Detector Modelling in Astroparticle Physics

Sergio Petrera, INFN and L'Aquila University

- Particle vs Astropart. Physics
- Detector Modelling
- Two examples:
  - Atmospheric neutrinos (MACRO)
  - UHE Cosmic Rays (Auger)
Particle vs Astroparticle Physics (my personal view)

- Both exploit particle detection
- ...but, the physics aim is different

In Particle Physics the beam (beam-target, beam-beam) is perfectly known
The interest is addressed to the outcome of the interaction: e.g.
Particle vs Astroparticle Physics (my personal view)

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In Particle Physics the beam (beam-target, beam-beam) is perfectly known
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In Astroparticle Physics the beam is unknown (partly or fully)
The interest is addressed to the knowledge of its features: e.g.
- particle identity
- energy
- direction
- origin

\[ \gamma \]
... their common feature: particle detection

Detector modelling usually done with dedicated codes:
- Experiment specific simulation program
- General purpose packages/toolkit (GEANT)

Simulation includes:
- Detailed geometry of detectors
- Geometry of passive elements
- Physics processes originating signals
- ...

Let's look at GEANT
The historical background

- **Geant** is a simulation tool, that provides a general infrastructure for:
  - the description of geometry and materials
  - particle transport and interaction with matter
  - the description of detector response
  - visualisation of geometries, tracks and hits

- **The user develops specific code** for:
  - the primary event generator
  - the geometrical description of the set-up
  - the digitisation of the detector response

- **Geant3**
  - has been used by most HEP experiments
  - used also in nuclear physics experiments, medical physics, radiation background studies, space applications etc.
  - frozen since March 1994 (Geant3.21)
  - ≈200K lines of code
  - equivalent of ≈50 man-years, along 15 years

- **The result is a complex system**
  - because its problem domain is complex
  - because it requires flexibility for a variety of applications
  - because its management and maintenance are complex

- **It was not self-sufficient**
  - hadronic physics is not native, it is handled through the interface to external packages
What is **Geant 4**?

- **OO Toolkit for the simulation of next generation HEP detectors**
  - ...of the current generation too
  - ...not only of HEP detectors
  - already used also in nuclear physics, medical physics, astrophysics, space applications, radiation background studies etc.

- It is also an experiment of distributed software production and management, as a large international collaboration with the participation of various experiments, labs and institutes

- It is also an experiment of application of rigorous software engineering methodologies and Object Oriented technologies to the HEP environment

Maria Grazia Pia, INFN Genova
Technology transfer

Particle physics software aids space and medicine

Geant4 is a showcase example of technology transfer from particle physics to other fields such as space and medical science [...].

CERN Courier, June 2002

Maria Grazia Pia, INFN Genova
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- Detector modelling is then extended to the *surrounding environment* where the secondaries are developed.
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Examples of this kind are e.g.
- neutrino detectors in underground experiments (+ rock)
- ground based cosmic ray experiments. (+ atmosphere)
Case I: MACRO

- The beam: atmospheric neutrinos
Case I: MACRO

The beam: atmospheric neutrinos

\[ \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2 \]
Case I: MACRO

- The beam: atmospheric neutrinos
- The physics phenomenon: $\nu_\mu \rightarrow \nu_\tau$ oscillation

$$P_{\nu_\mu \rightarrow \nu_\mu}(L, E_\nu) = 1 - \sin^2 2\theta \sin^2 \left[ \frac{\Delta m^2 L}{4E_\nu} \right]$$

![Diagram of atmospheric neutrinos and oscillation](image)

**ATMOSPHERIC NEUTRINOS**

- Up-Down Symmetric Flux (for $E_\nu > \text{few GeV}$)
- Isotropic flux of cosmic rays
Case I: MACRO

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- How do we detect $\nu_\mu$?

A different way to see Neutrinos: ($\nu_\mu$, $\bar{\nu}_\mu$)

$\mu$ and $\nu$ collinear to a good approximation
Case I: MACRO

- The beam: atmospheric neutrinos
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- How do we see it? $\nu_\mu$ as a function of angle $\theta$
- How do we detect $\nu_\mu$?

