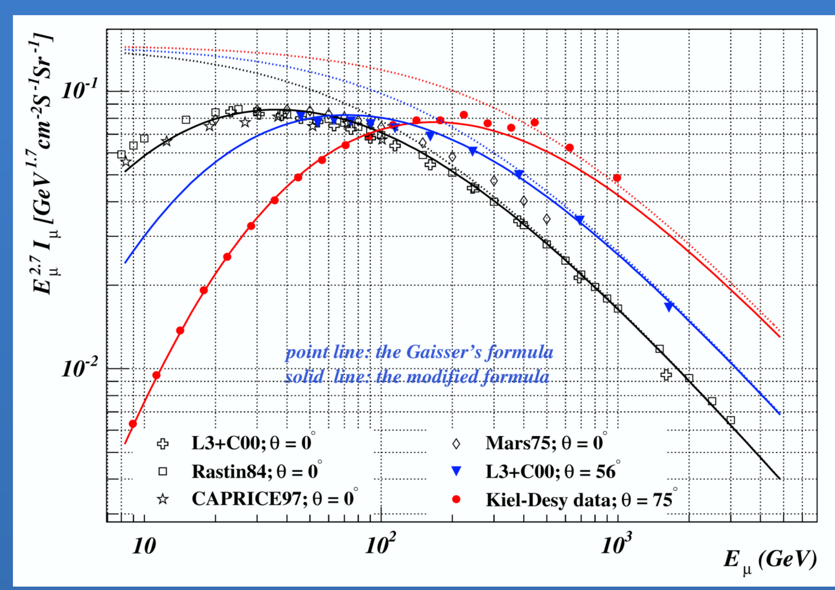
Underground Muon Flux in Daya Bay and JUNO experiments

Jilei Xu from IHEP
on behalf of the Daya Bay and JUNO Collaboration

Muon-induced background s are the main backgrounds of the Daya Bay experiment and are also critical backgrounds for JUNO. These backgrounds can be estimated by the muon flux at each experimental site, which is simulated using MUSIC, the Daya Bay mountain profile and a modified Gaisser formula at sea level. The underground muon fluxes were measured by different Daya Bay detectors, allowing cross checks of the measurements. The simulation results are validated by Daya Bay data. Based on the Daya Bay results and the simulation method, the muon flux of the JUNO experiment at minus 700 meter underground is obtained by using the JUNO mountain profile. This result could be used for JUNO detector design and background studies.

1. The Modified Gaisser Formula

The muon flux at sea level usually can be described by the standard Gaisser's formula[1]. The muon flux of deep underground experiments and at polar angles smaller than 70 degrees is well-described by the standard formula. For DayaBay, the mountain is shallow(~100m), so a modified Gaisser formula[2] was developed for Daya Bay.



$$\frac{dI^{\star}}{dE_{\mu}d\cos\theta} = 0.14\left(\frac{E_{\mu}^{*}}{GeV}\right)^{-2.7}\left[\frac{1}{1+\frac{1.1E_{\mu}\cos\theta^{*}}{115GeV}} + \frac{0.054}{1+\frac{1.1E_{\mu}\cos\theta^{*}}{850GeV}}\right]$$

$$\cos\theta^{*} = \sqrt{\frac{(\cos\theta)^{2}+P_{1}^{2}+P_{2}(\cos\theta)^{P_{3}}+P_{4}(\cos\theta)^{P_{5}}}{1+P_{1}^{2}+P_{2}+P_{4}}}$$

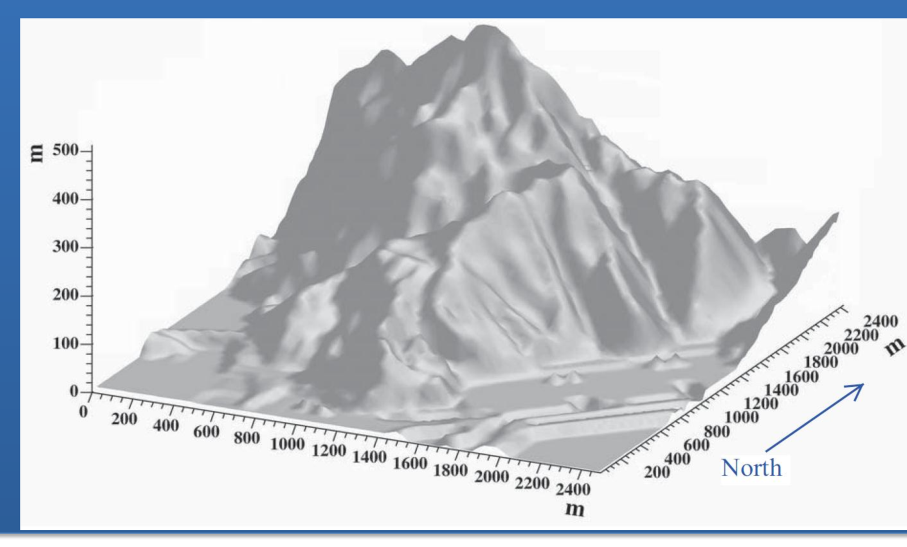
$$E_{\mu}^{*} = E_{\mu}\left(1+\frac{3.64GeV}{E_{\mu}(\cos\theta^{*})^{1.29}}\right)$$

