The atmospheric neutrino measurements by IceCube

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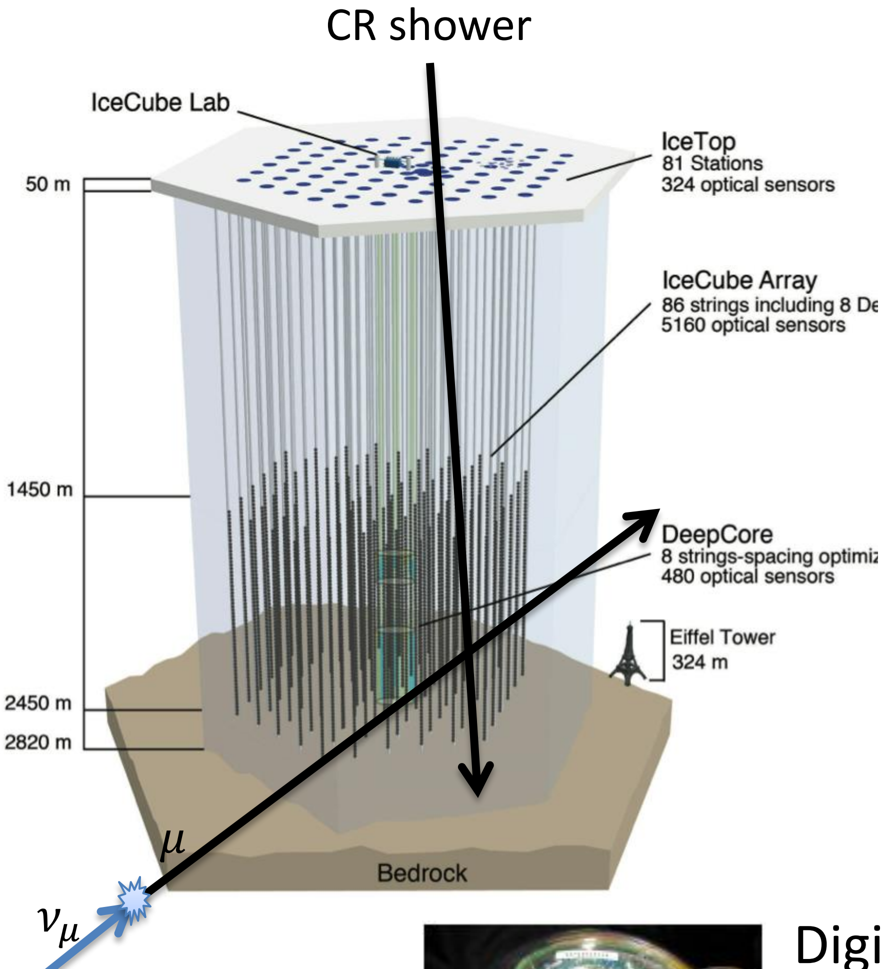
IceCube neutrino observatory

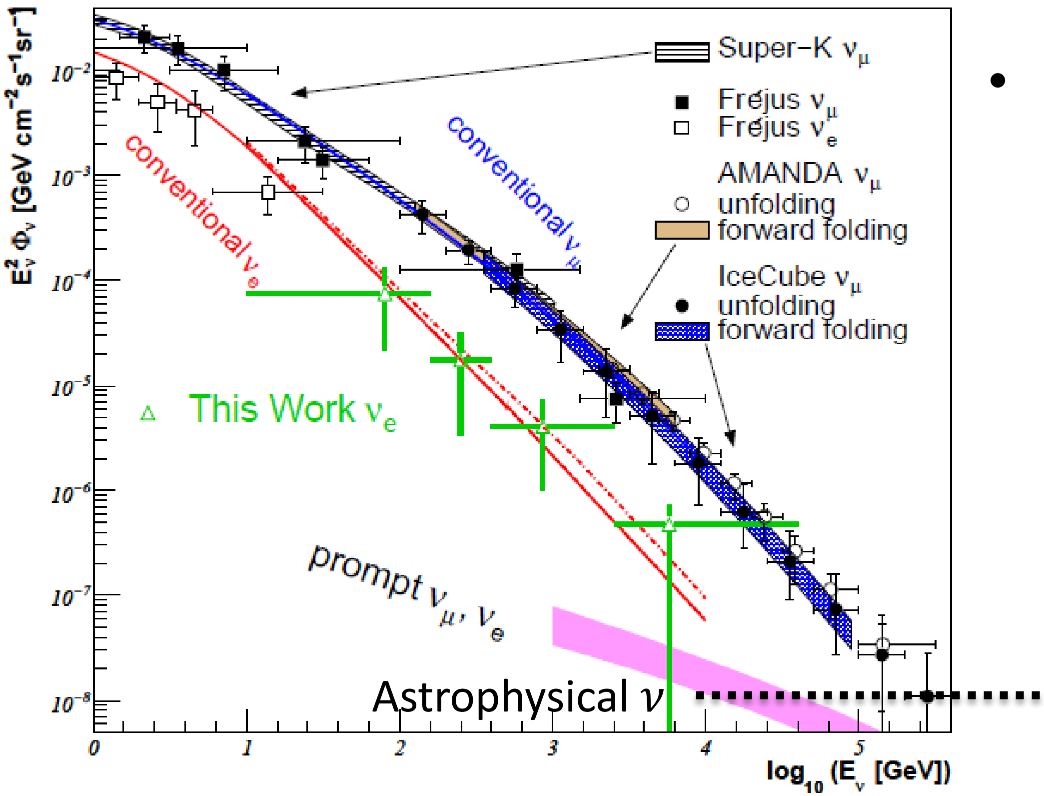


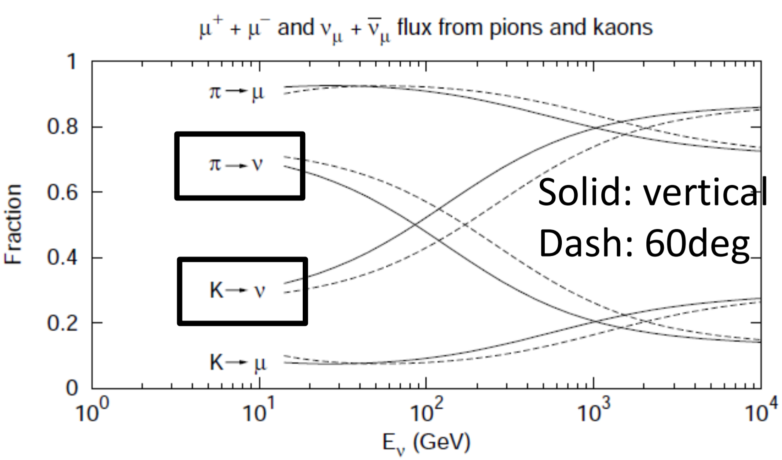
- 3D cosmic ray detector
  - Completed Dec 2010
    at SouthPole, 2835m
  - IceTop: Surface array of ice tank
  - IceCube Array:
    In-ice array of DOMs
  - DeepCore:
    Infill array for lowE extension

