Physics in Geant4 - part 2

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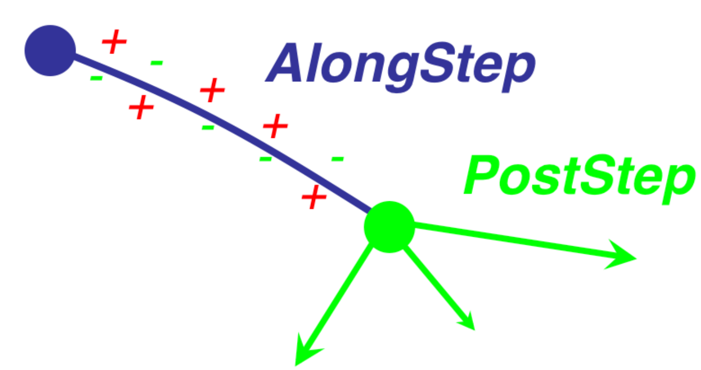
G4VProcess and Tracking

The G4VProcess

- Physics processes describe HOW particles interact with material
- Are derived from 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**



Geant4 Tracking

- G4Track keeps current information of the particle and has static information
- G4Track keeps information at the beginning of the step. After finishing all AlongStepDoIts, G4Track is updated. It is updated after each invocation of a PostStepDoIt.
- All Geant4 processes, including the transportation of particles, are treated generically. In spite of the name "*tracking*", particles are not *transported* in the tracking category.

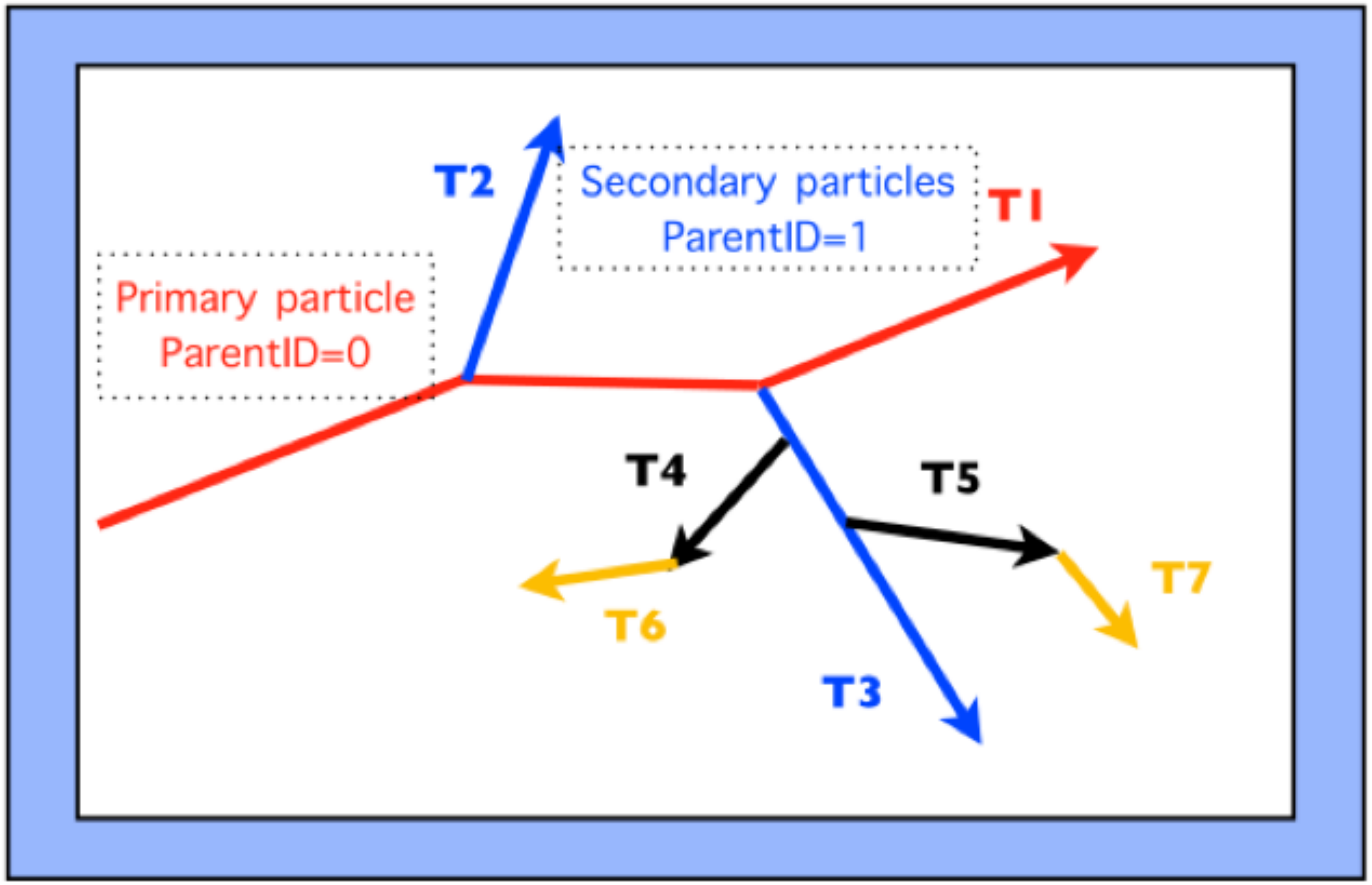
Tracking Verbosity

UI command: `/tracking/verbose 1`

```
*********************************************************************************************
* 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
```

