Tracking Muons with EGS4

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Introduction

The present Monte Carlo codes used for SNO detector simulations are all based on the EGS4 code system written at SLAC and NRCC [1]. EGS4 was designed to track electrons, positrons and γ's at low energies, but will in fact work well up to several hundreds of GeV. The user interface to EGS4 is very simple and gives one complete control over the geometry since the code does a call-back to the user every time it wants to move a particle (being defined here as a positron, electron or a γ). This is ideal for SNO since we are not so much interested in the energy loss or the range as in the production of Čerenkov photons. Because the geometry is external to EGS4 we can use the *same* routines for both particles and Čerenkov photons.

The alternative to EGS4 is GEANT developed at CERN [2]. GEANT can track just about all known particles, but a major drawback (at least from our perspective) is that the geometry is entirely internal to it. This means (at present anyway) different geometry routines for the Čerenkov photons and the particles. Furthermore, GEANT carries a lot of extra code with it in order to track exotic particles. None of this is needed for solar neutrinos. It simply just slows the code down. The bottleneck in the current detector simulations is β-γ's in the phototubes and these do not need quark or hadron physics. Also, GEANT is heavily geared towards high energies using only 91 data points for cross sections and stopping powers to span the region 10 keV to 8 TeV. It is in principle possible to change this but it would require major surgery to CERNLIB to do this.

This note describes an attempt at incorporating muons into the EGS4 framework. The idea was to write a piece of code which would do for muons what the ELECTR subroutine in EGS4 does for e^+/ e^-. This code would track the muons while secondary particles would be tracked by unmodified standard EGS4 code.

Physics Processes

The muon code is intended for relatively low energy muons (less than 1 TeV). Here the dominant energy loss is due to the production of δ-electrons with smaller contributions from direct muon bremsstrahlung, direct e^+ - e^- pair production and nuclear interaction. In order to avoid the logarithmic divergence at zero energy, the interaction below some cutoff value [1] is treated as continuum energy loss. This energy loss, which is of order α^2, is well described by the (restricted) Bethe-Bloch formula with density and shell corrections [3, 4, 5] [2]. Direct muon bremsstrahlung is of order α^3 whereas direct pair production is of order α^4. Analytic expressions derived from rigorous QED calculations keeping only the leading order terms may be found in [3]. This work also contains tables of stopping powers for various materials based on these expressions. An earlier work from CERN [6] gives tables of both dE/dx and ranges using simplified expressions for everything but the ionization contribution. The two agree well with each other for H_2O (see below). For the muon - nuclear interaction, the simplified expression from ref [6] is employed except that I use a slightly larger value for the average photonuclear cross section (140 μb instead of 120). This interaction is poorly understood and is probably uncertain to 30%.

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[1] See next section for more details

[2] Note that the expression in the Particle Data Handbook is not universally correct

In the code itself the actual expressions from [3] are used only to generate the secondary particle energies. Whenever the total cross sections or the dE/dx is needed a parametrization similar to the one found in GEANT is employed [7]. This saves a large amount of computing time without introducing significant errors.

Energy cuts

Doing a calculation with EGS4 is in effect a two stage process. In the first stage one runs the pre-processor to EGS4 (called PEGS4) to generate a suitably formatted data file with all the necessary cross section and dE/dx data. PEGS4 in turn gets its input from a relatively simply file which lists the elemental composition of the material(s) and the upper and lower cutoffs for electrons (positrons) and γ's. Stage 2 is the running of the EGS4 package itself. During the startup phase it reads the data file and does the actual simulation. The maximum allowed energy in the simulation is defined by the upper cutoffs (UE for charged particles and UP for γ's). The lower cutoffs are put in to avoid the infrared catastrophe. Below the lower cutoffs (AE for e^+/e^- and AP for γ's) any energy loss is treated as continuous energy loss (as a dE/dx); above everything is dealt with through discrete interactions. In addition EGS4 uses a cutoff (ECUT or PCUT) below which any particle is terminated immediately. The only restriction here is that ECUT is greater than AE and PCUT greater than AP.

