Physics in GEANT4 – part 2

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Mixed Monte Carlo: tracking cuts and cut-in-range

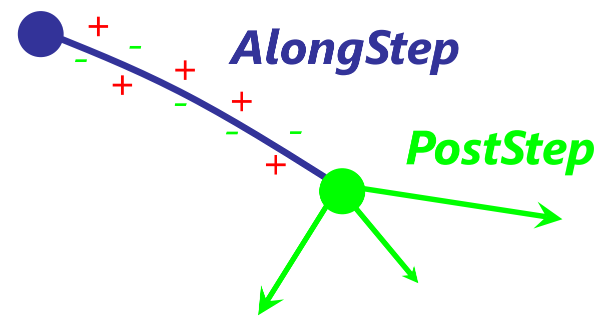
Solution: the mixed MC

- Simulate explicitly (i.e. force step) interactions **only if** energy loss (or change of direction) is above threshold W_0
  - Detailed simulation
  - "**hard**" interaction (like γ interactions)
- The effect of all sub-threshold interactions is described statistically
  - Condensed simulation
  - "**soft**" interactions
- Hard interactions occur much less frequently than soft interactions
  - Fully detailed simulation restored for $W_0=0$

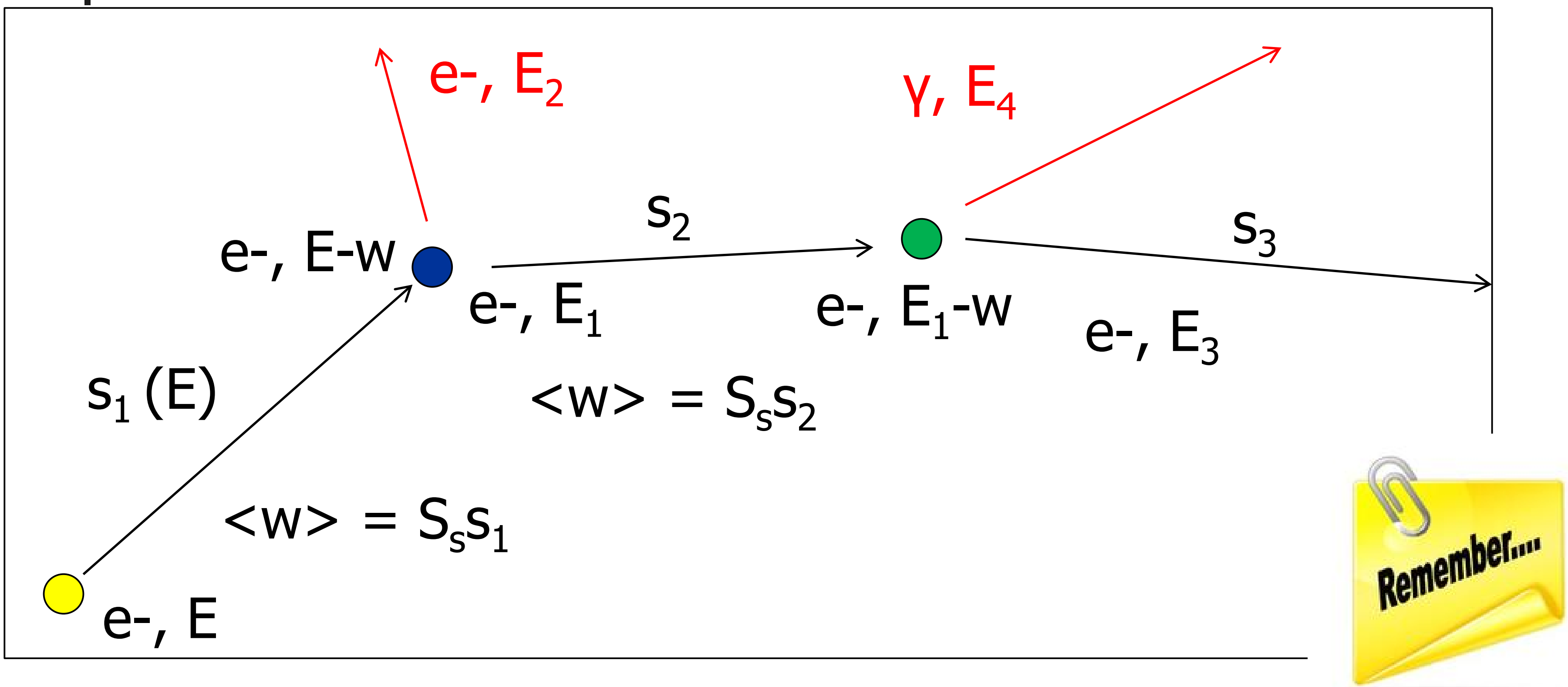
The G4VProcess

- Physics processes are derived from the **G4VProcess** base class
- Abstract class defining the common interface of all processes in Geant4, used by all physics processes

- Three kinds of "actions":
  - AtRest actions
    - Decays, e^+ annihilation
  - AlongStep actions
    - To describe continuous (inter)actions, occurring along the path of the particle, i.e. **"soft" interactions**
  - PostStep actions
    - To describe the point-like (inter)actions, like decay in flight, hadronic interactions, i.e. **"hard" interactions**

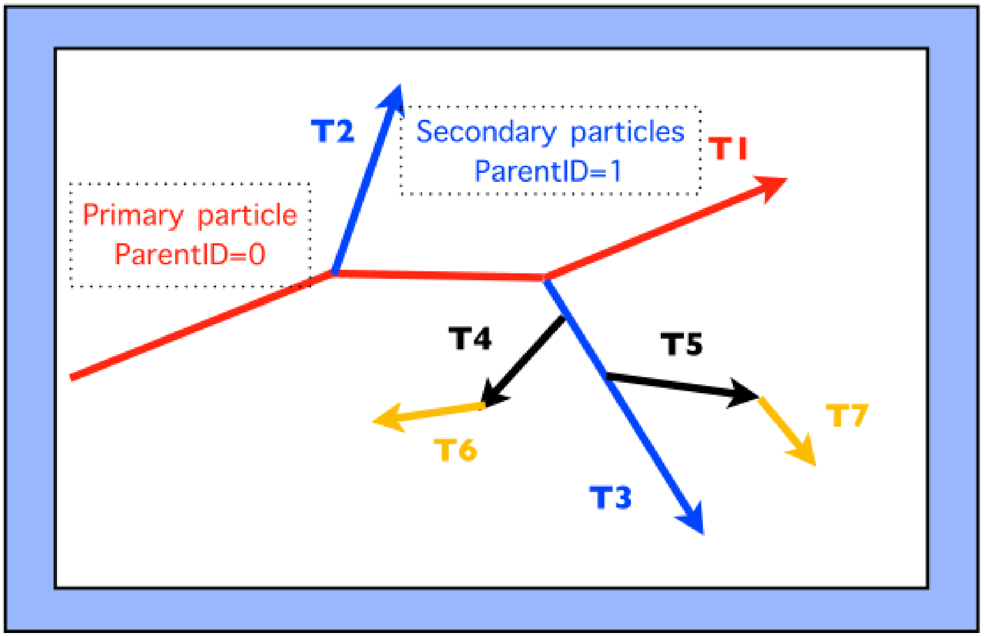


Particle tracking: mixed recipe



- Follow **all secondaries**, until absorbed or leave volume

Geant4 way of tracking



- **Force step** at geometry boundaries
- All AlongStep processes **co-work**, the PostStep **compete** (= only one selected)
- Call AtRest actions for particles at rest