- The role of detector simulation is fundamental!
  - Response of the detector (tracking, timing, etc.)
  - Neutrino induced muons (flux, cross section): the rock surrounding the detector becomes part of the simulation
  - Muon transport
  - Background evaluation: fake upward muons (...again the rock...)
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The detection and measurement of neutrino induced muons was very robust in MACRO. The oscillation search would have been impossible without an accurate simulation!
ν event topologies

Throughgoing: \( \text{Emedian} \approx 50 \text{ GeV} \) 180/yr
Internal Up: \( \text{Emedian} \approx 3.5 \text{ GeV} \) 50/yr
Internal Down + Stopping \( \mu \): \( \text{Emedian} \approx 4.2 \text{ GeV} \) 35+35/yr (expected)
Upward throughgoing $\mu$ analysis

T.o.F. technique:

Main cut:
- Position along scint. counter from ST track in agreement inside 70 cm with that from ToF
- $\sim 200$ gr/cm$^2$ in rock absorber to reduce at 1% background from upgoing $\pi$s
- No scanning, fully automatic

$-1.25 < 1/\beta < -0.75$

$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L}$

1/\beta distribution (full detector)
The backgrounds

Incorrect $\beta$: showering events, multiple $\mu$s; large $\beta$: $\mu$ decay

First study of physical background to $\nu$ underground measurement


Photonuclear interactions
atmospheric $\mu \downarrow$ produce upgoing soft particles

Important for shallow detectors
(Baksan, IMB while SK and Soudan2 have vetos)

243 upgoing particles between
$12.2 \cdot 10^6 \mu s \downarrow \Rightarrow \sim 10^{-4} \pi/\mu \downarrow$

$\sim 1\%$ in throughgoing $\mu$s $\uparrow$
$\sim 5\%$ in stopping $\mu$s
μ↑ flux angular distribution

χ² test on the angular distribution (10 bins) with prediction normalized to data:

χ²/dof=25.9/9 for no-oscillations ⇒ P = 0.2%
χ²/dof=9.6/9 for νμ → ντ (Δm² = 0.0025 eV² sin²2θ=1) ⇒ P = 37%
Internal Up events

Selection Criteria:
1. ToF between central/top scintillator layers
2. Vertex containment to reject up-throughgoing $\mu$s (~1% backg)
DATA 161 with $-1.3 < 1/\beta < -0.7$ (eff. livetime 5.58yr)
Backgrounds (wrong $\beta$, secondary hits) = 7 $\Rightarrow$ 154

[Graphs and diagrams showing data distributions and analyses with $\Delta m^2 = 0.0025$ eV$^2$]
Pierre Auger Observatory
studying the universe's highest energy particles
Simulating a Large Cosmic Ray Experiment: The Pierre Auger Observatory

T. Paul
Northeastern University
Boston, USA

An example of some ideas described at this workshop for case of one experiment
Pierre Auger Observatory

**Objective:** study the highest energy cosmic rays
- What is the shape of the energy spectrum?
- What is the composition
- Where do they come from (point sources, anisotropy)?

**Observatory:**
- Large exposure to capture rare events
- Each hemisphere for full sky coverage
- Complementary detection methods

*Colorado, USA*  
In planning stages

*Mendoza, Argentina*  
Nearing completion  
aperture $\sim 7000 \text{ km}^2 \text{ sr}$
Detection Techniques

Nitrogen fluorescence detected as shower develops

Particles detected as they reach ground

- **Fluorescence**
  - nearly calorimetric
  - direct view of shower evolution
  - 10% duty cycle
  - Acceptance depends on energy + atmosphere

- **Surface**
  - 100% duty cycle
  - Flat acceptance above threshold
  - Indirect measurements of primary energy and mass (relies on simulation)

*Hybrid = surface + fluorescence*
Southern observatory

Surface array
1600 detectors covering 3000 km²

Fluorescence detectors
4 buildings
6 telescopes each
Surface detector

Communication antenna

Electronics enclosure

GPS antenna for timing

3 Photomultiplier tubes

12 tons purified water radiates Cherenkov light

Tyvek bag acts as diffusive reflector
Fluorescence telescope
Fluorescence buildings ("Eyes")
Atmospheric monitoring
Understanding fluorescence data requires monitoring atmospheric conditions

Laser facilities
LIDAR at each eye
Weather stations & Radiosondes
The role of simulation

