Cosmic ray muons and hadronization: simulations by the FLUKA event generator vs. experimental data

M.V. Garzelli *on behalf of the* FLUKA Collaboration

The analysis of data from cosmic ray physics is highly sensitive to the models used to describe hadronic interactions and hadronization. In particular, in this talk we report on our study of cosmic ray muons at the atmospheric, underground and undersea levels, obtained in simulations with the **FLUKA Monte Carlo code** in standalone configuration and interfaced to DPMJET. We show how the study of some observables, as the **muon charge ratio** and the **lateral** and **multiplicity distributions** are **sensitive to the hadronic interactions and hadronization models** and how data from deep-underground experiments, like MACRO, or from undersea experiments, like ANTARES, can be complementary to the data from accelerator experiments, like LHC, in showing problematic issues in the hadronic models currently in use.

Workshop on Hadron-Hadron & Cosmic Ray Interactions at multi-Tev Energies, ECT* Trento, 29 November – 3 December, 2010

The FLUKA Collaboration

Giuseppe BATTISTONI[1], Francesco BROGGI[1], Markus BRUGGER[2], Mauro CAMPANELLA[1], Massimo CARBONI[5], Anton EMPL[10], Alberto FASSÒ[3], Ettore GADIOLI[1], Francesco CERUTTI[2], Alfredo FERRARI[2], Anna FERRARI[14], **Maria Vittoria GARZELLI**[15], Mattias LANTZ[13], Andrea MAIRANI[1], **Annarita MARGIOTTA**[8], Cristina MORONE[7], **Silvia MURARO**[1], Katia PARODI[9], Vincenzo PATERA[6], Maurizio PELLICCIONI[6], Lawrence PINSKY[10], **Johannes RANFT**[4], **Stefan ROESLER**[2], Sofia ROLLET[12], Paola R. SALA[1], Mario SANTANA[3], Lucia SARCHIAPONE[5], **Massimiliano SIOLI**[8], George SMIRNOV[2], Florian SOMMERER[9], Christian THEIS[2], Stefania TROVATI[2], Rosaria VILLARI[6], Heinz VINCKE[2], Helmut VINCKE[2], Vasilis VLACHOUDIS[2], Joachim VOLLAIRE[2], Neil ZAPP[11]

[1] INFN, Milano, Italy
[2] CERN, Geneva, Switzerland
[3] SLAC, Stanford, U.S.A.
[4] University of Siegen, Siegen, Germany
[5] INFN, Legnaro, Italy
[6] INFN, Frascati, Italy
[7] INFN and University of Roma II, Roma, Italy
[8] INFN and University Bologna, Bologna, Italy
[9] HIT, Heidelberg, Germany
[10] University of Houston, Houston, U.S.A.
[11] NASA, Houston, U.S.A.
[12] ARC Seibersdorf, Seibersdorf, Austria
[13] Uppsala University, Uppsala, Sweden
[14] FZD Dresden-Rossendorf, Dresden, Germany
[15] INFN, Italy and University of Granada, Spain

The FLUKA MC code

INFN-CERN agreement for its continuous development and maintainance
Available on the web at **http://www.fluka.org**
Main Authors: A. Fasso', A. Ferrari, P.R. Sala, J. Ranft
Increasing numbers of users.....

Multipurpose applications: beam design, detector response simulation, cosmic ray and neutrino fluxes, space and Earth radiation protection, hadrontherapy,......

FLUKA is used at LHC for radiation damage evaluation!

Model development philosophy:
- microscopic approaches
- minimization of the number of free parameters
- parameters fixed by means of benchmark with available experimental data
- energy, momentum and quantum number conservation
- correlations preserved
- code continuously updated

Other features:
- 3D geometry
- biasing

Cosmic ray library: collection of additional routines specifically designed to deal with important features concerning cosmic ray simulations
- primary spectrum generation (primary spectra from different fits are available)
- solar modulation
- terrestrial atmosphere 3D profiles (100 concentric atmospheric shells with different densities)
- geomagnetic effect

MuTeV:
recent extension of the FLUKA cosmic ray library to study TeV muon events

Self-consistent generator to handle in a **unified framework** all simulation steps leading to the **generation, propagation and final detection of muons with E up to** several **TeVs**, by including

- **primary interaction** in the atmosphere
- **shower development**
- **transport in the overburden** (rock or sea)
    - 3D profile of Gran Sasso mountain encoded in FLUKA geometry
    - 3D profile of the sea over two underwater experiments
    - flexibility to add profiles of new sites.....
- **detector active volume simulation**

Other features
- **optimization by** means of specific **biasing** to speed up the calculation

Overlap with the ANTARES, OPERA, MACRO and ICARUS Collaboration activities!

High energy muons (p > 100 GeV/c)

High energy muons can be produced in atmosphere as decay products of charged pions and K, originating from the interaction of energetic CR primaries with the atmospheric nuclei. They can propagate through the atmosphere down to the Earth surface, and cross sea and rocks, if their energy is high enough, before decaying in neutrinos.

Their **simulated rate** is **sensitive to**
- **hadronic interaction model**
- accurate description of the rock/sea environment
- **mu transport model inside the rock/sea**, including electroweak interaction effects

Typical signature underground ----> **muon bundles** (group of mu with non so different direction and energy, like jets)

Low energy muons (p < 100 GeV/c)

The **production** of low energy muons in atmosphere, as obtained by means of numerical simulations with FLUKA, is **sensitive to**

- hadronic interaction model (FLUKA standalone vs. FLUKA + DPMJET) and **location of primary interaction**
- **primary CR spectrum** and **solar modulation**
- **atmospheric model**
- **geomagnetic model**

Muon charge ratio:mu+/mu-

The **mu charge ratio** is **sensitive to the pion and the kaon charge ratio**.

First observation: the **mu charge ratio** is **sensitive to primary spectrum composition**. The **proton content** in the primary spectrum is larger than the neutron content. This is particularly important when looking at the **forward fragmentation region**. This is attenuated when one considers spectra including an higher proportion of heavy nuclei, since they are neutron rich.

As for the **pions (light unflavored mesons S=C=B=0)**: the charge ratio is > 1, not enhanced due to isospin symmetry, and the relative **fraction** of muons from pions (both positively and negatively charged) decreases with increasing energies.

As for the **kaons (strange mesons S=1,-1, C=B=0)**: the charge ratio is >1 and further enhanced, due to the fact that it is easier to create K+ than K-. This is because K+ includes a strange antiquark (S=1), whereas K- includes a strange quark (S=-1). This implies that K+ can be easily produced in association with a Lambda or Sigma baryon (that include strange quarks, S=-1), whereas, to produce K-, the simultaneous formation of a baryon including a strange antiquark is needed, that can be considered a superior-order process (standard life strange baryons Lambda, Sigma, Csi, Omega all have S < 0). Furthermore, the relative **fraction** of muons from Kaons (both positively and negatively charged) increases with increasing energies.

Uncertainties up to 20% on the pion and kaon production rates from hadronic iinteractions

Pion and Kaon critical energy

Critical energy of a species: **energy over which the interaction probability dominates over the decay probability.**

Pion Critical Energy = 115 GeV (decay length = 780 cm),
Kaon Critical Energy = 850 GeV (decay length = 371 cm)

At a given energy the probability that a kaon decays instead of interacting is larger than the probability that a pion decays instead of interacting!

At increasing energies the total fraction of muons (mu+ and mu-) from pion decays decreases, whereas the total fraction of muons from kaon decays increases...........

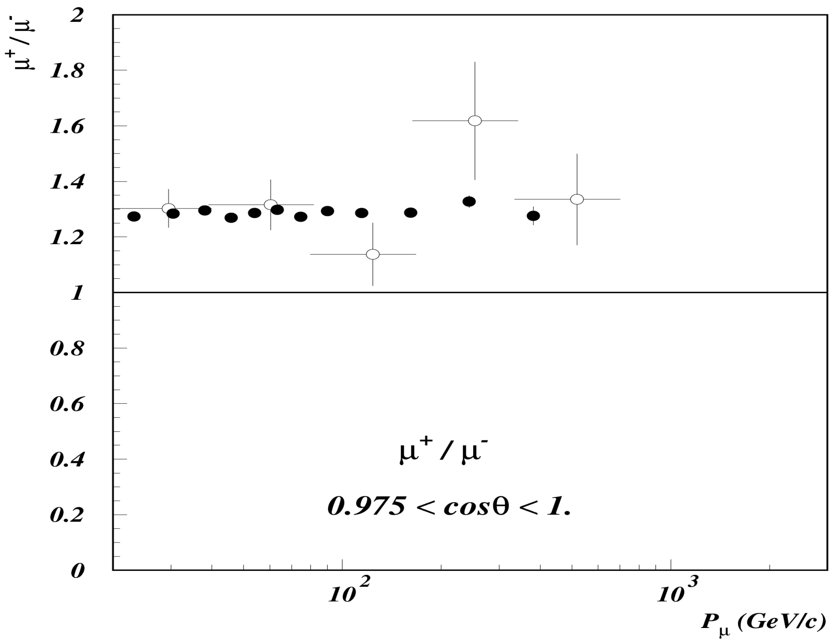
This **K dominance** implies that the **muon charge ratio is expected to increase with energy.**

