Standalone Geant4 validation on the ATLAS Tile Calorimeter beam test

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Preface

- Currently no realistic simulation of the ATLAS Tile Calorimeter test beam is available outside ATHENA (as far as I know)

  → this work is the only alternative.

- ATLAS is still running beam tests at the Prevessin North Area with the Tile Calorimeter modules

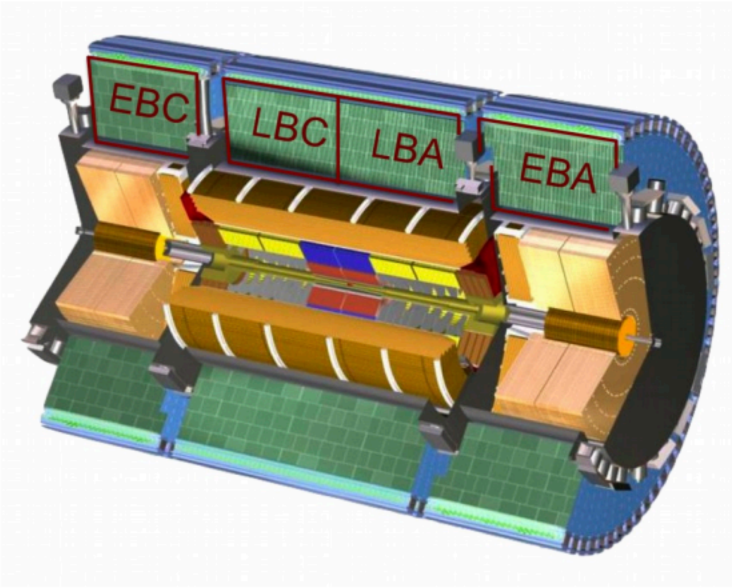
  → this work targets both past and future validation studies.

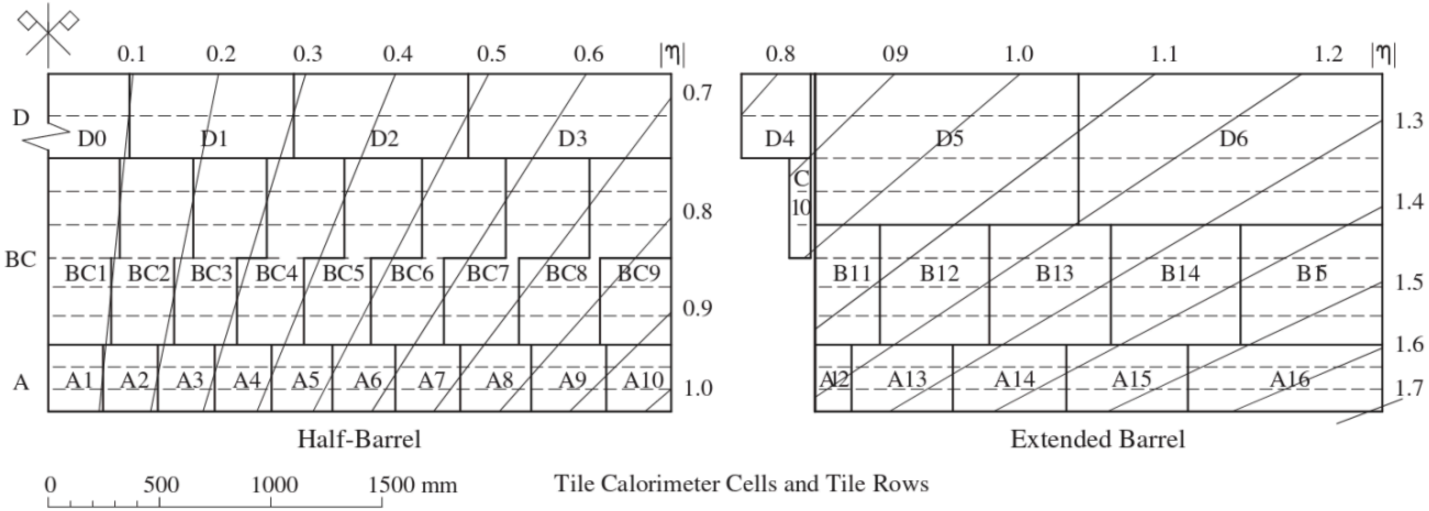
- ATLAS validates Geant4 on the Tile Cal test beams only with the Geant4 version selected for the current Run and the FTFP_BERT_ATL PL (*e.g.* G4 10.1 was used for a 2021 publication)

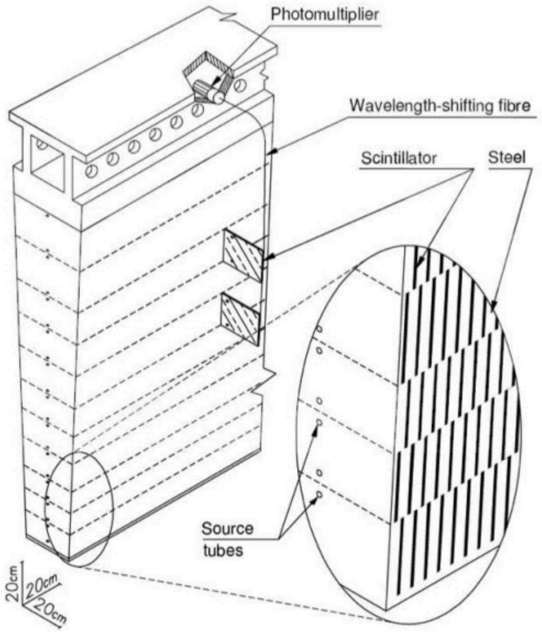
  → this work performs systematic validation on multiple PL and G4 versions.

The ATLAS Tile Calorimeter

- Mostly used to reconstruct hadronic jets in the range $|\eta| < 1.7$ thanks to 3 cylinders containing 64 modules each.
- Measure light in scintillating tiles brought to PMTs by WLS fibers. Readout is grouped in pseudo projective cells with each layer readout by two PMTs.
- Each barrel consists of 11 tile rows grouped in 3 longitudinal layers.

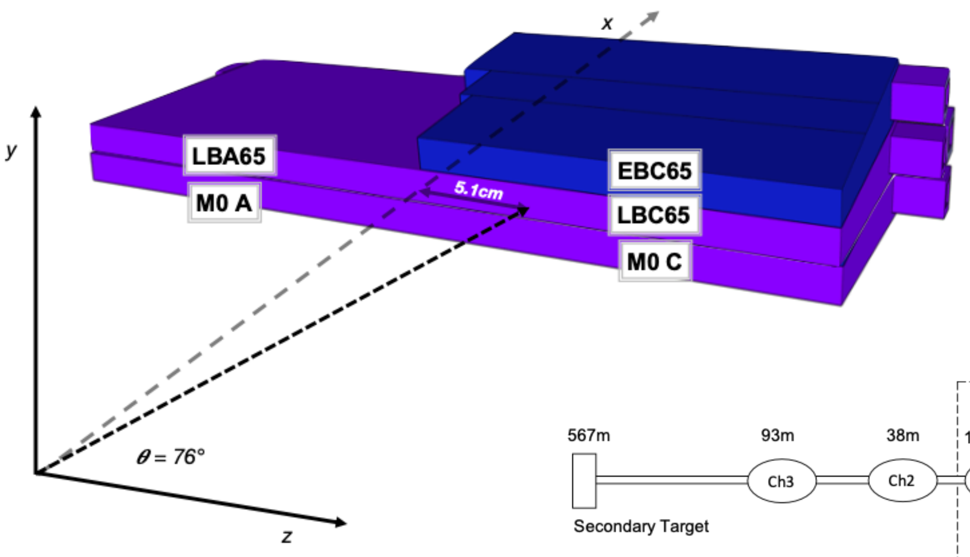




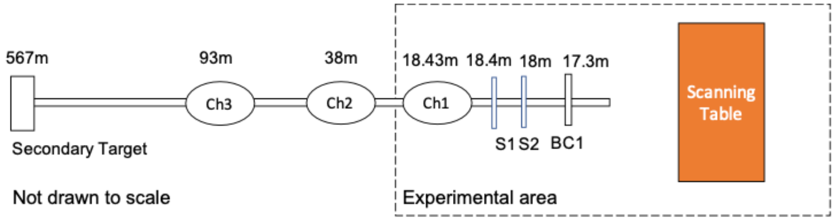


The ATLAS Tile Calorimeter beam test

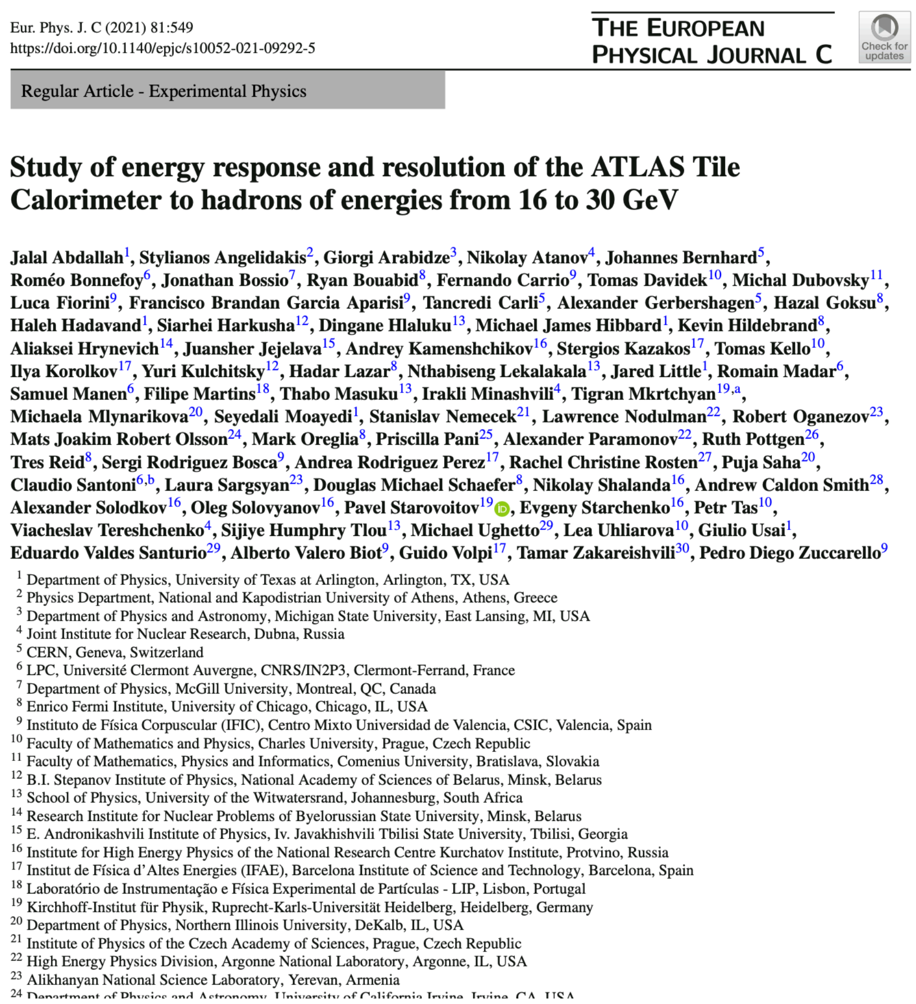
- 2 Long Barrel Modules and 1 Extended Barrel module are regularly exposed to the SPS particle beams.
- The 2017 beam test studied the calorimeter response and resolution for π^+, p and k^+ in the energy range 16-30 GeV.
- Cherenkov auxiliaries used to tag π^+, p and k^+.