Geant4 Tracking

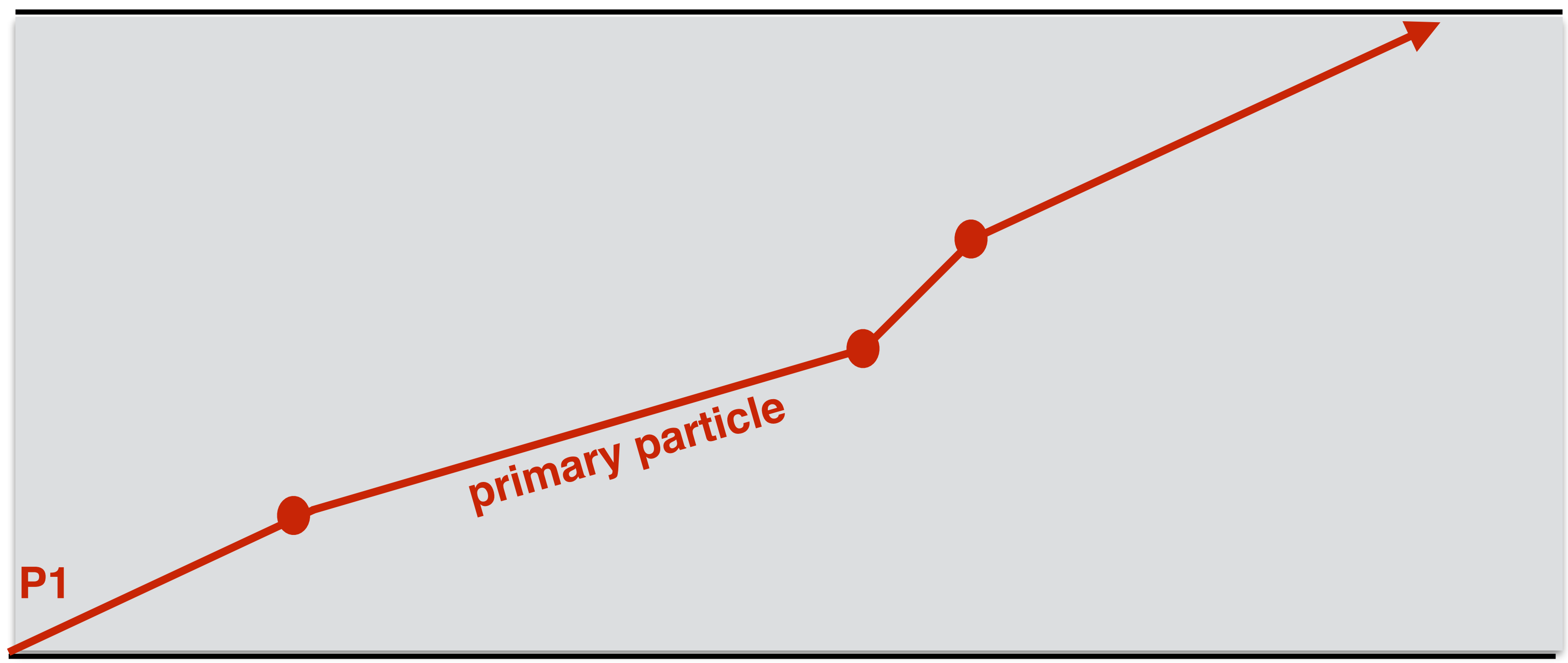


Secondary saved at the top of the stack: tracking order follows **'last in first out'** rule:
T1 → T3 → T5 → T7 → T4 → T6 → T2

Production Cuts

Geant4 production cuts

What is a cut???



You can set a **"range" production threshold**

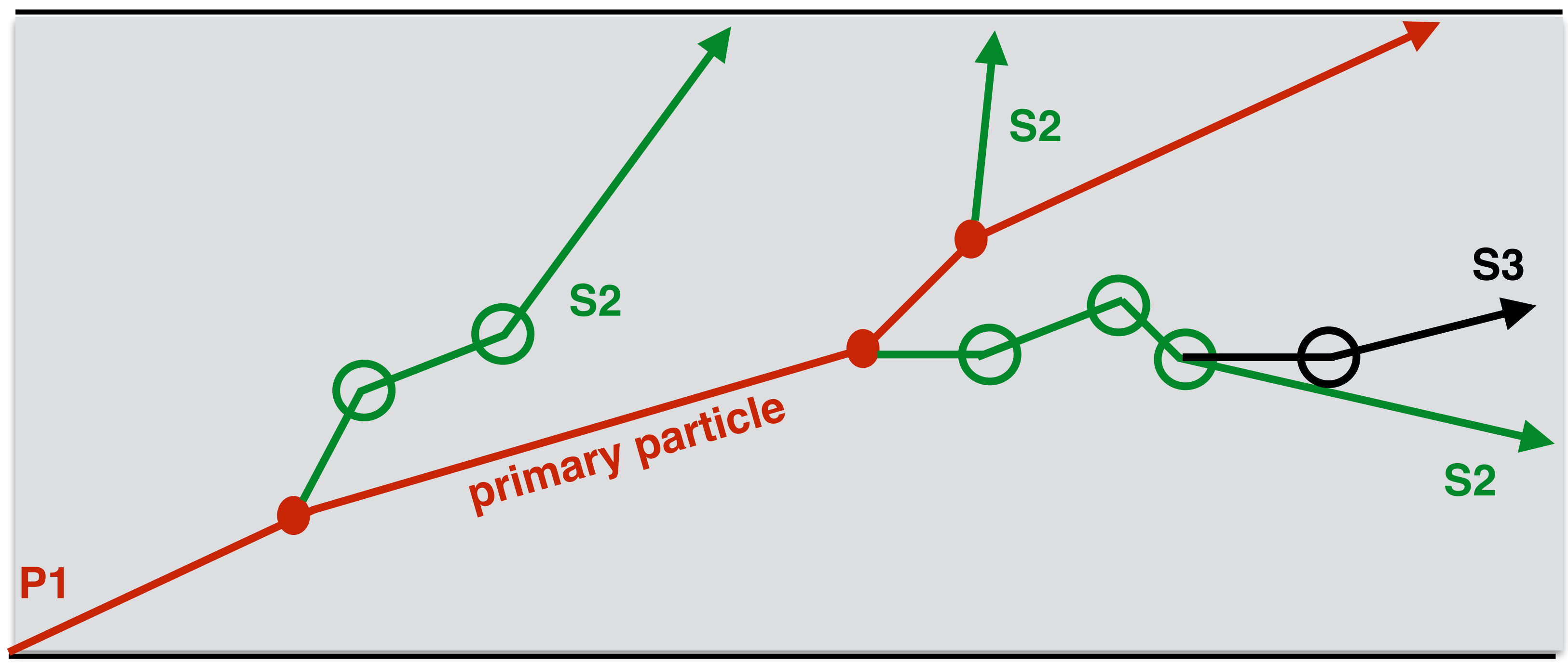
- this threshold is a distance, not an energy
- default = 1 mm
- Particles unable to travel at least the range cut value are not produced

