Physics in Geant4 (II)

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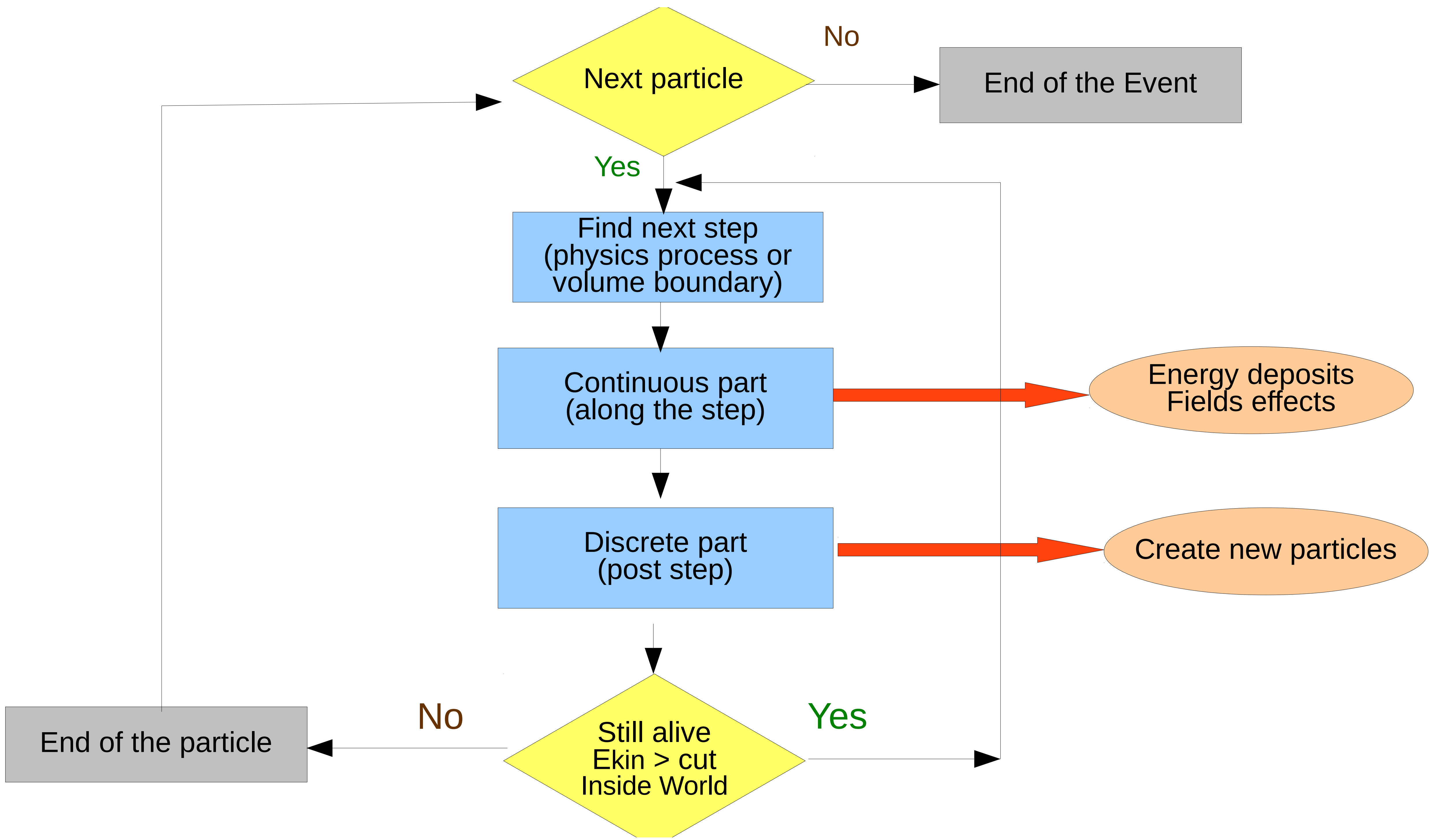
Tracking, not so easy…

- This basic recipe doesn't work well for charged particles
- The **cross sections** of some processes (ionisation and bremsstrahlung) **is very high**, so the **steps** would be very **small**
- In each interaction **only a small fraction of energy is lost** and the effect on the particle are small
- A lot of CPU time used to simulate many interactions having small effects

The solution: approximate

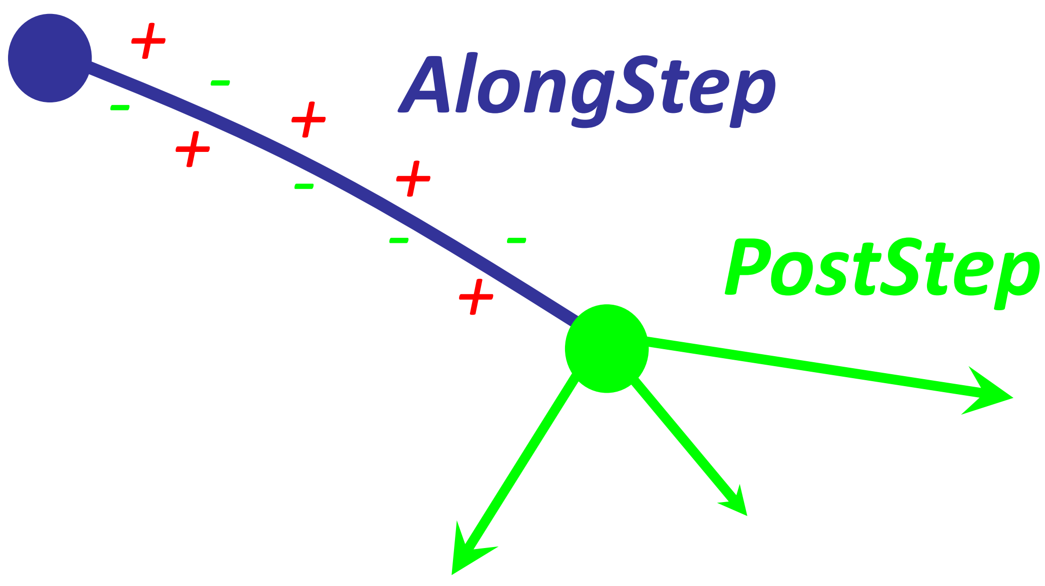
- Simulate explicitly interactions only if the energy loss is above a threshold E_0 (**hard** interactions)
  - Detailed simulation
- The effects of all sub-threshold interactions is described cumulatively (**soft** interactions)
- Hard interactions occur much less frequently than soft interactions

Flowchart of an event



The `G4VProcess`

- All physics processes derive from `G4VProcess`
- `G4VProcess` is an abstract class
- It defines the common interface of all processes in Geant4
- Three kind of "actions":
  - **AlongStep**
    all the soft interactions
  - **PostStep**
    all the hard interactions
  - **AtRest**
    decays, e+ annihilation



Let's cut it out… (cuts in MC)

- The traditional Monte Carlo solution is to set a tracking cut-off in energy:
  - a particle is stopped when its energy goes below it
  - its residual energy is deposited at that point
- Imprecise stopping and energy deposition location
- Particle and material dependence

Let's cut it out… (cuts in Geant4)

- Geant4 does not have tracking cuts
  i.e.: all tracks are tracked down to 0 energy

- A Cut in Geant4 is a production threshold

- It is applied only for physics processes that have infrared divergence
  - Bremsstrahlung
  - Ionisation e^- (δ rays)
  - Protons from hadronic elastic scattering

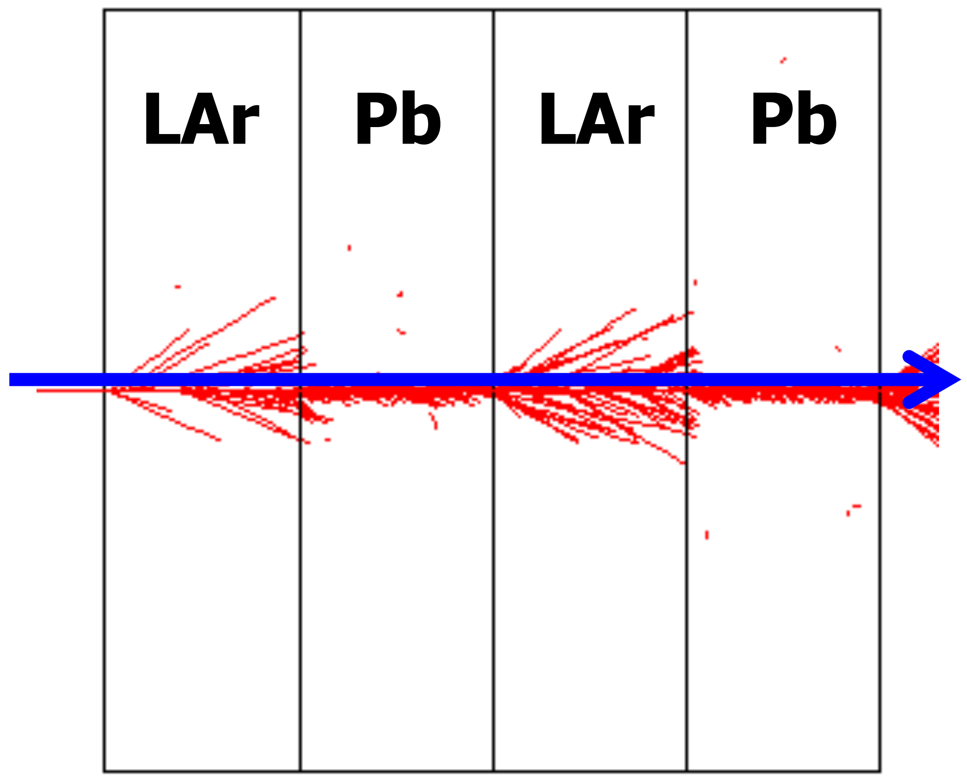
A range cut

- The threshold is a **distance**!
- Default = 1 mm
- Particles unable to travel at least the range cut value are not produced

