PMTs:

Ongoing Analysis & Future

CYGNO Collaboration Meeting

Frascati, 4-6 December, 2023

David Marques

& PMT analysis working group

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    a. **LIME** ⇒ Am(Be) ; PID ; 3D
    b. **MANGO** ⇒ NID longitudinal diffusion

PMT Overview

Reco → Simulation → Analysis

Legend: Done/Working | Next work | Planned | To Do | Today

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Reco → Simulation → Analysis

- Retrieving important parameters
- Merging with Cygno reco
- Association 1-to-1
- Single TTree with ionization event information (Giorgio)
- PMT Auto-Reco

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- ^{55}Fe PMT simulation
- Analysis of ^{55}Fe PMT simulation with reco
- Other particles/energies PMT simulation
- Multiple track simulation (for association / resolution purposes)

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PMT Overview

Reco	Simulation	Analysis
Retrieving important parameters	^{55}Fe PMT simulation	Tilted cosmics analysis
Merging with Cygno reco	Analysis of ^{55}Fe PMT simulation with reco	Head-tail / 3D
Association 1-to-1	Other particles/energies PMT simulation	AmBe analysis for ER vs. NR
Single TTree with ionization event information (Giorgio)	Multiple track simulation (for association / resolution purposes)	Longitudinal diffusion ⇒ Confirmation with other sources
PMT Auto-Reco		Am analysis for PID
		PMT intercalibration with multi-source

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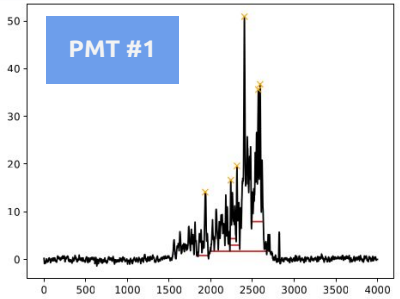
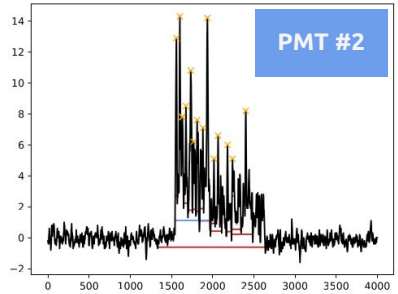
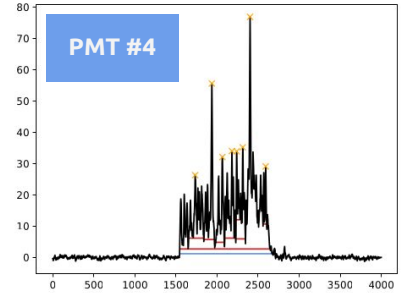
Time over Threshold

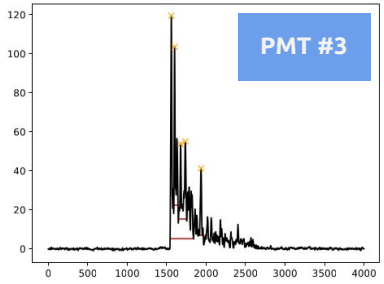
Time over Threshold

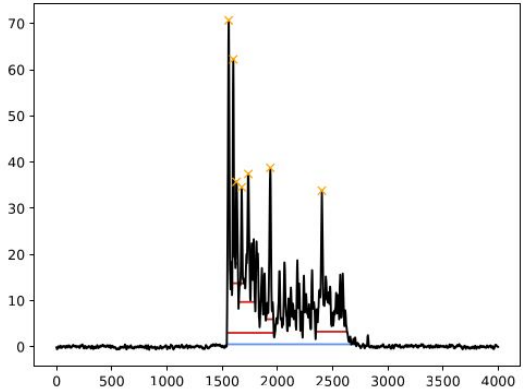
- Measurement of the **time length** of the signal which is **above a given threshold**.
  - Not trivial when each PMT sees a different signal intensity and tracks can have very complicated paths
  - I do a ***weighted average based on waveform's SNR*** ⇒ *Only correct for **timing** purposes*











Weighted average waveform

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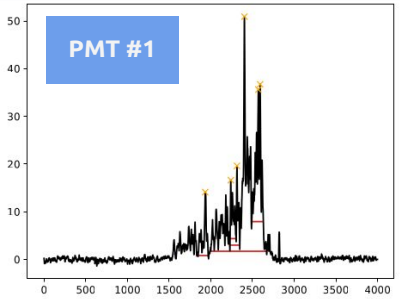
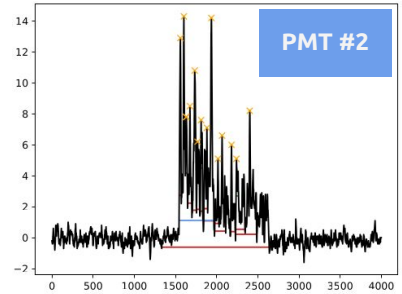
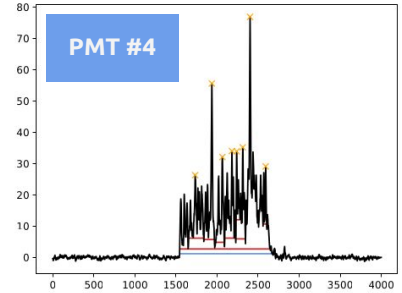
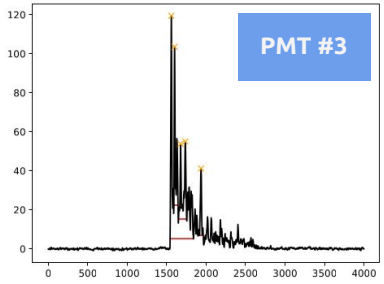
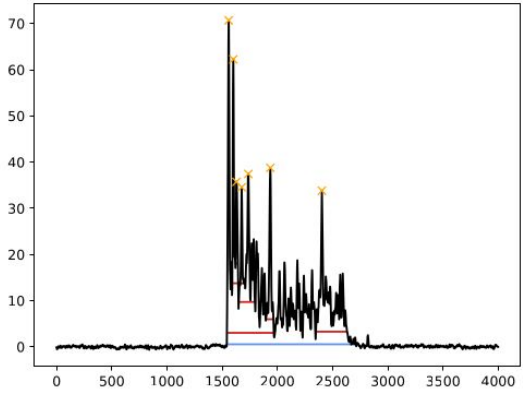










