Simulating ATLAS TileCal for Geant4 validation

Using 2017 SPS testbeam data of the ATLAS Tile Calorimeter (TileCal) for validation and regression testing of Geant4 with Geant Val

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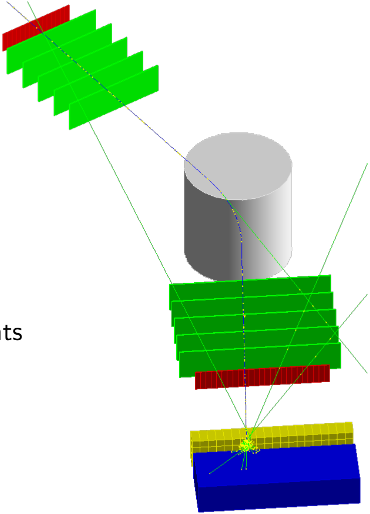
Goals of the project

- Develop a standalone Geant4 simulation of the ATLAS TileCal (hadronic calorimeter)
- Compare to 2017 SPS testbeam data from ATLAS [1]
- Interface simulation to Geant Val, the Geant4 validation testsuite (geant-val.cern.ch)
- Regression testing for the energy response and energy resolution
  - Test with different Geant4 versions and physics lists

Geant4 and Geant Val



- Geant4 widely used for simulating calorimeters
- Validation studies needed for systematic testing
- Geant Val is a validation framework for Geant4
  - Tool to ensure Geant4 is in agreement with experiments
  - Testbeams are the perfect benchmark for this

TileCal geometry

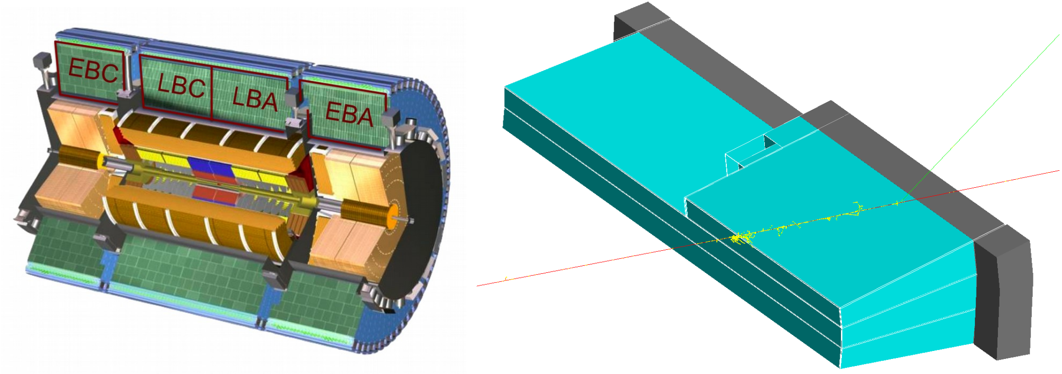
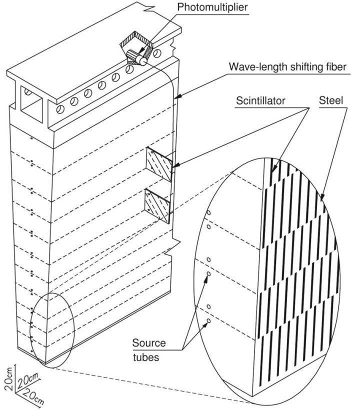


Fig.: TileCal in the detector [2] and testbeam setup with a $10\,\mathrm{GeV}$ muon traversing

Structure of a TileCal module



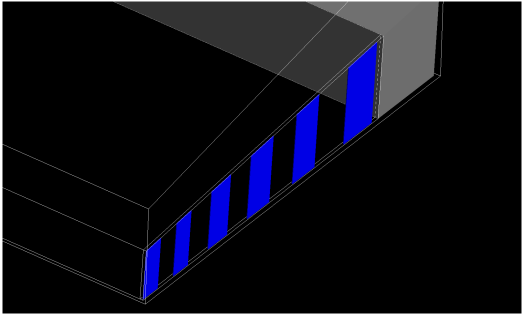


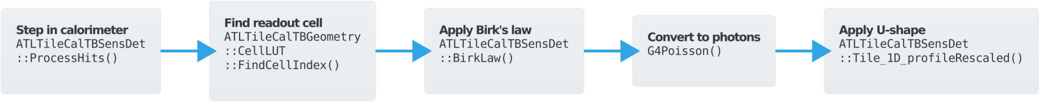
Fig.: TileCal schematic [3] (left) and geometry in the simulation [4] (right)