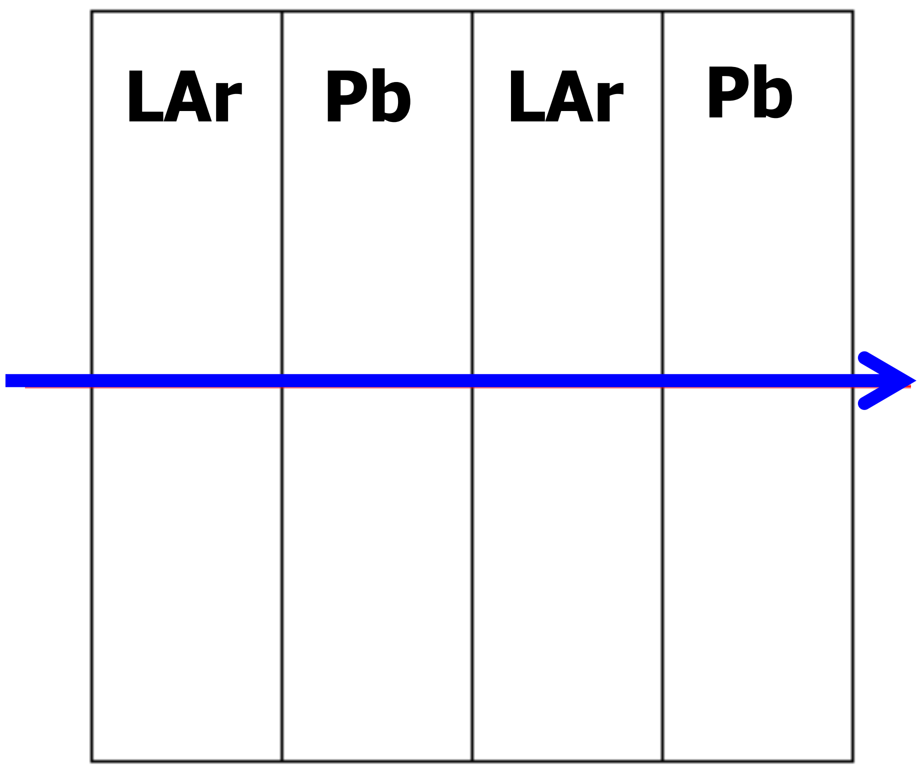
- Sets the "spatial accuracy" of the simulation
- Production threshold is internally converted to an energy threshold for each material

Cut in energy

- 460 keV
- good for LAr
- not for Pb

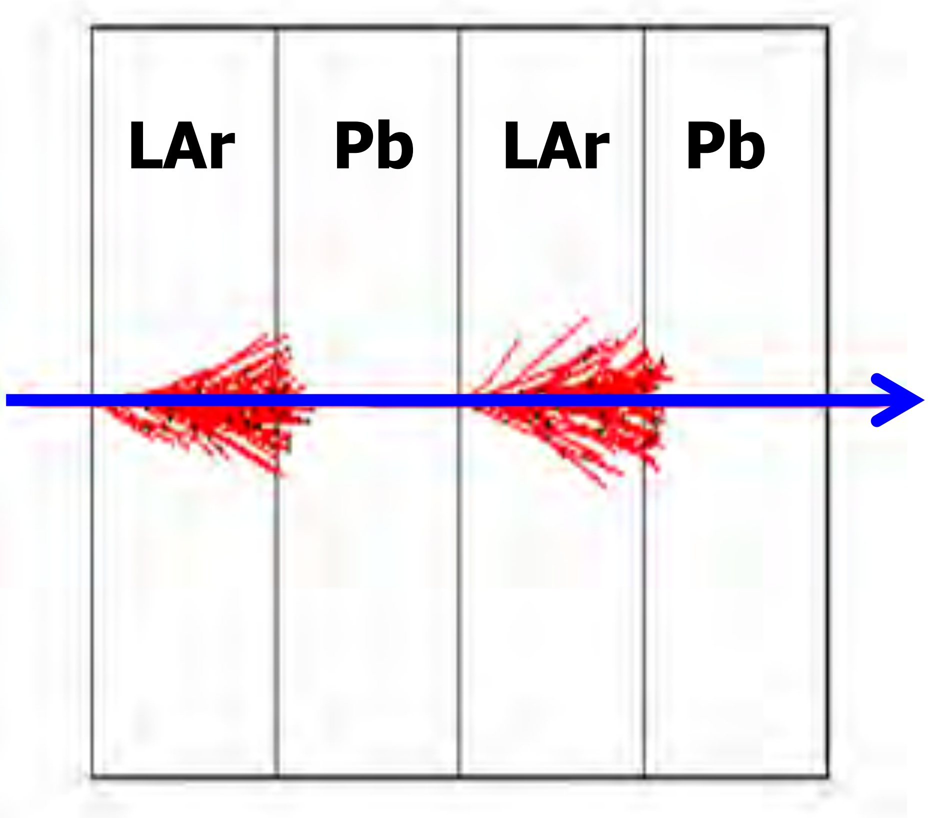


- 2 MeV
- good for Pb
- not for Lar



Cut in range

- 1.5 mm
- ~460 KeV in LAr
- ~2 MeV in Pb



run with the hares and hunt with the hounds...
(good for both!)

Setting the cuts

- Optional method in G4VPhysicsList

```
void MyPhysicsList::SetCuts()
{
    //G4VUserPhysicsList::SetCuts();
    defaultCutValue = 0.5 * mm;
    SetCutsWithDefault();

    SetCutValue(0.1 * mm, "gamma");
    SetCutValue(0.01 * mm, "e+");
  G4ProductionCutsTable::GetProductionCutsTable()
        ->SetEnergyRange(100*eV, 100.*GeV);
}
```

- not all models are able to work with very low production thresholds
- an energy threshold limit is used,
- its default value is set to 990 eV.
- You can change this value