Weighted average waveform

This approach resolves better the width of the signals for ***long tracks*** with tortuous paths

Tilted cosmics

Motivation & Math:

Possible results / analysis:

Tilted cosmics

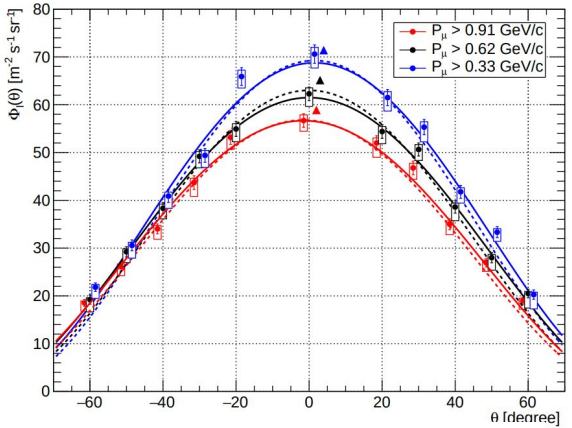
Motivation & Math:

- This measurement presents a ***clear dataset*** with tracks with ***well-defined orientation*** and energy deposit (MIP)
  - We have a specific **range of possible angles** of entering LIME (given by geometry of LIME + scintillators)
  - PMT measures the **Time over Threshold**
    - Multiplied by $v_{drift\ e^-}$ gives the **Δz**
  - Height of LIME (c1) is known (33 cm)
    - The tracks inclination (α) will be **$\tan^{-1}$ (Δz/c1)**

Possible results / analysis:

- We can **compare** it with the geometrical accepted angles.
- We can **calculate the flux** and compare it with the **cosmic muons angle distribution** at ground **(∝ $\cos^2(\Theta)$*)**

*https://dx.doi.org/10.1088/1475-7516/2023/04/025



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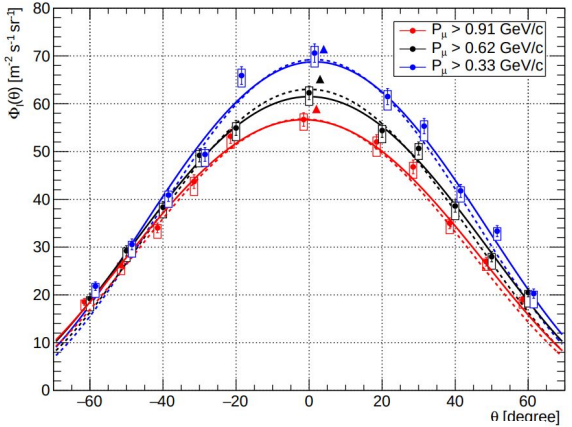


$$\text{Flux}\left[\text{cm}^{-2}\,\text{s}^{-1}\text{sr}^{-1}\right] = \frac{N/\varepsilon}{d\Omega dS dT},$$

Gives us a measurement of PMT Reco / ToT efficiency

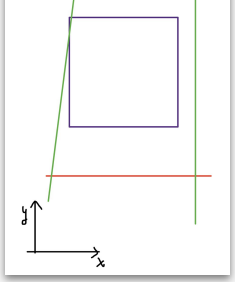
First CYGNO 3D analysis (on a distribution basis)

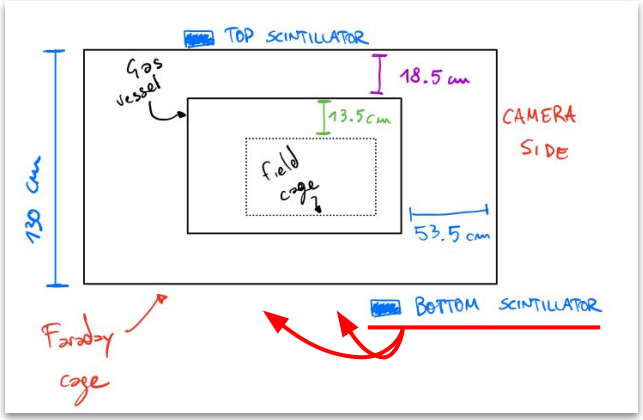
Tilted cosmics

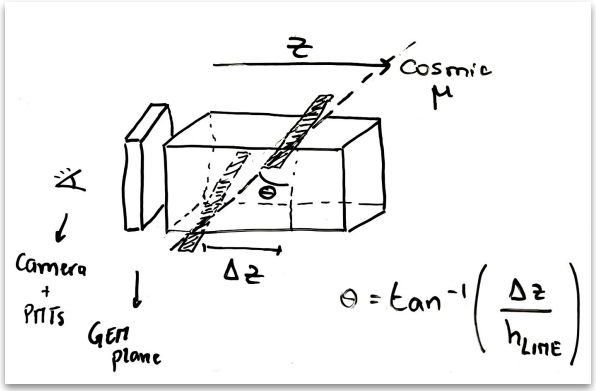
Setup:

Dimensions:

Accuracy:







Tilted cosmics

Setup:

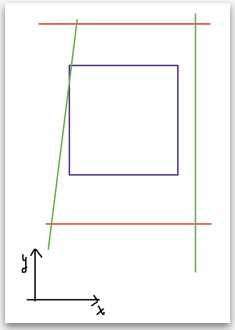
- ➔ Two scintillator bars were placed on top and bottom of LIME
- ➔ LIME DAQ triggered by coincidence of two scintillators
  - ◆ 3 different scintillator position were used
  - ◆ By geometry, only certains angles are possible

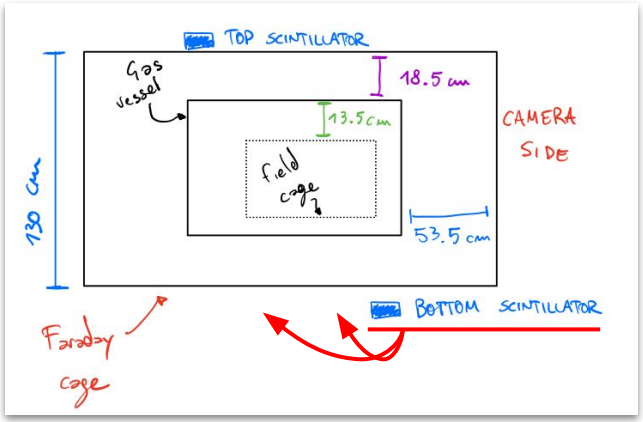
Dimensions:

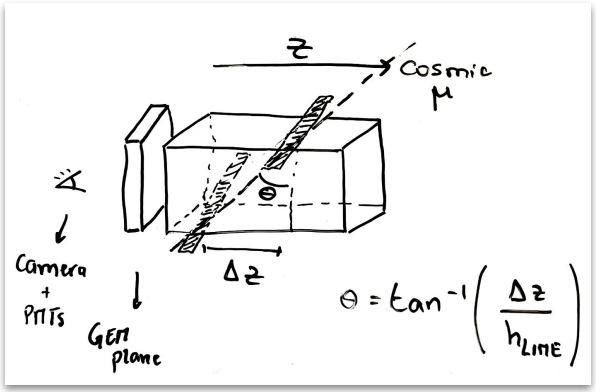
- ➔ LIME:
  - ◆ Z: 50 cm ; Y: 33 cm ; X: 33 cm
- ➔ Scintillator:
  - ◆ Z: ~5 cm ; Y: ~2 cm ; X: > 33 cm

Accuracy:

- This configuration actually allows for cosmics to enter and trigger **from the side** of LIME ⇒ Creates **long tails**
- **Random coincidences** from radioactivity or secondary particles are also possible







Tilted cosmics

Analysis method:

Tilted cosmics

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- Retrieve ***Time over threshold*** with weighted average
- Multiply with e- velocity in our gas to get ***travelled Z***
  - v_{e-} = 5.471 cm/us @ 800 V/cm, from Giorgio's thesis.
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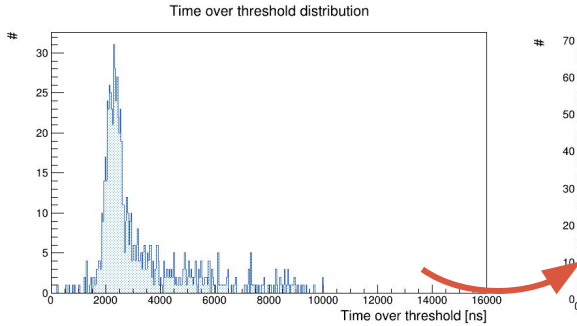

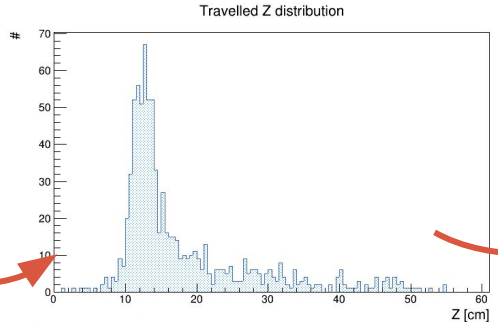

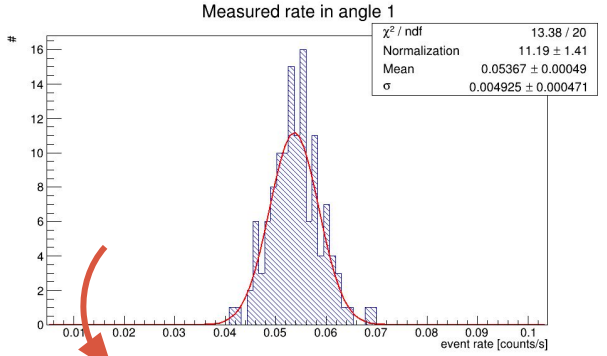

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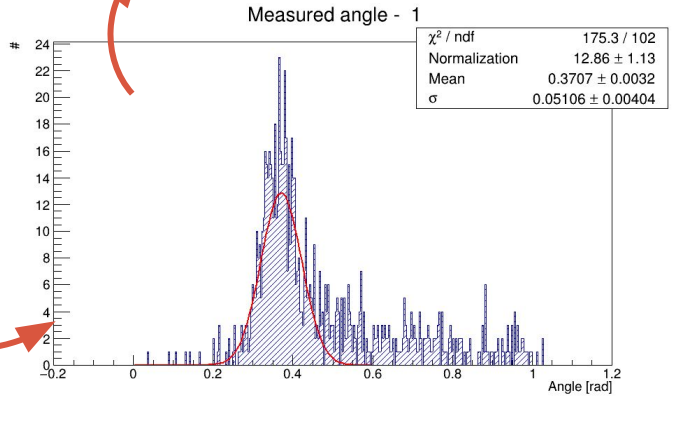

