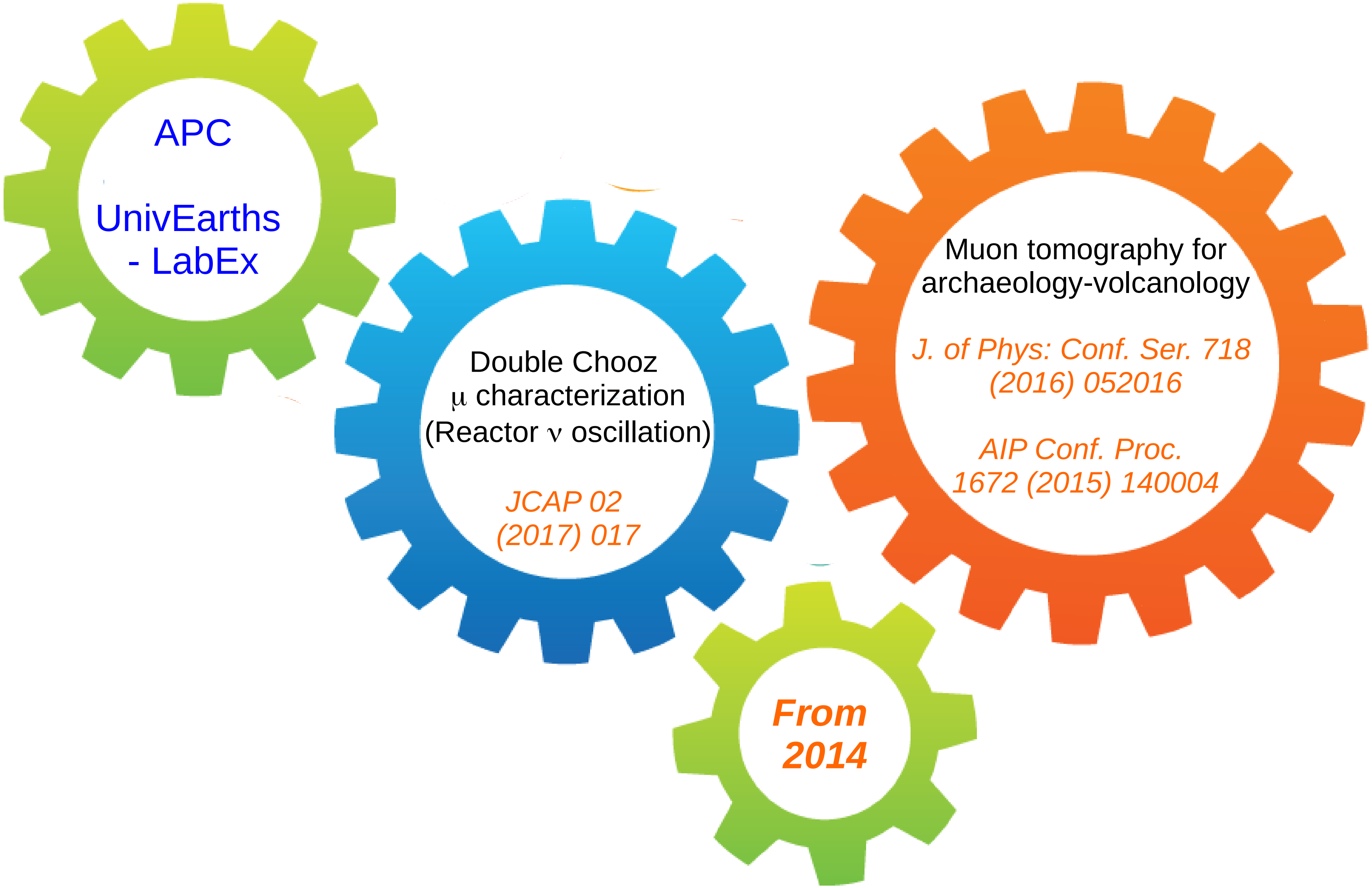
Squeezing atmospheric muons

From neutrino physics to imaging applications

Héctor Gómez

IRFU / DPhN / LSN

hector.gomez@cea.fr


APC
UnivEarths
- LabEx
Double Chooz
μ characterization
(Reactor ν oscillation)
JCAP 02
(2017) 017
Muon tomography for
archaeology-volcanology
J. of Phys: Conf. Ser. 718
(2016) 052016
AIP Conf. Proc.
1672 (2015) 140004
From
2014

My muon activities

All about synergies

APC

UnivEarths - LabEx

Double Chooz
μ characterization
(Reactor ν oscillation)

JCAP 02 (2017) 017

From 2014

Muon tomography for archaeology-volcanology

J. of Phys: Conf. Ser. 718 (2016) 052016

AIP Conf. Proc. 1672 (2015) 140004

DPhN

From 10/2017

Outline

➔ Atmospheric muons

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

➔ Atmospheric muons and Reactor Neutrino experiments

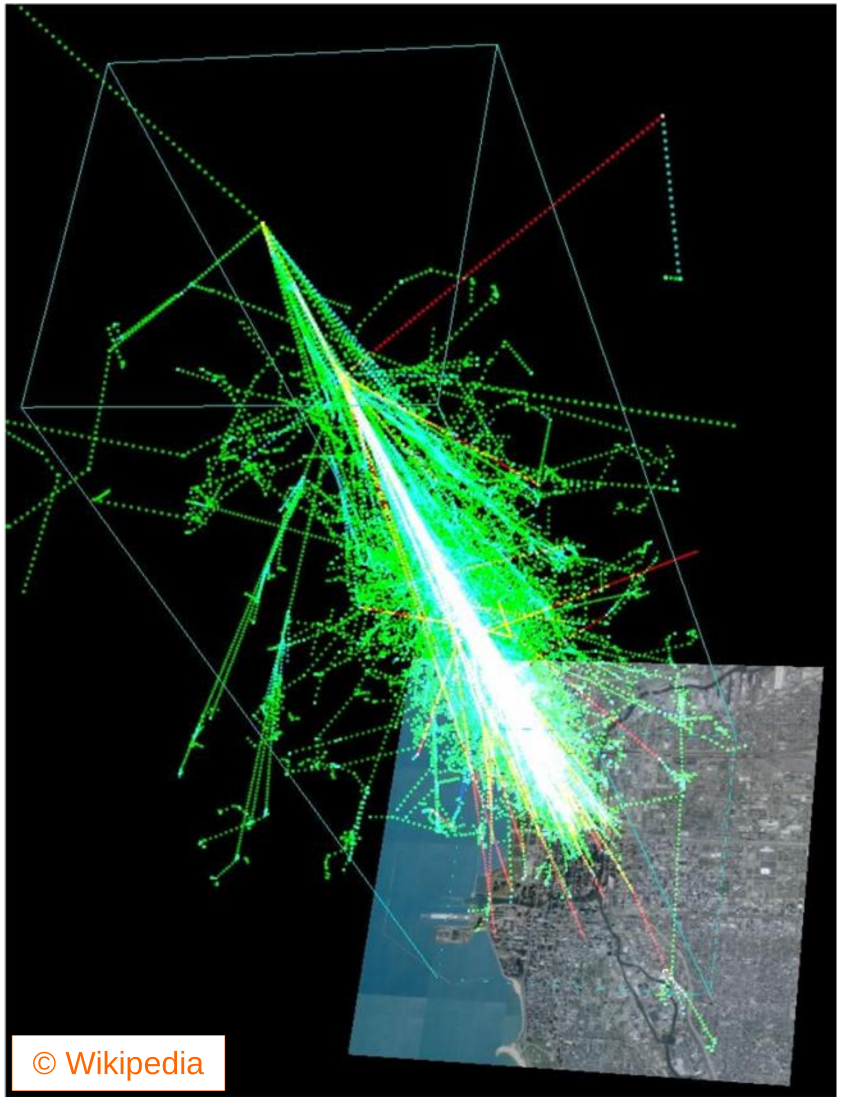
- The ***Double Chooz*** case
  - Muon characterization
    - Experimental data and Monte Carlo simulations → A “rough” muon tomography
  - Annual modulation: Effective temperature coefficient

➔ Taking advantage of muons

- The muon tomography
- The importance of simulations
  - Present and future applications

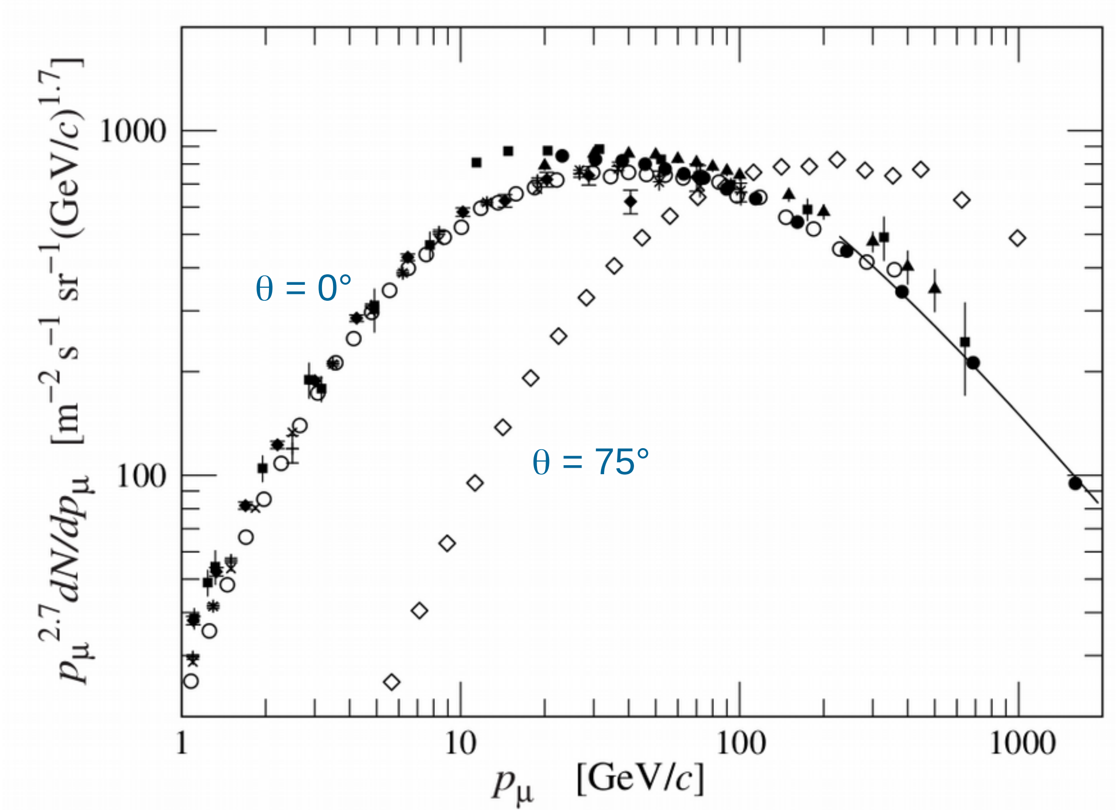
➔ Summary and conclusions

Main features



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

- Muons produced by the interaction of cosmic-rays with nuclei of the Atmosphere
  - 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
    - Steepens along energy (E_μ > 1 GeV)



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

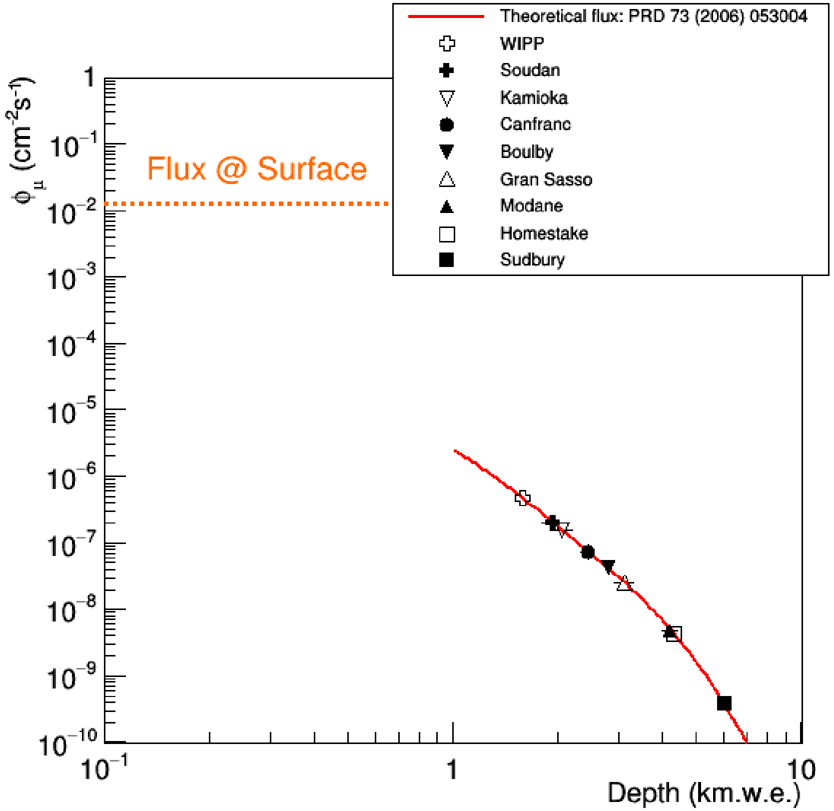
Muon flux @ surface (full θ range)

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

- 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:

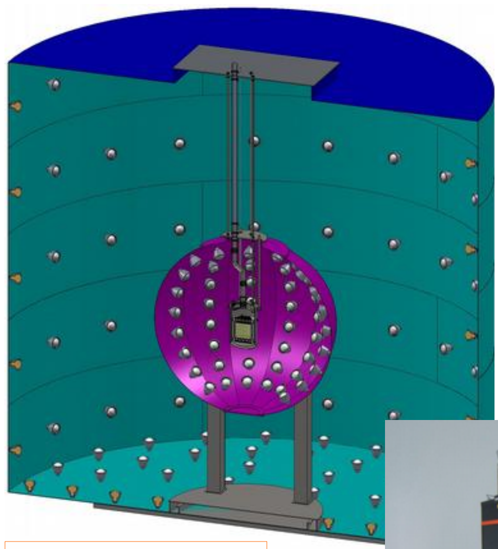
Passive methods

Going underground (Shielding): Mines, mountains...

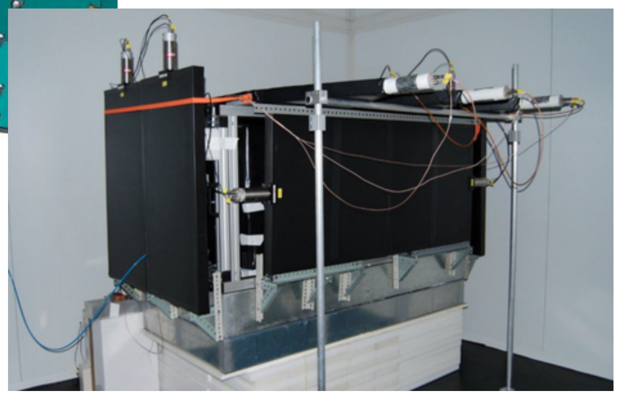


Active methods

Dedicated detectors, tagging + analysis...



Dark Side @ Gran Sasso



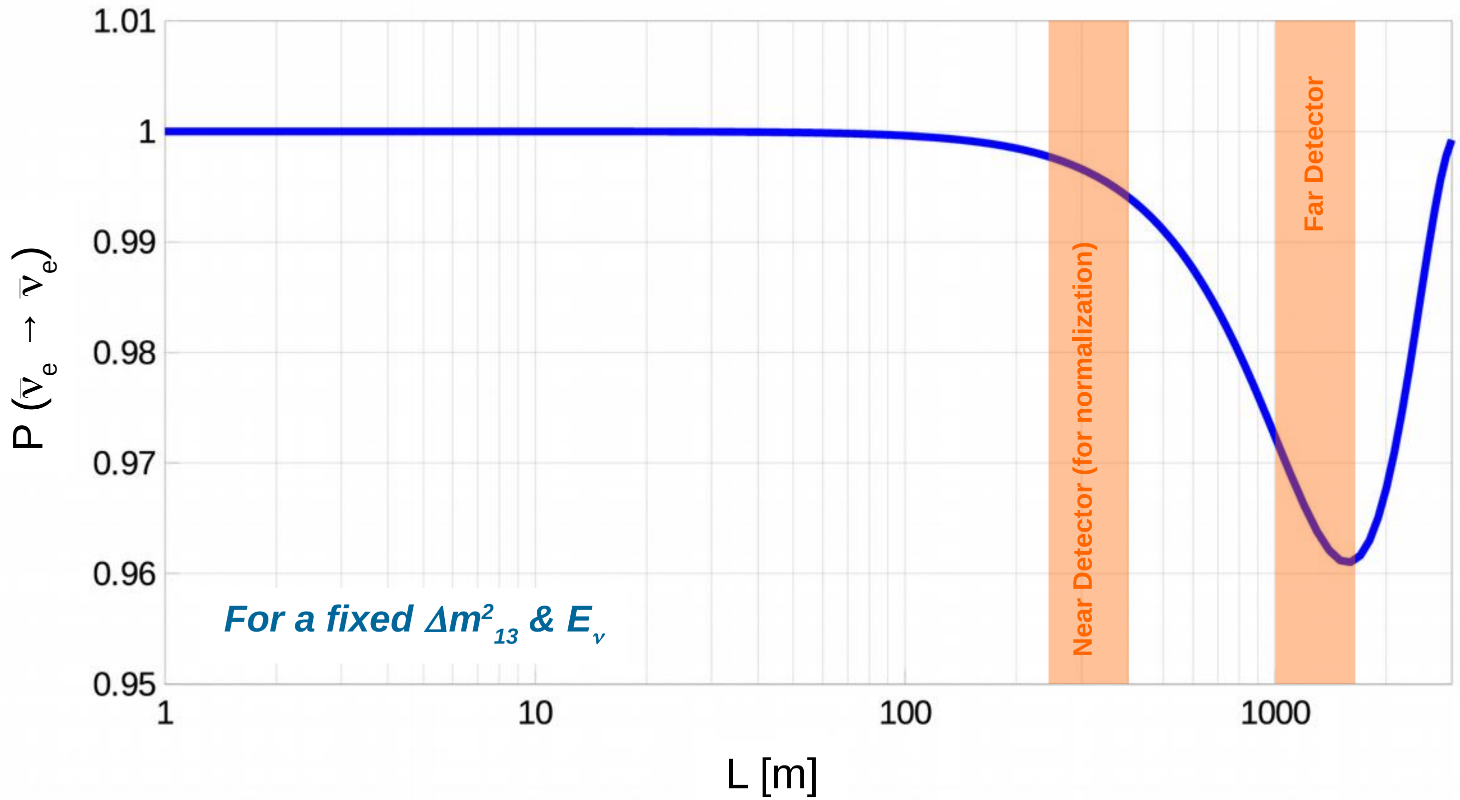
Anais @ Canfranc

- ***Short baseline*** *experiments* ***in a nutshell:***
  - Determination of θ_{13} measuring the ***deficit of detected anti-neutrinos*** coming from the nuclear reactor

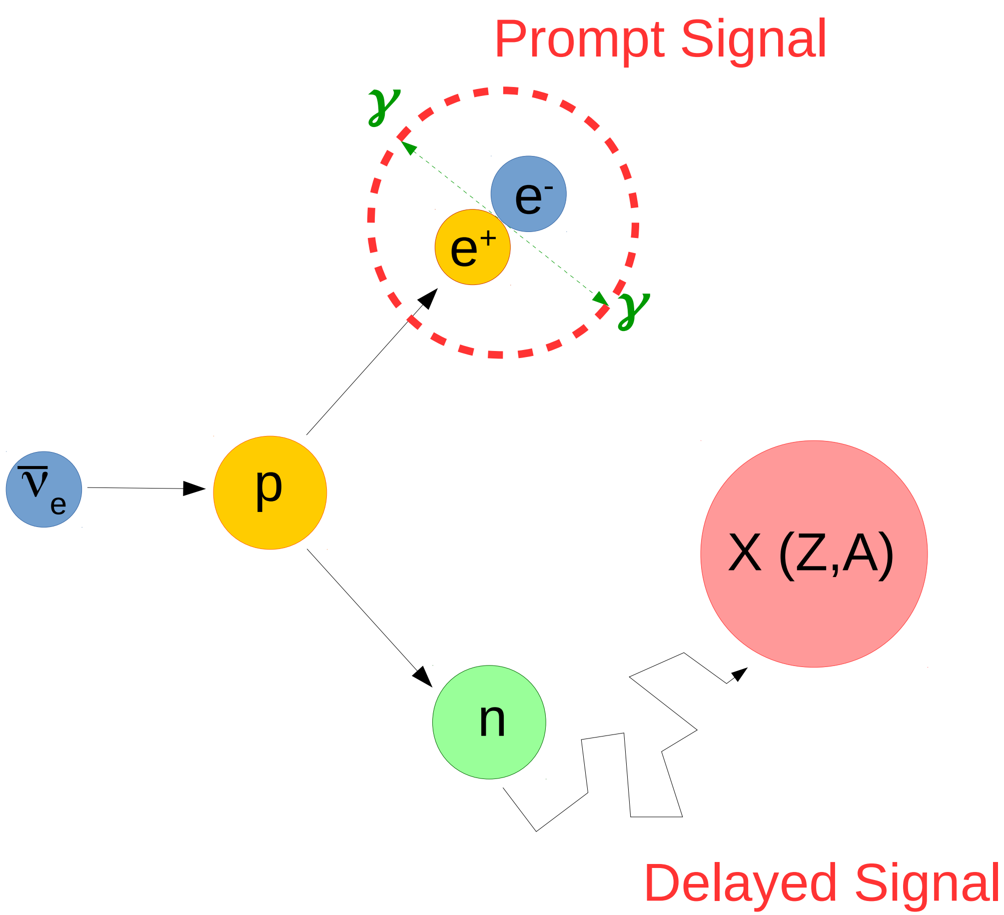
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{13} L}{4 E_\nu}\right) + o(10^{-3})$$