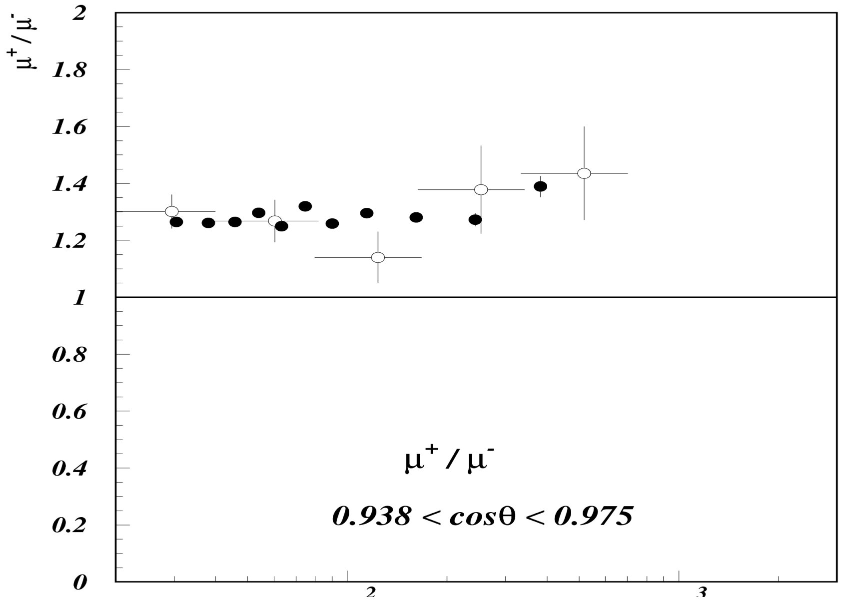
Muon charge ratio: mu+/mu-, comparison with experimental data

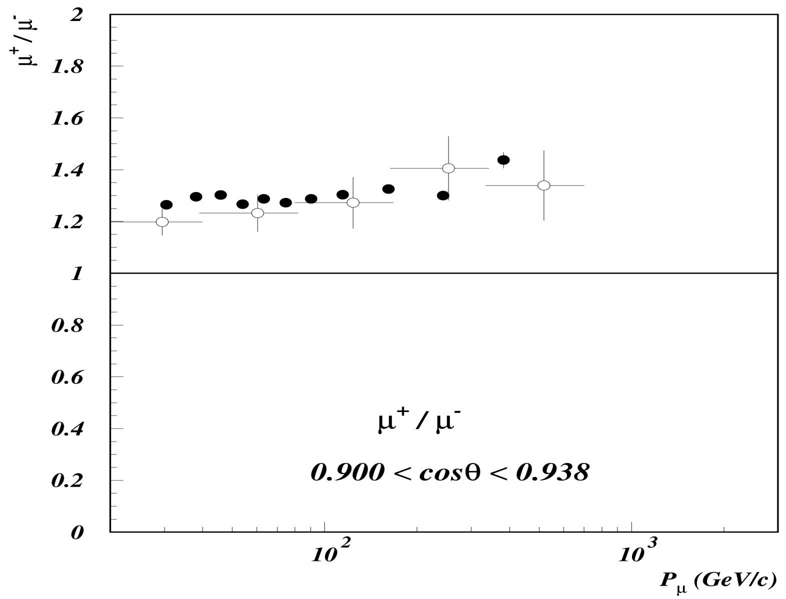
The **L3 + COSMIC** experiment provides **mu fluxes** and **mu+/mu- data as a function of mu momentum**, up to 1 TeV, **and of the azimuthal angle**.

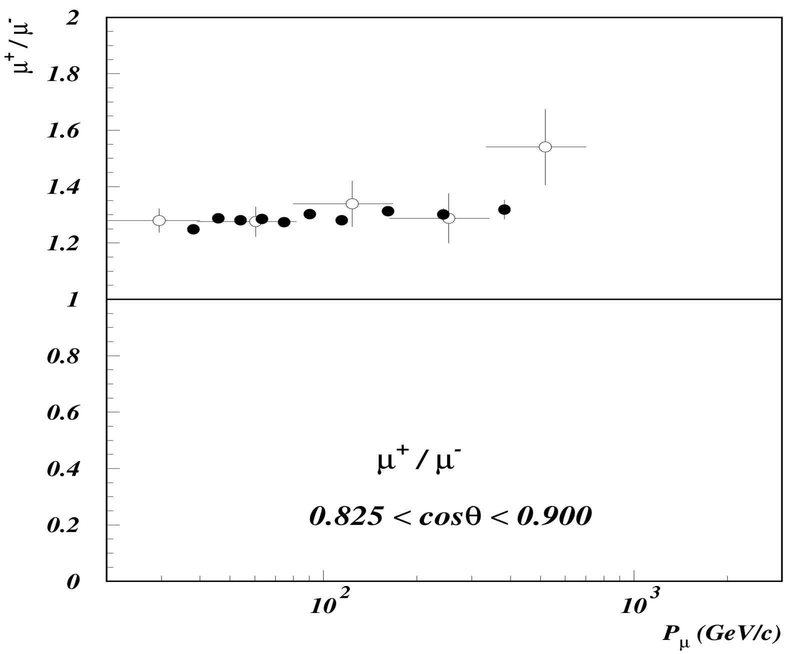
The **MINOS** experiment provides **mu+/ mu- data as a function of mu energy**, in the energy range 1 TeV < E_{mu} < 7 TeV.

Muon charge ratio: mu+/mu-, comparison of FLUKA simulations with angular dependent experimental data from the L3+C experiment









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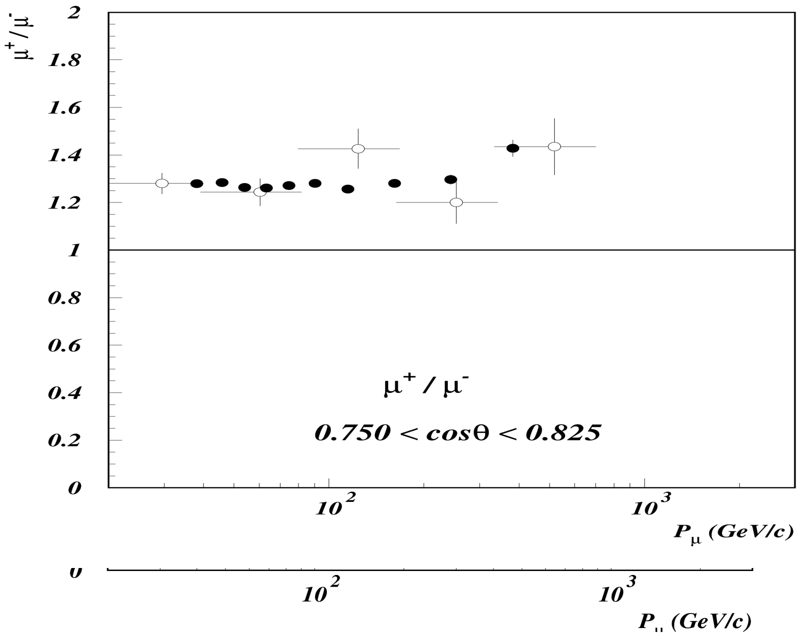
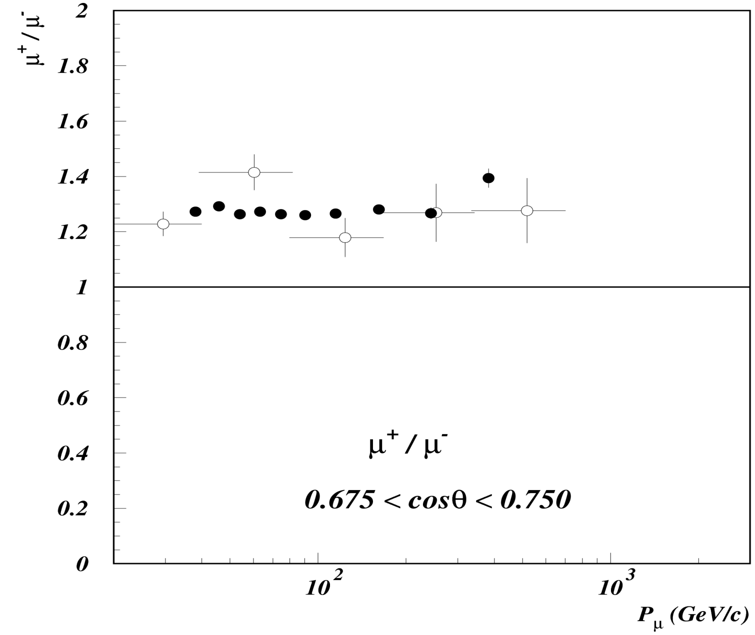
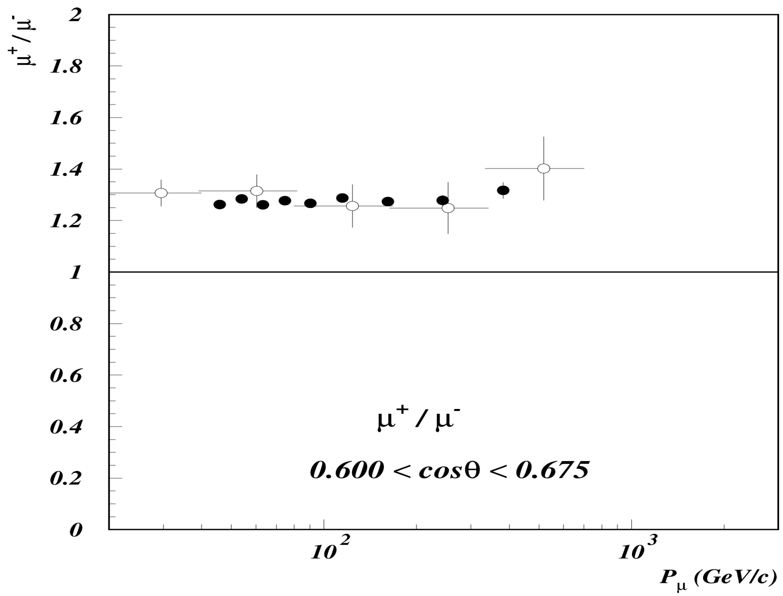
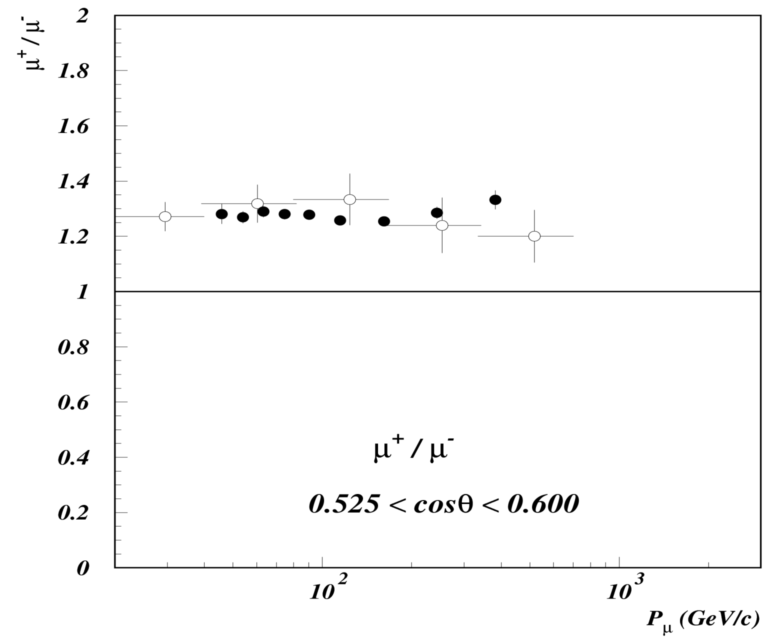
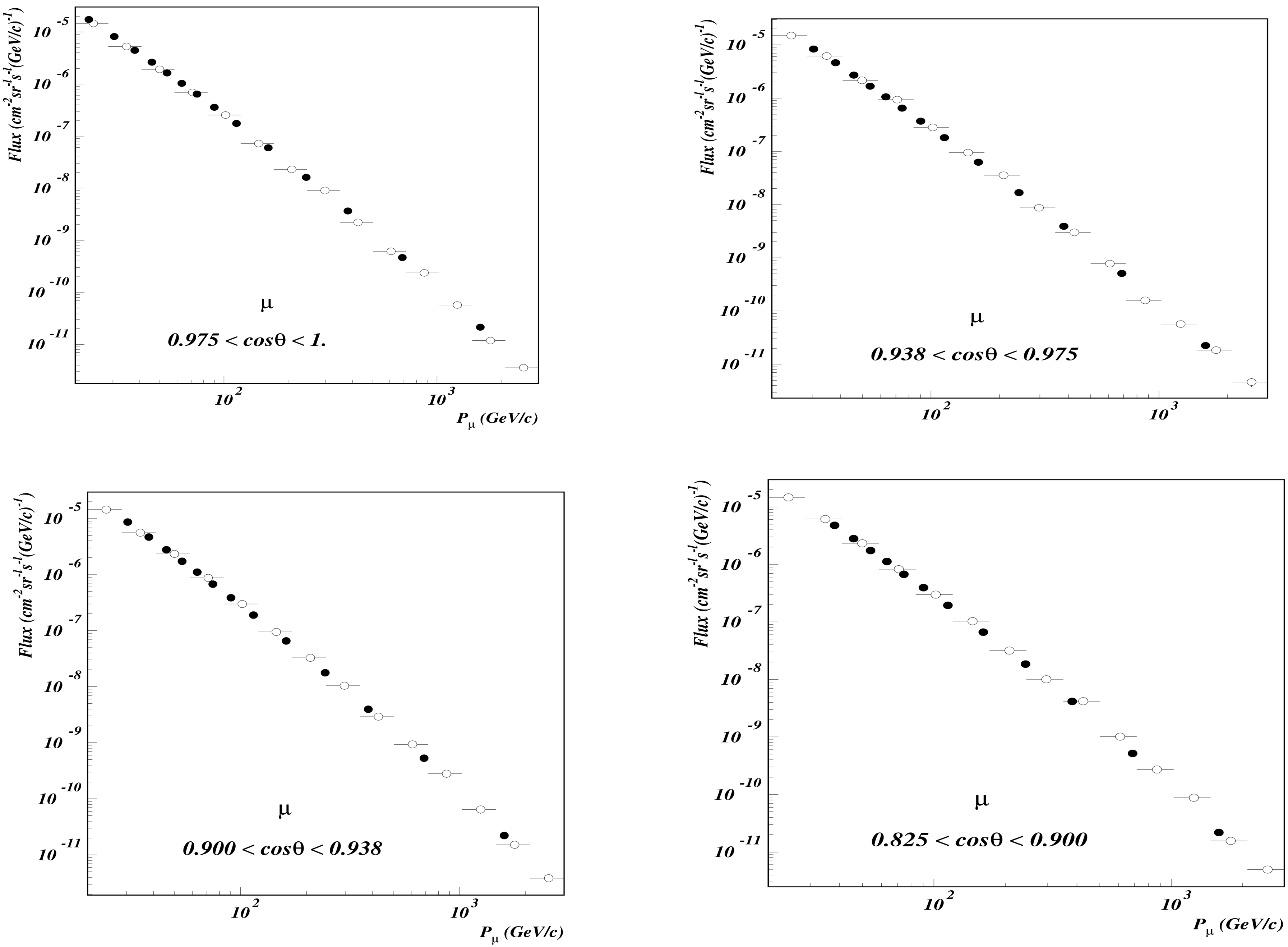




