Electron deposition in semi-infinite media / Electron backscatter

Geant4 Validation

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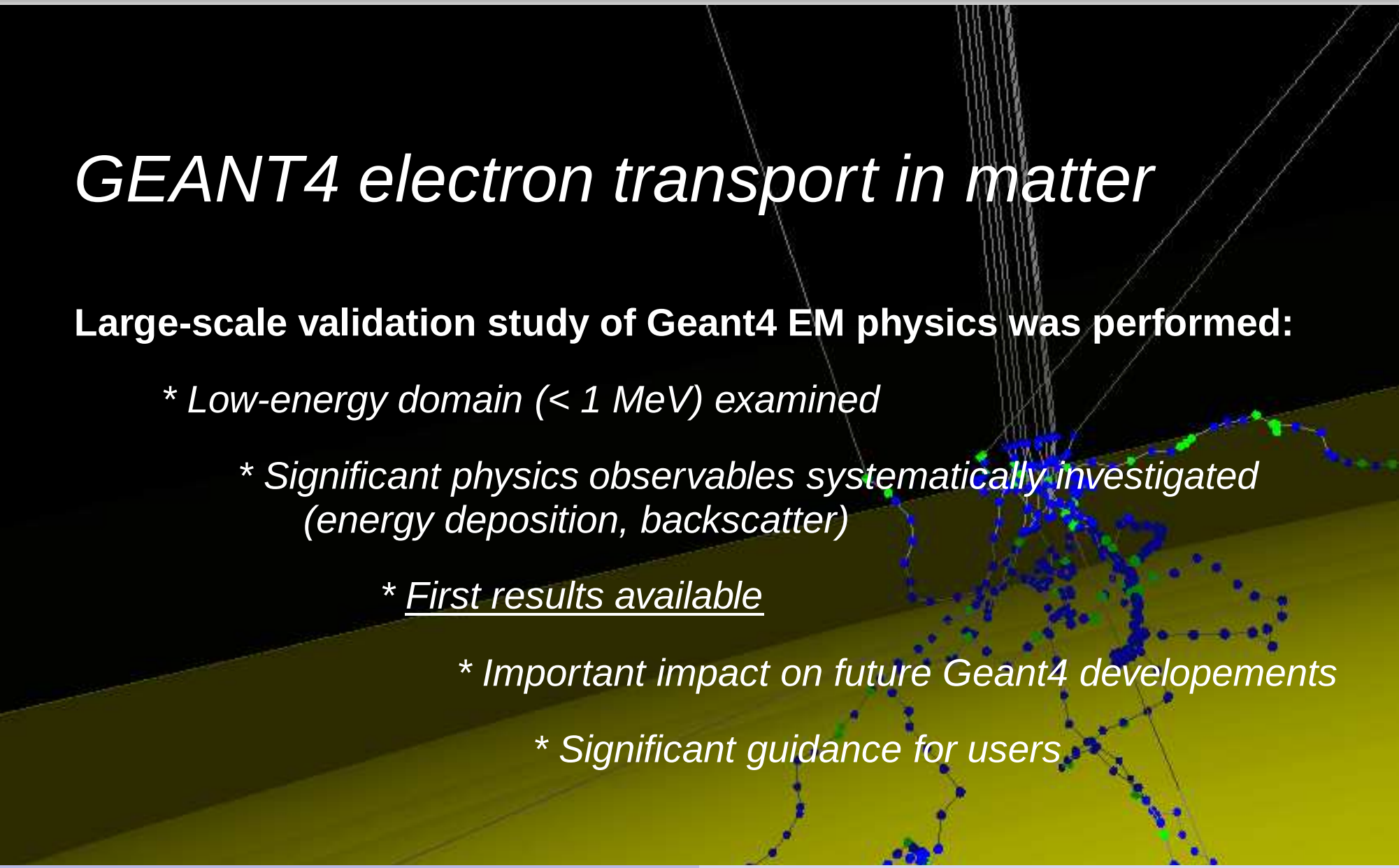


GEANT4 electron transport in matter

Large-scale validation study of Geant4 EM physics was performed:

** Low-energy domain (< 1 MeV) examined*

** Significant physics observables systematically investigated (energy deposition, backscatter)*

** First results available*

** Important impact on future Geant4 developements*

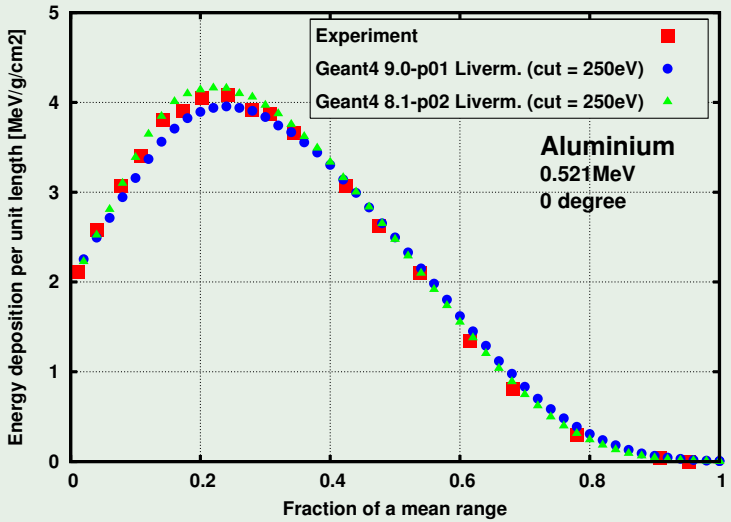
** Significant guidance for users*

Validation of Geant4 physics models

- **Major goals**
  - Guidance for users
    - Providing hints for optimal configuration of simulation parameters
    - Highlighting the abilities of physics models
  - Feedback for developers
    - Improvement of models based on findings
- **Systematic studies**
  - Investigation of systematic conditions (Many materials, beam energies,...)
  - Can enormously facilitate the interpretation of the overall behaviour of models

Validation of Geant4 physics models (cont.)

- **Strategy and methods**
  - Modeling physics scenarios
  - Building simulation applications
  - Computation of relevant physical quantities
  - Comparison against experim. data
  - Comparison against reference data
    - e.g. NIST



- **Experimental validation approach**
  - Not trivial, since experimental conditions must be reproduced
  - Precise geometry setup required in simulation application
  - Physical quantities computed according to experimental measurement

Physics observables in the current validation process

Low-energy electron beams (<1MeV) incident on diff. materials:

1. **Electron energy deposition in semi-infinite media**
   - Spatial energy delivery as a function of depth
2. **Backscattered particles**
   - Backscattered fractions of primary electrons and electron energy

Quantitative Geant4 Validation

- **Validation of low-energy electromagnetic physics models**
- **Comparison against experimental data**
  (Sandia reports SAND79-0410.UC-34a and SAND80-1968.UC-34a)

Sandia validation data

- Measured for Monte Carlo validation purposes (TIGER code)
- Electron energy deposition values are *absolute*
  - Important issue in a physics validation process
  - Hardly found in literature
  - Measured with a high spatial resolution
  - Uncertainty claimed to be < 2.2%
  - Potential drawback: Systematic erros fully considered?
- Many different materials covered
  - From beryllium to uranium
- Varying beam energies and incident angles considered
  - 300keV - 1MeV (Energy deposition measurements), 28keV - 1MeV (Backscatter measurements)
  - 0°and 60°(Energy deposition measurements), 0°, 15°, 30°, 45°, 60°, 85°(Backscatter measurements)

Low-energy EM physics in Geant4

- **Selectable physics models**
  - Process implementations based on different principles available
  - Parametrized and analytical models offered
  - Combining models adequately is the user's responsibility
    - Makes toolkit more versatile but requires certain experience by the user
    - Guidelines given in examples and in "Geant4 User's Guide for Application Developers"
    - Pre-prepared physics lists available
- **EM processes for e^- and γ in the low-energy domain**
  - Two packages: Low-Energy and Standard
  - Low-energy package: Two different approaches available
    - Library-based (Livermore) models
    - Penelope-like models

Low-energy EM physics in Geant4 (cont.)