Cuts UI command

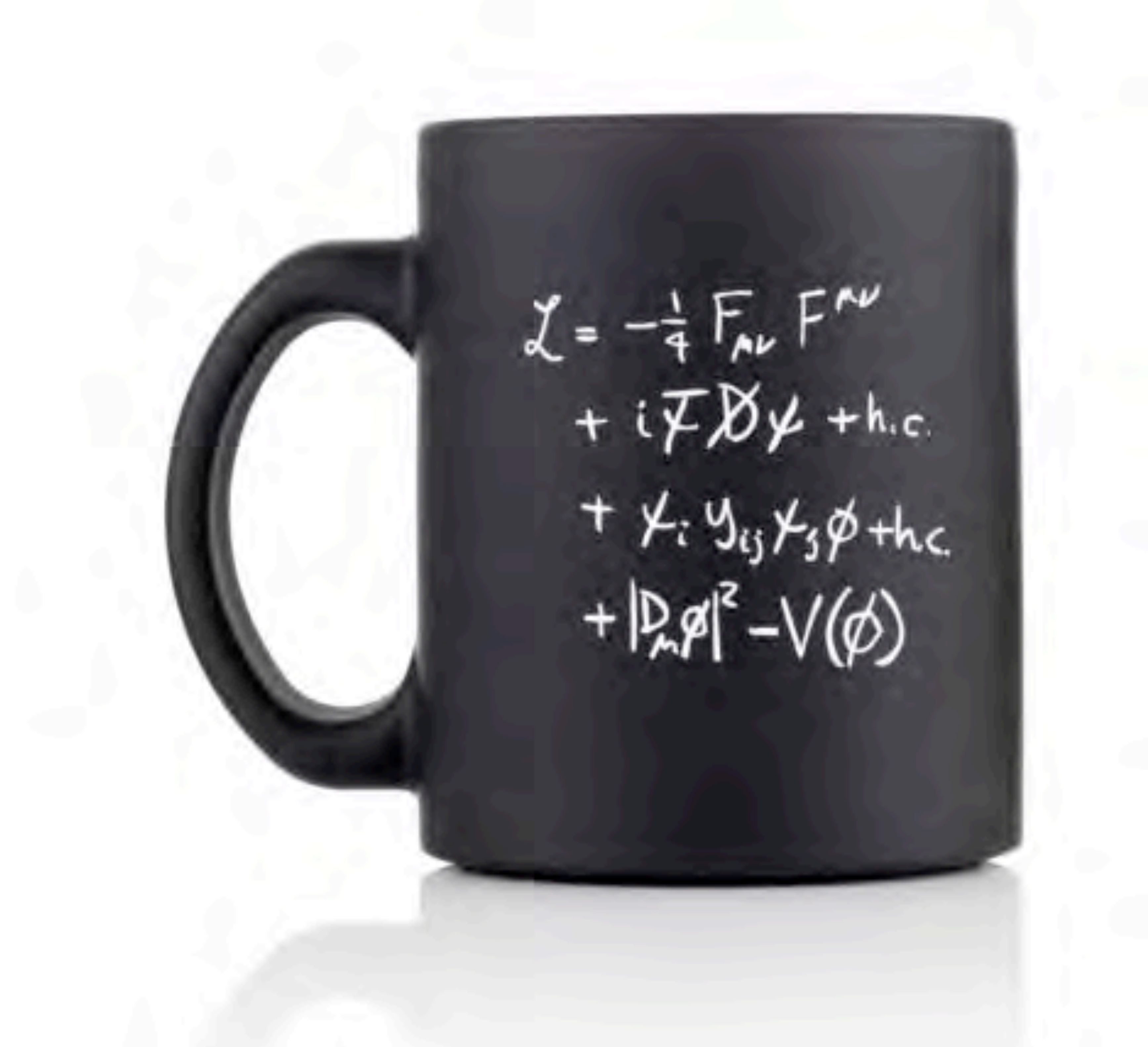
```
# Universal cut (whole world, all particles)
/run/setCut 10 mm

# Override low-energy limit
/cuts/setLowEdge 100 eV

# Set cut for a specific particle (whole world)
/run/setCutForAGivenParticle gamma 0.1 mm

# Set cut for a region (all particles)
/run/setCutForARegion myRegion 0.01 mm

# Print a summary of particles/regions/cuts
/run/dumpCouples
```

Cuts per region

- Complex detector may contain many different sub-detectors involving:
  - finely segmented volumes
  - position-sensitive materials (e.g. Si trackers)
  - large, undivided volumes (e.g. calorimeters)
- The same cut may not be appropriate for all of these
- User can define regions (independent of geometry hierarchy tree) and assign different cuts for each region
- A region can contain a subset of the logical volumes

To limit the step

- To have more precise energy deposition
- To increase precision in magnetic field
- Include `G4StepLimiter` in your physics list
  - as a Physics process
  - compete with the others



Physics models

an overview…

Principles

- Provide a general model framework that allows the implementation of complementary/alternative models to describe the same process (e.g. Compton scattering)
- A given model could work better in a certain energy range
- Decouple models for cross sections and of final state generation
- Provide processes containing
  - Many possible models and cross sections
  - Default cross sections for each model

γ model inventory

- Many models available for each process
- Differ for energy range, precision and CPU speed
- Final state generators

Model	E_{min}	E_{max}
G4LivermoreRayleighModel	100 eV	10 PeV
G4PenelopeRayleighModel	100 eV	10 GeV
G4KleinNishinaCompton	100 eV	10 TeV
G4KleinNishinaModel	100 eV	10 TeV
G4LivermoreComptonModel	100 eV	10 TeV
G4PenelopeComptonModel	10 keV	10 GeV
G4LowEPComptonModel	100 eV	20 MeV
G4BetheHeitlerModel	1.02 MeV	100 GeV
G4PairProductionRelModel	10 MeV	10 PeV
G4LivermoreGammaConversionModel	1.02 MeV	100 GeV
G4PenelopeGammaConversionModel	1.02 MeV	10 GeV
G4PEEFluoModel	1 keV	10 PeV
G4LivermorePhotoElectricModel	10 eV	10 PeV
G4PenelopePhotoElectricModel	10 eV	10 GeV

ElectroMagnetic models

- The same physics processes can be described by different models
- For instance: Compton scattering can be described by
  - `G4KleinNishinaCompton`
  - `G4LivermoreComptonModel` (low-energy, based on the Livermore database)
  - `G4PenelopeComptonModel` (low-energy, based on the Penelope analytical model)
  - `G4LivermorePolarizedComptonModel` (low-energy, Livermore database with polarization)
  - `G4PolarizedComptonModel` (Klein-Nishina with polarization)
  - `G4LowEPComptonModel` (full relativistic 3D simulation)
- Different models can be combined, so that the appropriate one is used in each given energy range (à performance optimization)

Standard models

- Complete set of models for $e^{\pm}$, γ, ions, hadrons, $\mu^{\pm}$
- Tailored to requirements from HEP applications
  - "Cheaper" in terms of CPU
  - Include high-energy corrections
- Theoretical or phenomenological models
  - Bethe-Bloch, corrected Klein-Nishina, …
- Specific high-energy extensions available
  - Extra processes, as $\gamma \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-$
- Dedicated sub-library for optical photons
  - Produced by scintillation or Cherenkov effect

Livermore (and polarized) models

- Based on publicly available evaluated data tables from the Livermore data library: e^-, γ
  - EADL : Evaluated Atomic Data Library, EEDL : Evaluated Electrons Data Library, EPDL97 : Evaluated Photons Data Library, Binding energies: Scofield
  - Tables go down to ~10 eV
- Applications: medical, underground and rare events, space
- Polarized models
  - Same cross section, different final state
  - Application: space missions for the detection of polarized photons

Penelope

- Geant4 includes the low-energy models for electrons, positrons and photons from the Monte Carlo code PENELOPE (PENetration and Energy LOss of Positrons and Electrons)
  - Nucl. Instr. Meth. B 207 (2003) 107
  - Geant4 implements v2008 of Penelope
- Physics models specifically developed by the group of F. Salvat et al.
  - Great care dedicated to the low-energy description
  - Atomic effects, fluorescence, Doppler broadening...
- Mixed approach: analytical, parameterized and database-driven
  - Applicability energy range: 100 eV – 1 GeV
- Include positrons
  - Not described by Livermore models

When use Low Energy Models

- Use Low-Energy models (Livermore or Penelope), as an alternative to Standard models, when you:
  - need precise treatment of EM showers and interactions at low-energy (keV scale)
  - are interested in atomic effects, as fluorescence x-rays, Doppler broadening, etc.
  - can afford a more CPU-intensive simulation
  - want to cross-check an other simulation (e.g. with a different model)
- Do not use when you are interested in EM physics > MeV
  - same results as Standard EM models, performance penalty

EM Physics constructors

G4EmStandardPhysics – default
G4EmStandardPhysics_option1 – HEP fast but not precise
G4EmStandardPhysics_option2 – Experimental
G4EmStandardPhysics_option3 – medical, space
G4EmStandardPhysics_option4 – optimal mixture for precision
G4EmLivermorePhysics
G4EmLivermorePolarizedPhysics
G4EmPenelopePhysics
G4EmLowEPPhysics
G4EmDNAPhysics_option…
…

Combined Physics
Standard > 1 GeV
LowEnergy < 1 GeV

- Advantage of using of these classes – they are tested on regular basis and are used for regular validation

Hadronic processes

- At rest
  - Stopped muon, pion, kaon, anti-proton
  - Radioactive decay
  - Particle decay (decay-in-flight is PostStep)
- Elastic
  - Same process to handle all long-lived hadrons (multiple models available)
- Inelastic
  - Different processes for each hadron (possibly with multiple models vs. energy)
  - Photo-nuclear, electro-nuclear, mu-nuclear
- Capture
  - Pion- and kaon- in flight, neutron
- Fission

Hadronic physics challenge

- Three energy regimes
  - < 100 MeV
  - resonance and cascade region (100 MeV - 10 GeV)
  - > 20 GeV (QCD strings)
- Within each regime there are several models
- Many of these are phenomenological

