

PHYSICS CONTENT OF GEANT4

“MORE ON PHYSICS”

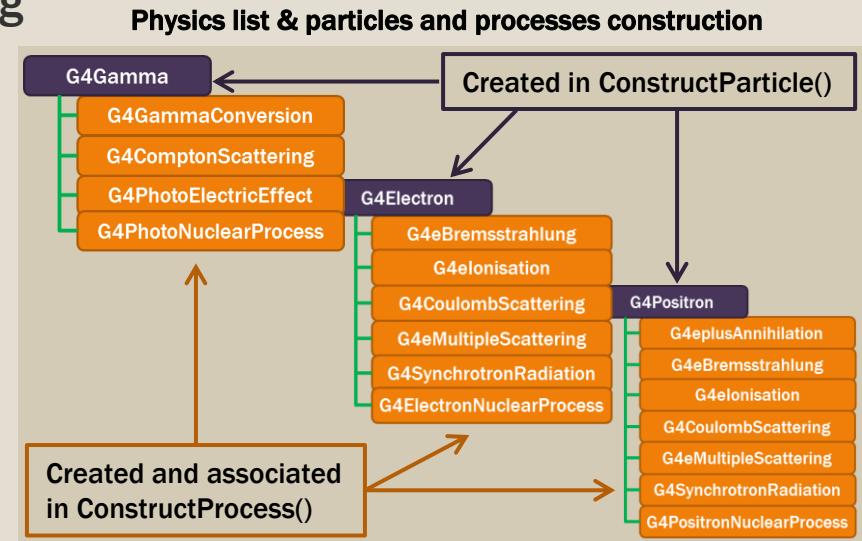
Geant4 PHENIICS
& IN2P3 Tutorial,
13 - 17 May 2019,
Orsay

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INTRODUCTION

- We have seen that:

- Geant4 organizes physics modeling with the “physics list” concept.
- Physics lists create in memory
 - particle types,
 - processes,
 - and bind these processes to the particles.
- Tools (constructors, modular physics lists, etc.) help to build these more easily.



- We now look into more details to the physics content(s) provided in the concrete implementation of processes
 - Eg : what is there in **G4ionlonisation** ?

CREDITS

- For the EM physics, Vladimir Ivanchenko (CERN) and Mihaly Novak, Michel Maire and Sébastien Incerti (IN2P3).
- For Hadronic physics, Dennis Wright, Tatsumi Koi (SLAC) and Alberto Ribon (CERN) presentations.
- Both sources may have more filiation.

OUTLINE

- I. Generalities
- II. EM physics
- III. Optical Physics
- IV. Decay Physics
- V. Hadronic Physics (tomorrow)

I. GENERALITIES

THE PHYSICS PACKAGES

- The processes are located under
 - `geant4/source/processes`
- Which holds the packages:
 - biasing
 - cuts
 - decay
 - electromagnetic
 - hadronic
 - management
 - optical
 - parameterisation
 - phonon
 - scoring
 - transportation

THE PHYSICS PACKAGES

- The processes are located under the directory
 - `geant4/source/processes`
- Which holds the packages:

▪ <code>biasing</code> ,	technical,	interfaces for biasing
▪ <code>cuts</code> ,	technical,	utilities for production thresholds
▪ <code>decay</code> ,	<code>physics</code> ,	decay of particles with lifetime > 0
▪ <code>electromagnetic</code> ,	<code>physics</code> ,	gamma, X-ray & charged particles
▪ <code>hadronic</code> ,	<code>physics</code> ,	hadron& gamma-/lepto-nuclear
▪ <code>management</code> ,	technical,	general interfaces to all processes
▪ <code>optical</code> ,	<code>physics</code> ,	optical photon processes
▪ <code>parameterisation</code> ,	technical,	interfaces for fast simulation
▪ <code>phonon</code> ,	<code>physics</code> ,	phonon transport
▪ <code>scoring</code> ,	technical,	interfaces for scoring
▪ <code>transportation</code> ,	technical,	geometry boundaries and field

PHYSICS MODELLING APPROACHES

- Physics packages have evolved their own designs
 - Driven by physics specificities
- They share however similar approaches:
 - Physics quantities (cross-sections, stopping powers, final states) are computed by means of:
 - **Parameterizations**
 - “Heuristic” formulae established on some measurements
 - Approach gradually deprecating in Geant4
 - **Databases**
 - Usually large data sets of direct measurements of quantities (cross-sections, final states, etc.)
 - Very much used in hadronic physics
 - low energy neutrons, radioactive decays, etc.
 - But also in electromagnetic physics, specially at low energy
 - effects of detailed atomic structure, etc.
 - **Theory-driven models**
 - Based partly or fully on theoretical considerations
 - More often the case at high energies
 - Approaches are mixed in processes and/or physics lists
 - trying to provide “at best” combinations.

THE PHYSICS DATASETS (GEANT4 V10.5)

Details at http://geant4.web.cern.ch/support/data_files_citations

Name	Version	Env. Var. Name	Physics coverage	#Mb
G4NDL	4.5	G4NEUTRONHPDATA	Neutron data files with thermal cross-sections	402.2
G4EMLOW	7.7	G4LEDATA	data files for low energy electromagnetic processes	102.3
G4PhotonEvaporation	5.3	G4LEVELGAMMADATA	data files for photon evaporation (from ENSDF)	9.4
G4RadioactiveDecay	5.3	G4RADIOACTIVEDATA	data files for radioactive decay hadronic processes (from ENSDF)	1.0
G4SAIDDATA	2.0	G4SAIDXSDATA	data files from evaluated elastic cross-sections in SAID data-base	0.037
G4PARTICLEXS	1.1	G4PARTICLEXS DATA	data files for evaluated particle XS on natural composition of elements	3.2
G4ABLA	3.1	G4ABLADATA	data files for nuclear shell effects in INCL/ABLA hadronic model	0.105
G4INCL	1.0	G4INCLDATA	data files for proton and neutron density profiles in INCL	0.094
G4PII	1.3	G4PIIDATA	data files for shell ionization cross-sections	4.1
RealSurface	2.1.1	G4REALSURFACEDATA	Optional data files for measured optical surface reflectance	127
G4ENSDFSTATE	2.2	G4ENSDFSTATEDATA	Data files for nuclides properties	0.284
G4TENDL	1.3.2	G4TENDL DATA DIR (+ dir. / particle)	Optional data files for incident particles	558

LAST GENERAL PAPER

- Take advantage of recently published paper !
 - Provides a fresh full overview of Geant4,
 - including physics options,
 - All this in one single paper

The screenshot shows a ScienceDirect article page for 'Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment'. The article is titled 'Recent developments in GEANT4' and is from Volume 835, 1 November 2016, Pages 186–225. It features highlights, abstract, keywords, and a detailed article outline. The right sidebar includes recommended articles, recent developments in Geant4, non-DSB clustered DNA lesions, clinical utility of combined FDG-PET/MR, and related book content.

- Available in open access

II. EM PHYSICS

GEANT4 EM PHYSICS PACKAGES

■ Standard

- γ , e^\pm up to 100 TeV
- hadrons up to 100 TeV
- ions up to 100 TeV

■ Muons

- up to 1 PeV
- energy loss propagator

■ X-rays

- X-ray and optical photon production

■ High-energy

- processes at high energy ($E > 10$ GeV)
- physics for exotic particles

■ Polarization

- simulation of polarized beams

■ Low-energy

- Livermore library
 - γ , e^- from 10 eV up to 1 GeV
 - polarized processes
- PENELOPE rewrite (2008 version)
 - γ , e^- , e^+ from 100 eV up to 1 GeV
 - hadrons and ions up to 1 GeV
- Atomic de-excitation
 - fluorescence + Auger
- Geant4-DNA
 - microdosimetry models for radiobiology
 - from 0.025 eV to 10 MeV
- Adjoint
 - New sub-library for reverse Monte Carlo simulation from the detector of interest back to source of radiation

EM DESIGN : PROCESSES & MODELS

- A **physics process** is described by a process class (**G4VEmProcess**):
 - Naming scheme : « G4**ProcessName** »
 - For example: G4Compton for photon Compton scattering
- A physics process can be hold **several models**, each model being described by a model class (**G4VEmModel**):
 - Naming scheme : G4**ModelNameProcessNameModel** or G4**ModelNameModel** ...
 - For example: G4LivermoreComptonModel
 - Models are valid in certain **energy ranges** and can be assigned to **G4Regions**
 - Meaning the **EM physics level description** can be adapted to the regions
- Models implement the **physics contents**, ie:
 - Cross section and stopping power
 - Sample selection of atom in compound
 - Final state (kinematics, production of secondaries...)

EXAMPLE : MULTIPLE SCATTERING FOR e⁻

- In G4EmStandardPhysics constructor:

```
...
G4double highEnergyLimit = 100*MeV;
...
G4eMultipleScattering* msc = new G4eMultipleScattering;
G4UrbanMscModel* msc1 = new G4UrbanMscModel();
G4WentzelVIModel* msc2 = new G4WentzelVIModel();
msc1->SetHighEnergyLimit(highEnergyLimit);
msc2->SetLowEnergyLimit(highEnergyLimit);
msc->AddEmModel(0, msc1);
msc->AddEmModel(0, msc2);
```

EXAMPLE : MULTIPLE SCATTERING FOR e^-

- In G4EmStandardPhysics constructor:

```
...  
G4double highEnergyLimit = 100*MeV;  
...  
G4eMultipleScattering* msc = new G4eMultipleScattering;  
G4UrbanMscModel* msc1 = new G4UrbanMscModel(); ← creation  
G4WentzelVIModel* msc2 = new G4WentzelVIModel(); ← creation  
msc1->SetHighEnergyLimit(highEnergyLimit);  
msc2->SetLowEnergyLimit(highEnergyLimit);  
msc->AddEmModel(0, msc1);      attachment to msc process  
msc->AddEmModel(0, msc2);      attachment to msc process
```

creation of the physics process (G4VProcess)

creation

the physics models for the multiple-scattering

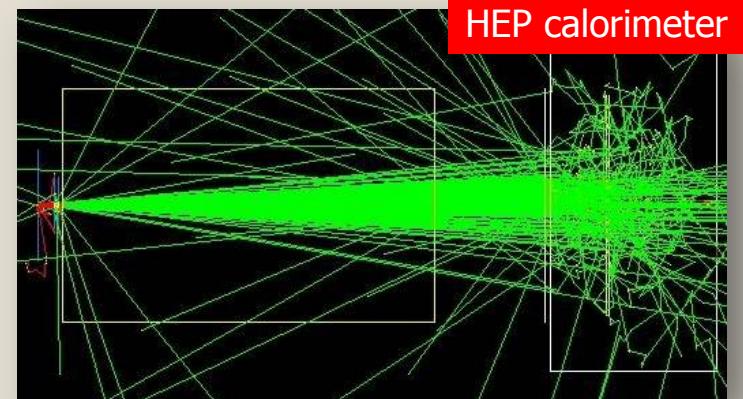
The diagram illustrates the sequence of operations in the G4EmStandardPhysics constructor. It starts with the creation of a G4eMultipleScattering object (highlighted in blue). Two G4UrbanMscModel objects (highlighted in red) and two G4WentzelVIModel objects (highlighted in green) are then created. These models are attached to the msc process using the AddEmModel method. Arrows indicate the flow from the creation of each model to its addition to the msc object.

II.1 - OVERVIEW OF EM STANDARD PHYSICS

STD EM PROCESSES FOR GAMMA AND ELECTRON TRANSPORT

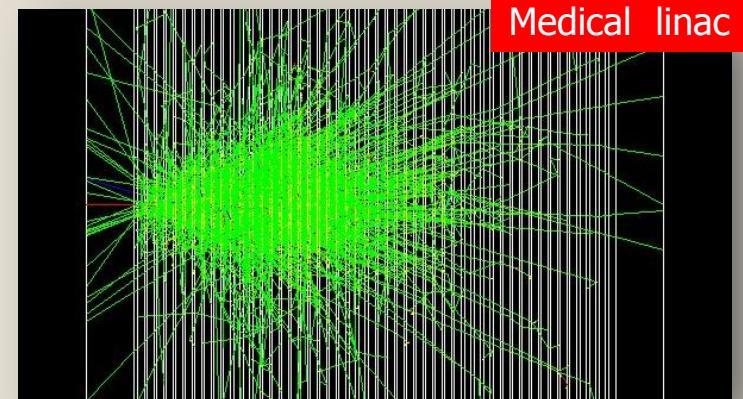
Photon processes

- γ conversion into e^+e^- pair
 - Bethe Heitler $E < 80$ GeV
 - Includes LPM effect $E > 80$ GeV
- Compton scattering
 - Klein Nishina + atomic effects
- Photoelectric effect
 - Photo-electric + atomic deexcitation
- Rayleigh scattering
 - (except for basic EM standard)



Electron and positron processes

- Ionization
 - Moller Bhabha for cross-section
 - Berger Seltzer + atomic data for dE/dx from ion.
- Coulomb scattering
 - Used alone or with MSC for large angles scattering.
- Bremsstrahlung
 - Berger Seltzer $E < 1$ GeV
 - Includes LPM effect $E > 1$ GeV
- Positron annihilation



- Suitable for HEP & many other Geant4 applications with e^- and γ beams

II.2 – CONDENSED HISTORY MODELS

Ionization,
Multiple
Scattering

STD EM PROCESS FOR HADRON AND ION TRANSPORT : IONIZATION

- EM processes take care of ionization by hadron & ion tracks
- If $\sigma(E, e)$ = cross-section for ion of energy E to eject e^- of energy e in current material with $n_{at.}$ atoms per unit volume:

Continuous loss from soft e^- ($e < e_{cut}$)

Mean energy loss:

$$\left\langle \frac{dE}{dx} \right\rangle_{loss}^{soft} = n_{at.} \int_0^{e_{cut}} \frac{d\sigma(E, e)}{de} \cdot e \cdot de$$

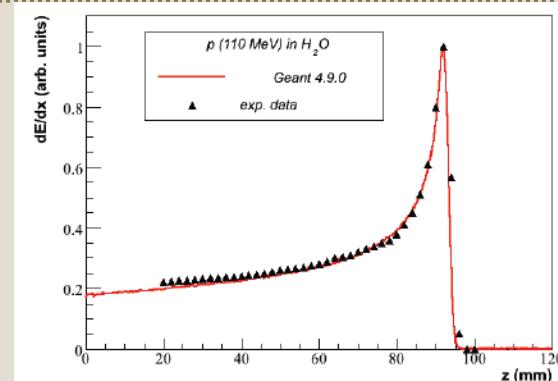
Discrete loss from hard e^- ($e > e_{cut}$)

Total XS for δ -ray production:

$$\sigma_{total}^{hard} = \int_{e_{cut}}^{e_{max}} \frac{d\sigma(E, e)}{de} \cdot de$$

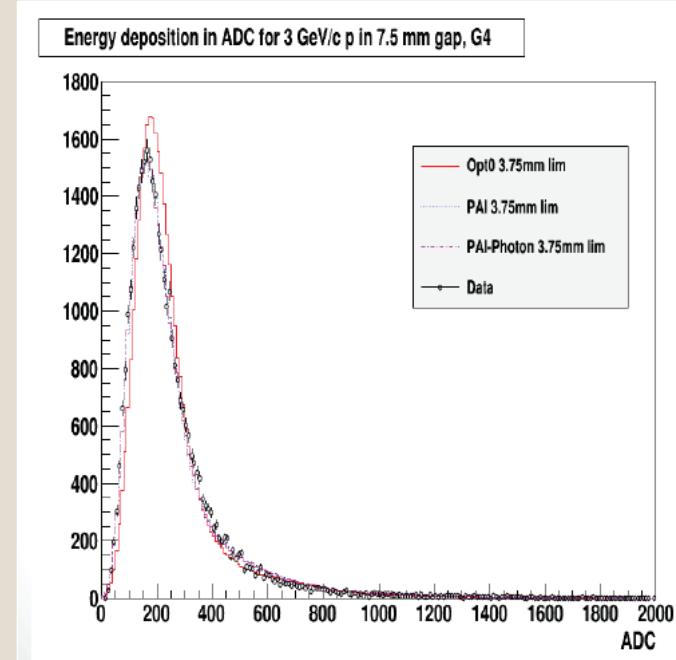
- For ions, continuous loss described:

- By Bethe-Bloch for $E > 2$ MeV
 - [G4BetheBlochModel](#)
- Bragg peak parameterization $E < 2$ MeV
 - Using ICRU'49
 - and NIST data
 - [G4BragglonModel](#)



FLUCTUATION ON (MEAN) IONIZATION

- As stochastic process, ionization has fluctuations:
 - Simulation of discrete part (δ -ray) intrinsically takes these into account
 - Model for fluctuations must be added to the continuous part
- Two models are proposed:
 - Urban Modelling:
 - Based on simplified atomic model:
 - Assumed only two levels E_1 , E_2
 - Particle-atom interactions can be:
 - An excitation of atom with energy loss $E = E_1 - E_2$
 - An ionization, with energy loss distribution $\sim 1/E^2$
 - G4UniversalFluctuation class
 - PAI (photo-absorption ionization)
 - Use photo-absorption cross-section data
 - Energy transfers sampled with production of e^- and γ
 - Very slow model, to be used in sensitive area
 - Meant for (very) thin detectors
 - G4PAIModel (e^-) & G4PAIPhotModel (e^-, γ)



Energy deposition in ALICE TPC Geant4

Nucl. Instr. Meth. A, 565, 551-560 (2006)
Int. J. Mod. Phys. E, 16, 2457-2462 (2007)

SUMMARY OF IONIZATION PROCESSES AND MODELS

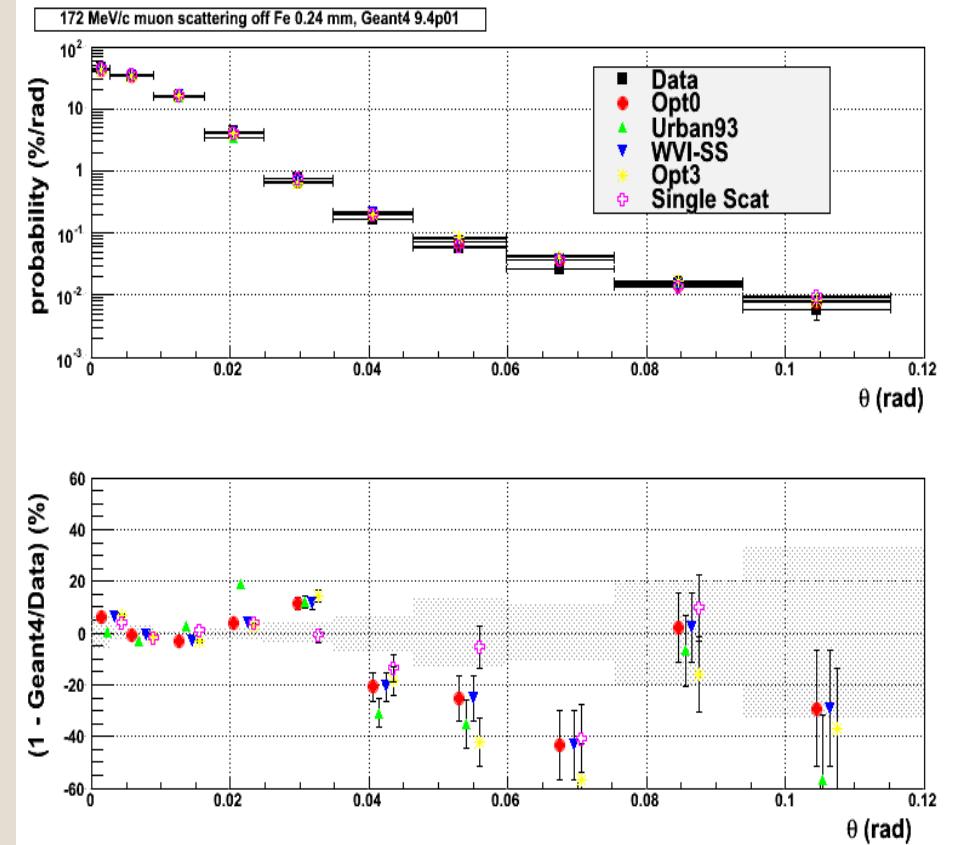
Table 2

List of GEANT4 ionization processes and models with recommended energy range.

Particle	Process	Model	Energy range
e^-/e^+	G4eIonisation	G4MollerBhabhaModel	10 keV–10 TeV
e^-/e^+		G4PenelopeIonisationModel	0.1 keV–5 GeV
e^-		G4LivermoreIonisationModel	0.1 keV–1 MeV
All		G4PAIModel	0.1 keV–10 TeV
All		G4PAIPhotModel	0.1 keV–10 TeV
Muons	G4MuIonisation	G4BraggModel	0.1 keV–0.2 MeV
		G4BetheBlochModel	0.2 MeV–1 GeV
		G4MuBetheBlochModel [51]	1 GeV–10 PeV
Hadrons	G4hIonisation	G4BraggModel	1 keV–2 MeV
		G4BetheBlochModel	2 MeV–10 TeV
		G4ICRU73QOModel [52]	5 keV–10 MeV
Ions	G4ionIonisation	G4BraggIonModel	(1 keV–2 MeV)/u
		G4BetheBlochModel	(2 MeV–10 TeV)/u
		G4IonParametrisedLossModel [53]	(1 keV–1 GeV)/u

MULTIPLE COULOMB SCATTERING (MSC)

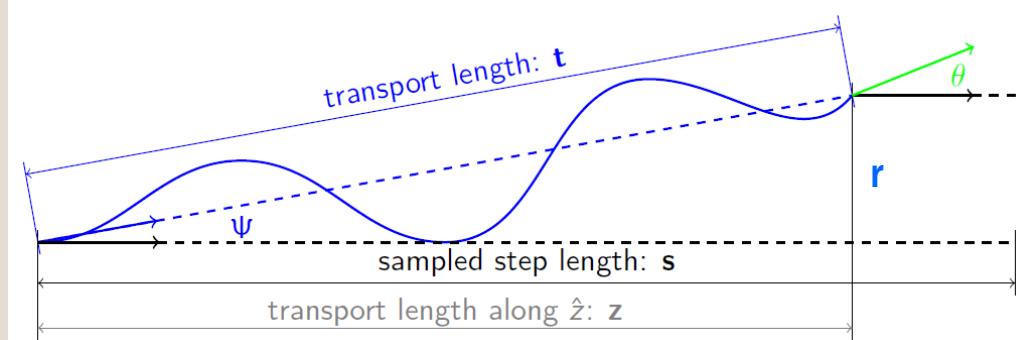
- Charged particles traversing a finite thickness of matter suffer *numerous* elastic Coulomb scattering
 - $> 10^6 / \text{mm} !$
- The **cumulative effect** of these small angle scatterings is a **net deflection** from the original particle direction
- MSC implementation determines accuracy and CPU performance of simulation



MSC ALGORITHM

Legend

- True path length : t
- Geometrical displacement : z
- Lateral displacement : r
- Angular deflection : (θ, ψ)



- The algorithm performs several steps for the simulation of MSC which are essentially the same for many « condensed » simulations
 - The physics processes and the geometry select the step length; MSC performs the $t \leftrightarrow z$ transformation only
 - The transport along the initial direction is not MSC's business
 - Sampling of scattering angle (θ, ψ)
 - Computing of lateral displacement and relocation of particle

