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

G. BATTISTONI

INFN MILANO

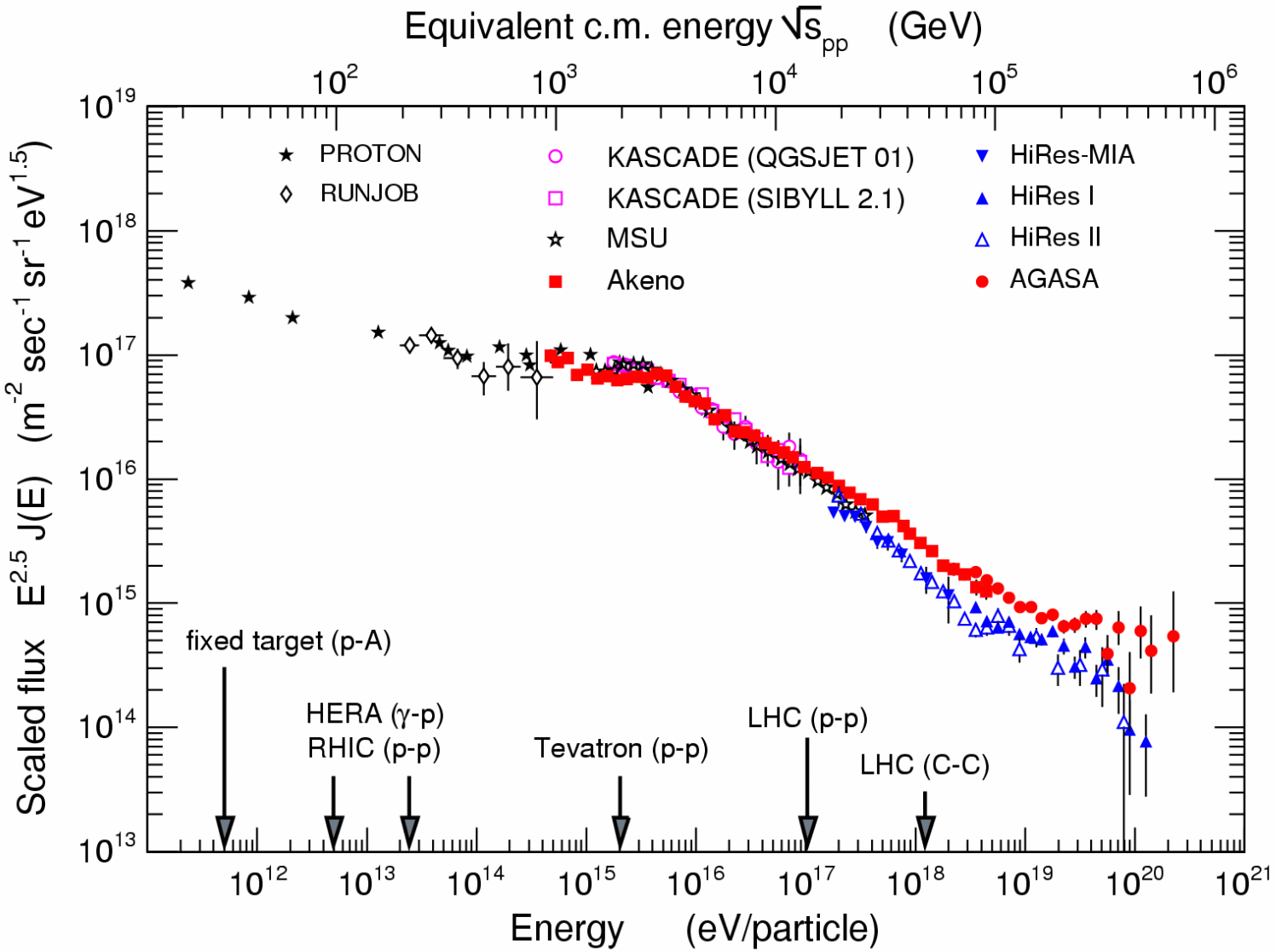
The Physics Case

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, …

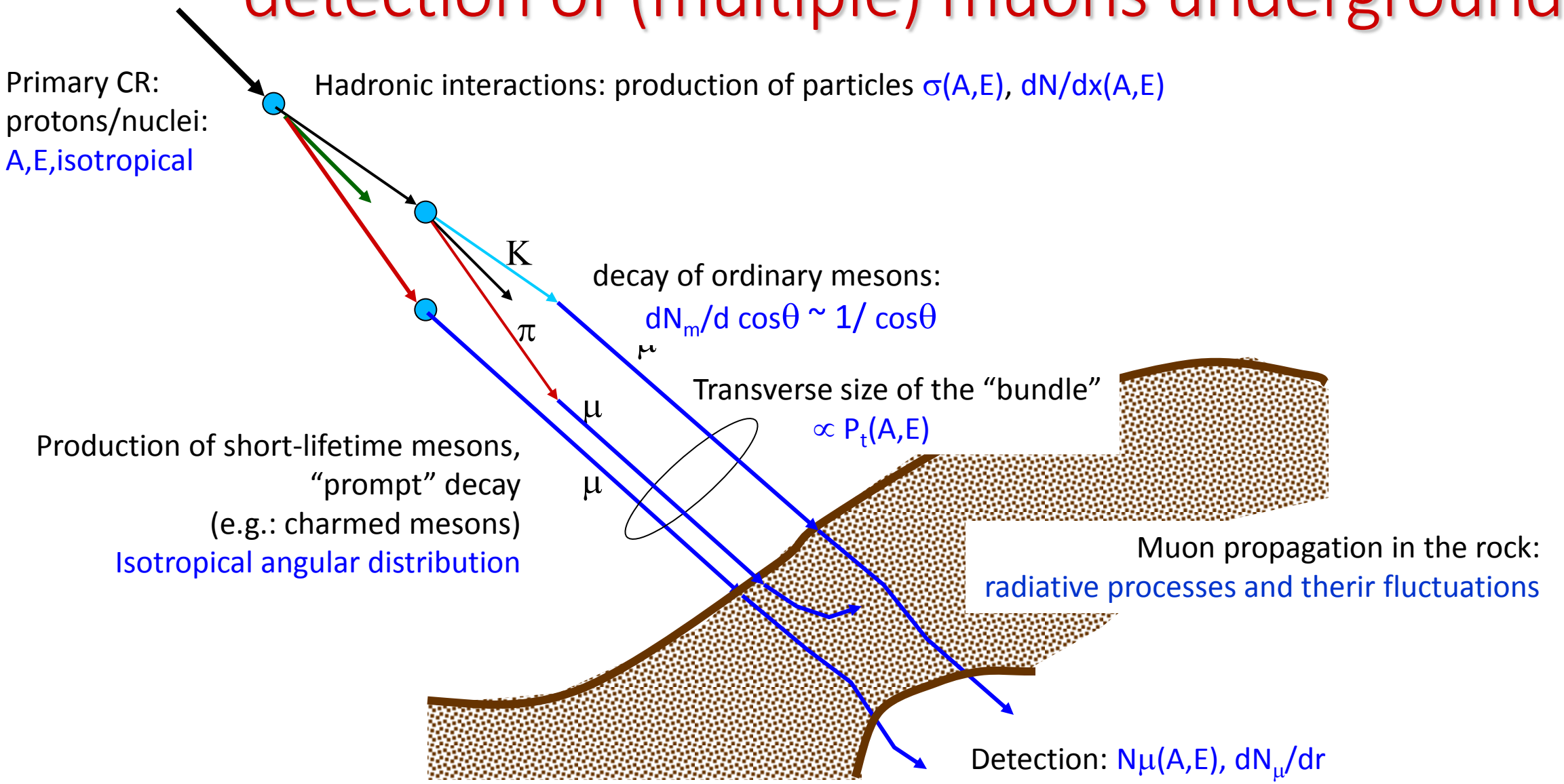
By-products (more successful than P-Decay…): atmospheric neutrinos, re-birth of solar neutrinos, supernova neutrinos, magnetic monopoles (predicted by GUTs), Cosmic Ray Physics



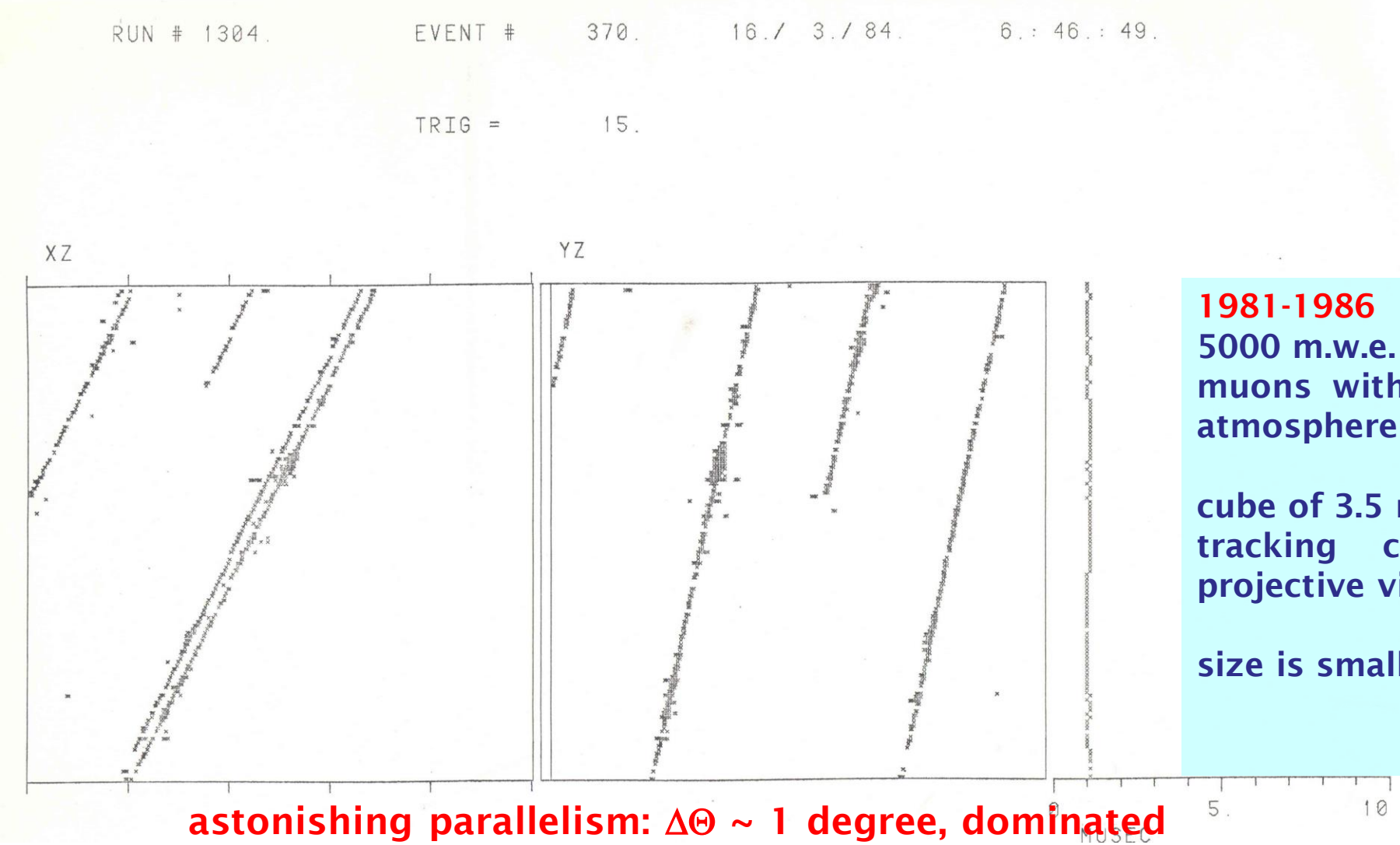
Questions (still open):

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



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

Nuclear Instruments and Methods in Physics Research A235 (1985) 183–192
North-Holland, Amsterdam

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

$N_\mu = N_\mu(E,A,\theta)$

MUON BUNDLES IN UNDERGROUND DETECTORS

T.K. GAISSER and Todor STANEV *

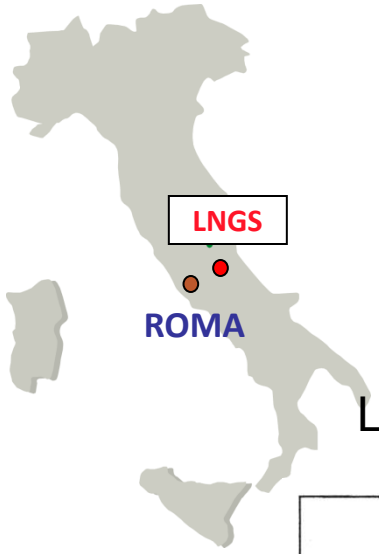
Bartol Research Foundation of the Franklin Institute, University of Delaware, Newark, DE 19716, USA

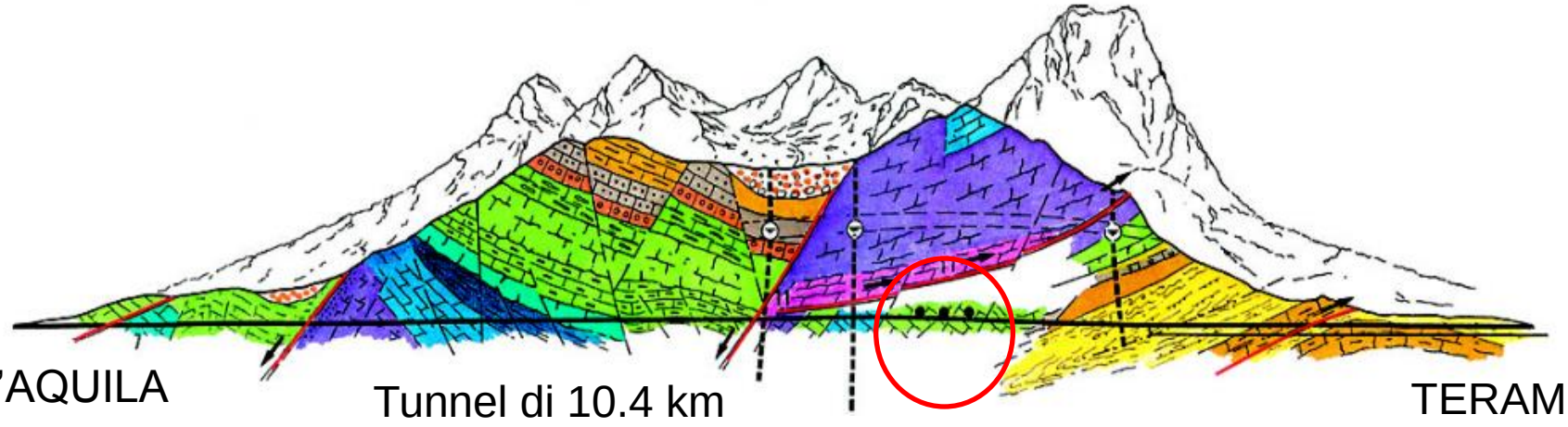
TeV muons are closer to the first primary interaction and therefore preserve some memory of primary properties

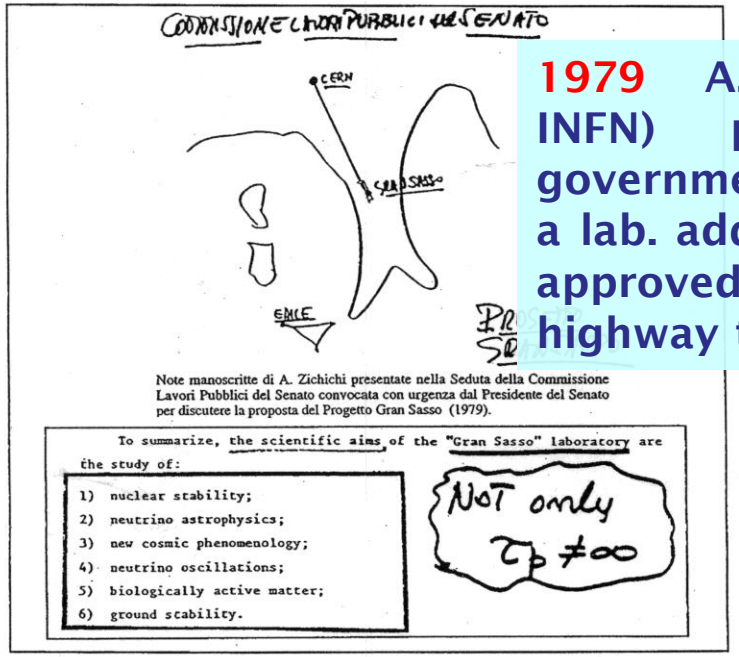
Received 28 August 1984

We give a simple set of parametrizations that can be used as the basis for Monte Carlo simulations of multiple, coincident cosmic ray muons as detected with deep, sub-surface detectors such as those designed to search for nucleon decay, monopoles, etc. The simulations are relevant to design studies, systematic intercomparison of different experiments and preliminary data analysis.