L [m] / E [MeV] ≤ 1

No matter effects



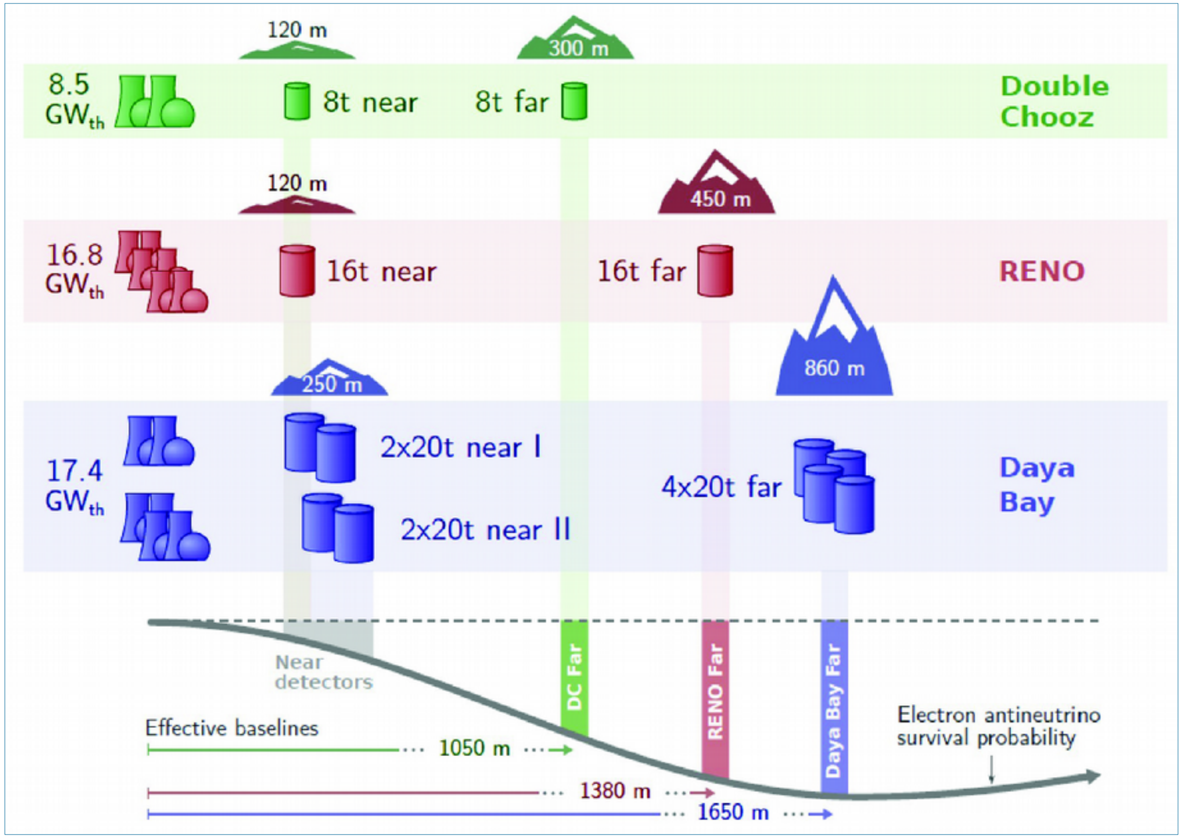
- ***Short baseline** experiments **in a nutshell:***
  - Determination of θ_{13} measuring the ***deficit of detected anti-neutrinos*** coming from the nuclear reactor
  - Anti-neutrinos detection (E_ν < 10 MeV) via ***Inverse Beta Decay*** (IBD)

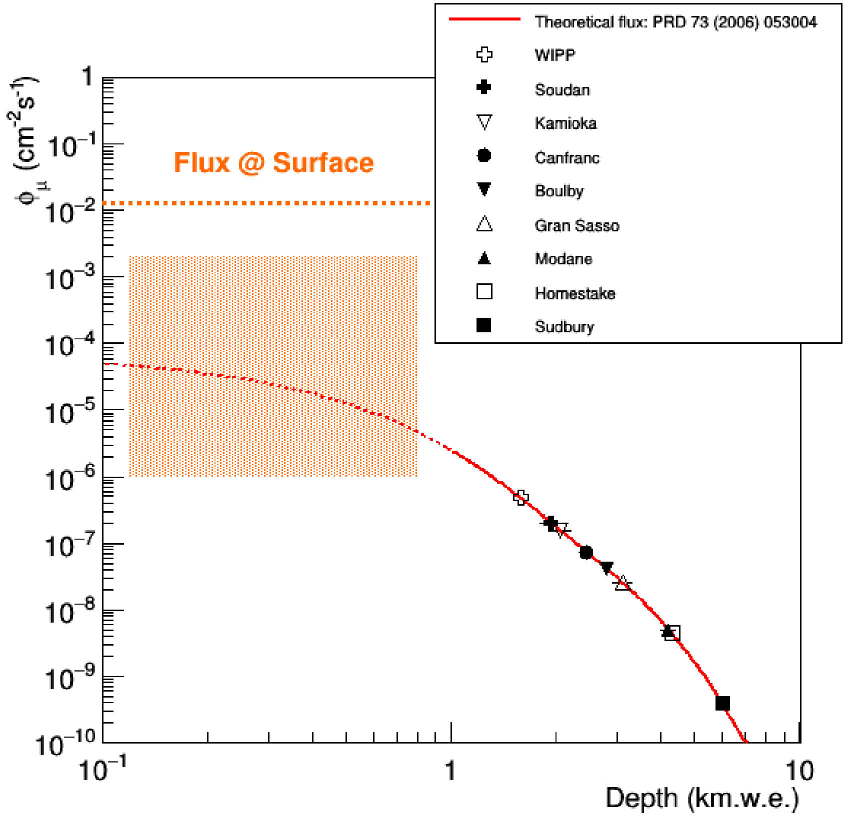


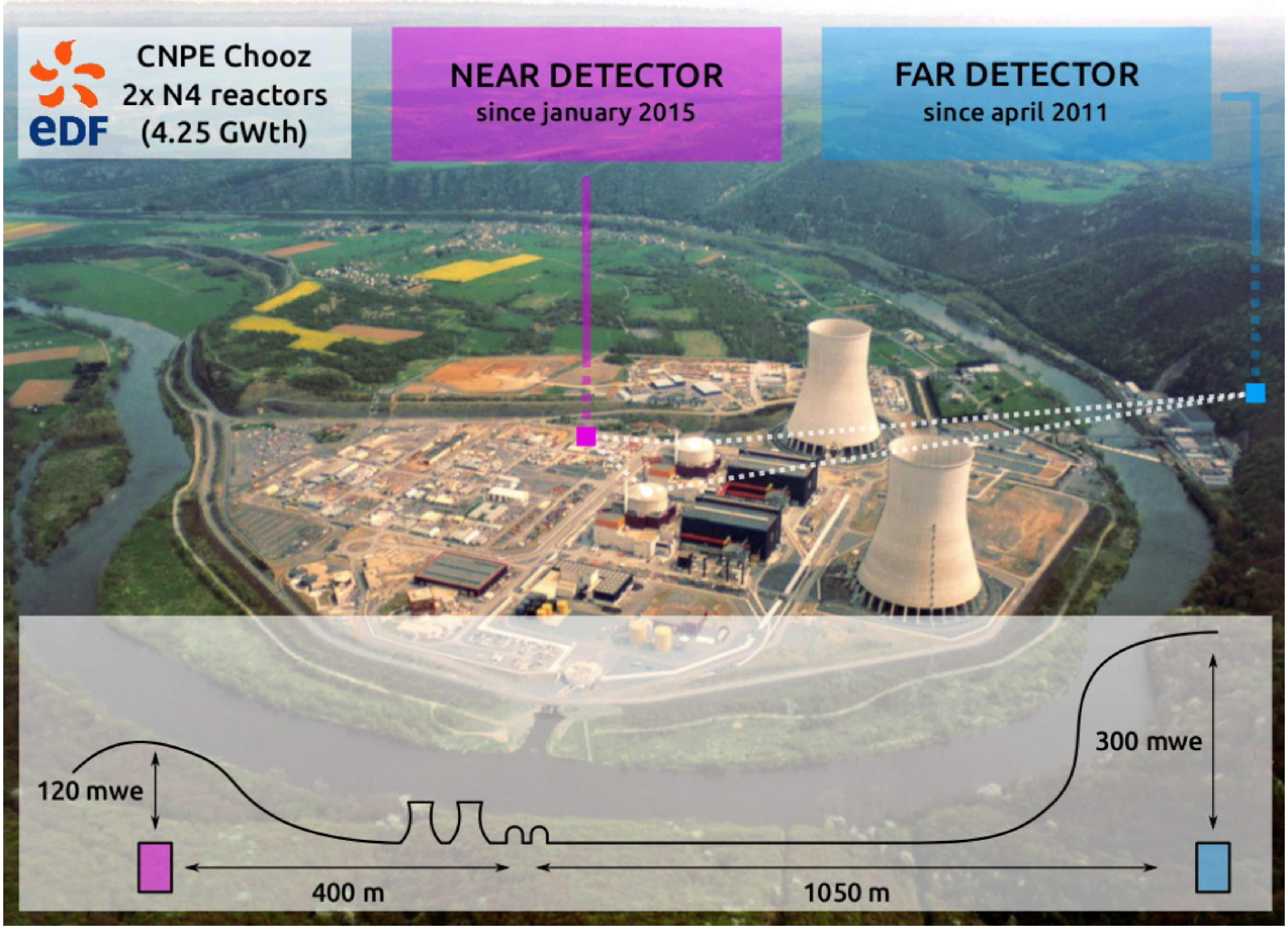
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

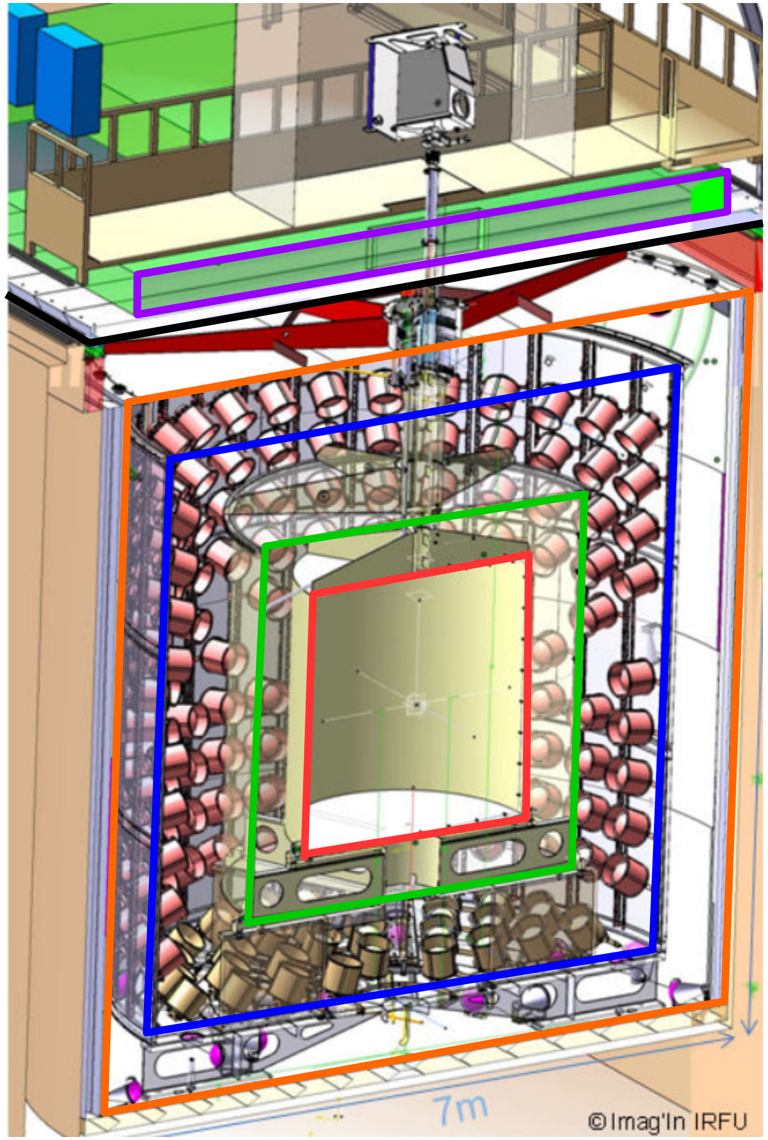
- Expected signal: Delayed coincidence
  - Prompt Signal: positron ionisation and annihilation
    - $E(e^+) \sim E(\bar{\nu}_e) - 0.8$ MeV
    - Localized energy deposit
  - Delayed signal: nuclear neutron capture
    - Features depending on the nucleus
      - Energy released, delay time

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



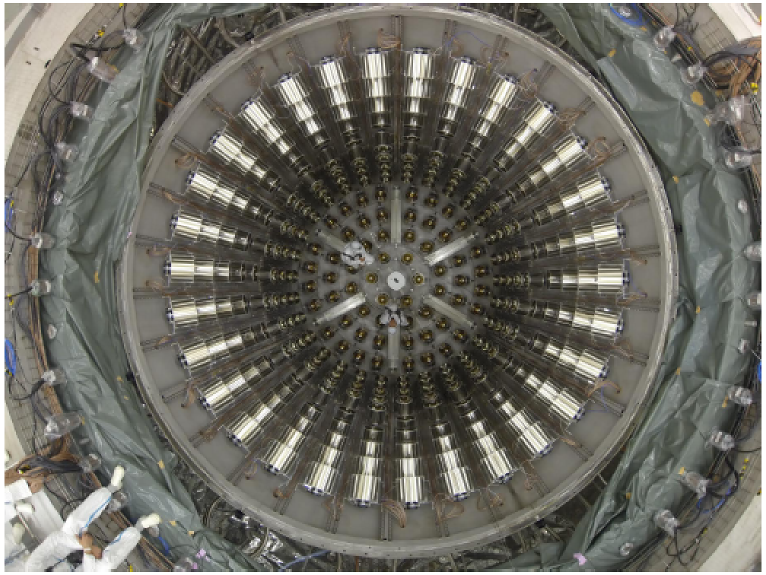


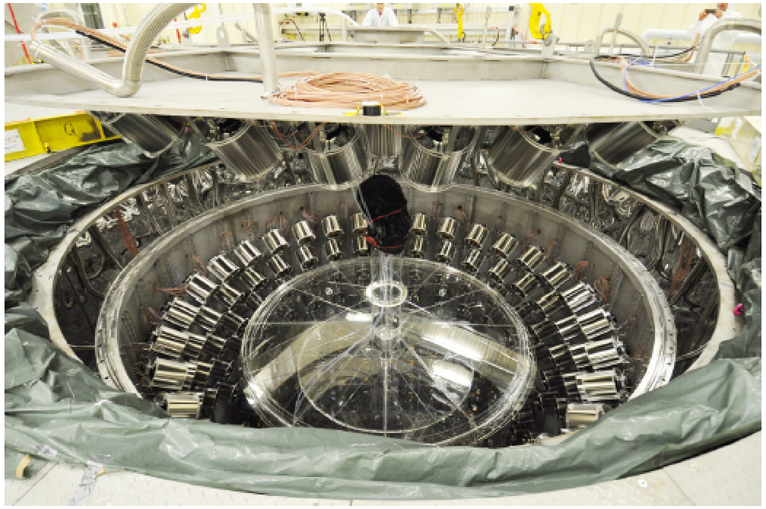

CNPE Chooz
2x N4 reactors
(4.25 GWth)
eDF
NEAR DETECTOR
since january 2015
FAR DETECTOR
since april 2011
120 mwe
300 mwe
400 m
1050 m



LAYOUT:

ν – Target	10.3 m³ liquid scintillator, doped with 1 g/l of Gd in an 8 mm thick acrylic vessel.
Gamma Catcher	22.6 m³ liquid scintillator in a 12 mm thick acrylic vessel
Buffer	110 m³ 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 m³ 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





***LAYOUT*:** *Inner detector (ID)*

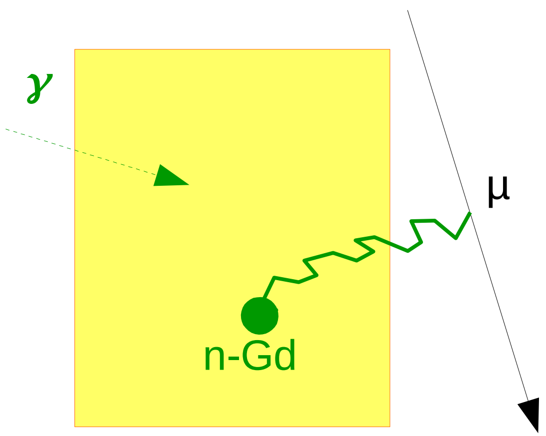
ν – Target	10.3 m³ liquid scintillator, doped with 1 g/l of Gd in an 8 mm thick acrylic vessel.
Gamma Catcher	22.6 m³ liquid scintillator in a 12 mm thick acrylic vessel
Buffer	110 m³ of mineral oil (non-scintillating) in a 3 mm thick Stainless Steel vessel. It holds ***390 PMTs (10 inches)*** working as readout
Inner Veto	90 m³ 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

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

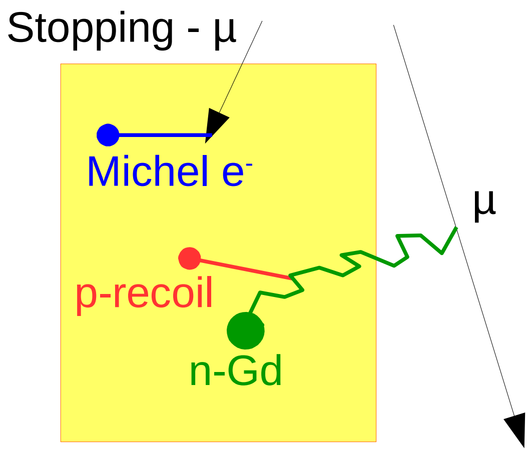
Backgrounds



Accidental Coincidences

Natural Radioactivity

e.g. γ + spallation n

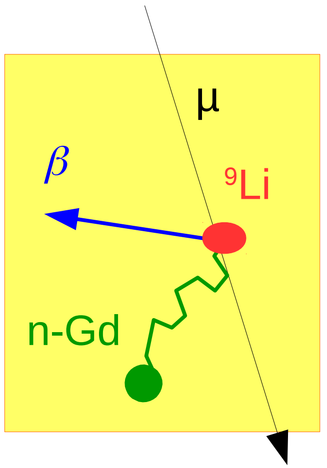


Correlated Events

Fast neutrons & Stopping – μ

n +p → p + n

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

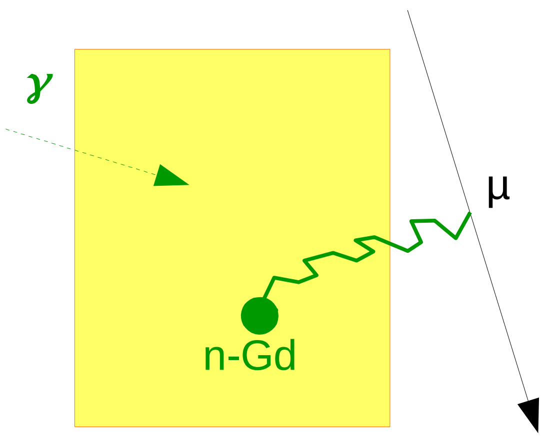


Cosmogenic Isotopes

β - n emitters (^{9}Li & ^{8}He)

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

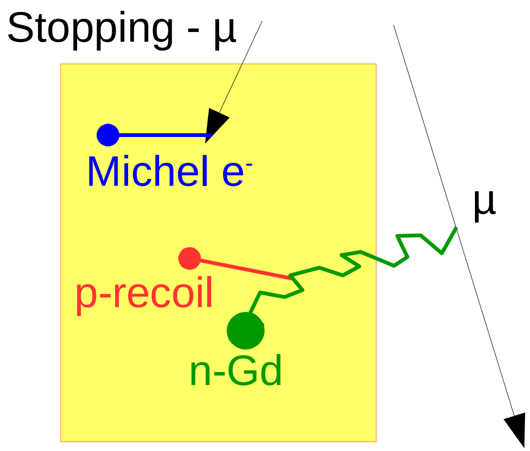
Backgrounds



Accidental Coincidences

Natural Radioactivity

e.g. γ + spallation n

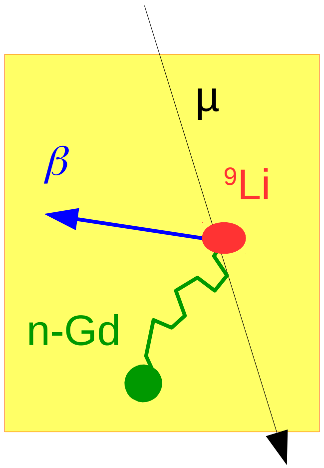


Correlated Events

Fast neutrons & Stopping – μ

$n + p \rightarrow p + n$

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



Cosmogenic Isotopes

β - n emitters (^{9}Li & ^{8}He)

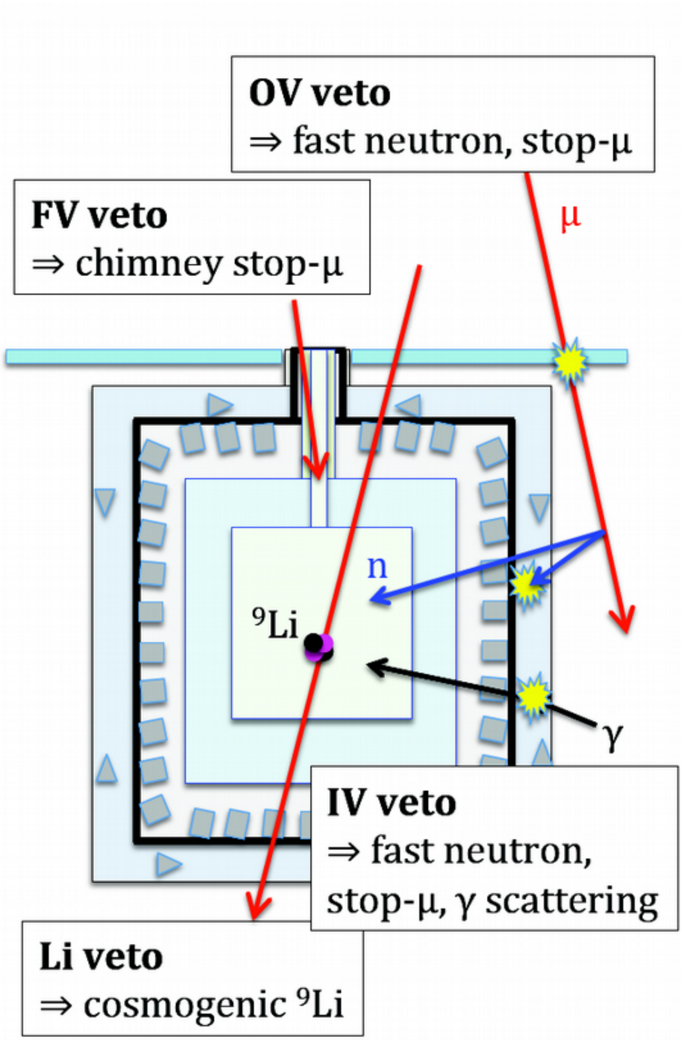
$^{9}Li \rightarrow \alpha + \alpha + e + \nu + n$

Prompt signal

Delayed signal

Development of dedicated background rejection techniques...

