Method to measure muon content of extensive air showers with LHAASO KM2A-WCDA synergy

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Muon Selection Method

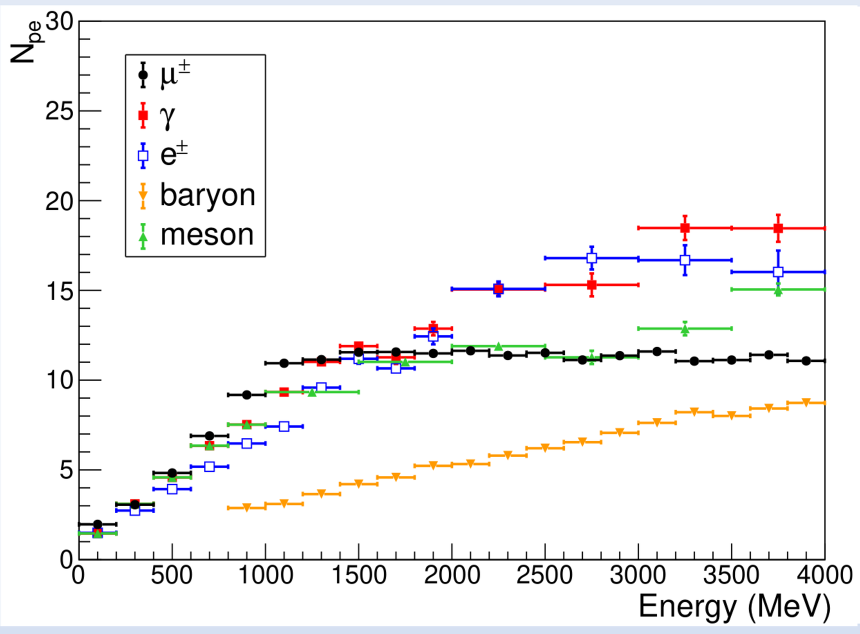


Figure 1: Average response of a WCD with an 8-inch PMT to different EAS secondaries.

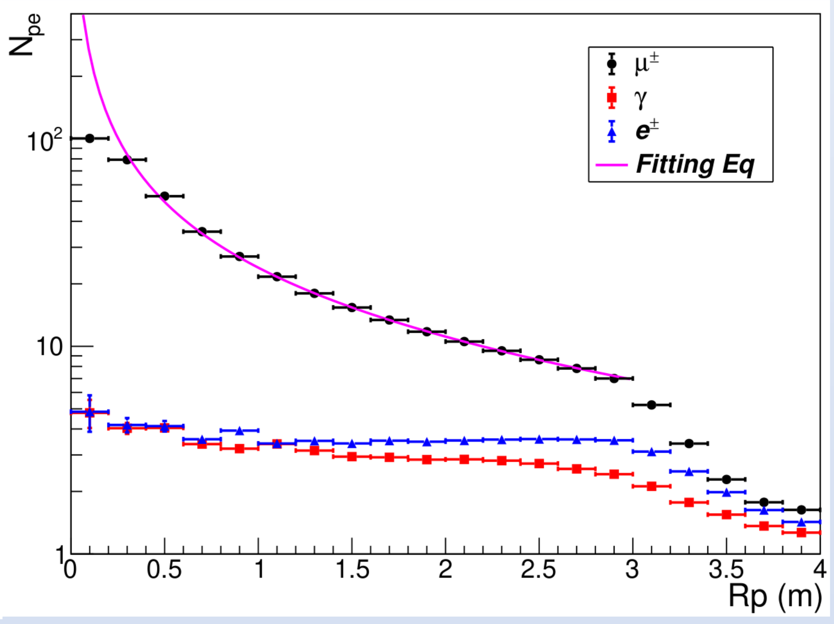


Figure 2: The N_{pe} of EAS muons as a function of the impact parameter, R_p, from Monte Carlo simulation.

- ***Introduction***

1. ***A finite KM2A-MD array coverage ratio*** may limit the muon measurement[1,2];
2. To utilize an unburied water Cherenkov detector, WCDA as muon detector!
3. But WCDA are sensitive to ***both electromagnetic and muon contents*** of EAS[2].

- ***WCD response to EM particles ($e^{\pm},\gamma$)***
  - N_{pe} has a linear correlation with incident energy;
  - $e^{\pm}$ yields about 30% less than γ;
- ***WCD response to Muons***
  - Muons (> 1 GeV) can penetrate through the WCD cell, N_{pe} are ***dependent of the incident muon trajectory***.