Using the modified angle ϑ and energy *E*, the formula is consistent with experimental results in the low energy range.

2. Simulation

To deploy simulation:

- Generate a statistical sample of sea-level muon events according to a modified standard Gaisser's formula;
- Calculate the slant depth of muons passing through the mountain using an interpolation method based on the digitized data of the mountain;
- Get the underground muon sample and underground muon flux with MUSIC[3].

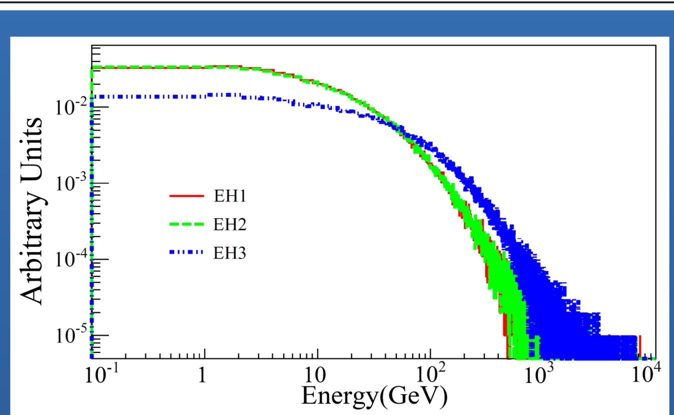


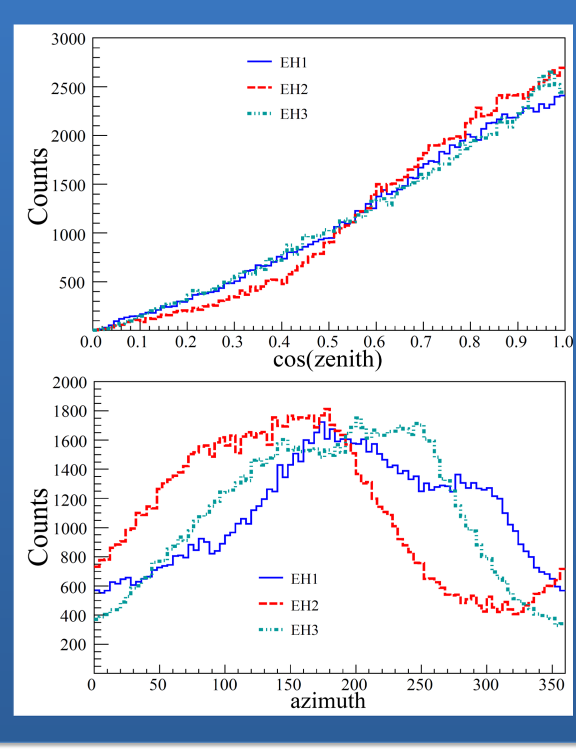
3. Simulation Results

Muon flux and energy at Daya Bay underground halls (MC).

- The average flux in experimental hall (EH) 1 is ~1.27Hz/m^2, and in EH3 is about 0.056Hz/m^2, about 23 times smaller than EH1's.
- The average energy is ~57GeV in EH1 and 137GeV in EH3.

Hall	Overburden m	Overburden mwe	Muon flux Hz/m^2	Average Energy GeV
EH1	93	250	1.27	57
EH2	100	265	0.95	58
EH3	324	860	0.056	137





