Testing ATLAS calorimeters with Geant4 and FLUKA.CERN

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GEANT4 A SIMULATION TOOLKIT

CERN

Outline

In the last two years we developed and ported to geant-val, the Geant4 validation and testing suite, the test-beam simulations of the ATLAS hadronic calorimeters (HEC & TileCal).

- The standalone simulations were found to be (almost always) in good agreement with ATLAS experimental data and in excellent agreement with the ATLAS simulation. They were described in several talks and are not repeated here. See, for instance:
  - ATLAS HEC: Regression testing and physics list comparison with ATLHECTB
  - ATLAS TileCal: Standalone Geant4 validation on the ATLAS Tile Calorimeter beam test

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  - Compare the Geant4 performance with the new Geant4-to-FLUKA.CERN interface
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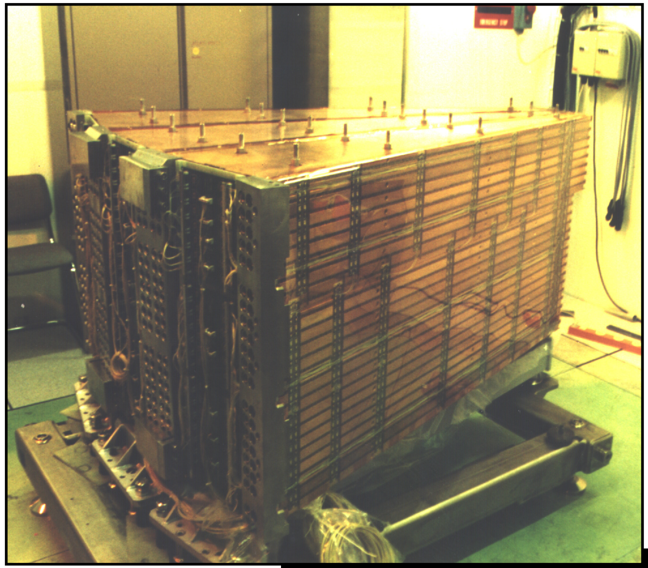
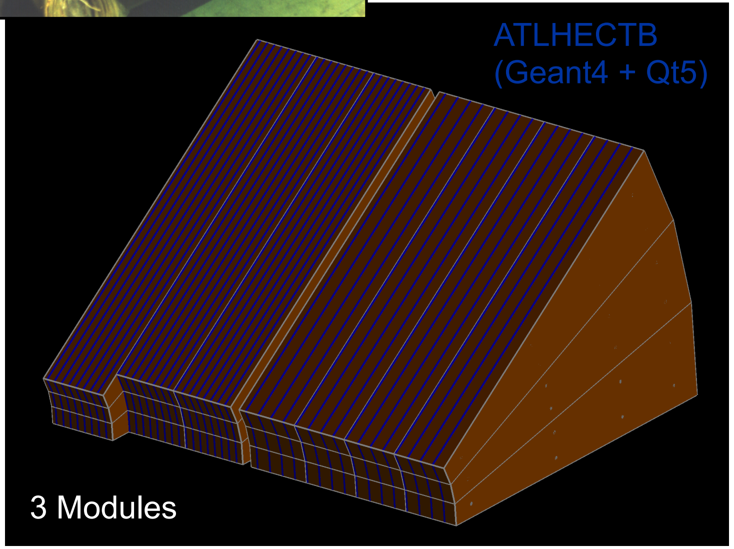
  - Compare the Geant4 performance with the new Geant4-to-FLUKA.CERN interface
  - Show how to correct Geant4 for its largest discrepancy with ATLAS data
- Recently, we ported to geant-val a standalone simulation of the ATLAS LArBarrel calorimeter.
  It will be used for fine tuning of Geant4 EM models and speed-up solution, therefore it is not discussed today.