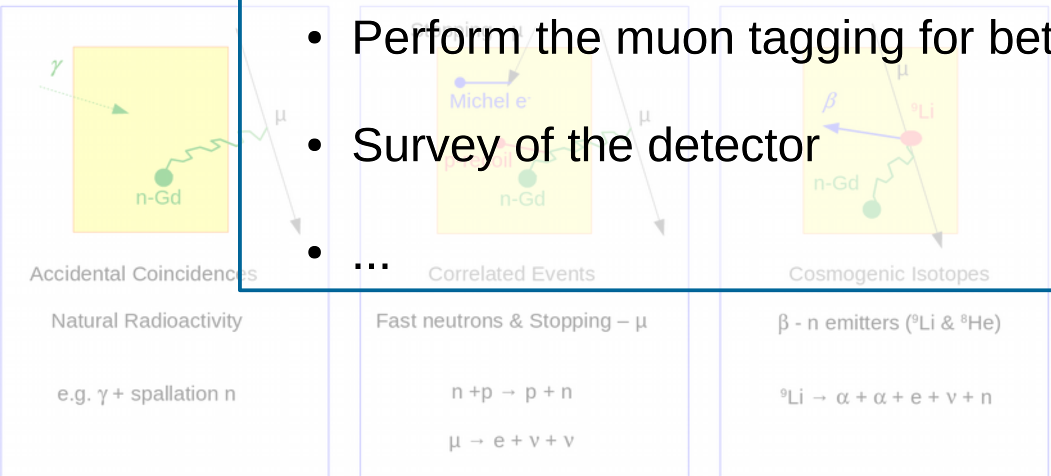
Backgrounds

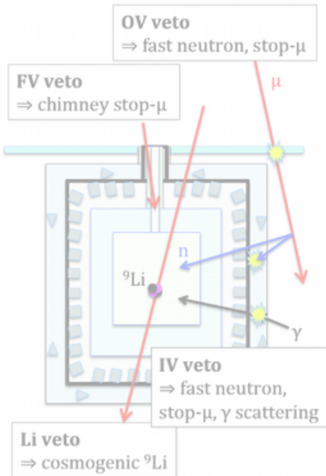


Cut	*Information used*	*Target of cut*
μ veto	1 ms veto after μ	μ, cosmogenics
Multiplicity	Uniqueness condition	Multiple n's
FV veto	Vertex likelihood	Chimney stopping μ
IV veto	IV activity	Fast n, stopping μ, γ scattering
OV veto	OV activity	Fast n, stopping μ
Li veto	Li Likelihood	Cosmogenics
LN cut	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
  - ...

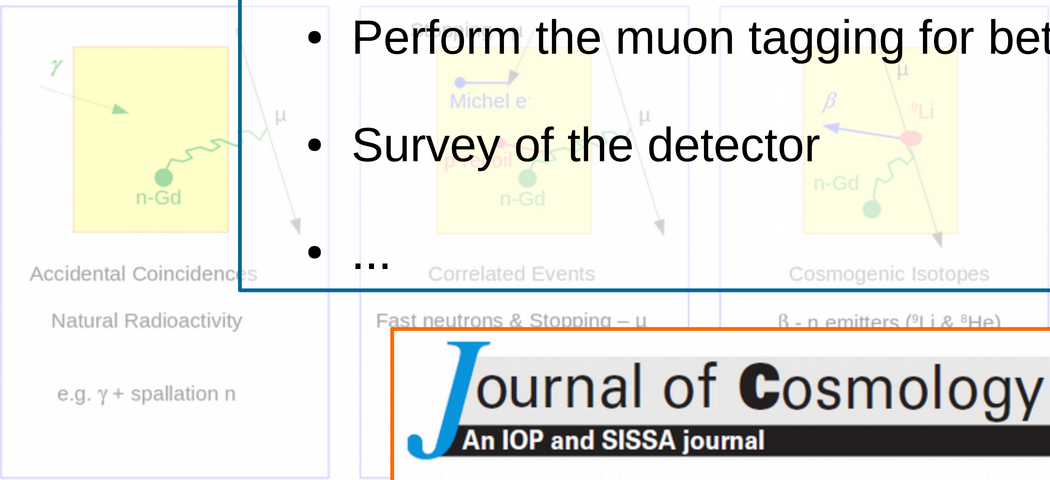




Cut	Information used	Target of cut
μ veto	1 ms veto after μ	μ, cosmogenics
Multiplicity	Uniqueness condition	Multiple n's
FV veto	Vertex likelihood	Chimney stopping μ
IV veto	IV activity	Fast n, stopping μ, γ scattering
OV veto	OV activity	Fast n, stopping μ
Li veto	Li Likelihood	Cosmogenics
LN cut	PMT 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
  - ...



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

...tion used	Target of cut
...to after μ	μ, cosmogenics
...ss condition	Multiple n's
...ikelihood	Chimney stopping μ
...ctivity	Fast n, stopping μ, γ scattering
...ctivity	Fast n, stopping μ
...elihood	Cosmogenics
...t pattern ...time	Light emission from PMT
..., ΔT, ΔR	Accidentals
...start time	Fast n
...likelihood	Stopping μ
.../ Tot. Q	ND Buffer stopping μ

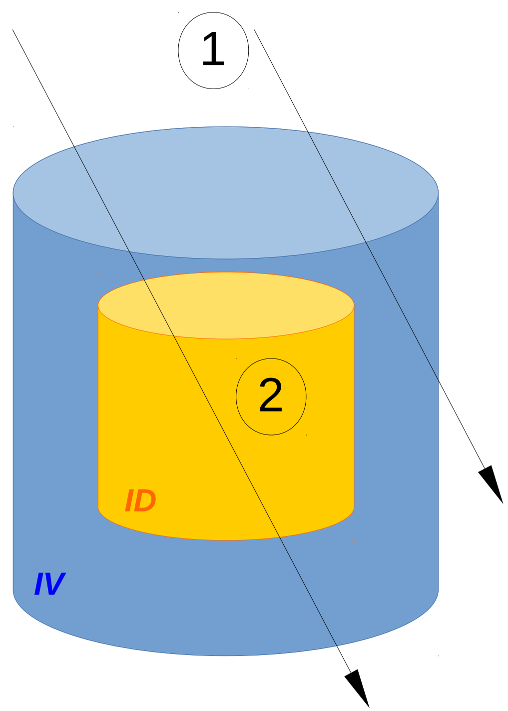
Only applied in n – H analysis
Only applied in the multi-detector analysis

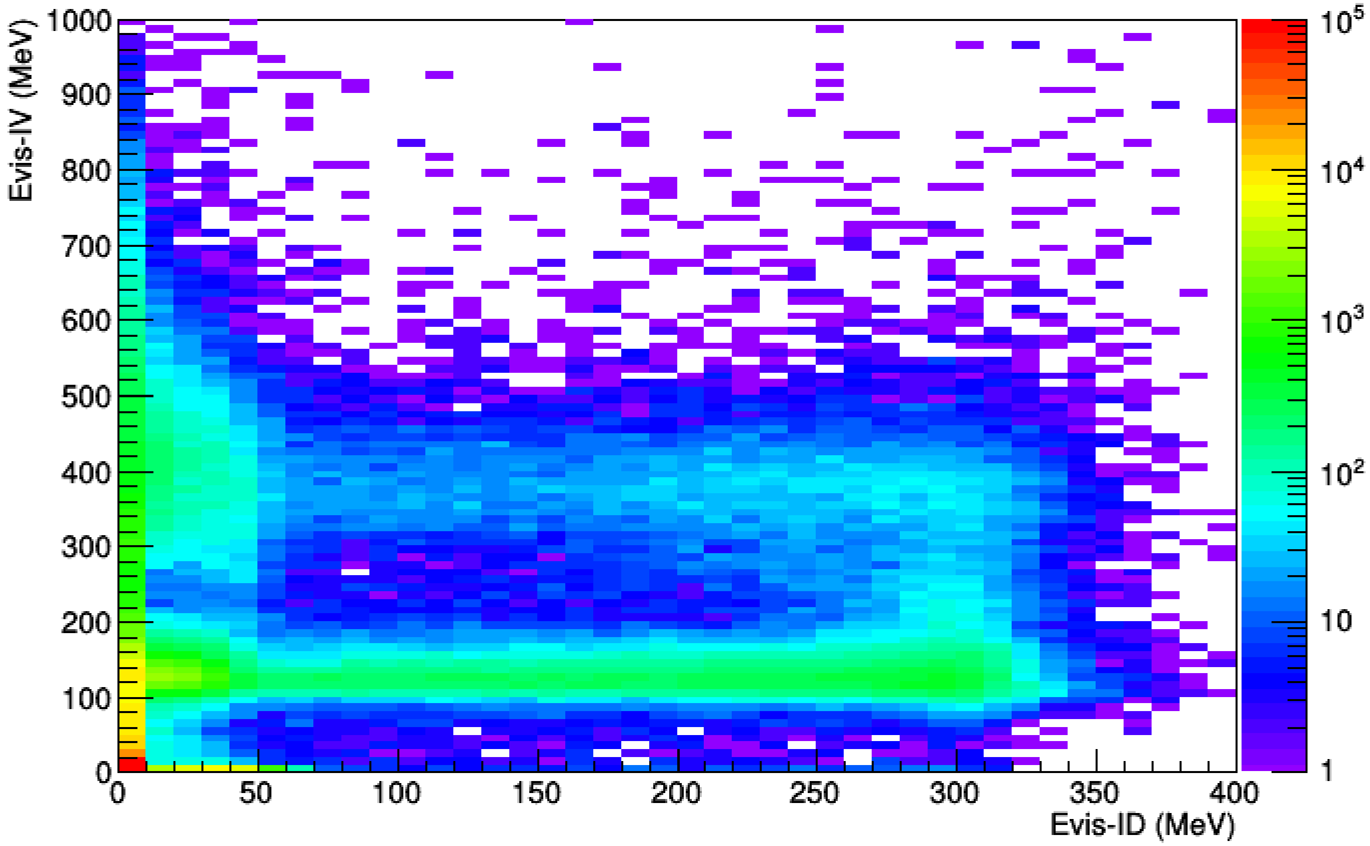

Tagging
Simulation
Track
Reconstruction

Tagging

- Muons deposit large amounts of energy (***~2 MeV cm² / g for liquid scintillators***) if compared with other particles when they traverse the sensitive volumes of Double Chooz detectors i.e. Inner Detector (ID) and Inner Veto (IV)

$$\frac{-dE}{dX}=4\pi N_0 r_e^2 m_e c^2 Z_a^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right)-\beta^2-\frac{\delta(\beta\gamma)}{2}-\frac{C}{Z}\right]$$

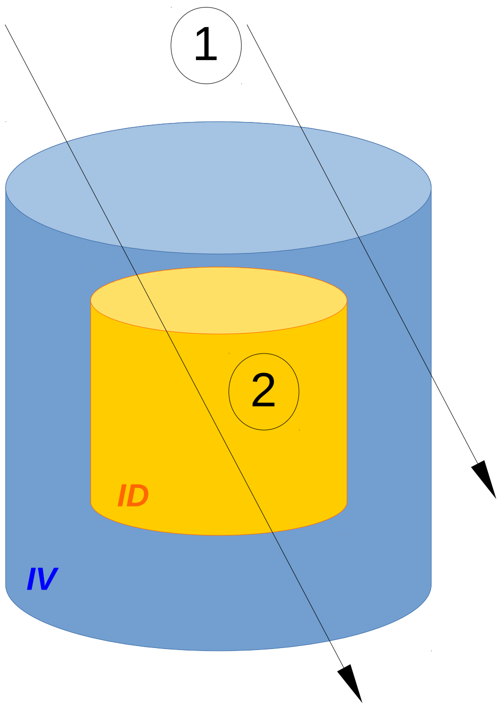




Tagging

- Muons deposit large amounts of energy (***~2 MeV cm² / g for liquid scintillators***) if compared with other particles when they traverse the sensitive volumes of Double Chooz detectors i.e. Inner Detector (ID) and Inner Veto (IV)

$$\frac{-dE}{dX}=4\pi N_0 r_e^2 m_e c^2 Z_a^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right)-\beta^2-\frac{\delta(\beta\gamma)}{2}-\frac{C}{Z}\right]$$



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*:

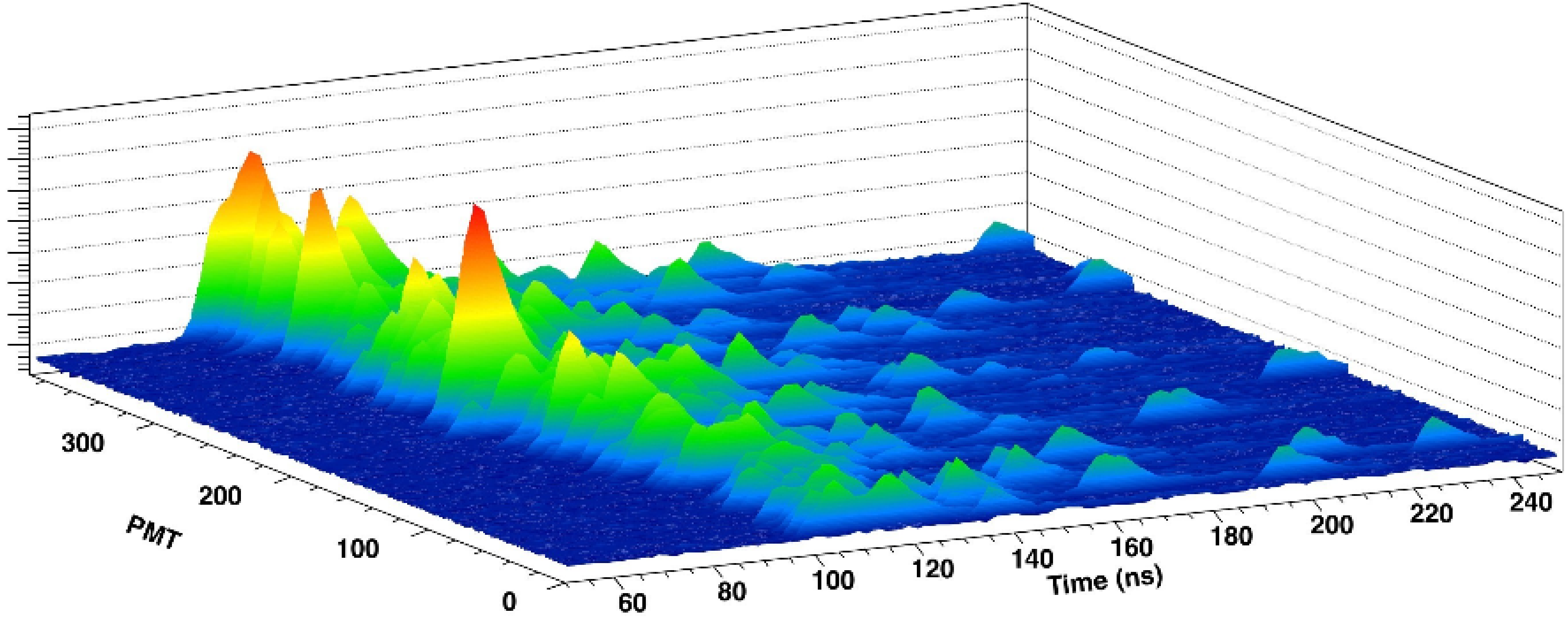
Near detector: $<R_\mu>$ = 242.75 ± 4.81 Hz → ~75 % of the total rate

Far detector: $<R_\mu>$ = 46.16 ± 1.04 Hz → ~[8 – 20] % of the total rate

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

Track Reconstruction

Nucl. Instrum. Meth. A 764 (2014) 330



Ingredients:

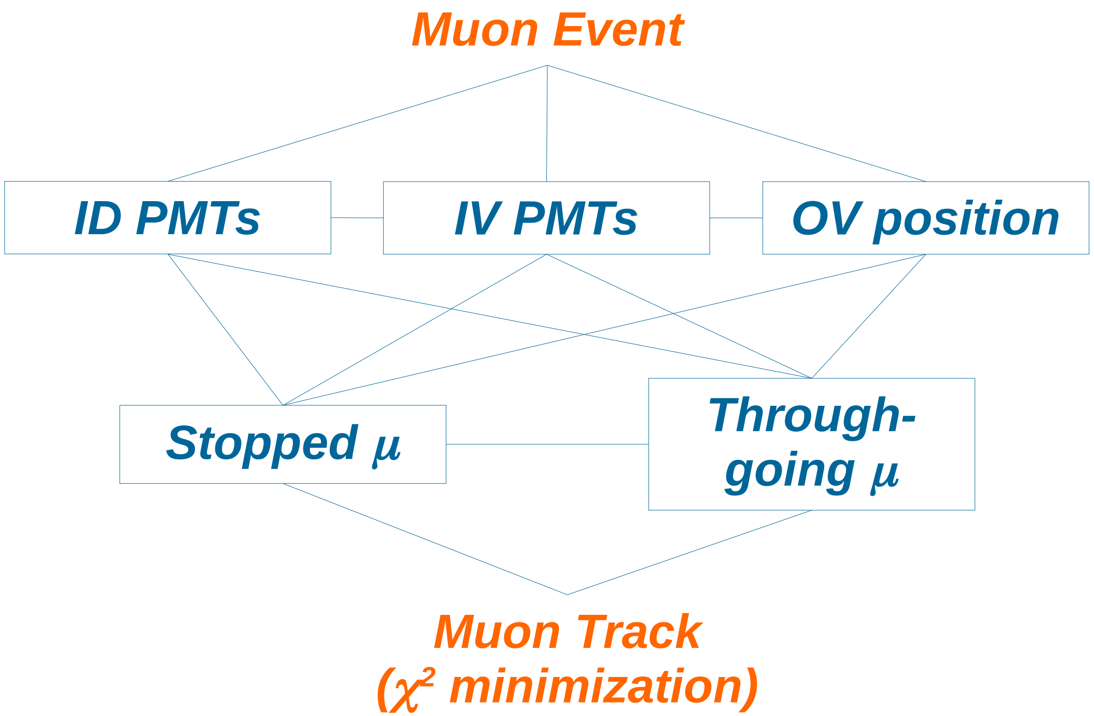
- Pulse reconstruction for all the fired (ID and IV) PMTs → Charge and Time information
- Spatial information of the Outer Veto

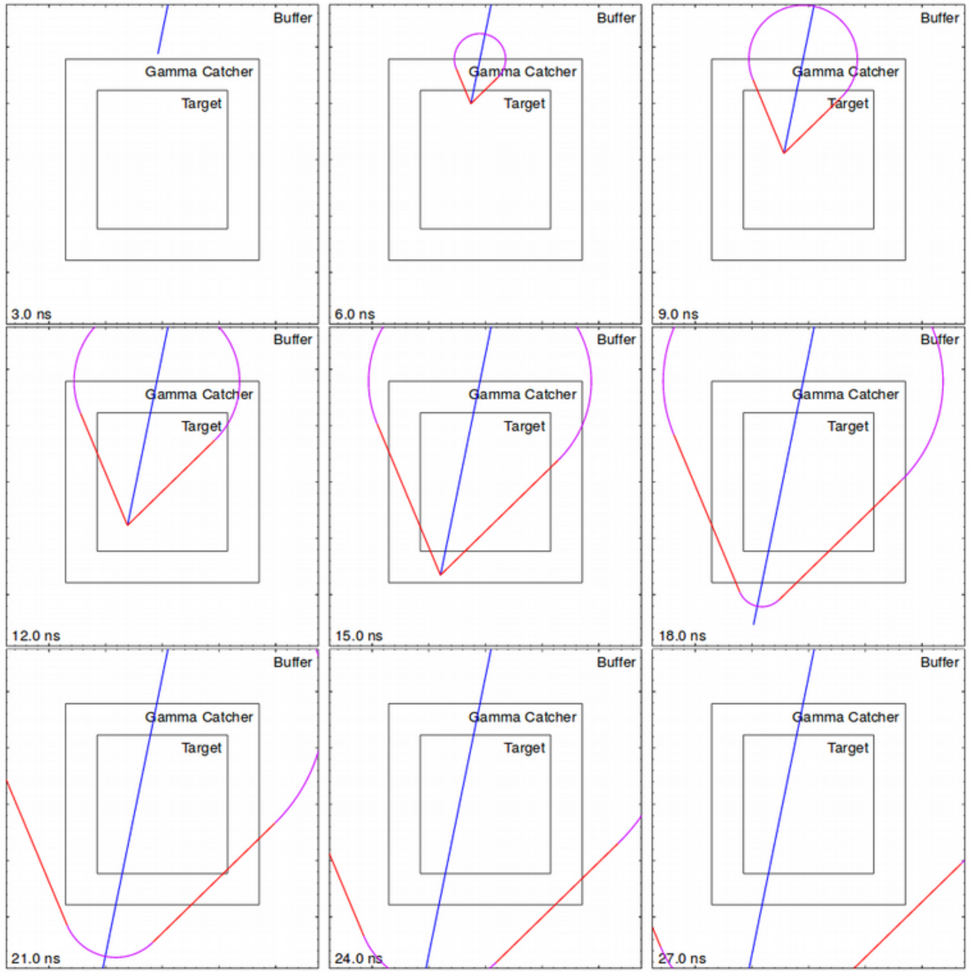
Track Reconstruction

Nucl. Instrum. Meth. A 764 (2014) 330

Fit process:

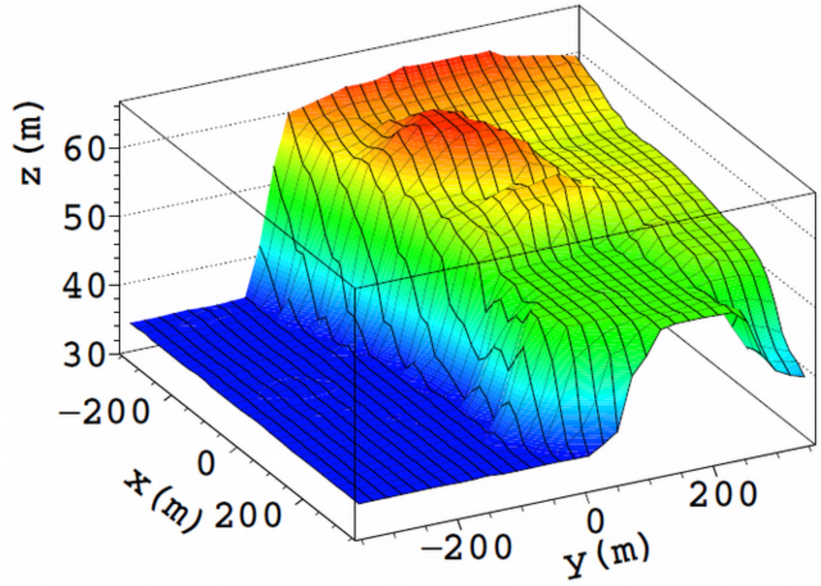
- Multiple fits with different combinations
- All assuming Cherenkov and scintillation light

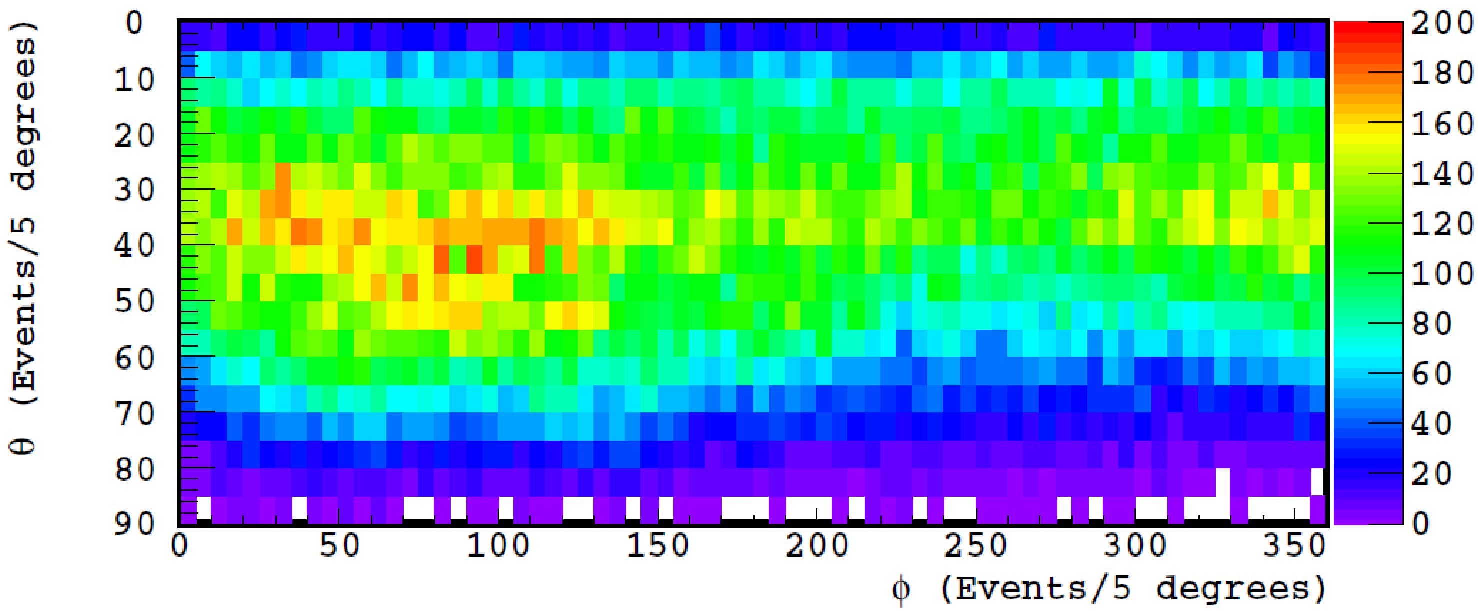




Tagging + Tracking → Angular distributions

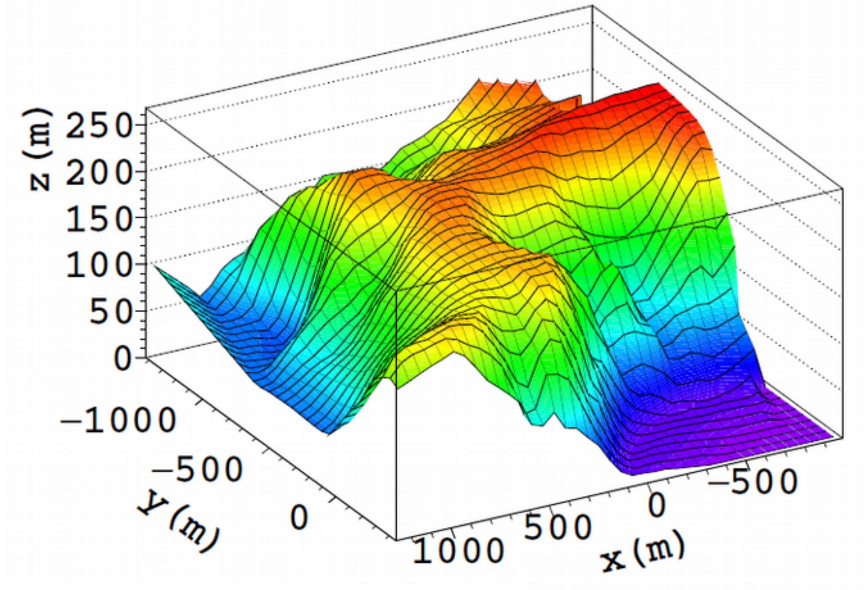
- ***Near detector:***
    - Digitized overburden profile from IGN
    - Homogeneous sampling mesh of 5x5 m

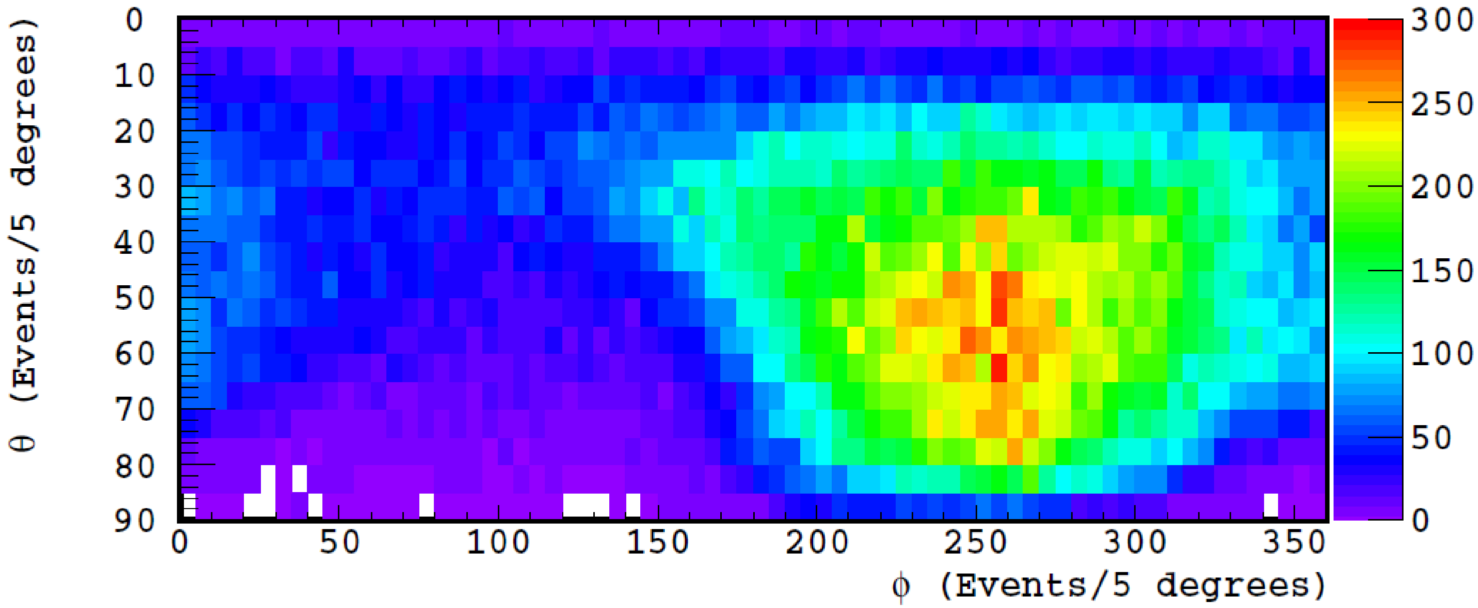




Tagging + Tracking → Angular distributions

- ***Far detector:***
  - 3DField digitization from a topographic study
  - Smaller mesh for less inhomogeneous regions





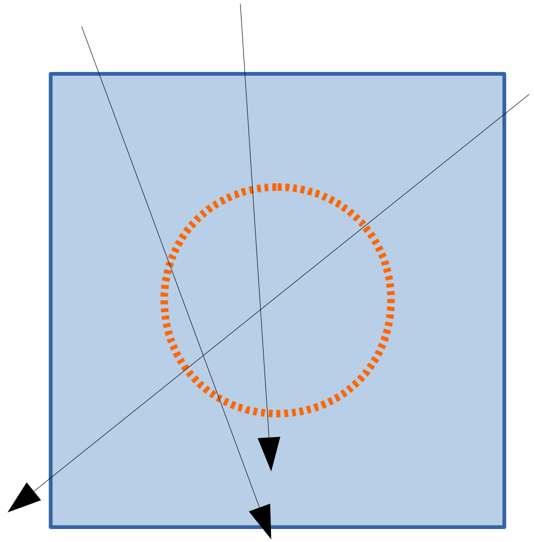
Tagging + Tracking → Muon flux

- Flux reconstructed via the so-called "***sphere method***" which uses the muon rate (tagging) 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

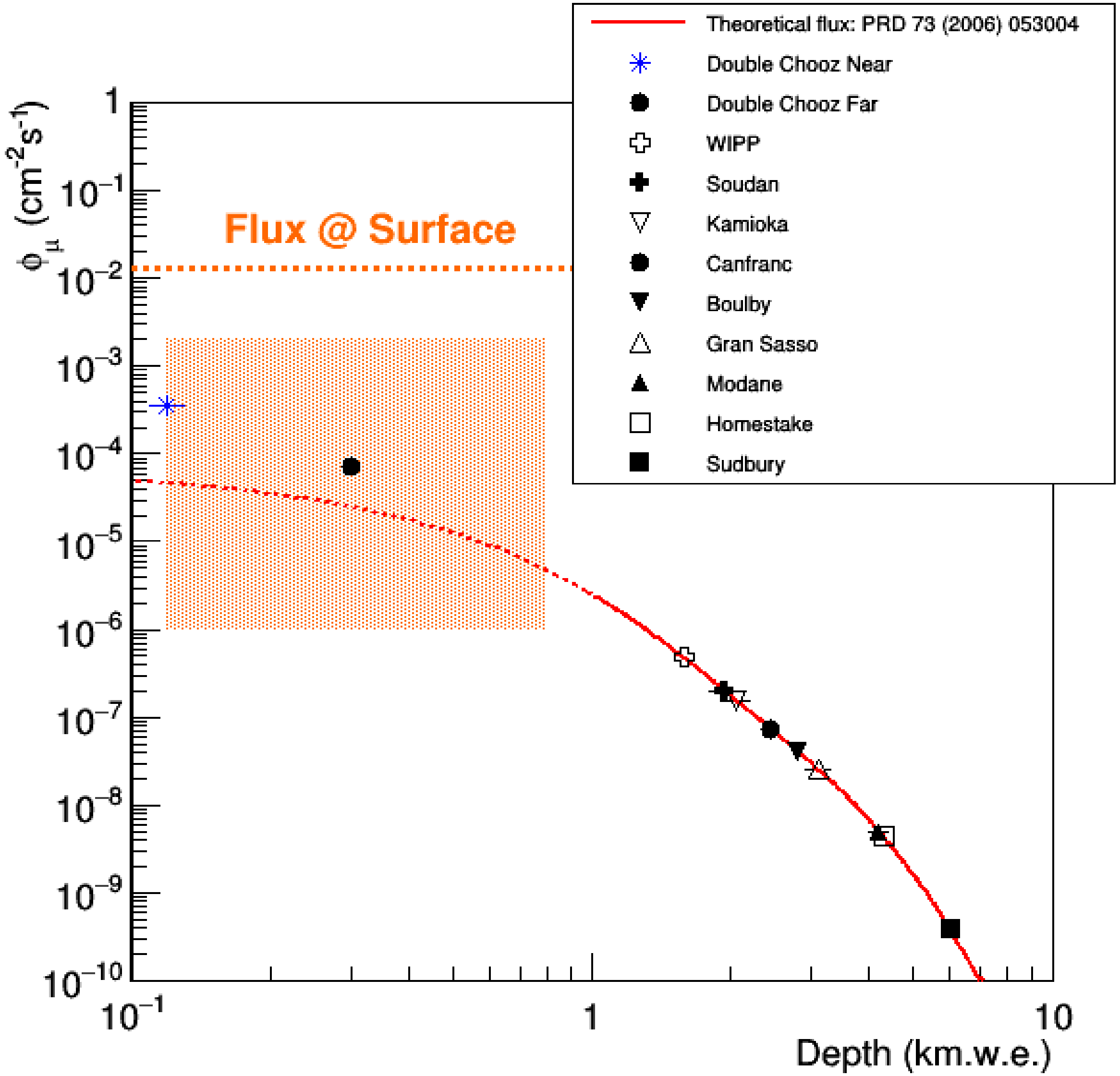
- For a spherical detector, $S_{eff} = \pi R^2$ for all directions
  → Simpler and with lower uncertainties



- 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 + Tracking → Muon flux



Near Detector:	ϕ_μ = 3.64 ± 0.04 10^{-4} cm^{-2} s^{-1}
Far Detector:	ϕ_μ = 7.00 ± 0.05 10^{-5} cm^{-2} s^{-1}

~1% accuracy

Simulations

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

→ Routine to implement in your code to simulate the transport of muons through materials

✔ Faster than other simulations packages (e.g. Geant 4) → Specially useful for long μ paths

✔ Versatile: Not difficult to implement the digitized overburden profiles

✖ Consider internal structures/anomalies → Concatenate simulations

✖ Detector response to do “off-line”

Overburden Profile and Composition

Muon Distribution at Surface

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

Simulations

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

  → Routine to implement in your code to simulate the transport of muons through materials

  ✔ Faster than other simulations packages (e.g. Geant 4) → Specially useful for long μ paths

  ✔ Versatile: Not difficult to implement the digitized overburden profiles

  ✖ Consider internal structures/anomalies → Concatenate simulations

  ✖ Detector response to do “off-line”

Overburden Profile and Composition

Muon Distribution at Surface

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

Simulations

- 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

Simulations

- 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

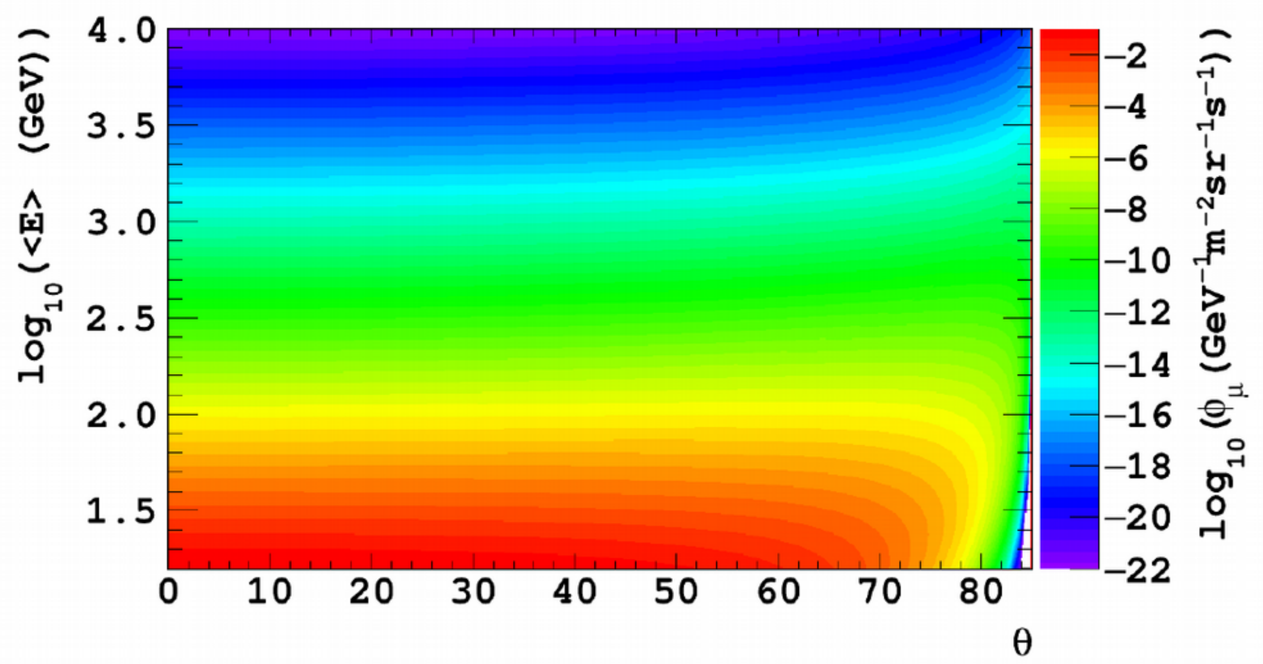
    ➔ It is for low energies where muon models present more differences

- 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

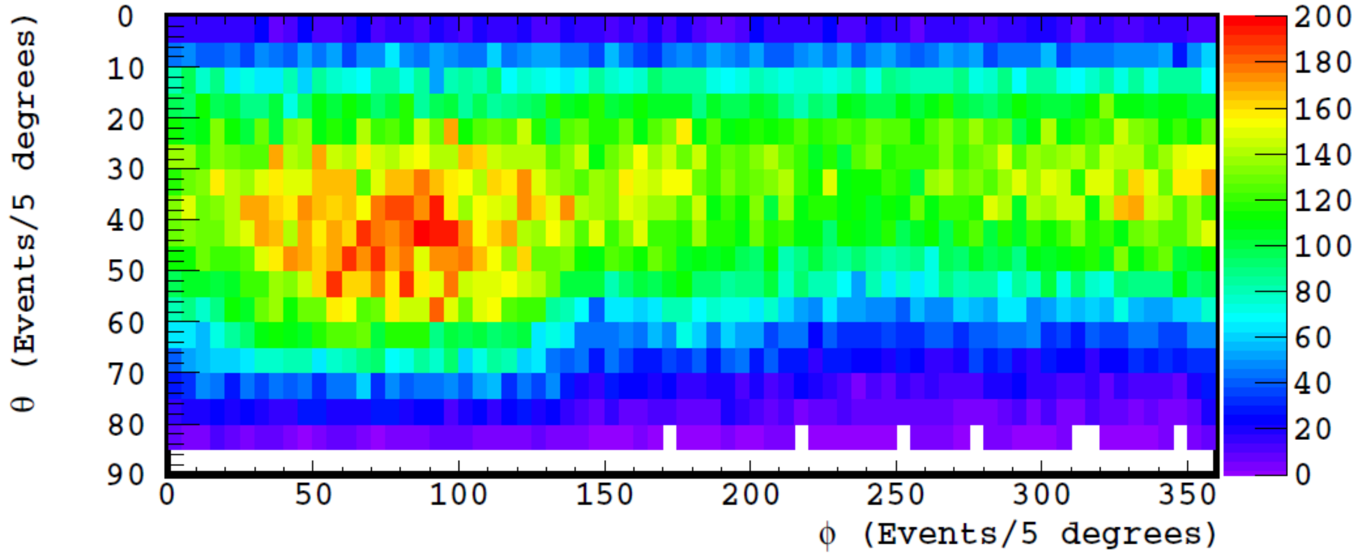
✔ Based on Gaisser analytical formula ($E_\mu > 100/\cos(\theta)$ GeV)

Originally not valid for low energy; valid extension?