- Secondaries saved at the top of the stack: tracking order follows **'last in first out'** rule: T1 → T3 → T5 → T7 → T4 → T6 → T2

Tracking verbosity

UI command: **`/tracking/verbose 1`**

Primary γ

```
*****************************************************************************
* G4Track Information:   Particle = gamma,   Track ID = 1,   Parent ID = 0
*****************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     47.4      -53     -150         6        0        0         0    Envelope initStep
    1     47.4      -53      -58     0.844        0       92        92    Envelope compt
    2      -46     15.9     5.55      0.47        0      132       224    Envelope compt
    3     -100     6.37    -3.62      0.47        0     55.6       280       World
Transportation
    4     -120     2.84    -7.02      0.47        0     20.6       301  OutOfWorld
Transportation
*****************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 3,   Parent ID = 1
*****************************************************************************
Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0      -46     15.9     5.55     0.375        0        0         0    Envelope initStep
    1    -46.1     16.4     5.98    0.0482    0.327     1.16      1.16    Envelope eIoni
    2    -46.1     16.3     5.98         0   0.0482   0.0408       1.2    Envelope eIoni
```

Compton e⁻

Geant4 production cuts

- The traditional Monte Carlo solution is to set a **tracking cut-off** in energy:
  - particles are stopped when this energy is reached and the residual energy is deposited at that point
  - May yield cause imprecise stopping location and deposition of energy
    - Particle and material dependence
- **Geant4 does not have tracking cuts**
  - All tracks are followed down to zero energy
    - ..or until they leave the world volume or are destroyed in interactions
  - Could be implemented manually by the user
- Geant4 uses only a **production cut** (→ W_0)
  - i.e. cuts deciding whether a **secondary** particle to be produced or not
    - AlongStep vs. PostStep
  - Applies **only** to: γ from bremsstrahlung, e^- from ionization and low-energy protons from hadronic elastic scattering

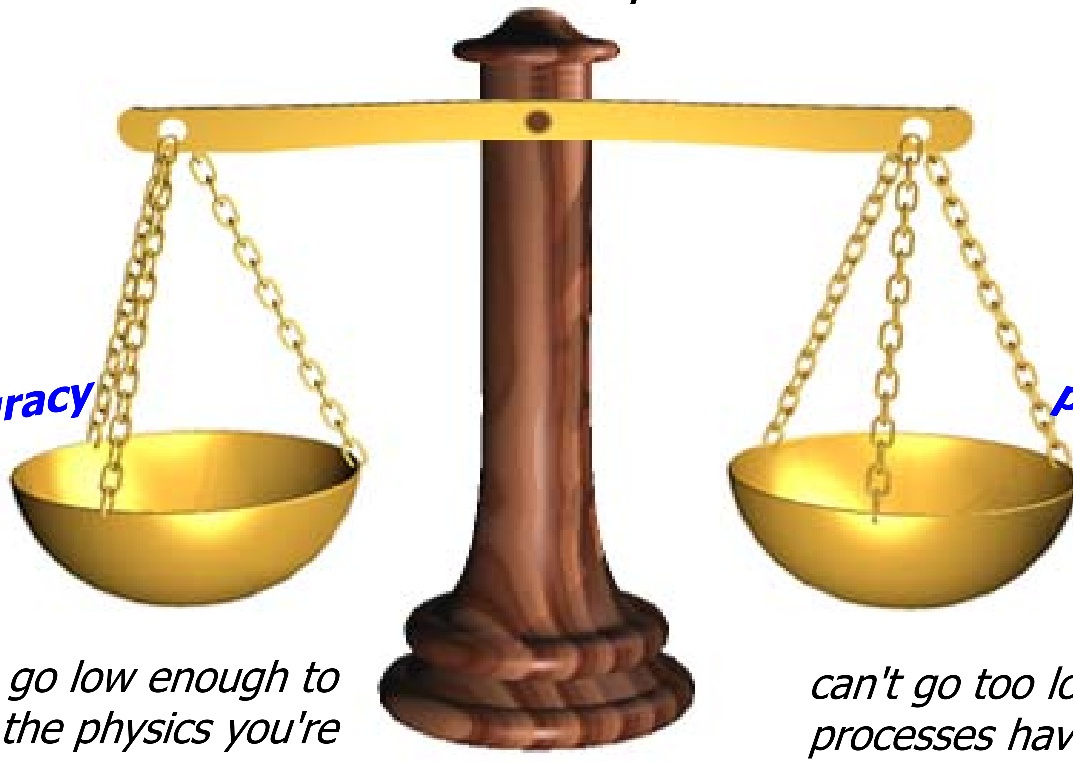
Geant4 way of cuts: cut-in-range

- Geant4 solution: set a **“range” production threshold**
  - this threshold is a distance, not an energy
  - default = 1 mm
  - Particles unable to travel at least the range cut value are not produced
    - They contribute to the AlongStep!
- One production threshold is uniformly set
  - Sets the **"spatial accuracy"** of the simulation
- Production threshold is internally converted to the energy threshold W_0, depending on *particle* type and *material*
  - Effective energy threshold is different in each material

Production cut

- Key ingredient of the mixed MC: energy threshold W_0

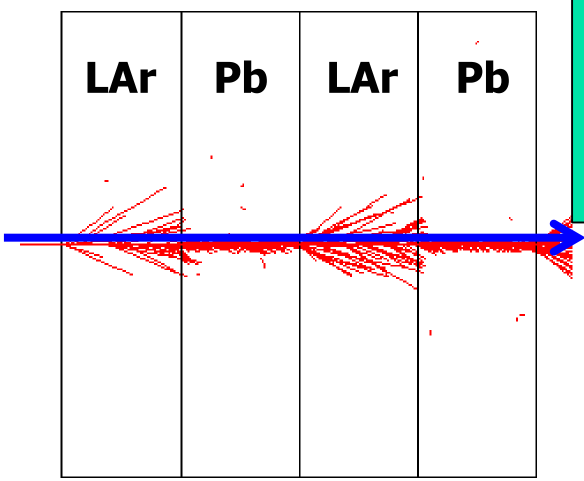
the best compromise



need to go low enough to get the physics you're interested in

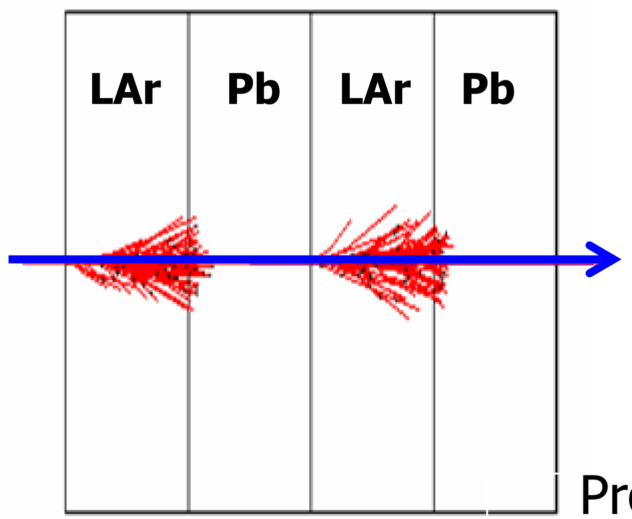
can't go too low because some processes have infrared divergence causing huge CPU time

