平成26年度　東京大学宇宙線研究所
共同利用研究成果発表会

IceCube実験によるニュートリノ観測
atmospheric ν_μ spectrum analysis

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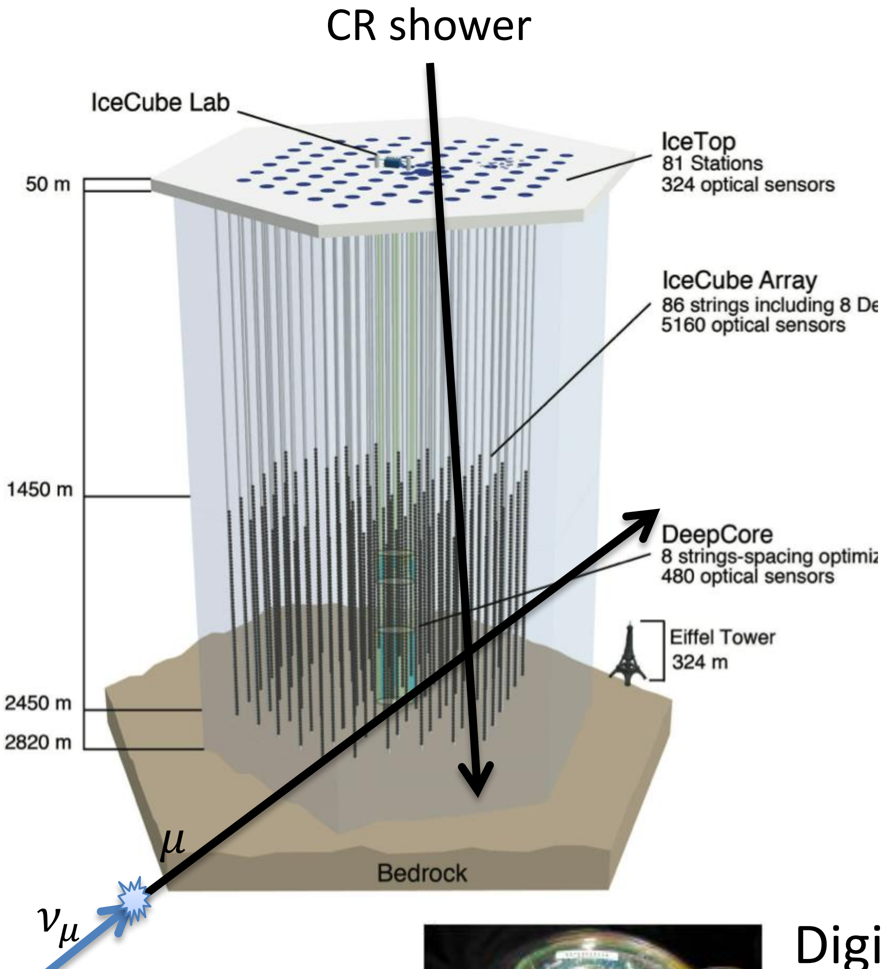
謝辞
旅費（千葉⇔柏）: 50千円

