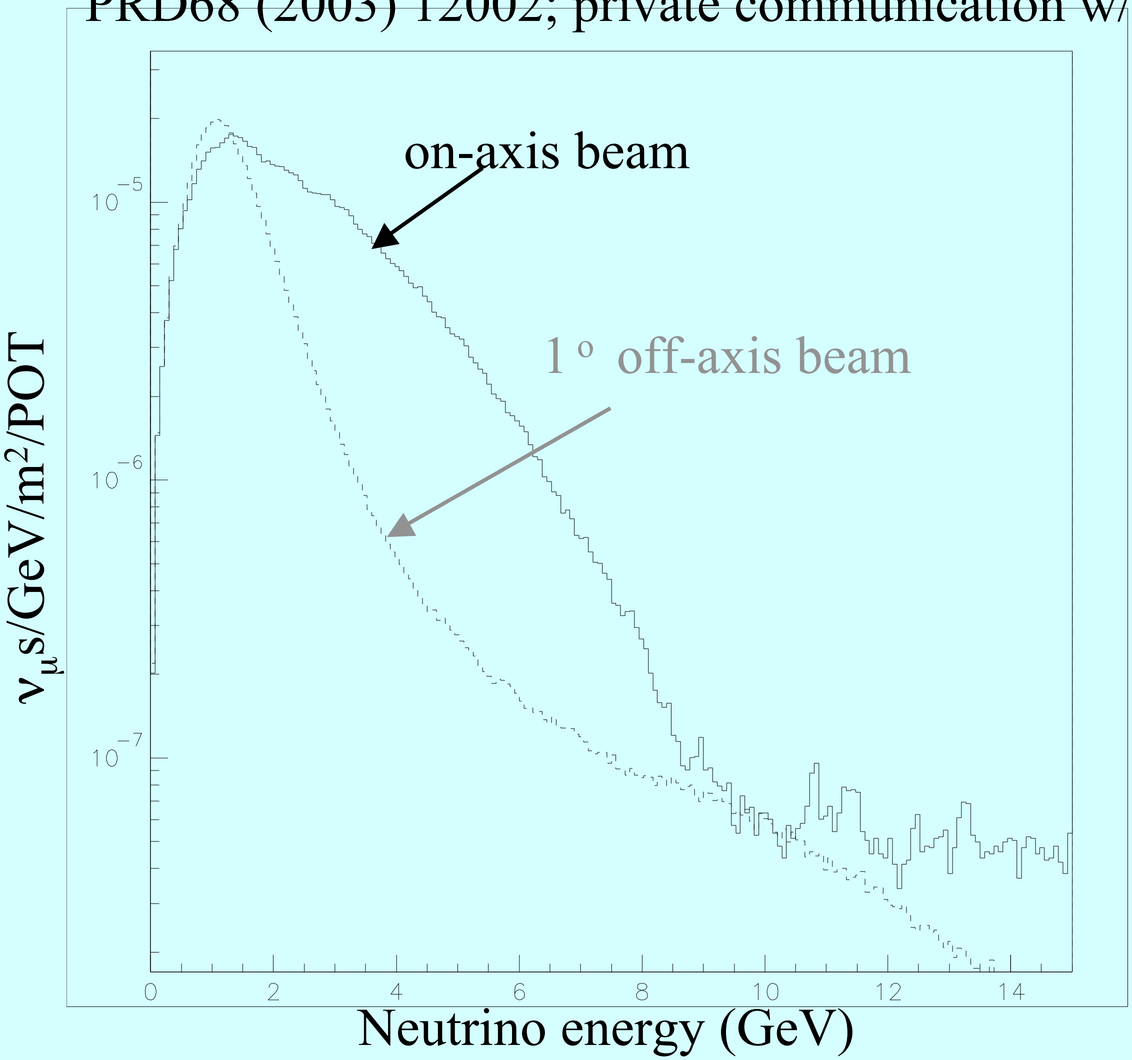
How do we find the signal for $\nu_\mu \rightarrow \nu_e$?

- **$\nu_\mu \rightarrow \nu_e$ and ν_e +N-> e + invisible N' + (invisible nπs,n>=0)**
- **Look for single electron events**
- **Major background**
  - $\nu_{\mu,\tau,e}$ + N -> $\nu_{\mu,\tau,e}$ + N' + π^0 + (invisible nπs,n>=0), $\pi^0 \rightarrow \gamma\ (\gamma)$
  - ν_e contamination in beam (typically 0.7%)

BNL Superbeam

- Spectra of on- and off-axis beams

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



UNO detector

otal mass: 650 ktons

id.vol :

440 ktons for pdecays

for sol. nu.

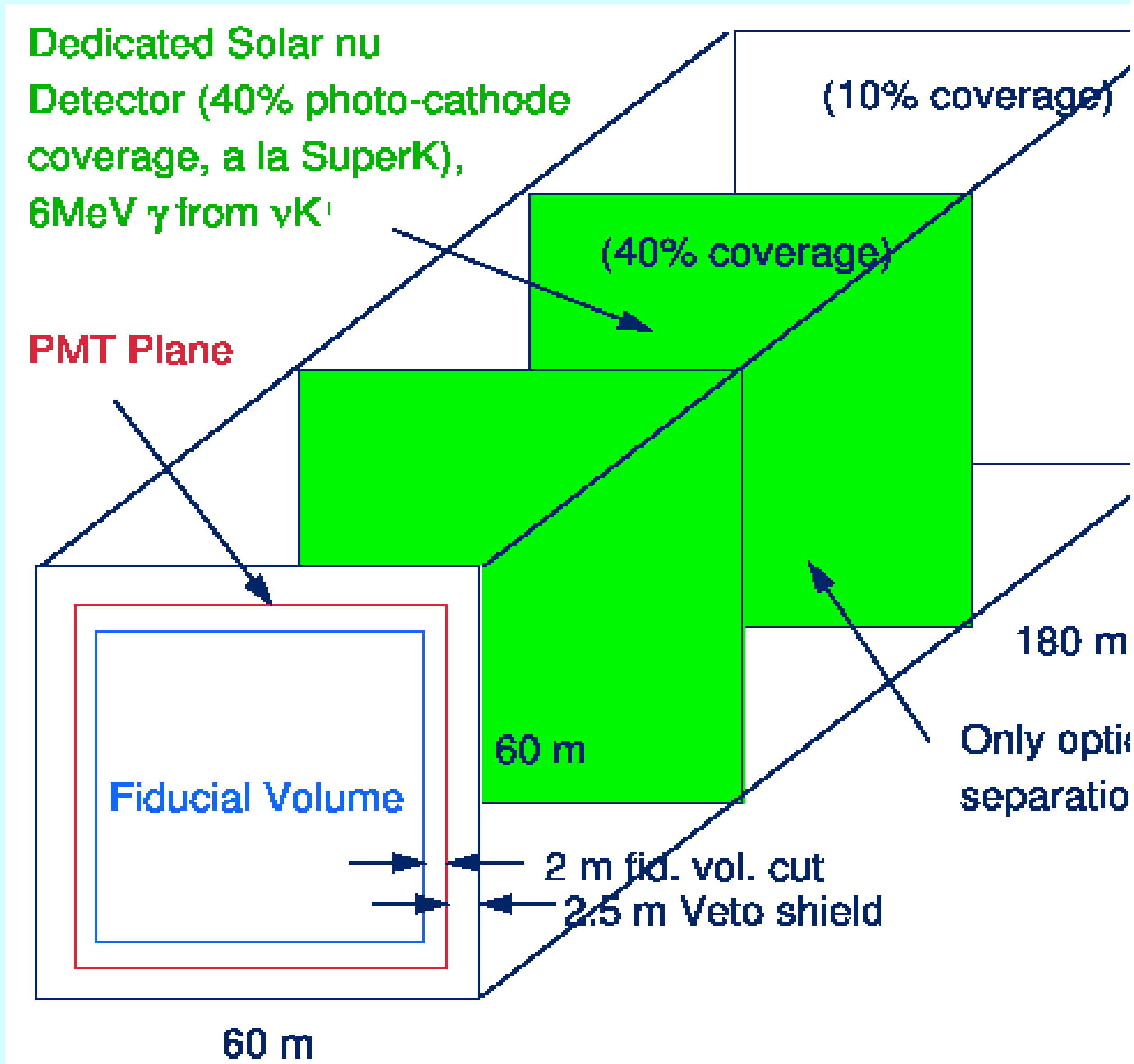
580 ktons for SN

otal size : 60x60x180 m^3

hotocathode coverage:

1/3 40%, 2/3 10%

An physicist's view of conceptual detector of UNO



- 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 km baseline

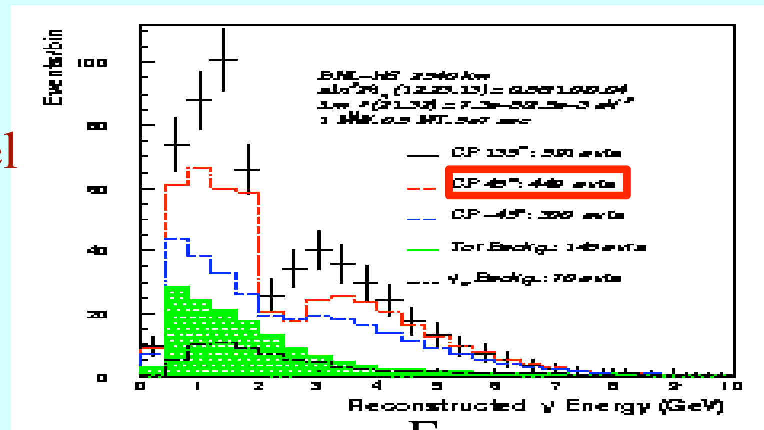
      distance from BNL to Homestake
    - Reweight with oscillation probabilities for ν_μ and for ν_e
  - **Oscillation parameters used:**
    - **Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x $10^{-3}$$eV^2$**
    - **$\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=+45,+135,-45,-135°**

Probability tables from Brett Viren of BNL

- Previous results ν_e QE for signal, all ν_μ , ν_e , ν_τ NC $1\pi^0$ for bkg

BNL report

Based on 4-vector level MC



E_{rec}

CP+45^o

Signal 303 events

All bkgs 146

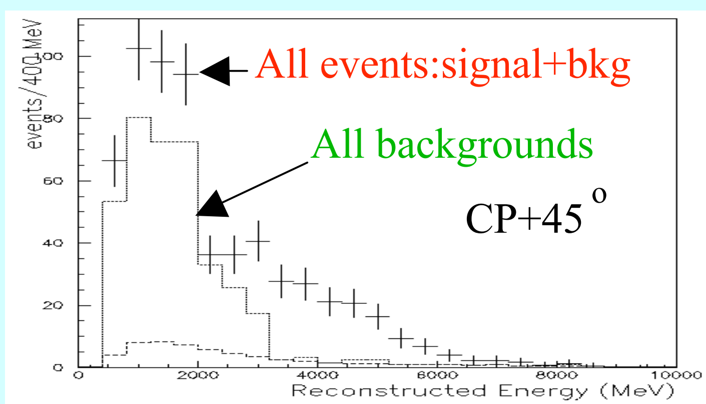
(76 from π^0)

(70 from ν_e)

Compare .... with +

My first study with full SK simulation

Using traditional SK variables + π^0 mass; similar to BNL cuts



E_{rec}

Signal 242 events

All bkgs 380

(324 from π^0)

(56 from ν_e)

Selection criteria

- 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

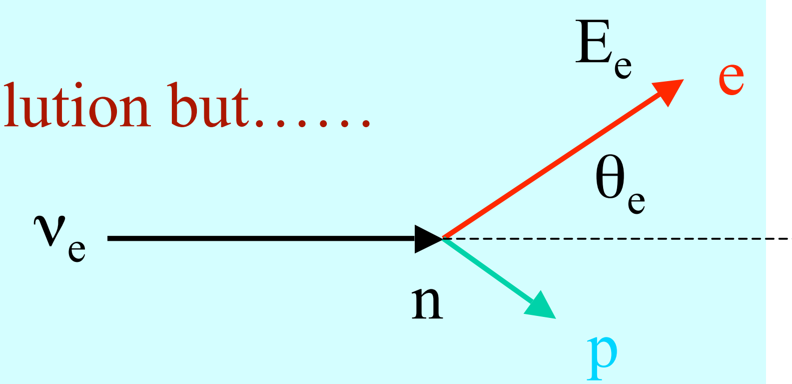
To reduce events with invisible charged pions

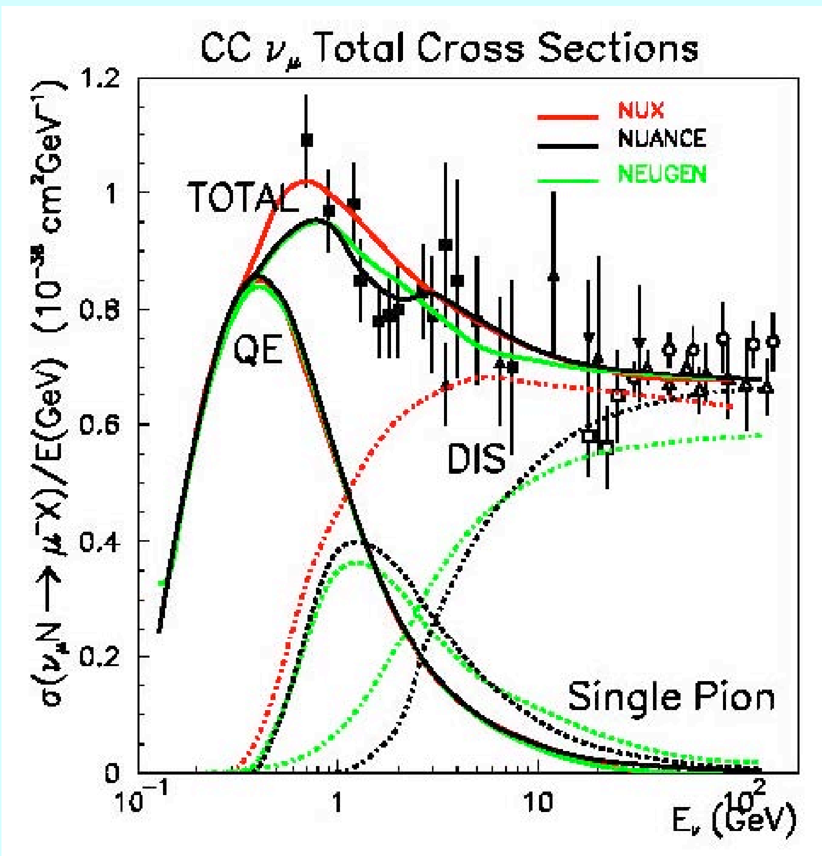
- Likelihood analysis using the following eight variables: With π^0 finder
  - pi0-likelihood, e-likelihood, energy fraction, costh, pi0mass
  - Δ pi0-likelihood, total charge/electron energy, Cherenkov angle

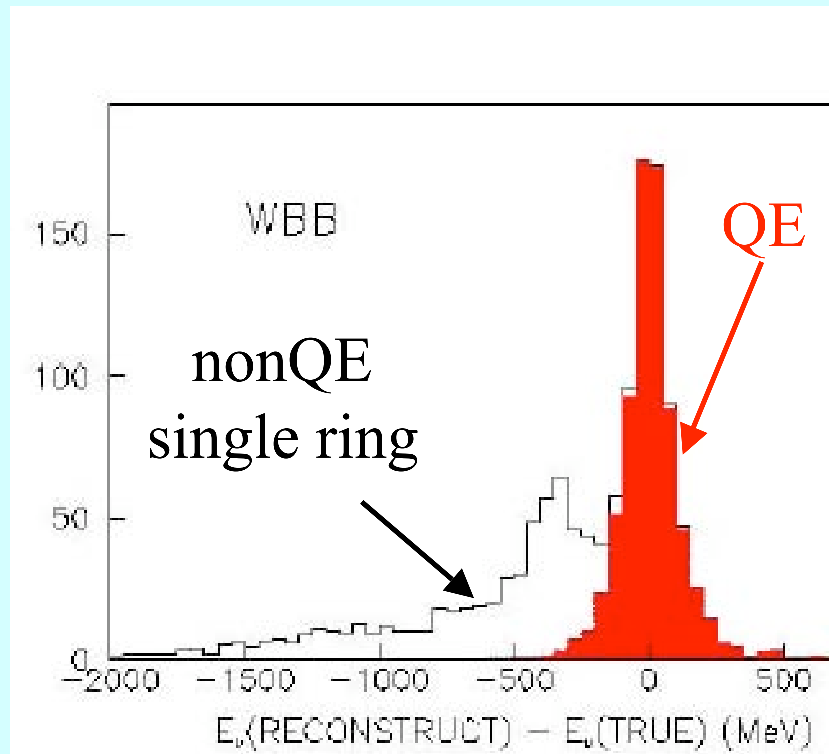
- What is the signal?
  - **Neutrino energy reconstruction**