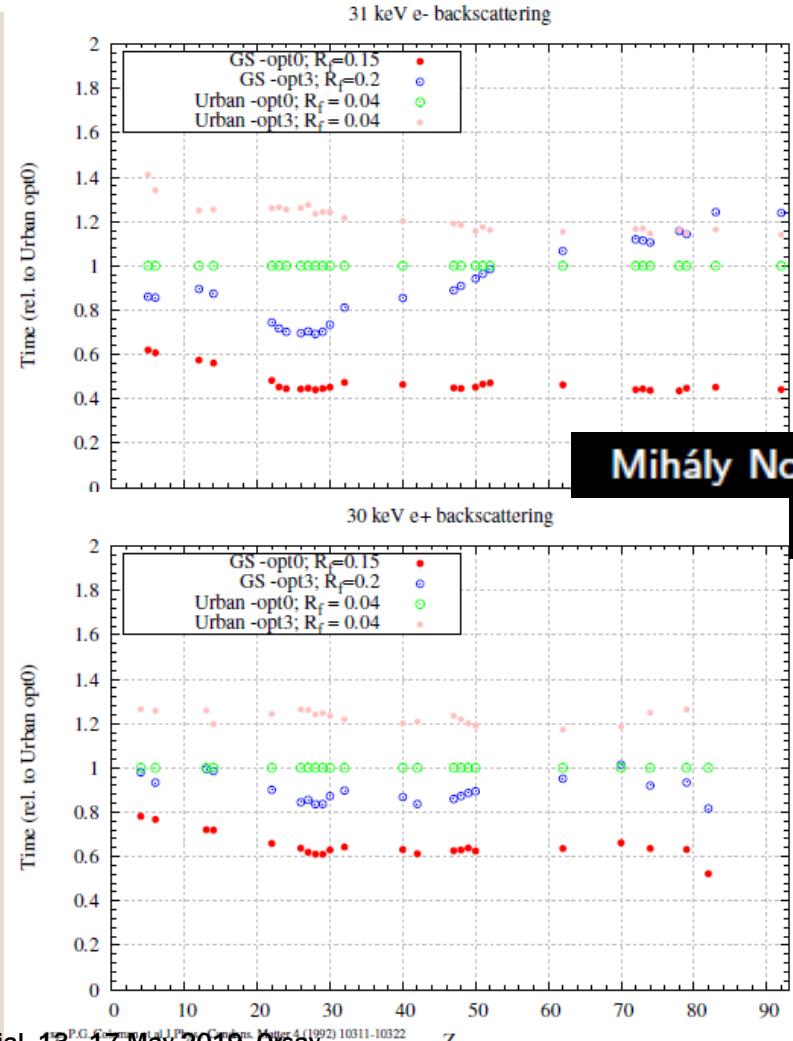
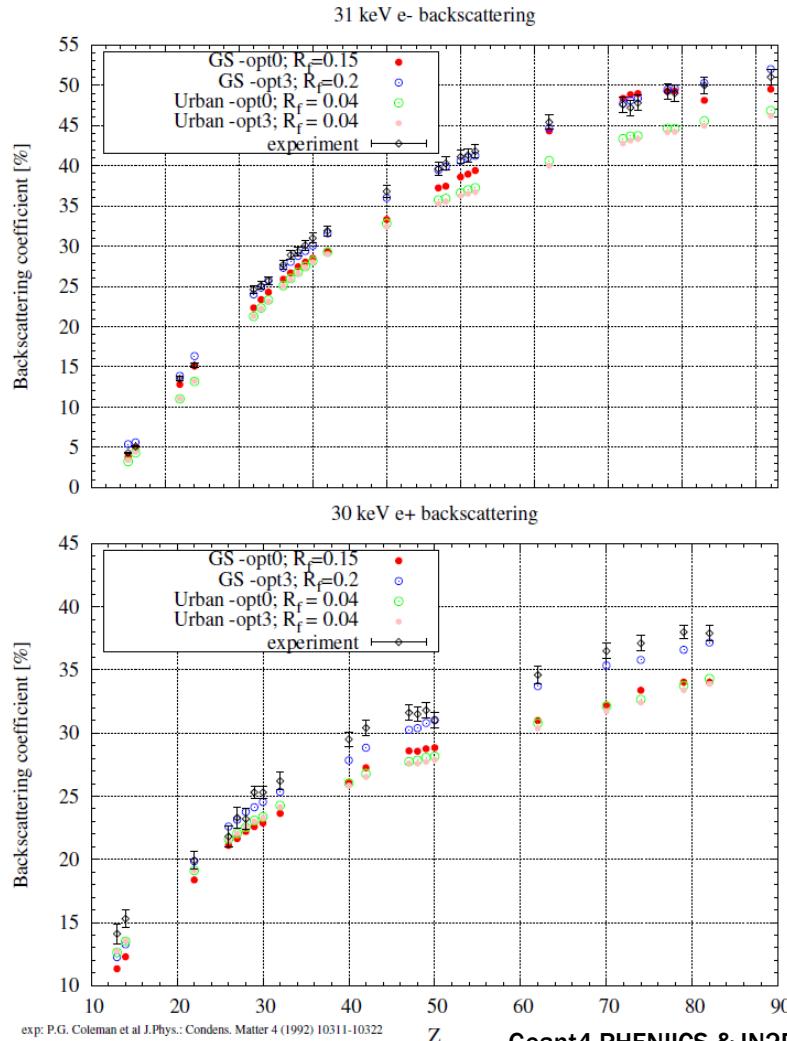
MSC AND SINGLE SCATTERING MODELS

Model	Particle type	Energy limit	Specifics and applicability
Urban (Urban 2006)	Any	-	Default model for electrons and positrons below 100 MeV, (Lewis 1950) approach, tuned to data, <u>used for LHC production</u> .
Screened Nuclear Recoil (Mendenhall and Weller 2005)	p, ions	< 100 MeV/A	Theory based process, providing simulation of nuclear recoil for sampling of radiation damage, focused on precise simulation of effects for space app.
Goudsmit-Saunderson (Kadri 2009)	e ⁺ , e ⁻	< 1 GeV	Theory based cross sections (Goudsmit and Saunderson 1950). EPSEPA code developed by Penelope group, final state using EGSnrc method (Kawrakov et al. 1998), precise electron transport
Coulomb scattering (2008)	any	-	Theory based (Wentzel 1927) single scattering model, uses nuclear form-factors (Butkevich et al. 2002), focused on muons and hadrons
WentzelVI (2009)	any	-	MSC for small angles, Coulomb Scattering (Wentzel 1927) for large angles, focused on simulation for muons and hadrons .
Ion Coulomb scattering (2010) Electron Coulomb scattering (2012)	Ions e ⁺ , e ⁻	-	Model based on Wentzel formula + relativistic effects + screening effects for projectile & target. From the work of P. G. Rancoita, C. Consolandi and V. Ivantchenko.

MSC CLASSES

- Processes per particle type are available
 - **G4eMultipleScattering** for e+/e-
 - **G4MuMultipleScattering** for μ^+/μ^-
 - **G4hMultipleScattering** for hadrons and ions
- L. Urban model
 - **G4UrbanMscModel** :
 - The most established Geant4 scattering model
- Combined multiple and single scattering model:
 - **G4WentzelVIModel + G4eCoulombScatteringModel**
 - Applied for high energy e+-, muons, hadrons
- Alternative single and multiple scattering models are available to users
 - see **extended examples...**

COMING NOW : COMPLETE REWRITE OF GOUDSMIT-SAUNDERSON MODEL



II.3 - ATOMIC DE-EXCITATION

Fluo-
rescence,
Auger &
PIXE

ATOMIC DE-EXCITATION/RELAXATION

- Atom's shell configuration can be disturbed:

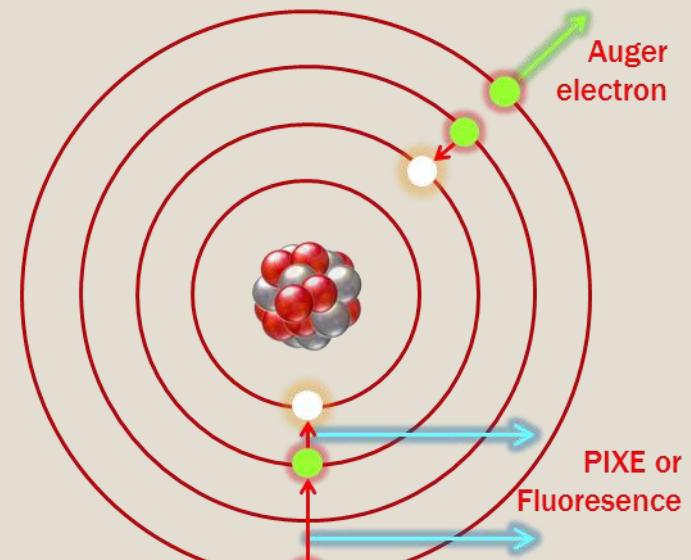
- Directly for electromagnetic interactions :
 - photo-electric, Compton, ionization, ...
- Or by Z change of nucleus:
 - Radioactive decay :
 - with Z change (β^\pm , α , electronic capture)
 - Nuclear evaporation, etc.

- Atomic relaxation follows and atom can de-de-excite through:

- Fluorescence
- Auger
- PIXE (Particle Induced X-Ray Emission)

- Simulation requires detailed atomic structure:

- EADL transition probability data used (Livermore)
- radiative**: fluorescence
- non-radiative**:
 - Auger (initial & final vacancies in \neq sub-shells)
 - Coster-Kronig (same sub-shells)



INCLUDING/ACTIVATING ATOMIC EFFECTS

- Atomic de-excitation can be activated for any EM physics options
 - See more in **X-Ray Spec. 40 (2011) 135-140**
- By default, reference physics include atomic deexcitation
 - As they use EM physics constructors, which include the deexcitation
- Then, atomic deexcitation can be easily (de)activated via UI commands
 - `/run/initialize`
 - `/process/em/deexcitation regionName true false false`
 - region where to activate, can be World
 - or, individually
 - `/process/em/fluo true`
 - `/process/em/auger true`
 - `/process/em/pixe true`

} if no region specified (as before), World is assumed
- To do the same with C++ code, use the **G4EmParameters** class:
 - `G4EmParameters* param = G4EmParameters::Instance();`
 - `param->SetDeexActiveRegion(regionName,true,false,false);`
 - or, individually
 - `param->SetFluo(true);`
 - `param->SetAuger(true);`
 - `param->SetPixe(true);`

INCLUDING/ACTIVATING ATOMIC EFFECTS

- Fluorescence is activated by default in all EM constructors
 - except in the Standard one, **G4EmStandardPhysics**;
- Last, no least:
 - Deexcitation module *takes into account production thresholds*
 - But deexcitation particles are generally of low energy
 - They hence might not be produced...
 - To **force** deexcitation particles to be produced:
 - `/process/em/deexcitationIgnoreCut true`
 - or, with C++:
 - `param->SetDeexcitationIgnoreCut(true);`

OPTIONS FOR SHELL CROSS SECTION MODELS

- Ionisation cross section models for PIXE can be changed:

- /run/initialize
- ...
- /process/em/pixeXSmodel **Empirical**
 - or **ECPSSR_FormFactor** or **ECPSSR_Analytical**
- param->SetPIXECrossSectionModel("Empirical");
 - or "ECPSSR_FormFactor" or "ECPSSR_Analytical"

"Energy-Loss Coulomb-Repulsion Perturbed-Stationary-State Relativistic Theory"

- Shell cross sections are available for **K**, **L** and selected **M** shells:

- Empirical** models:
 - from Paul "reference values" (for p and α for **K**-Shell) and Orlic empirical model for **L** shells (only for p and ions with $Z>2$);
- ECPSSR_FormFactor** models:
 - derive from A. Taborda et al. calculations of ECPSSR values directly from Form Factors and it covers **K**, **L** shells in the range 0.1-100 MeV and **M** shells in the range 0.1-10 MeV;
- ECPSSR_Analytical** models:
 - derive from an in-house analytical calculation of the ECPSSR theory.

- By default "Empirical" models are used and "ECPSSR_Analytical" models take over out of related energy ranges. Default setting is recommended.

- Shell cross section can also be selected for e^- , eg:

- /process/em/pixeElecXSmodel **Livermore** (or **Penelope**)

X-Ray Spec. 40 (2011) 127-134

X-Ray Spec. 40 (2011) 135-140

II.4 - LOW EM ENERGY

Livermore
Penelope
Ion energy
loss

PURPOSE OF LOW ENERGY EM PACKAGE

- Extend coverage of Geant4 EM interactions with matter
 - for photons, electrons, positrons and ions
 - down to sub-keV scale energies
- Choices of physics models include
 - Livermore : electrons and photons [250 eV - 1 GeV]
 - Penelope : electrons, positrons and photons [100 eV - 1 GeV]
 - Microdosimetry models
 - Geant4-DNA project: [eV - ~ few 100 MeV]
 - MuElec for Silicon : [eV - 1 GeV/u]
- Possible domains of applications
 - Space science
 - Medical physics
 - Underground experiments
 - Microdosimetry for radiobiology and microelectronics
 - ...

LIVERMORE MODELS

ELECTRON AND GAMMA INCIDENT (but no e⁺)

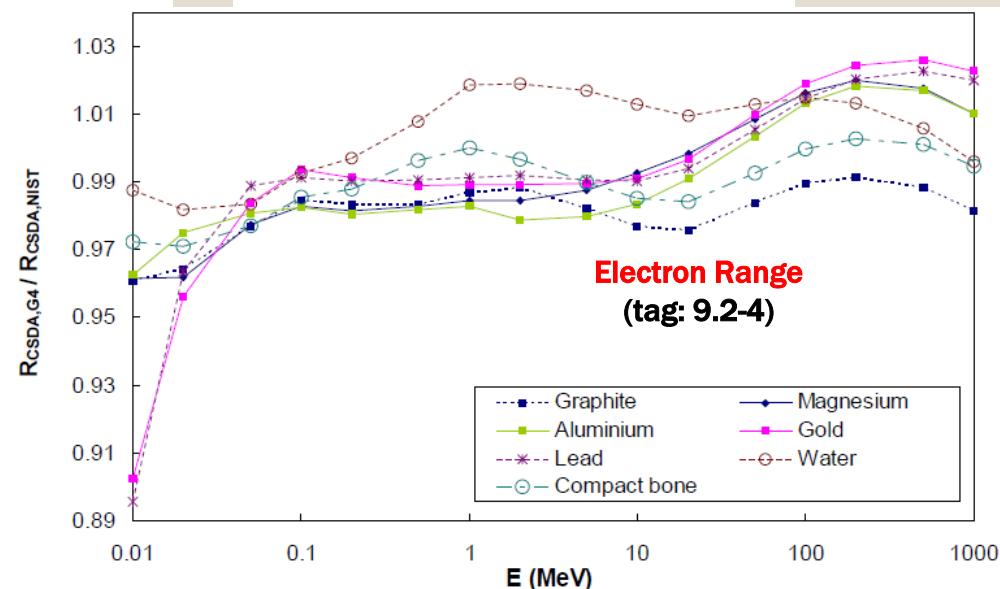
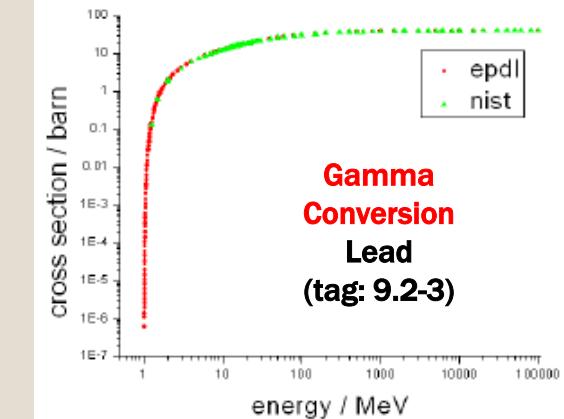
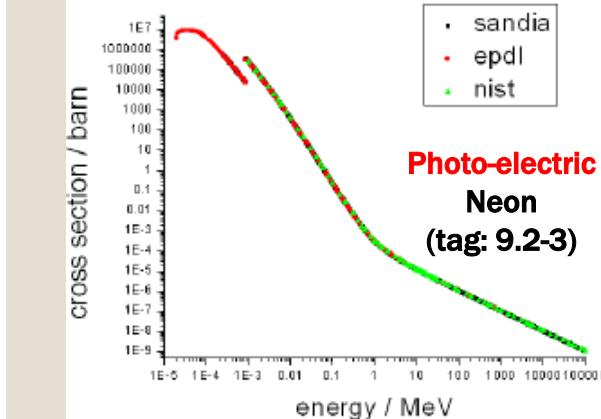
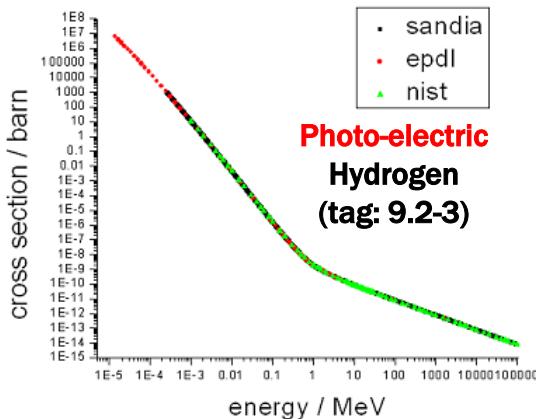
- Based on publicly available **evaluated data tables** from the Livermore data library
 - **EADL** : Evaluated Atomic Relaxation Data Library
 - **EEDL** : Evaluated Electrons Interaction Data Library
 - **EPDL97** : Evaluated Photons Interaction Data Library
 - Mixture of experiments and theories
 - Binding energies: **Scofield**
- Include elements from **Z=1 to Z=100**
 - Include atomic effects (fluorescence, Auger)
 - Atomic relaxation : $Z > 5$ (EADL transition data)
- Data tables are **interpolated** by Livermore model classes to compute
 - Total cross sections: photoelectric, Compton, Rayleigh, pair production, Bremsstrahlung
 - Shell integrated cross sections: photo-electric, ionization
 - Energy spectra: secondary e- processes
- Validity range (recommended) : **250 eV - 100 GeV**
 - Processes can be used down to 100 eV, with a reduced accuracy
 - In principle, down to ~10 eV
- Naming scheme: **G4LivermoreXXXModel** (eg. G4LivermoreComptonModel)
- Models also available as **polarized photon interactions**
- Naming scheme: **G4LivermorePolarizedXXXModel**
 - eg. G4LivermorePolarizedComptonModel

<http://www-nds.iaea.org/epdl97>

AVAILABLE LIVERMORE MODELS

Physics Process	Process Class	Model Class	Low Energy Limit	High Energy Limit
Gammas				
Compton	G4ComptonScattering	G4LivermoreComptonModel	250 eV (kill)	100 GeV
Polarized Compton	G4ComptonScattering	G4LivermorePolarizedComptonModel	250 eV (kill)	100 GeV
Rayleigh	G4RayleighScattering	G4LivermoreRayleighModel	10 eV (kill)	100 GeV
Polarized Rayleigh	G4RayleighScattering	G4LivermorePolarizedRayleighModel	250 eV (kill)	100 GeV
Conversion	G4GammaConversion	G4LivermoreGammaConversionModel	1.022 MeV	100 GeV
Polarized Conversion	G4GammaConversion	G4LivermorePolarizedGammaConversionModel	1.022 MeV	100 GeV
Photo-electric	G4PhotoElectricEffect	G4LivermorePhotoElectricModel	~ few eV	100 GeV
Polarized Photo-electric	G4PhotoElectricEffect	G4LivermorePolarizedPhotoElectricModel	10 eV	100 GeV
Electrons				
Ionization	G4elionisation	G4LivermoreIonisationModel	100 eV	100 GeV
Bremsstrahlung	G4eBremsstrahlung	G4LivermoreBremsstrahlungModel	10 eV	100 GeV

VERIFICATION OF LIVERMORE MODELS



NIM A 618 (2010) 315-322

PENELOPE PHYSICS

ELECTRON, POSITRON AND GAMMA INCIDENT

- Re-implementation of the low-energy models from the Monte-Carlo code **PENELOPE** (PENetration and Energy LOss of Positrons and Electrons) version **2008**:
 - Nucl. Instrum. Meth. B 207 (2003) 107-123
- 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 & database-driven
 - Applicability energy range: **100 eV – 1 GeV**
- Also include **positrons**
 - Not described by Livemore models
- **G4PenelopeXXXModel** (e.g. G4PenelopeComptonModel)

AVAILABLE PENELOPE MODELS

Physics Process	Process Class	Model Class	Low Energy Limit	High Energy Limit
Gammas				
Compton	G4ComptonScattering	G4PenelopeComptonModel	100 eV	1 GeV
Rayleigh	G4RayleighScattering	G4PenelopeRayleighModel	100 eV	1 GeV
Conversion	G4GammaConversion	G4PenelopeGammaConversionModel	1.022 MeV	1 GeV
Photo-electric	G4PhotoElectricEffect	G4PenelopePhotoElectricModel	100 eV	1 GeV
Electrons/Positrons				
Ionization	G4elionisation	G4PenelopelonisationModel	100 eV	1 GeV
Bremsstrahlung	G4eBremsstrahlung	G4PenelopeBremsstrahlungModel	100 eV	1 GeV
Positrons				
Annihilation	G4eplusAnnihilation	G4PenelopeAnnihilationModel	100 eV	1 GeV

ION ENERGY LOSS MODEL

- Describes the energy loss of **ions heavier than Helium** due to interactions with **atomic shells** of target atoms
 - **G4IonParametrisedLossModel** class
- Primarily of interest for medical and space applications
 - See more in Nucl. Instrum. Meth. B 268 (2010) 2343-2354
- Modelling:
 - **Restricted stopping powers** are calculated from
 - $T < T_{\text{Low}}$: Free electron gas model
 - $T_{\text{Low}} \leq T \leq T_{\text{High}}$: parameterization (ICRU'73) approach
 - $T > T_{\text{High}}$: Bethe-Bloch formula (using eff. charge + higher ord. corr.)
 - With energy limits
 - $T_{\text{High}} = 10 \text{ MeV/u}$ (except Fe ions: $T_{\text{High}} = 1 \text{ GeV/u}$)
 - $T_{\text{Low}} = 0.025 \text{ MeV/u}$ (lower boundary of ICRU'73 tables)
- **ICRU'73** parameterization
 - Large range of ion-materials combination:
 - Incident ions : Li to Ar, and Fe
 - 25 elemental materials, 31 compounds
 - Stopping powers based on the binary theory, effective charge approach for Fe
 - Special case: water (revised ICRU'73 tables by P. Sigmund, mean ionization potential is **78 eV**)

LOW ENERGY EM WG TWIKI

<https://twiki.cern.ch/twiki/bin/view/Geant4/LowEnergyElectromagneticPhysicsWorkingGroup>

TWiki > Geant4 Web > LowEnergyElectromagneticPhysicsWorkingGroup (26-Mar-2013, Sébastien Incerti)

 Edit  Attach  PDF

The Geant4 Low Energy Electromagnetic Physics Working Group

This web site is the [official web site](#) of the Geant4 collaboration Low Energy Electromagnetic Physics working group.

Purpose

The Geant4 Low Energy Electromagnetic Physics Working Group develops and maintains a set of models to describe the **electromagnetic interactions of photons, electrons, hadrons and ions with matter down to very low energies (eV scale)**, including the [Geant4-DNA project](#) ([link1](#) - [link2](#) - [link3](#)). Applications of such models range from high energy physics experiments to space science and astrophysics to the medical and biological fields. After several years of separation, these activities now take place in **full collaboration** with the [Standard Electromagnetic Physics working group](#) of the Geant4 collaboration.

What's new in Geant4 9.6+P01 ? (February 2013)

- [Overview](#) of our most recent developments.
- Version **6.32** of the set of Low Energy electromagnetic data files is required.
- [Bug notification](#) affecting the **G4EmLivermorePhysics** constructor in releases Geant4 9.6 and 9.6P01.

Physics

- [Processes](#) is a link to the catalog of **Geant4 low energy electromagnetic Physics processes** and to other useful information related to these processes.
- [Physics Lists](#) describes **recommended Physics lists** for applications involving low energy electromagnetic Physics processes.
- [Examples](#) recommended for the usage of Geant4 electromagnetic Physics.

Tools

- [Geant4 for VMware & VirtualBox](#) is a link to a **ready-to-use software suite allowing you to run entirely freely Geant4 (a so-called Geant4 Virtual Machine) and associated tools on a Windows PC or Mac** under the VMware or VirtualBox software without software installation needed .
- Follow [Geant4VM](#) on Twitter for updates.
- Overview of [testing coverage](#)

Support

- [Release notes](#) is a summary of changes in the low energy package for each Geant4 release.
- [User support](#) is a link to the user forum electromagnetic processes category, where you can post your questions.

Communication and tutorials

- [Journal publications](#) lists all publications of the Geant4 collaboration, including electromagnetic Physics. In addition, our publications related to the **Geant4-DNA project** are available from this [page](#).
- Tutorials are announced on the [Geant4 home page](#), in the **Events** and **Past events** sections.

Collaborators

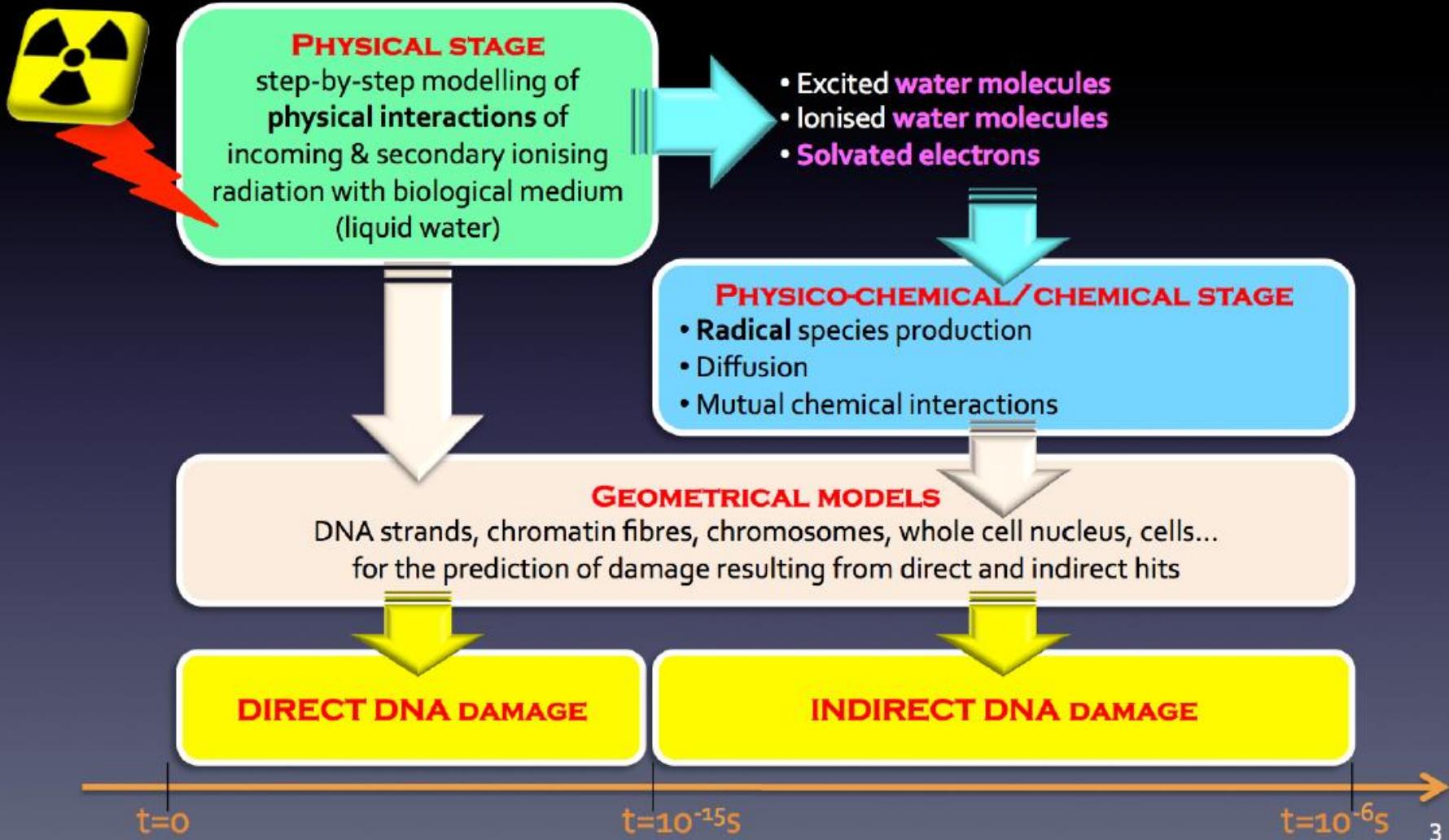
- The [official list of Geant4 collaboration members](#) belonging to this working group for the current year is available from this [page](#).
- [Institutions](#) gives links to Geant4 web sites of institutions involved in this working group.