Overview of EM processes

Focus on Liverm. models →	Low-energy package		Standard package
	Library-based (Livermore)	*Penelope-like*	
Electrons			
Ionisation	G4LowEnergyIonisation	G4PenelopeIonisation	G4eIonisation
Bremsstrahlung	G4LowEnergyBremsstrahlung	G4PenelopeBremsstrahlung	G4eBremsstrahlung
Multiple-Scattering	*	*	G4MultipleScattering
Photons			
Photoelectric effect	G4LowEnergyPhotoelectric	G4PenelopePhotoelectric	G4PhotoElectricEffect
Compton scattering	G4LowEnergyCompton	G4PenelopeCompton	G4ComptonScattering
Rayleigh scattering	G4LowEnergyRayleigh	G4PenelopeRayleigh	
Conversion	G4LowEnergyGammaConversion	G4PenelopeGammaConversion	G4GammaConversion

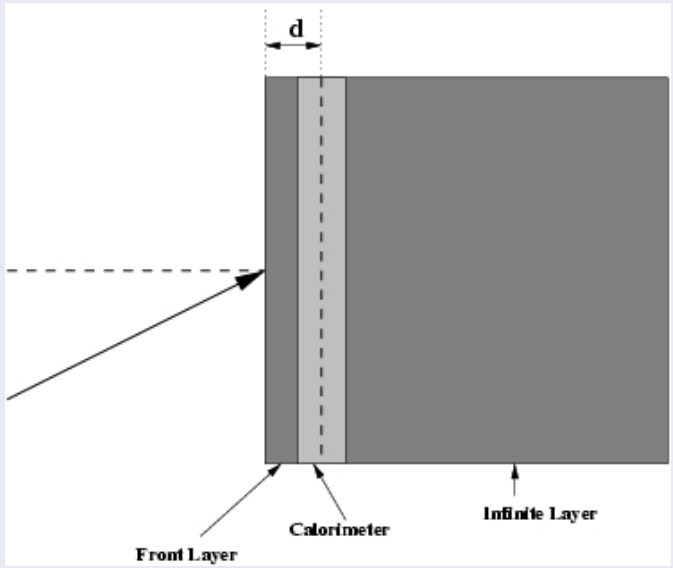
* *Standard G4MultipleScattering used for simulations involving processes of the Low-energy package*

Simulation configuration

- **Parameters (optionally handled by the user)**
  - Maximum step size of particle
    - Determines accuracy of spatial resolution
    - Recommended: Size of the order of the scoring bins
  - Production threshold for generating secondaries
    - Lower limits: Liverm. 250eV, Penelope $\sim$100eV, Standard 1keV
    - Handled through a range cut parameter
    - δ-ray production can significantly alter energy deposition
  - Multiple-scattering step limitation
    - More Multiple-scattering parameters exists (not further considered)
- **Tracking**
  - No tracking cut exists in Geant4
    - All (produced and accepted) particles tracked to zero range
    - Secondary *production* can be controlled though (prod. threshold)

Calorimetric measurements

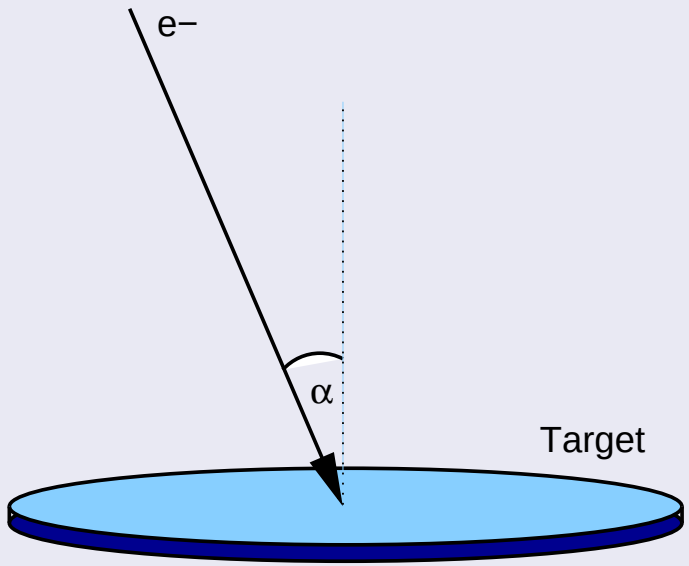
- **Spatial energy delivery pattern**
  - Calorimeter foil placed between front layer and “infinite” layer
  - Calorimeter consists of same material as target
  - Energy deposition measured for different front layer thicknesses
  - Measurement depth = Front layer thickness + half the calorimeter thickness



- **Backscattered energy**
  - Energy deposition determined in *target* (bulk calorimeter)
  - Backscattered energy calculated as complement of measurement
  - (Theoretical) Bremsstrahlung-correction applied

Geometry

- **Semi-infinite target medium**
  - Lateral dimensions and thickness > maximum e^--range
- **Primary particle vertex**
  - Direction determined by angle α between surface normal and beam axis
  - Beam impinges at target surface center



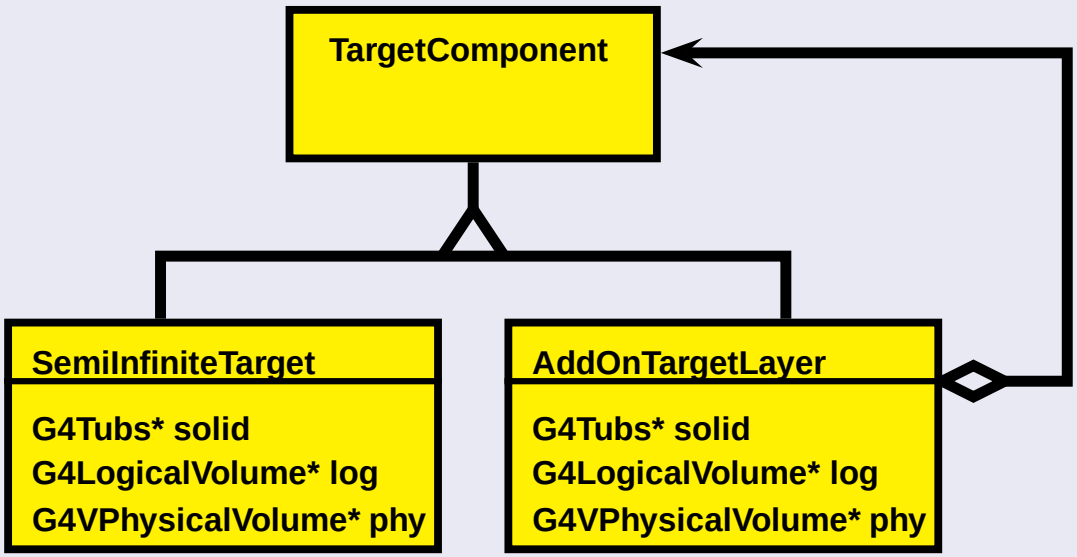
Simulation code

- **Geant4 application**
  - Simulation application was developed according to the experimental setup

Target/Detector modeling

Elaborate software design for describing target/detector geometry:

* *Decorator design pattern applied (see figure)*
  - *Add-on layer can be placed dynamically in front of semi-infinite slab*
  - *Multi-slab geometry by nesting decorator (AddOnTargetLayer) recursively*
* *Facilitates future work involving multi-layer configurations*



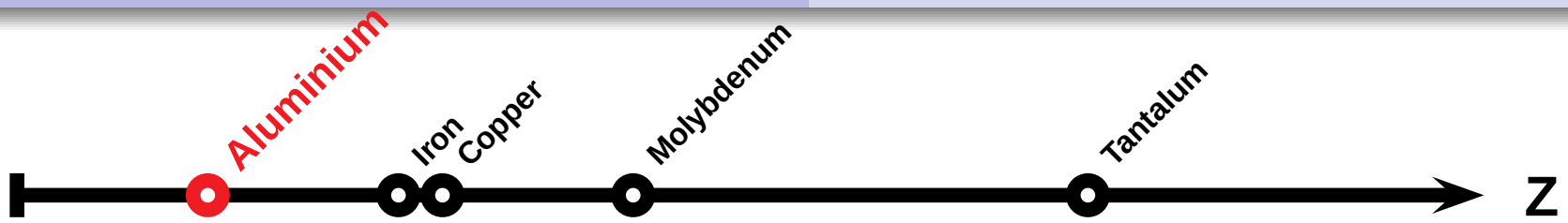
* *Geometry parameters controlled through macro commands*
  - *Layer thickness, materials,...*
  - *Easy simulation control*
  - *No recompiling necessary to update geometry*

