Update on GFlash parametrisation

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24th Geant4 Collaboration Meeting

23/09/2019

GFlashShowerModel

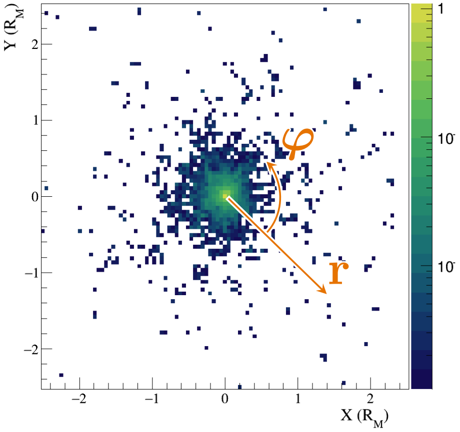
- The only implementation of G4VFastSimulationModel in GEANT4 (outside `examples/`).
- Based on `arXiv:hep-ex/0001020`, details also in physics reference manual, chapter 18
- Parametrisation of electromagnetic cascades:

$$dE(\bar{r}) = Ef(t)dtf(r)drf(\varphi)d\varphi$$

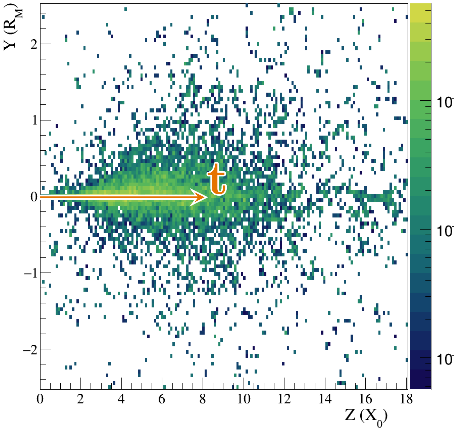
  - flat distribution in azimuthal angle $f(\varphi) = \frac{1}{2\pi}$
  - $f(t)$ and $f(r)$ parameterised as a function of particle's energy (E) and medium (Z)
  - t and r are expressed in units of X_0 and R_M
  - Parameterised number of created energy deposits

Shower profiles

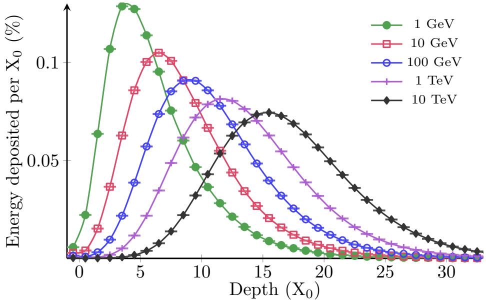
lateral profile

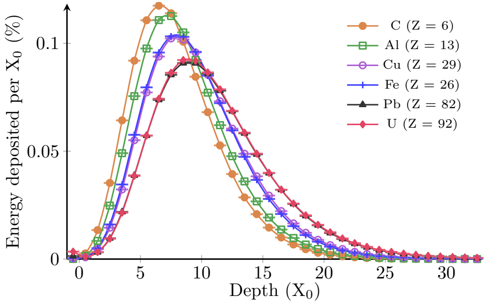


longitudinal profile



Longitudinal profile





$T \sim \ln E$

Longitudinal profile

$$f(t) = \left\langle \frac{1}{E}\frac{dE(t)}{dt} \right\rangle = \frac{(\beta t)^{\alpha-1}\beta e^{-\beta t}}{\Gamma(\alpha)}$$

- shower maximum $T = \frac{\alpha-1}{\beta}$
- Description dependent on $y = \frac{E}{E_c}$:

$$\boldsymbol{T = \ln y + l_1}$$
$$\boldsymbol{\alpha = l_2 + (l_3 + \frac{l_4}{Z}) \ln y}$$