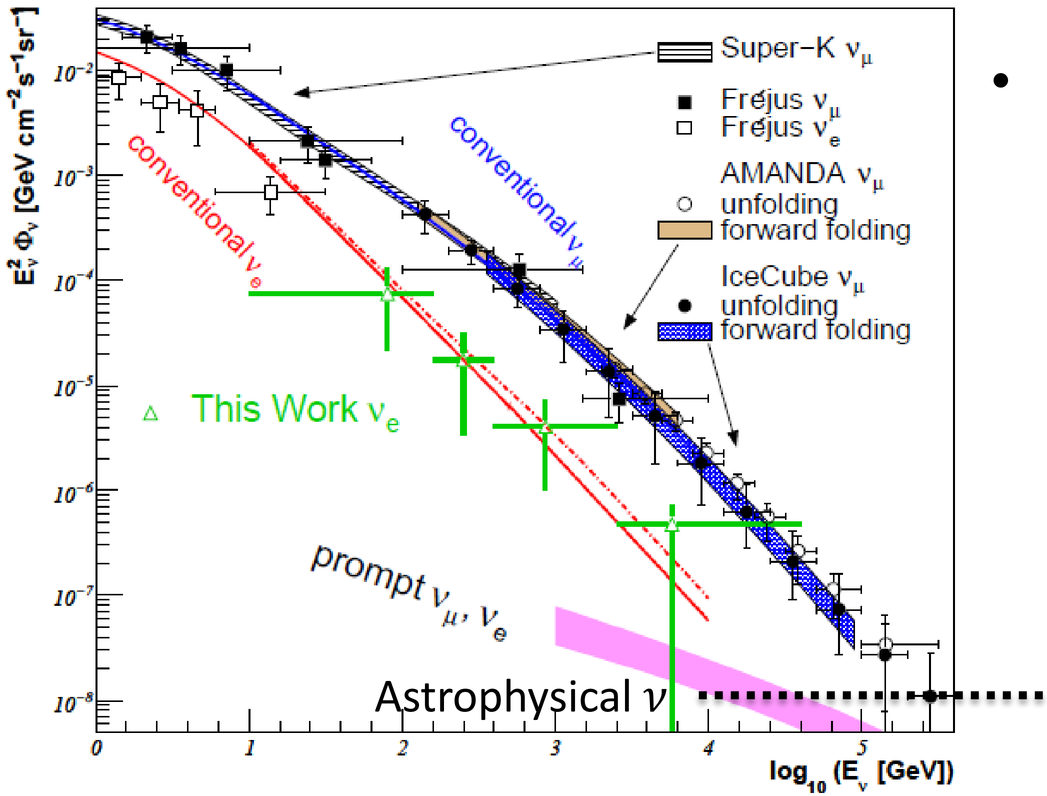
IceCube neutrino observatory

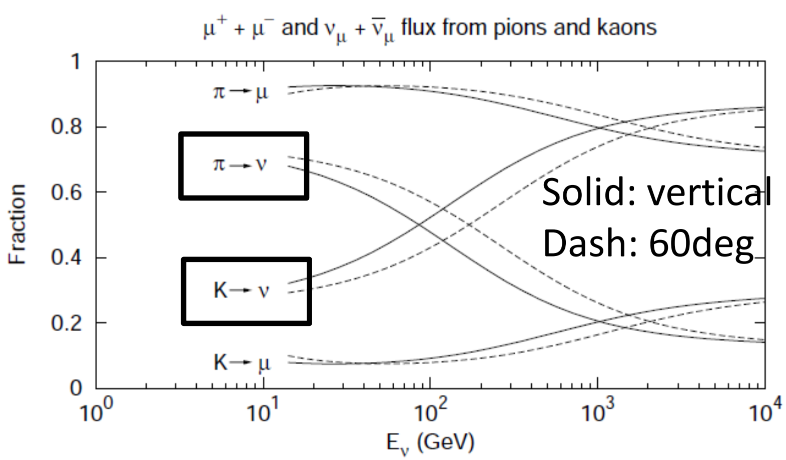


- 3D cosmic ray detector
  - Completed Dec 2010 at SouthPole, 2835m
  - IceTop: Surface array of ice tank
  - IceCube Array: In-ice array of DOMs
  - DeepCore: Infill array for lowE extension
- IceCube measures
  - Cosmic ray showers from above
  - Neutrinos from all directions
    - ν_μ-induced μ from below
    - all flavors starting inside detector

Digital Optical Modules
- 86 in-ice strings
- 60 DOMs per string
- 125m inter-string spacing 17m DOM spacing

Atmospheric Neutrino Flux

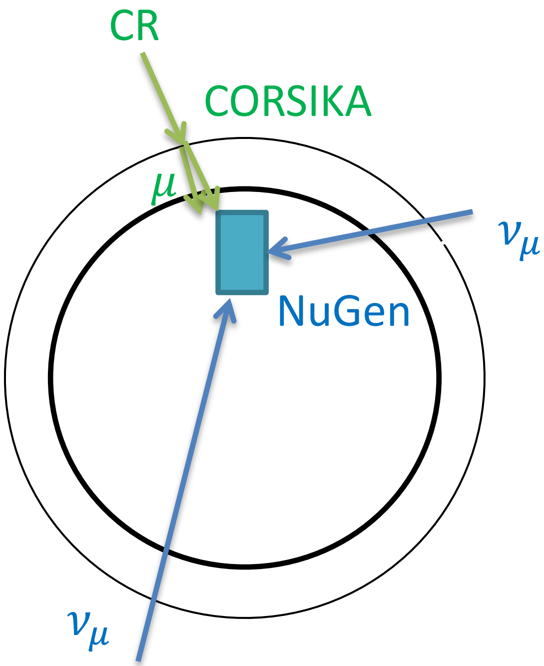




- Conventional ν_μ and ν_e
  - Important background to evaluate prompt ν and astrophysical ν
  - From π and K decay
    Shape of spectrum depends on π to K ratio
  - Several IceCube works at past
    Still large systematic uncertainties left
  - For complete understanding, combined analysis with low energy experiment, like Super-K, is strongly required

This analysis will determine ν_μ spectrum from first year of completed IceCube 86 string data

Atmospheric CR μ and ν_μ flux simulation



Muon bundles with CORSIKA

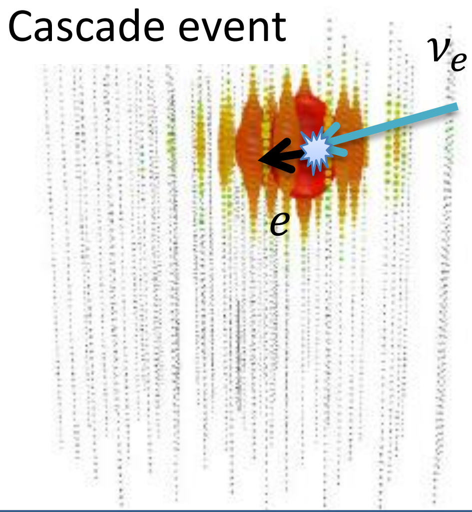
- Input CR spectrum :E_{cr}^{-2}
- 5 component (P, He, N, Al, Fe)
- Weight: Polygonato
- Zenith angle: 0 – 90 deg