Fitting Eq: $N_{pe} \propto \frac{e^{-R_p/(sin\theta_c\cdot\lambda_{att})}}{R_p}$

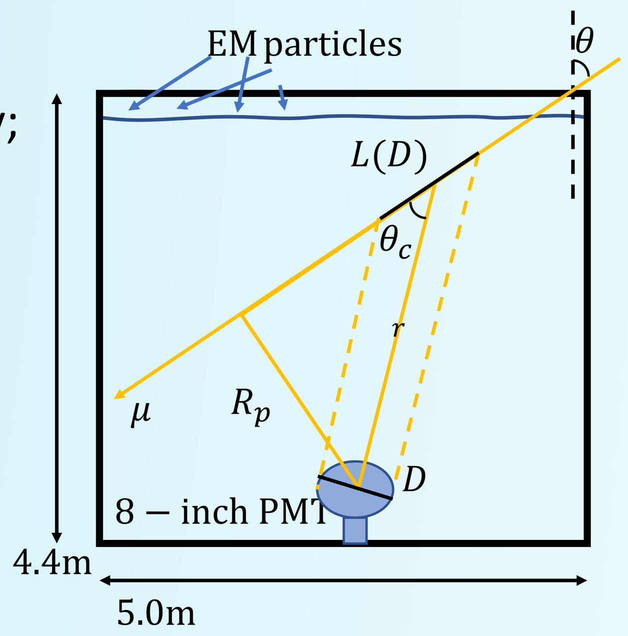


Figure 3: The schematic of a muon trajectory which sweeps a PMT.

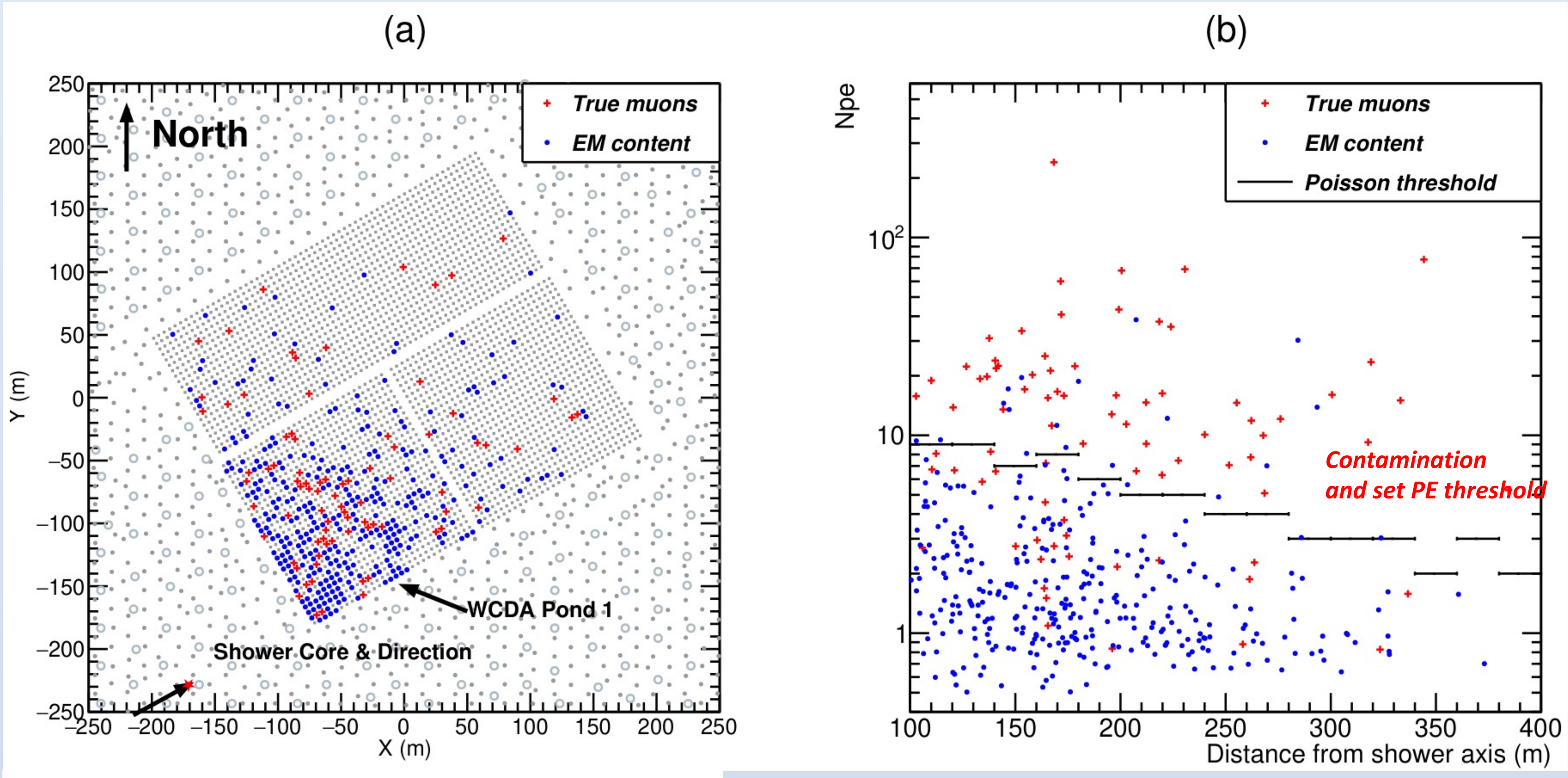
- ***Muon Selection in "Low triggered ratio" in WCDA***