QE events give the best energy resolution but……

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

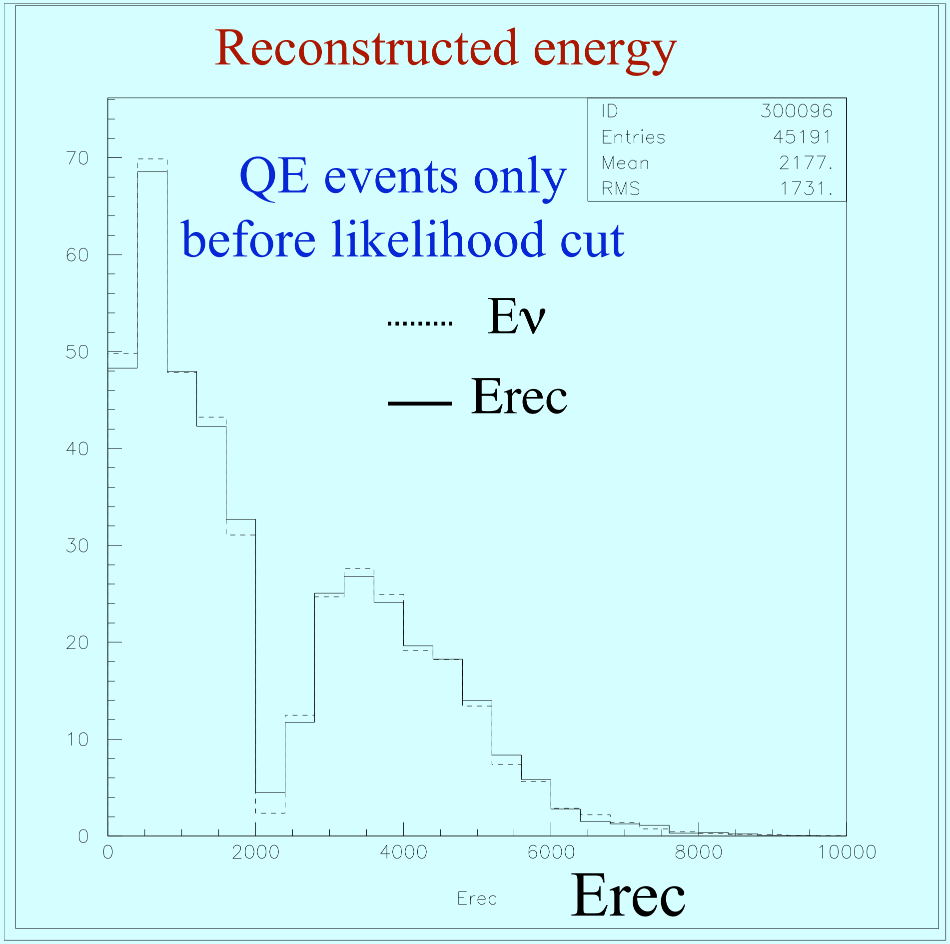


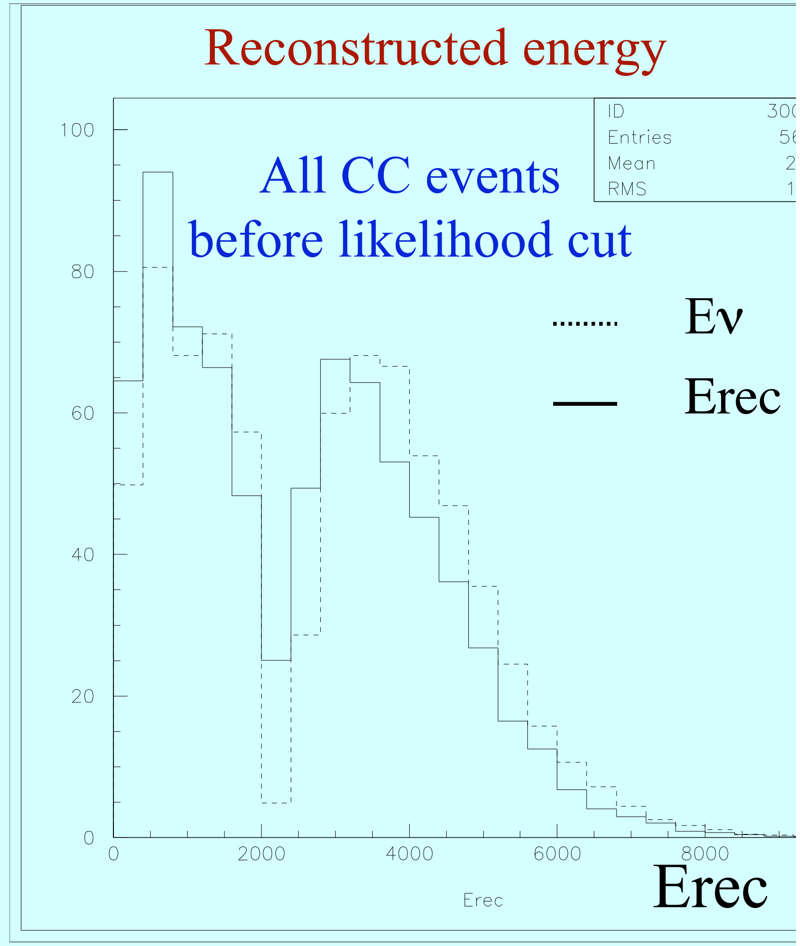




- What is the signal? Single e-like events after initial cut

- **What is the signal and what is the background?**



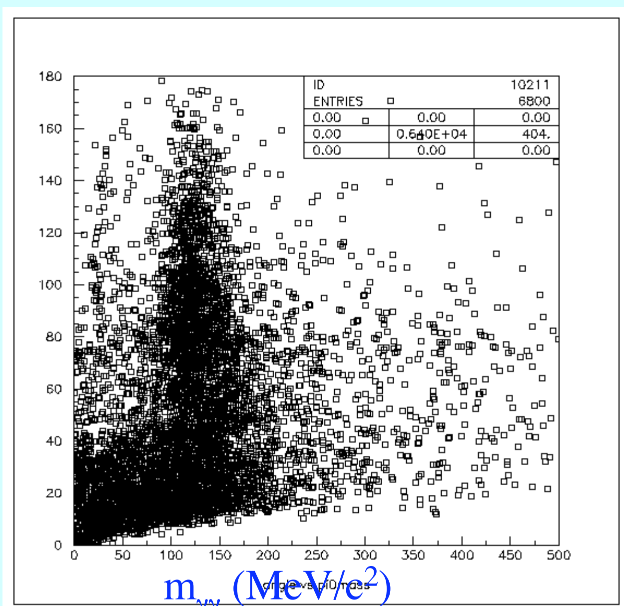


Why not accept all CC events as signals?

_ π^0 Finder

- π^0 finder — Always finds an extra ring in a single ring event
  - π^0 detection efficiency with standard SK software
  - measured opening angle vs. π^0 mass with π^0 finder

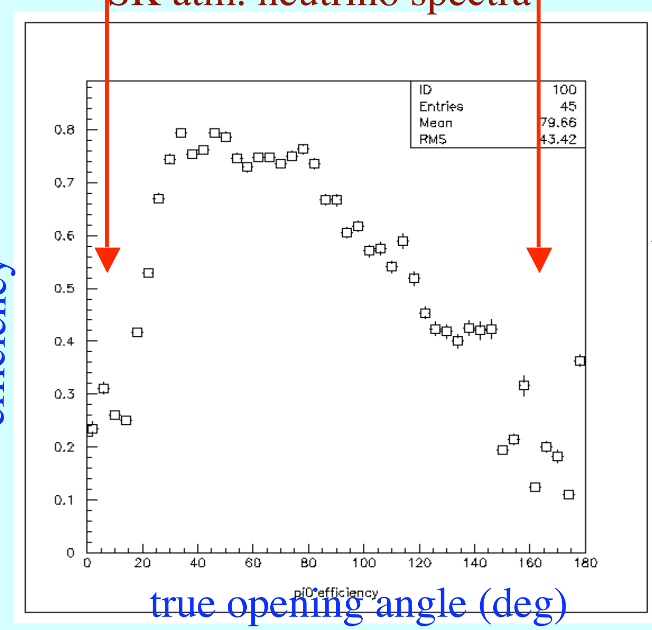
Single e-like events from single π^0 int.



inefficiency due to overlap

inefficiency due to weak 2^{nd} ring

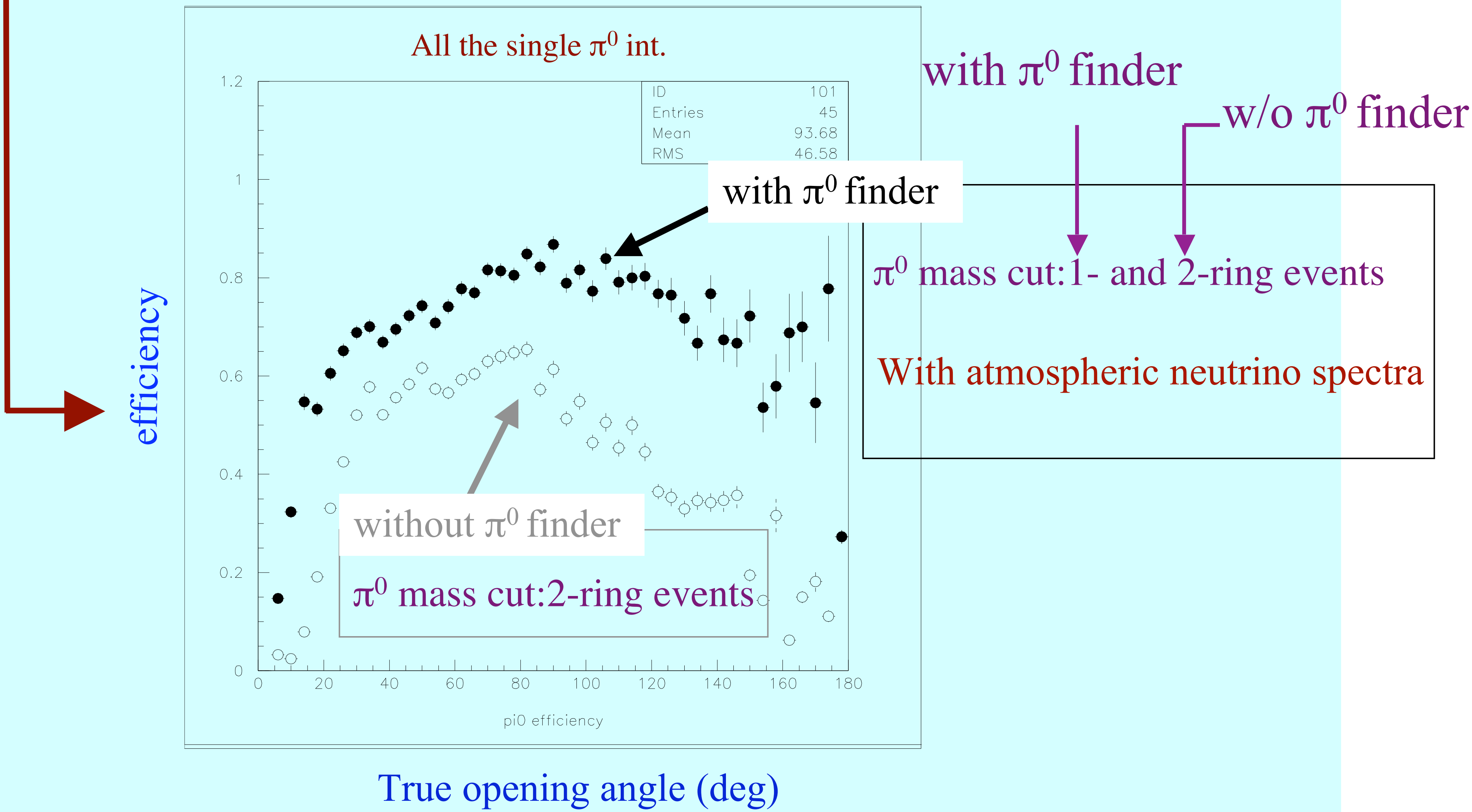
All single π^0 interactions
SK atm. neutrino spectra



π^0 finder

π^0 efficiency

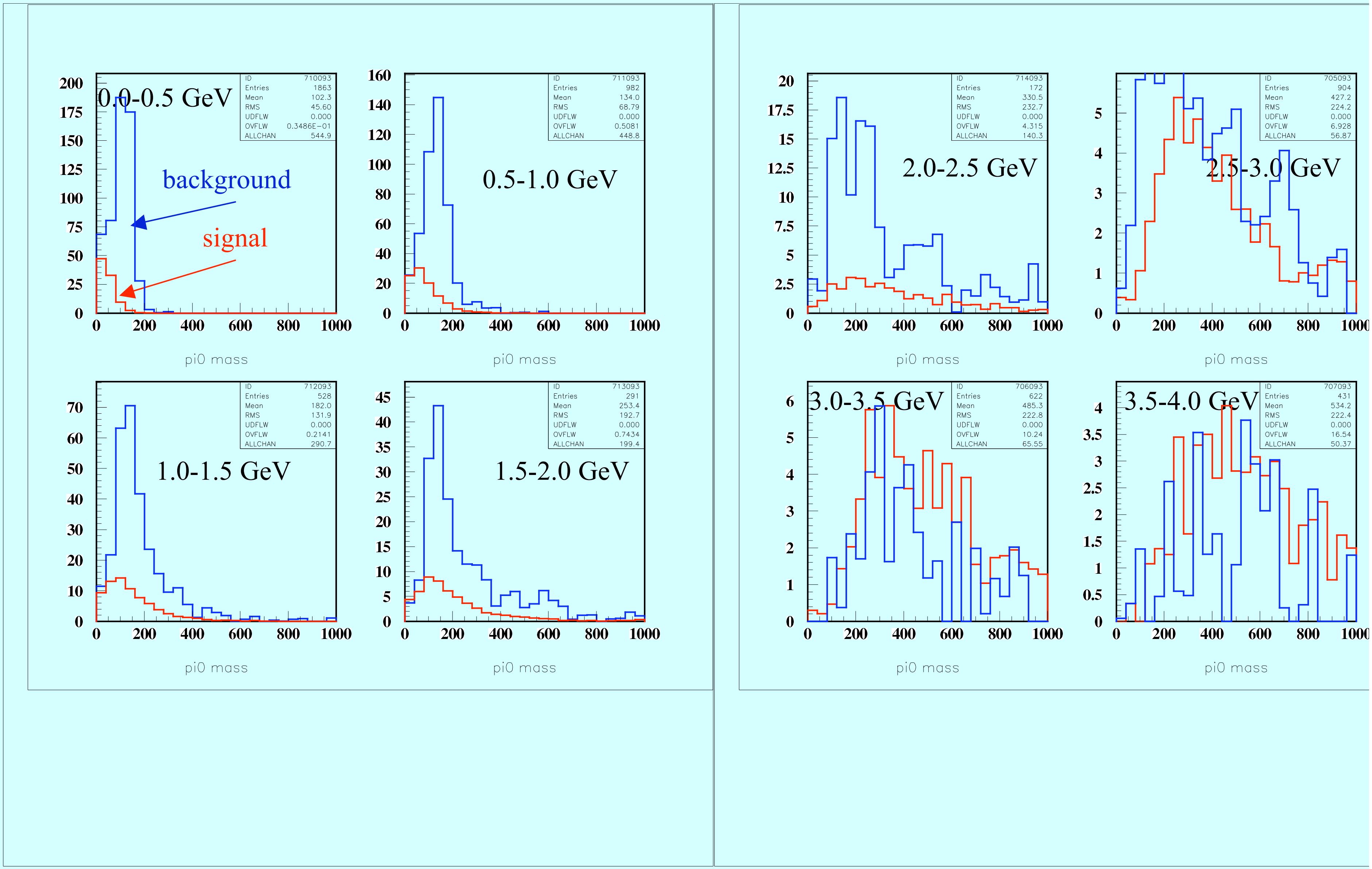
- **π^0 detection efficiency with standard SK + π^0 finder**



• Useful Variables

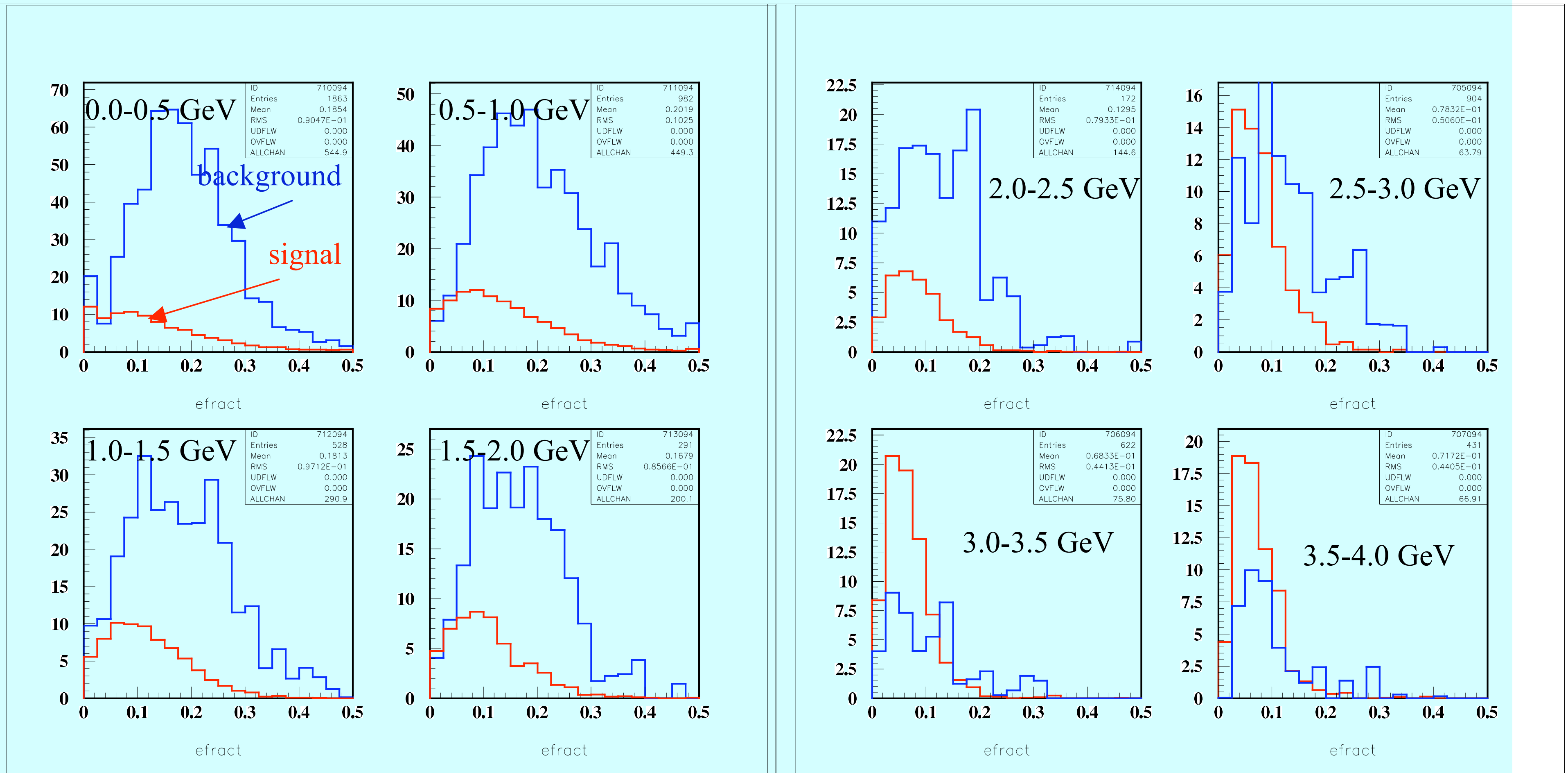
All the distributions of useful variables are obtained with neutrino oscillation on with CPV phase angle $+45^0$