Cut in range

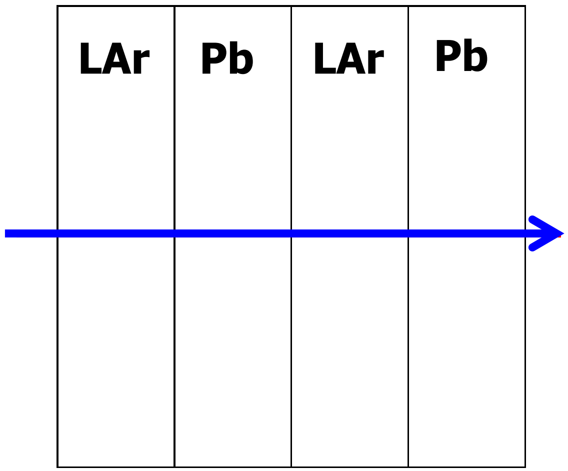


Cut = 455 keV
(range in LAr = 1.5 mm)

500 MeV p in
LAr-Pb sampling
calorimeter



Production range =1.5 mm



Cut = 2 MeV

Threshold in range: 1.5 mm

455 keV electron energy in liquid Ar

2 MeV electron energy in Pb

SetCuts()

- Define all **production** cuts for gamma and electrons
  - Lowest W_0 is 990 eV (but can be changed)
- Remember: this is a **production cut**, not a tracking cut

In **G4VUserPhysicsList** class

```
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);
}
```

Default value: 1.0 mm

Lower the possible W_0 from 990 eV **to 100 eV**

Cuts – UI commands

```
# 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
```

G4StepLimiter

- Alternative to define the level of tracking detail
- Why?
  - you want to see the exact track of the particle
  - you don't trust the chord finder for your magnetic field
- How?
  - Include **`G4StepLimiter`** process in your physics list
    - Formally seen as a physics process, **competing** with all others: always proposing the same step length
    - Can be done by using the Geant4 constructor **`G4StepLimiterPhysics`** in a modular physics list

```
physicsList->RegisterPhysics(new G4StepLimiterPhysics());
```

  - Set "user limits" for the logical volumes of interest: **`SetUserLimits()`**

```
logVol->SetUserLimits(new G4UserLimits(1.0 * mm));
```

Cuts per region

G4Region class

- 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)
  - inert materials
- 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

Physics processes and models

Philosophy

- 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** modeling of cross sections and of final state generation

- Provide **processes** containing
  - Many possible models and cross sections
  - Default cross sections for each model

Models under continuous development

Electromagnetic physics

Inventory (and specs) of the models for γ-rays

1 MeV γ in Al

- Many models available for each process
  - Plus one full set of polarized models
- Differ for energy range, precision and CPU speed
  - Final state generators
- Different mixtures available the Geant4 EM constructors

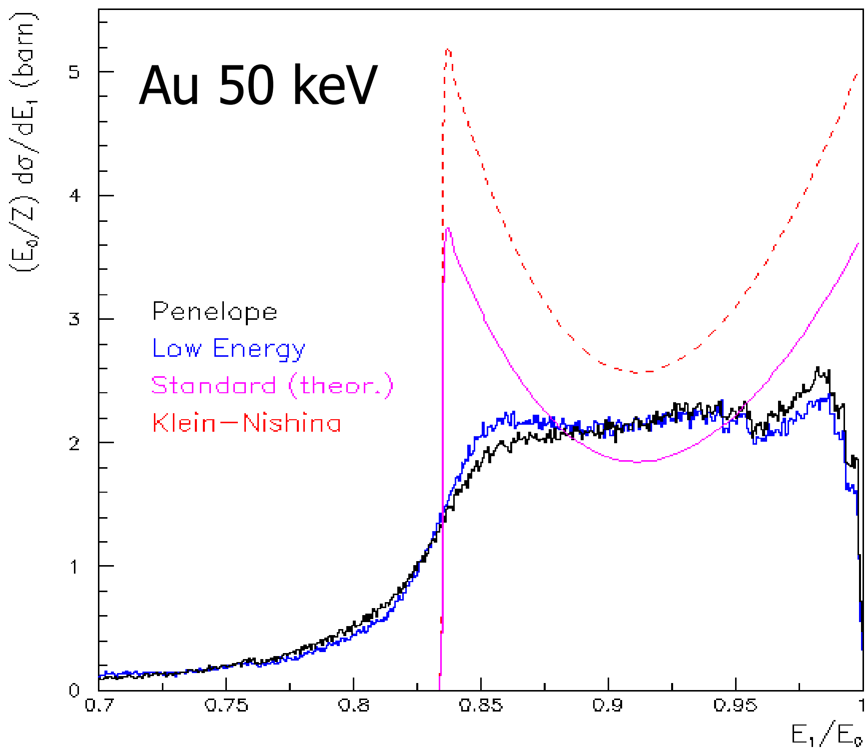
Model	E_{min}	E_{max}	CPU
G4LivermoreRayleighModel	100 eV	10 PeV	1.2
G4PenelopeRayleighModel	100 eV	10 GeV	0.9
G4KleinNishinaCompton	100 eV	10 TeV	1.4
G4KleinNishinaModel	100 eV	10 TeV	1.9
G4LivermoreComptonModel	100 eV	10 TeV	2.8
G4PenelopeComptonModel	10 keV	10 GeV	3.6
G4LowEPComptonModel	100 eV	20 MeV	3.9
G4BetheHeitlerModel	1.02 MeV	100 GeV	2.0
G4PairProductionRelModel	10 MeV	10 PeV	1.9
G4LivermoreGammaConversionModel	1.02 MeV	100 GeV	2.1
G4PenelopeGammaConversionModel	1.02 MeV	10 GeV	2.2
G4PEEFluoModel	1 keV	10 PeV	1
G4LivermorePhotoElectricModel	10 eV	10 PeV	1.1
G4PenelopePhotoElectricModel	10 eV	10 GeV	2.9

Similar situation for $e^{\pm}$

EM concept

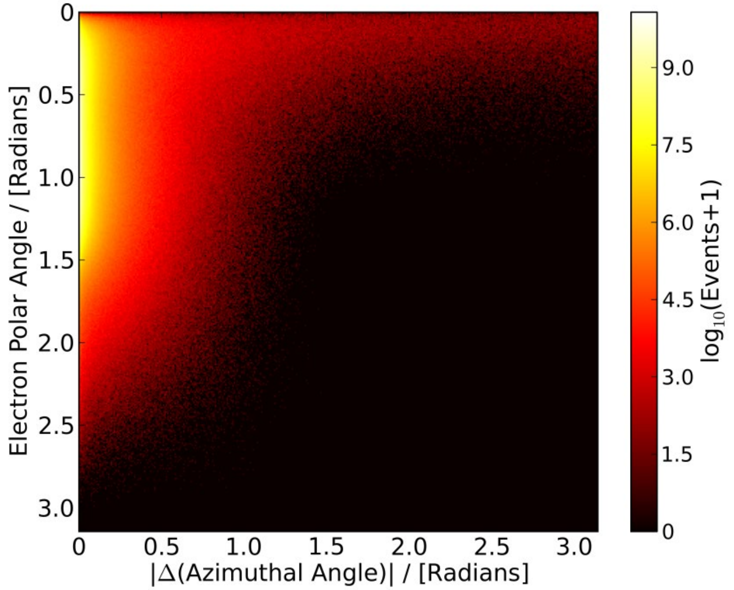
- The same physics processes (e.g. Compton scattering) can be described by different models, that can be **alternative** or **complementary** in a given energy range
- For instance: Compton scattering can be described by
  - **`G4KleinNishinaCompton`**
  - **`G4LivermoreComptonModel`** (specialized low-energy, based on the Livermore database)
  - **`G4PenelopeComptonModel`** (specialized low-energy, based on the Penelope analytical model)
  - **`G4LivermorePolarizedComptonModel`** (specialized 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 (→ performance optimization)