Beam line composition



ATLAS Article



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Regular Article - Experimental Physics

Study of energy response and resolution of the ATLAS Tile Calorimeter to hadrons of energies from 16 to 30 GeV

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ATLTileCalTB

- A new standalone Geant4 simulation of the ATLAS TileCal beam tests.
- v1.0 released in August:
  - Essentially feature complete.
- Documentation at [link].

- A complete validation data-set consists of 16 runs (e^-, p, π^+, k^+ at 16, 18, 20, 30 GeV), 300k events per run, using 5 G4 releases and 4 PLs:

  $\rightarrow 96 \times 10^6$ events simulated using HTCondor + GeantVal exploiting 1280 threads.

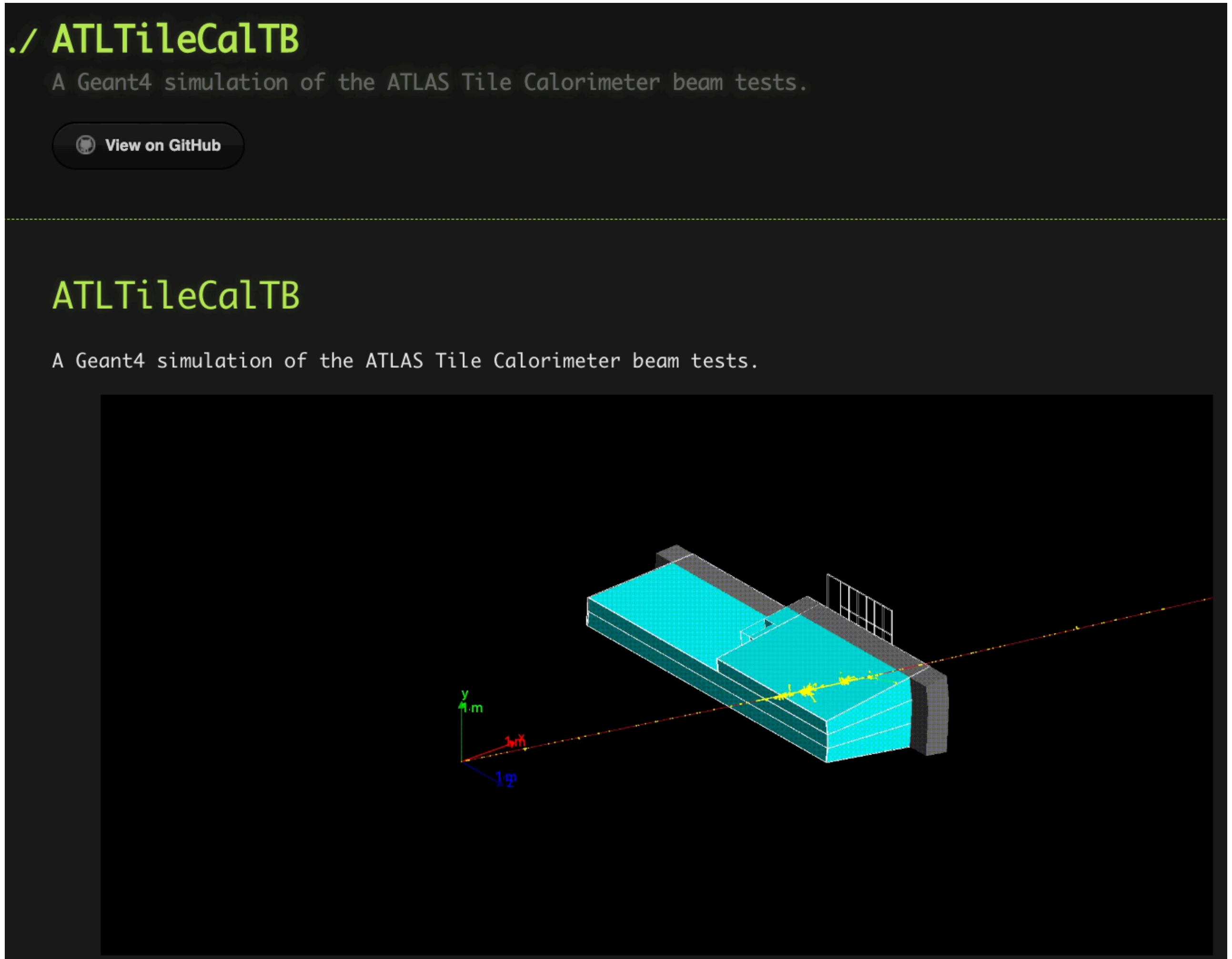
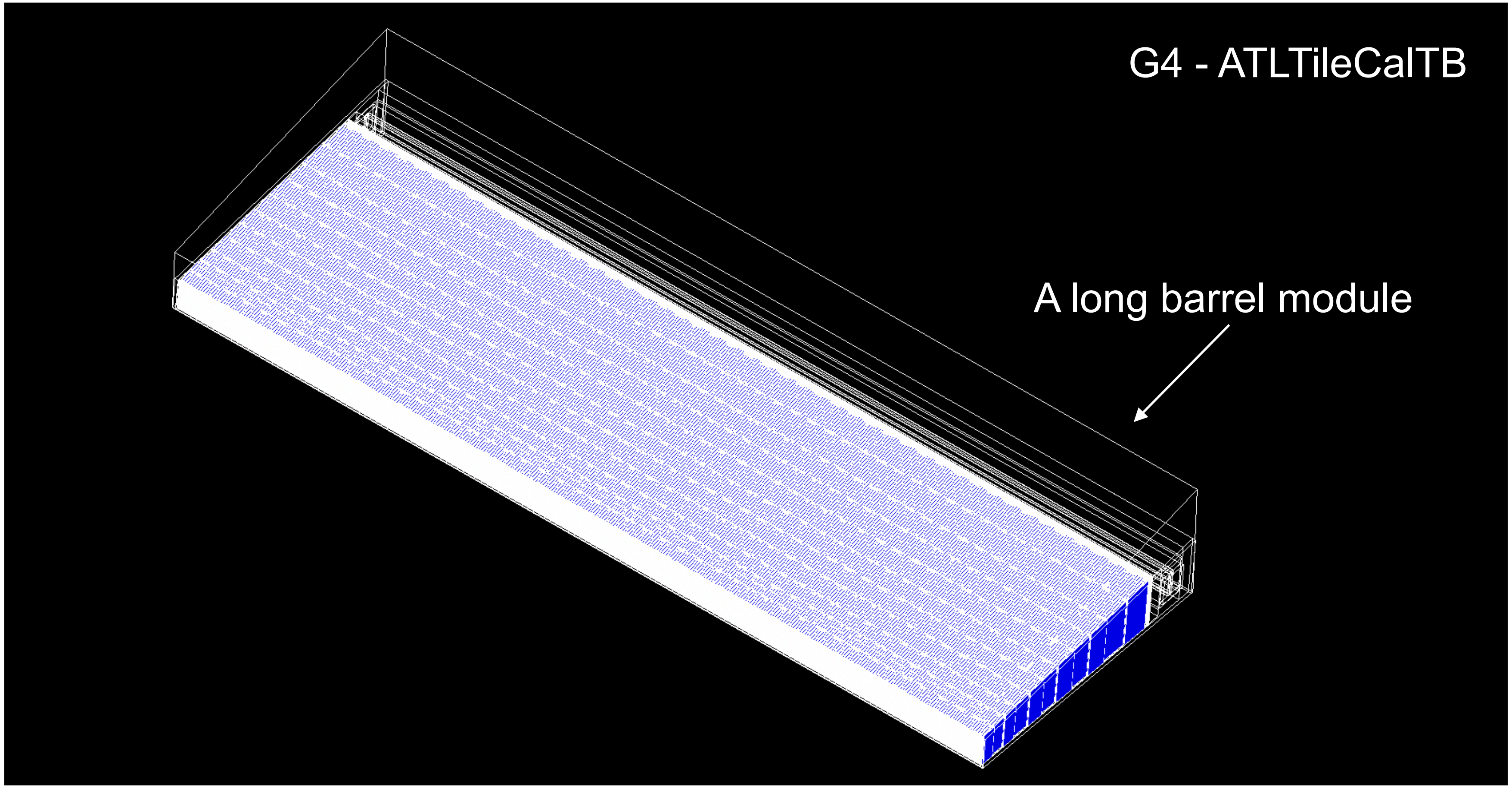


Fig. - 10 GeV muon passing through the ATLAS TileCal.

Geometry

Main geometry ingredients:

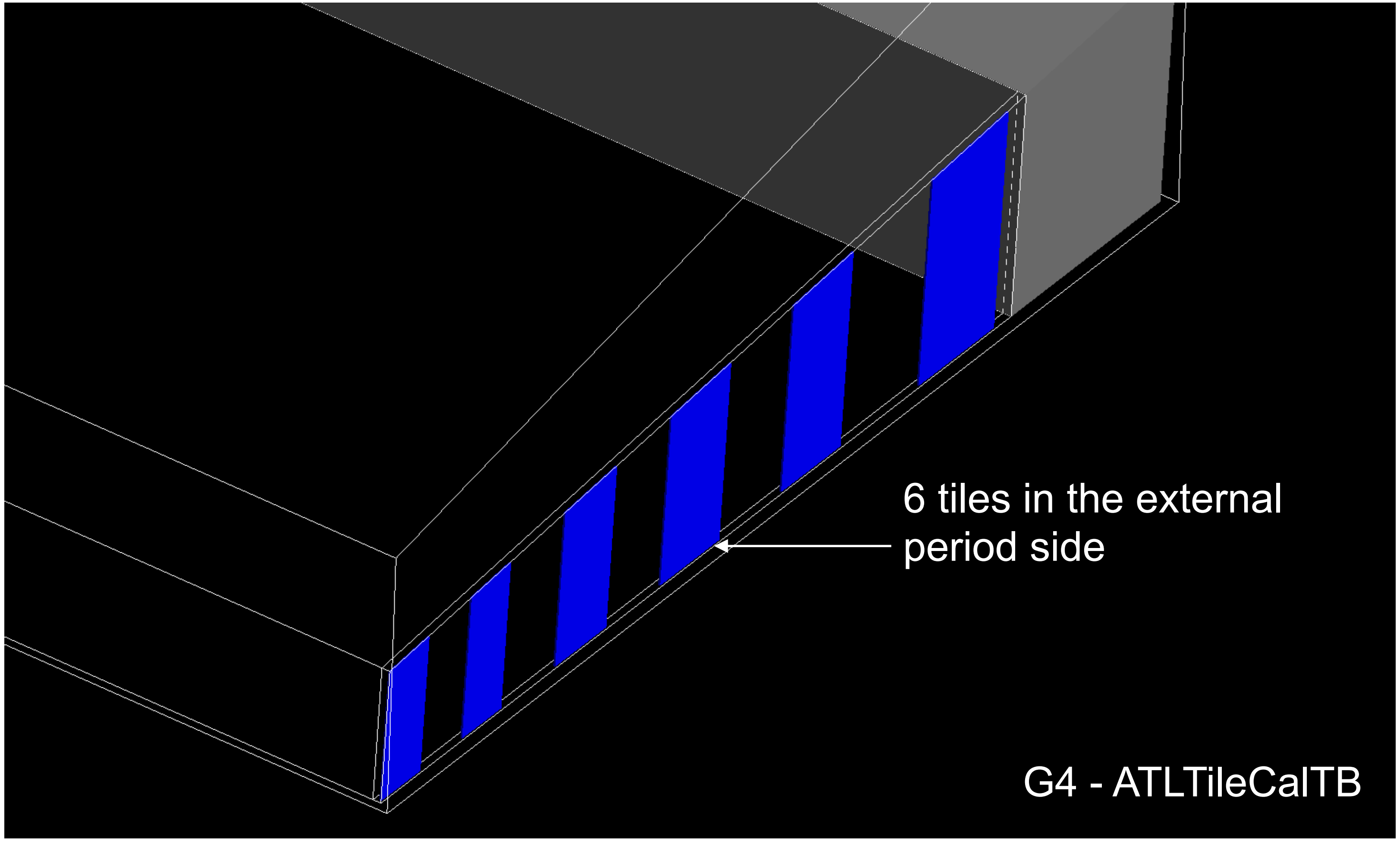
- A single TileCal long barrel module is made of 307 Tile::Period volumes.