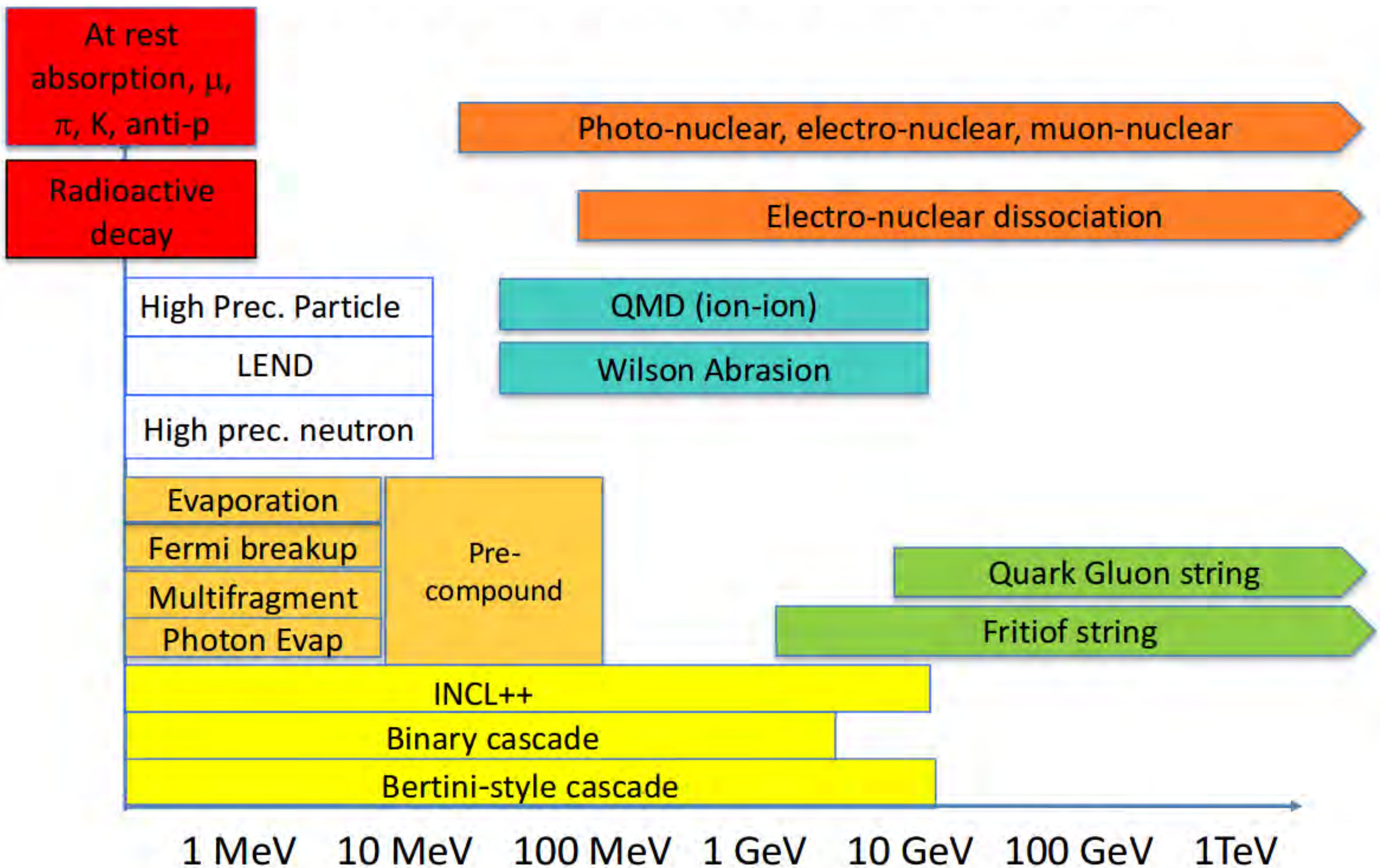
Hadronic models

- Two families of builders for the high-energy part
  - **QGS**, or list based on a model that use the Quark Gluon String model for high energy hadronic interactions of protons, neutrons, pions and kaons
  - **FTF**, based on the FTF (FRITIOF like string model) for protons, neutrons, pions and kaons
- Three families for the cascade energy range
  - **BIC**, binary cascade
  - **BERT**, Bertini cascade
  - **INCLXX**, Liege Intranuclear cascade model

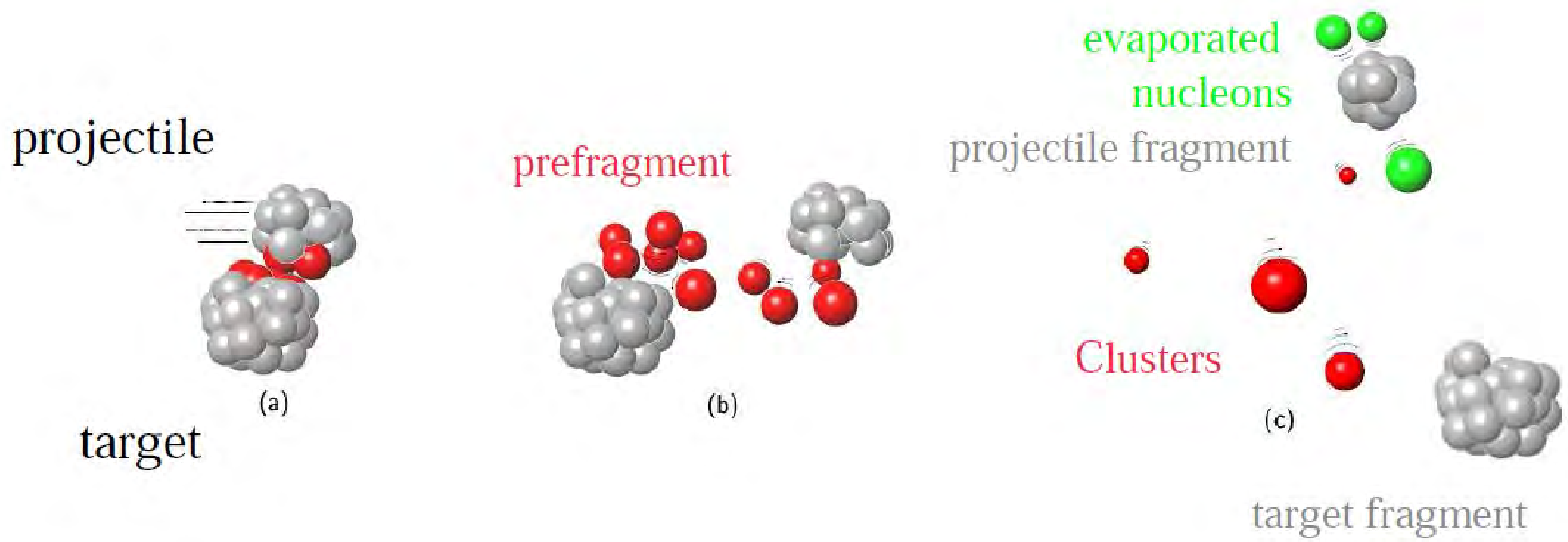
ParticleHP

- Data-driven approach for inelastic reactions for n (in place since many years, named NeutronHP) p, d, t, 3He and α
- Data based on TENDL-2014 (charged particles) and ENDFVII.r1 (neutrons).
- For neutrons, includes information for elastic and inelastic scattering, capture, fission and isotope production
- Range of applicability: from thermal energies up to 20 MeV
- Very precise tracking, but also very slow
- Use it with care: thermal neutron tracking is very CPU-demanding