A.1 Homogeneous Media

A.1.1 Average longitudinal profiles

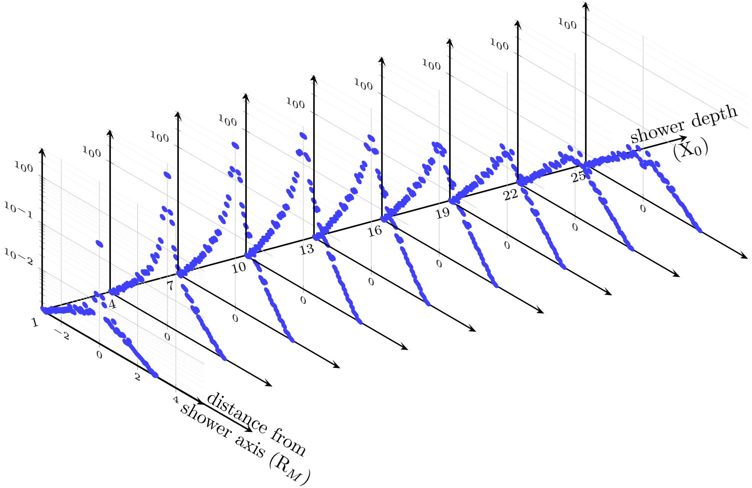
$$\begin{aligned} T_{hom} &= \ln y - 0.858 \\ \alpha_{hom} &= 0.21 + (0.492 + 2.38/Z) \ln y \end{aligned}$$

A.1.2 Fluctuated longitudinal profiles

$$\begin{aligned} \langle \ln T_{hom} \rangle &= \ln(\ln y - 0.812) \\ \sigma(\ln T_{hom}) &= (-1.4 + 1.26 \ln y)^{-1} \\ \langle \ln \alpha_{hom} \rangle &= \ln(0.81 + (0.458 + 2.26/Z) \ln y) \\ \sigma(\ln \alpha_{hom}) &= (-0.58 + 0.86 \ln y)^{-1} \\ \rho(\ln T_{hom}, \ln \alpha_{hom}) &= 0.705 - 0.023 \ln y \end{aligned}$$

arXiv:hep-ex/0001020

Lateral profile



Lateral profile

$$f(r) = \left\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \right\rangle = p f_{\mathrm{core}}(r) + (1-p) f_{\mathrm{tail}}(r) =$$

$$= p \frac{2 r R_{\mathrm{core}}^2}{(r^2 + R_{\mathrm{core}}^2)^2} + (1-p) \frac{2 r R_{\mathrm{tail}}^2}{(r^2 + R_{\mathrm{tail}}^2)^2}$$

Description dependent on $\tau = \frac{t}{T}$:

$$\boldsymbol{R_{\mathrm{core}}(\tau) = r_1 + r_2 \tau}$$

$$\boldsymbol{R_{\mathrm{tail}}(\tau) = r_3 \left(\mathrm{e}^{r_4(\tau - r_5)} + \mathrm{e}^{r_6(\tau - r_7)} \right)}$$

$$\boldsymbol{p(\tau) = r_8 \exp\left(\frac{r_9 - \tau}{r_{10}} - \exp\left(\frac{r_9 - \tau}{r_{10}} \right) \right)}$$

A.1.3 Average radial profiles

$$\begin{aligned} R_{C,hom}(\tau) &= z_1 + z_2 \tau \\ R_{T,hom}(\tau) &= k_1 \{ \exp(k_3(\tau - k_2)) + \exp(k_4(\tau - k_2)) \} \\ p_{hom}(\tau) &= p_1 \exp\left\{ \frac{p_2 - \tau}{p_3} - \exp\left(\frac{p_2 - \tau}{p_3} \right) \right\} \end{aligned}$$

with

$$\begin{aligned} z_1 &= 0.0251 + 0.00319 \ln E \\ z_2 &= 0.1162 + -0.000381 Z \\ k_1 &= 0.659 + -0.00309 Z \\ k_2 &= 0.645 \\ k_3 &= -2.59 \\ k_4 &= 0.3585 + 0.0421 \ln E \\ p_1 &= 2.632 + -0.00094 Z \\ p_2 &= 0.401 + 0.00187 Z \\ p_3 &= 1.313 + -0.0686 \ln E \end{aligned}$$

