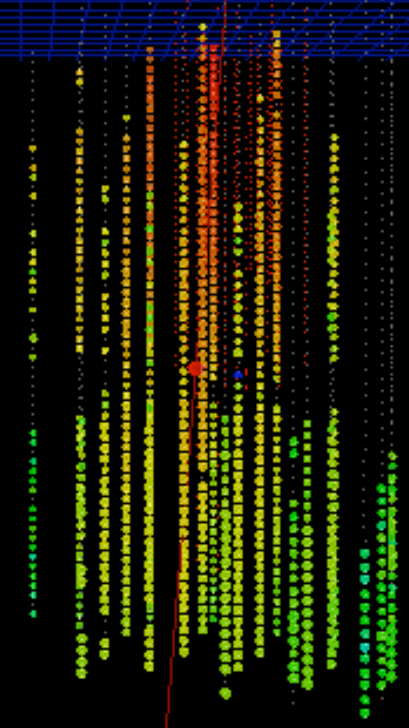
IceCube

The extremely high energy neutrino search with IceCube



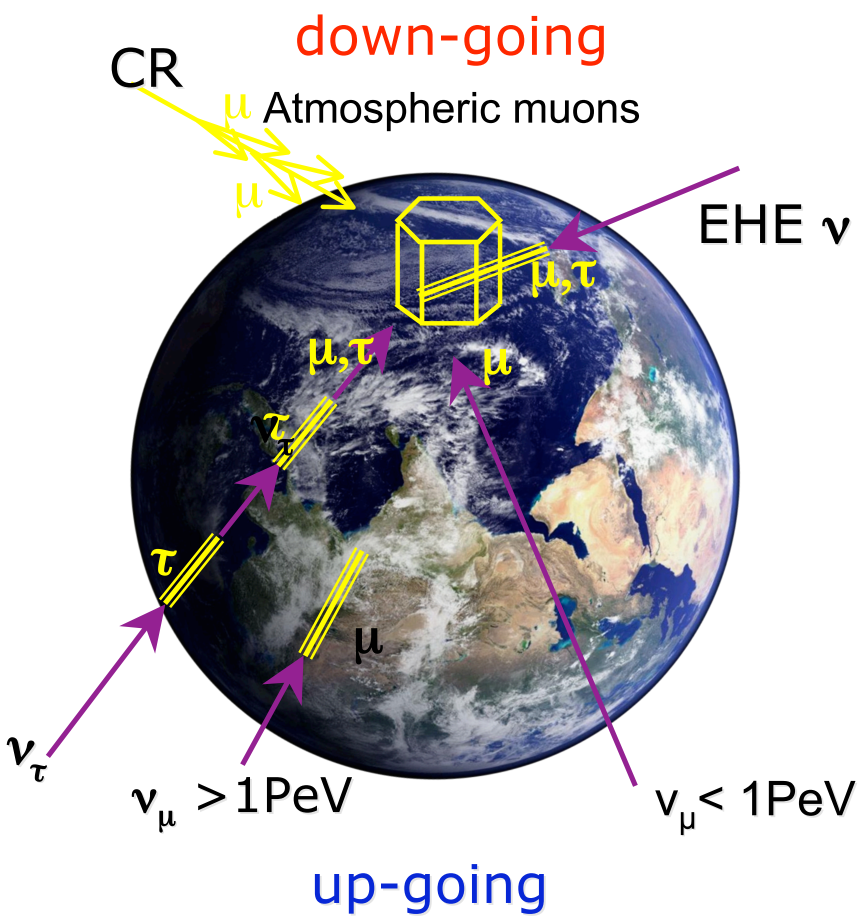
K. Mase, A. Ishihara and S. Yoshida,
Chiba Univ.
for the IceCube collaboration

千葉大学
Chiba University

EHE neutrinos and How to detect them

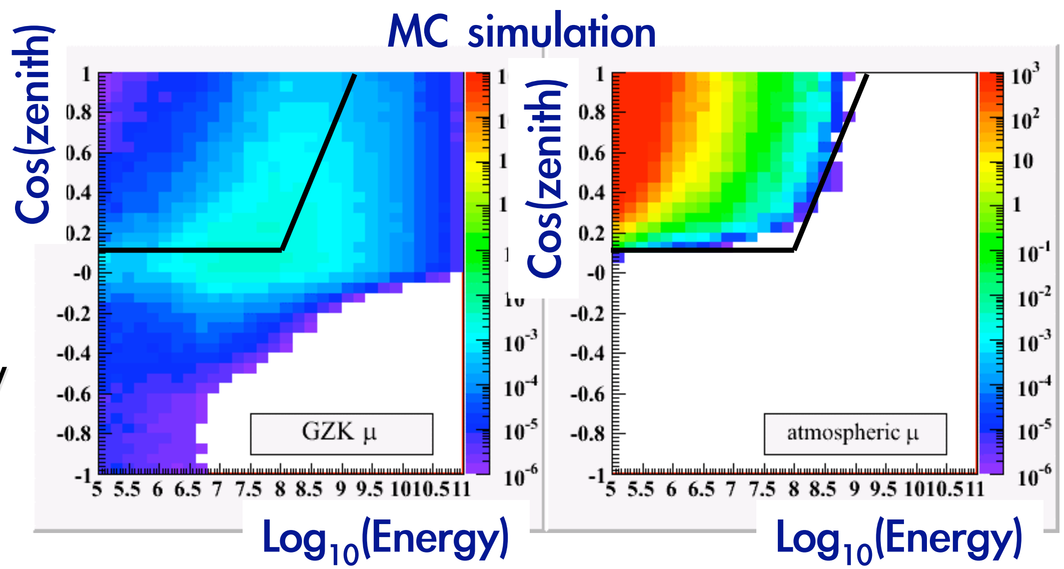
Extremely high energy (EHE) cosmogenic neutrinos (mainly >10^8 GeV) were searched for.

$$p\gamma_{2.7K} \rightarrow \pi^{\pm} + X \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + \nu's$$

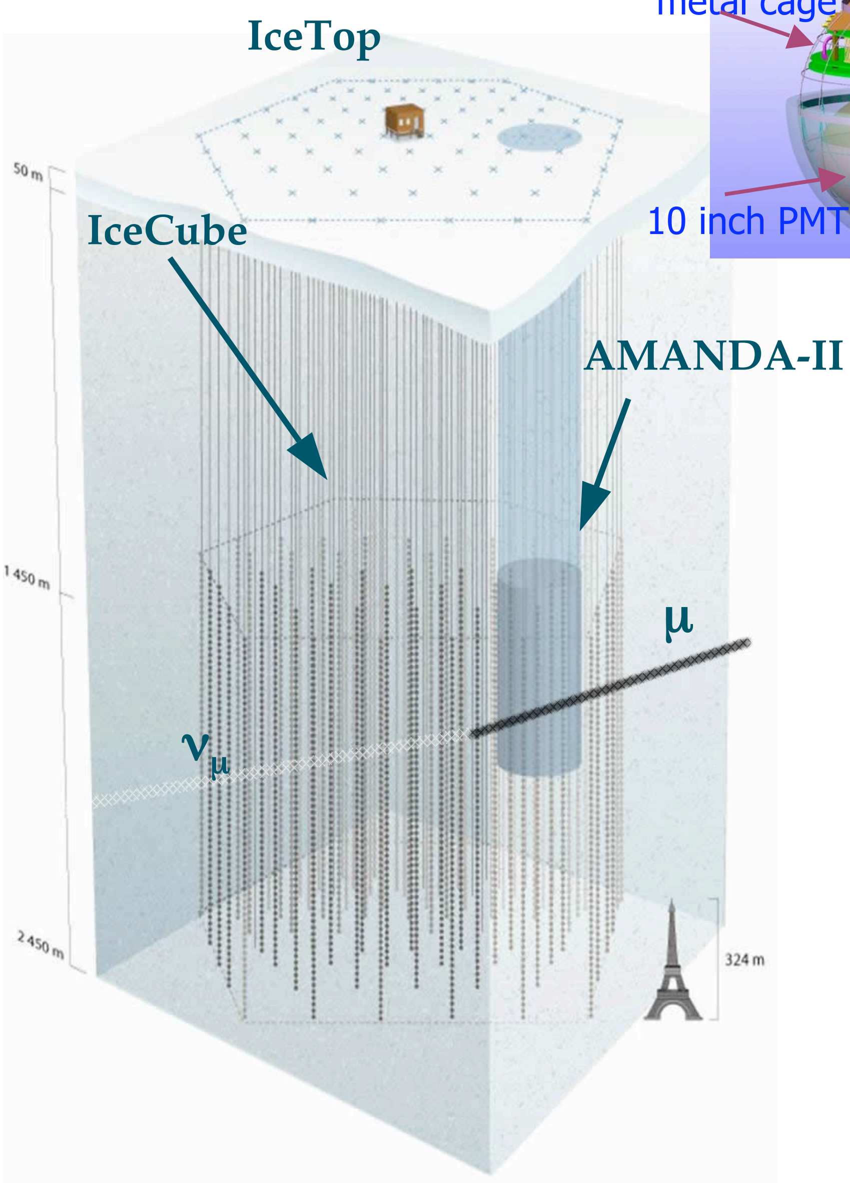


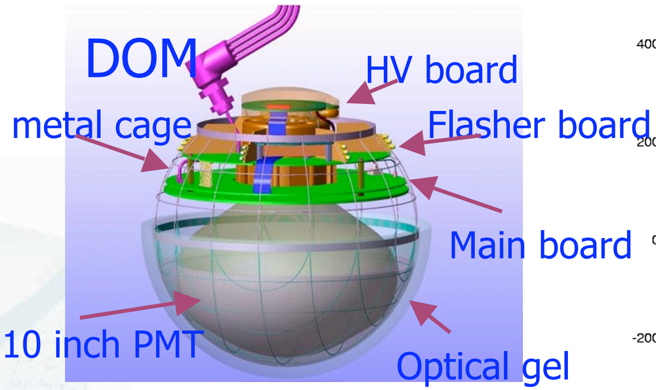
- EHE neutrino signal
  - horizontally-coming (opaque to the earth)
  - extremely high energy

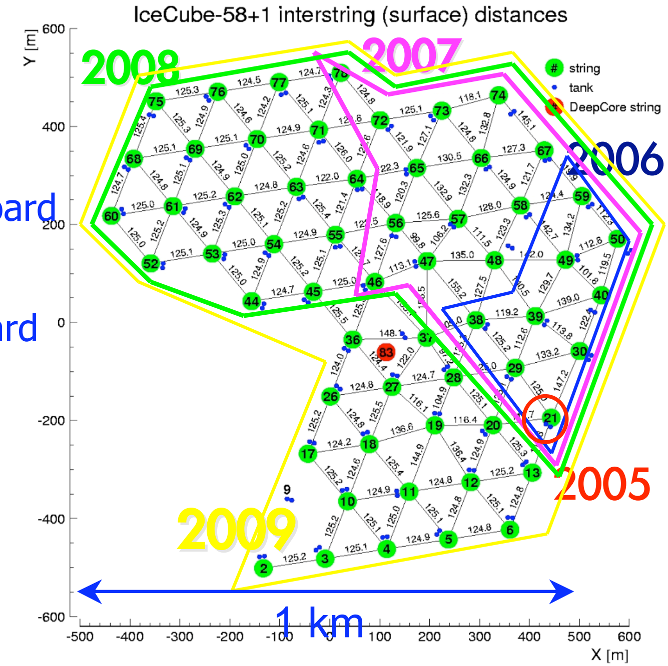
- Atmospheric muon background
  - down-going
  - relatively low energy (the energy spectrum is steep ($E^{-(3-4)}$))



❑ IceCube







- HE neutrino telescope, being constructed at the South Pole.
- $1km^3$ detector volume (when completed).
- 3/4 completed (58+1 strings), running smoothly
- ~5,000 Digital Optical Modules (DOMs) will be deployed in total that enclose PMTs as well as HV suppliers and signal digitizers.
- data taken in 2007 with 22 string configuration (IC22) were used in this analysis.

Dataset

Three datasets used in this analysis:

1. Observational data

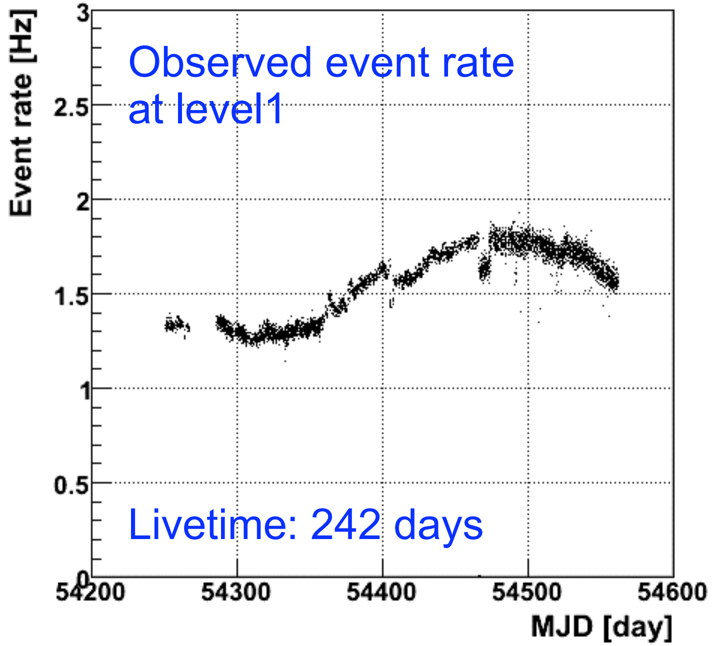
   - livetime: 242.1 days (May, 2007-April, 2008)
   - with a trigger condition which requires minimum number of 80 DOMs

2. MC data (single lepton/neutrino tracks)

   - For signals and backgrounds
   - An empirical model was constructed with this dataset (explained later)

3. CORSIKA data

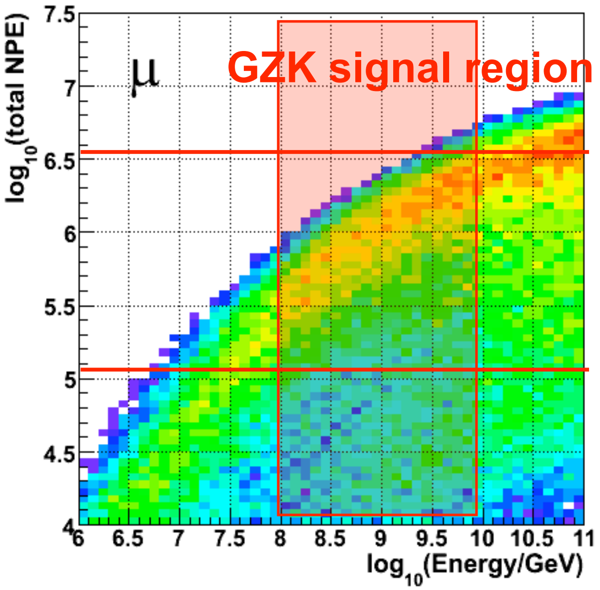
   - pure protons and irons with SIBYLL and QGSjet II
   - Used for redundant check of the empirical model and estimation of systematics by different hadronic interaction models.