The muon code is structured in a similar way. It has an initialization section (subroutine hatch_m) which must be called before any tracking is done. hatch_m scans the PEGS4 data file again for a few pieces of information and determines the maximum allowed muon energy. This is done by setting the maximum electron recoil energy for Møller scattering to UE. The lower recoil electron cutoff (am) is read from an auxiliary data file which also contains the mean ionization potential and parameters relating to the Sternheimer density correction. These quantities are not present in the PEGS4 data file but PEGS4 writes their values to the associated list file. For an extensive discussion of these consult the EGS4 Users Manual [1]. am should be consistent with the lower electron cutoff (at least as large).

Several other energy cuts are read from the file. The first is the threshold for muon bremsstrahlung **bm** and the associated minimum γ energy b2 (must be at least as large as UE). The second is the threshold for the production of e^+/e^- pairs pm and its associated minimum particle energy **p2em**. Note that the code demands certain minimum values to some of these parameters. **bm** and pm should be larger than about 600 MeV for the parametrizations to be valid and **p2em** cannot be less than $4 \times m_e c^2$ for kinematics reasons. The code will print a summary of all these parameters.

Interface to EGS4

Because the interaction of muons with matter is similar to the interaction electrons with matter and is dominated by the creation of δ-electrons, the cross-sections and stopping powers for muons can be parametrized exactly the same way as in EGS4 (on a logarithmic energy scale). However, this presents one minor problem in the interface to the EGS4 code system. For the solar neutrinos and for supernovas there is no need to go beyond about 60 MeV electron energy. The pre-processor for EGS4 (PEGS4) by default tabulates everything in tables with 150 entries indexed by $log(E - m_e c^2)$. Since we want to go to much higher energies for muons (about 1 TeV) but want to keep the same accuracy at the low end for compatibility reasons, the PEGS4 code was modified to use up to 450 points instead. This was done by changing a few parameter statements in PEGS4 [3] and re-compiling. This version of PEGS4 is backward compatible in the sense that it will generate a default dataset by adding the keywords NALE=150 and NALG=200 in the PWLF control card.

By matching UE and UP such that entry 150 corresponds to the 'old' maximum energy, a data set was generated for all materials in the SNO detector which matches all old calculations and expands well beyond 1 TeV.

The rest of the interfacing to EGS4 is trivial; it requires a call to **hatch_m** (after the call to **hatch** but before any shower calls) and a call to **shower_m** instead of **shower** :

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[3] A number of minor bugs had to be fixed in PEGS4 for this to work properly

```
character*64 name        !Name of PEGS4 data file
character*64 name1       !Name of optional x-c and dE/dx
                         ! list file
real*4 ecutm(...)

...
call hatch

ecutm(...)= ...          !Minimum muon tracking energy

call hatch_m(name)
...

call pmuon(name1)        !Optional call to print x-c and
                         !dE/dx data
...
call shower_m(iq,e,x,y,z,u,v,w,ir,wt)
...
```

The variable `iq` should be set to the values ±3 for μ^+/μ^- and `e` is the total muon energy (kinetic plus the restmass).

Comparison with other data

Figure 1 shows ranges of muons in H_2O for energies up to 100 GeV predicted by GEANT and the new code. Also shown in figure 1 are the ranges calculated from the range tables in references [6] and [3]. The agreement is quite good which is not too surprising since the stopping power is dominated by ionization losses. The next largest component above 10 GeV is the nuclear interaction which rises to a few percent at 100 GeV.

A low energy comparison between MUON, GEANT and the Kamiokande Monte Carlo code is shown in figure 2. The GEANT and K-II data is from ref. [8]. Again there is good agreement with GEANT. However, the K-II code predicts significantly smaller ranges.

The effect of varying the value below which recoil electrons are treated in a continuum fashion is shown in figure 3 for a 40 GeV μ^- beam. The top set of points shows the projected range (left axis) and the bottom set shows the transverse deviation. The error bars are set to the second moments of the distributions. Each points represent 1,000 muons. The range is essentially independent of the cutoff as long as the cutoff is reasonably small compared to the energy whereas the transverse deviation does increase when the number of discrete δ-electrons goes up.

The total deposited energy for any case calculated is within one electron volt of the muon kinetic energy irrespective of the cuts. The code does not consider any possible decay of the muons. It just tracks them until their energy is below `ecutm`.

References

[1] SLAC Report 265, 1985.

[2] GEANT version 3.15, CERN, 1992.

