A.G. Bogdanov, october-november 2011

Validation of the implementation of the muon interactions in Geant4 (ver. 9.4.p02)

To verify the correctness of implementation of the processes of electromagnetic interactions of muons (bremsstrahlung, ionization, photonuclear interaction, the electron-positron pairs production) in the current version of the Geant4 toolkit standard TestEm17 of the electromagnetic group has been used.

As a result, the distributions of the number of single muon interactions in the relative energy transfer was calculated by means of Monte Carlo method (G4) and analytically (see AG Bogdanov et al., IEEE Trans. Nucl. Science, 53 (2006) 513) for later comparison.

As a target five different materials was used: a layer of carbon C of 5 m thickness, calcium carbonate CaCO3 (5 m), iron Fe (1 m), hydrogen iodide HI (5 m), tin Sn (1 m). Test was performed at a wide range of muon energies from 100 GeV to 100 PeV (100, 300, 350 GeV; 1, 3, 3.5, 10, 30, 35, 100, 300, 350 TeV; 1, 3, 3.5, 10, 30, 35, 100 PeV). Production thresholds (cuts) 1 mm (default) and 1 cm were used.

Analyzing the results one can make the following conclusions.

1. Distributions for the bremsstrahlung process implemented in G4 are consistent with the theory (Fig. 1) in the whole energy range and for all materials.

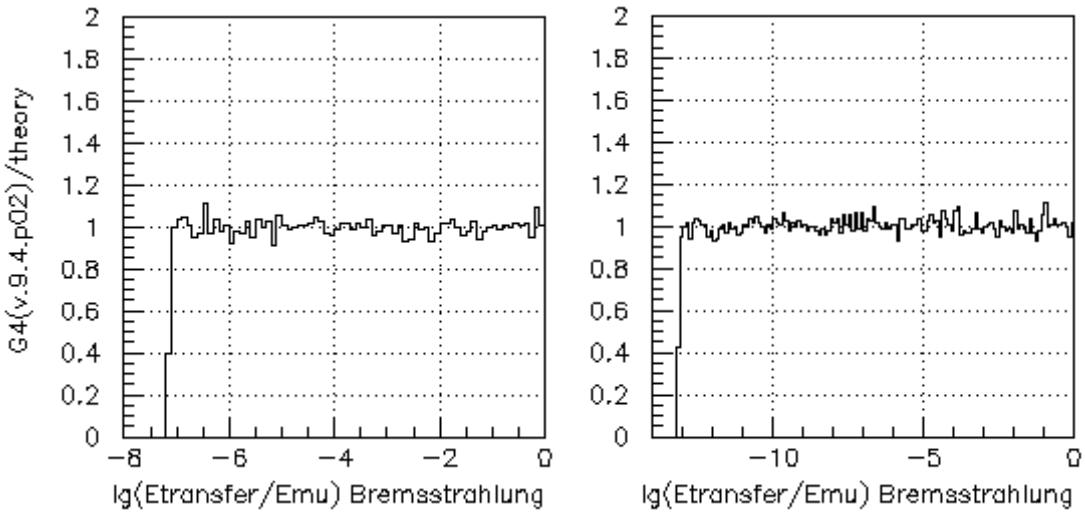

Fig. 1. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the bremsstrahlung; muon energies 100 GeV (left) and 100 PeV (right), target $CaCO_3$.

2. In the process of ionization realized in G4 systematic underestimation of the number of muon interactions in comparison with the theory is observed, it increases with muon energy from 1-2% percent at 100 GeV up to 10% at 100 PeV (see Fig. 2a). Furthermore, its dependence on cut is observed (Fig. 2b) and difference from the theory becomes more at large cuts.