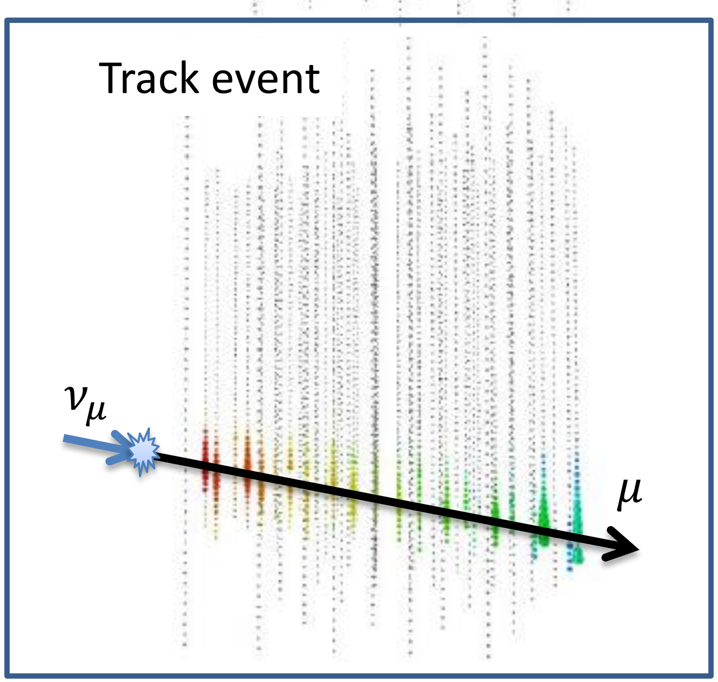
Neutrinos with NuGen (neutrino generator)

- Input ν_μ spectrum : E_ν^{-2}
- Weight: Honda, GaisserH3a, +Enberg
- Zenith angle: 0-360 deg

ICRR computer facility is used to improve our background simulations

ν_μ Event Selection





Level-1 data (>2kHz)

require typical Trigger Condition
(recording > 8 channels in 5 μsec)
by the DOMs passed Coincidence Condition
(one of nearby DOMs has record in ± 1 μsec)

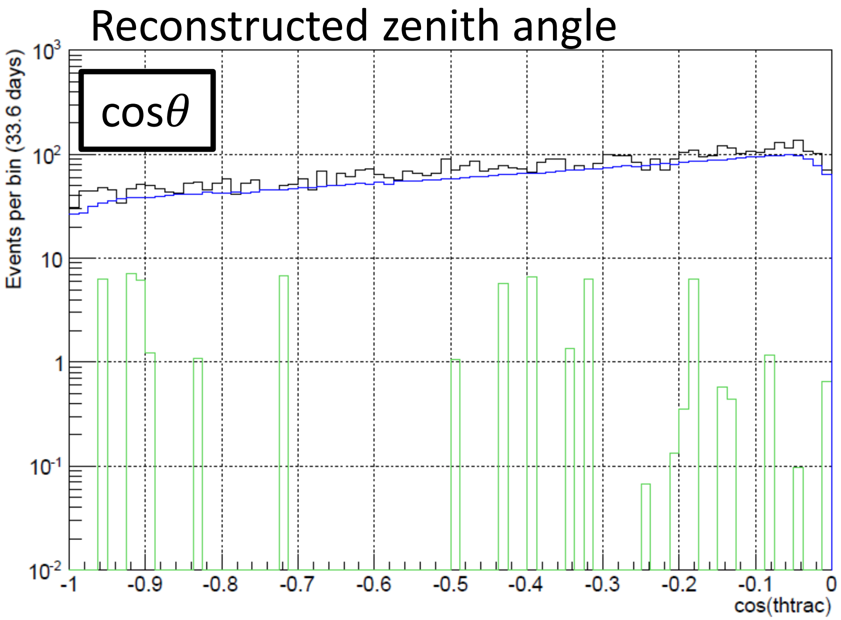
Level-2 data (~40Hz)

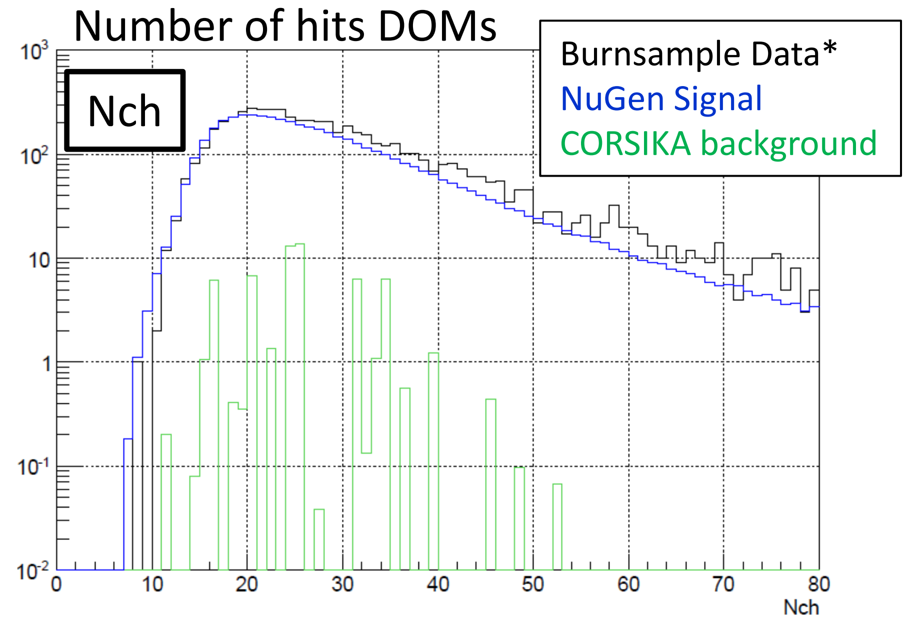
- min quality of first angular reconstruction
- down-going events with small charges (CR muon dominates) are rejected.
- high back ground muon (>99.9%)