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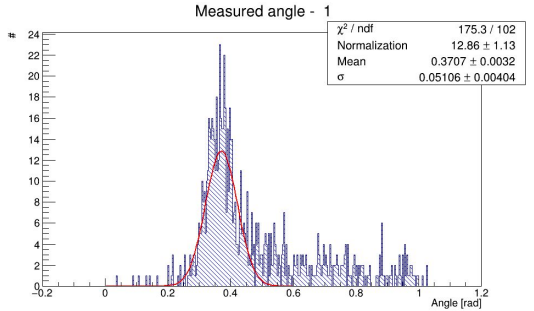

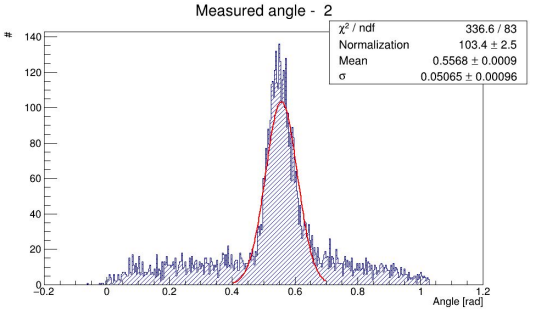

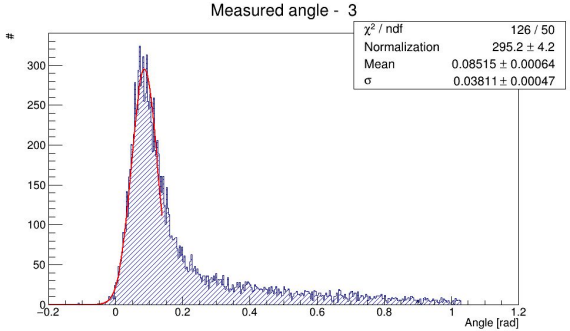

Tilted cosmics

Results - Angles comparison:

- Measured angles:
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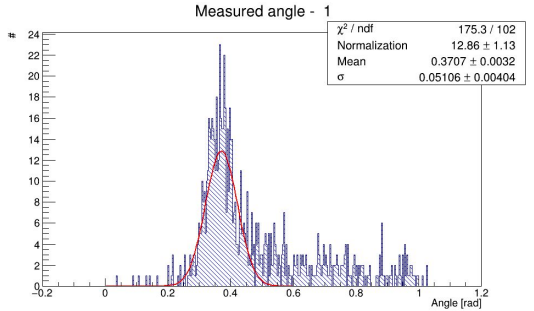
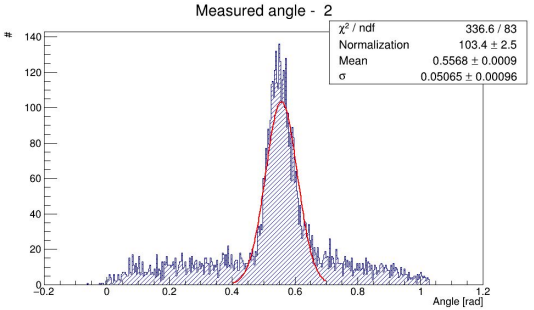
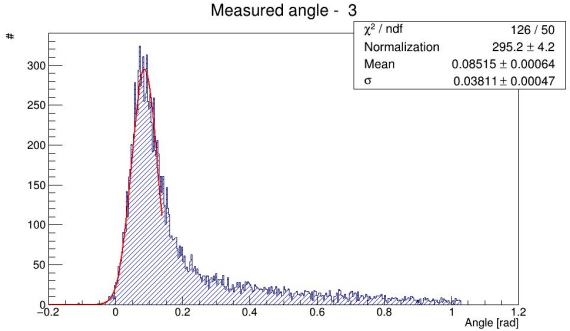
  - 31.90 deg
  - 4.88 deg







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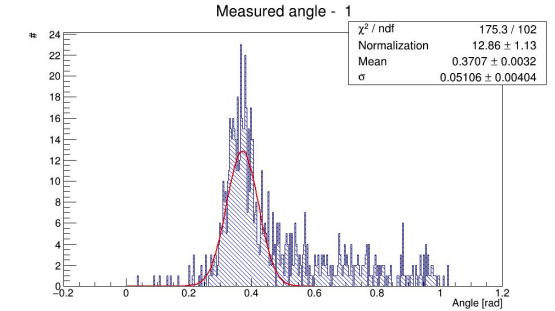
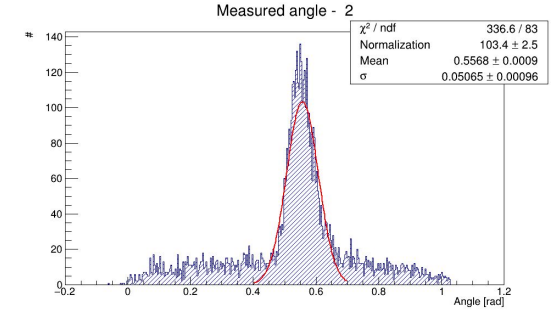
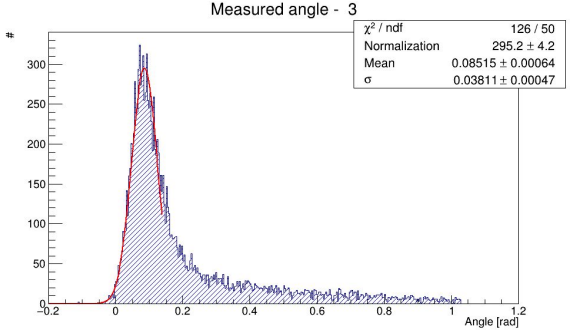
- Geometry allowed angles (hand calculated):
  - 20.27 - 24.04 deg
  - 28.64 - 31.93 deg
  - 0 deg - 4.4 deg (Parallel case is special)

