# Comments on modeling of hadron-nucleus interactions

- Correct (at least statistically) modeling of hadron is of fundamental importance for the simulation of hadron calorimeters (LHC, novel calorimeters, etc..)
- Calorimeters measure the energy, hence the correct simulation of the deposited energy and its fluctuations is of primary importance.
- Comparison of the simulated response with the test beam results are important cross check of the quality of modeling, but it is complicated because of a convolution of multitude of physics processes involved
- Much simpler, and in some instances  even more direct verification can be performed by studies of the actual instances of the simulated hadron-nucleus interactions.

# Method

- Instrument G4SteppingVerbose, for every instance of hadron-nucleus interaction analyze a list of particles produced in the interaction
- Compare sum of KINETIC energies of all secondaries with the kinetic energy of the interacting particle

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50  2212   0.0137   0.0171     -610          0  4.96e+04    4.65  1.39e+03     Target ProtonInelastic
n_sec    19
 :     0.0137     0.0171       -610  2.54e+03     4.65                pi-
 :     0.0137     0.0171       -610  2.55e+04     4.65            neutron
 :     0.0137     0.0171       -610  1.62e+03     4.65              kaon+
 :     0.0137     0.0171       -610       344     4.65                pi0
 :     0.0137     0.0171       -610  3.15e+03     4.65            neutron
 :     0.0137     0.0171       -610       416     4.65                pi0
 :     0.0137     0.0171       -610       637     4.65             proton
 :     0.0137     0.0171       -610      65.9     4.65                pi+
 :     0.0137     0.0171       -610       273     4.65             proton
 :     0.0137     0.0171       -610  5.52e+03     4.65                pi+
 :     0.0137     0.0171       -610  6.36e+03     4.65              kaon-
 :     0.0137     0.0171       -610       308     4.65                pi0
 :     0.0137     0.0171       -610       603     4.65                pi+
 :     0.0137     0.0171       -610       119     4.65            neutron
 :     0.0137     0.0171       -610      19.1     4.65           deuteron
 :     0.0137     0.0171       -610      4.31     4.65           deuteron
 :     0.0137     0.0171       -610      17.1     4.65             triton