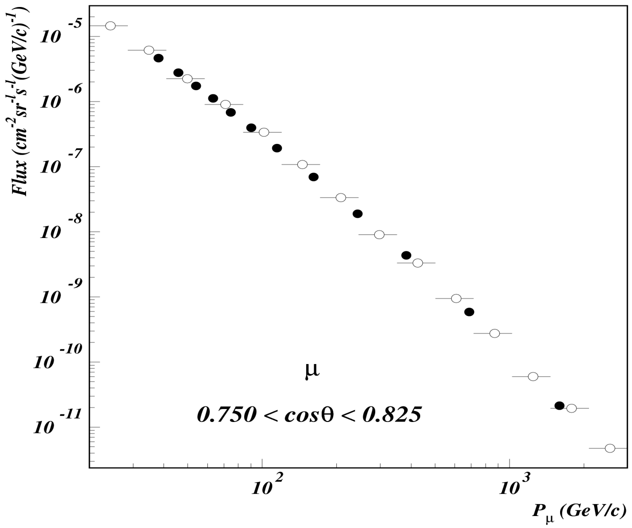


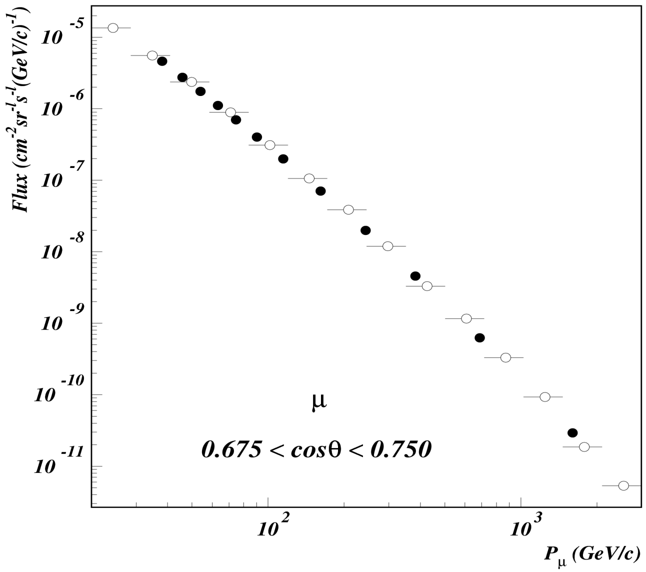


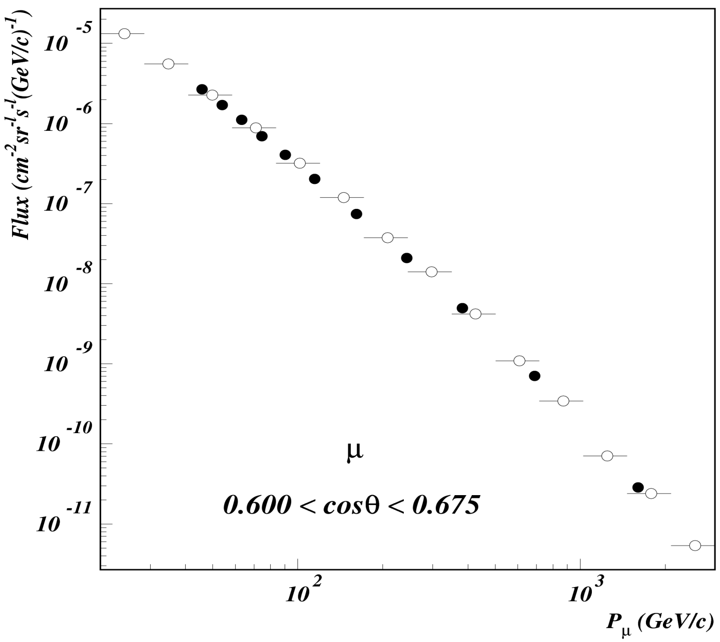
Muon flux: comparison with angular dependent experimental data