For example: Compton scattering



- New model: **`G4LowEPComptonModel`** (Monash U.)
  - Two-body relativistic 3-dim framework
  - Relativistic impulse approximation
  - Bound atomic electrons
  - Electron distribution not uniform in φ wrt photon scattering plane

250 keV γ Pb



CPU time is the **price to pay** for better precision

Packages overview

- Models and processes for the description of the EM interactions in Geant4 have been grouped in several packages

Package	Description
Standard	γ-rays, $e^{\pm}$ up to 100 TeV, Hadrons, ions up to 100 TeV
Muons	Muons up to 1 PeV
X-rays	X-rays and optical photon production
Optical	Optical photons interactions
High-Energy	Processes at high energy (> 10 GeV). Physics for exotic particles
Low-Energy	Specialized processes for low-energy (down to 250 eV), including atomic effects
Polarization	Simulation of polarized beams

EM processes for γ-rays, $e^{\pm}$

Particle	Process	G4Process
Photons	Gamma Conversion in $e^{\pm}$	`G4GammaConversion`
	Compton scattering	`G4ComptonScattering`
	Photoelectric effect	`G4PhotoElectricEffect`
	Rayleigh scattering	`G4RayleighScattering`
$e^{\pm}$	Ionisation	`G4eIonisation`
	Bremsstrahlung	`G4eBremsstrahlung`
	Multiple scattering	`G4eMultipleScattering`
e^{+}	Annihilation	`G4eplusAnnihilation`

EM processes muons

Particle	Process	G4Process

$\mu^{\pm}$	Ionisation
	Bremsstrahlung
	Multiple scattering
	$e^{\pm}$ pair production
		`G4MuIonisation`
		`G4MuBremsstrahlung`
		`G4MuMultipleScattering`
		`G4MuPairProduction`

Only one model available for these processes (but in principle users may write *their own* models, if needed)

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 (e.g. LPM), assumptions made in the low-energy regime
- Theoretical or phenomenological models
  - Bethe-Bloch, corrected Klein-Nishina, …
  - Photoabsorption Ionization (PAI)
    - ionization energy loss of a relativistic charged particle in matter
- Specific high-energy extensions available
  - Extra processes, as $\gamma \rightarrow \mu+\mu-$, $e^+e^- \rightarrow \mu+\mu-$
- Dedicated sub-library for optical photons
  - Produced by scintillation or Cherenkov effect

Livermore (& 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
  - Mixture of experiments and theories
  - In principle, tables go down to ~10 eV
- Applications: medical, underground and rare events, space
- **Polarized** models
  - Same calculation of the cross section, different way to produce the final state
  - Describe in detail the kinematics of polarized photon interactions
  - Application: space missions for the detection of polarized photons

Penelope models

- 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/why to 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 for Geant4 10.5.p01 - ready-for-the-use

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 physics

(a very quick overview)

Hadronic Physics

- Data-driven models
- Parametrised models
- Theory-driven models

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

Reference physics lists for Hadronic interactions

- 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

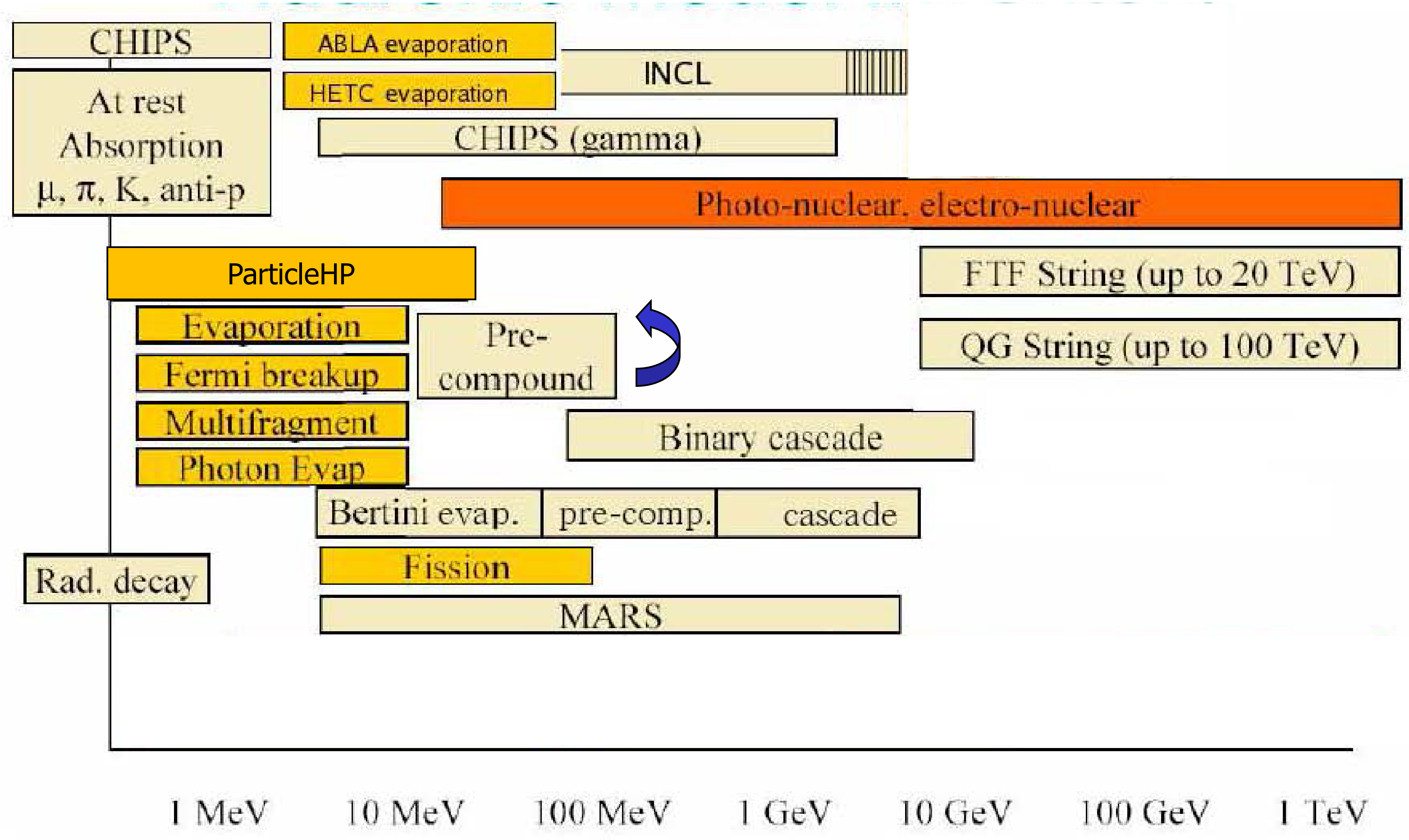
ParticleHP Models

NEW!