Our working group is open to any new collaborator. New collaborators will have the possibility to join officially the Geant4 collaboration after significant contribution to this working group and after approval by the Geant4 steering committee.
Geant4 PHENIX & IN2P3 Tutorial, 13 - 17 May 2019, Orsay

II.5 – ULTRA-LOW EM ENERGY

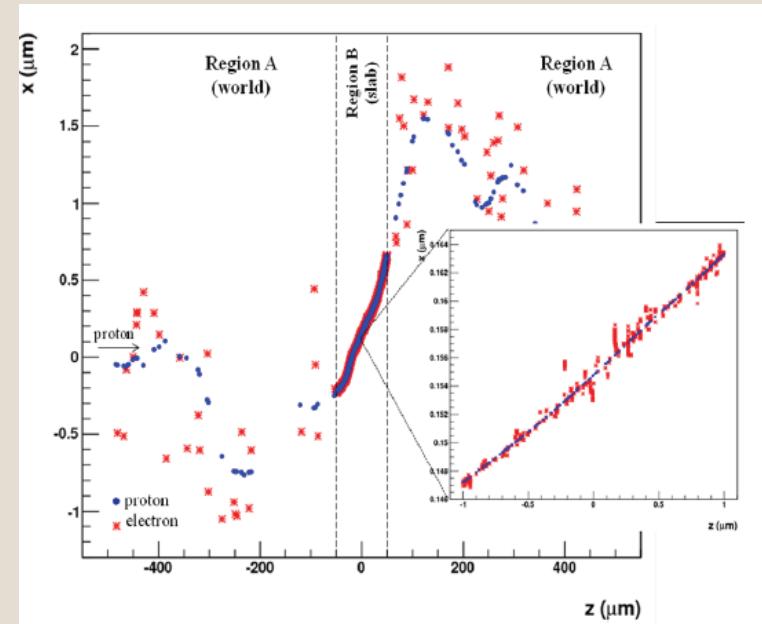
Micro-dosimetry
in DNA
& Silicon

How can Geant4-DNA model early DNA damage ?



GEANT4 FOR MICRODOSIMETRY IN RADIobiology

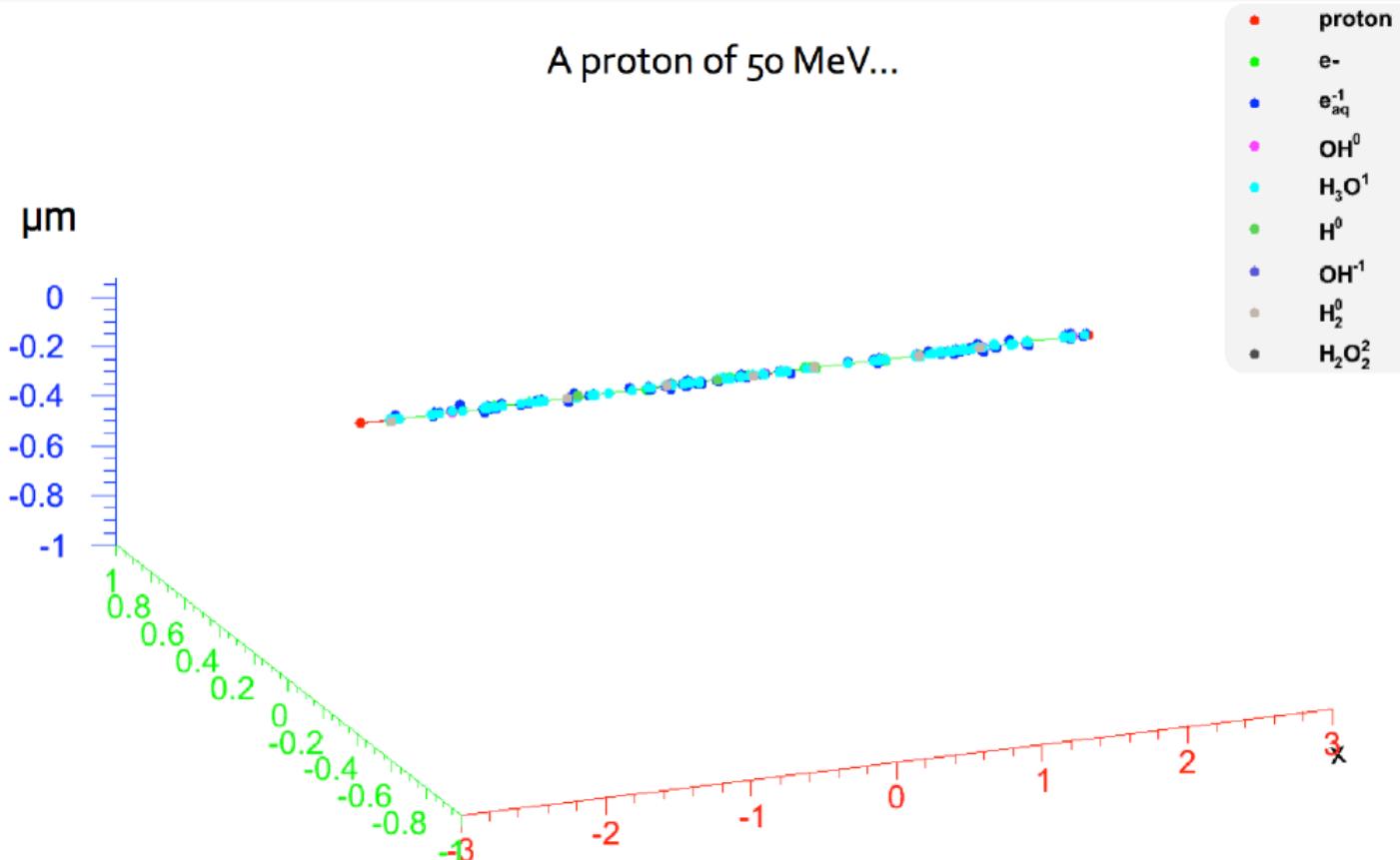
- Dedicated models for incident e^- , p , H , He , $He^{+/2+}$, C^{6+} , N^{7+} , O^{8+} , Fe^{26+}
 - They are all **discrete** processes
 - i.e.: no “condensed history” approach applied
 - See [examples/advanced/dnaphysics](#)
 - Include **elastic scattering, excitation (electronic + vibrations), ionisation and charge exchange**
- For now, these models are valid for **liquid water medium only**
- Models available in Geant4-DNA
 - may be purely analytical or use interpolated cross section data
 - are published in the literature
- Can be **combined** with other EM categories (Standard, Low Energy)
 - Combination done **per region**
 - DNA models set by [G4EmConfigurator](#)
 - See [examples/advanced/microdosimetry](#)



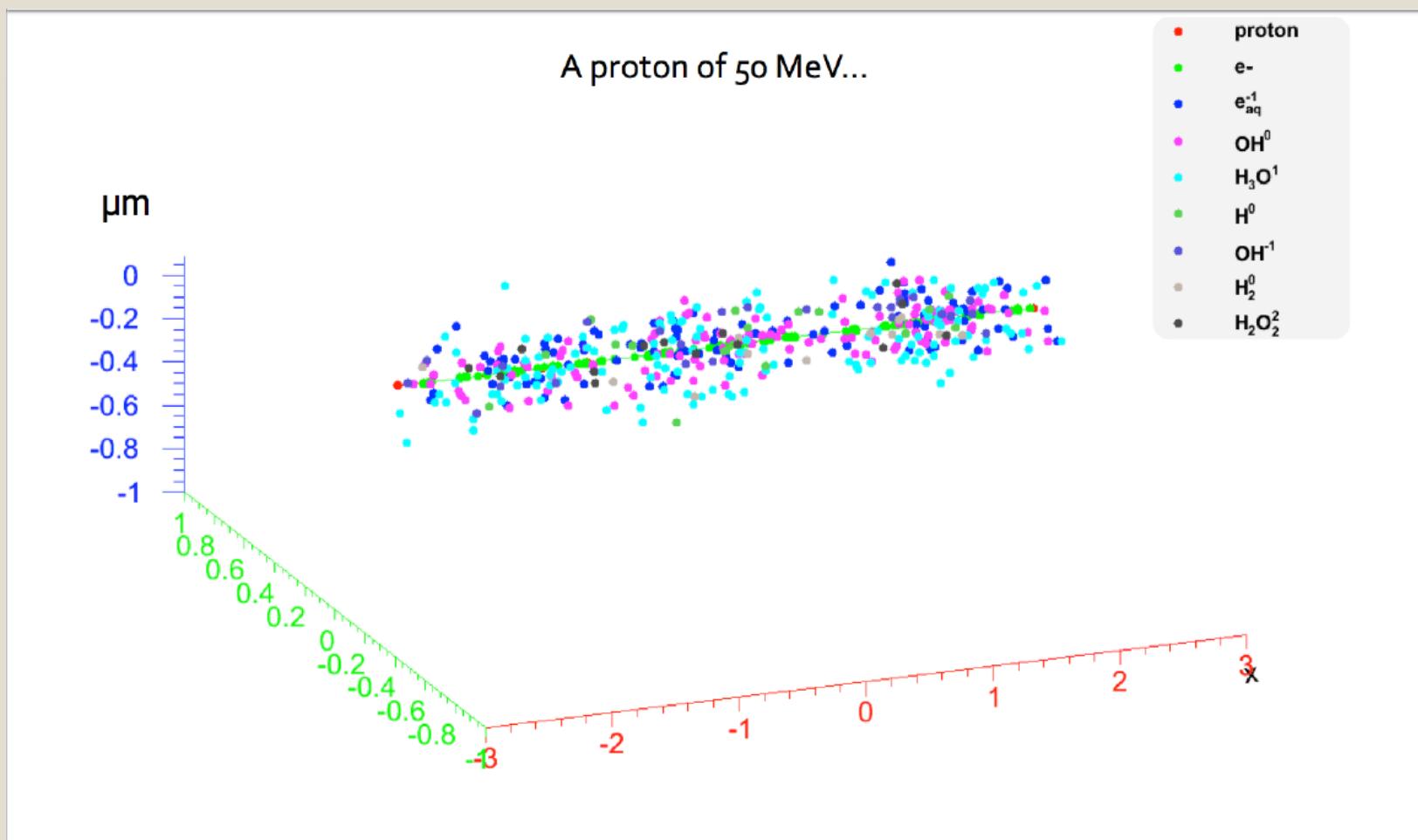
GEANT4-DNA PHYSICS PROCESSES AND MODELS

Particles	e-	p	H	He ⁺⁺ , He ⁺ , He ⁰	C, N, O, Fe,...
Elastic scattering	> 9 eV – 1 MeV Screened Rutherford >7.4 eV – 1 MeV Champion	-	-	-	-
Excitation	9 eV – 1 MeV Born	10 eV – 500 keV Miller Green 500 keV – 100 MeV Born	10 eV – 500 keV Miller Green	Effective charge scaling from same models as for proton	-
Charge Change	-	100 eV – 100 MeV Dingfelder	100 eV – 100 MeV Dingfelder		-
Ionisation	11 eV – 1 MeV Born	100 eV – 500 keV Rudd 500 keV – 100 MeV Born	100 eV – 100 MeV Rudd	1 keV – 400 MeV	Effective charge scaling 0.5 MeV/u – 10 ⁶ MeV/u
Vibrational excitation	2 – 100 eV Michaud et al.	-			
Attachment	4 – 13 eV Melton	-			

1 PICOSECOND AFTER IRRADIATION...

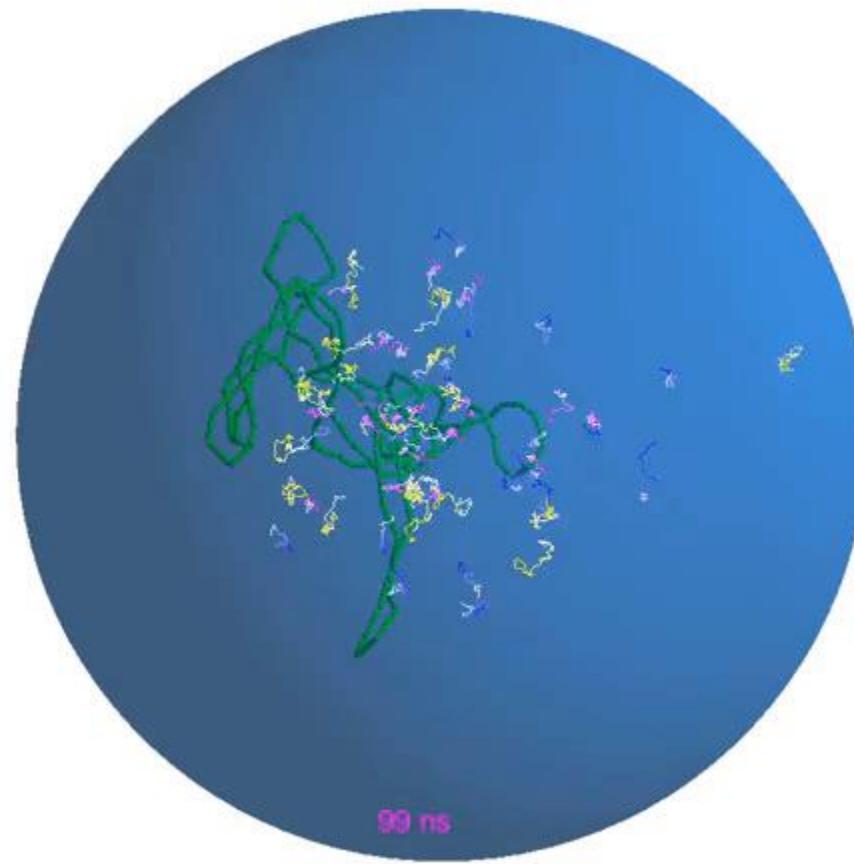


1 MICROSECOND AFTER IRRADIATION...



IRRADIATION OF A PBR322 PLASMID, INCLUDING RADIOLYSIS

- MOVIE COURTESY OF V. STEPAN (NPI-ASCR/CENBG/CNRS/IN2P3/ESA) -



DEDICATED WEB SITE

- <http://geant4-dna.org/> :

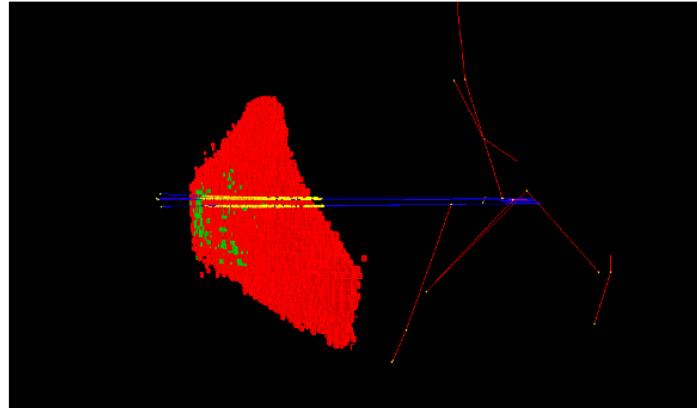
The Geant4-DNA project

Extending the Geant4 Monte Carlo simulation toolkit for radiobiology

Geant4-DNA Software Physics Chemistry Examples & tutorials Publications Collaboration Funding

Welcome to the Internet page of the **Geant4-DNA project**.

The **Geant4** general purpose particle-matter Monte Carlo simulation toolkit is being extended with processes for the **modeling of early biological damage induced by ionising radiation at the DNA scale**. Such developments are on-going in the framework of the Geant4-DNA project, originally initiated by the [European Space Agency/ESTEC](#).



Microbeam irradiation of a keratinocyte with alpha particles
(see the « microbeam » Geant4 advanced example)
- courtesy of L. Garnier (CNRS/IN2P3) -

Recent posts

March 8th, 2016: our virtual machine has been updated to Geant4 10.2+P01

Dec. 4th, 2015: Geant4 10.2 has been released

Dec. 1st, 2015: a new review paper on Geant4-DNA is available, see Publications.

MicroElec : PROCESSES AND MODELS FOR MICROELECTRONICS

■ Purpose

- Extend Geant4 for the simulation of particle-matter interactions in highly integrated microelectronic components
- for electrons, protons, heavy ions in Silicon

■ Approach:

- Same step-by-step approach as Geant4-DNA
 - ie no “condensed history”
- Applicable to the « G4_Si » NIST material

Nucl. Instrum. Meth B 288 (2012) 66 – 73
Nucl. Instrum. Meth B 287 (2012) 124 – 129
IEEE Trans. Nucl. Sci. 59 (2012) 2697 – 2703
Nucl. Instrum. Meth B 325 (2014) 97 - 100

Physics Process	Process Class	Model Class	Low Energy Limit	High Energy Limit
Electrons				
Elastic scattering	G4MicroElecElastic	G4MicroElecElasticModel	5 eV (kill < 16.7 eV)	100 MeV
Ionization	G4MicroElecInelastic	G4MicroElecInelasticModel	16.7 eV	100 MeV
Protons and heavy ions				
Ionization	G4MicroElecInelastic	G4MicroElecInelasticModel	50 keV/u	1 GeV/u

II.6 – UTILS

USER INTERFACES AND HELPER CLASSES

- Physics configuration and control:
 - **G4EmParameters** (G4EmProcessOptions obsoleting)
 - C++ interface to EM options alternative to UI commands
 - **G4EmConfigurator**
 - add models per energy range and geometry region
- Physics calculations:
 - **G4EmCalculator**
 - easy access to cross sections and stopping powers
 - **G4EmSaturation**
 - Birks effect (recombination / “quenching” effects)
 - **G4ElectronIonPair**
 - sampling of ionisation clusters in gaseous or silicon detectors

EXAMPLE OF PHYSICS CALCULATION

- Possible to retrieve Physics quantities using a **G4EmCalculator** object
- Physics List should be **initialized**
- Example for retrieving the total cross section of a process with name **procName**, for **particle** and material **matName**

```
#include "G4EmCalculator.hh"
...
G4EmCalculator emCalculator;

G4Material* material =
    G4NistManager::Instance()->FindOrBuildMaterial(matName);
G4double density = material->GetDensity();
G4double massSigma =
    emCalculator.ComputeCrossSectionPerVolume(energy,
                                              particle,
                                              procName,
                                              material )/density;
G4cout << G4BestUnit(massSigma, "Surface/Mass") << G4endl;
```

- See **RunAction.cc** in **\$G4INSTALL/examples/extended/electromagnetic/TestEm0**, for example.

II.6 – EM PHYSICS CONSTRUCTORS

GEANT4 STANDARD EM PHYSICS CONSTRUCTORS FOR HEP APPLICATIONS

- Constructors with variation of MSC stepping algorithms and/or parameters for speed vs. accuracy tradeoff

Constructor	Components	Comments
G4EmStandardPhysics	Default: nothing or _EM0 (QGSP_BERT, FTFP_BERT,...)	for ATLAS and other HEP simulation applications
G4EmStandardPhysics_option1	Fast: due to simpler MSC step limitation, cuts used by photon processes (FTFP_BERT_EMV)	similar to one used by CMS; good for crystals but not good for sampling calorimeters (i.e. with more detailed geometry)
G4EmStandardPhysics_option2	Experimental: similar to option1 with updated photoelectric model but no displacement in MSC (FTFP_BERT_EMX)	similar to one used by LHCb

COMBINED GEANT4 EM PHYSICS CONSTRUCTORS

- Constructors with focus on **physics accuracy**
- More accurate models for e^\pm MSC (Goudsmit-Saunderson(GS)) and/or more accurate stepping algorithms (compared to HEP)
- Stronger continuous step limitation due to ionisation

Constructor	Components	Comments
G4EmStandardPhysics_option3	Urban MSC model for all particles	proton/ion therapy
G4EmStandardPhysics_option4	Most accurate combination of models (particle type and energy); GS MSC model with Mott correction and error-free stepping for e^\pm)	the ultimate goal is to have the most accurate EM physics description
G4EmLivermorePhysics	Livermore models for e^- , γ below 1 GeV and standard above; same GS MSC for e^\pm as in option4)	accurate Livermore based low energy e^- and γ transport
G4EmPenelopePhysics	PENELOPE models for e^\pm , γ below 1 GeV and standard above; same GS MSC for e^\pm as in option4)	accurate PENELOPE based low energy e^- , e^+ and γ transport
G4EmDNA	DNA models in selected regions	For dedicated applications

EXPERIMENTAL GEANT4 EM PHYSICS CONSTRUCTORS

- Primarily meant for developers and model validations

Constructor	Components	Comments
G4EmStandardPhysicsGS	standard EM physics and the GS MSC model for e^\pm with HEP settings	may be considered as an alternative to EMO i.e. for HEP
G4EmStandardPhysicsWVI	WentzelWVI + Single Scattering mixed simulation model for Coulomb scattering	high and intermediate energy applications
G4EmStandardPhysicsSS	single scattering (SS) model description of the Coulomb scattering	validation and verification of the MSC and mixed simulation models
G4EmLowEPPhysics	Monash University Compton scattering model, 5D gamma conversion model, WVI-LE model	testing some low energy models
G4EmLivermorePolarized	polarized gamma models	a (polarized) extension of the Livermore physics models

II.6 – WHERE TO FIND HELP ?

WEB SITES

- A **unique** reference web page on Geant4 EM Physics
 - <http://geant4.cern.ch/collaboration/EMindex.shtml>
- From there, links to
 - Geant4 **Standard Electromagnetic Physics working group** pages
 - Geant4 **Low Energy Electromagnetic Physics working group** pages
- Also from Geant4 web site
 - <http://geant4.org>
 - Who we are
 - Standard Electromagnetic Physics
 - Low Energy Electromagnetic Physics

TO LEARN MORE

\$G4INSTALL/EXAMPLES/EXTENDED/ELECTROMAGNETIC

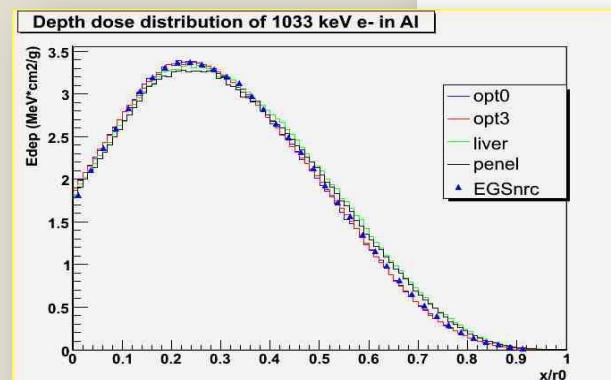
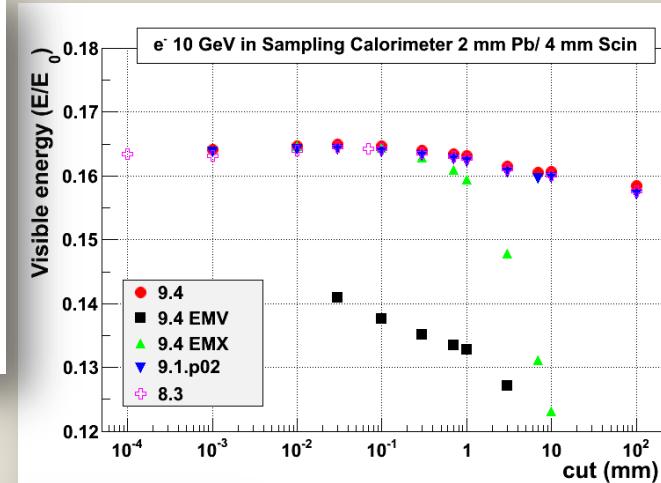
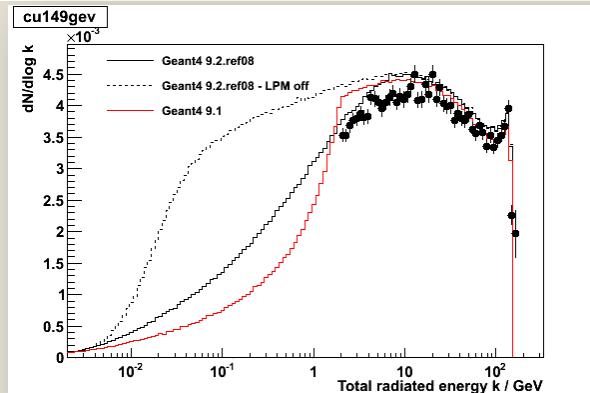
Check basic quantities	
Total cross sections, mean free paths ...	TestEm0, Em13, Em14
Stopping power, particle range ...	Em0, Em1, Em5, Em11, Em12
Final state : energy spectra, angular distributions	Em14
Energy loss fluctuations	Em18
Multiple Coulomb scattering	
as an isolated mechanism	Em15
as a result of particle transport	Em5
More global verifications	
Single layer: transmission, absorption, reflexion , atomic deexcitation, msc	Em5
Bragg curve, tallies	Em7
Depth dose distribution	Em11, Em12
Shower shapes, Moliere radius	Em2
Sampling calorimeters, energy flow	Em3
Crystal calorimeters	Em9
Other specialized programs	
High energy muon physics	Em17
Other rare, high energy processes	Em6
Synchrotron radiation	Em16
Transition radiation	Em8
Photo-absorption-ionization model	Em10

Refer to section on
extended examples in
App. User Guide.