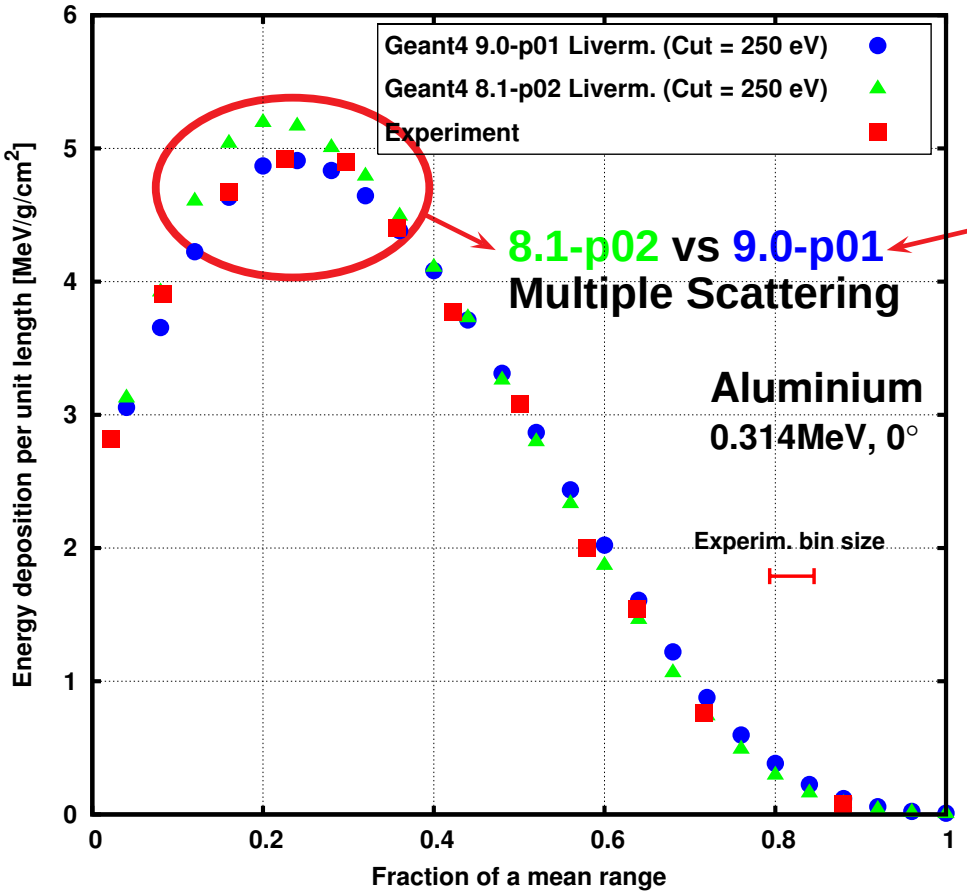
Simulation results

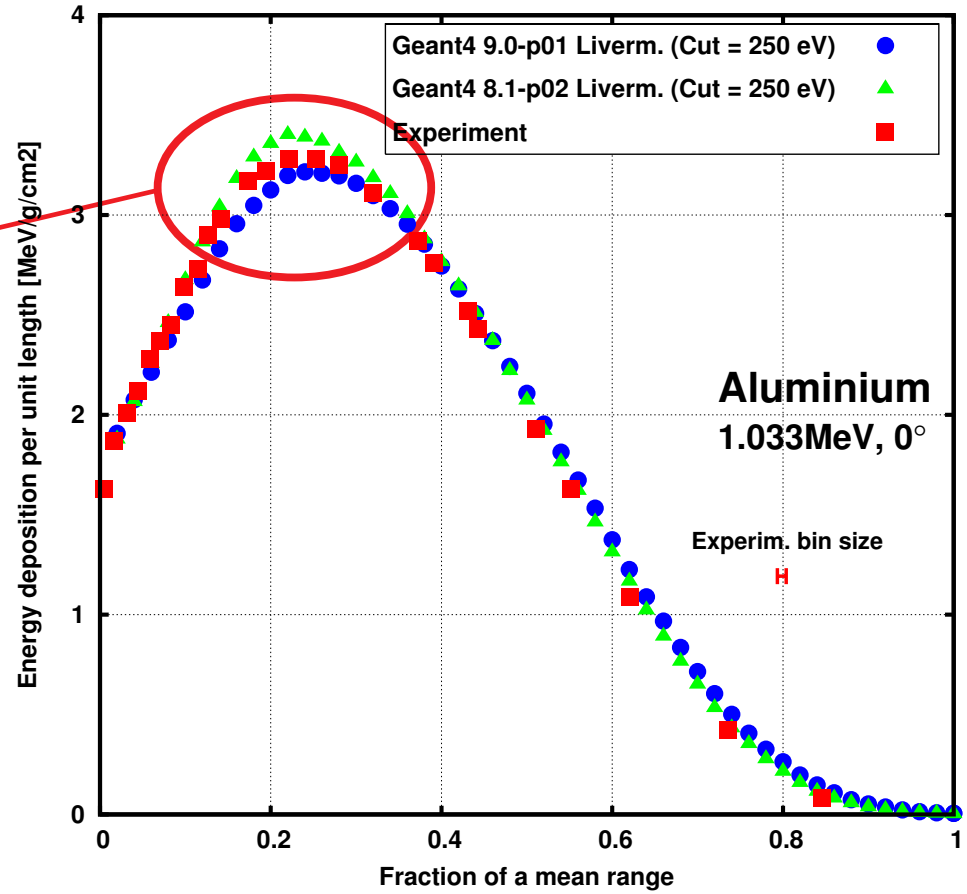
- **Systematic validation approach against Sandia data**
  - Various experimental configurations were investigated
    - Different target materials
    - Varying beam energies and incident angles
  - Several simulation configurations evaluated
  - Small subparts covered earlier by other authors (but no comprehensive collection)
    - E.g. O. Kadri *et al*,"Geant4 simulation of electron energy deposition in extended media", NIM B 258 (2007) 381-87
- **Due to lack of time only a subset of results can be presented**
  - Focus is on certain aspects
  - Paper with a complete collection of results in preparation with

Simulation results (cont.)

- **Setups and configurations considered in the presentation**
  - Systematic results presented for a few materials
  - Few beam energies considered
  - Geant4 versions 8.1-p02 and 9.0-p01 compared (for energy deposition results only)
    - Differences due to Multiple-Scattering model (Standard package)
    - Low-Energy package (Livermore, Penelope models) remains the same in both versions
  - Secondary particle production threshold evaluated
- **Further settings**
  - Maximum step size always set to 0.001 mm (lower recommended value)
  - Default value taken for Multiple-Scattering step limitation