Hadronic model inventory



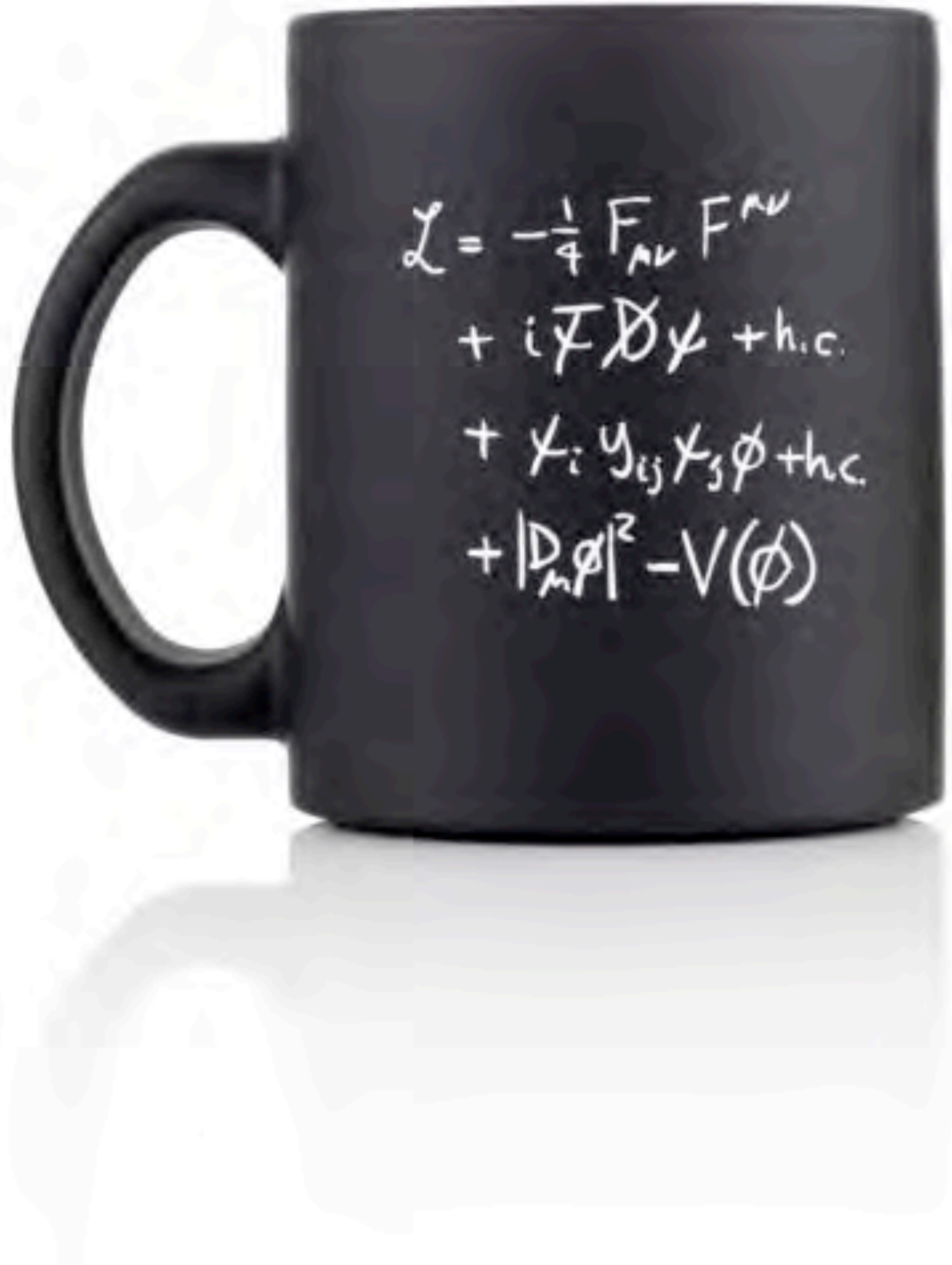
Nuclear interactions



- Hadronic interactions are simulated in two different stages:
    - The first one describes the interaction from the collision until the excited nuclear species produced in the collision are in equilibrium
    - The second one, such as the Fermi break-up, models the emission of such excited, but equilibrated, nuclei