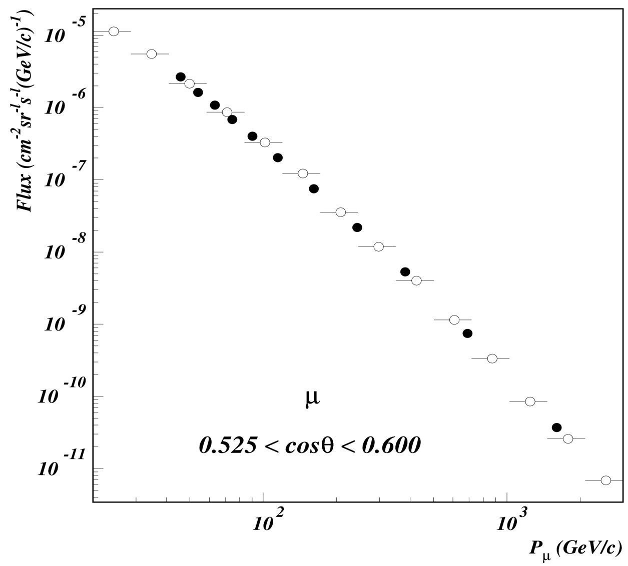


Muon flux: comparison with angular dependent experimental data

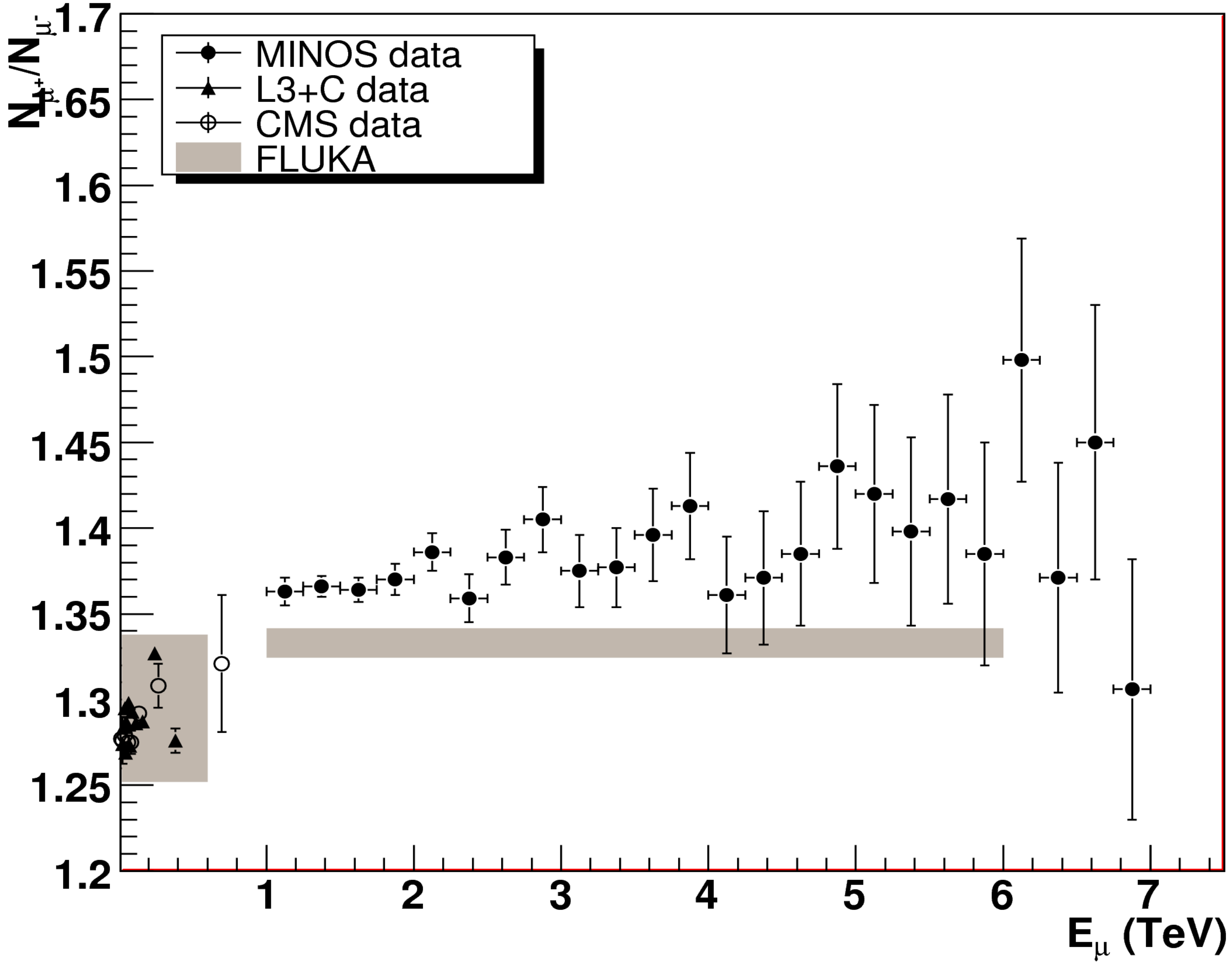








Muon charge ratio: mu+/mu-, comparison with MINOS experimental data



Muon charge ratio: mu+/mu-, comparison with experimental data

The **L3 + COSMIC** experiment provides mu+/mu- **data as a function of mu momentum**, up to 1 TeV, **and of the azimuthal angle**. The FLUKA predictions agree with the data, at all angles.

The **MINOS** experiment provides mu+/ mu- **data as a function of mu energy**, in the energy range 1 TeV < E_{mu} < 7 TeV. The FLUKA predictions slightly underestimates the data, by ~3%.

Possible reasons of the discrepancy:

* FLUKA underestimates K production and/or overestimates pi production ?
* K production in FLUKA has been validated only up to 400 GeV and over a very restricted forward region (during the project/validation of the CNGS nu beam) -----> **high-energy accelerator data to benchmark K production are needed**!
* Primary spectrum (the number of primary nuclei is overestimated with respect to the number of primary protons ?). Indeed we verified that the charge ratio decreases as a function of the primary mass!

  To further investigate this possibility one can consider experimental data concerning muon bundles, since muon bundles are preferentially produced by the interactions of high-energy and high-mass primaries (heavy nuclei).

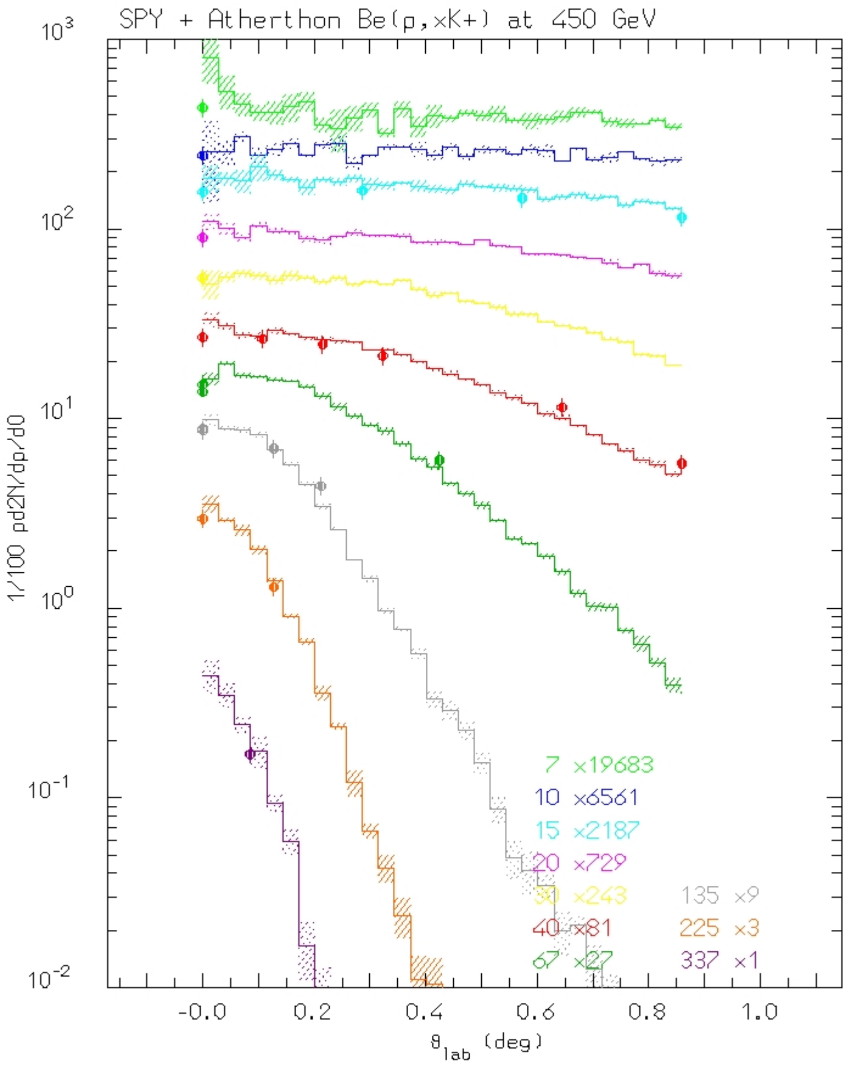
K production validation: SPY experiment (CERN-North)

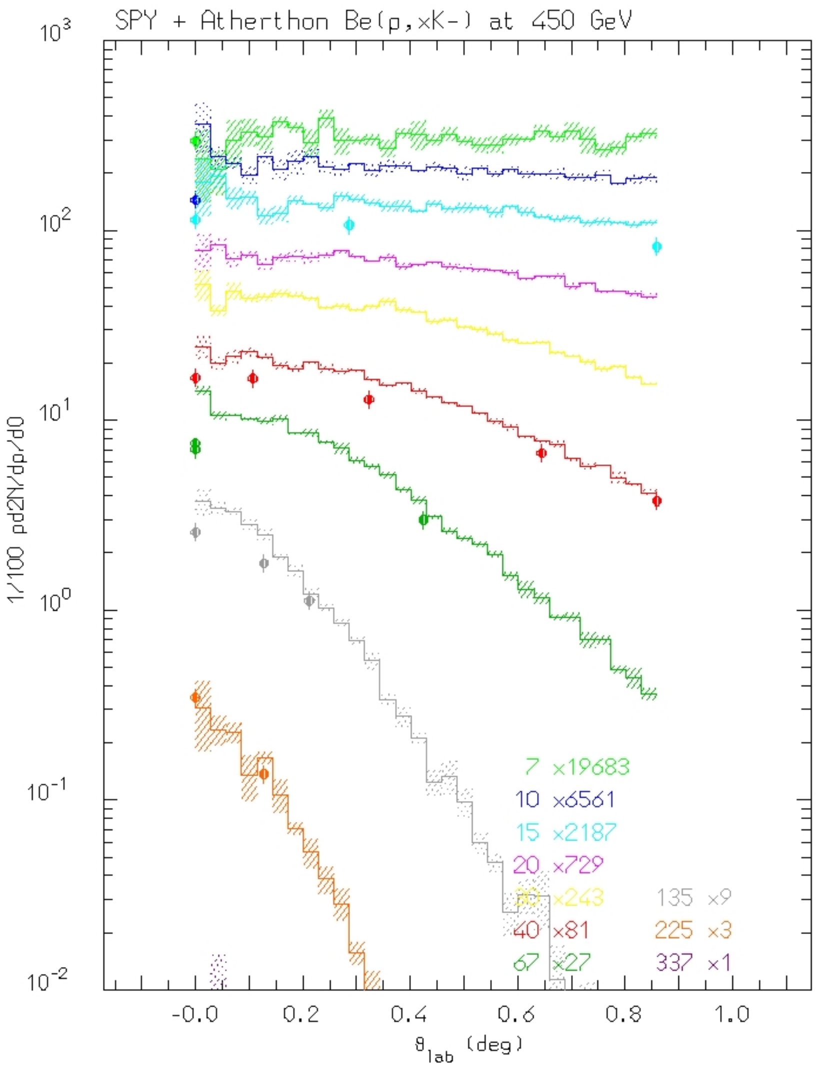
Nucl. Instr. Meth. A449, 609 (2000)