- Since Geant4 10.2 → **`ParticleHP`**
  - Data-driven approach for *inelastic* reactions for n (in place since many years, named **`NeutronHP`**) p, d, t, ^{3}He and α
  - Data based on TENDL-2014 (charged particles) and ENDFVII.r1 (neutrons). Compressed binary files
    - 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
    - A thermal neutron can have 100's of thermal scatterings before being captures
    - No cut applied on low-energy protons from elastic scattering
- **`NeutronHP`** fully merged with **`ParticleHP`** since 10.3
  - **`NeutronHP`** headers are still included the release 10.3 for backwards compatibility, but **they will be removed**
- Neutron models debugged since a long while, but it is a fresh development for the other particles

Hadronic model inventory

http://geant4.cern.ch/support/proc_mod_catalog/models



Cross sections

- Default cross section sets are provided for each type of hadronic process:
  - Fission, capture, elastic, inelastic
- Can be **overridden** or **completely replaced**
- Different types of cross section sets:
  - Some contain only a few numbers to parameterize cross section
  - Some represent large databases (data driven models)
- Cross section management
  - **`GetCrossSection`**`()` → sees last set loaded for energy range

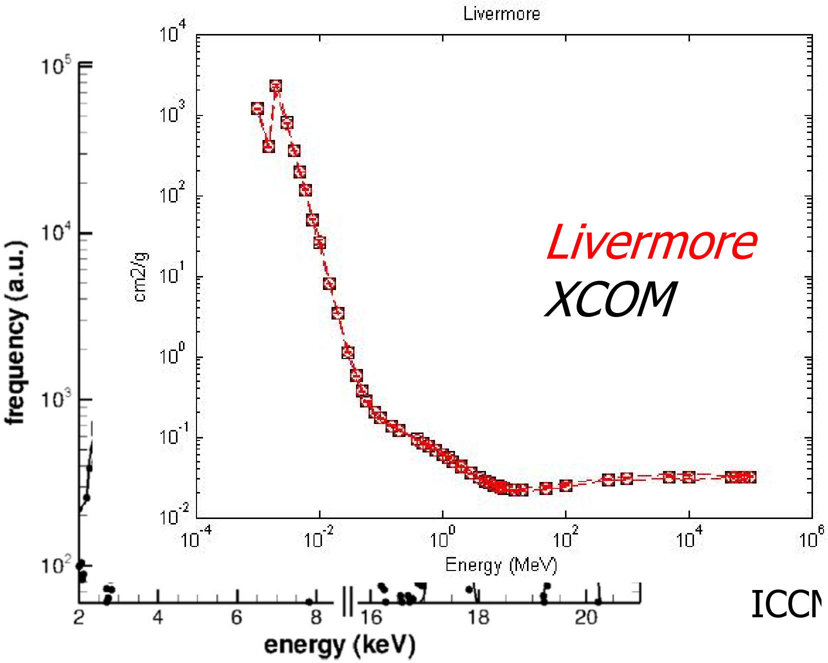
Geant4 extensions / exotic

- The tracking implemented in Geant4 is very general and transparent
  - Possible to accommodate for custom particles and processes
  - Possible to accommodate for alternative models, also to be used together with the Geant4 ones
- Recent development: add the possibility to simulate **solid state effects** (e.g. channeling) NEW!
  - Extension of the **`G4Material`** to include lattice properties
    - E.g. unit cell
  - Framework generic enough to include other kinds of auxiliary material properties
- See **`examples/extended/exoticphysics`**

Quick overview of validation

EM validation - 1

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



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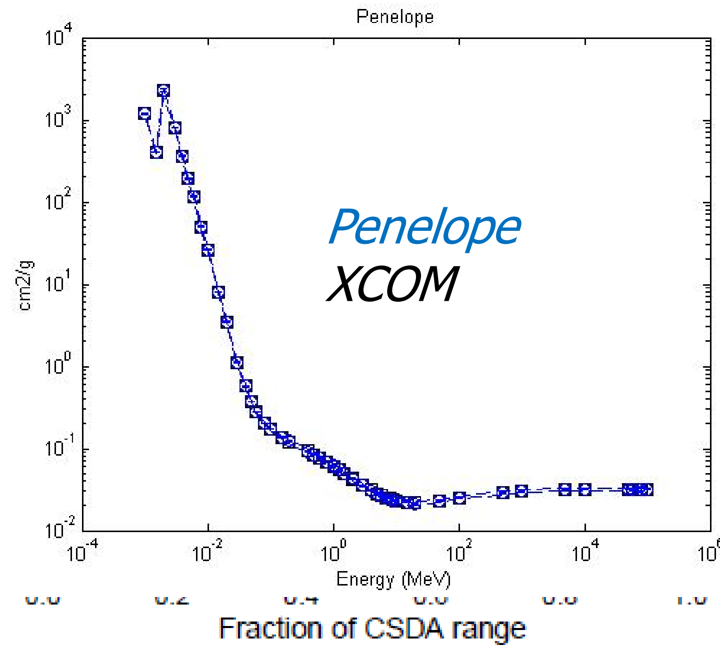
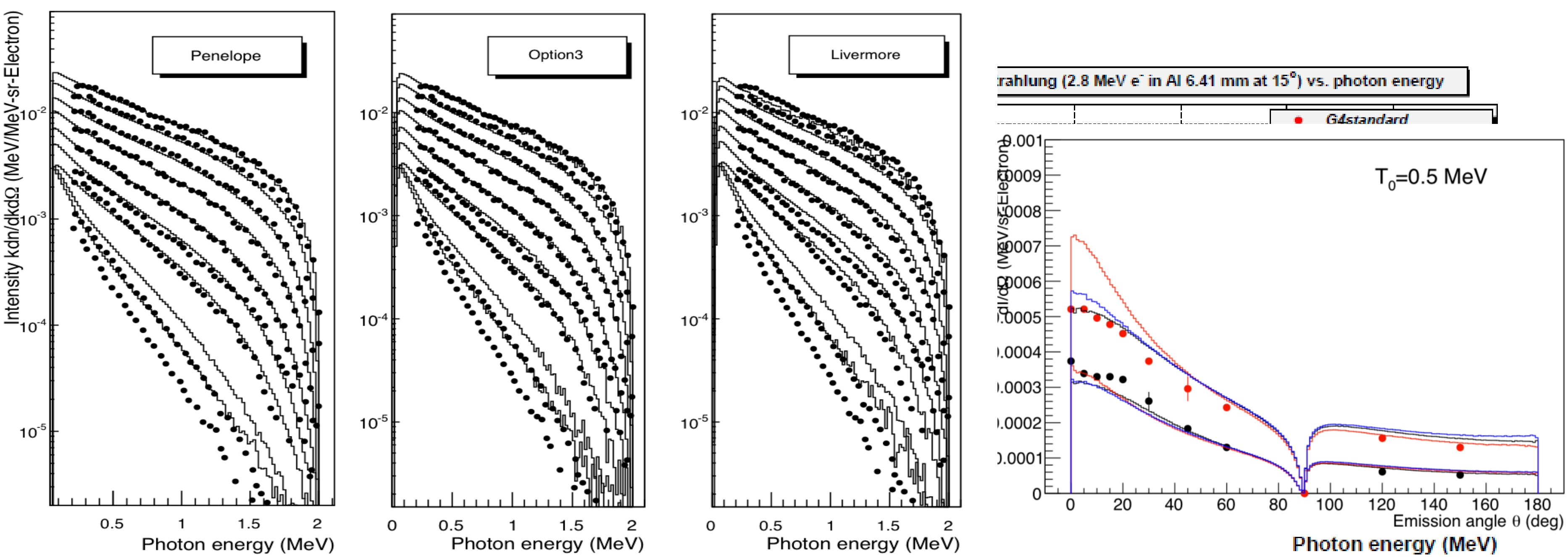


