# Electromagnetic and Hadronic Physics requirements for detector simulation in 2020s

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1. Current experiments rely heavily on Geant4 simulations (analyses and design):
   → General satisfaction on Geant4 performance,
   → but few discrepancies on shower simulations reported
2. Developments are guided by thin target data whereas feedback from experiments is mostly at the thick target level (showers in calorimeters)
   → Some of the recent progress at thin target level did not translate fully to improved shower description
3. Substantial progress in multiple scattering and revision of major electromagnetic processes included in Geant4 10.4
   ➠ Expected to improve lateral EM showers!

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GOAL: Cope with experimental needs for modeling next generation detectors in the coming decade: HL-LHC

- More experimental data $\longrightarrow$ higher statistics $\longrightarrow$ smaller errors $\longrightarrow$ higher precision needed
- Full simulation occupies a significant part of computing resources (which varies depending on the experiment), $\longrightarrow$ Simulation of EM showers takes a substantial part
  - *also in HAD showers the EM component dominates the CPU time*
- **Need to improve precision of physics models (EM + HAD) & speed up simulations (particularly for EM)**

**Review main physics processes:**

- To reach the level of accuracy needed by experiments in the future: review assumptions and approximations
- Crucial for HL-LHC (to limit the systematic error)
- Extend validity of models up to FCC energies and beyond

**Improve CPU performance:**

- Speedup by reviewing algorithms and their implementations (in particular for EM physics)

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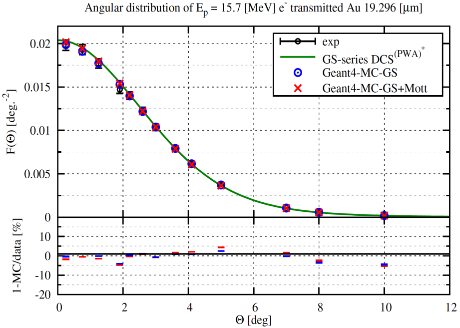
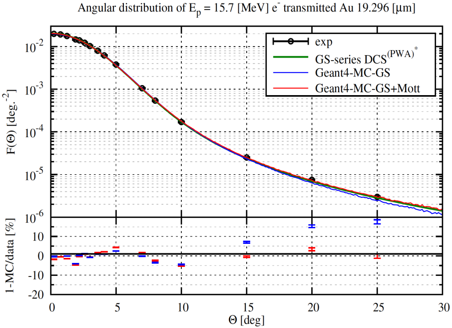
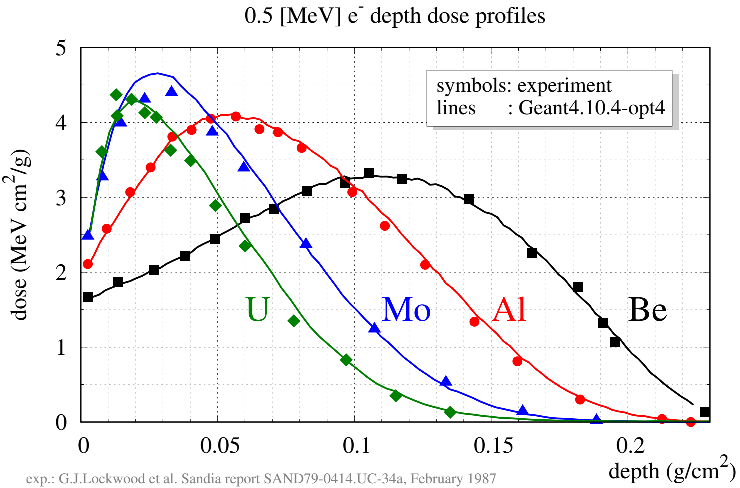
# Multiple Scattering: new treatment of angular distributions