π^0 mass



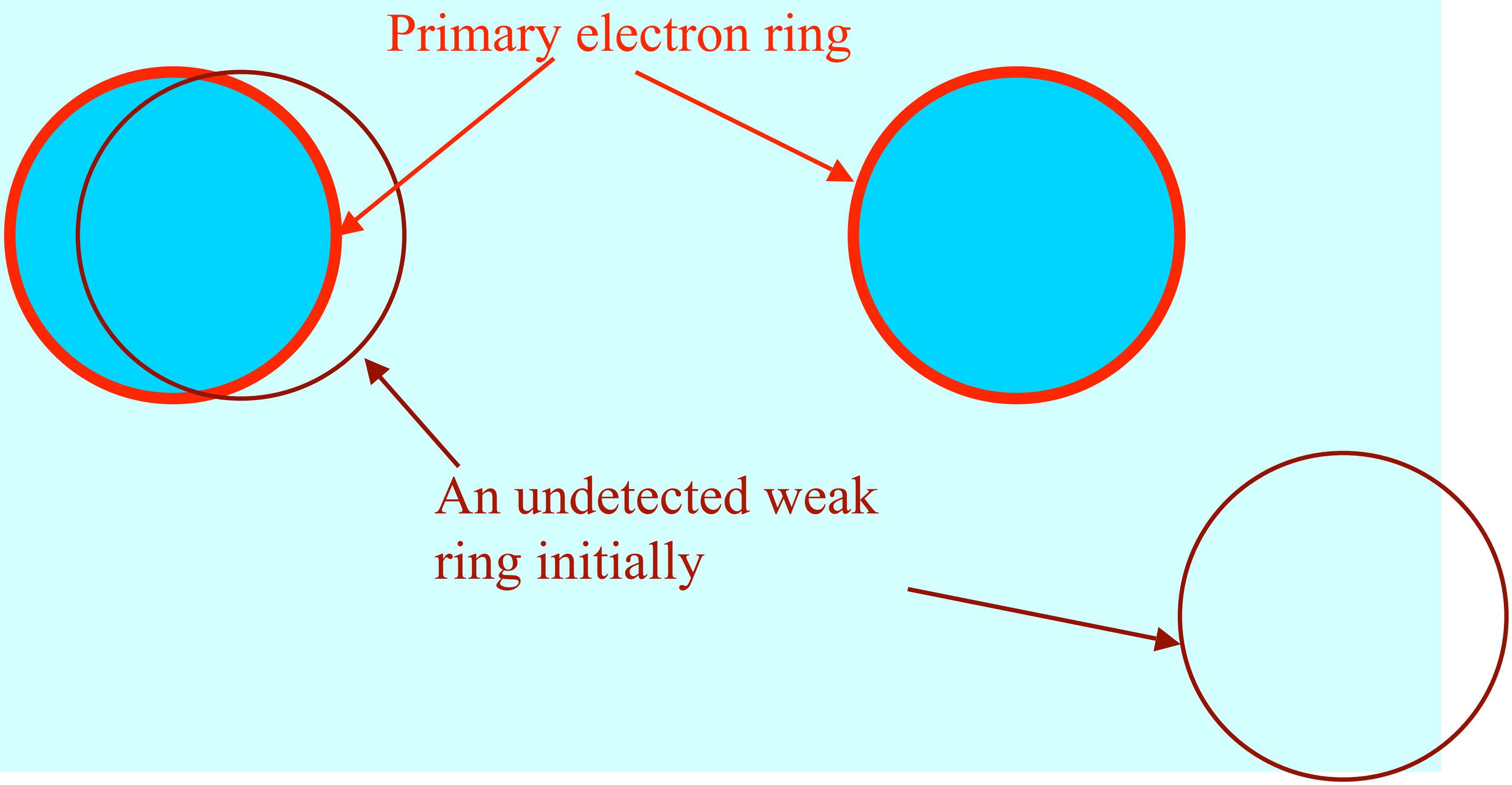
- Energy fraction of 2nd ring

Fake ring has less energy than real one

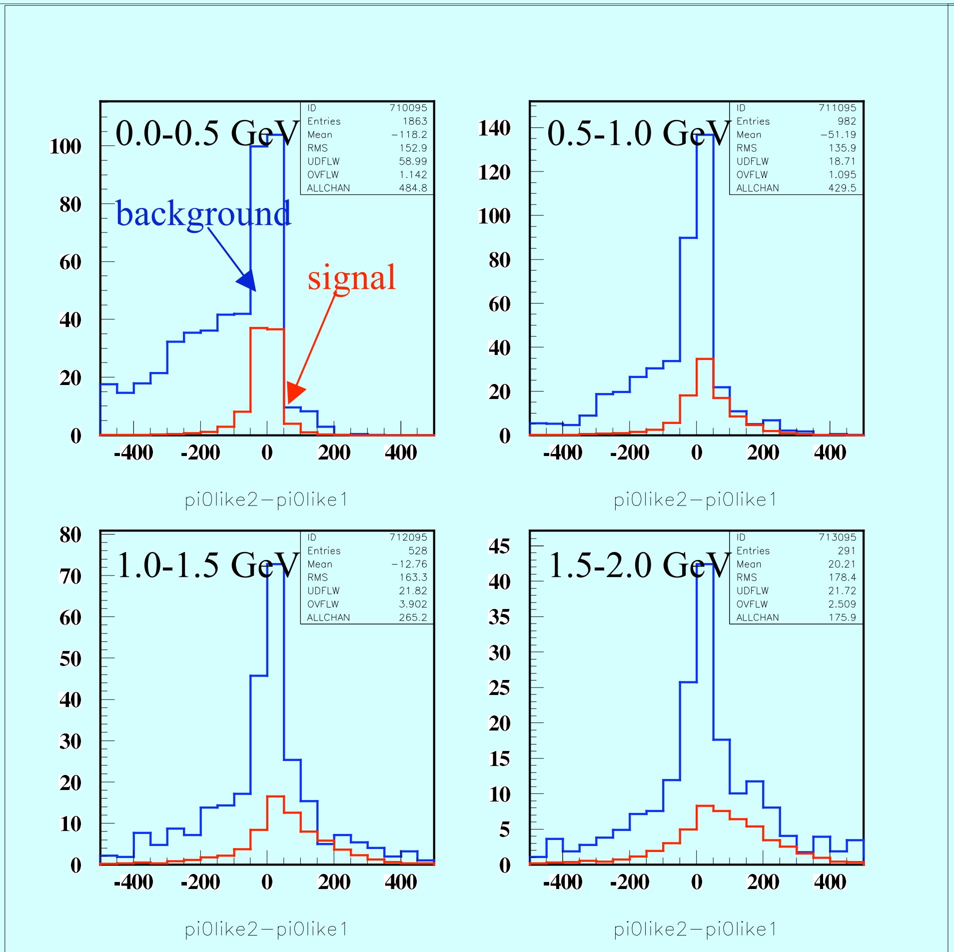


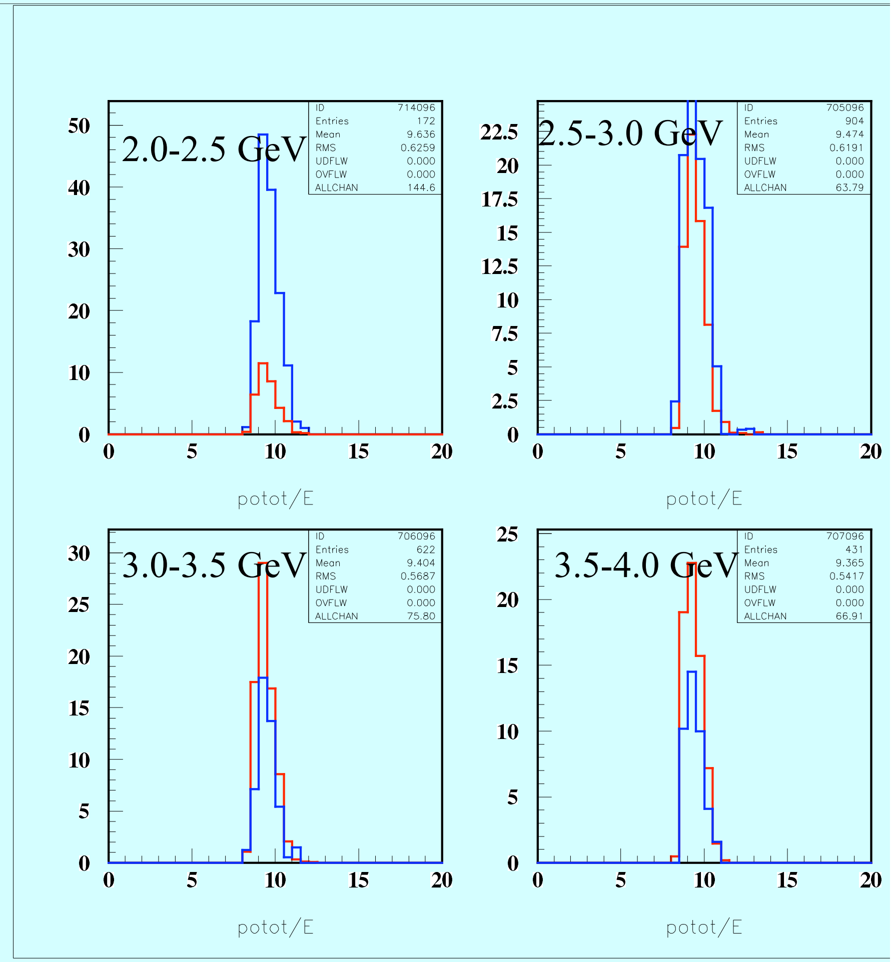
- Difference in two pi0likelihoods

  - One algorithm optimized to find an extra ring near the primary ring (forward region)
  - Another algorithm optimized to find an extra ring in wider space (wide region)
  - See the difference pi0lh(fowrad)-pi0lh(wide)



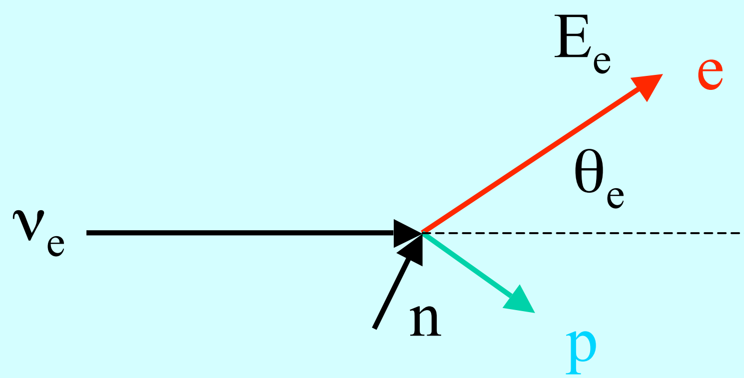
- Difference between two pi0likelihoods (wide vs. forward)





- costh = cos θ_e

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

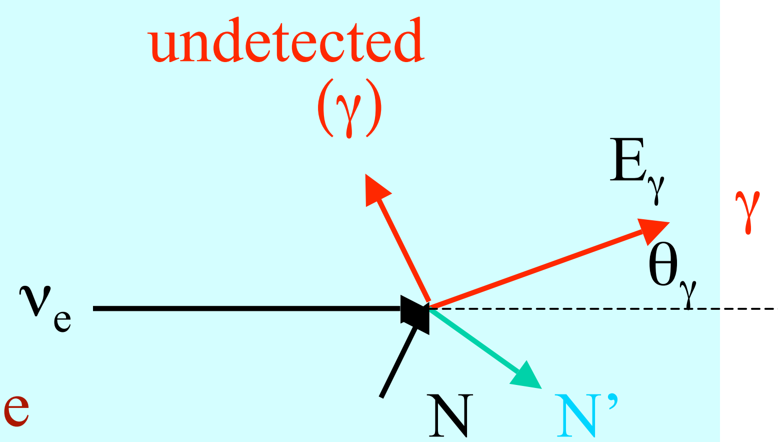


It is not clear why the distributions of costh behave as shown in the following.

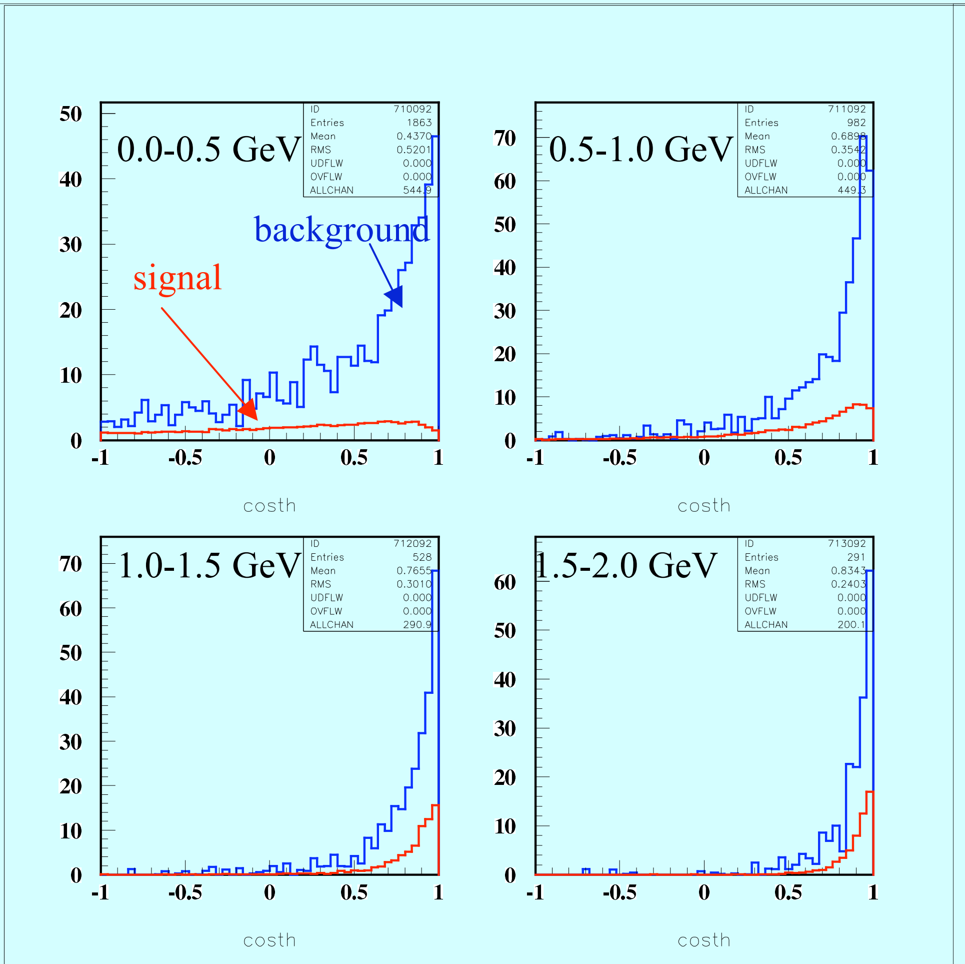
My speculation:

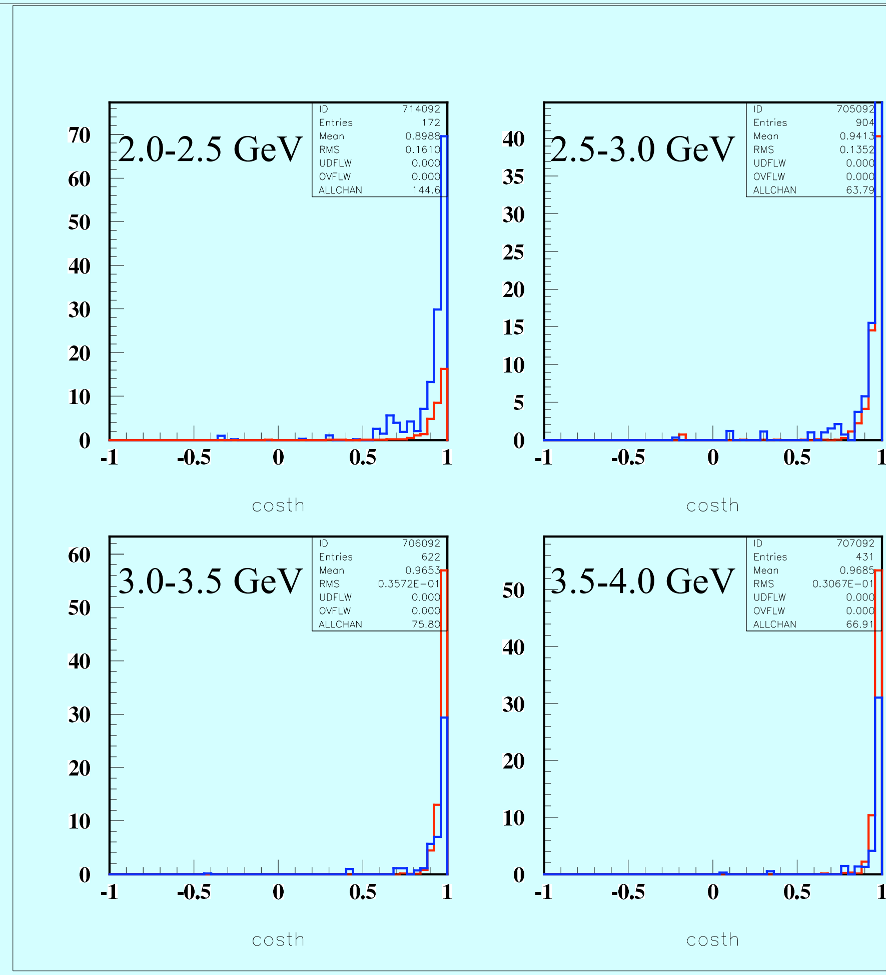
1) The signal events from QE scattering have larger θ_e due to the Fermi motion of the target neutron in oxygen in the low energy region.