Geometry

Main geometry ingredients:

- A single TileCal long barrel module is made of 307 Tile::Period volumes.
- Each Tile::Period consists of 11 Scintillating tiles. Tiles are alternated, 6 on one side and 5 on the other side.
  Each Tile::Period also contains glue and tile-wrappers.



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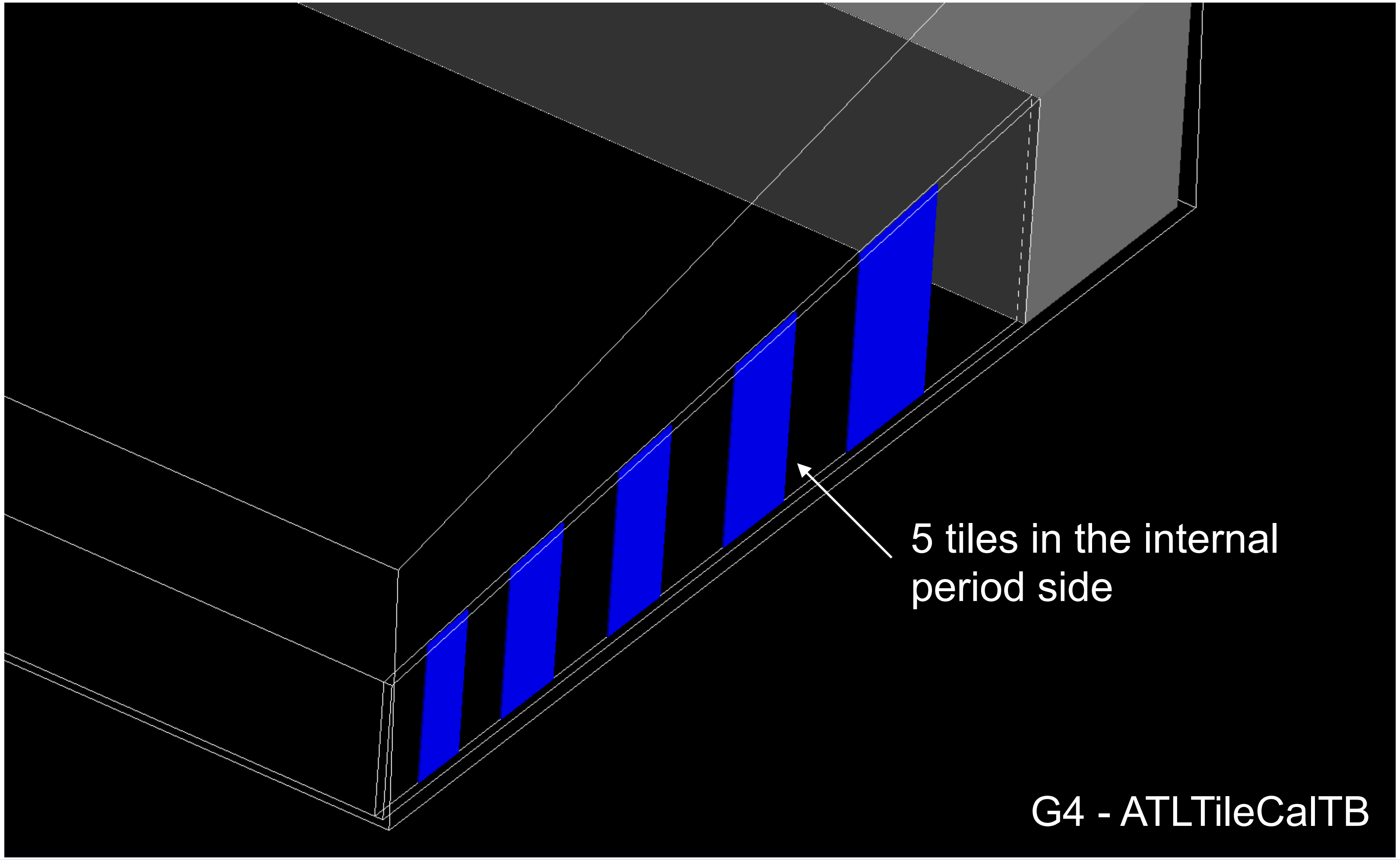
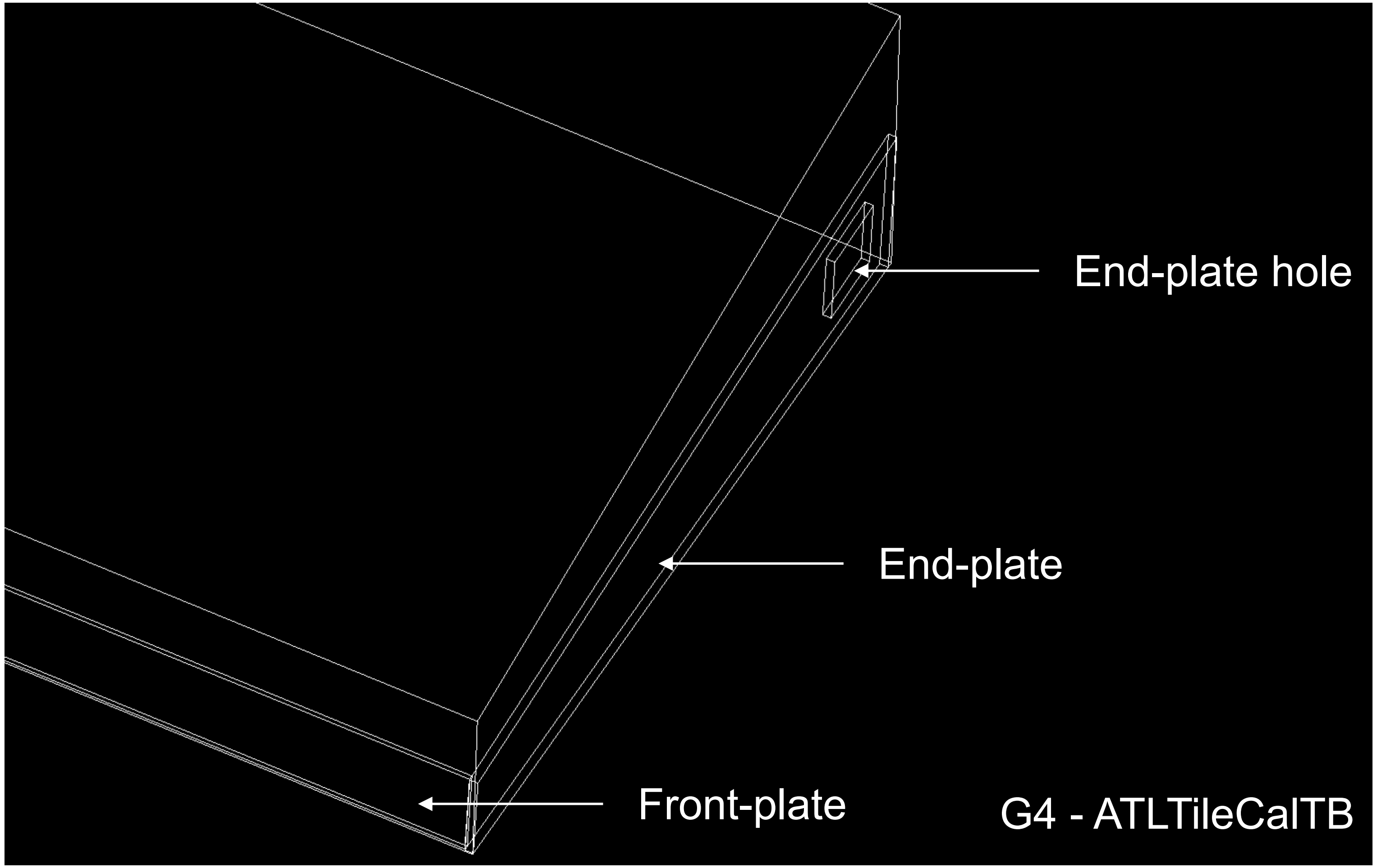


Geometry

Main geometry ingredients:

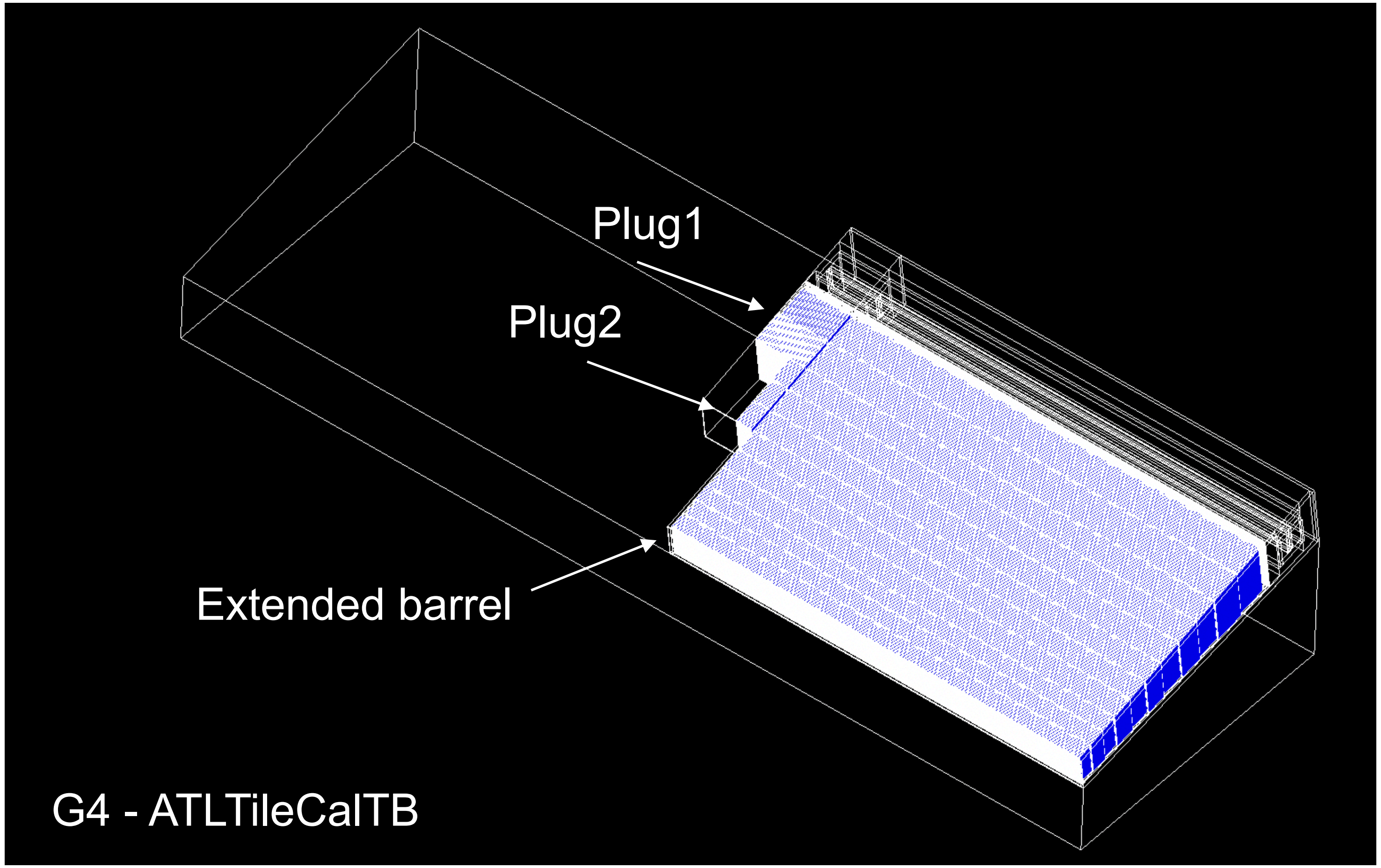
- A single TileCal long barrel module is made of 307 Tile::Period volumes.
- Each Tile::Period consists of 11 Scintillating tiles. Tiles are alternated, 6 on one side and 5 on the other side.
  Each Tile::Period also contains glue and tile-wrappers.
- End-plates and front-plate included.