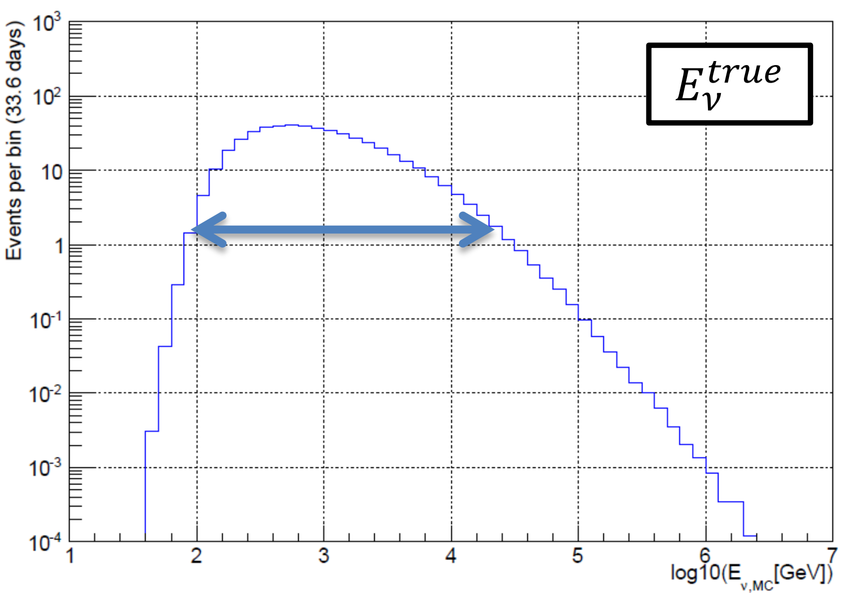
Level-3 data (~2mHz)

- good angular reconstruction (σ<5deg)
- up-going event only
- low back ground muon (~1%)