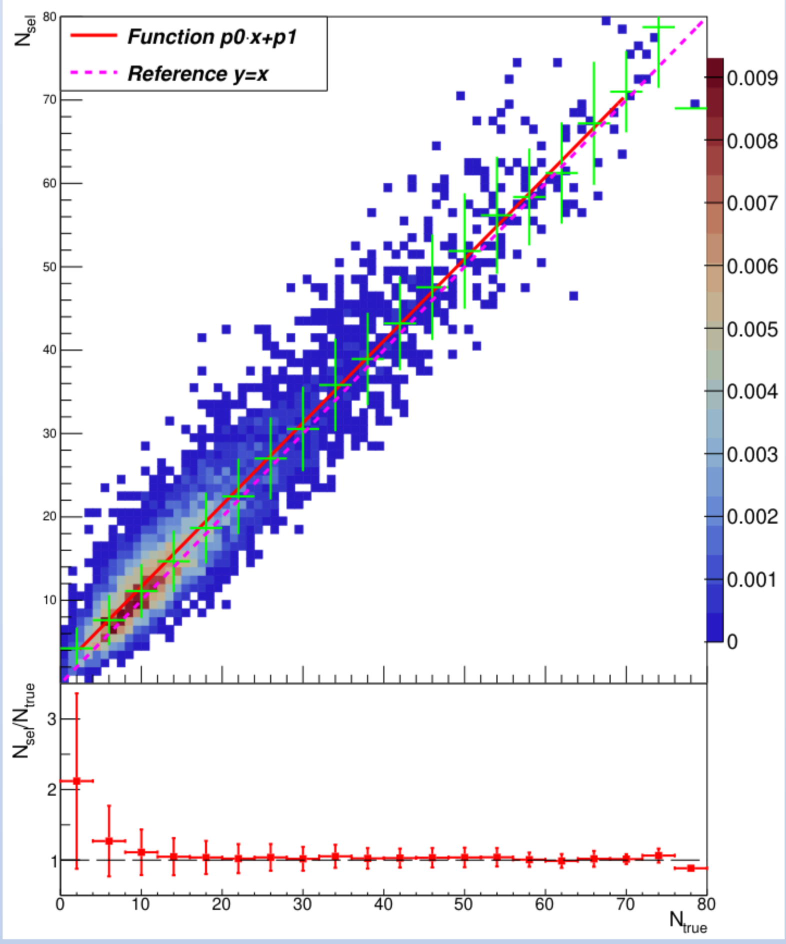
1. Low EM punch-through contaminations (r_M);
2. Muon signal is greater than EM signal;
3. Pick out the signal that meet certain criteria.

- ***Muon selection criteria basic assumptions***

1. As known from the NKG function, the number of the secondary particles of EAS fall ***in the annulus with equal probability***.
2. The Npe that a WCD unit collects from electromagnetic components conforms approximately to ***a Poisson distribution***.
3. Every WCD collects secondary particles ***independently.****

Monte Carlo Result





PE threshold	Detection Efficiency	Selection Purity	A_{eff} (m^2)
> 2.5 PEs	79.2%	62.3%	39,570
> 5.0 PEs	75.3%	68.2%	37,650
> 7.5 PEs	63.5%	74.9%	31,740
> 10.0 PEs	49.8%	77.5%	24,910

Figure 4: A simulated shower event with primary energy of 72.81 TeV. (a) The trigger pattern of WCDA hits after the noise-filtering process. (b) N_{pe} for WCD hits as a function of the distance from the shower axis.