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.



- costh = cos θ_e

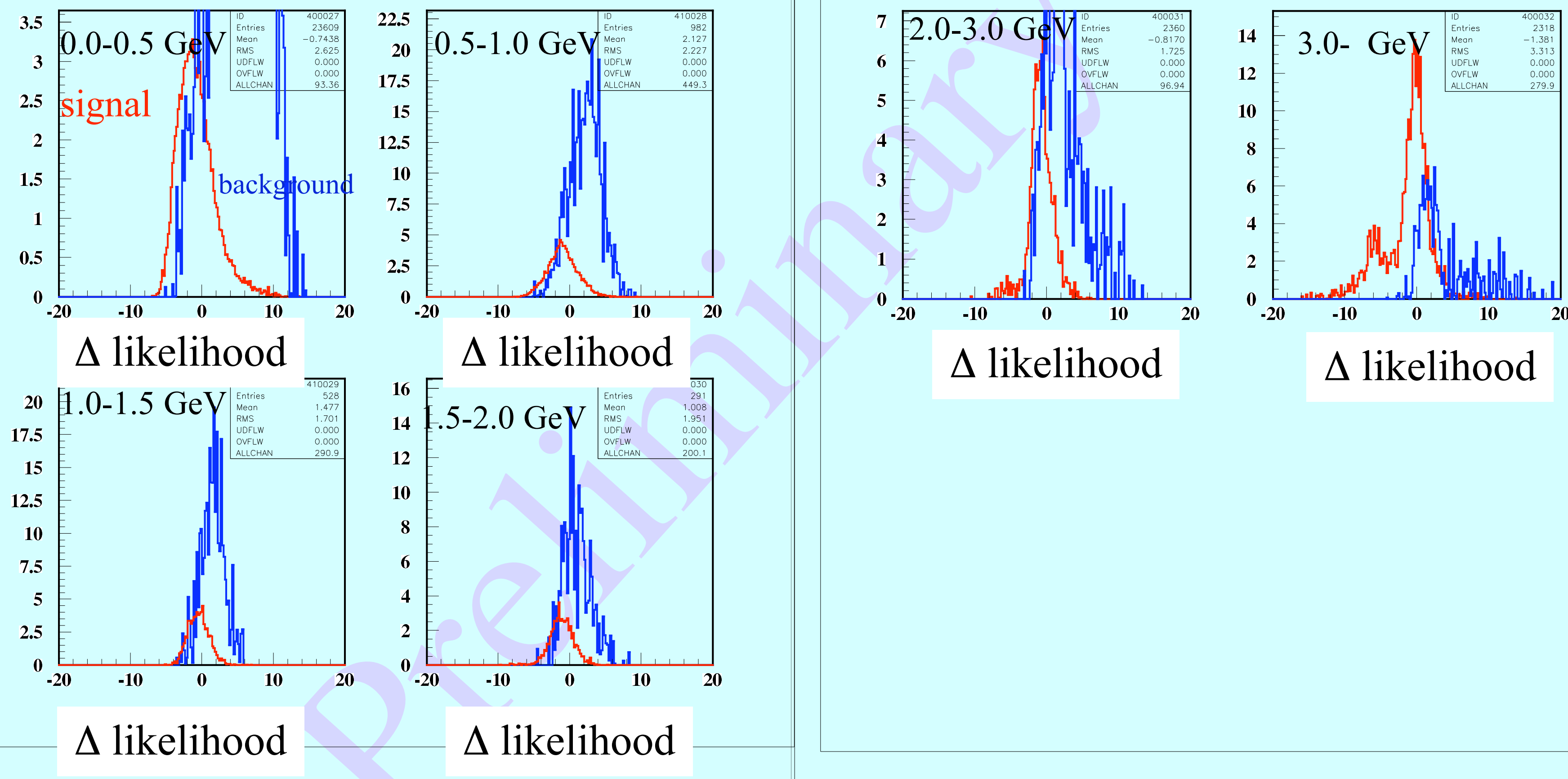




likelihood cu

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

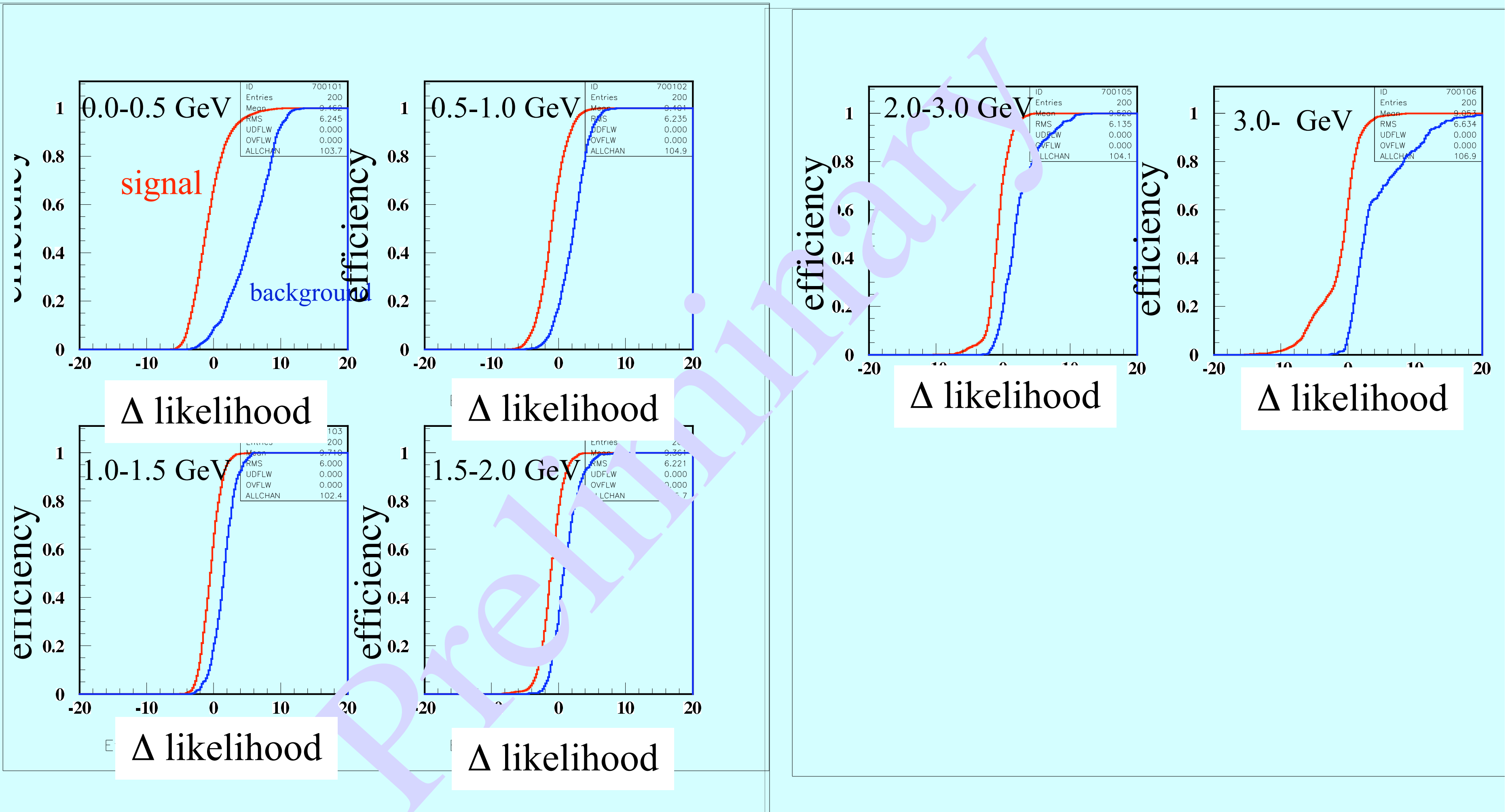
Δ likelihood distributions Difference in likelihood between signal and bkg



likelihood cu

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

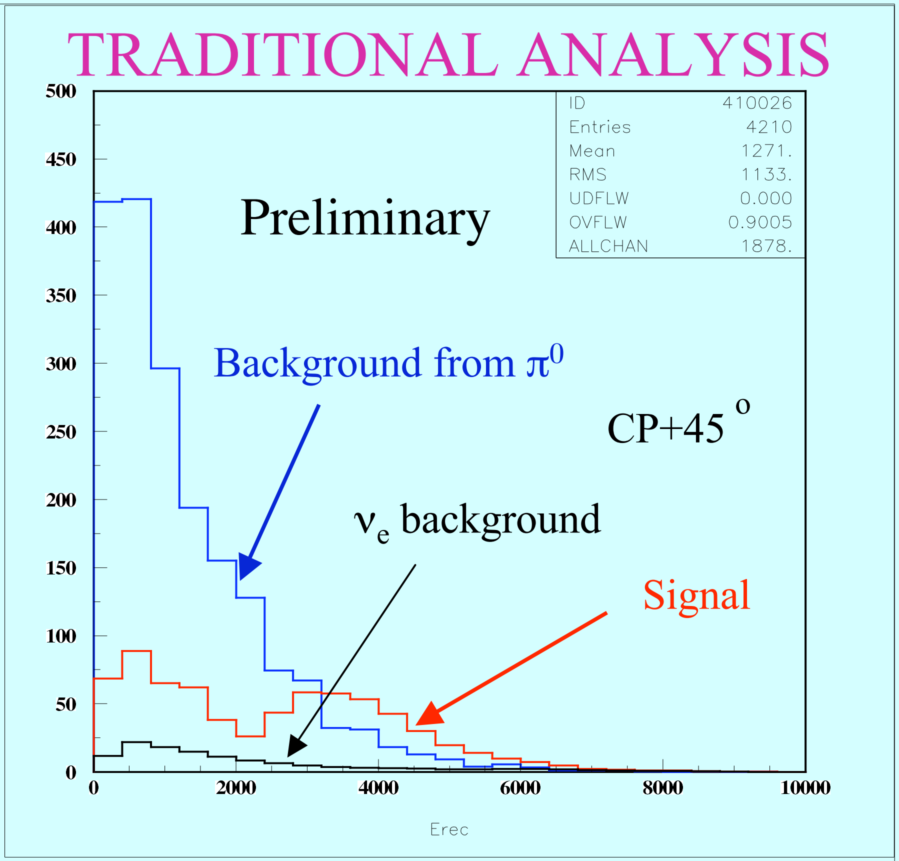
- Efficiency of a cut on Δ likelihood



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

- Effect of cut on Δ likelihood

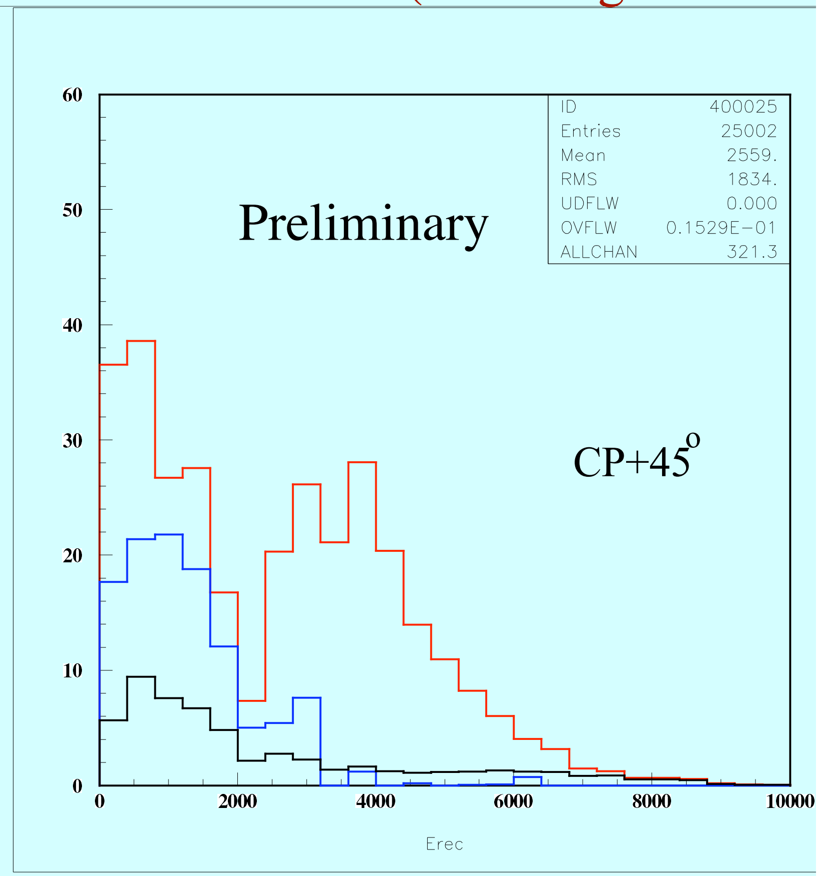
Δlikelihood cut (100% signal retained)



E_{rec}

Signal 700 ev Bkgs 2005
(1878 from π^0+others)
(127 from ν_e)

Δlikelihood cut (~50% signal retained)



E_{rec}

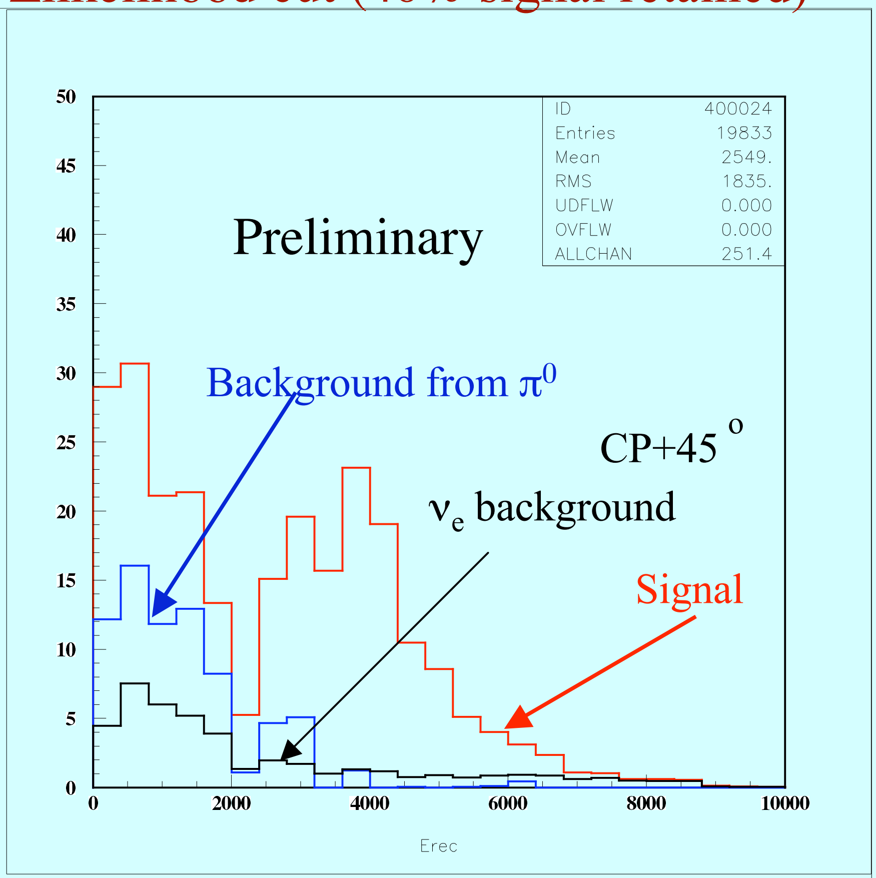
Signal 321 ev Bkgs 169
(112 from π^0+others)
(57 from ν_e)

