The collaboration of J. Ranft with the MACRO Experiment at Gran Sasso: 
the use of DPMJET in VHE Cosmic Ray Physics

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The Physics Case

Starting from the early ‘80s, an intensive program to search for Proton (Nucleon) Decay, as predicted by GUTs, started all over the world

“Underground Physics”: detectors with large volume (mass) -> large area as well

Kolar Gold Field, IMB, Kamioka, Monte Bianco, Frejus, Soudan, ... 

By-products (more successful than P-Decay...): atmospheric neutrinos, re-birth of solar neutrinos, supernova neutrinos, magnetic monopoles (predicted by GUTs), Cosmic Ray Physics
Questions (still open):
1) Which is the origin of the “knee”?
2) What is the composition in mass of primary C.R. as a function of energy?
An indirect measurement technique: detection of (multiple) muons underground

Primary CR: protons/nuclei: \( A,E, \text{isotropical} \)

Hadronic interactions: production of particles \( \sigma(A,E), \frac{dN}{dx}(A,E) \)

Production of short-lifetime mesons, "prompt" decay (e.g.: charmed mesons)

Isotropical angular distribution

Decay of ordinary mesons:

\[ \frac{dN_m}{d\cos\theta} \sim \frac{1}{\cos\theta} \]

Transverse size of the "bundle"

Muon propagation in the rock:

Radiative processes and their fluctuations

Detection: \( N\mu(A,E), \frac{dN_\mu}{dr} \)
The NUSEX experiment at Mt Blanc

1981-1986
5000 m.w.e. depth
muons with energy > 3 TeV in atmosphere
cube of 3.5 m x 3.5 m x 3.5 m
tracking calorimeter with 2 projective views
size is small...

astonishing parallelism: $\Delta\Theta \sim 1$ degree, dominated by multiple scattering in 2 km of rock!
The first reference for analysis

Empirical laws from the parametrization of results of early, simplified, interaction models (mostly parametrization of results of particle production experiments)

\[ N_\mu = N_\mu (E, A, \theta) \]

TeV muons are closer to the first primary interaction and therefore preserve some memory of primary properties.
1979 A. Zichichi (President of INFN) proposes to Italian government the construction of a lab. adding that to the already approved project of a new highway tunnel.
The MACRO experiment (the first one)


72 m x 12 m x 12 m

Proposal for a large area detector (1984):
Magnetic monopoles
Atmospheric neutrinos
Cosmic Rays with muons
....

Construction started in Oct. 1987
A multimuon event in MACRO

one 10 muon event
The development of a new MC code

Simulation of atmospheric cascades and deep-underground muons

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We describe a new hadronic-interaction model for the calculation of high-energy cosmic-ray cascades in the atmosphere. High-energy muons above 0.5 TeV at production are transported through 7000 kg/cm² of rock in order to obtain the multiplicity and lateral distributions at different depths. These distributions are parametrized to facilitate the calculation of the muon-bundle rates deep underground. As an illustration, these results are applied to calculate the rates of coincident multiple muons in a detector of finite area at the Gran Sasso Laboratory. We study in particular the sensitivity of rates of high-multiplicity events to chemical composition of the primary cosmic radiation and to uncertainties in the interaction model. Our results point to the importance of the coincident measurement of showers at the surface to maximize the power of an underground detector to study the primary composition.
High energy cosmic ray physics with underground muons in MACRO. I. Analysis methods and experimental results

Work lasted several years... Strongly based upon HEMAS. In the meanwhile, before the paper was ready it appeared interesting to make a new HEMAS, using it as shower and muon propagation code, interfaced to a microscopic model. J.Ranft’s DTUNUC applied to nucleus-nucleus collisions, which will become DPMJET, appeared as an appealing solution.
\[ R(N_\mu) = \sum_A \int \int \int d\Omega \ dS \ dE \ \Phi_A(E) \sum_{M_\mu \geq N_\mu} \mathcal{P}_A(E, \theta, \phi, M_\mu) \mathcal{D}(\{r_i\}_{i=0}; M_\mu \rightarrow N_\mu), \]