You are warmly
invited to study these
examples !

VALIDATION REPOSITORY

- A web-based verification tool for easy comparison of EM physics results obtained with different Geant4 version, and with measurements



https://geant4.cern.ch/collaboration/working_groups/electromagnetic/indexv.shtml

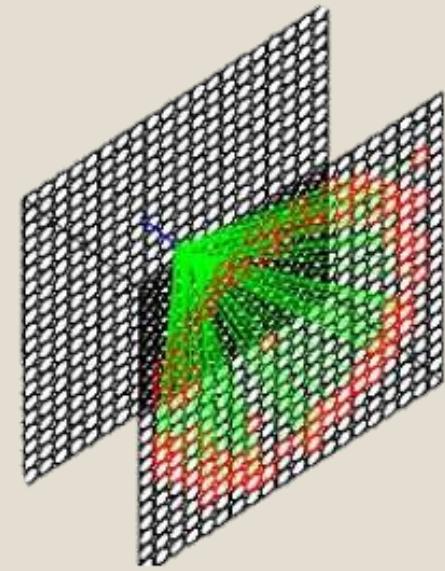
SUMMARY : WHEN/WHY USING “LOW ENERGY” EM MODELS

- **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 or below
 - Are interested in atomic effects:
 - fluorescence x-rays, Doppler broadening, etc.
 - Can afford more CPU-intensive simulation
 - Or want to cross-check another simulation:
 - eg with a different physics list
 - For systematic studies
- **Do not use** when you are interested in EM physics > MeV
 - Same results as Standard EM
 - But with strong CPU penalty

III. OPTICAL PHYSICS

OPTICAL PHOTON ASSUMPTIONS & LIMITATIONS

- Geant4 offers some production and transport capabilities for optical photons.
 - **G4OpticalPhoton** is the class representing them
 - “**opticalphoton**” is their particle name
- As for other Geant4 particles, they are treated as “**point-like**” objects:
 - Allows simulating “**point like**” interactions ✓
 - Scattering, absorption, reflection...
 - But excludes any “**wave-like**” behaviors ✗
 - No phase treatment \Rightarrow no interferences simulated !
 - Don't expect Geant4 to simulate Young's slits experiment !
- Optical photons are treated separately from EM processes:
 - Wavelengths are much larger than atomic spacing
 - **G4OpticalPhoton** \neq **G4Gamma**; and there is no smooth transition defined.
- Energy/momentum not generally conserved in G4 optics



OPTICAL PHOTON PROCESSES

■ Production processes:

- G4Cerenkov
- G4Scintillation

■ Transport processes:

- G4OpBoundaryProcess
- G4OpWLS (wavelength shifting)
- G4OpAbsorption
- G4OpRayleigh

■ Activating optical physics:

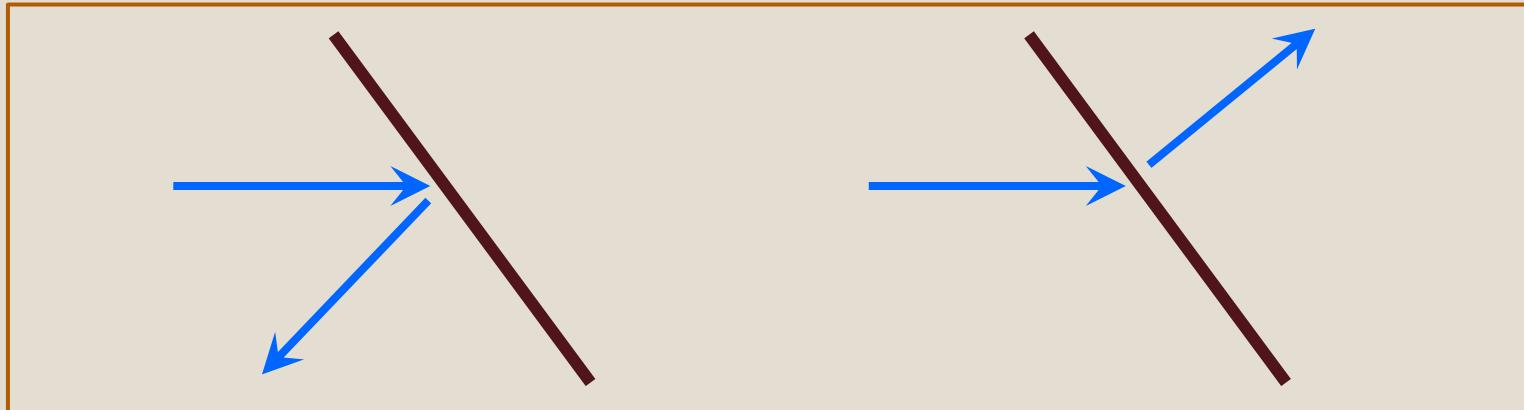
- The physics constructor **G4OpticalPhysics** can be used to create/activate optical physics.
- For example, in your main(...):
 - `G4VModularPhysicsList* myModularPhysicsList = new FTFP_BERT;`
 - `myModularPhysicsList->RegisterPhysics(new G4OpticalPhysics);`

■ Optical properties definition:

- Optical properties **attached to G4Material** (by user code)
 - reflectivity, transmission efficiency, dielectric constants, surface properties, including binned wavelength/energy dependences
- Photon spectrum **attached to G4Material** (by user code)
 - scintillation yield, time structure (fast, slow components)

BOUNDARY PROCESSES

- **G4OpBoundaryProcess**
 - Reflection
 - Refraction
- User must supply surface properties using **G4OpticalSurfaceModel**
- **Boundary properties**
 - Dielectric-dielectric
 - Dielectric-metal
 - Dielectric-black material
- **Surface properties**
 - Polished
 - Ground
 - Front- or back-painted, etc...



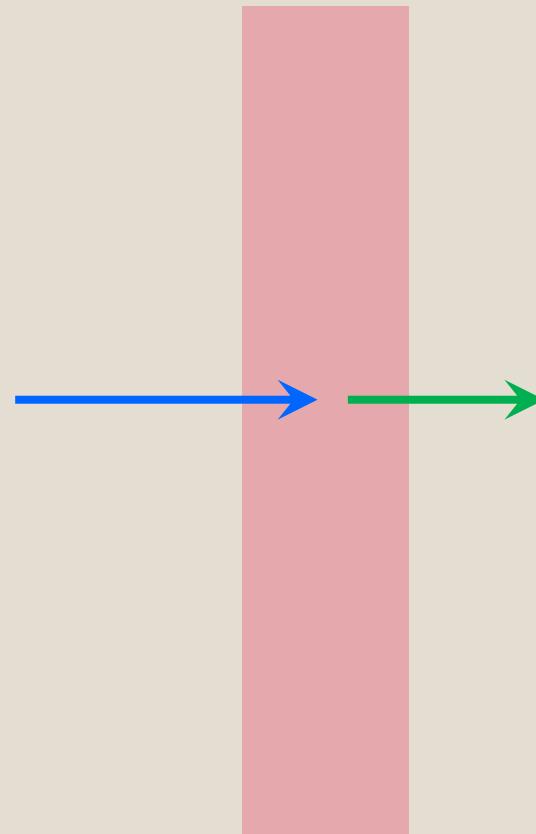
WAVELENGTH SHIFTING

■ G4OpWLS:

- Simulates wavelength shifting of photons crossing material.
- Initial photon is killed, and a “daughter” photon is created with new energy.

■ User must supply:

- **Absorption length** as function of photon energy
- **Emission spectra parameters** as function of energy
- **Time delay** between absorption and re-emission



BULK PROCESS & RAYLEIGH

- **G4OpAbsorption:**

- Uses photon attenuation length from material properties to sample path length before absorption
- Photon is simply killed after sampled path length

- **G4OpRayleigh:**

- Optical photon version of Rayleigh scattering
 - G4Gamma's have their Rayleigh version too
- Elastic scattering including polarization of initial and final photons

IV. DECAY PHYSICS

PARTICLE DECAYS

- Applies to all unstable long-lived particles
 - In flight, or at rest
 - Not used for radioisotopes (handled by G4RadioactiveDecay)
- Specificity of decay process:
 - Mean free path is $\lambda = \beta\gamma c\tau$
 - While it is $\lambda = (\mathcal{N}\rho\sigma/A)^{-1}$ for other processes
- Same process used for all eligible particles
 - Retrieves branching ratio and decay modes from decay table stored for each particle
 - No such data provided by Geant4 for heavy flavor particles
 - eg: B mesons
 - In what case user must supply “pre-assign” decay
 - Specifying lifetime, decay modes, decay products
 - Or delegate to an external generator, using the **G4ExtDecayer** interface

DECAY MODES AVAILABLE

- **Phase space:**

- 2-body: $\pi^0 \rightarrow \gamma\gamma$
- 3-body: $K_L^0 \rightarrow \pi^0\pi^+\pi^-$
- Many body

- **Dalitz decay:**

- $\pi^0 \rightarrow \gamma l^+l^-$

- **V-A:**

- For muon and tau decays
- No radiative corrections, mono-energetic neutrinos

- **Semi-leptonic kaon decay:**

- $K \rightarrow \pi l\nu$

SPECIALIZED PARTICLE DECAYS

■ **G4DecayWithSpin**

- Produces Michel electron/positron spectrum with first order radiative corrections
- Initial muon spin is required
- Propagates muon spin in magnetic field (precession)

■ **G4UnkwonDecay**

- For not yet discovered particles
 - Eg : SUSY
- For in-flight decays only
- User must supply pre-assigned decay, or interface to generator

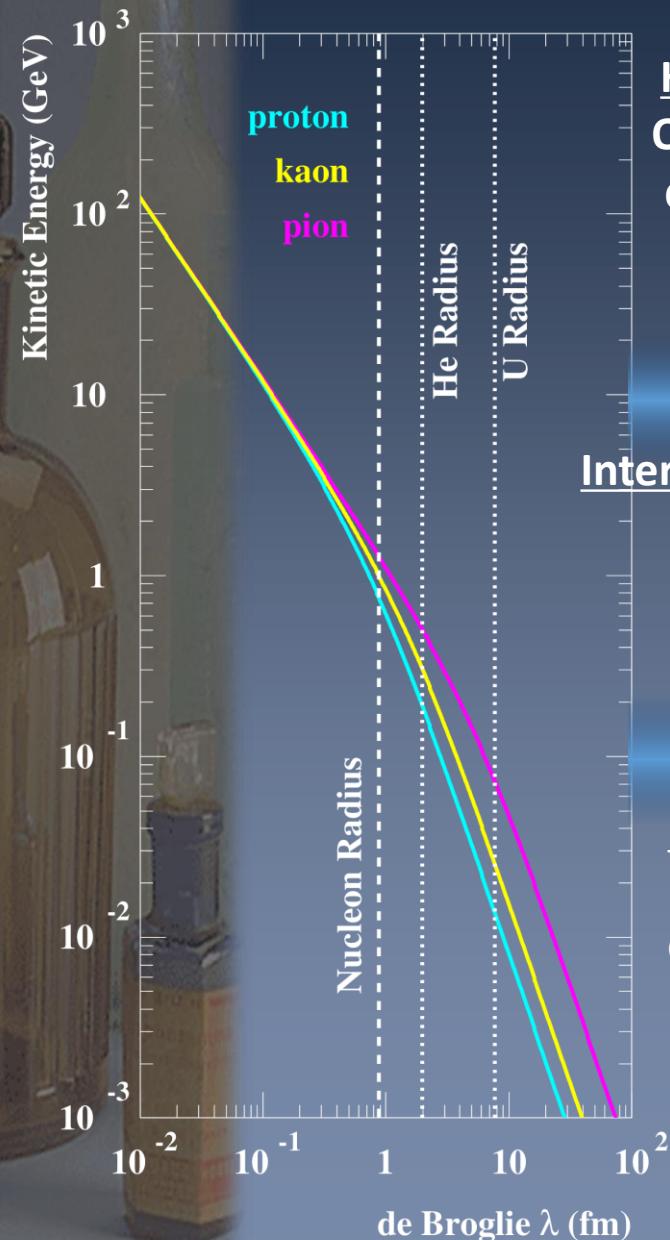
V. HADRONIC PHYSICS

OVERVIEW

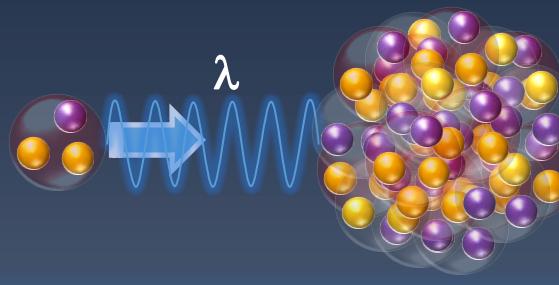
- 1. Generalities**
- 2. The Hadronic Framework**
- 3. Hadron Elastic**
- 4. High Energy : String Models**
- 5. Intermediate Energies : Intra-nuclear cascades**
- 6. Nucleus “Cooling Down” Models**
- 7. Low Energies : Capture, Stopping, Fission**
- 8. Low Energy (< 20 MeV) Particle Transport, including Neutrons**
- 9. Radioactive Decays**
- 10. Ion-ion Physics**
- 11. Gamma-, Lepto-Nuclear**

V.1 - GENERALITIES

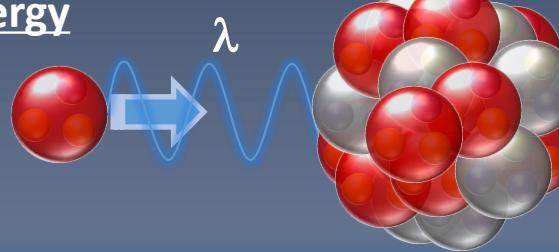
Variety of Hadronic Physics Models



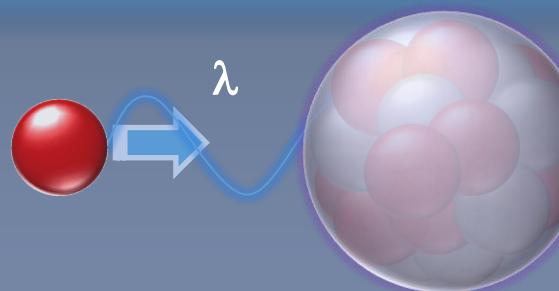
High Energy
Quark/gluon
dominating
behavior



Intermediate Energy
Nucleon
dominating
behavior



Low Energy
Nucleus
dominating
behavior



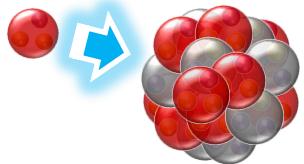
Main Models

String Models:
Quark Gluon
String,
Fritiof

Intra-Nuclear
Cascade Models:
Binary,
Bertini

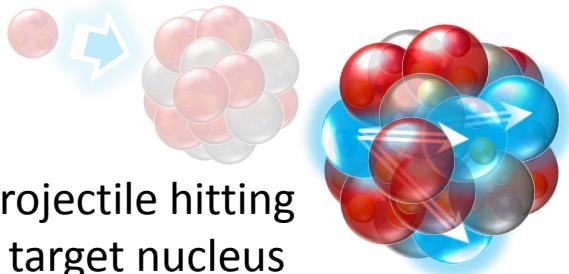
Precompound
Fission /
evaporation
 γ evaporation
Radioactive decay
Capture at rest

One hadronic collision = sequence of many hadronic interactions



Projectile hitting
a target nucleus

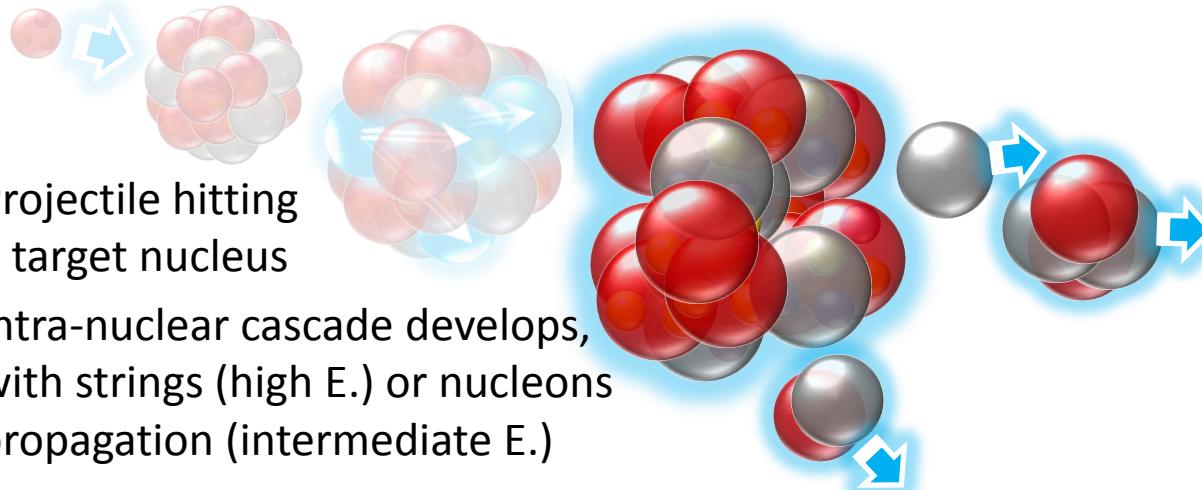
One hadronic collision = sequence of many hadronic interactions



Projectile hitting
a target nucleus

Intra-nuclear cascade develops,
with strings (high E.) or nucleons
propagation (intermediate E.)

One hadronic collision = sequence of many hadronic interactions

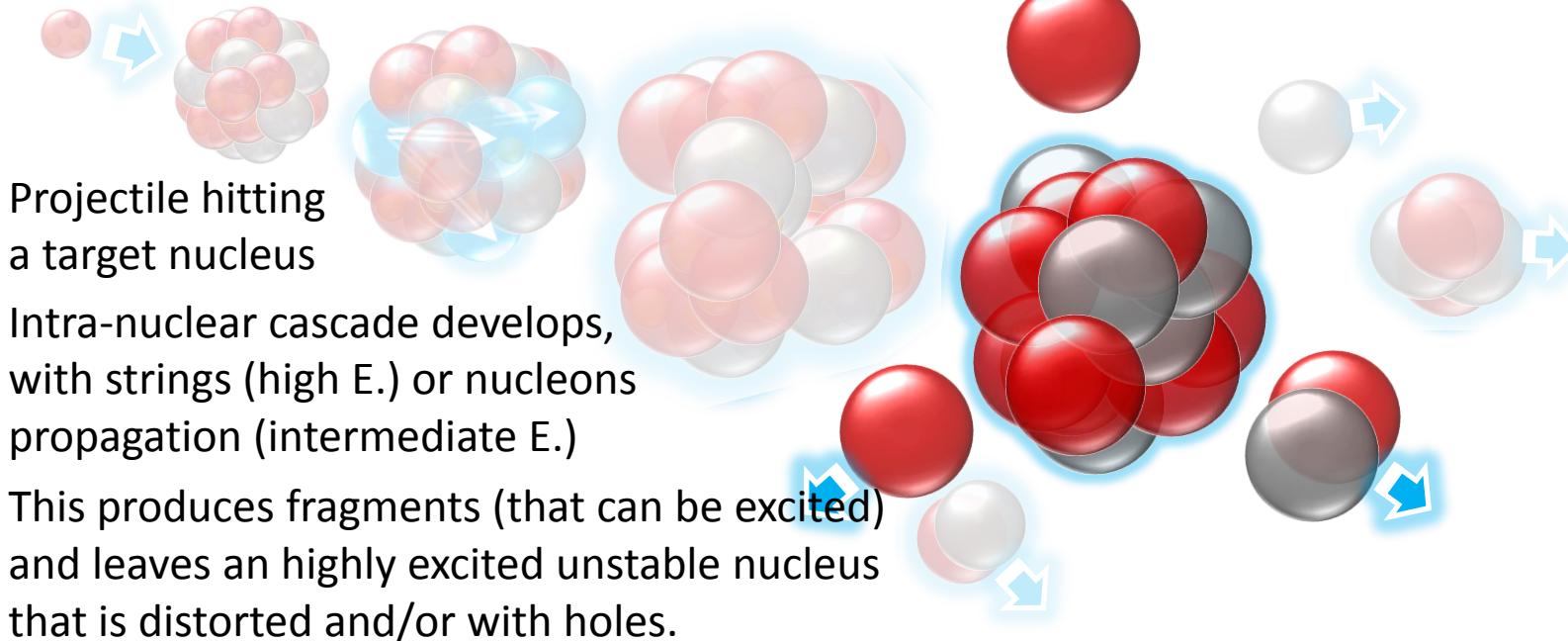


Projectile hitting
a target nucleus

Intra-nuclear cascade develops,
with strings (high E.) or nucleons
propagation (intermediate E.)

This produces fragments (that can be excited)
and leaves an highly excited unstable nucleus
that is distorted and/or with holes.

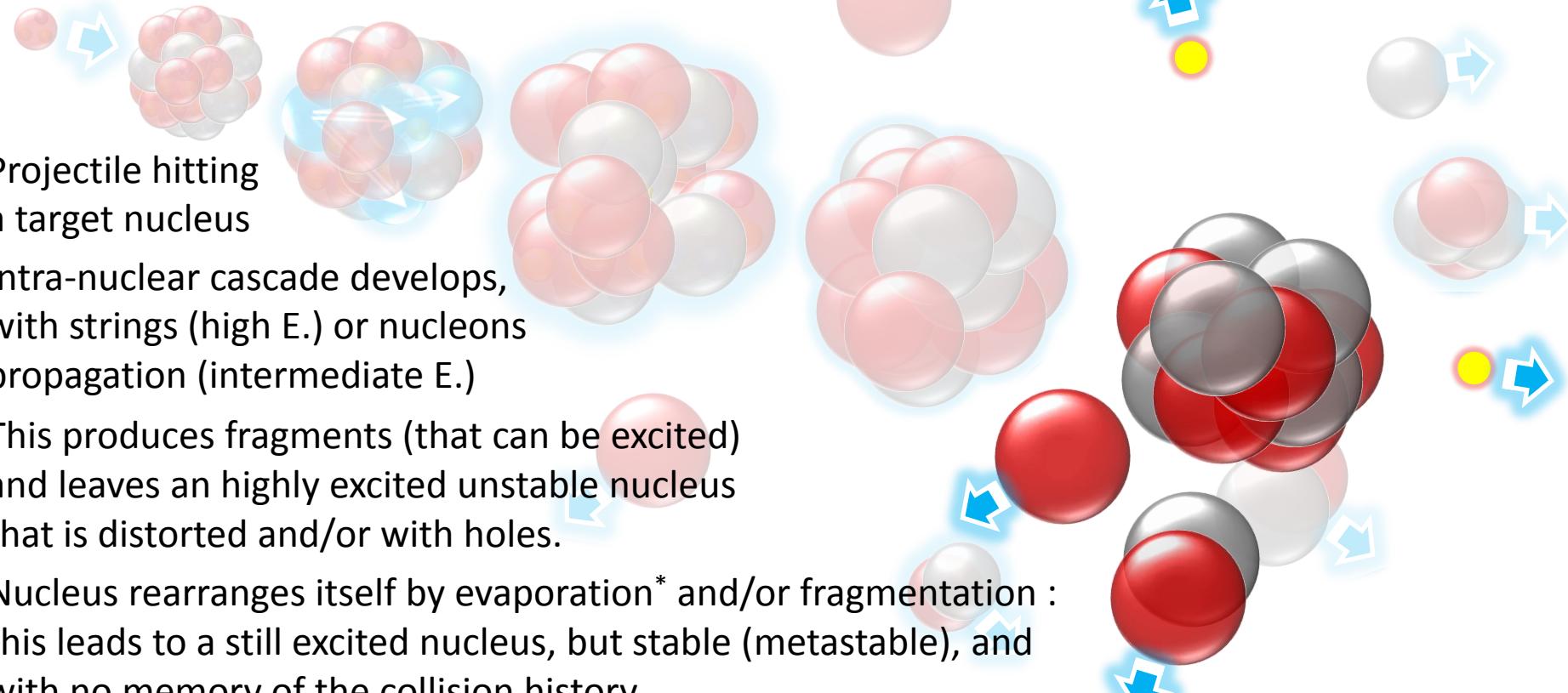
One hadronic collision = sequence of many hadronic interactions



Nucleus rearranges itself by evaporation* and/or fragmentation : this leads to a still excited nucleus, but stable (metastable), and with no memory of the collision history.

