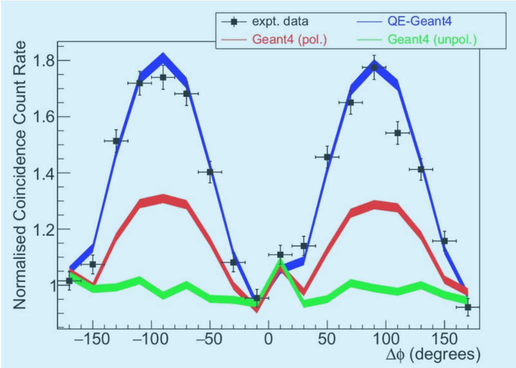
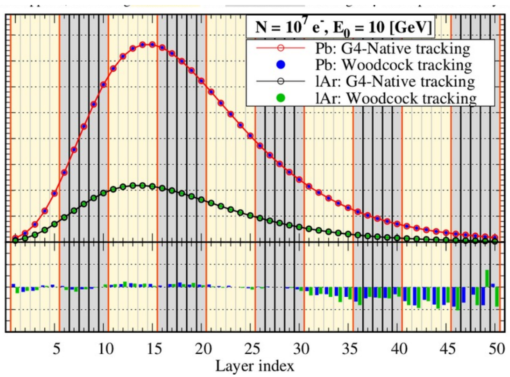
Geant4 electromagnetic physics for Run3 and Phase2 LHC





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CHEP, May 11, 2023

Outline

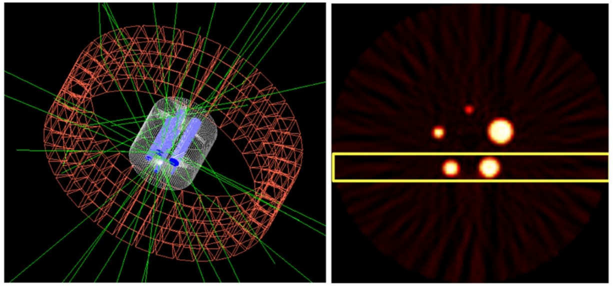
- Physics improvements
  - Accuracy
- Tracking improvements
  - Speed
- G4HepEm
  - R&D project
- Technical enhancements *(not going to talk about today)*
  - Code clean-up, obsolete classes removed

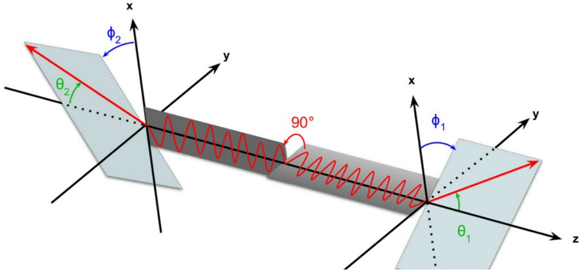
Physics improvements

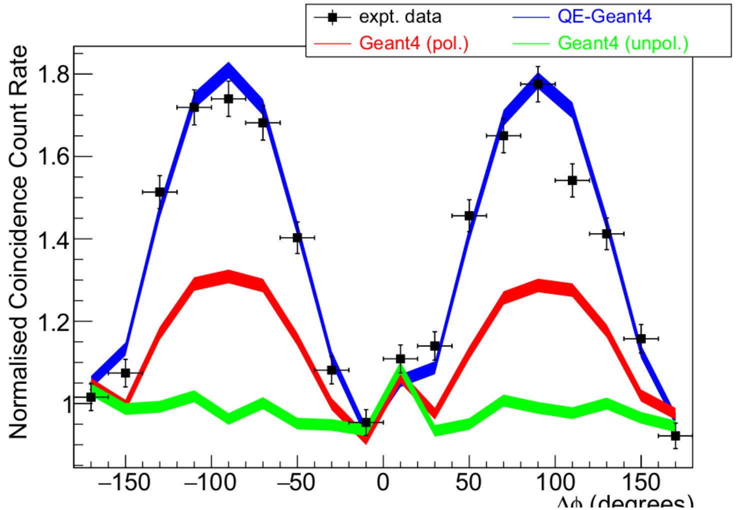
- New process
    - Muon pair production by muon
- Enhanced processes
    - Positron annihilation entanglement
    - Optical thin film interference phenomena
- Improved accuracy or speed
    - EPICS2017 photon database
    - Fluctuation model
- Updated physics lists
    - Penelope e- ionisation
    -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