A.1.4 Fluctuated radial profiles

$$\begin{aligned} \tau_i &= \frac{t}{\langle t \rangle_i} \frac{\exp(\langle \ln \alpha \rangle)}{\exp(\langle \ln \alpha \rangle) - 1} \\ N_{Spot} &= 93 \ln(Z) E^{0.876} \\ T_{Spot} &= T_{hom}(0.698 + 0.00212 Z) \\ \alpha_{Spot} &= \alpha_{hom}(0.639 + 0.00334 Z) \end{aligned}$$

arXiv:hep-ex/0001020

GFlash - parameters

Parameters in GEANT4 are (hardcoded) from arXiv:hep-ex/0001020, and were calculated:

- on grid of 1 X_0 in depth, 0.2 R_M laterally
- for homogeneous and sampling calorimeters: Cu, Fe, W, Pb, U, sci, LAr
- with 1–100 GeV electrons
- scaling laws (material, energy) extracted from average profiles in homogeneous media
- fluctuations and correlations introduced on top
- sampling calorimeter treated as effective medium
- material distribution in the sampling calorimeter taken into account (in paper, not G4)

Number of deposits

$$N(t) = N_N \cdot \frac{(\beta_N t)^{\alpha_N - 1} \beta_N \mathrm{e}^{-\beta_N t}}{\Gamma(\alpha_N)}$$

Follows a modified average longitudinal (Gamma) profile:

$$T_N = T_{hom} \left(n_1 + n_2 Z \right)$$

$$\alpha_N = \alpha_{hom} * \left(n_3 + n_4 Z \right)$$

$$N_N = n_5 \ln Z \left(y E_c \right)^{n_6}$$

- Parameters T_{hom} and α_{hom} describe the longitudinal profile
- 6 new parameters to modify the profile

GFlash - how it is applied

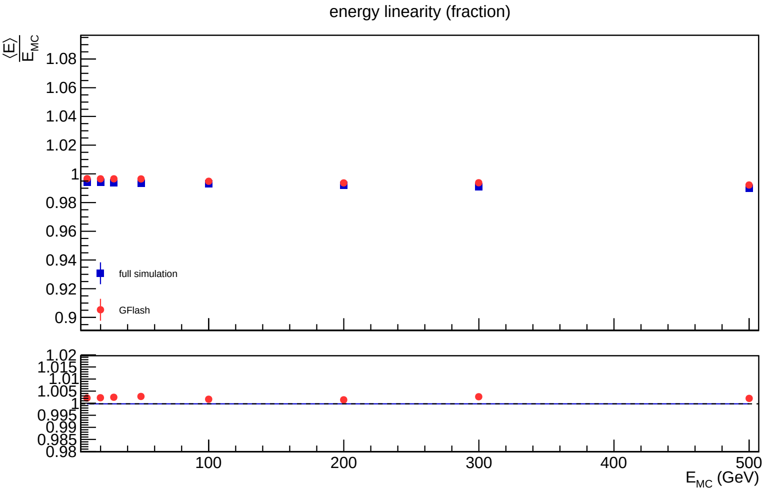
1. if triggered (envelope, electron/positron)
2. check average containment (90%)
3. deposit energy in slices along beam direction
   - get a slice of 1 X_0
   - get energy from longitudinal profile E_{slice} (integrated over slice)
   - get number of spots/deposits N (integrated over slice)
   - get φs from flat distribution
   - create deposits: E_{slice}/N according to radial profile
   - locate volume, check if SD, add to hit collection

Example: homogeneous calorimeter

- $PbWO_4$ homogeneous calorimeter
- $25 \times 25 \times 25$ 10 mm cells
- 5k electrons per energy
- comparison of GFlash to the full simulation:
  - total deposited energy and longitudinal profile well reproduced (few %)
  - accuracy of the transverse profile ∼20%
  - energy deposited in $2 - 3$ times less cells
  - simulation speed-up independent on energy