- 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

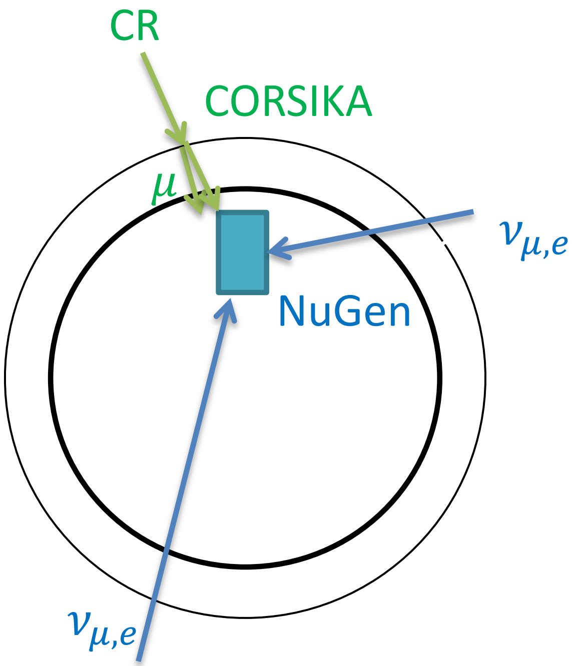




- Conventional ν_μ and ν_e
  - Important background to evaluate prompt ν and astrophysical ν
  - From π and K decay
    Shape of spectrum depends on π to K ratio
  - Several IceCube works at past
    Still large systematic uncertainties left
  - For complete understanding, combined analysis with low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

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

Atmospheric CR μ and $\nu_{\mu,e}$ flux simulation



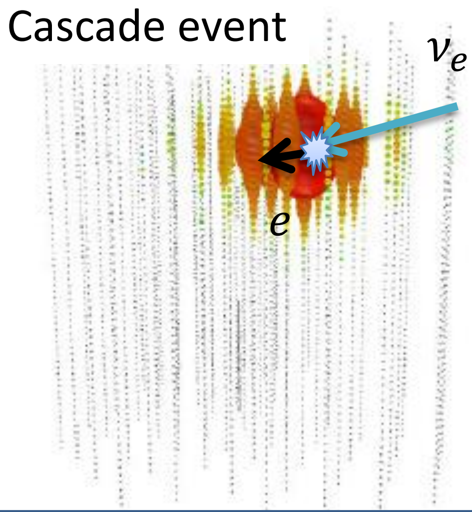
Muon bundles with CORSIKA

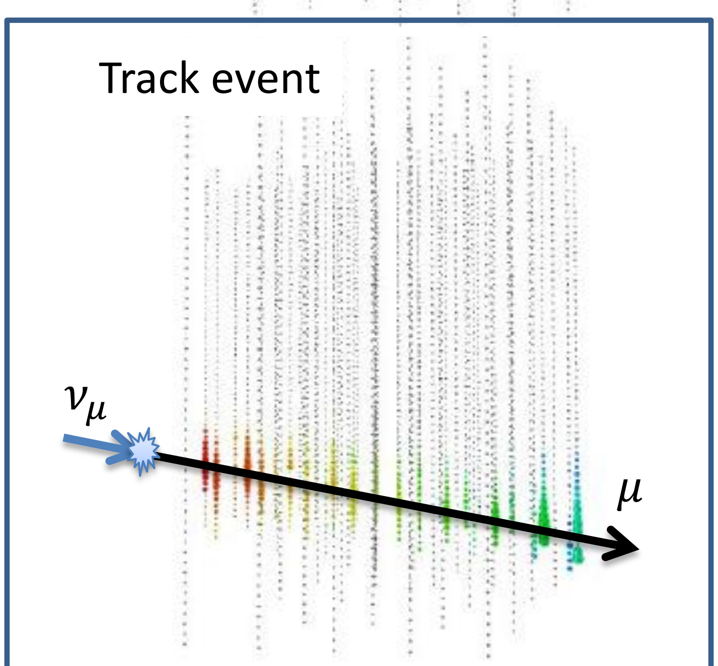
- Input CR spectrum :E_{cr}^{-2}
- 5 component (P, He, N, Al, Fe)
- Weight: Polygonato
- Zenith angle: 0 – 90 deg

Neutrinos with neutrino generator (NuGen)

- Input $\nu_{\mu,e}$ spectrum : E_{ν}^{-2}
- Weight: Honda+GaisserH3a, Enberg
- Zenith angle: 0-360 deg

ν_μ Track 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 $\pm$1 μsec)

Level-2 data (~40Hz)

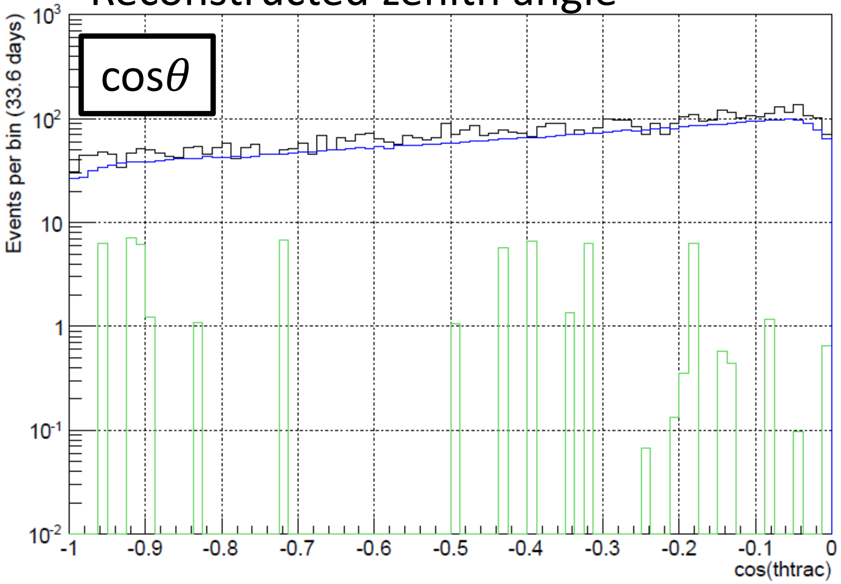
- first angular reconstruction (min quality)
- up-going + large-charge down-going events
- sig/bkg ~ 10^{-3}