- **Good agreement** at first order
- Long tails visible as expected







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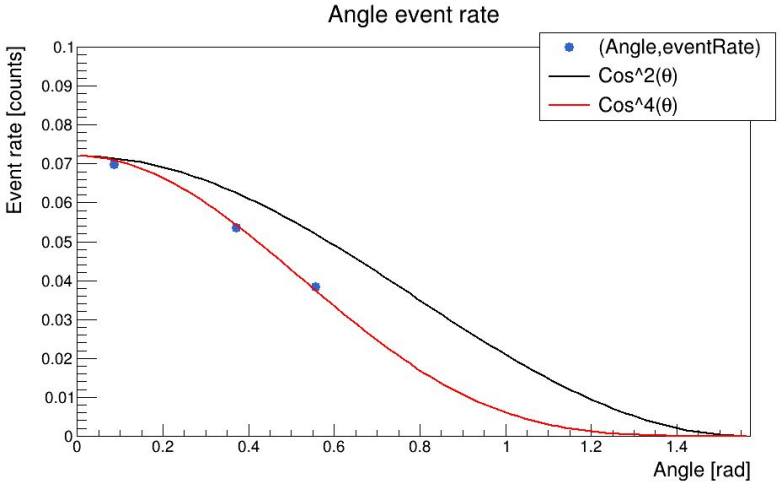

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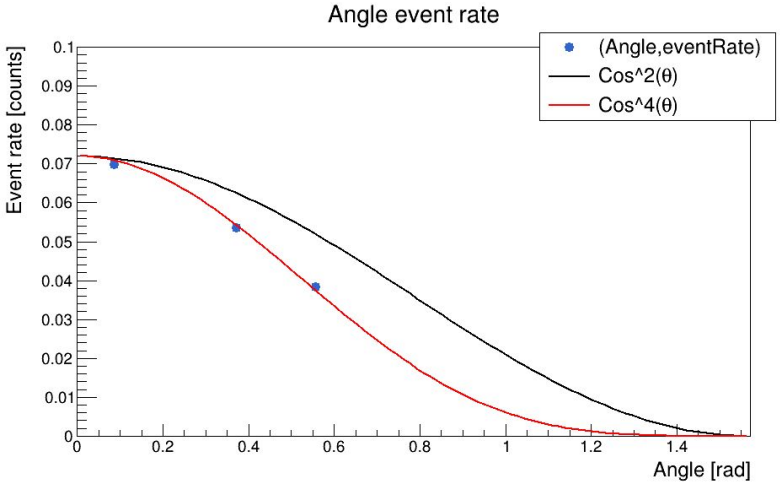


Data clearly fits a $\cos^4$ instead of a $\cos^2$

↓

.. what are we missing?

Let's revisit the theory

$$\text{Flux}\left[\text{cm}^{-2}\,\text{s}^{-1}\text{sr}^{-1}\right] = \frac{N/\varepsilon}{d\Omega dS dT},$$

$$d\Omega = \sin\theta\, d\theta\, d\varphi, \qquad \Omega = \iint_S \frac{\hat{r}\cdot\hat{n}}{r^2}\, dS = \iint_S \sin\theta\, d\theta\, d\varphi,$$

The [muon flux] takes into account the [acceptance / geometry factor] of the detectors

↓

Each of our configurations is different ⇒ To properly retrieve the $\cos^2$ dependency of the flux, one needs to do this calculation.

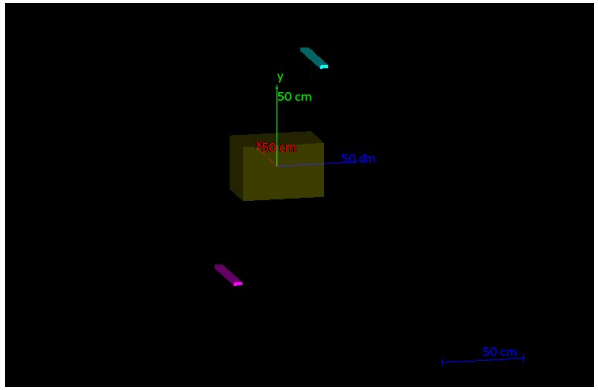
Tilted cosmics

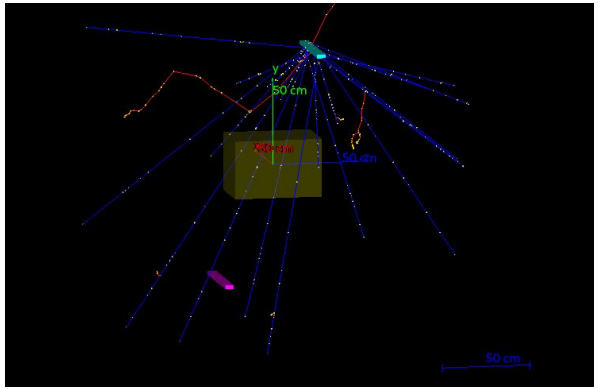
Simulation - Flux measurement:

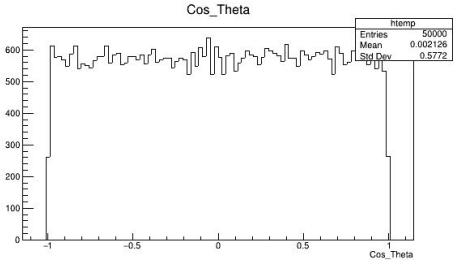
Tilted cosmics

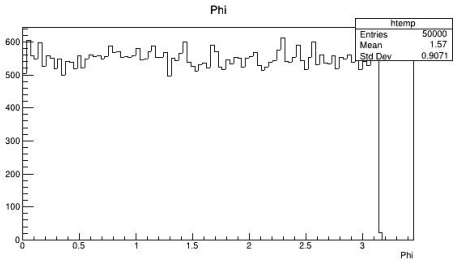
Simulation - Flux measurement:

- Basic **GEANT4 simulation** was created (with some help from Samuele)
- Particle (2 GeV muon) shot randomly from top scintillator with flat direction distribution









Tilted cosmics

Simulation - Flux measurement:

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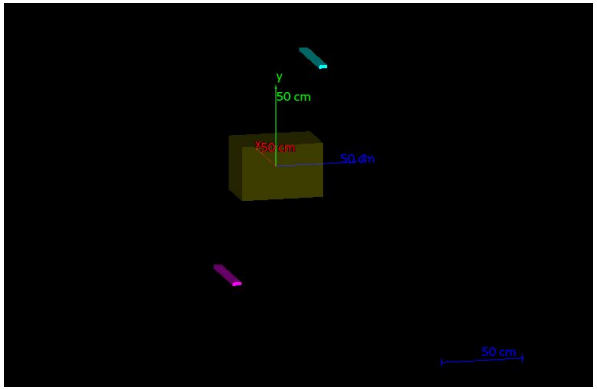
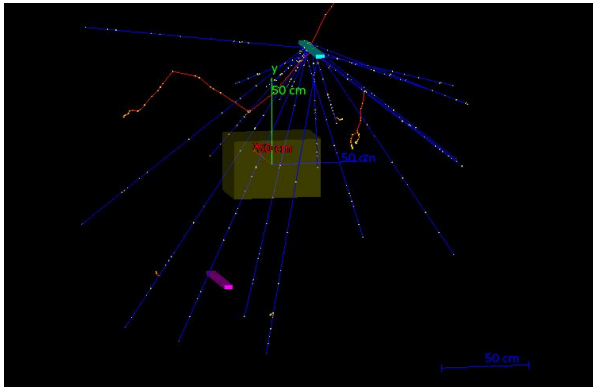
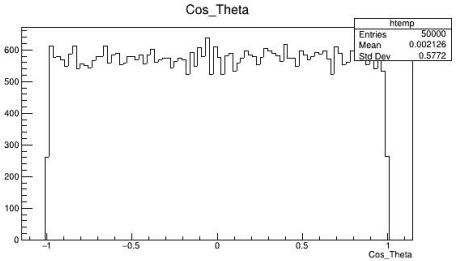
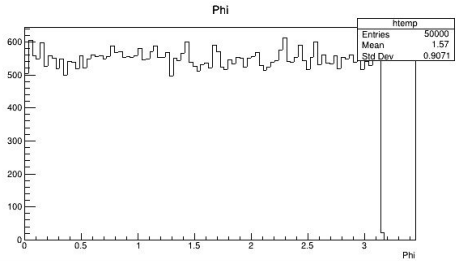
- Particle (2 GeV muon) shot randomly from top scintillator with flat direction distribution
- **Geometrical acceptance** calculated from ratio between triple coincidence and total shot particles
  - **Recalculated muon flux**










```
// Angles ~ = { 20 , 30, 0} deg
vector<double> dOmega = {0.00208,0.0018,0.002247};
```

Tilted cosmics

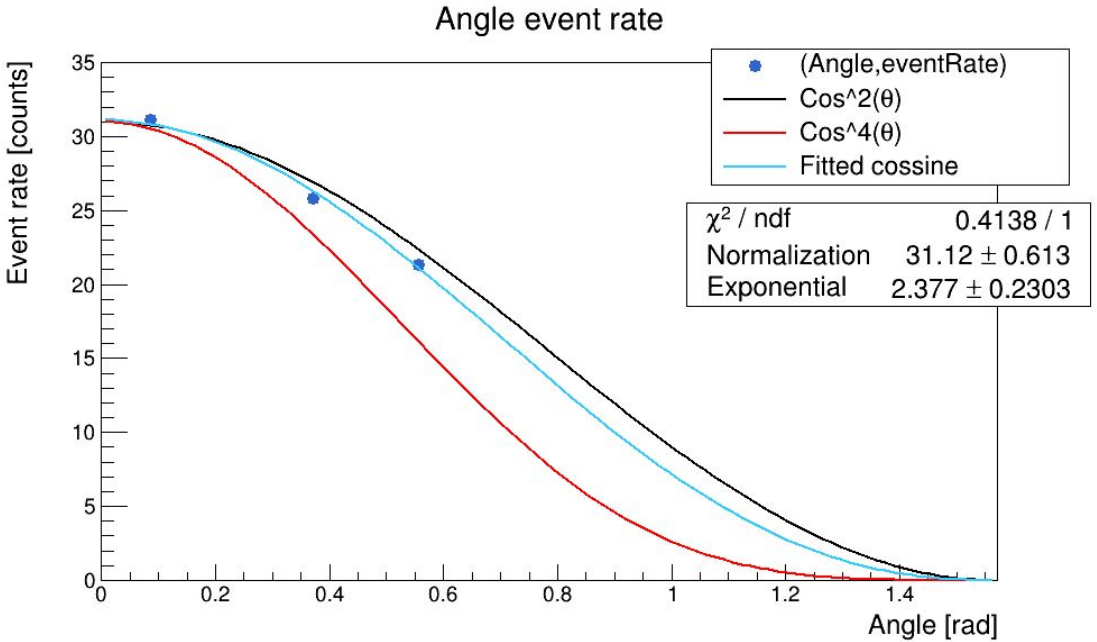
Results - Flux measurement:

- Final result:

Tilted cosmics

Results - Flux measurement:

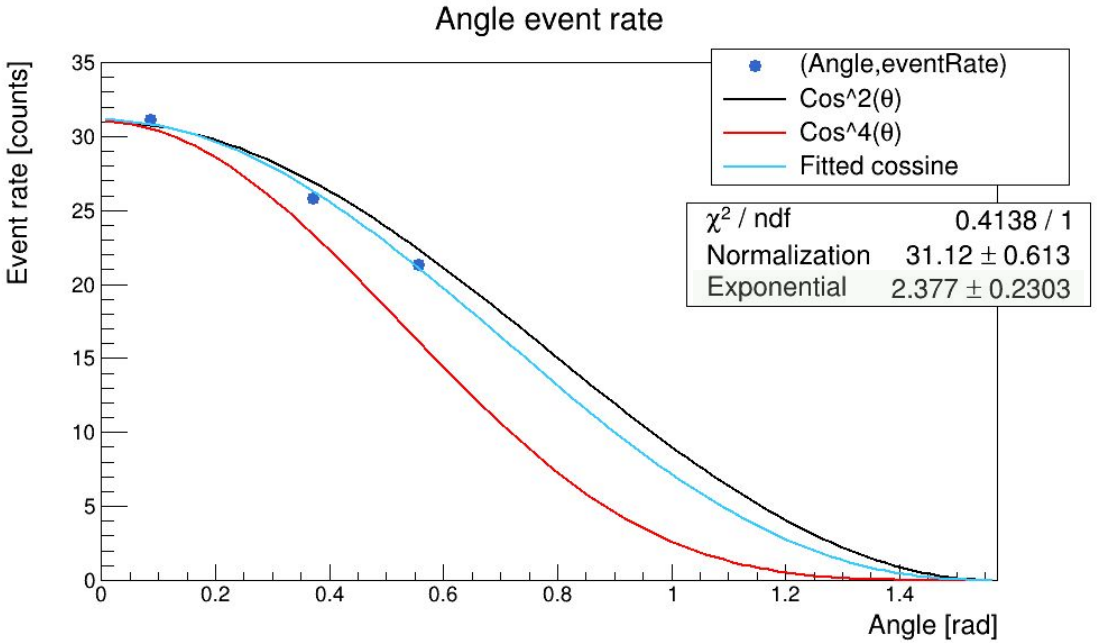
- Final result:



Tilted cosmics

Results - Flux measurement:

- Final result:



Doesn't fit a $\cos^4$ anymore

↓

More consistent with a $\cos^2$ distribution as expected from literature

(missing error bars)

↓

Still not the real muon flux since I miss the area (***dA***) normalization ⇒ With this we can compare with real data

Authors	P_c (GV)	Alt. (m)	P_μ (GeV/c)	n value	$\Phi_I(0°)$ $(m^2\ sr\ s)^{-1}$
Pethuraj et al. [34]	17.6	160	≥0.11	2.00±0.16	70.07±5.26
Sogarwal et al. [35]	16.38	SL	≥0.25	2.10±0.25	66.70±1.54
S. Pal et al. [36]	16	SL	≥0.28	2.15±0.01	62.17±0.05
Bhattacharyya [37]	14	24	≥0.4	1.91±0.1	—
			≥1.	1.85±0.11	—
Arneodo et al. [38]	14	SL	≥0.04	1.91±0.18	75.4±1.4
Present data	9.6	38	≥0.33	1.82±0.11	68.77±1.94
			≥0.62	1.72±0.10	61.49±1.44
			≥0.91	1.72±0.10	56.66±1.60
CRY [25]	9.6	SL	≥0.33	2.02	69.26
			≥0.62	1.95	63.02
			≥0.91	1.87	56.80
Riggi et al. [33]	8	3100	≥0.2	1.83±0.13	83.±8
Judge and Nash [39]	2.5	SL	≥0.7	1.96±0.22	—

Tilted cosmics

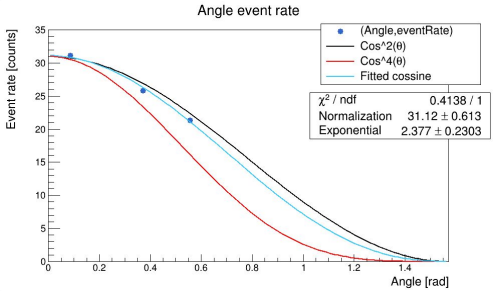
Conclusions:

Geometry allowed angles (hand calculated):

- 20.27 - 24.04 deg
- 28.64 - 31.93 deg
- 0 deg - 4.4 deg

Measured angles:

- 21.24 deg
- 31.90 deg
- 4.88 deg



Tilted cosmics

Conclusions:

- Results are at first order satisfactory.
  - ***ToT is a reliable variable*** and is already in the CYGNO ***reconstruction***
- Interesting study on the ***CYGNO PMT analysis*** ⇒ Could eventually be used in a paper
- Some caveats:
  - A small correction on the ToT was applied since theta = 0 does *not* produce a ToT = 0 (Perhaps a **longitudinal σ_0** for MIPs is necessary?)
  - There were some uncertainties regarding the dimensions of the scintillators
    - I will redo the simulations and ***add more statistics***
- *If* you think this would be relevant, the same study could be performed with GIN, adding more angles, and measuring longitudinal diffusion with MIP.