The birth of Gran Sasso Laboratory







Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

Fig. I.1.1: (Figure from Reference 5). In the upper part, a detail of the Gran Sasso project presented by A. Zichichi in the Public Work Committee of the Italian Senate. In the lower part the reproduction of page 13 of the original project [6a].

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)

Operation: 1989-2000

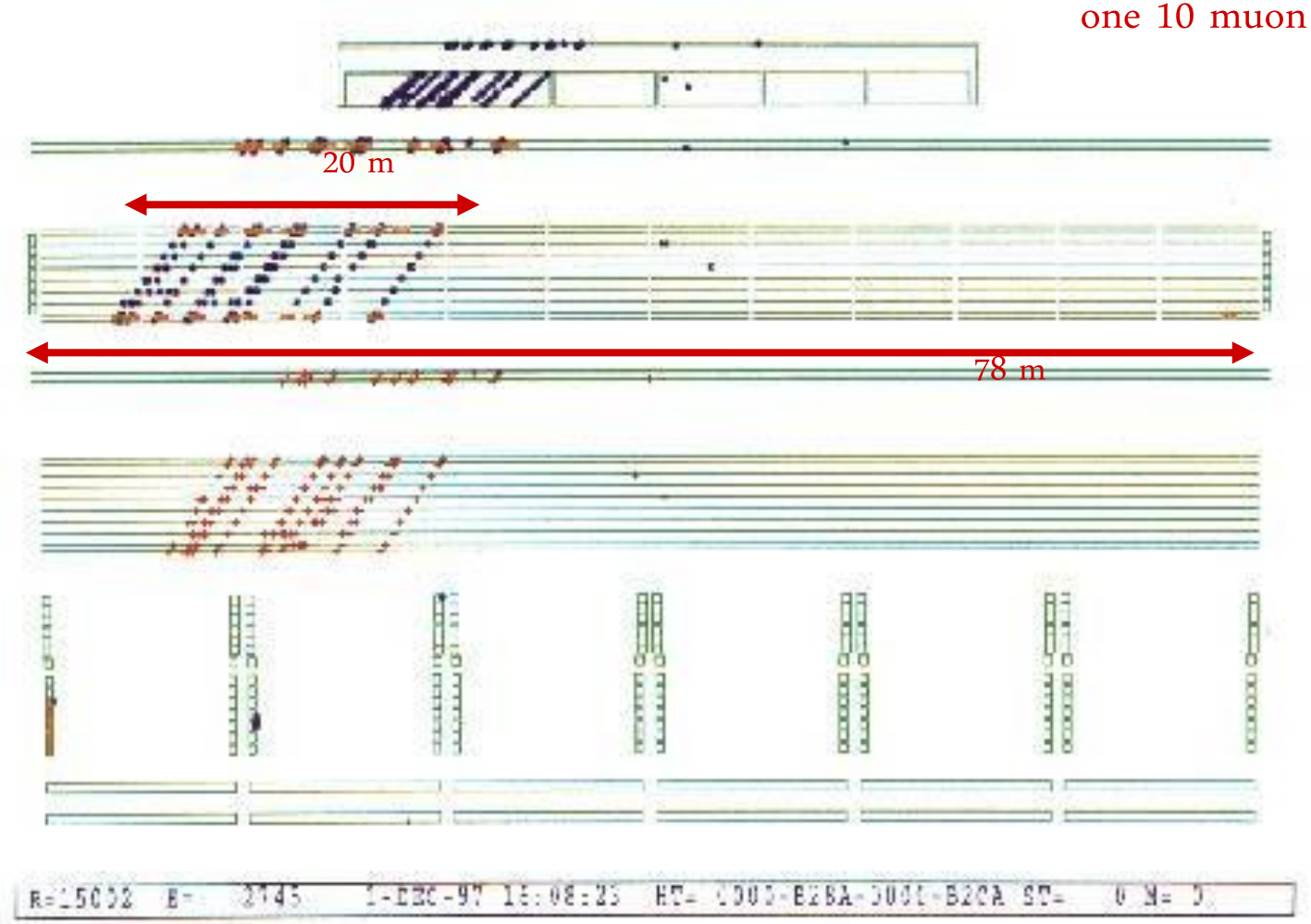
72 m x 12 m x 12 m

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

PHYSICAL REVIEW D VOLUME 42, NUMBER 11 1 DECEMBER 1990

Simulation of atmospheric cascades and deep-underground muons

C. Forti and H. Bilokon
Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, Frascati, Rome, Italy

B. d'Ettorre Piazzoli
Istituto di Cosmogeofisica del Consiglio Nazionale delle Ricerche, Torino, Italy

T. K. Gaisser
Bartol Research Institute, University of Delaware, Newark, Delaware 19716

L. Satta*
Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, Frascati, Rome, Italy

Todor Stanev
Bartol Research Institute, University of Delaware, Newark, Delaware 19716
(Received 25 June 1990)

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 hg/cm^2 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.

HEMAS

Not as naif as the original Gaisser and Stanev model

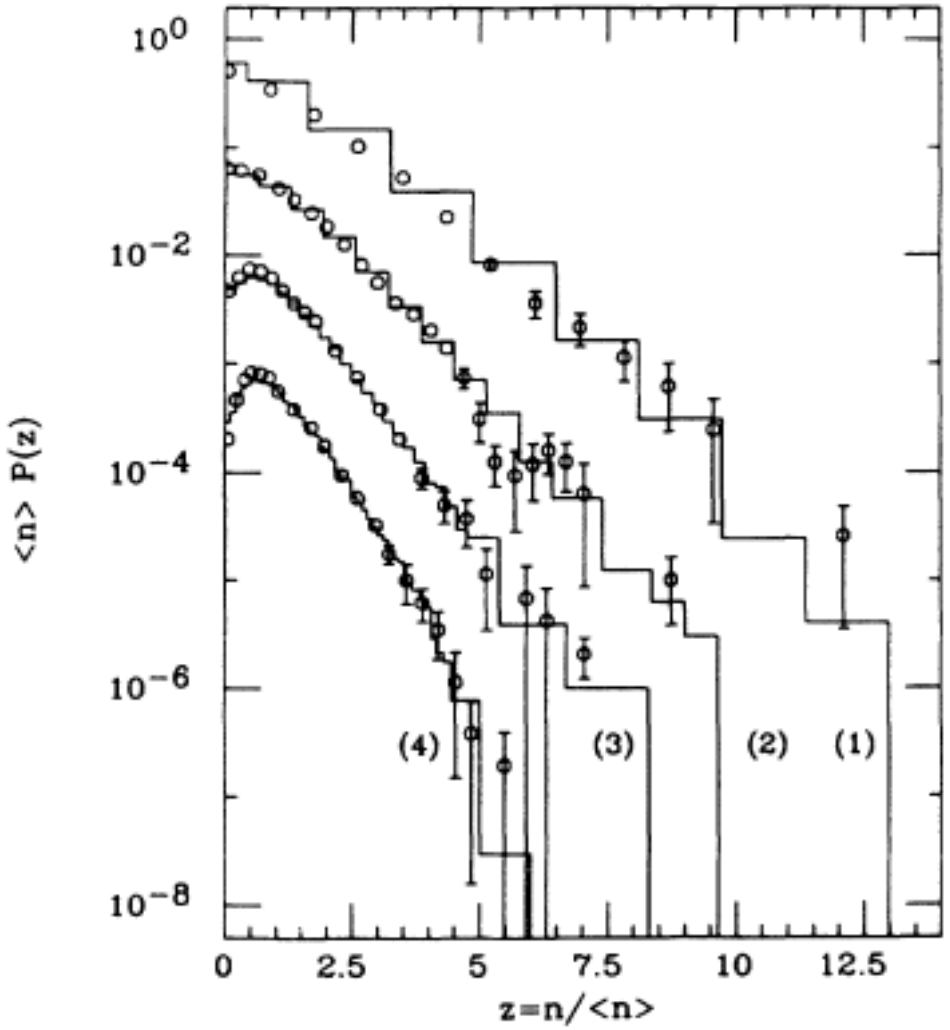
Still not a "microscopic" model

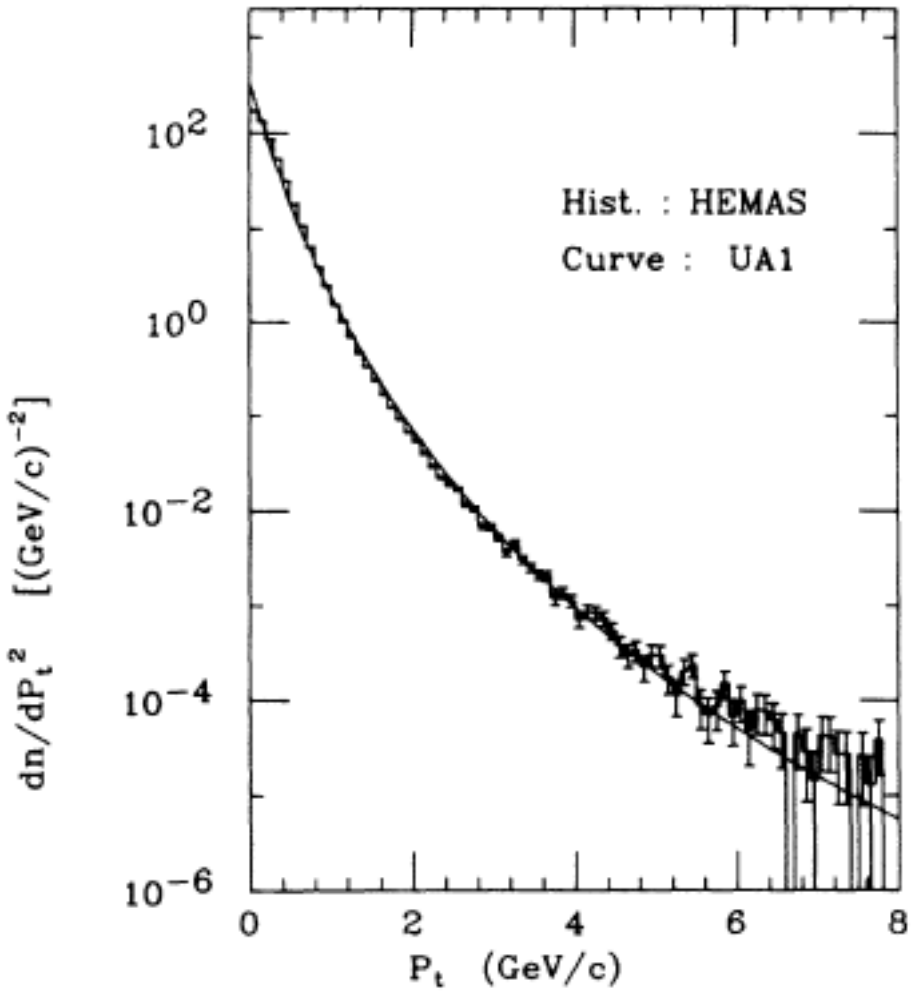
Benchmarked on recent UA5 and similar data

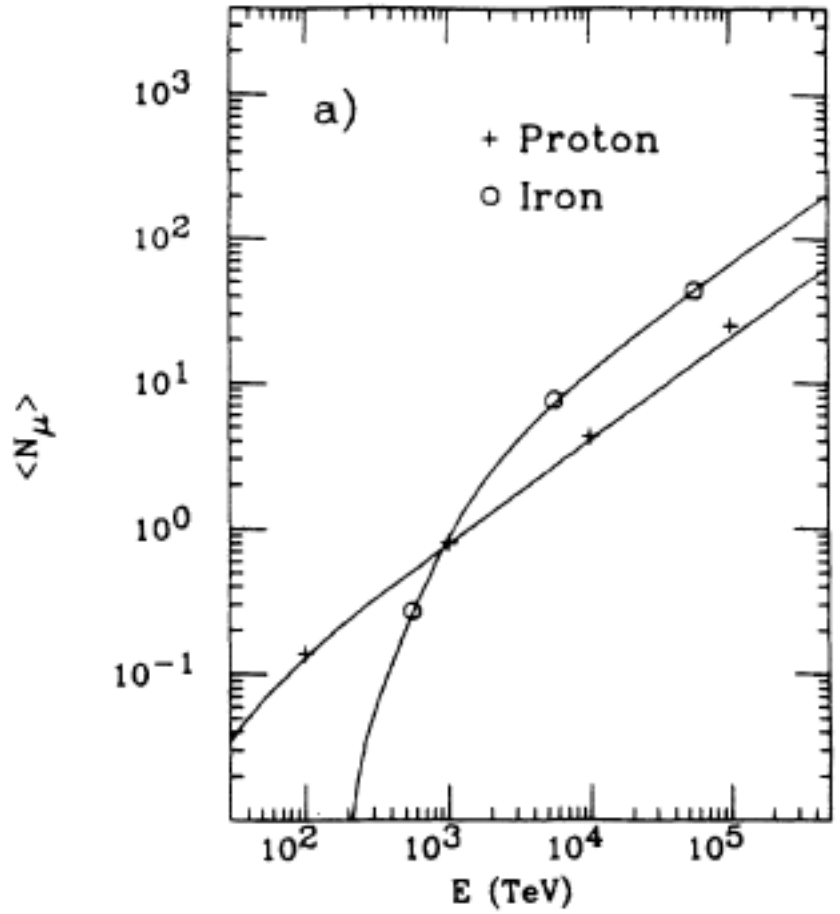
Introduces the considerations of modifications due to A-A with respect to h-A