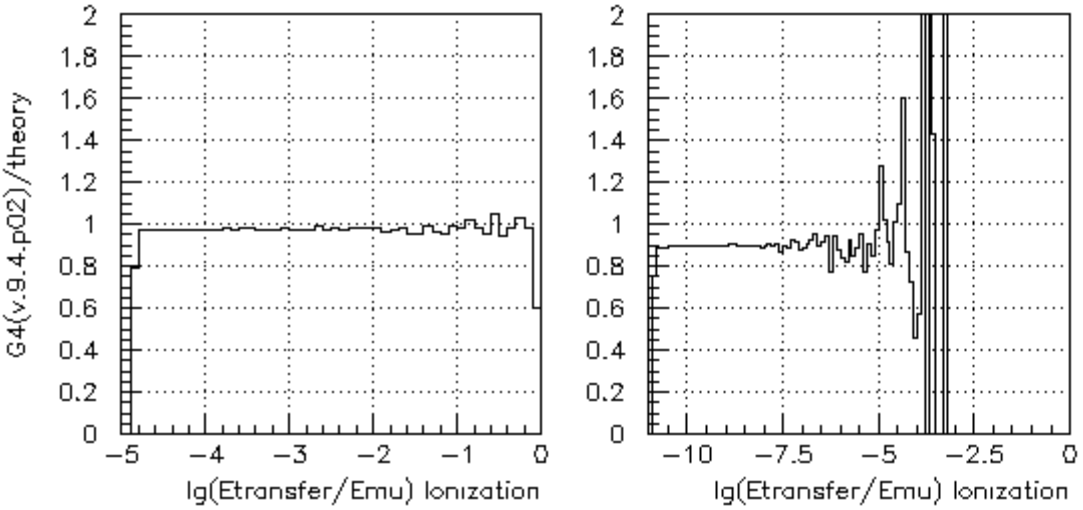

Fig. 2a. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the ionization; muon energies 100 GeV (left) and 100 PeV (right), target Fe, cut 1 mm.

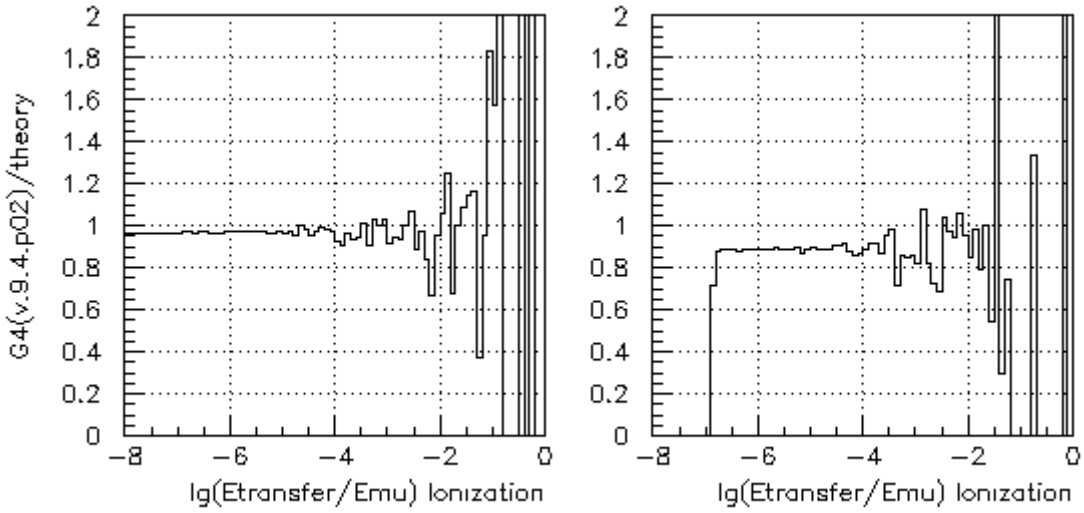

Fig. 2b. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the ionization; muon energy 100 TeV, cut 0.1 mm (left) and 1 cm (right), target Fe.

At more detailed consideration it was found that incorrect behavior of the simulated distributions for the ionization is related with bugs of G4EmModelManager.cc code which have been corrected in the version G4 9.4.ref10 (see Fig. 2c,d).