(*) **Evaporation** = de-excitation by emission of light nuclei $\in \{n, p, d, 3d, 3\text{He}, \alpha\}$ or photon

One hadronic collision = sequence of many hadronic interactions

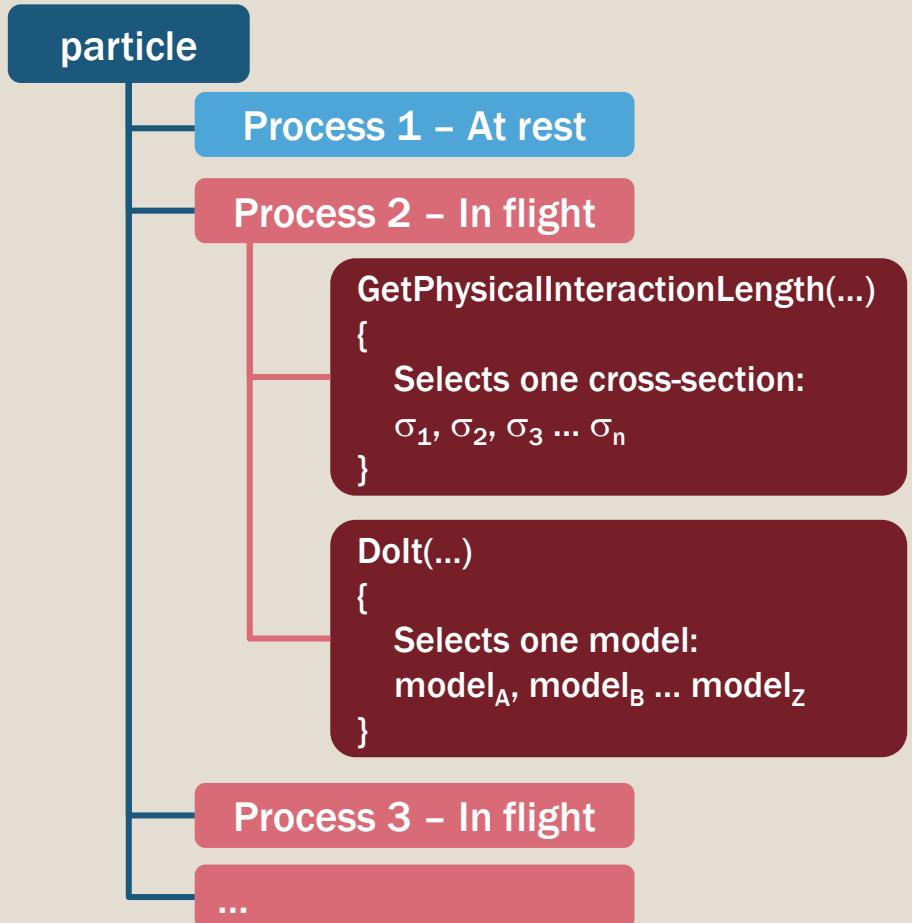


(*) **Evaporation** = de-excitation by emission of light nuclei $\in \{n, p, d, t, {}^3\text{He}, \alpha\}$ or photon

V.2 - THE HADRONIC FRAMEWORK

CROSS-SECTIONS & MODELS

- Hadronic interactions are all “point-like”:
 - Either at-rest (AtRest processes)
 - Or in flight (PostStep processes)
- One process often needs:
 - Several cross-sections
 - To cover a wide range of energy
 - GetPhysicalInteractionLength(...) selects one of these, valid at proper energy
 - Several final-state models
 - To again cover a wide range of energy
 - “final-state models” simply called “models” by hadronic people
 - Used in “Dolt(...)"
- The hadronic framework is designed to handle these sets of cross-sections and models



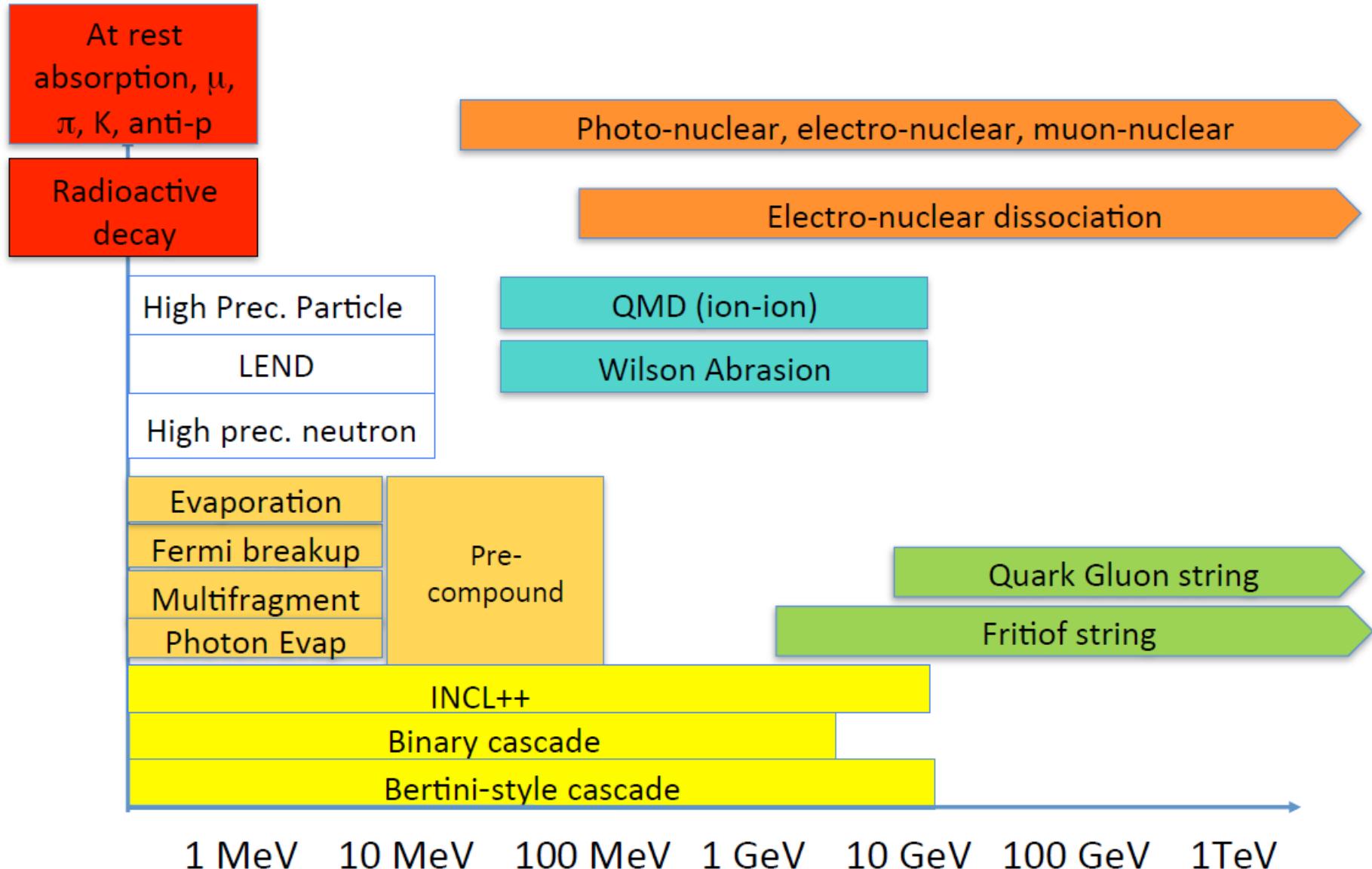
Hadronic Framework: Cross Sections

- Default cross section sets are provided for each type of hadronic process
 - **elastic, fission, capture, inelastic**
 - can be overridden or completely replaced
- Different types of cross section sets
 - some are parameterizations
 - some represent large databases
 - some are purely theoretical
- Cross section sets are **inclusive**
 - i.e. integrated (total), not differential

Available Inelastic Hadronic Cross Sections

- Low-energy neutron cross sections (below 20 MeV)
 - G4NDL available as Geant4 distribution files
 - Livermore database (LEND) also available
 - Available with or without thermal cross sections
- Medium-energy neutron- and proton-nuclear reaction cross sections
 - $14 \text{ MeV} < E < 20 \text{ GeV}$
 - Barashenkov cross sections; Glauber-Gribov-Grichine extension at high energies
- Nucleus-nucleus reaction cross sections
 - Tripathi, Shen, Kox : good for $E/A < 10 \text{ GeV}$
 - Glauber-Gribov-Galoyan-Uzhinskiy : all energies; also for anti-baryons
- Pion-nuclear reaction cross sections
 - Barashenkov cross sections; Glauber-Gribov-Grichine extension at high energies
- Kaon-, hyperon- and anti-hyperon - nuclear cross sections
 - Kossov cross sections (extracted from CHIPS)

Partial Model Inventory



V.3 - HADRON ELASTIC

Elastic Process

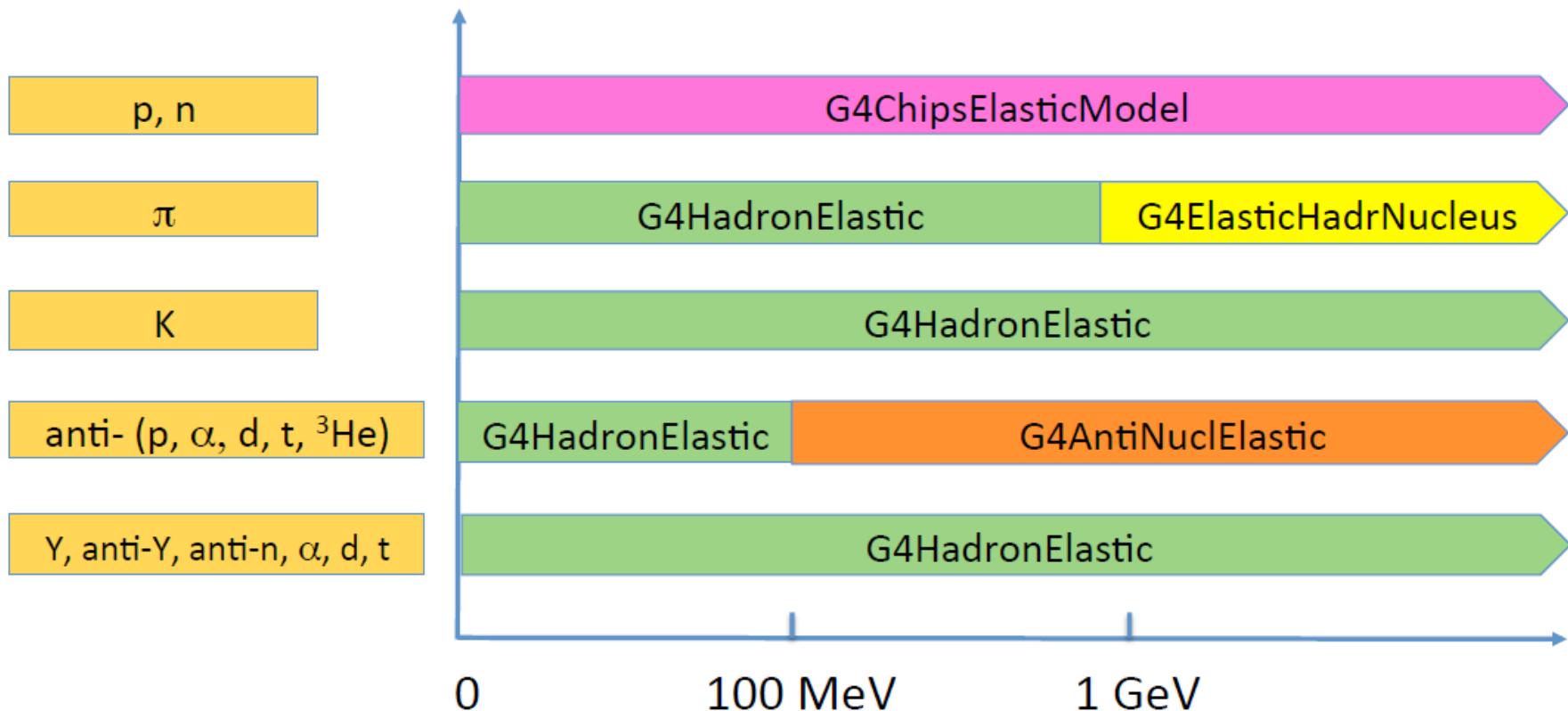
G4HadronElasticProcess

- “*hadElastic*” is the name of this process
- As usual in Geant4 hadronics, also for hadron elastic the **cross sections** are used to sample the mean free path and **models** for sampling the final state
- The **proton production cut** is applied to the recoil nucleus for all types of projectile hadrons
 - The default **0.7 mm** corresponds to **70 keV**; here is how to change it, e.g. **0.1 mm** corresponding to **10 keV**
/run/setCutForAGivenParticle proton 0.1 mm
 - If a hadron scatters elastically on a nucleus, the recoiling nucleus becomes a new G4Track (i.e. a particle to be transported by Geant4) only if its kinetic energy is above the value:
(100* keV) * proton_production_cut_in_mm

Hadron Elastic Cross Sections

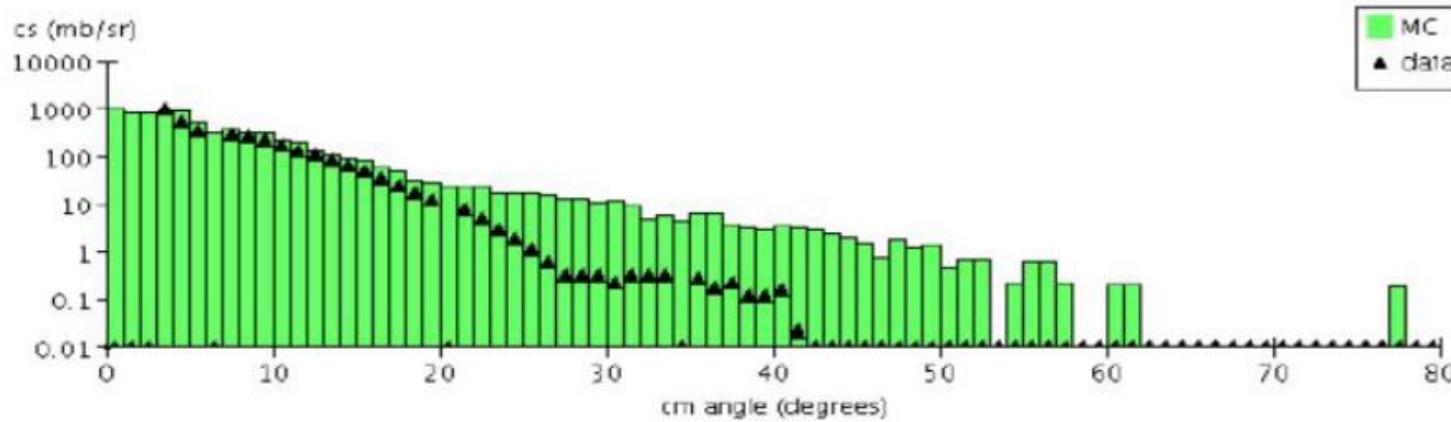
- G4HadronElasticDataSet (from Geant4/Gheisha)
- G4ComponentAntiNuclNuclearXS
 - anti-nucleon and anti-light nucleus elastic scattering from nuclei using Glauber approach
- G4BGGPionElasticXS
 - Barashenkov-Glauber-Gribov elastic scattering of pions and from nuclei using Barashenkov parameterization below 91 GeV and Glauber-Gribov parameterization above
- G4ChipsNeutron(Proton)ElasticXS
 - elastic cross sections extracted from CHIPS framework

Hadronic Models Implementing G4HadronElasticProcess

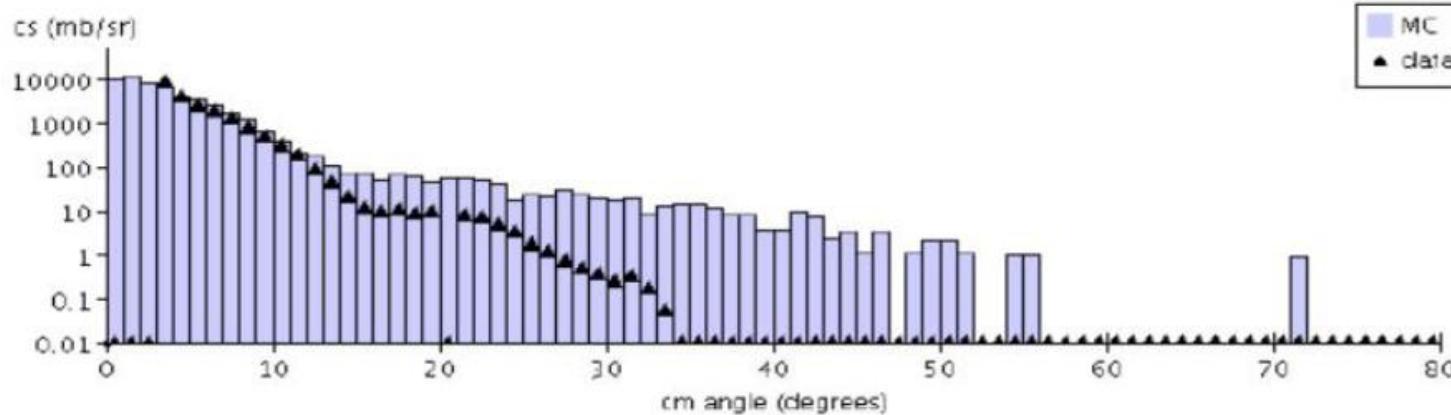


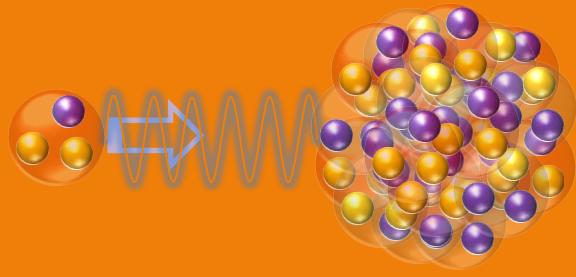
Elastic Scattering Validation (G4HadronElastic)

Elastic K⁺ scattering from C at 800 MeV/c



Elastic K⁺ scattering from Ca at 800 MeV/c





V.4 - HIGH ENERGIES : STRING MODELS

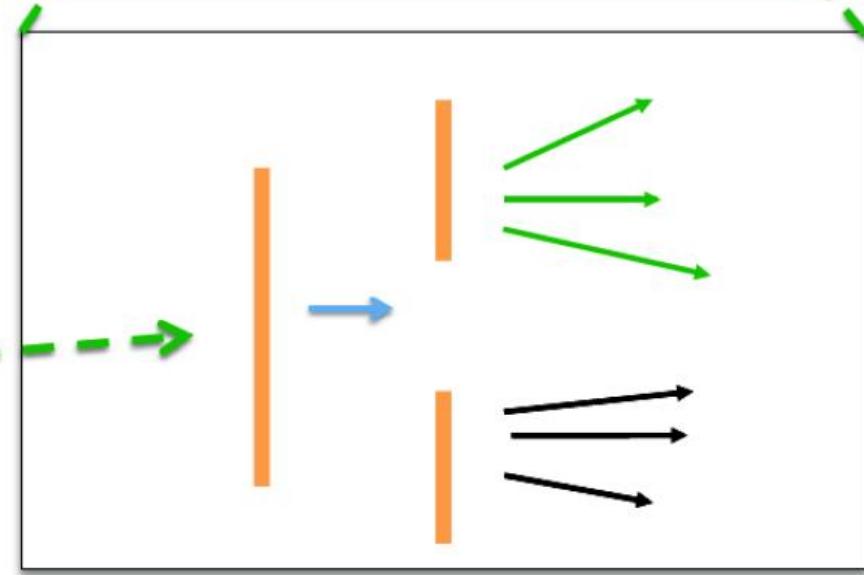
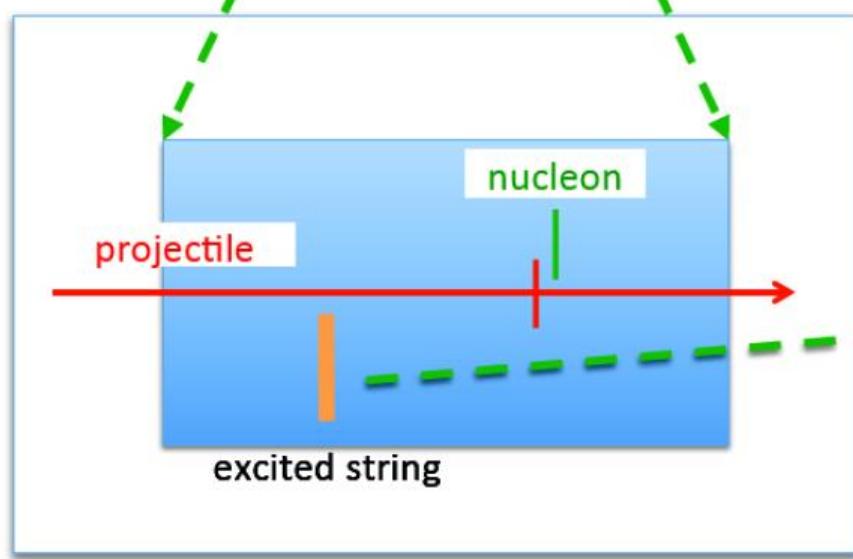
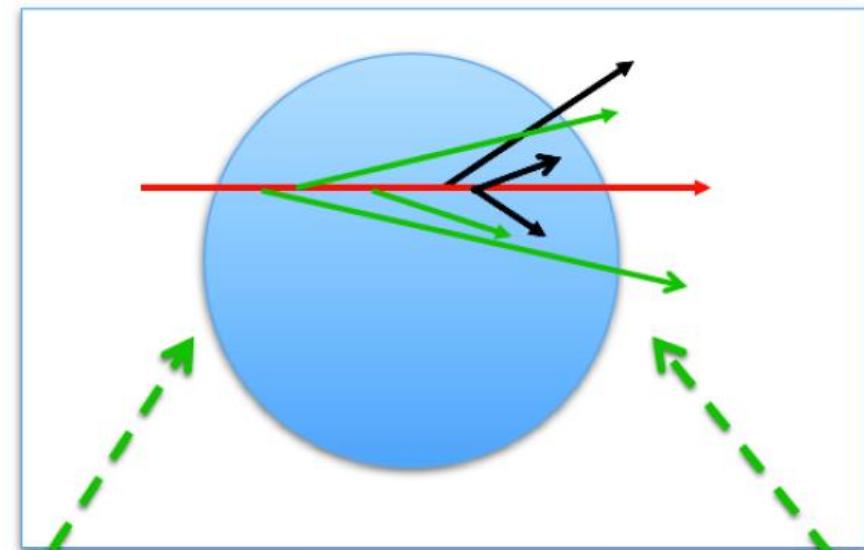
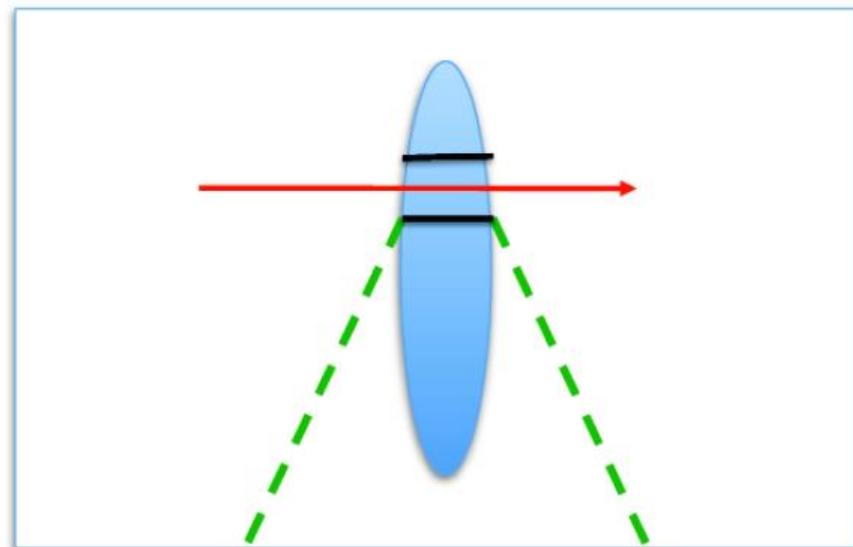
How the String Model Works (FTF Model)

- Lorentz contraction turns nucleus into pancake
- All nucleons within 1 fm of path of incident hadron are possible targets
- Excited nucleons along path collide with neighbors
 - $n + n \rightarrow n\Delta, NN, \Delta\Delta, N\Delta, \dots$
 - essentially a quark-level cascade in vicinity of path → Reggeon cascade
- All hadrons treated as QCD strings
 - projectile is quark-antiquark pair or quark-diquark pair
 - target nucleons are quark-diquark pairs

How the String Model Works (FTF Model)

- Hadron excitation is represented by stretched string
 - string is set of QCD color lines connecting the quarks
- When string is stretched beyond a certain point it breaks
 - replaced by two shorter strings with newly created quarks, anti-quarks on each side of the break
- High energy strings then decay into hadrons according to fragmentation functions
 - fragmentation functions are theoretical distributions fitted to experiment
- Resulting hadrons can then interact with nucleus in a traditional cascade