4. Measured Muon Flux in Daya Bay

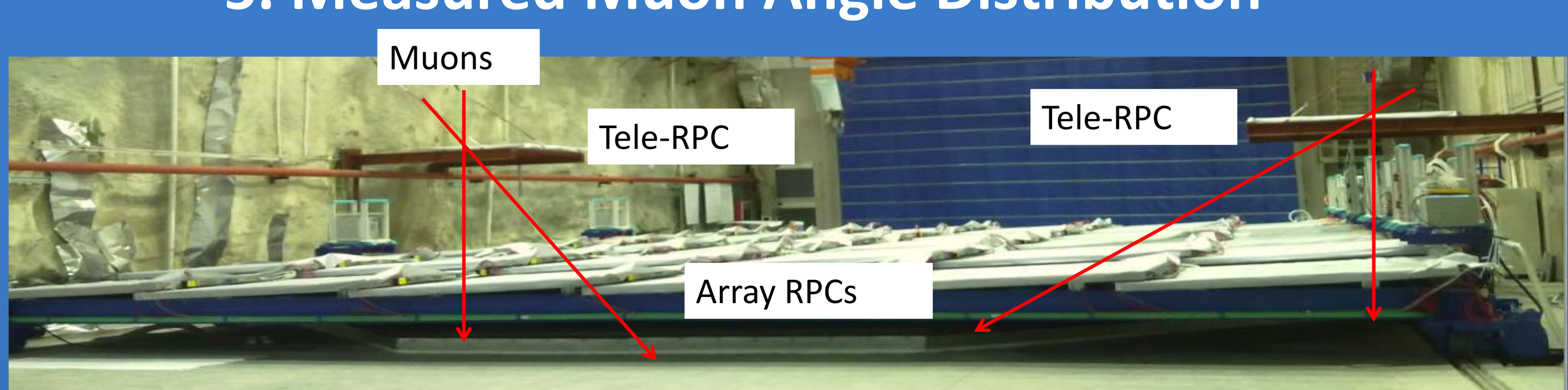
- 4 independent detectors of Daya Bay: antineutrino detector (AD), inner water shield (IWS), out water shield (OWS), resistive plat chamber (RPC). Detectors have different shape and area.
- To cross check each other, simulation is used to translate different results into same coordinate. First we measure the muon flux on each detector top plane. Then it is translated into spherical coordinates, which can be compared with simulation results in part 3.

$$F_{\mu}(\mathrm{Hz/m^2}) = \frac{R_{\mu Trig}(\mathrm{Hz})}{Eff_{Cut}} \times \frac{R_{simOfTop}(\mathrm{num/m^2})}{N_{sim}(\mathrm{num})}$$

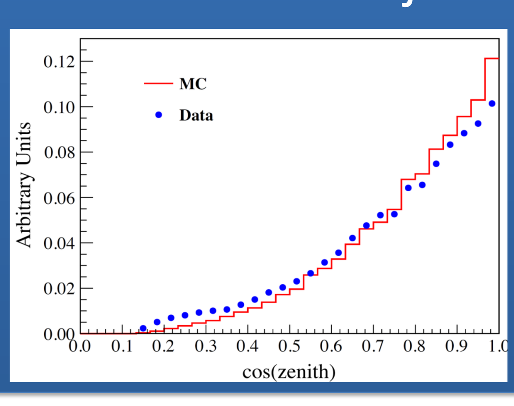
Detector	EH1	EH2	EH3
AD	1.21 ± 0.12	0.87 ± 0.09	0.056 ± 0.006
IWS	1.15 ± 0.12	0.86 ± 0.09	0.055 ± 0.005
OWS	1.12 ± 0.11	0.84 ± 0.08	0.053 ± 0.005
RPC	1.17 ± 0.09	0.87 ± 0.11	0.053 ± 0.006
Average	1.16 ± 0.11	0.86 ± 0.09	0.054 ± 0.006
Simulation	1.27 ± 0.13	0.95 ± 0.10	0.056 ± 0.006

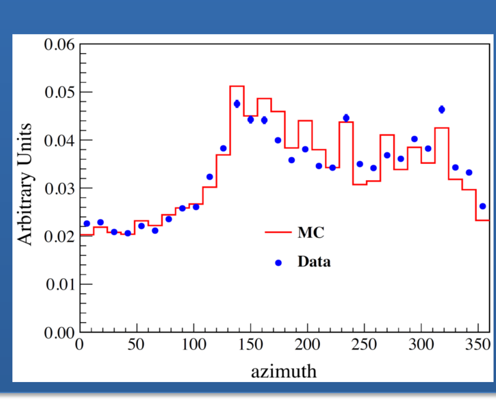
Each detector is consistent with each other, and the average of each detector is also consistent with simulation results.