Coding aspects

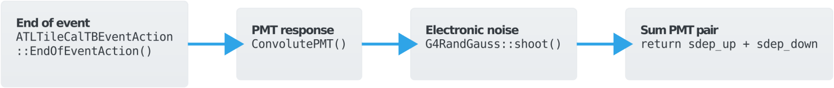
- Needs to be run on different versions of Geant4, going back as far as version 10.4 from 2017
- Maintainable for reuse with future versions of Geant4 $\rightarrow$ good documentation required
- Validation one of the most computationally heavy tasks:
  300k events $\times$ [e^-, π^+, K^+, p^+] $\times$ [16, 18, 20, 30 GeV] $\times$ 4 PL $\times$ 5 G4 versions
  - Almost 100 million events $\rightarrow$ parallised to 1280 threads with Geant Val + HTCondor
- Realistic simulation with detector effects, not just simulated energy deposit

Physics aspects

Signal treatment during the event:



Digitization at the end of the event:



Example: U-shape correction

- Inefficiencies in tiles decreases amount of photons
- Depends on relative position of hit within tile
  - More photons collected if hit is closer to a readout fiber $\rightarrow$ drops from $80\,\%$ to $30\,\%$
- U-shape given by the combined effect of the two readout fibers located at the tile ends
- Taken from Athena [5]

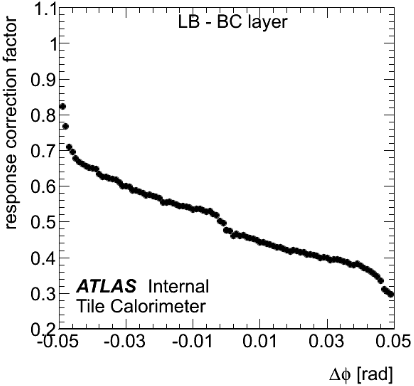


Fig.: Correction for a single PMT [6]

Example: PMT response

- Time dependent response
- Signal stored in each step in array with time bins
- Convolution at end of event
- Implemented from scratch

```
auto ConvolutePMT = [](const std::array<double, ATLTileCalTBConstants::frames>& sdep) {
    constexpr auto pmt_response_size = ATLTileCalTBConstants::pmt_response.size();
    auto outvec = std::array<double, ATLTileCalTBConstants::frames>();
    for (std::size_t k = 0; k < outvec.size(); ++k) {
        double outsum = 0.;
        auto jmax = (k >= pmt_response_size) ? pmt_response_size - 1 : k;
        for (std::size_t j = 0; j <= jmax; ++j) {
            outsum += sdep.at(k - j) * ATLTileCalTBConstants::pmt_response.at(j);
        }
    outvec.at(k) = outsum;
    }
    return outvec;
};
```

Example: PMT response

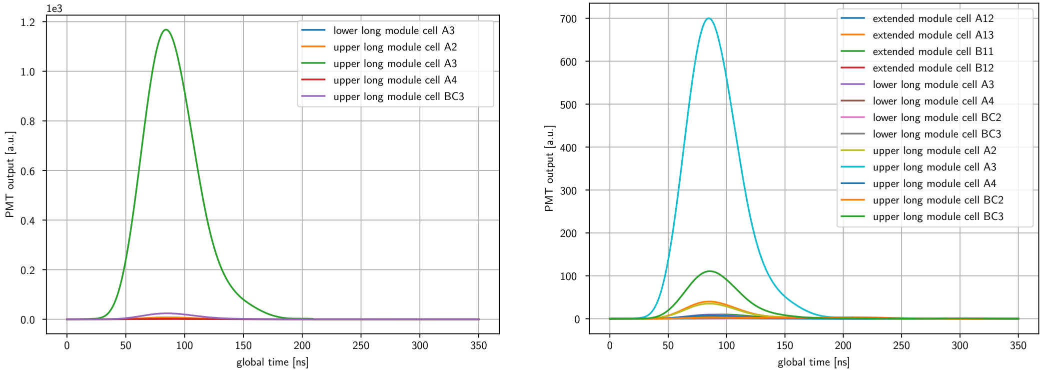


Fig.: PMT response for an $18\,\mathrm{GeV}$ electron (left) and pion (right)

Analysis code

- Simulated and analysed data stored in ROOT files
- Using modular C++ design and modern ROOT RDataFrame
- Calibration of reconstructed energy using electron beam
- Extract energy response and energy resolution for hadron beams

