Studying Atmospheric Muons:

From neutrino physics to archaeological applications

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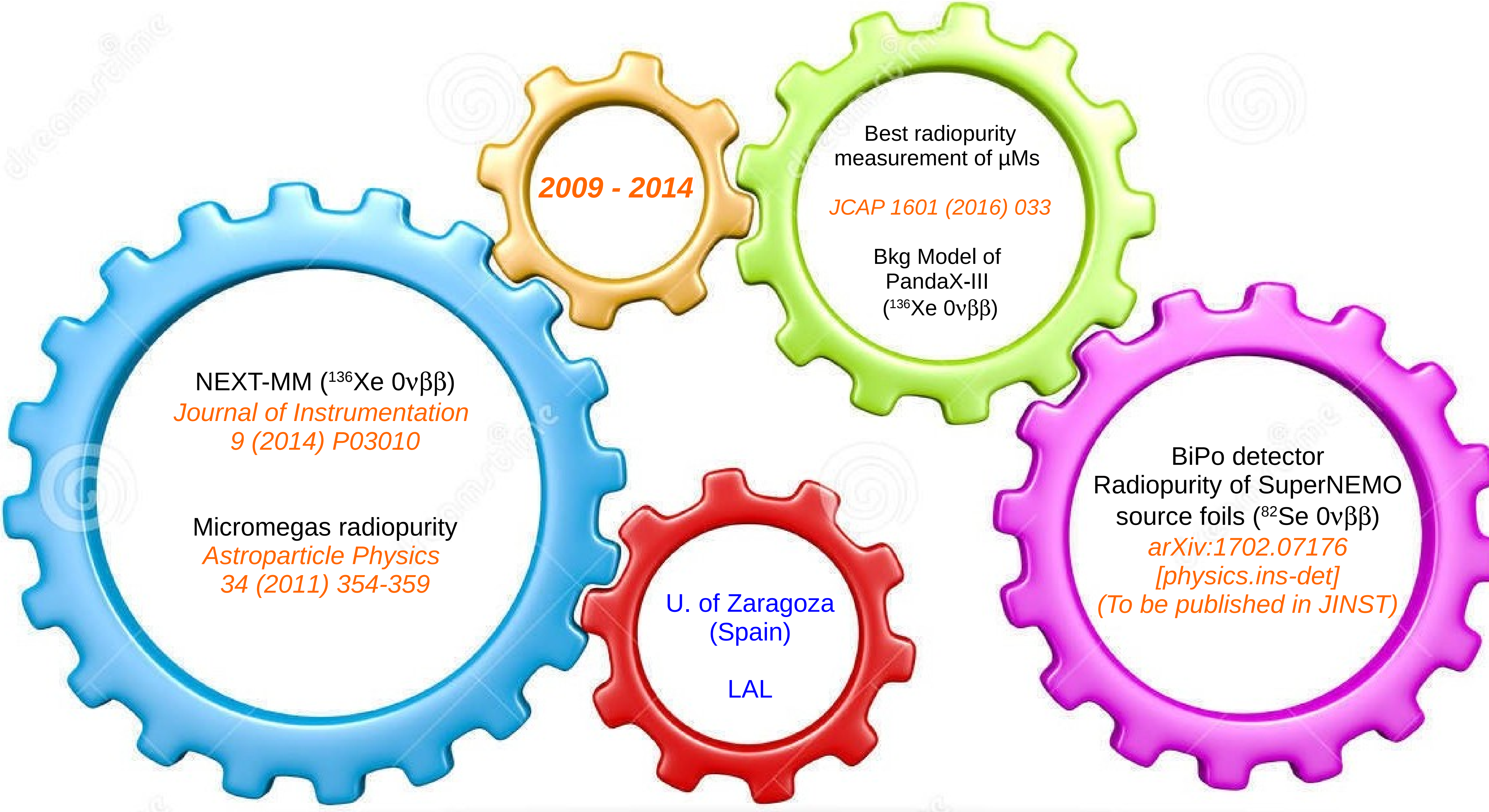
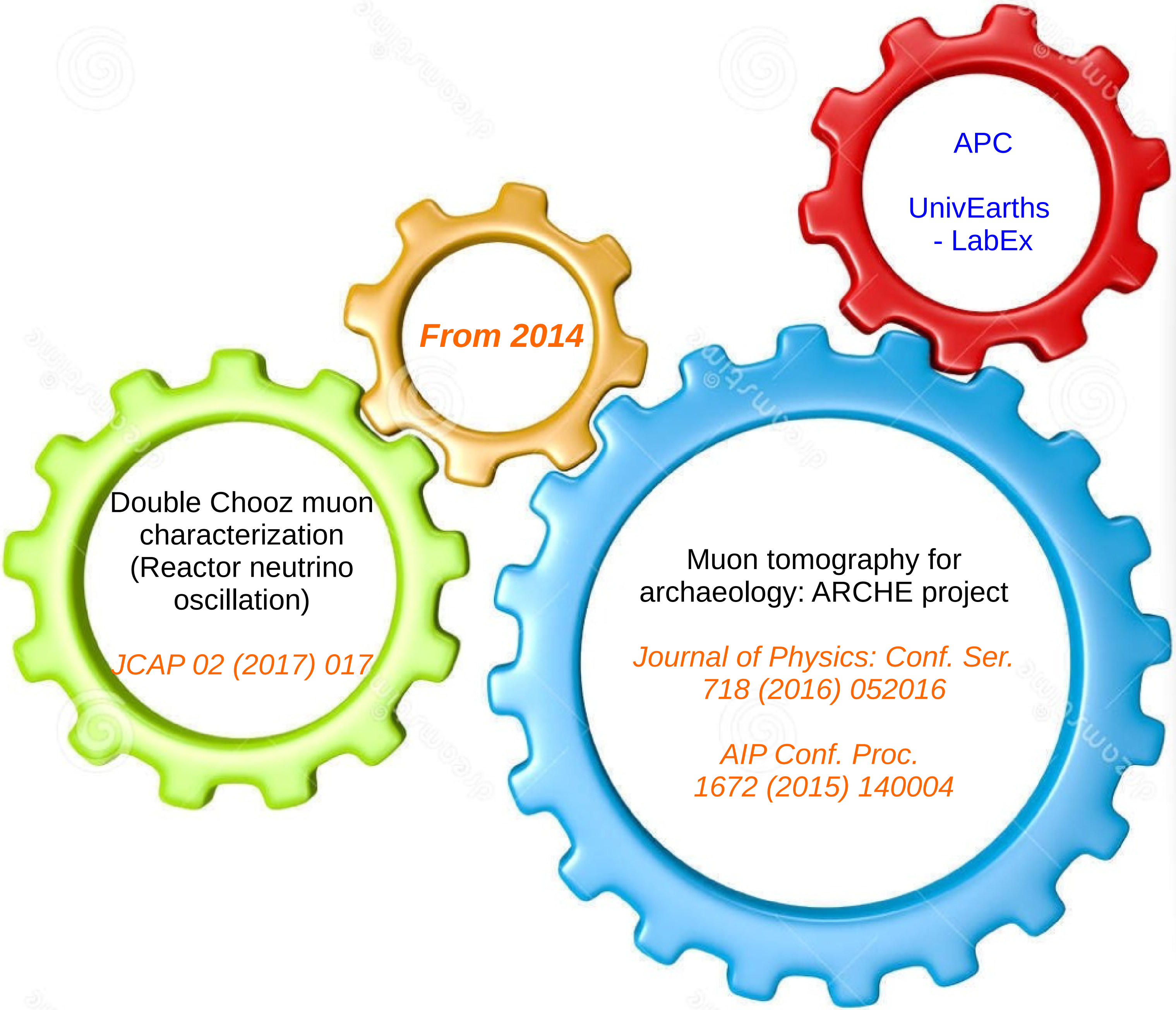
Labex UnivEarthS

Investissements d'avenir

USPC Université Sorbonne Paris Cité


2009 - 2014
Best radiopurity measurement of µMs
JCAP 1601 (2016) 033
Bkg Model of PandaX-III
(^{136}Xe 0νββ)
NEXT-MM (^{136}Xe 0νββ)
Journal of Instrumentation 9 (2014) P03010
Micromegas radiopurity
Astroparticle Physics 34 (2011) 354-359
U. of Zaragoza (Spain)
LAL
BiPo detector
Radiopurity of SuperNEMO source foils (^{82}Se 0νββ)
arXiv:1702.07176 [physics.ins-det]
(To be published in JINST)


APC
UnivEarths - LabEx
From 2014
Double Chooz muon characterization (Reactor neutrino oscillation)
JCAP 02 (2017) 017
Muon tomography for archaeology: ARCHE project
Journal of Physics: Conf. Ser. 718 (2016) 052016
AIP Conf. Proc. 1672 (2015) 140004

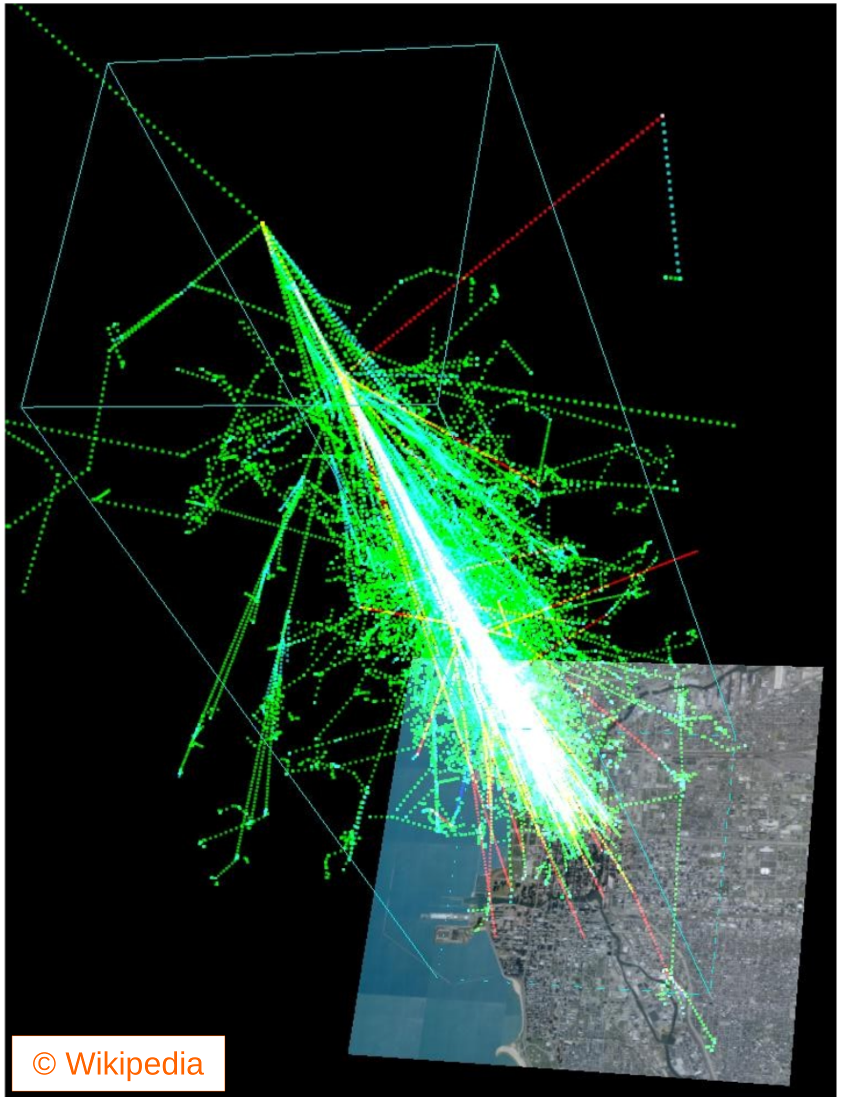
Outline

- Atmospheric muons
  - Main features
  - Background on Particle Physics: How to deal with them?

- Atmospheric muons and Reactor Neutrino experiments
  - The ***Double Chooz*** case
    - Muon characterization
      - Experimental data and Monte Carlo simulations
    - Annual modulation: Effective temperature coefficient
  - Outlook

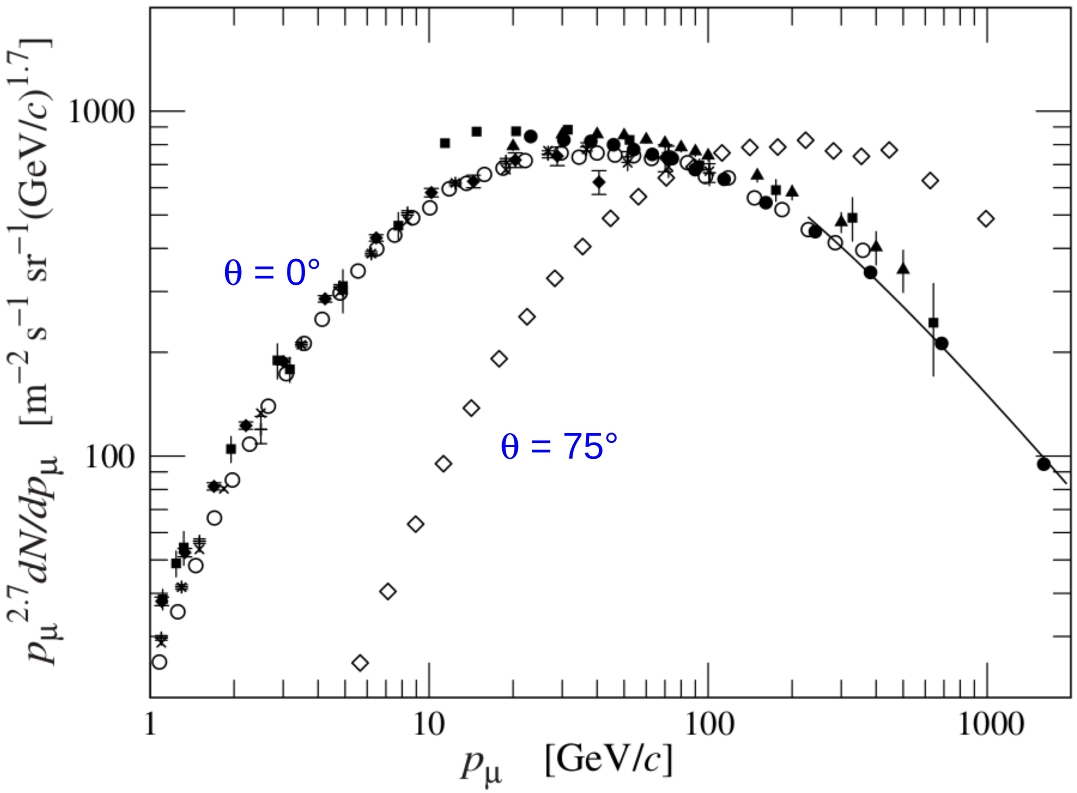
- Taking advantage of muons
  - The muon tomography
  - ***Arche*** project
    - Feasibility studies

- Summary and conclusions



Simulation of the air-shower produced by a 1 TeV proton interacting in the atmosphere @ 20 km

- Muons produced in the Atmosphere by the interaction of cosmic-rays (also referred as cosmic-ray muons)
  - Main component of the air-shower (together with the associated ν_μ, $e^\pm$ and $\pi^\pm$).
  - Most of them produced high in the atmosphere
  - @ Earth's surface
    - E and angular distribution (θ) at surface is driven by:
      - Production spectrum
      - Energy loss along the path in the atmosphere
      - Muon decay
    - Mean energy 4 GeV
    - Constant number below 1 GeV
    - Steepens along energy



Spectrum of muons for θ = 0° and 75° obtained from different measurements (markers) and from the Gaisser parametrization (line)
PDG. Chin. Phys. C, 40, 100001 (2016)

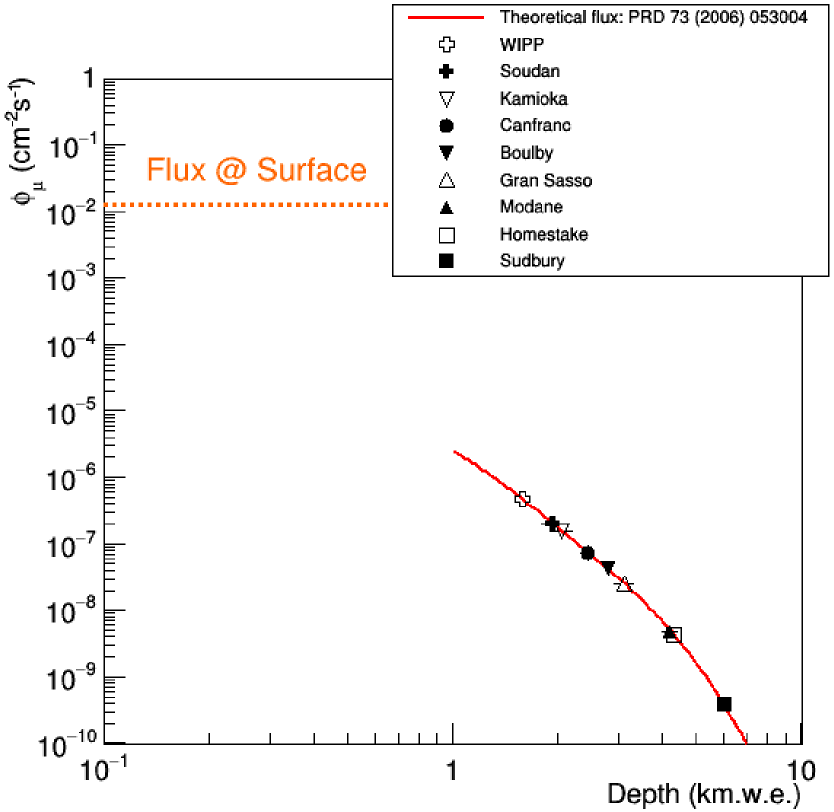
Muon flux @ surface (full θ range)

$$\phi_\mu \sim 1.3\ 10^{-2}\ cm^{-2}\ s^{-1}$$

- Atmospheric muons themselves and other muon-induced particles represent one of the most important background for Particle Physics experiments
- Ways to reduce / deal with this background

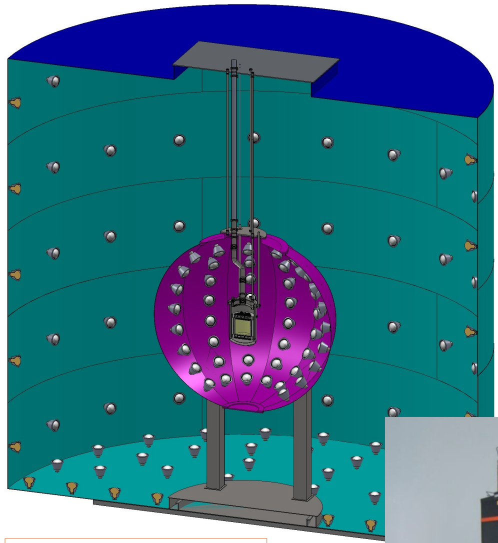
Passive methods

Shielding: Mines, mountains...



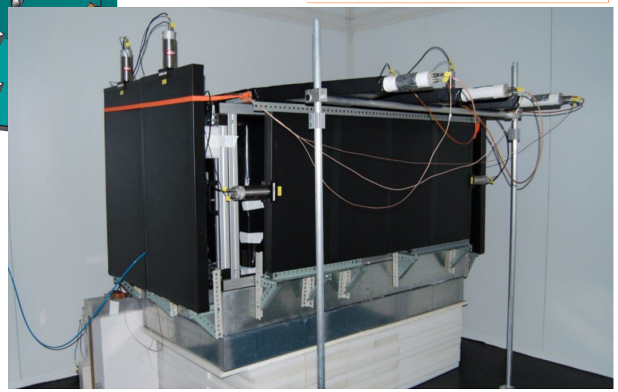
Active methods

Dedicated detectors, tagging...