Event distribution, Level 3 data



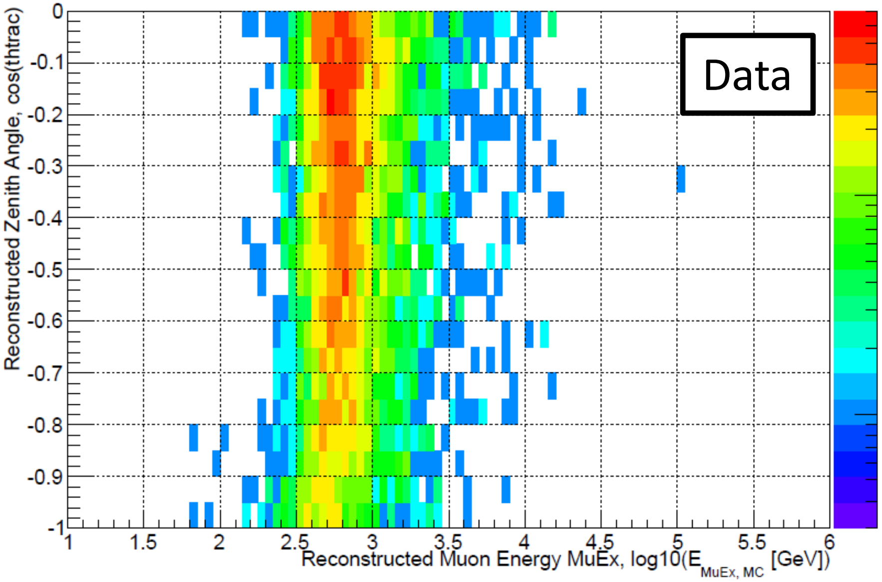


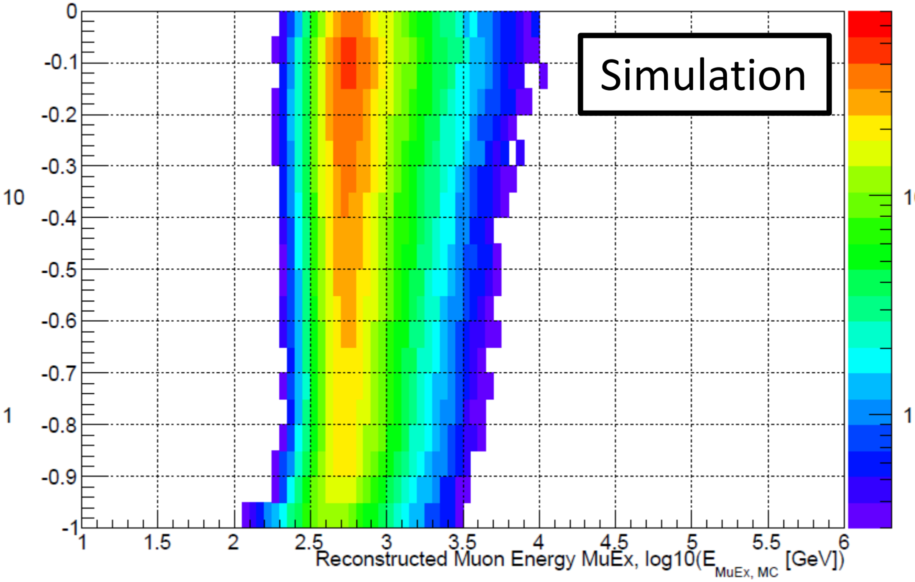


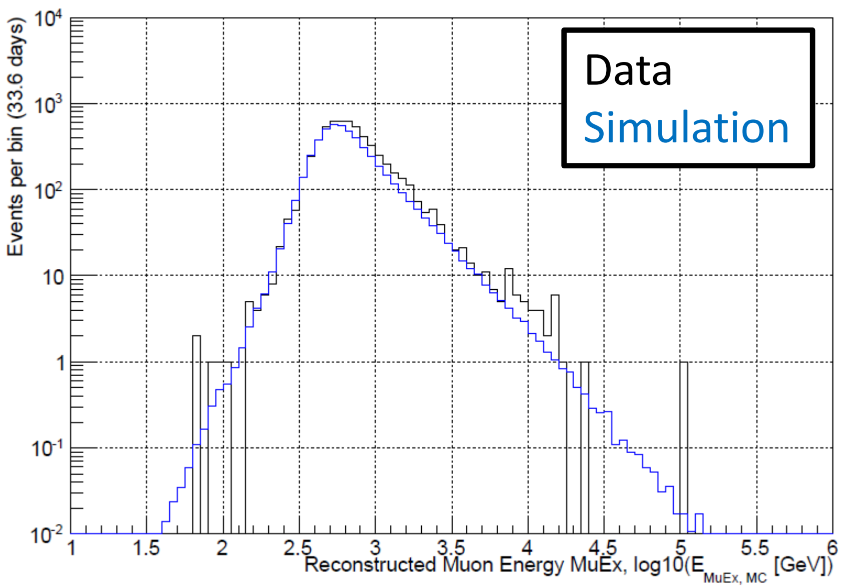
* Burnsample = 10% statistics data

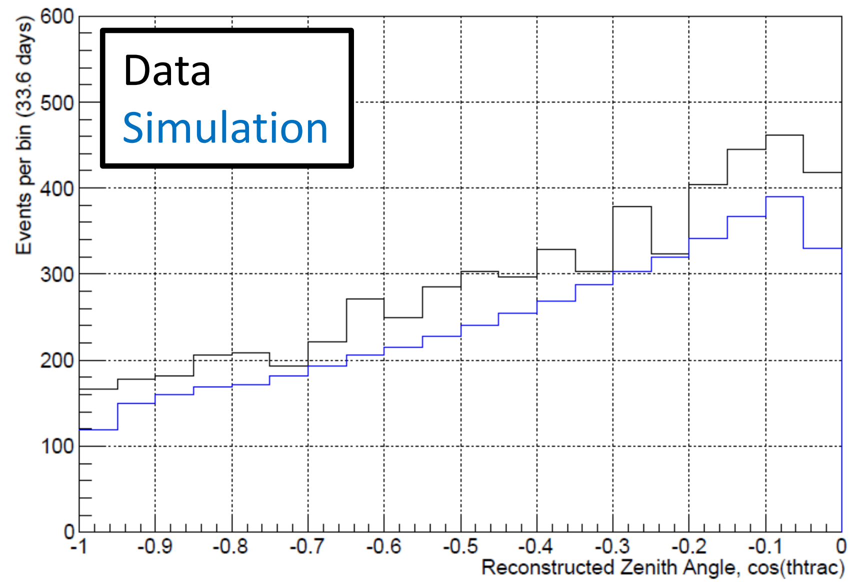
- 5823 burn sample events remained after cuts
- Good data/MC agreement
- Primary energy range:
  100GeV-20TeV (99% events)
  Median ~ 800GeV