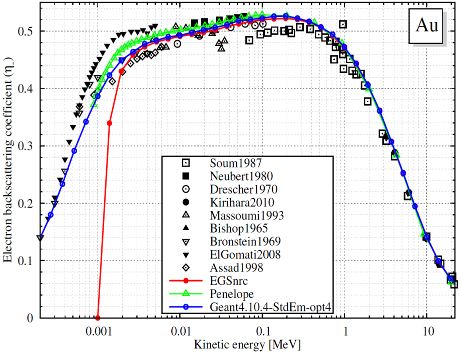



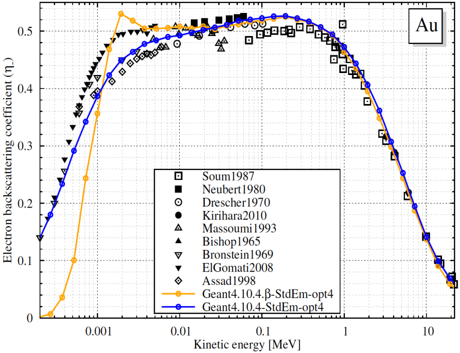
# Energy deposit as a function of depth
# Using SANDIA experimental data




exp.: G.J.Lockwood et al. Sandia report SAND79-0414.UC-34a, February 1987

# Electron backscattering in Au



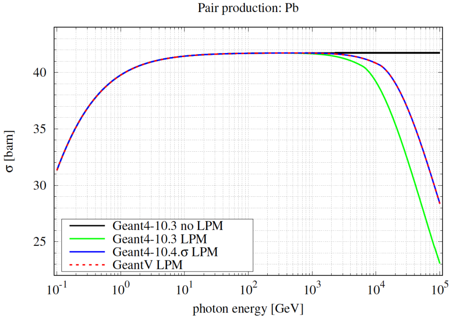
# Improved Landau-Pomeranchuk-Migdal (LPM) description

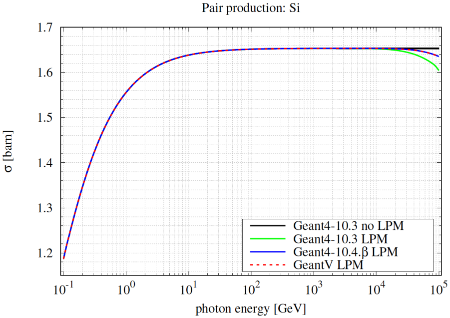
- Reviewing the pair production model including LPM suppression showed an inconsistent calculation of the LPM suppression variable and the material dependent LPM energy in the model used by *Geant4* $\leq$ *10.3*

- **Pair-production** differential cross-section including LPM:

$$\frac{d\sigma}{d\epsilon} = 4\alpha r_e^2 Z(Z+\eta(Z))\,\xi(s) \times \left\{\left[\frac{1}{3}G(s)+\frac{2}{3}\phi(s)\right]\left[\epsilon^2+(1-\epsilon)^2\right]\left[\frac{1}{4}\phi_1-\frac{1}{3}lnZ-f_c\right] + \frac{2}{3}G(s)\,\epsilon(1-\epsilon)\left[\frac{1}{4}\phi_2-\frac{1}{3}lnZ-f_c\right]\right\}$$

with $\epsilon \equiv E_+/E_\gamma$



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# Geant4 evolution in simulation of Hadronic Showers: past ~ 10 years

| | |
|---|---|
| **LHEP** | Gheisha parameterized model |
| ↓ | |
| **QGSP** | Theory models (string + precompound/excitation) at high energies |
| ↓ | |
| **QGSP_BERT** | Added intra-nuclear cascade model |
| ↓ | |
| **FTFP_BERT** | Low-energy extension of string model → no parameterized model any longer |

# Geant4 simulation of Hadronic Showers: next ∼ 10 years

| | |
|---|---|
| FTFP_BERT | FTF phenomenological model reaches its best |
| QGSP_BERT | More theory-based string model |
| EposP_BertBicIncl | Extension to very high energies and heavy flavours. Best combinations of the 3 intra-nuclear cascades (according to the projectile particle and energy) |