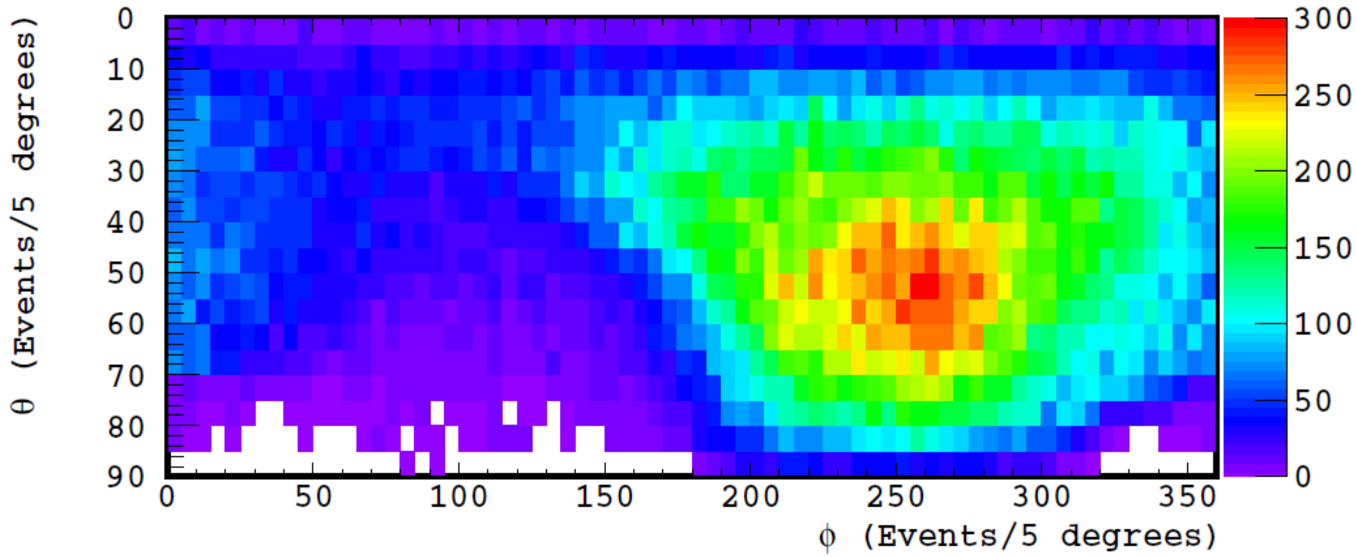


Simulations → Angular distributions

Near detector

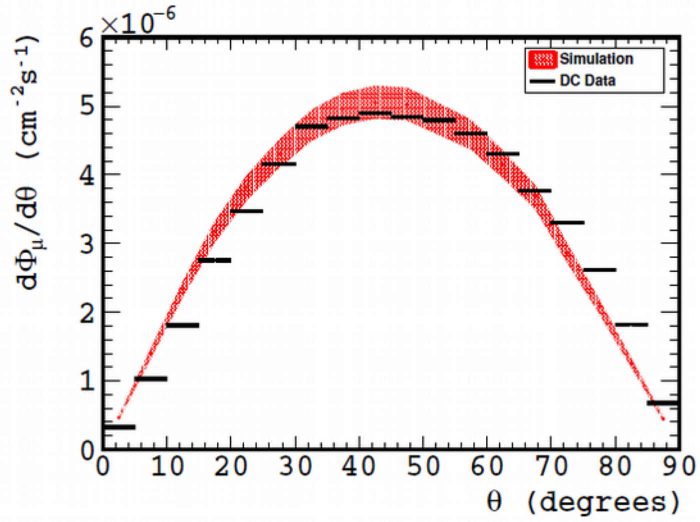


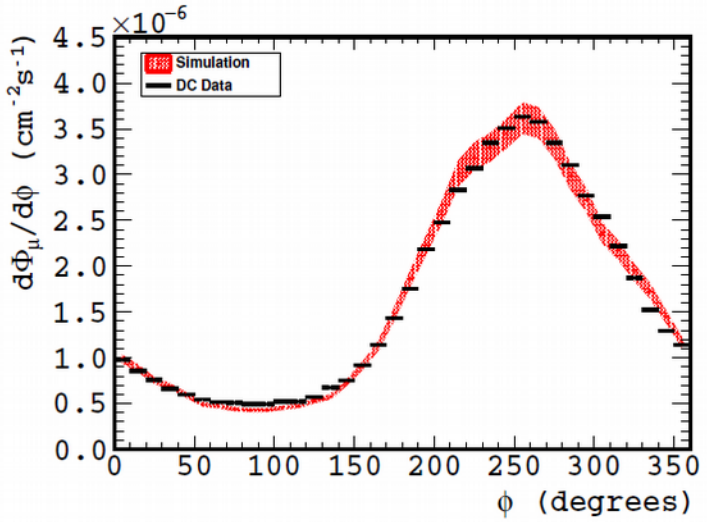
Far detector



Data / MC comparisons

Far detector





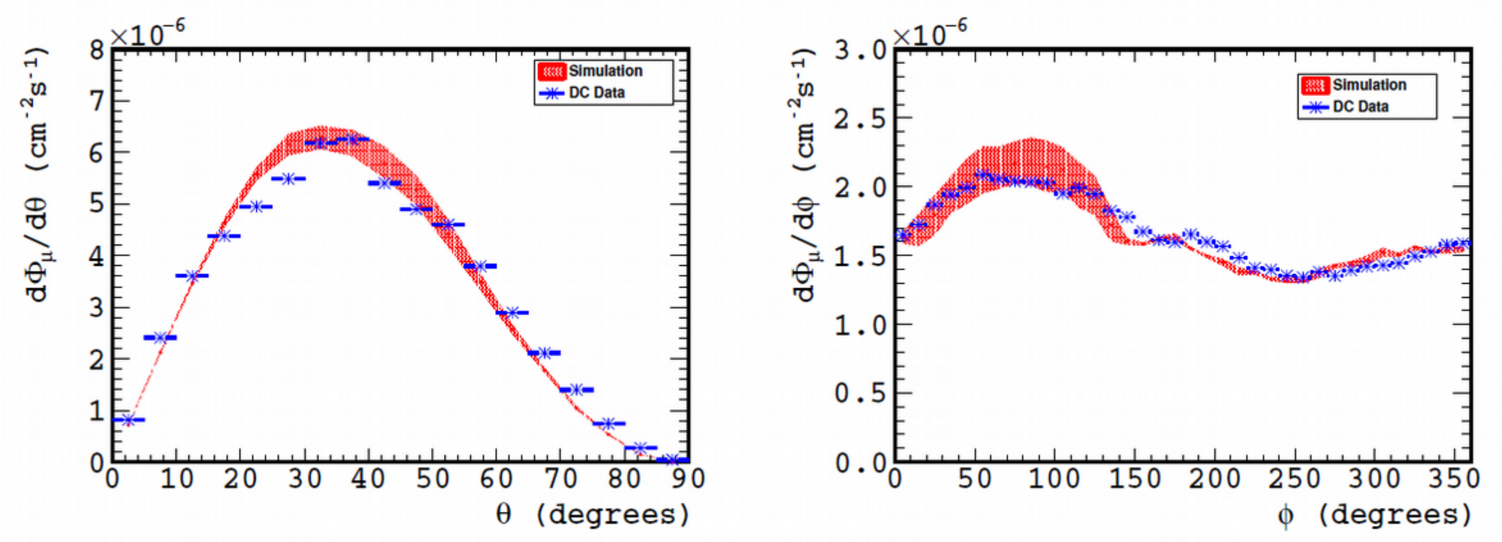
Data:	$\phi_\mu = 7.00 \pm 0.05\ 10^{-4}\ cm^{-2}\ s^{-1}$
Simulations:	$\phi_\mu = 7.24 \pm 0.33\ 10^{-5}\ cm^{-2}\ s^{-1}$

In agreement within:

- Simulations precision (due to profile digitization)
- Track reconstruction algorithm accuracy

Data / MC comparisons

Near detector



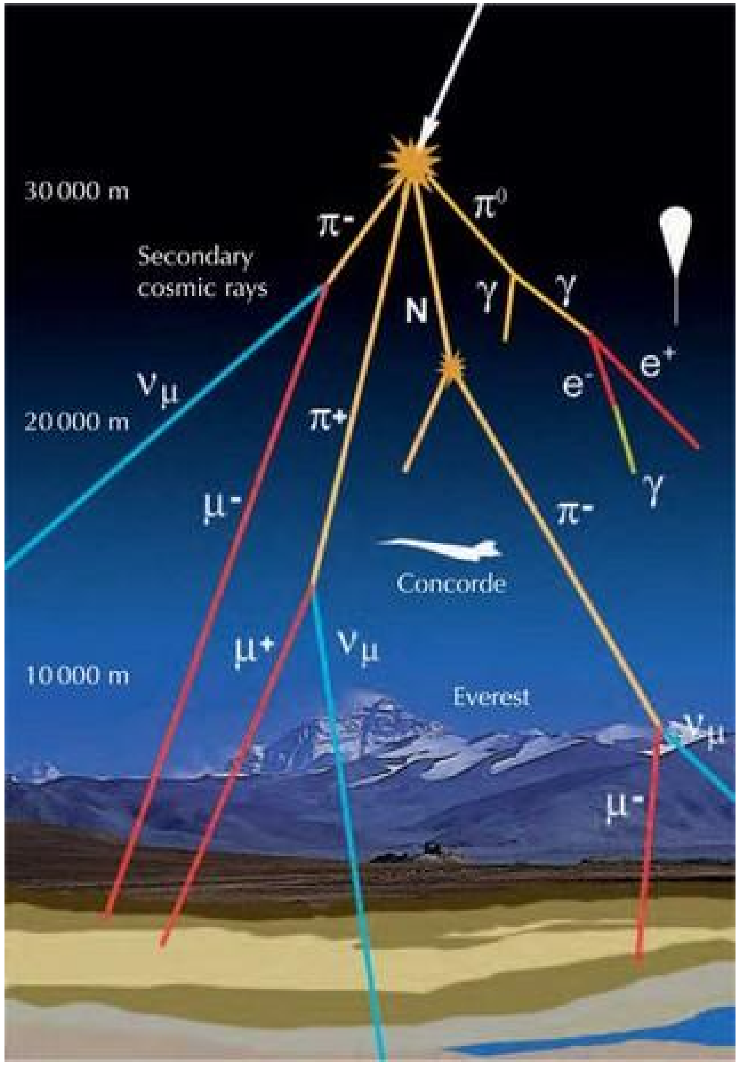
Data:	$\phi_\mu = 3.64 \pm 0.04\ 10^{-4}\ cm^{-2}\ s^{-1}$
Simulations:	$\phi_\mu = 3.47 \pm 0.12\ 10^{-5}\ cm^{-2}\ s^{-1}$

Differences due to:

- Uncertainties in the low energy muon parametrization
  - Is still valid the extended Gaisser parametrization?
- Lower precision in the profile digitization
  - Inhomogeneities along the overburden?

- Even if (don't forget) ***Double Chooz*** was conceived as a ***neutrino detection 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
    - Overall agreement
- 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:



- 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***

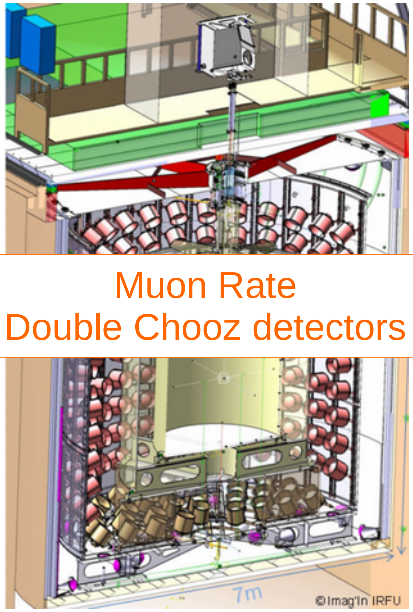
- p + N → Mesons (mostly π but also K)

  → Decay to muons $\tau_{\pi(K)}$ = 26.0 (12.4) ns

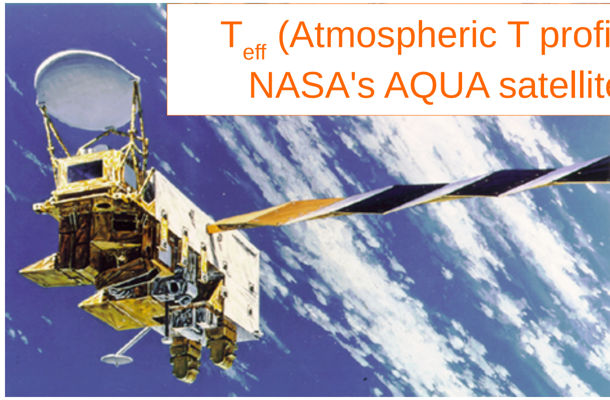
- Muons loose energy along their path through the atmosphere (and the rock over the detector)

- ***Deeper detectors → Higher E_μ required***

- Ingredients to study the annual modulation:



Muon Rate
Double Chooz detectors



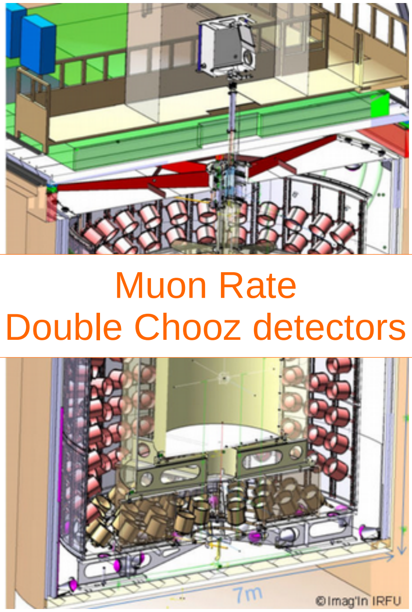
T_{eff} (Atmospheric T profile)
NASA's AQUA satellite

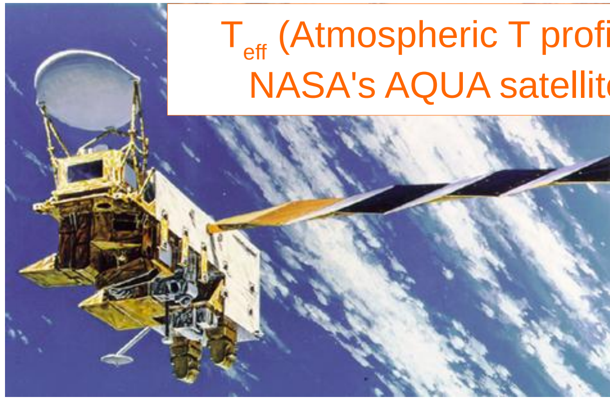
$$T_{\mathrm{eff}} = \frac{\sum_{n=0}^{N-1} \Delta X_n \cdot T(X_n)(W_\pi(X_n) + W_K(X_n))}{\sum_{n=0}^{N} \Delta X_n (W_\pi(X_n) + W_K(X_n))}$$

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

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

- Ingredients to study the annual modulation:

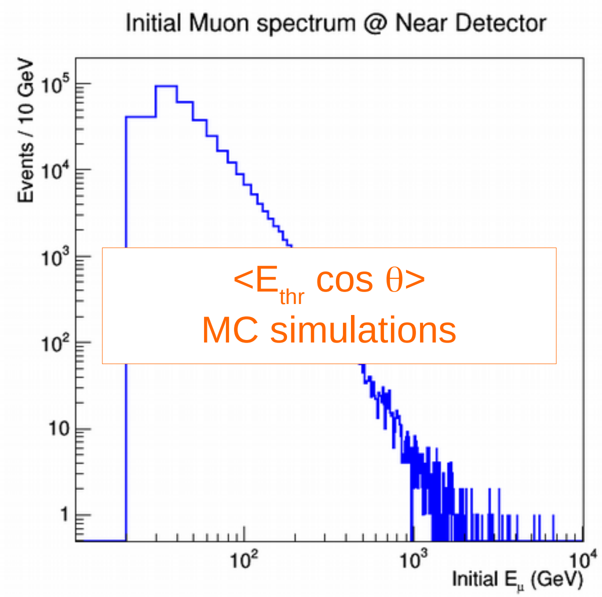




$$T_{\mathrm{eff}} = \frac{\sum_{n=0}^{N-1} \Delta X_n \cdot T(X_n)(W_\pi(X_n) + W_K(X_n))}{\sum_{n=0}^{N} \Delta X_n (W_\pi(X_n) + W_K(X_n))}$$

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

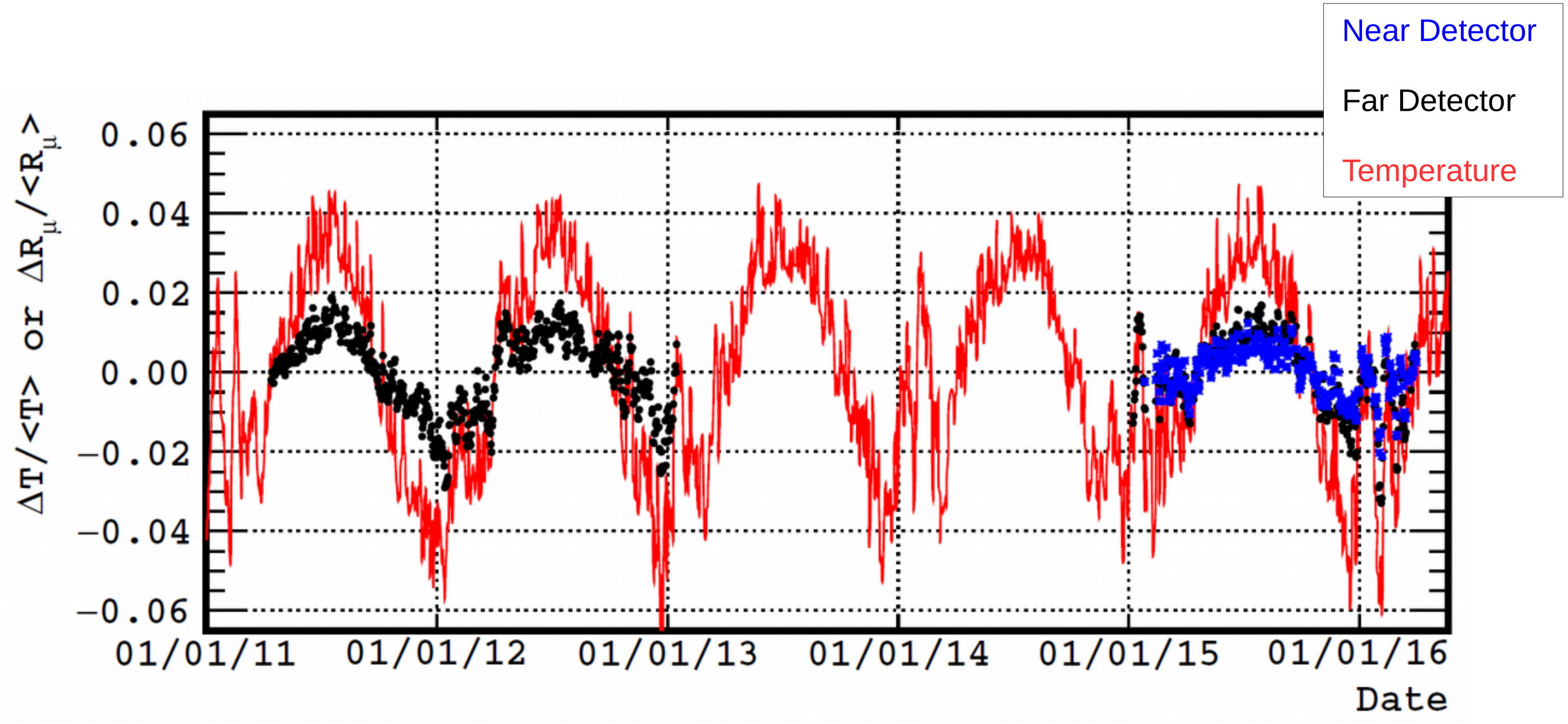
$$K_{\pi,K}(X) = \frac{(1 - X/\Lambda'_{\pi,K})^2}{(1 - e^{-X/\Lambda'_{\pi,K}})\Lambda'_{\pi,K}/X}$$



$$\langle E_{thr} \cos\theta \rangle = \int_{\theta=0}^{\pi/2} E_{thr}(\theta) \Phi^{\mu}_{norm}(\theta) \cos\theta \, d\theta$$

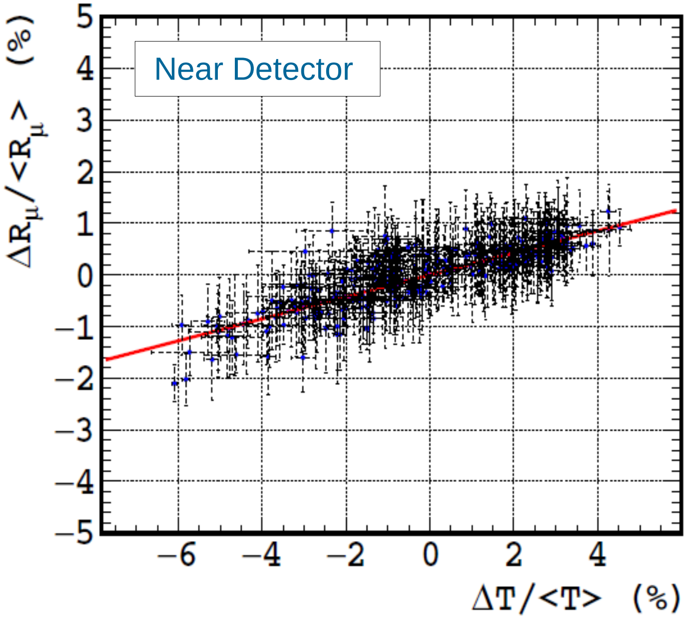
Near detector	$\langle E_{thr} \cos\theta \rangle = 22.3 \pm 4.8$ GeV
Far detector	$\langle E_{thr} \cos\theta \rangle = 46.0 \pm 10.0$ GeV