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

Geant4 production cuts

What is a cut???



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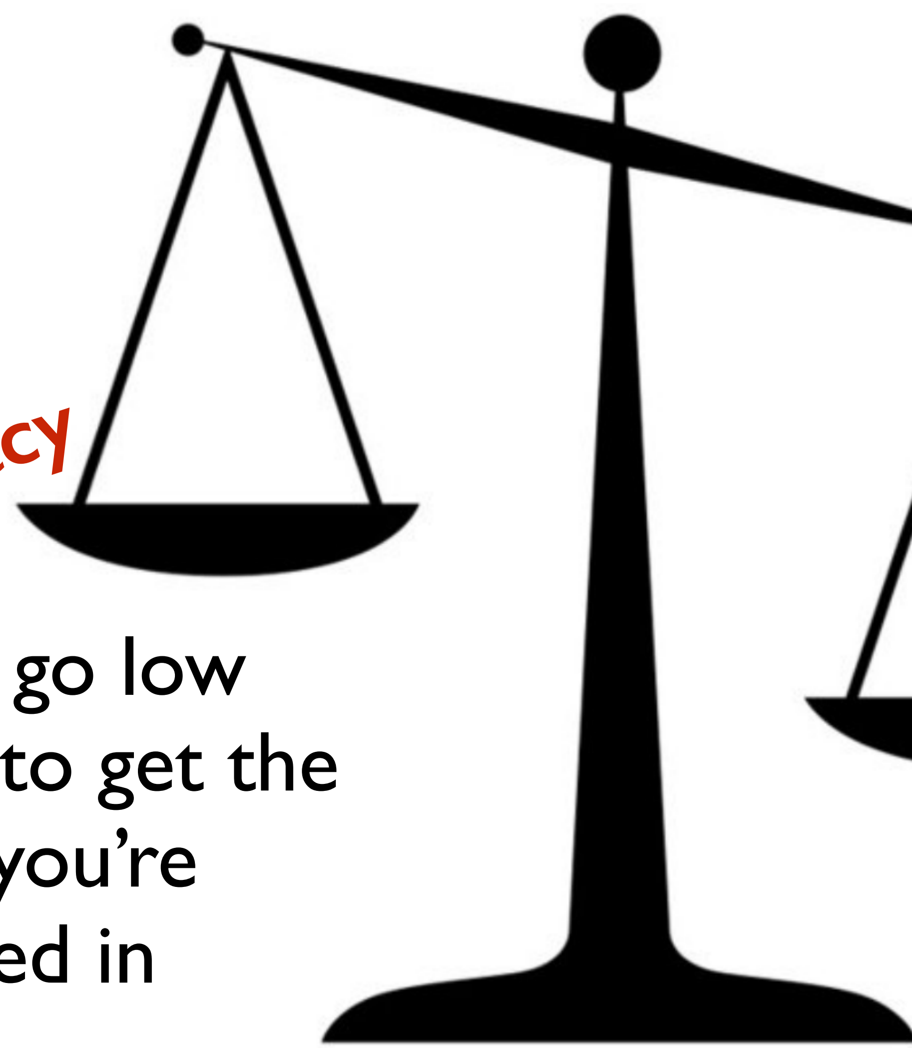
Geant4 production cuts

The general principles in Geant4 are the followings:

- Each process has its **intrinsic limit** to produce secondary particles
- All particles produced (and accepted) will be tracked **up to zero range**
- Each particle has a **suggested cut in range** (which is converted to energy for all materials) and defined via SetCut() method

Production Cuts

What you prefer?