\[ \chi^2_M = \sum_{N_\mu} \frac{[R_{\text{meas}}(N_\mu) - R(N_\mu | \text{parameters})]^2}{\sigma^2[R_{\text{meas}}(N_\mu)] + \sigma^2[R(N_\mu | \text{parameters})]} \]

\[ \Phi_A(E) = K_1(A)E^{-\gamma_1(A)} \quad \text{for} \quad E < E_{\text{cut}}(A), \]

\[ \Phi_A(E) = K_2(A)E^{-\gamma_2(A)} \quad \text{for} \quad E > E_{\text{cut}}(A), \]
The “MACRO model” (Strongly based upon HEMAS)
Nobody trusted this results: too many protons!!
Main reason to explore new interaction models
Main result after the first period of work of J. Ranft in INFN (Frascati)

Dual parton model at cosmic ray energies

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(Received 15 July 1994)

The dual parton model for hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions is studied in the fragmentation region up to the cosmic ray energy region. Because of the excellent Feynman scaling behavior of the model outside the regions around $x_F = 1$ and $x_F = 0$, it is found that accelerator data in the fragmentation region are indeed relevant for the cosmic ray energy region. However, not enough data are available in the fragmentation region of hadron collisions with light target nuclei. Therefore many features of hadron production in collisions involving nuclei can only be extracted from the study of models.

PACS number(s): 13.85.Hd, 13.85.Ni, 13.85.Tp
Other attempts from the Bartol school, started a little bit earlier

SIBYLL: An event generator for simulation of high energy cosmic ray cascades

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We describe the physical basis and some applications of an efficient event generator designed for Monte Carlo simulations of atmospheric cascades at ultrahigh energies. The event generator (SIBYLL) incorporates many features of the Lund programs, but emphasizes the fragmentation region and the production of minijets. A consistent treatment of hadron-hadron and hadron-nucleus interactions is emphasized. Examples of applications are the calculation of coincident muons observed in deep underground detectors and the simulation of the longitudinal development of air shower components in the atmosphere.

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Study of the high energy cosmic ray cascades using the dual parton model

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Superposition model or “direct interaction”? 

Several contributions at 1995 ICRC in Roma
A second period of work of J. Ranft in INFN (Gran Sasso Lab.)

DPMJET version II.3 and II.4

J. Ranft
New MC simulation for MACRO using HEMAS/DPMJET-II.3

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New Fit to same MACRO data (now 1998)

Much more reasonable!
DPMJET as an option for CORSIKA

CORSIKA, initially based on a DPM implementation by J.N. Capdevielle (~1990, later called HDPM) started around 1996 to offer the choice for different high energy interaction models:

VENUS
QGSJET
SIBYLL
DPMJET

Unfortunately, mostly for sociological reasons, the preferred choices were QGSJET and SIBYLL.

Around 2003: also a FLUKA interface to CORSIKA for E<80 GeV...

Later for high energies: EPOS
Useful for the analysis of surface-underground coincidence experiments between EAS-TOP and MACRO.

Potentially powerful but statistics remained not sufficient.

We started to have hints that it was difficult to accommodate different observables with a single simulation model: e.m. component, Cherenkov light, low energy muons, TeV muons, surviving hadrons.
Another idea of those days...

Clustering inside muon bundles...

Does this pattern carry useful information?
Search for high-$P_t$ phenomena?

Our hypothesis

G. Battistoni, C. Bloise, C. Forti, J. Ranft, E. Scapparone, M. Sioli
Another investigation...

Calculation of the TeV prompt muon component in very high energy cosmic ray showers

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What came next...

- Most of the physics questions still remain unsolved.
- Multiple muon events at large depth are no more a fashionable issue. There is the consciousness that a single observable cannot constraint sufficiently a model.
- Data from multi-component experiment at surface still have different interpretation in terms of mass composition: the difference between interaction models prevents from giving a satisfactory answer in the knee region and beyond.
- Fluka+DPMJET for cosmic rays: some attempt...
- From DPMJET-II to DPMJET-III: unfortunately we never succeeded to use it for an extensive analysis at high energies...
- Can data from LHC really help to improve our present models for C.R. physics?
The images depict the comparison of different models with experimental data for the differential energy spectrum of primary nuclei. The models include QGSJet and SIBYLL 2.1, and the data points represent measurements for protons, helium, silicon, and iron.