p + Be => K^+ + X

E_{lab} = 450 GeV

p + Be => K^- + X





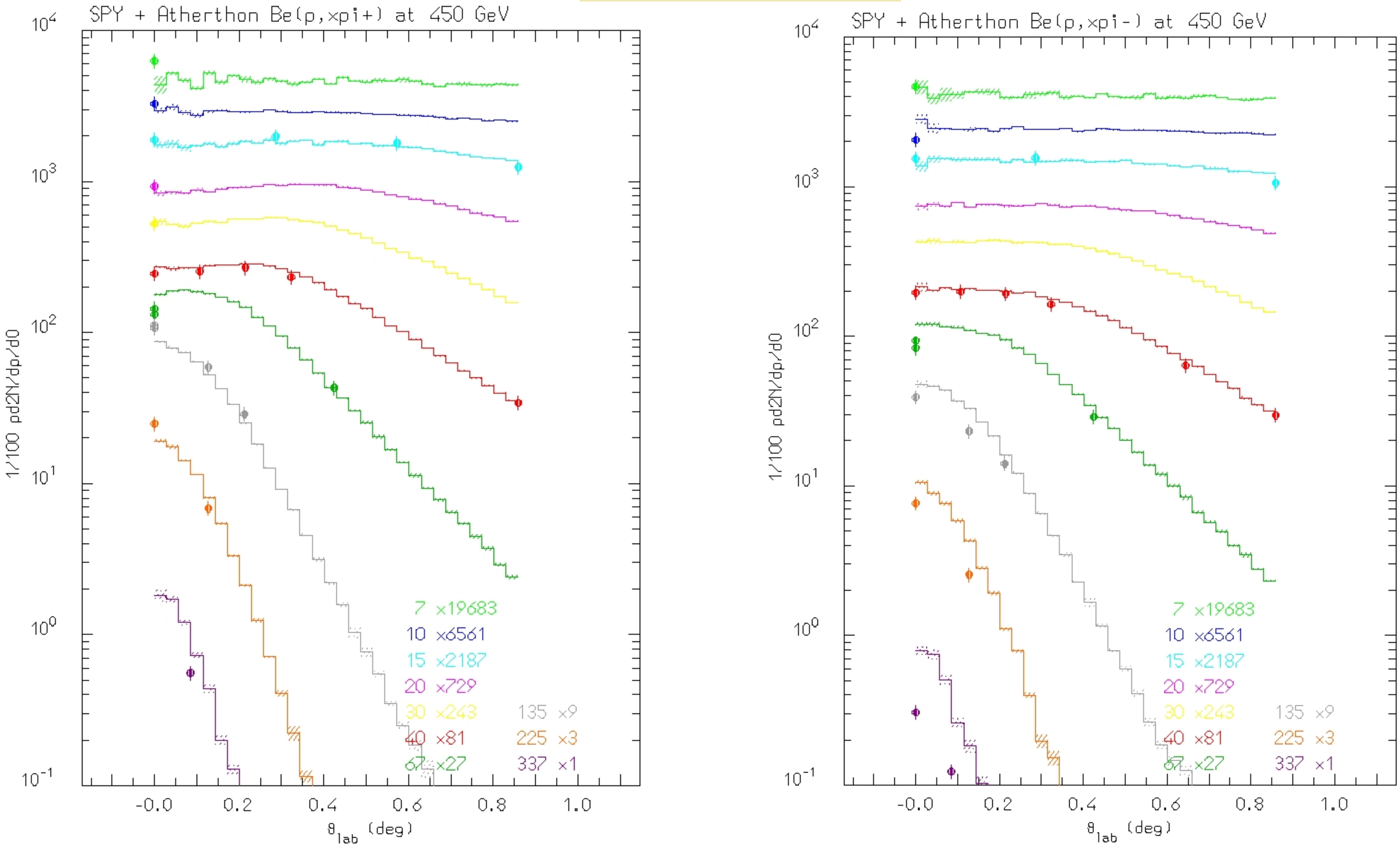
SPY experiment (CERN North Area)

Nucl. Instr. Meth. A449, 609 (2000)

p + Be => π^+ + X

E_{cm} = 450 GeV

p + Be => π^- + X



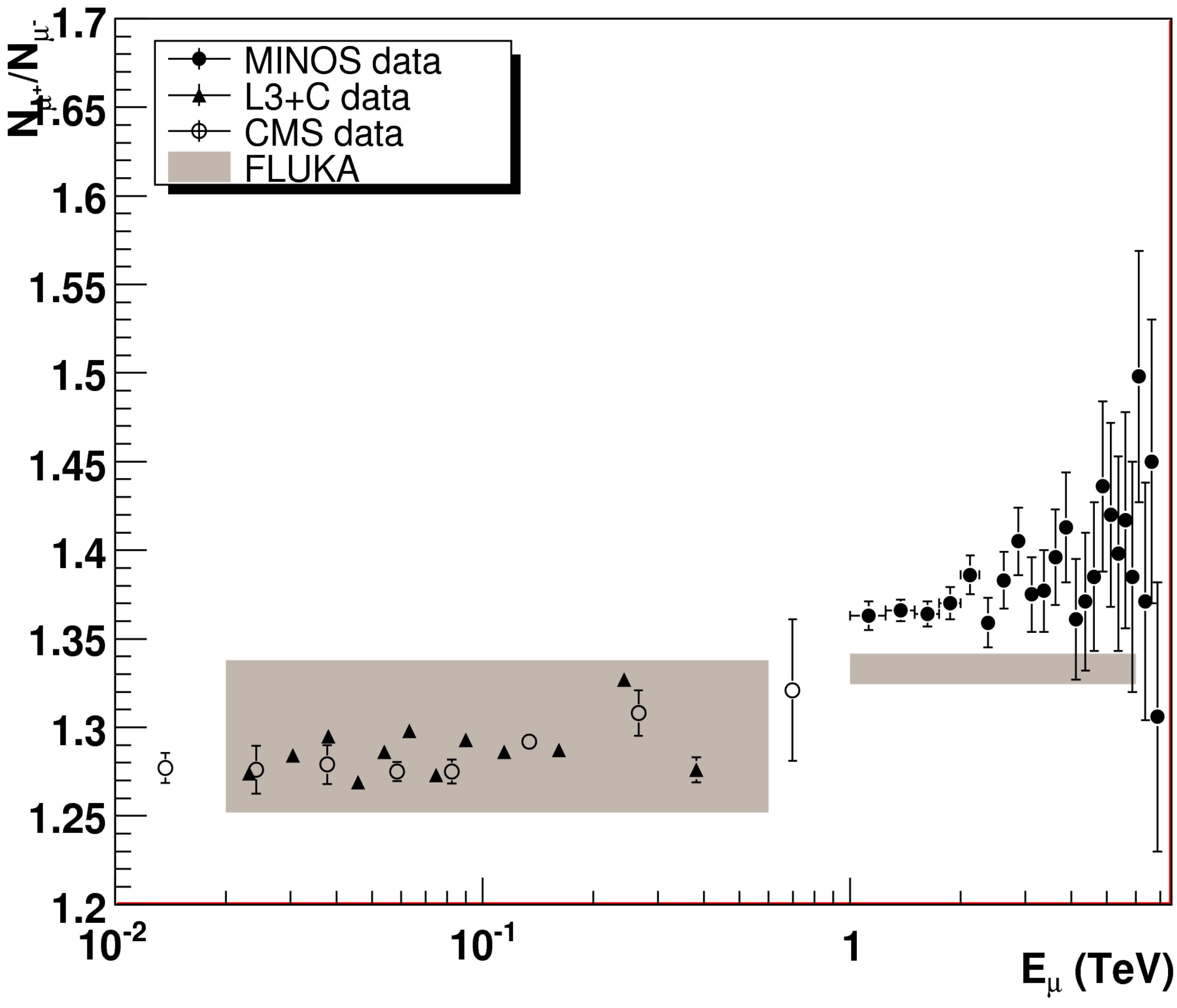
Muon charge ratio: mu+/mu-, most recent data confirm the old ones!

The **CMS** experiment provides mu+/mu- data as a function of mu momentum, in the range 10 GeV/c < p_{mu} < 1 TeV. At present, this can be considered the most comprehensive measurement of mu charge ratio, since this experiment is sensitive to both low energy and high energy muons. Angular dependence of data is not reported in first publications.
The FLUKA predictions agree with the data.

The **ALICE** experiment provides mu+/ mu- data as a function of mu momentum, at higher energies with respect to CMS (p_{mu} > 100 GeV/c) . The difficulty to use ALICE to detect lower energy muons is due to the low magnetic field of this experiment.
The FLUKA predictions still to be compared with the data......

The **OPERA** experiment, located at the Gran Sasso laboratory, provides a complementary measure of mu+/mu-. Due to its location, under ~1.5 Km of rocks, it is sensitive to high energy muons.
Interpretation of its data is still controversial (see last energy bin.....).