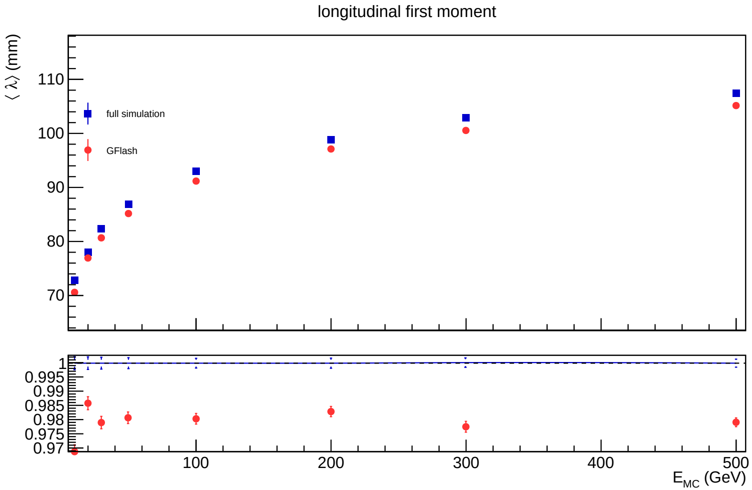
    (time spent mostly in volume look-up: higher E = more cells)

Example: homogeneous calorimeter



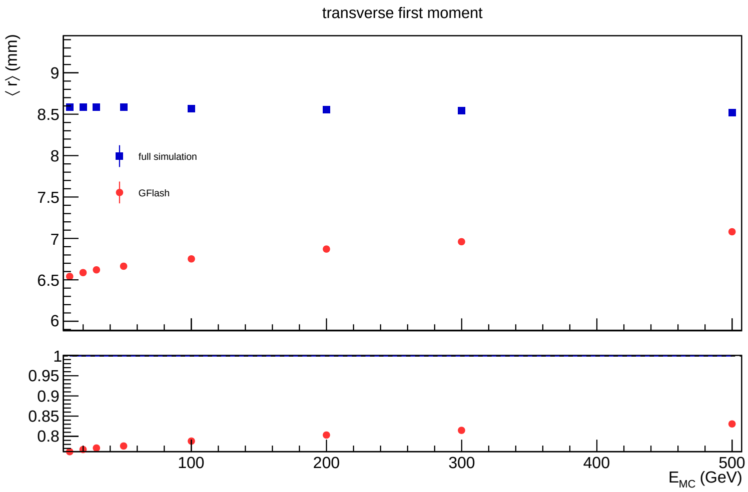
Total deposited energy well reproduced (few %)

Example: homogeneous calorimeter



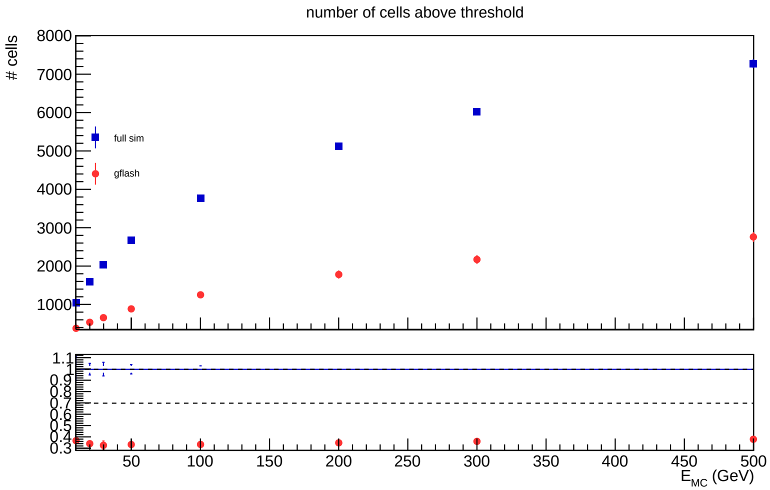
Longitudinal profile well reproduced (few %)