Reconstructed muon energy vs zenith angle distribution





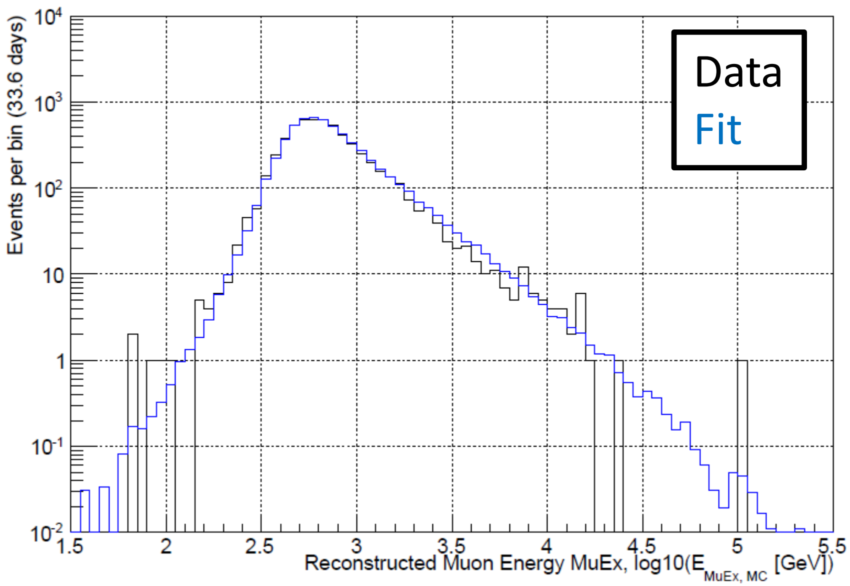


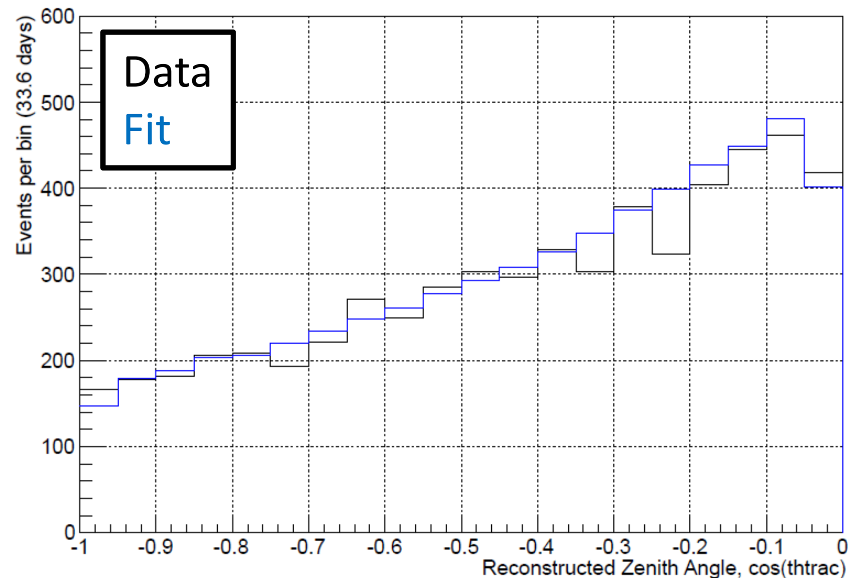


Likelihood fit analysis

- 2D distribution of reconstructed muon energy and zenith angle for fitting
- Physics parameter
  - 1+α, Deviation from reference conventional flux (Honda+H3a model)
  - $\Delta\gamma$, Change in spectrum slope
  - $R_{K/\pi}$, ratio of spectrum weighted moments to produce K and π (baseline $R_{K/\pi}$ = 0.149)
- Nuisance parameter
  - ϵ, DOM efficiency
- Minimizer (ROOT Minuit2)

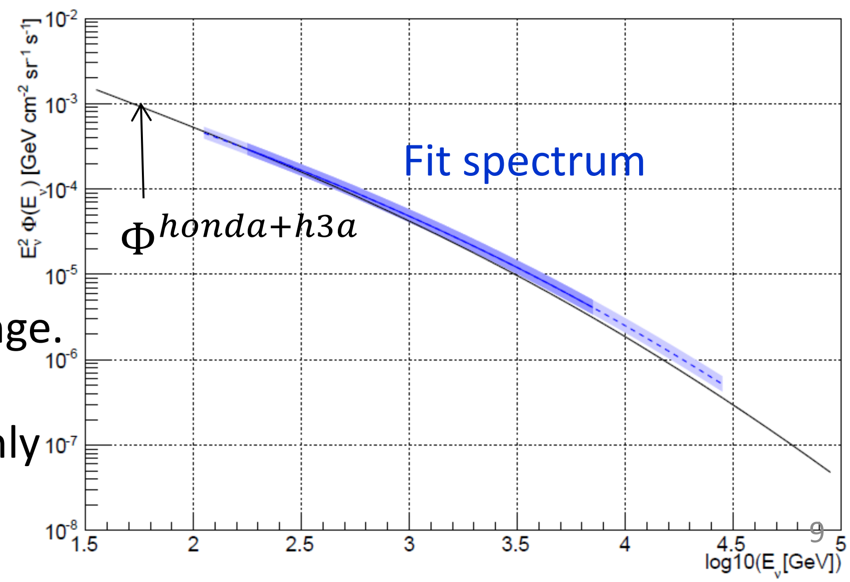
Preliminary Fit Result





Para-meter	$1+\alpha$	$\Delta\gamma$	$R_{K/\pi}$	$\Delta\varepsilon$
Best Fit Value	1.07 $\pm$0.18	+0.07 $\pm$0.04	+11 $\pm$42%	+5.8 $\pm$0.6%

- Spectrum shape : higher flux + flatter slope.
  Difference with model is ~ 90% confidence range.
- Large uncertainty in $R_{K/\pi}$
  Not determined well from high energy data only
- Higher DOM efficiency
  Some technical issue need to be figure out