Muon charge ratio: mu+/mu-, comparison with CMS experimental data

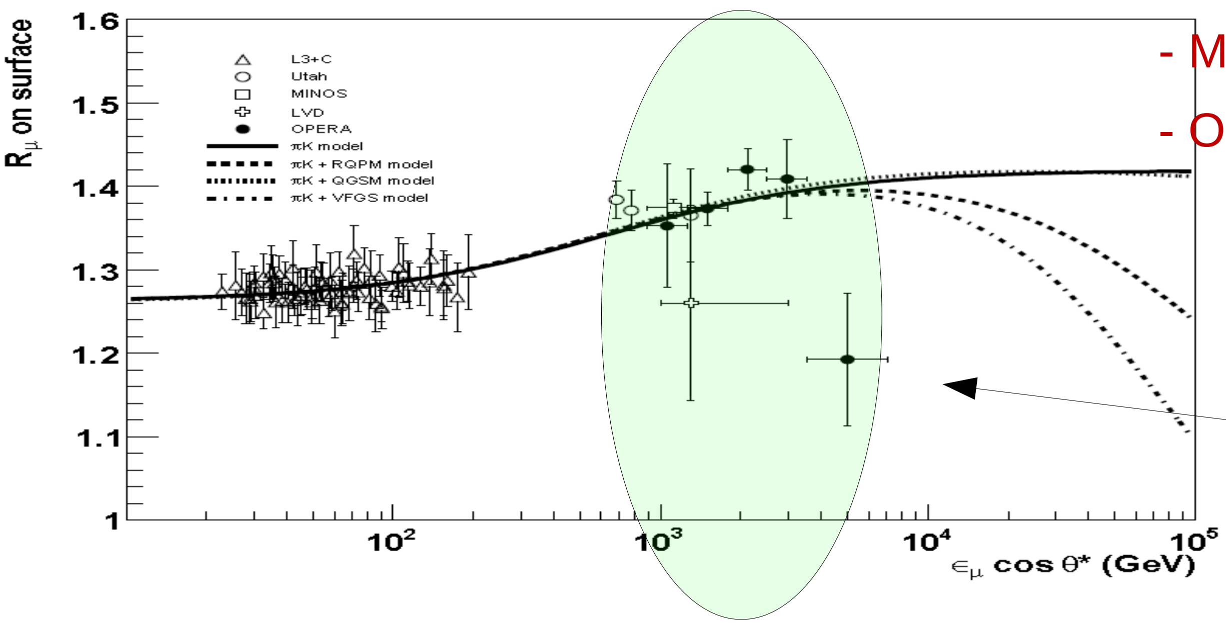


Atmospheric muon charge ratio from OPERA

FLUKA-μTeV used as the (full) Monte Carlo in the OPERA paper
ArXiv:1003.1907[hep-ex], published in EPJC
Mainly used as a tool to unfold the underground energy spectrum and to reconstruct the surface muon energy.

OPERA is the experiment with the largest $E_\mu \cos\theta$

- UTAH (1975): $<E_\mu \cos\theta>$ ~ 500 GeV
- MINOS (2007): $<E_\mu \cos\theta>$ ~ 1000 GeV
- OPERA (2009): $<E_\mu \cos\theta>$ ~ 2000 GeV



Anomalous last bin confirmed by experimental data from the last run:
physics motivation
or detector problem ?

Figure 7: R_μ values measured by OPERA in bins of $\mathcal{E}_\mu \cos\theta^*$ (black points). Also plotted are the data in the low energy region from L3+C [22] and in the high energy region from the Utah [9], MINOS [10] and LVD [23] experiments. The result of the fit of OPERA and L3+C data to Eq. 16 is shown by the continuous line. The dashed, dotted and dash-dot lines are, respectively, the fit results with the inclusion of the RQPM, QGSM [2] and VFGS [24] models for prompt muon production in atmosphere.

Underground muon charge ratio: OPERA results

FLUKA-μTeV

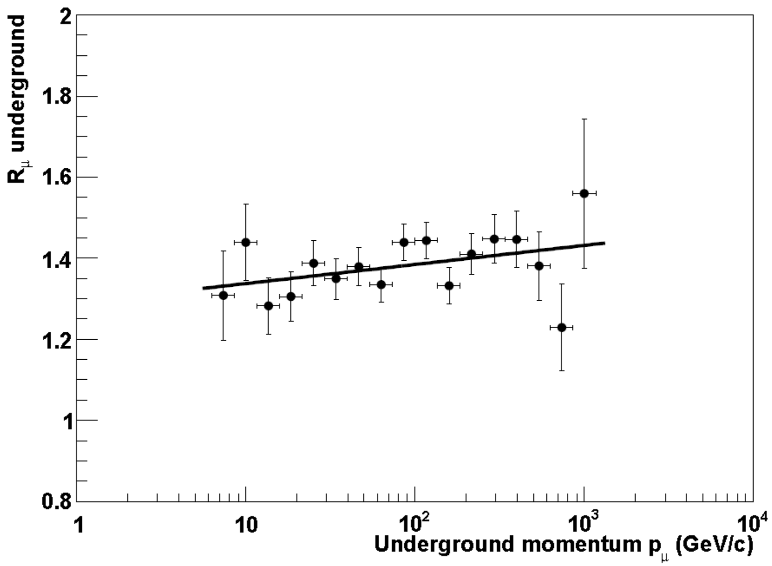
1) Underground muon charge ratio:

N_μ	$\langle A \rangle$	$\langle E/A \rangle_{primary}$	H fraction	N_p/N_n	R_μ^{unf}
=1	3.35±0.09	(19.4±0.1) TeV	0.667±0.007	4.99±0.05	1.377±0.014
>1	8.5±0.3	(77±1) TeV	0.352±0.012	2.09±0.07	1.23±0.06

Systematic error ~ statistical error

Difference at ~2.4 σ level

2) Charge ratio vs underground muon energy:

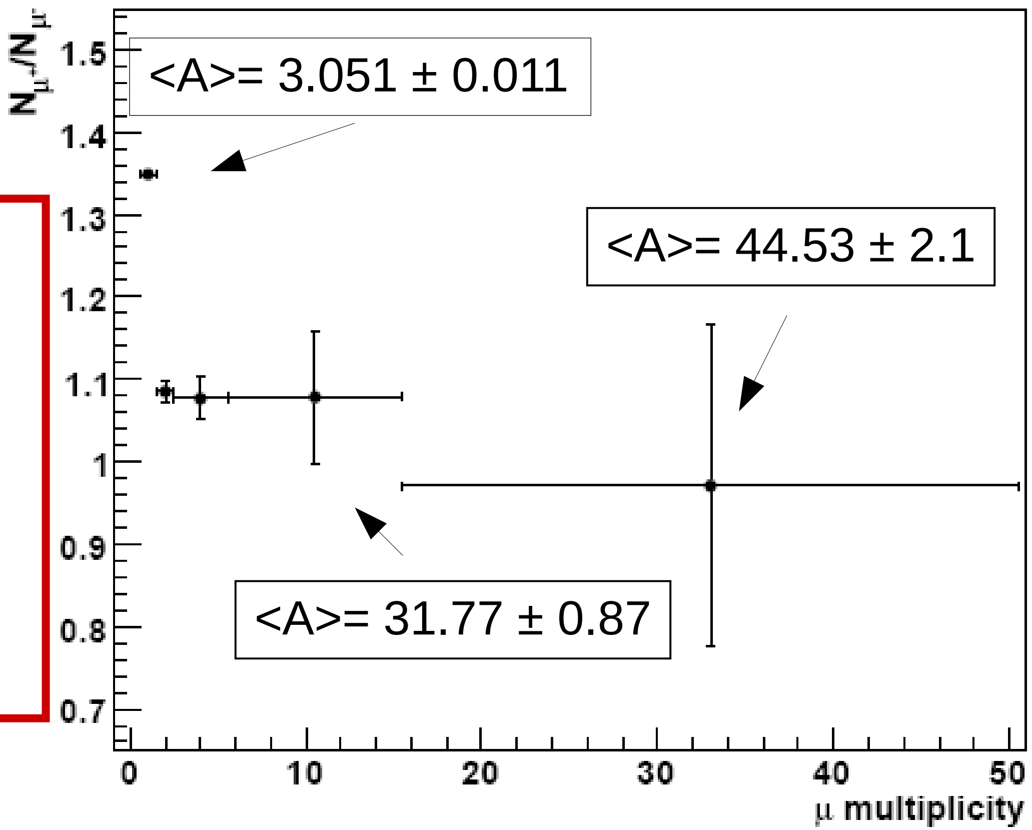


Energy dependence ~1.6 σ far from constant hypothesis

Muon charge ratio vs. average muon multiplicity per bundle

Theoretical simulations by FLUKA: muon charge ratio decreases with growing multiplicity

In the simulation, this can be explained in terms of **primary composition.....**



OPERA has provided R_μ separately for single and multiple muon events, testing the hypothesis of the "dilution" of the ratio in case of neutron-rich primaries.

mu decoherence distribution

The measure of the shape of **muon lateral distribution in experiments deep-underground** allows the study of the **transverse structure of hadronic interactions**.

In fact these experiments, due to the overburden, are only sensitive to high-energy muons (E> TeV).