Example: homogeneous calorimeter



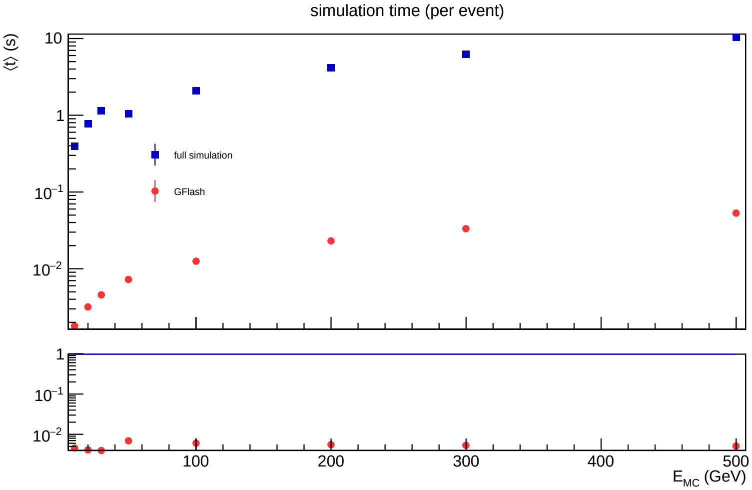
Accuracy of the transverse profile ∼20%

Example: homogeneous calorimeter



Energy deposited in 2 – 3 times less cells

Example: homogeneous calorimeter



Simulation speed-up independent on energy (costly volume look-up: higher E = more deposits)

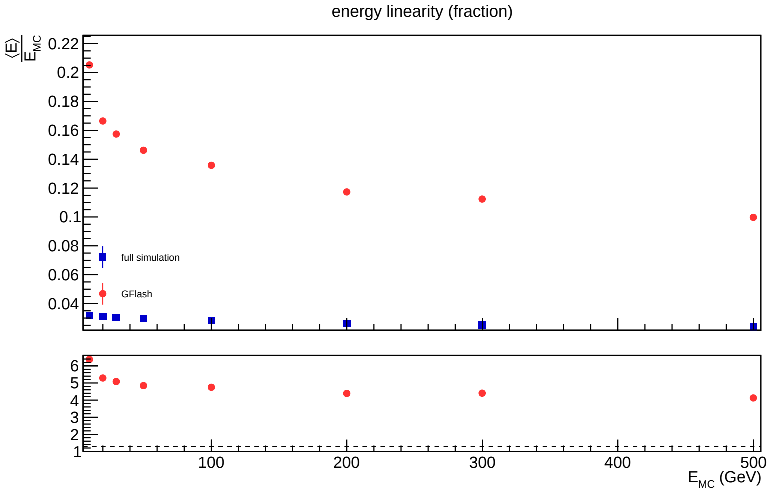
Example: sampling calorimeter

- SiW sampling calorimeter (1.9 mm W, 0.5 mm Si)
- $25 \times 25 \times 25$ 5 mm cells
- 5k electrons per energy
- comparison of GFlash to the full simulation:
  - no distinction of the material distribution

    $4-6$ times more energy deposited in Si than in full simulation

    not visible if deposit from both active and passive material is registered

Example: sampling calorimeter



Energy collected only from the active material (Si), but no distinction between materials in parametrisation, hence overestimation.

Existing shower parametrisation

- ‘general’ parameters extracted (in arXiv:hep-ex/0001020)
  - for few materials (Cu, Fe, W, Pb, U, sci, LAr)
  - for 1-100 GeV electrons
  - on a fixed segmentation/grid (1 $X_0 \times 0.2 R_M$)
- offers limited precision
- no special treatment of sampling calorimeters (same density of deposits in active and passive material)

Tuning the parameters

- parameters may be extracted for specific geometry (material, granularity)
- better accuracy
- less parameters (no material dependency)
- currently, tuning =
  - reimplement few classes
  - hardcode new parameters
  - recompile application
- on-going work on more user-friendly approach

Towards user-friendly tuning

- Model parameters stored in a file, read in at the initialization
- Path to the parameters can be given by user - facilitate testing of several parametrisations

How to obtain the new parameters?

- Run full simulation, store energy deposits
- Analyse shower distributions (average profiles, individual profiles, number of deposits) - one recipe, can be automated
  - one recipe if following GFlash, more flexibility can be added (which formula fits radial profile, fit of either $\ln \alpha$ or α distributions for individual longitudinal profiles, etc...)
- Save generated parameters in a file ready to be read by GEANT4
- Ready and working for longitudinal profile, radial profile on-going...