[3] W. Lohmann, R. Kopp and R. Voss, CERN Report 85-03, 1985.

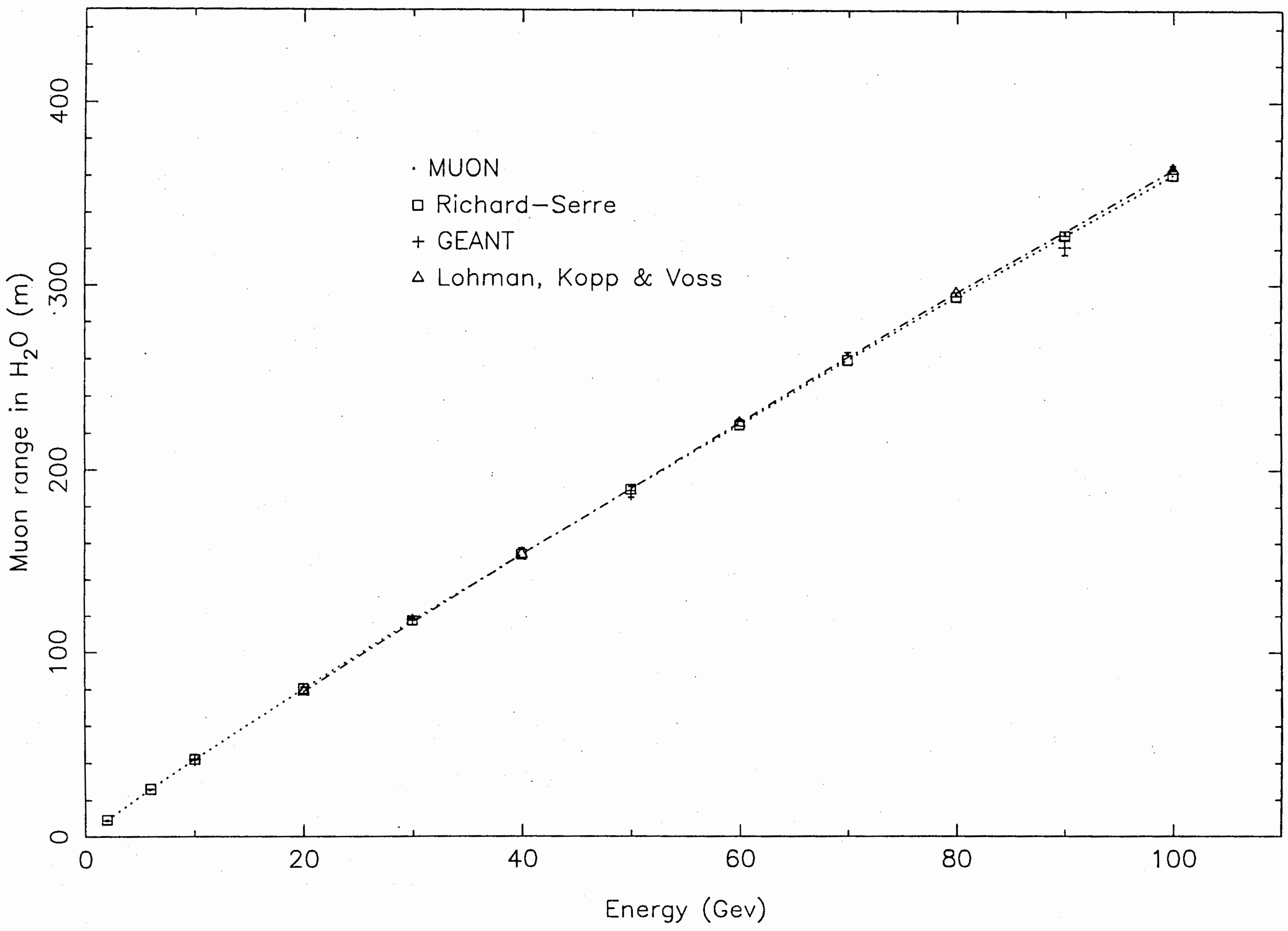
[4] The Atomic Nucleus, R.D. Evans, McGraw-Hill, 1955.