5. Measured Muon Angle Distribution

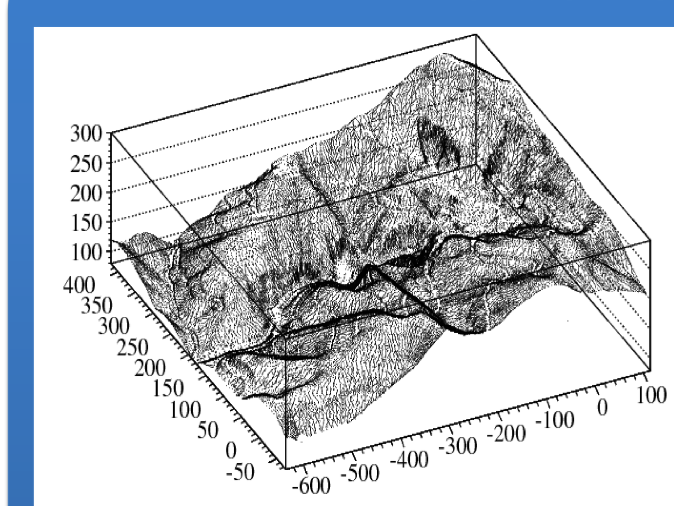


- 2 Telescope-RPC about 2m above bottom array RPC in each hall;
- Muon position resolution of RPC tracking system ~0.1m;
- The combined telescope-RPC and and array RPC system can measure the muon trajectory as shown below.



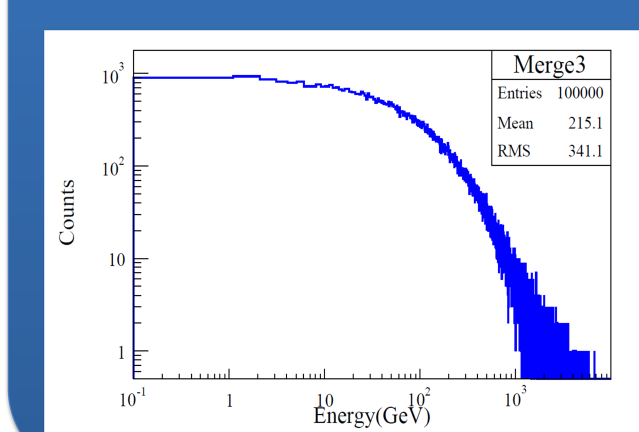


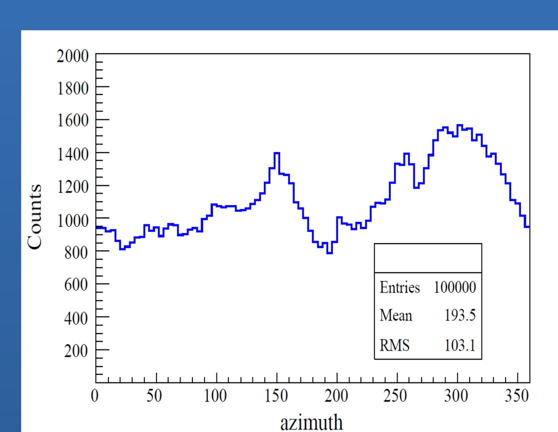
6. JUNO Muon Flux Prediction

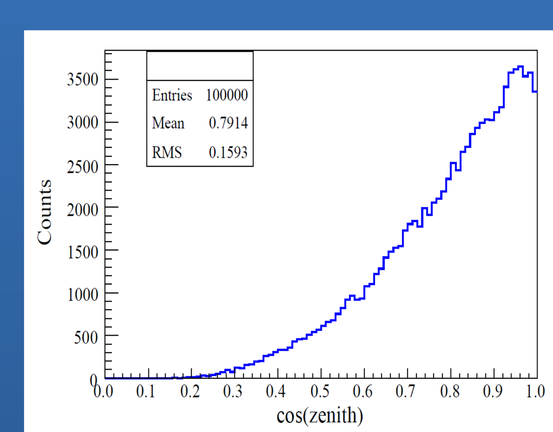


Based on Daya Bay's experience, the muon flux in the JUNO neutrino experiment's underground site was simulated. The Overburden in JUNO is ~748m of rock.

- Muon rate: 0.0030Hz/m^2.
- Average energy: ~215GeV.







Summary

(1) We developed a simulation method based on MUSIC to get the underground muon flux.

(2) The measured results are consistent with simulation results within the uncertainties. The measurements in the different Daya Bay detectors are consistent with each other.

(3) Based on the Daya Bay's experience, the JUNO experiment underground site muon flux has been calculated. The results can be used in the background estimation.

References

[1] T .K. Gasser and T.Stanev, "cosmic rays", review of particle physics, J. Phys. G: Nucl. Part. Phys. 33 (2006) 1

[2] Mengyun Guan, http://www.escholarship.org/uc/item/6jm8g76d

[3] V.A. Kudryavtsev, Computer Physics Communications, 180 (2009) 339-346; P. Antonioli, et al., Astroparticle Physics, 7 (1997) 357-368

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