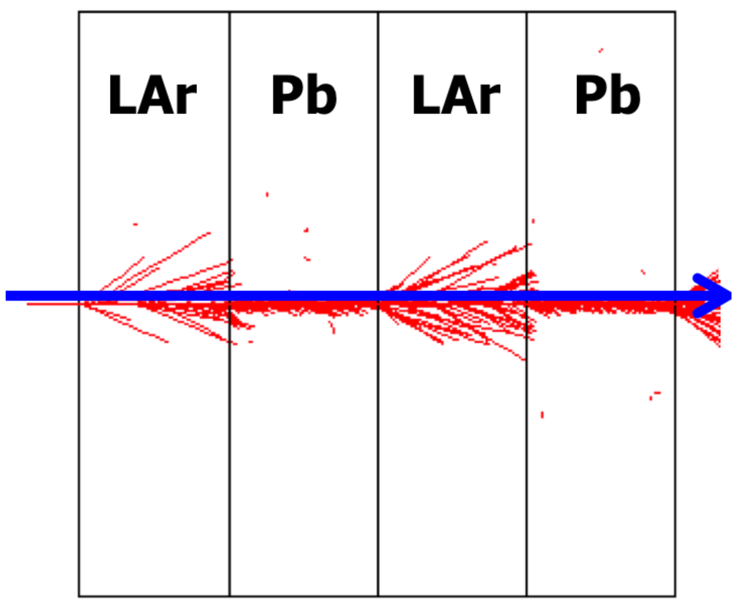
accuracy

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

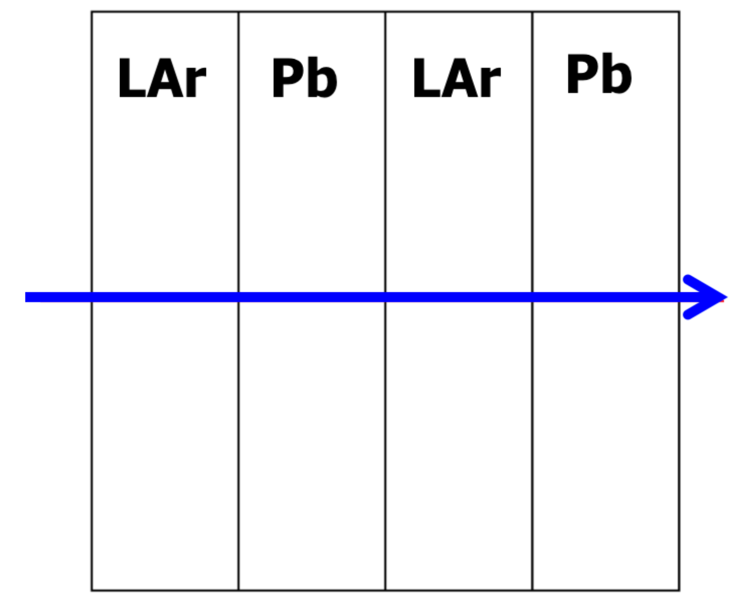
performance

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

Cut in range: an example



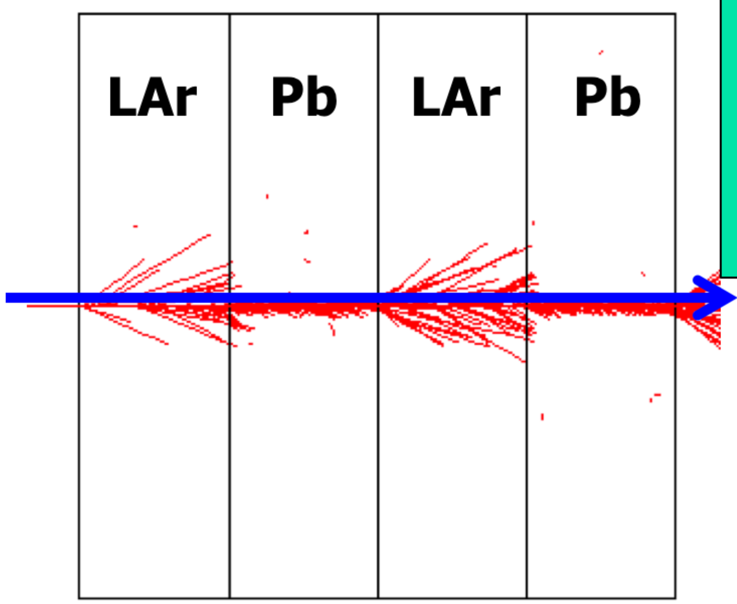
Cut = 455 keV



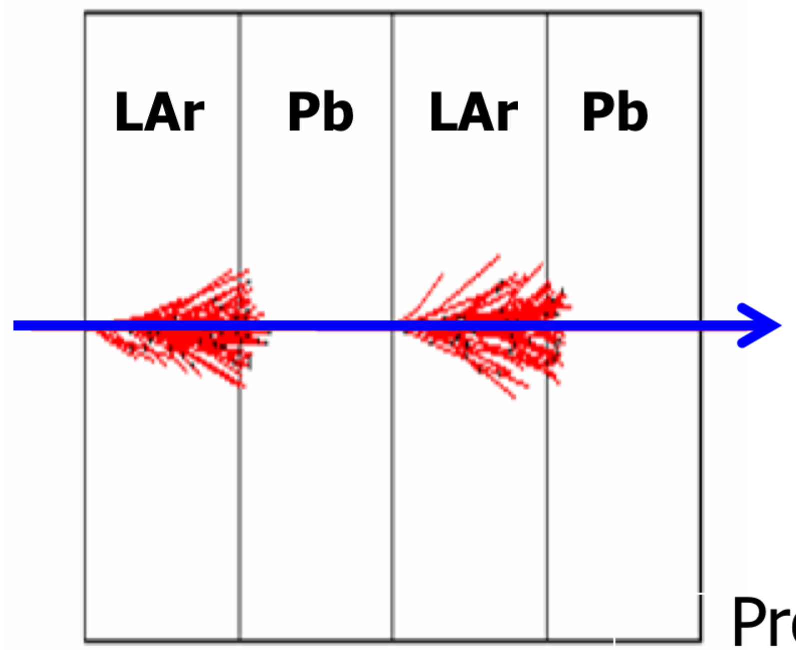
Cut = 2 MeV

Cut in range: an example

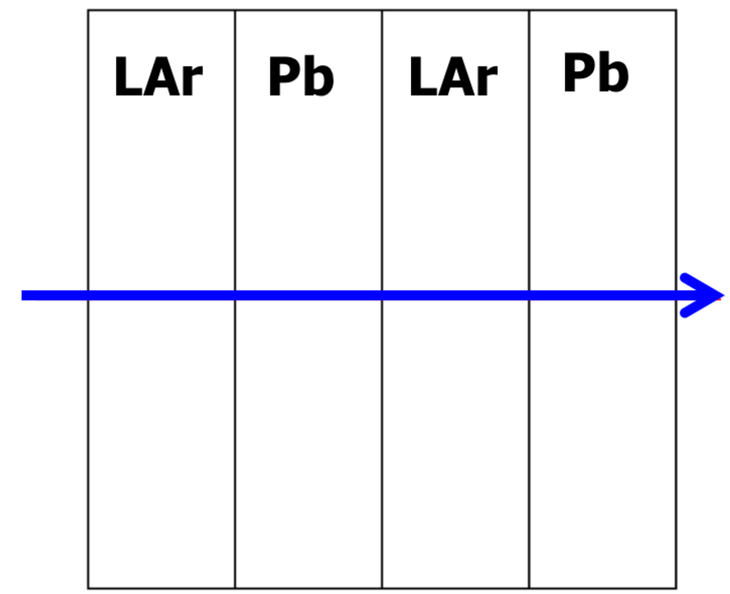
500 MeV p in
LAr-Pb sampling
calorimeter



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



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()

Production threshold values should be defined in SetCuts() which is a virtual method of the 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