Level-3 data (~2mHz)

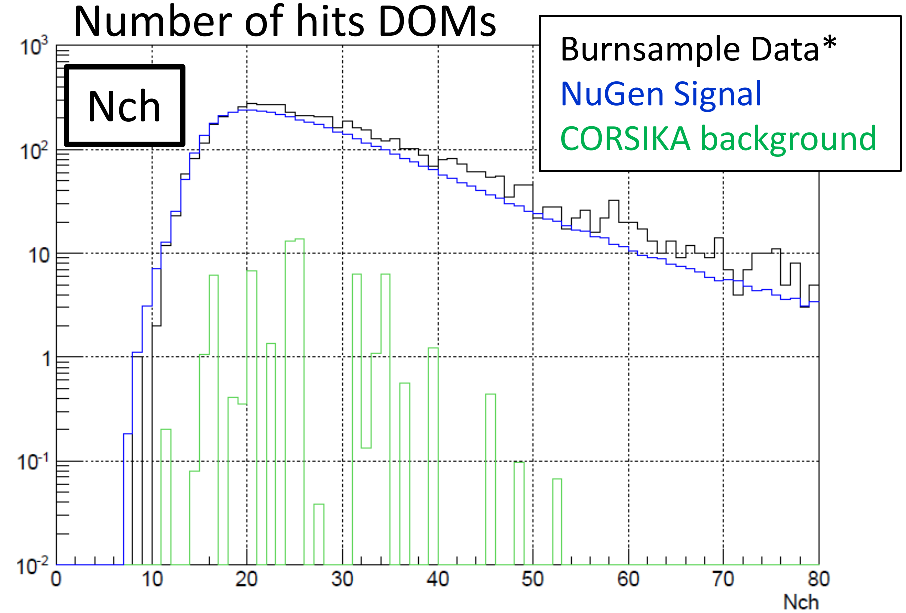
- good angular reconstruction (σ<5deg)
- up-going event only
- bkg CR muon ~1%

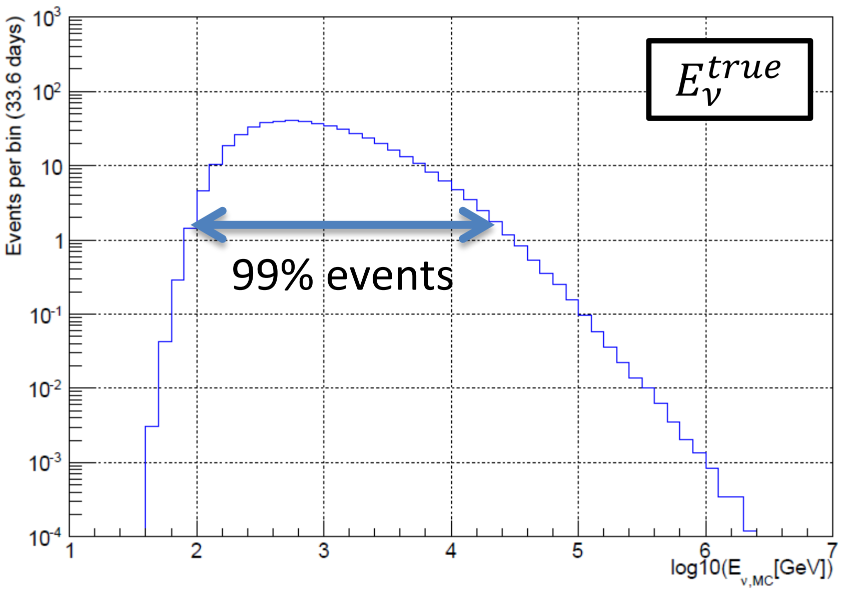
ν_μ Track Event distribution, Level 3 data