Signal/Background

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

Effect of cut on Δ likelihood

Δlikelihood cut (40% signal retained)



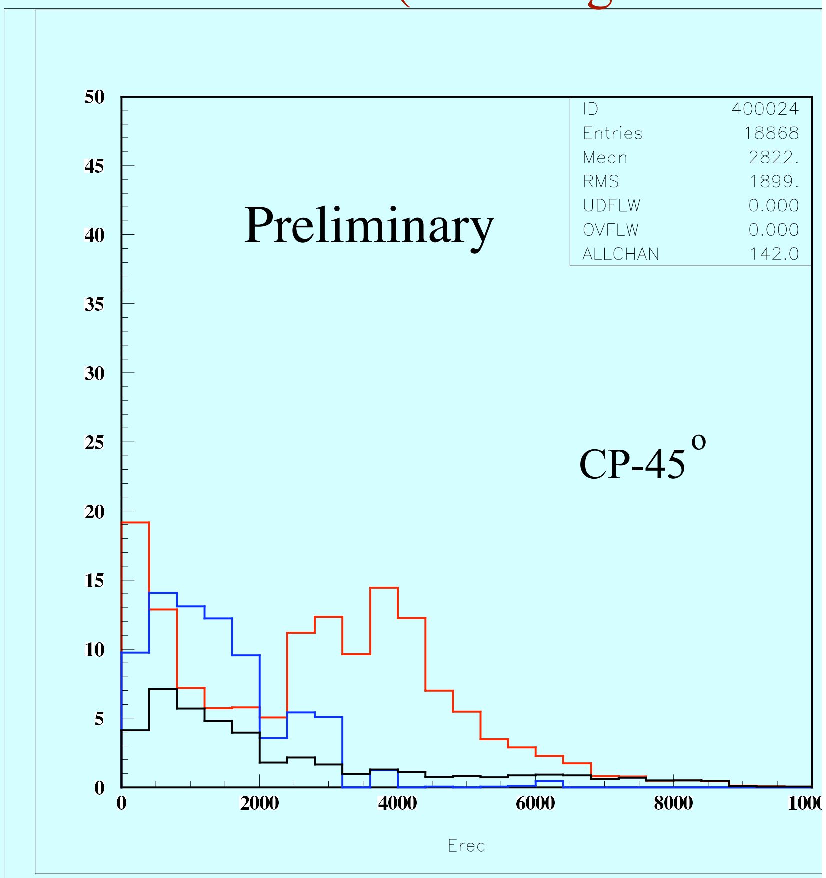
E_{rec}

Signal 251 ev Bkgs 118

(74 from π^0+others)

(44 from ν_e)

Δlikelihood cut (~40% signal retained)



E_{rec}

Signal 142 ev Bkgs 118

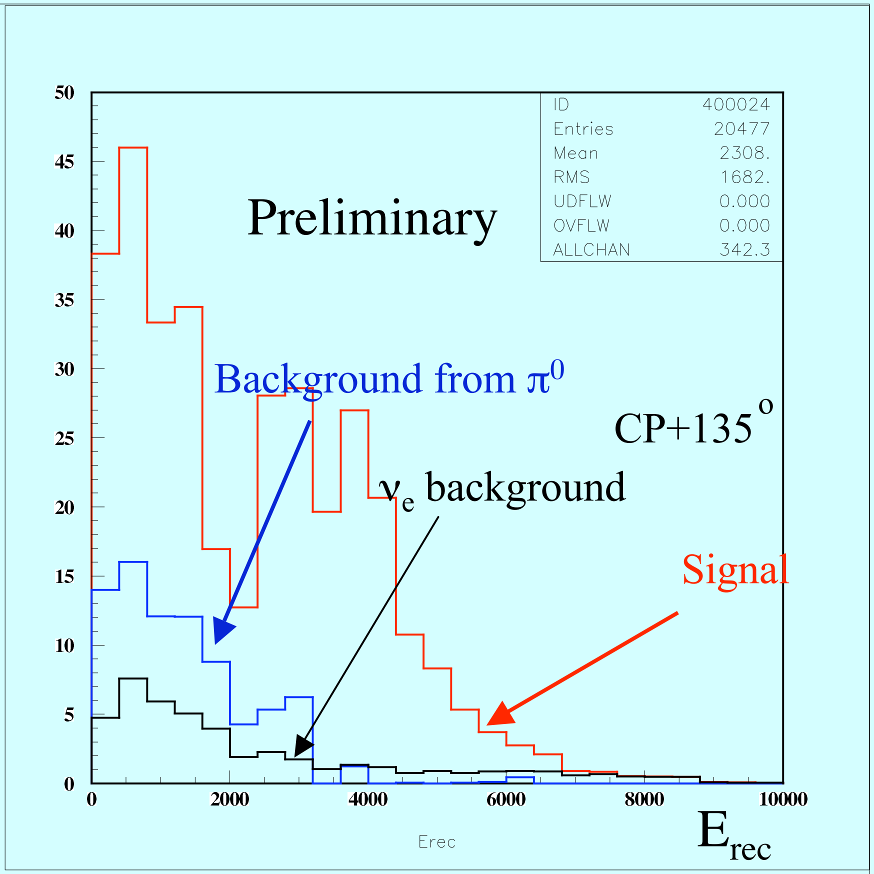
(75 from π^0+others)

(43 from ν_e)

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

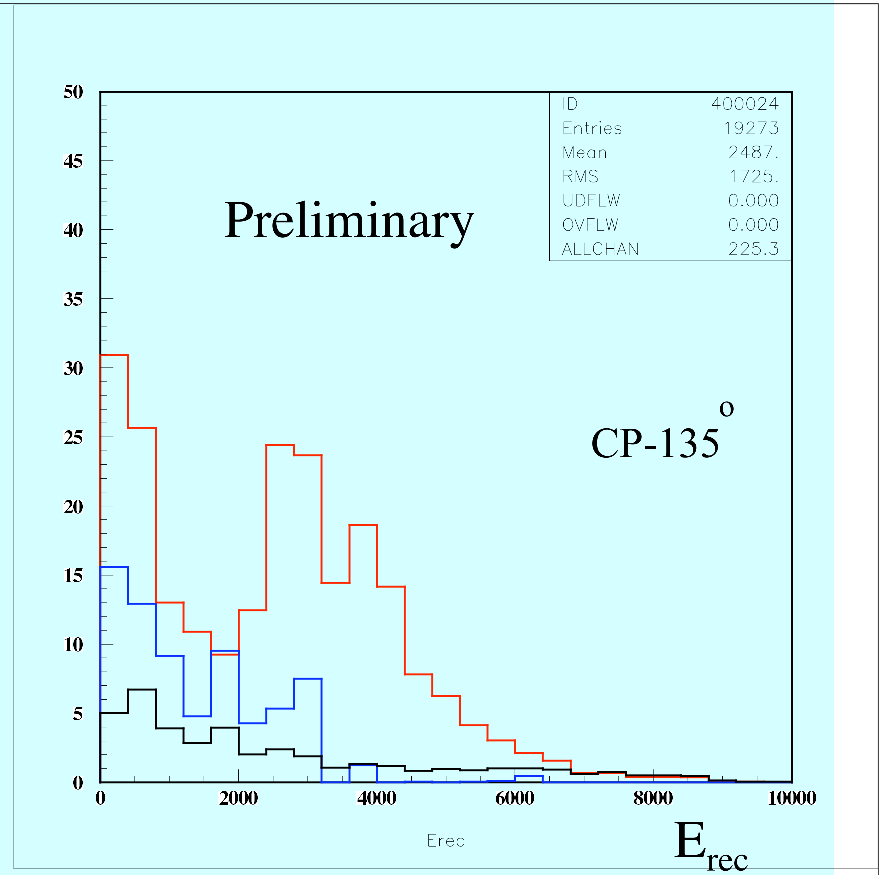
- Effect of cut on likelihood

Δlikelihood cut (~40% signal retained)



Signal 342 ev   Bkgs   126
(81 from π^0+others)
(45 from ν_e)

Δlikelihood cut (~40% signal retained)



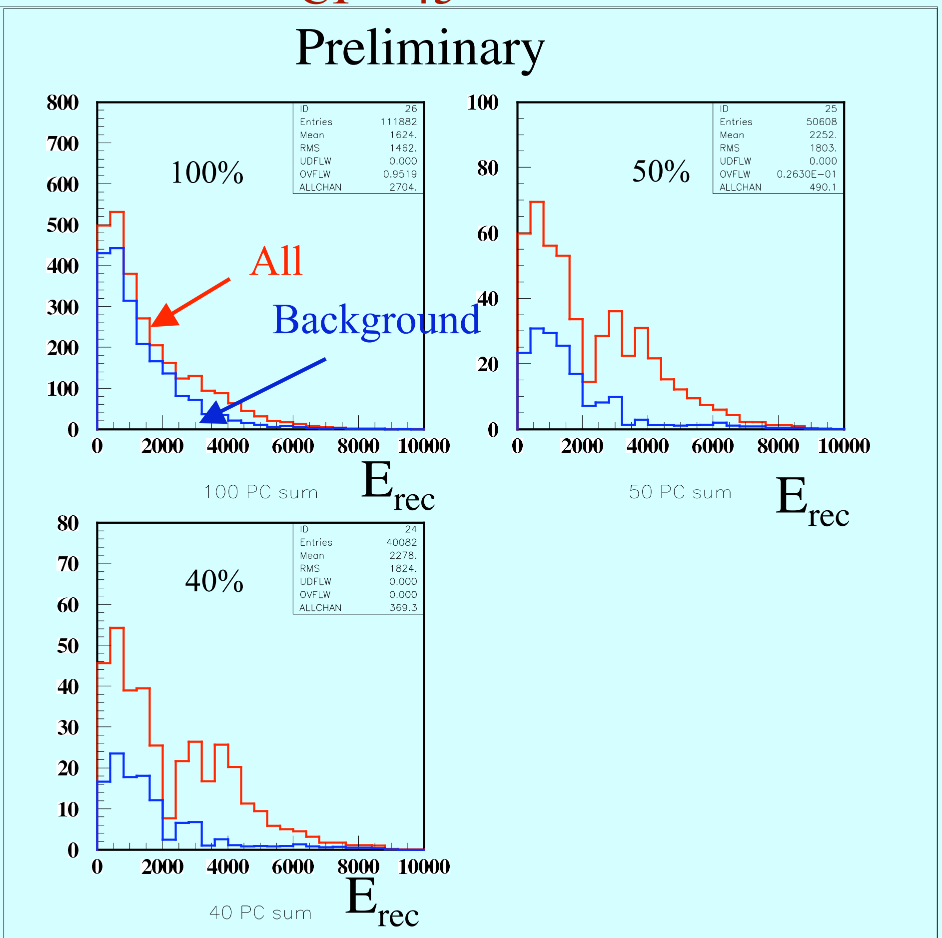
Signal 233 ev   Bkgs   122
(78 from π^0+others)
(44 from ν_e)

S/B

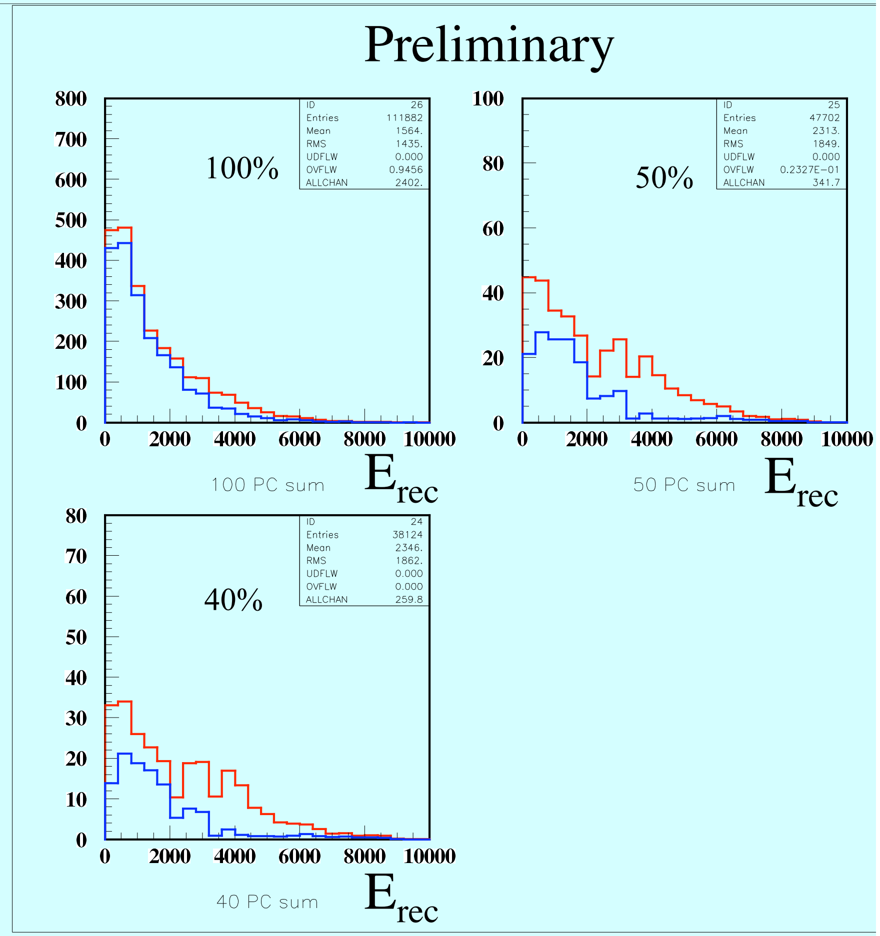
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for bkg