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
```

Cut 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)
- 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

Physics model and processes

Phylosophy

- Provide a **general model framework** that allows the implementation of **complementary/alternative models** to **describe the same process**

  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 are under continuous development!

Phylosophy

- Building a physics list or choosing from already built physics lists is highly dependent on your use-case
- In either case, you need to be familiar with the major physics processes used to build them
  - the process-model catalog is useful for this
  - see Geant4 web page under User Support
- Geant4 provides several "reference physics lists" which are routinely validated and updated with each release
  - these should be considered only as starting points which you may need to modify for your application
- There are also many physics list in the examles which can copy
  - these are usually very specific to agiven use-case

Phylosophy

There are currently **28 “packaged” physics lists available**

- but you will likely interested in only a few, namely the “reference physics lists”

- many physics lists are either developmental or cutomized in some way, and so not very useful to new users

Reference physics lists

- QGSP_BERT, QGSP_BERT_EMV, QGSP_BERT_HP, QGSP_BIC, FTFP_BERT, LBE, LHEP
- plus a few more

Conventional Physics List

INFN GEANT

- "QGS" Quark gluon string model (>~20GeV)
- "FTF" Fritiof Model (>~10GeV)
- "LHEP" Low and High energy parameterization model
- "BIC" Binary Cascade Model (<~10 GeV)
- "BERT" Bertini Cascade Model (<~10 GeV)
- "HP" High Precision Neutron Model (<20MeV)
- "PRECO" Pre compound Model (<~150MeV)