Figure 5: the distribution of N_{sel} and N_{true} with > 5.0 PEs in simulated primary proton events.

Table 1: The detection efficiency, selection purity and effective coverage area of WCDA as muon counter.

- ***Muon Selection Strategy***

1. Project the WCDA hits to the simulated shower front;
2. Our interested region is the ***radius from the shower axis 180m - 380m***;
3. Calculated the PE threshold according to the muon selection criteria based ***the basic assumptions***;
4. Apply additional PE threshold to filter muon hits with small signal.

- ***Comparison of muon content selected by this method and true value***

N_{sel}→ The number of WCD selected as μ candidate hits;
N_{true}→ The number of WCD with any μ contribution from μ

1. A strong linear relationship with slope = 0.98;
2. The relative difference shrinks with N_{true} grows;
3. Achieved purity 68.2%, efficiency 75.3% with PE threshold > 5.0 PEs;
4. Gain an extra muon-counter coverage area 37,650m^2 theoretically.

Experiment Result

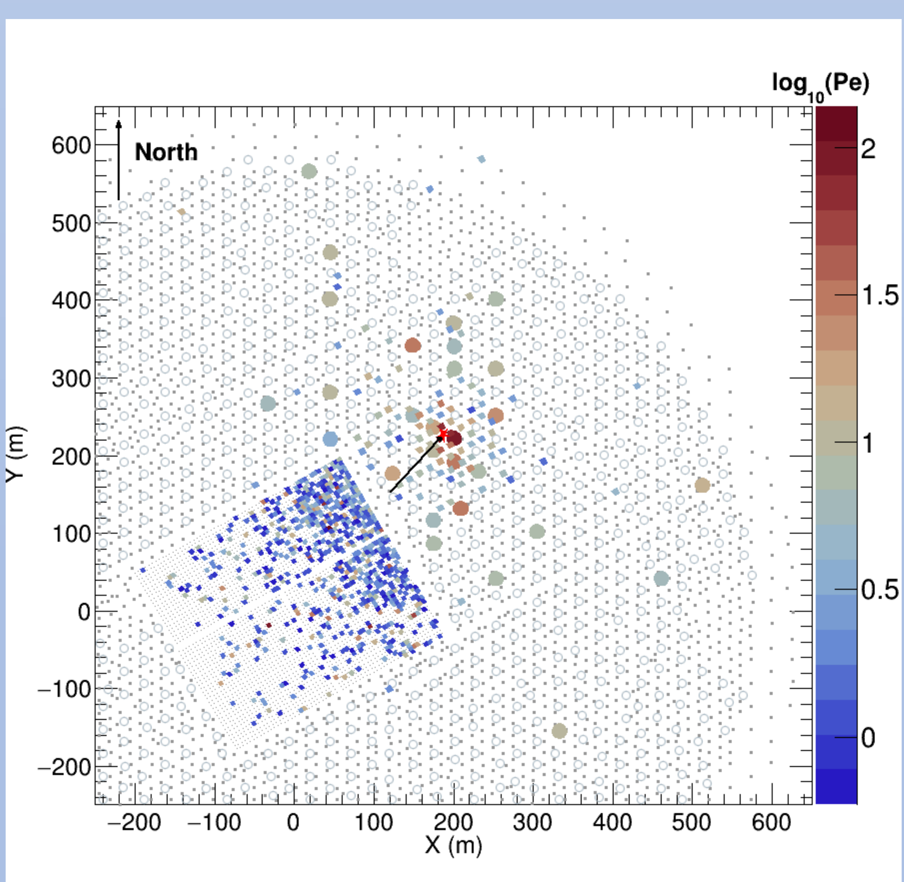


Figure 6: An observed shower event with reconstructed primary energy of 45.99 TeV.