Dark Side @ Gran Sasso

Anais @ Canfranc

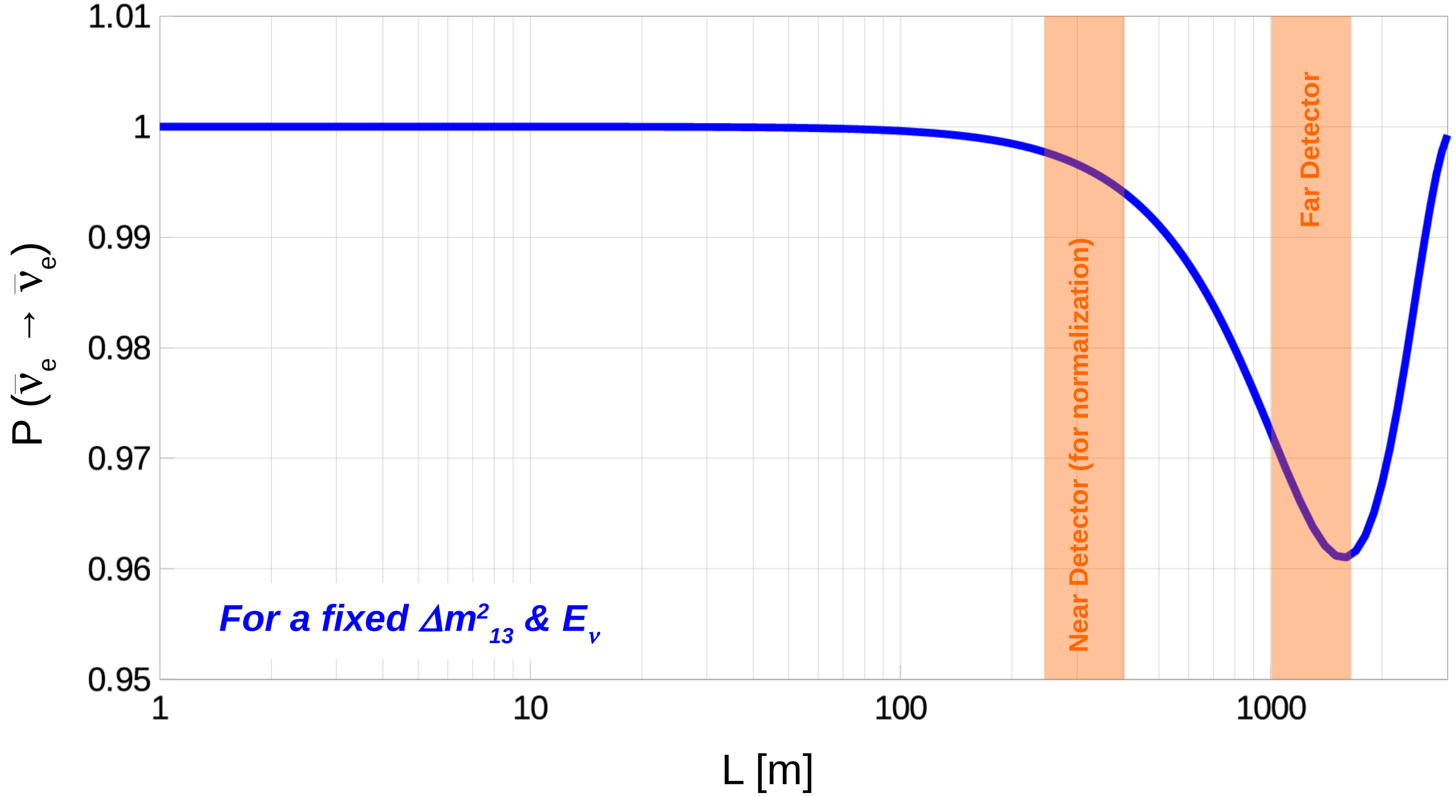


- ***In a nutshell (short baseline):***
  - Determination of $\boldsymbol{\theta_{13}}$ by measuring the ***deficit of detected anti-neutrinos*** coming from the nuclear reactor

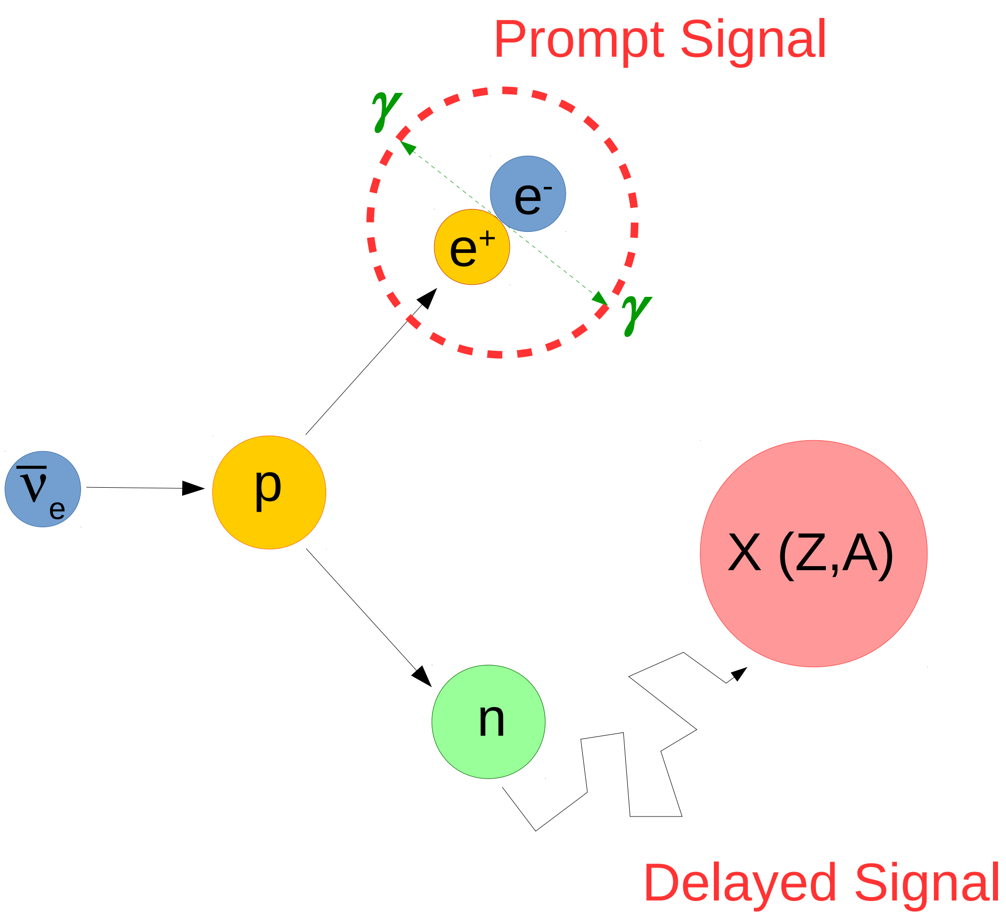
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{13}^2 L}{4 E_\nu}\right) + o(10^{-3})$$

L [m] / E [MeV] ≤ 1

No matter effects



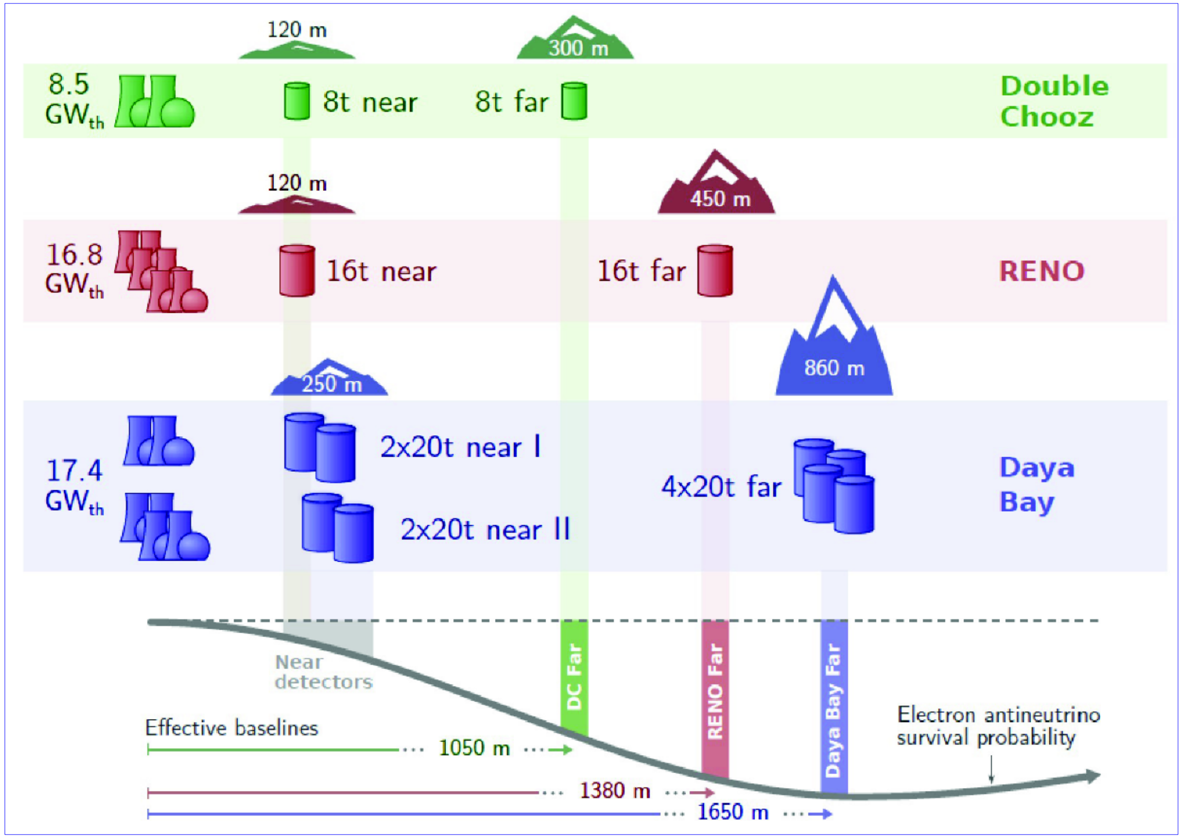
- ***In a nutshell (short baseline):***
  - Determination of θ_{13} by measuring the ***deficit of detected anti-neutrinos*** coming from the nuclear reactor
  - Anti-neutrinos detection (E_ν < 10 MeV) via ***Inverse Beta Decay*** process (IBD)

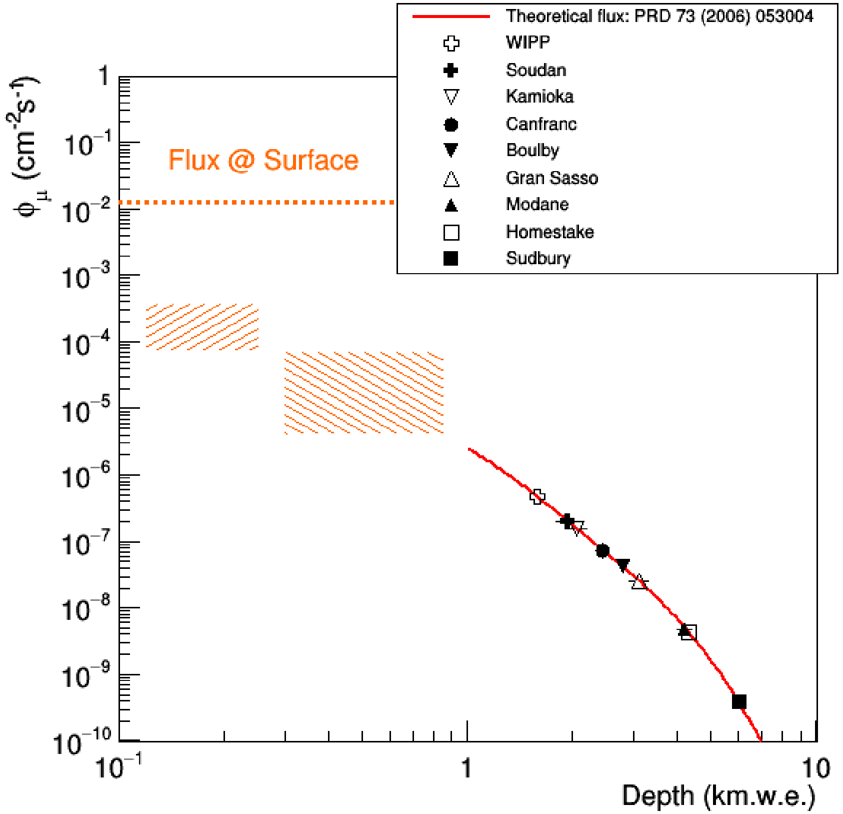


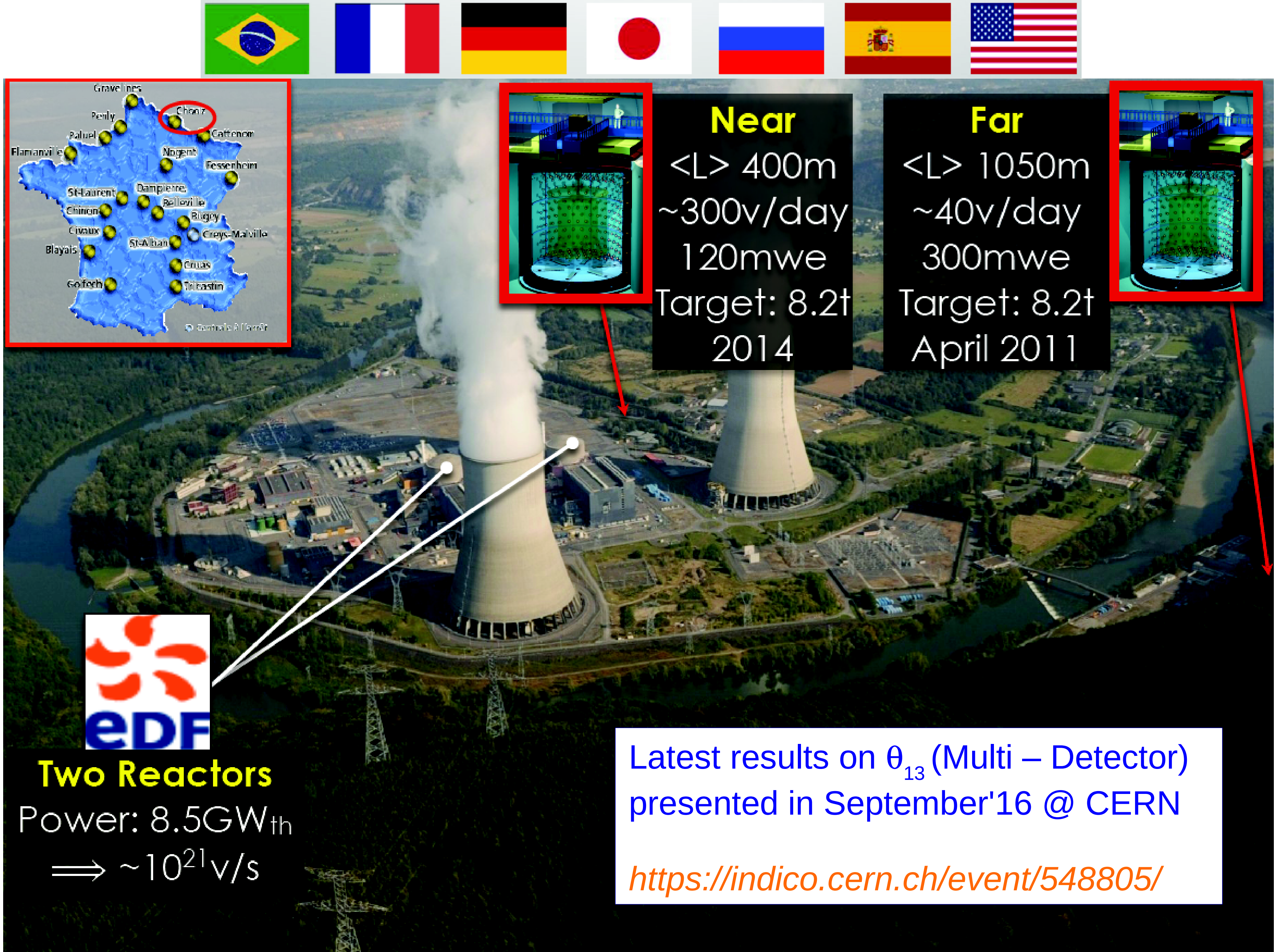
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Expected signal: Delayed coincidence
  - Prompt Signal: positron ionisation and annihilation
    - $E(e^+) \sim E(\bar{\nu}_e) - 0.8$ MeV
    - Localized energy deposit
  - Delayed signal: nuclear neutron capture
    - Features depending on the nucleus
      - Energy released, delay time

- ***In a nutshell (short baseline):***
  - Determination of θ_{13} by measuring the ***deficit of detected anti-neutrinos*** coming from the nuclear reactor
  - Anti-neutrinos detection (E_ν < 10 MeV) via ***Inverse Beta Decay*** process (IBD)
  - Three main experiments in the world: Daya Bay, ***Double Chooz*** and Reno

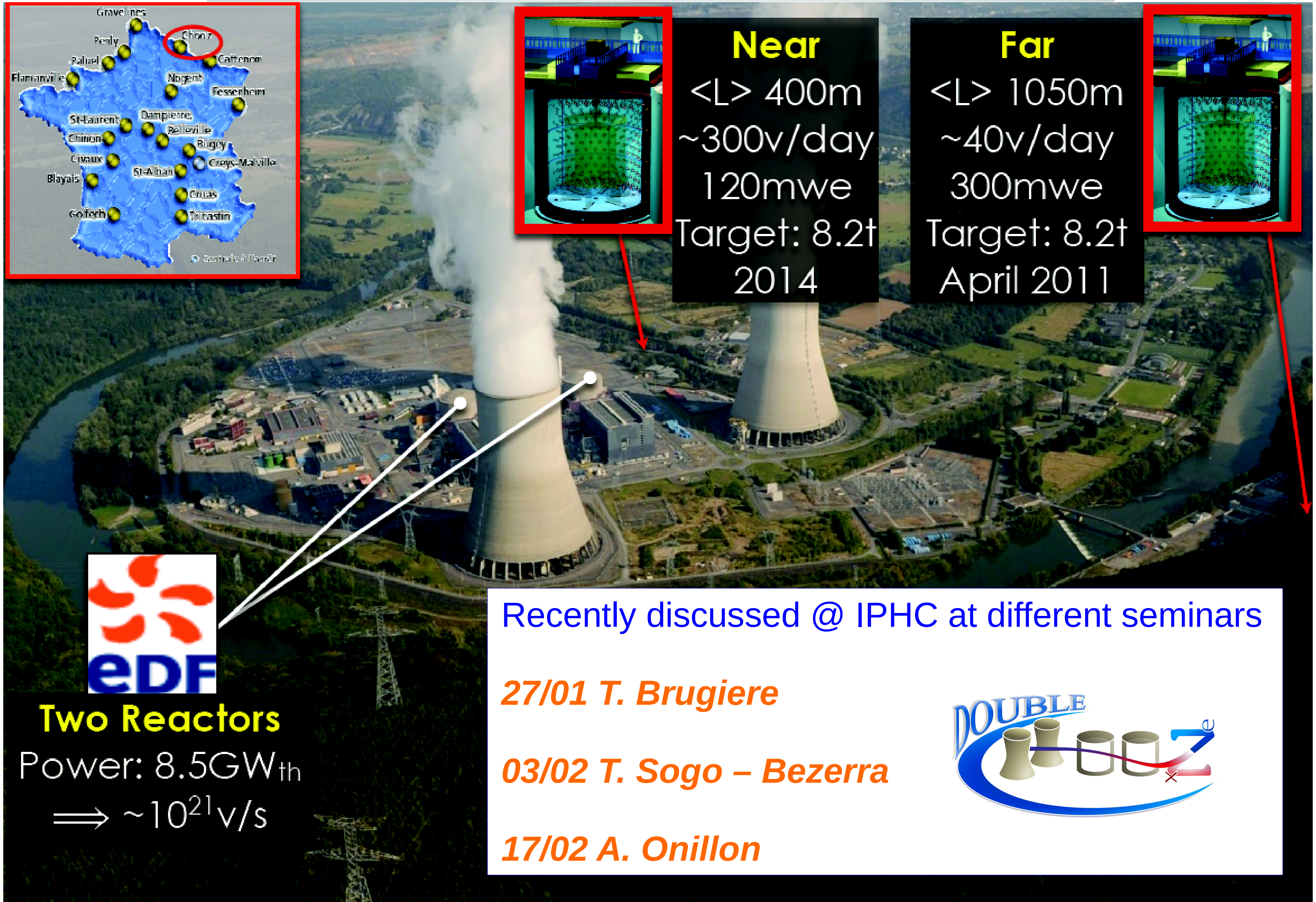






Latest results on θ_{13} (Multi – Detector) presented in September'16 @ CERN

https://indico.cern.ch/event/548805/

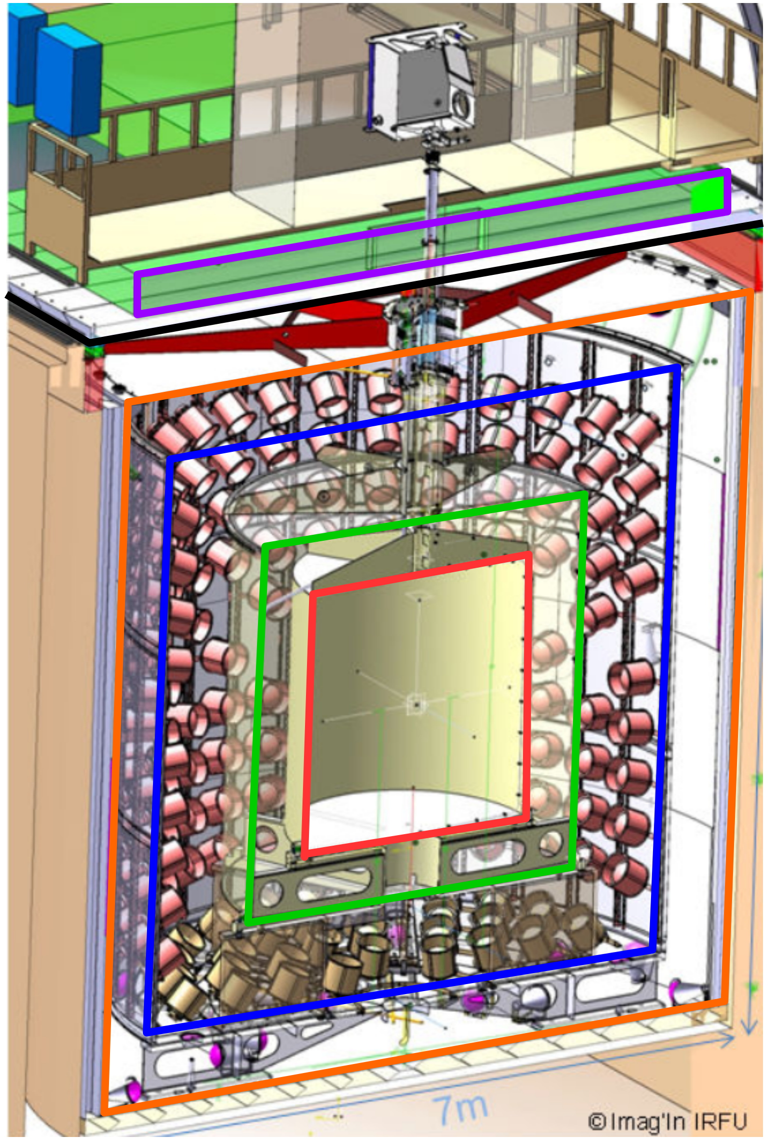


Recently discussed @ IPHC at different seminars

27/01 T. Brugiere

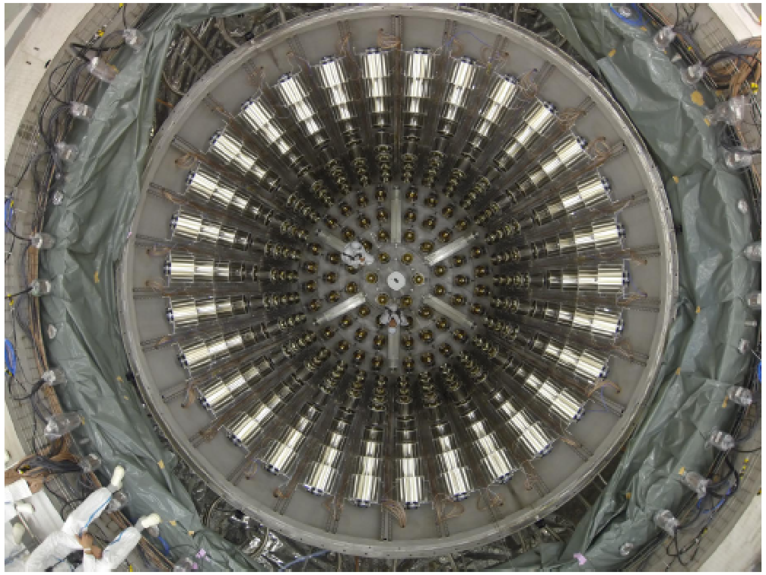
03/02 T. Sogo – Bezerra

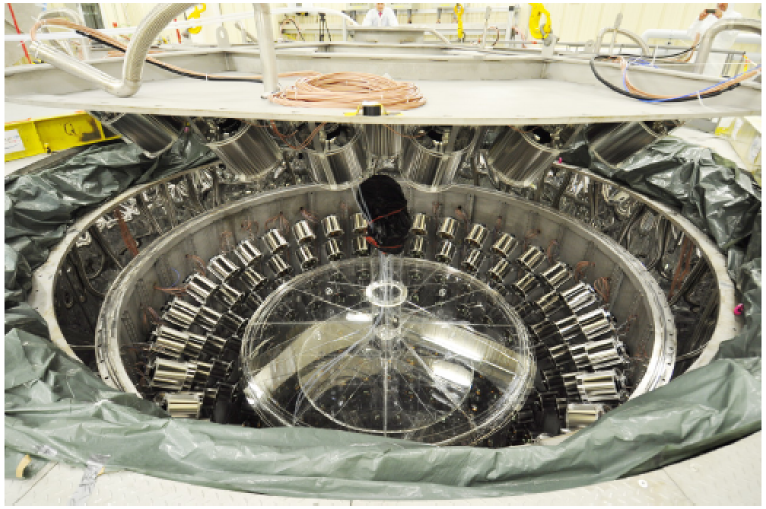
17/02 A. Onillon



LAYOUT:

ν – Target	10.3 m^3 liquid scintillator, doped with 1 g/l of Gd in an 8 mm thick acrylic vessel.
Gamma Catcher	22.6 m^3 liquid scintillator in a 12 mm thick acrylic vessel
Buffer	110 m^3 of mineral oil (non-scintillating) in a 3 mm thick Stainless Steel vessel. It holds ***390 PMTs (10 inches)*** working as readout
Inner Veto	90 m^3 liquid scintillator in a 10 mm thick Stainless Steel vessel equipped with 78 PMTs (8 inches)
Upper Shielding	15 cm thick steel plates
Outer Veto	Plastic scintillator panels





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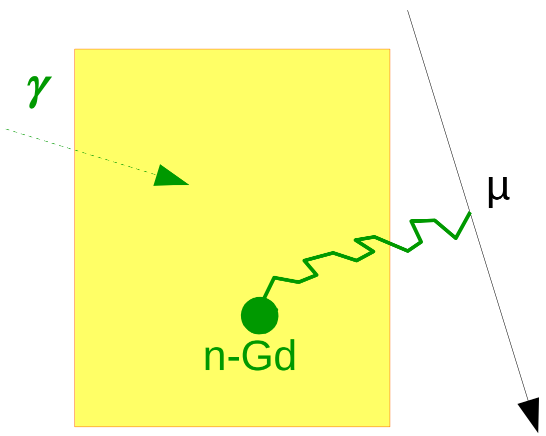
Signal

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- ***Two*** antineutrino identification ***channels*** (both based on IBD)
  - Neutron capture by ***Gd*** nuclei (***baseline***)
    - Delayed signal: ***E ~ 8 MeV; Δt ~ 30 µs***
      - ✔ Well above natural background
      - ✖ Limited fiducial volume (ν - target)
  - Neutron capture by ***H*** nuclei
    - Delayed singal: ***E ~ 2.2 MeV; Δt ~ 200 µs***
      - ✔ Increase of the sensitive volume (ν – target + gamma catcher)
      - ✖ More background expected
        - ✖ Natural background
        - ✖ Accidentals (bigger delay) → Additional background rejection tools required

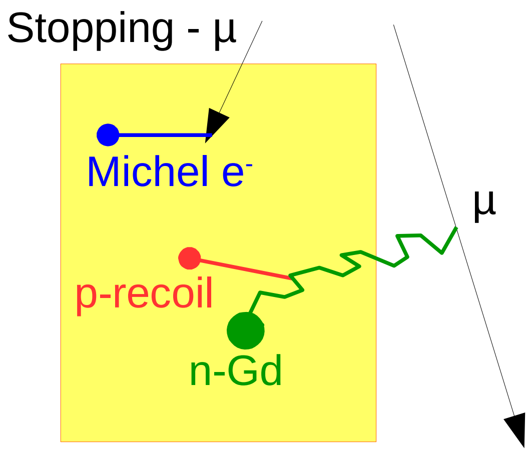
Backgrounds



Accidental Coincidences

Natural Radioactivity

e.g. γ + spallation n

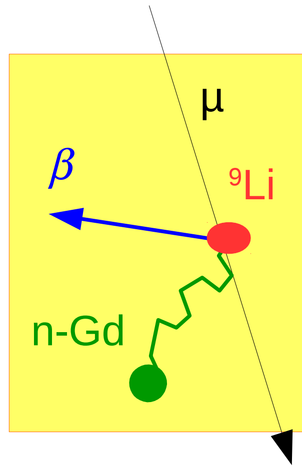


Correlated Events

Fast neutrons & Stopping – μ

$n + p \rightarrow p + n$

$\mu \rightarrow e + \nu + \nu$

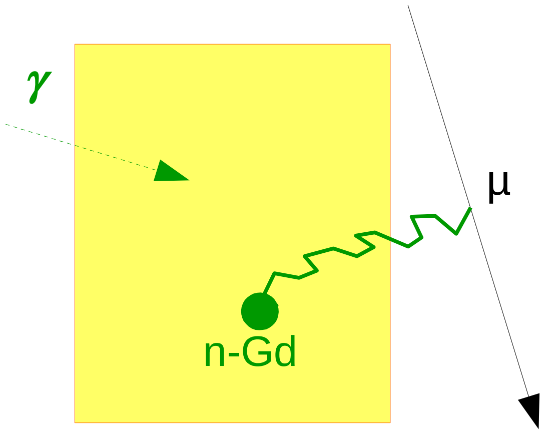


Cosmogenic Isotopes

β - n emitters (^{9}Li & ^{8}He)

$^{9}Li \rightarrow \alpha + \alpha + e + \nu + n$

Backgrounds



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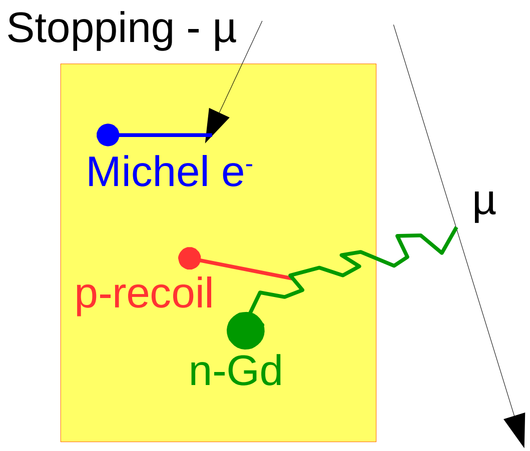
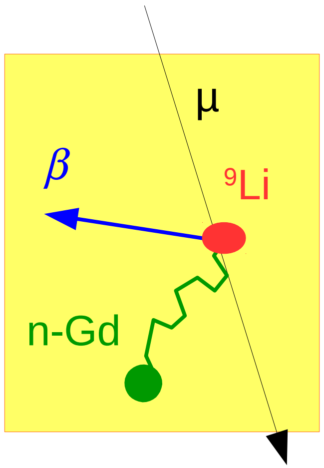


Correlated Events

Fast neutrons & Stopping – μ

n +p → p + n

μ → e + ν + ν



Cosmogenic Isotopes

β - n emitters (^{9}Li & ^{8}He)

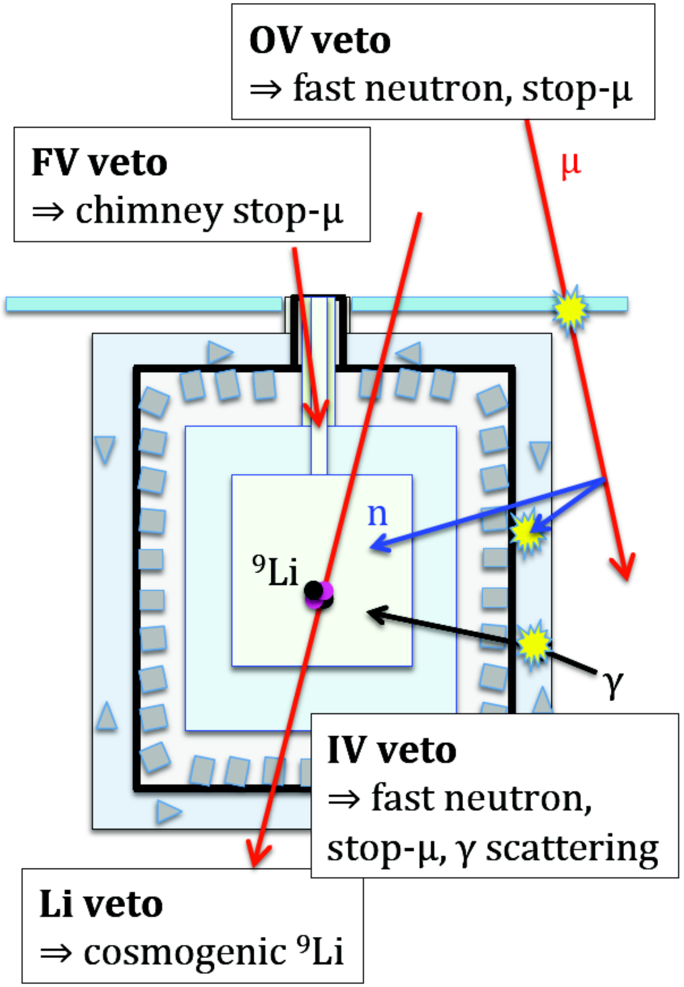
^{9}Li → α + α + e + ν + n

Prompt signal

Delayed signal

Development of dedicated background rejection techniques...

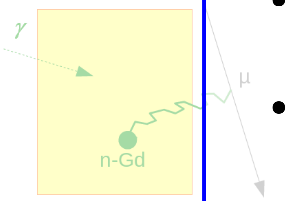
Backgrounds



Cut	*Information used*	*Target of cut*
μ veto	1 ms veto after μ	μ, cosmogenics
Multiplicity	Uniqueness condition	Multiple n's
FV veto	Vertex likelihood	Chimney stopping μ
IV veto	IV activity	Fast n, stopping μ, γ scattering
OV veto	OV activity	Fast n, stopping μ
Li veto	Li Likelihood	Cosmogenics
LN cut	PMT hit pattern and time	Light emission from PMT
ANN	$E_{delayed}$, ΔT, ΔR	Accidentals
MPS veto	Pulses start time	Fast n
CPS veto	Chimney likelihood	Stopping μ
Q ratio	Max. Q / Tot. Q	ND Buffer stopping μ

Only applied in n – H analysis
Only applied in the multi-detector analysis

- Complete muon characterization is useful to:
  - Better understand Double Chooz background features
  - Perform the muon tagging for better identification of μ – induced events
  - Survey of the detector
  - ...



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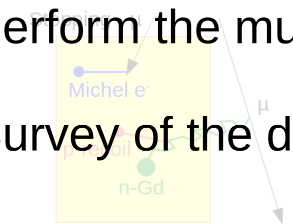


Correlated Events

Fast neutrons & Stopping – μ

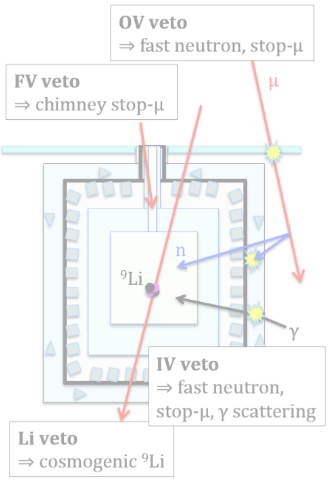
n +p → p + n

μ → e + ν + ν

Cosmogenic Isotopes

β - n emitters (⁹Li & ⁸He)

⁹Li → α + α + e + ν + n



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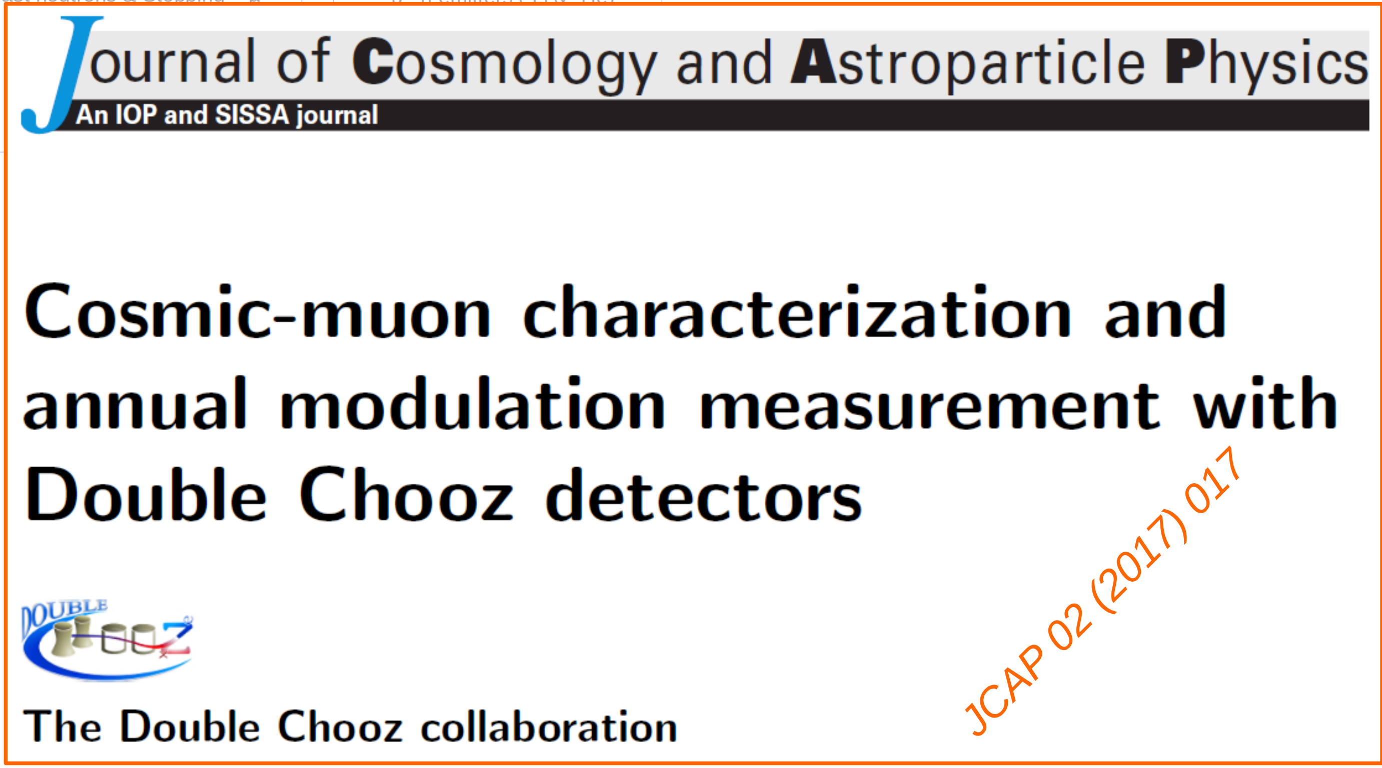


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

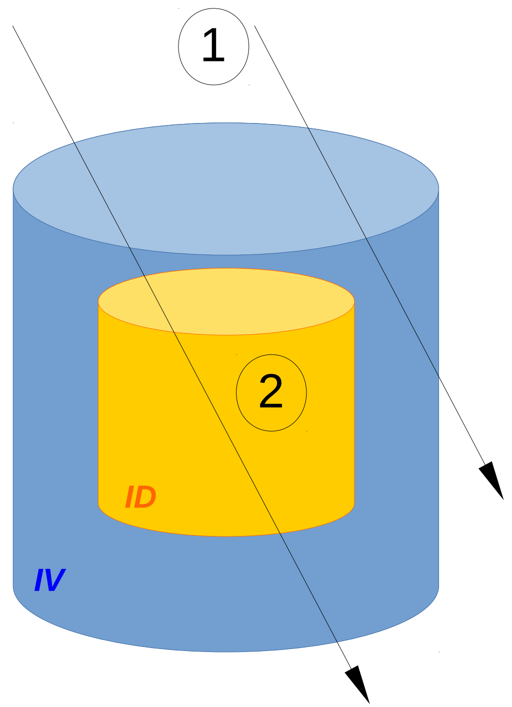
Cosmic-muon characterization and annual modulation measurement with Double Chooz detectors

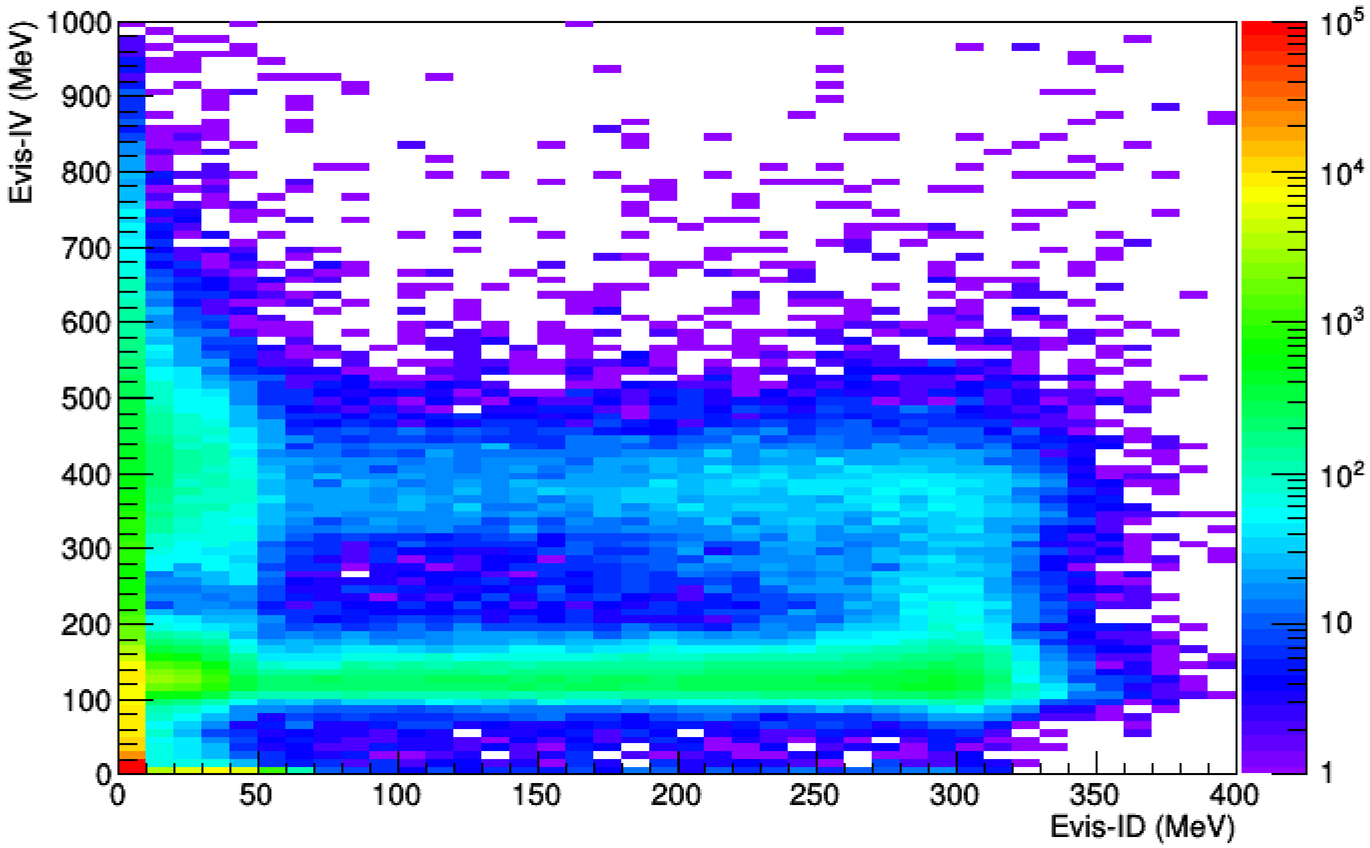
The Double Chooz collaboration

JCAP 02 (2017) 017

Tagging Muons → Rate

- Muons deposit large amounts of energy (if compared with other particles) when they traverse the sensitive volumes of Double Chooz detectors i.e. Inner Detector and Inner Veto





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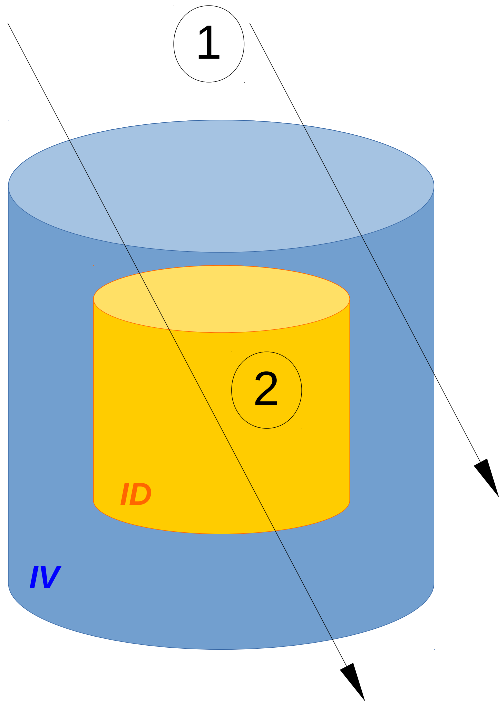


Standard selection (deposited energy in scinitillating volumes)

1: Evis-IV > 25 MeV

2: Evis-ID > 30 MeV and Evis-IV > 5 MeV

Mean Muon Rate*:

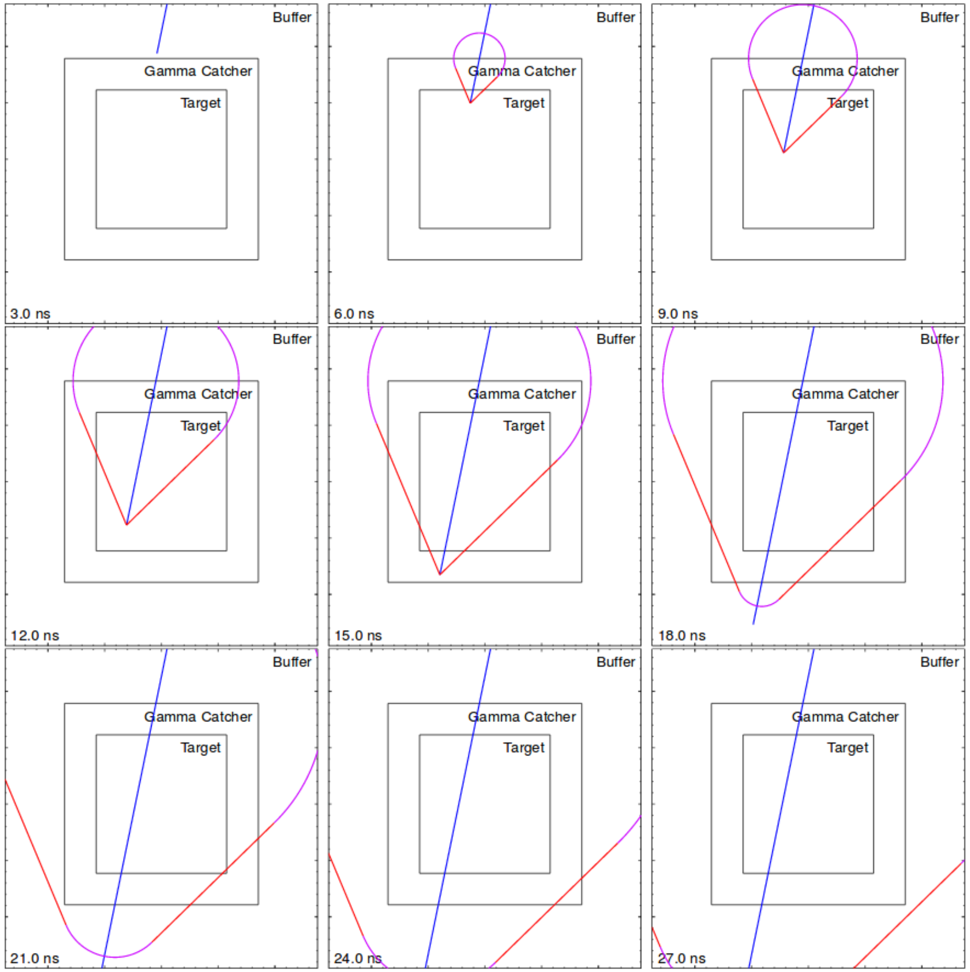
Near detector: $\langle R_{\mu} \rangle = 242.75 \pm 4.81$ Hz