- Is crucial for:
  - CR interaction and shower development
  - Photon transport to FD telescopes
  - Detector simulation (in SD tanks, ray tracing to PMT pixels)

- Even in this case detector simulation extends to the surrounding environment: the atmosphere

A graded approach for each basic detector:
- Fast simulators with home made code
- Geant4 fast simulation
- Geant4 full simulation
The most time consuming simulation used as a reference
Detector simulations used for:

- Inferring **composition** from measured quantities (see talk from J. Knapp)

Shower front curvature
(from arrival times at each station)

Shower risetime
(from signal timing in surface detectors)

Risetime and curvature determined from surface detector measurements!
Simulations are required to relate these measurements to properties of the primary.
Detector simulation use for (cont.)

- Developing and validating reconstruction algorithms
  (reconstruction = turning measured quantities into shower properties)

- Estimating systematic errors

- Crosschecking calibration procedures

- Computing the fluorescence detector exposure

\[ J(E) = \frac{N(E)}{\varepsilon(E) \Delta E} \]

\[ \varepsilon(E) = \int_T \int_\Omega \int_{S(T)} \varepsilon(T) \cos \theta dS d\Omega dT \]

- Design studies for enhancements (or whole new observatories)
Steps for simulating surface array

Each simulation step encapsulated in a module

corsika
aires
conex
seneca

station triggering
various combinations:
coincidences
threshold
time-over-threshold

Central triggering
space-time clustering
of tank signals

Event building

shower core placement

Shower Unthinning
(particles hitting tanks)

Tank response to particles

Phototube and electronics

40 MHz sampling

counts

time bin

time

Station triggering

various combinations:
coincidences
threshold
time-over-threshold

Shower Unthinning
(particles hitting tanks)
Example: simulating tank response

**Entering particles**
- Particle interactions in tank material
- Cherenkov light generated in water
  - entering $e^\pm, \mu^\pm$
  - entering $\gamma \rightarrow \gamma e^-, \gamma \rightarrow e^+ e^-$
- $\delta$ ray production
- energy loss

**Optical photons**
- Tank properties tuned to measurements
  - Reflectivity vs. $\lambda$
  - Specular / diffuse reflection
- Absorption in water vs. $\lambda$
- Optical interfaces at phototube
- Phototube quantum efficiency vs $\lambda$
Tank model vs. data

Tank models are verified with data.

Example: muon hodoscope used to trigger on atmospheric muons

Details like this are important for understanding detector response vs. zenith
Tank model vs. data

Tanks self-triggering by phototube coincidence

Signal shape affected by:
- Different $\mu^\pm$ trajectories through tanks make different signal sizes
- Energy and angular distributions
  - $e^\pm, \gamma$
  - $\mu^\pm \rightarrow e^\pm \nu_e \bar{\nu}_\mu$

![Graph 1](image1.png)
![Graph 2](image2.png)
Steps for simulating fluorescence telescopes

- **Shower light sim**
  - Fluorescence Cherenkov
  - \(dE/dx\)

- **Light propagation up to diaphragm**
  - Propagation:
    - Direct fluorescence attenuation
  - Indirect Cherenkov:
    - Rayleigh scattered
    - Aerosol scattered

- **Raytracing in telescope**

- **Electronics simulation**
  - Photons to ADC counts
  - Noise

- **Background sim**

- **Calibration sim**

- **Trigger simulation**
  - Event Building
Geant4 modelling
of the FD telescope
A visualization in Geant4:

Mercedes light collectors
Assembled camera

PMTs described as hexagonal volumes (shown in red) and defined as sensitive volumes.
Simulation and reconstruction
(surface and fluorescence)

- Simulation ➔ data acquisition format ➔ reconstruction

**Simulation and Reconstruction Diagram:**
- **Shower direction**
- **Lateral profile**
- **Shower front shape**
- **Signal risetimes**
- **Longitudinal profile**
- **Depth of maximum (related to composition)**

**Graphs and Plots:**
- Graphs illustrating shower direction, lateral profile, shower front shape, and signal risetimes.
Summary

- Astroparticle physics experiments derive detector simulation from the wide experience of HEP accelerator experiments
- Generally detectors are simpler and less numerous than in modern accelerator experiments
- Nonetheless the detector simulation needs the insertion of the detector surrounding material to reproduce the data
- As for physics generators big progresses in the last 10 years
The end