- "EMV(X)" Variation of Standard EM package

Electromagnetic Physics

EM concept

The electromagnetic physics domain includes Geant4 sub-packages for simulation of electromagnetic (EM) interactions of charged particles, gammas and optical photons.

EM processes usually have no applicability limitation by energy of media.
Physics tables with pre-computed cross sections, energy losses, ranges are build by default from 0.1 keV to 100 TeV.

Basic EM processes utilizing model approach allowing to include one or several models applied for different energy interval and geometrical region.

EM processes and models design for Monte Carlo simulation in High Energy Physics (HEP) are developed and maintained by the Electromagnetic Standard working group.

EM concept

Many models available for each process (plus one full set of polarized models):

Different for energy range, precision and CPU speed

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

EM concept

- The same physics processes **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)

Packages overview

Models and processes for the description of the EM interaction in Geant4 have been prouped 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 gamma and electron

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 for muons

Particle	Process	G4Process
$\mu^{\pm}$	Ionisation	`G4MuIonisation`
	Bremsstrahlung	`G4MuBremsstrahlung`
	Multiple scattering	`G4MuMultipleScattering`
	$e^{\pm}$ pair production	`G4MuPairProduction`

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

EM Standard models

- Complete set of models for $e^{\pm}$, γ, ions, hadrons, $\mu^{\pm}$

  "Cheaper" in terms of CPU
  Include high-energy corrections
  Include assumptions made in the low-energy regime

- Both Theoretical and phenomenological models
  Bethe-Bloch, corrected Klein-Nishina, …