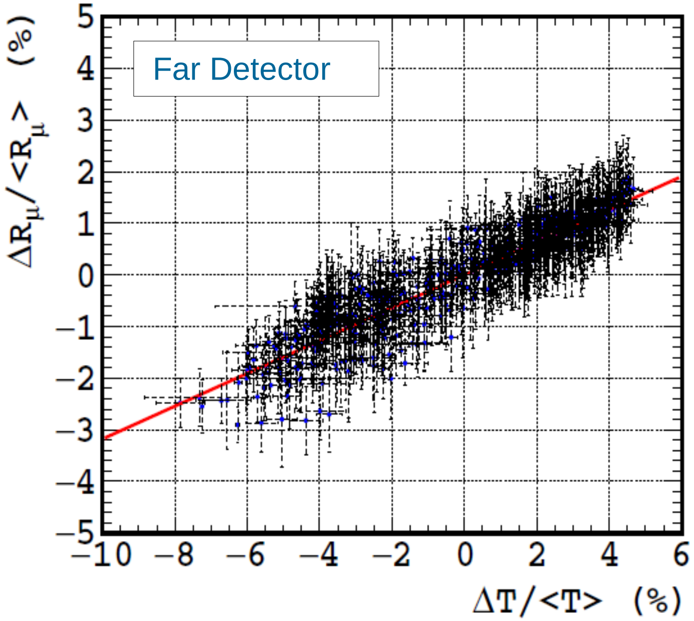
Annual modulation



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

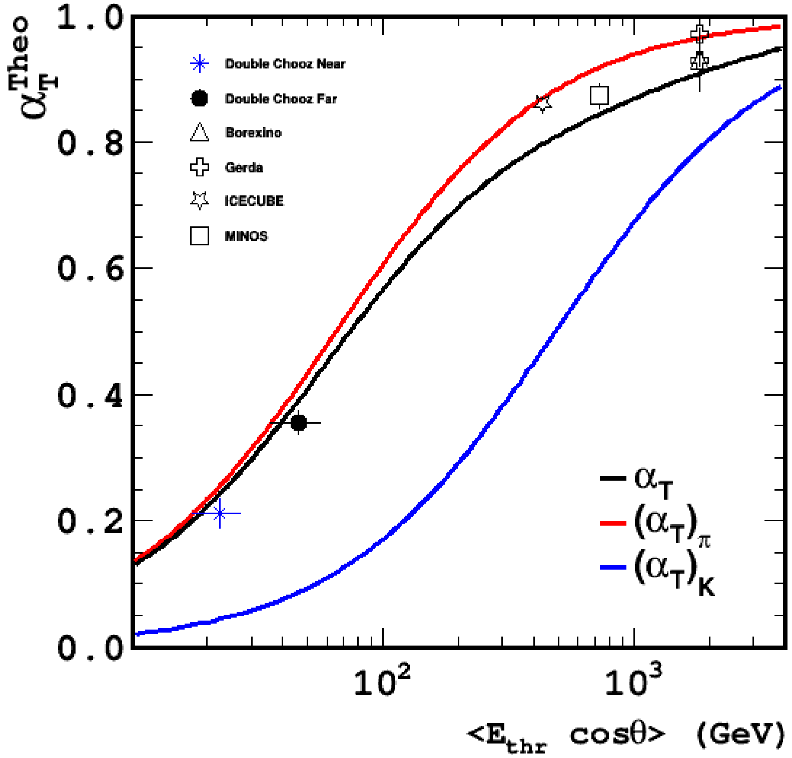
- Double Chooz results for α_T can be used to compare / validate theoretical models

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

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

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

$r_{K/\pi}$ = 0.149 ± 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 <E_{thr} cos θ>

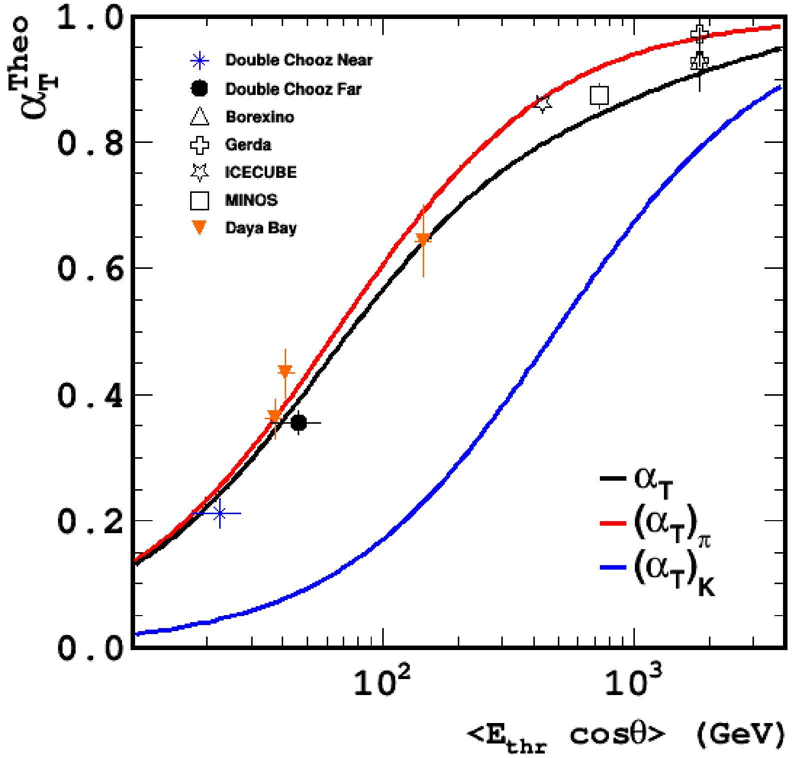
- Double Chooz results for α_T can be used to compare / validate theoretical models

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

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

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

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



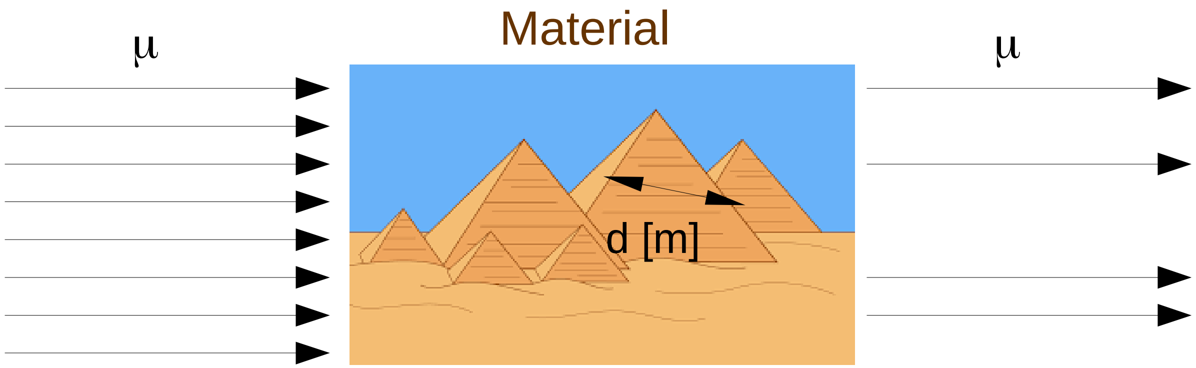
- Double Chooz measurements in agreement with theoretical model
- One of the first validations for low values of $\langle E_{thr} \cos\theta \rangle$
- Trigger for equivalent studies for other reactor ν experiments
  - Daya Bay → JCAP 01 (2018) 001

Taking advantage of muons

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

Even More Physics is possible...

More Physics is possible...



Initial flux ϕ_i

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

Density: ρ [g/cm3]

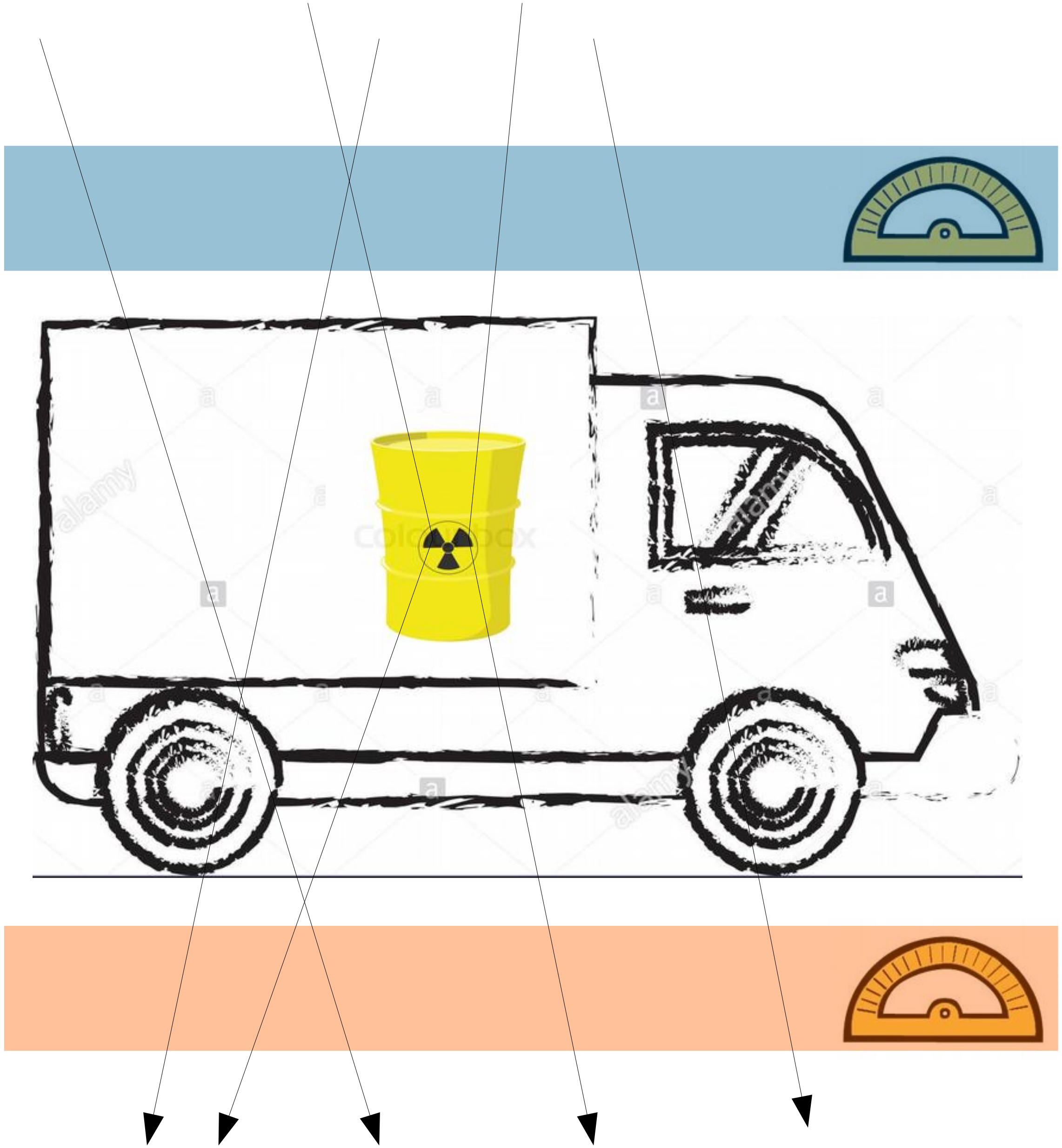
Opacity: δ **[g/cm²]** = ρ d

Final flux ϕ_f

Detected muons for a given direction

- Ratio between initial and final fluxes is directly related with Opacity
- Differences in final flux (after normalization) for different directions also points to Opacity differences

Muon tomography (Deviation)

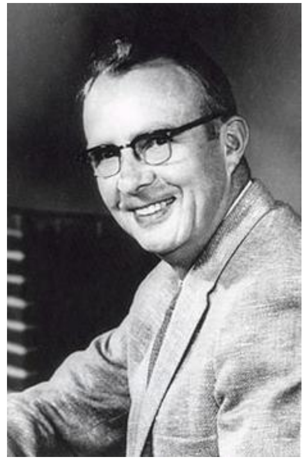


- Muon trajectory deviation is related with the material density (Moliere Theory)
- Comparing ***initial*** ***vs*** ***final*** directions for each point of the studied object, a mean deviation angle can be obtained, then a density map.

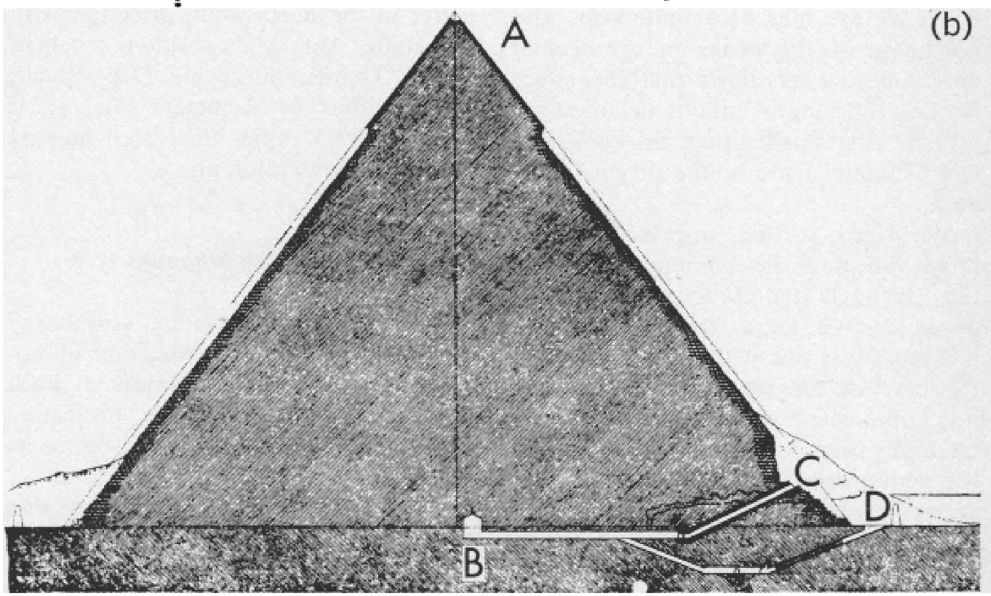
✔ Faster

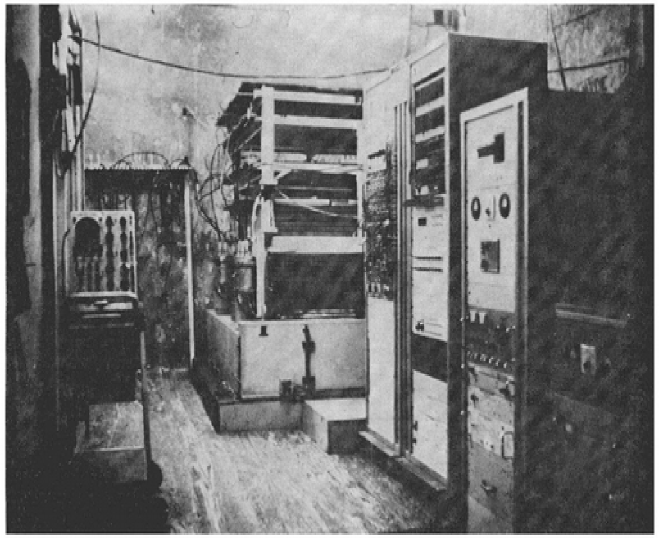
✔ For smaller objects with no big opacities

- 1955: Study of the rock overburden over a tunnel in Australia
  - *E.P. George, Cosmic rays measure overburden of tunnel, Commonwealth Engineer 455 (1955)*



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





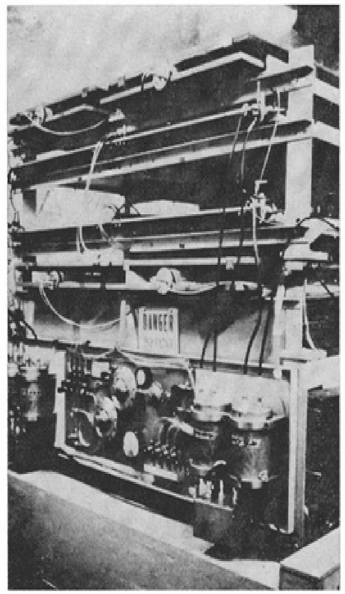
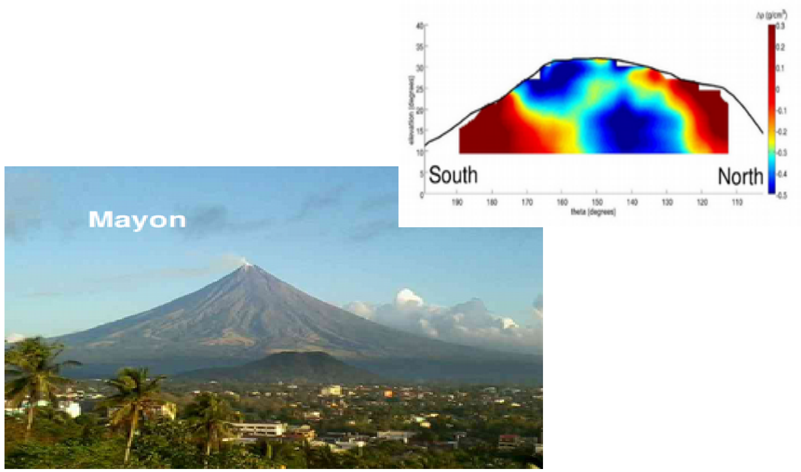


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.

Transmission



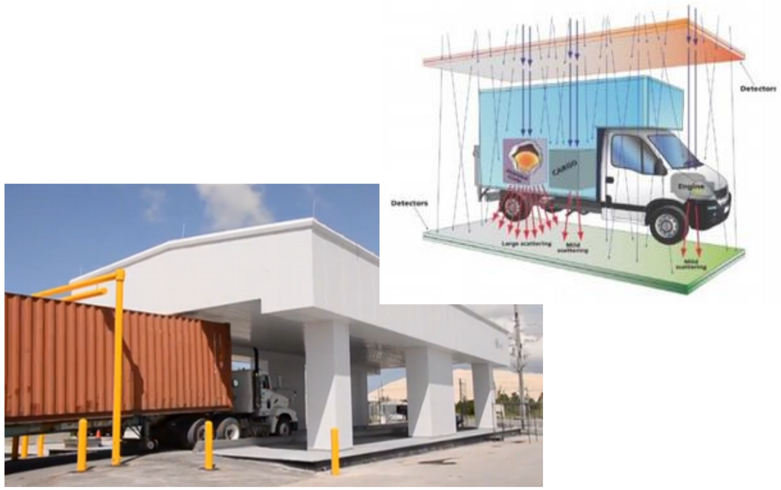
Volcano Tomography

Archeology

Deviation

Fukushima scanning

Nuclear control and safety



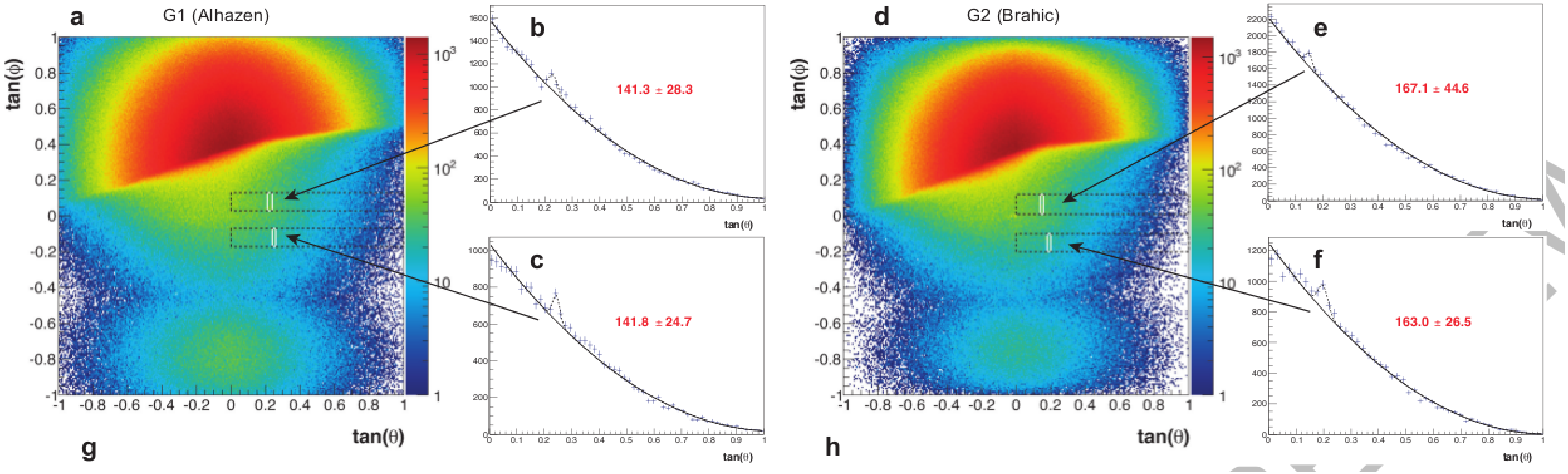
Homeland security

- ***Simulations*** represent a ***useful tool*** in muon tomography to:
  - Perform feasibility studies
  - Choose best detector position
  - Data analysis and interpretation

Improve measurement sensitivity

- To achieve that, the simulation framework ***requires***:
  - The precise implementation of :
    - The studied geometry
    - The muon parametrization at Earth surface
  - Consider all the muon physics process
  - Definition of the used detector features and performance

Nature 552 (2017) 386 -390



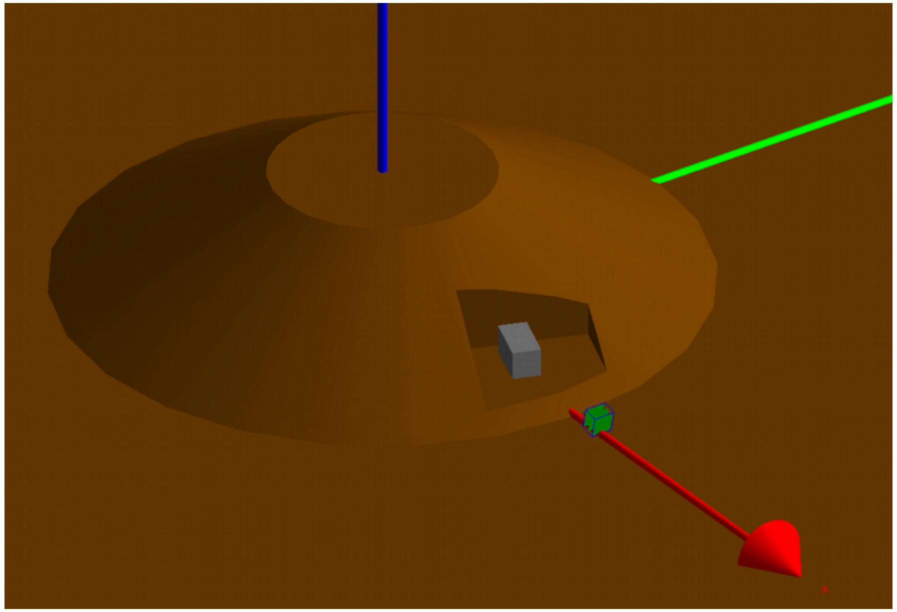
- Outstanding (Nature indeed) result taking advantage of:
  - State-of-the-art detector technology
  - Size of the "anomaly"
    - ~30 m over ~100 m of muon path across the pyramid
  - Position of the "anomaly"
    - Zentih angle anomaly – detector ~60º → Not optimal but still considerable muon flux

Example: Scanning of the Apollonia Macedonian Tumulus (Greece).
Feasibility study of a transmission measurement.