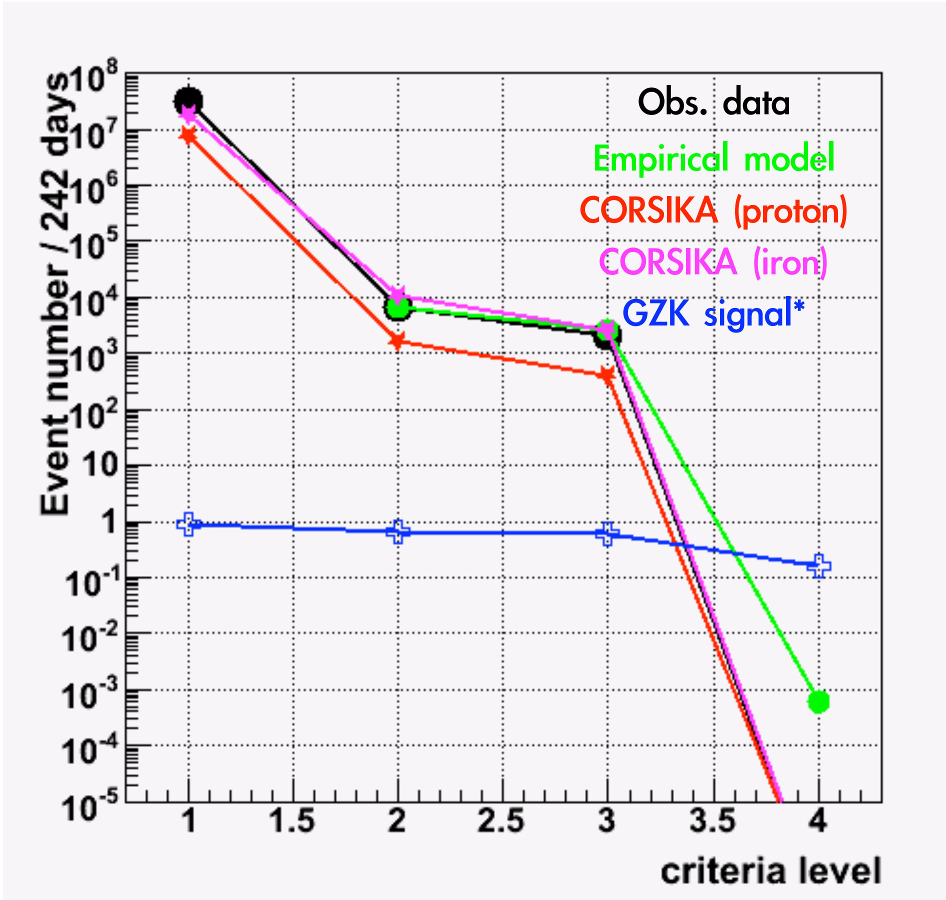


Data filtering

Data filter flow

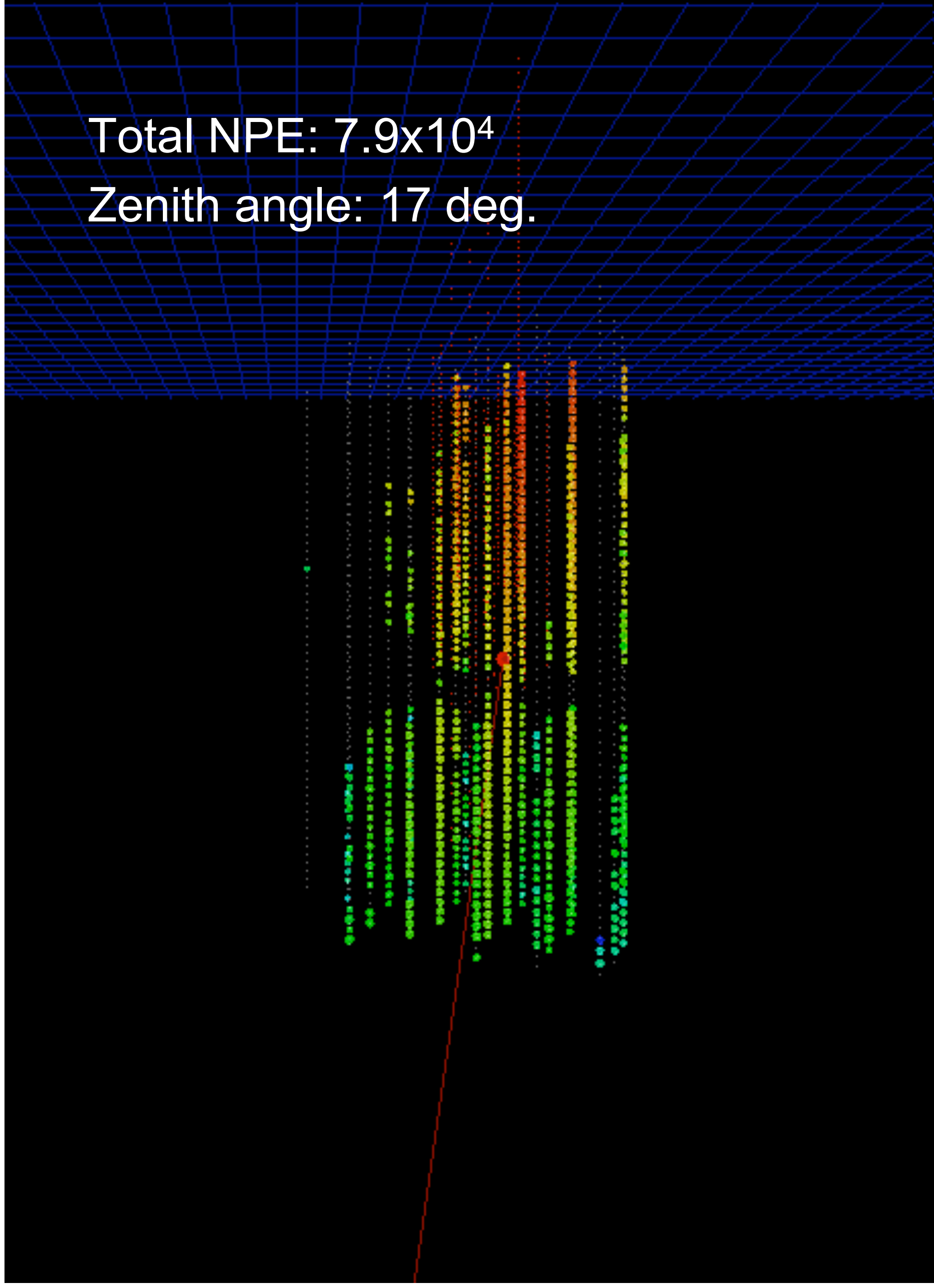
Level0: raw data
↓
Level1: EHE filter (DOM#>=80) (3.2×10^7 events)
↓
Level2: total NPE > 10^4 (6528 events)
↓
Level3: cos(zenith angle) < 0.8 (2014 events)
↓
Level4: signal selection criteria (? events)

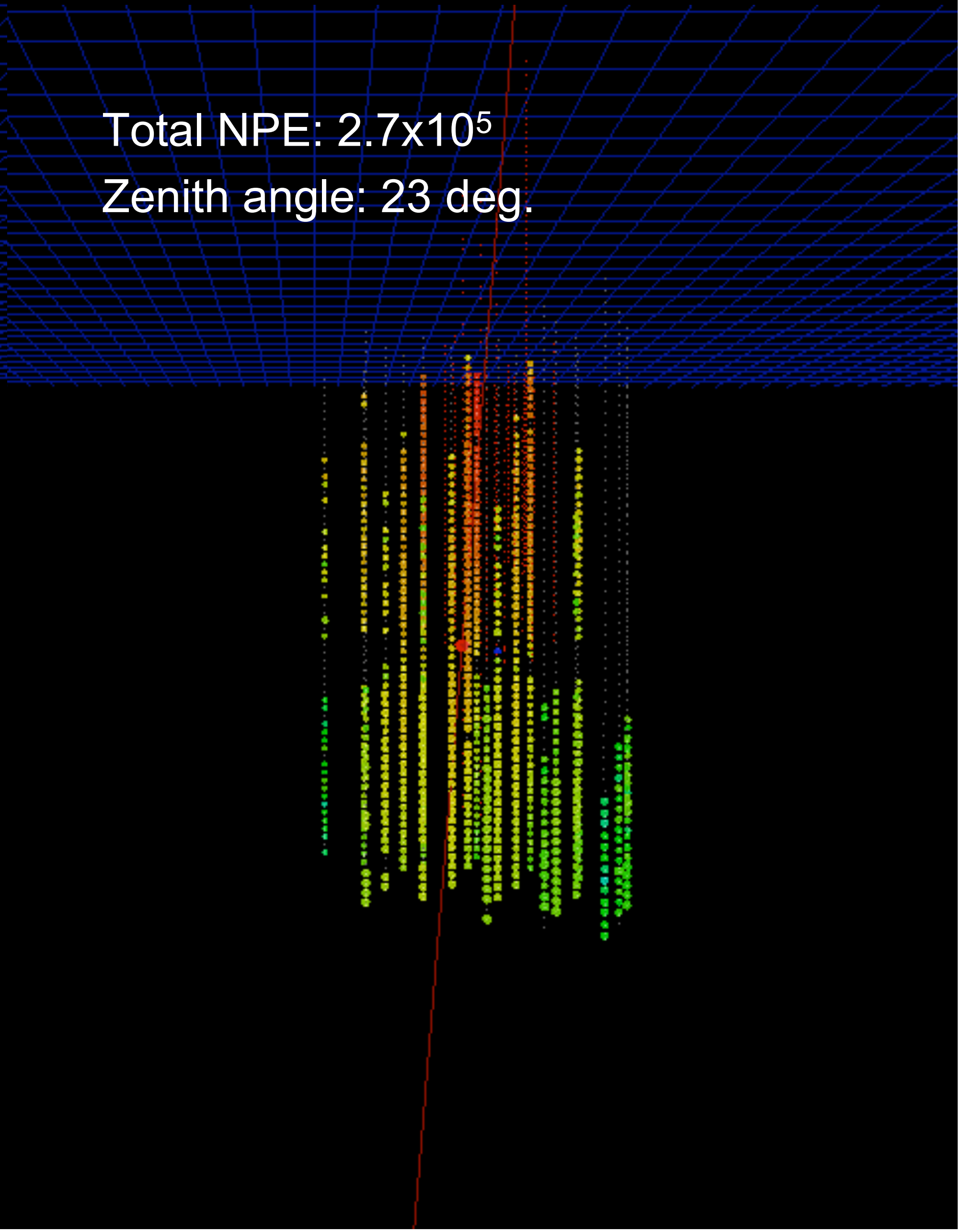




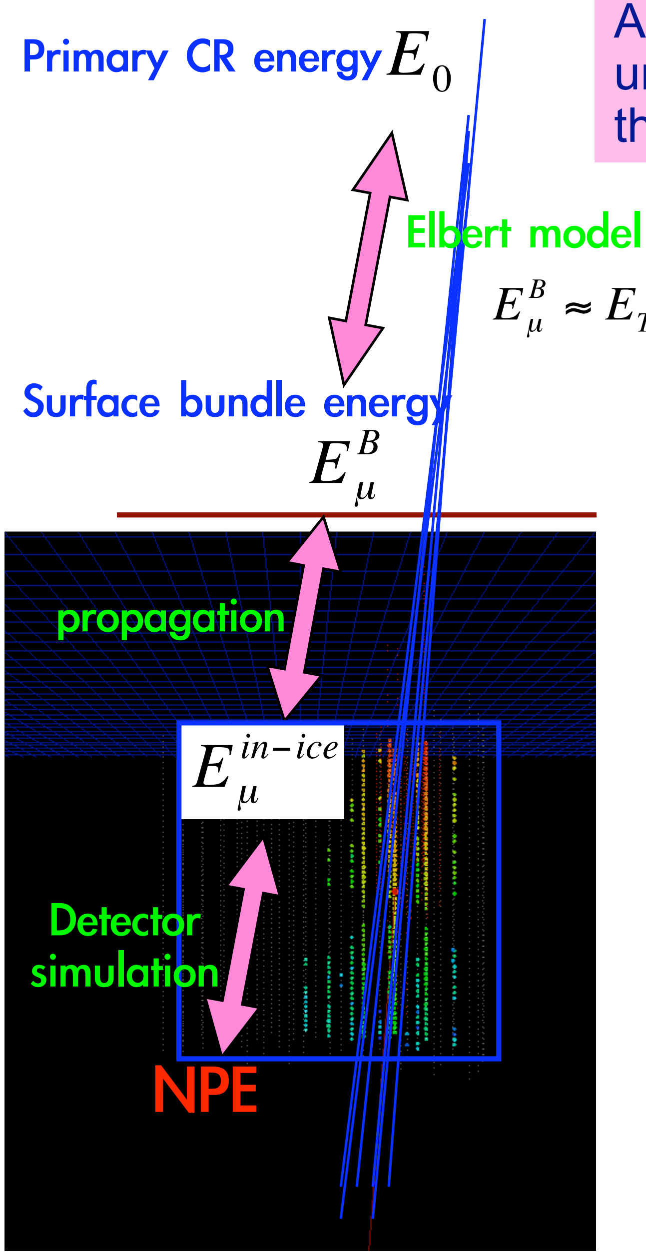
*) S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833 (1993)