Far detector: $\langle R_{\mu} \rangle = 46.16 \pm 1.04$ Hz

*Mean rate for all the analysed data: ~151 and ~673 days for the near and far detectors respectively

Tagging Muons → Angular Distributions

- Muon track reconstruction based on time information of the Inner Detector and the Inner Veto and the spatial information of the Outer Veto. *Nucl. Instrum. Meth. A 764 (2014) 330*



- Assuming Cherenkov and scintillation light
- Pulse reconstruction for all the fired PMTs

Multiples combined fits (`Minuit` minimization)

ID & IV PMTs

ID & IV PMTs + OV constrain

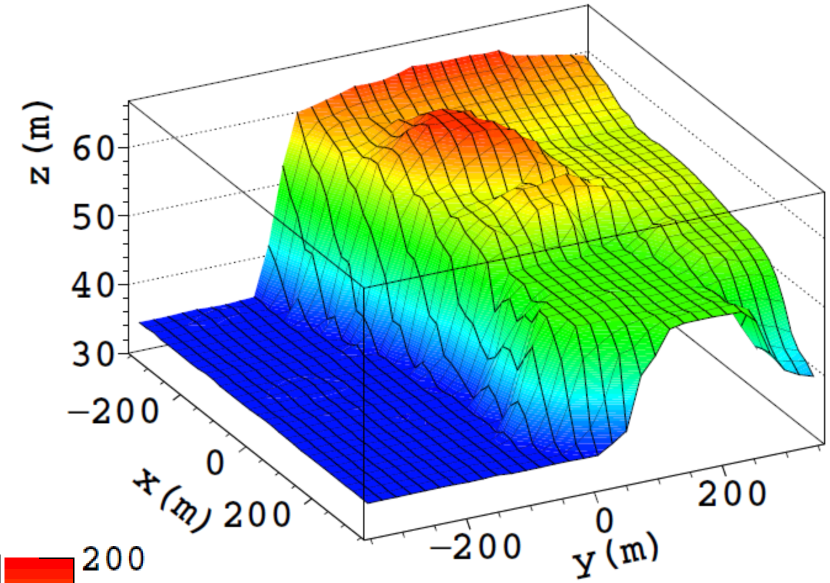
Through-going μ

Stopped μ

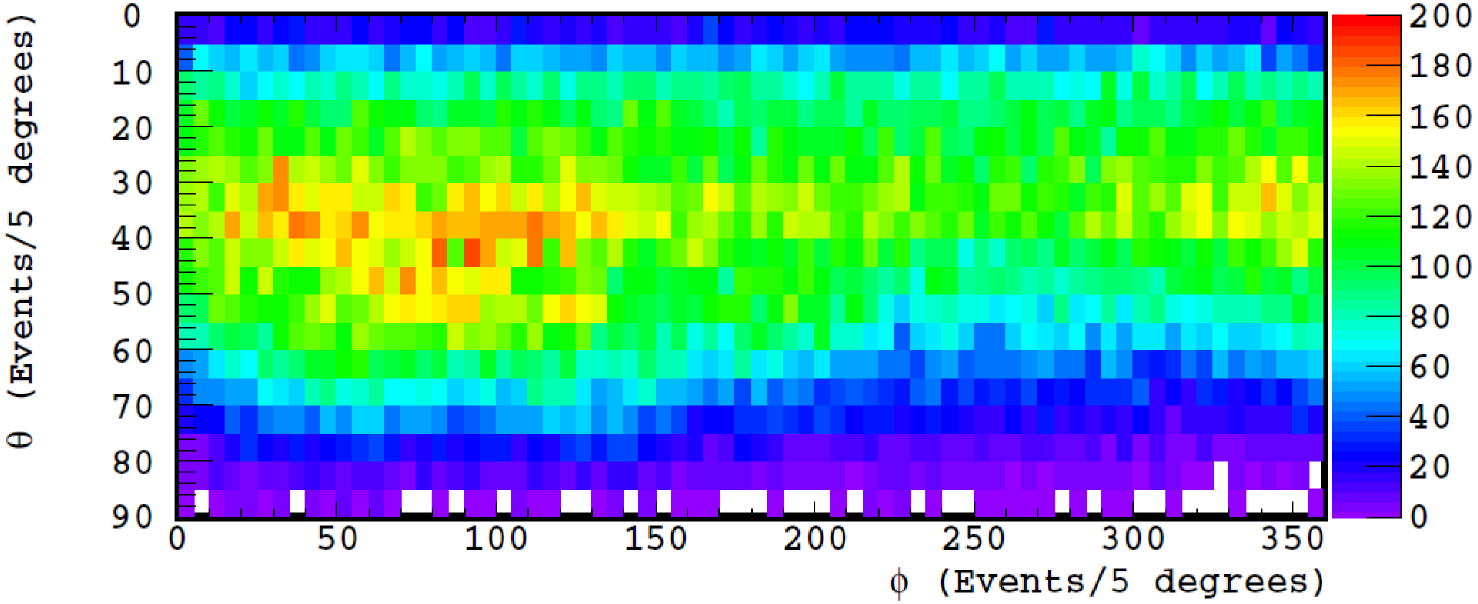
Final decision based on $\chi 2$ minimization

Tagging Muons → Angular Distributions

Near detector

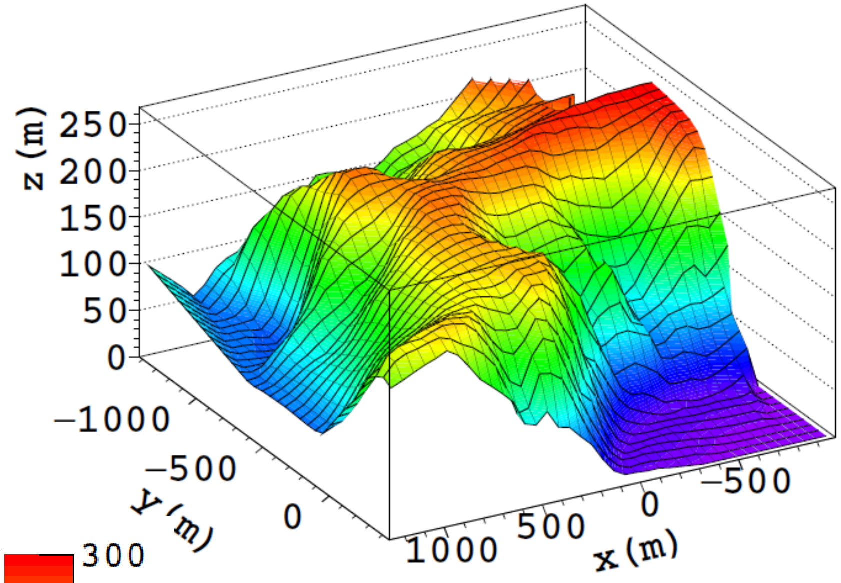


Digitized overburden profile



Tagging Muons → Angular Distributions

Far detector



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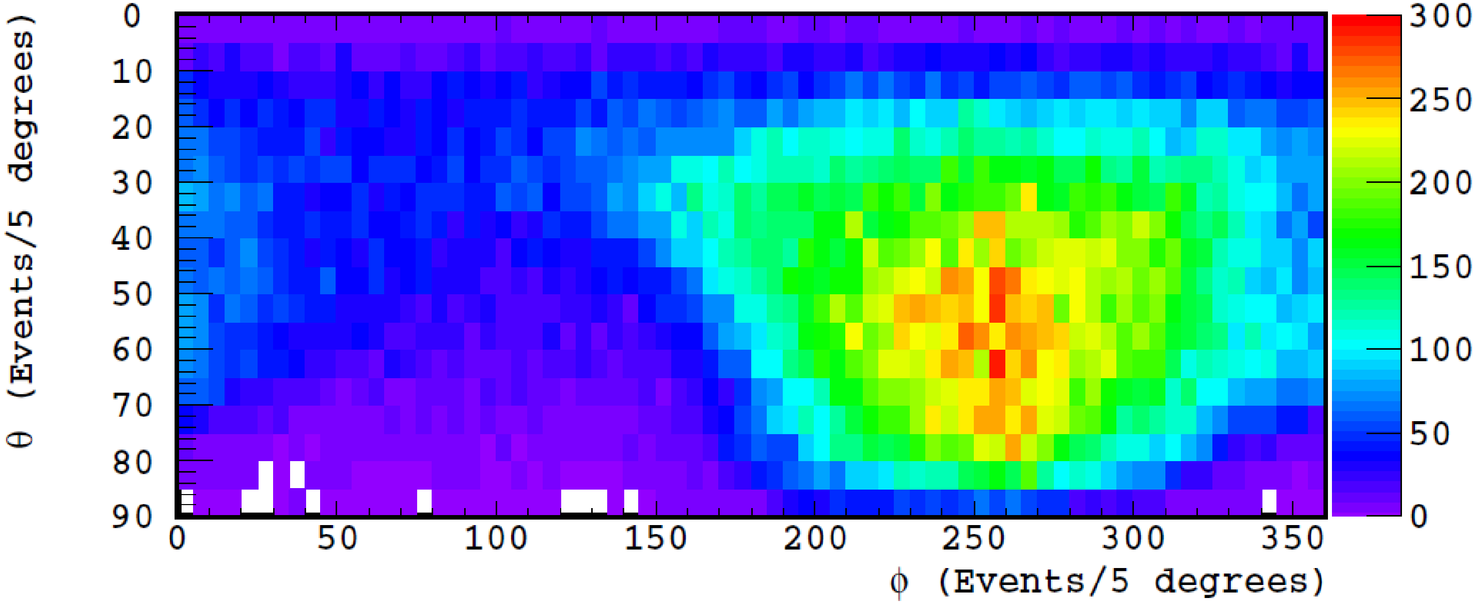
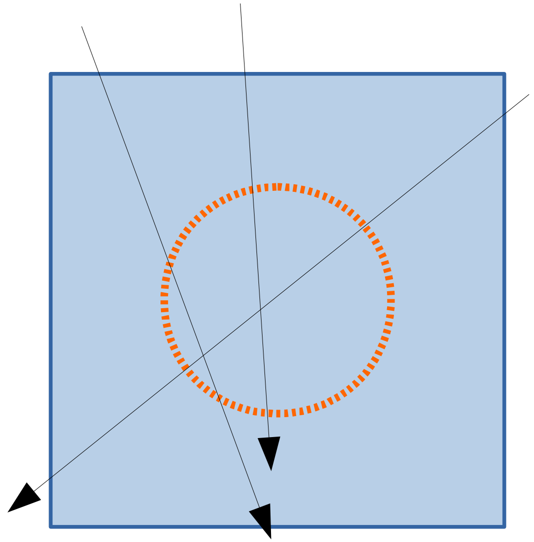


Tagging Muons → Muon Flux

- Flux reconstructed via the so-called "sphere method" which uses the muon identification itself and the track information (minimum track distance to detector centre)

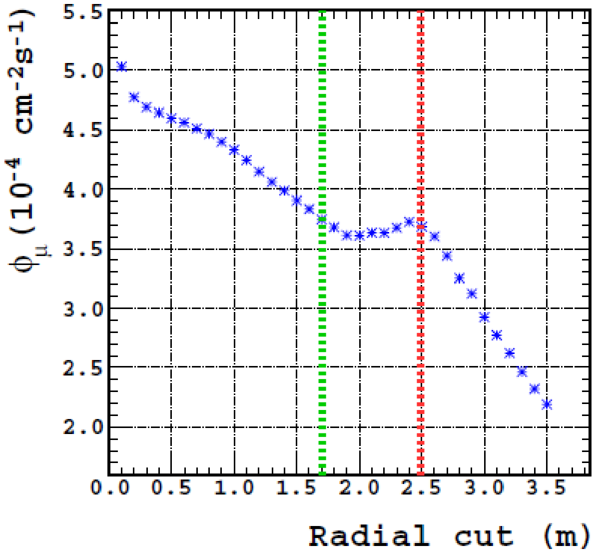
$$\phi_\mu = \frac{\langle R_\mu \rangle}{S_{eff}}$$

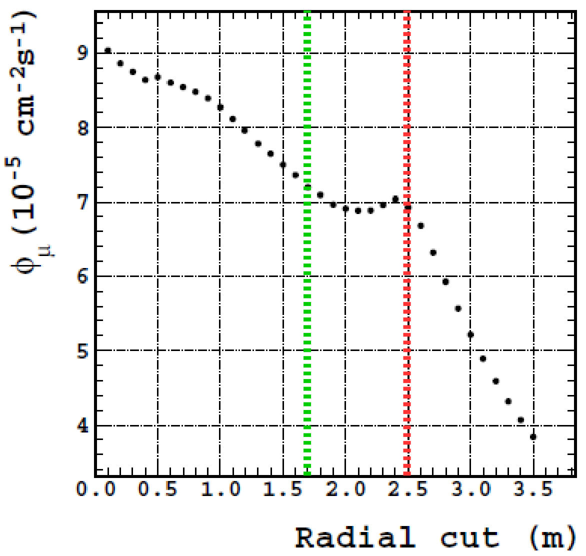


- For a cylindrical detector, S_{eff} is a function of θ and ϕ
  → More difficult to compute
- For a spherical detector, $S_{eff} = \pi R^2$ for all directions
  → Simpler and with lower uncertainties

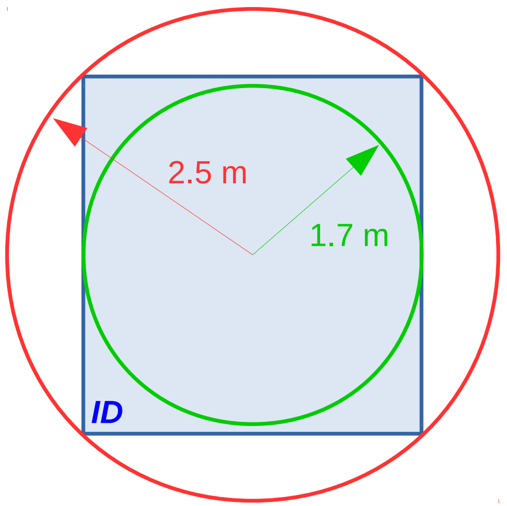
- Selecting μ crossing at a radial distance smaller than ***R*** → $S_{eff} = \pi \boldsymbol{R}^2$
- This radial distance can be computed from the track reconstruction algorithm

Tagging Muons → Muon Flux





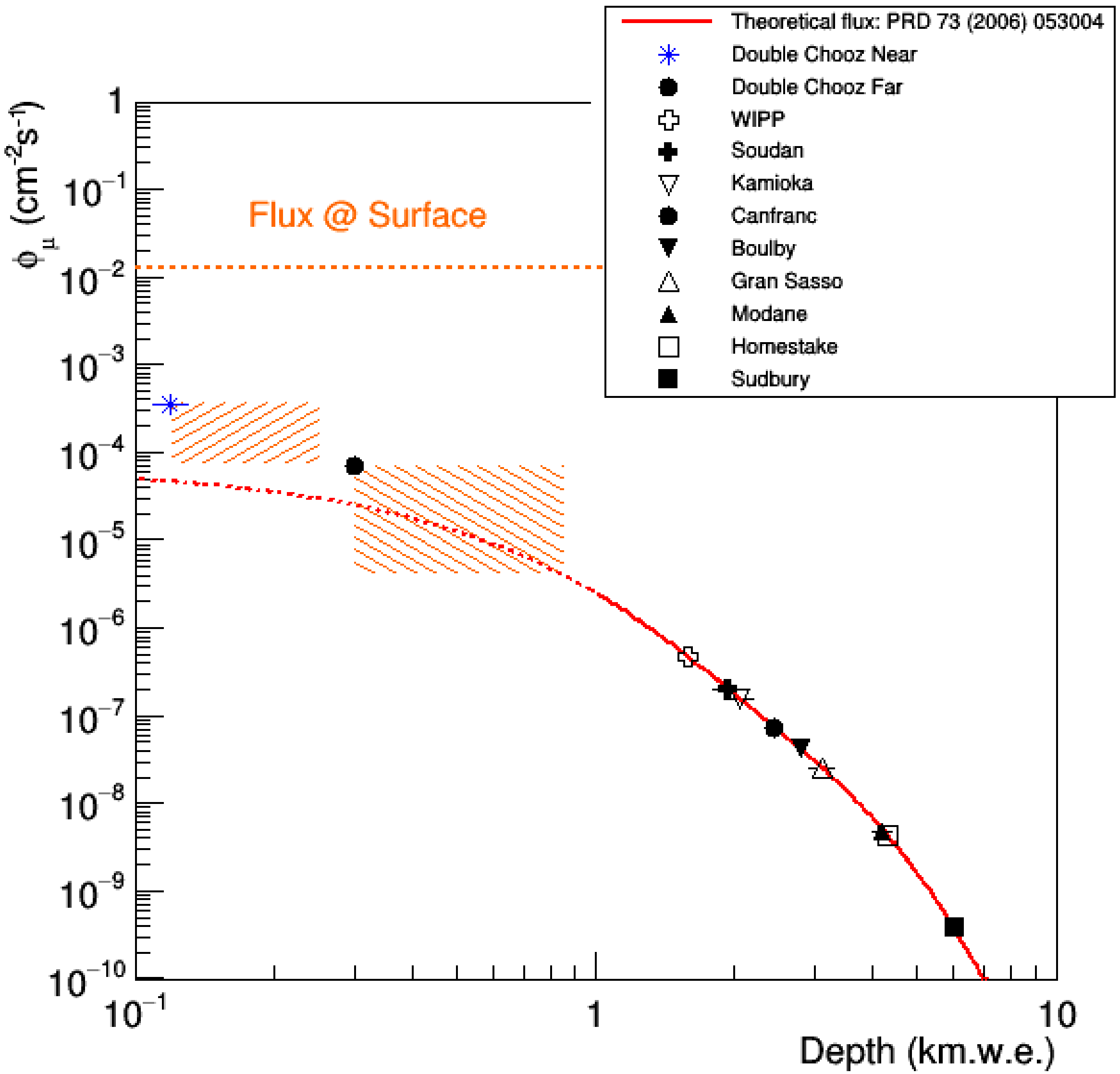
- Bad ϕ_μ reconstruction for low Radial cut:
  - Less statistics
  - Inward shift in the track reconstruction (but keeping direction)
- Spheres contained in the detector and which contain the detector delimit the good range to extract ϕ_μ



ϕ_μ as the mean value in the [1.7 – 2.5] m window:

Near Detector:	$\phi_\mu = 3.64 \pm 0.04\ 10^{-4}\ cm^{-2}\ s^{-1}$
Far Detector:	$\phi_\mu = 7.00 \pm 0.05\ 10^{-5}\ cm^{-2}\ s^{-1}$

Tagging Muons → Muon Flux



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Simulating muons

- Simulations have been performed using the ***MUSIC*** simulation package
  Astroparticle Physics 7 (1997) 357 – 368

  - ✔ Faster than other simulations packages (e.g. Geant 4) → Specially for long μ paths
  - ✔ Versatile: Easy to implement overburden profiles
  - ✖ Not possible to define internal structures/anomalies
  - ✖ Not possible to include detector performance (to do “offline”)

Overburden Profile and Composition

Muon Distribution at Surface

$N_{\mu}\ (E_{\mu},\ \theta,\phi)$

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Overburden Profile and Composition

Muon Distribution at Surface

$N_\mu\ (E_\mu, \theta,\phi)$

Simulating muons

- Due to the low overburden (120 and 300 m.w.e.) muons down to 20 and 40 GeV respectively are able to reach the detectors

  ➔ It is for low energies where muon models present more differences

- Comparing simulations between them and w.r.t experimental data would allow to validate these models

Extended Gaisser parametrization:
Phys. Rev. D 74 (2006) 053007

- ✔ Based on Gaisser analytical formula ($E_\mu > 100/\cos(\theta)$ GeV)
- Originally not valid for low energy; valid extension?

CRY generation:
http://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry.pdf

- Generated from data tables of MCNPX 2.5.0
- ✖ Discretization effects
- ✔ Validated with experimental measurements in the 4 – 3000 GeV energy range
  Nucl. Part. Phys. 10 (1984) 1609

Reyna parametrization:
arXiv:hep-ph/0604145

- ✔ Analytical formula from different measurements
- ✔ Valid in the 1 - 4000 GeV energy range

Simulating muons

- Due to the low overburden (120 and 300 m.w.e.) muons down to 20 and 40 GeV respectively are able to reach the detectors

  ➔ It is for low energies where muon models present more differences

- Comparing simulations between them and w.r.t experimental data would allow to validate these models

Extended Gaisser parametrization:
Phys. Rev. D 74 (2006) 053007

- ✔ Based on Gaisser analytical formula ($E_\mu > 100/\cos(\theta)$ GeV)
- ● Originally not valid for low energy; valid extension?