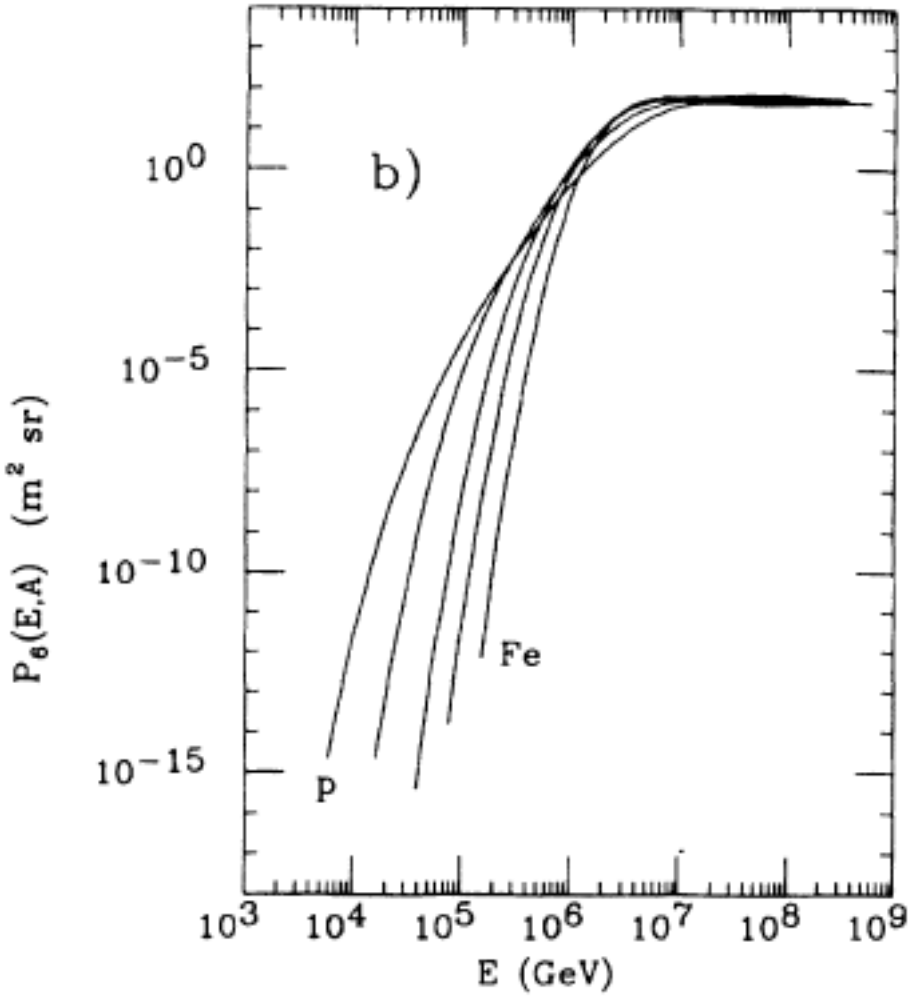
Atmospheric shower with Greisen-like electron component

Muon propagation with radiative processes


<n> P(z)
z=n/<n>
(1)
(2)
(3)
(4)


Hist. : HEMAS
Curve : UA1
dn/dP_t^2 [(GeV/c)^-2]
P_t (GeV/c)


a)
+ Proton
o Iron
10^3
10^2
10^1
10^0
10^{-1}
$<N_\mu>$
10^2
10^3
10^4
10^5
E (TeV)


b)
10^0
10^{-5}
10^{-10}
10^{-15}
$P_\delta(E,A)$ (m^2 sr)
p
Fe
10^3
10^4
10^5
10^6
10^7
10^8
10^9
E (GeV)

MACRO results on multiple muons

PHYSICAL REVIEW D VOLUME 56, NUMBER 3 1 AUGUST 1997

High energy cosmic ray physics with underground muons in MACRO. I. Analysis methods and experimental results

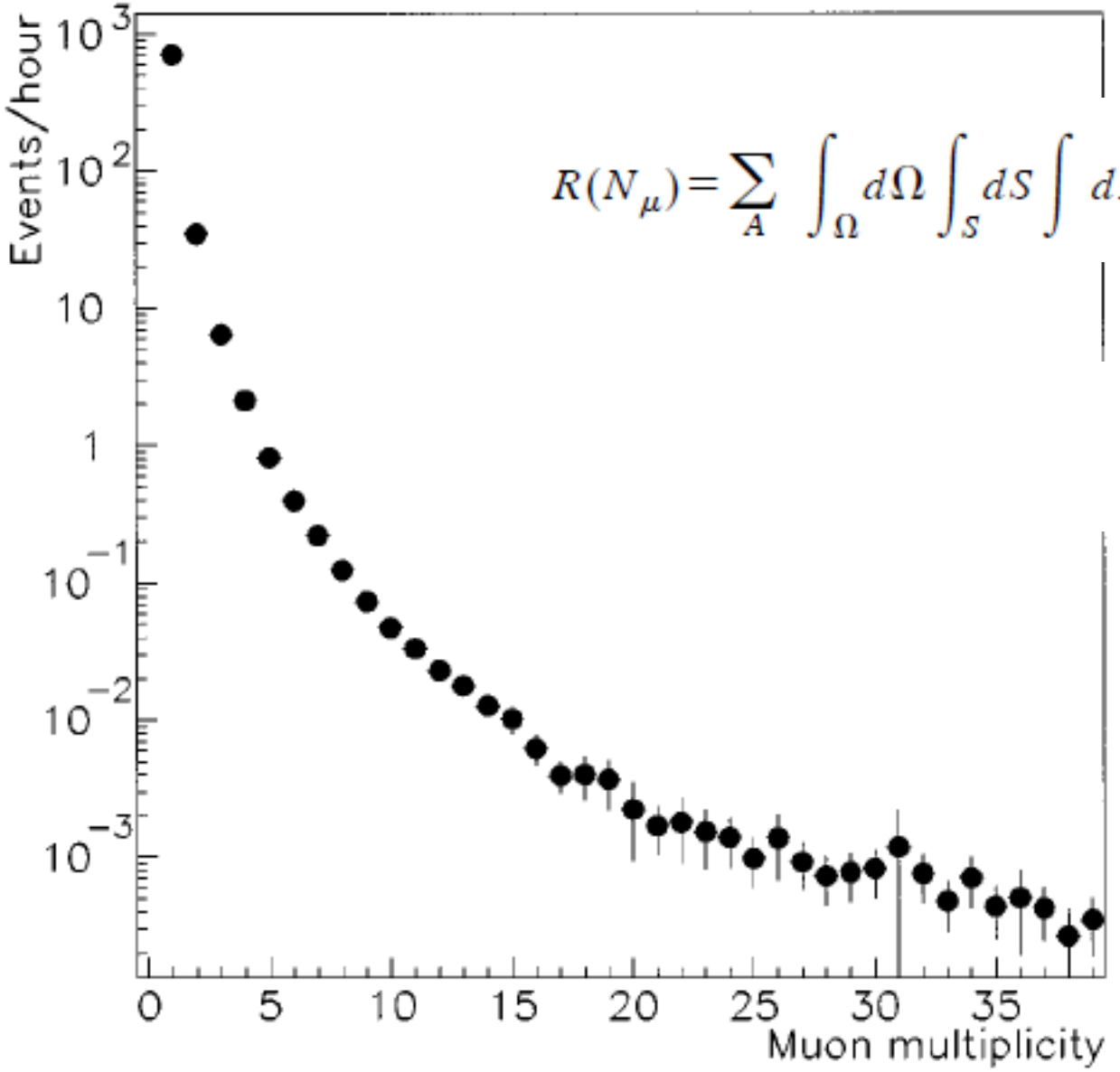
PHYSICAL REVIEW D VOLUME 56, NUMBER 3 1 AUGUST 1997

High energy cosmic ray physics with underground muons in MACRO. II. Primary spectra and composition

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

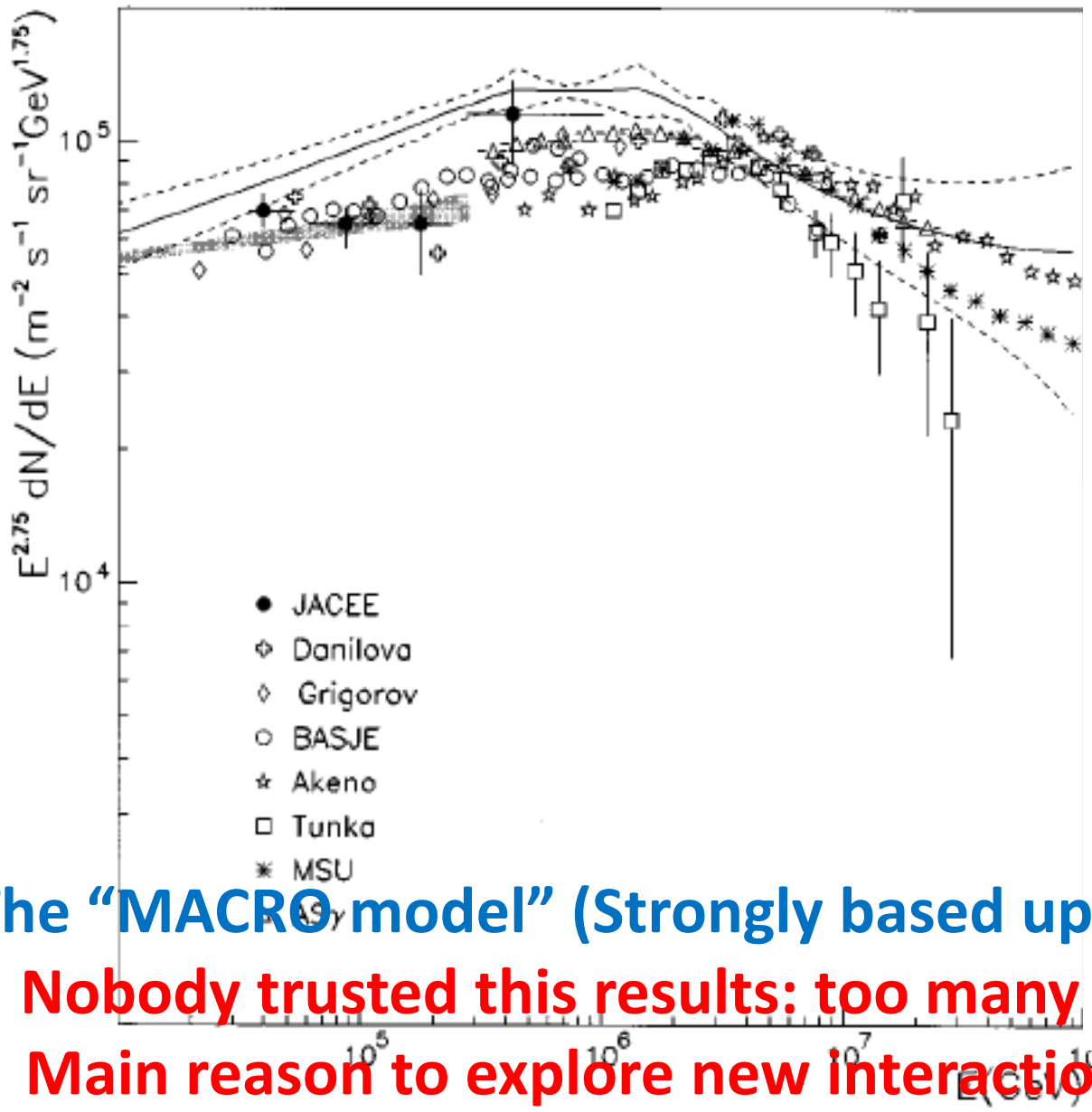


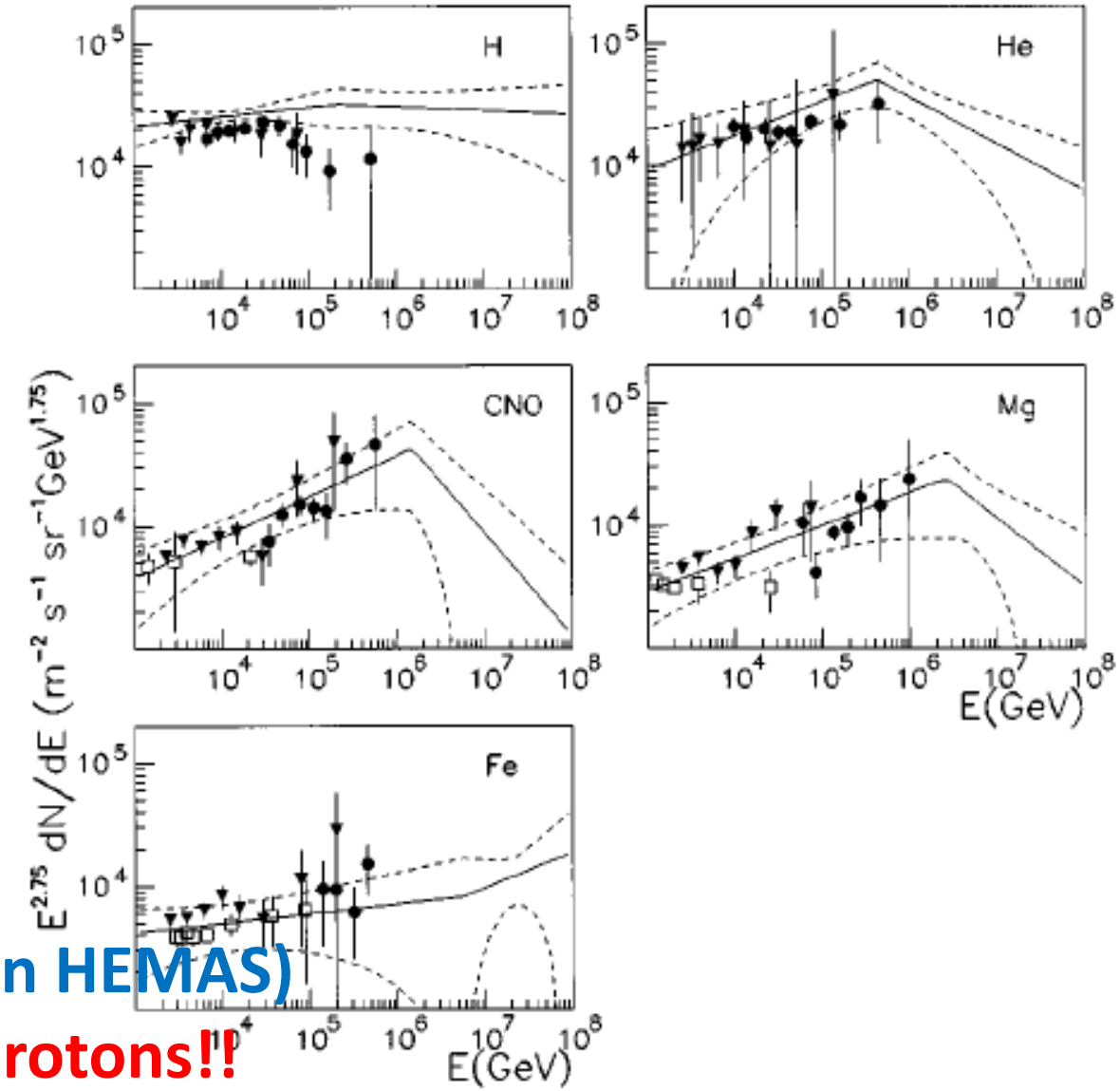
$$R(N_\mu)=\sum_A \int_\Omega d\Omega \int_S dS \int dE \;\; \Phi_A(E) \sum_{M_\mu \geqslant N_\mu} \mathcal{P}_A(E,\theta,\phi,M_\mu)\cdot \mathcal{D}(\{\vec{r}_i\}_{X_0}; M_\mu \rightarrow N_\mu),$$

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

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

$$\Phi_A(E)=K_2(A)E^{-\gamma_2(A)} \quad \text{for} \quad E>E_{\text{cut}}\;(A),$$





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)

PHYSICAL REVIEW D VOLUME 51, NUMBER 1 1 JANUARY 1995

Dual parton model at cosmic ray energies

J. Ranft
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionale di Frascati, I-00044 Frascati, Roma, Italy
(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

PHYSICAL REVIEW D VOLUME 50, NUMBER 9 1 NOVEMBER 1994

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

R. S. Fletcher,[1,3] T. K. Gaisser,[1] Paolo Lipari,[2] and Todor Stanev[1]
[1] *Bartol Research Institute, University of Delaware, Newark, Delaware 19716*
[2] *INFN sezione di Roma, and Dipartimento di Fisica Universitá di Roma I, Piazzale Aldo Moro 2, Rome, Italy*
[3] *Department of Physics, The Johns Hopkins University, Baltimore, Maryland 21218**

(Received 26 January 1994)

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.