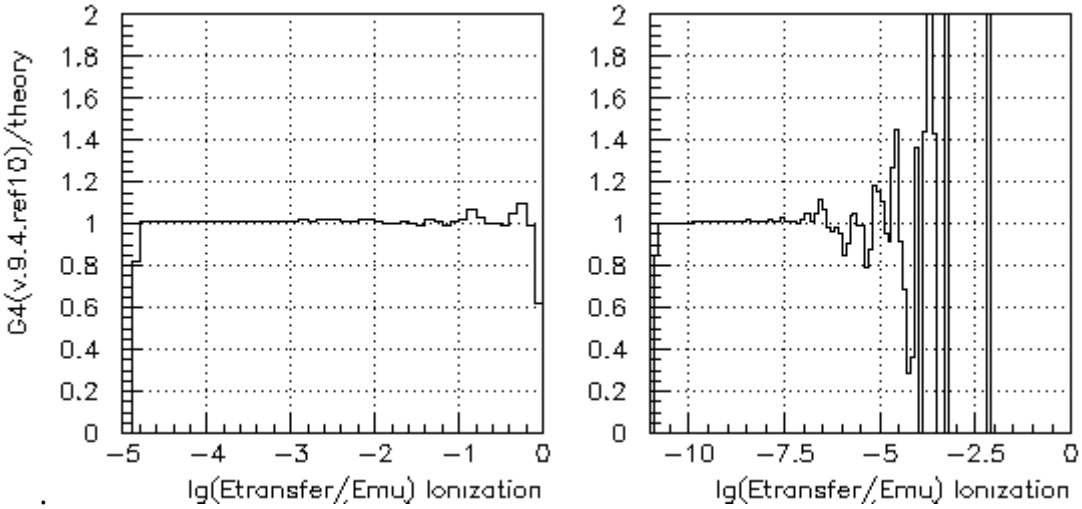

Fig. 2c. The ratio of simulated (G4 corrected) and theoretical distributions in the relative energy transfers for the ionization; muon energies 100 GeV (left) and 100 PeV (right), target Fe, cut 1 mm.

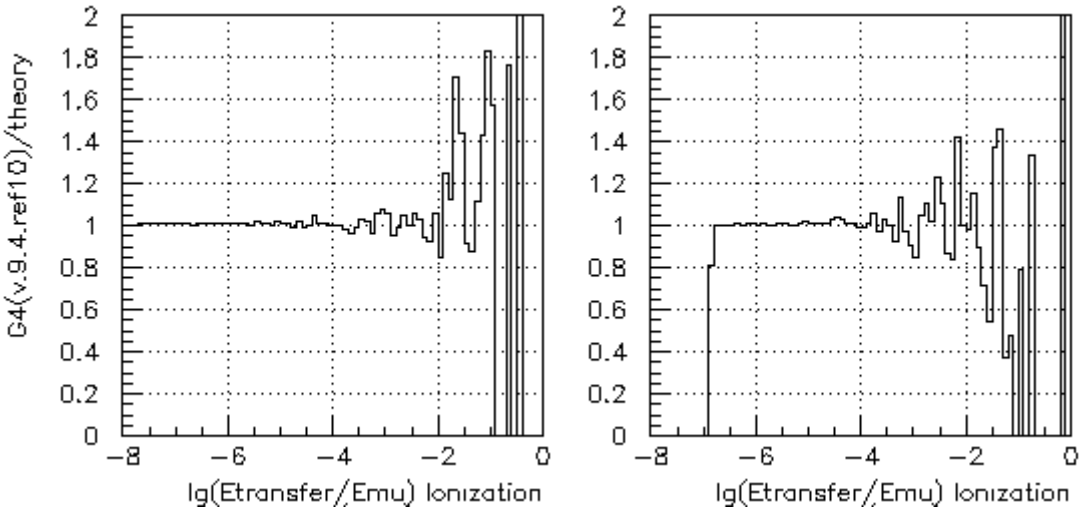

Fig. 2d. The ratio of simulated (G4 corrected) and theoretical distributions in the relative energy transfers for the ionization; muon energy 100 TeV, cut 0.1 mm (left) and 1 cm (right), target Fe.

3. The number of muon interactions for the photonuclear process implemented in G4 fluctuates relative to the theory over the entire range of energy transfers more or less evenly within 10-20% (more for heavy materials) at energies of 100 GeV, 1, 10 TeV, etc. (Fig. 3a). At the “inconvenient” but close energies (e.g., 300 and 350 GeV, or 30 and 35 TeV) the G4 distributions are distorted of 15-20% relative to the theoretical in opposite directions (Fig. 3b).