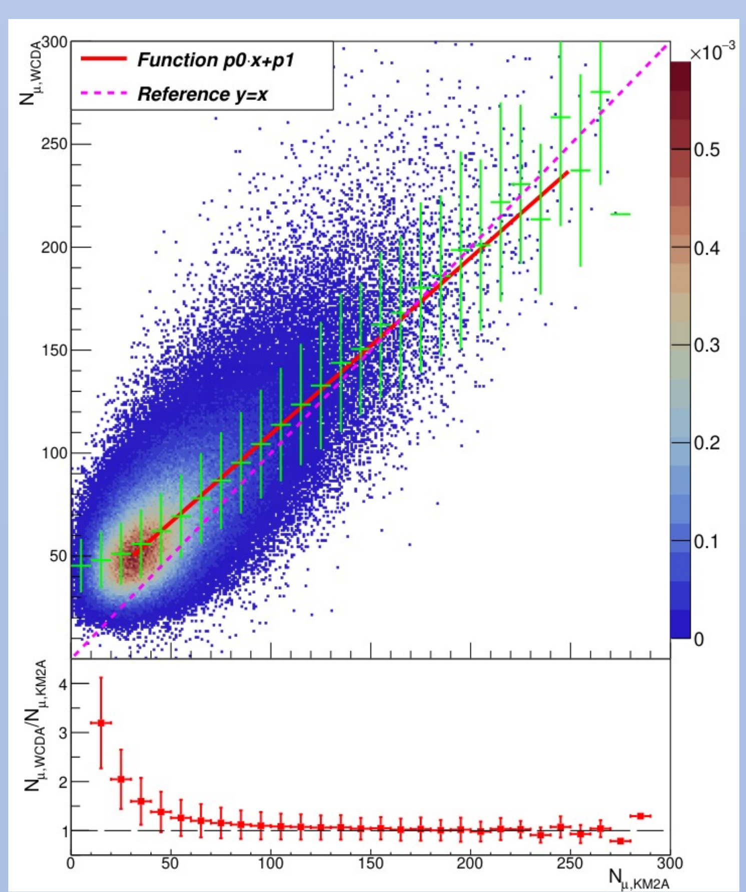


Figure 7: The distribution of the number of muons measured by KM2A-MD and WCDA with > 5 Pes in EXP.

- ***An EAS could be measured by LHAASO with KM2A-WCDA Synergy simultaneously***
- ***Comparison of muon content measured by KM2A and WCDA***

$N_{\mu,WCDA}$→ The number of WCD selected as μ candidate hits;
$N_{\mu,KM2A}$→The inferred number of WCD with any μ contribution based on the MD array measurement.

1. A moderate linear relationship with slope = 0.86;
2. Inferior to KM2A-MD as muon counter when $N_{\mu,KM2A}$>150;
3. Approximately equivalent to KM2A-MD when $N_{\mu,KM2A}$<50;
4. ***$N_{\mu,WCDA}$>0, when $N_{\mu,KM2A}$ = 0; (may help the muon-free event in KM2A !)***
5. The relative difference shrinks with $N_{\mu,KM2A}$ grows.

Conclusion

1. ***Achieve muon content measurement event by event rather in statistics***;
2. The WCDA simulation investigated the theoretical efficiency and purity performance (***ρ_S =68.2%, η_S =75.3% @ > 5.0 PEs***), and A_{eff} achieves 37,650 m^2, which ***endorsed the feasibility and the performance*** of this muon selection method;
3. ***A strong linear relationship*** (N_{sel} ***vs.*** N_{true}) confirms that this method could select muon content in EAS effectively in simulation data; ***A moderate linear relationship*** ($N_{\mu,WCDA}$ ***vs.*** $N_{\mu,KM2A}$) confirms the basic hypothesis of muon selection rule in WCDA in experiment data;
4. The performance of this muon selection method was verified for muon-poor showers, and the additional muon sensitivity of WCDA enhanced the gamma/hadron separation. Please refer to the forthcoming paper.

Reference

1. Z. Cao, D. della Volpe, S. Liu, X. Bi, Y. Chen, B. Piazzoli, L. Feng, H. Jia, Z. Li, X. Ma, et al., The Large High Altitude Air Shower Observatory (LHAASO) Science Book (2021 Edition), arXiv preprint arXiv:1905.02773 (2019)
2. C. Li, H. He, G. Xiao, S. Feng, X. Zuo, L. Wang, Y. Zhang, X. Li, N. Cheng, S.-Z. Chen, et al., Measurement of muonic and electromagnetic components in cosmic ray air showers using LHAASO-KM2A prototype array, Physical Review D 98 (4) (2018) 042001.