EM validation – 2

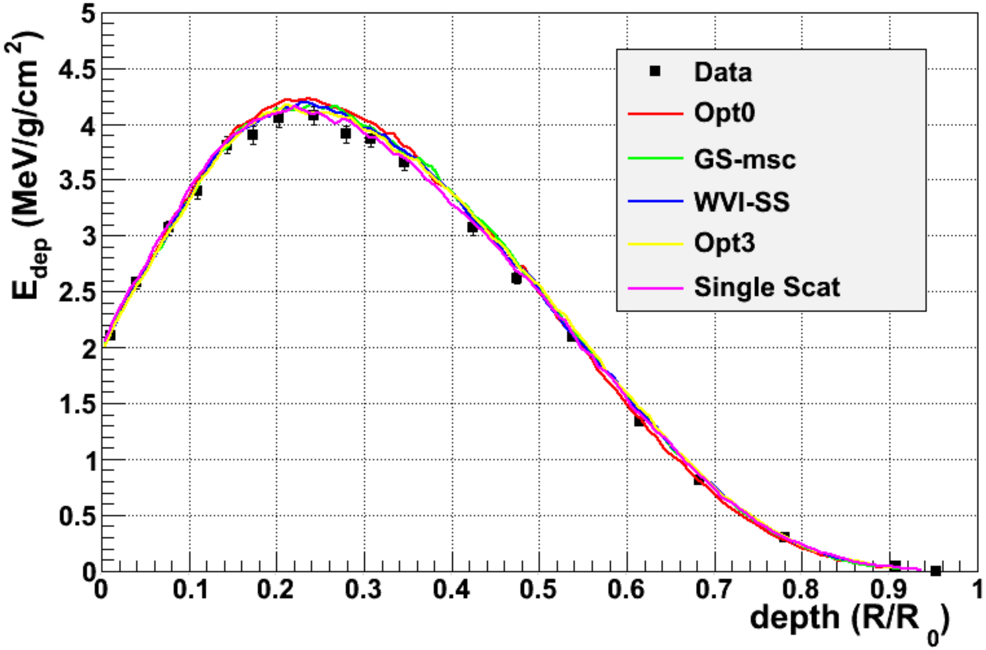
- In general satisfactory agreement
- Validation/verification repository available on web

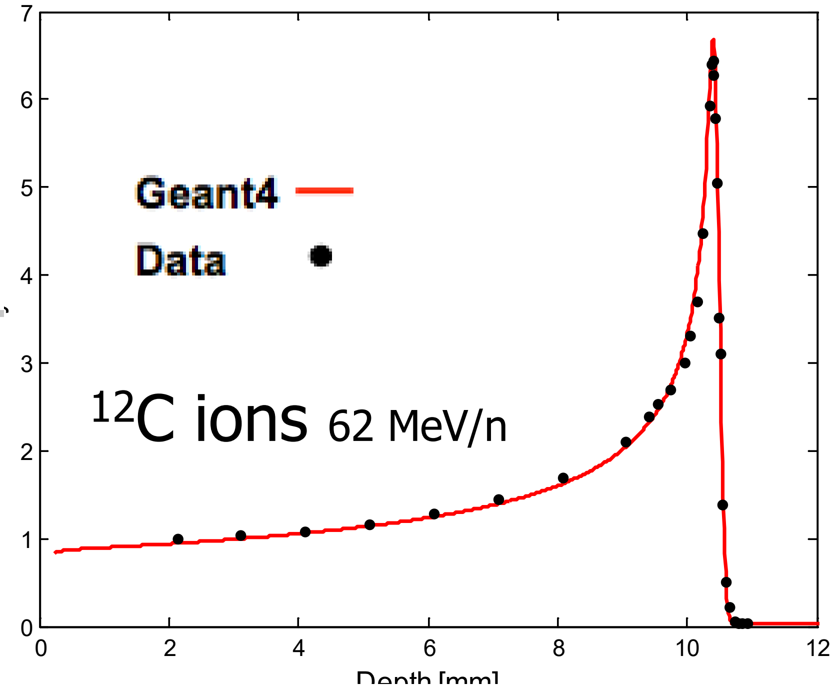
http://cern.ch/vnivanch/verification/verification/electromagnetic/