 :     0.0137     0.0171       -610      19.7     4.65              alpha
 :     0.0137     0.0171       -610      7.38     4.65            neutron
```

# Energy conservation

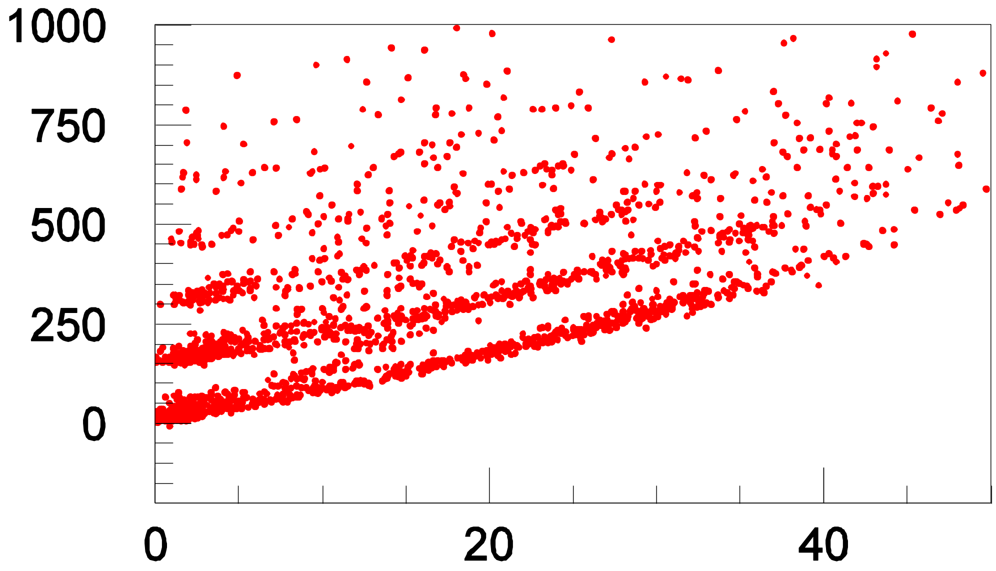
- Energy is conserved. Total energy, not just kinetic energy.
- In hadron-nucleus interaction the kinetic energy is, in general not conserved:
  - Particles are produced in strong interactions (mostly pions, some kaons, etc..). Their masses are produced ‘at the expense’ of the kinetic energy of the interacting particle
  - In nuclear cascade there might be several nucleons (mostly neutrons) or light fragments (deuterons, tritons, alphas) ejected from the nucleus. Work necessary to overcome the binding energy is performed at the expense of the kinetic energy.
  - In fact, occasionally , the final kinetic energy can be greater that the interacting particle kinetic energy, if the nucleus undergoes fission
- It is a great success of GEANT that  hadron interaction modeling that all these effects are correctly (more or less) modeled
- Several physics lists, tested including most current **FTFP_BERT** (plots)

# At least at low energies, below 10 GeV

•A mount of the missing energy rises with the number neutrons (~8 MeV per neutron)

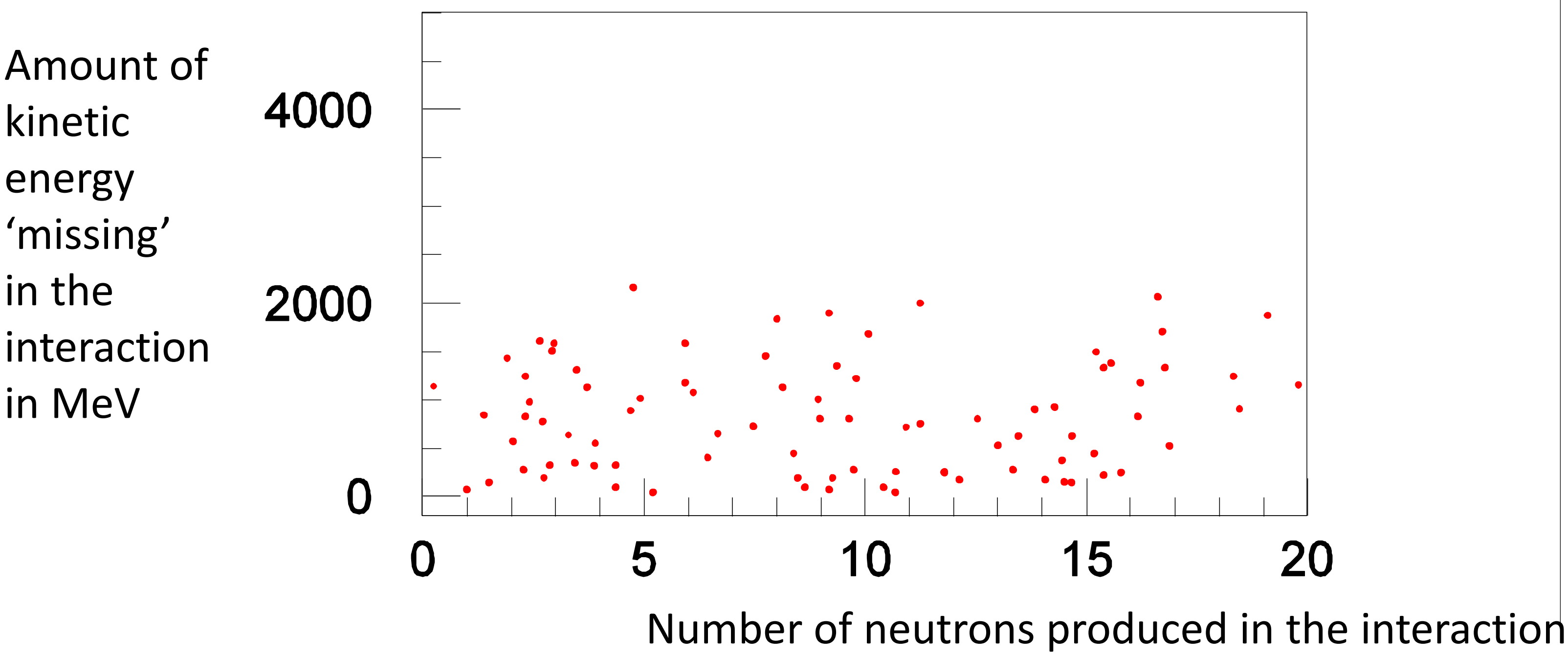
• bands correspond to the number of produced pions (1,2,3) times 140 MeV

Amount of kinetic energy 'missing' in the interaction in MeV




Number of neutrons produced in the interaction

# However, at higher energies (> 10 GeV)




- number of neutrons much smaller
- missing energy not reflecting the kinematics of the interaction (number of pions/neutrons)
- missing energy unreasonably large
- FTFP (shown here) much 'better', CHIPS and QGSP much worse (missing energies up to 4 GeV)

# Wishes/Suggestions

- Somehow implement the nuclear part of Bertini cascade into the high energy model, or equivalent (i.e. provide an even-by-event energy conservation)
- If this is not possible or too difficult, then at least correlate the amount of the missing energy with the number of pions and neutrons produced. Tune the neutrons distribution (important for scintillator-based sampling calorimeters)
- Or at least tune the average amount of the missing energy, even of the event-by-event fluctuations cannot be correlated with the specific final state.