## Basic ingredients for Hadronics in HEP:

- Hadronic cross sections
  → Glauber-Gribov approach
- Elastic scattering
  → Diffuse model
- String models
  → Fritiof (FTF), Quark-Gluon-String (QGS), EPOS
- Intra-nuclear cascade models
  → Bertini (BERT), Binary (BIC), Liege (INCLXX)
- Precompound/de-excitation models

- Other low-energy hadronic models, used in medical, nuclear and space sciences
  → Precise transportation of low-energy neutrons, protons, etc.
  → Radioactive Decay Model

## Hadronic Cross Sections

- Cross sections

$\rightarrow$ Important for CPU performance of hadronic physics simulations

$\rightarrow$ Continue to review xsec and make them more efficient

$\rightarrow$ *Glauber-Gribov* approach: most general & promising

## Elastic Model

- Hadronic Elastic Model

→ Need to review cross sections and final-state models

→ Particularly important for hadronic showers in scintillator-based calorimeter is neutron-proton elastic scattering

→ *DiffuseElastic* model approach: most promising

# String Models

- Consolidate **FTF**

→ Reaching its full maturity

- Improve and extend **QGS**

→ Useful to provide an alternative, more theory-based, to the phenomenological FTF model, for hadronic showers

- **Extend validity of String model for multi TeV**

→ Useful for accelerator applications, FCC-hh, ultra high-energy cosmic rays. e.g. rewrite **EPOS** inside Geant4 (C++)

- **Include treatment of hadronic interactions for charmed and bottom hadrons**, useful for interactions of boosted particles in trackers for LHC & FCC

## Intranuclear Cascade Models

- Bertini **BERT**

→ The current Geant4 workhorse, reasonably good and fast. Significantly improved and extended in recent years, expected to remain stable in the next future

- Binary **BIC**

→ Stable since many years; possible extensions/improvements

- Liège **INCL**XX

→ State-of-the-art for spallation studies

→ Recent extension to higher energies & under further development

# Precompound/De-excitation

- **Not only important for low energy, but also for high-energy jets simulations**
- Physics and code implementation have been carefully revisited and improved recently

→ Further consolidation and validation

→ Additional physics effects (e.g. correlation of emitted gammas), revision of models currently not used (e.g. multi-fragmentation), and perhaps even new, specialized models will be driven by medical, nuclear and space applications

## Low Energy Hadronic Physics

- **Not used for HEP analyses, but useful for activation, radiation and shielding studies, and with a growing interest in: medical physics, nuclear physics, space science**
- High-precision transportation of low-energy neutrons

→ Moving to the new Livermore approach and format

- High-precision transportation of low-energy charged particles (protons, deuterons, tritons, He3 and alphas)

→ Implementation needs consolidation & extensive validation

- Radioactive Decay model

→ Undergoing a major revision and extension

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## Roadmap for detector simulation

- Review main physics processes both for precision and for extension to higher energies.

  → Whenever possible, prefer theory-based approach to phenomenological / parametrized / data-driven approach (safer extrapolation outside known data)

- Consolidation of the validation testing suite

- Revise algorithm implementations for better performance in full simulation. Improvement of existing fast simulation techniques and investigating novel ones

## Planned activities

- Electromagnetic Physics:
  - ➠ Theory-based fluctuation model
  - ➠ Inclusion of leading & next to leading order corrections
  - ➠ ...
- Hadronic Physics:
  - ➠ Extension of string models to higher energies and heavier projectiles
  - ➠ Refinement of low-energy nuclear physics
  - ➠ ...

*We heavily rely on physics validation feedback from experiments and users!*

## Outlook

Besides improving capabilities for *conventional* HEP application domains of Geant4, medical, space and nuclear physics fields can be further extended, e.g.

- Hadron therapy
- Activation, Radiation, Shielding
- More low-energy nuclear applications : e.g. ISOLDE

and open new domains, e.g.

- Ultra high-energy cosmic rays

*Given the required efforts, the community should consider investing on more people working full time on physics simulation and connecting with experiments*