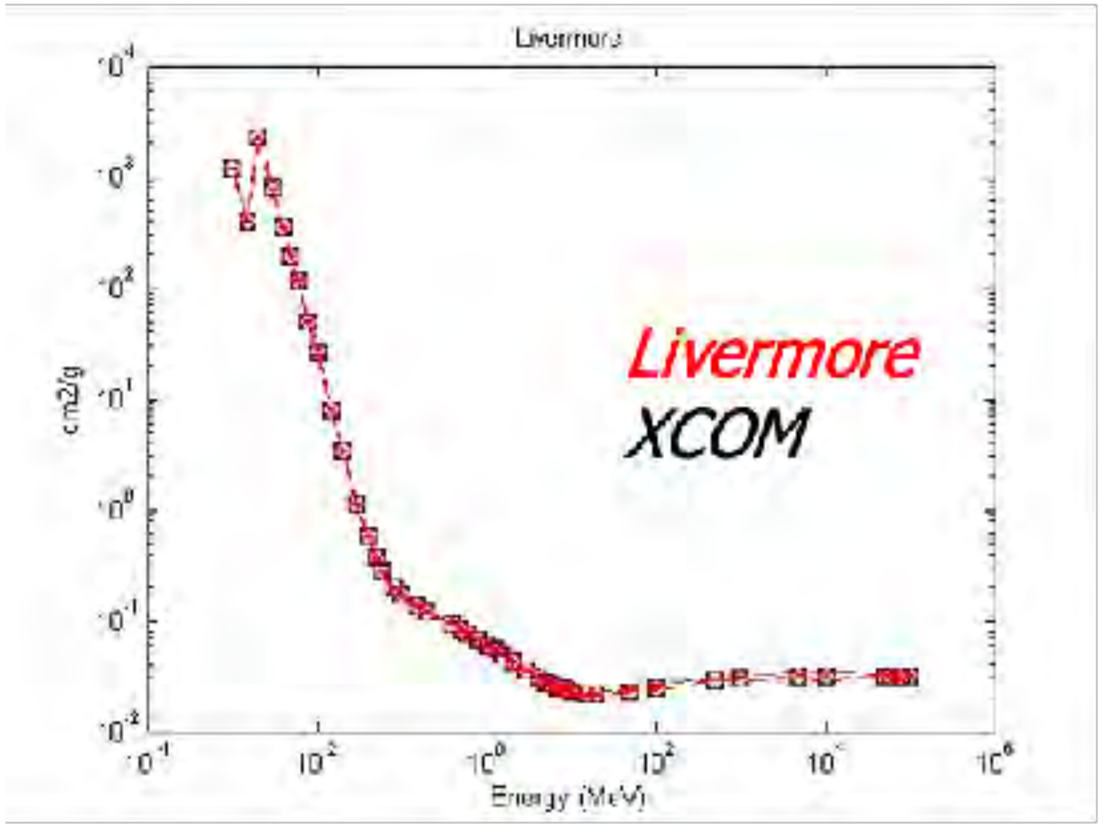
Validation overview

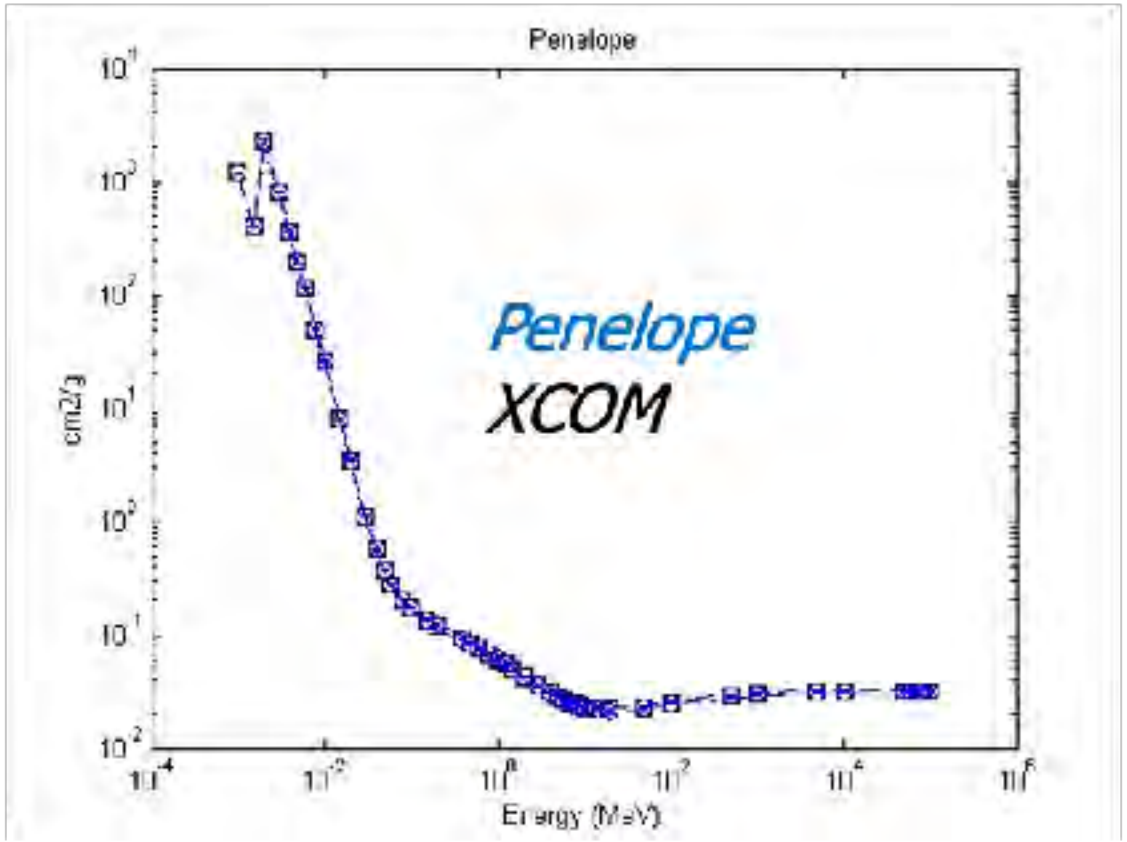
Quick…



EM Validation

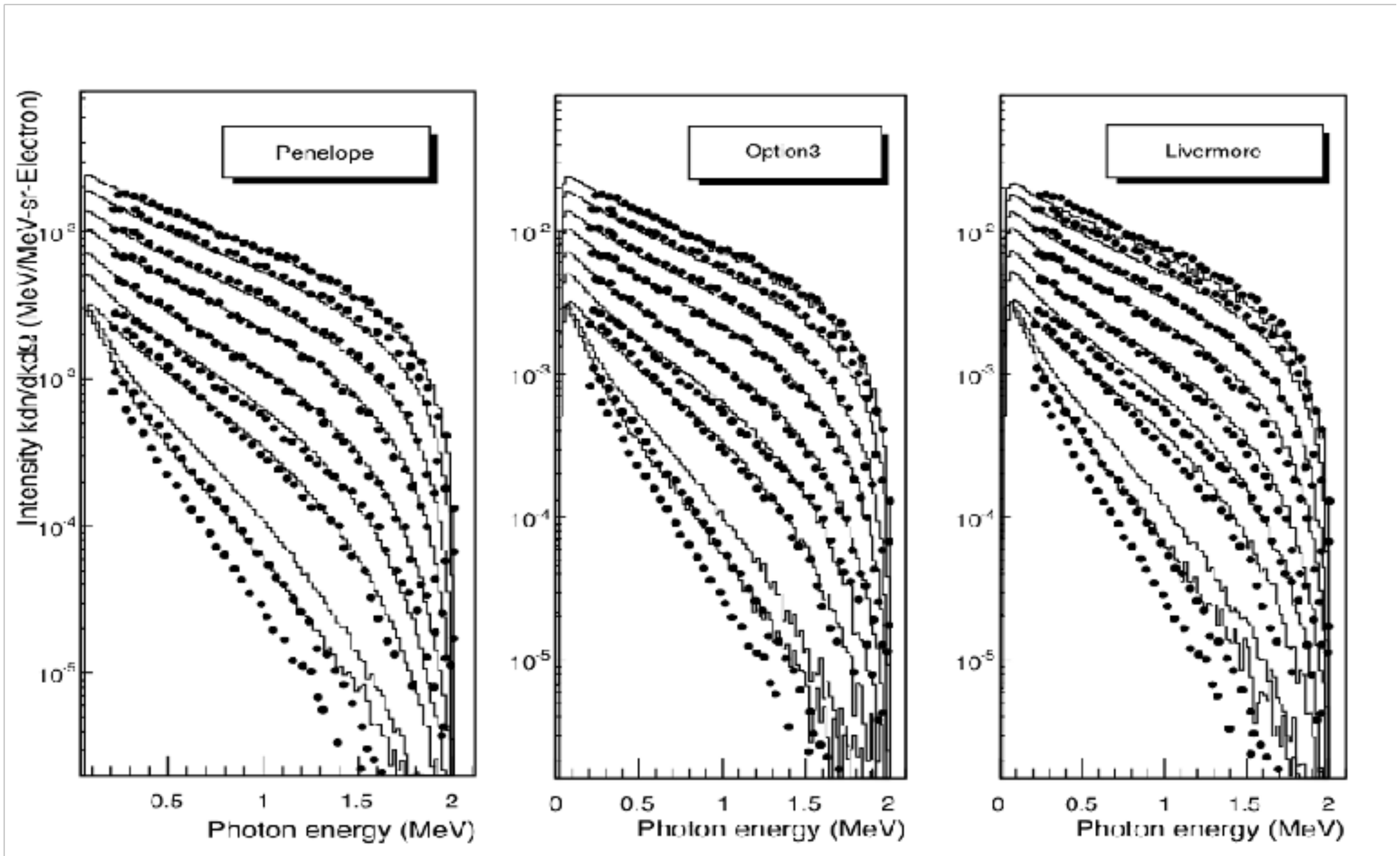
- Tens of papers and studies published
  - Geant4 Collaboration + User Community
- Results can depend on the specific observable/reference
  - Data selection and assessment critical





EM Validation

- In general satisfactory agreement



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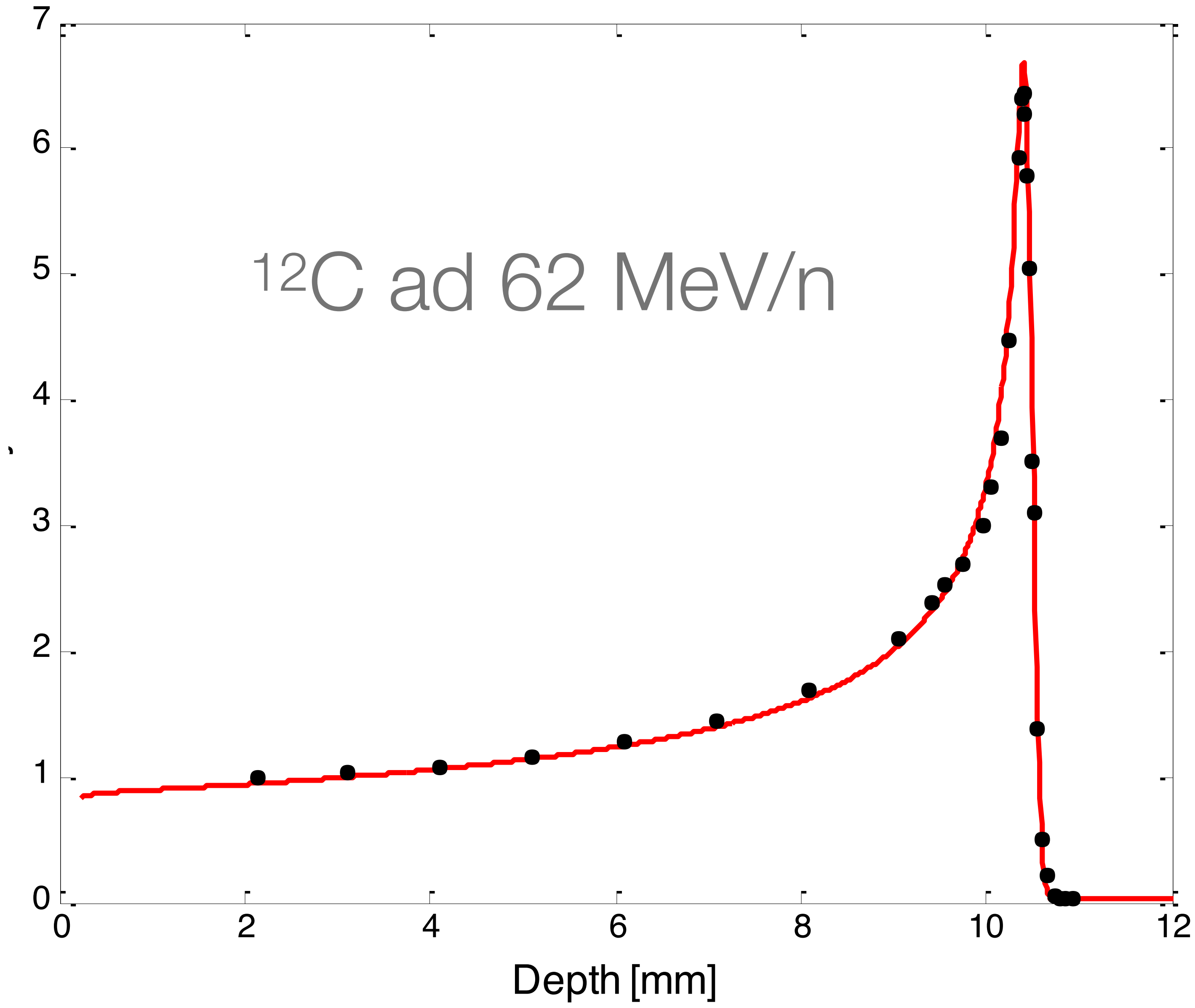
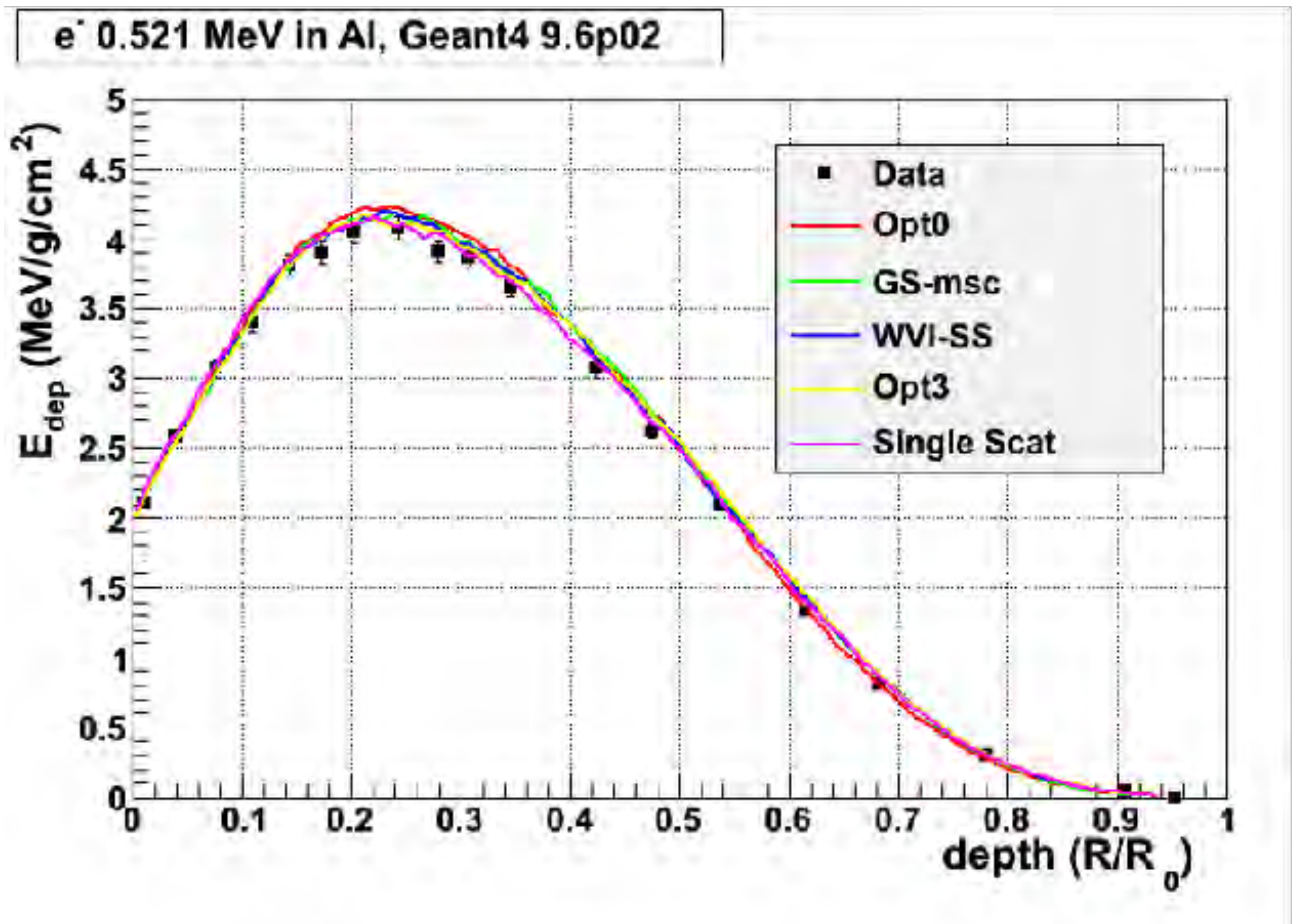