Recap: ATLAS HEC

- The ATLAS HEC covers the range $1.5 < |\eta| < 3.2$
- Divided into two wheels (HEC1-2) each consisting of 32 azimuthal modules.
- It uses 8.5-mm-gap LAr sampling regions inserted between parallel copper plates, with 2.5 cm (HEC1) and 5.0 cm (HEC2) thickness.
- It has four longitudinal layers with a thickness of $\simeq 103 X_0$ or $\simeq 9.7 \lambda_{int}$.
- Beam-tests:
  - Tested in 2000-2001 at CERN-SPS-H6 beam line (ATL-LARG-PUB-2022-001)
  - Tests performed with 3 $\phi-$wedges
  - Involving e^-, μ^- and hadrons with $6 \leq E_{Beam} \leq 200$ GeV

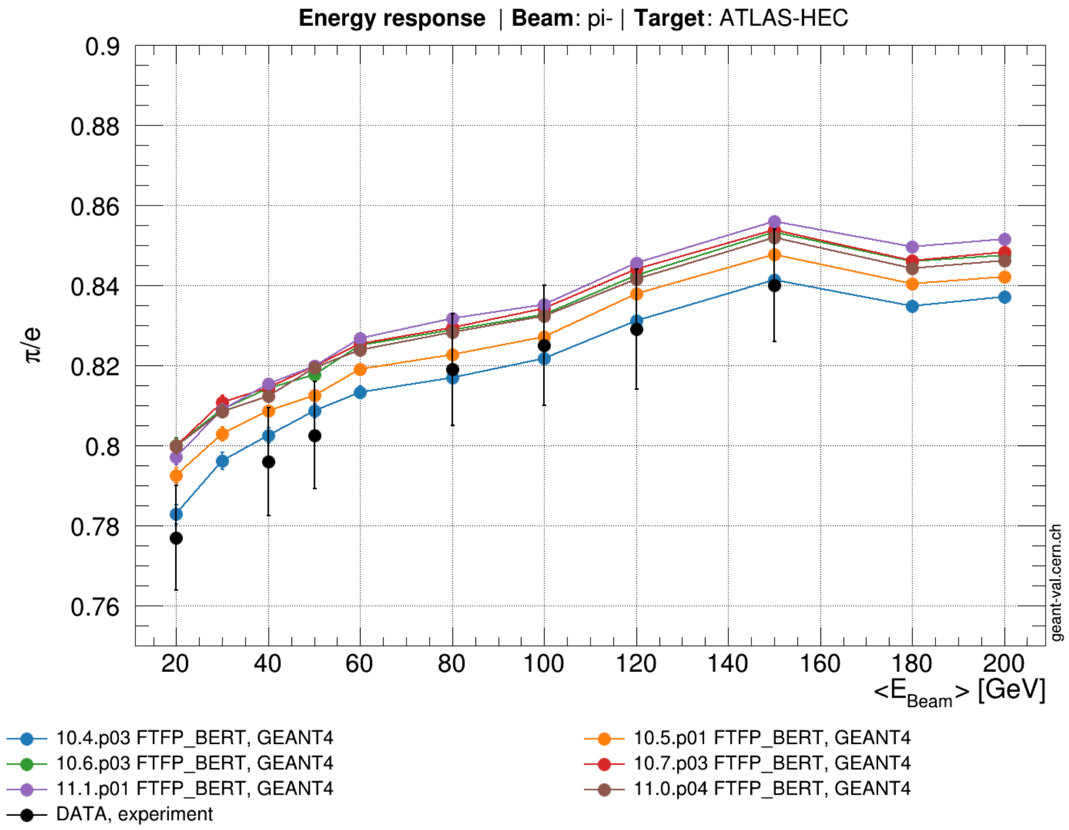
ATL-PHO-LARG-2001-013





Recap: ATLAS HEC response

- π/e extracted as the average π^- reconstructed energy, using the calibration at the electromagnetic scale, divided by the average value for same energy e^- beams.
- Today focusing only on the FTFP_BERT PL, all results with other PLs are available at geant-val.cern.ch (not relevant for this talk).
- Results obtained with ATLHECTB_2.5 (data tag 2.5_2).
  - **FTFP_BERT** regression testing:
    - Increase in π observed from Geant4.10.4 (2017) to Geant4.10.6 (2019), driven by inputs from thin target results.
    - FTFP_BERT currently overestimates π/e of $\simeq 2\% - 3\,\%$.