Summary

- ν_μ sample has been selected from the first year of the completed IceCube data
- Applied preliminary likelihood fit analysis
  - Flux normalization : 1.07 ± 0.18 x (Honda+H3a)
  - Spectrum index : $+0.07 \pm 0.04$ flatter
  - $R_{K/\pi}$: $+11 \pm 42\%$ from baseline
- Next…
  - Joint analysis with Super-K
    - Super-K reported their spectrum (at Neutrino2014)
    - High statistical Super-K result at low energy -> reduce systematic uncertainty at high energy end
    - Wide energy range coverage -> good $R_{K/\pi}$ determination
  - Use DeepCore trigger
    - Extend energy (E_ν^{min}: 100GeV->10GeV)
    - Makes overlap with Super-K energy range
  - ν_e spectrum
    - Analysis of cascade events is on-going

Back up

K/pi ratio

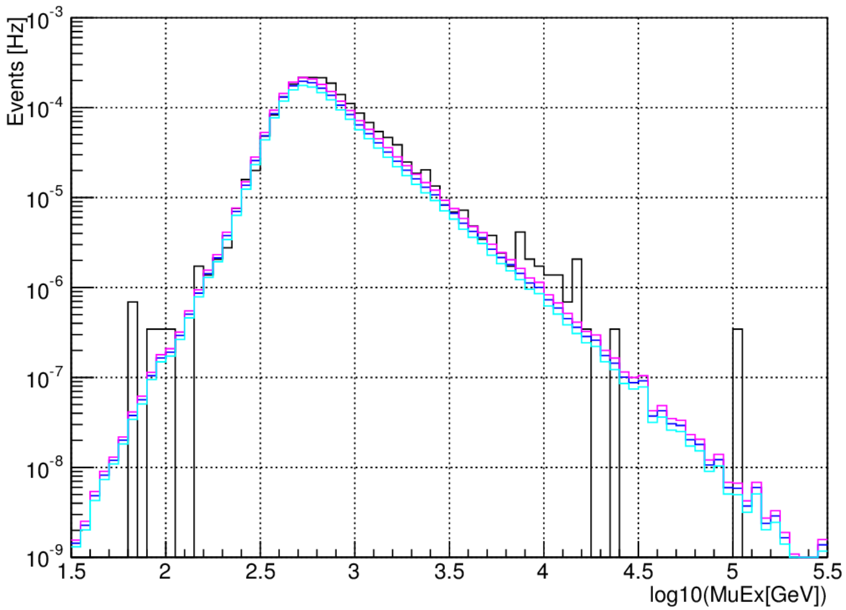
$$\Phi_\nu = \Phi_N(E_\nu)\left(\frac{A_{\pi\mu}}{1 + B_{\pi\mu}\cos\theta^* E_\nu/\epsilon_\pi} + \frac{A_{K\mu}}{1 + B_{K\mu}\cos\theta^* E_\nu/\epsilon_K}\right)$$

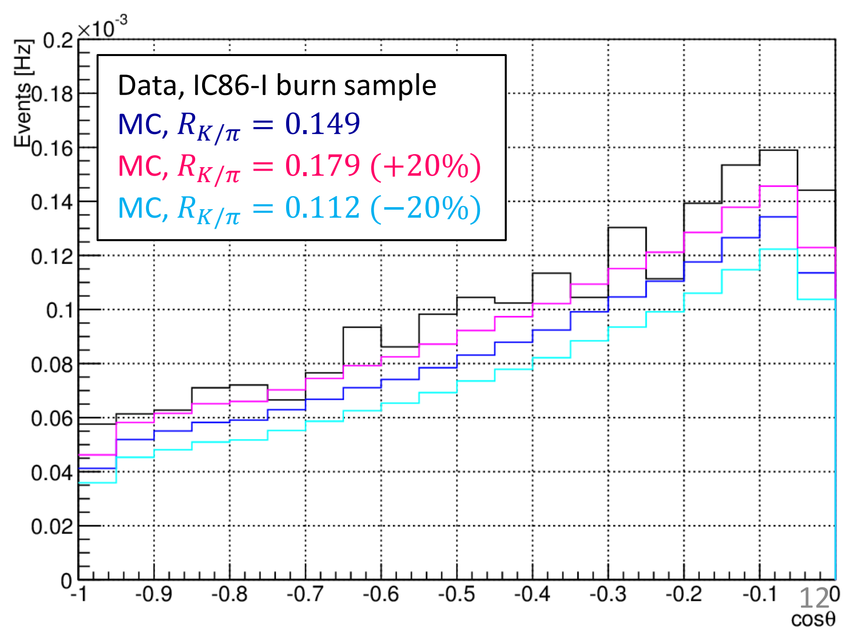
$$A_{\pi\nu} = BR_{\pi\nu} Z_{N\pi} \frac{(1-r_\pi)^\gamma}{\gamma+1} \qquad B_{\pi\nu} = \frac{\gamma+2}{\gamma+1}\frac{1}{1-r_\pi}\frac{\Lambda_\pi - \Lambda_N}{\Lambda_\pi \ln(\Lambda_\pi/\Lambda_N)}$$

Ratio of Z-factor

$$R_{K/\pi} = \frac{Z_{NK}}{Z_{N\pi}} = \frac{0.0118}{0.079} = 0.149 \pm 0.060$$

Constraint
The sum $Z_{NK} + Z_{N\pi}$ is kept constant to its nominal value 0.0908