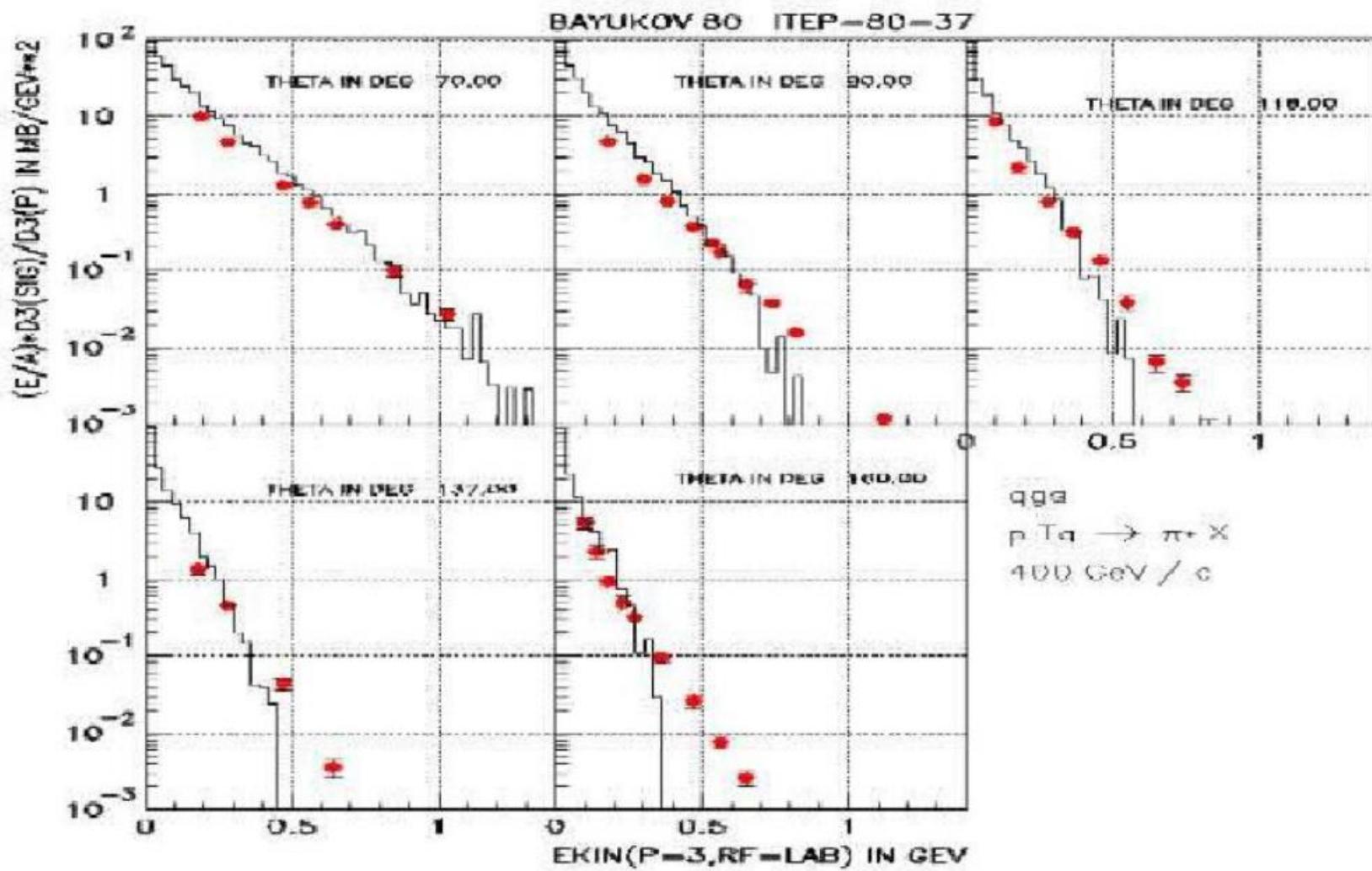
High-Energy Nuclear Reaction



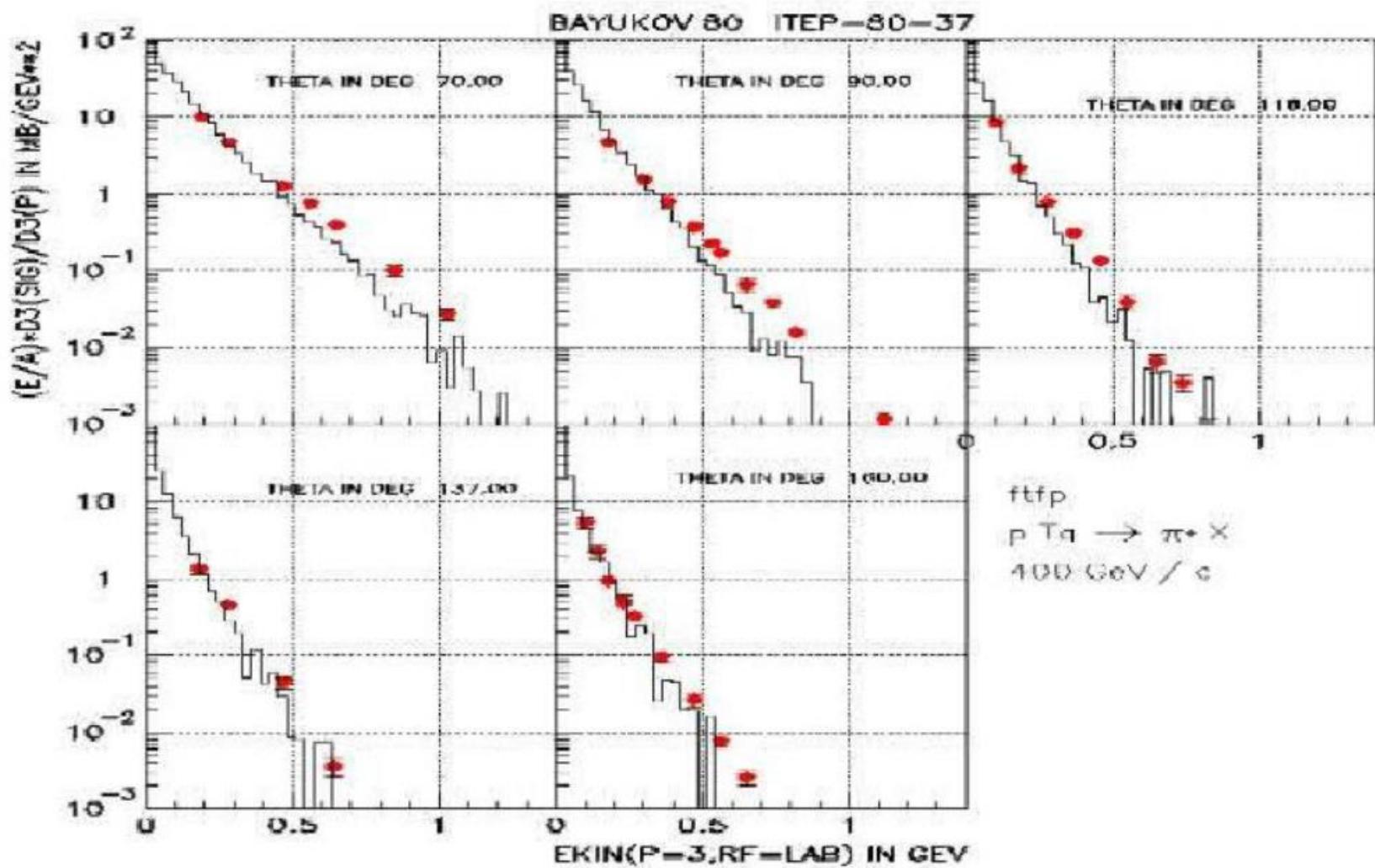
Two QCD String Models Available

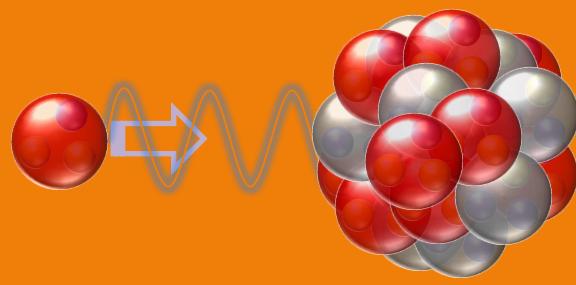
- Fritiof (FTF) valid for
 - p, n, π , K, Λ , Σ , Ω from 3 GeV to \sim TeV
 - anti-proton, anti-neutron, anti-hyperons at all energies
 - anti-d, anti-t, anti- ${}^3\text{He}$, anti- α with momenta between 150 MeV/nucleon and 2 GeV/nucleon
- Quark-Gluon String (QGS) valid for
 - p, n, π , K from 15 GeV to \sim TeV
- Both models handle:
 - building 3-D model of nucleus from individual nucleons
 - splitting nucleons into quarks and di-quarks
 - formation and excitation of QCD strings
 - string fragmentation and hadronization

QGS Validation



FTF Validation





V.5 - INTERMEDIATE ENERGIES : INTRA-NUCLEAR CASCADES

Intra-nuclear Cascade Models

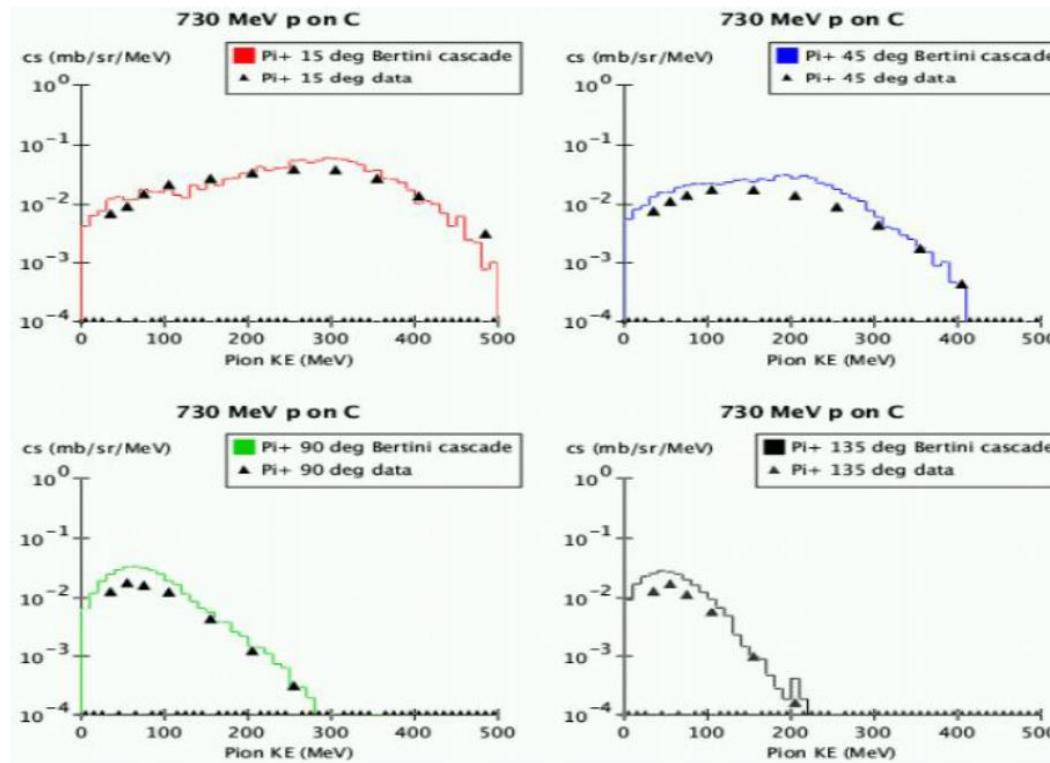
- Typical intra-nuclear cascade energies are inconvenient
 - too high for nuclear physics treatments
 - too low for QCD
- Must use Monte Carlo techniques to propagate hadrons within the target nucleus in order to produce a final state
 - “Monte Carlo within a Monte Carlo”
 - one of the first applications of Monte Carlo methods to nuclear interactions
 - time-consuming
- Specific channels not produced
 - do not use data to produce, for example $^{14}\text{N}(\text{p},\text{n})^{14}\text{O}$

Bertini-style Cascade Model

- A classical (non-quantum mechanical) cascade
 - average solution of a particle traveling through a medium (Boltzmann equation)
 - no scattering matrix calculated
 - can be traced back to some of the earliest codes (1960s)
- Core code:
 - elementary particle collisions with individual protons and neutrons: free space cross sections used to generate secondaries
 - cascade in nuclear medium
 - pre-equilibrium and equilibrium decay of residual nucleus
 - target nucleus built of three concentric shells

Using the Bertini Cascade

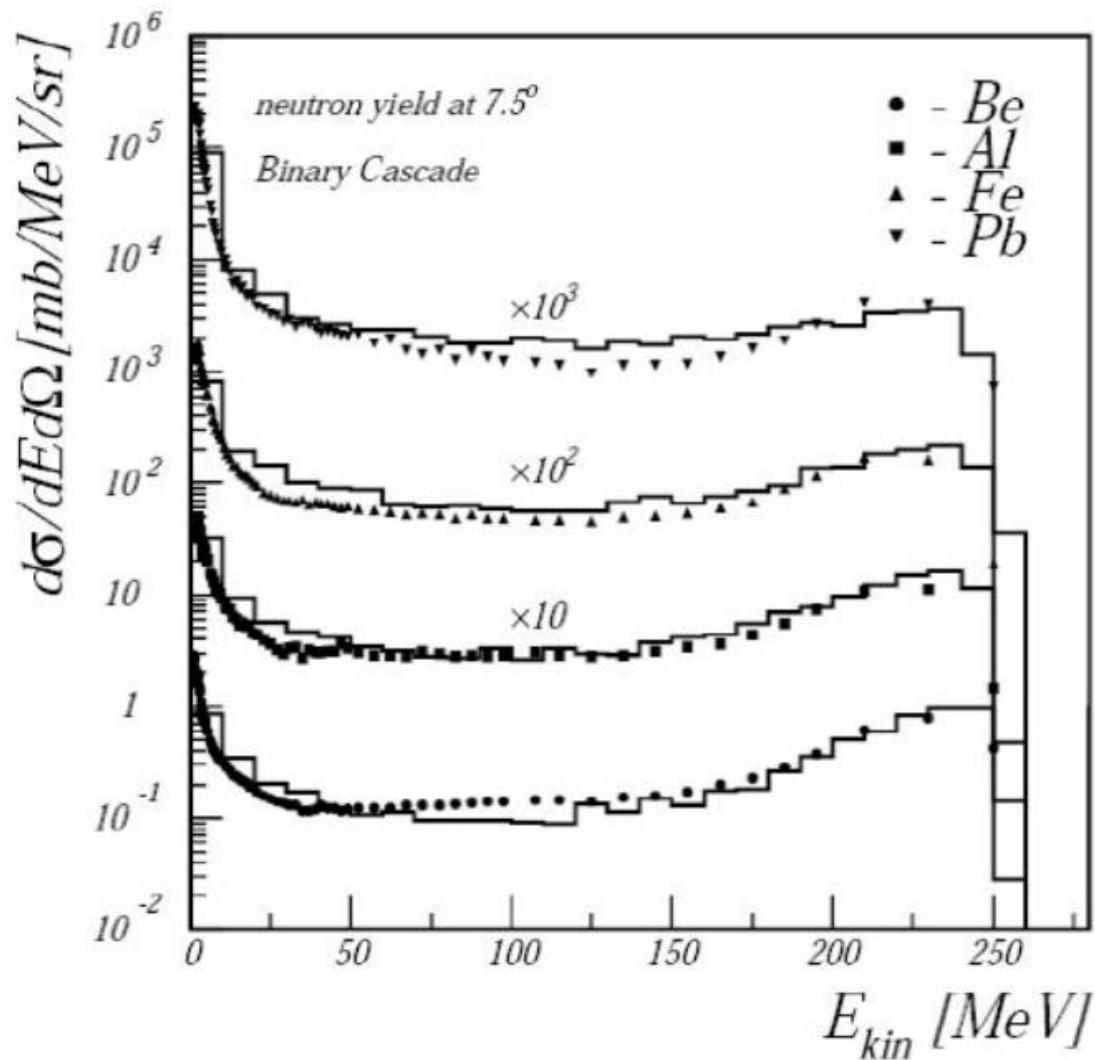
- In Geant4 the Bertini cascade is used for p , n , π^+ , π^- , K^+ , K^- , K^0_L , K^0_S , Λ , Σ^0 , Σ^+ , Σ^- , Ξ^0 , Ξ^- , Ω^-
 - valid for incident energies of 0 – 10 GeV
 - can also be used for gammas



Binary Cascade Model

- Modeling sequence similar to Bertini, except
 - it's a time-dependent model
 - hadron-nucleon collisions handled by forming resonances which then decay according to their quantum numbers
 - particles follow curved trajectories in smooth nuclear potential
- Binary cascade is currently used for incident p, n and π
 - valid for incident p, n from 0 to 10 GeV
 - valid for incident π^+ , π^- from 0 to 1.3 GeV
- A variant of the model, G4BinaryLightIonReaction, is valid for incident ions up to $A = 12$ (or higher if target has $A < 12$)

Validation of Binary Cascade 256 MeV protons

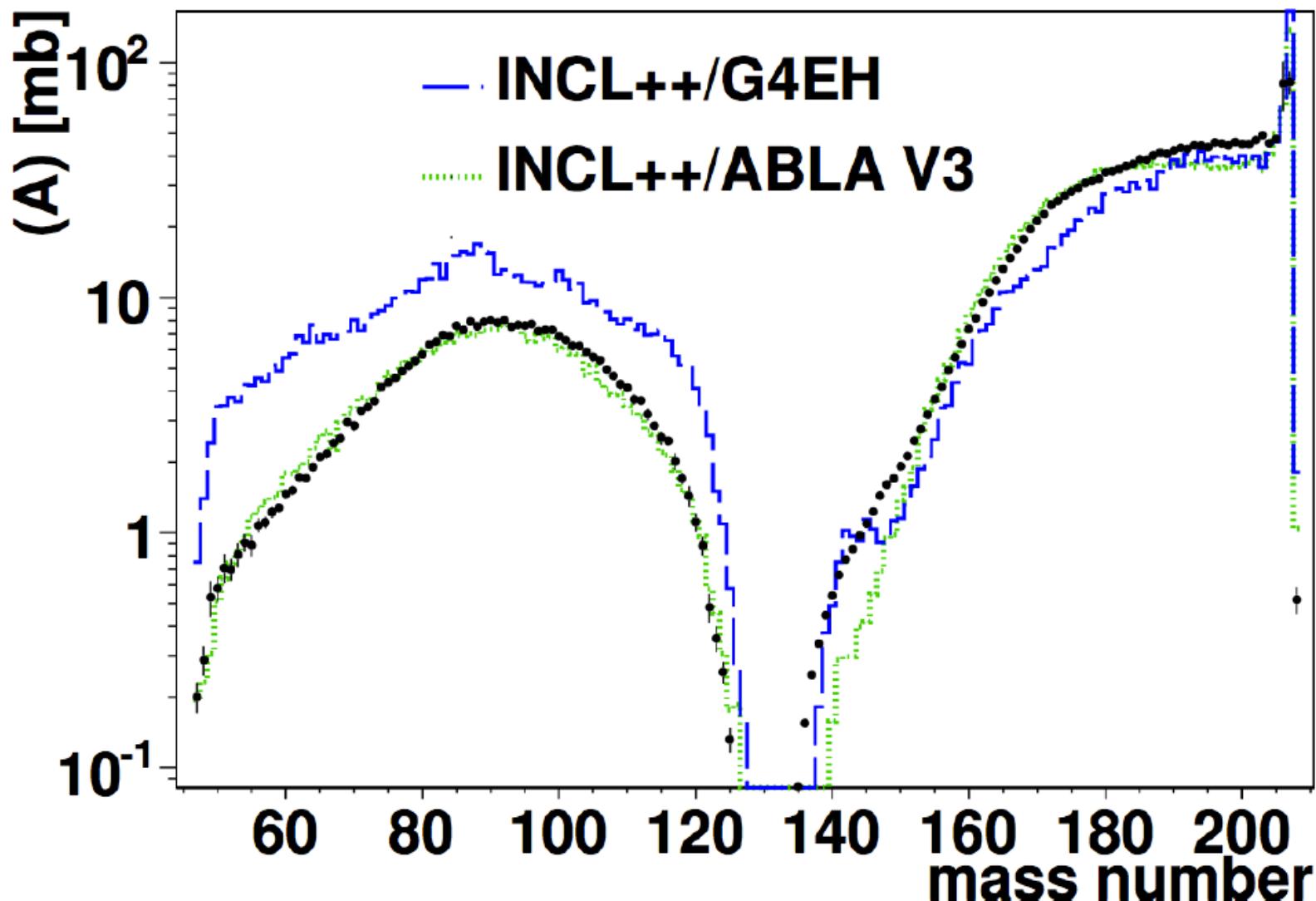


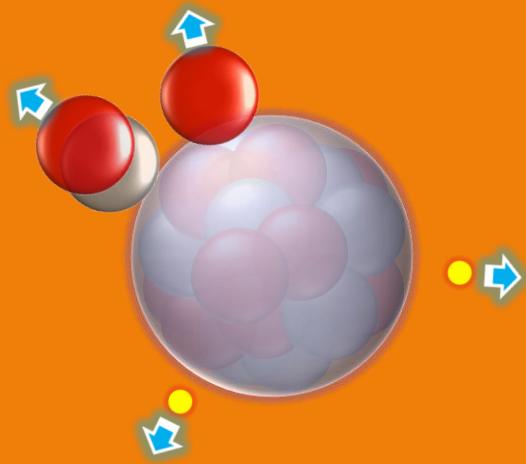
INCL++ Cascade Model

- Model elements
 - time-dependent model
 - smooth Woods-Saxon or harmonic oscillator potential
 - particles travel in straight lines through potential
 - delta resonance formation and decay (like Binary cascade)
- Valid for incident p, n and π , d, t, ${}^3\text{He}$, α from 150 MeV to 10 GeV
 - also works for projectiles up to $A = 12$
 - targets must be $11 < A < 239$
 - ablation model (ABLA) can be used to de-excite nucleus
- Used successfully in spallation studies
 - also expected to be good in medical applications

Validation of INCL++ Model

Spallation residues from p + ^{208}Pb





V.6 - NUCLEUS “COOLING DOWN” MODELS

Precompound Models

- G4PrecompoundModel is used for nucleon-nucleus interactions at low energy and as a nuclear de-excitation model within higher-energy codes
 - valid for incident p, n from 0 to 170 MeV
 - takes a nucleus from a highly excited set of particle-hole states down to equilibrium energy by emitting p, n, d, t, ${}^3\text{He}$ and α
 - once equilibrium is reached, four sub-models are called to take care of nuclear evaporation and break-up
 - these 4 models not currently callable by users
- Two Geant4 cascade models have their own version of nuclear de-excitation models embedded in them

De-excitation Models

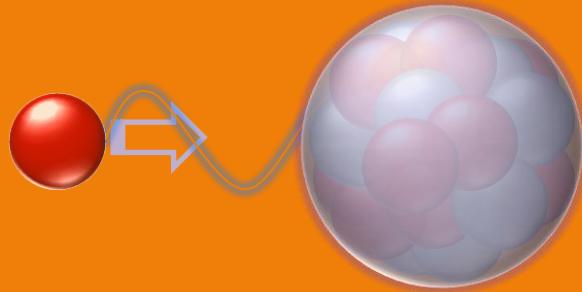
- Four sub-models typically used to de-excite a remnant nucleus
 - Fermi break-up
 - photon evaporation
 - multi-fragmentation
 - fission
- These models are not intended to be assigned directly to a process
 - instead they are meant to be linked together and then assigned to the G4Precompound model through the class `G4ExcitationHandler`

De-excitation Model Details

- Fermi break-up
 - remnant nucleus is destroyed – nothing left but p, n, t, a
 - valid only for $A < 17$ and high excitation energies
- Fission
 - splits excited nucleus and emits fission fragments + n
 - valid only for $A > 65$
- Multi-fragmentation
 - statistical breakup model with propagation of fragments in Coulomb field
 - for excitation energies $E/A > 3$ MeV