- ***Tumulus:***
  - Top Ø= 32 m; Base Ø = 92 m
  - Height = 17 m
  - Made of Soil with a Rock-wall chamber

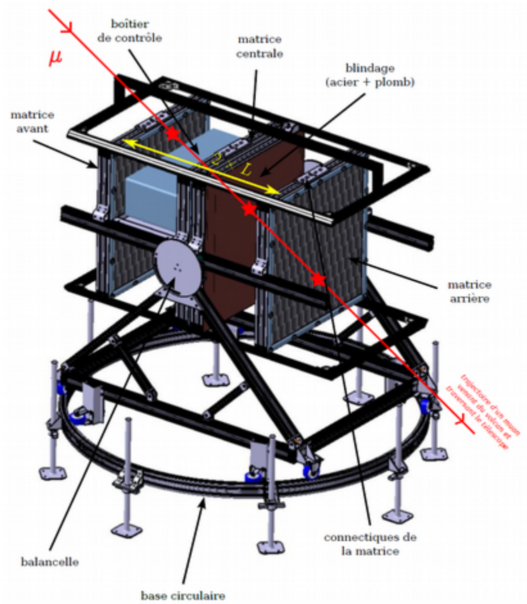
Incident θ = [70 – 80]^o

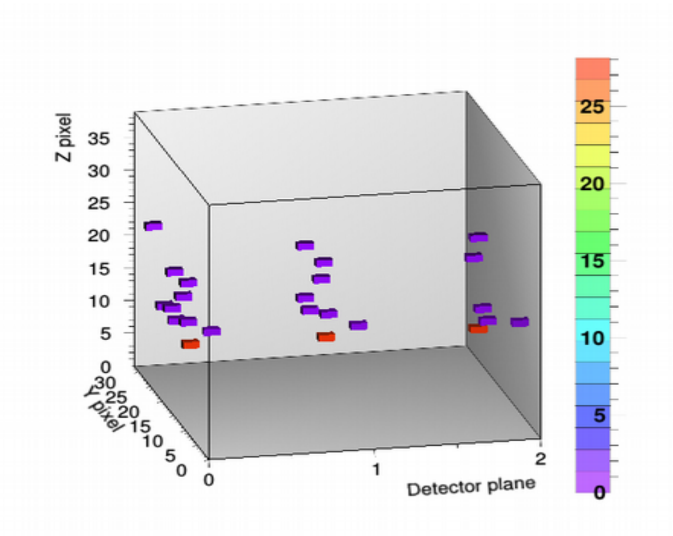
Anomaly ~ 10/100 m

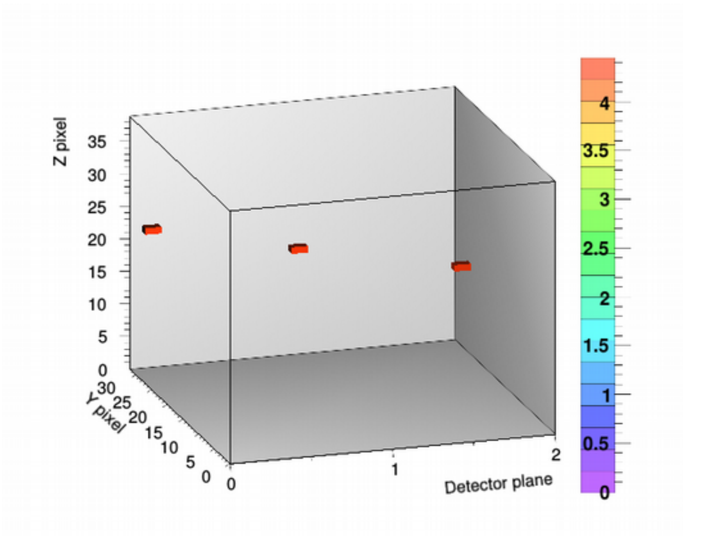


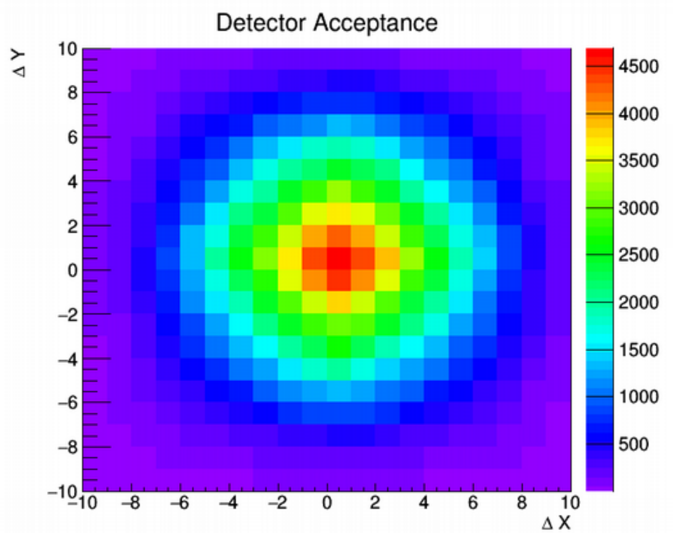
Example: Scanning of the Apollonia Macedonian Tumulus (Greece).
Feasibility study of a transmission measurement.

- ***Detector:***
  - Muon telescope based on plastic scintillators
  - Evolution of those already used for volcanoes scanning
  - Assumed angular resolution ***1º***



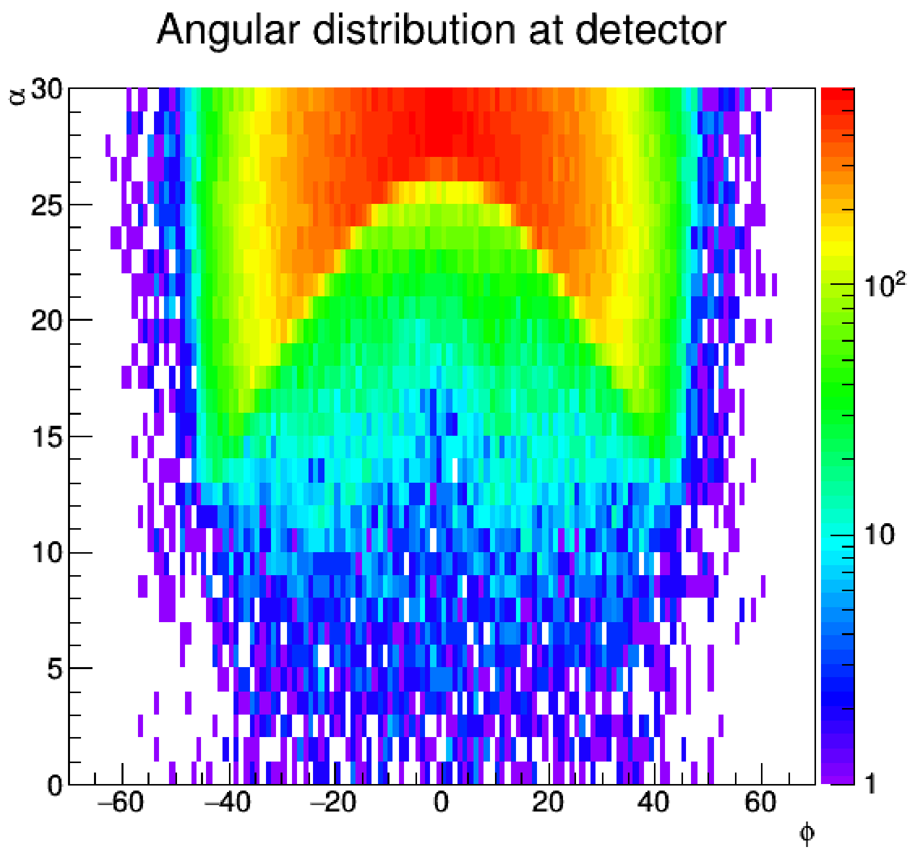






Example: Scanning of the Apollonia Macedonian Tumulus (Greece).
Feasibility study of a transmission measurement.

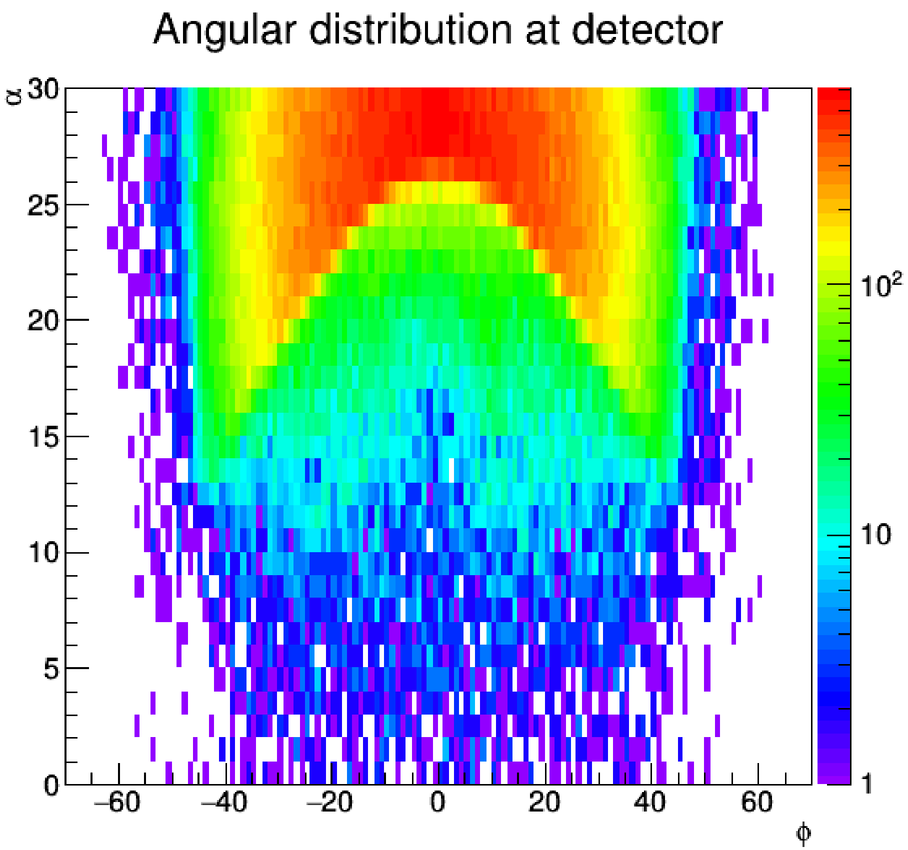
- ***Results:***



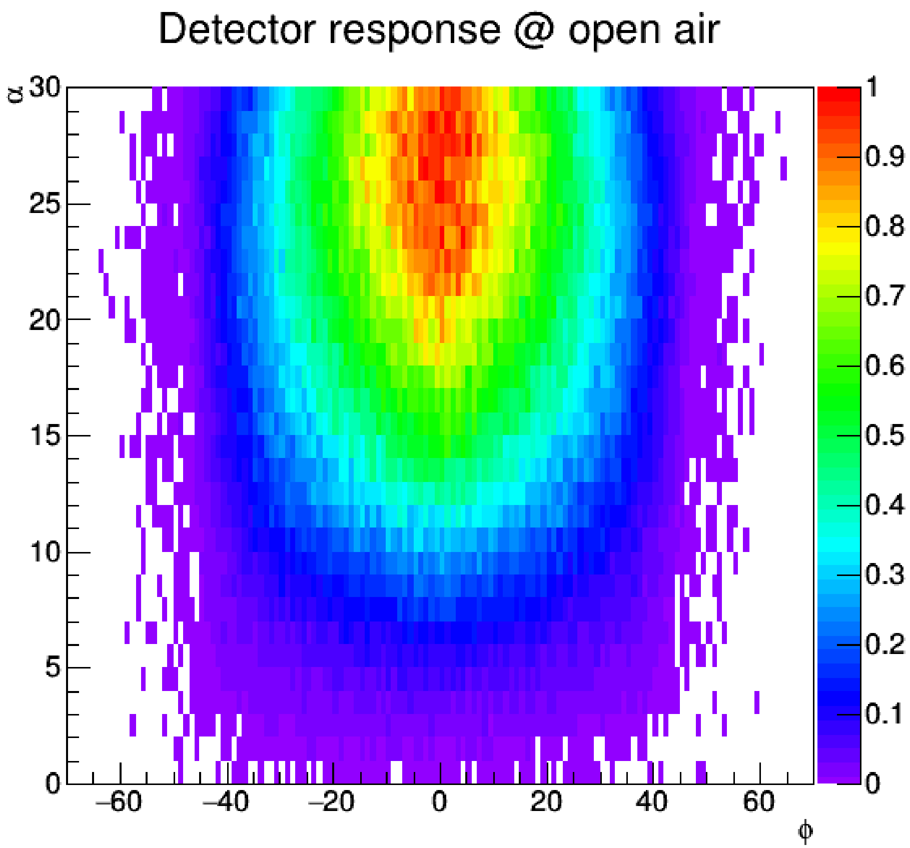
Raw results

Example: Scanning of the Apollonia Macedonian Tumulus (Greece).
Feasibility study of a transmission measurement.

- ***Results:***



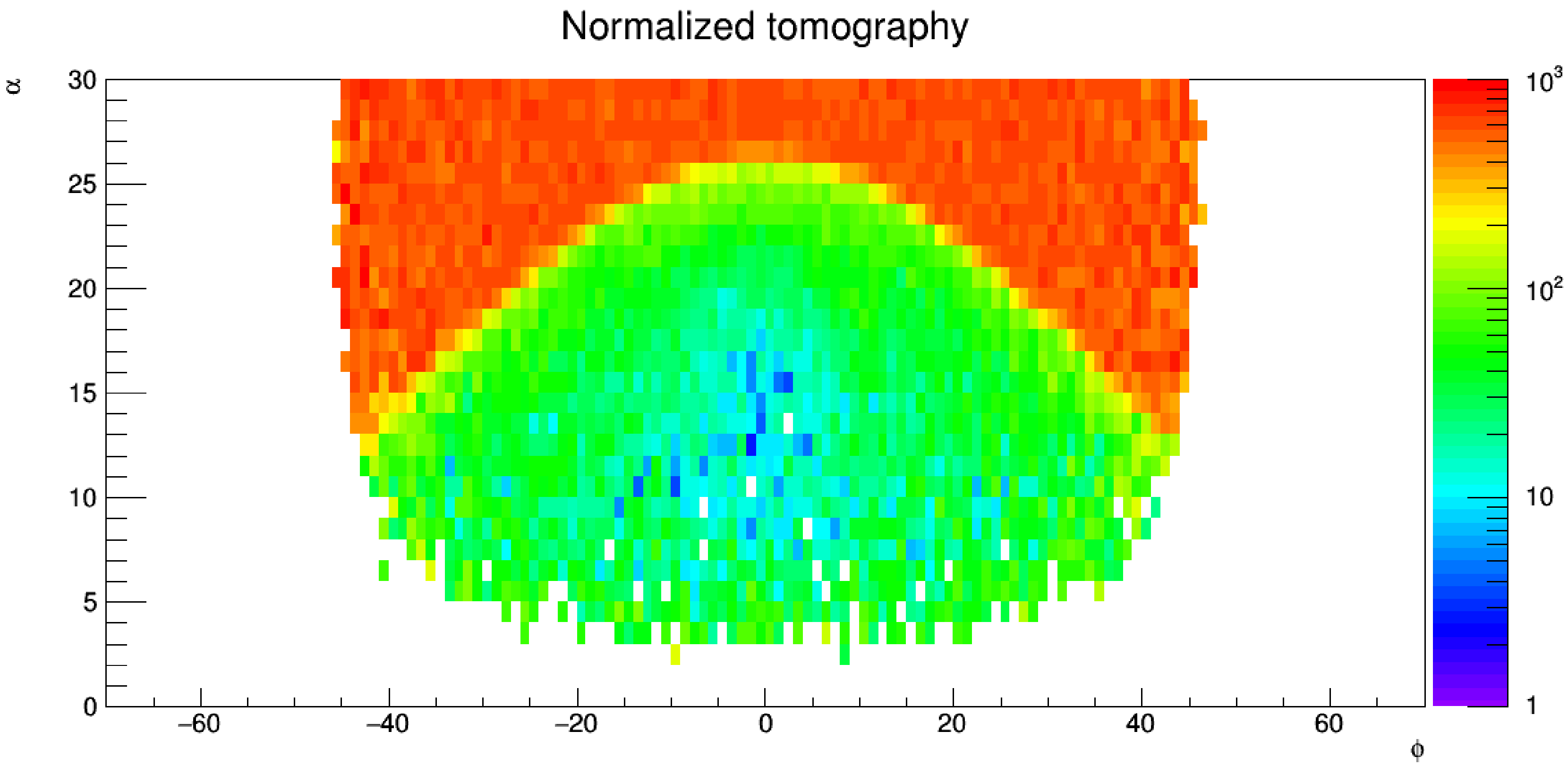
Raw results



Normalized results at open air with the same inclination

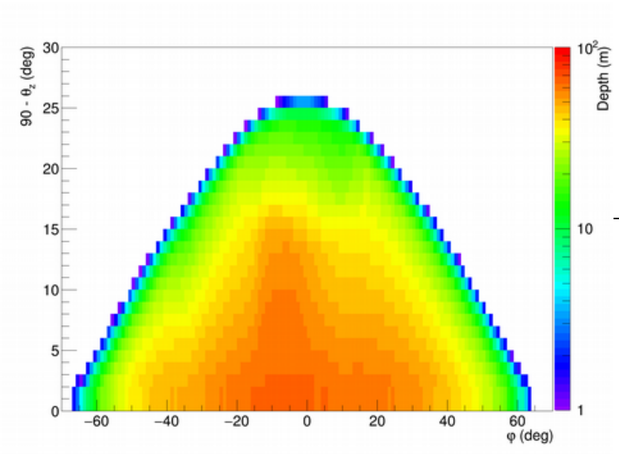
Example: Scanning of the Apollonia Macedonian Tumulus (Greece). Feasibility study of a transmission measurement.

