Monte Carlo simulation of the muon flux in DEAP-3600

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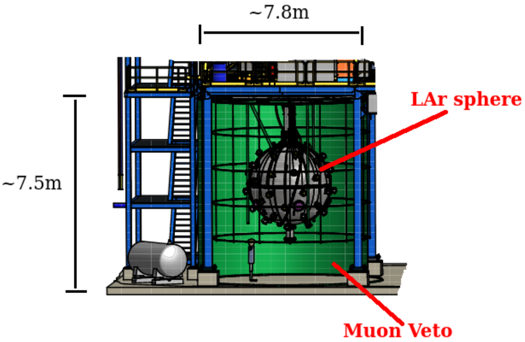
Canadian Astro-Particle Physics Summer Student Talk Competition

Cagliari state university

15-16/08/2022

Placed at SNOLAB
2 km underground ($\sim$ 6 km.w.e.)
flat overburden
Main goal: search for WIMP!

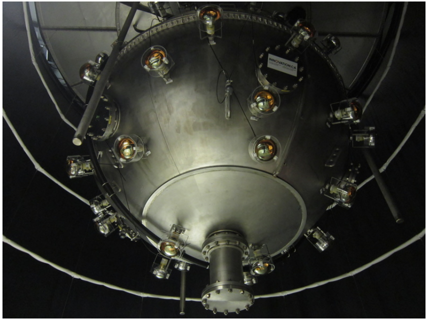
Detector based on:
- Acrylic sphere filled with $\sim$3.3 Ton of Liquid Ar (LAr)
- tank filled with $\sim$300 Ton of pure water for muon rej.

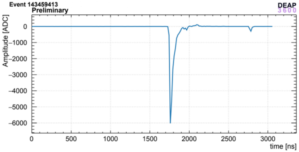


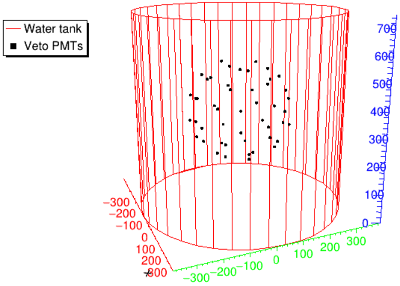
DEAP collaboration. *Design and construction of the DEAP-3600 dark matter detector.* URL: https://doi.org/10.1016%2Fj.astropartphys.2018.09.006

Consisting of 48 veto PMTs placed outside sphere structure to detect cherenkov radiation

Rejection thanks to coincidence events in MV and LAr







[axes are in cm]

Cosmogenic muons

- cosmic rays interaction with atmosphere produce μ

- μ can reach high depths

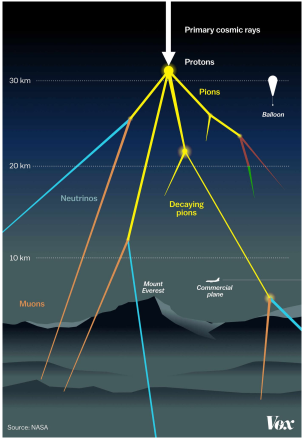
- μ can produce n or cosmogenic radioisotopes after interacting with rocks

$\Rightarrow$ backgrounds for WIMP search!

Until now only the SNO experiment has performed a measurement of muon flux at SNOLAB

$$h_{SNOLAB} = 6.011 \text{ km.w.e.}$$

$$\Phi_{\mu}^{SNO} = (3.31 \pm 0.01\ stat\ \pm 0.09\ syst) \cdot 10^{-10}\ \mu/\text{s}/\text{cm}^2$$



SNO collaboration . *Measurement of the Cosmic Ray and Neutrino-Induced Muon Flux at the Sudbury Neutrino Observatory.* URL: *https://doi.org/10.1103%2Fphysrevd.80.012001*

DEAP-3600 is performing an independent measurement!