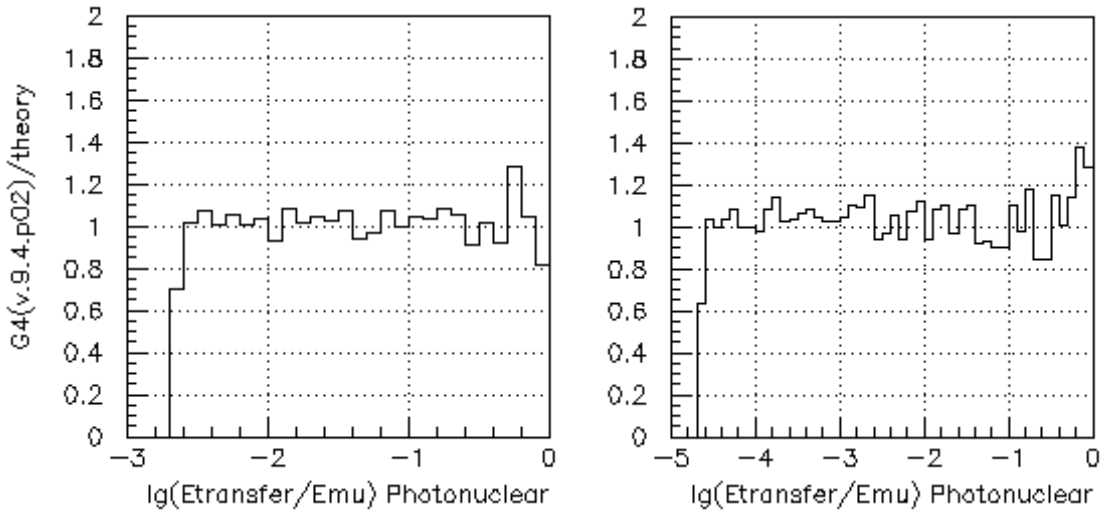

Fig. 3a. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the photonuclear process; muon energy 100 GeV, target HI (left) and 10 TeV, Sn (right).

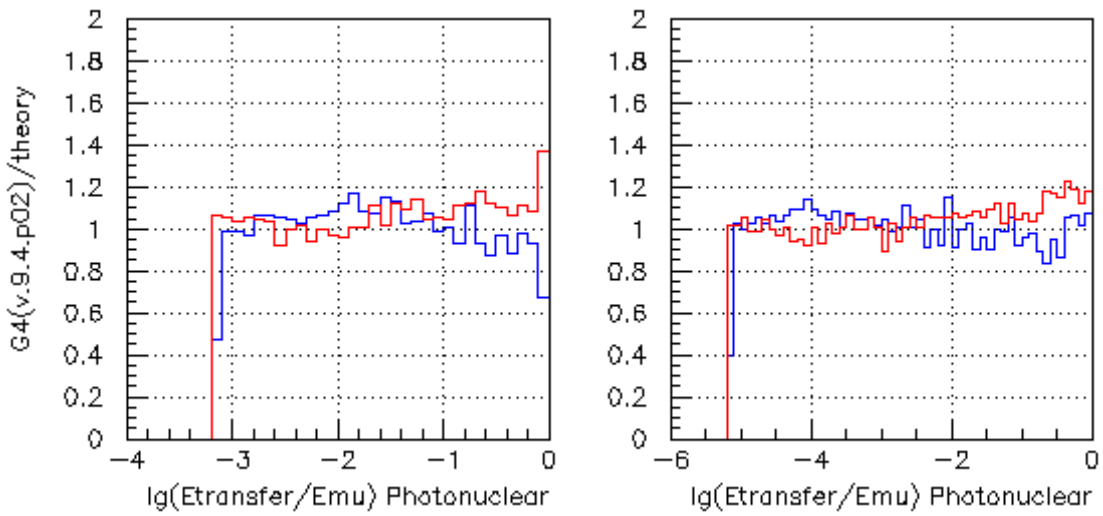

Fig. 3b. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the photonuclear process; muon energies 300, 350 GeV (left) and 30, 35 TeV (right), target C.

4. The number of muon interactions for electron-positron pair production, realized in the G4, exceeds the theoretical values of approximately by 10% at the “inconvenient” energies 300 and 350 GeV in the range of relative energy transfers of 0.01-0.1. This difference decreases to 5% with the increasing of muon energy up to 3 and 3.5 TeV (Fig. 4a). At the muon energies of 100 TeV, 1, and PeV for G4 distributions the underestimation up to 10% of the number of muon interactions is observed at the relative energy transfers above 0.01. At very high energies of muons (30, 35 and 100 PeV) this difference is about 15-20% (Fig. 4b).