❑ Bright Events





❑ Construction of an empirical model



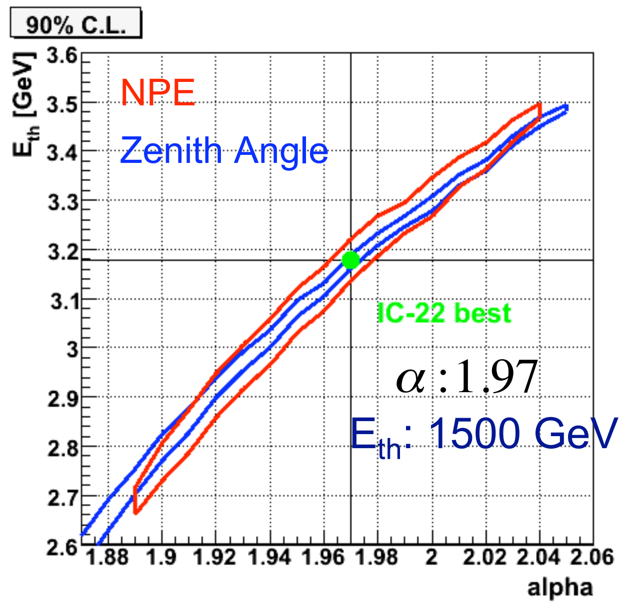
An empirical model was constructed because understandings of the hadronic interaction and the composition are limited in EHE region.

$$E_\mu^B \approx E_T \frac{A}{\cos\theta} \frac{\alpha}{\alpha - 1} \left(\frac{A E_{th}(E_{th}^{in-ice}(X))}{E_0} \right)^{-\alpha+1}$$

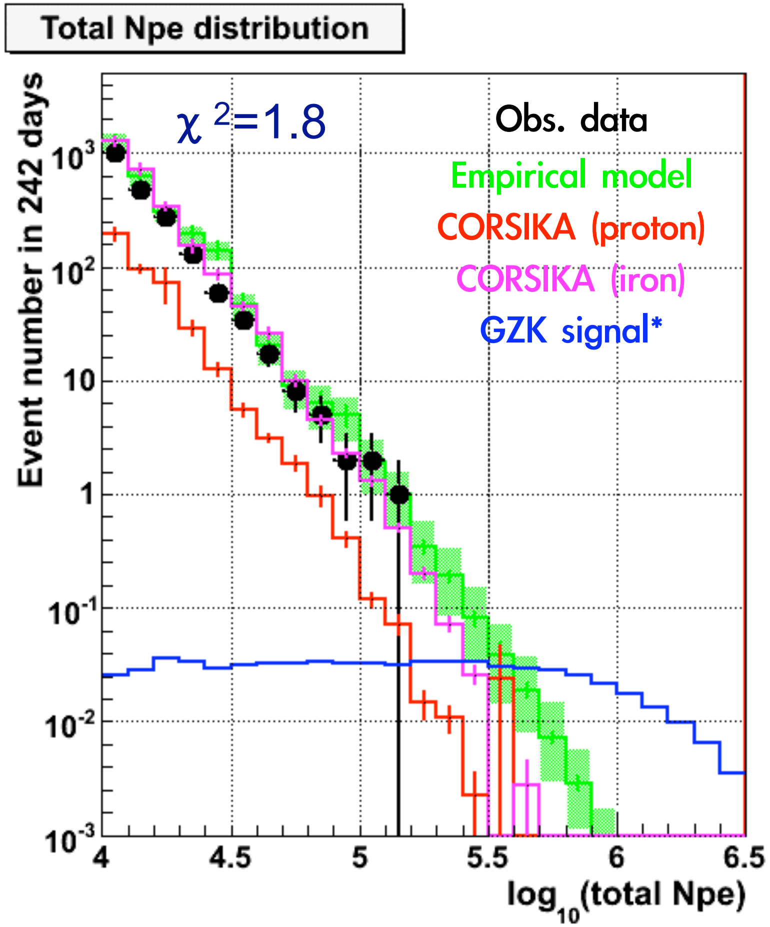
- The key is to relate CR primary energy with observables such as total NPE.
- Only 2 free parameters (α and E_{th}) are needed and optimized with obs. data.
- Consistent 90% C.L. regions both from NPE and zenith angle distributions.

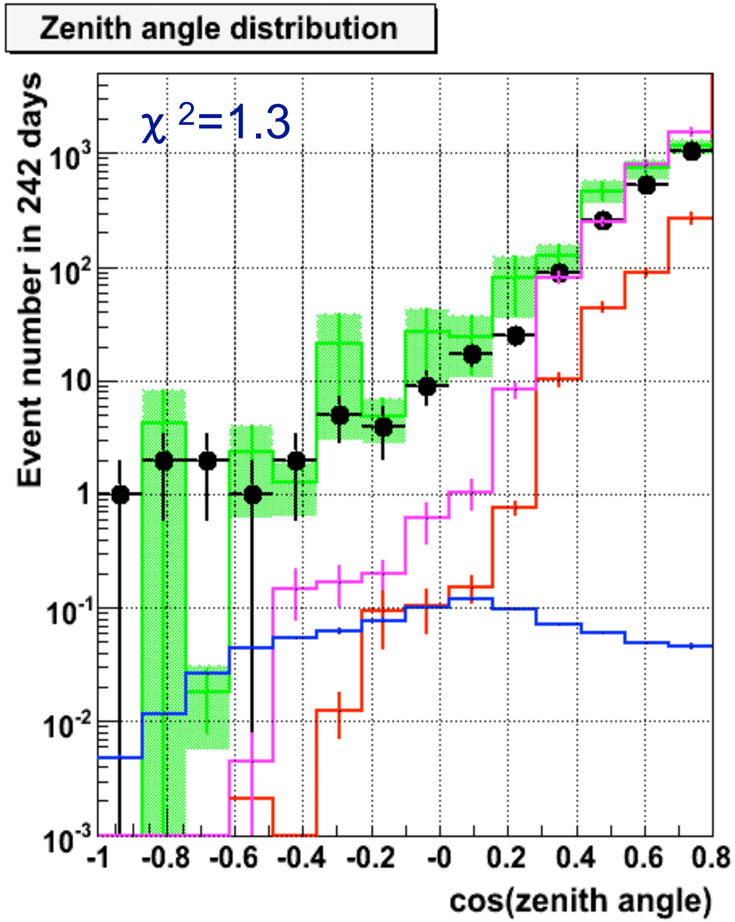
→ the empirical model express the NPE and zenith angle distributions at a time with same parameters.

- Confirmed by using IceTop information independently.



❑ Comparisons between data and MC (at level3)



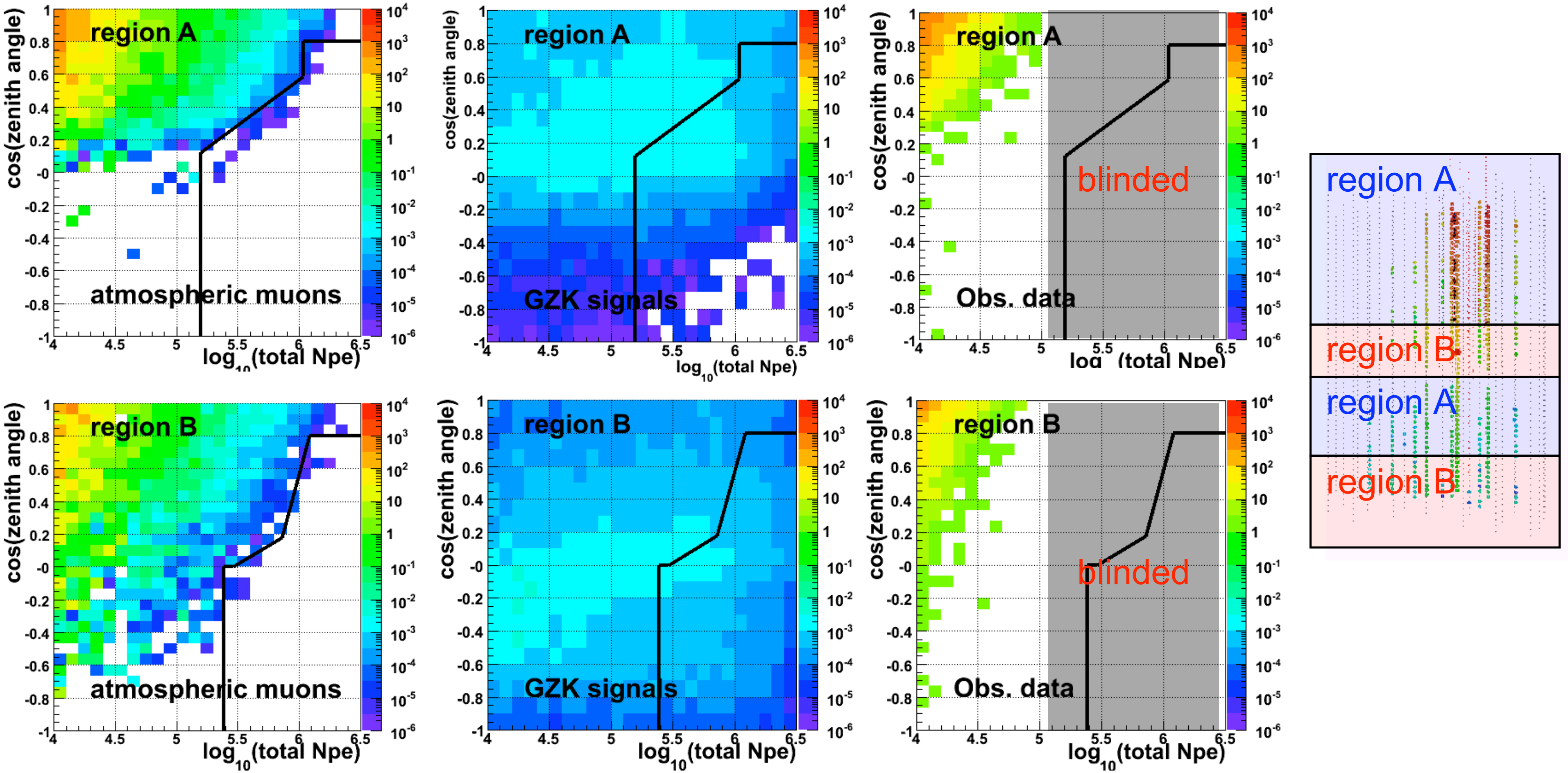


- The empirical model reasonably expresses the data.
- Signals are placed at high NPE and horizontal direction.
- Obs. data are bracketed by CORSIKA pure protons and irons.
- CORSIKA data exhibit a slight difference in zenith angle distribution, underestimating the BGs.

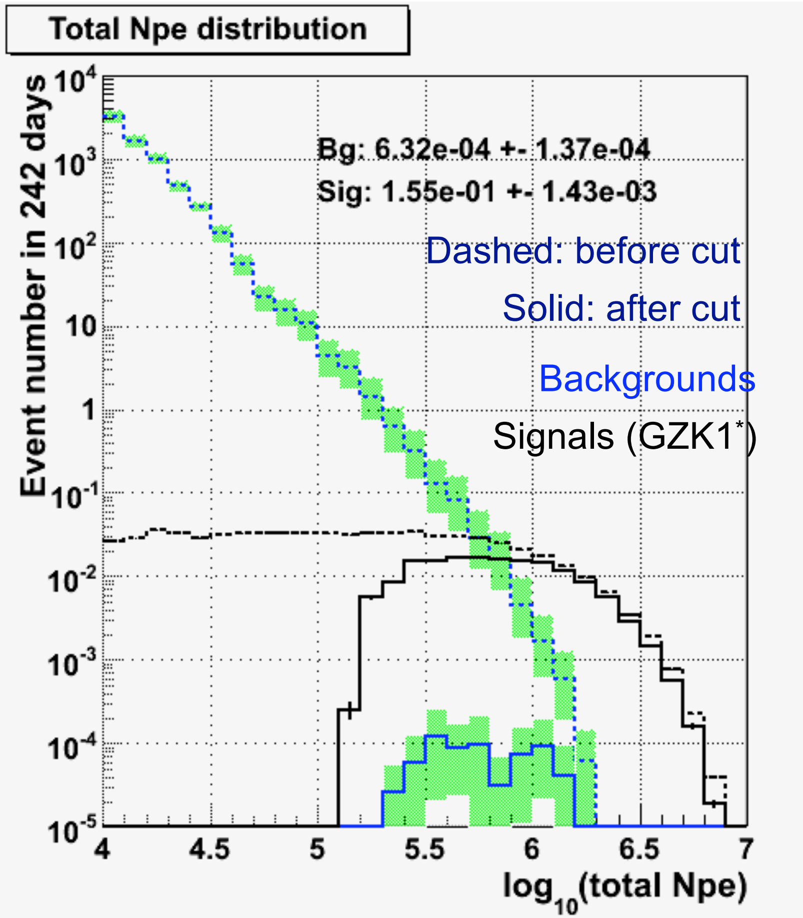
*) S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833 (1993)

The signal selection criteria (level4)

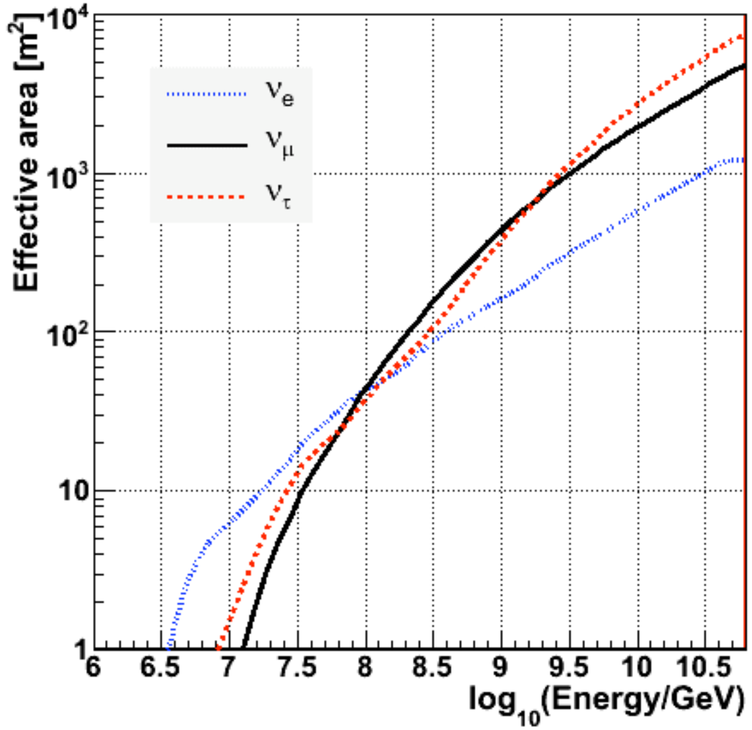
- The angular resolution was found to be worse at some depths.
- Data were divided into two, depending on depth (CoGZ: z position of event gravity center).
  - region A: -250 < CoGZ < -50 m and CoGZ > 50 m
  - region B: CoGZ < -250 m and -50 < CoGZ < 50m
- The criteria was determined, requiring S/B > 200.



