Geant4 Detector Simulations for Future HEP Experiments

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Outline:

1. Simulation needs for HL-LHC & Future Colliders
2. Electromagnetic physics
3. Hadronic physics
4. Perspectives in Simulation for Future HEP Experiments
Simulation needs for HL-LHC & Future Colliders

Electromagnetic physics

Hadronic physics

Perspectives in Simulation for Future HEP Experiments
Simulation: crucial for detector conception, design & analyses

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

- More experimental data $\rightarrow$ higher statistics
  $\rightarrow$ smaller errors $\rightarrow$ higher precision needed

- Full simulation occupies a significant part of computing resources (which varies depending on the experiment),
  $\rightarrow$ 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
Needed Actions

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)
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New Multiple Scattering Model

Angular distribution of $E_p = 15.7$ [MeV] $e^-$ transmitted Au 19.296 [µm] (Geant4.10.4)

→ 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)
For simplicity, let us consider the bremsstrahlung process:

- Ultrarelativistic electron emits a low-energy photon $q_{\parallel}$ 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

\[ \frac{dN}{d(\ln k)} \]

\[ k \text{ [MeV]} \]

\[ E_{el} = 25 \text{ [GeV]}, \text{ Target: Pb, 0.15 [mm]} \]

\[ \exp: \text{P.L.Anthony et. al, Phys.Rev.D. 56}(1997)1373 \]

- Revised theoretical treatment of LPM suppression
- New model gives better agreement with the available experimental data

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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
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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
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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, \( \gamma \) 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**
- Nuclear Instruments and Methods in Physics Research A 835 (2016) 186-225