$\Downarrow$

Starting point:

Mei et Hime effective model of $I(\theta, h)$

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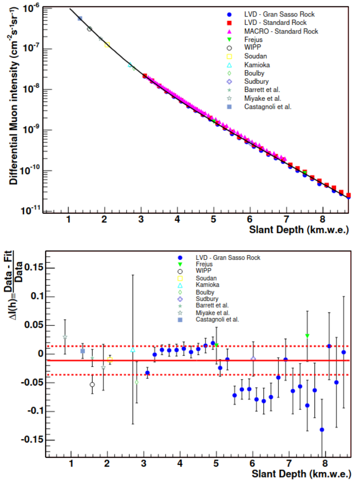
$$\frac{1}{cos(\theta)} \cdot \left(I_1 \cdot e^{-h/\lambda_1/cos(\theta)} + I_2 \cdot e^{-h/\lambda_2/cos(\theta)}\right)$$

valid for flat overburdens!



D.-M. Mei and A. Hime. 'Muon-induced background study for underground laboratories'. In: 658 Physical Review D 73.5 (Mar. 2006)

Flux and rate are related by:

$$R_\mu = A_{eff} \cdot \Phi_\mu$$

where $A_{eff} \neq A_{cylinder}$ as...

...muon angular distribution is not flat!

$$I(\theta, h) = \frac{1}{cos(\theta)} \cdot \left(I_1 \cdot e^{-h/\lambda_1/cos(\theta)} + I_2 \cdot e^{-h/\lambda_2/cos(\theta)}\right)$$

Aim of this work: evaluate expected rate in DEAP using:

$\Phi_\mu^{SNO} = 3.31 \cdot 10^{-10} \mu/\mathrm{s}/\mathrm{cm}^2$ and A_{eff}

But how can we estimate A_{eff}?

Coordinates:
- center of MV bottom surf ⇒ (0,0,0)

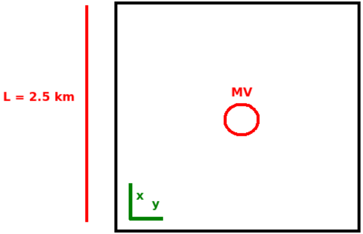
Muon starting point:
- $z_0 = 40$ m $\gg h_{MV} \sim 7.5$ m
- x_0 y_0 chosen random in -0.5 L $\leq x, y \leq$ 0.5 L
L$\gg r_{MV} \sim 3.9$ m ⇒ avoid systematics!

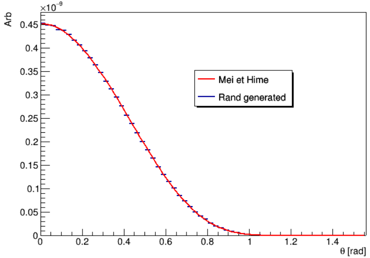
Muon kinematics:
- θ from Mei et Hime
- cylindric symm ⇒ $0 \leq \phi < 2\pi$ with flat distr

⇓

$$A_{eff} = L^2 \cdot \varepsilon$$

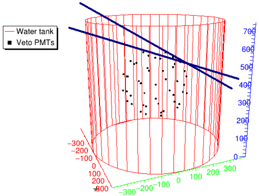
where $\varepsilon = \frac{N_{enter}}{N_{gen}}$ ⇒ need to estimate it!



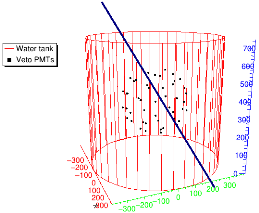


Three different cases!

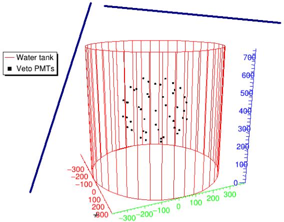
at least one hit on lateral surface



hit on upper and lower surfaces



missed



The μ trajectory and their discrimination

How can we understand if a μ is entering in the MV?

$$\vec{r}(t) = \begin{cases} x(t) = x_0 + t \cdot sin(\theta)cos(\phi) \\ y(t) = y_0 + t \cdot sin(\theta)sin(\phi) \\ z(t) = z_0 - t \cdot cos(\theta) \end{cases}$$

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μ position parameterized as a function of t!