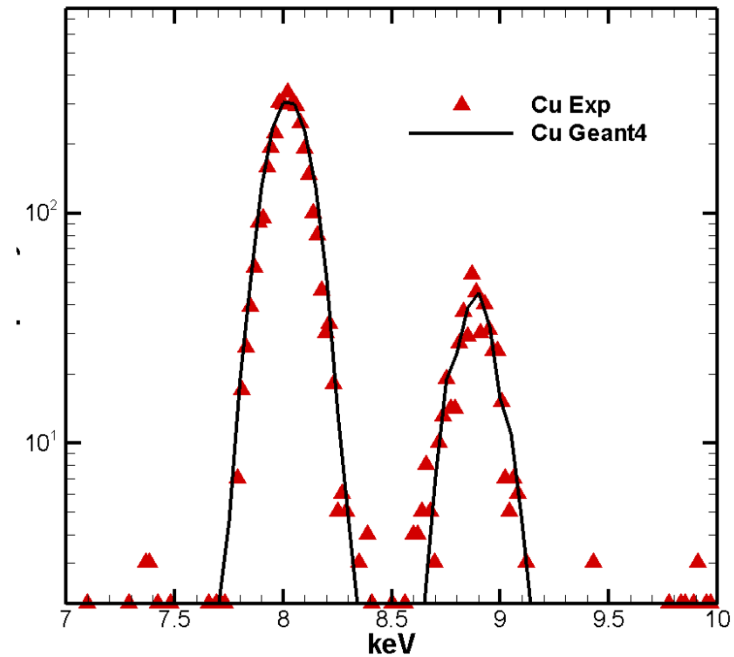


EM validation - 3

e- showers, longitudinal profiles







Hadronic validation

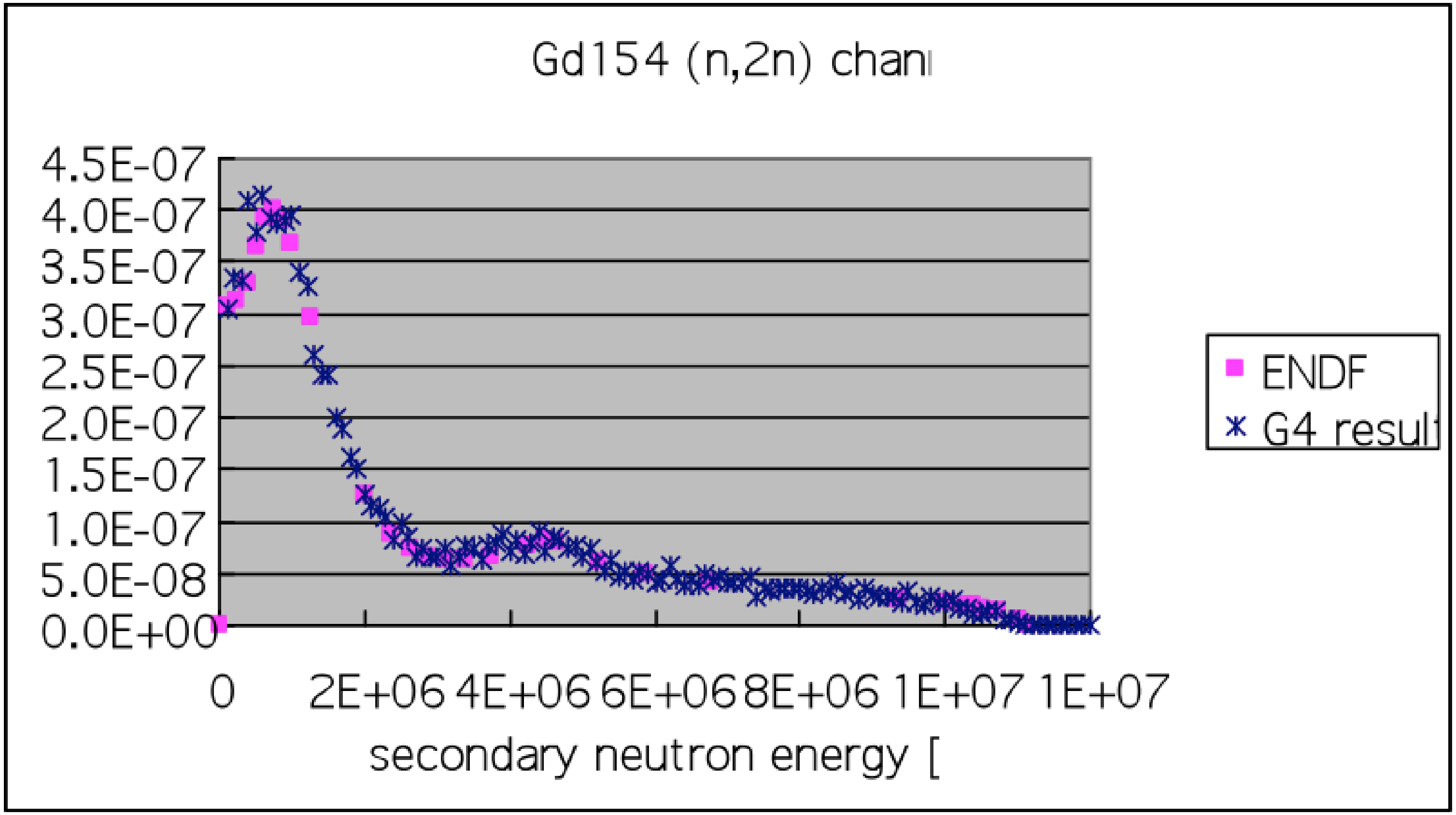
- A website is available to collect relevant information for validation of Geant4 hadronic models (plots, tables, references to data and to models, etc.)

`http://geant4.cern.ch/results/validation_plots.htm`

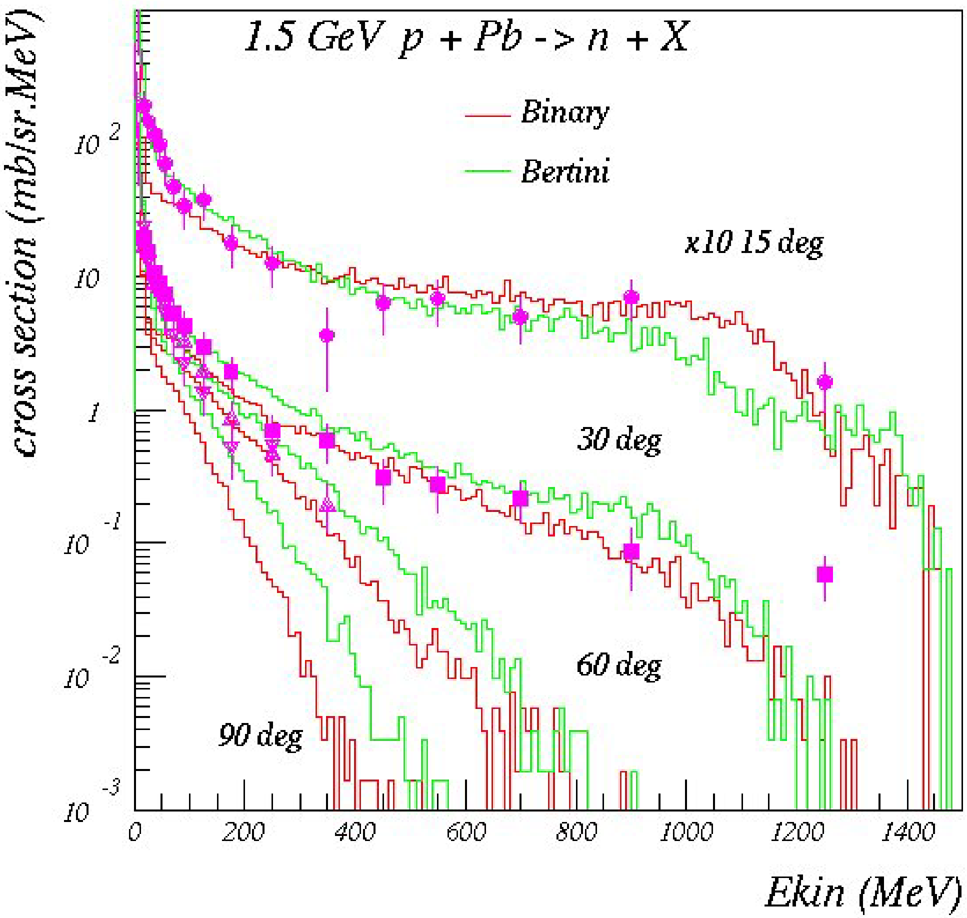
`http://g4validation.fnal.gov:8080/G4ValidationWebApp/`

- Several physics lists and several use-cases have been considered (e.g. thick target, stopped particles, low-energy)
- Includes final states and cross sections