- Effect of cut on likelihood

CP +45°



CP-45°

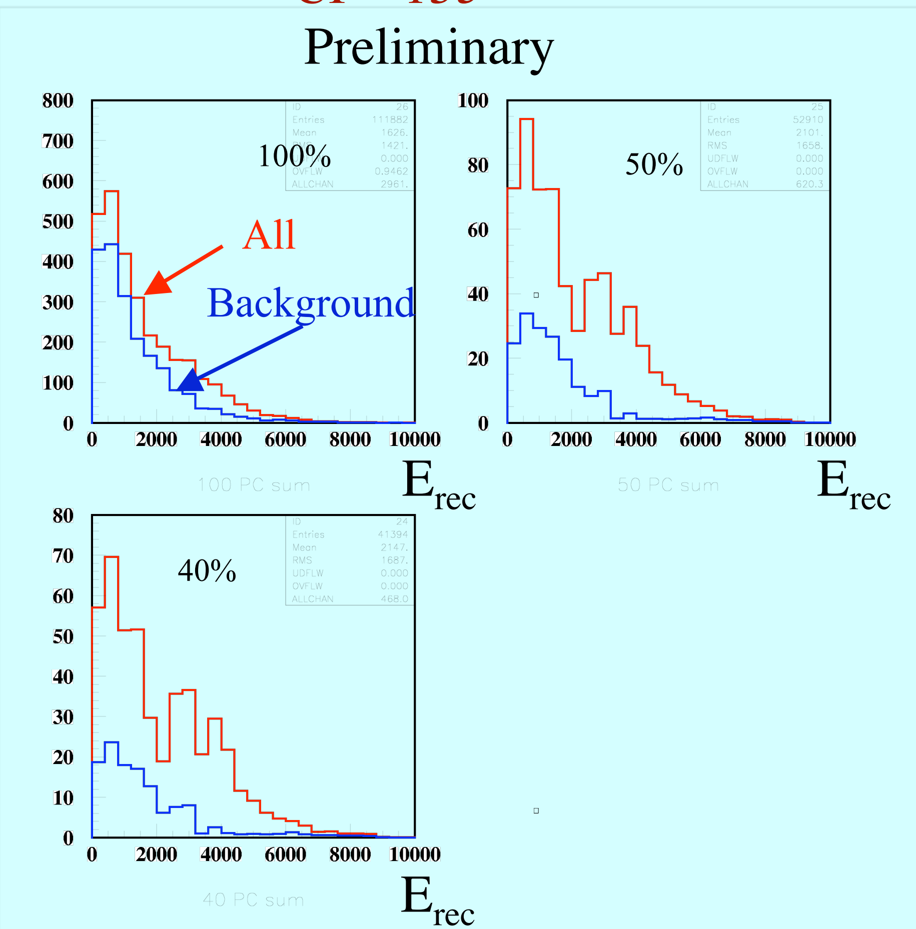


S/B

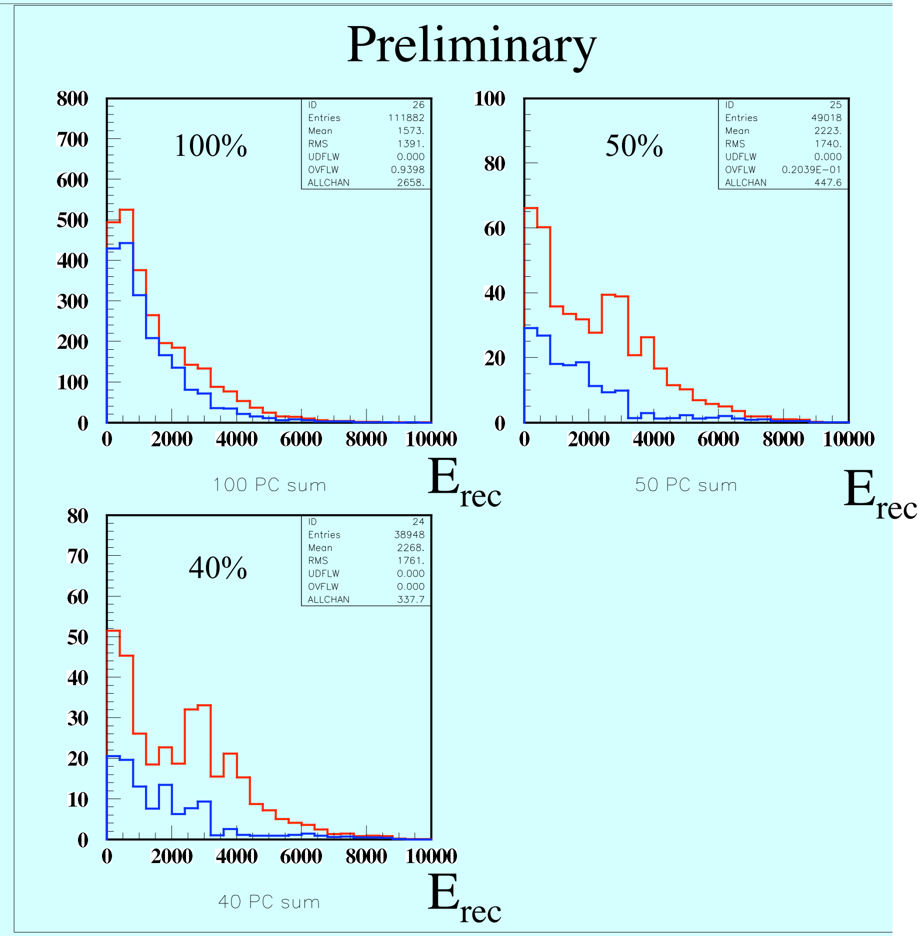
Effect of cut on likelihood

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

CP +135°



CP-135°



Signal/background

_ S/B

Summary of BNL superbeam@UNO

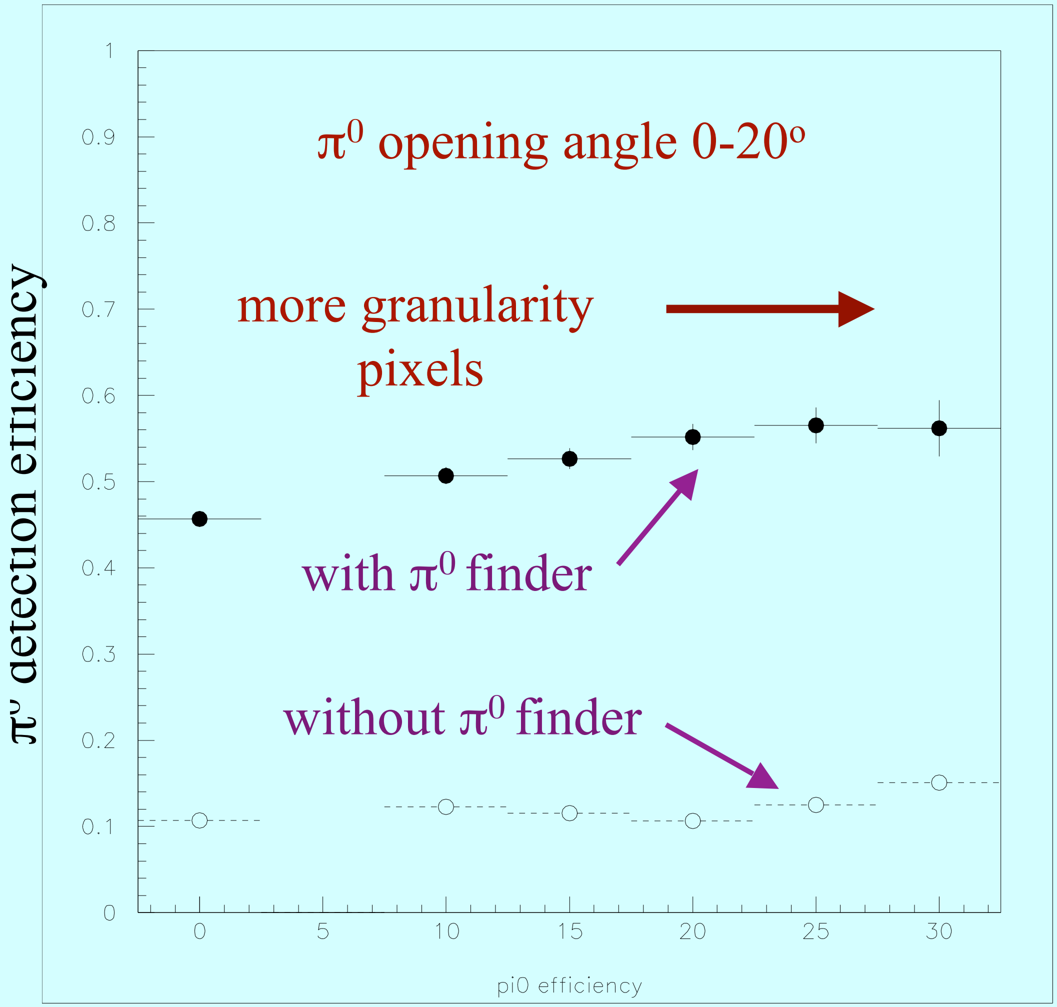
CP phase	Signal	Bkg	Effic	Signal	Bkg	Beam ν_e
0^o	ν_e CC	ν_μ all, ν_e NC	40%	178	75	43
-135^o	ν_e CC	ν_μ all, ν_e NC	40%	233	78	44
$+135^o$	ν_e CC	ν_μ all, ν_e NC	40%	342	81	45
-45^o	ν_e CC	ν_μ all, ν_e NC	40%	142	75	43
$+45^o$	ν_e CC	ν_μ all, ν_e NC	100%	700	1878	127
			50%	321	112	57
			40%	251	74	44

with traditional water Chrenkov cuts

• Granularity and π^0 efficiency

Expected improvement with UNO?

Compared with SK size detector



Minimum distance to wall in π^0 direction (m)

- For smaller π^0 opening angle finer granularity needed
- π^0 efficiency improves when min. distance increases (up to 20%)
- See power of π^0 finder

One issue I never mentioned before is that 2/3 of UNO volume is cover only 10% by PMTs and that we nee to check the detector performance w 10% PMT coverage

• 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?

Conclusions

- Realistic MC simulation studies have been performed for BNL very long baseline with a water Cherenkov detector and it was found that BNL VLB combined with UNO seems to DO GREAT JOB – Very exciting news but need confirmation
- It was demonstrated that there is some room to improve S/B ratio by reducing the background level while keeping a reasonable signal detection effciency with currently available software
  - We need to do similar analysis using a MC package that simulates the UNO baseline design (2 x 10% + 40% coverage and size)
  - We may need further improvement of algorithm/software, which is quite possible
  - Detailed studies on sensitivity on oscillation parameters needed
  - A larger detector such as UNO has an advantage over a smaller detector such as SK (we learned a lesson from 1kt at K2K)

Need a detailed Monte Carlo package for UNO!

Contents

_ Introduction — Set the stage

_ π^0 Finder — Performance of π^0 finder

_ Useful variables — Variables used for likelihood

_ S/B — Status of signal/background

_ Some issues — Addressing some issues

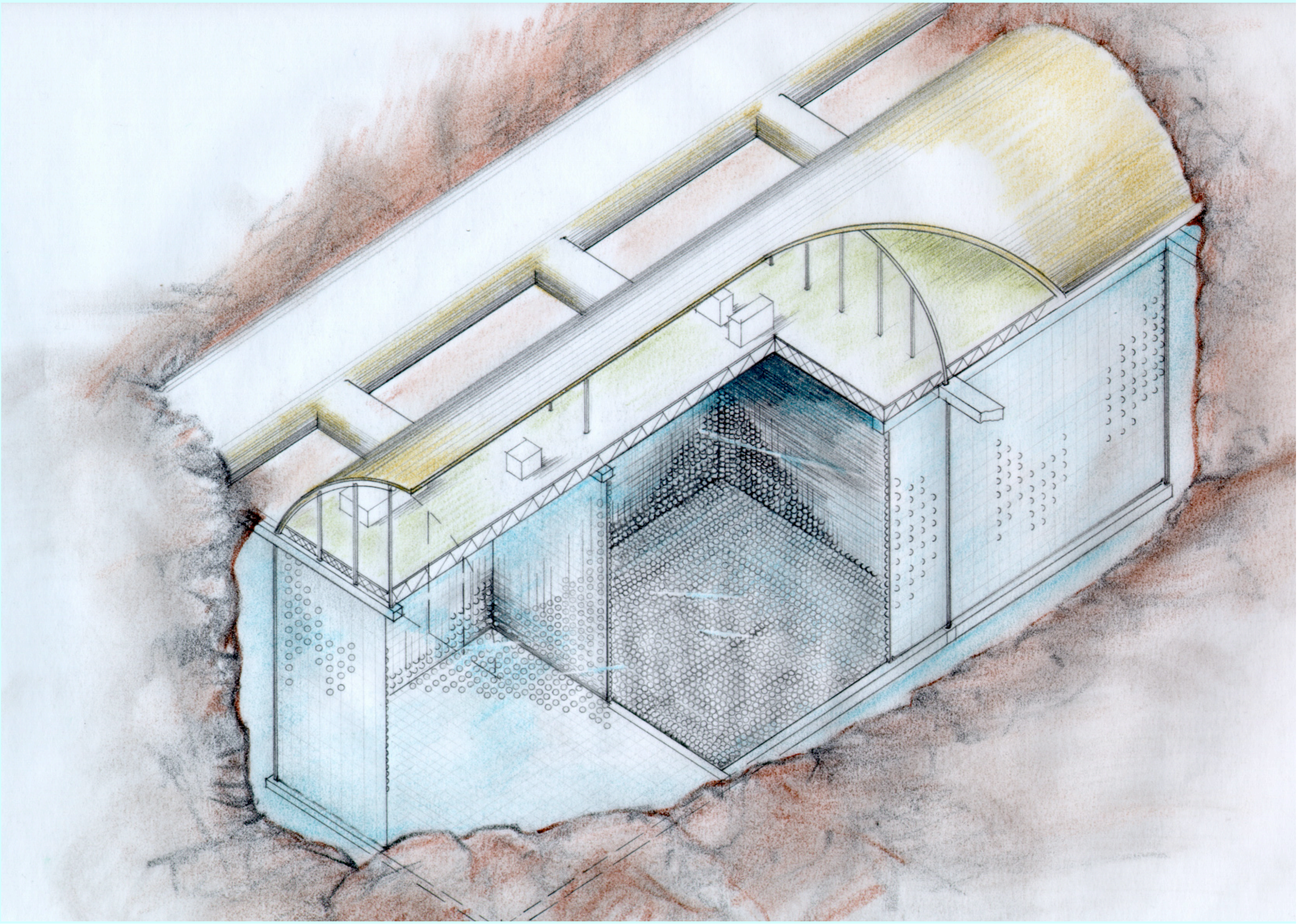
_ Prospect/plans — Things to be done

_ Conclusions

All numbers and distributions are preliminary in this talk

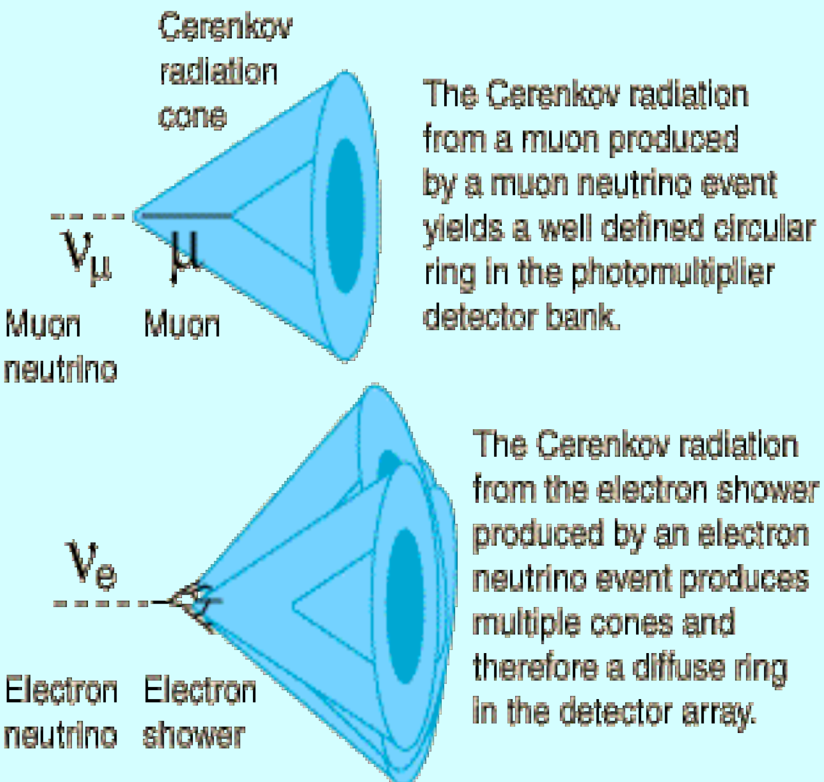
UNO detector

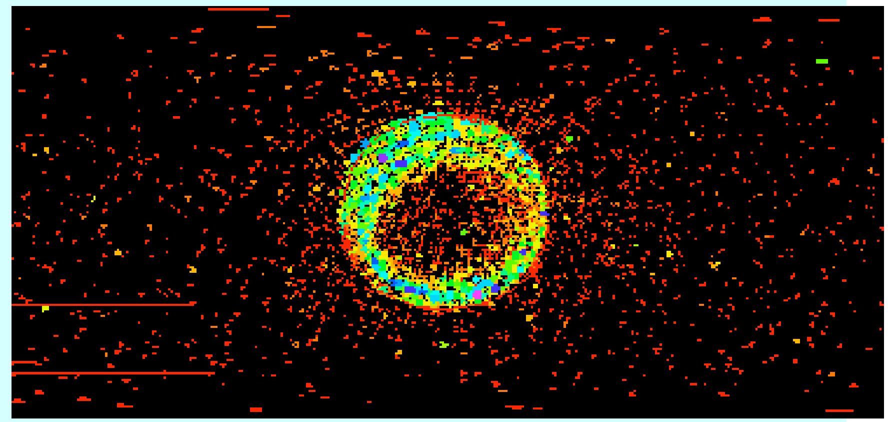
An artist's view of conceptual detector of UNO



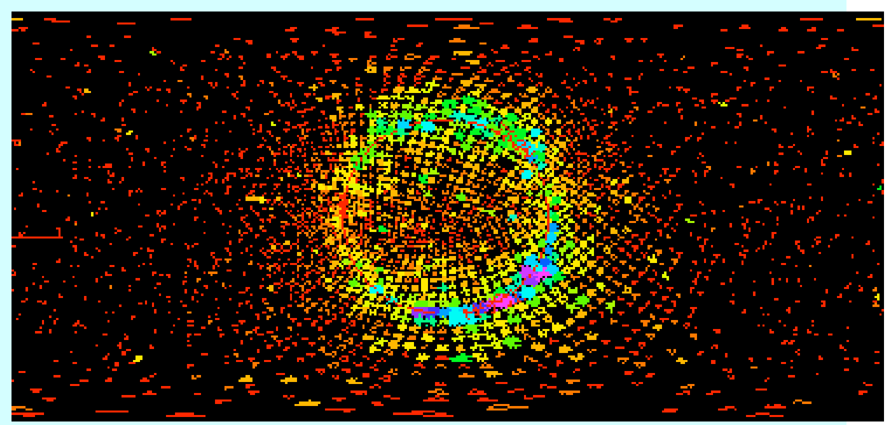
Electron-like vs. muon-like ring

How do we detect atmospheric muon and electron neutrinos ?





muon-like ring



electron-like ring

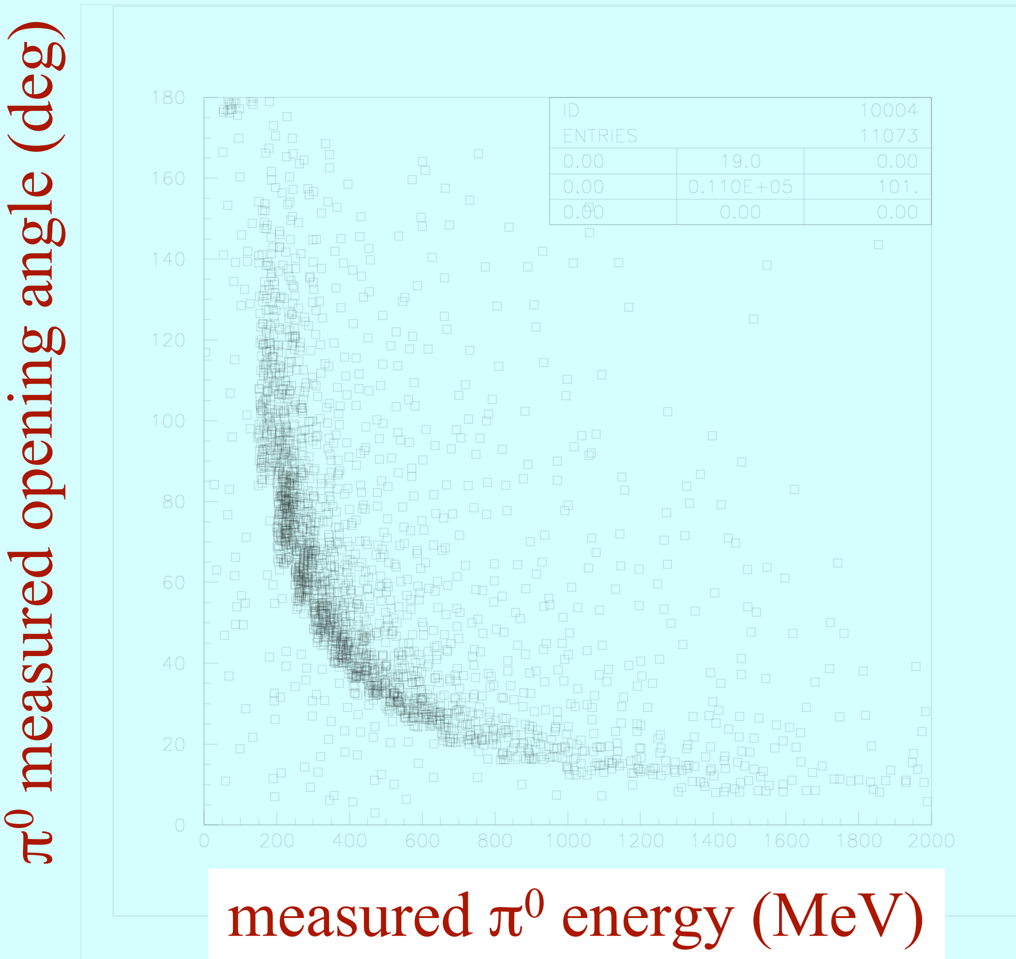
Major interactions:

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

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

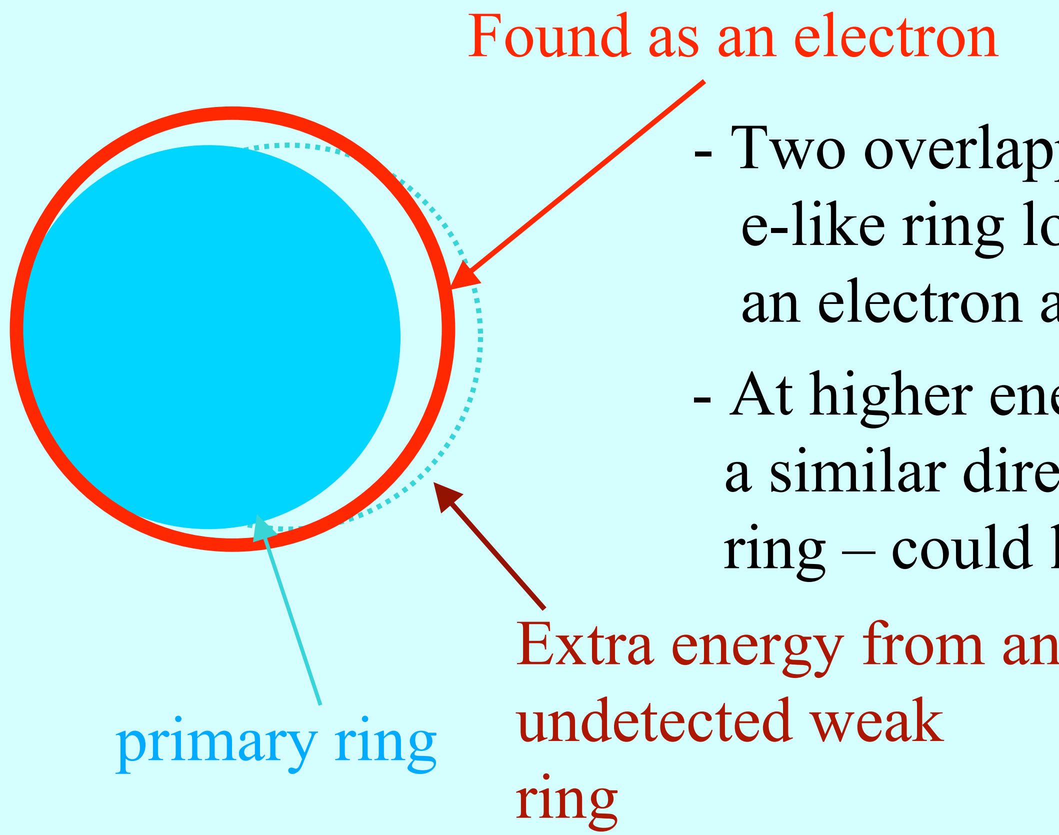
Most of time invisible

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



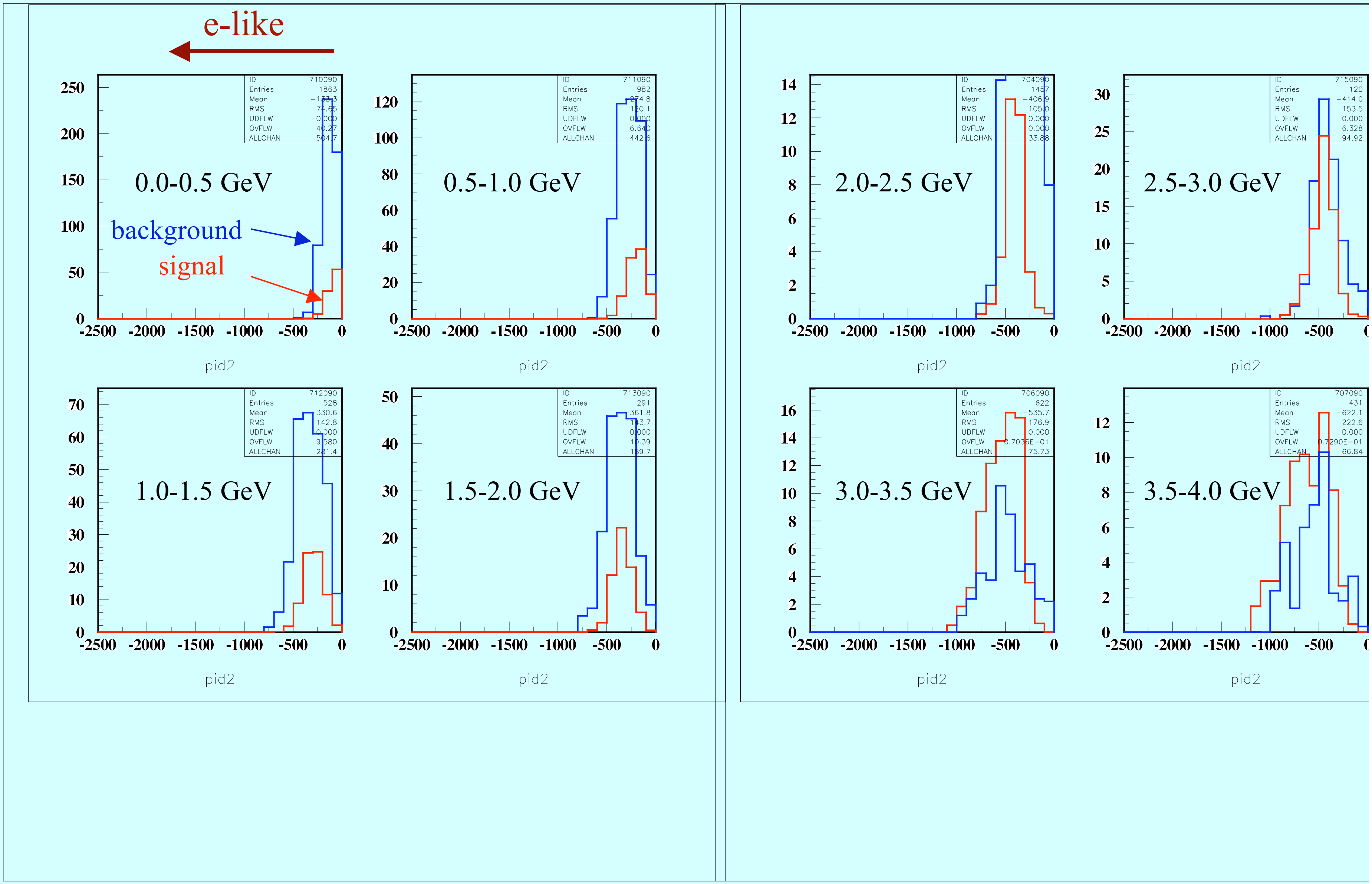
Note: The energy spectrum of π^0 is that of SK atm. ν interactions

- e-likelihood

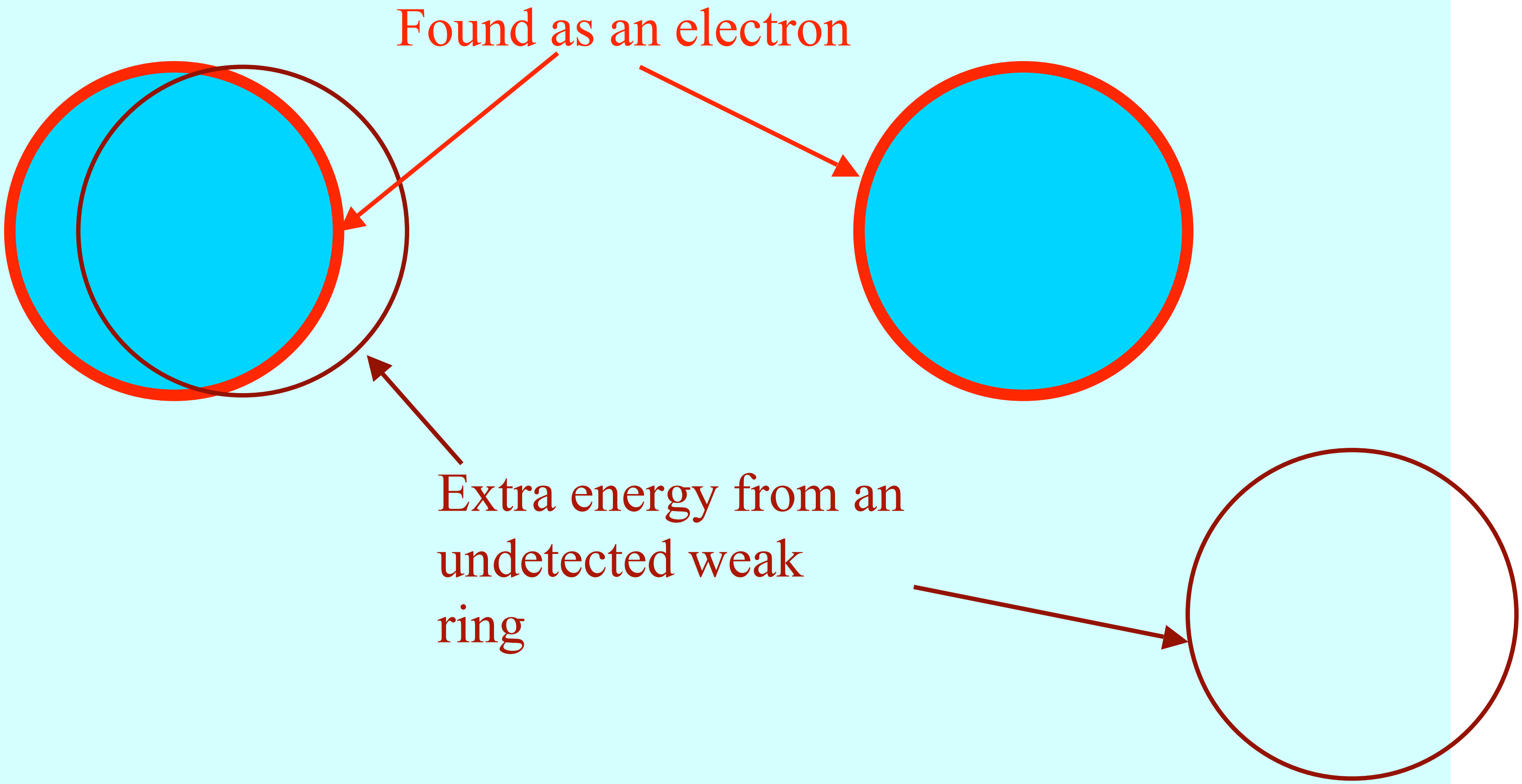


- Two overlapped e-like rings identified as an e-like ring look like a fuzzier electron than an electron at lower energy
- At higher energy multiple particles go into a similar direction and identified as an e-like ring – could look less fuzzy than an electron