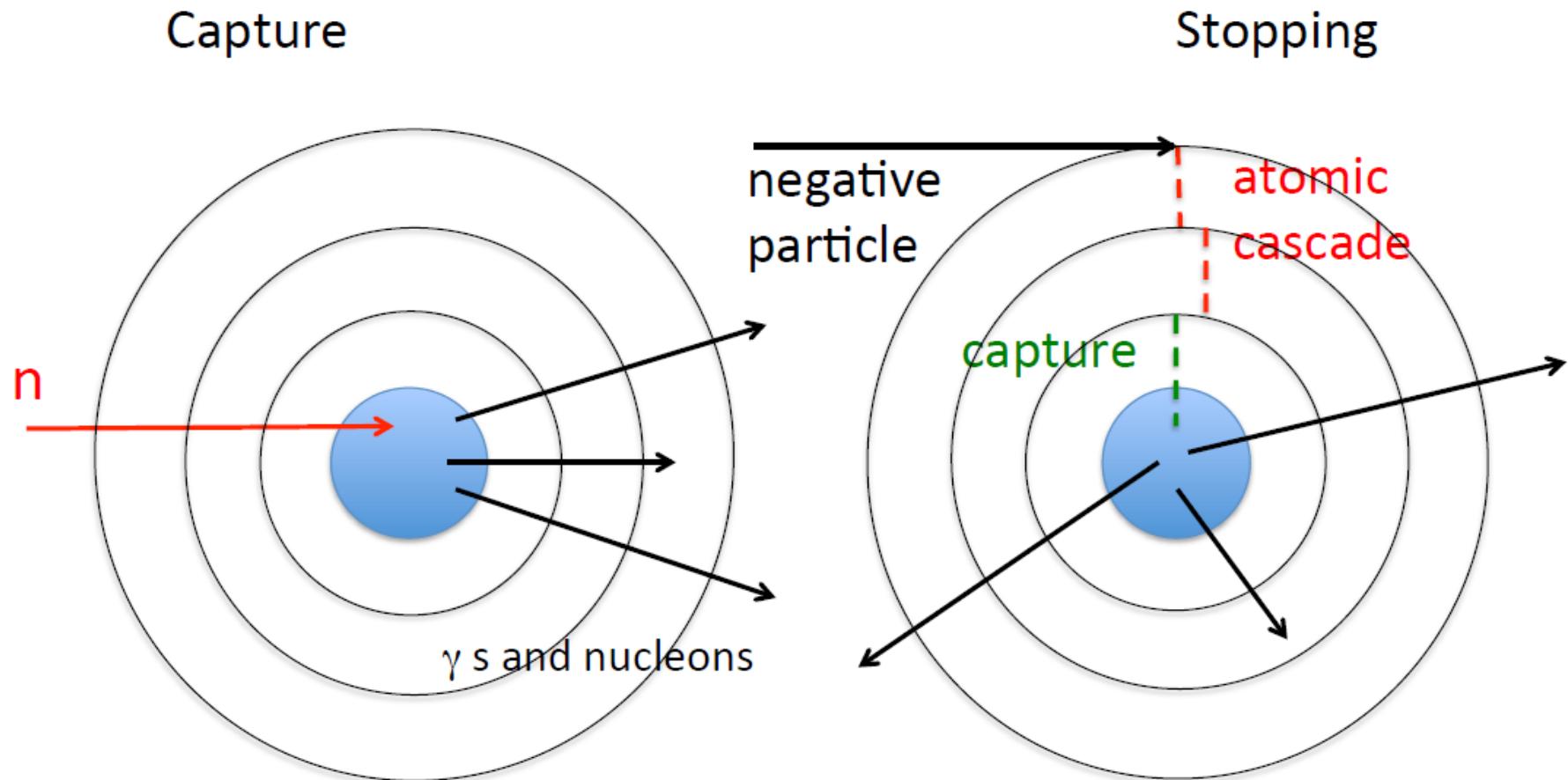
De-excitation Model Details

- Photon evaporation
 - usually final stage of nuclear de-excitation
 - data-driven: uses ENSDF database
 - currently have up to hundreds of gamma levels for 2071 nuclides in PhotonEvaporation3.1
 - handles gamma cascades, does electron emission in case of internal conversion
 - currently no correlation when more than one gamma emitted (but that's coming)



V - LOW ENERGIES: CAPTURE, STOPPING, FISSION

Capture and Stopping Models



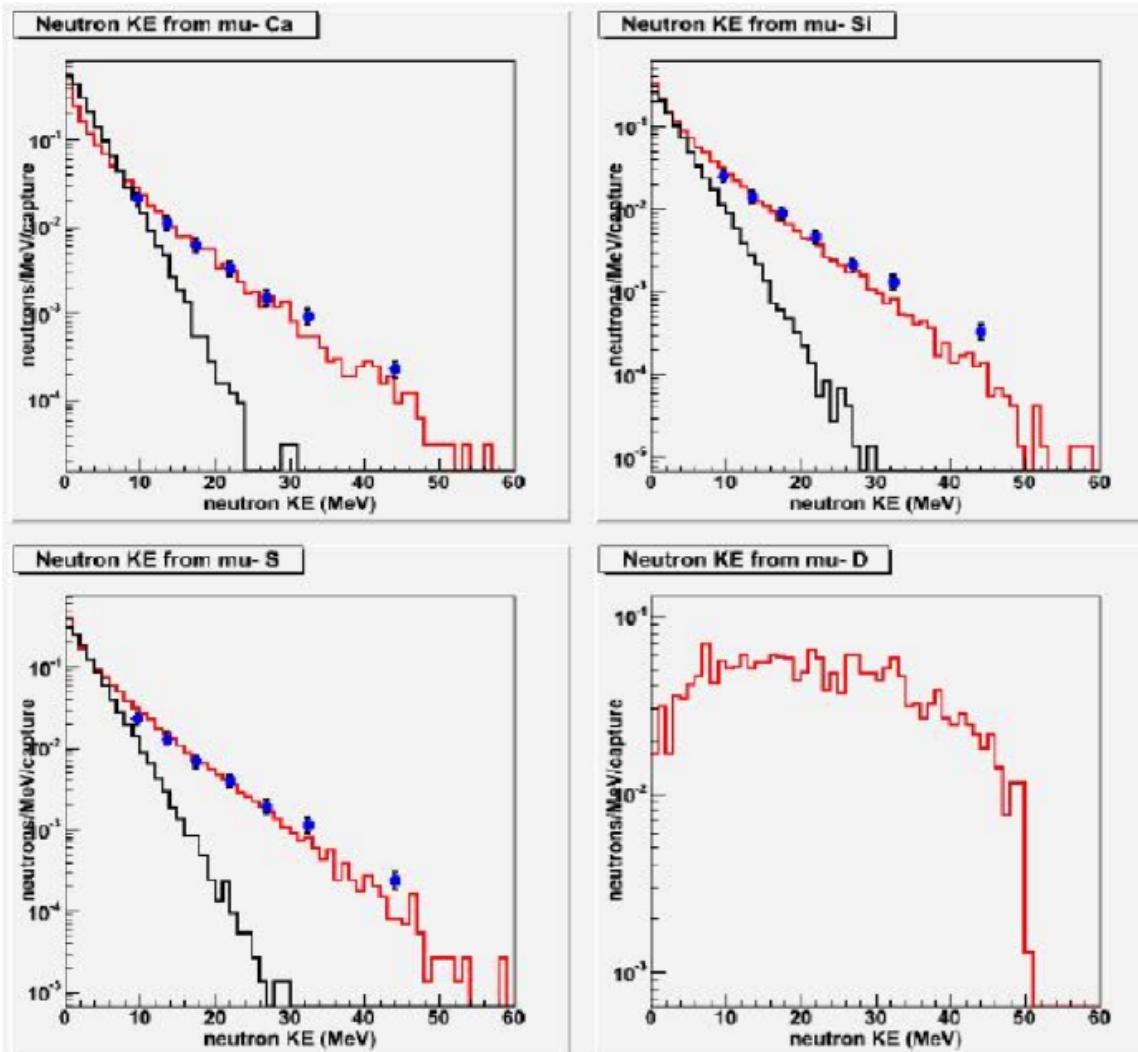
Stopped Hadron Models

- G4PiMinusAbsorptionBertini, G4KaonMinusAbsorptionBertini, G4SigmaMinusAbsorptionBertini
 - at rest process implemented with Bertini cascade model
 - G4Precompound model used for de-excitation of nucleus
 - includes atomic cascade but not decay in orbit
- G4AntiProtonAbsorptionFritiof, G4AntiSigmaPlusAbsorptionFritiof
 - FTF model used because > 2 GeV available in reaction
 - G4Precompound model used for de-excitation of nucleus
 - includes atomic cascade but not decay in orbit

Stopped Muon Models

- G4MuonMinusCapture
 - atomic cascade, with decay in orbit enabled
 - K-shell capture and nuclear de-excitation implemented with Bertini cascade model
 - used in most physics lists
- G4MuonMinusCaptureAtRest
 - atomic cascade, with decay in orbit enabled
 - K-shell capture uses simple particle-hole model
 - nuclear de-excitation handled by G4ExcitationHandler

Muon Capture using Bertini Model (red), old model (black)



Capture Models

- Neutrons, anti-neutrons never really stop, they just slow down from elastic scattering or are absorbed
 - kinetic energy must be taken into account
- G4HadronCaptureProcess
 - in-flight capture for neutrons
 - model implementations:
 - G4ParticleHPCapture (below 20 MeV)
 - G4NeutronRadCapture (all energies)
- G4AntiNeutronAnnihilationAtRest
 - implemented by GHEISHA parameterized model

Fission Processes and Models

- Many hadronic models already include fission implicitly
 - included in nuclear de-excitation code
 - in that case don't add fission process to physics list -> double counting
 - usually only needed in special cases
- G4HadronFissionProcess can use two models
 - G4ParticleHPFission
 - specifically for neutrons below 20 MeV
 - fission fragments produced if desired
 - G4FissLib: Livermore Spontaneous Fission
 - handles spontaneous fission as an inelastic process
 - no fission fragments produced, just neutron spectra

Fission Processes and Models

- Fission fragments can be produced with Wendt fission model
 - automatically available when ParticleHPFission is used
 - invoke by setting two environment variables:
 - G4NEUTRONHP_PRODUCE_FISSION_FRAGMENTS
 - G4NEUTRON_HP_USE_WENDT_FISSION_MODEL
 - see extended example `geant4/examples/extended/hadronic/FissionFragment`
- Model developed by Geant4 user who needed fission fragments in addition to emitted neutrons for reactor studies
 - worked with Geant4 developer and contributed code

V.8 - LOW ENERGY (<20 MEV) PARTICLE TRANSPORT

Low Energy Hadron Physics

- Below 20 MeV incident energy, Geant4 provides several models for treating n, p, d, t, ${}^3\text{He}$ and α interactions in detail
- The high precision models (ParticleHP) are data-driven and depend on a large database of cross sections, etc.
 - the G4NDL database is available for download from the Geant4 web site
 - TENDL optional database is also available
 - elastic, inelastic, capture and fission models all use this isotope-dependent data
- There are also models to handle thermal scattering from chemically bound atoms

High Precision Particles

- ParticleHP models provide elastic, inelastic, capture and fission for incident n, p, d, t, ${}^3\text{He}$, α
 - mostly below 20 MeV for n
 - $0 < E < 200$ MeV for charged
 - also depends on large database (ENDF)
 - alternative dbs ready: TENDL, IAEA medical, IBANDL
 - recently merged with NeutronHP
- Code currently available
 - good comparisons so far with MCNP

Geant4 Neutron Data Library (G4NDL)

- Contains the data files for the high precision neutron models
 - includes both cross sections and final states
- From Geant4 9.5 onward, G4NDL is based solely on the ENDF/B-VII database
 - G4NDL data is now taken only from ENDF/B-VII, but still has G4NDL format
 - use G4NDL 4.0 or later
- Prior to G4 9.5 G4NDL selected data from 9 different databases, each with its own format
 - Brond-2.1, CENDL2.2, EFF-3, ENDF/B-VI, FENDL/E2.0, JEF2.2, JENDL-FF, JENDL-3 and MENDL-2
 - G4NDL also had its own (undocumented) format

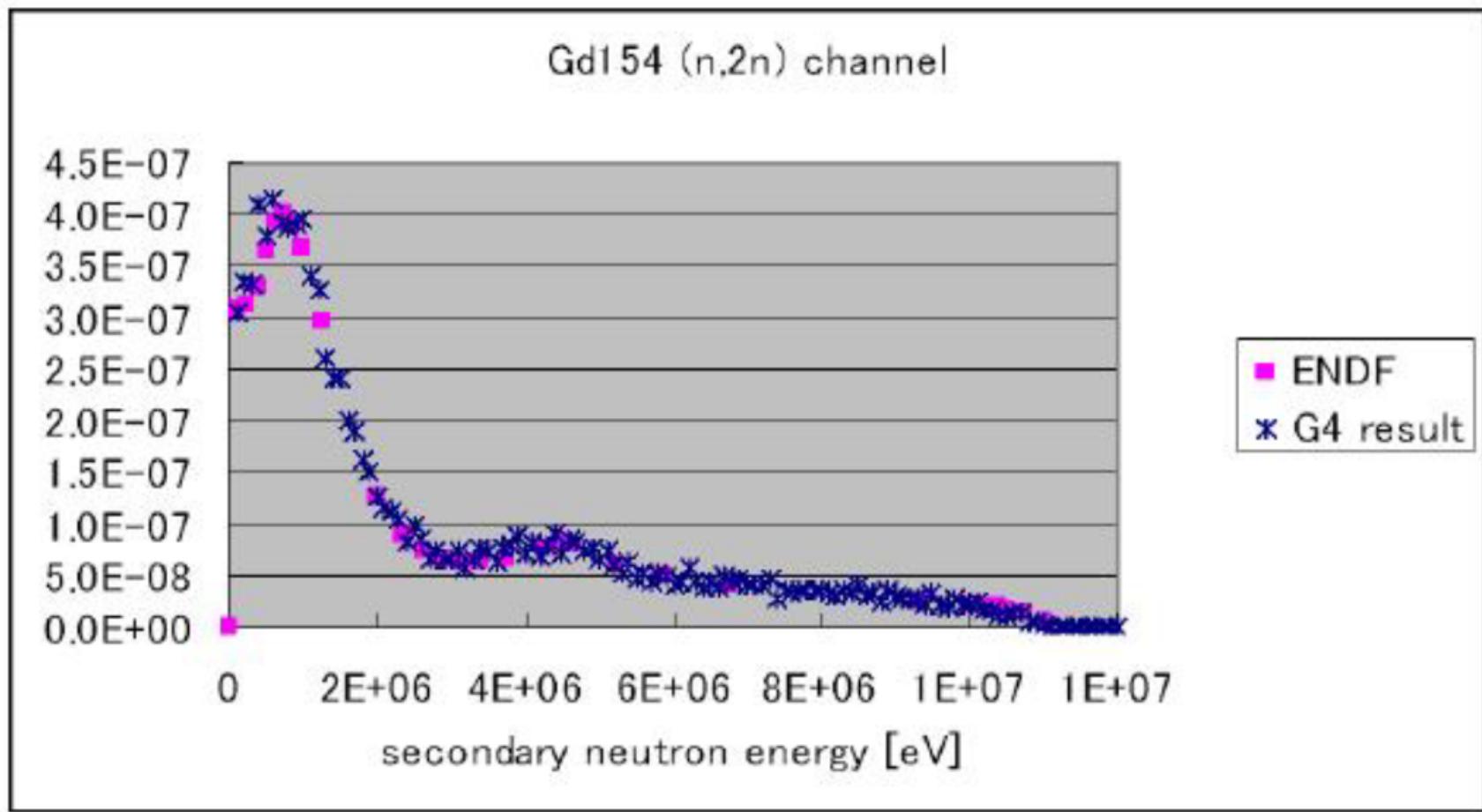
G4ParticleHPElastic

- Handles elastic scattering of n, p, d, t, ${}^3\text{He}$, α by sampling differential cross section data
 - interpolates between points in the cross section tables as a function of energy
 - also interpolates between Legendre polynomial coefficients to get the angular distribution as a function of energy
 - scattered particle and recoil nucleus generated as final state
- Note that because look-up tables are based on binned data, there will always be a small energy non-conservation
 - true for inelastic, capture and fission processes as well

G4ParticleHPInelastic

- Currently supports many inelastic final states + n gamma (discrete and continuum)
 - $n (A,Z) \rightarrow (A-1, Z-1) n p$
 - $n (A,Z) \rightarrow (A-3, Z) n n n n$
 - $n (A,Z) \rightarrow (A-4, Z-2) d t$
 -
- Secondary distribution probabilities
 - isotropic emission
 - discrete two-body kinematics
 - N-body phase space
 - continuum energy-angle distributions (in lab and CM)

Neutron Inelastic: ^{154}Gd (n,2n) Comparison to Data



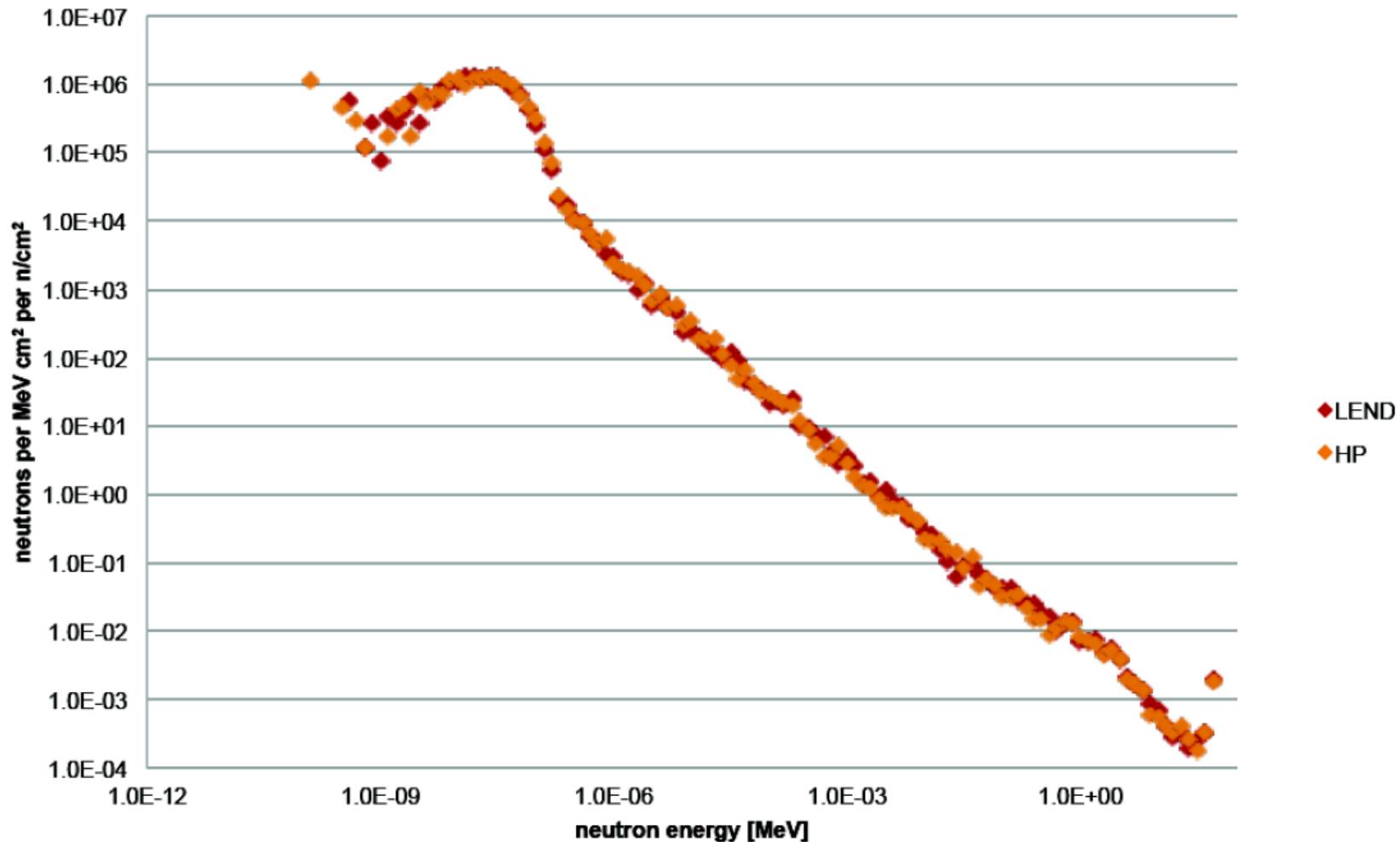
Thermal Neutron Scattering from Chemically Bound Atoms

- At thermal energies, atomic motion, vibration, rotation of bound atoms affect neutron scattering cross sections and the angular distribution of secondary neutrons
- The energy loss (or gain) of such scattered neutrons may be different from those from interactions with unbound atoms
- Original HP models included only individual Maxwellian motion of target nucleus (free gas model)
- New behavior handled by model and cross section classes
 - `G4HPTermalScatteringData`, and
 - `G4HPTermalScattering`

LEND – the new Livermore Neutron Models

- An alternative to the HP models
 - better code design
 - faster
 - Livermore database not yet as extensive G4NDL
- Corresponding model for each model in HP
 - elastic, inelastic, capture, fission
- Invocation in physics list:
 - use model names G4LENDElastic, G4LENDInelastic, G4LENDCapture, G4LENDFission, and cross sections G4LENDElasticCrossSection, G4LENDInelasticCrossSection, G4LENDCaptureCrossSection, G4LENDFissionCrossSection
- Database to use: go to <ftp://gdo-nuclear.ucllnl.org/pub/> and select G4LEND, then ENDF-B-VII.0.targ.gz

45-50 MeV neutron bombarding a concrete slab: neutron energy spectrum at depth of 1 m

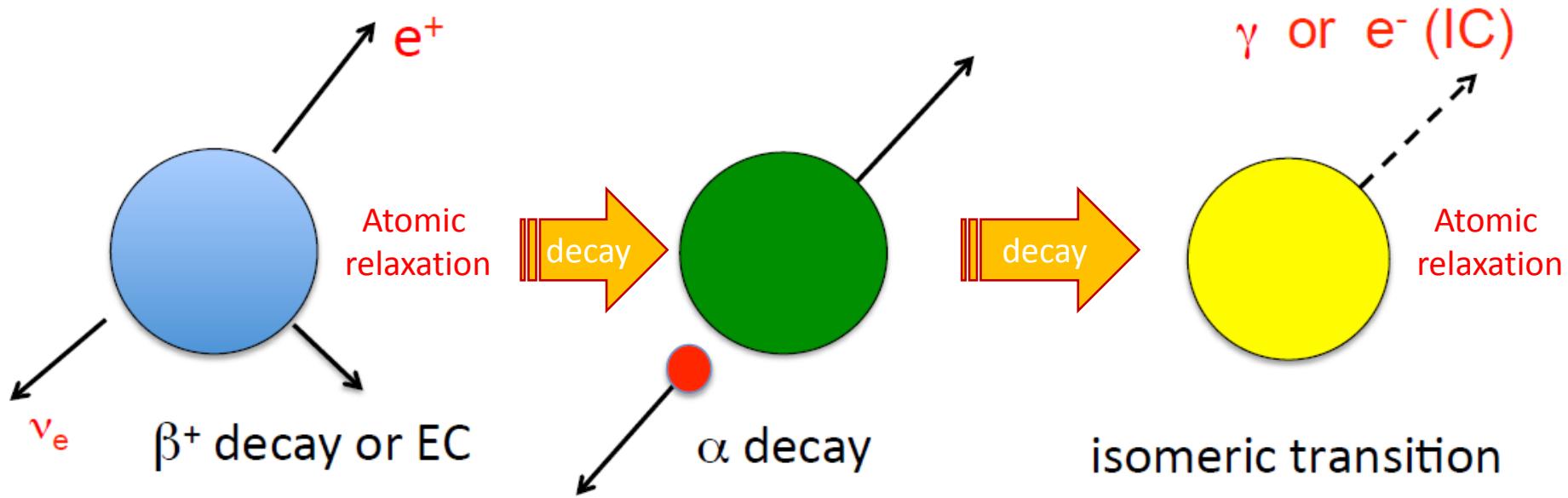


V.9 – RADIOACTIVE DECAYS

Radioactive Decay

- Process to simulate radioactive decay of nuclei
 - in flight
 - at rest
- α , β^+ , β^- , γ decay, electron capture (EC) implemented
- Empirical and data-driven
 - data files taken from Evaluated Nuclear Structure Data Files (ENSDF)
 - As of Geant4 10.4, these are in RadioactiveDecay5.2
 - half lives, nuclear level structure for parent and daughter nuclides, decay branching ratios, energy of decay process
 - currently 2792 nuclides, including all meta-stable states with lifetimes > 1 ns

Radioactive Decay Chain



EC: electron capture

IC: internal conversion

Gamma (or electron) Emission

- If daughter of nuclear decay is an isomer, prompt de-excitation is done by using G4PhotonEvaporation
 - uses ENSDF files with all known gamma levels for 2071 nuclides
 - As of Geant4 10.4, these are in PhotonEvaporation5.2
 - internal conversion is enabled as a competing process to gamma de-excitation
- Nuclides with $LT < 1$ ns decay immediately
- Option to enable atomic relaxation after decay
 - atomic cascade
 - Auger
 - fluorescence

Biased Mode

- G4RadioactiveDecay has several biasing options
 - amplify rare decay branches
 - set all decay branches equal
 - “splitting” : perform nuclear decay N times for each event
 - activation: integrate decay chain over time windows using Bateman equations
 - collimation of decay products
 - enable/disable decay in various geometry volumes
- Options activated by UI commands

V.10 – ION-ION PHYSICS

Ion-Ion Inelastic Scattering

- Up to now we've considered only hadron-nucleus interactions, but Geant4 has five different nucleus-nucleus collision models
 - G4BinaryLightIon
 - G4WilsonAbrasion/G4WilsonAblation
 - G4EMDissociationModel
 - G4QMD
 - G4Incl
 - FTF
- Also provided are several ion-ion cross section data sets
- Currently no ion-ion elastic scattering models provided