Geometry

Main geometry ingredients:

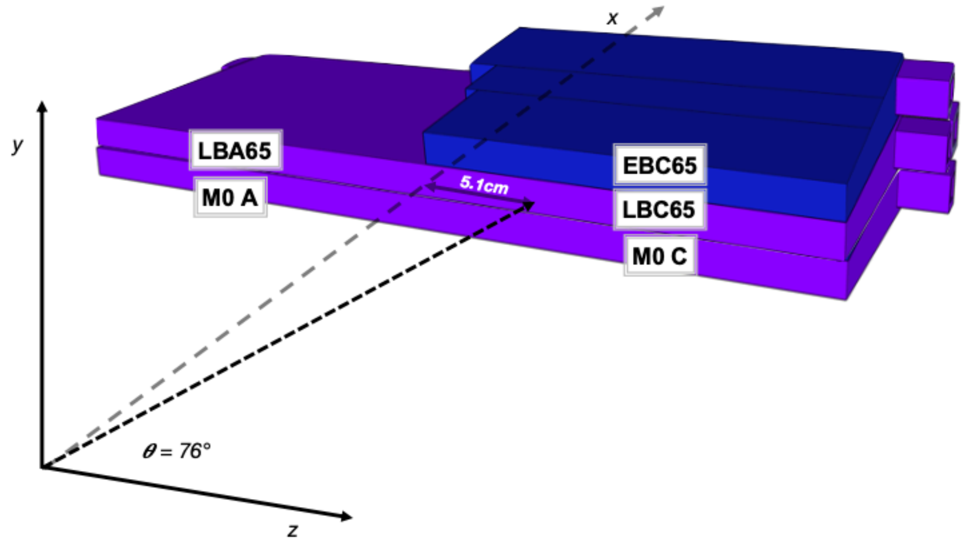
- A single Extended Barrel Module consists of 140 periods, front plates and end plates, and two plug volumes (Plug1 and Plug2) inside the so-called ITC.

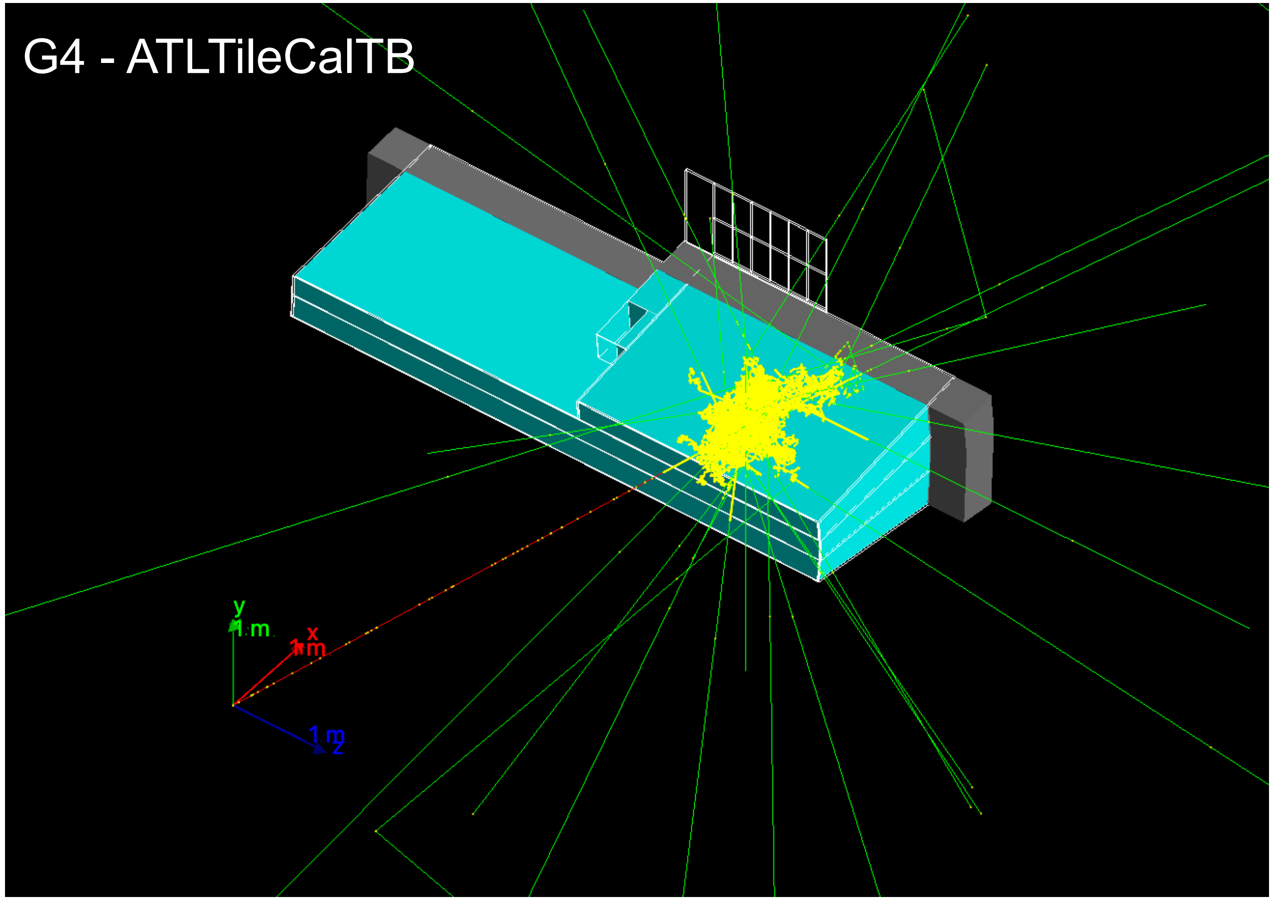


Test-beam geometry

Test-beam setup uses two long barrel modules and one extended barrel module piled up.

From ATLAS article





A realistic standalone simulation

Step-level actions

1. **Step in calo** — `ATLTileCalTBSensDet::ProcessHit()`
2. **Find RO cell** — `ATLTileCalTBGeometry::CellLUT::FindCellIndex()`
3. **Briks' Law and Photo-electrons** — `ATLTileCalTBSensDet::BirkLaw()`
4. **U-shape correction** — `ATLTileCalTBSensDet::Tile_1D_profileRescaled()`

Event-level actions

1. **End of Event** — `ATLTileCalTBEventAction::EndOfEventAction()`
2. **PMT-Digitization** — `ConvolutePMT()`
3. **Electronic noise** — `G4RandomGauss::shoot()`
4. **PMT-pair sum** — `sdep_up + sdep_down`

Navigating through the RO cells

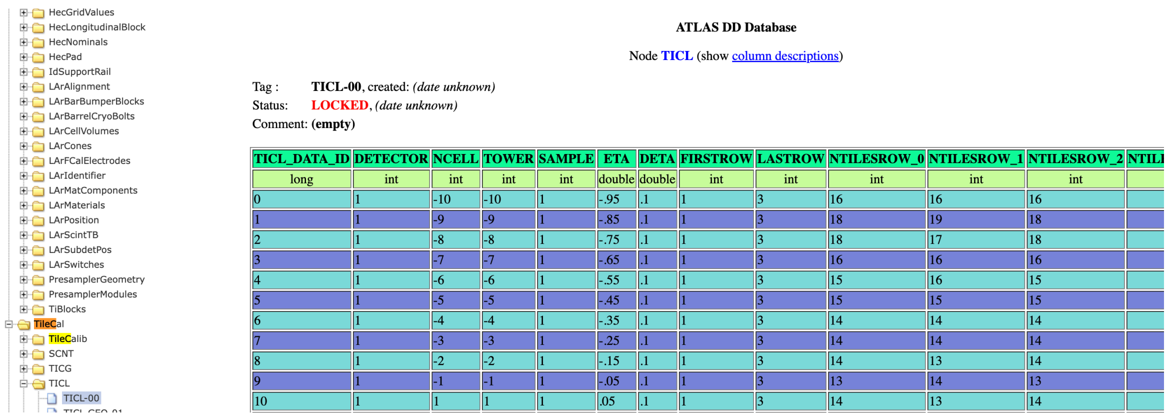
- Each G4Hit corresponds to a RO cell of the TileCal, 104 hits are preallocated at the initialization of the sensitive detector.
- Each step in a tile provides copy numbers of the corresponding period and tile row.
  → need to retrieve the corresponding RO cell and link it to the proper G4Hit.

```
G4bool ATLTileCalTBSensDet::ProcessHits( G4Step* aStep, G4TouchableHistory* ) {

    auto edep = aStep->GetTotalEnergyDeposit();

    // we only record data within the time window of the digitization
    auto time = aStep->GetPreStepPoint()->GetGlobalTime();
    if ( time > ATLTileCalTBConstants::frame_time_window ) return false;

    auto cellLUT = ATLTileCalTBGeometry::CellLUT::GetInstance();
    auto cellIndex = FindCellIndexFromG4( aStep );
    auto cell = cellLUT->GetCell( cellIndex );

    auto hit = (*fHitsCollection)[cellIndex];
}
```

Get cell LUT singleton

Find cell index

Get reference to cell object



- HecGridValues
- HecLongitudinalBlock
- HecNominals
- HecPad
- IdSupportRail
- LArAlignment
- LArBarBumperBlocks
- LArBarrelCryoBolts
- LArCellVolumes
- LArCones
- LArFCalElectrodes
- LArIdentifier
- LArMatComponents
- LArMaterials
- LArPosition
- LArScintTB
- LArSubdetPos
- LArSwitches
- PresamplerGeometry
- PresamplerModules
- TiBlocks
- TileCal
  - TileCalib
  - SCNT
  - TICG
  - TICL
    - TICL-00

ATLAS DD Database

Node **TICL** (show column descriptions)

Tag : **TICL-00**, created: *(date unknown)*
Status: **LOCKED**, *(date unknown)*
Comment: **(empty)**

TICL_DATA_ID	DETECTOR	NCELL	TOWER	SAMPLE	ETA	DETA	FIRSTROW	LASTROW	NTILESROW_0	NTILESROW_1	NTILESROW_2	NTILI
long	int	int	int	int	double	double	int	int	int	int	int	
0	1	-10	-10	1	-.95	.1	1	3	16	16	16	
1	1	-9	-9	1	-.85	.1	1	3	18	19	18	
2	1	-8	-8	1	-.75	.1	1	3	18	17	18	
3	1	-7	-7	1	-.65	.1	1	3	16	16	16	
4	1	-6	-6	1	-.55	.1	1	3	15	16	15	
5	1	-5	-5	1	-.45	.1	1	3	15	15	15	
6	1	-4	-4	1	-.35	.1	1	3	14	14	14	
7	1	-3	-3	1	-.25	.1	1	3	14	14	14	
8	1	-2	-2	1	-.15	.1	1	3	14	13	14	
9	1	-1	-1	1	-.05	.1	1	3	13	14	13	
10	1	1	1	1	.05	.1	1	3	14	13	14	