EM Validation

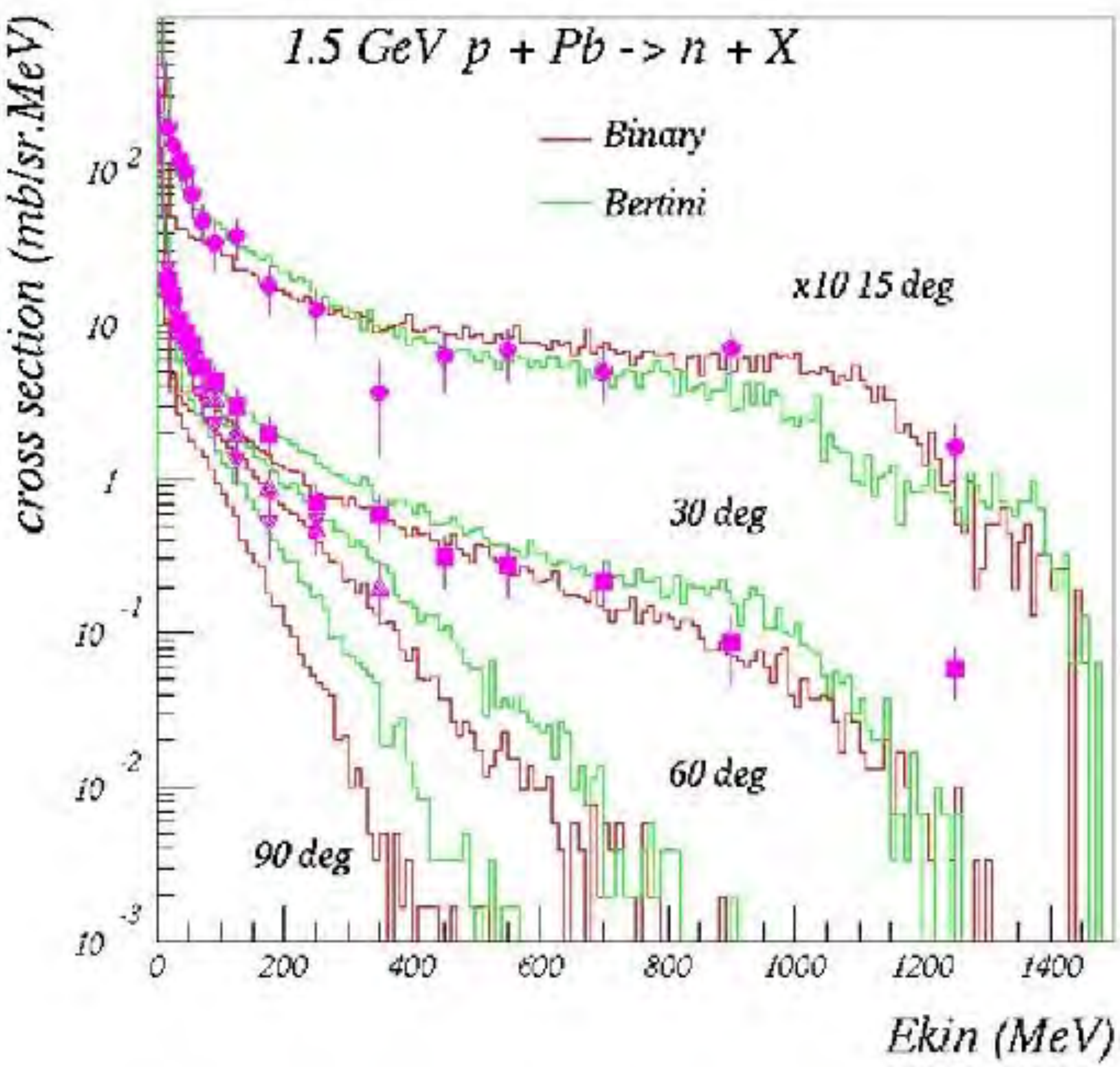
- In general satisfactory agreement



e- showers (longitudinal profile)

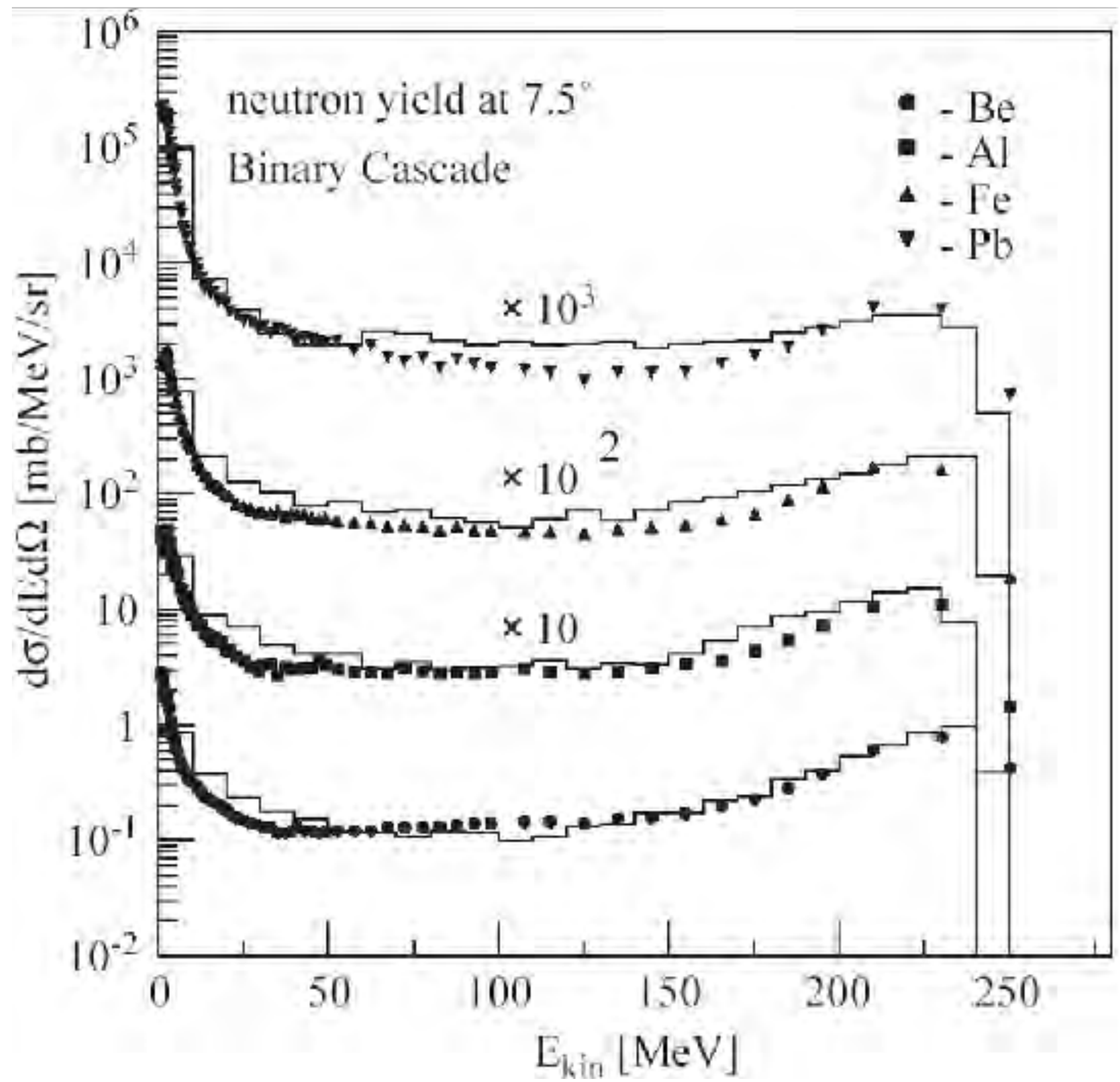
Nuclear fragmentation

- Bertini and Binary cascade models
- neutron production vs. angle
- 1.5 GeV protons
- Lead target