Reconstructed zenith angle



Number of hits DOMs

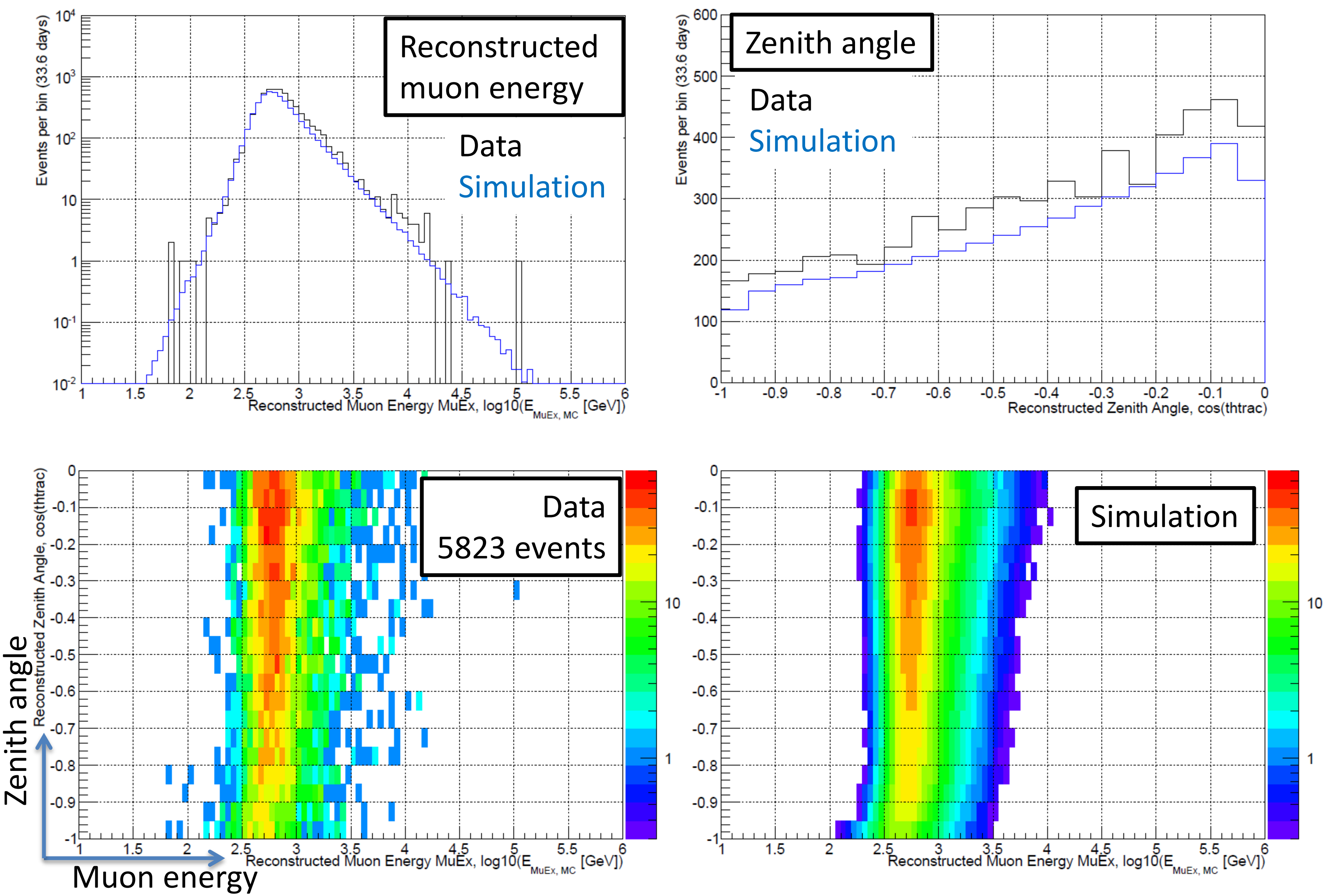




* Burnsample = 10% statistics data

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

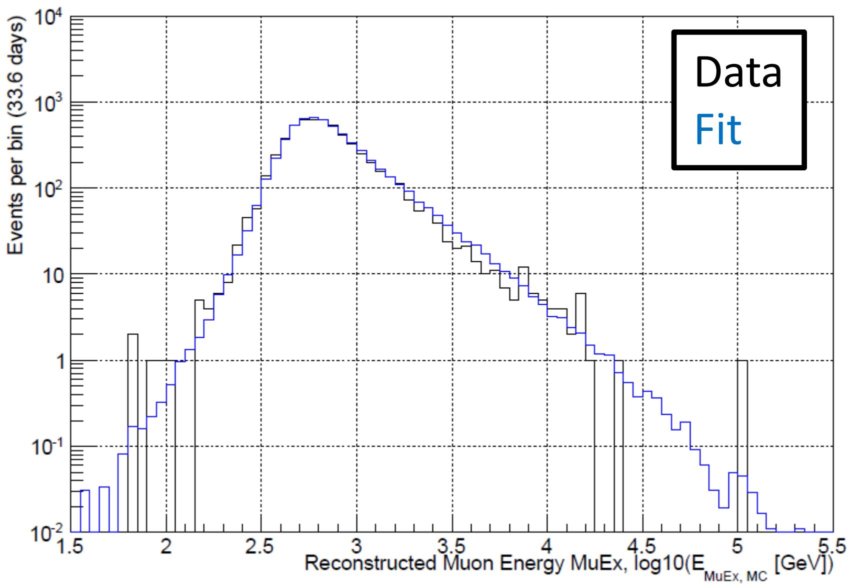
Reconstructed muon energy and zenith angle distribution

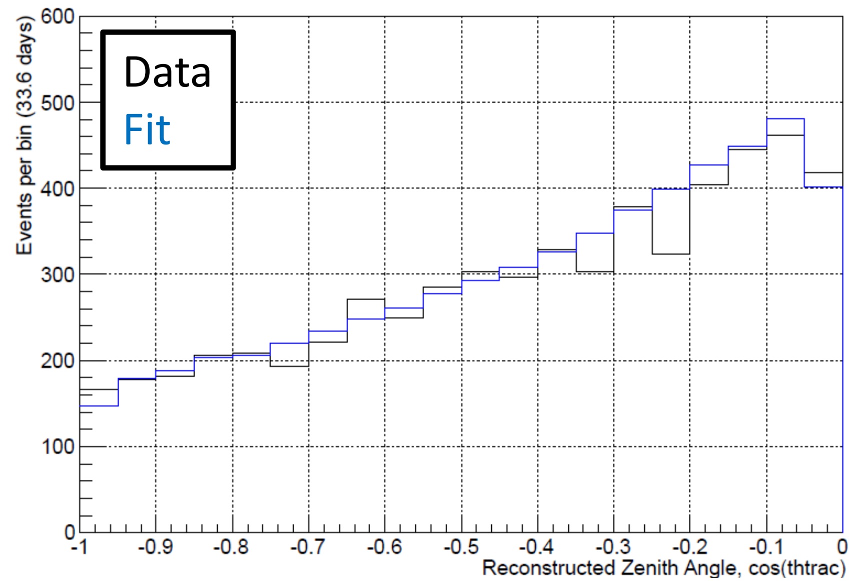


Likelihood fit analysis (ν_μ track)

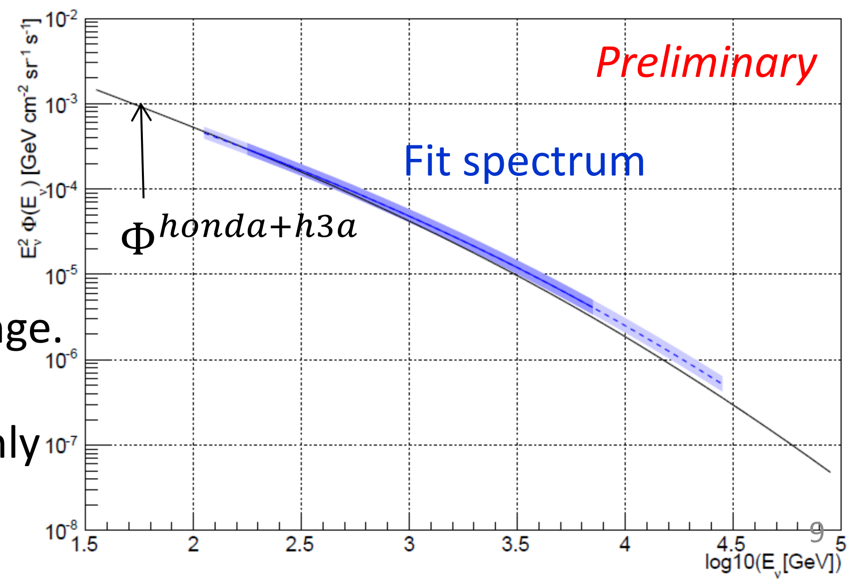
- 2D distribution of reconstructed muon energy and zenith angle for fitting
- Physics parameter
  - 1+α, Deviation from reference conventional flux (Honda+H3a model)
  - $\Delta\gamma$, Change in spectrum slope
  - $R_{K/\pi}$, ratio of spectrum weighted moments to produce K and π (baseline $R_{K/\pi}$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