CRY generation:
http://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry.pdf

- ● Generated from data tables of MCNPX 2.5.0
- ✖ Discretization effects
- ✔ Validated with experimental measurements in the 4 – 3000 GeV energy range
  Nucl. Part. Phys. 10 (1984) 1609

Reyna parametrization:
arXiv:hep-ph/0604145

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- ✔ Valid in the 1 - 4000 GeV energy range

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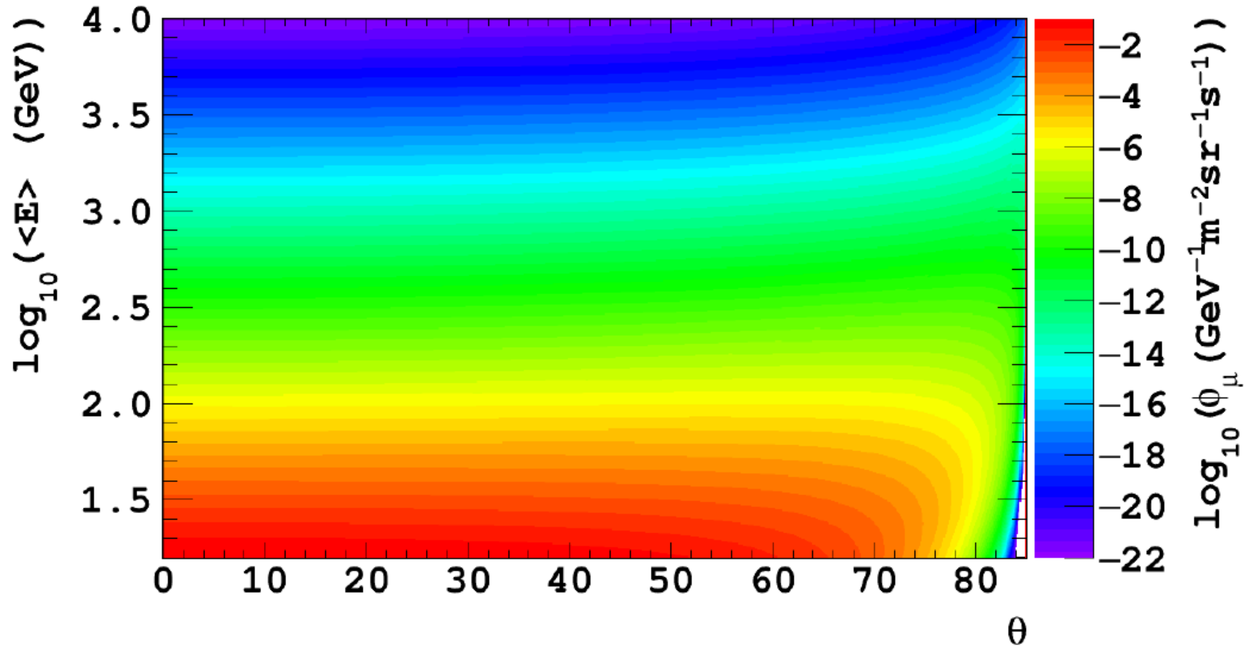
Extended Gaisser parametrization:
Phys. Rev. D 74 (2006) 053007

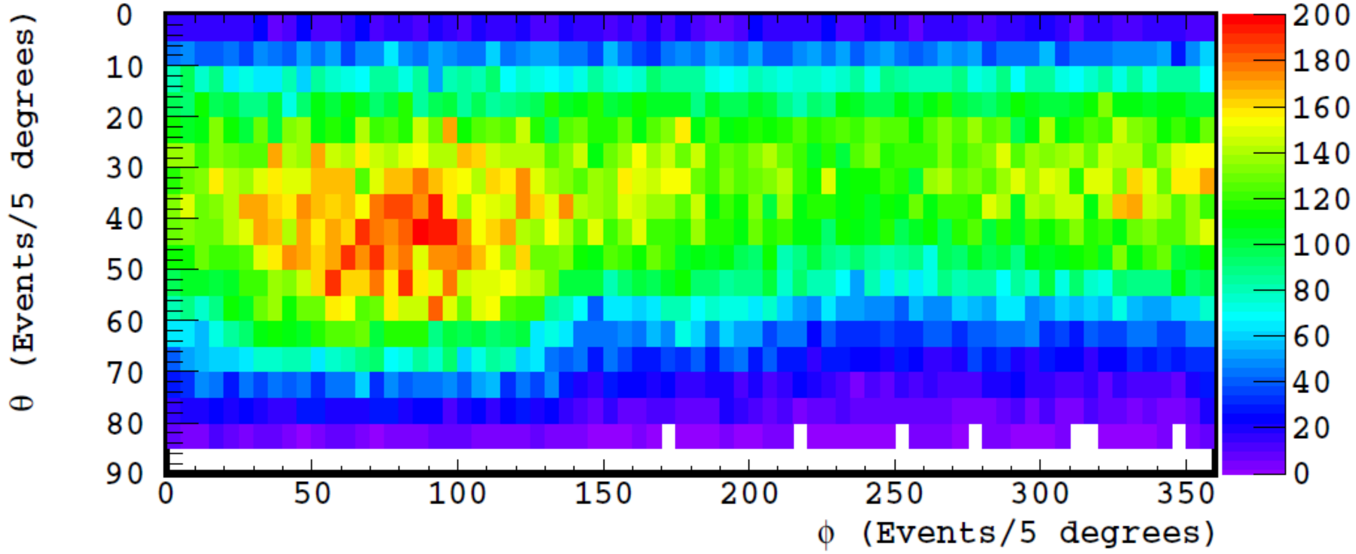
✔ Based on Gaisser analytical formula ($E_{\mu} > 100/\cos(\theta)$ GeV)

Originally not valid for low energy; valid extension?

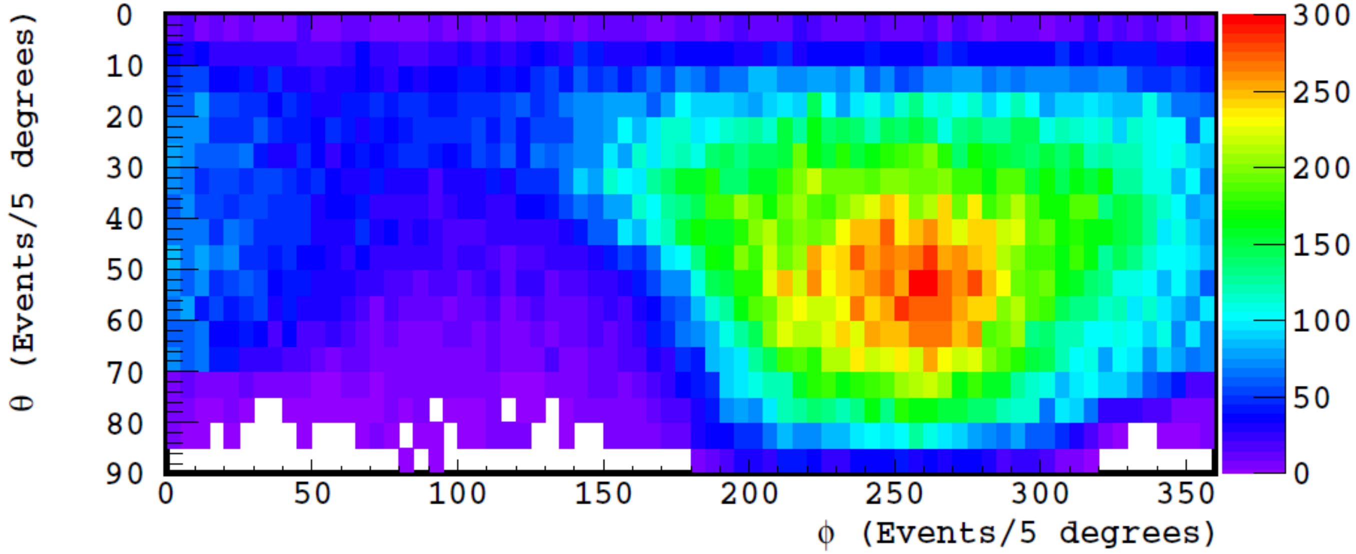


Simulating muons → Angular distributions

Near detector

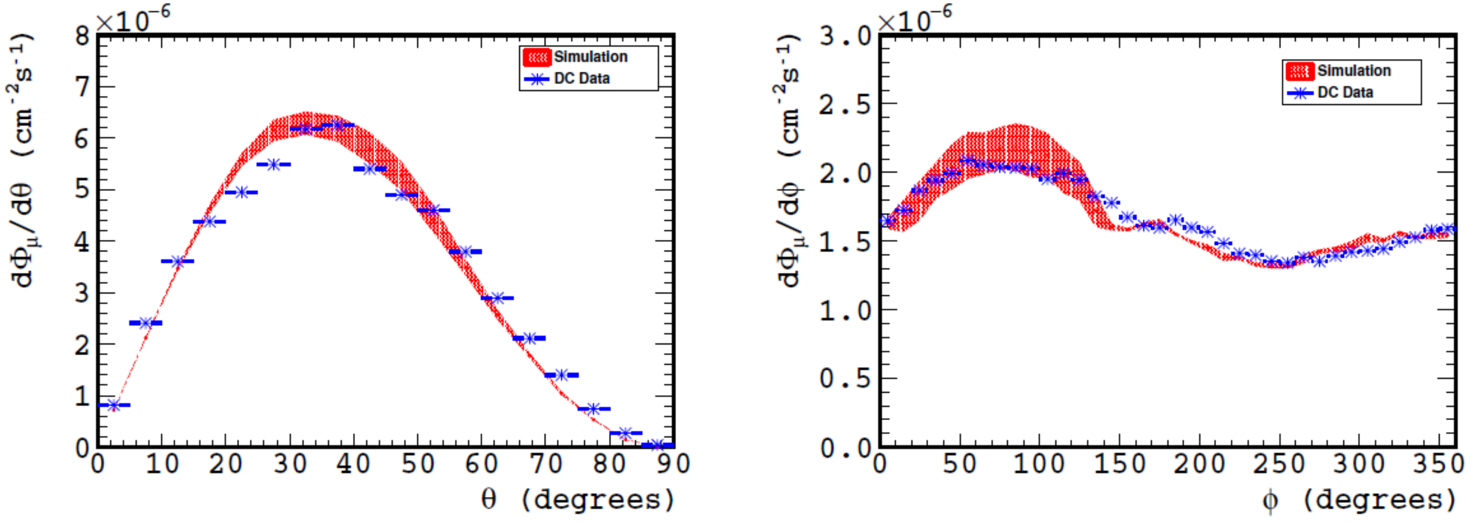


Far detector



Simulating muons → Data/MC comparison

Near detector



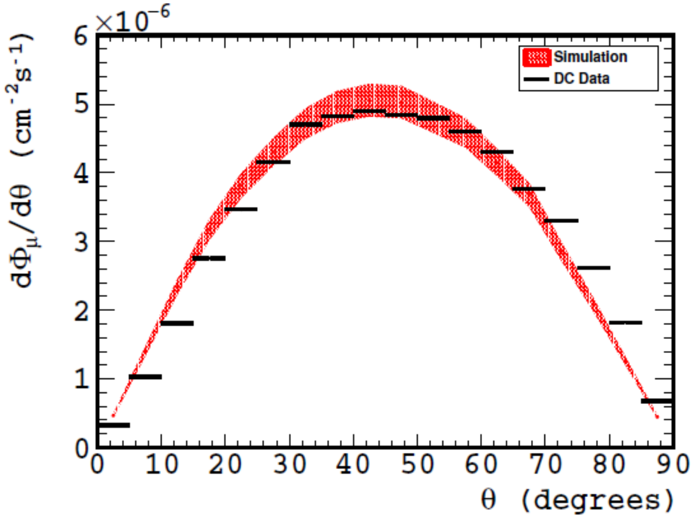
Data:	$\phi_\mu = 3.64 \pm 0.04\ 10^{-4}\ cm^{-2}\ s^{-1}$
Simulations:	$\phi_\mu = 3.47 \pm 0.12\ 10^{-5}\ cm^{-2}\ s^{-1}$

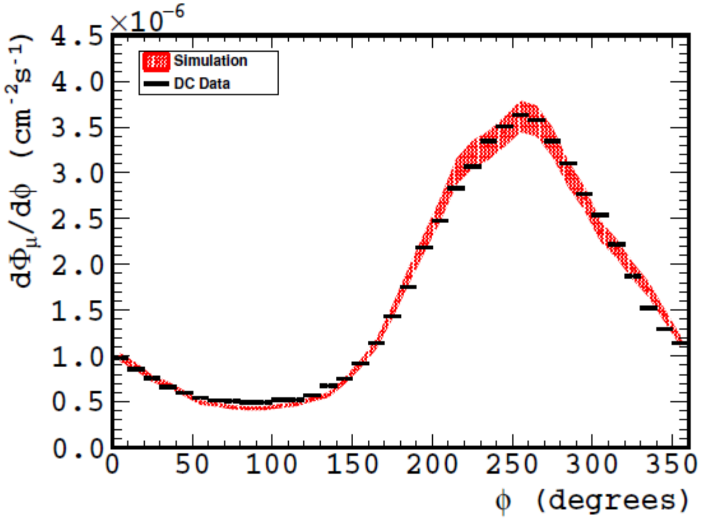
Differences due to:

- Uncertainties in the low energy muon parametrization
- Lower precision in the profile digitization for Near Detector

Simulating muons → Data/MC comparison

Far detector





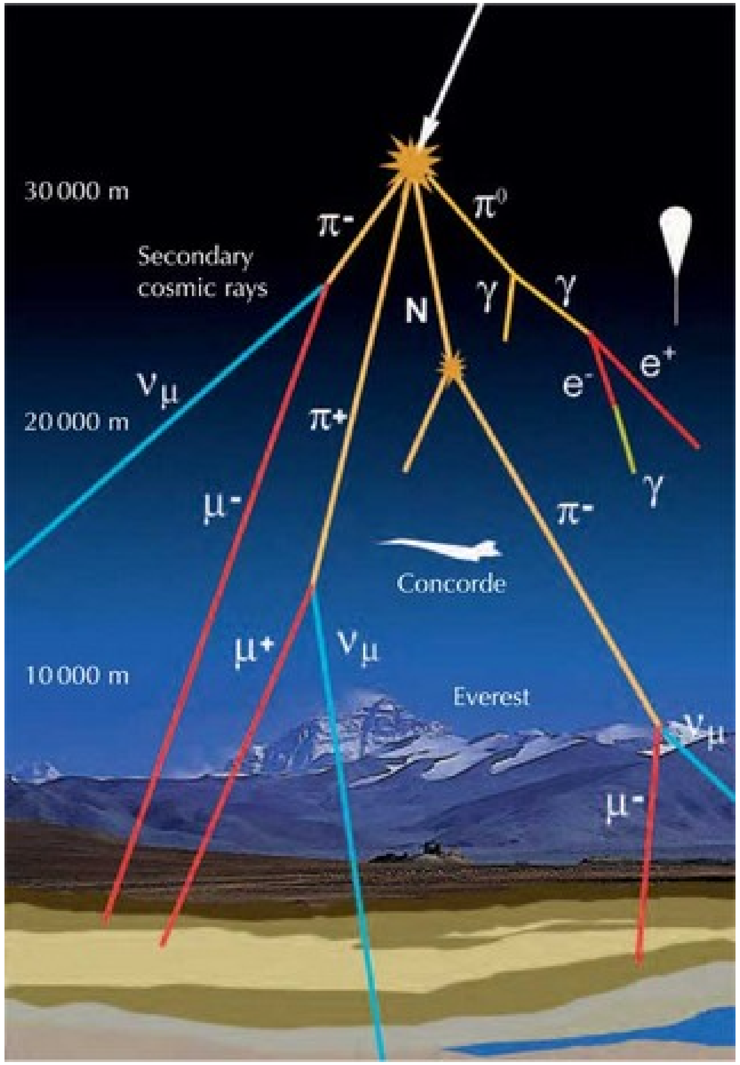
Data:	$\phi_\mu = 7.00 \pm 0.05\ 10^{-4}\ cm^{-2}\ s^{-1}$
Simulations:	$\phi_\mu = 7.24 \pm 0.33\ 10^{-5}\ cm^{-2}\ s^{-1}$

Differences due to:

- Uncertainties in the low energy muon parametrization
- Lower precision in the profile digitization for Near Detector

- Even if (don't forget) ***Double Chooz*** was conceived as a ***neutrino detector experiment***
- Muon characterization has revealed:
  - Muons are efficiently detected
  - Corresponding tracks has been successfully reconstructed
  - Simulation framework has been performed and cross-checked with experimental data
- Moreover:
  - Double Chooz has been (it is being actually) operated from 2011 → High muon statistics
  - Simulation provides additional information not available from experimental data

- Annual modulation on the detected muon flux is expected:



- pN → Mesons (mostly π but also K)
  → Decay to muons
- Muons loose energy along their path through the atmosphere (and the rock over the detector)
- ***Deeper detectors*** → ***Higher E_μ required***

- Fraction of mesons decaying to muons depends on the air density:

→ ***Higher temperature***

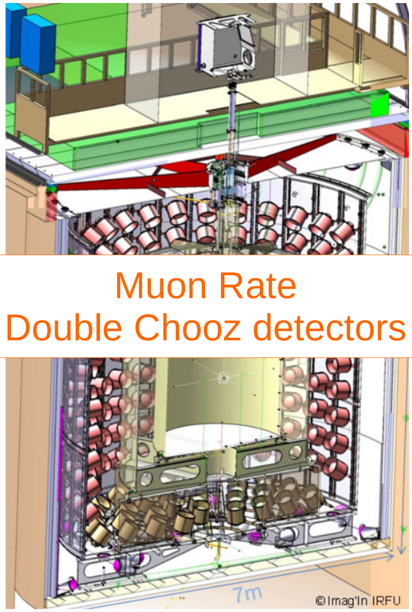
→ Lower density

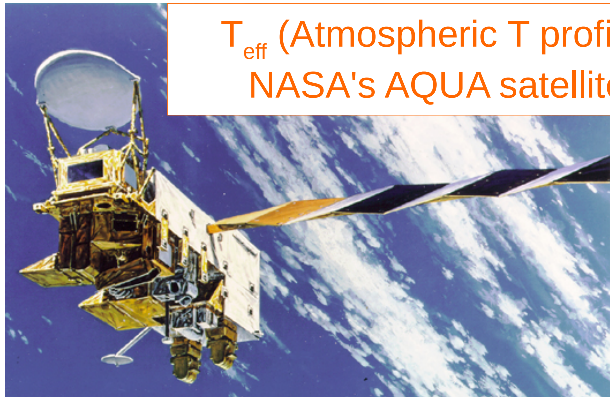
→ Mesons mean free path longer

→ Higher fraction of mesons decaying (to muons) before interacting

→ ***Higher muon rate***

- Ingredients to study the annual modulation:



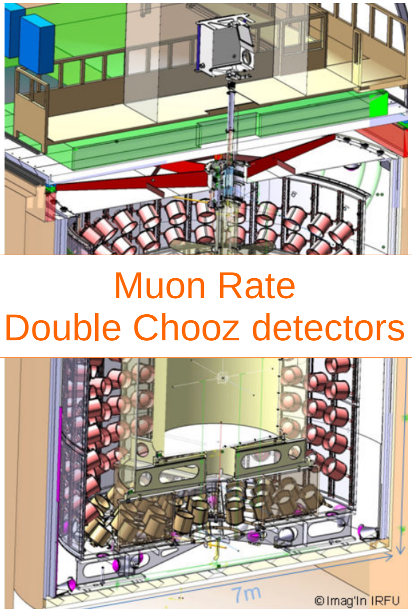


$$T_{\text{eff}} = \frac{\sum_{n=0}^{N-1} \Delta X_n \cdot T(X_n)(W_\pi(X_n) + W_K(X_n))}{\sum_{n=0}^{N} \Delta X_n (W_\pi(X_n) + W_K(X_n))}$$

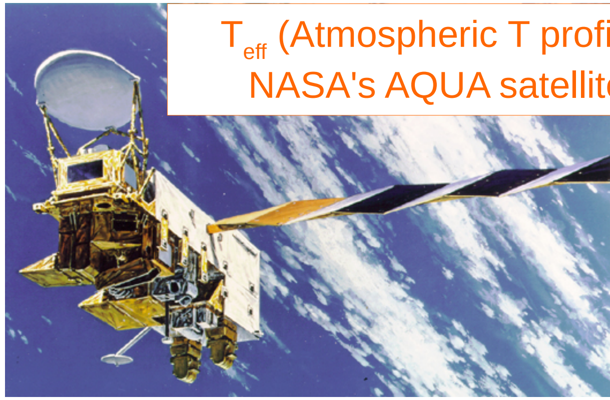
$$W_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2 e^{-X/\Lambda_{\pi,K}} A^1_{\pi,K}}{\gamma + (\gamma+1) B^1_{\pi,K} K_{\pi,K}(X) (\langle E_{\text{thr}} \cos\theta \rangle / \epsilon_{\pi,K})^2}$$

$$K_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2}{(1 - e^{-X/\Lambda'_{\pi,K}}) \Lambda'_{\pi,K}/X}$$

- Ingredients to study the annual modulation:



Muon Rate
Double Chooz detectors

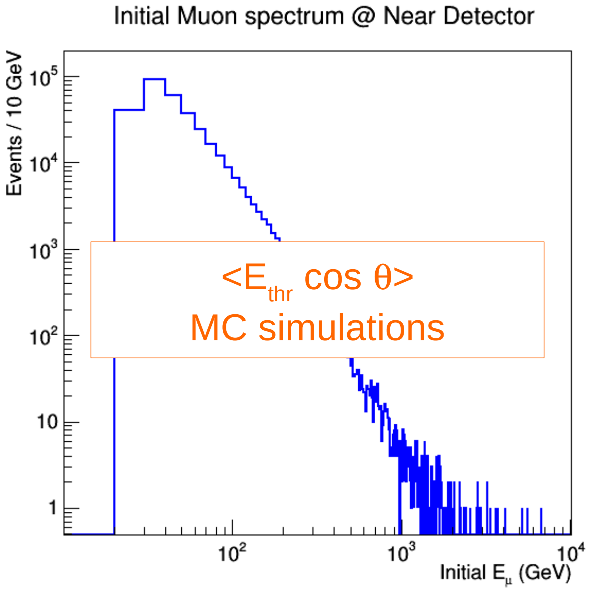


T_{eff} (Atmospheric T profile)
NASA's AQUA satellite

$$T_{\rm eff} = \frac{\sum_{n=0}^{N-1} \Delta X_n \cdot T(X_n)(W_\pi(X_n) + W_K(X_n))}{\sum_{n=0}^{N} \Delta X_n (W_\pi(X_n) + W_K(X_n))}$$