❑ Total NPE distribution before and after the final criteria and the effective area



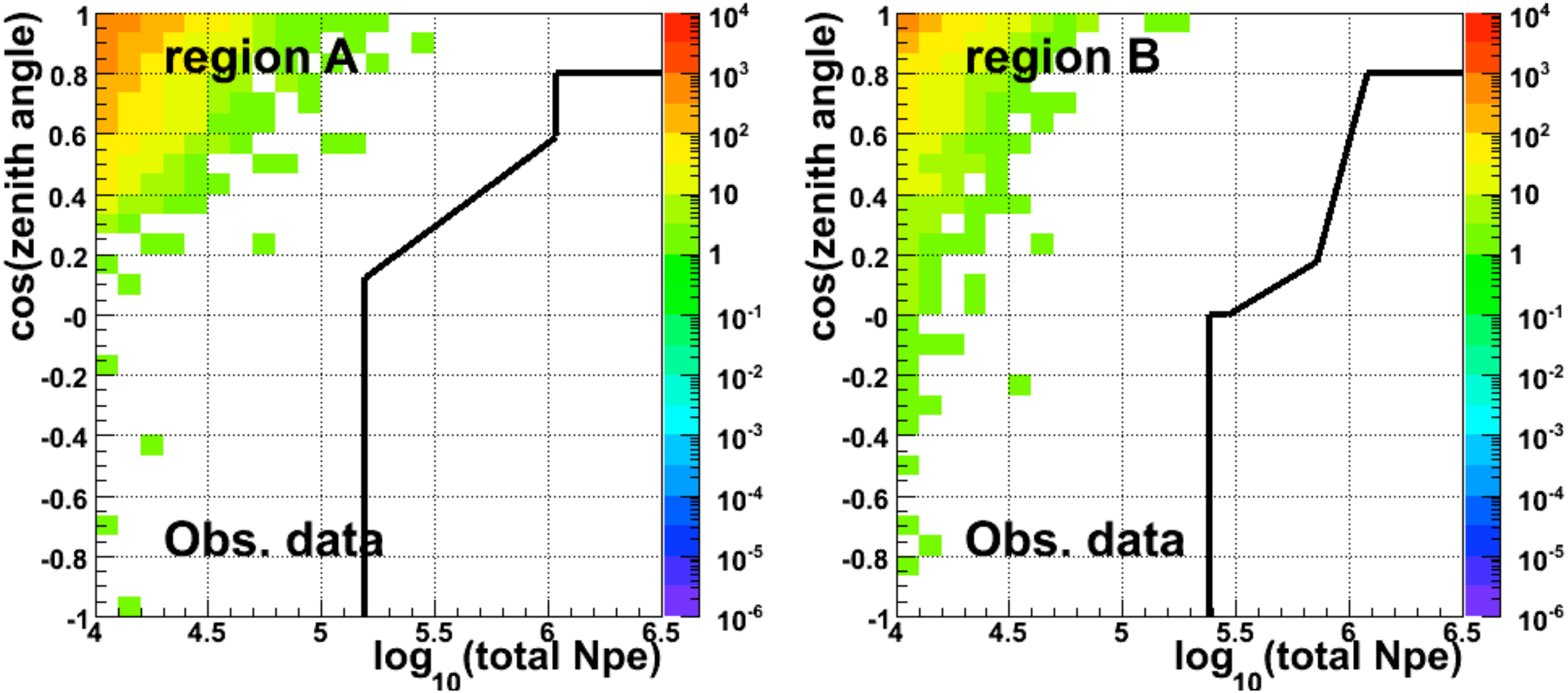
	Event rate / 242 days
Signals (GZK1*)	0.16±0.01(stat.)
Backgrounds	$(6.3\pm1.4(\text{stat.}))\times10^{-4}$



Backgrounds are reduced to the negligible level, while keeping substantial signals.

*) S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833 (1993)

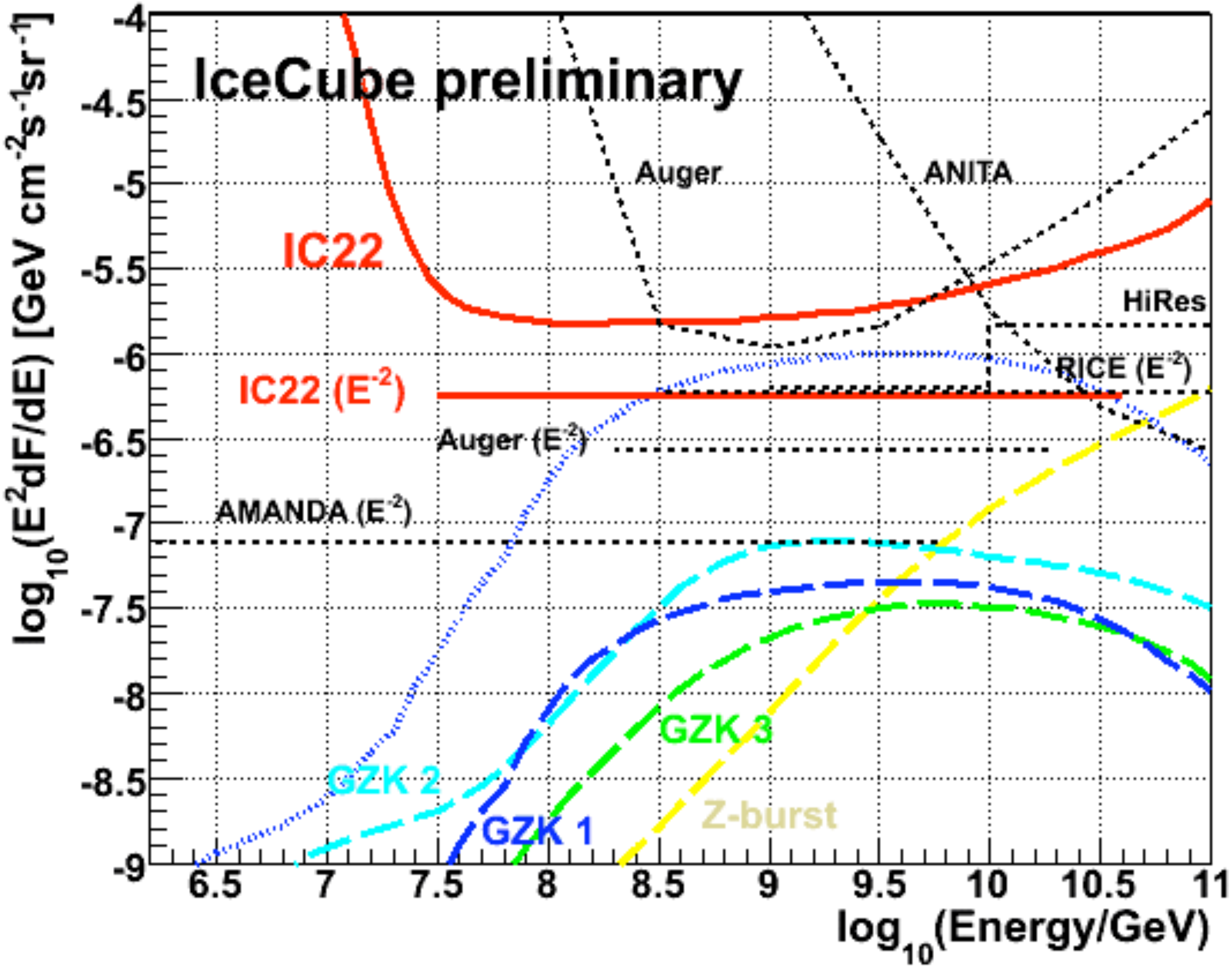
The unblinded results



No signal event was found.

The upper limit

livetime = 242 days



GZK1) S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833 (1993)

GZK2) O. E. Kalashev *et al.*, Phys. Rev. D **66**, 063004 (2002)

GZK3) R. Engel, D. Seckel and T. Stanev, Phys. Rev. D **64**, 093010 (2001)

Z-burst) S. Yoshida, G. Sigl and S. Lee, Phys. Rev. Lett. **81**, 5505 (1998)

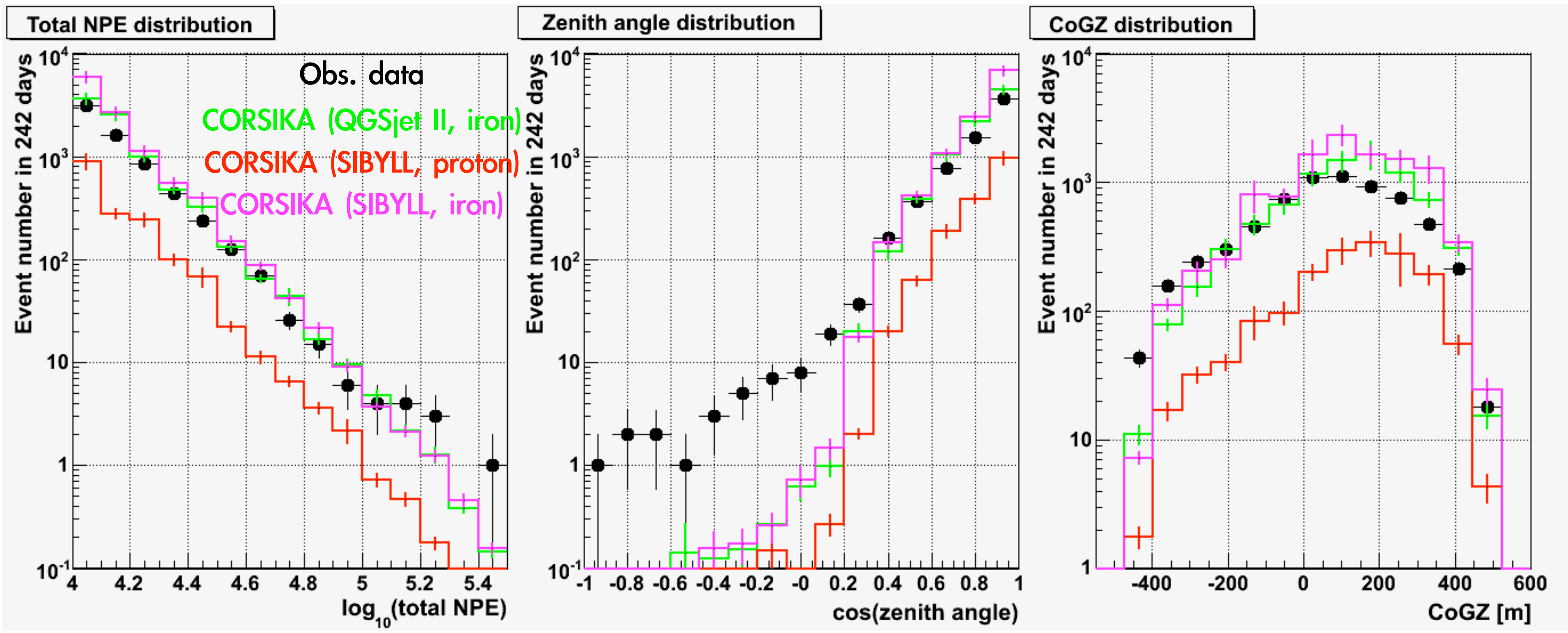
- The upper limit derived from this analysis is competitive to the Auger and RICE limits at the relevant energy (~10^9 GeV).
- The difference between GZK models and the limit is ~20 times.
- The sensitivity of the full IceCube detector will reach the model flux with ~5 year observation.