Longitudinal profile parameters (Pb)

$$f(t) = \frac{((\alpha - 1)\, t)^{\alpha - 1} (\alpha - 1) \exp^{-\beta t}}{T \cdot \Gamma(\alpha)} \tag{1}$$

$$T = 1.056 \cdot \ln y - 1.266 \tag{2}$$

$$\alpha = 0.55 \cdot \ln y - 0.253 \tag{3}$$

$$\langle \ln T \rangle = \ln (1.066 \cdot \ln y - 1.39) \tag{4}$$

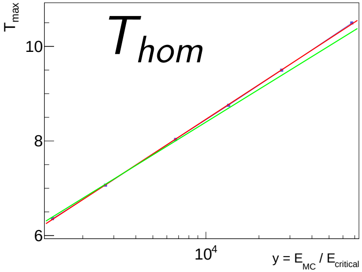
$$\sigma (\ln T) = (1.171 \cdot \ln y + 0.046)^{-1} \tag{5}$$

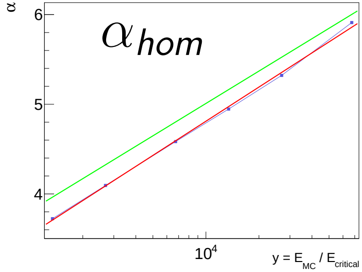
$$\langle \ln \alpha \rangle = \ln (0.598 \cdot \ln y - 0.456) \tag{6}$$

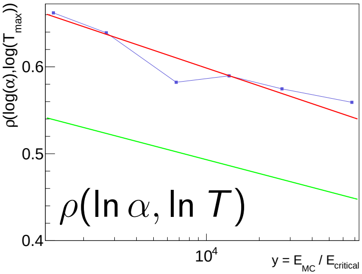
$$\sigma (\ln \alpha) = (0.509 \cdot \ln y + 4.43)^{-1} \tag{7}$$

$$\rho (\ln T, \ln \alpha) = -0.03 \cdot \ln y + 0.871 \tag{8}$$

Longitudinal profile parameters (Pb)





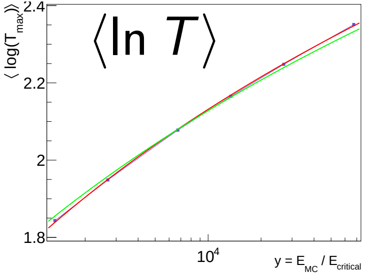


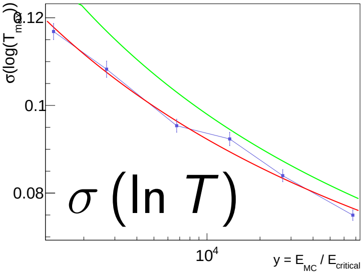
green line - original parameters from `arXiv:hep-ex/0001020`

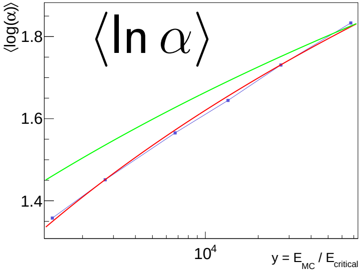
blue points - from full simulation on Pb

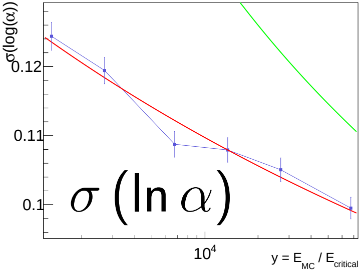
red line - fit to full simulation, new parameters (no Z dependency)

Longitudinal profile parameters (Pb)









Summary

On-going work on the shower parametrisation in GEANT4:

- Revision of current implementation of shower parametrisation:
  - investigate and address the sampling calorimeter issue
  - efficient creation of deposits/location of volumes
  - more technical code revision (by Igor & Marc, LLR)
- Work on user-friendly tuning facilities:
  - specific to given geometry
  - less parameters (no material dependency)
  - better accuracy
  - in good shape for longitudinal profile, on-going work on the radial profile and validation
- Other items:
  - introduction of shower start point parametrisation
  - rethinking the parametrisation of the number of created energy deposits