PACS number(s): 13.85.Tp, 96.40.Pq, 96.40.Tv

Our new investigation

ELSEVIER

Astroparticle Physics 3 (1995) 157–184

Astroparticle Physics

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

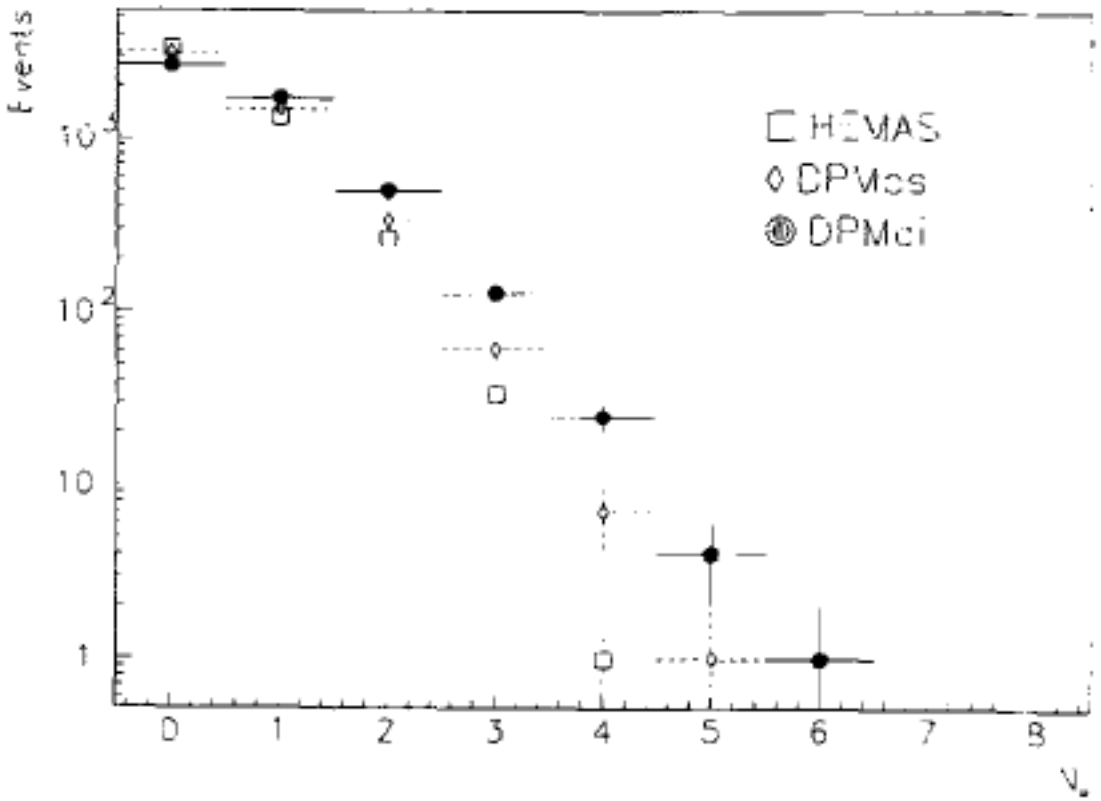
G. Battistoni [a,b], C. Forti [a], J. Ranft [a]

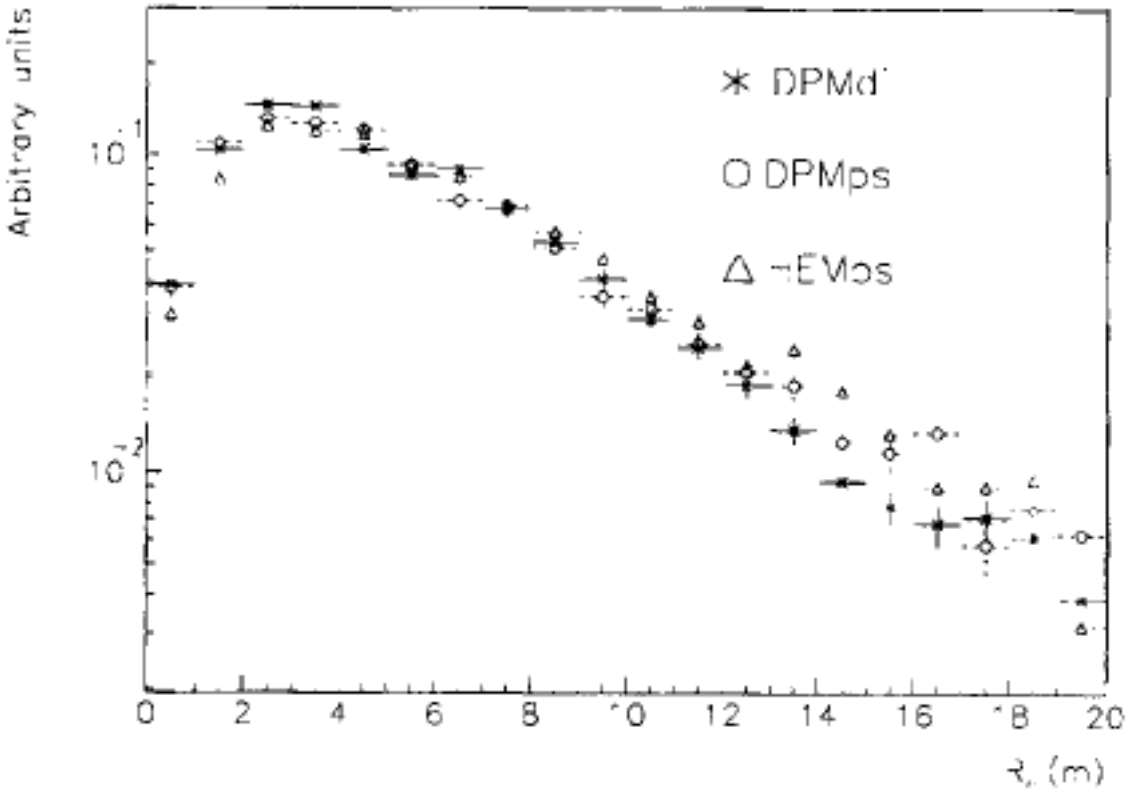
[a] *INFN, Laboratorio Nazionali di Frascati, I-00044 Frascati (Rome), Italy*

[b] *INFN, Sezione di Milano, I-20133 Milan, Italy*

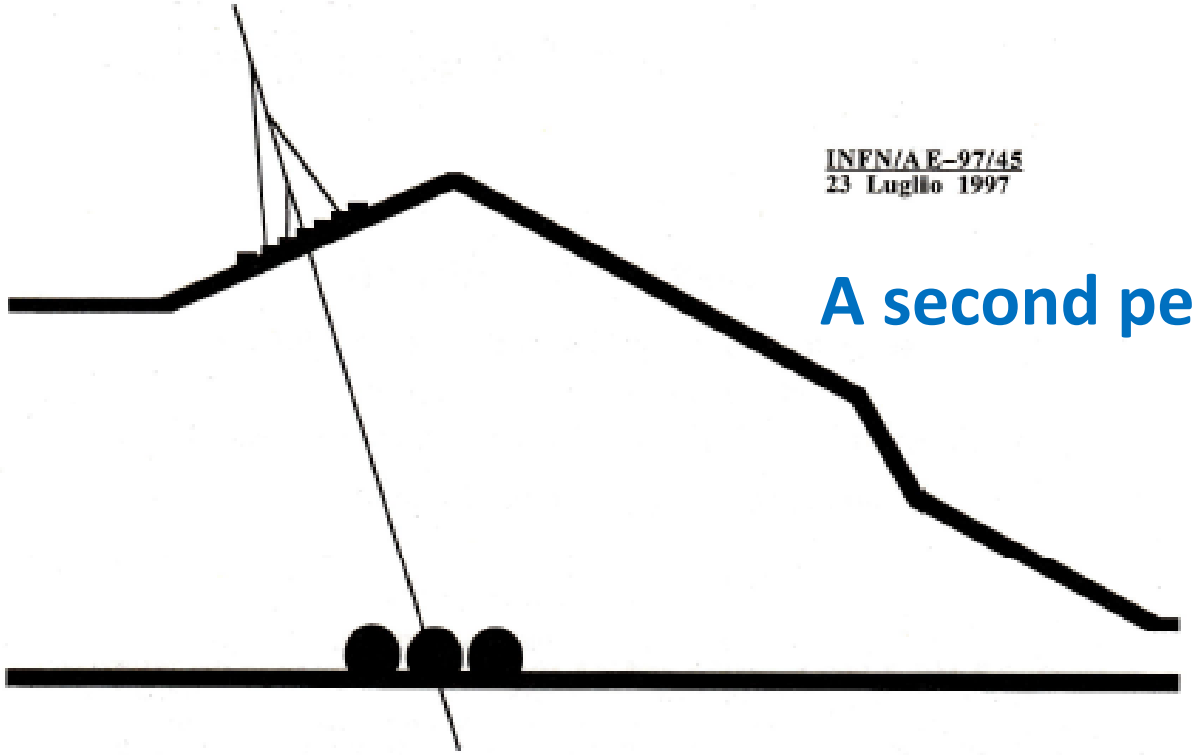
Received 8 October 1994

Superposition model or “direct interaction” ?





Several contributions at 1995 ICRC in Roma



INFN/AE–97/45
23 Luglio 1997

A second period of work of J.Ranft in INFN (Gran Sasso Lab.)

DPMJET version II.3 and II.4

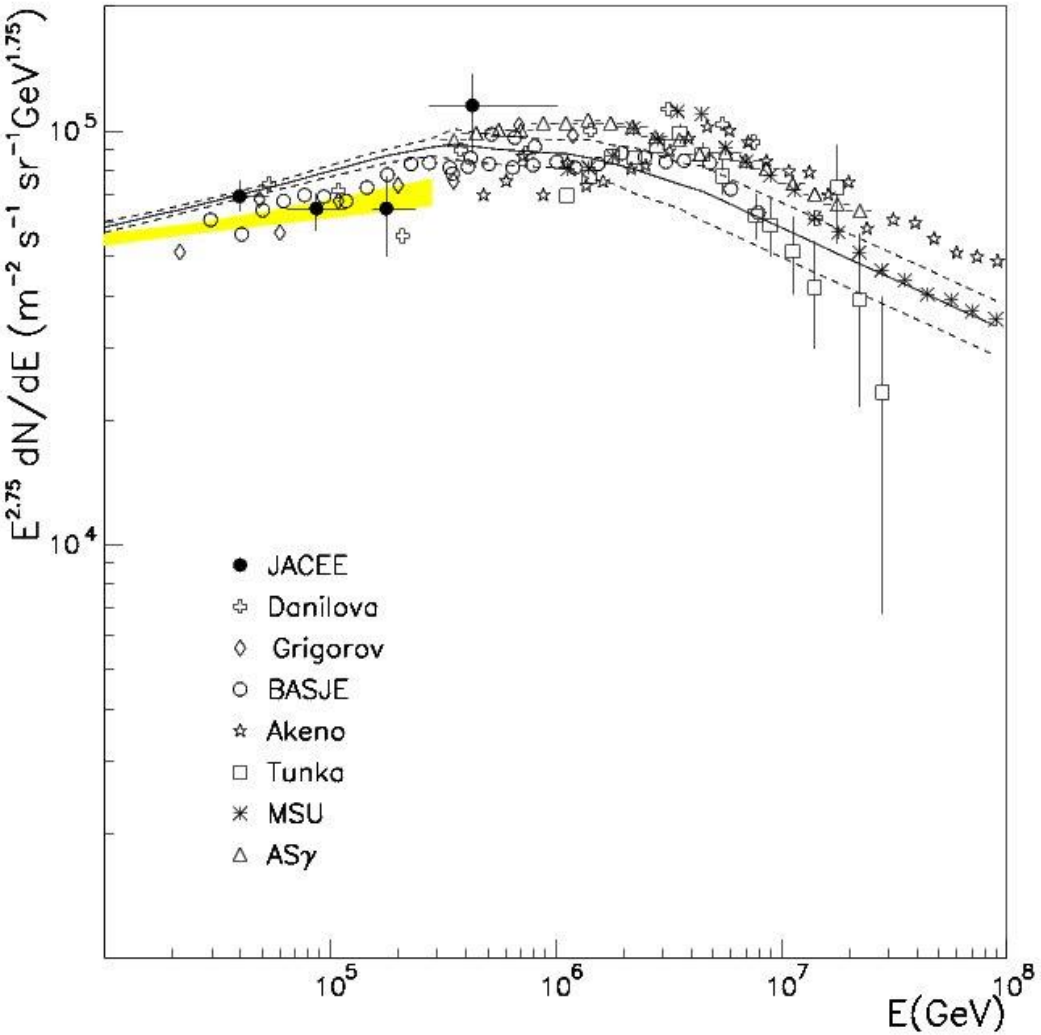
J. Ranft

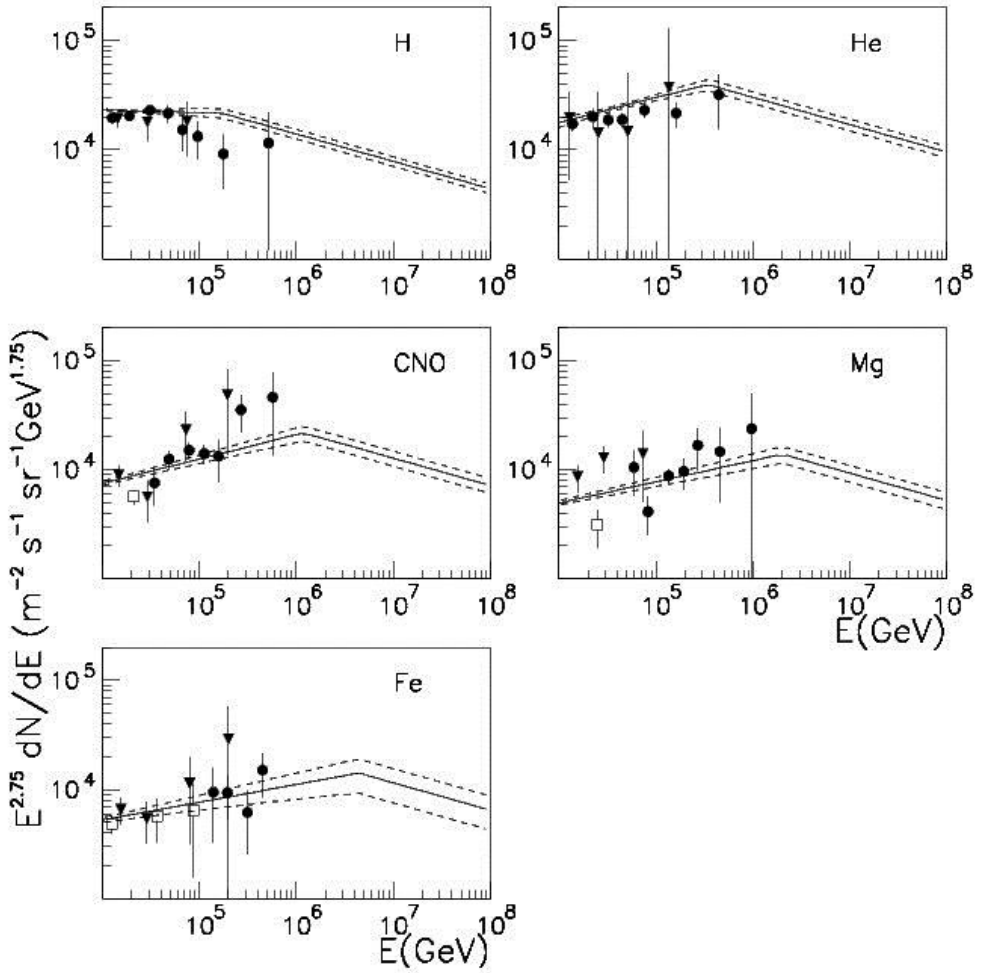
New MC simulation for MACRO using HEMAS/DPMJET-II.3

