Geant4 electromagnetic physics for Run3 and Phase2 LHC

Daren Sawkey, Varian Medical Systems on behalf of the Geant4 Collaboration
daren.sawkey@{varian.com, cern.ch}

Primary authors: V. Ivantchenko, J.Hahnfeld, M.Novak, L.Pandola, D.Sawkey

CHEP, May 11, 2023
Outline

- Physics improvements
  - Accuracy
- Tracking improvements
  - Speed
- G4HepEm
  - R&D project
- Technical enhancements (*not going to talk about today*)
  - Code clean-up, obsolete classes removed
Physics improvements

- New process
  - Muon pair production by muon
- Enhanced processes
  - Positron annihilation entanglement
  - Optical thin film interference phenomena
- Improved accuracy or speed
  - EPICS2017 photon database
  - Fluctuation model
- Updated physics lists
  - Penelope e- ionisation
  - Lindhard-Sorenson ion ionisation
Quantum entanglement

- Positron annihilation produces entangled photons (polarisation)
- Now enabled in Geant4
- Validated by double Compton scattering cross section measurements
- Potential applications for removing in-patient scatter

*Watts et al, Nature Comm 12, 2646 (2021); arxiv:2012.04939*
Optical thin film coatings

- Interference phenomena at interfaces of thin coatings
- Simulate in Geant4 with CoatedDielectricDielectric boundary process
- Specify thickness, refractive index of thin film
- Simulation agrees with theory
- Try example OpNovice2 with coated.mac macro

Laurie Cappellugola et al, Aix Marseille Univ
Implementation of EPICS2017 for photons

- For Geant4 11.1 this is the default for the G4EmLivermore models
- More data points
- Linear interpolation (rather than logarithmic)
- Better agreement with XCOM

*Zhuxin Li et al., Physica Medica 95, 94-115 (2022)*
Fluctuations

- Choice of model for fluctuation
  - G4UrbanFluctuation
    - most accurate model
  - G4UniversalFluctuation
    - Opt1, Opt2 default
    - Save 1-2% simulation time but less accurate for thin targets
  - G4LossFluctuationDummy
    - no fluctuations
  - Or own concrete class
Physics list modifications

- **G4EmStandardPhysics**
  - Gamma general process
  - G4UrbanFluctuation

- **G4EmStandardPhysics_option1**
  - G4TransportationWithMsc

- **G4EmStandardPhysics_option3**
  - Gamma general process
  - G4UrbanFluctuation
  - G4LinhardSorenson ion ionisation model
  - MSC RangeFactor = 0.03

- **G4EmStandardPhysics_option4**
  - Gamma general process
  - Penelope (instead of Livermore) ionisation for e- below 100 keV
  - G4UrbanFluctuation
  - G4LinhardSorenson ion ionisation model

- **G4EmLivermorePhysics**
  - G4UrbanFluctuation
  - G4LinhardSorenson ion ionisation model
  - EPICS2017 gamma cross sections

- **G4EmPenelopePhysics**
  - G4UrbanFluctuation
  - G4LinhardSorenson ion ionisation model
Tracking improvements

- General goal is to reduce simulation time by reducing number of step length calculations
  - Fewer steps
  - or fewer calculations per step
- Physics is unchanged
  - As always, it is recommended for users to test as well
- Several approaches
Gamma general process

- Geant4 kernel sees only Transportation, and 1 physical process, for gamma
- 6 gamma interactions combined into 1 interaction length
- At interaction point, concrete process selected randomly according to partial cross sections
- 5% reduction in CPU usage (HEP applications)
  - Strongly depends on geometry, cuts
- Enabled by default in 11.1 (present since 10.5)
  - Disable with UI command
- EPJ Web Conf. 245 (2020) 02009

**G4GammaGeneralProcess**

- Photoeffect
- Rayleigh
- Compton
- e+e- pair
- Gamma-nuclear
- µ+µ- pair
Combined MSC/transport

- Combine multiple scattering and transportation into one process
- Handle msc steps internally by switching between MSC and transportation until a real, discrete interaction occurs
- Provides identical physics but fewer steps
- New G4TransportationWithMsc process, released with Geant4-11.1
- Enabled in G4EmStandard_option1
- For 10 GeV e- with TestEm3 example, 50% fewer charged particle steps; 16% performance gain

```
<table>
<thead>
<tr>
<th></th>
<th>default</th>
<th>Msc+Trans (multiple internal steps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_{dep} [MeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PbWO₄</td>
<td>6729.5</td>
<td>6731.3</td>
</tr>
<tr>
<td>Ar</td>
<td>2567.0</td>
<td>2564.5</td>
</tr>
<tr>
<td>#secondary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>γ</td>
<td>4.27e+03</td>
<td>4.28e+03</td>
</tr>
<tr>
<td>e⁻</td>
<td>7.70e+03</td>
<td>7.70e+03</td>
</tr>
<tr>
<td>e⁺</td>
<td>429</td>
<td>429</td>
</tr>
<tr>
<td>#steps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>charged</td>
<td>35975.5</td>
<td>18467.9</td>
</tr>
<tr>
<td>neutral</td>
<td>40465.5</td>
<td>40463.8</td>
</tr>
<tr>
<td>Rel. perf. gain</td>
<td>0</td>
<td>16.7 [%]</td>
</tr>
</tbody>
</table>
```

Jonas Hahnfeld & Mihály Novák
Woodcock tracking

- In a standard simulation particle stops at each volume boundary
  - Interaction lengths recomputed at each boundary
- Becomes time-intensive for geometries with many small volumes
- Woodcock tracking aims to reduce number boundary crossing steps
- Total macroscopic cross-section constant along step
  - Largest across all materials
  - Relevant for medical simulations (CT)

*Jonas Hahnfeld & Mihály Novák*
Woodcock tracking (2)

- Physics is not altered
- 10 GeV e- results:
  - 75% reduction in neutral steps
  - 10% reduction in simulation time
  - 16-18% reduction in ATLAS simulation time
- Important convention, that particles stop at boundaries, does not hold!
  - May be relevant for scoring, e.g. surface flux
- So far, not part of main Geant4 repository
  - Planned to be part of G4HepEm
  - Can be shared as example

*Jonas Hahnfeld & Mihály Novák*
G4HepEm

- Geant4 EM physics R&D project
- Goal is to reduce computing performance bottleneck experienced by HEP simulations
  - Physics modelling libraries
  - $e^{-}/e^{+}$ and $\gamma$ transport (EM shower)
  - $\sim$ keV to 100 TeV
- Alternative stepping, highly specialised for particle types
- Gateway for GPU use for EM physics
  - E.g., all physics data on main device memory

https://github.com/mnovak42/g4hepem
https://g4hepem.readthedocs.io/en/latest/index.html
Thank you!