→ Decoupled from the the ATLAS DD Database

Navigating through the RO cells

- Each G4Hit corresponds to a RO cell of the TileCal, 104 hits are preallocated at the initialization of the sensitive detector.
- Each step in a tile provides copy numbers of the corresponding period and tile row.
  → need to retrieve the corresponding RO cell and link it to the proper G4Hit.
- The CellLUT class stores the RO cell information as in the ATLAS DataBase and provides direct link with the corresponding G4Hit.

```
class CellLUT {
        friend class G4ThreadLocalSingleton<CellLUT>;

        public:
            // Returns pointer to Singleton
            static CellLUT* GetInstance() {
                static G4ThreadLocalSingleton<CellLUT> instance {};
                return instance.Instance();
            }

            // Returns the total number of cells
            inline constexpr std::size_t GetNumberOfCells() const { return fNoOfCells; };

            // Finds the cell index given a module, the row index and the cell index
            std::size_t FindCellIndex(Module module, std::size_t rowIdx, std::size_t tileIdx) const;

            // Returns a constant reference of the cell corresponding to the cell index
            inline constexpr Cell GetCell(std::size_t index) const { return fCellVector[index]; };

        private:
            // Private constructor
            CellLUT() = default;

            // Total numbers of cells
            static constexpr std::size_t fNoOfCells = 104;

            // Cell vector
            // https://atlas-geometry-db.web.cern.ch/atlas-geometry-db/node_tag_browser.php
            // TileCal -> TICL -> TICL-00
            static constexpr std::array<const Cell, fNoOfCells> fCellVector {
                // Lower long module
                Cell(Module::LONG_LOWER,   Row::A, -10,  1,  3, 16, 16, 16,  0,  0,  0), //   0
                Cell(Module::LONG_LOWER,   Row::A,  -9,  1,  3, 18, 19, 18,  0,  0,  0), //   1
                Cell(Module::LONG_LOWER,   Row::A,  -8,  1,  3, 18, 17, 18,  0,  0,  0), //   2
                Cell(Module::LONG_LOWER,   Row::A,  -7,  1,  3, 16, 16, 16,  0,  0,  0), //   3
```

Birks' Law

- Implemented as in ATHENA: $\Delta E' = \dfrac{\Delta E}{1 + m_{birk1} * de/dx + m_{birk2} * (de/dx)^2}$

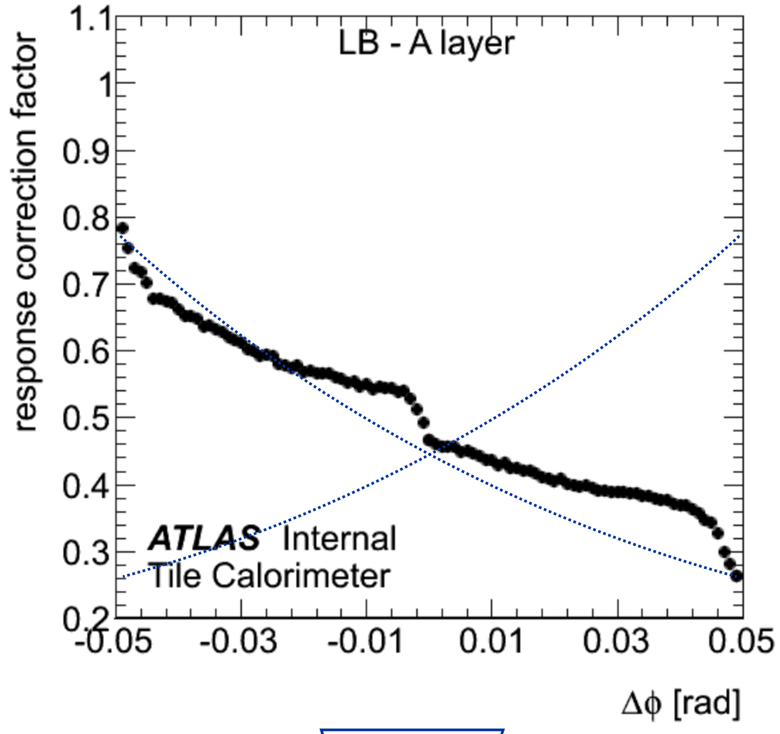
```
G4double ATLTileCalTBSensDet::BirkLaw( const G4Step* aStep ) const {

    const G4double destep = aStep->GetTotalEnergyDeposit() * aStep->GetTrack()->GetWeight();
    const G4Material* material = aStep->GetPreStepPoint()->GetMaterial();
    const G4double charge = aStep->GetPreStepPoint()->GetCharge();

    G4double response = 0.;
    G4double rkb = 0.02002 * CLHEP::g / (CLHEP::MeV * CLHEP::cm2);      //m_birk1 in athena
    G4double m_birk2 = 0.0 * CLHEP::g / (CLHEP::MeV * CLHEP::cm2) * CLHEP::g / (CLHEP::MeV * CLHEP::cm2);

    if ( charge != 0 && aStep->GetStepLength() != 0) {
        //Comment from atlas athena
        // --- correction for particles with more than 1 charge unit ---
        // --- based on alpha particle data (only apply for MODEL=1) ---
        if ( fabs(charge) > 1.0 ) { rkb *= 7.2 / 12.6; }
        const G4double dedx = destep / (aStep->GetStepLength()) / (material->GetDensity());
        response = destep / (1. + rkb * dedx + m_birk2 * dedx * dedx);
    }
    else { response = destep; }

    return response;
```

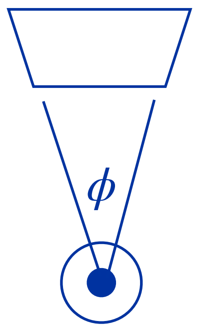
- Photo-statistical smearing to get a light yield of 70 p.e./GeV:

```
G4Poisson(ATLTileCalTBConstants::photoelectrons_per_energy * sdep));
```

U-shape correction

- Correction needed to take into account the light collection efficiency.
- Parametrized as a correction factor over the number of p.e. as a function of the ϕ angle.
- Implemented as 99 numbers x 3 cylinders (LB, EBA, EBC) x 3 longitudinal rows (A, BC, D) → 891 correction factors!





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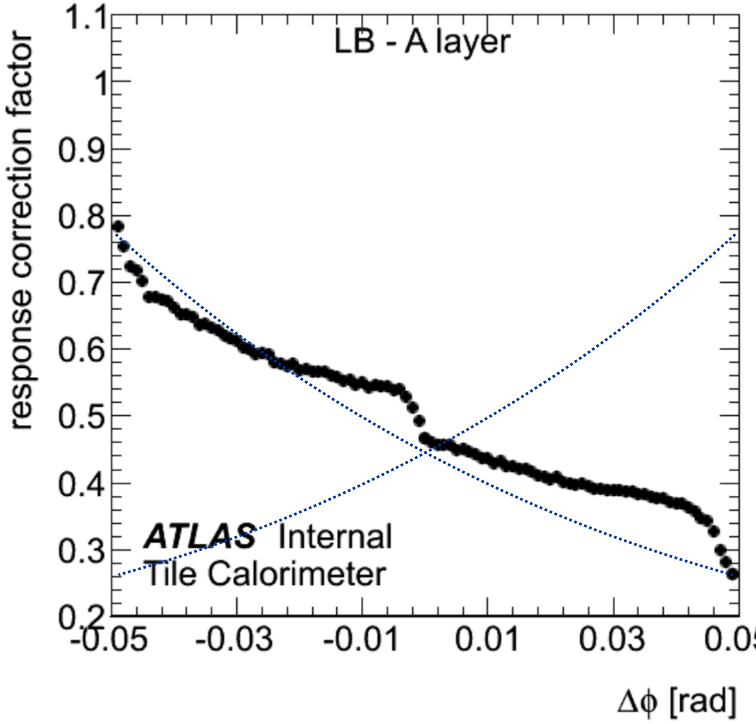
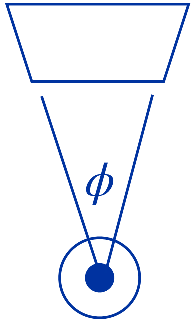
```
G4double ATLTileCalTBSensDet::Tile_1D_profileRescaled( G4int row, G4double x, G4double y, G4int PMT, ATLTileCalTBGeometry::Cell cell ){

    if (PMT) x *= -1.;
    const double xlow = -0.0495; //dPhi low [rad]
    const double xup = 0.0495; //dPhi up [rad]
    const double range = (xup - xlow); //dPhi range
    const int size = 99;
    const G4double LB_A_TilePMT[size] = { 0.797741, 0.767611, 0.737482, 0.731121, 0.715537, 0.689929, 0.690055, 0.687185,
                                        0.685124, 0.673707, 0.664842, 0.663197, 0.660089, 0.647501, 0.650303, 0.644465,
                                        0.639813, 0.631315, 0.627008, 0.622707, 0.614297, 0.61109, 0.604147, 0.605184,
                                        0.603651, 0.592072, 0.588977, 0.585351, 0.588941, 0.578247, 0.580187, 0.576195,
                                        0.576942, 0.57606, 0.570978, 0.568398, 0.563464, 0.565646, 0.557544, 0.56112,
                                        0.552727, 0.556008, 0.555573, 0.554079, 0.548542, 0.551241, 0.538841, 0.523046,
                                        0.501209, 0.474613, 0.46968, 0.465796, 0.465135, 0.466067, 0.456968, 0.458314,
                                        0.454288, 0.450544, 0.445219, 0.444452, 0.437612, 0.440608, 0.432754, 0.432117,
                                        0.429496, 0.427993, 0.42394, 0.419026, 0.41752, 0.412359, 0.416317, 0.408531,
                                        0.40574, 0.405237, 0.407231, 0.403318, 0.398811, 0.39869, 0.396117, 0.396753,
                                        0.395918, 0.393898, 0.39377, 0.390499, 0.390835, 0.38526, 0.385113, 0.383958,
                                        0.37829, 0.375895, 0.375872, 0.370231, 0.364742, 0.353429, 0.349633, 0.333518,
                                        0.305173, 0.287103, 0.269032 };

    const G4double LB_BC_TilePMT[size] = { 0.83904, 0.781078, 0.723117, 0.708466, 0.691473, 0.680283, 0.673512, 0.668259,
                                         0.663925, 0.661599, 0.66064, 0.645793, 0.638767, 0.638648, 0.633753, 0.632288,
                                         0.62912, 0.621557, 0.610724, 0.611454, 0.608478, 0.598683, 0.599413, 0.59475,
                                         0.591156, 0.585141, 0.58734, 0.582087, 0.581133, 0.577544, 0.565483, 0.565771,
                                         0.566045, 0.562009, 0.558788, 0.554103, 0.554569, 0.552122, 0.55021, 0.544131,
                                         0.546458, 0.545739, 0.542813, 0.539188, 0.539949
```