G. Battistoni[1], M. Carboni[2]

1. *INFN Milano, via Celoria 16, 20133 Milano, Italy*
2. *Lab. Nazionali di Frascati, via E. Fermi 40, 00044 Frascati (Roma), Italy*

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 offere the choice for different high energy interaction models:

VENUS
QGSJET
SIBYLL
DPMJET

Unfortunately, mostly for sociological region, the preferred choices were QGSJET and SIBYLL
Around 2003: also a FLUKA interface to CORSIKA for E<80 GeV…
Later for high energies: EPOS

Corsika at Gran Sasso

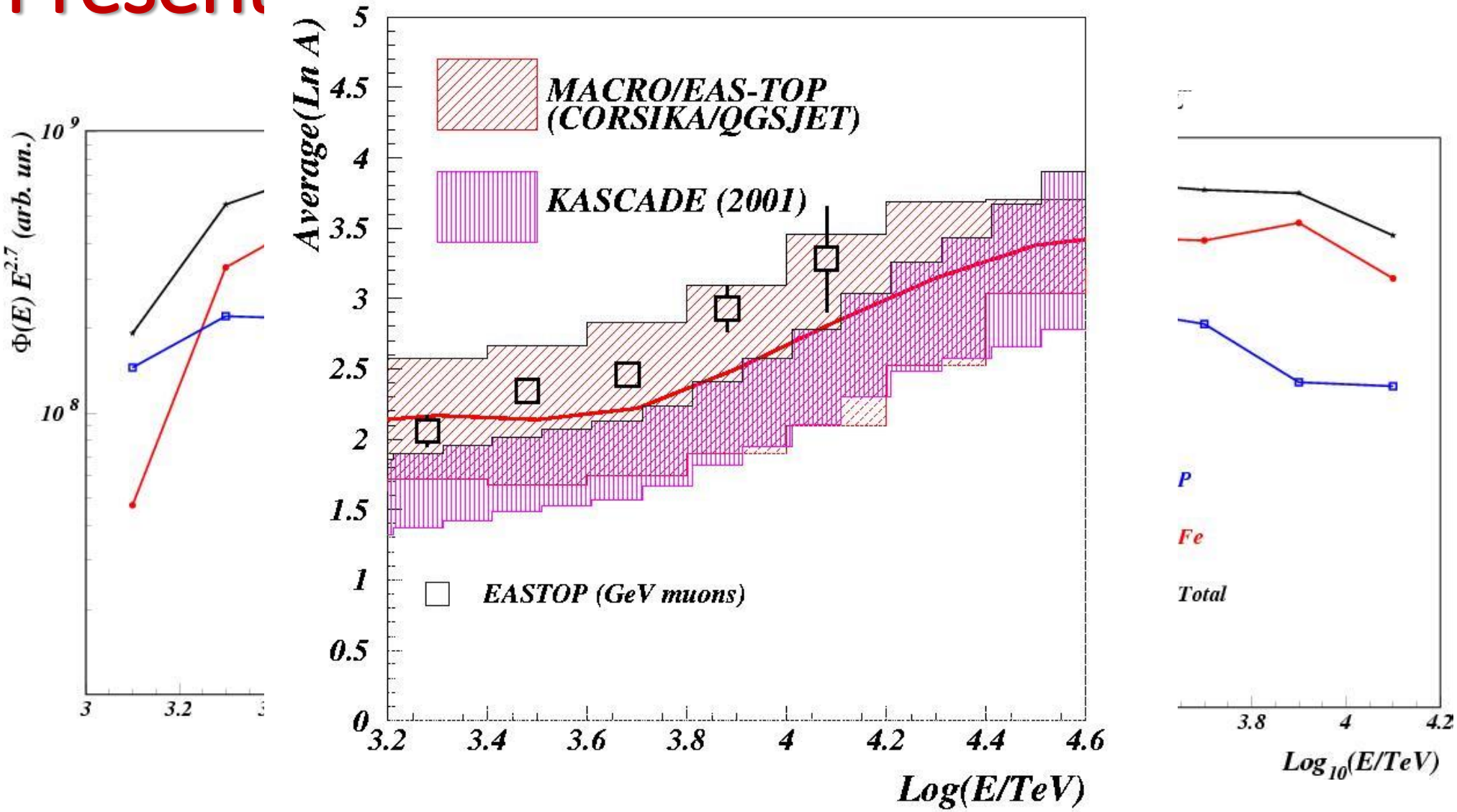
Useful for the ana
coincid
between E

Potentially pc
statistics re

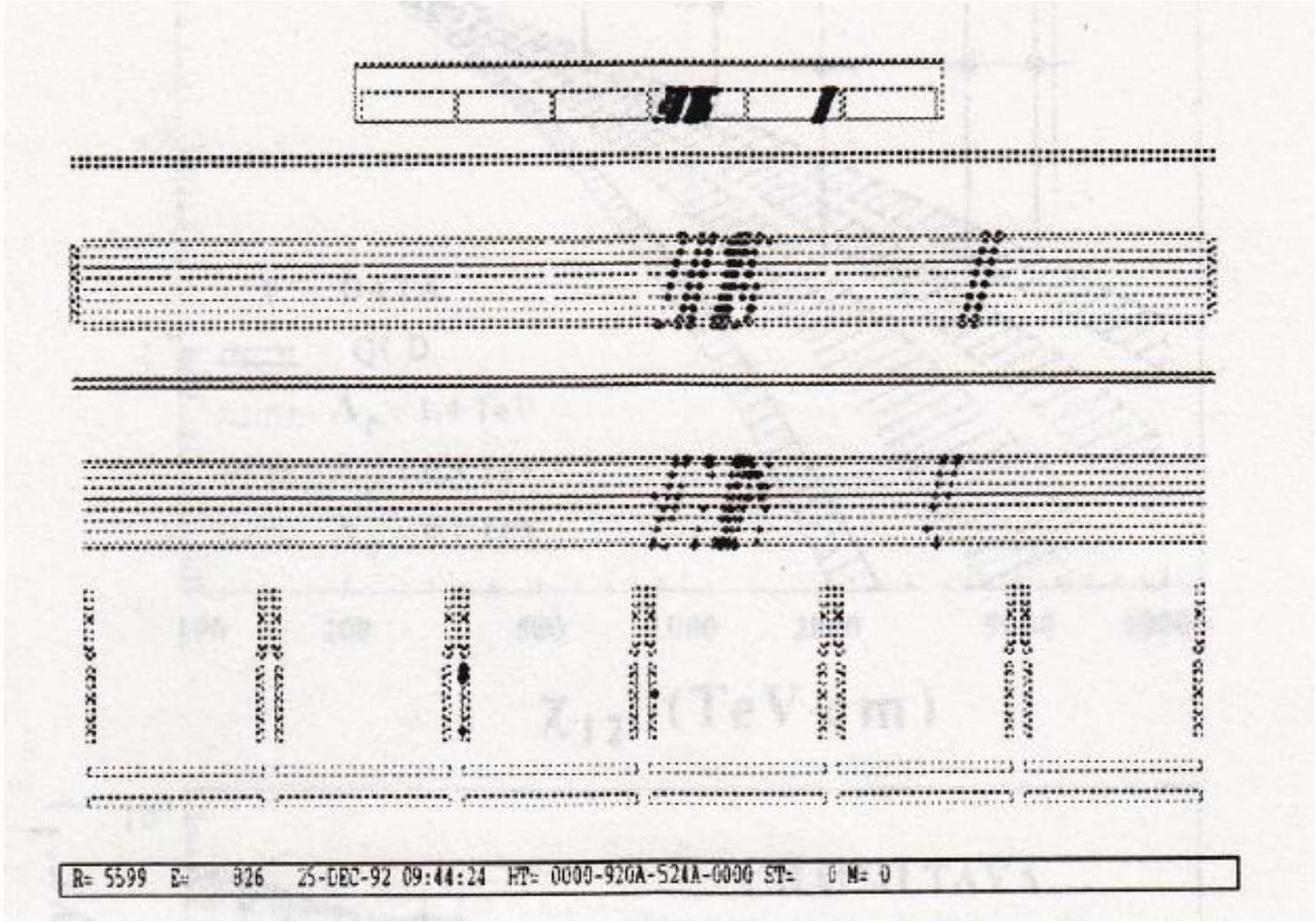
We started to hav
to accommodate
a single
e.m. compo
low energy
surv

t Aquila
m (a.s.l.)
30'
CRO
963 m (a.s.l.)

Present


Average(Ln A)
MACRO/EAS-TOP
(CORSIKA/QGSJET)
KASCADE (2001)
EASTOP (GeV muons)
Log(E/TeV)
P
Fe
Total
Log10(E/TeV)

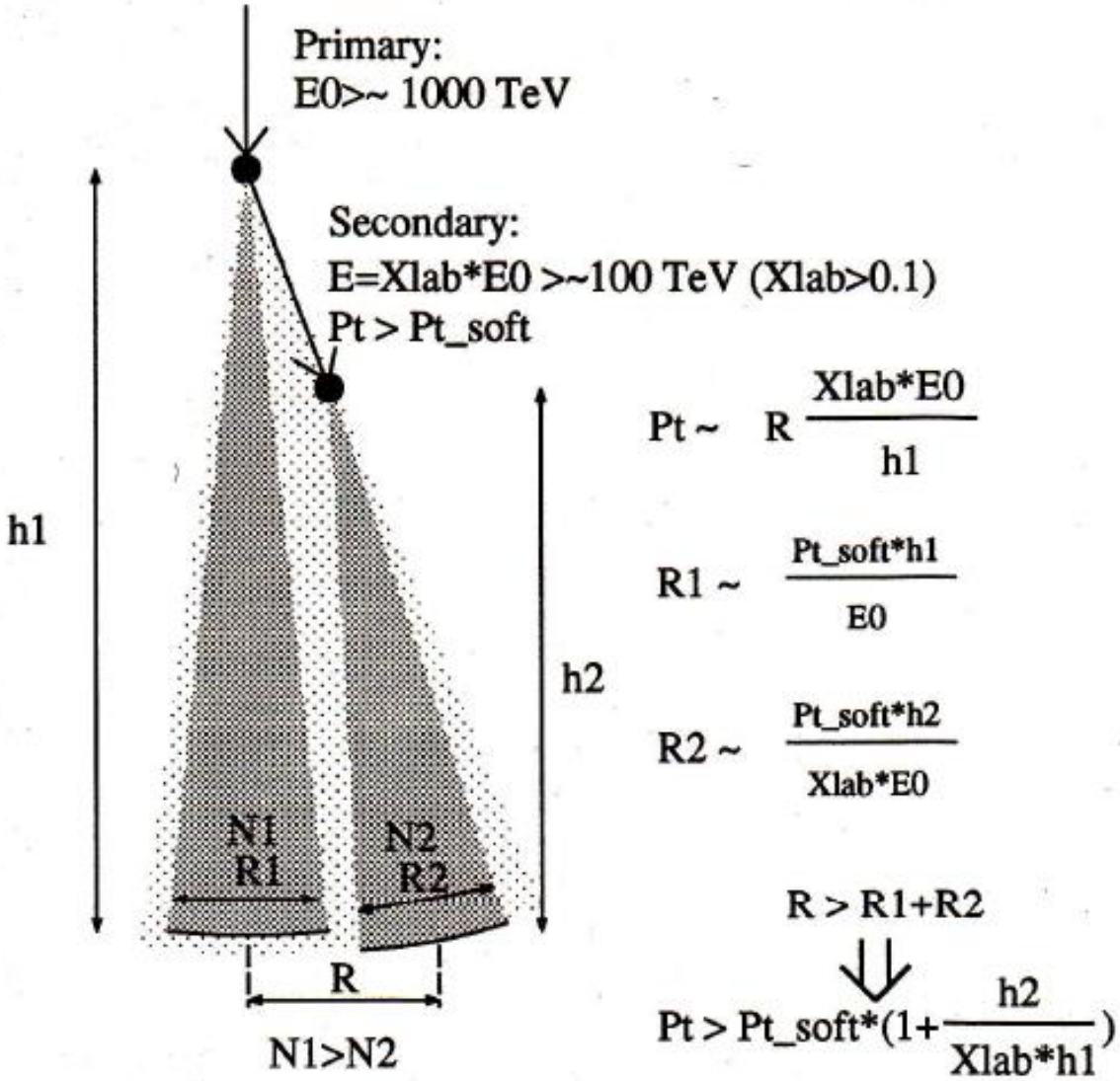
Another idea of those days…



Clustering inside muon budles…

Does this pattern carry useful information?