Aluminium
Iron
Copper
Molybdenum
Tantalum
Z


Geant4 9.0-p01 Liverm. (Cut = 250 eV)
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
8.1-p02 vs 9.0-p01
Multiple Scattering
Aluminium
0.314MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm^2]
Fraction of a mean range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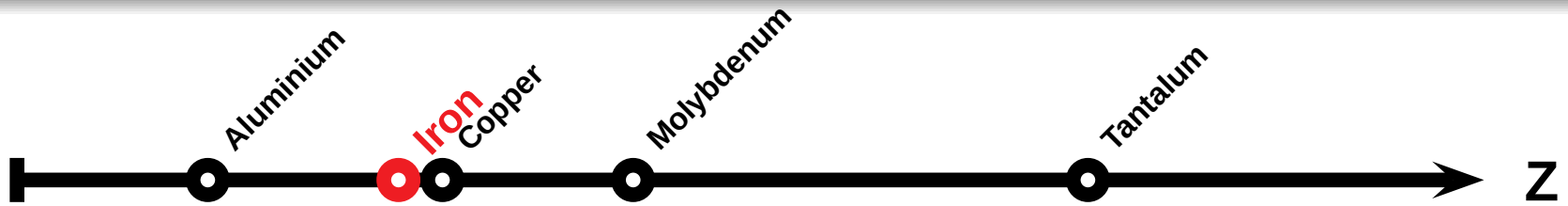
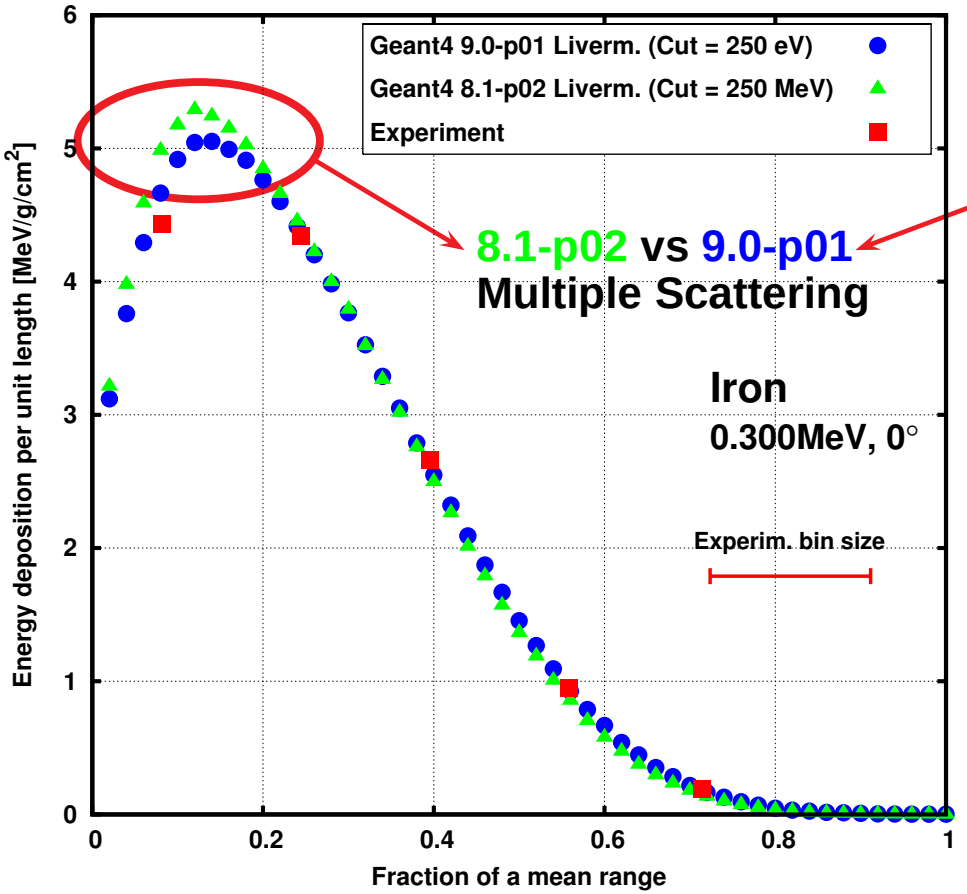
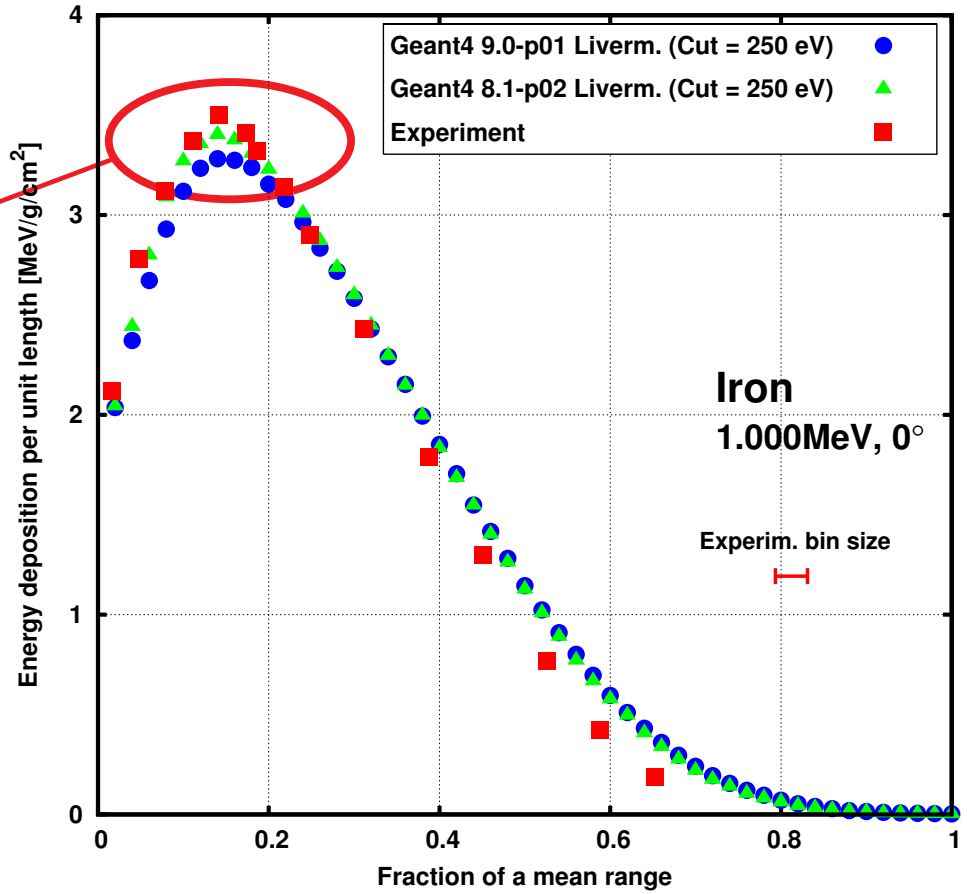
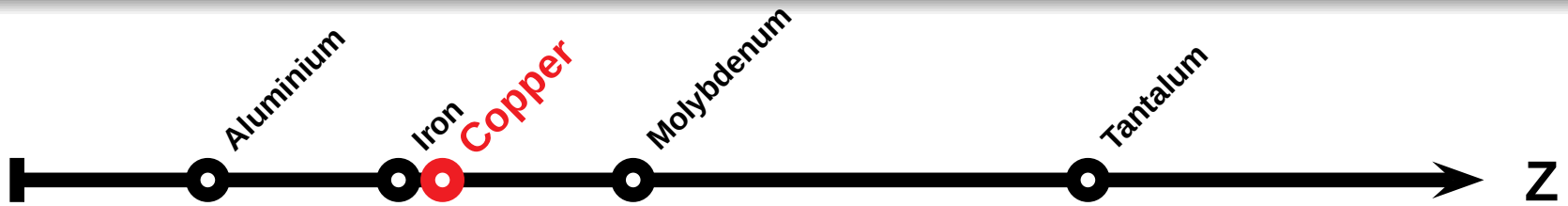
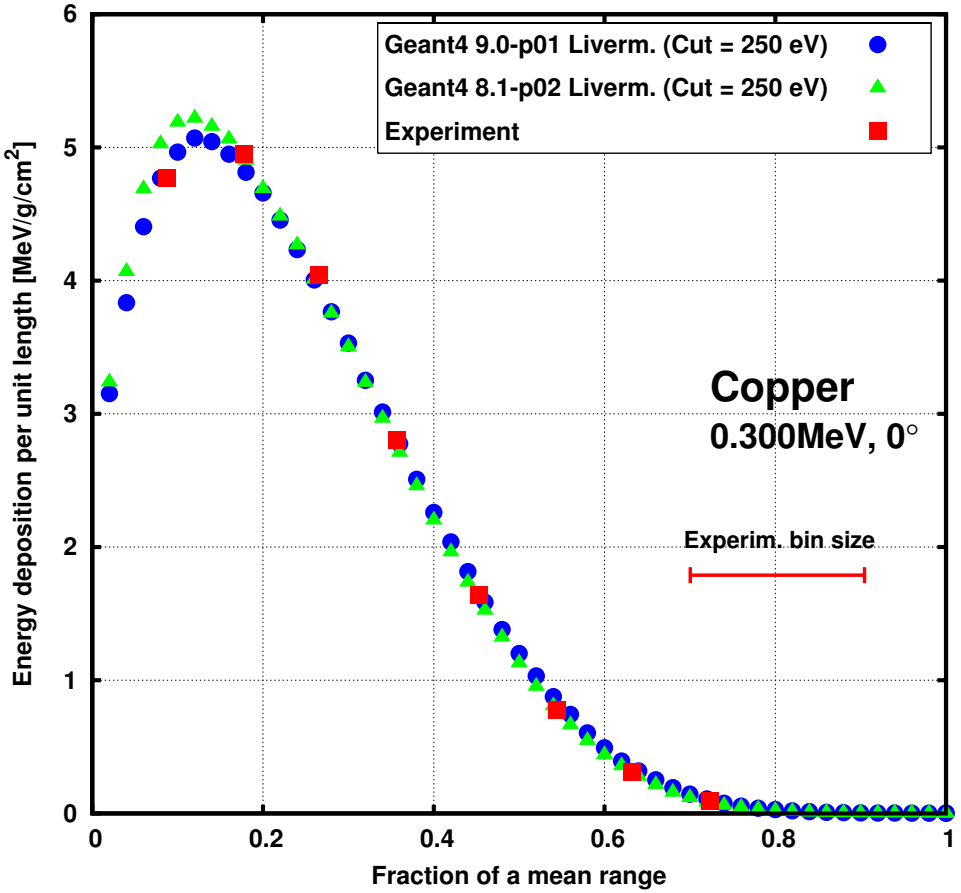
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Aluminium
1.033MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm2]
Fraction of a mean range

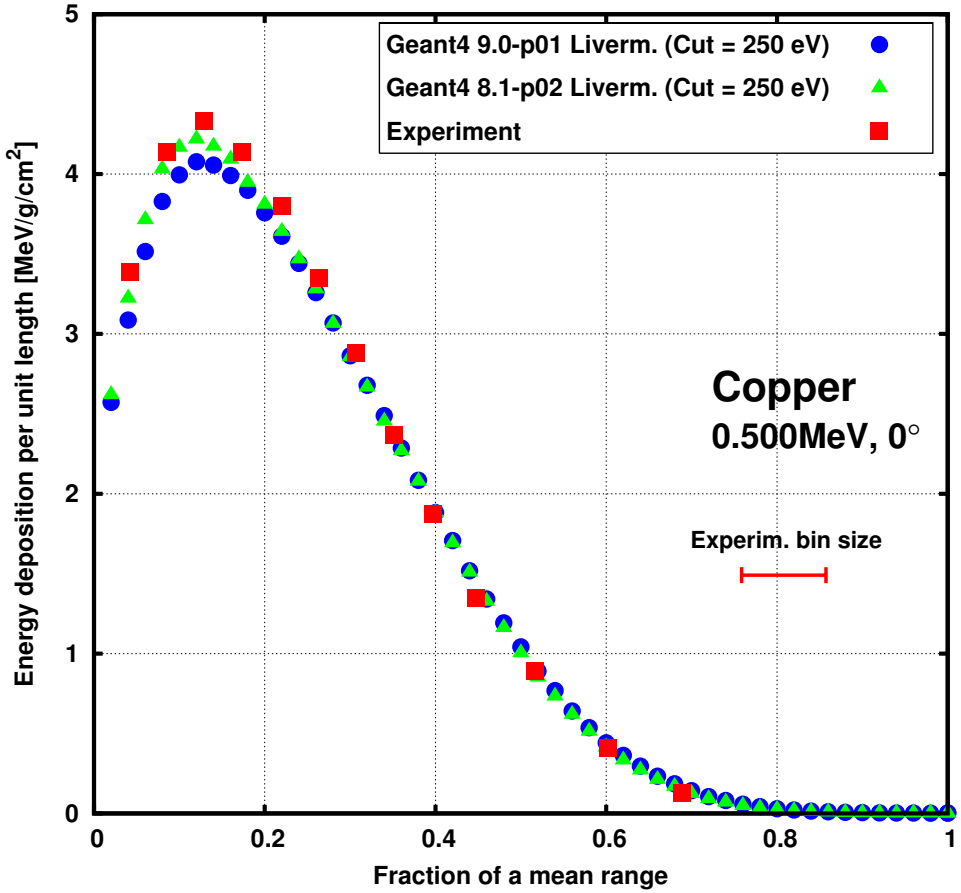

Aluminium
Iron
Copper
Molybdenum
Tantalum
Z


Geant4 9.0-p01 Liverm. (Cut = 250 eV)
Geant4 8.1-p02 Liverm. (Cut = 250 MeV)
Experiment
8.1-p02 vs 9.0-p01
Multiple Scattering
Iron
0.300MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range


Geant4 9.0-p01 Liverm. (Cut = 250 eV)
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Iron
1.000MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range