- **QGSJet 01** shows a smooth fit with data points for silicon and iron, with proton and helium data plotted as different markers.

- **SIBYLL 2.1** provides a detailed comparison with experimental data, highlighting the fit for silicon and iron, and showing data for proton and helium.

The graphs illustrate the energy dependence of the differential cross-section, with axes labeled as primary energy in GeV.
$X_{\text{max}}$ measured over two decades of energy

Syst error on $X_{\text{max}} < 15 \text{ g/cm}^2$ ($< A > \sim 5$)

Mass composition: protons, light nuclei, Fe? Only protons at UHE presently is not favoured.
MINOS  
hep-ex 0705.3815
Charge Ratio at the Surface = 1.371 ± 0.003

\[ R_{\text{FLUKA}} \mu^+/\mu^- = 1.362 ± 0.012 \]

\[ R_{\text{DPMJET II}} \mu^+/\mu^- = 1.27 ± 0.01 \]

L3 + COSMIC (hep-ex/0408114).
\[ R_{\text{FLUKA}} = 1.295 ± 0.048 \]
\[ R_{\text{exp}} = 1.28 ± 0.48 \]

VERY PRELIMINARY WORK IN PROGRESS (BUT NEVER FINISHED)
An example: a problem remained unsolved at home:

DPMJET II.5 & FLUKA

\[ p + N \rightarrow K^\pm + X \quad E_p = 10 \text{ TeV} \]

DPMJET II.5 standalone & by means of FLUKA
\( p + N \rightarrow K^\pm + X \)
\( E_p = 10 \text{ TeV} \)

DPMJET II.5 & DPMJET III

DPMJET II.5 & DPMJET II.5 with rejection of strange sea-quark pairs
1) The Dual parton model at cosmic ray energies

2) Study of the high-energy cosmic ray cascades using the dual parton model

3) The dual parton model and hadron production at cosmic ray energies

4) Hadron production at cosmic ray energies, the dual parton model

5) Clusters of muons underground: A New tool for cosmic ray studies

6) Calculation of the TeV prompt muon component in very high-energy cosmic ray showers

7) Prompt muons in cosmic ray showers
By G. Battistoni, C. Bloise, C. Forti, Mario Greco, J. Ranft, A. Tanzini.

9) Cosmic ray particle production

10) DPMJET versions II.3 and II.4: Sampling of hadron hadron, hadron nucleus and nucleus nucleus interactions at cosmic ray energies according to the dual parton model description of the model and code manual
By J. Ranft.

11) DPMJET version II.5: Sampling of hadron hadron, hadron - nucleus and nucleus-nucleus interactions at accelerator and cosmic ray energies according to the two component dual parton model: Code manual

12) Baryon stopping in high-energy collisions and the extrapolation of hadron production models to cosmic ray energies

14) The Event generator DPMJET-III at cosmic ray energies
By S. Roesler, R. Engel, J. Ranft.

15) DPMJET-III, learning from RHIC data for cosmic ray particle production

16) The FLUKA Monte Carlo, non-perturbative QCD and cosmic ray cascades

17) The Hadronic models for cosmic ray physics: The FLUKA code solutions
By G. Battistoni, M.V. Garzelli, E. Gadioli, S. Muraro, P.R. Sala, A. Fasso, A. Ferrari, S. Roesler et al..

18) Secondary Cosmic Ray particles due to GCR interactions in the Earth's atmosphere
By G. Battistoni, F. Cerutti, A. Fasso, A. Ferrari, M.V. Garzelli, M. Lantz, S. Muraro, L.S. Pinsky et al..

19) Hadron-Hadron and Cosmic-Ray Interactions at multi-TeV Energies
By B. Alessandro, D. Bergman, M. Bongi, A. Bunyatyan, L. Cazon, D. d'Enterria, I. de Mitri, P. Doll et al..