Neutron production

- Binary cascade model
- double differential cross-section for neutrons produced
- 256 MeV protons
- different targets



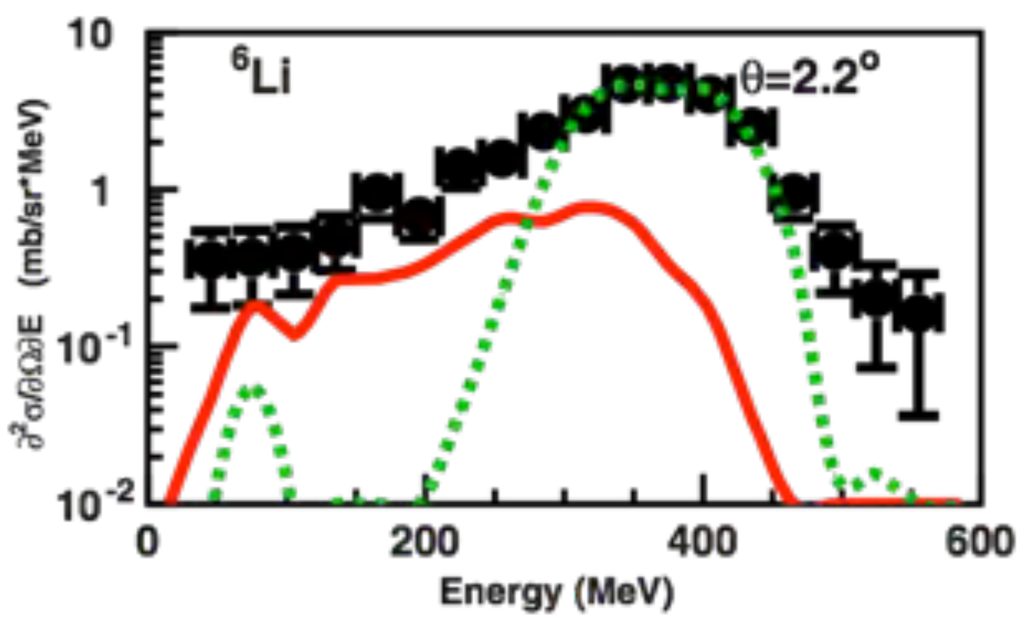
Nuclear interactions below 100 MeV/u

- Despite the numerous and relevant application would use it, there is no dedicated model to nuclear interaction below 100 MeV/u in Geant4

- Many papers showed the difficulties of Geant4 in this energy domain:
  - Braunn et al. have shown discrepancies up to one order of magnitude in ^{12}C fragmentation at 95 MeV/u on thick PMMA target
  - De Napoli et al. showed discrepancy specially on angular distribution of the secondaries emitted in the interaction of 62 MeV/u ^{12}C on thin carbon target
  - Dudouet et al. found similar results with a 95 MeV/u ^{12}C beam on H, C, O, Al and Ti targets

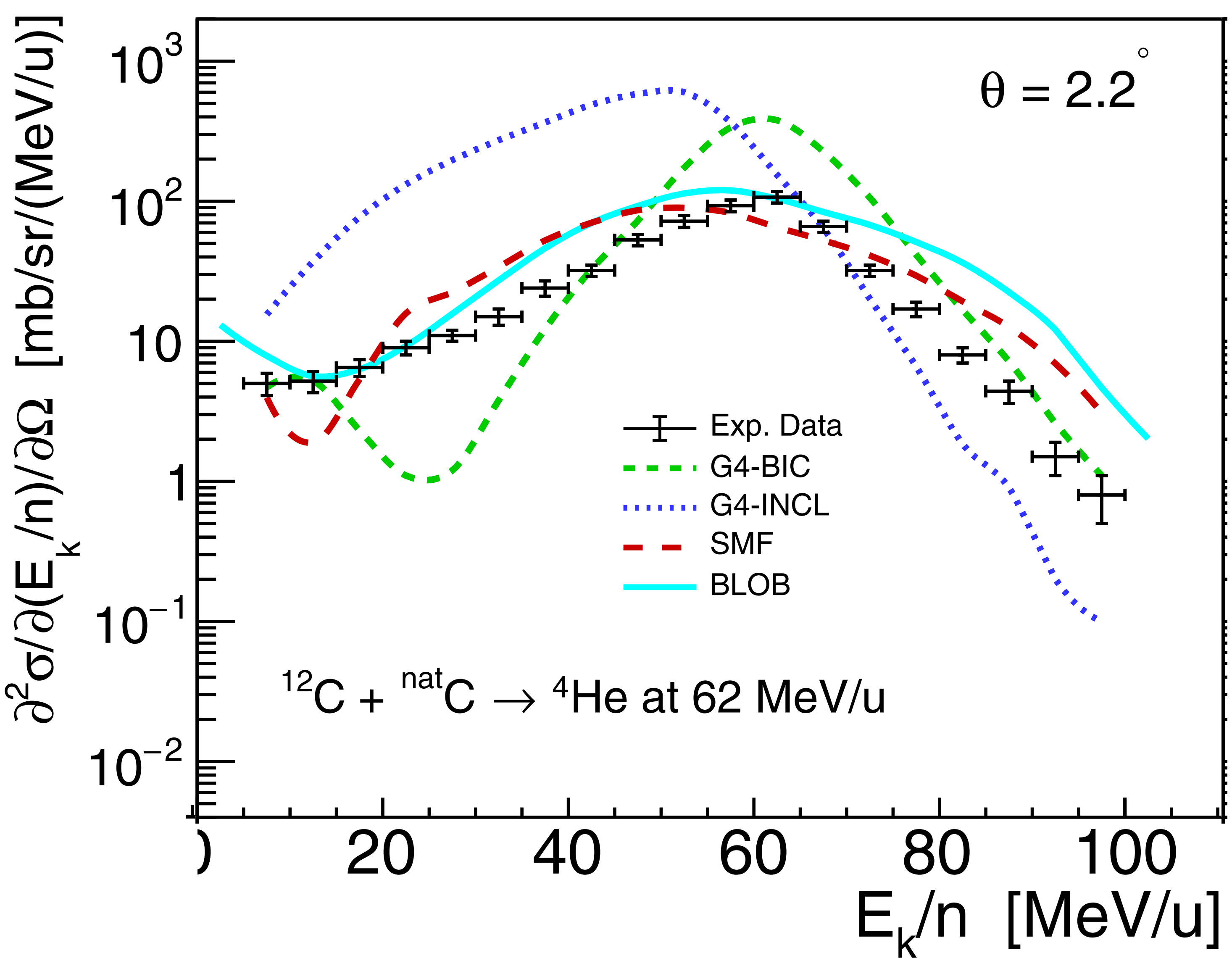
- **Exp. data**
- **G4-BIC**
- **G4-QMD**

[Plot from De Napoli et al. Phys. Med. Biol., vol. 57, no. 22, pp. 7651–7671, Nov. 2012]



Cross section of the ^{6}Li production at 2.2 degree in a ^{12}C on ^{nat}C reaction at 62 MeV/u.

Interfacing new low-energy models



- C. Mancini-Terracciano et al. *Preliminary results in using Deep Learning to emulate BLOB, a nuclear interaction model*. Submitted to Phys. Med
- C. Mancini-Terracciano et al. *Preliminary results coupling SMF and BLOB with Geant4* Phys. Med. vol. 67, no. 22, Nov. 2019
- C. Mancini-Terracciano et al. *Validation of Geant4 nuclear reaction models for hadron therapy and preliminary results with BLOB* IFMBE Proceedings Series 68/1 (mar. 2018)
- P. Napolitani, M. Colonna and C. Mancini-Terracciano. *Cluster formation in nuclear reactions from mean-field inhomogeneities*. In: Journal of Physics: Conference Series 1014.1 (mar. 2018)

Geant-val

- https://geant-val.cern.ch/