Aluminium
Iron
Copper
Molybdenum
Tantalum
Z


Geant4 9.0-p01 Liverm. (Cut = 250 eV)
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Copper
0.300MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range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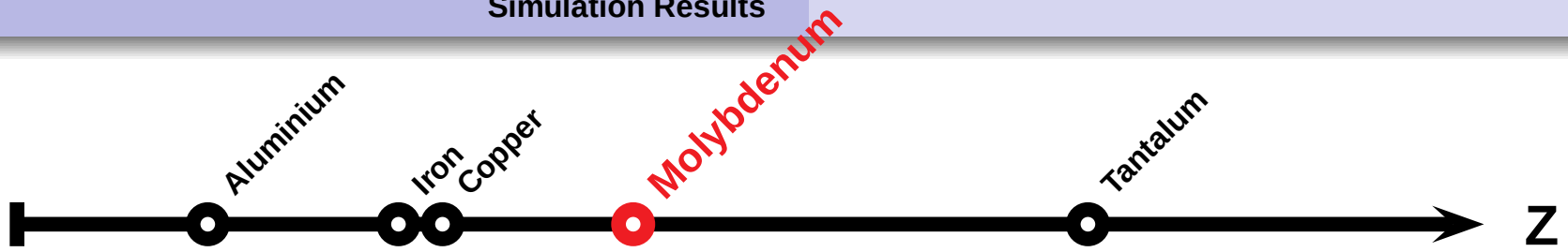
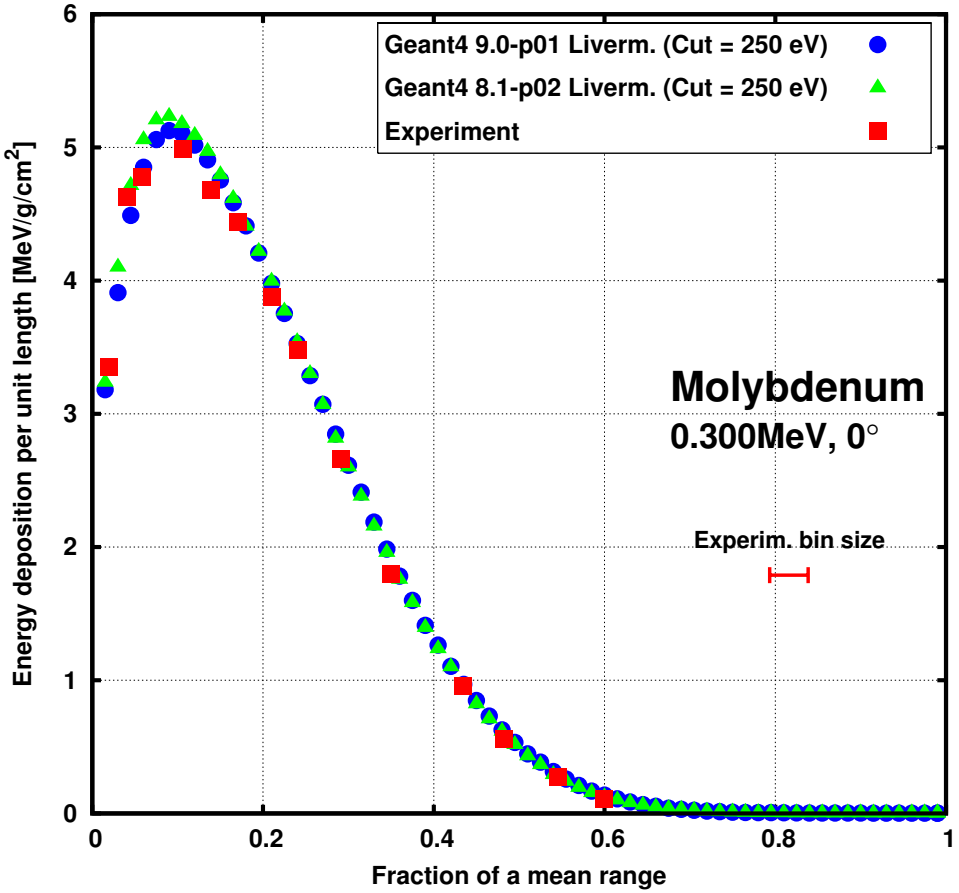
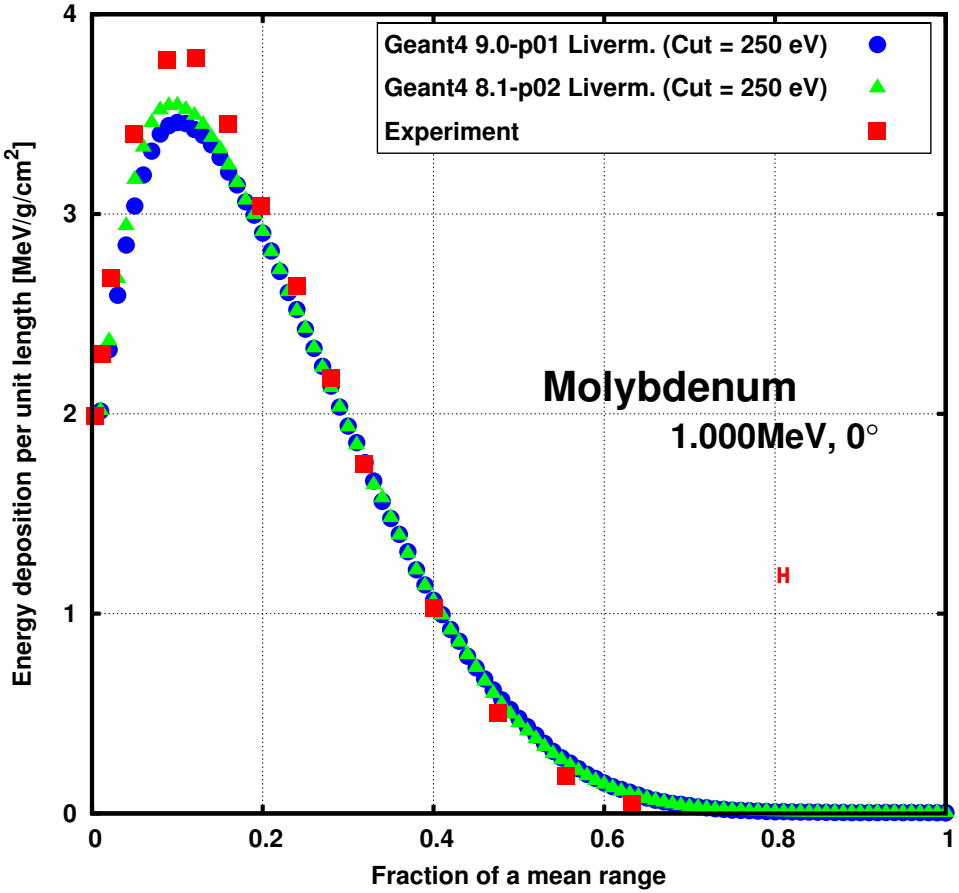
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Copper
0.500MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range