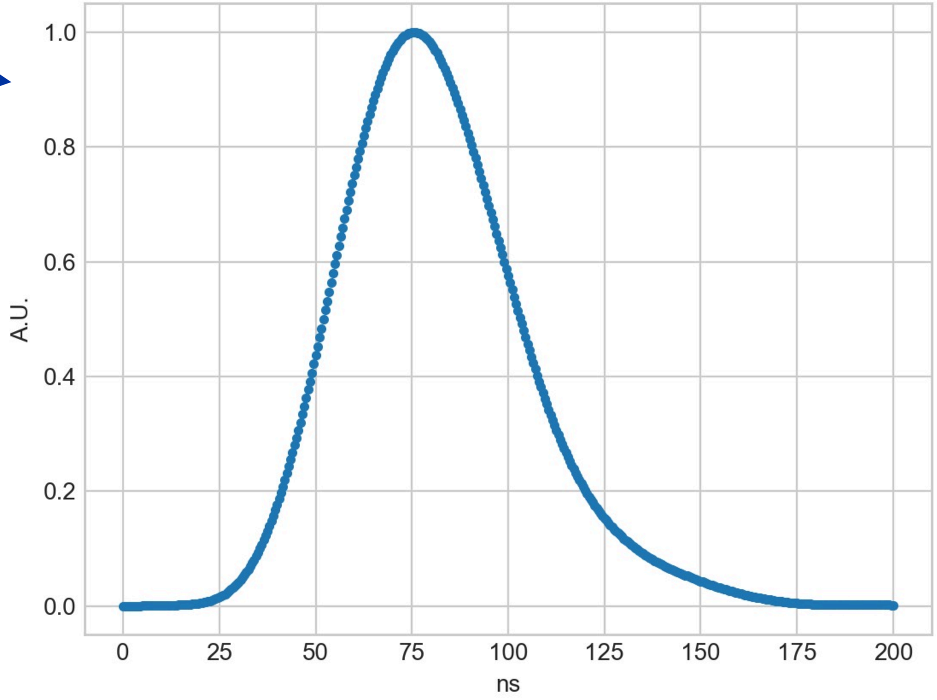




PMT digitization

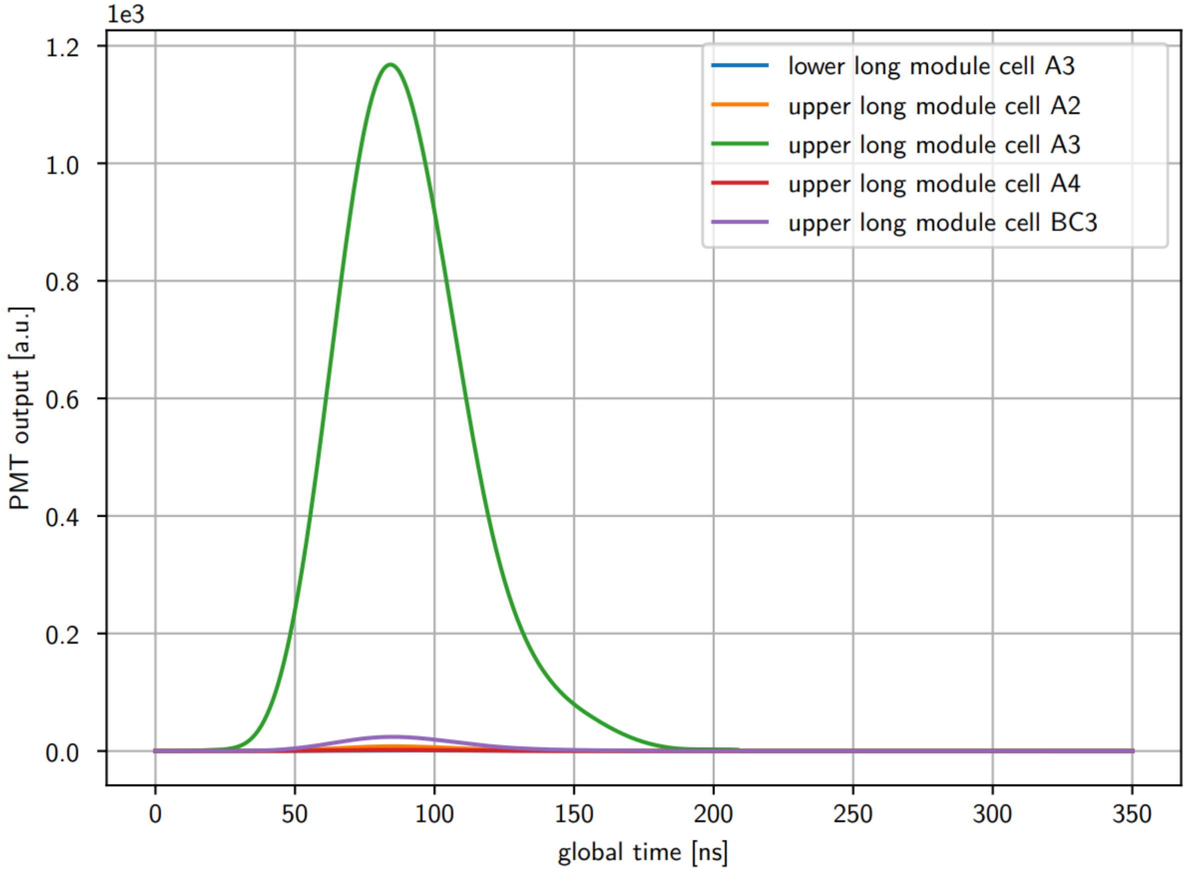
- Need to convolute the hit time-stamp and p.e. content with the PMT response.
  - TileCal PMT signal shape is known with a 0.5 ns precision.
  - Every step contribution creates a signal and signals from each PMT are convoluted.
  - Stored signal is the digitized maximum of the PMT signal (no analog signal kept in root format).
- Signals from the 2 PMTs of each RO cell are summed-up.
  - Gaussian noise of 12 MeV is over-imposed over each RO cell.
  - Only RO cell with a signal $> 2\sigma_{noise}$ are kept for analysis.