- ***Results:***

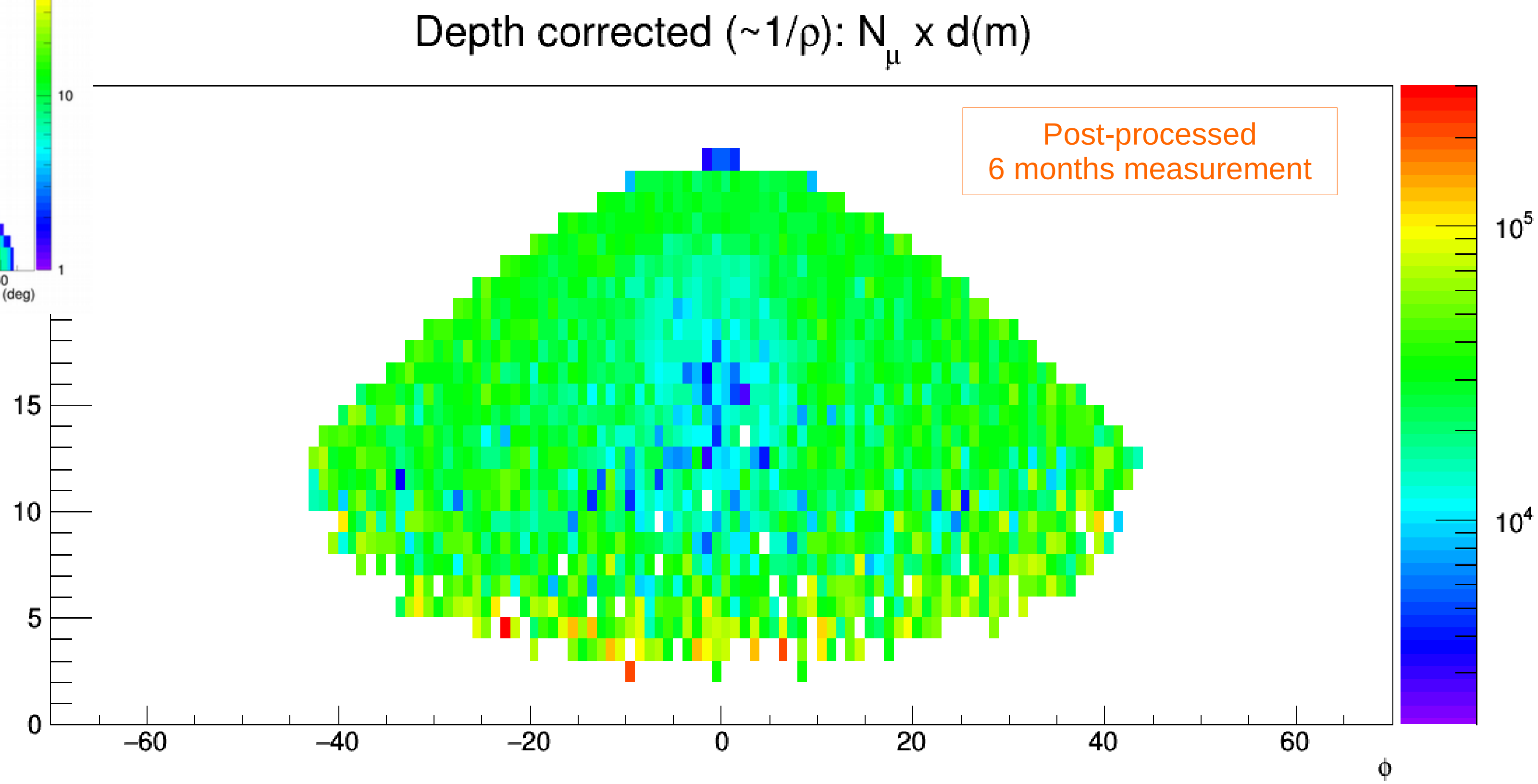


Example: Scanning of the Apollonia Macedonian Tumulus (Greece). Feasibility study of a transmission measurement.

- ***Results:***

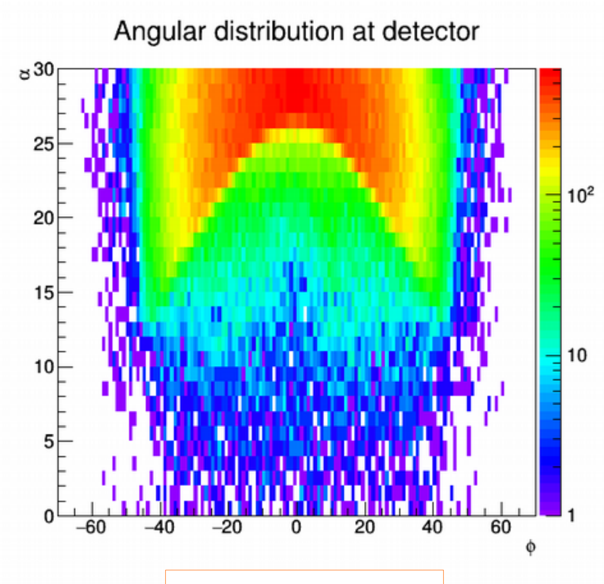


External shape

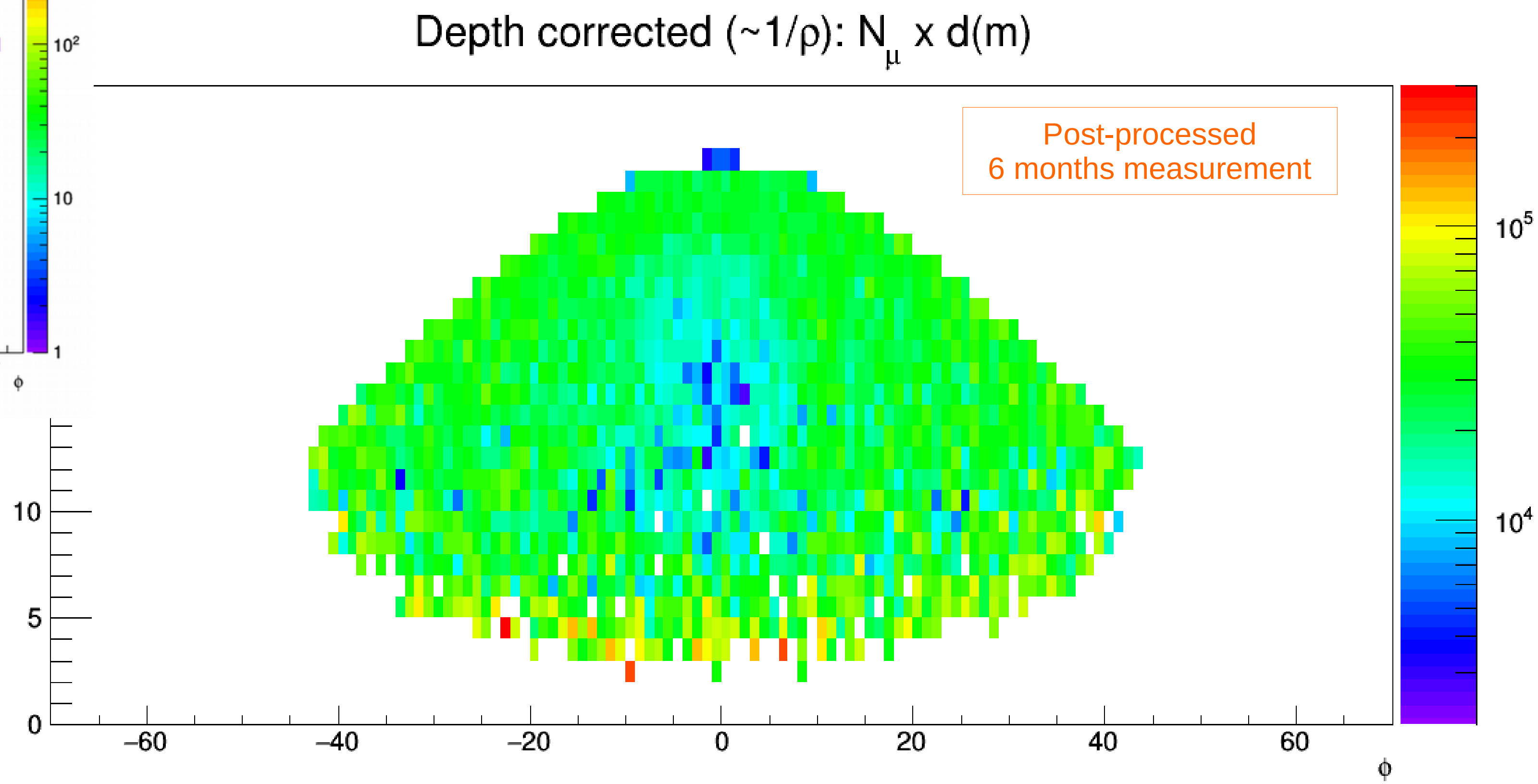


Example: Scanning of the Apollonia Macedonian Tumulus (Greece). Feasibility study of a transmission measurement.

- ***Results:***



Raw

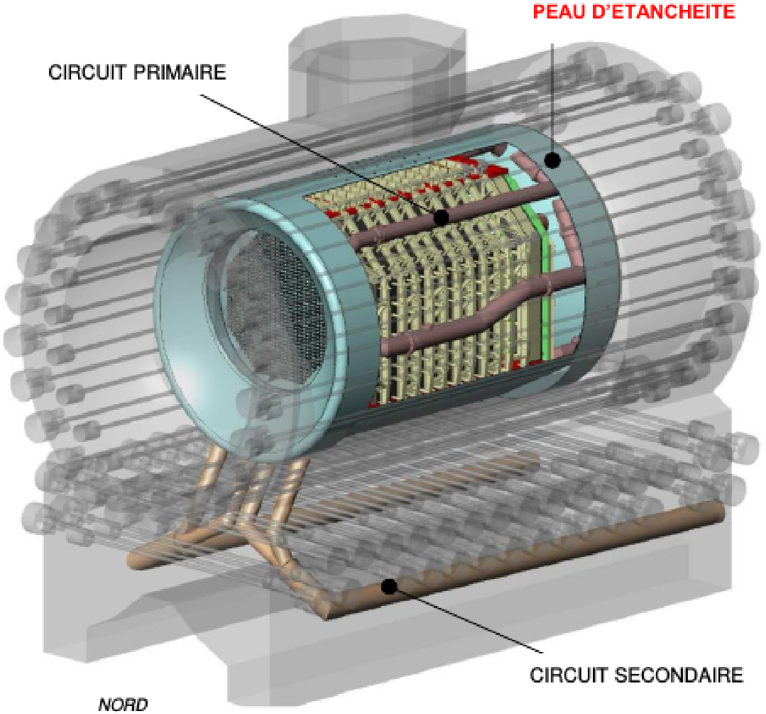


Towards high precision simulations: Implementation of geometries

From CAD designs

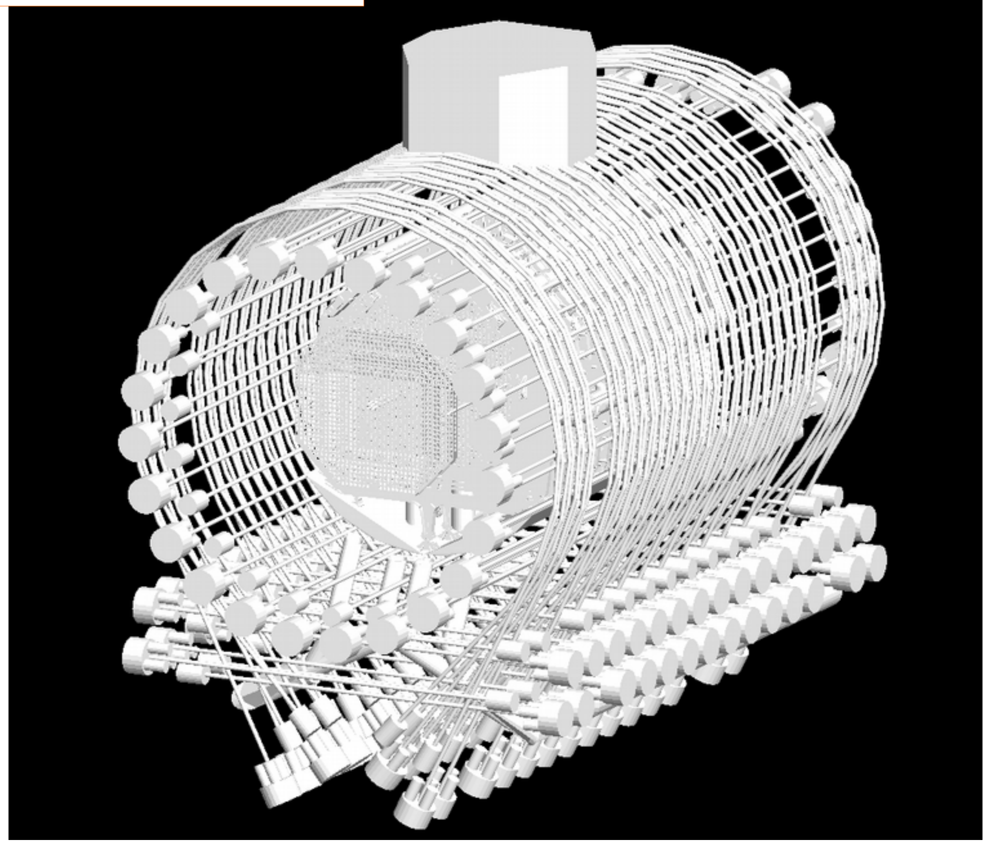
From objects 3D models: Topography, photo-grammetry...

G2-G3 reactors
CEA-Marcoule



CAD design composed by 866 different components

G4 implementation
22136 volumes

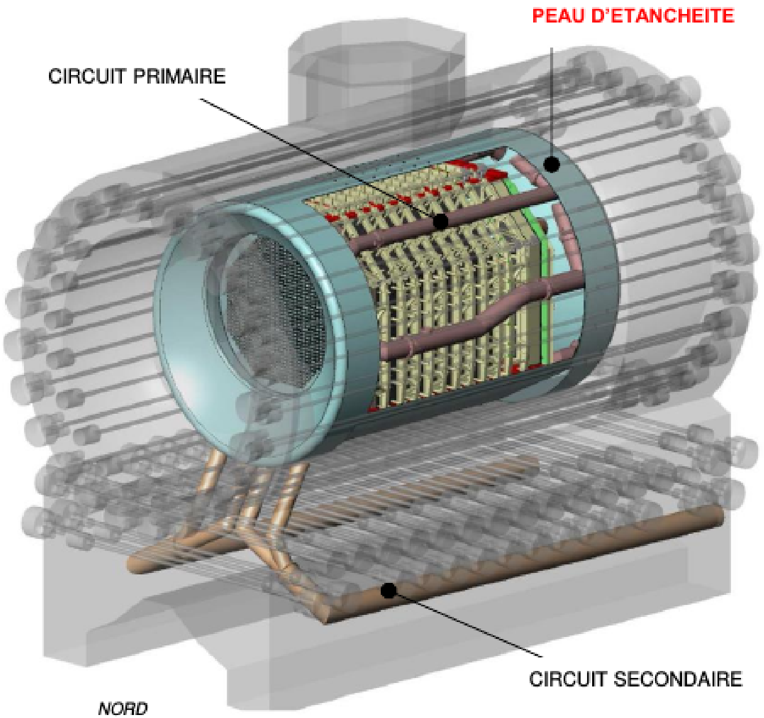


Towards high precision simulations: Implementation of geometries

From CAD designs

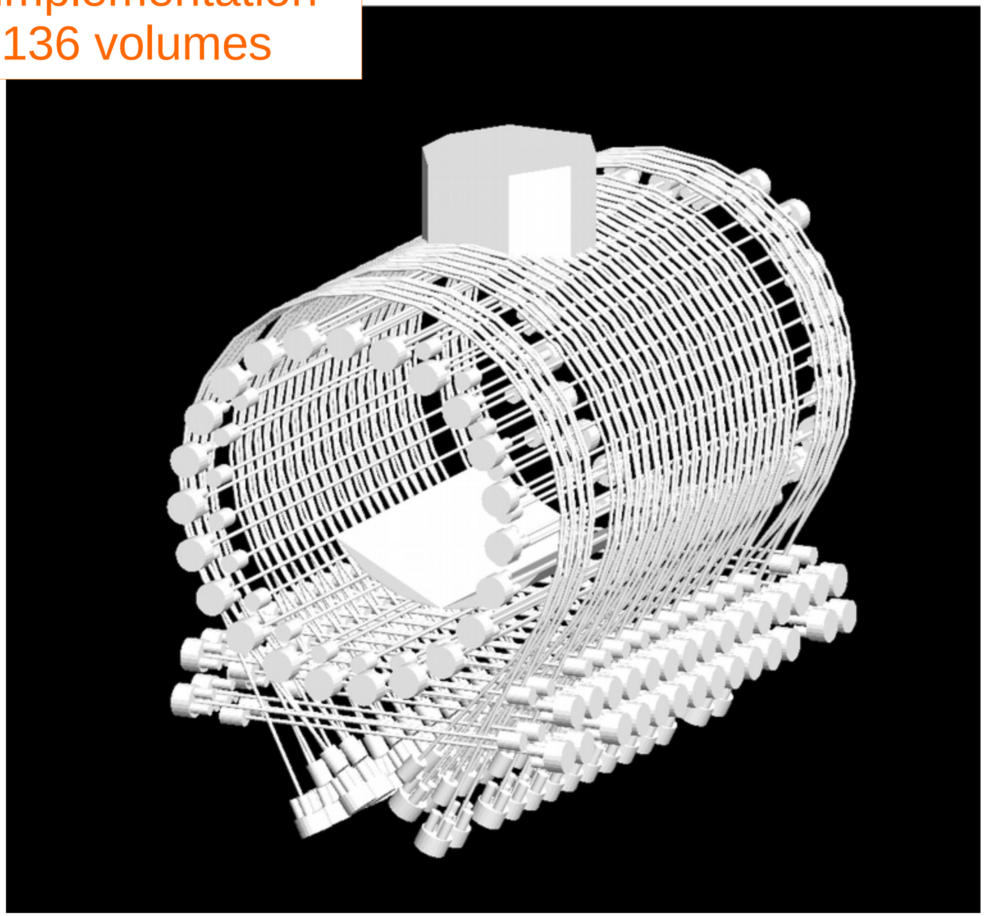
From objects 3D models: Topography, photo-grammetry...

G2-G3 reactors
CEA-Marcoule



CAD design composed by 866 different components

G4 implementation
22136 volumes

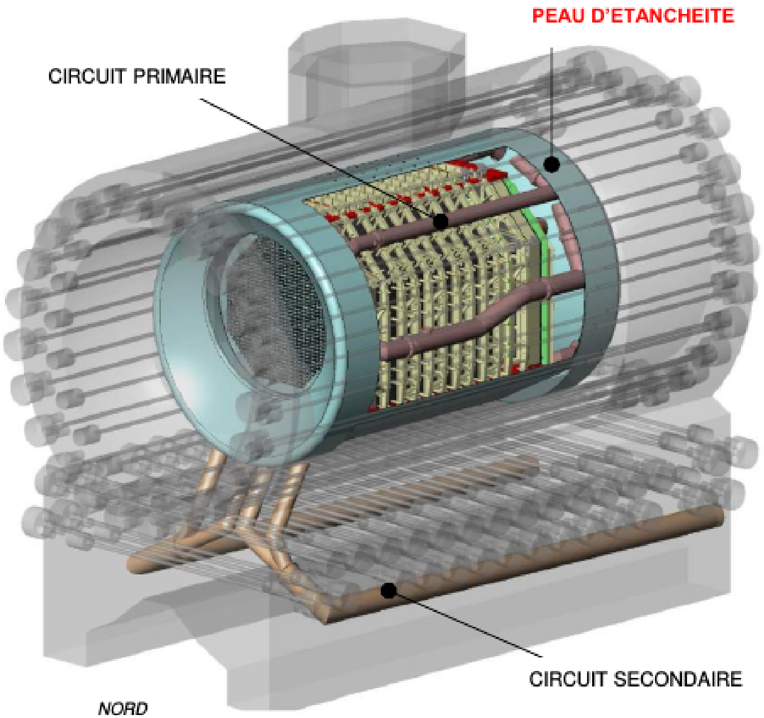


Towards high precision simulations: Implementation of geometries

From CAD designs

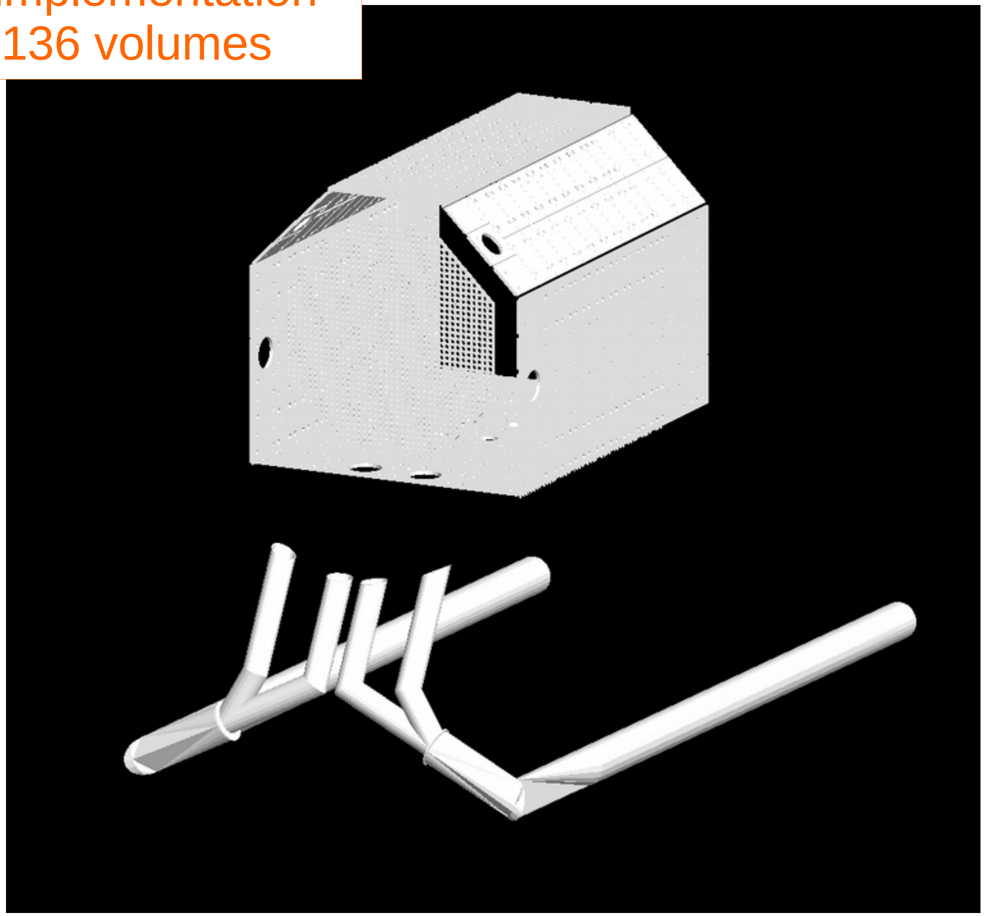
From objects 3D models: Topography, photo-grammetry...

G2-G3 reactors
CEA-Marcoule



CAD design composed by 866 different components

G4 implementation
22136 volumes



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
    - ***Accurate simulations*** could help to improve the sensitivity of this technique
      - Some preliminary studies have been already performed
      - More complete, versatile and precise framework is being implemented

Squeezing atmospheric muons

From neutrino physics to imaging applications

Héctor Gómez

IRFU / DPhN / LSN

hector.gomez@cea.fr