Calibration at the EM-Scale

- Recalibration in each run using simulated electrons
- $C_{e-} = \text{Signal}/E_{\text{beam}}$ (roughly) constant for electrons
- $E^{\text{raw}} = \text{Signal}/C_{e-}$ reconstructed energy for hadrons
- Almost gaussian distribution of E^{raw}
- Energy response $R^{E^{\text{raw}}} = \langle E^{\text{raw}} \rangle / E_{\text{beam}}$
- Energy resolution $R^{\sigma^{\text{raw}}} = \sigma^{E^{\text{raw}}} / E_{\text{beam}}$

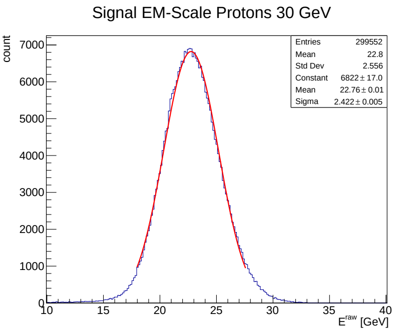


Fig.: Example of E^{raw} distribution

FTFP_BERT regression testing

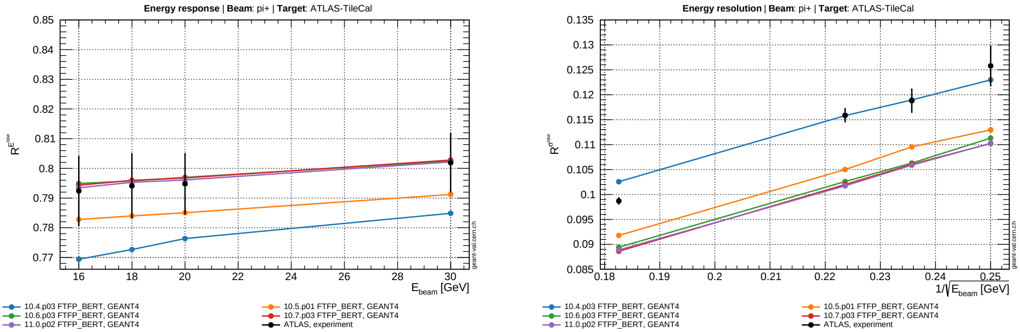


Fig.: Version comparison for the FTFP_BERT physics list with pions

Geant4 11.0 physics list comparison

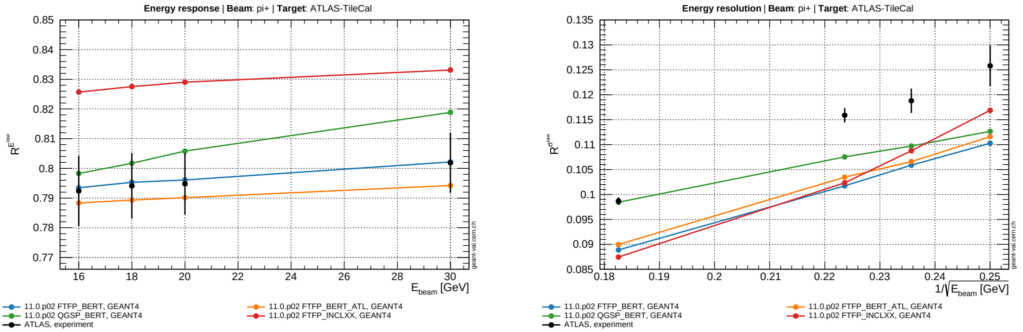


Fig.: Physics list comparison for version 11.0.p02 with pions

Particle response comparison

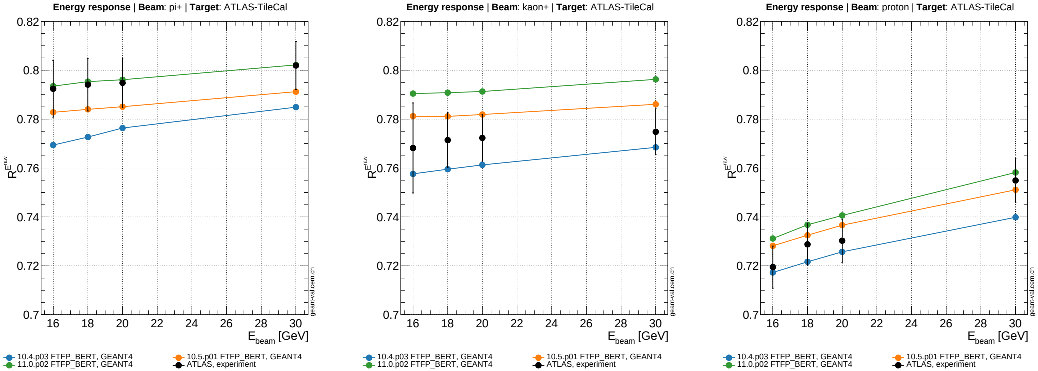
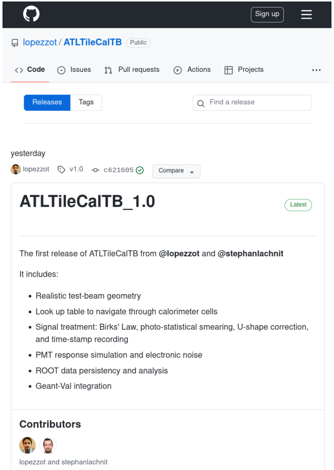


