Geant4 Detector Simulations for Future HEP Experiments

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Outline:

Contents

Simulation: crucial for detector conception, design & analyses

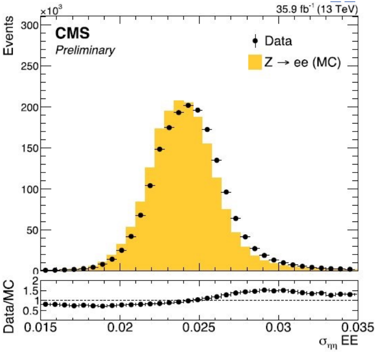
GOAL: Cope with experimental needs for modeling next generation detectors in the coming decade

- More experimental data ⟶ higher statistics ⟶ smaller errors ⟶ higher precision needed
- Full simulation occupies a significant part of computing resources (which varies depending on the experiment), ⟶ Simulation of EM showers takes a substantial part

• Need to improve precision of physics models & extend their validity to multi-TeV energies
• Need to speed up simulations

➠ Current experiments rely heavily on Geant4 simulations (analyses and design):

- General satisfaction on Geant4 performance,
- but few discrepancies on shower simulations reported



→ Shower shapes wider in data than simulation both for electrons and positrons in the endcap

→ Developments are guided by data taken from thin target whereas feedback from experiments is mostly from showers in calorimeters

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 100 TeV (FCC, CEPC)

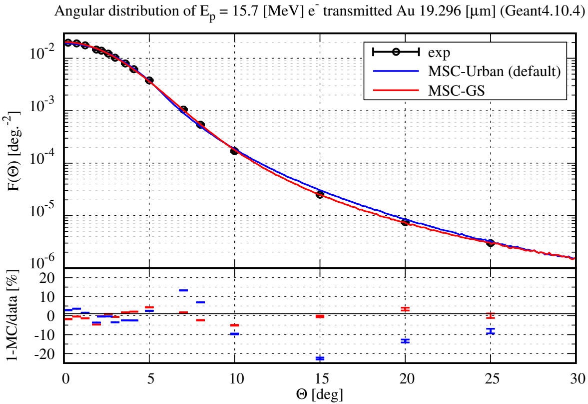
Substantial progress in multiple scattering and revision of major electromagnetic processes included in Geant4 10.4
➠ Expected to improve lateral electromagnetic showers!

Improve CPU performance:

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

Contents

New Multiple Scattering Model



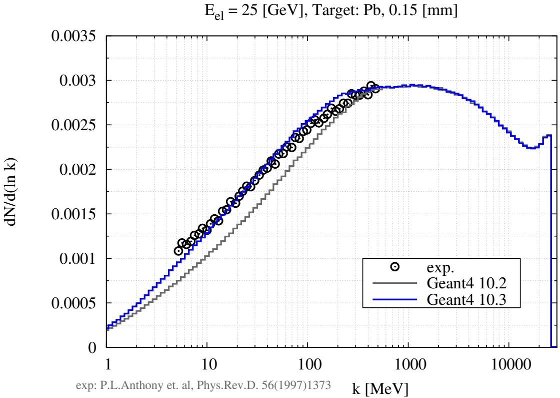
⟶ New theoretical model of multiple scattering based on the most accurate computation of scattering parameters, not sensitive to geometry and step size of electrons (no artefacts)

The Landau-Pomeranchuk-Migdal (LPM) effect

For simplicity, let us consider the bremsstrahlung process:

- Ultrarelativistic electron emits a low-energy photon $\Longrightarrow q_{//}$ can be very small
- Uncertainty principle $\rightarrow$ interaction takes place over a long distance, called *formation length*
- If anything happens to the electron or photon along this distance that disturbs their coherence, the emission of the photon will be suppressed
- The *Landau-Pomeranchuk-Migdal (LPM)* effect is the suppression due to *multiple scattering*

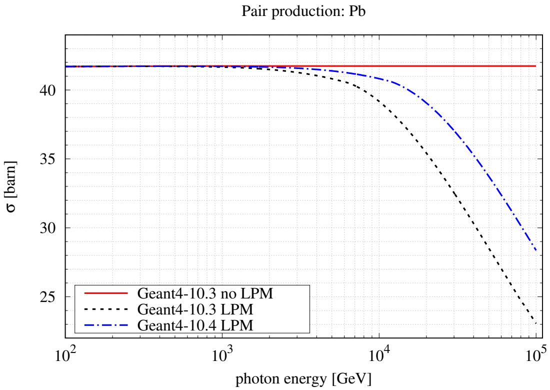
Bremsstrahlung: improved description of the LPM effect



⟶ Revised theoretical treatment of LPM suppression

⟶ New model gives better agreement with the available experimental data

Pair-production: improved description of the LPM effect



⟶ Revised theoretical treatment of LPM suppression

⟶ New model shows a reduction in the DCS: oversuppression expected from cross-symmetry with Bremsstrahlung, leading to significant improvement for highly energetic gammas, of importance for FCC

Contents

Hadronic Physics

➠ *Simulation of hadronic showers is essential for jets*

String Models (FTF, QGS)

- Extend validity for multi TeV, useful for accelerator applications, future hadron colliders, high-energy cosmic rays
- Include treatment of hadronic interactions for charmed and bottom hadrons, for interactions in trackers

Intranuclear Cascade Models (BERT, BIC, INCL++)

- Find optimal combination of existing models

Low energy nuclear models

- Improvements driven by medical and nuclear applications but also relevant for HEP

Contents

Outlook for detector simulation activity

➠ Substantial amount of work needed for precise modeling of showers for HL-LHC and future HEP experiments

- Electromagnetic physics:
  - Improve precision of EM models by including leading and next to leading order corrections
  - Extend EM models to higher energies is crucial for FCC: *investigate nuclear recoil effects, and other channels necessary at extreme relativistic energies like: triplet production, γ conversion to hadron pairs, etc...*
- Hadronic physics:
  - Extend validity of String models to multi-TeV energies
  - Include charm and bottom hadrons

Summary

- Reviewing main physics processes for precision and extension to higher energies allowed to improve simulation

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

- These improvements will impact the showers possibly reducing the discrepancies reported by experiments

  → We are eager to get feedback from test-beams & collider data

- Revising algorithm implementations is important for better performance in full simulation, therefore allowing to better match the expected higher statistics in the future

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- IEEE Transactions on Nuclear Science 53 No. 1 (2006) 270-278
- Nuclear Instruments and Methods in Physics Research A 835 (2016) 186-225
- HEP Software Foundation Community White Paper Working Group- Detector Simulation (2018)
- Recent progress of Geant4 electromagnetic physics for calorimeter simulation. Journal of Instrumentation 13.02 (2018): C02054.