Search for high-P_t phenomena?



$$Pt \sim R\frac{Xlab*E0}{h1}$$

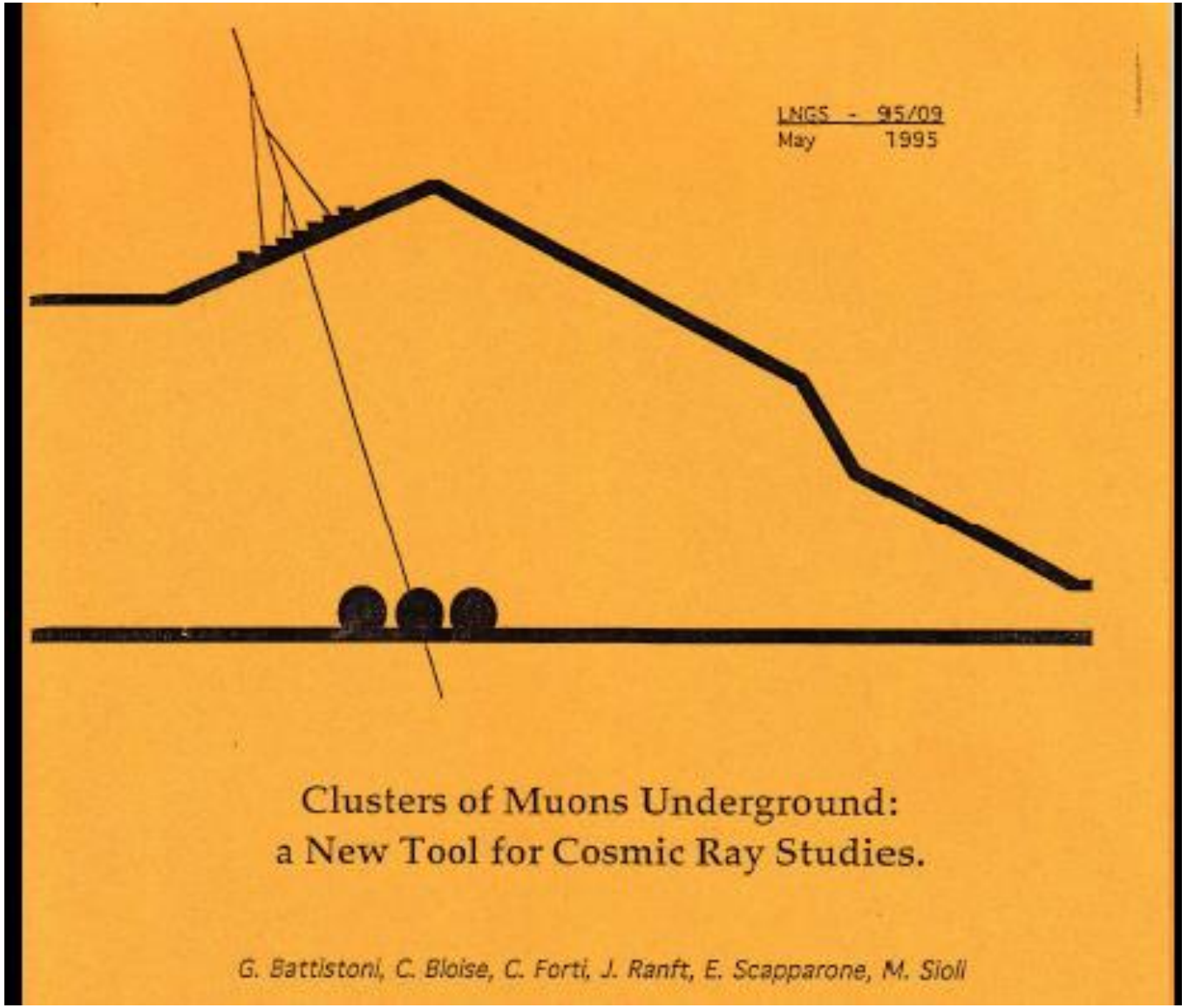
$$R1 \sim \frac{Pt_soft*h1}{E0}$$

$$R2 \sim \frac{Pt_soft*h2}{Xlab*E0}$$

$$R > R1+R2 \Downarrow$$

$$Pt > Pt_soft*\left(1+\frac{h2}{Xlab*h1}\right)$$

Our hypothesis


LNGS - 95/09
May 1995
Clusters of Muons Underground:
a New Tool for Cosmic Ray Studies.
G. Battistoni, C. Bloise, C. Forti, J. Ranft, E. Scapparone, M. Sioli

Another investigation…

ELSEVIER

Astroparticle Physics 4 (1996) 351–363

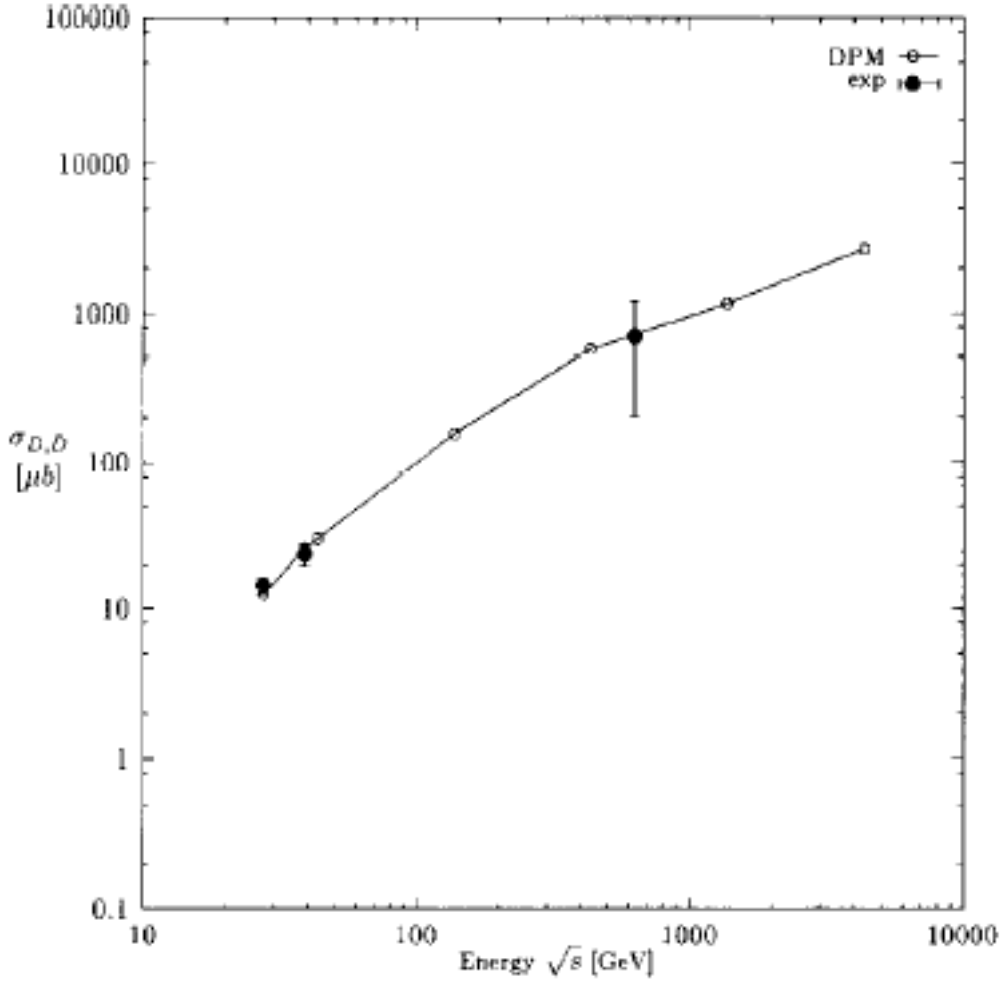
Astroparticle Physics

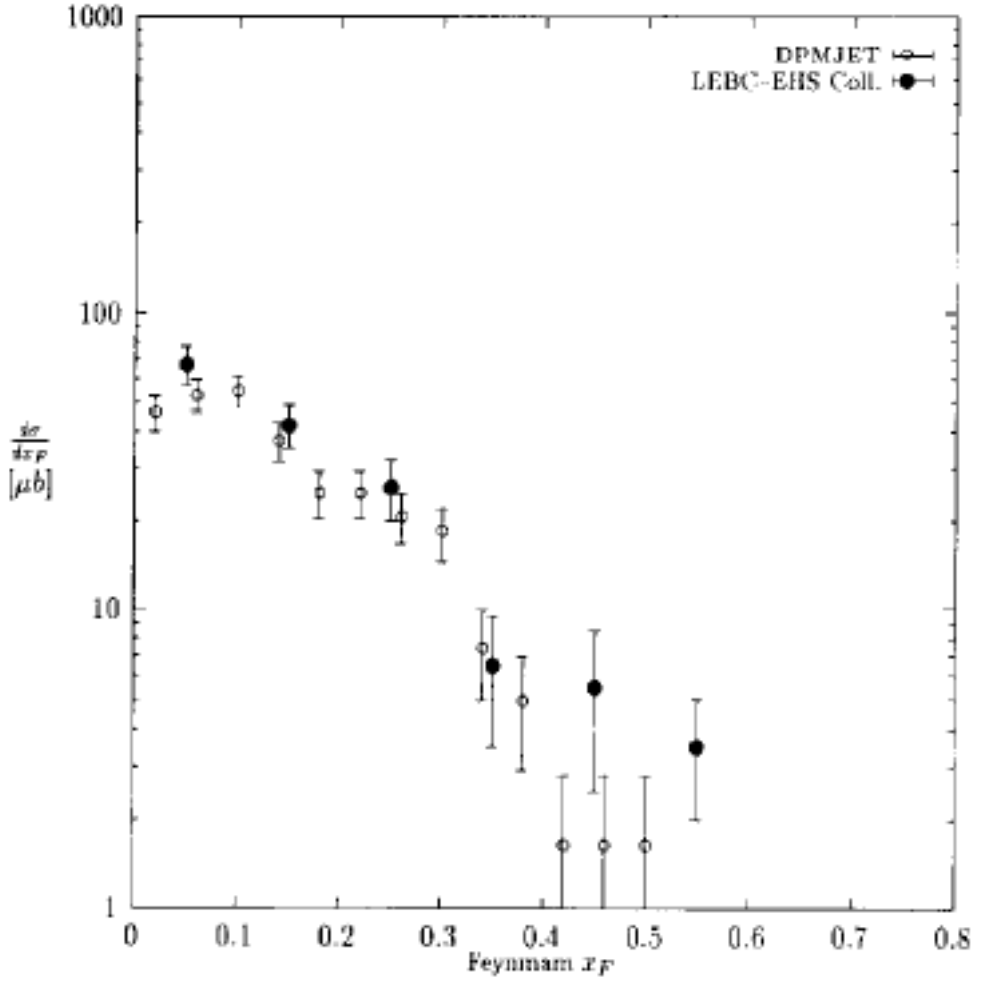
Calculation of the TeV prompt muon component in very high energy cosmic ray showers

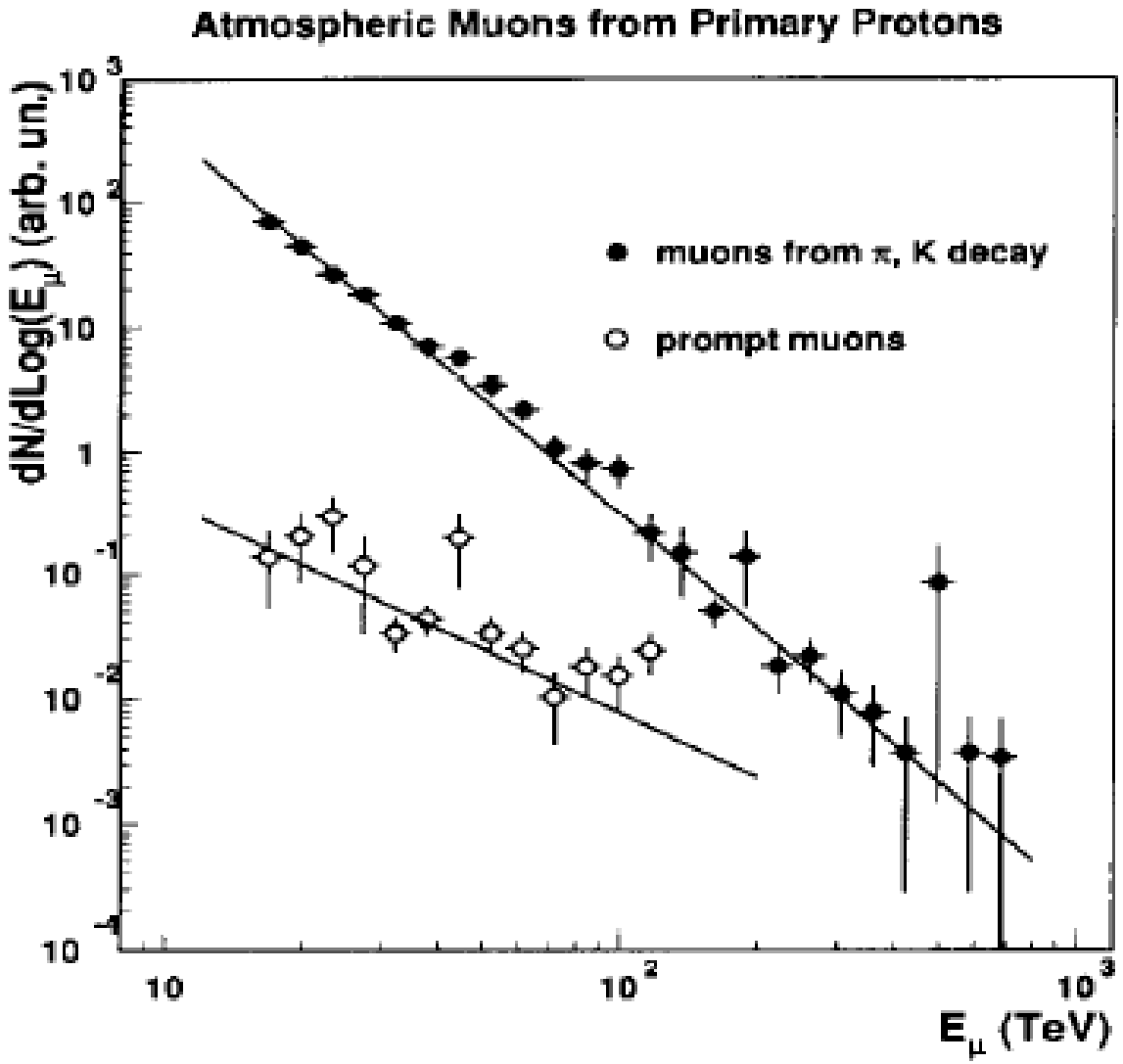
G. Battistoni [a], C. Bloise [b], C. Forti [b], M. Greco [b,c], J. Ranft [d], A. Tanzini [e]