Preliminary Fit Result (ν_μ track)



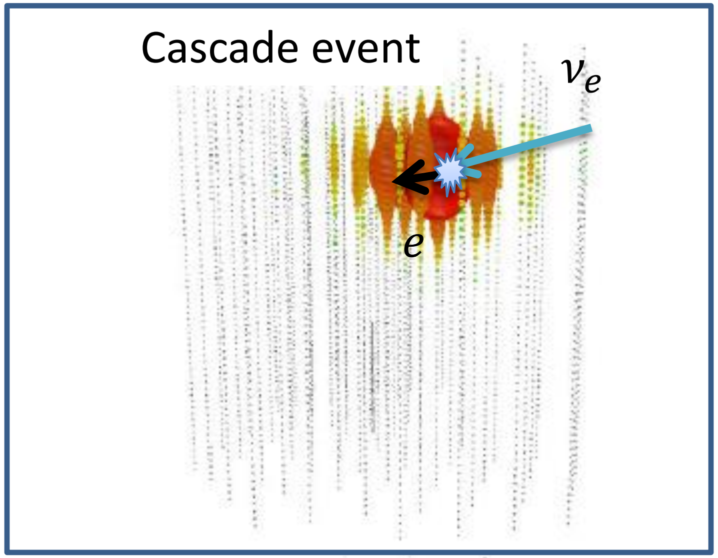


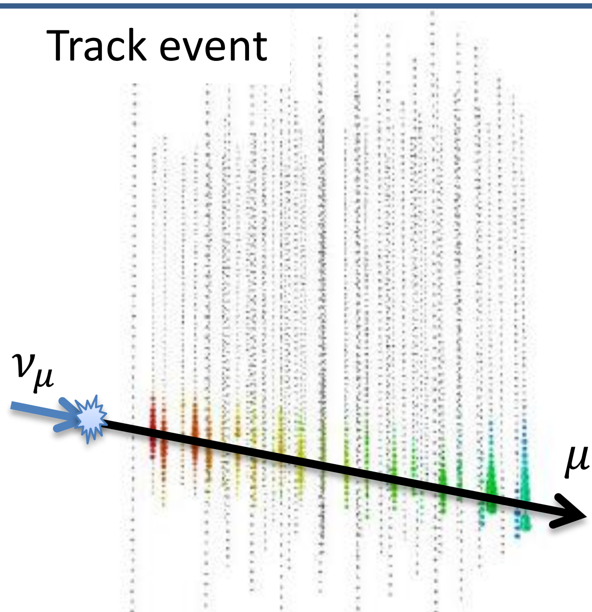
Para-meter	$1+\alpha$	$\Delta\gamma$	$R_{K/\pi}$	$\Delta\varepsilon$
Best Fit Value	1.07 $\pm$0.18	+0.07 $\pm$0.04	+11 $\pm$42%	+5.8 $\pm$0.6%



- 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

ν_e Cascade 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 (~20Hz)

- first cascade reconstruction
- sig/bkg ~ 10^{-6}

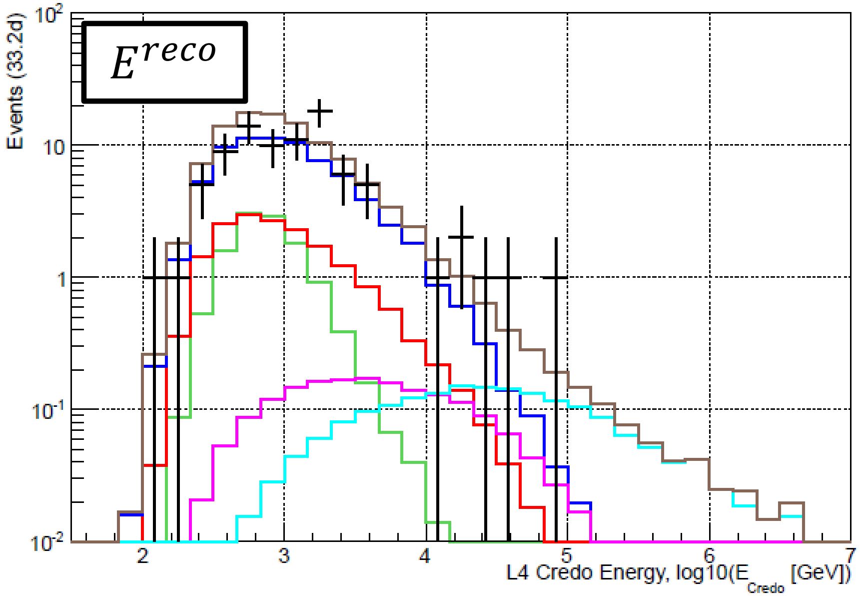
Level-3 data (~0.1Hz)

- containment cut
- sig/bkg ~ 10^{-4}

Level-4 data (~40μHz)

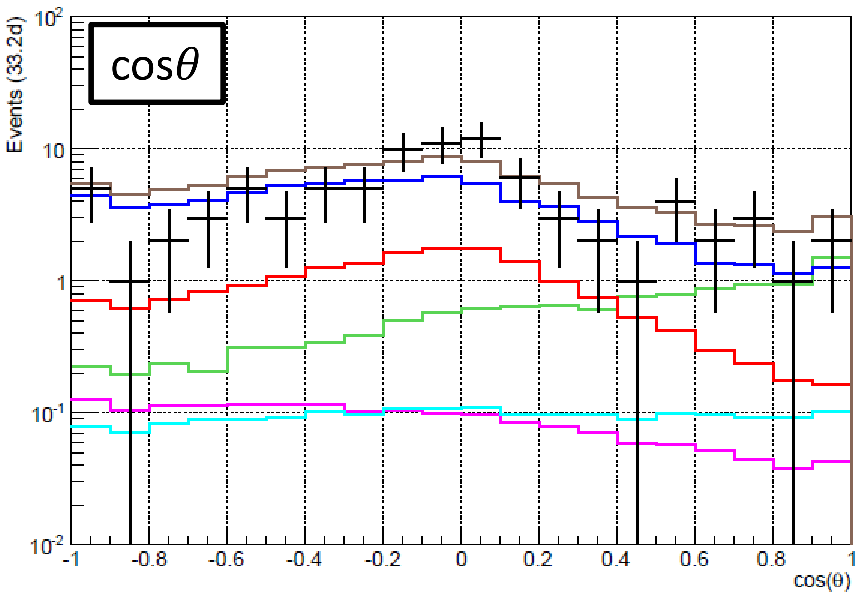
- BDT selection
- Conventional ν_μ (69% [CC 60%, NC 40%])
- **Conventional ν_e (17% [CC 92%, NC 8%])**
- CR muon (11%)
- Prompt+Astro (3%)