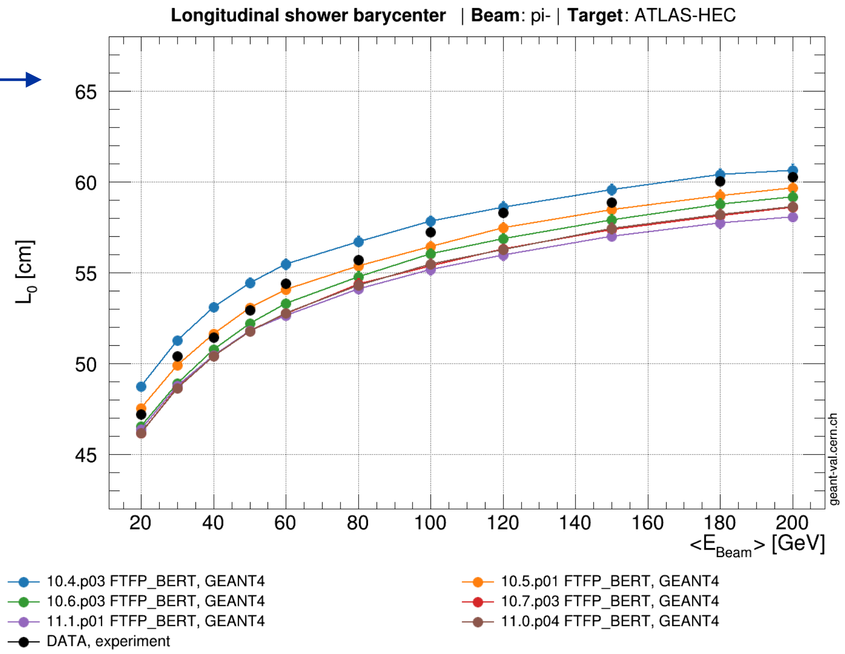


Recap: ATLAS HEC hadronic shower shape

- The ATLAS HEC is made of 4 longitudinal layers.
- It is possible to measure the energy profile as the energy fraction deposited in each layer: $F_i = < E_i > / E_{sum}, E_{sum} = \Sigma < E_i >$
- and the F_i dependence over E_{Beam}.
- Average shower depth:
  - Extracted as the mean (L_0) of the energy profile, as a function of E_{Beam}.
  - Barycenter shortened from 10.4 (2017) to 10.7 (2020). Currently underestimating ATLAS data by $\simeq 2 - 3\,\%$.

HEC longitudinal structure

HEC layer	Number of LAr gaps	HEC length [cm]	HEC length [λ_{int}]
1	8	28.05	1.45
2	16	53.60	2.75
3	8	53.35	2.87
4	8	46.80	2.66



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- and the F_i dependence over E_{Beam}.
- Average shower length:
  - Extracted as the RMS (σ_L) of the energy profile.
  - Currently G4 showers are $\simeq 1\,\%$ shorter than the ATLAS ones.