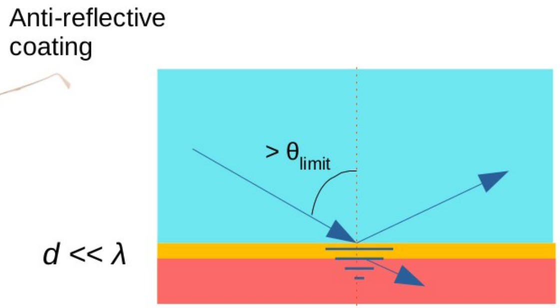


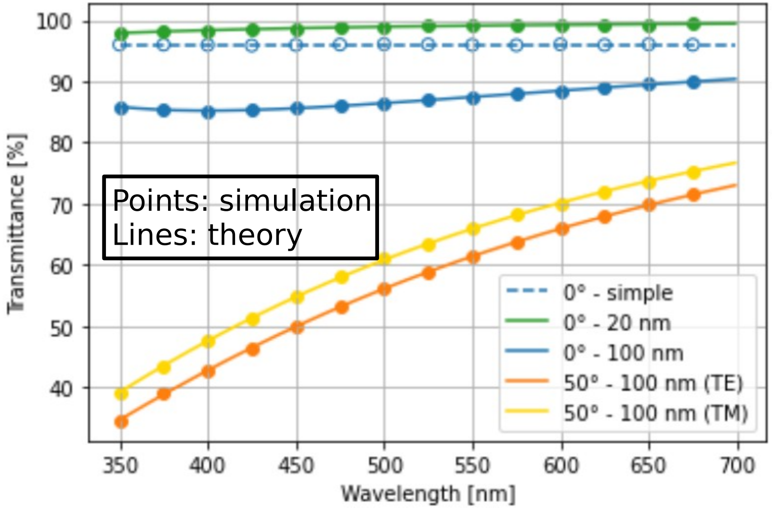
$$\frac{d^2\sigma_{\text{double}}}{d\Omega_1 d\Omega_2} = \frac{r_0^4}{16}\left(K_a(\theta_1,\theta_2) - K_b(\theta_1,\theta_2)\cdot\cos(2\Delta\phi)\right)$$