μ are discriminated with

$$x^2(t) + y^2(t) = r^2_{DEAP}$$

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$$\frac{\Delta}{4} = r^2_{DEAP} - (x_0 \cdot sin(\phi) - y_0 \cdot cos(\phi))^2$$

$$\Downarrow$$

- if $\frac{\Delta}{4} < 0 \Rightarrow$ muon discarded
- else $\Rightarrow t_{\pm}$ solutions of the equation

$$t_{\pm} = \frac{-(\ x_0 cos(\phi) + y_0 sin(\phi)\ ) \pm \sqrt{\Delta/4}}{sin(\theta)}$$

The height is checked for both $t_\pm$:

$$0 \leq z(t_\pm) \leq h_{MV}$$

if at least once this is satisfied

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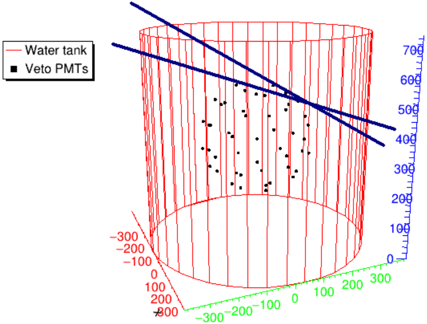
muon accepted!



Might happen that the μ crosses the upper and lower surfaces

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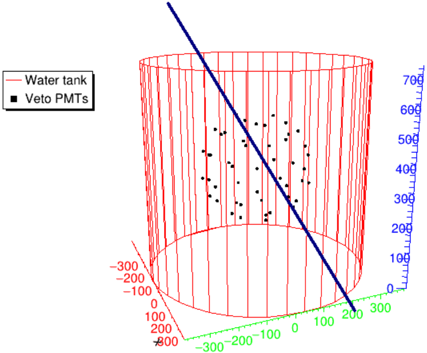
this results in $z(t_\pm)$ outside the limits!

Counted checking:

$$z(t_h) = h_{MV} \Rightarrow t_h = \frac{z_0 - h_{MV}}{cos(\theta)}$$

$$\text{if } x^2(t_h) + y^2(t_h) \leq r^2_{MV}$$

the μ is accepted since it is on the MV upper surface



Results

From 10^8 generated μ 1020 entered in the MV

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$$\varepsilon = \frac{N_{enter}}{N_{gen}} = (1.02 \pm 0.03) \cdot 10^{-5}$$

(error calculated with binomial approach $\sqrt{\frac{\varepsilon\cdot(1-\varepsilon)}{N_{gen}}}$)

$$\Downarrow$$

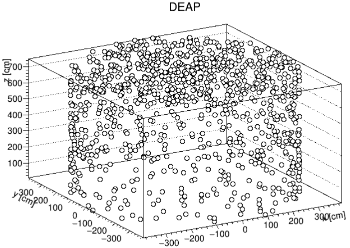
$$A_{eff} = L^2 \cdot frac = (63.5 \pm 1.9)\ \text{m}^2$$

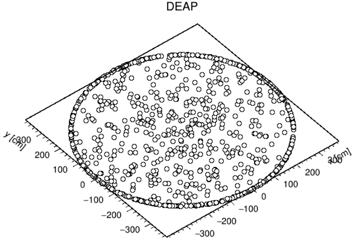
$$\Downarrow$$

Using

$$\Phi_{\mu}^{SNO} = (3.31 \pm 0.01\ stat\ \pm 0.09\ syst) \cdot 10^{-10}\ \mu/\text{s}/\text{cm}^2$$

$$R_{DEAP} = (18.2 \pm 0.5\ stat\ \pm 0.5\ syst)\mu/\text{day}$$





Recap and conclusions

- DEAP-3600 consists of LAr sphere surrounded by a water tank (Muon Veto)
- Until now the SNO experiment performed the only measurement of ϕ_μ at SNOLAB
- DEAP-3600 is performing an independent measurement $\Rightarrow$ which is the expected rate?
- Used Mei et Hime effective model to describe μ angular distribution
- With a Monte Carlo approach A_{eff} has been evaluated $\Rightarrow$ (63.5 ± 1.9) m^2
- Assuming SNO flux $\Rightarrow$ $R_{DEAP} = (18.2 \pm 0.5\, stat\ \pm 0.5\, syst)\mu/$day

Next steps:

- Try to parallelize the process in python
- Finalize the muon event selection with DEAP-3600 MV data

THANK YOU!