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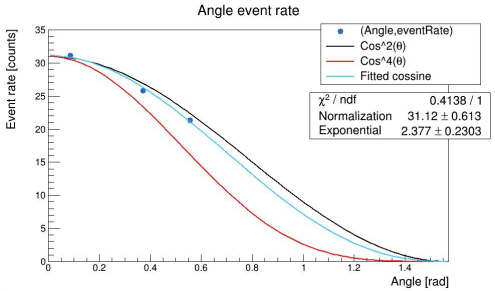


Next steps

Finalization of Tilted Cosmics study

Next steps

Finalization of Tilted Cosmics study

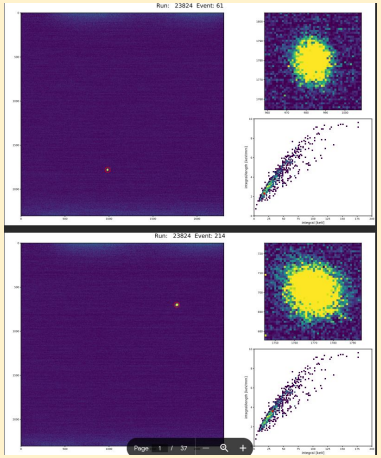
AmBe dataset analysis

↓

Attempts on PID and dE/dx analysis

↓

Already have the “most likely NR” data selected from Matteo



Next steps

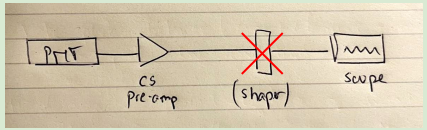
Finalization of Tilted Cosmics study

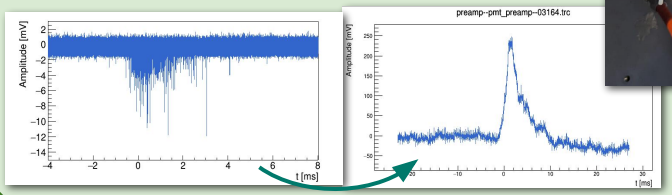
Negative Ion Drift ⇒

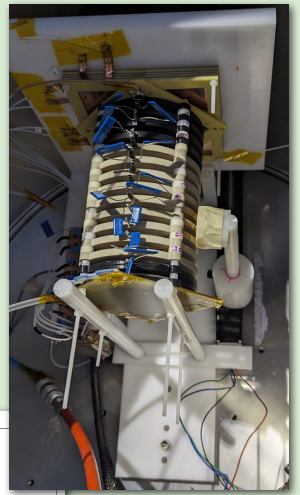
⇒ **Longitudinal diffusion**

↓

Stronger and ***independent*** confirmation of ***below thermal*** behaviour of NID







AmBe dataset analysis

↓

Attempts on **PID** and **dE/dx analysis**

↓

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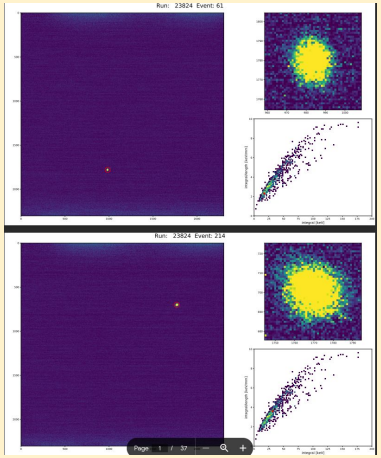

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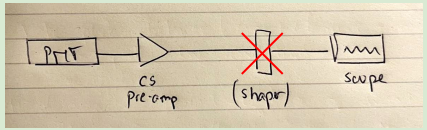

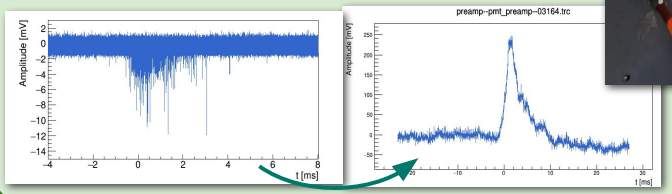

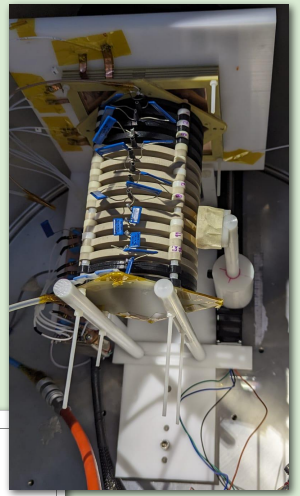

AmBe dataset analysis

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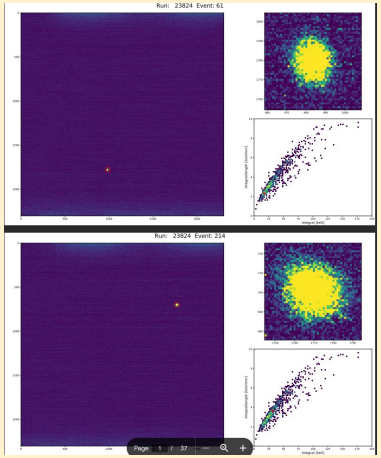
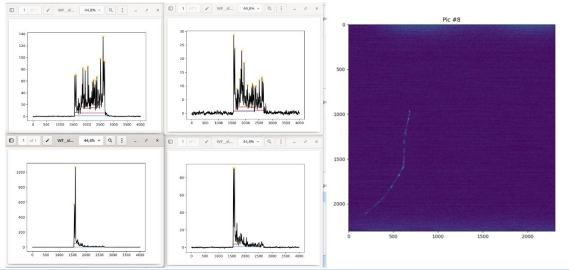


3D and/or **head-tail**

PMT – *3D & position & Head-tail exercise -2*



https://agenda.infn.it/event/38032/

Thank you for your attention!

The CYGNO Project counts with the collaboration of several international researchers coming from:




(And given the amount of portuguese speakers, we could also think of changing the name of the experiment to Cisne)