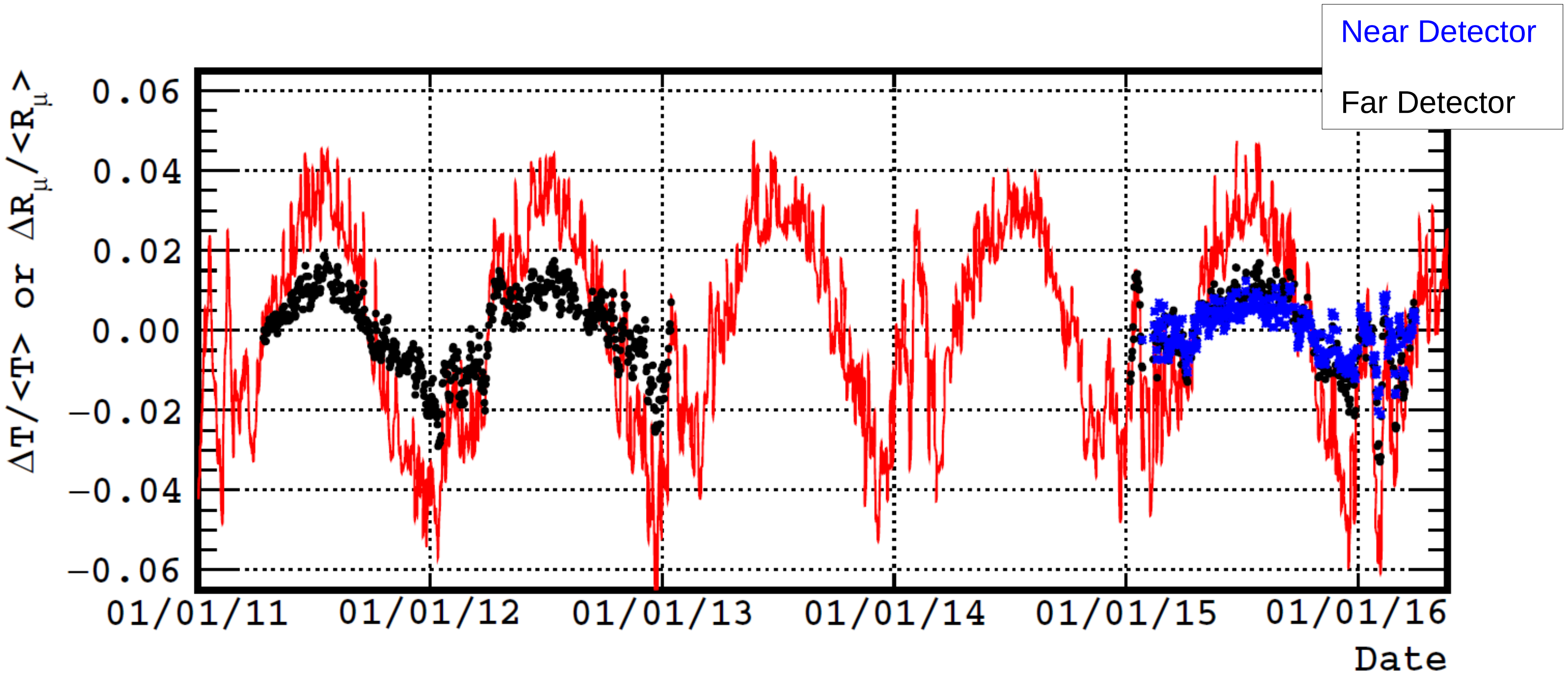
$$W_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2 e^{-X/\Lambda_{\pi,K}} A^1_{\pi,K}}{\gamma + (\gamma+1) B^1_{\pi,K} K_{\pi,K}(X) (\langle E_{\rm thr} \cos\theta \rangle / \epsilon_{\pi,K})^2}$$

$$K_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2}{(1 - e^{-X/\Lambda'_{\pi,K}})\Lambda'_{\pi,K}/X}$$



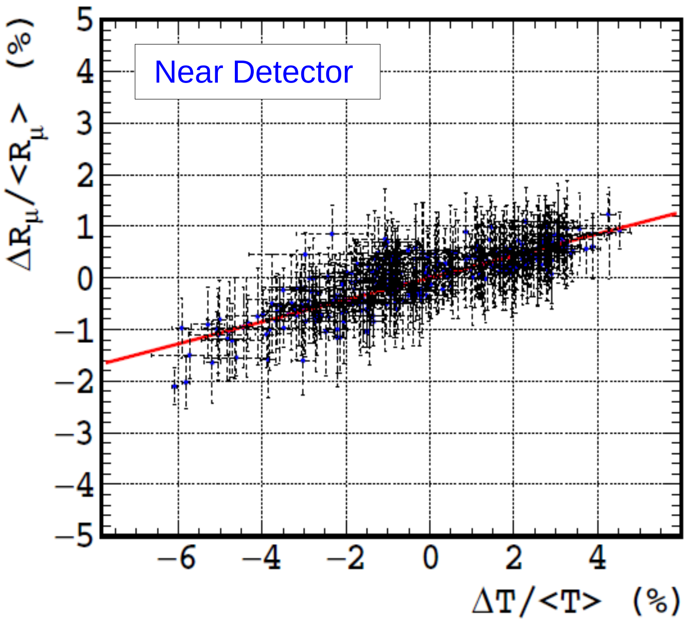
$<E_{thr} \cos\theta>$
MC simulations

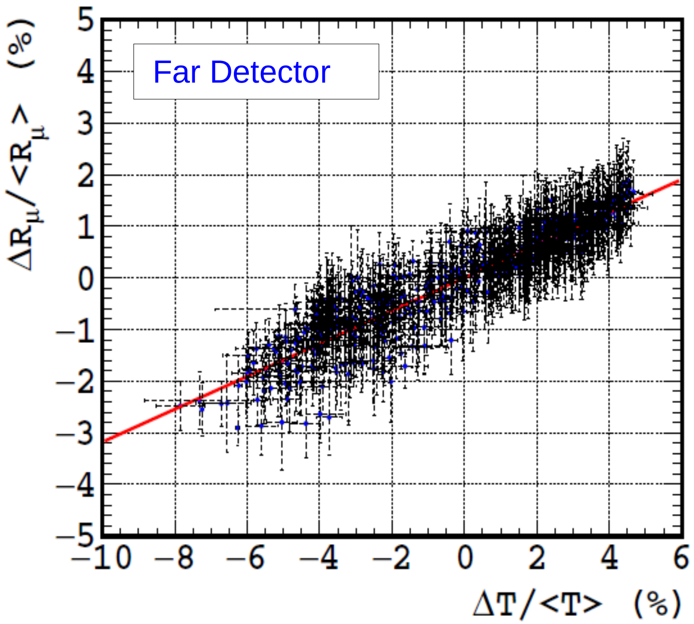
Near detector	$<E_{thr} \cos\theta> = 22.3 \pm 4.8$ GeV
Far detector	$<E_{thr} \cos\theta> = 46.0 \pm 10.0$ GeV



Effective temperature coefficient (α_T) :

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$





Effective temperature coefficient (α_T) :

Near detector: α_T = 0.212 ± 0.013 (stat) ± 0.011 (sys)	Correlation (R_μ, T_{eff}) = 0.855
Far detector: α_T = 0.355 ± 0.002 (stat) ± 0.017 (sys)	Correlation (R_μ, T_{eff}) = 0.923

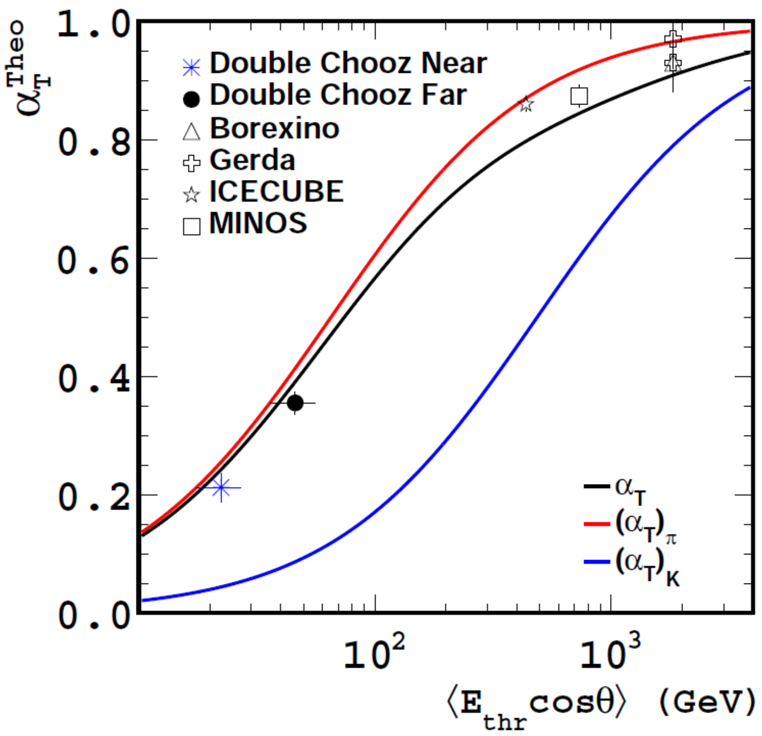
- Double Chooz results for α_T can be used to compare / validate theoretical models

$$\alpha_T^{\mathrm{Theo}} = \frac{1}{D_\pi} \frac{1/\epsilon_K + A_K^1 (D_\pi/D_K)^2/\epsilon_\pi}{1/\epsilon_K + A_K^1 (D_\pi/D_K)/\epsilon_\pi}$$

$$D_{K,\pi} = \frac{\gamma}{\gamma+1} \frac{\epsilon_{K,\pi}}{1.1\langle E_{\mathrm{thr}} \cos\theta\rangle} + 1$$

It depends, via A^1_K, of the assumed Pion to Kaon ratio

$r_{K/\pi} = 0.149 \pm 0.060$ *T.K. Gaisser, Cosmic rays and particle physics, Cambridge University Press, Cambridge U.K., (1990)*



- Double Chooz measurements in agreement with theoretical model
- One of the first validations for low values of $\langle E_{\mathrm{thr}} \cos\theta\rangle$

- Focused on reactor neutrino experiments, muon understanding in future projects is a must:
  - Background identification and control
  - Use them for calibration
  - Long – term data taking → Annual modulation studies for different $\langle E_{thr} \cos\theta \rangle$ value

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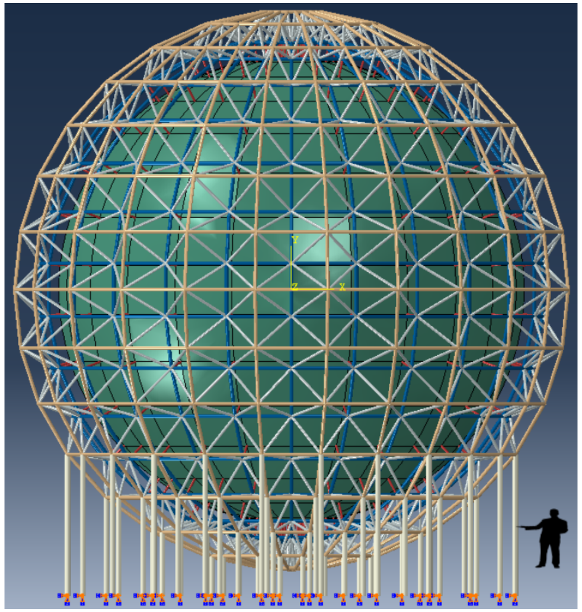

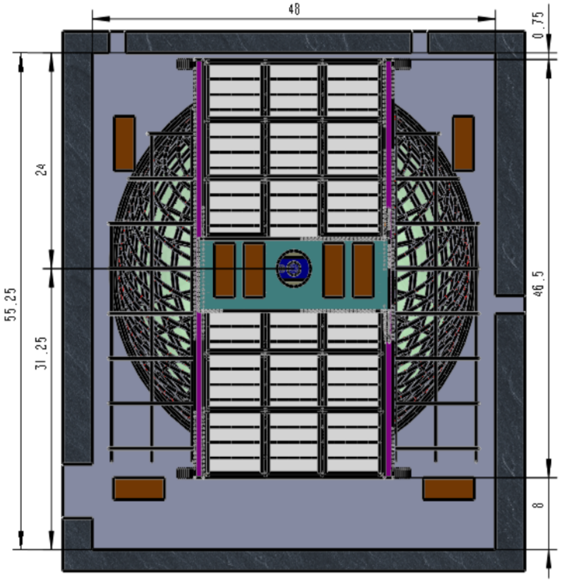

JUNO

- Rejects and identify muons by:
    - ***~1900 m.w.e.*** overburden (it should be considered underground physics)
    - Active muon veto
        - Water Cherenkov
        - Top tracker (from OPERA)
    - ***$\langle R_\mu \rangle \sim \mathcal{O}(10)$ Hz expected***

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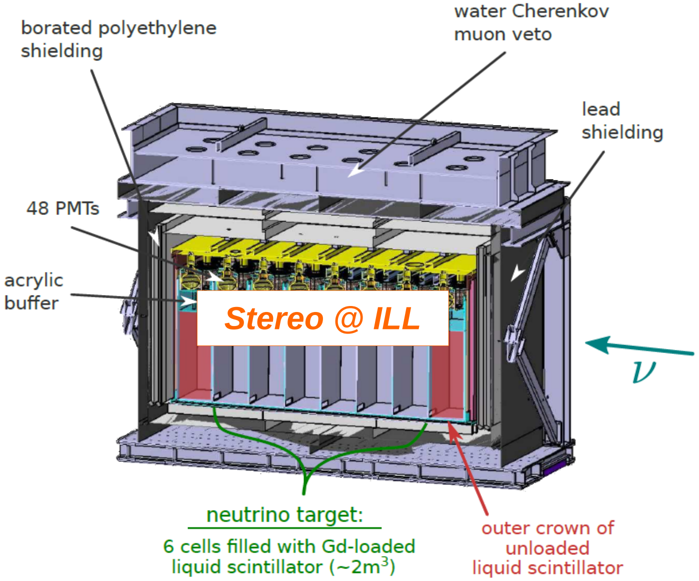

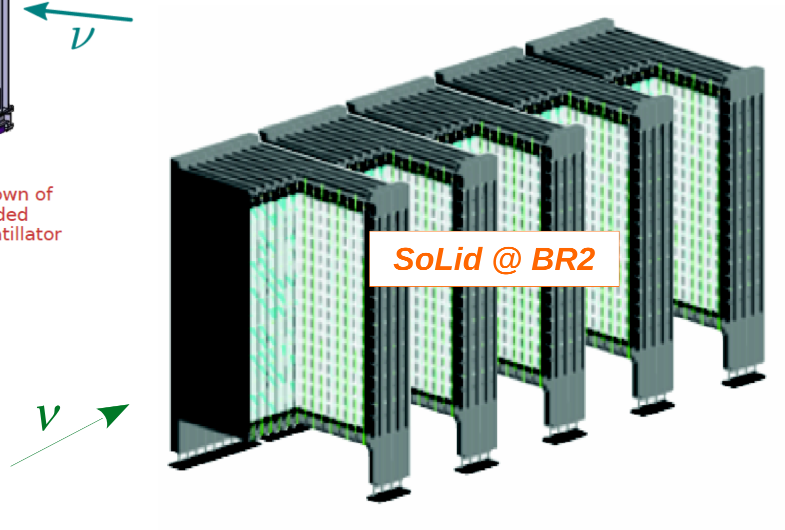

Sterile ν

- ***At Surface!!***
  - Rejection by active muon veto
    - Stereo → Water Cherenkov
    - Solid → Track identification
      - ✔ Detector Calibration

- Focused on reactor neutrino experiments, muon understanding in future projects is a must:
  - Background identification and control
  - Use them for calibration
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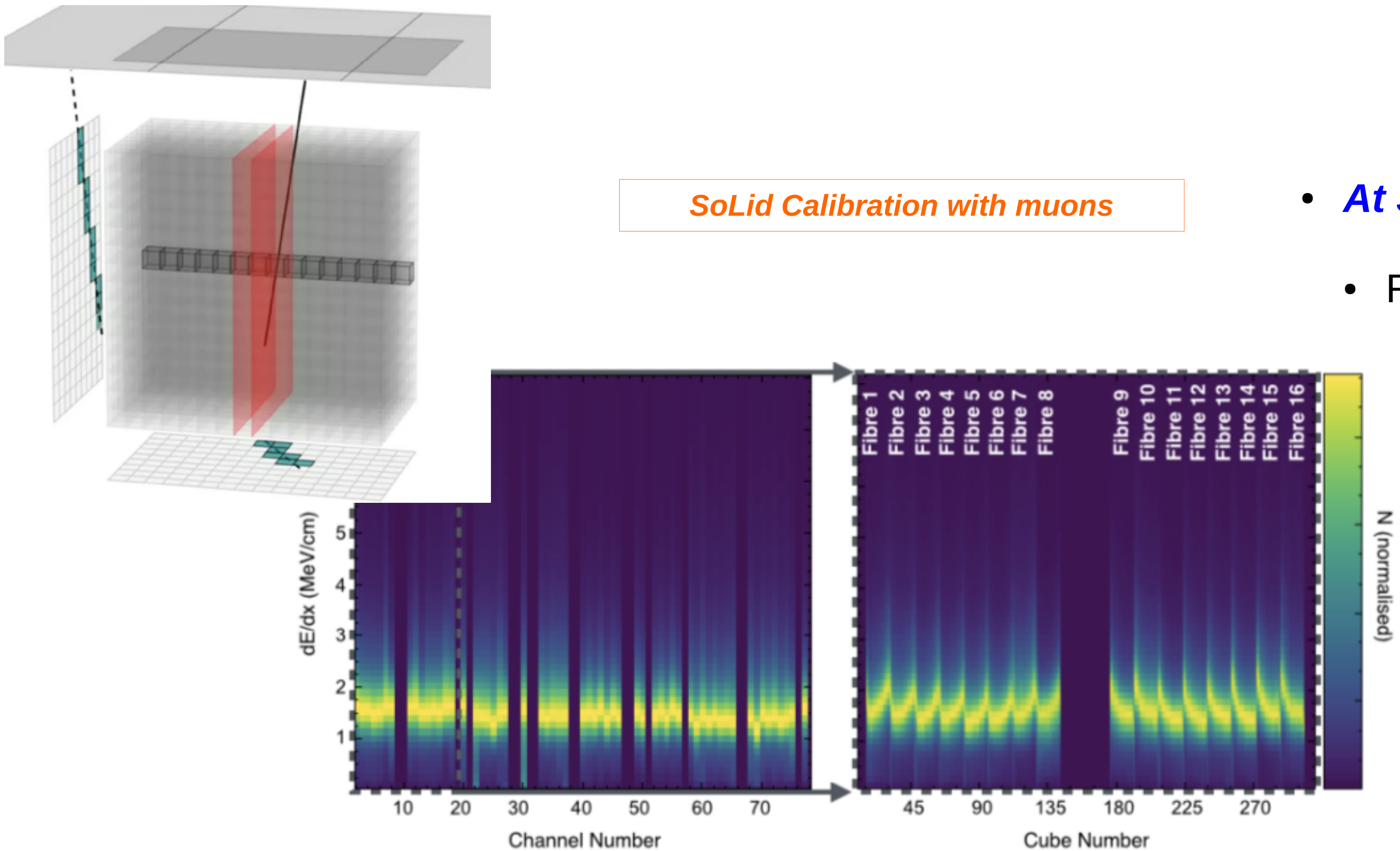
SoLid Calibration with muons



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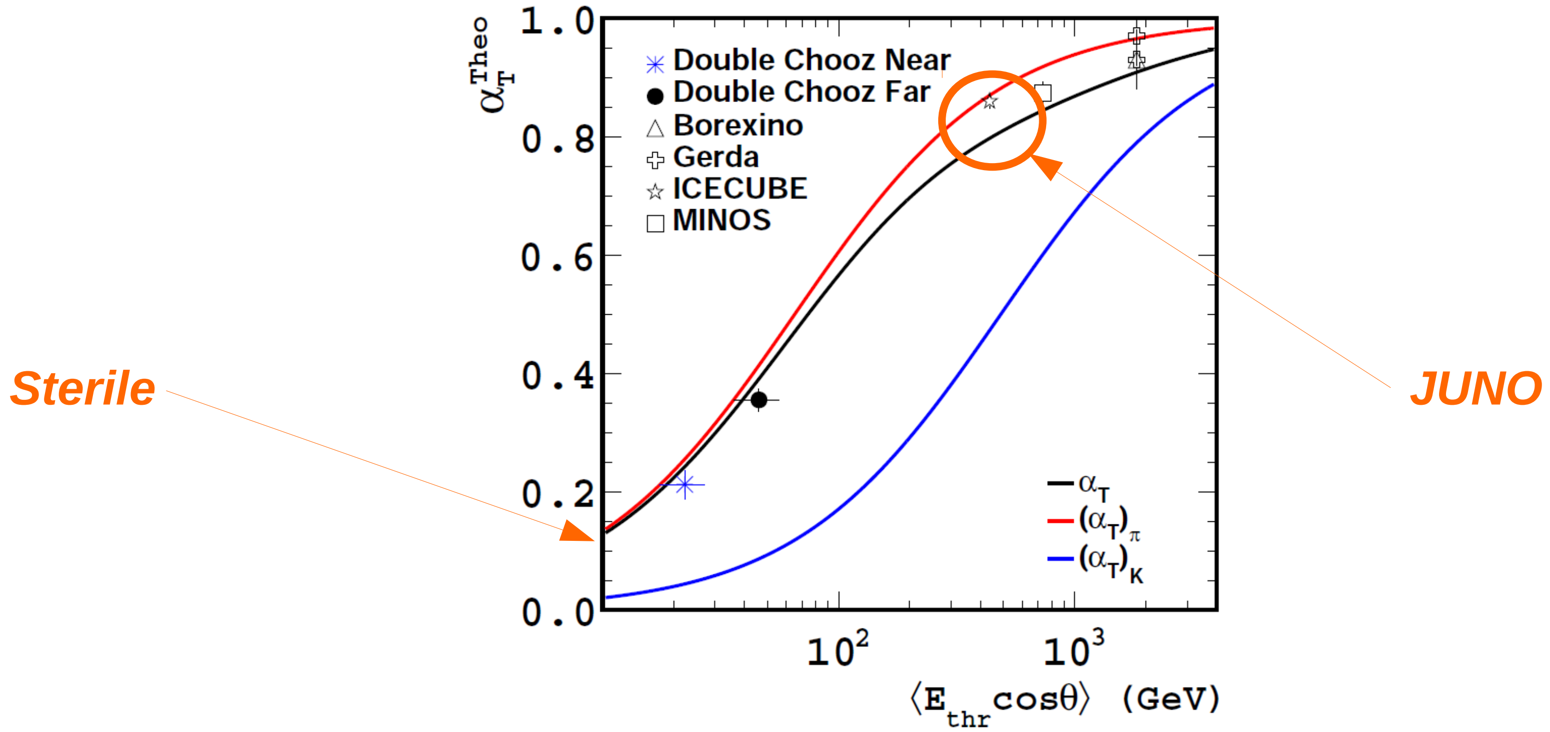
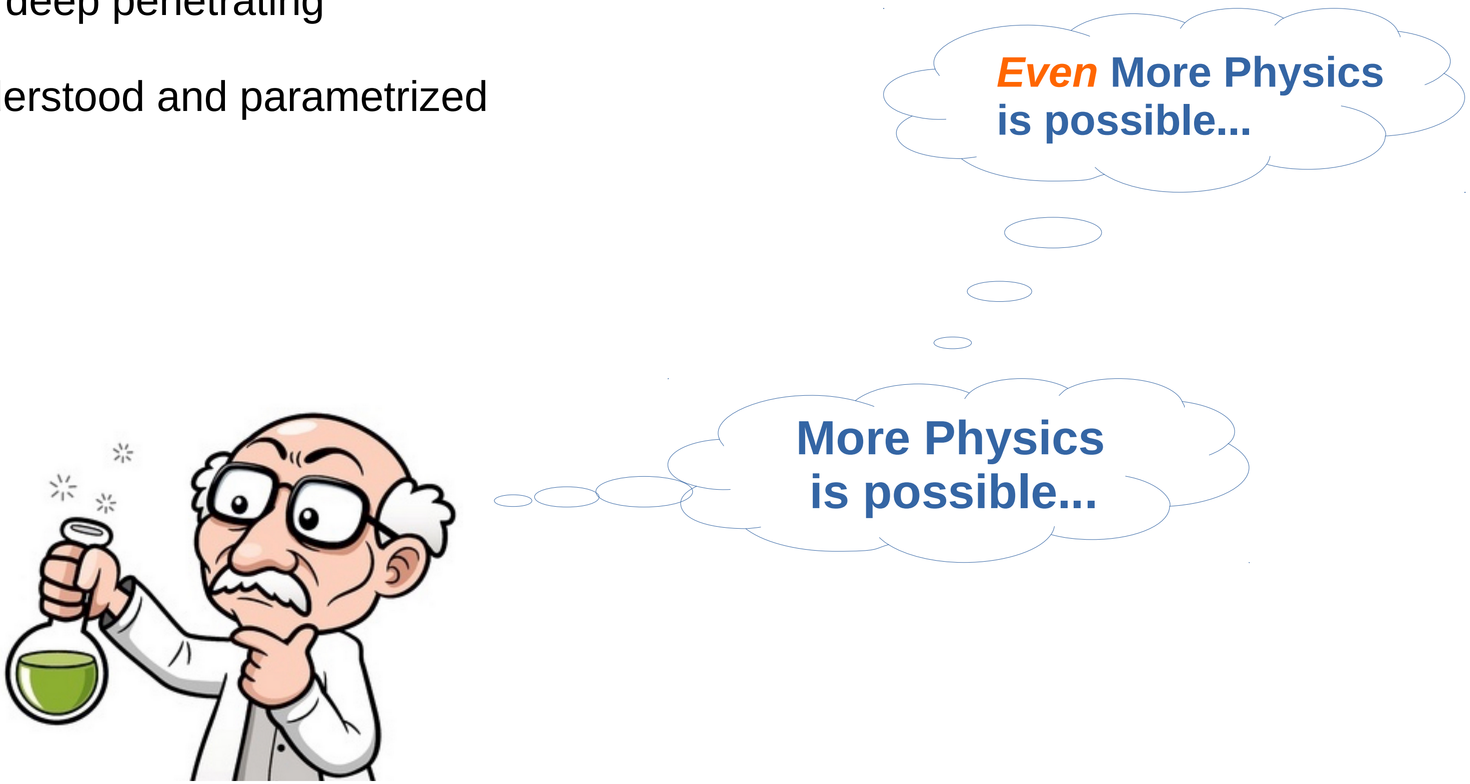