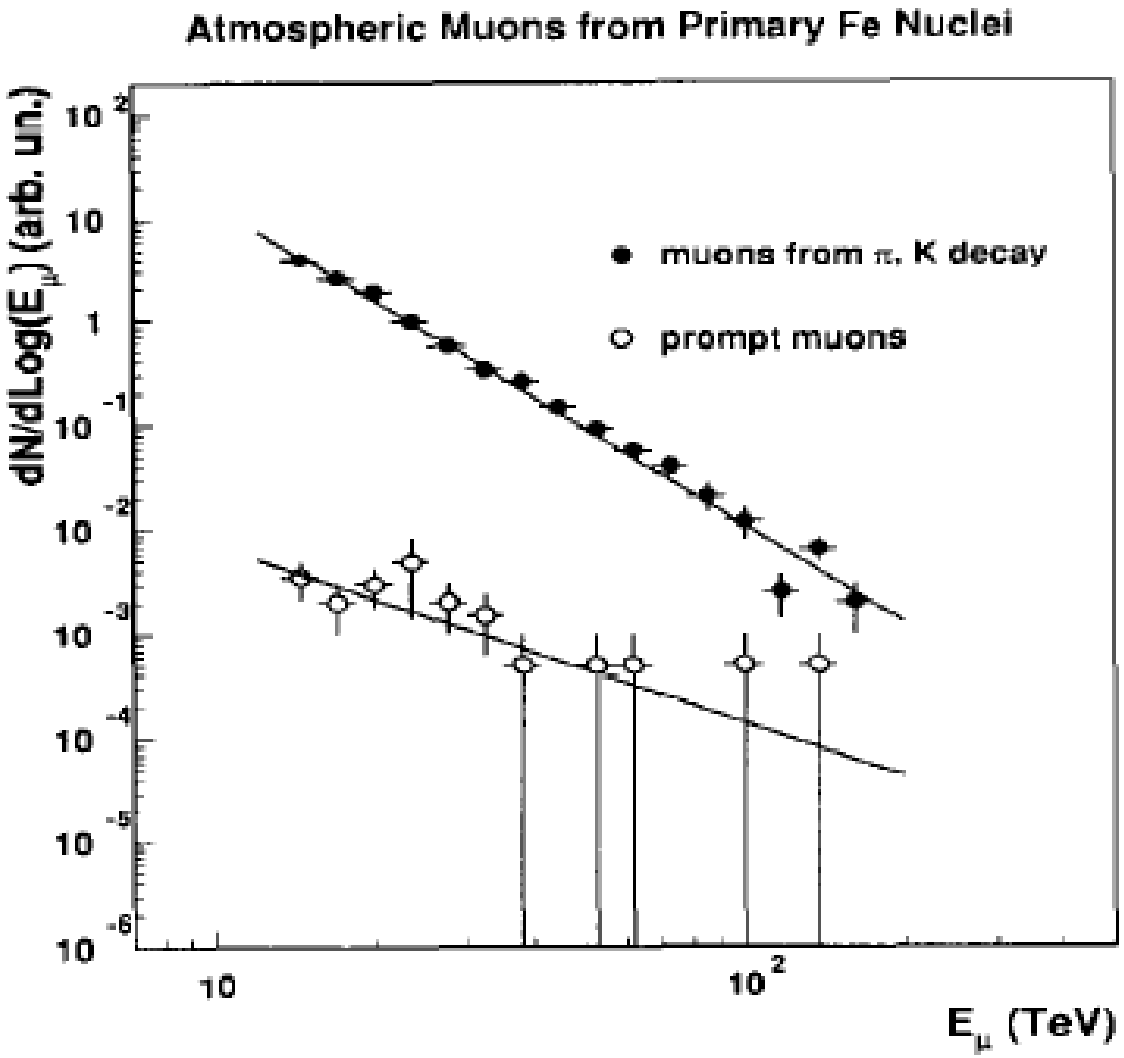
[a] *INFN, Sezione di Milano, Italy*
[b] *INFN, Laboratori Nazionali di Frascati, Italy*
[c] *Dipartimento di Fisica della III Università di Roma, Italy*
[d] *LAPP, Annecy-le-Vieux, France*
[e] *Dipartimento di Fisica della II Università di Roma, Italy*

Received 27 July 1995; revised 20 November 1995


DPM
exp
100000
10000
1000
100
10
1
0.1
$\sigma_{D,\bar{D}}$ [μb]
10
100
1000
10000
Energy $\sqrt{s}$ [GeV]

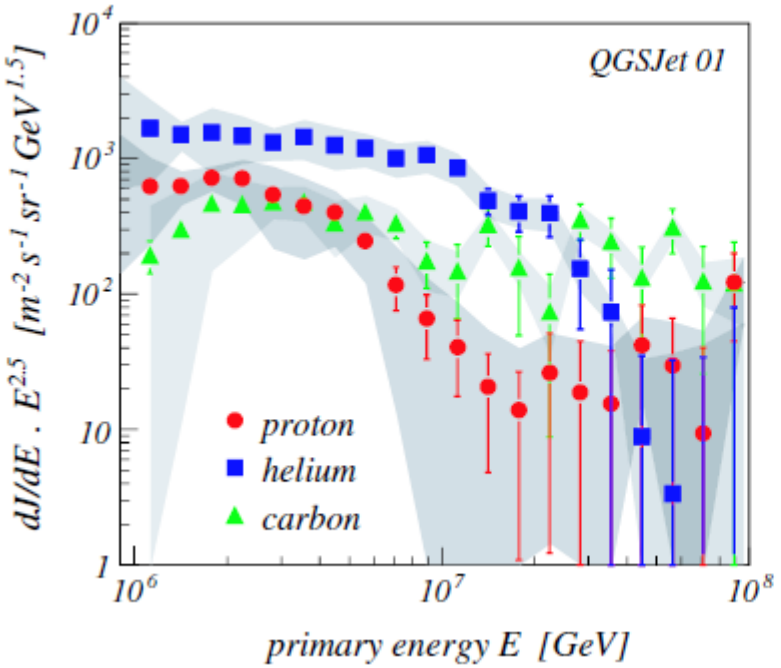

DPMJET
LEBC-EHS Coll.
1000
100
10
1
$\frac{d\sigma}{dx_F}$ [μb]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Feynman x_F

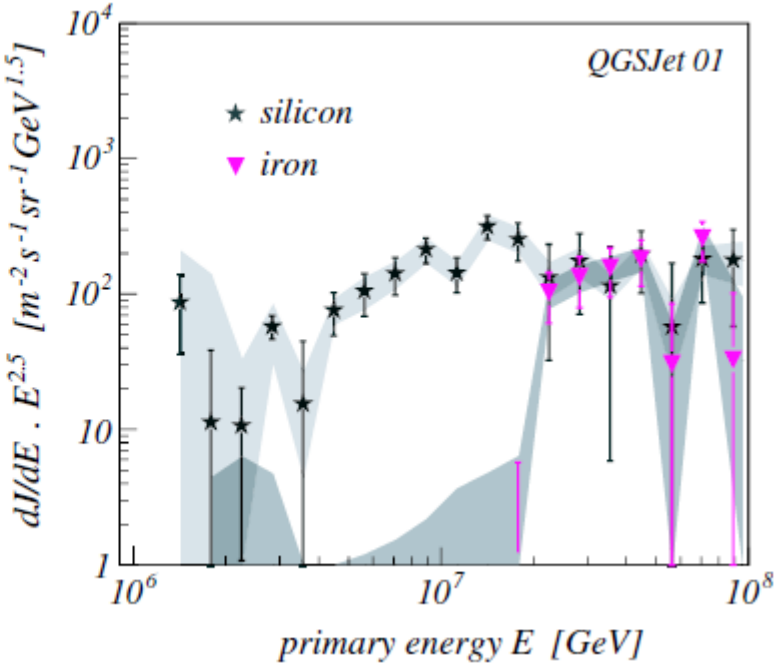

Atmospheric Muons from Primary Protons
dN/dLog(E$_\mu$) (arb. un.)
muons from π, K decay
prompt muons
E$_\mu$ (TeV)

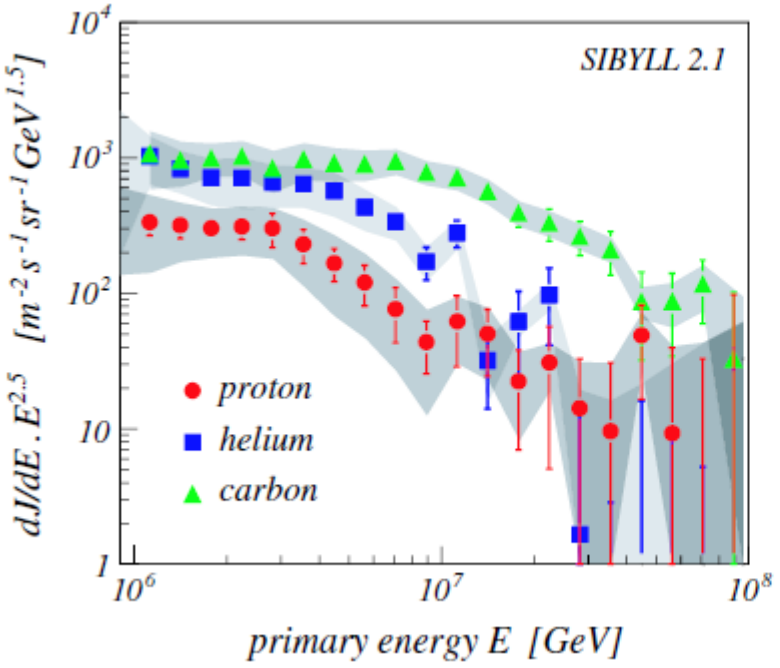

Atmospheric Muons from Primary Fe Nuclei
dN/dLog(E$_\mu$) (arb. un.)
muons from π, K decay
prompt muons
E$_\mu$ (TeV)

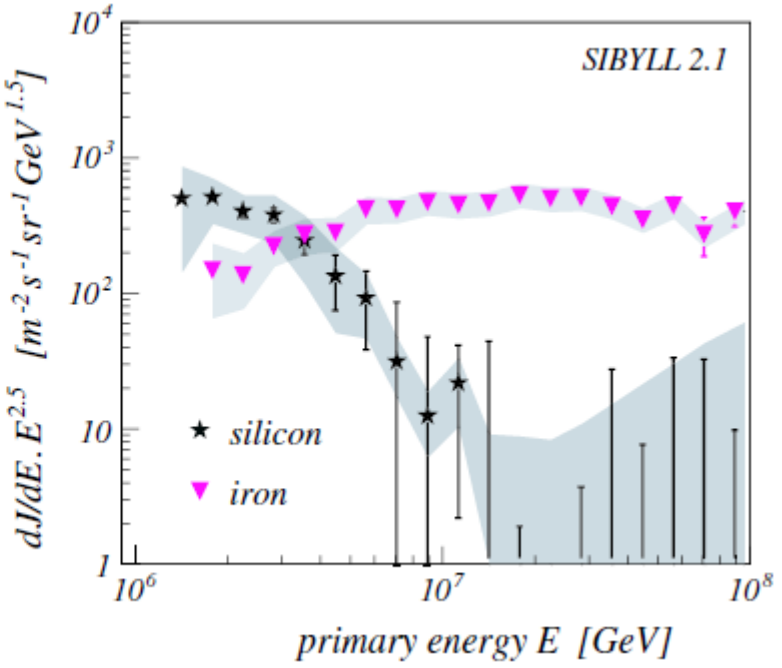
What came next…

- 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?


QGSJet 01
proton
helium
carbon
dJ/dE . E^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
primary energy E [GeV]


QGSJet 01
silicon
iron
dJ/dE . E^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
primary energy E [GeV]

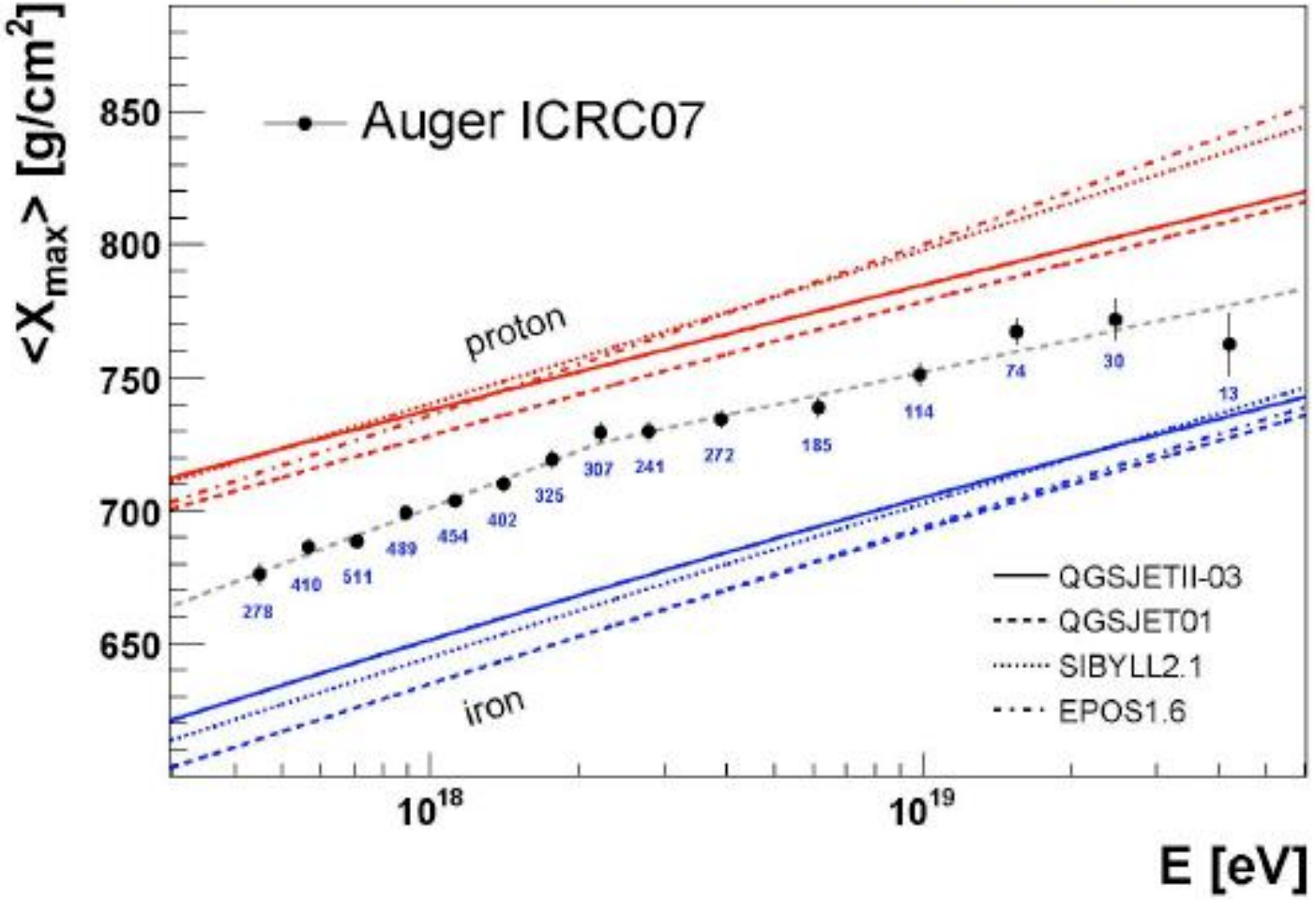

SIBYLL 2.1
proton
helium
carbon
dJ/dE . E^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
primary energy E [GeV]


SIBYLL 2.1
silicon
iron
dJ/dE . E^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
primary energy E [GeV]

X_{max} measured over two decades of energy

Syst error on Xmax < 15 g /cm^2

(< A> ~ 5)



Mass composition: protons, light nuclei, Fe ?

Only protons at UHE presently is not favoured.