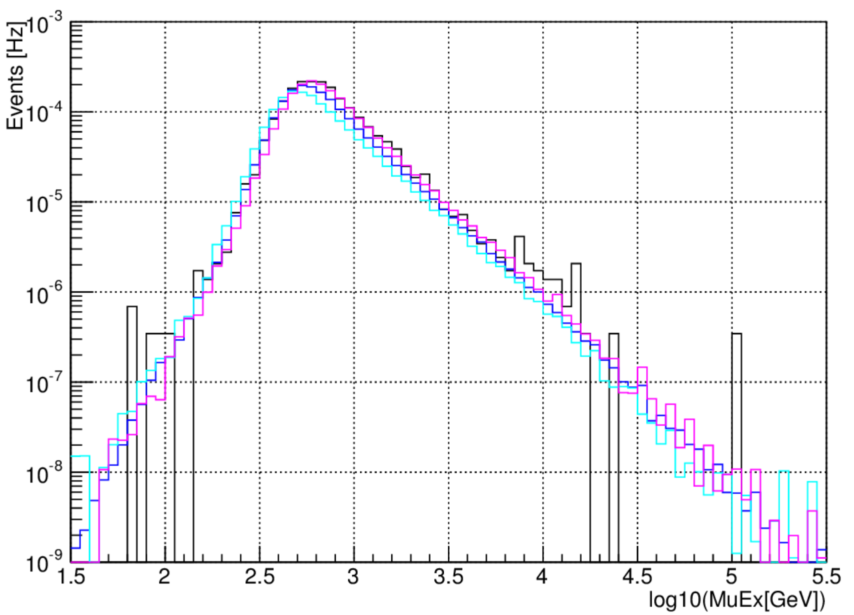


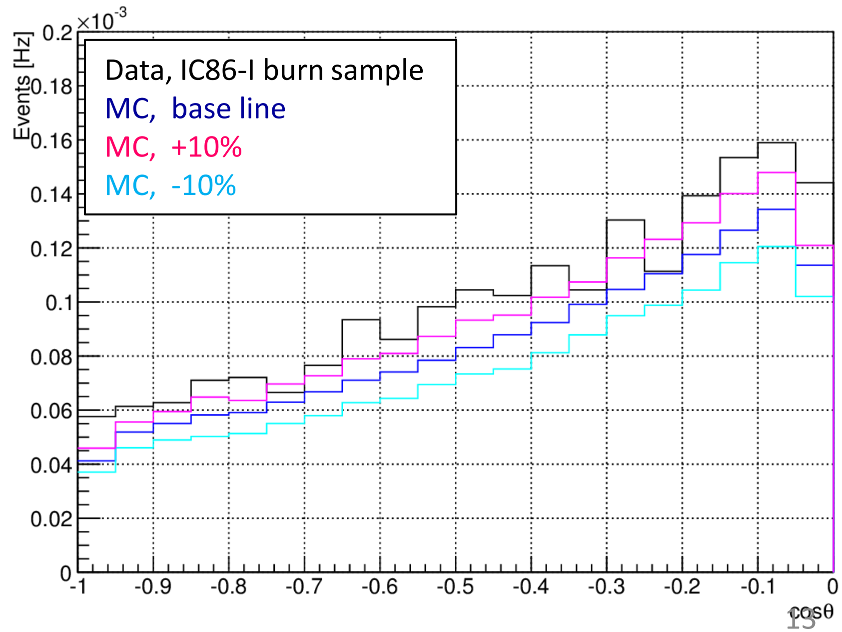


DOM Efficiency

NuGen Data Set	DOM Efficiency
10602	**0.99 (baseline)**
10437	0.891 (-10%)
10561	0.9405 (-5%)
10562	1.0395 (+5%)
10438	1.089 (+10%)

Produce simulation data sets with different DOM efficiency





Likelihood Function

Flux Change from $R_{K/\pi}$

$$W_{K/\pi} = \frac{\Phi_\nu(R_{K/\pi})}{\Phi_\nu^0(R_{K/\pi}=1)}$$

Reference model spectrum

Φ_ν^{model} : Honda+GaisserH3a

Fit spectrum

$$\Phi_\nu = (1+\alpha)\left(\frac{E_\nu}{E_\nu^{med}}\right)^{\Delta\gamma} W_{K/\pi}\Phi_\nu^{model}$$

Poisson probability

$$P(n_i|\mu_i(\theta_r,\theta_s)) = \prod_i \frac{\mu_i^{n_i}}{n_i!}e^{-\mu_i}\prod_j \exp\left(-\frac{1}{2}\frac{(\theta_{s_j}-\theta_{s0_j})^2}{\sigma^2_{\theta_{s_j}}}\right)$$

n_i: observed count at i-th bin

μ_i: expected count at i-th bin

θ_r: physics parameters

θ_s: nuisance parameters

Negative log likelihood function to minimize

$$\mathcal{L}(\theta_r,\theta_s) = -2\ln P = 2\sum_i\left[\mu_i - n_i\ln\mu_i + \ln n_i!\right] + \sum_j\frac{(\theta_{s_j}-\theta_{s0_j})^2}{\sigma^2_{\theta_{s_j}}}$$