Some verification: secondary energy spectrum

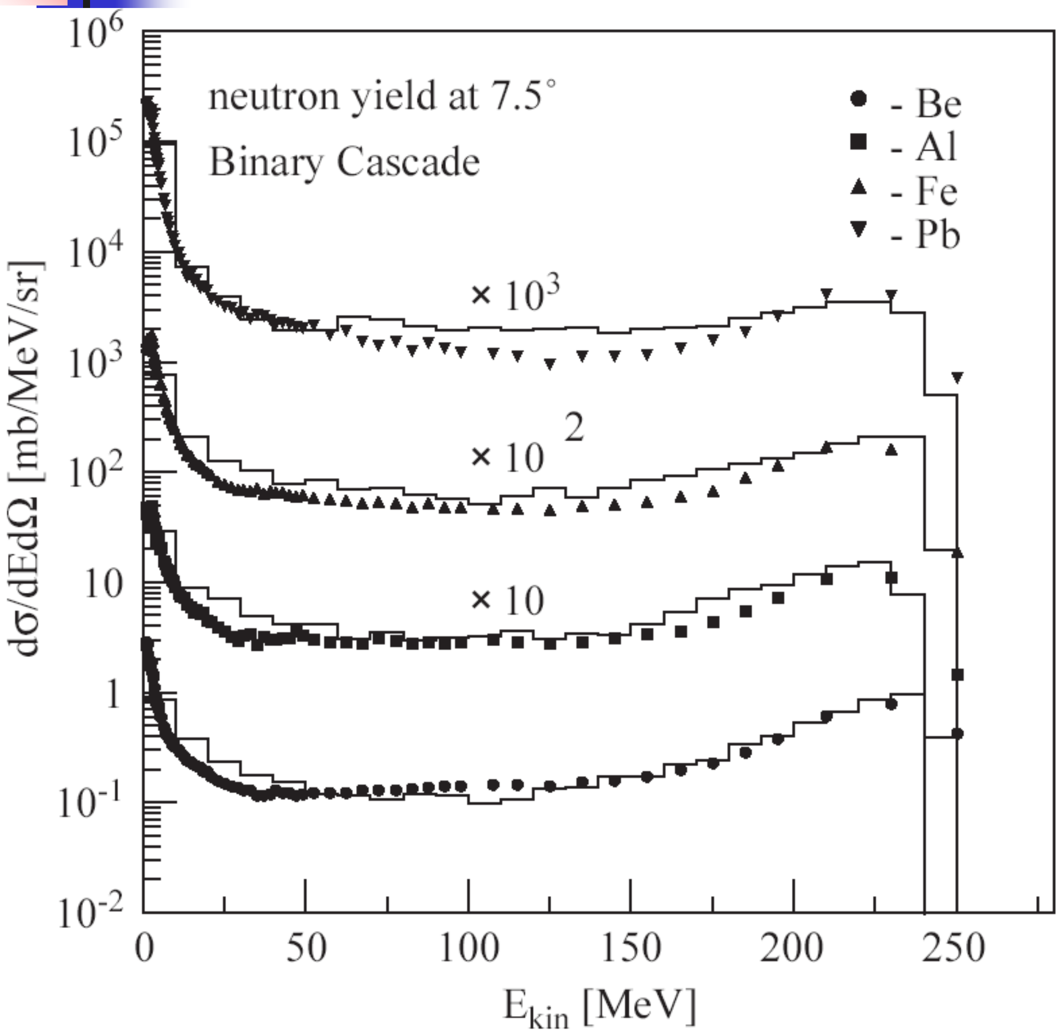


Nuclear fragmentation



Bertini and **Binary cascade** models: neutron production vs. angle from 1.5 GeV protons on Lead

Neutron production by protons



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

Hands-on session

- Task3c
- **http://geant4.lngs.infn.it/belgrade2019/task3**

Backup

EM concept - 2

- A physical interaction or process is described by a process class
  - Naming scheme : « G4ProcessName »
  - Eg. : « G4Compton » for photon Compton scattering

- A physical process can be simulated according to several models, each model being described by a model class
  - The usual naming scheme is: « G4ModelNameProcessNameModel »
  - Eg. : « G4LivermoreComptonModel » for the Livermore Compton model
  - Models can be alternative and/or complementary on certain energy ranges
  - Refer to the Geant4 manual for the full list of available models

NeutronHP Models

- Dedicated **`NeutronHP`** models in Geant4 since many years
  - HP = **high-precision**
- Cross sections and final state information based on ENDF/BVII.1 tabulated data (G4LEND)
  - Includes information for *elastic* and *inelastic scattering, capture*, *fission* and *isotope production*
- Applicable from thermal energies to 20 MeV
  - Very precise tracking, but also very slow
  - Use it with care: thermal neutron tracking is very CPU-demanding
    - A thermal neutron can have 100's of thermal scatterings before being captures
- Included in all physics lists ending with **`_HP`** and **`Shielding`**

Cuts per region – C++ code

```
void MyPhysicsList::SetCuts()
{
  // default production thresholds for the world volume
  SetCutsWithDefault();

  // Same cuts for all particle types
  G4Region* region = G4RegionStore::GetInstance()->GetRegion("myRegion1");
  G4ProductionCuts* cuts = new G4ProductionCuts;
  cuts->SetProductionCut(0.01*mm); // same cuts for gamma, e-
  region->SetProductionCuts(cuts);

  // individual production thresholds for different particles
  region = G4RegionStore::GetInstance()->GetRegion("myRegion2");
  cuts = new G4ProductionCuts;
  cuts->SetProductionCut(1 * mm, "gamma");
  cuts->SetProductionCut(0.1 * mm, "e-");
  region->SetProductionCuts(cuts);

     // ... or (simpler)
  SetCuts(0.01 * mm, "gamma", "absorber");
}
```

Code Example (1/2)

```
G4ParticleDefinition* neutron=
     G4Neutron::NeutronDefinition();
G4ProcessManager* protonProcessManager =
     proton->GetProcessManager();
```

retrieve the process manager for neutron

```
// Elastic scattering
G4HadronElasticProcess* neutronElasticProcess =
 new G4HadronElasticProcess();
```

create the **process** for elastic scattering

```
G4NeutronHPElastic* neutronElasticModel =
 new G4NeutronHlastic();
neutronElasticModel->SetMaxEnergy(20.*MeV);
```

get the HP **model** for elastic scattering

```
neutronElasticProcess->
 RegisterMe(neutronElasticModel);
```

register the model to the process

```
neutronProcessManager->
 AddDiscreteProcess(protonElasticProcess);
```

attach the process to neutron

Code example (2/2)

```
// Inelastic scattering
G4ProtonInelasticProcess* protonInelasticProcess
  = new G4ProtonInelasticProcess();
```

creates the **process** for inelastic scattering

Model 1

```
G4BinaryCascade* protonInelasticModel1
 = new G4BinaryCascade();
protonInelasticModel1->SetMaxEnergy(4*GeV);
```

gets the Binary **model** up to 4 GeV

```
protonInelasticProcess->
   RegisterMe(protonInelasticModel1);
```

registers model to the process

Model 2

```
G4TheoFSGenerator* protonInelasticModel2 =
   new G4TheoFSGenerator("FTFB");
protonInelasticModel2->SetHighEnergyGenerator(
 new G4FTFModel);
```

gets the FTF **model** from 4 GeV

```
protonInelasticModel2->SetMinEnergy(4.0*GeV);
protonInelasticProcess
   ->RegisterMe(protonInelasticModel2);
```

registers model to the process

Example: PhysicsList, γ-rays

Only PostStep

```
G4ProcessManager* pmanager =
   G4Gamma::GetProcessManager();
pmanager->AddDiscreteProcess(new G4PhotoElectricEffect);
pmanager->AddDiscreteProcess(new G4ComptonScattering);
pmanager->AddDiscreteProcess(new G4GammaConversion);
pmanager->AddDiscreteProcess(new G4RayleighScattering);
```

- Use **AddDiscreteProcess** because γ-rays processes have only PostStep actions
- For each process, the default model is used among all the available ones (e.g. **G4KleinNishinaCompton** for **G4ComptonScattering**)

Alternative cross sections

- To be used for specific applications, or for a given particle in a given energy range, for instance:
- Low energy neutrons
  - elastic, inelastic, fission and capture (< 20 MeV)
- Neutron and proton inelastic cross sections
  - 20 MeV < E < 20 GeV
- Ion-nucleus reaction cross sections (several models)
  - Good for E/A < 1 GeV
- Isotope production data
  - E < 100 MeV
- Photo-nuclear cross sections

Information on the available cross sections at

`http://geant4.cern.ch/support/proc_mod_catalog/cross_sections/`