Aluminium
Iron
Copper
Molybdenum
Tantalum
Z


Geant4 9.0-p01 Liverm. (Cut = 250 eV)
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Molybdenum
0.300MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range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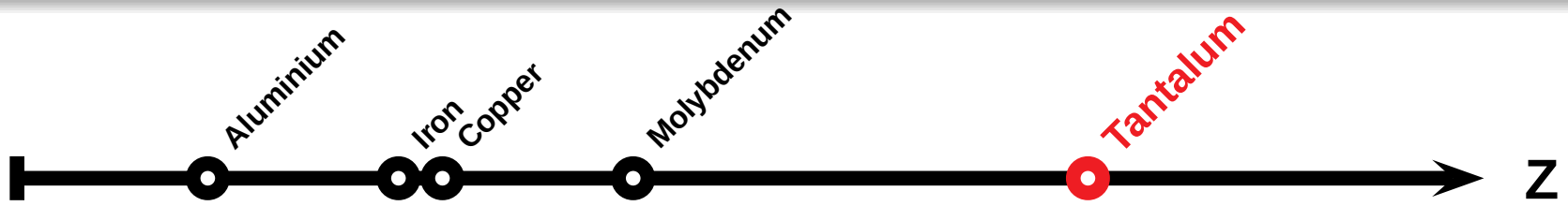
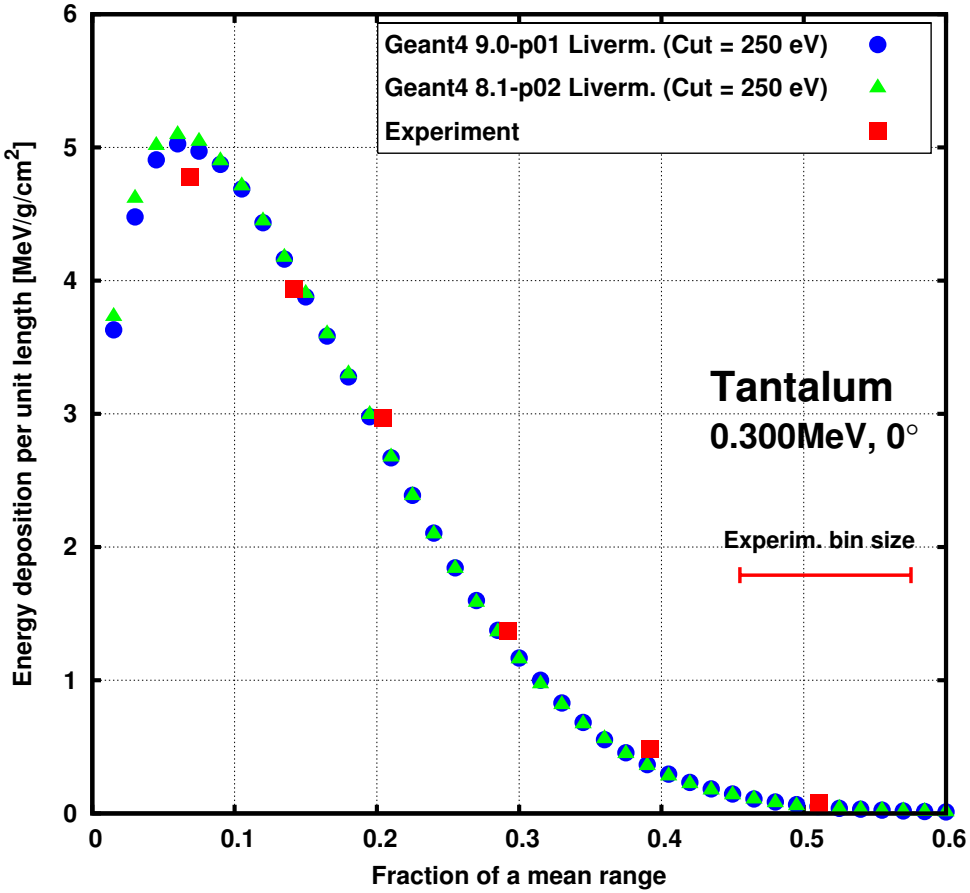
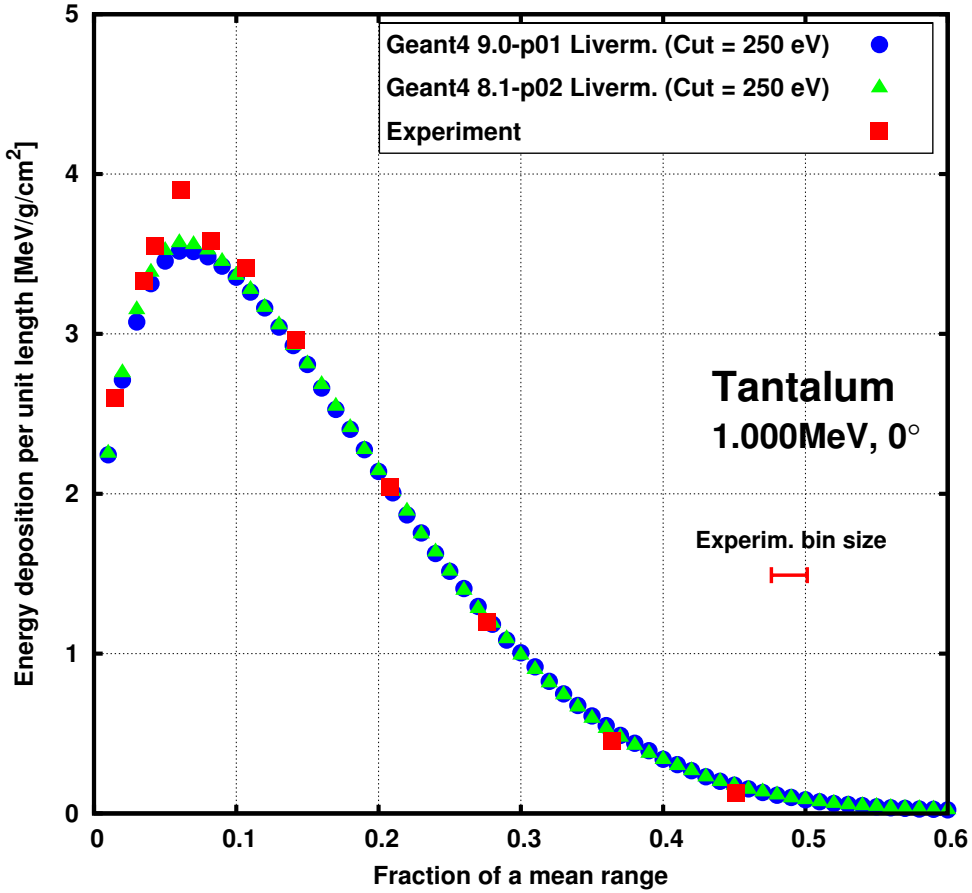
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Molybdenum
1.000MeV, 0°
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range


Aluminium
Iron
Copper
Molybdenum
Tantalum
Z


Geant4 9.0-p01 Liverm. (Cut = 250 eV)
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Tantalum
0.300MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range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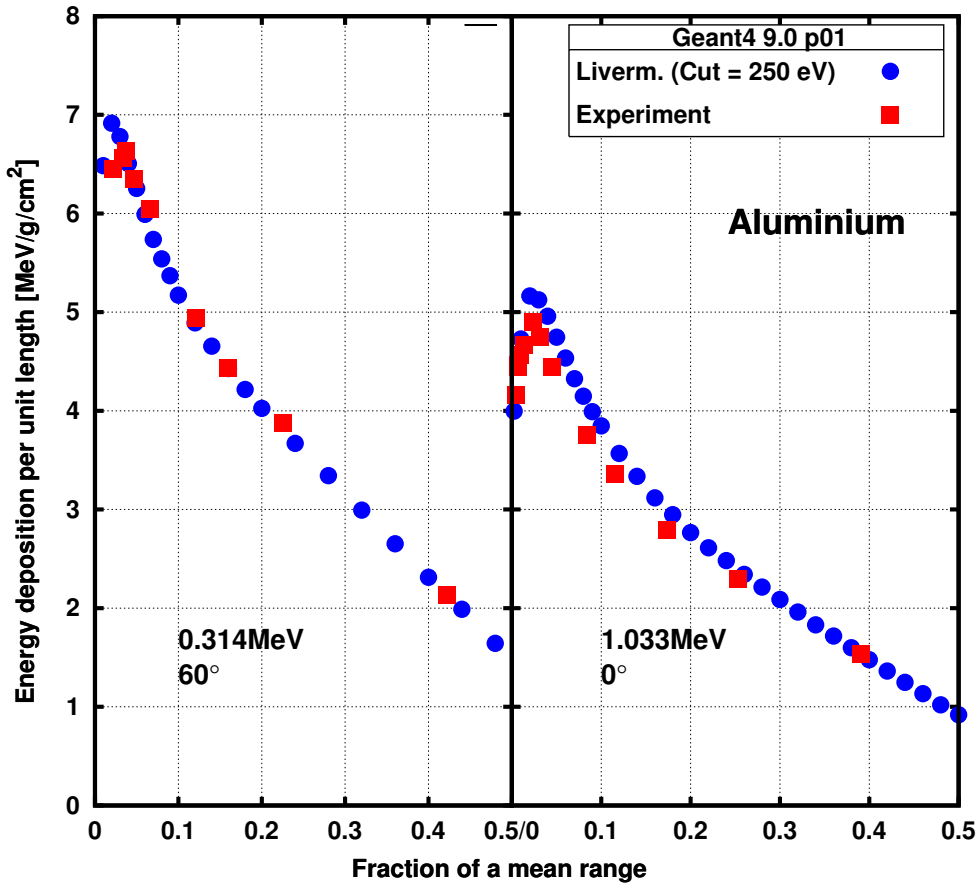
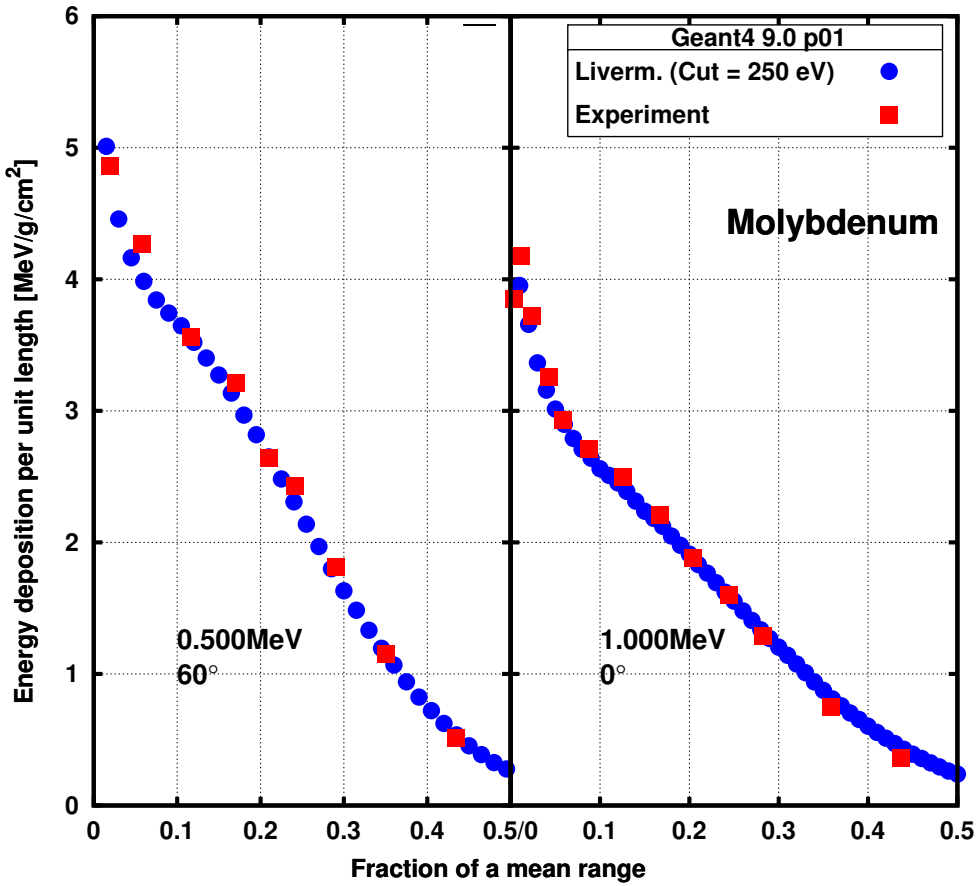
Geant4 8.1-p02 Liverm. (Cut = 250 eV)
Experiment
Tantalum
1.000MeV, 0°
Experim. bin size
Energy deposition per unit length [MeV/g/cm²]
Fraction of a mean range