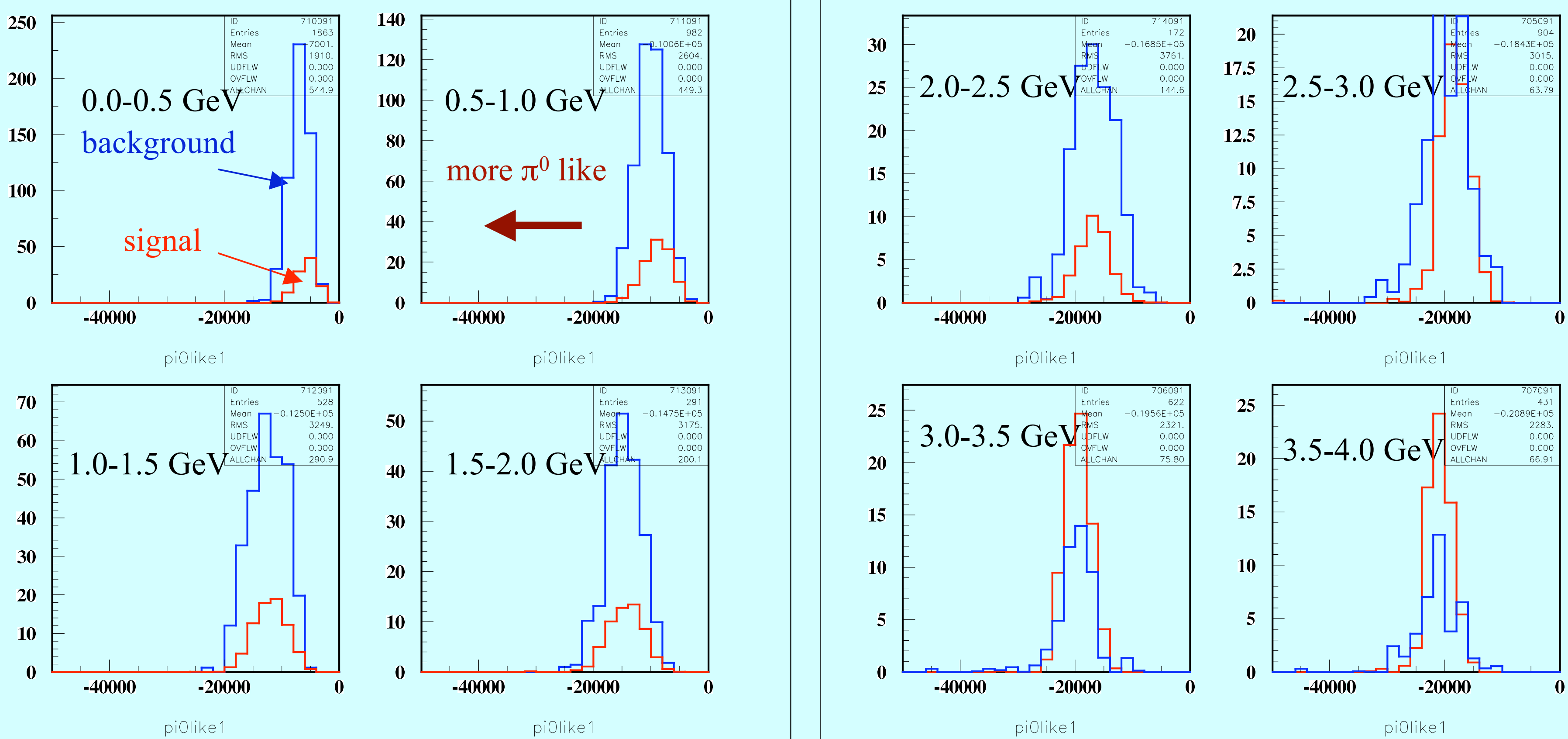
e-likelihood



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

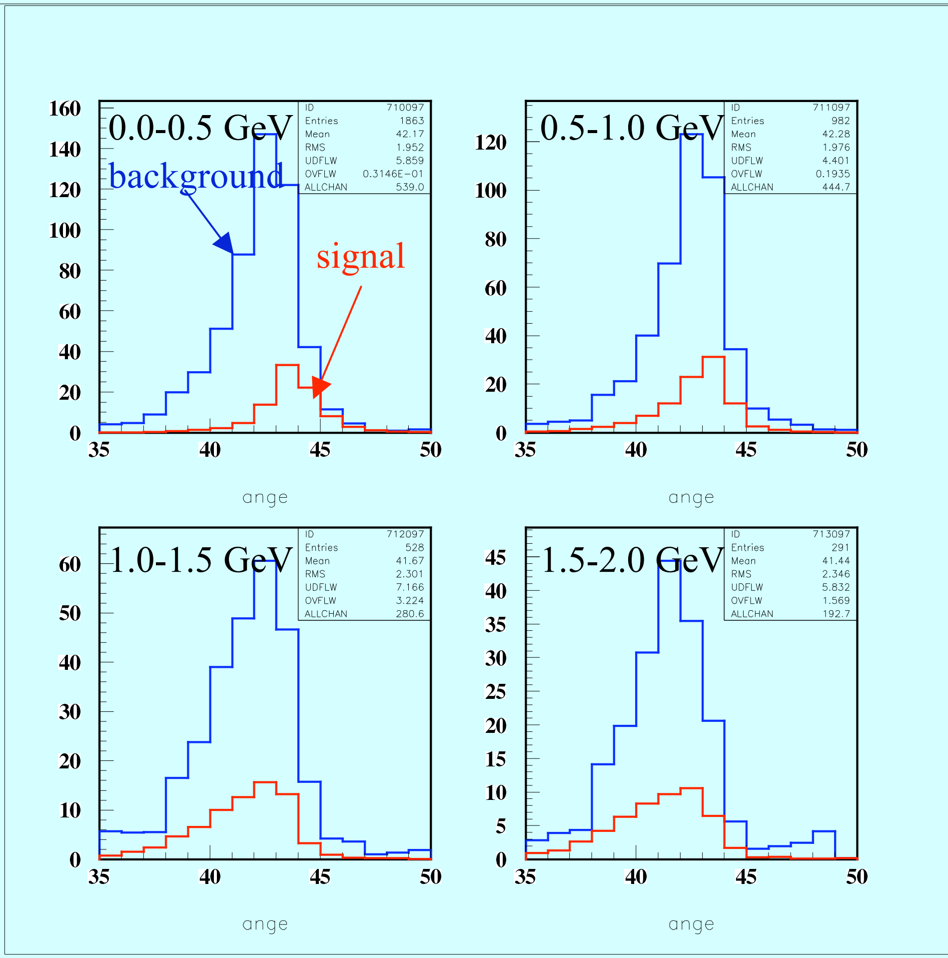


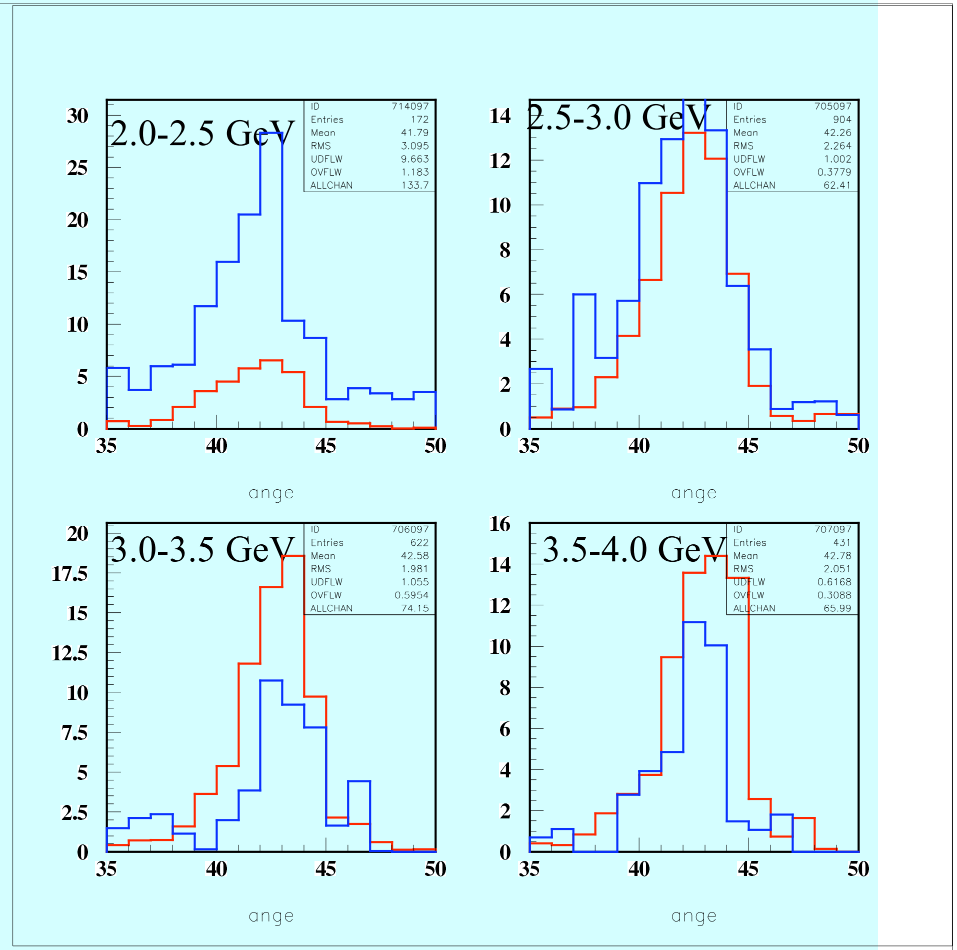
π^0 likelihood



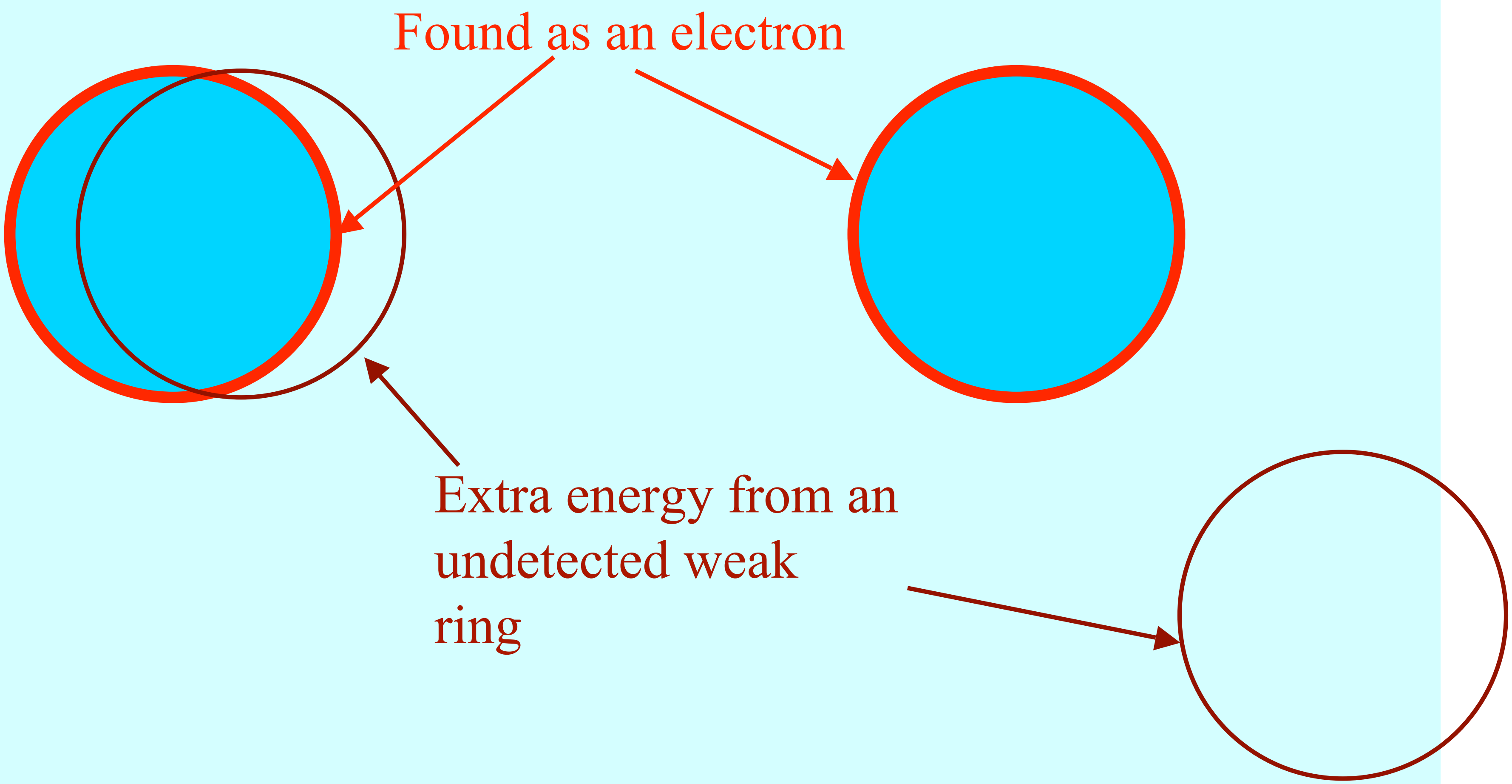
Variables

- Measure Cherenkov angle



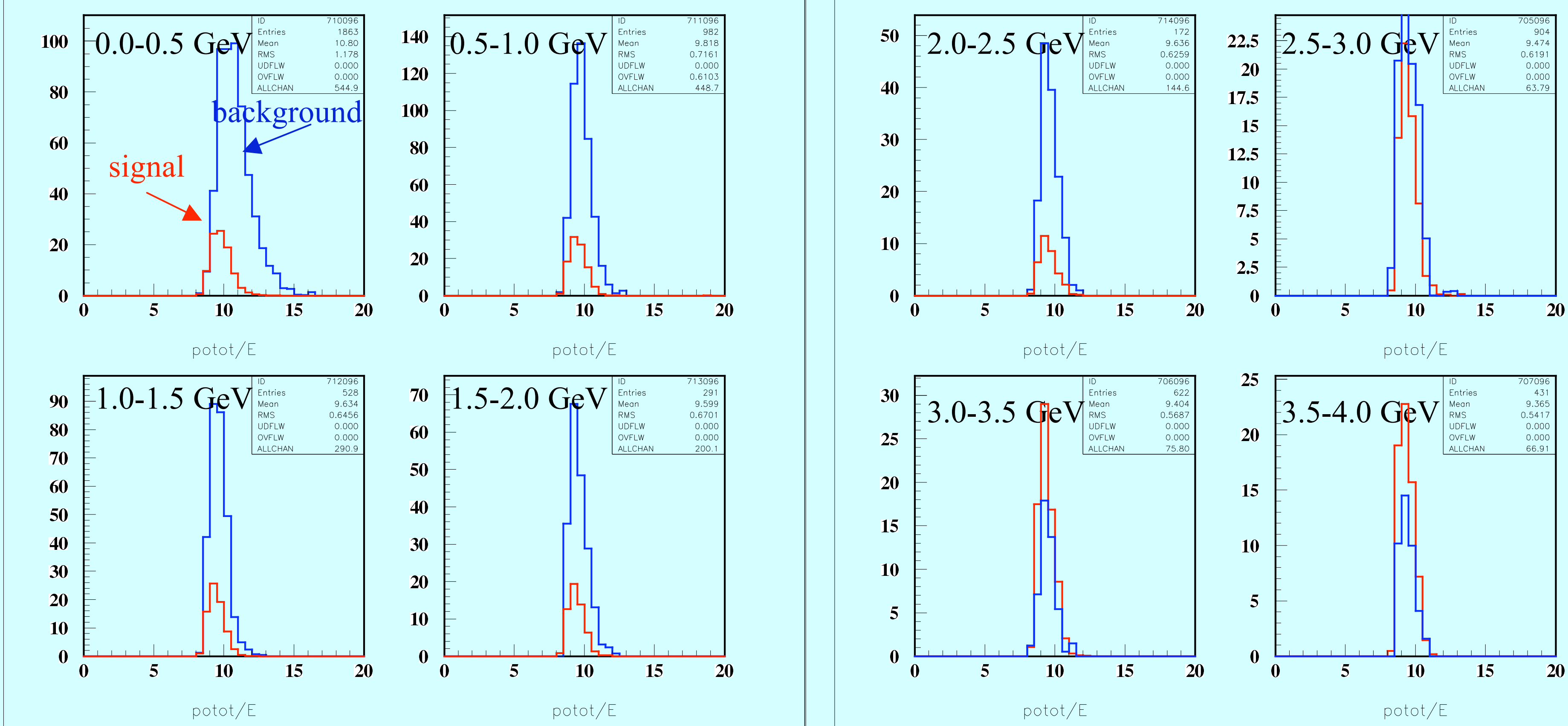


- Total charge/primary ring energy (poa)



Useful variables

- Total charge/primary ring energy (poa)

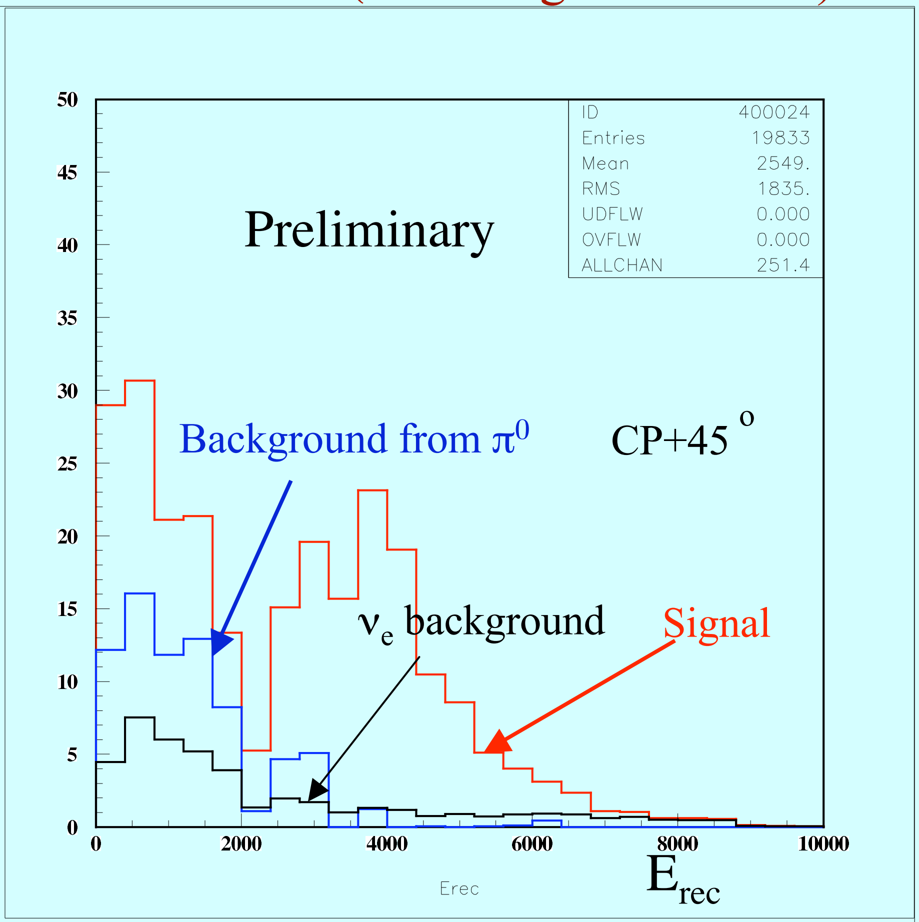


S/B

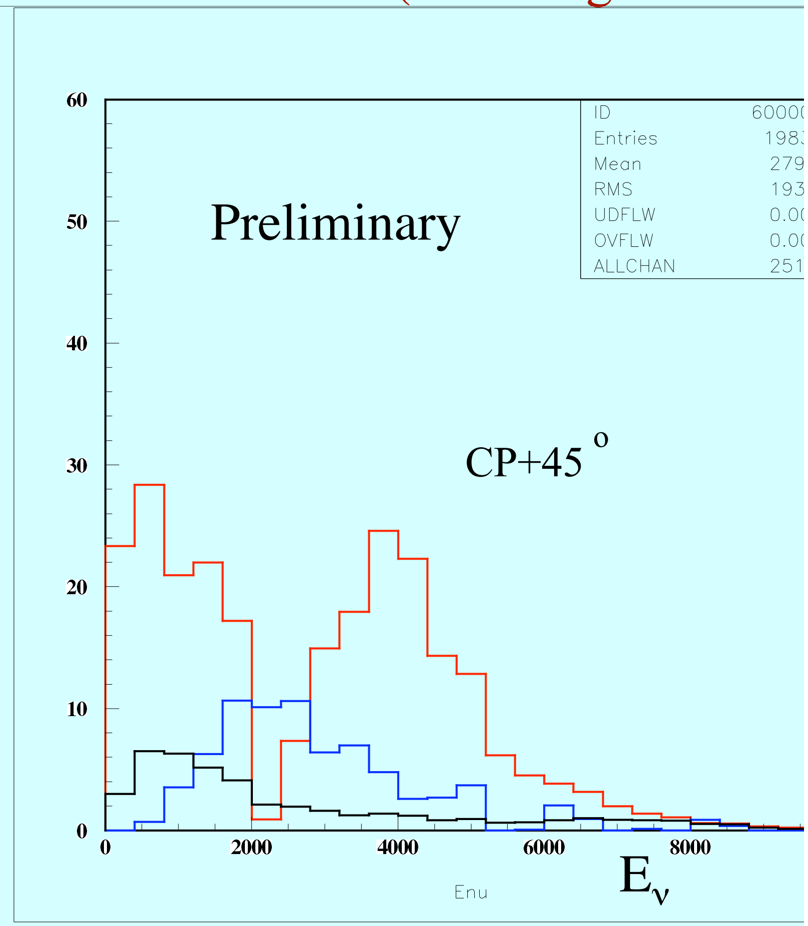
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for bkg

- E_{rec} vs. E_ν

Δlikelihood cut (~40% signal retained)



Δlikelihood cut (~40% signal retained)



S/B

_ 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
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%

Issues

Some issues

_ S/B and variables

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

Summary of BNL superbeam@UNO

Variable removed	Signal	Bkg	Effic	Signal	Bkg	Beam ν_e	$S/B(\pi^0)$
None	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	321	112	57	2.86
Δpi0lh	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	321	119	59	1.80
poa	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	316	126	56	2.51
pi0-lh	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	303	116	52	2.61
e-lh	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	311	127	55	2.53
efrac	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	333	167	60	1.99
pi0mass	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	310	143	56	2.17
costh	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	322	146	57	2.21
ange	ν_e CC	ν_μ all, ν_e,ν_τ NC	50%	321	119	55	2.70