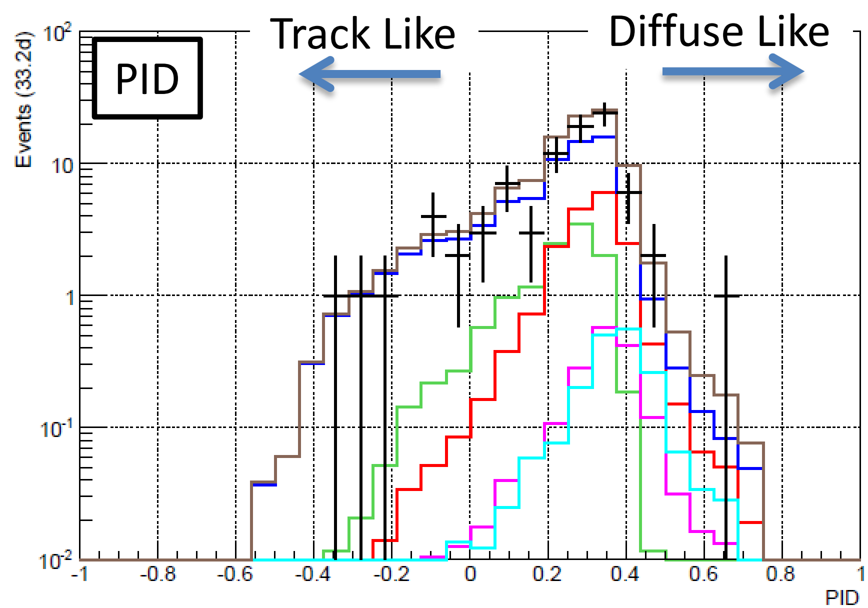
Cascade events



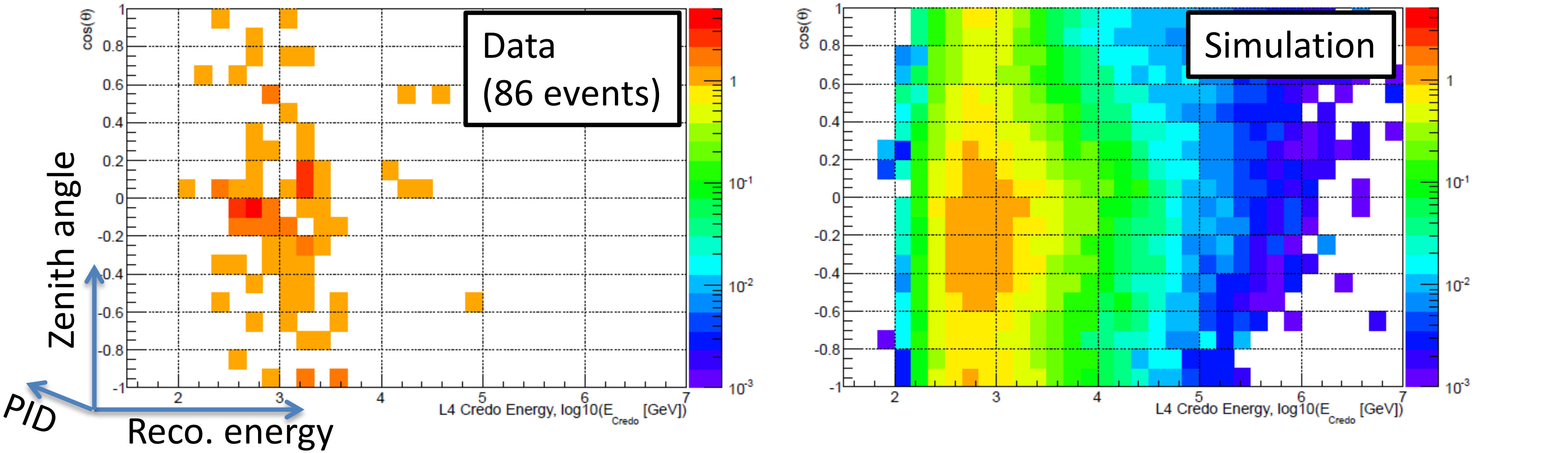
- Data (10% burn sample 86 events)
- Total Simulation
- Conventional ν_μ
- Conventional ν_e
- CR muon
- Prompt $(\nu_\mu+\nu_e)$
- Astrophysical $(\nu_\mu+\nu_e+\nu_\tau)$

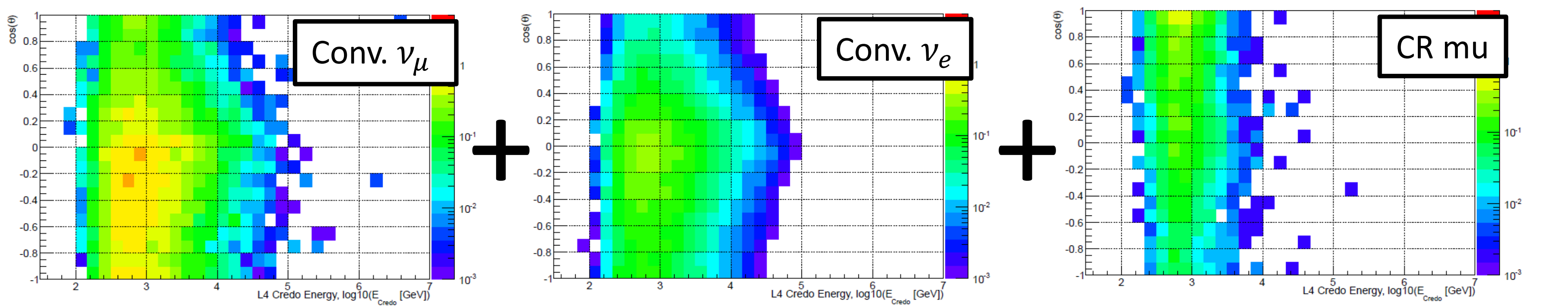
Baseline distribution: expected from Honda+H3a, ERS, and $10^{-8}E^{-2}$ astrophysical