PMT signal shape

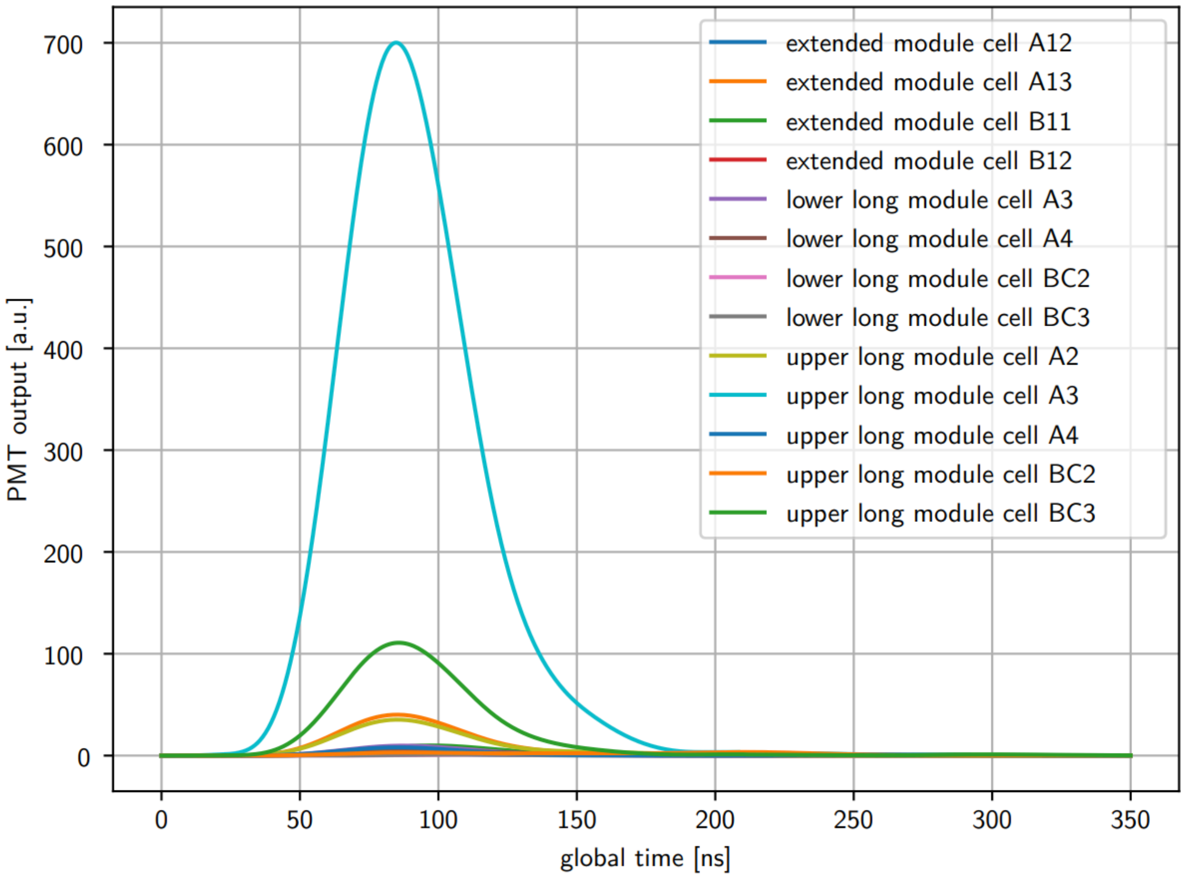


PMT digitization - examples

18 GeV e^-

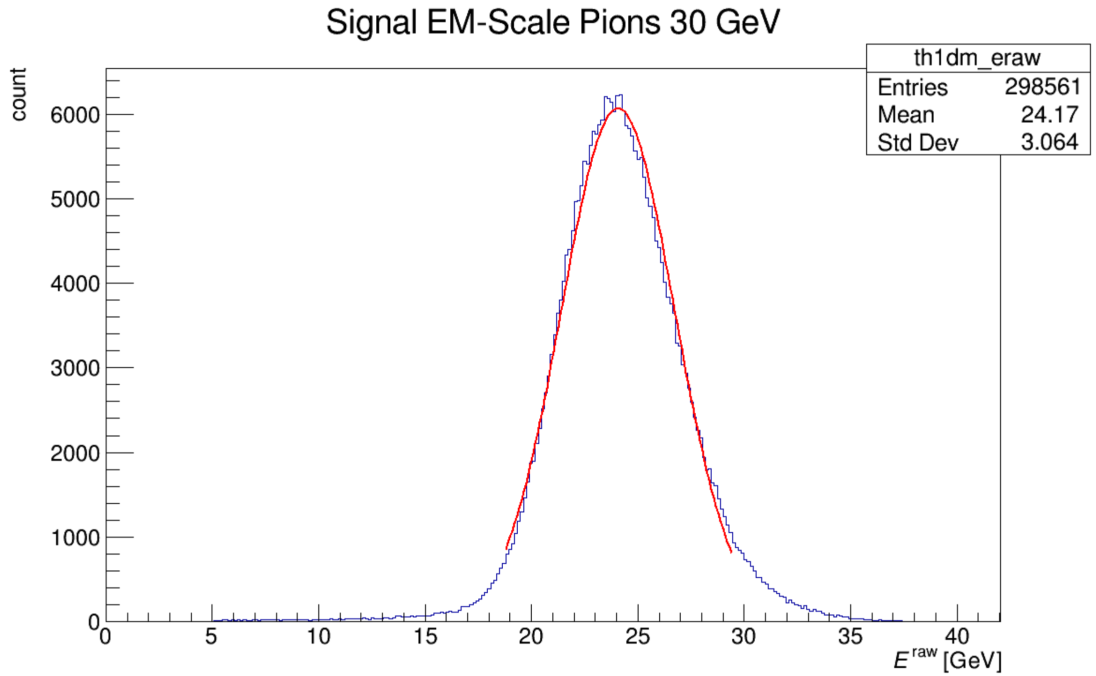


18 GeV π^-



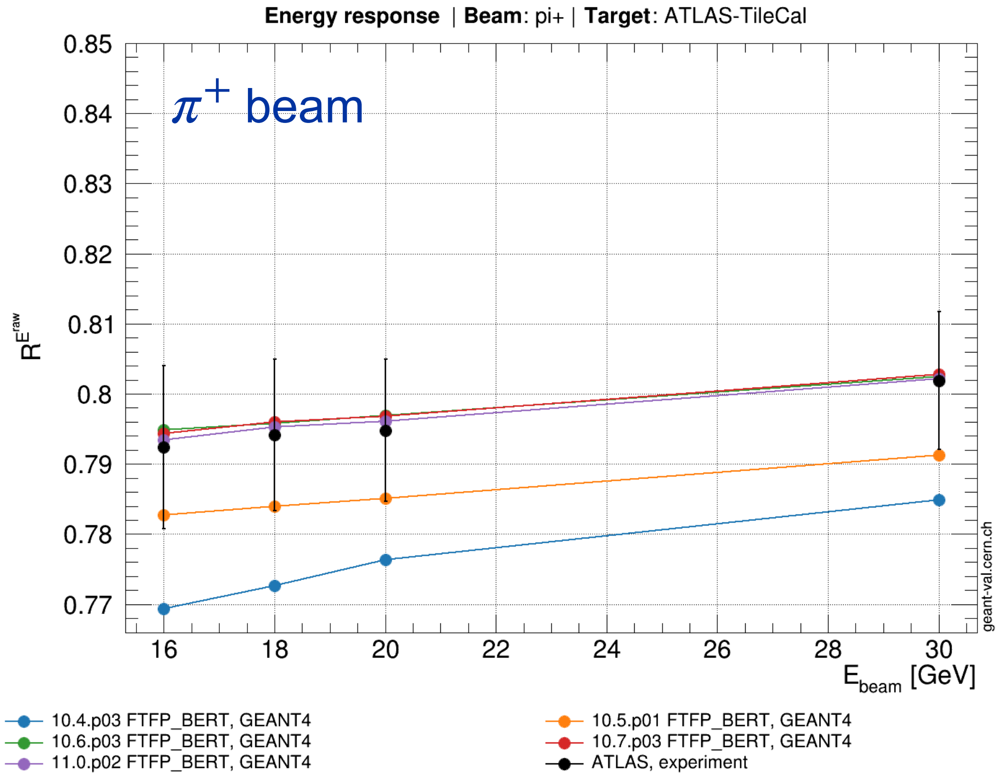
Calibration and energy reconstruction

- Hadron energies are obtained exploiting a single calibration constant at the electromagnetic scale, *i.e.* with e^-:
  - $C_{e^-} = <S>/E_{beam}$ → constant value, *i.e.* TileCal is linear for e^- detection
  - $E^{raw} = S/C_{e^-}$ → underestimating hadron energies, *i.e.* undercompensating calorimeter $h/e < 1$
- Geant4 validated over the hadronic energy response and resolution:
  - $R^{E^{raw}} = <E^{raw}>/E_{beam}$ → energy response normalized to incident beam energy
  - $R^{\sigma^{raw}} = \sigma^{E^{raw}}/E_{beam}$ → energy resolution normalized to incident beam energy



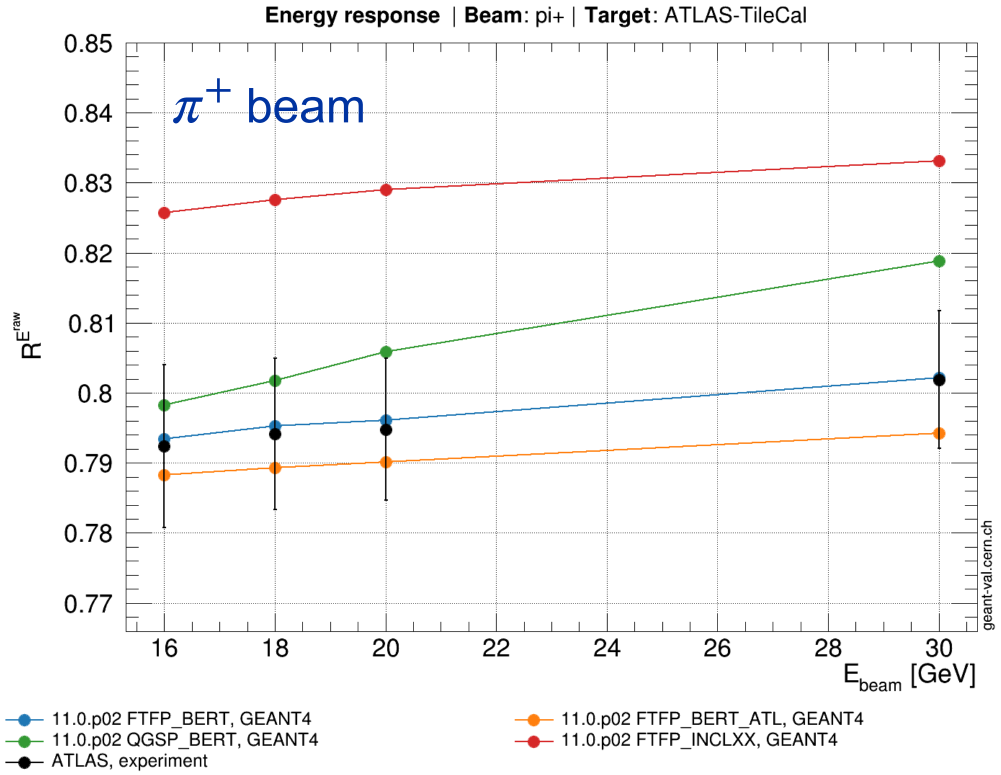
Hadronic response - FTFP_BERT (2017-2021)

- FTFP_BERT regression testing:
  - Hadronic response properly described by FTFP_BERT for G4 10.6, 10.7, 11.0
  - Constant increase in the hadronic response (π/e) observed from G4 10.4 to 10.5 to 10.6.



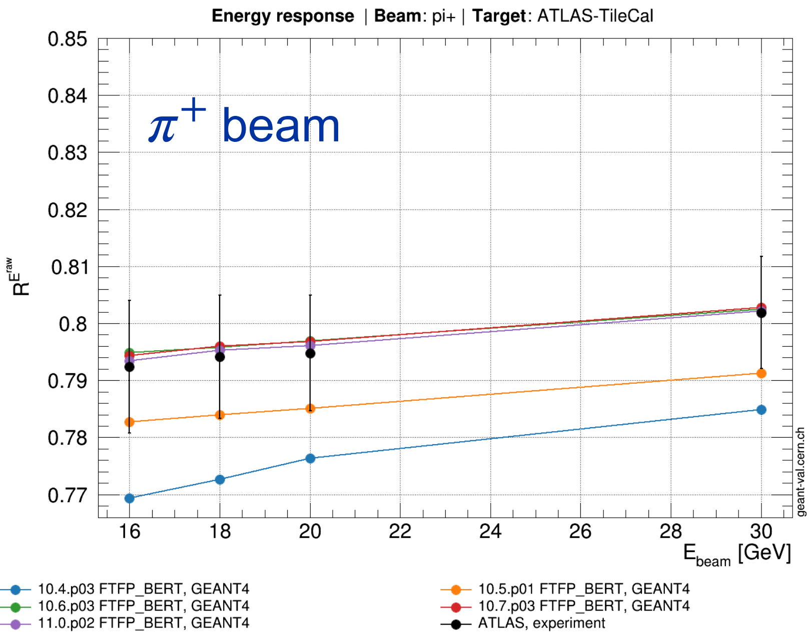
Hadronic response - G4 11.0 PL comparison

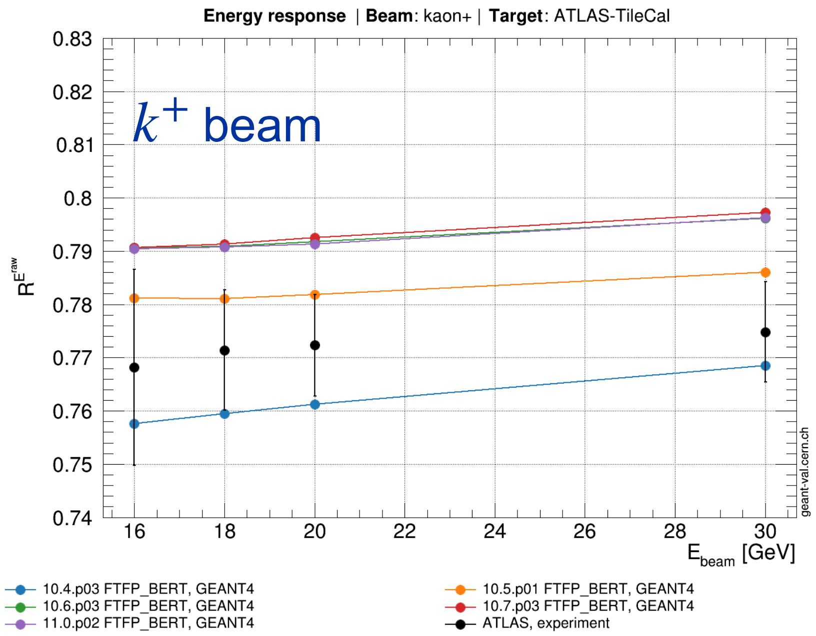
- FTFP_BERT regression testing:
  - Hadronic response properly described by FTFP_BERT for G4 10.6, 10.7, 11.0
  - Constant increase in the hadronic response (π/e) observed from G4 10.4 to 10.5 to 10.6.
- G4 11.0 PL comparison:
  - Current description is in good agreement with data for FTFP_BERT and FTFP_BERT_ATL.
  - FTFP_INCLXX producing shower responses $\simeq 5\,\%$ higher than the experimental reference.

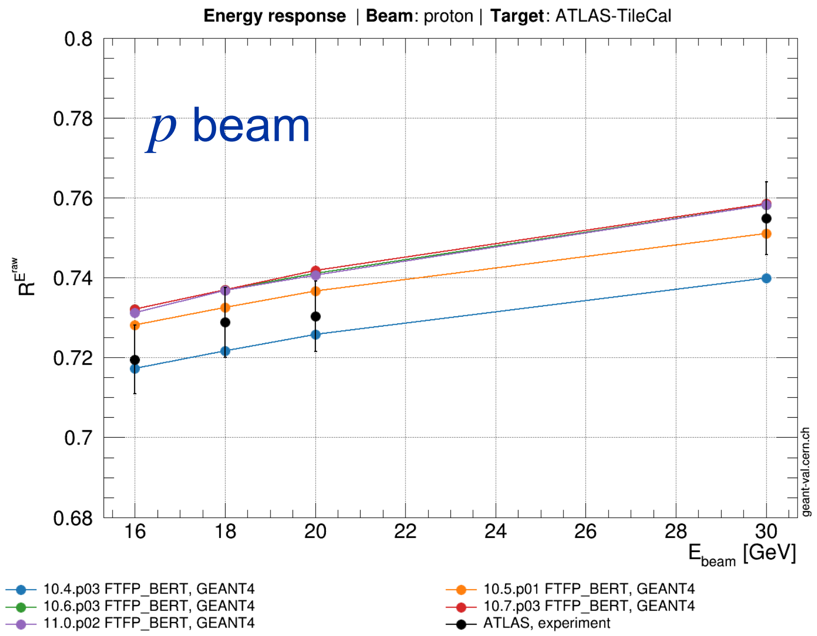


Hadronic response - π^+, k^+, p

- Excellent work by ATLAS to disentangle contributions from π^+, k^+ and p thanks to the Cherenkov counters:
  - Visible difference in the response to p and π^+: (my opinion) it is due to the baryon number conservation law for which high f_{em} processes (*e.g.* $\pi^+ + n \rightarrow \pi^0 + p$) are prohibited for p-induced events.
  - Overall good description from FTFP_BERT of these effects.