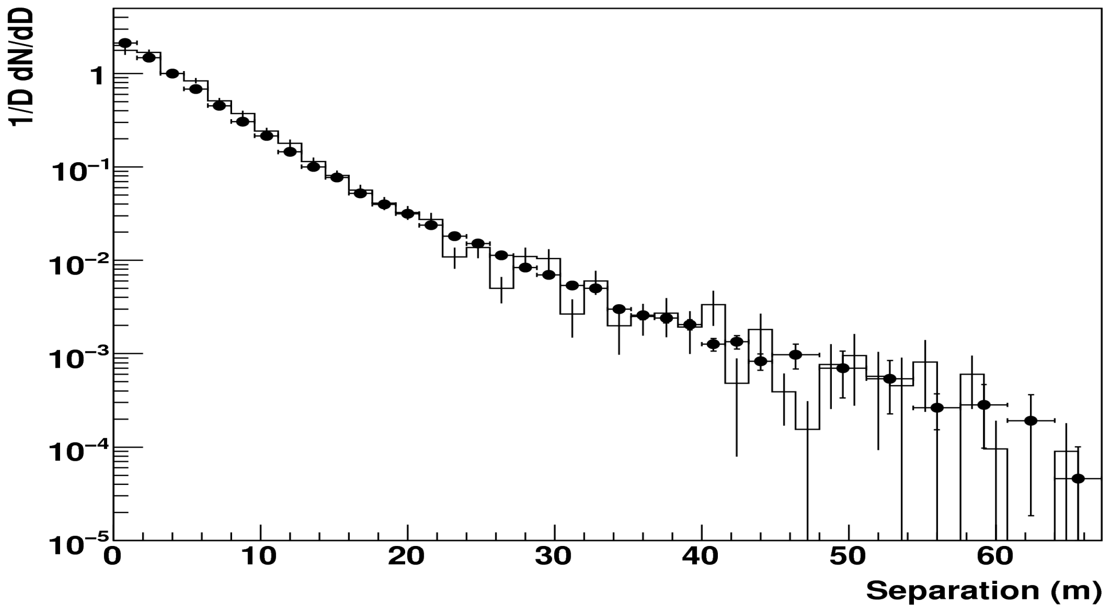
The **transverse momenta of the mesons** produced by primary interactions determine the relative separation of the muons finally detected, by **introducing a loss of collinearity (decoherence)** with respect to the direction of shower axis.

Decoherence function = distribution of the distance between muon pairs in a bundle

N.B. The decoherence function is also affected by
- multiple scattering in the rock
- geomagnetic deflection

Decoherence has been **measured by MACRO** and simulated by means of FLUKA standalone and FLUKA+DPMJET

mu decoherence distribution: theoretical simulations vs experimental data

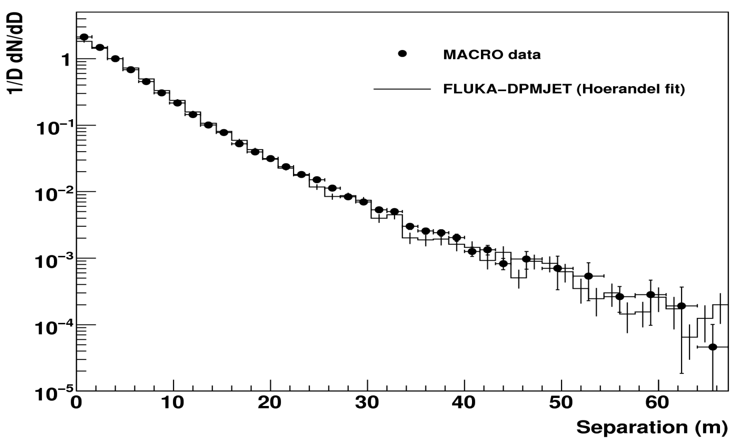


Experimental data from MACRO, Phys. Rev. D 60 (1999) 032001

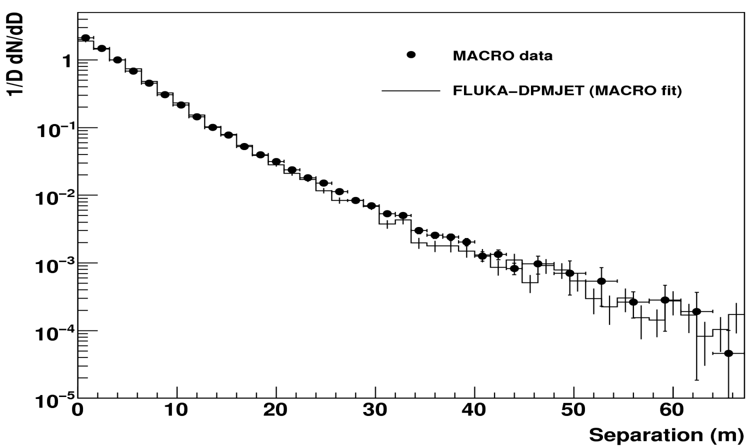
Simulations by DPMJET + FLUKA

The mu decoherence distribution is insensitive to the primary spectrum (at least, in case of realistic primary spectra......)