Fig.: Energy response for different particle beams

Current State

- Code hosted on GitHub (github.com/lopezzot/ATLTileCalTB)
- Simulation results for Geant4 10.4, 10.5, 10.6, 10.7 and 11.0 with `FTFP_BERT`, `QGSP_BERT`, `FTFP_BERT_ATL` and `FTFP_INCLXX`
- Final results published on geant-val.cern.ch
- Essentially feature complete



Conclusion

- Realistic standalone simulation of the ATLAS TileCal developed
- Extensive documentation available at lopezzot.github.io/ATLTileCalTB
- Successfully added a new test to Geant Val
- Significant changes in energy response and resolution in version 10.5 and 10.6 $\rightarrow$ consistent with previous findings [7]

Appendix

References

[1] Jalal Abdallah et al. "Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV". In: *Eur. Phys. J. C* 81.6 (2021), p. 549. DOI: 10.1140/epjc/s10052-021-09292-5. arXiv: 2102.04088 [physics.ins-det].

[2] Tamar Zakareishvili. "Studies of the response of the ATLAS Tile Calorimeter to beams of particles at the CERN test beams facility". In: (2019-01). URL: https://cds.cern.ch/record/2654416.

[3] The ATLAS Collaboration et al. "The ATLAS Experiment at the CERN Large Hadron Collider". In: *Journal of Instrumentation* 3.08 (2008-08), S08003–S08003. DOI: 10.1088/1748-0221/3/08/s08003. URL: https://doi.org/10.1088/1748-0221/3/08/s08003.

[4] Lorenzo Pezzotti. *Towards a Geant4 simulation of the ATLAS TileCal test beams*. 2022-06. URL: https://cernbox.cern.ch/index.php/s/gJhXVx13EuHUIPY.

[5] ATLAS Collaboration. *Athena*. DOI: 10.5281/zenodo.2641996. URL: https://gitlab.cern.ch/atlas/athena.

[6] A Durglishvili et al. *Determination of the cells response as a function of the tracks impact point coordinates*. Tech. rep. Geneva: CERN, 2014-09. URL: https://cds.cern.ch/record/1754960.

[7] Lorenzo Pezzotti. *Including calorimeter test-beams into geant-val*. 2022-05. URL: https://indico.cern.ch/event/847884/contributions/4833199/.

Cell layout

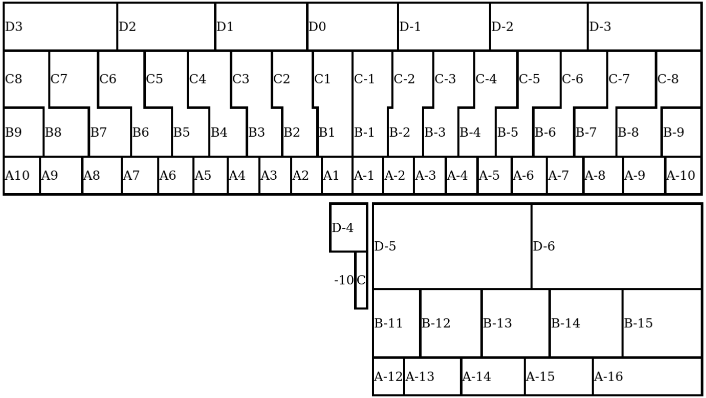


Fig.: Cell layout (from zenis.dnp.fmph.uniba.sk/tile.html)

Other validation work using testbeam data

- ATLAS hadronic end-cap calorimeter (lopezzot.github.io/ATLHECTB)
  - same $10\,\%$ to $20\,\%$ lower energy resolution found
- CALICE SiW calorimeter (lopezzot.github.io/CALICESiWTB)