❑ Summary

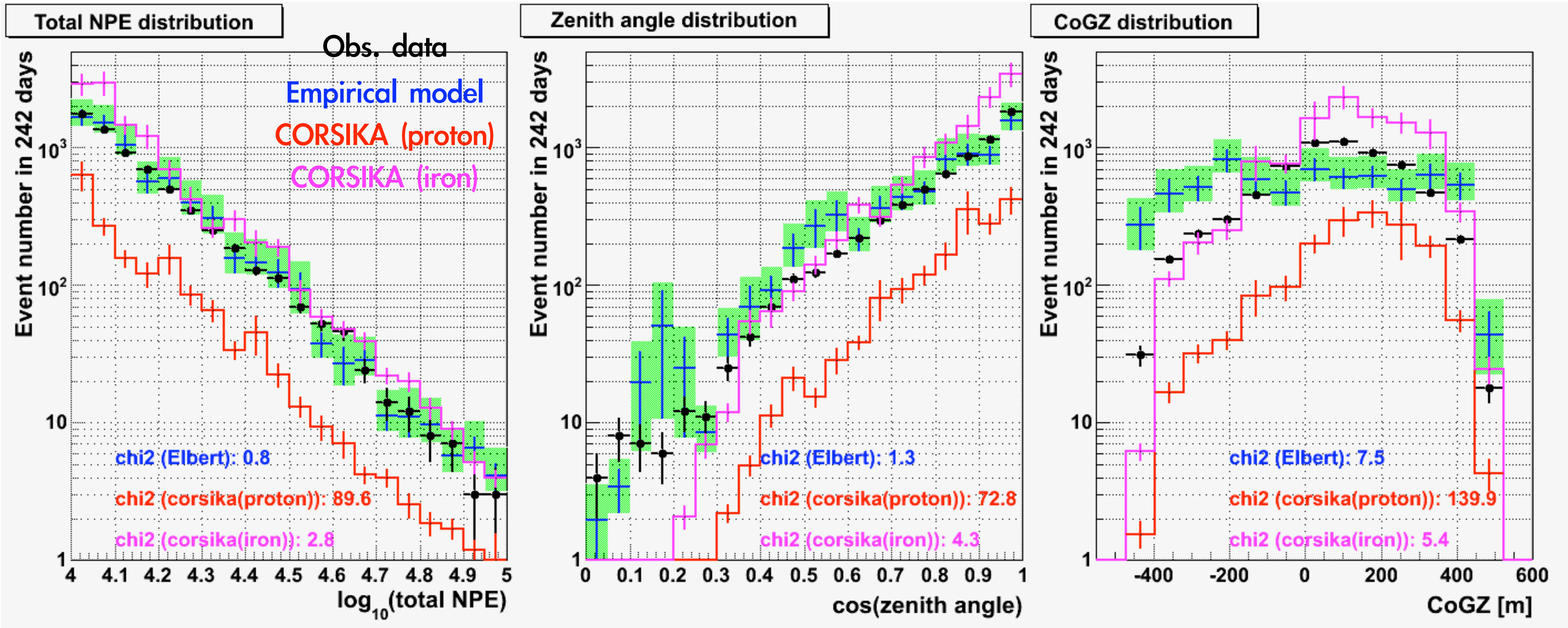
- EHE cosmogenic neutrinos were searched for with 22 string configuration data.
- An empirical model was constructed, and it reasonably expresses the observational data.
- No EHE neutrino signal was found.
- The derived IC22 upper limit is competitive to Auger and RICE limits at relevant energy.
- The full IceCube detector will have better sensitivity approximately proportional to the detector size.
- ~5 year observation with the full IceCube detector is capable of detecting the GZK neutrinos.

Backup

The comparison between obs. and CORSIKA data

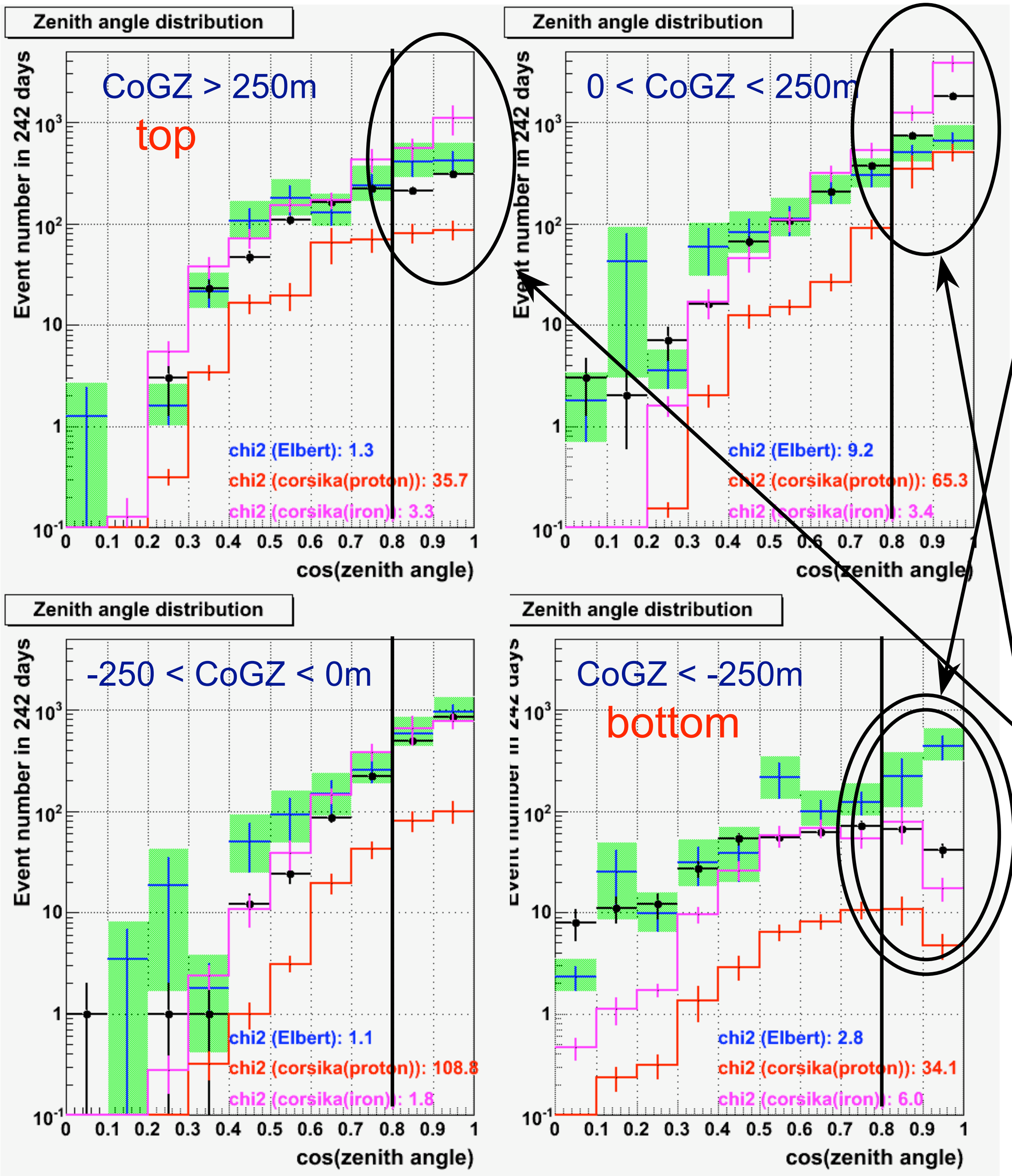


The data comparisons (level2 (NPE>10^4~10^7GeV))



- The empirical model express obs. data well except the CoGZ distribution at level2 cut.
- The pure CORSIKA protons and irons (SIBYLL) bracket the obs. data as expected.
- Less events in large ZA region for CORSIKA
- The CoGZ distribution is not perfectly expressed by any MCs.

Comparisons of ZA distributions for each CoGZ position (level2)



Obs. data

Empirical model

CORSIKA (proton)

CORSIKA (iron)

Difference is seen for the vertical events for the empirical model.

The vertical events penetrate into deep part (CoGZ < -250m).

→ due to simple single muon assumption

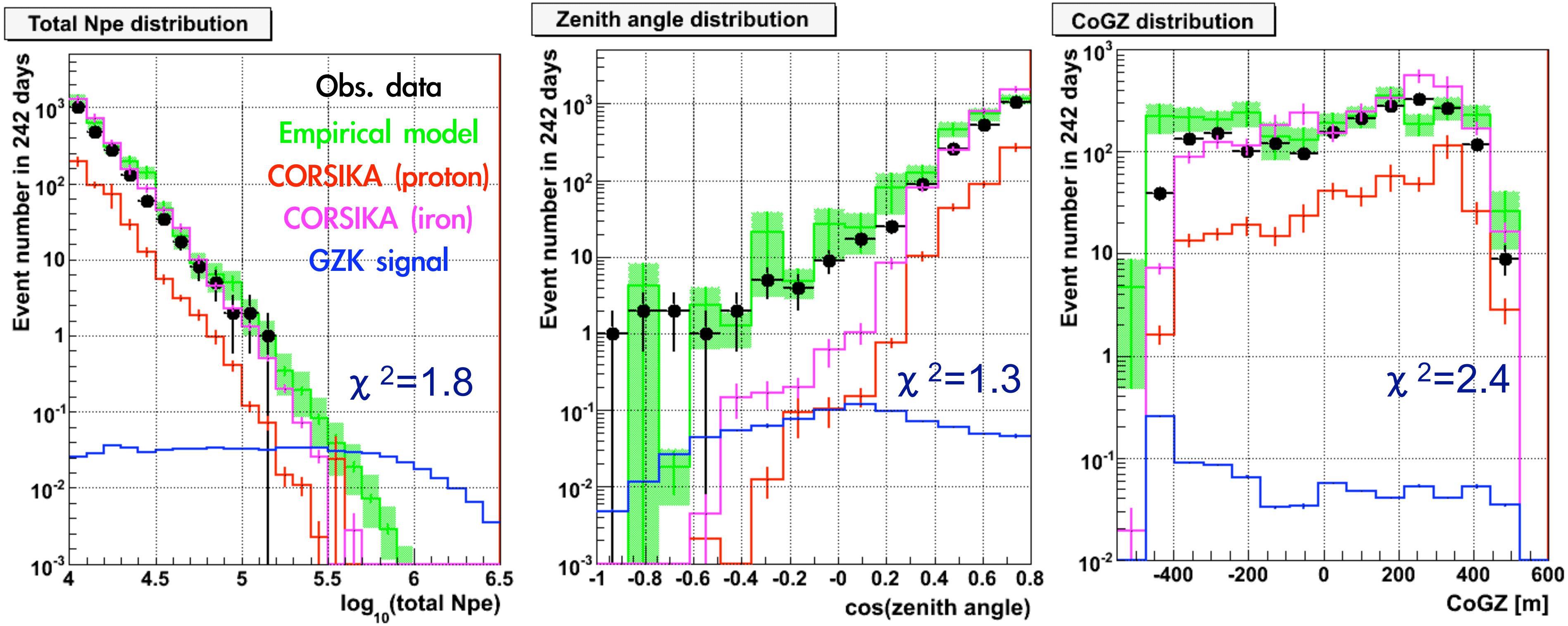
But, relatively good agreement for cos(ZA)<0.8.

→ cut cos(ZA)>0.8

On the other hand, vertical CORSIKA events attenuate at the top of the detector.

Less horizontal events for CORSIKA is universal, not depending on the CoGZ position.

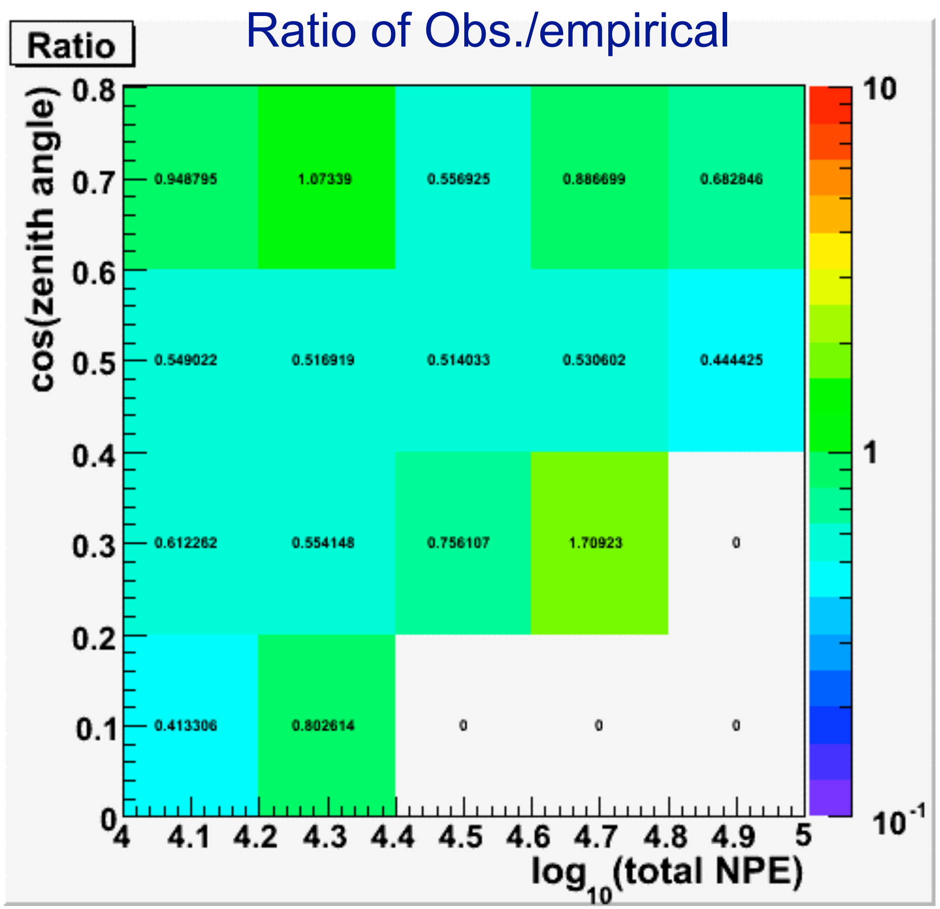
Comparisons between data and MC (at level3)

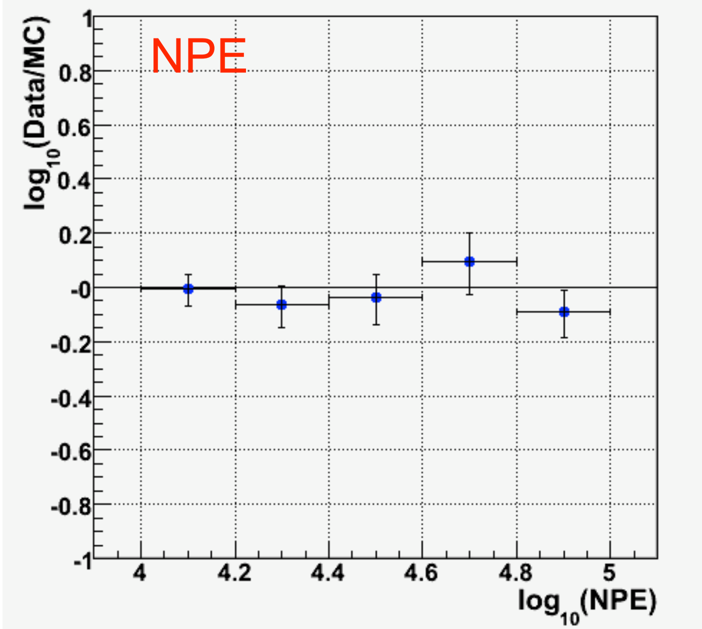


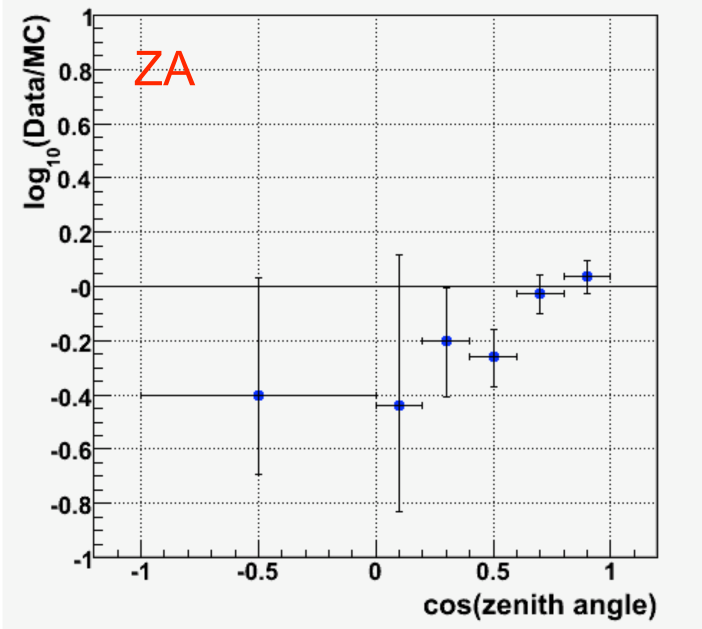
CoGZ: z position of event gravity center

- The empirical model reasonably expresses the data.
- Signals are placed at high NPE and horizontal direction.
- Obs. data are bracketed by CORSIKA pure protons and irons.
- CORSIKA data exhibit a slight difference with data in zenith angle distribution, underestimating the BGs.