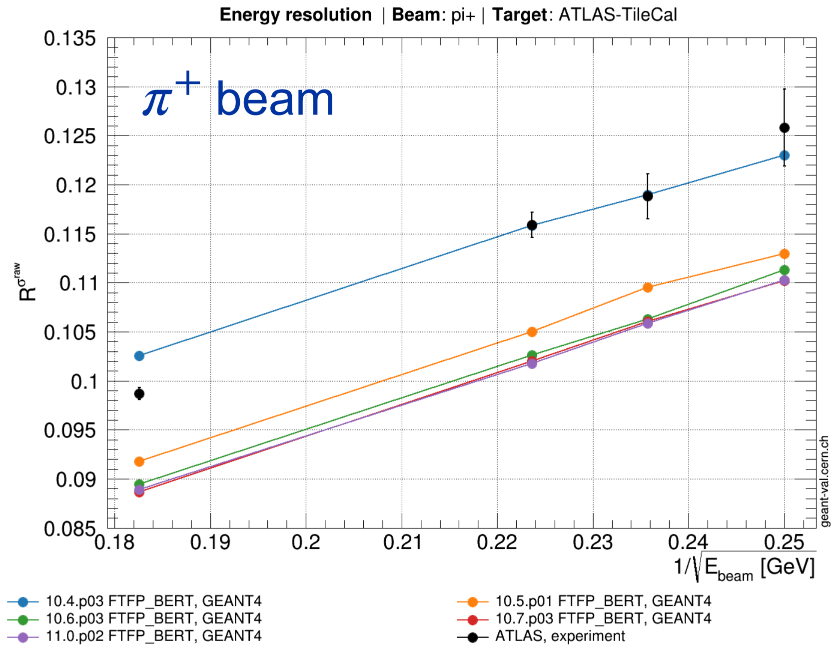






Hadronic (π^+) resolution - FTFP_BERT (2017-2021)

- ATLAS TileCal:
  - FTFP_BERT regression testing for the π^+ response fluctuations shows good agreement with data for G4 10.4.
  - We observe a constant reduction of the response fluctuations from 10.4 to 10.5 to 10.6.
    Currently FTFP_BERT is $\simeq 20\,\%$ off w.r.t. ATLAS.



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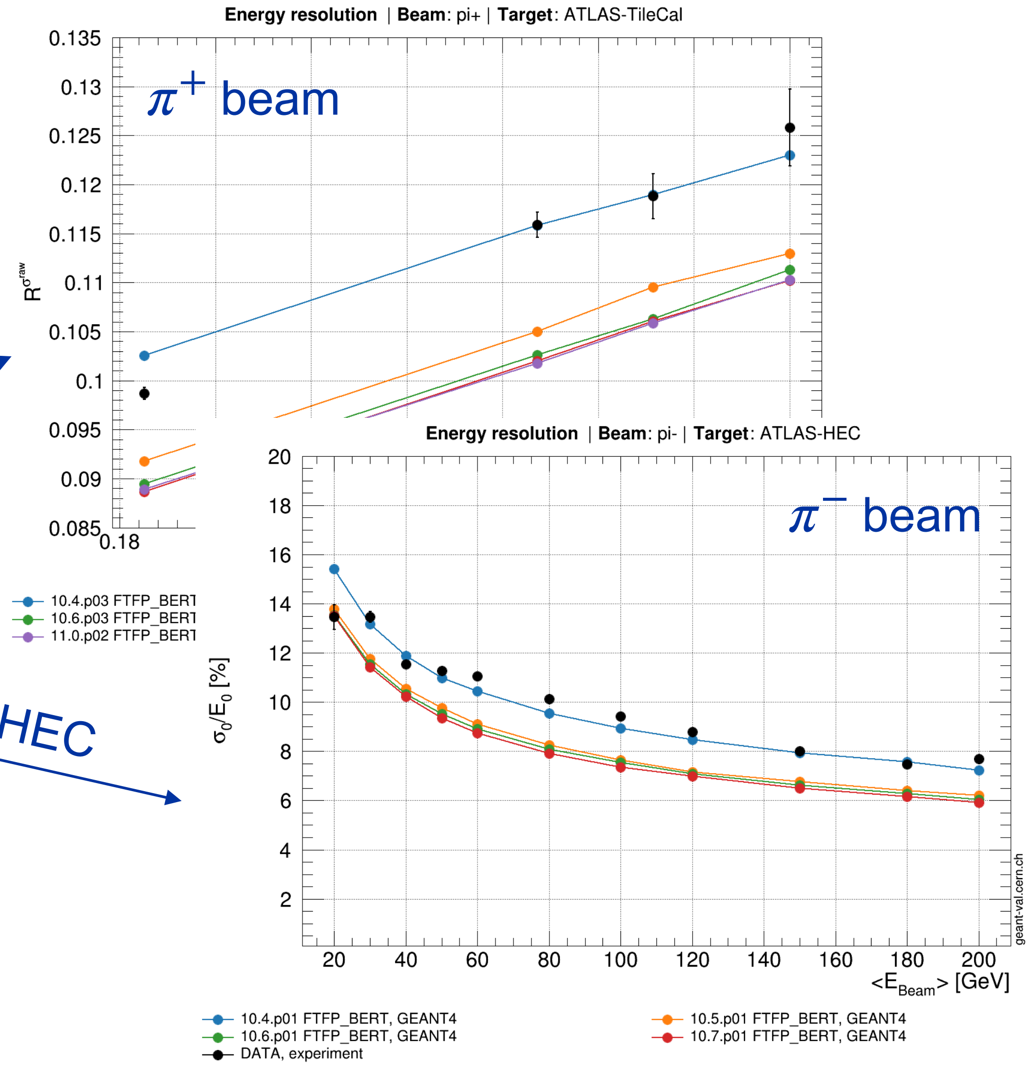
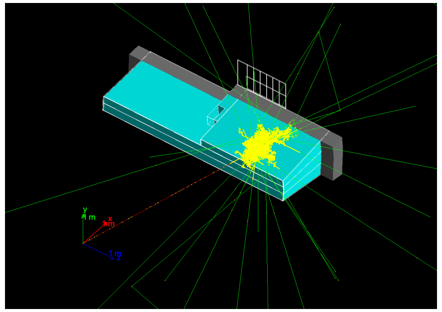
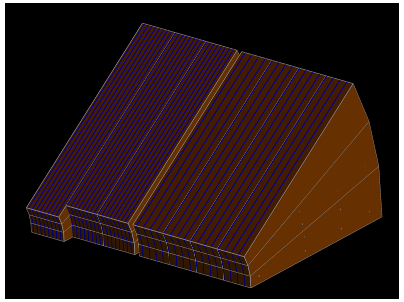
  - FTFP_BERT regression testing for the π^+ response fluctuations shows good agreement with data for G4 10.4.
  - We observe a constant reduction of the response fluctuations from 10.4 to 10.5 to 10.6. Currently FTFP_BERT is $\simeq 20\,\%$ off w.r.t. ATLAS.
- ATLAS HEC:
  - Previous Geant4 validation study on the ATLAS HEC shows the same pattern w.r.t. ATLAS.

TIleCal

HEC



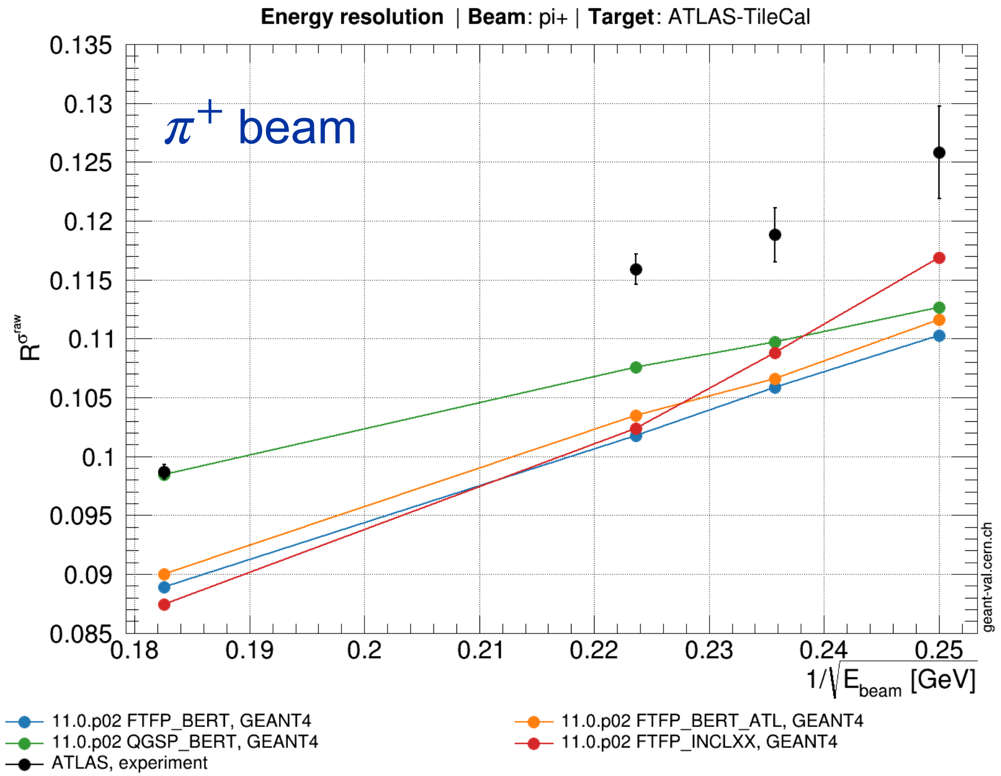




Hadronic (π^+) resolution - G4 11.0 PL comparison

- QGSP_BERT currently leading to response fluctuations $\simeq 5\,\%$ broader w.r.t. FTFP_BERT in the energy range 16-20 GeV and $\simeq 10\,\%$ around 30 GeV.
- Negligible differences observed between FTFP_BERT and FTFP_BERT_ATL.
- FTFP_INCLXX compatible with FTFP_BERT in the 20-30 GeV energy range while systematically broader in the 16-18 GeV energy range (with a non-linear scaling w.r.t. $1/\sqrt{(E)}$).

G4 10.4 using FTFP_BERT is the only configuration for which π^+ response fluctuations are properly reproduced.



Conclusions and next steps

- Conclusions:
  - We developed a new Geant4 based simulation of the 2017 ATLAS TileCal test-beam.
  - It features all the main ingredients for a realistic simulation (RO cell description, Birks' Law, U-shape correction, PMT emulation and energy calibration) without any ATHENA dependency.
  - Tested with $\simeq 100 \times 10^6$ events using HTCondor+Geant-Val with no crashes and no warnings.
  - Currently Geant4 can reproduce π/e results with great accuracy but investigations are needed for a better description of the response fluctuations (similarly to what found with the HEC study).
- Next steps:
  - We will shows this study to a ATLAS Simulation Meeting in September and discuss with TileCal expert about improvements and results.
  - Discussion ongoing with TIleCal experts to extend this validation with the upcoming test-beam in November 2022 (*e.g.* higher energies and longitudinal shapes measurements).