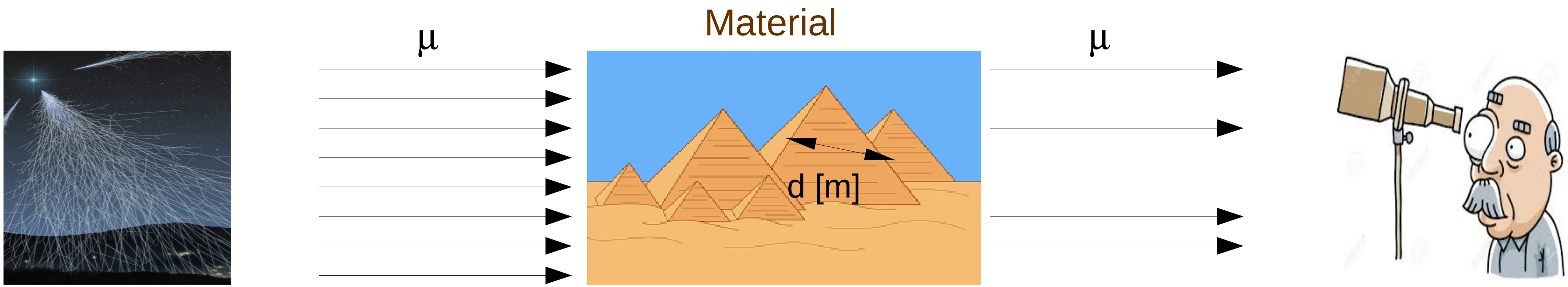
Taking advantage of muons

- Atmospheric muons as radioactive source:
  - ✔ Natural – Non human risky
  - ✔ Free
  - Rather intense
  - ✔ Extended and deep penetrating
  - Fairly well understood and parametrized



Muon tomography

In a nutshell



Initial flux ϕ_i

Basically dependant on the μ energy and zenith angle (E, θ)

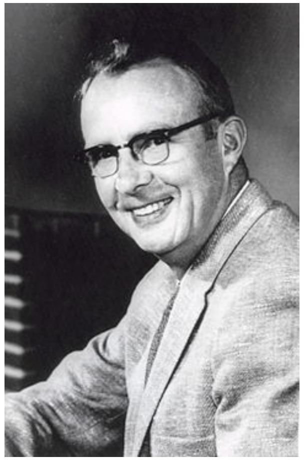
Density: ρ [g/cm3]

Linear Density: **δ [g/cm²]** = ρ d

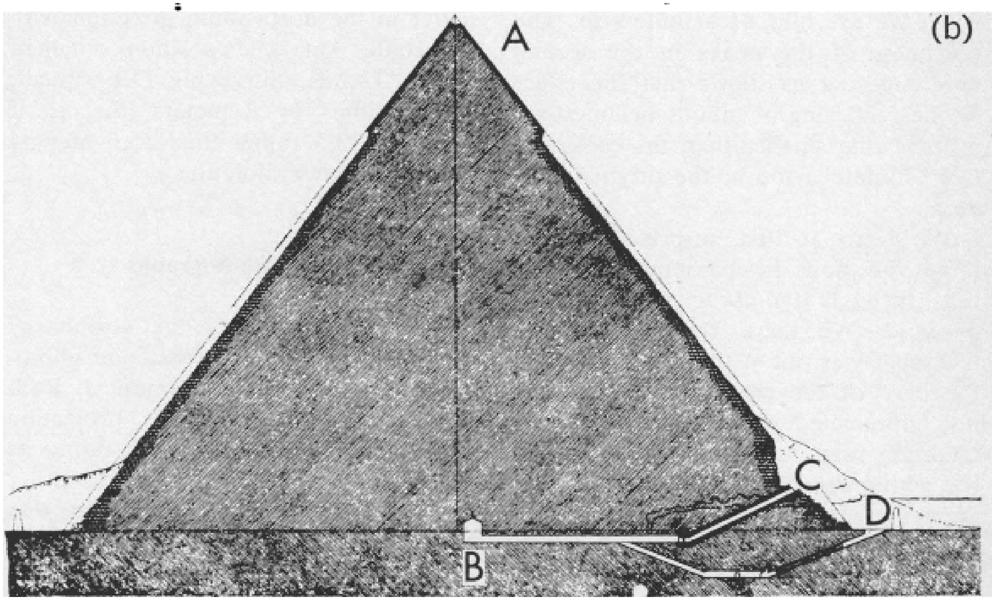
Final flux ϕ_f

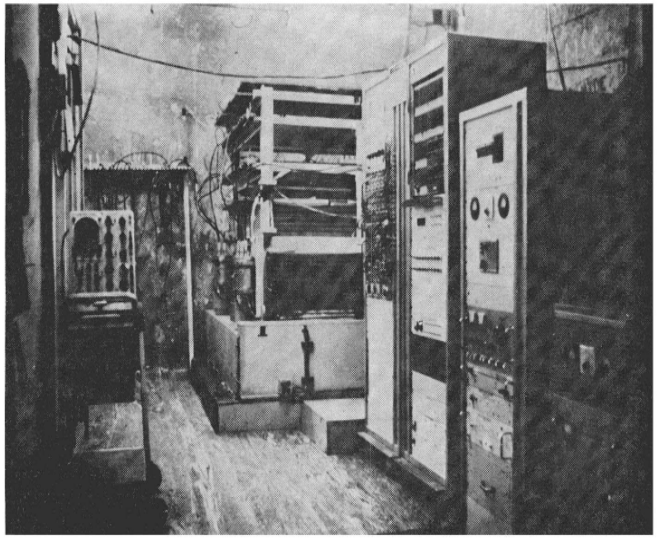
Detected muons for a given direction

- Ratio between initial and final fluxes is directly related with Linear Density
- Differences in final flux (after normalization) for different directions also points to Linear Density differences
- Muon deflection could also imply the existence of high density anomalies



- ***1970: L.W. Alvarez (1968 Physics Nobel Prize)***
  - Scanning of Chefren Pyramid looking for internal vaults
  - Nothing found
  - *Alvarez, L.W. (1970). "Search for hidden chambers in the pyramids using cosmic rays". Science 167: 832*





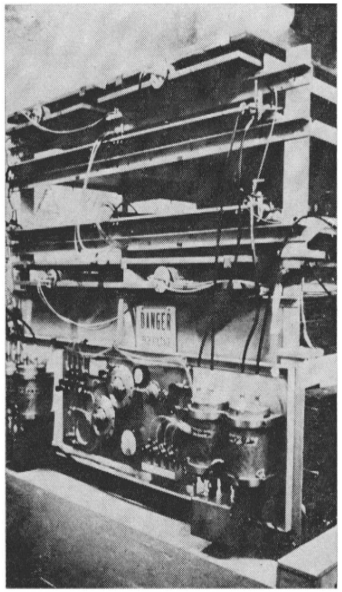
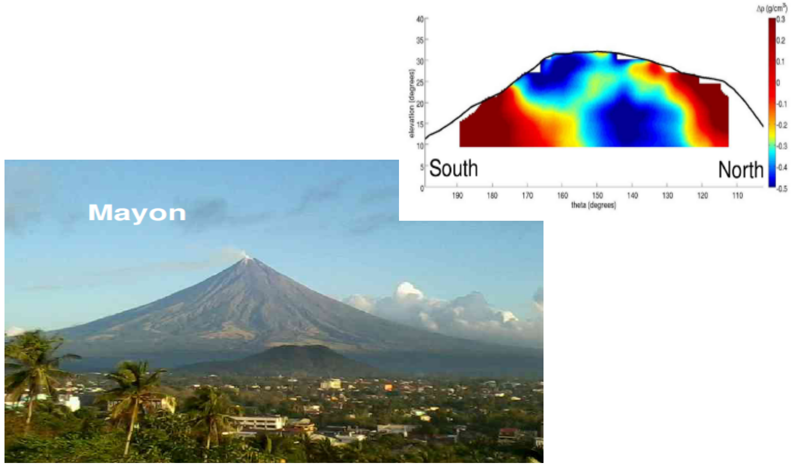


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.

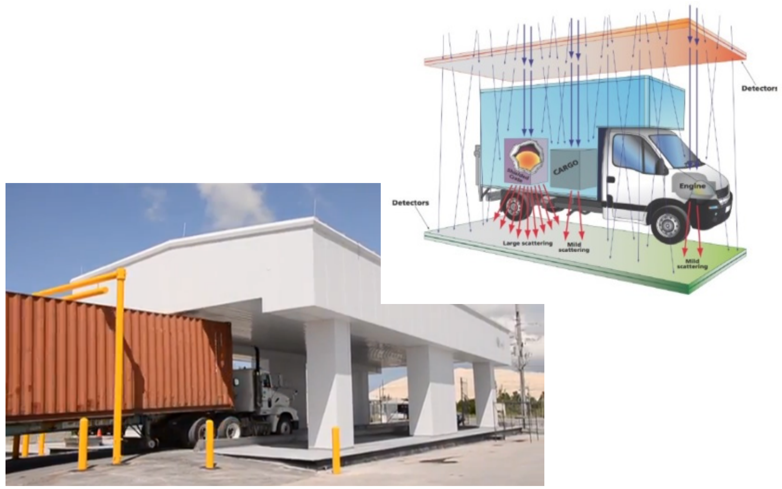


Volcano Tomography

Fukushima scanning

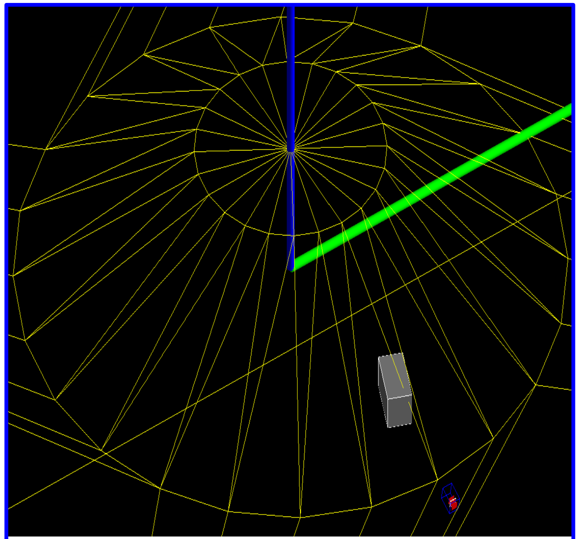
Nuclear control and safety

Archaeology



Merchandise scanning

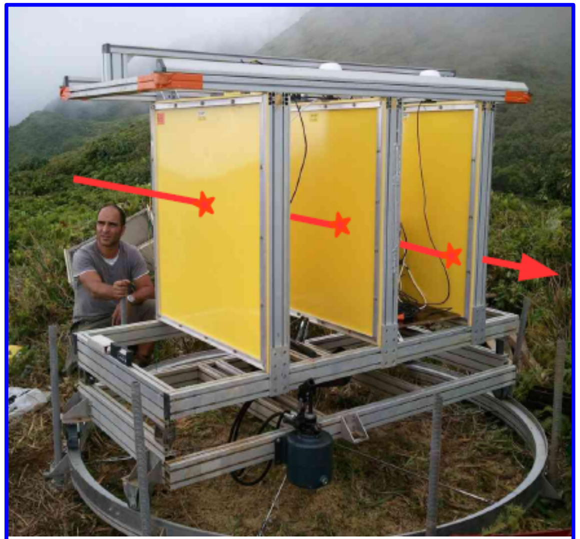
Archéologie avec des ***R***ayons ***C***osmiques, pour sonder les tumuli ***HE***lléniques



Feasibility studies by
Monte Carlo simulations

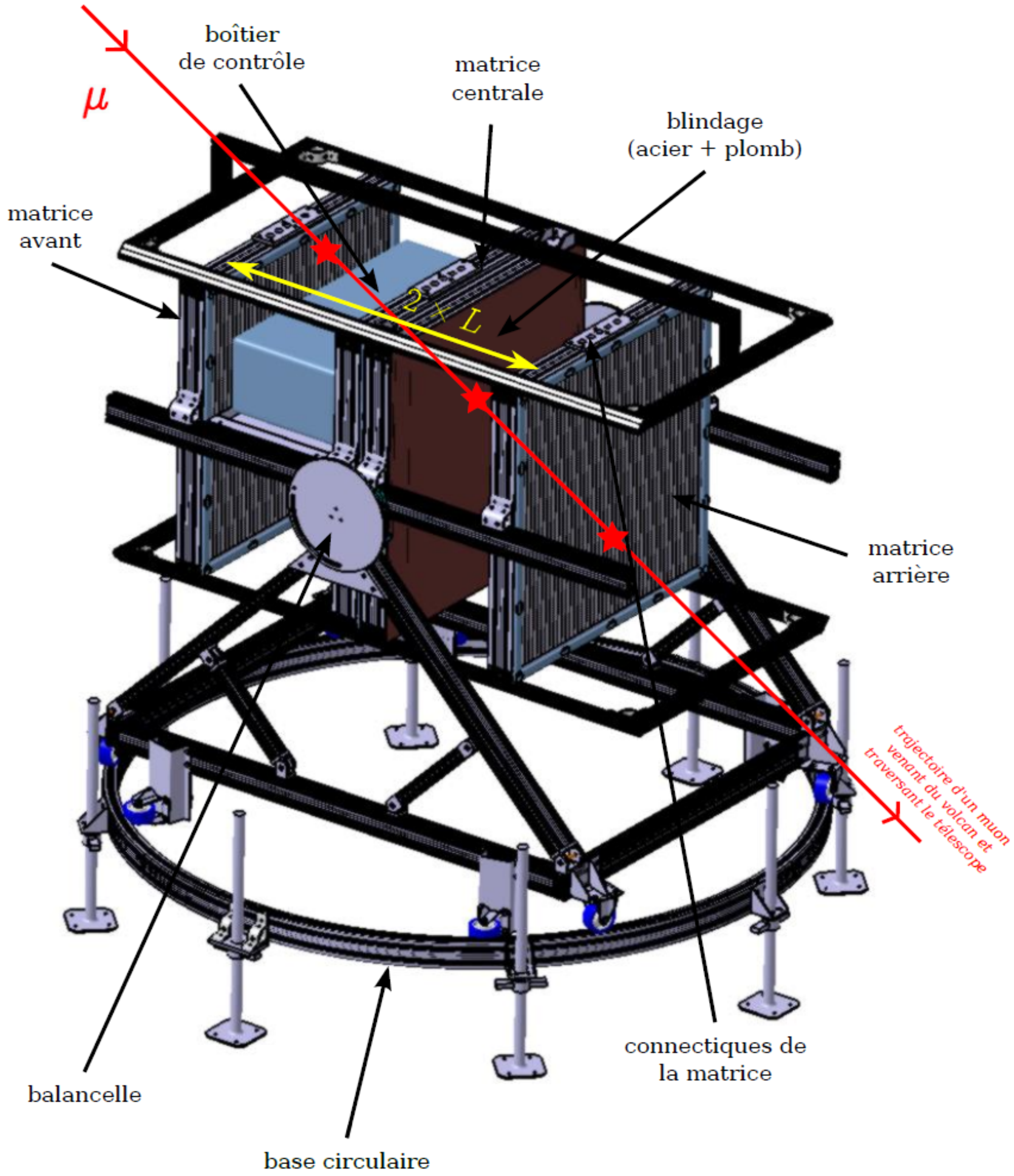
First deployment and measurements in the ***Apollonia Tumulus*** (near Thesalonikki – Greece)

Expected Spring 2017



Preparation of the
"muon telescope"

Muon telescope



- Already used for volcano scanning
  - www.diaphane-muons.com
- Constructed to be:
  - Autonomous
  - Robust
  - Light and Portable
- Coincidence of the 3 pixelized – scintillator planes

  → Reconstruction of the μ trajectory

Muon telescope

Detector Calibration @ IPNL

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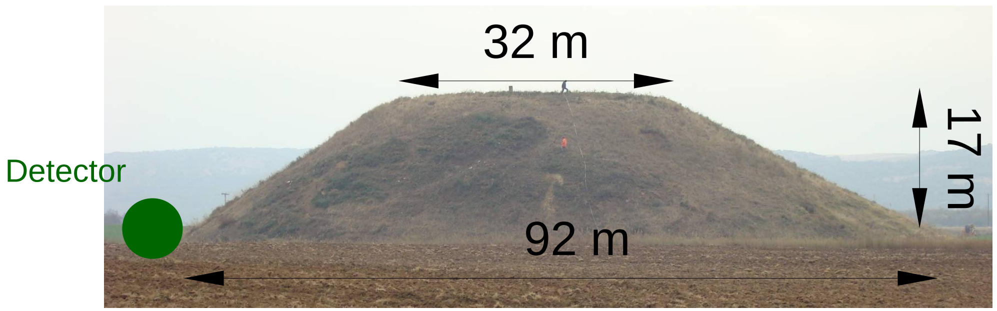
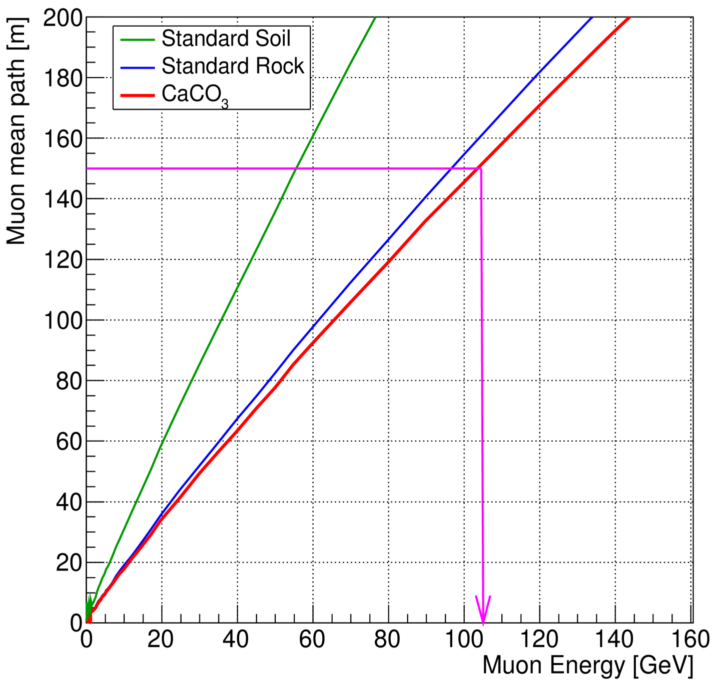
  → Reconstruction of the μ trajectory

Monte Carlo simulations

- ***Double Chooz*** work demonstrated the reliability of the MUSIC software and extended Gaisser muon parametrization down to 20 GeV muons.
- Due to tumulus dimensions, muons in the ***[1 – 100] GeV*** energy window are the most interesting for the scanning.
- ***MUSIC*** simulations have some limitations but can provide an idea about the potential of the technique.