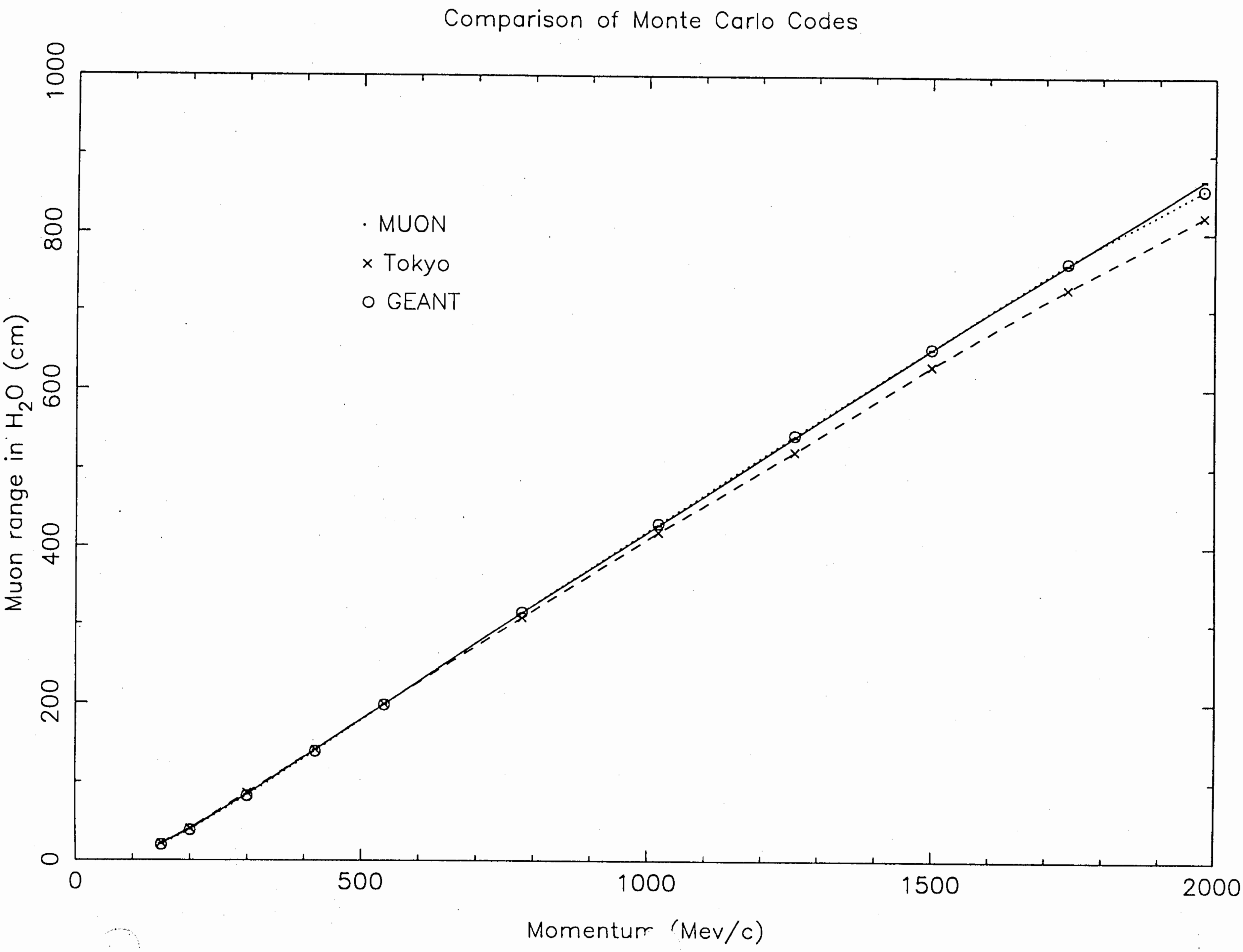
[5] Review of Particle Properties, 1984.