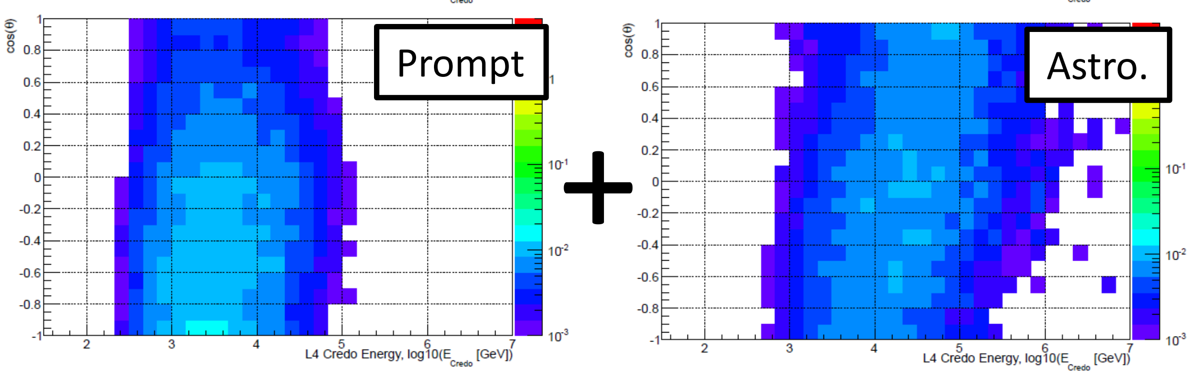




Likelihood fit in 3D space (Cascade)



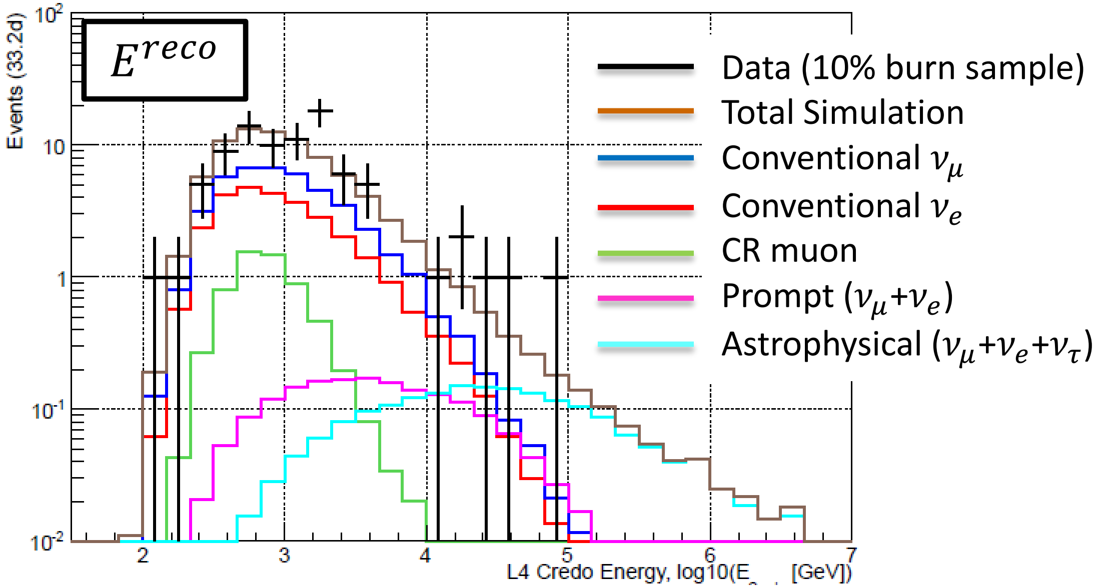




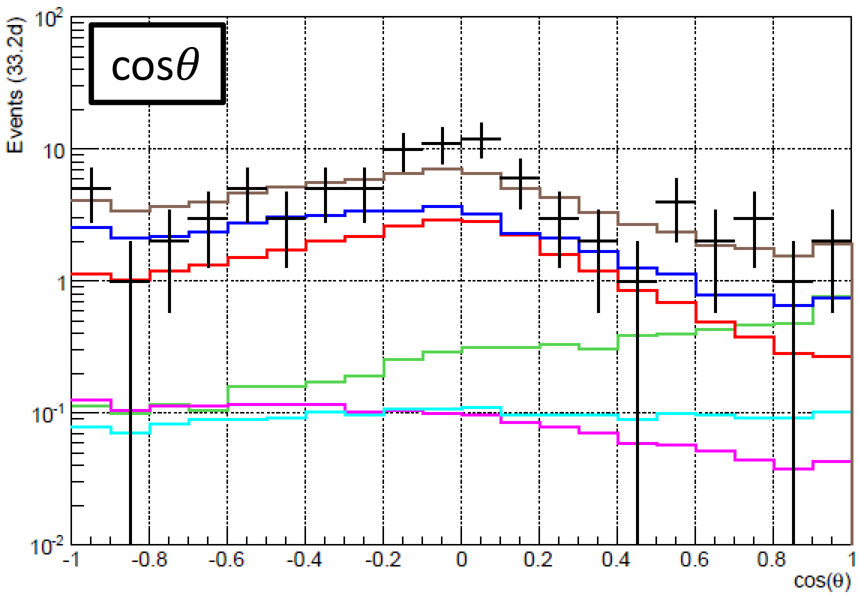
Simply determine
three normalization parameters

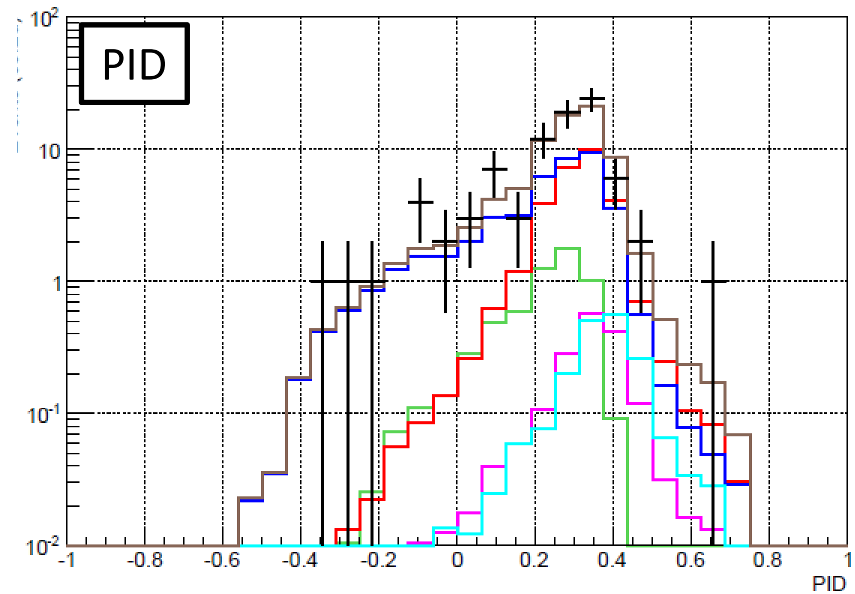
$$\phi = C_e^{conv} \cdot \phi_e^{conv} + C_\mu^{conv} \cdot \phi_\mu^{conv} + C_{cr} \cdot \phi_{cr} + \phi_{prom} + \phi_{astro}$$