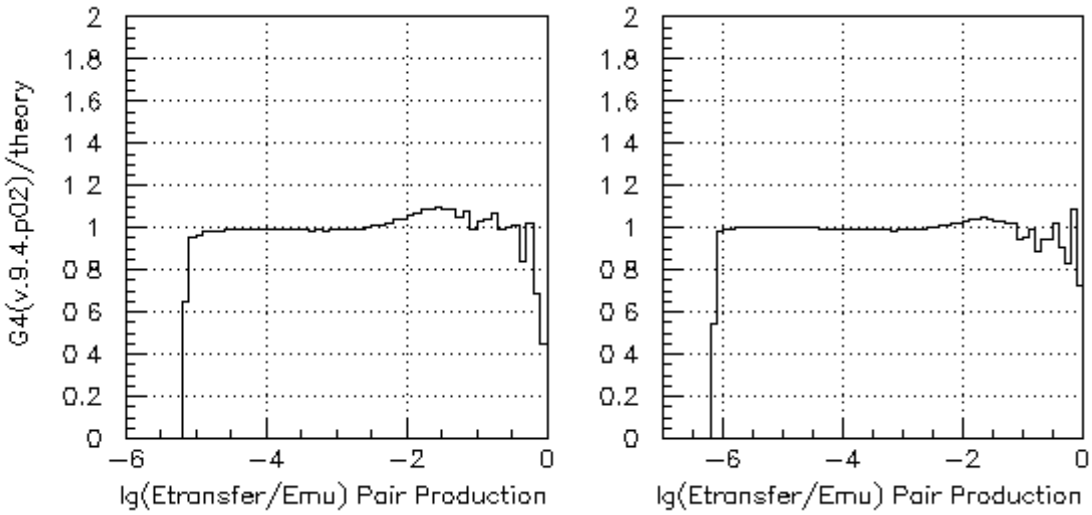

Fig. 4a. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the pair production; muon energies 300 GeV (left) and 3 TeV (right), target HI.

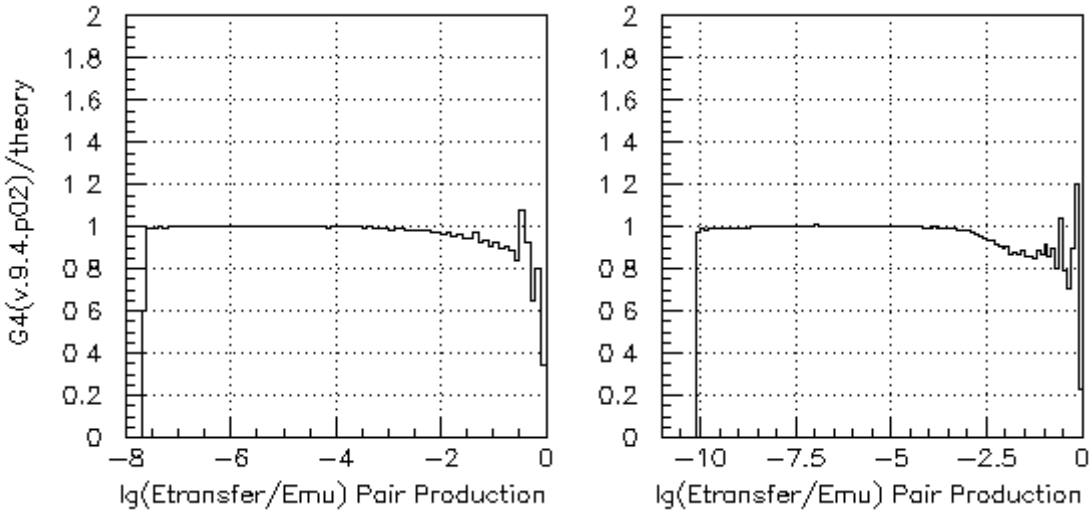

Fig. 4b. The ratio of simulated (G4) and theoretical distributions in the relative energy transfers for the pair production; muon energies 100 TeV (left) and 30 PeV (right), target Sn.