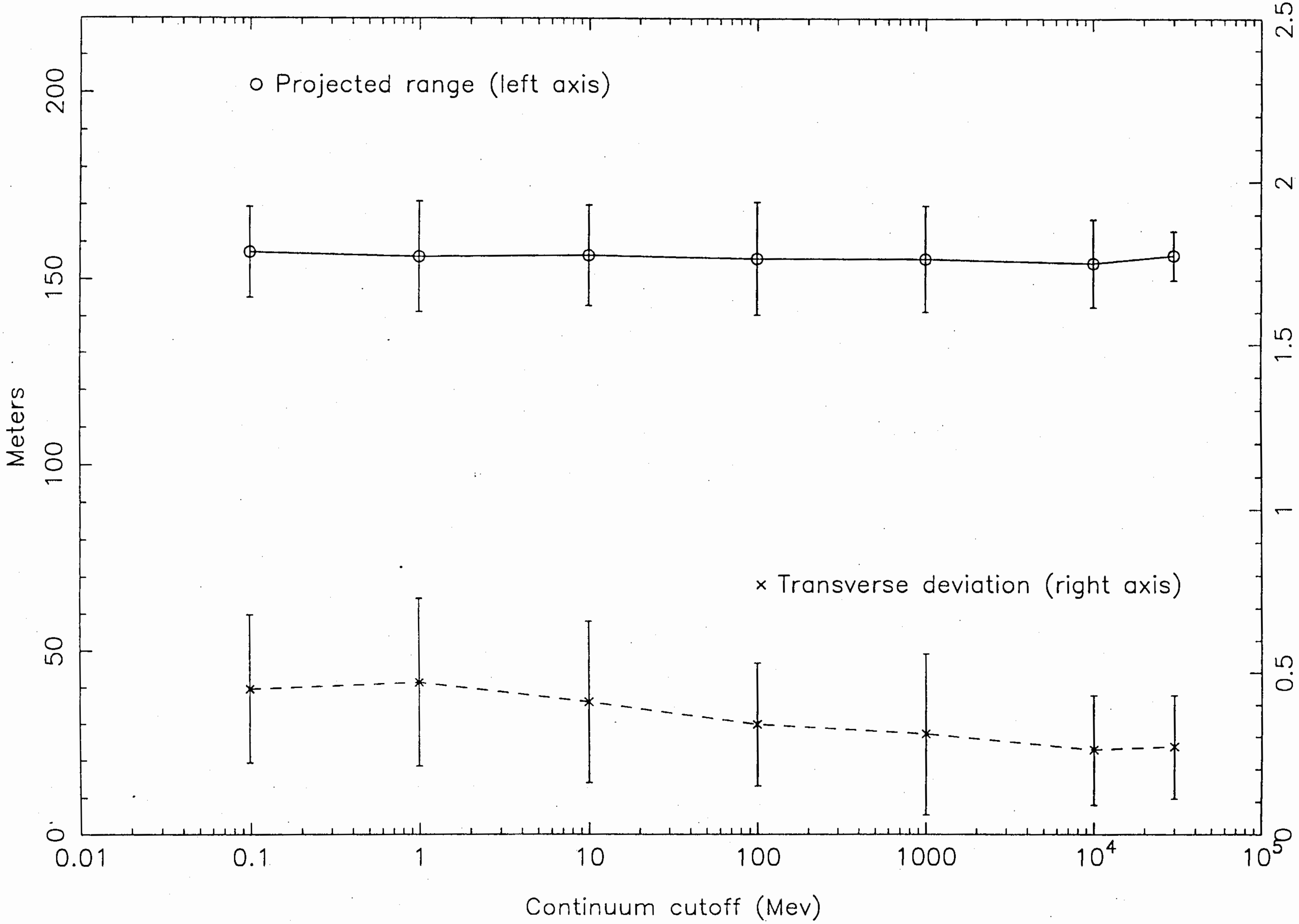
[6] C. Richard-Serre, CERN Report 71-18, 1971.

[7] GEANT 3.11 Users Manual, CERN, 1987.

[8] W.F. Frati, private communication, 1992.


· MUON
□ Richard–Serre
+ GEANT
△ Lohman, Kopp & Voss
Muon range in H_2O (m)
0
100
200
300
400
0
20
40
60
80
100
Energy (Gev)


Comparison of Monte Carlo Codes
· MUON
× Tokyo
○ GEANT
Muon range in H_2O (cm)
0
200
400
600
800
1000
0
500
1000
1500
2000
Momentum (Mev/c)


o Projected range (left axis)
× Transverse deviation (right axis)
Meters
0
50
100
150
200
0
0.5
1
1.5
2
2.5
0.01
0.1
1
10
100
1000
10^4
10^5
Continuum cutoff (Mev)