Preliminary Fit Result (Cascade)

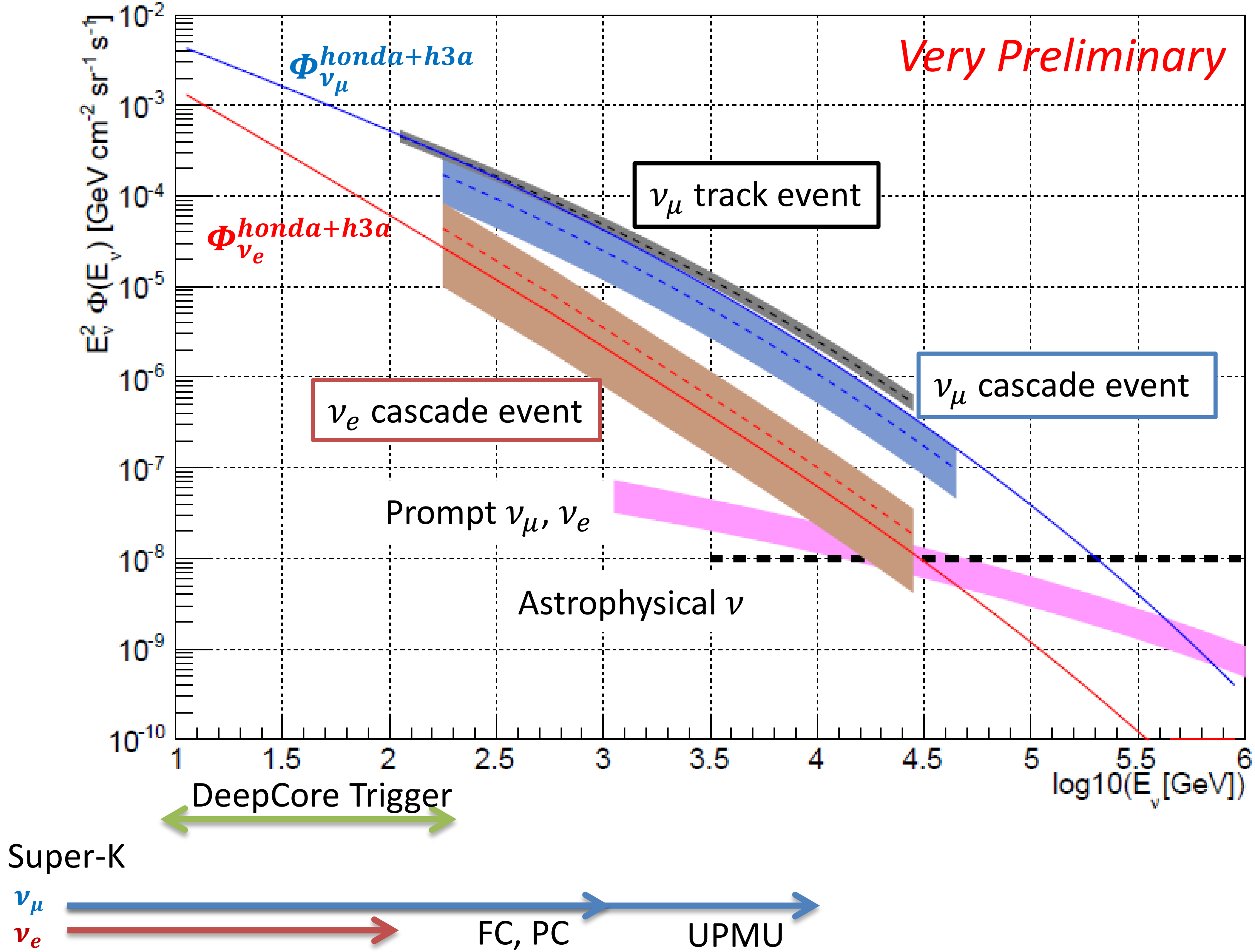


Norm. factor	Fit value
C_μ^{conv}	$0.59^{+0.40}_{-0.30}$ x H3a
C_e^{conv}	$1.62^{+1.48}_{-1.25}$ x H3a
C_{cr}	$0.50^{+1.27}_{-0.61}$ (5.8 events)





Results



$E_\nu^2\ \Phi(E_\nu)$ [GeV cm^{-2} sr^{-1} s^{-1}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
log10(E_ν[GeV])
Very Preliminary
$\Phi_{\nu_\mu}^{honda+h3a}$
$\Phi_{\nu_e}^{honda+h3a}$
ν_μ track event
ν_μ cascade event
ν_e cascade event
Prompt ν_μ, ν_e
Astrophysical ν
DeepCore Trigger
Super-K
ν_μ
ν_e
FC, PC
UPMU

Summary

- ν_μ track events and $\nu_\mu + \nu_e$ cascade events have been selected from the first year of the completed IceCube data
- Applied preliminary likelihood fit analysis
  - ν_μ track events
    - Flux normalization : 1.07$\pm$0.18 x (Honda+H3a)
    - Spectrum index : +0.07$\pm$0.04 flatter
    - $R_{K/\pi}$: +11$\pm$42% from baseline
  - Cascade ($\nu_\mu$and ν_e) events
    - Very preliminary, $\Delta\gamma$ and $R_{K/\pi}$ are not implemented yet
    - Flux normalization of ν_μ: $0.59^{+0.40}_{-0.30}$ x (Honda+H3a)
    - Flux normalization of ν_e:$1.62^{+1.48}_{-1.25}$x (Honda+H3a)
      more K contribution?

Outlook

- 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 IceCube/DeepCore trigger
  - to extend energy (E_{ν}^{min}: 100GeV->10GeV)
  - to make overlap with Super-K energy range