Comparison on NPE and ZA plane (level2)







The ratio is unity within the statistical error in every NPE and ZA plane.

(The empirical model gives higher background compared to the obs. data at large ZA, though it's more conservative and within the error.)

❑ The CORSIKA issue

The small difference between the CORSIKA (SIBYLL) data and the obs. data is found.

- ➢ The CoGZ distribution

  More events concentrate on the top of the detector

- ➢ Less horizontal events indicating too good angular resolution

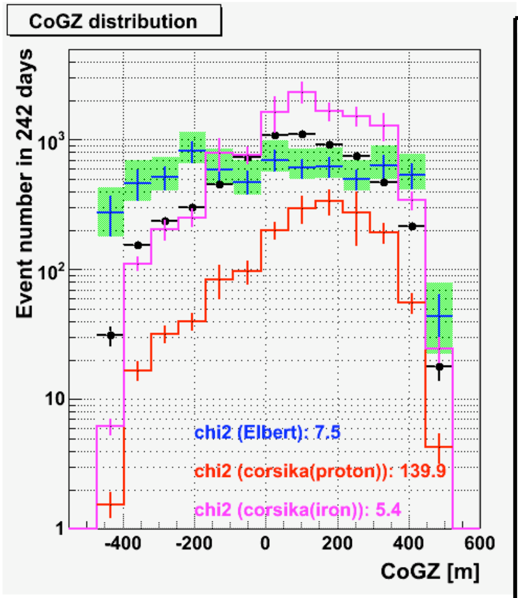
  → See right plots

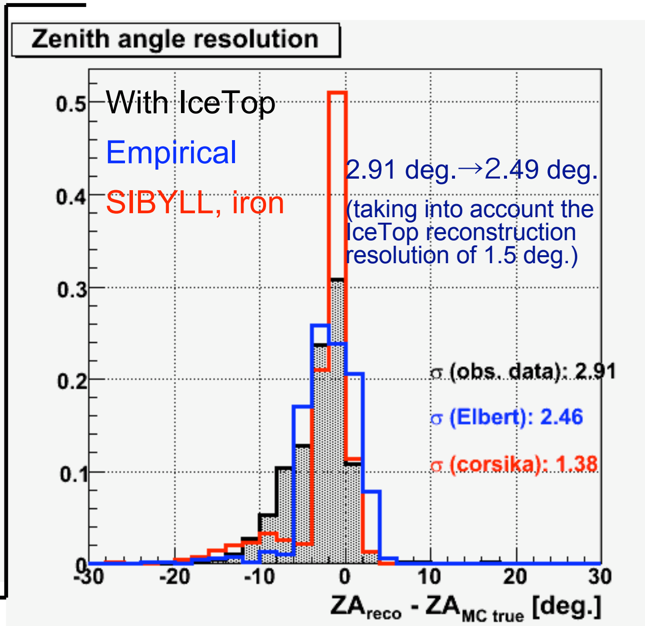
- ➢ NPE Vs CR energy relation

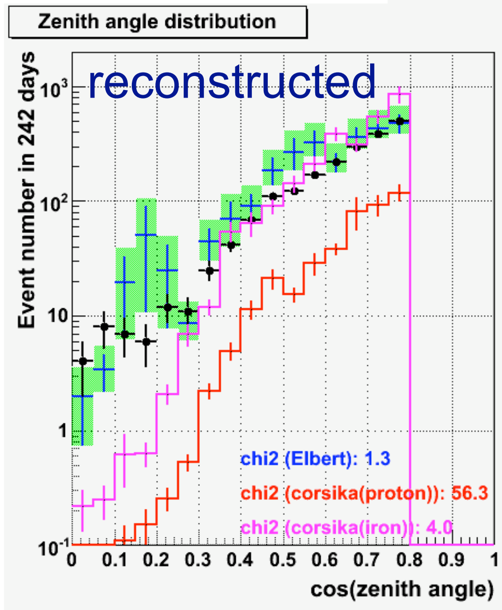
  →See next page

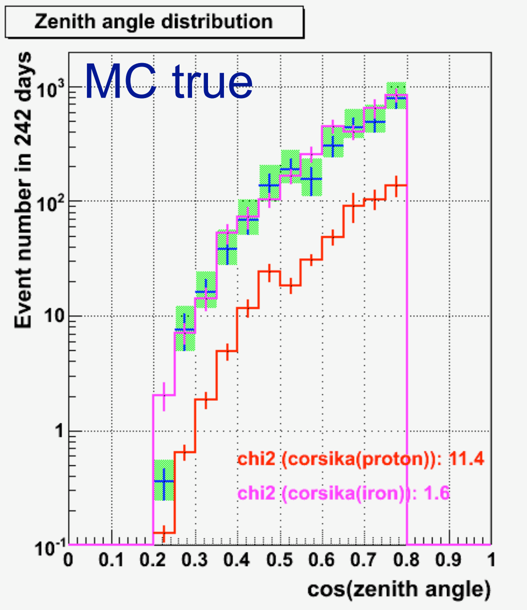
All these results seem to indicate that the muon bundles in CORSIKA consists of more lower energy muons in a bundle (higher multiplicity) which leads to less stochastic nature of the bundles.

The NPE and MC true ZA distributions agrees with the empirical model, so CORSIKA data is consistent with the empirical model to some level, but not perfect. (The empirical model express the obs. data better.)



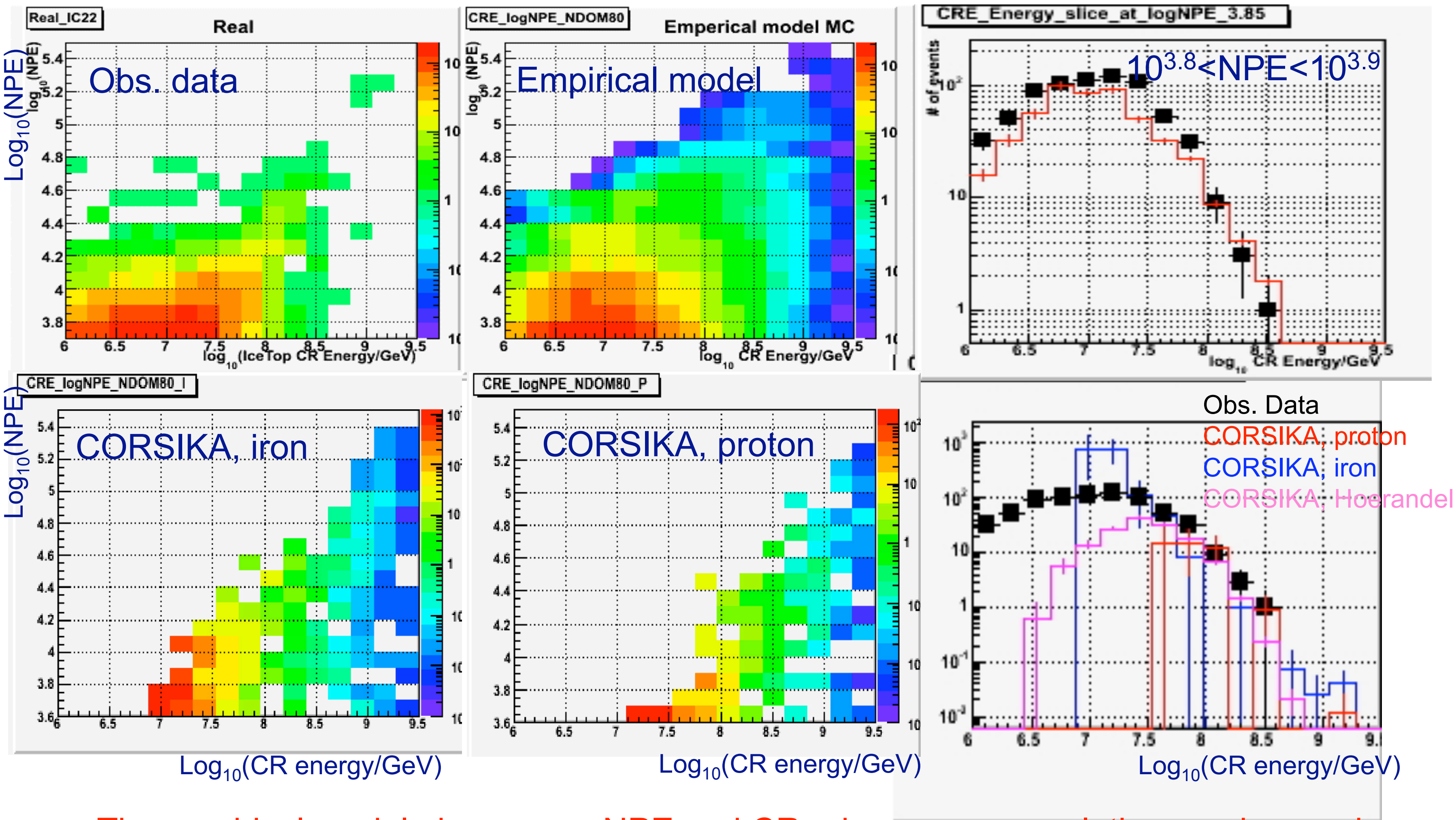






The confirmation of the empirical model with IceTop

The IceTop coincidence events are used to confirm the empirical model.

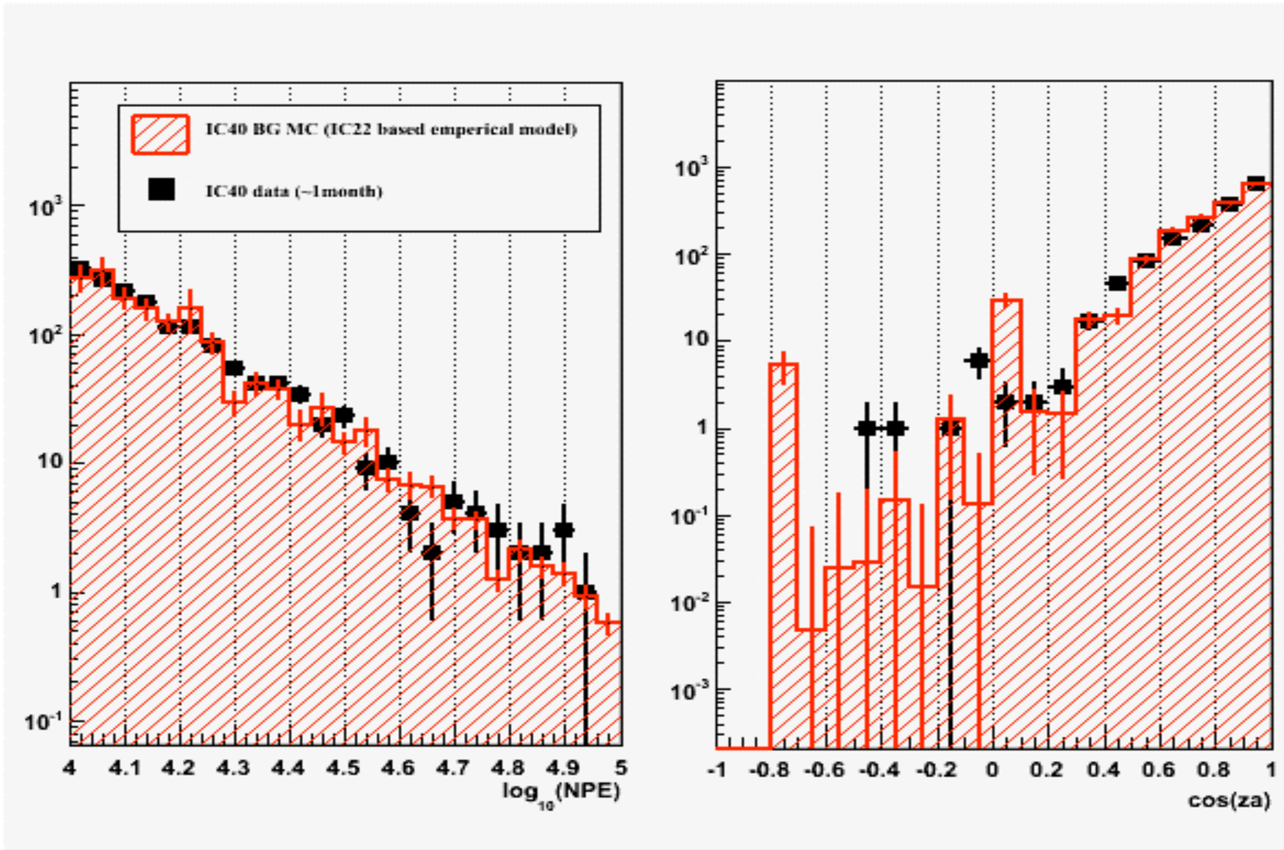


The empirical model gives same NPE and CR primary energy relation as observed.