  Photoabsorption Ionization

- Ionization energy loss of a relativistic charged partigle in matter
- Specific high-energy extensions available
- Extra processes, as γ μ+μ-, e^+e^- -> μ+μ-
- Dedicated sub-library for optical photons

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

- Mixture of experiments and theories

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 model

- 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

EM Physics Constructors for Geant4.10.03.p01

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

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

How to use an already implemented EM physics list?

Physics list classes derive from the G4VPhysicsConstructor

- A good implementation example of PhysicsList class that use EM models is already available_

  $G4INSTALL/examples/extended/electromagnetic/TestEm2

In your PhysicsList class, you need to :

- Create a dynamic Physics List object in the constructor
  - For eg. `emPhysicsList = new G4EmLivermorePhysics();`
- Delete it in the destructor
- Define particles in the `PhysicsList::ConstructParticle()` method
- Eventually set your production cuts

Hadronic Physics

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 list for Hadronic interactions

Two families of builders for the high-energy part

- **QGSP**, 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

Reference physics list for QGSP

- QGSP_BERT
  - the physics list most recommended for HEP
  - used by ATLAS
  - contains standard EM processes
  - uses Bertini cascade for hadrons of energy below ~10 GeV
  - uses QGS model for high energies (> 20 GeV)

- QGSP_BERT_EMV
  - also recommended for HEP
  - same as QGSP_BERT, but with EM processes tuned for better CPU performance
    - increase in speed comes with a slight decrease in EM precision