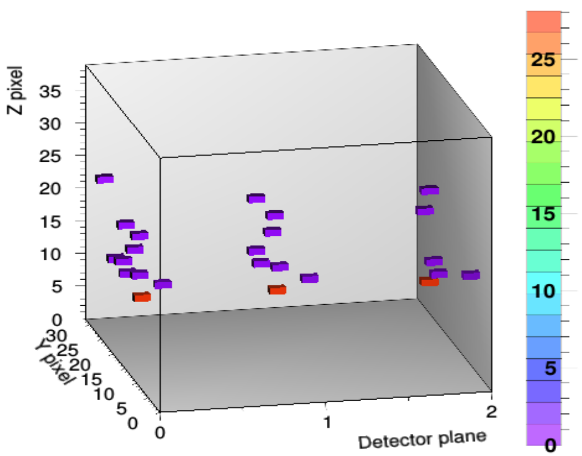


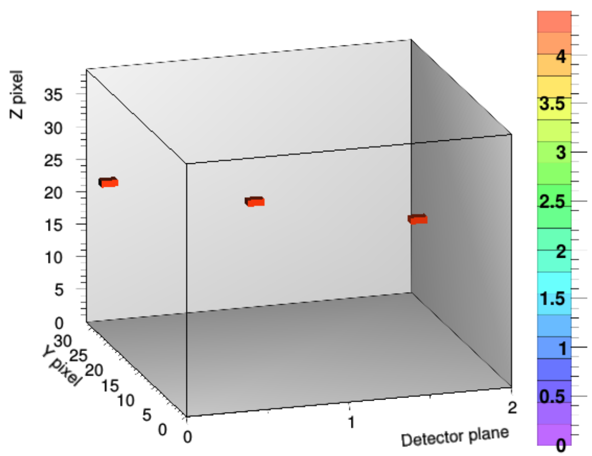
Journal of Physics: Conference Series 718 (2016) 052016

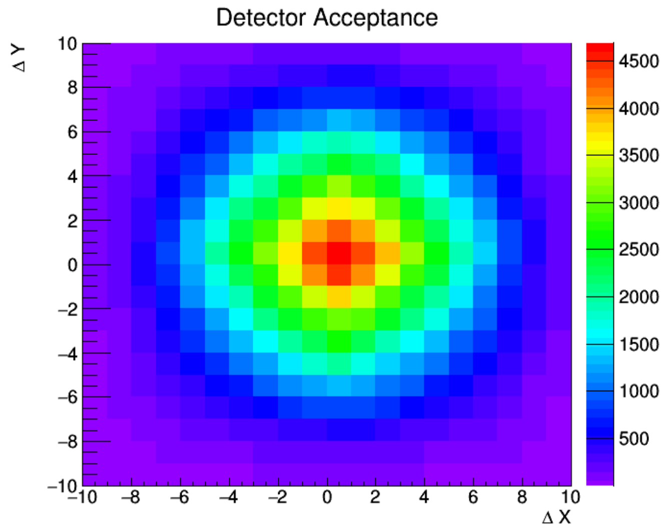
AIP Conference Proceedings 1672 (2015) 140004

Monte Carlo simulations

- New ***Geant4*** framework has been performed:
  - More precise definition of the tumulus geometry and the internal structures
  - Possibility to include detector performance (efficiency, pixelization, angular acceptance...)







Muon events reconstructed in the pixelized detectors

Monte Carlo simulations

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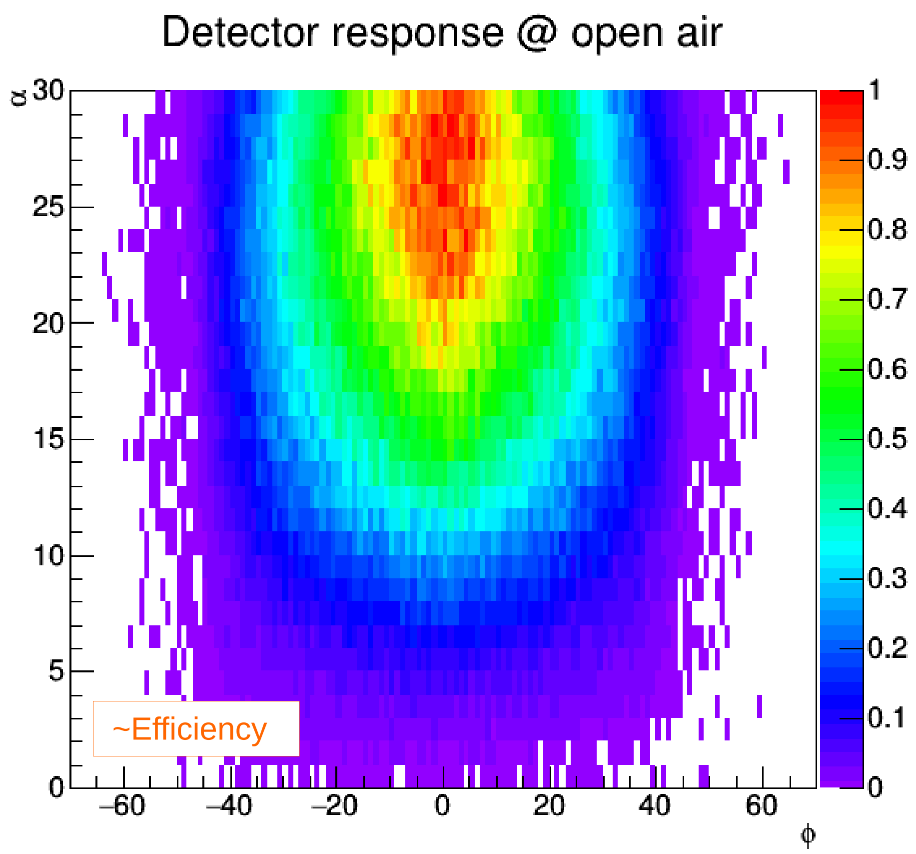

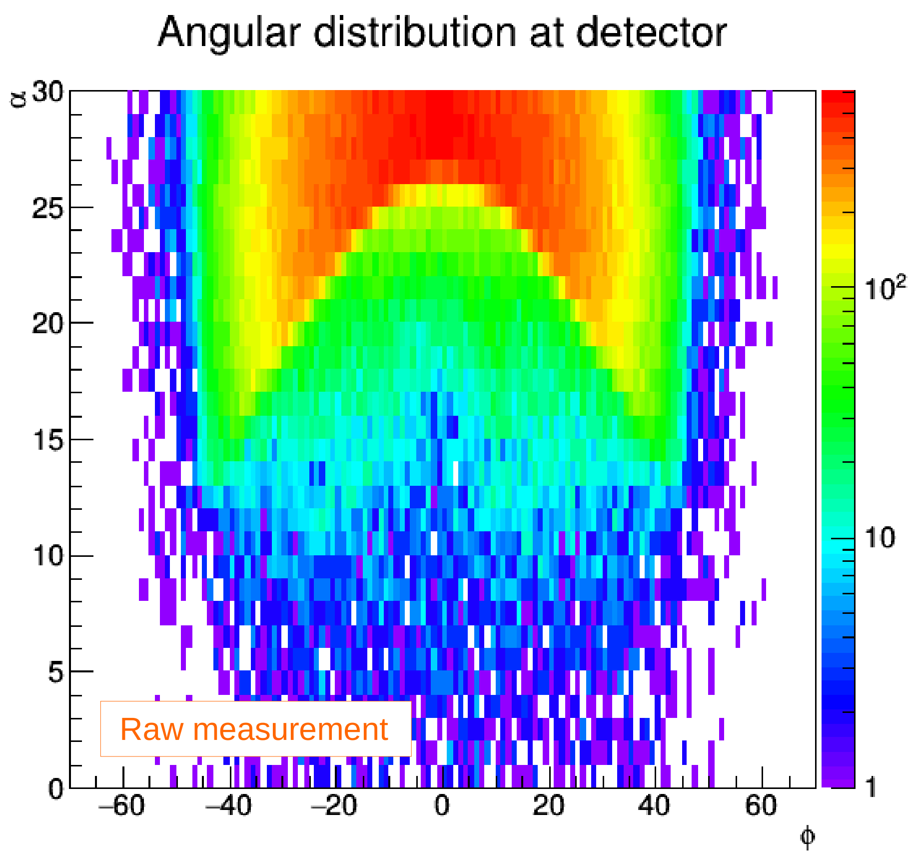

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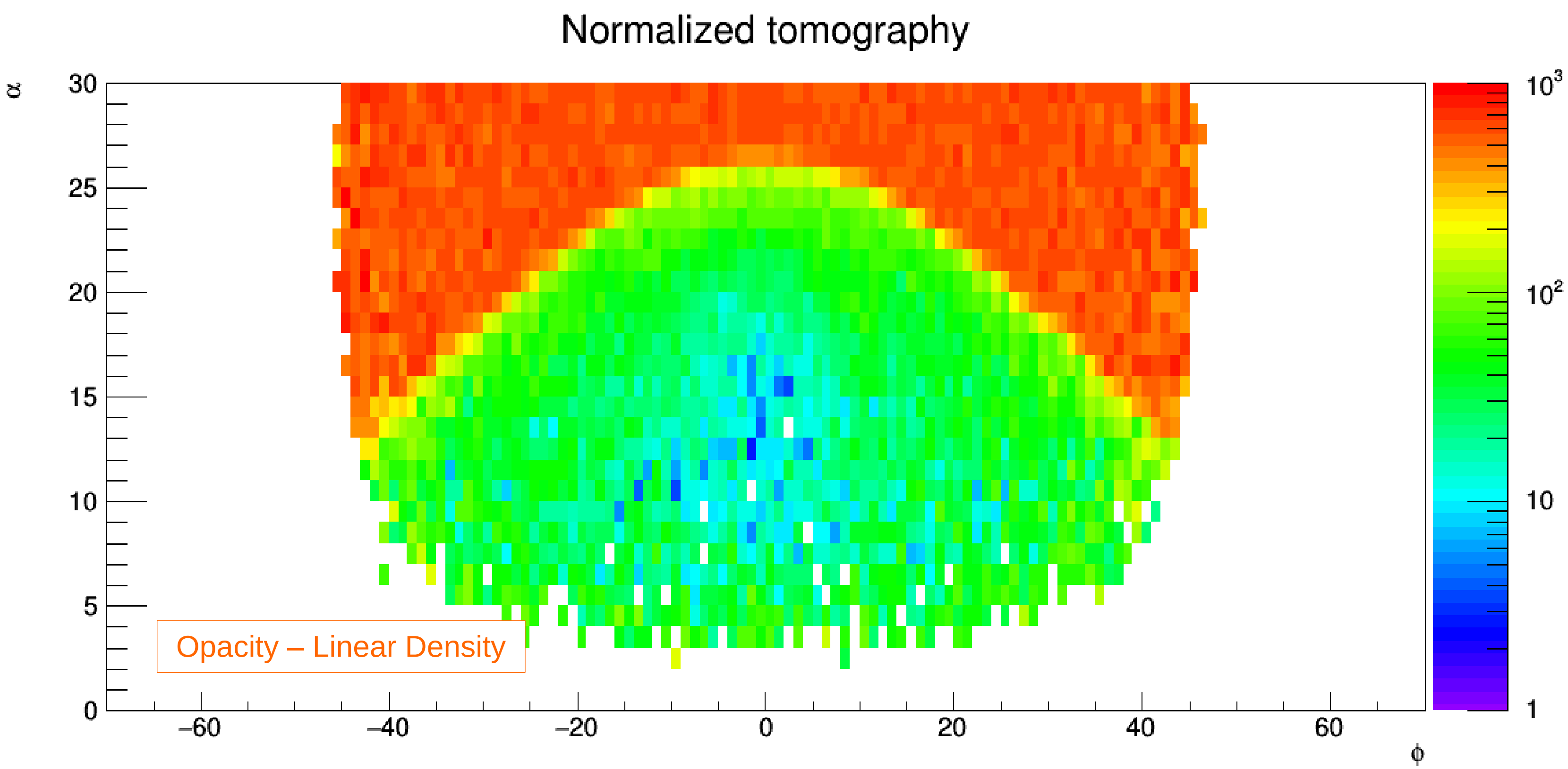

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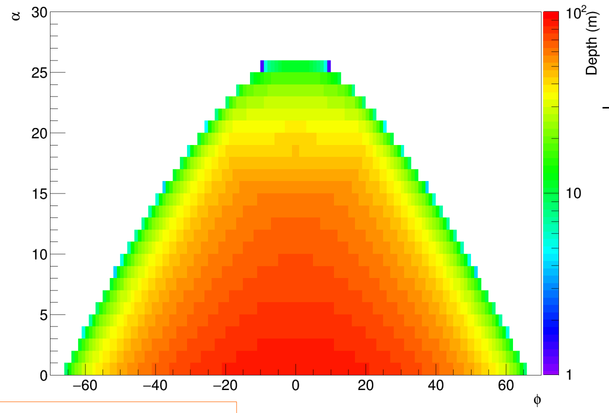
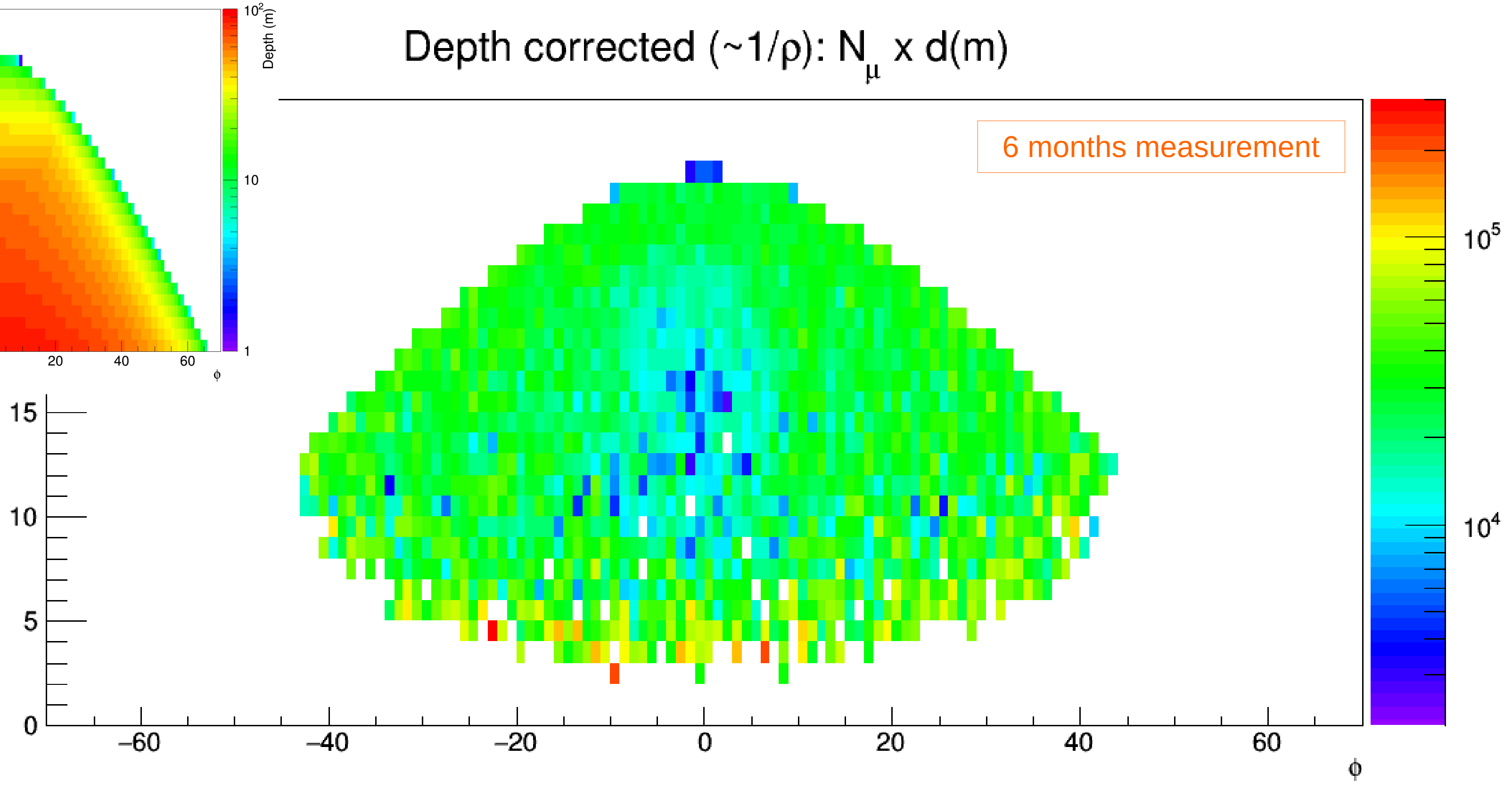


External shape



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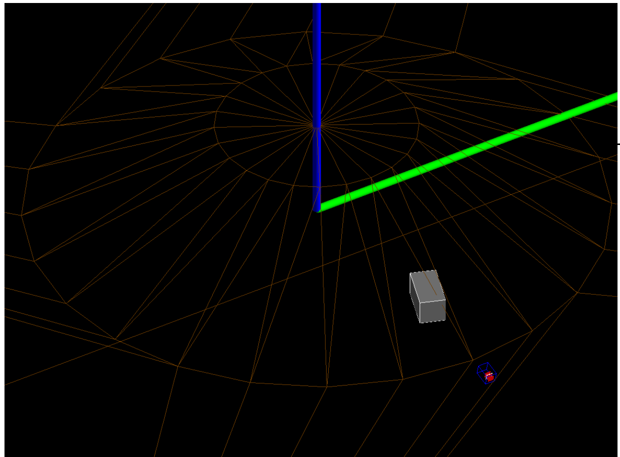
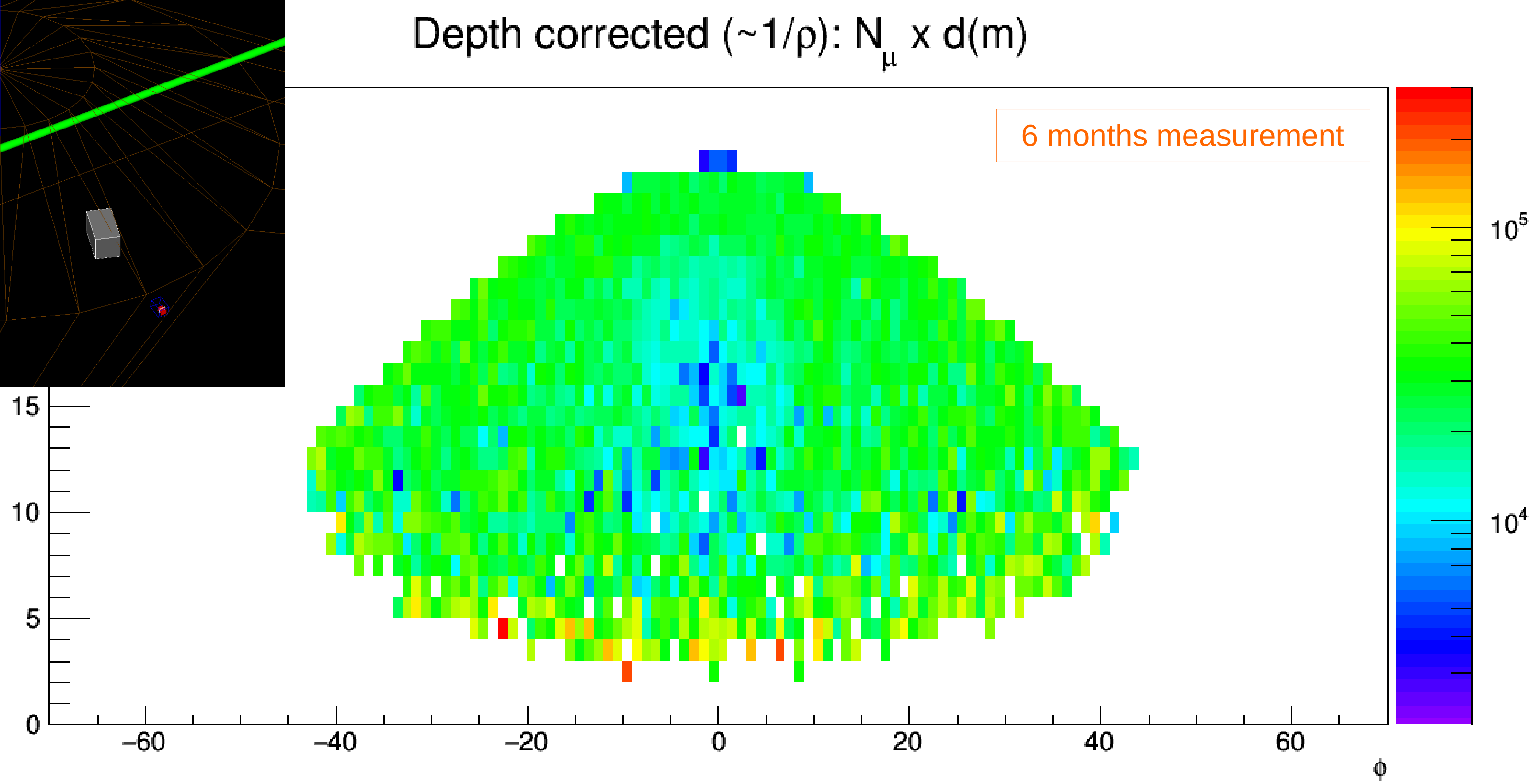
  - Possibility to include detector performance (efficiency, pixelization, angular acceptance...)





Summary and Conclusions

- ***Atmospheric muons*** is the main component of the air shower reaching the Earth's Surface.
  - They represent themselves, or by muon-induced events, one of the main background for particle physics
    - Reactor neutrino experiments
      - Going underground
      - Active vetoes
- ***Double Chooz*** has performed a full muon characterization combining data analysis and Monte Carlo simulations
  - Muon Rate and Flux, Angular distributions
  - Also annual modulation phenomenon → Validation of the theoretical models
- However, atmospheric muons represent an interesting radiation source utilisable for other applications
  - ***Muon tomography*** is a non-invasive exploration technique suitable for big objects
  - ***Arche project*** studies the feasibility of muon tomography for archaeological applications
    - First detector deployment expected next spring

Studying Atmospheric Muons:

From neutrino physics to archaeological applications

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$$T_{\text{eff}} = \frac{\sum_{n=0}^{N-1} \Delta X_n \cdot T(X_n)(W_\pi(X_n) + W_K(X_n))}{\sum_{n=0}^{N} \Delta X_n (W_\pi(X_n) + W_K(X_n))}$$

ΔX_n → Difference of pressure between two adjunct levels

$T(X_n)$ → Temperature @ X_n pressure

W_π and W_k → Weighting functions for μ production

$$W_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2 e^{-X/\Lambda_{\pi,K}} A^1_{\pi,K}}{\gamma + (\gamma+1) B^1_{\pi,K} K_{\pi,K}(X)(\langle E_{\text{thr}} \cos\theta \rangle / \epsilon_{\pi,K})^2}$$

$$K_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2}{(1 - e^{-X/\Lambda'_{\pi,K}})\Lambda'_{\pi,K}/X}$$

$A^1_{\pi k}$ → Inclusive meson production + masses of mesons and μ + μ spectral index

$B^1_{\pi k}$ → Relative atmospheric attenuation of mesons

ε_π, ε_k → Mesons critical energy

γ → μ sppectral index

Λ_N, Λ_π, Λ_k → Attenuation lengths

$$1/\Lambda'_{\pi,k} = 1/\Lambda_N - 1/\Lambda_{\pi,k}$$

Parameter	Value	Unit
A^1_π	1	-
A^1_K	$0.38 \times r_{K/\pi}$	-
$r_{K/\pi}$	0.149 ± 0.060	-
B^1_π	1.460 ± 0.007	-
B^1_K	1.740 ± 0.028	-
ϵ_π	114 ± 3	GeV
ϵ_K	851 ± 14	GeV
γ	1.7 ± 0.1	-
Λ_N	120	$\mathrm{g/cm^2}$
Λ_π	180	$\mathrm{g/cm^2}$
Λ_K	160	$\mathrm{g/cm^2}$

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