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



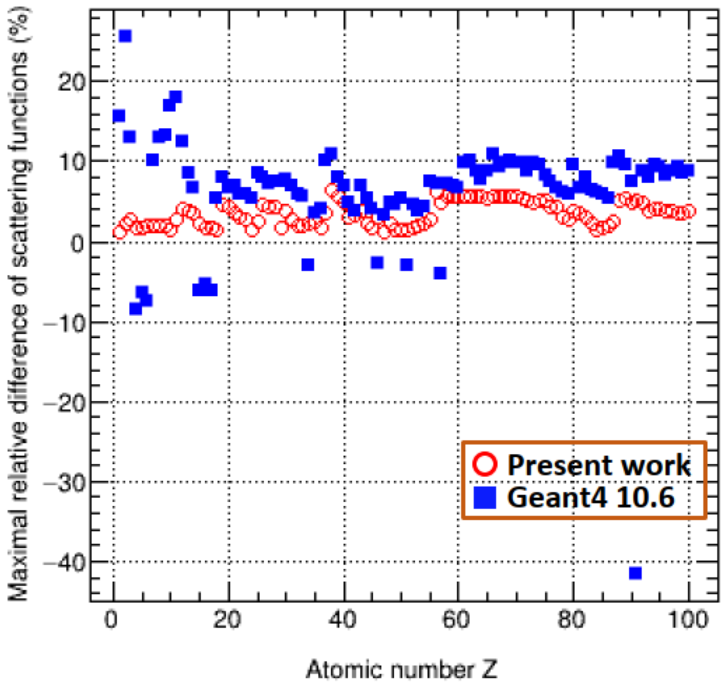


Laurie Cappellugola et al, Aix Marseille Univ

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

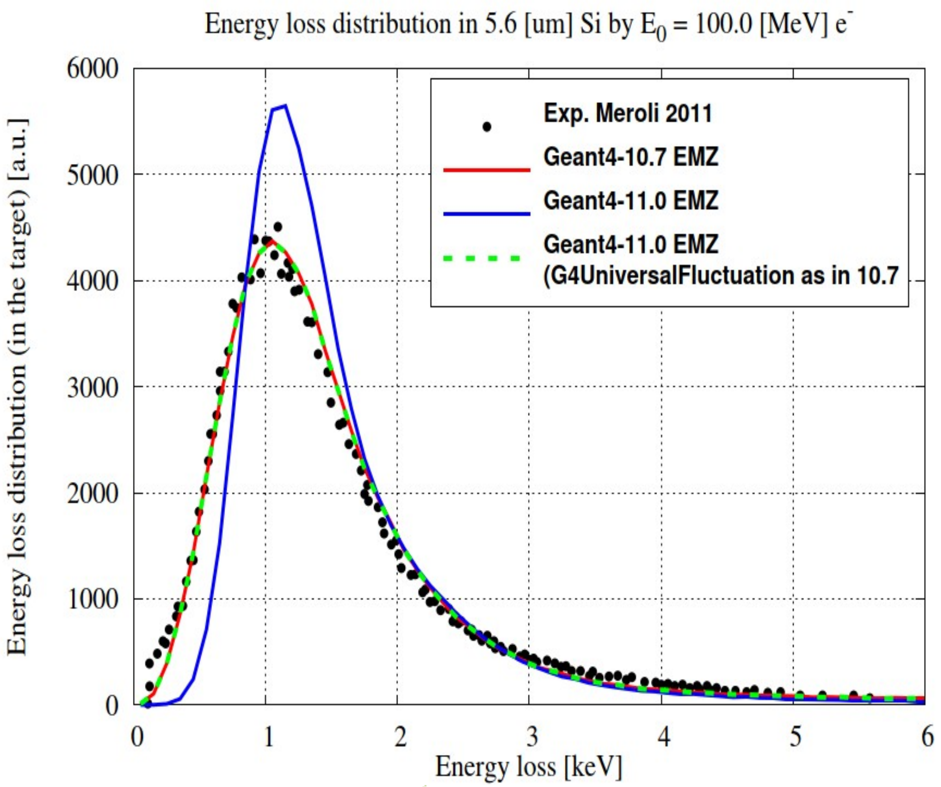
Compton scattering



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

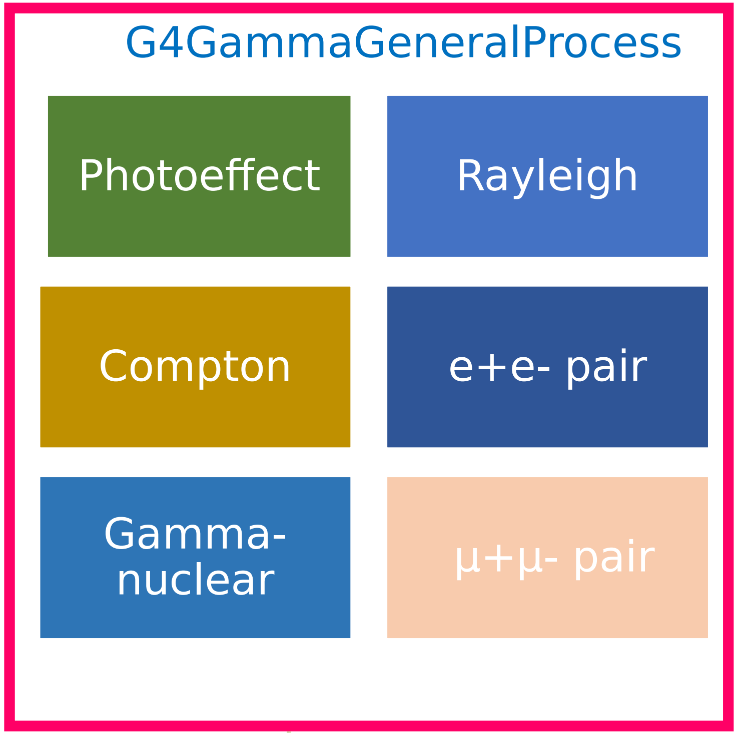
- G4EmStandardPhysics
  - Gamma general process
  - G4UrbanFluctuation
- G4EmStandardPhysics_option1
  - G4TransportationWithMsc
- G4EmStandardPhysics_option3
  - Gamma general process
  - G4UrbanFluctuation
  - G4LinhardSorenson ion ionisation model
  - MSC RangeFactor = 0.03
- G4EmStandardPhysics_option4
  - 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