  - used by CMS

- QGSP_BERT_HP
  - same as QGSP_BERT, but with high precision neutron model
  - used for neutrons below 20 MeV
  - significantly slower than QGSP_BERT when full thermal cross sections used
    - can speed up significantly by turning off thermal scattering
  - can be used for radiation protection and shielding applications

ParticleHP Models

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).

- 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

NEW!

NeutronHP fully merged with **ParticleHP** since 10.3

Quick overview of validation

Geant4 Validation

Geant 4

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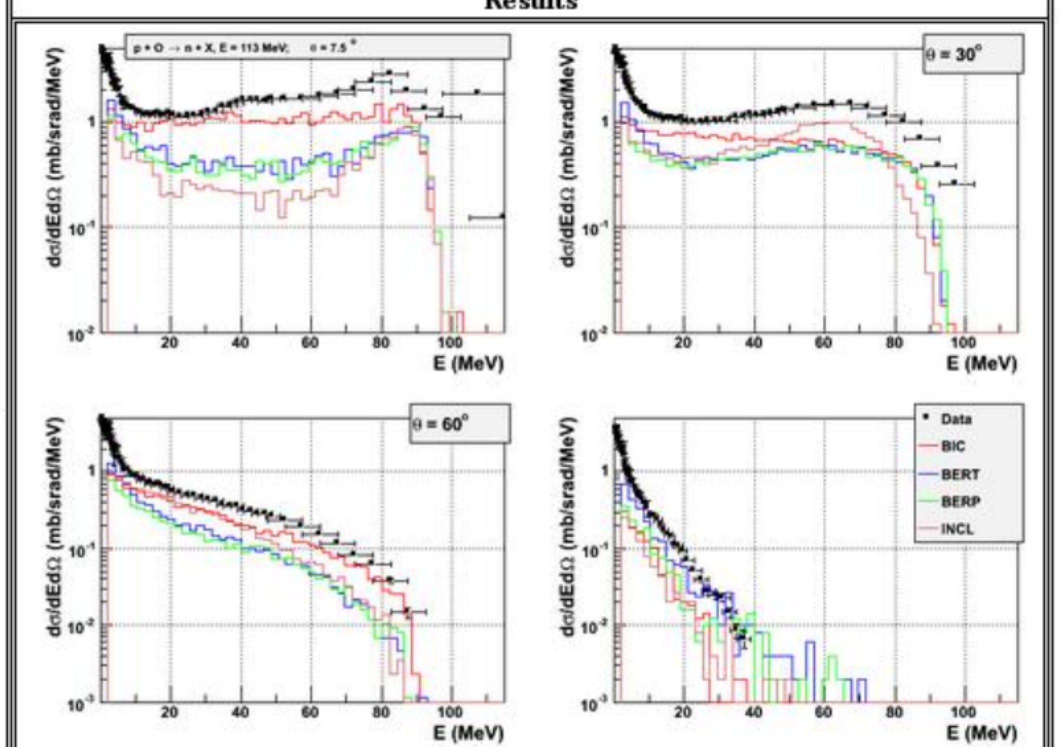
Name of the Test:	test30
Responsible:	V. Ivanchenko
Description:	Test of hadronic generators of inelastic processes

Geant4 Version:	geant4-09-06-ref-00a
Observable:	pn_o_113
Reaction:	p + O -> n + X, 113 MeV/c
Status:	public

Test Conditions	
Name	**Description**
Target	Oxygen
Particle	proton
Observable	dSigma/dEdOmega
Energy	113 MeV/c
Upload date	Thu Dec 20 17:44:00 CET 2012
Description	Neutron spectra
Data Source	Meier et al., Nucl. Sci. Eng. 104, 1990
last-modified	2012-12-27 13:41:33 CST
Score:	passed
Type:	expert

Results

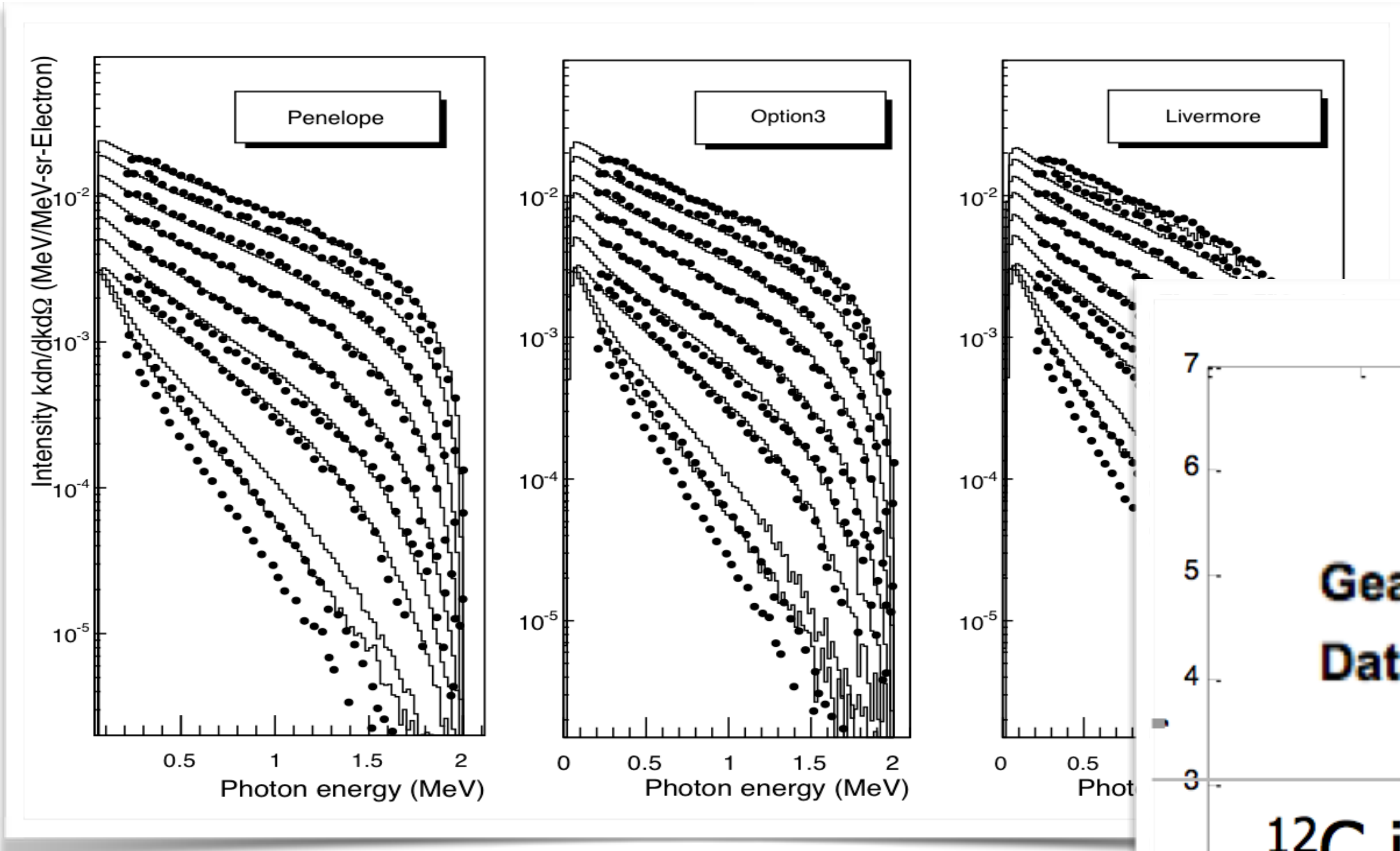


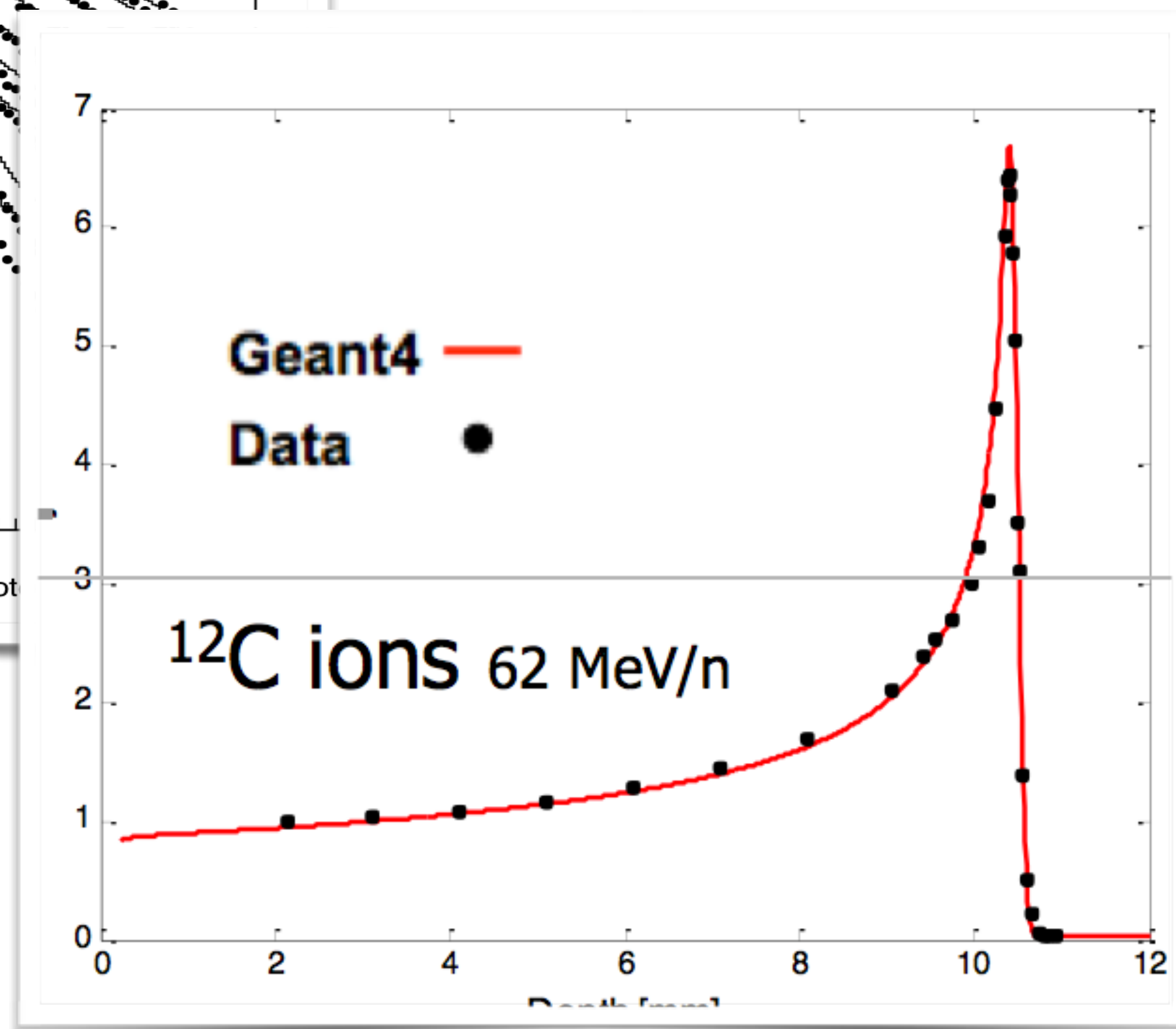
List of hadronic Tests

- HadrIon
- HadrXS
- IAEA
- Testfragm
- simplifiedCalo
- test19
- test22
- test30
  - geant4-09-06-ref-00
  - p + O -> n + X, 113 MeV/c
- test35
- test45
- test47
- test48
- test75

EM Validation

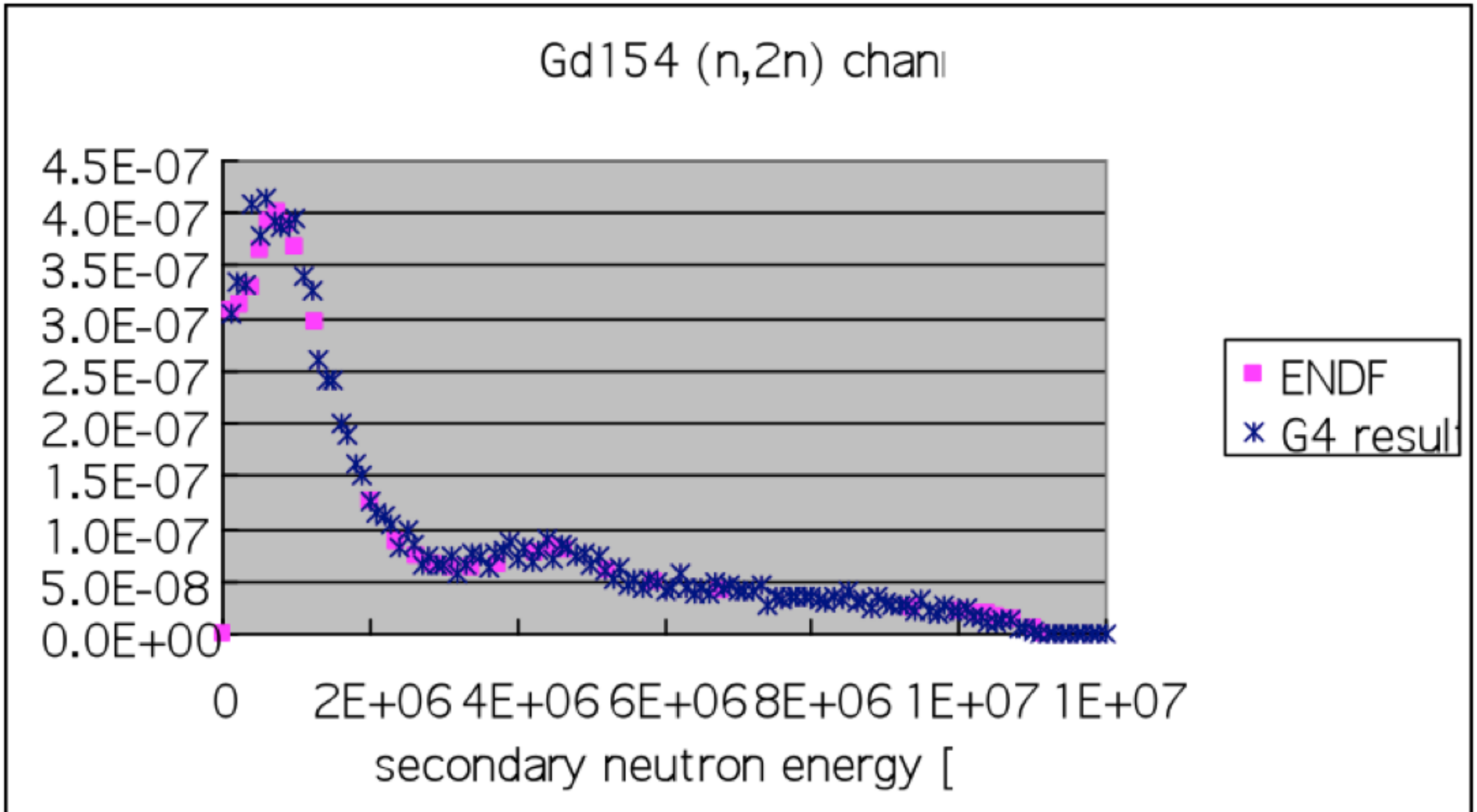
http://cern.ch/vnivanch/verification/verification/electromagnetic/





Hadronic Validation

http://geant4.cern.ch/results/validation_plots.htm
http://g4validation.fnal.gov:8080/G4ValidationWebApp/



Thank you for your attention!