The CORSIKA shows less fluctuation.

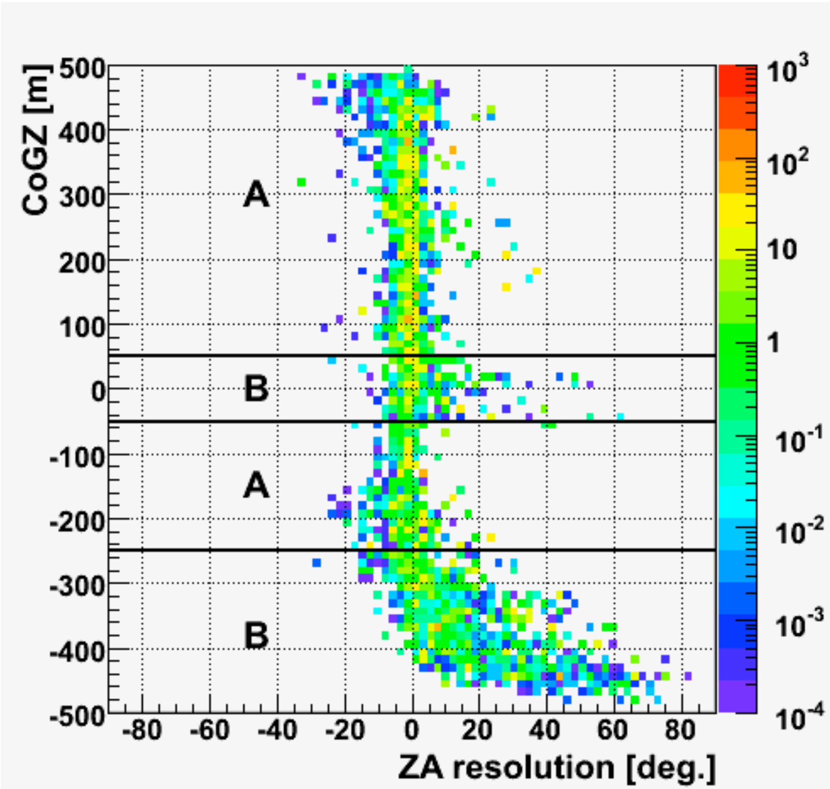
Confirmation of the empirical model by IC40 data

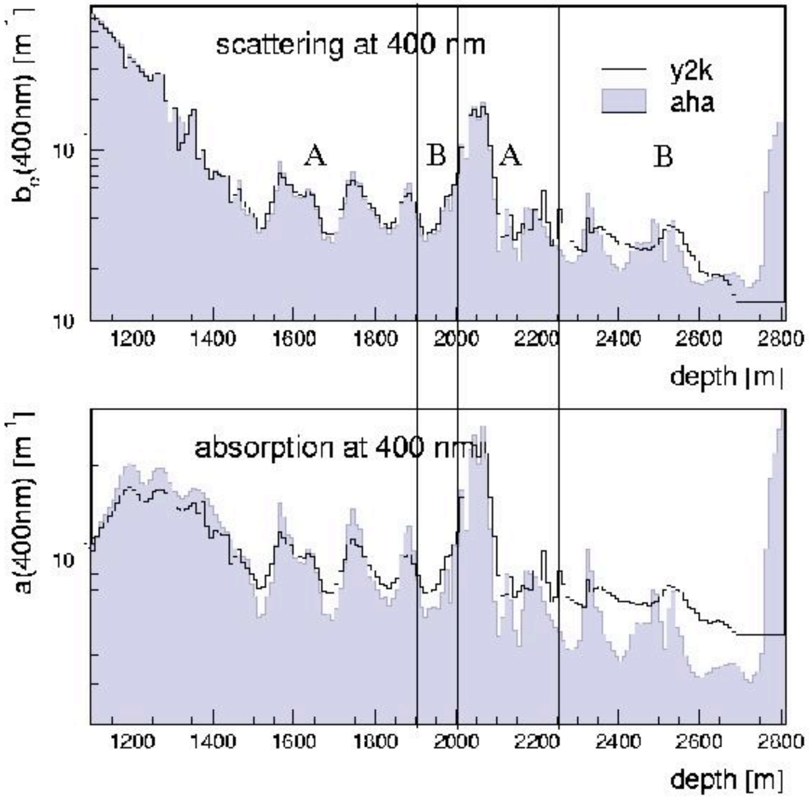
The empirical model effectively relates surface bundle energy and CR primary energy. → The relation is universal.



The empirical model derived from IC22 expresses IC40 data.

❑ using CoGZ information

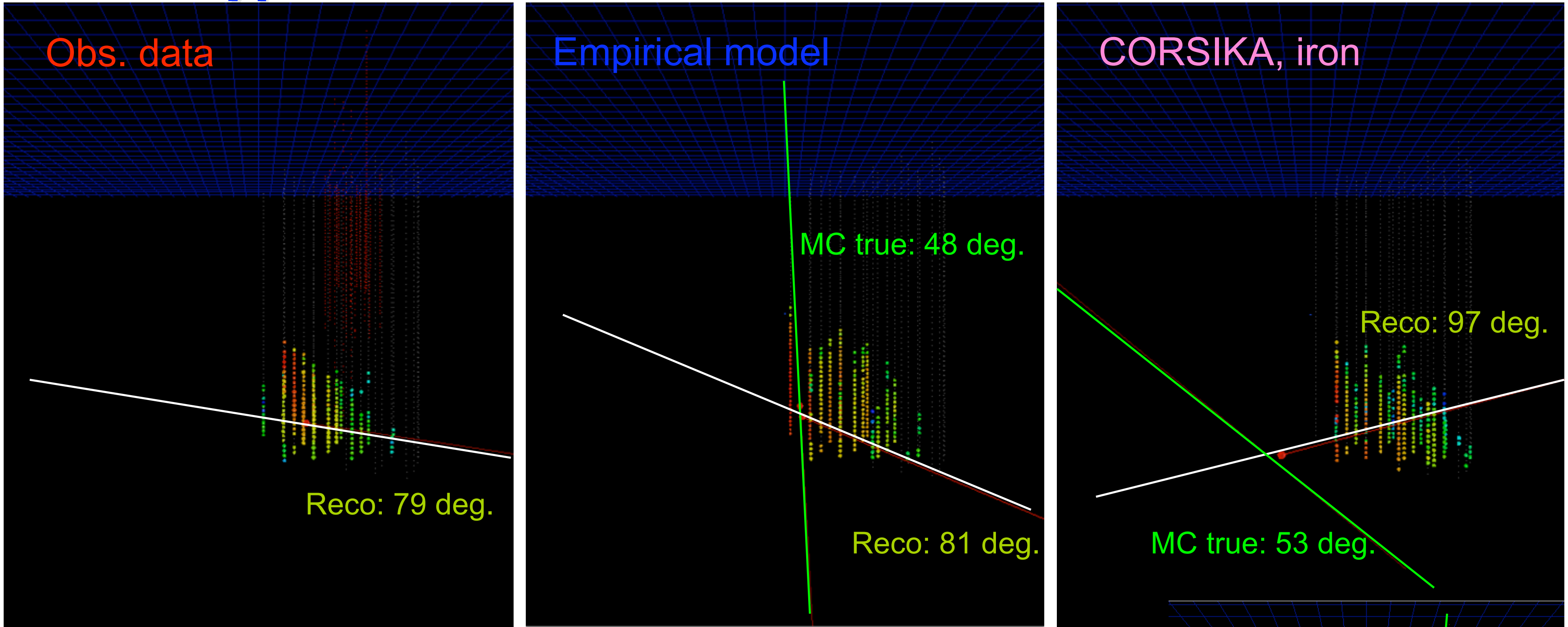




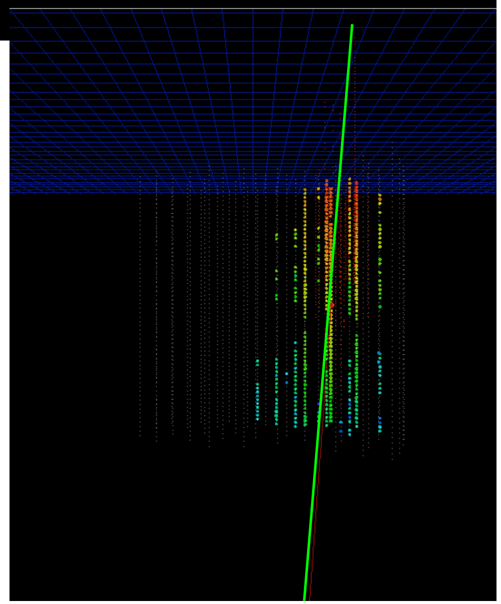
Mis-reconstucted events are correlated with CoGZ position.

We use the CoGZ information to cut the mis-reconstructed events effectively, dividing samples into two (region A and B).

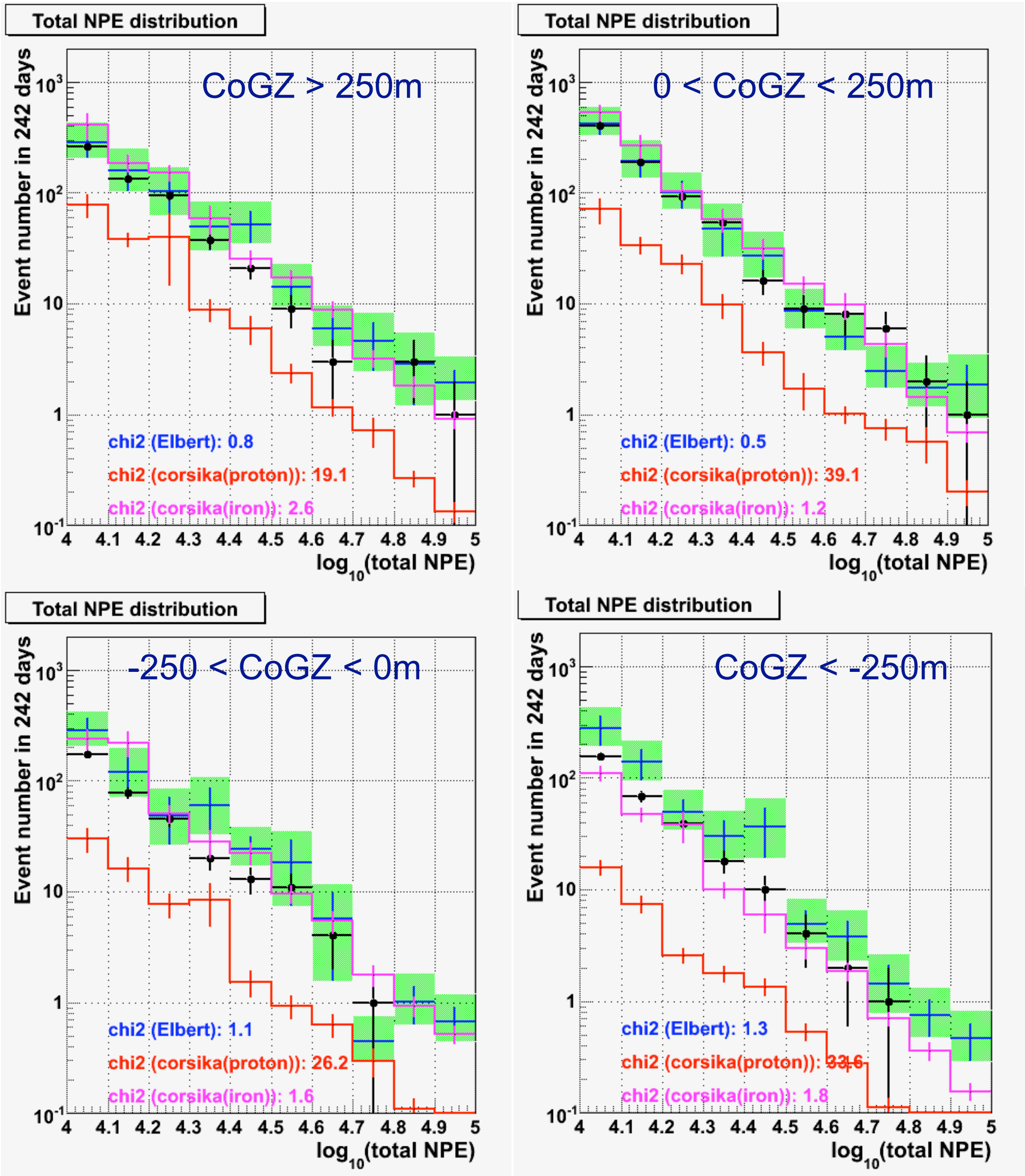
The typical mis-reconstructed events



- When a track pass near the outside (or edge) of the bottom part of the detector, the track is mis-reconstructed.
- Since such mis-reconstruction is found both in the empirical model and CORSIKA MCs and the observed events are similar to those MCs, we are confident that the same thing is happening in reality.
- This is due to the boundary effect. The clean ice at bottom and the big dust layer also enhance the mis-reconstruction.
- The similar phenomenon is happening at above big dust layer.
- The big dust layer divide our detector into two.



Comparisons of NPE distributions for each CoGZ position (level3)



Obs. data

Empirical model

CORSIKA (proton)

CORSIKA (iron)

The empirical model express the observed NPE distribution very well for each CoGZ position.