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
- `/process/em/transportationWithMsc MultipleSteps` or `Enabled`

10 GeV e-		default	Msc+Trans (multiple internal steps)
E_{dep} [MeV]	$PbWO_4$	6729.5	6731.3
	lAr	2567.0	2564.5
#secondary	γ	4.27e+03	4.28e+03
	e^-	7.70e+03	7.70e+03
	e^+	429	429
#steps	charged	**35975.5**	**18467.9**
	neutral	40465.5	40463.8
Rel. perf. gain		0	**16.7 [%]**

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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)

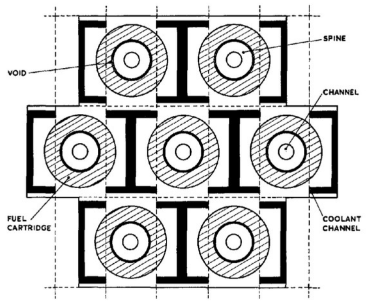
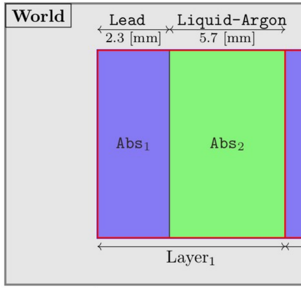
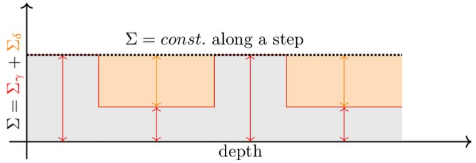


Fig. 5. Fuel Element (See 10.3)

Woodcock (1965) nuclear fuel rods

Simplified sampling calorimeter





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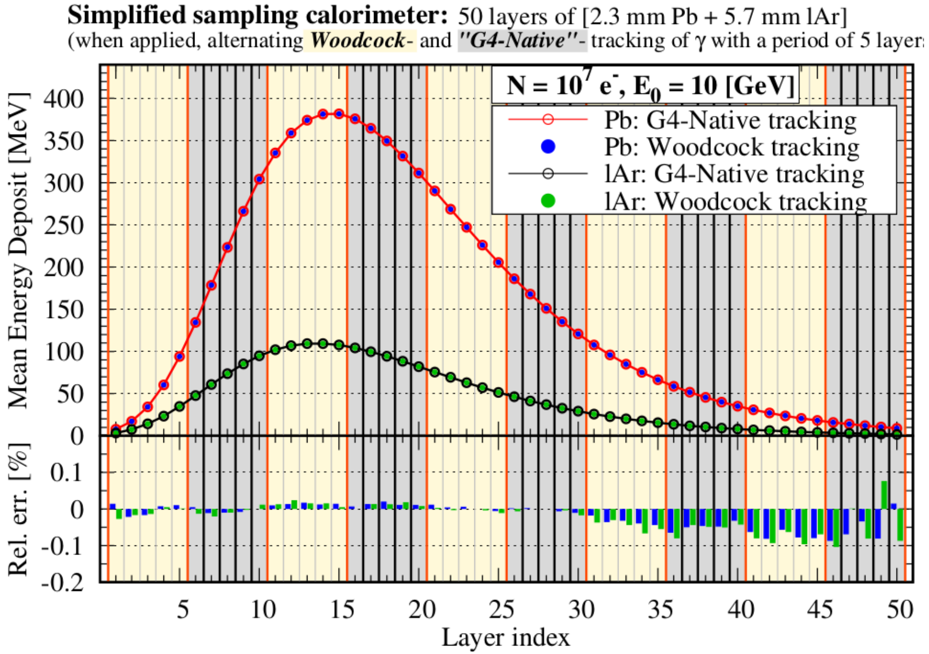
Woodcock tracking (2)

- 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



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G4HepEm

- Geant4 EM physics R&D project
- Goal is to reduce computing performance bottleneck experienced by HEP simulations
  - Physics modelling libraries
  - e^-/e^+ and γ transport (EM shower)
  - ~ 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!