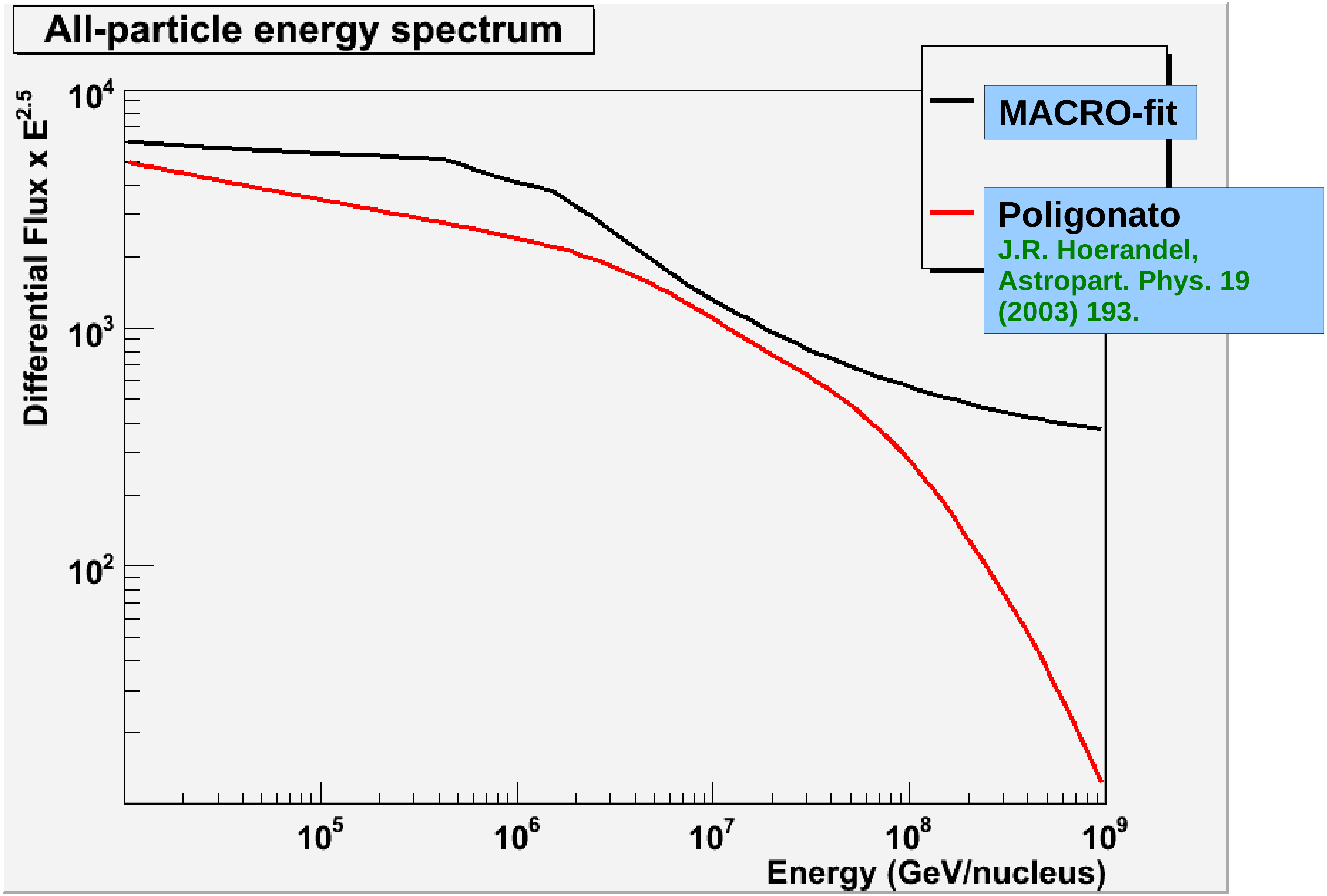
Hoerandel-Poligono



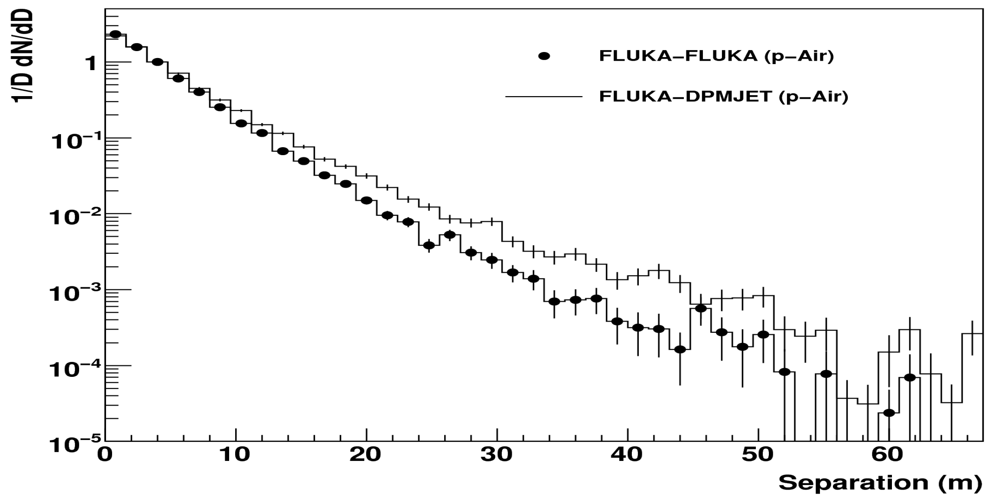
Macro-fit



Primary spectra used for the decoherence simulation

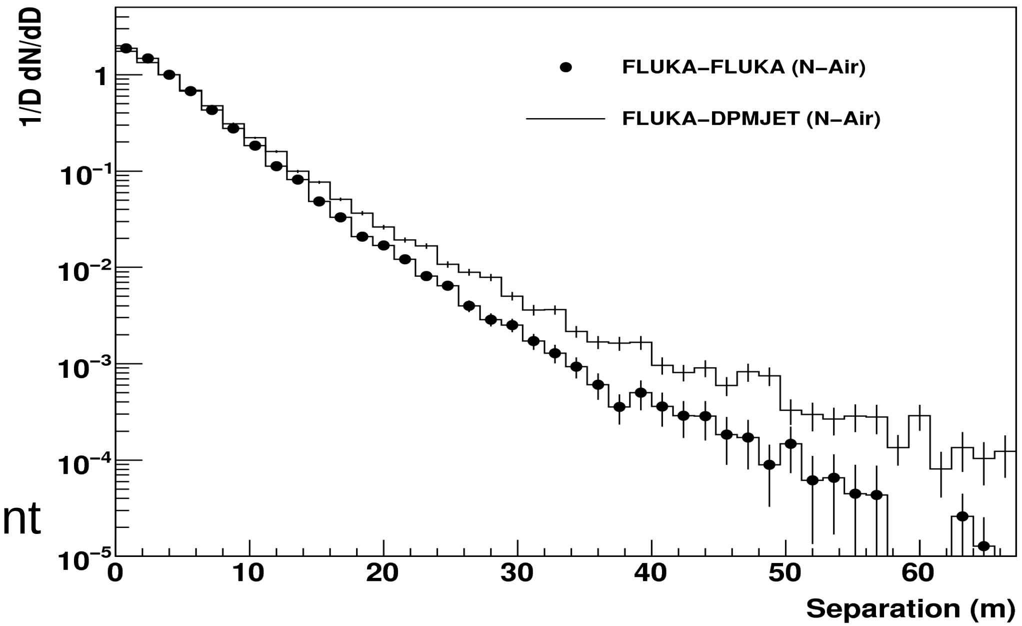


FLUKA standalone – FLUKA+DPMJET discrepancy in simulating mu Decoherence is **comparable both in case of proton induced primary interactions and in case of nucleus induced primary interactions**



Proton primary

Nucleus primary



FLUKA uses the **superposition model** to describe a nucleus like a set of independent nucleons.

DPMJET describe a **nucleus** like a **composite object**, by taking into account **correlations** among nucleons

Some observations concerning the DPMJET-FLUKA interface

The **FLUKA** code has been **interfaced to both DPMJET-II and DPMJET-III**.

In both interfaces **all** DPMJET **parameters** are **fixed**. There is no way for the user to change them. This also means that we obtain **all results presented in this talk with one set of parameters only**. The same is true for FLUKA. We did not change any parameter entering the FLUKA hadronic interaction and hadronization module to perform all our simulations.

DPMJET-II includes **charm** treatment, **DPMJET-III not yet** (it would be desirable to extend it......)!

DPMJET-II can **run up to high energies**, even if non always reproduces experimental data concerning cosmic ray showers......, DPMJET-III is supposed to be **more accurate**, but its model has still to be extended at high energies.......

DPMJET-III standalone is consistent with LHC data (all LHC data were reproduced with 10 sets of parameters; these sets differ each other for only very few parameters). However, we have not interfaced yet the last version of DPMJET-III, i.e. the one that is used to analyze the data for LHC, with FLUKA. This means, for instance, that in the FLUKA version of DPMJET-III are not included chain fusion effects......
It is **mandatory** to do the **interface with the last DPMJET version!**

Charm production in DPMJET-II
(P. Berghaus, T. Montaruli and J. Ranft, JCAP 06 (2008) 003)

Charm production in high-energy h-h interactions is important, since the **decay of charmed particles with energies > 100 TeV** becomes the **dominant background for diffuse** extraterrestrial **neutrino flux searches**.

Charmed mesons tend to **decay promptly** without interacting in the atmosphere.
Prompt charm decay gives rise to a **nu spectrum with a power law E^{-2}**
Pion and Kaons decay gives rise to a nu spectrum with a power law $E^{-3.7}$

IceCube, ANTARES, AUGER.....are all sensitive to prompt charm decay!

Mechanisms of charm production implemented **in DPMJET-II**

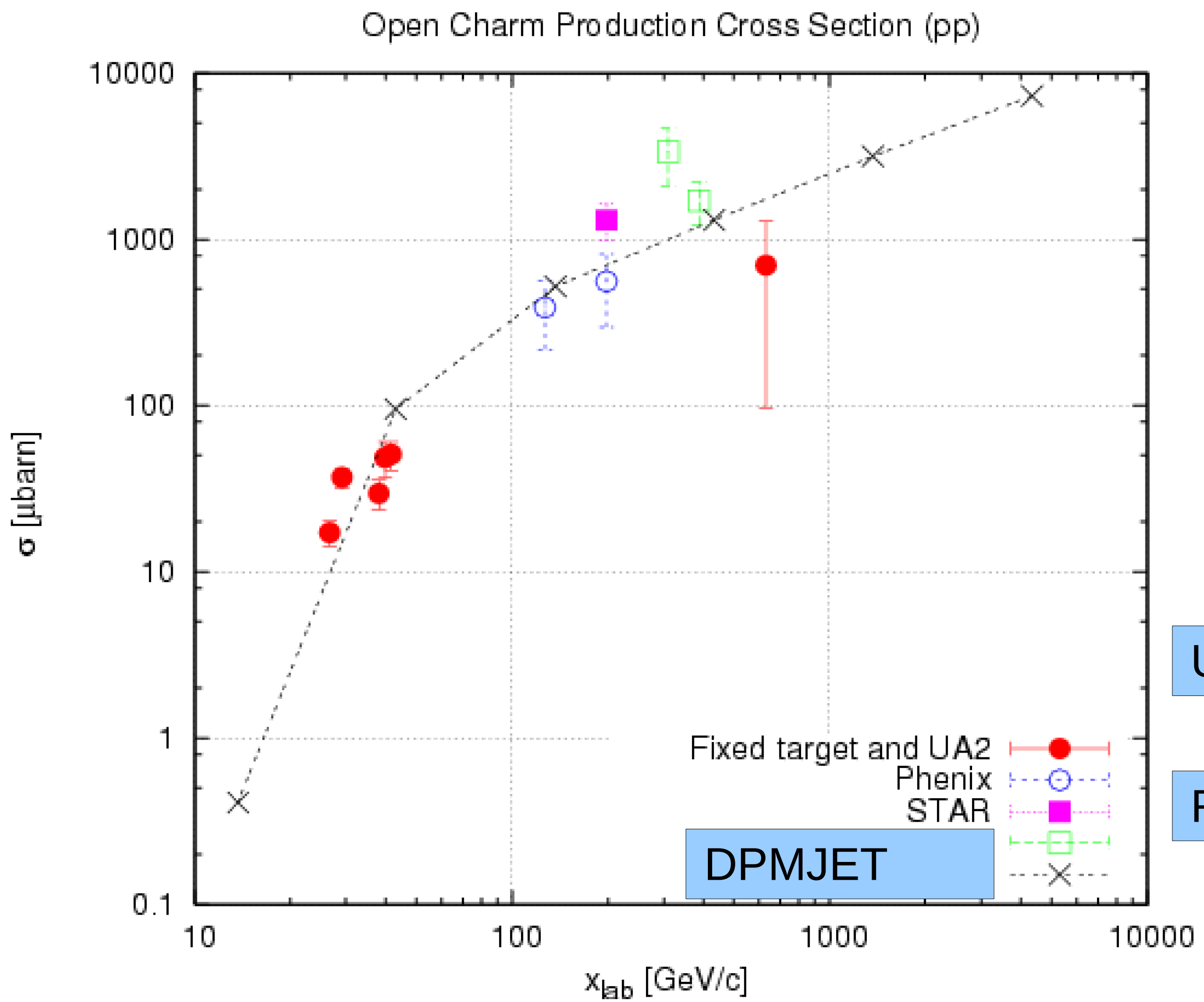
- charmed quarks produced **at the end of hard and semi-hard chains (dominant)**
- charmed quarks produced **at the end of soft sea chains** (P_{cc} joint smoothly to the previous one)
- charm production **inside the chain**, during its fragmentation: according to the PYTHIA version implemented in DPMJET, charm production during chain fragmentation is **highly suppressed**:

u-ubar:d-dbar:s-sbar:c-cbar= 1:1:0.3:10^{-11}

The **probability to produce a couple c-cbar near a diquark was increased in DPMJET** to reach a better agreement with SELEX **experimental data**.

Open charm production in DPMJET-II

(P. Berghaus, T. Montaruli and J. Ranft, JCAP 06 (2008) 003)



UA2 experimental data

Phys.Lett. B 236 (1990) 488

RICH experimental data

PHENIX
Phys.Rev.Lett. 88 (2002) 192303
Phys.Rev.Lett. 97 (2006) 252002
STAR
nucl-ex/0606010

Some work to be done......

Study the sensitivity of the muon decoherence function on the hadronization parameters included in the FLUKA code.

Benchmark FLUKA K production vs. new experimental data concerning K emitted at high energies and over a wide spectrum of angles,. We expect these data will be available from high-energies accelerator experiments. Also new data concerning pions emitted at high energies are important for the validation of the relative contribution of pion and kaon production in hadronic interactions.

Add **hard scattering processes** in the hadron-hadron collisions in FLUKA (so far only the soft scattering processes are described by means of a DPM-like model).

Comparisons with Corsika in the high energy regime......

Study the cosmic ray shower process formation in case of exceptionally heavy-nuclei: these nuclei have a **neutron content** much **larger** than the proton content, and this can indeed have an **effect on** the shower evolution process and on the asymmetry in the number of muons (the **muon charge ratio** becomes lower).
Experimental data that can identify the charge of the muons can give some indication on the primary composition.

Use **FLUKA interfaced to DPMJET-III for a full simulation at LHC** (forward emissions from p-p collision + detector effect simulation): LHCf ?