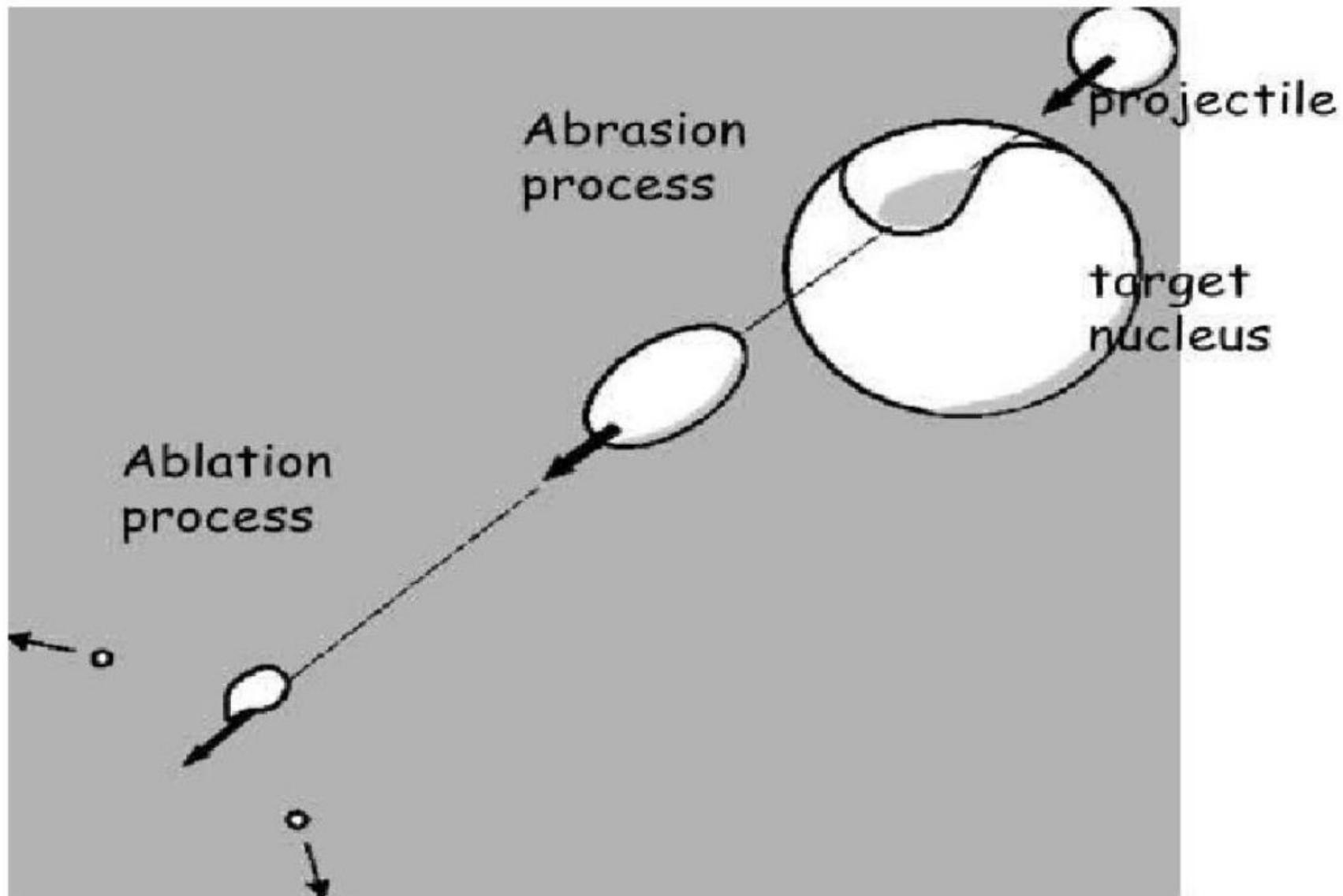
G4BinaryLightIonReaction

- This model is an extension of the G4BinaryCascade model (to be discussed later)
- The hadron-nuclear interaction part is identical, but the nucleus-nucleus part involves:
 - preparation of two 3D nuclei with Woods-Saxon or harmonic oscillator potentials
 - lighter nucleus is always assumed to be the projectile
 - nucleons in the projectile are entered with their positions and momenta into the initial collision state
 - nucleons are interacted one-by-one with the target nucleus, using the original Binary cascade model

G4WilsonAbrasion and G4WilsonAblation

- A simplified macroscopic model of nucleus-nucleus collisions
 - based largely on geometric arguments
 - faster than Binary cascade or QMD models, but less detailed
- The two models are used together
 - G4WilsonAbrasion handles the initial collision in which a chunk of the target nucleus is gouged out by the projectile nucleus
 - G4WilsonAblation handles the de-excitation of the resulting fragments
- Based on the NUCFRG2 model (NASA TP 3533)
- Can be used up to 10 GeV/n

Wilson Abrasion/Ablation

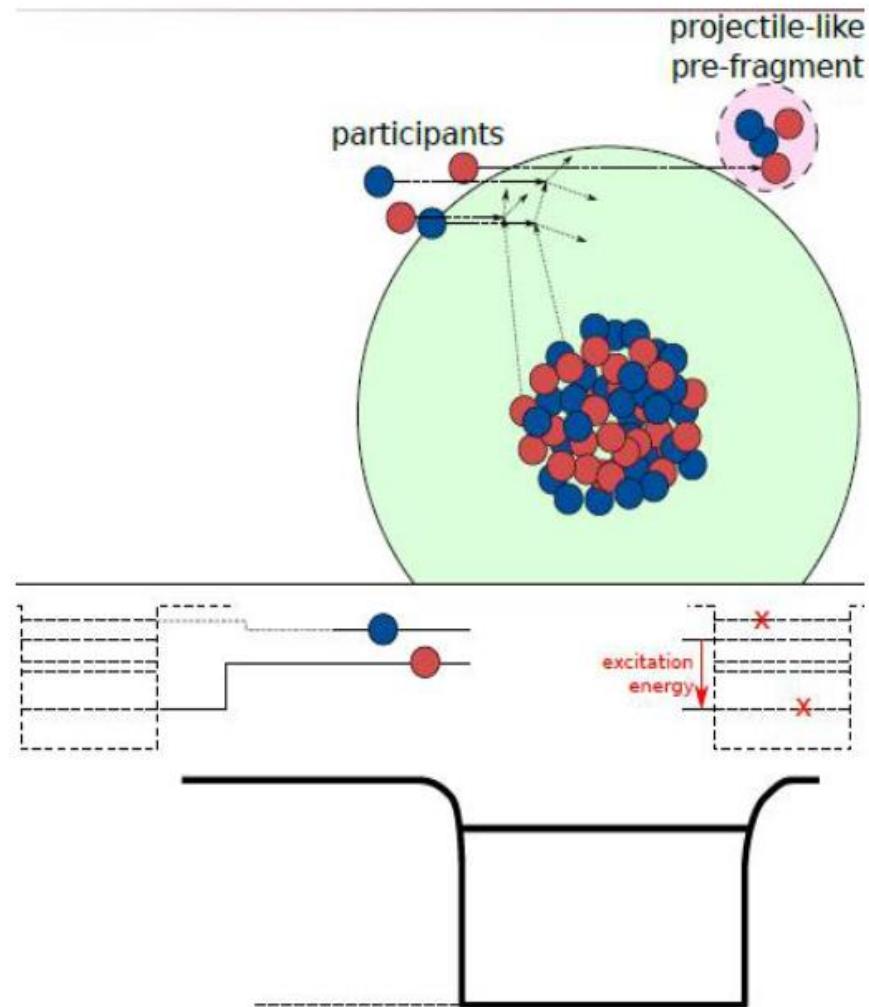


G4EMDissociation Model

- Electromagnetic dissociation is the liberation of nucleons or nuclear fragments as a result of strong EM fields
 - as when two high-Z nuclei approach
 - exchange of virtual photons instead of nuclear force
- Useful for relativistic nucleus-nucleus collisions where the Z of the nucleus is large
- Model and cross sections are an implementation of the NUCFRG2 model (NASA TP 3533)
- Can be used up to 100 TeV

INCL Nucleus-Nucleus

- INCL hadron-nucleus model used to interact projectile nucleons with target
- True potential is not used for projectile nucleus, but binding energy is taken into account
- True potential is used for target
- Projectile nucleons can pass through to form fragment or interact with nucleus

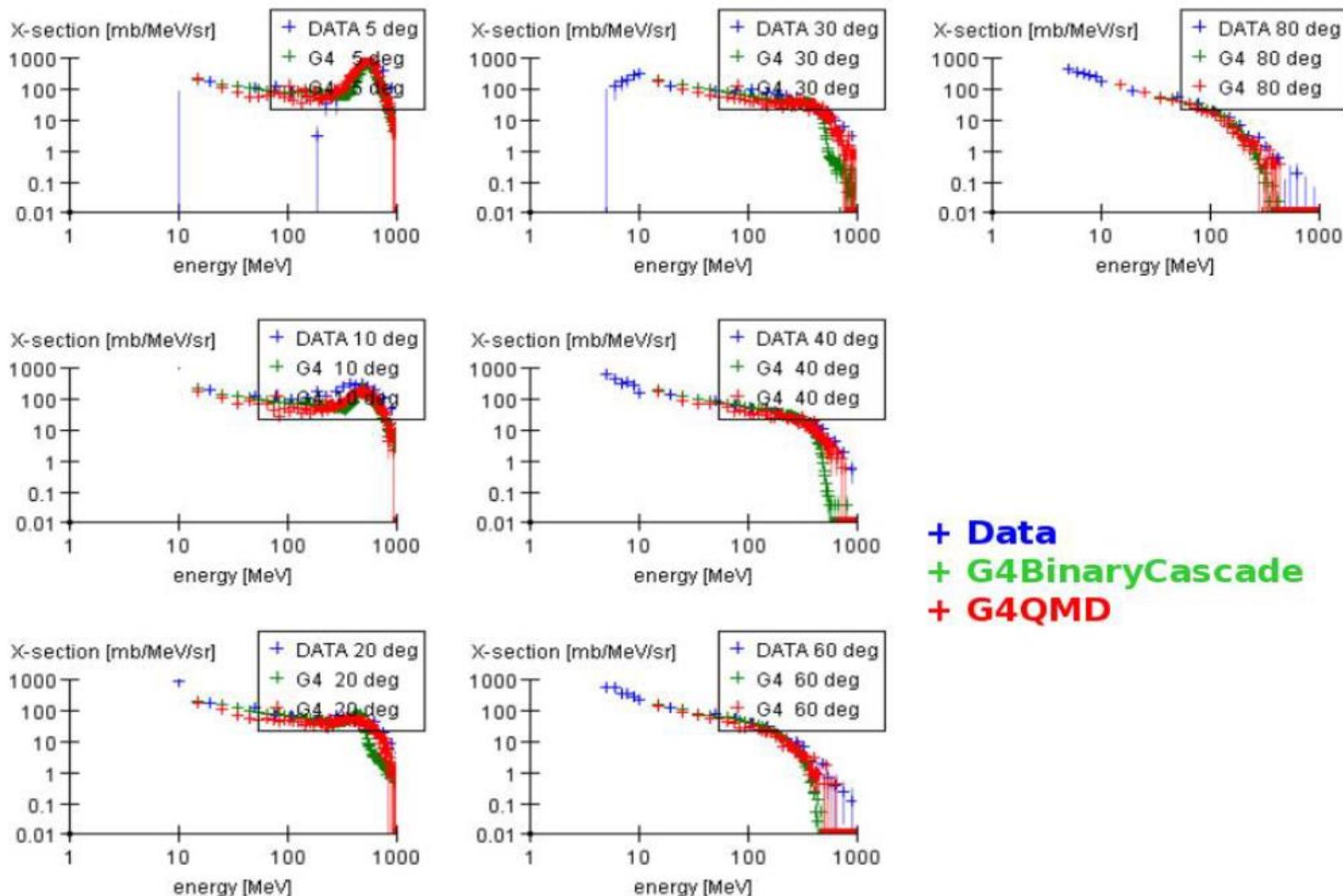


G4QMD Model

- BinaryLightIonReaction has some limitations
 - neglects participant-participant scattering
 - uses simple time-independent nuclear potential
 - imposes small A limitation for target or projectile
 - Binary cascade base model can only go to 5-10 GeV
- Solution is QMD (quantum molecular dynamics) model
 - an extension of the classical molecular dynamics model
 - treats each nucleon as a gaussian wave packet
 - propagation with scattering which takes Pauli principal into account
 - can be used for high energy, high Z collisions

QMD Validation

Ar40 560MeV/n on Lead

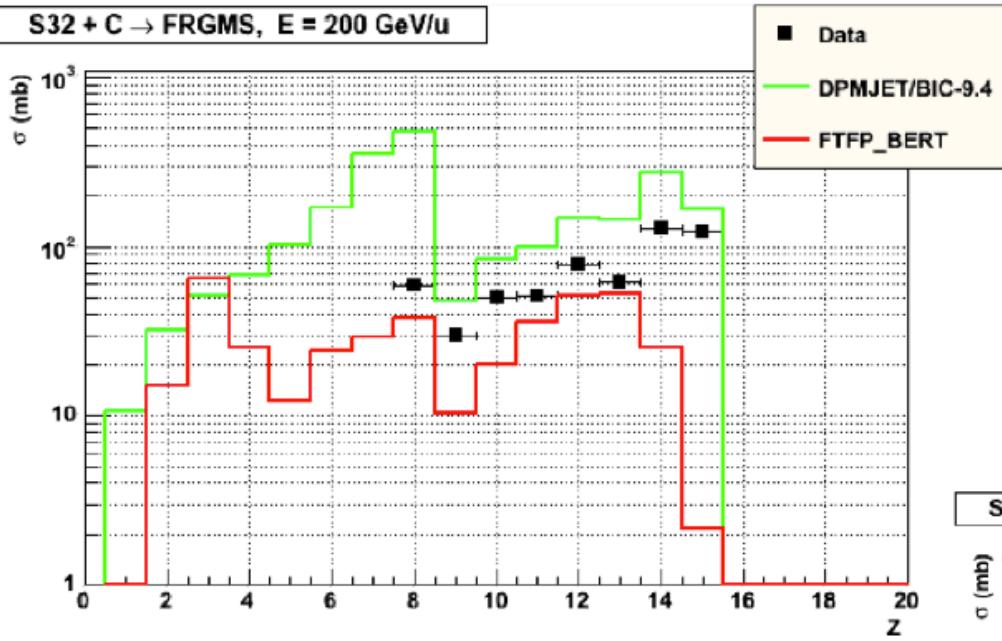


+ Data
+ G4BinaryCascade
+ G4QMD

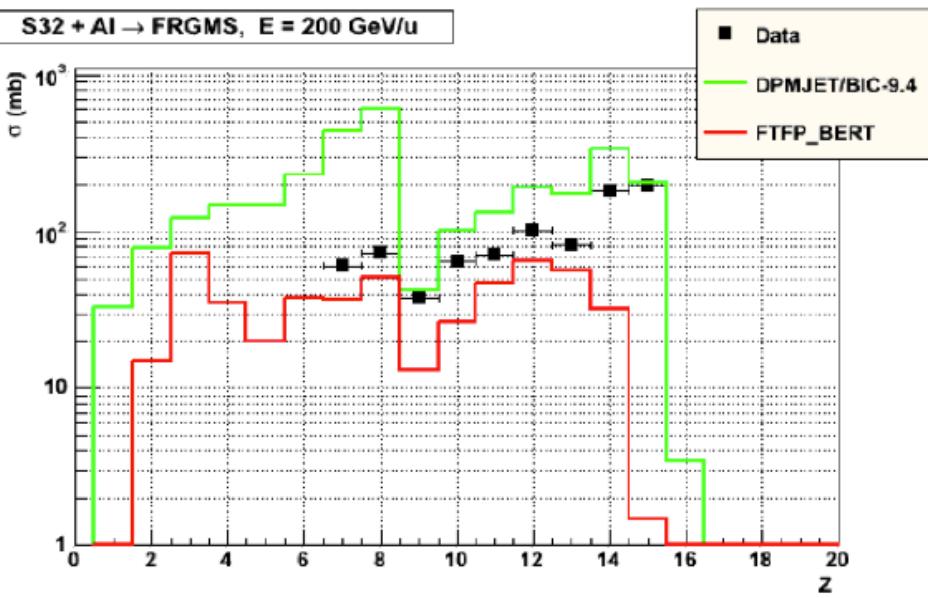
High Energy Nucleus-nucleus Models

- Most Geant4 nucleus-nucleus models so far have been low to medium energy ($< 20 \text{ GeV/N}$)
 - until recently we used interface to DPMJET-II for higher energies but this came with restrictions and was difficult to maintain
- We began looking for a native Geant4 solution
 - Fritiof (FTF) is now being developed for this
 - for light to medium nuclei, as good or better than DPMJET

S32 + C → FRGMS, E = 200 GeV/u



S32 + Al → FRGMS, E = 200 GeV/u

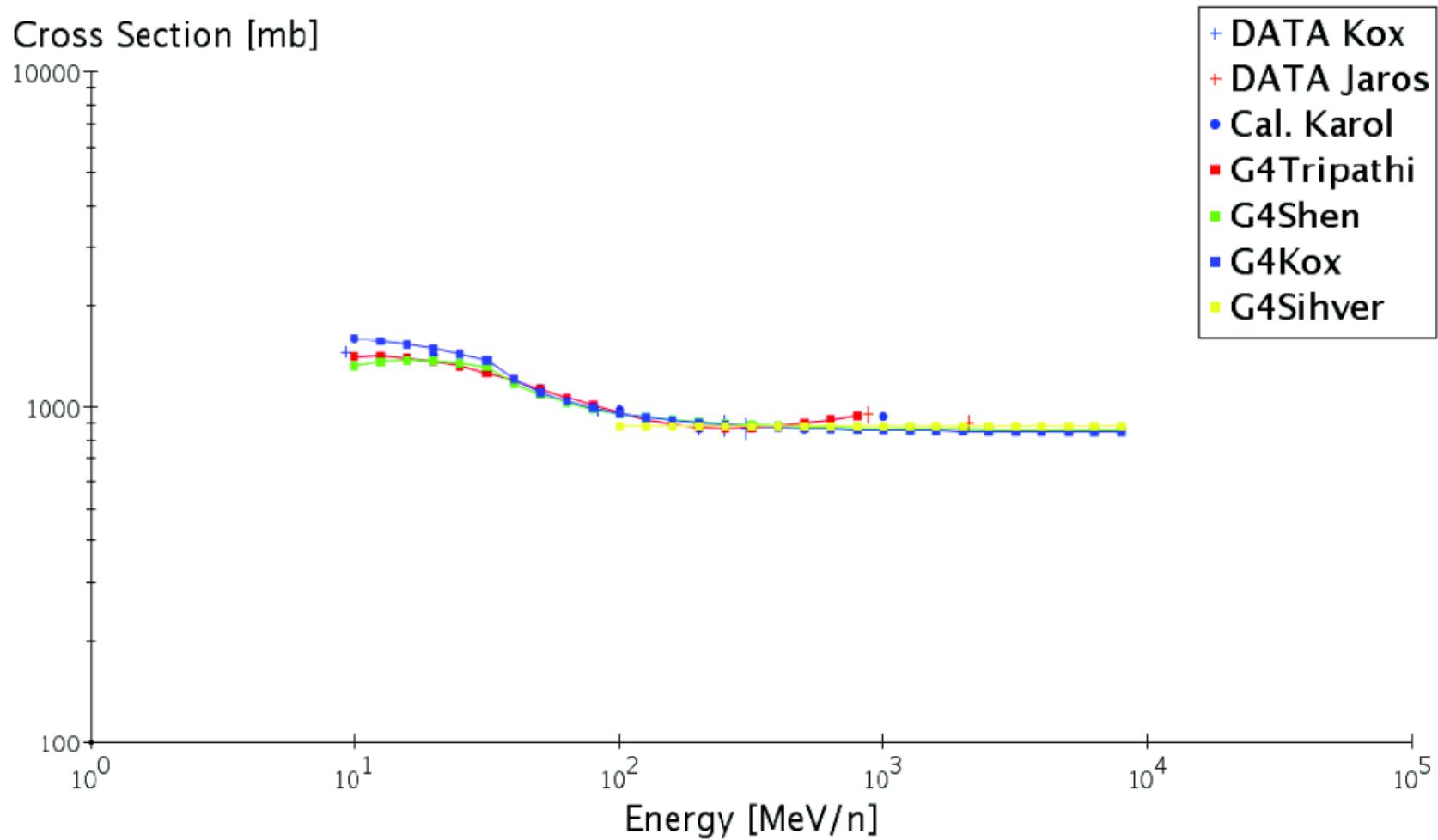


Ion Physics: Inelastic Cross Sections

Nucleus-nucleus inelastic cross sections existing in Geant4:

- [Tripathi , Shen , Kox , Sihver](#)
 - These are empirical and parameterized formulas with theoretical insights
- [Glauber-Gribov-Grichine](#)
 - Calculates **total** and **inelastic** cross section, derives **elastic = total - inelastic** according to Glauber model with Gribov correction calculated in the dipole approximation on light cone
 - Most reference physics lists use this cross section for nucleus-nucleus interactions

Inelastic Cross Section C12 on C12



5.11 - GAMMA- & LEPTO- NUCLEAR

Gamma- and Lepto-nuclear Processes

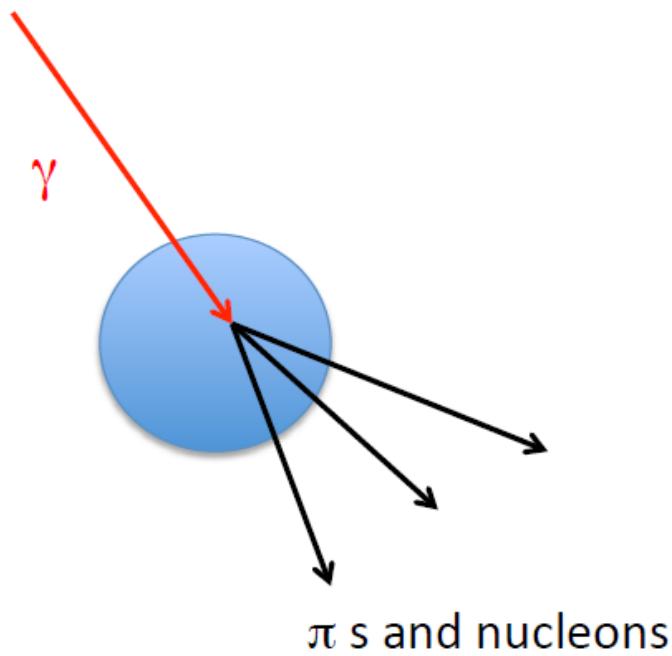
- Geant4 models which are neither exclusively electromagnetic nor hadronic
 - gamma-nuclear
 - electro-nuclear
 - muon-nuclear
- Geant4 processes available:
 - G4PhotoNuclearProcess (implemented by two models)
 - G4ElectronNuclearProcess (implemented by one model)
 - G4PositronNuclearProcess (implemented by one model)
 - G4MuonNuclearProcess (implemented by two models)

Gamma- and Lepto-nuclear Processes

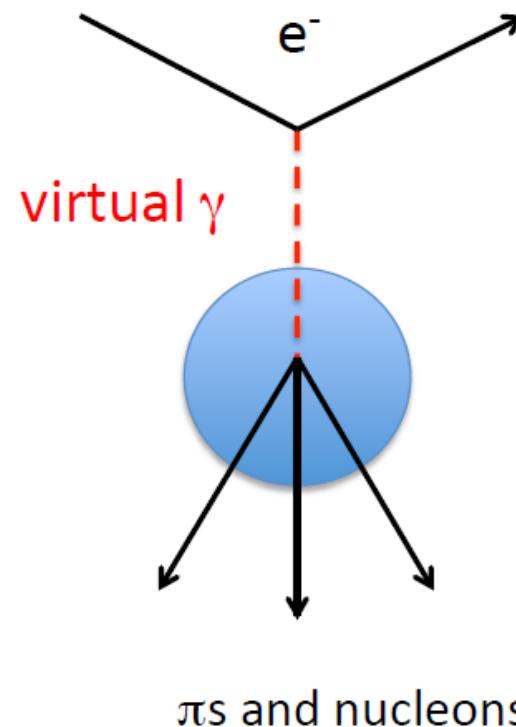
- Gammas interact directly with the nucleus
 - at low energies they are absorbed and excite the nucleus as a whole
 - at high energies they act like hadrons (pion, rho, etc.) and form resonances with protons and neutrons
- Electrons and muons cannot interact hadronically, except through virtual photons
 - electron or muon passes by a nucleus and exchanges virtual photon
 - virtual photon then interacts directly with nucleus (or nucleons within nucleus)

Gamma- and Lepto-nuclear Models

Gamma-nuclear



Lepto-nuclear



Gamma- and Lepto-nuclear Models

- G4MuonVDNuclearModel
 - Kokoulin model of EM cross section and virtual photon generation
 - Weizsacker-Williams conversion of virtual to real gamma
 - For $E_\gamma < 10$ GeV, direct interaction with nucleus using Bertini cascade
 - For $E_\gamma > 10$ GeV, conversion of γ to π^0 , then interaction with nucleus using FTFP model
- G4ElectroVDNuclearModel
 - Kossov model of EM cross section and virtual photon generation
 - all else identical to that in G4MuonVDNuclearModel
- For gamma-nuclear reaction
 - Bertini cascade below 3.5 GeV
 - QGSP from 3 GeV to 100 TeV

SUMMARY (1/2)

- The Geant4 hadronic framework is structured to allow cross-sections and models to cooperate in various energy ranges
- Various cross-sections and models are available for elastic interactions.
- Two QCD string models are available for high energy interactions:
 - Fritiof and QGS
- The intermediate energy range is covered by intra-nuclear cascade models
 - BIC, BERT and INCLXX
- Nucleus “cooling down” after interaction by higher energy models (FTF, QGS, INCL) is handled by pre-compound and de-excitation models.

SUMMARY (2/2)

- Capture, stopping (for negative particles) and fissions are available.
- Low energy hadrons (< 20 MeV) are handled by means of databases.
 - This is a recent extension of the HP approach
- Radioactive decays, is available.
 - And includes (post-decay) atomic relaxation .
- The hadronic package includes ion-ion interactions,
- And gamma- lepto-nuclear processes.