❑ The expected event rate for several models

models	Event rate / 242 days
GZK1	0.16±0.01(stat.)+0.03-0.05(sys.)
GZK2	0.25±0.01(stat.)+0.04-0.05(sys.)
GZK3	0.083±0.01(stat.)+0.013-0.026(sys.)
Z-burst	0.40±0.01(stat.)+0.06-0.10(sys.)
Backgrounds	(6.3±1.4(stat.)+6.4-3.9(sys.))x10^{-4}

GZK1) S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833 (1993)
GZK2) O. E. Kalashev *et al.*, Phys. Rev. D **66**, 063004 (2002)
GZK3) R. Engel, D. Seckel and T. Stanev, Phys. Rev. D **64**, 093010 (2001)
Z-burst) S. Yoshida, G. Sigl and S. Lee, Phys. Rev. Lett. **81**, 5505 (1998)

Systematics (preliminary)

- Largest uncertainty for BG: empirical model uncertainty (fit uncertainty to obs. data)

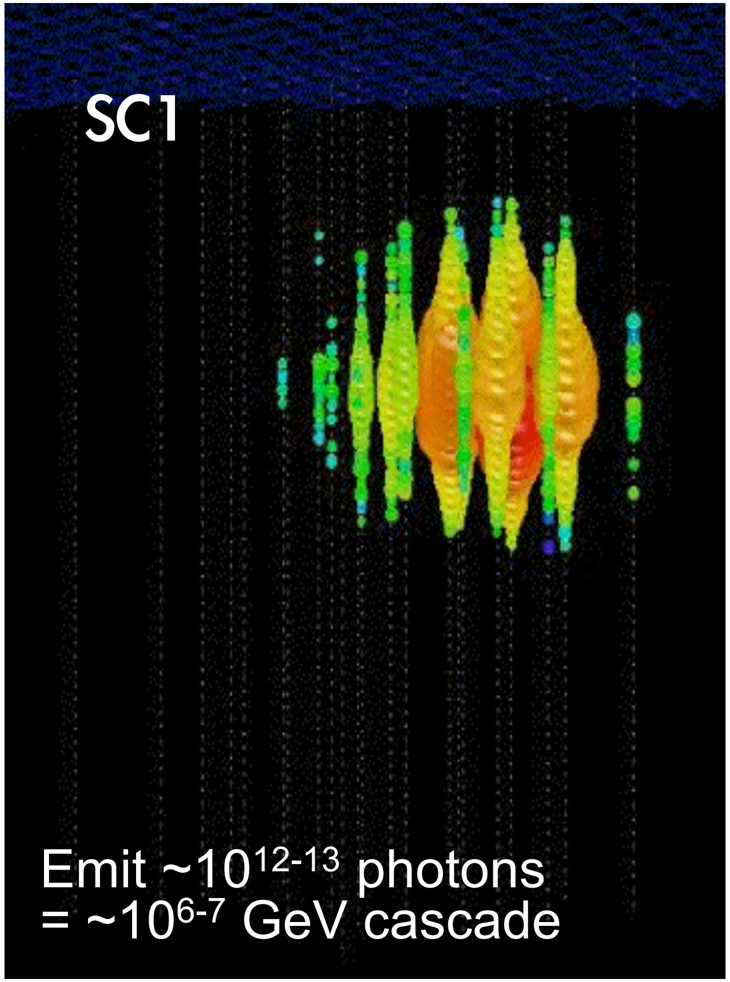
  → absorbed by a small NPE shift

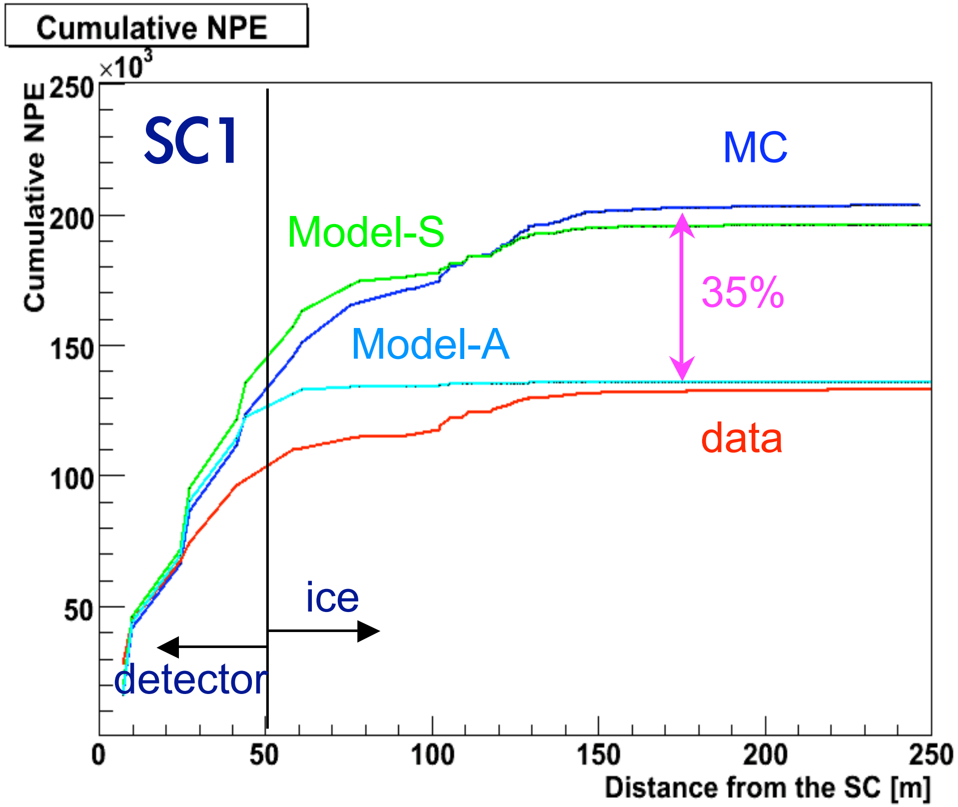
- Largest uncertainty: total NPE difference observed in data and MC of 35% with an absolutely calibrated source.
- The main part (27%) is contributed by uncertainty of ice property.
- Note that obs. data are not bracketed by pure proton and iron CORSIKA data by the 35% NPE shift. → only 10% shift is allowed.
- The allocated 35% NPE shift is very conservative.

	BG	Signal (GZK)
Statistical error	±22%	±0.6%
Detector sensitivity	-	±8%
Yearly variation	±17%	-
Empirical model uncertainty	**+99% -59%**	-
Hadronic interaction model	±4%	-
NPE shift (detector response+ice)	-	**-32%**
Neutrino cross section	-	±9%
Photo-nuclear interaction	-	+10%
LPM effect	-	±1%
Total	±22% (stat.) +101% -62% (sys.)	±0.6% (stat.) +16 -34% (sys.)

The NPE difference

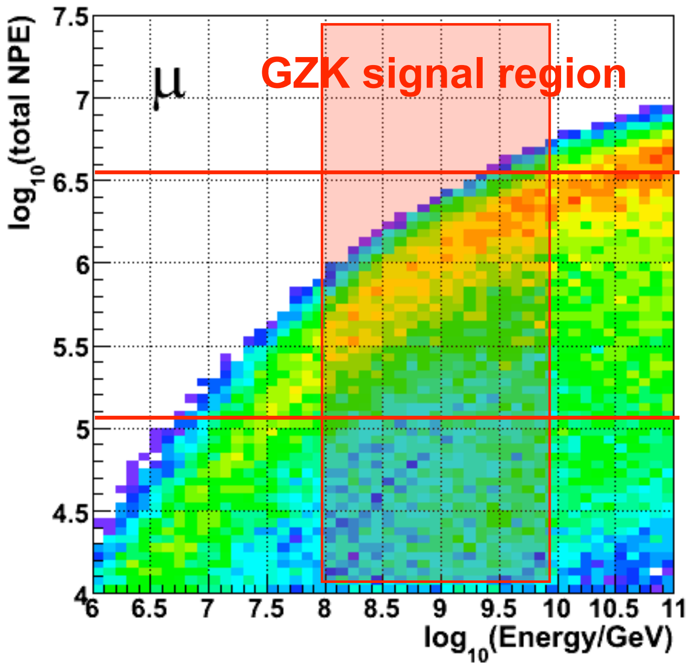
We calibrated our energy scale with an absolutely calibrated light source in situ (called "Standard Candle" (SC)).





	NPE_{data}-NPE_{MC}	Detector	Ice
SC1	- 34.9%	- 17.5%	- 41.2%
SC2	- 18.4%	- 14.9%	+ 4.4%

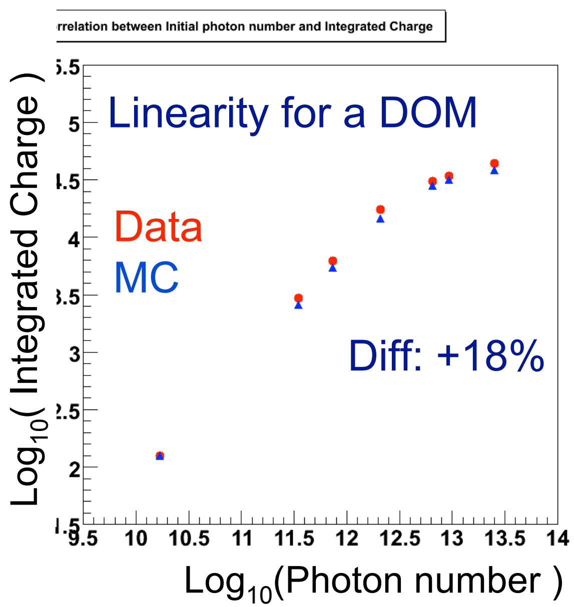
❑ Total NPE as energy estimator and detector response to luminous event

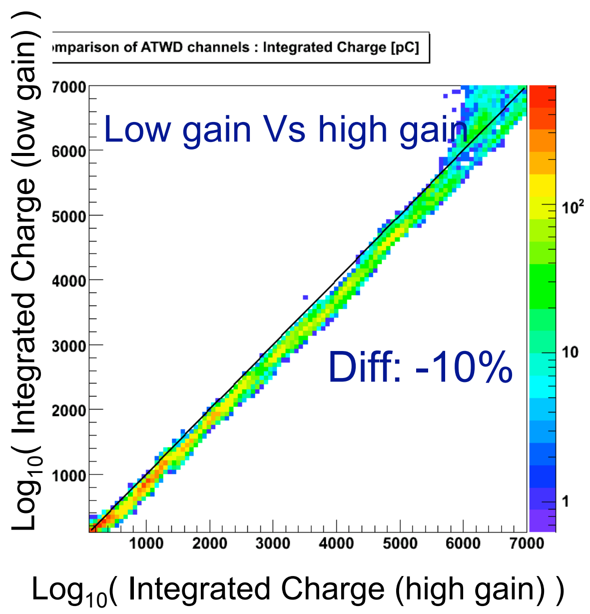


- Event-wise total NPE detected by all DOMs is used as the energy estimator.
- correlation with the energy.
- Nonlinear behaviour due to the detector response

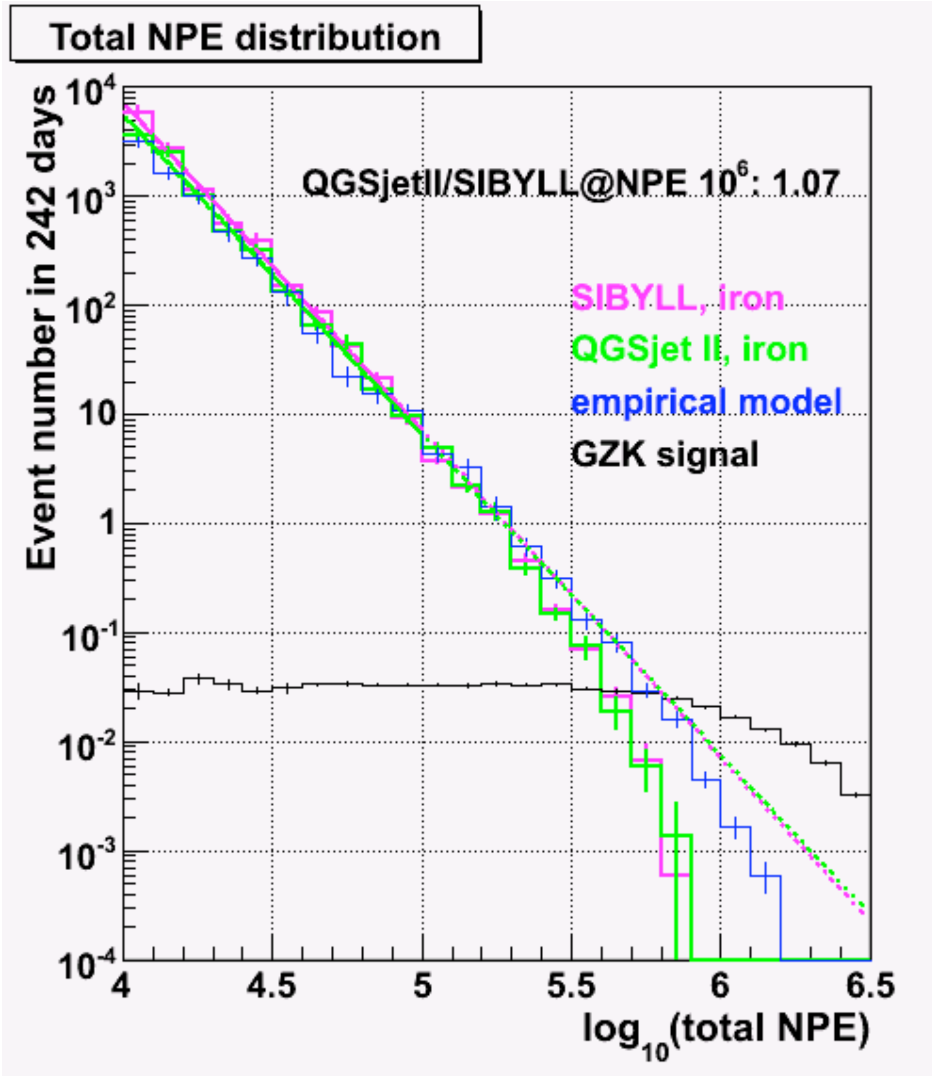
- The key: Detector response to luminous event

  → performed absolute calibration with calibrated sources in situ
- NPE_{data}-NPE_{MC} = -16% (distance < 50m)
- Several possible sources were investigated
- the difference is not perfectly understood. → systematics
- Smaller than a systematics of ice property.





Effect of hadronic interaction models



The difference at relevant NPE range is 7%.