~95 researchers from 9 countries: Canada, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA

BACKUP SLIDES

Over the past ~ 100 years

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from several astrophysical and cosmological observations

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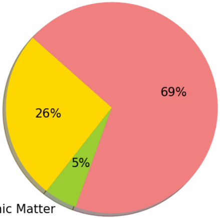
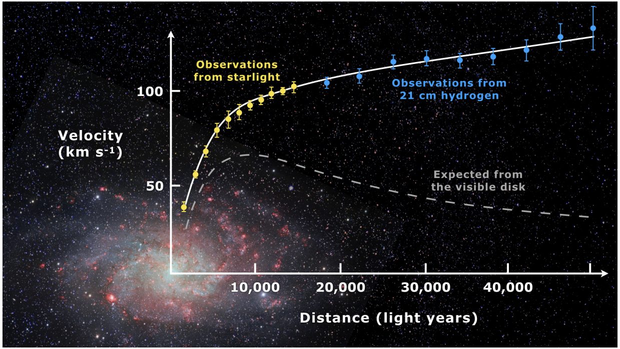
missing mass

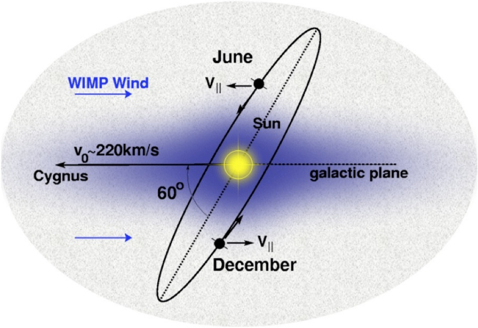




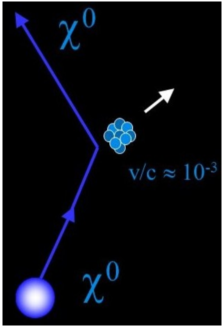
WIMP direct detection

Weakly Interacting Massive Particle (WIMP) $\Rightarrow$ one of the most promising models

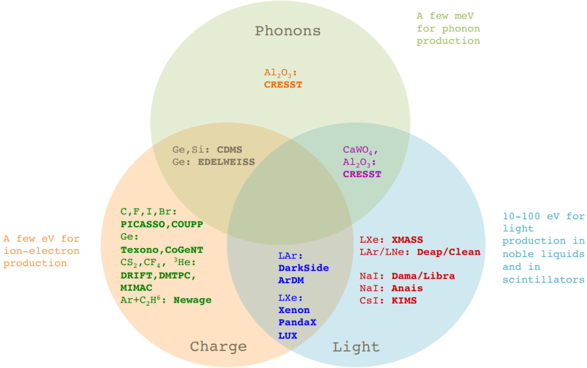
Sun moving around center of Galaxy
$\Rightarrow$ WIMP wind



Direct detection:
reveal energy left in interaction with ordinary matter

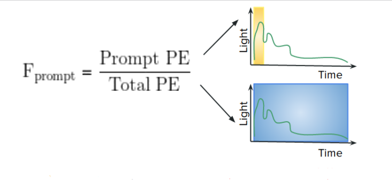


How can we reveal the deposited energy?



LAr characteristics:
- transparent at its own scintillation light
- SG discrimination from BG using scintillation time profile

Pulse Shape Discrimination:



Particle Type	F_{prompt}
LAr Alpha	0.75
Nuclear Recoil (WIMPs)	0.7
Beta/Gamma	0.3
GAr Alpha	0.12

With the courtesy of C. Mielnichuk

URL: https://indico.in2p3.fr/event/13380/contributions/14079/attachments/11726/14444/Theorie_LHC.pdf

DEAP collaboration. *Pulse-shape discrimination against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data.* URL: Eur. PHys. J. C 81,823 (2021)