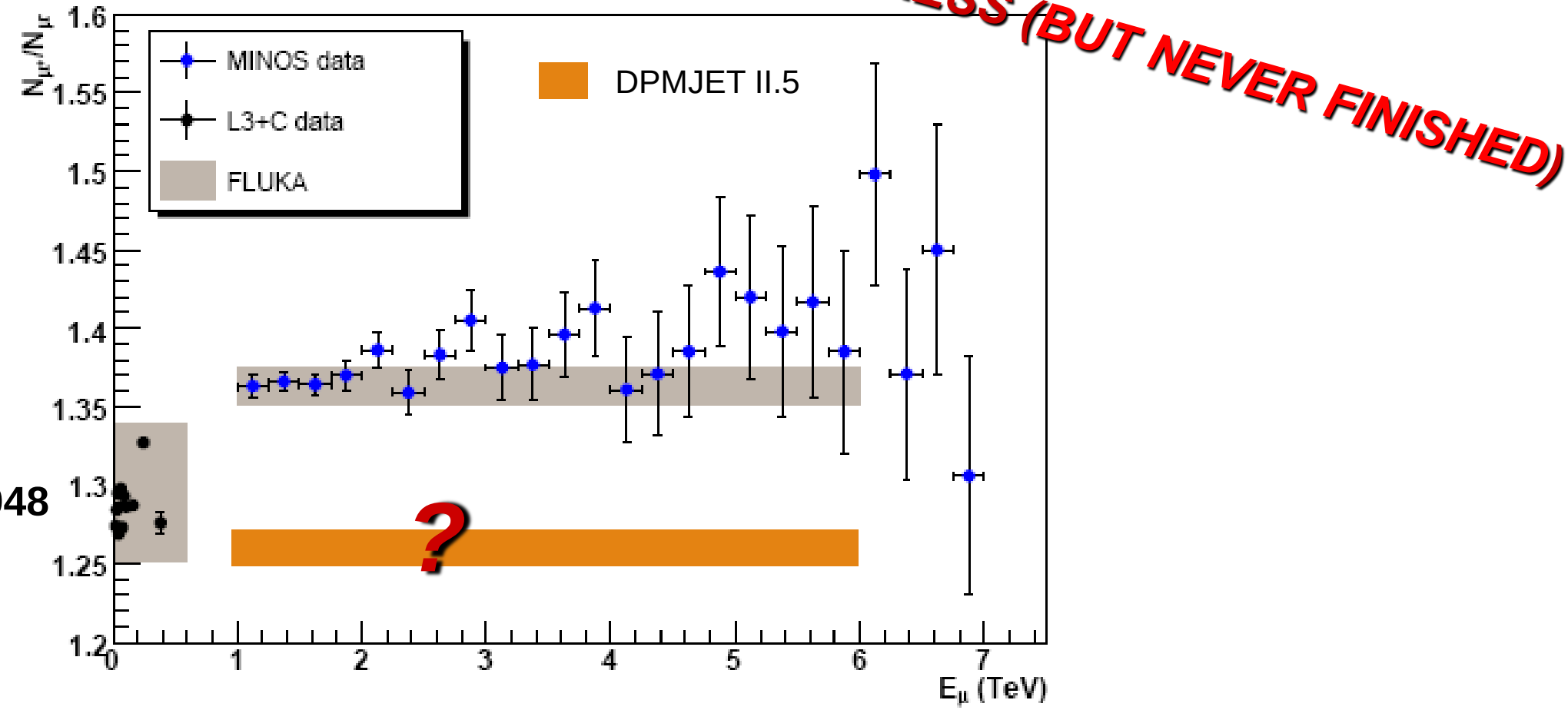
MINOS hep-ex 0705.3815

Charge Ratio at the Surface = **1.371± 0.003**

$R_{FLUKA}\ \mu^+/\mu^- = 1.362 \pm 0.012$

$R_{DPMJET\ II}\ \mu^+/\mu^- = 1.27 \pm 0.01$?

VERY PRELIMINARY
WORK IN PROGRESS (BUT NEVER FINISHED)



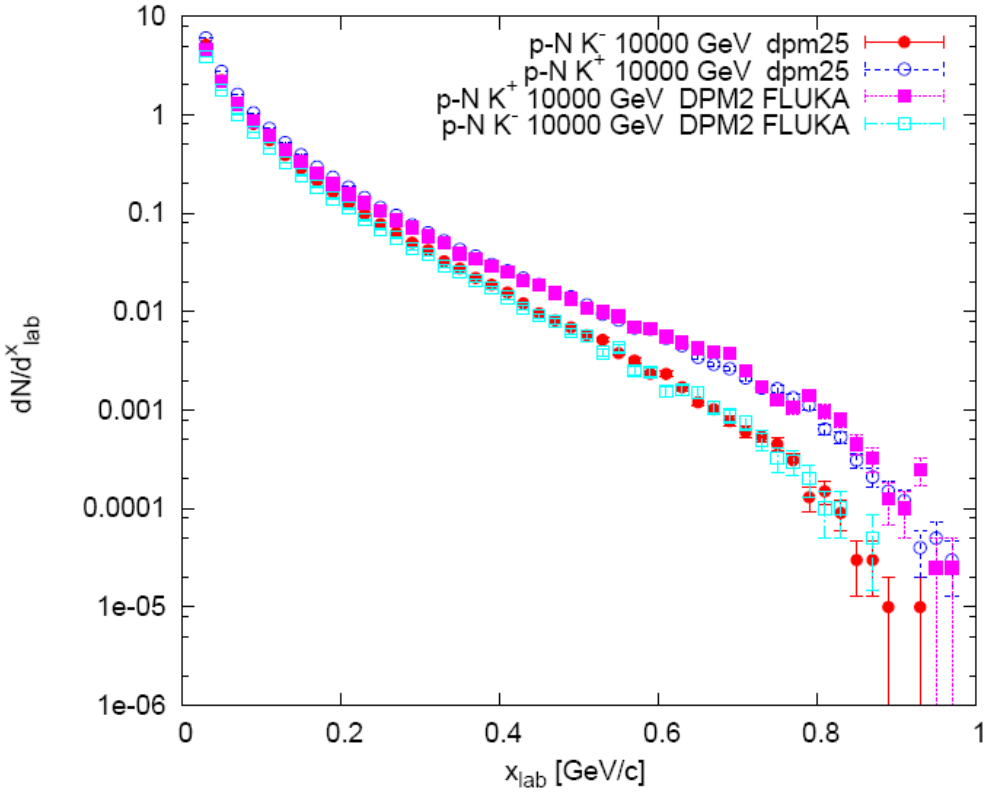
L3 + COSMIC
(hep-ex/0408114).
$R_{FLUKA} = 1.295 \pm 0.048$
$R_{exp} = 1.28 \pm 0.48$

An example: a problem remained unsolved at home:

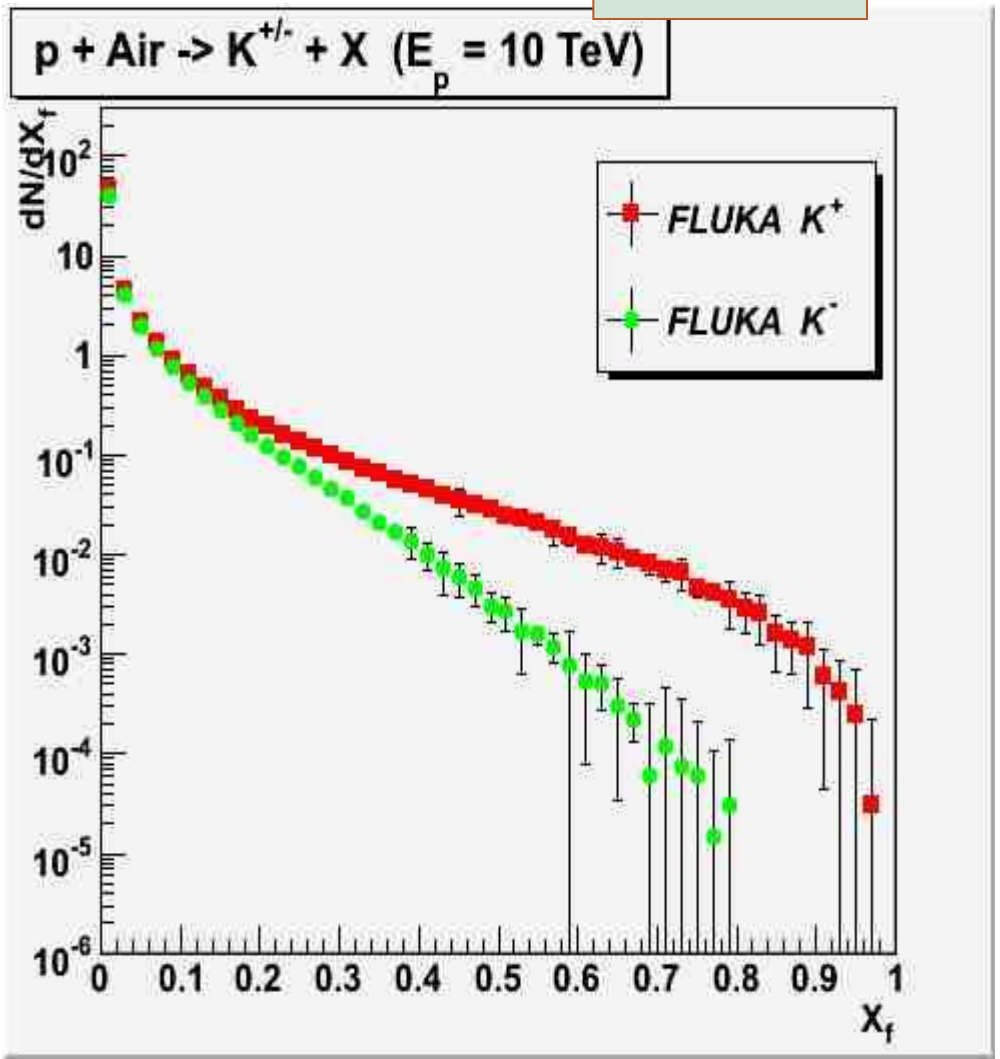
DPMJET II.5 & FLUKA

$p + N \rightarrow K^{\pm} + X \qquad E_p = 10\ TeV$

DPMJET II.5 standalone & by means of FLUKA



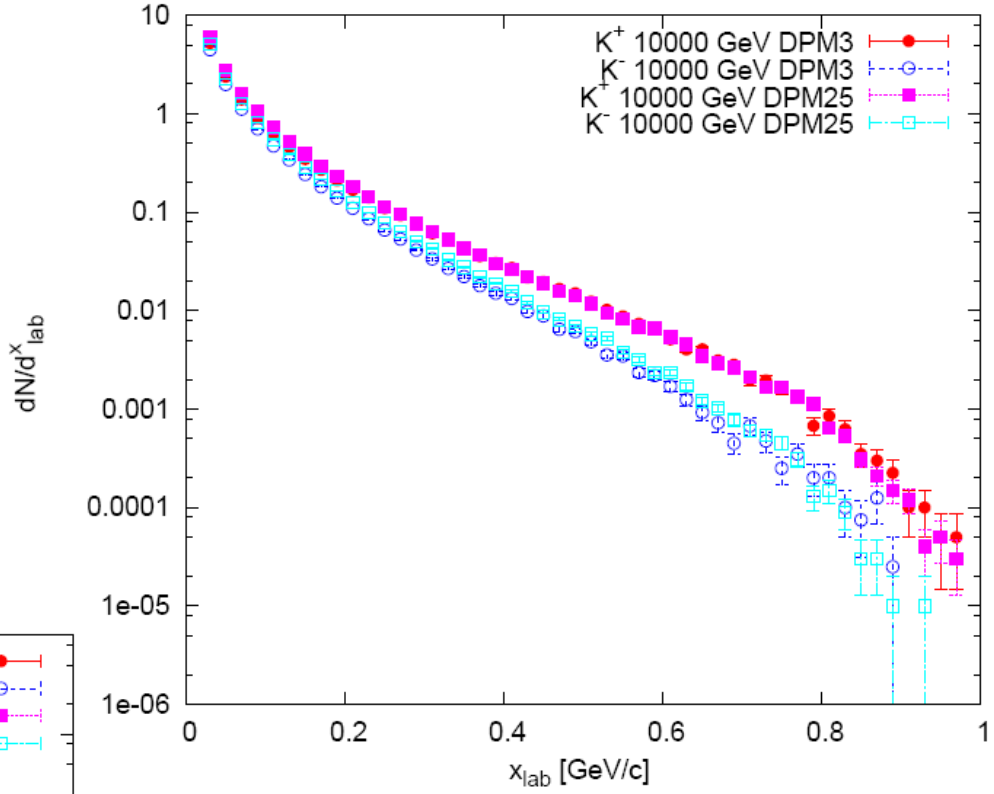
FLUKA

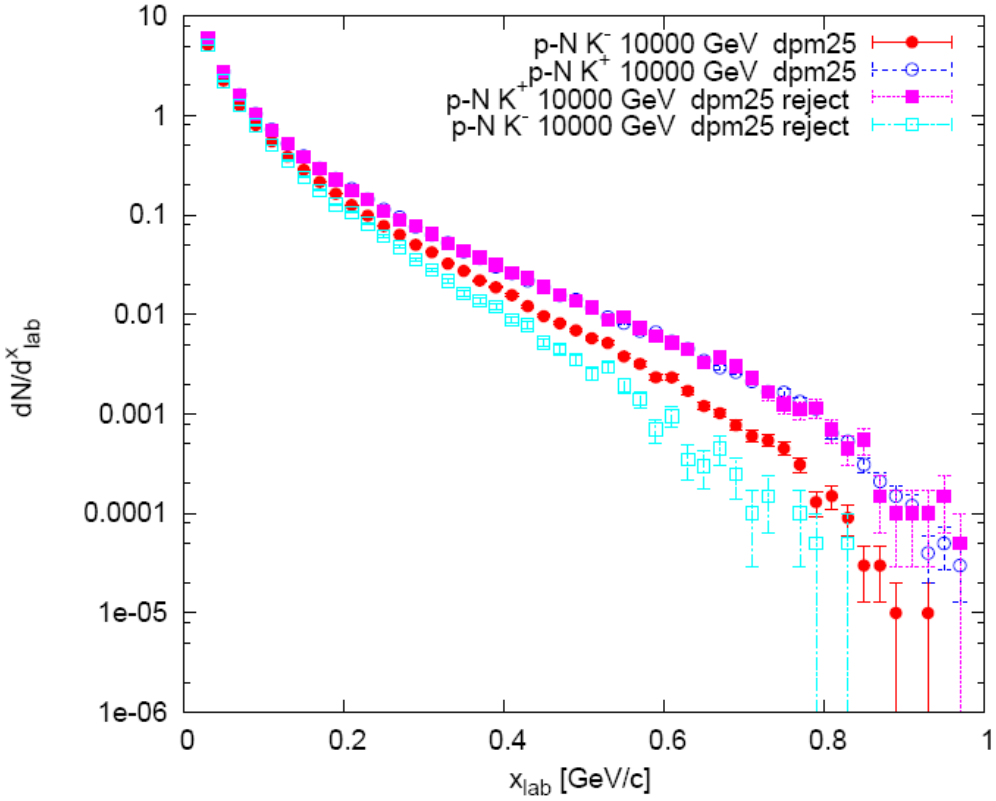


$p + N \rightarrow K^{\pm} + X$

$E_p = 10$ TeV

DPMJET II.5
&
DPMJET III





DPMJET II.5
&
DPMJET II.5
with rejection of
strange sea-quark pairs

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