Beam axis $\neq$ surface normal: Incident angle of 60°





Generation of secondaries: Influence of production threshold

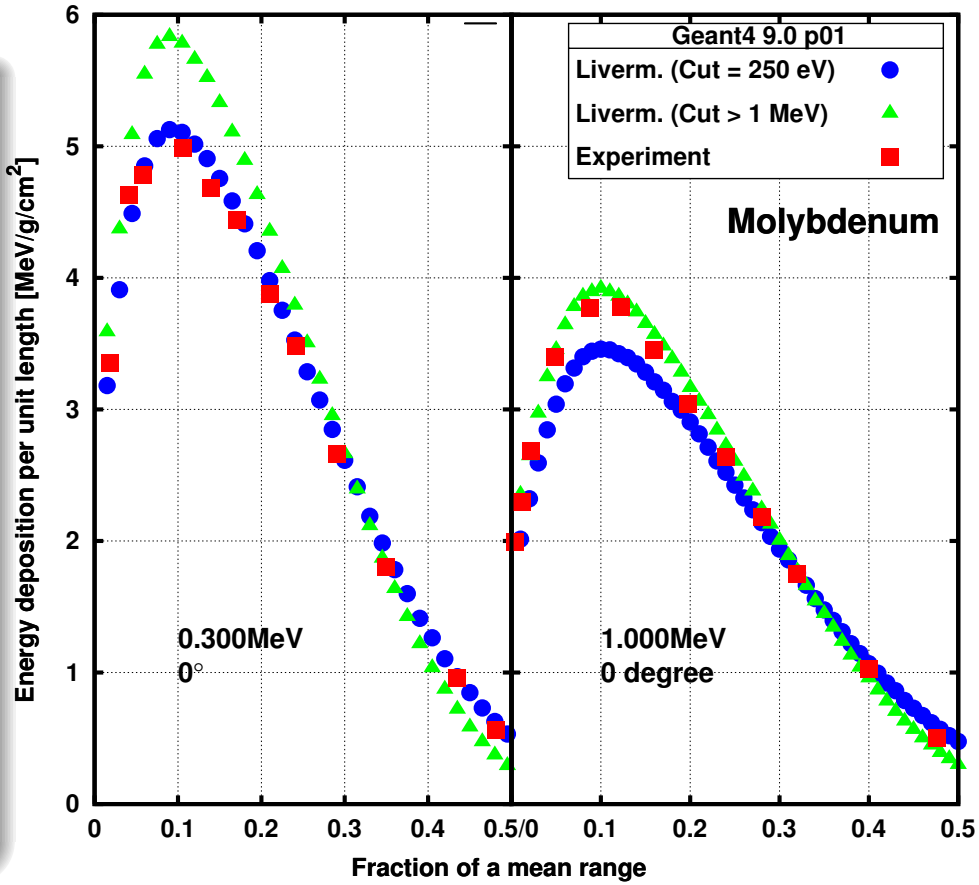
Liverm. library based processes

Energy deposition

- Significant dependence on cut in range for Fe, Cu, Mo, Ta (for all considered beam energies)
- Peak: Differences up to 15% observed
- Effects due to angular distribution of secondary particles

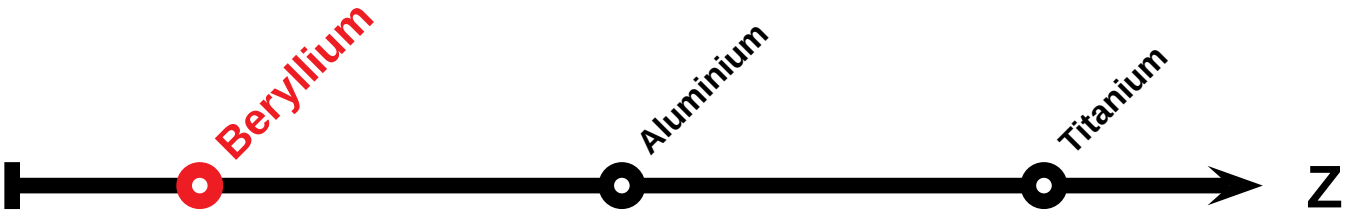
Low prod. threshold (250eV)

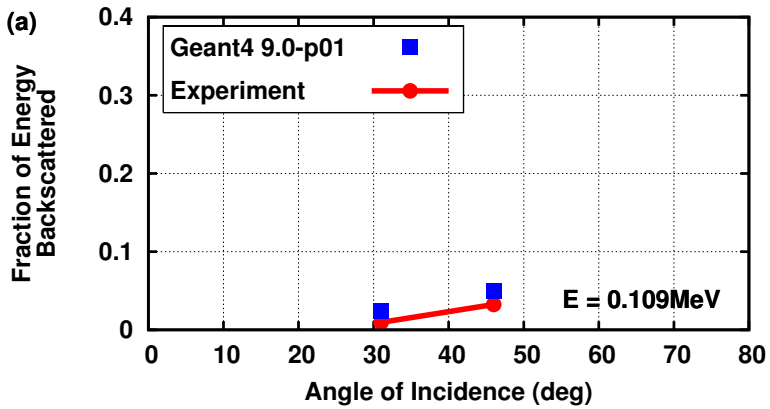
- Underestimation of peak height for 1MeV beams
- Was rather stopping power measured? (Then higher cut would apply)

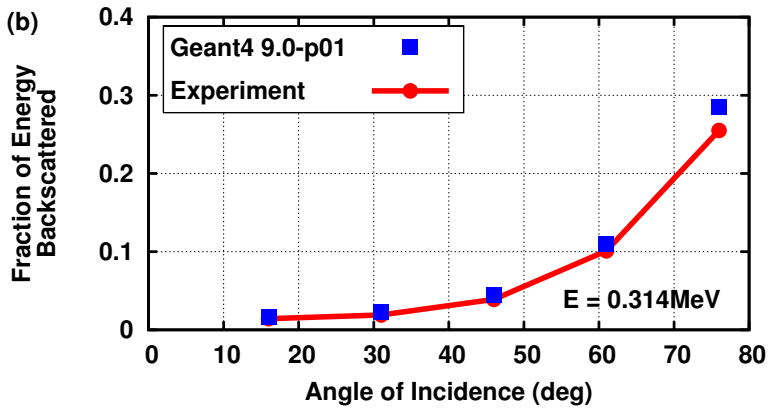


Summary (Part I)

- **Geant4 Livermore models**
  - Capable of reproducing experimentally measured spatial energy deposition for most materials with good precision
  - Some deficiencies in peak region observed (Experimental conditions correctly reproduced?)
  - Choice of production threshold for generating secondary particles significantly influences spatial energy deposition in high-Z materials
- **8.1-p02 vs 9.0-p01 (latest release)**
  - Considerable difference for low-Z materials
  - Effects due to Multiple-Scattering model





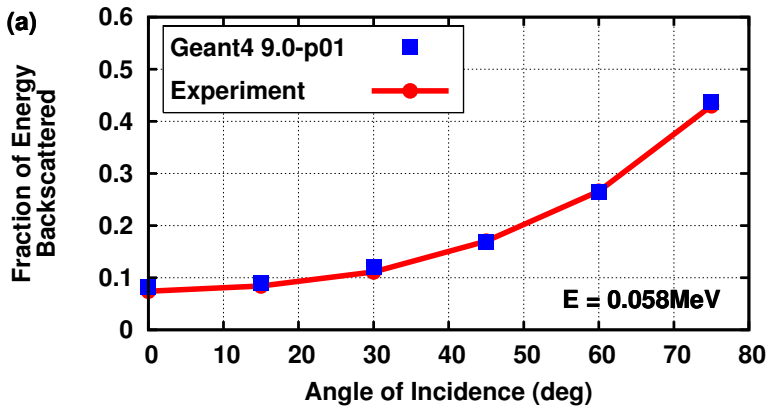


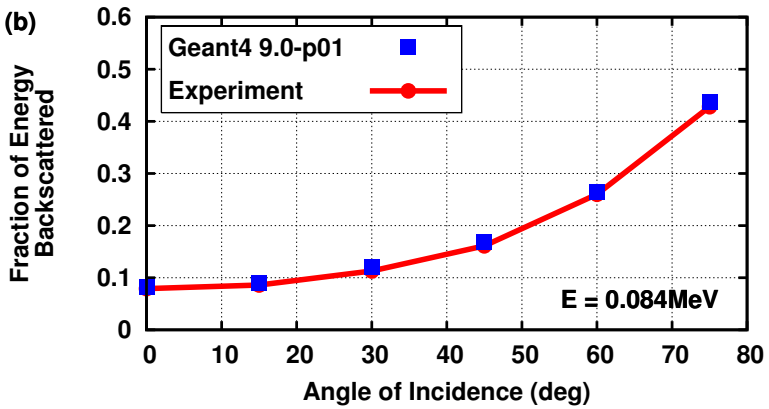
Low-Z material:

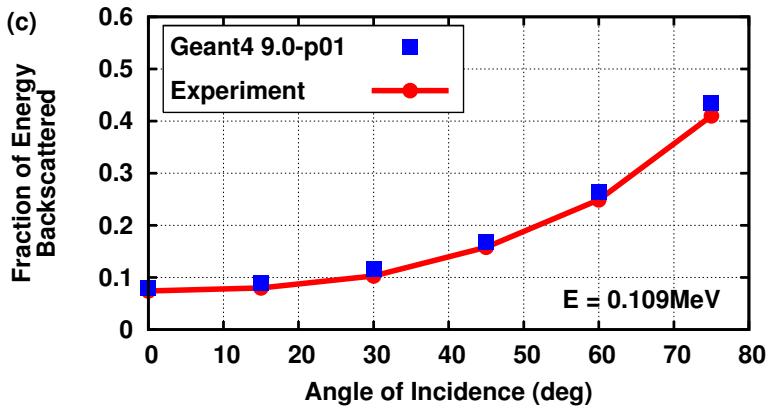
** Good agreement between simulation and experimental data for some angles*

** Underestimation at low beam energies (109keV) and large angles*

⇒ Playground for further investigation of Multiple-Scattering parameters

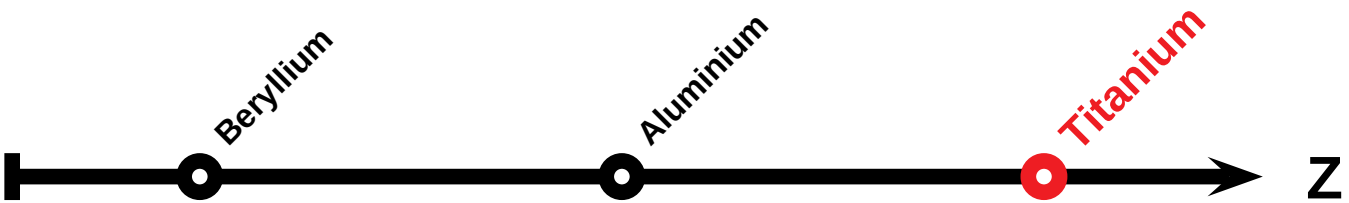


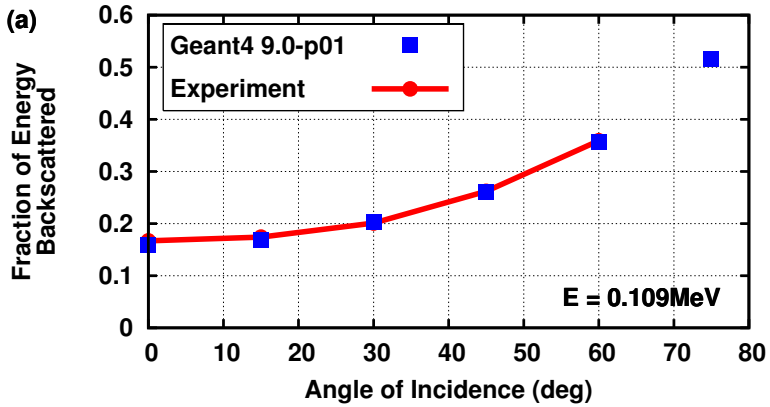


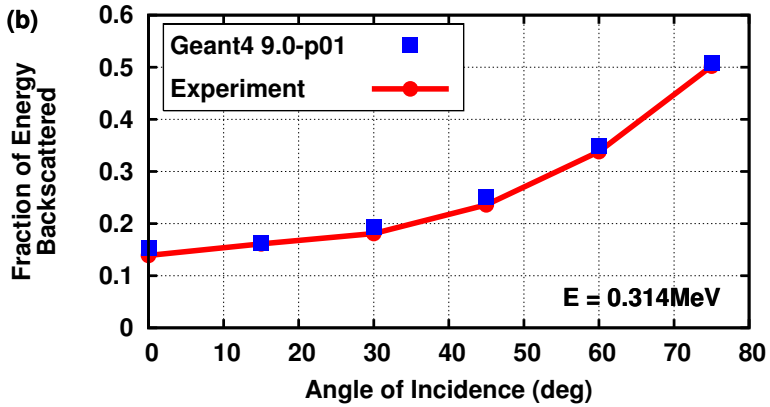


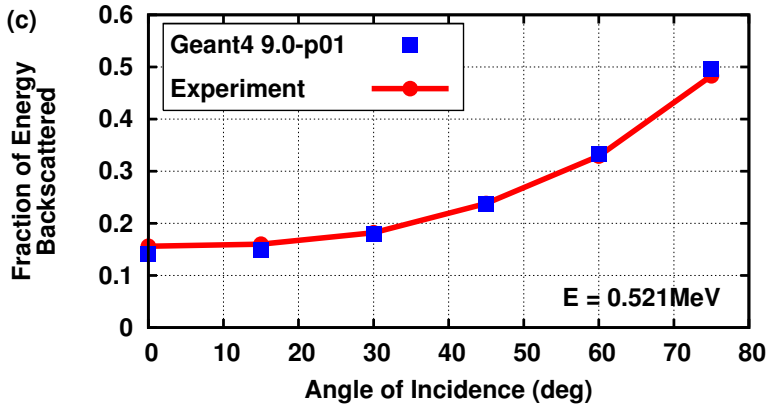
Aluminium:

** Good agreement for all considered and angles*







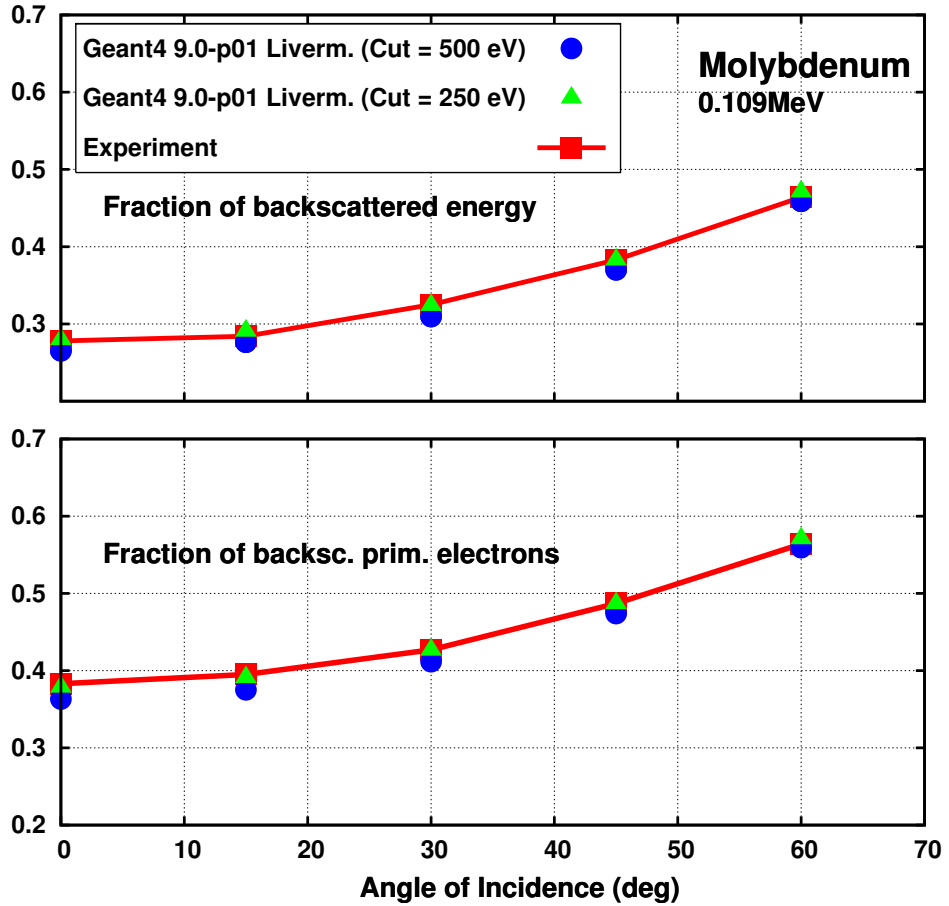


Titanium:

** Good agreement observed for aluminium continues for titanium*

Generation of secondaries: Influence of production threshold

- **Low production threshold (250eV)**
  - Can improve backscatter results (both, backscattered fraction of energy and charge)
  - See plots (Molybdenum, 109keV beam)
  - Systematics not discussed here (More information to be found in publication)



Summary (Part II)

- **Geant4 Livermore models**
  - Very good reproducibility of backscattered fractions of energy except for some deficiencies at beryllium
  - Multiple-Scattering parameters to be investigated in more detail for low-Z materials

Thank for your attention!