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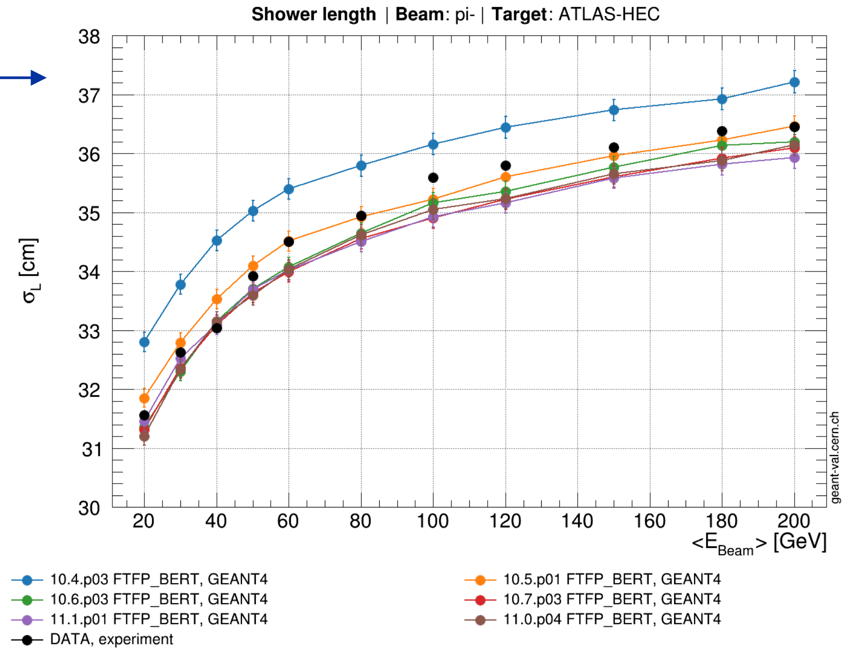
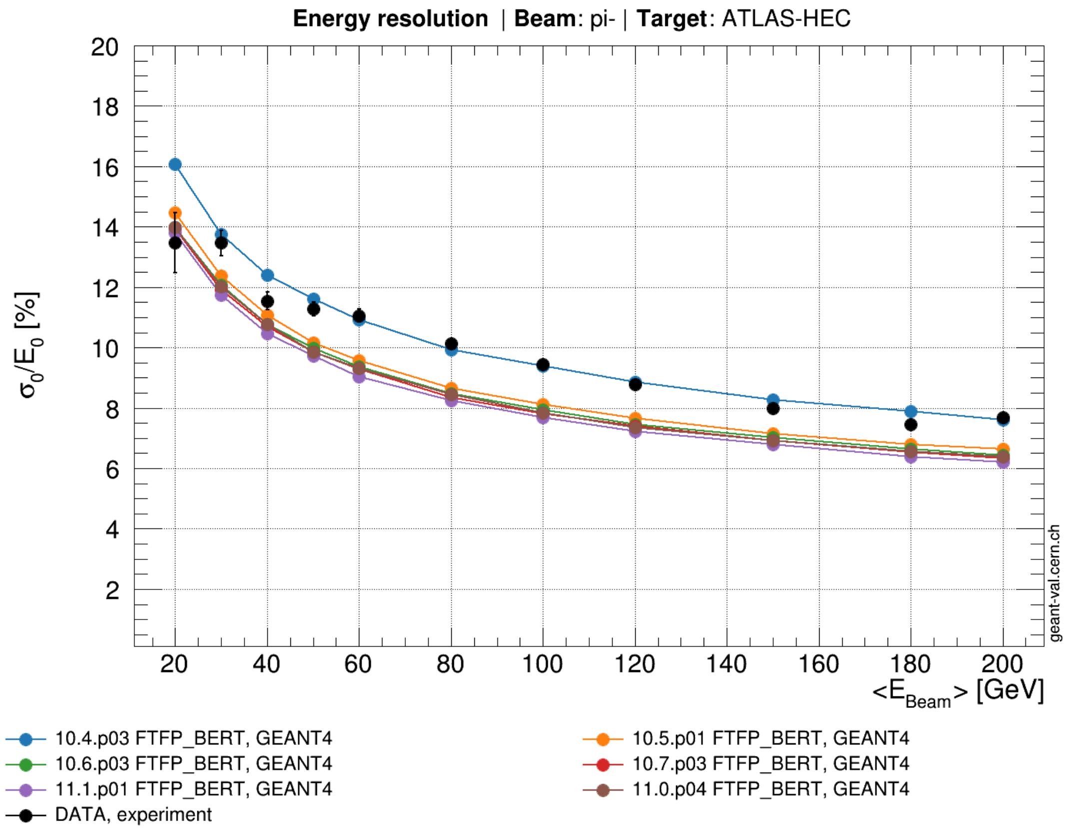


Recap: ATLAS HEC energy resolution

- σ/e extracted as the ratio of parameters taken from a gaussian fit to energy distributions.
  - **FTFP_BERT** regression testing:
    - Geant4.10.4 (2017) was found to be in good agreement with ATLAS data.
    - A big drop in the hadronic signals fluctuations happened between Geant4 10.4 and 10.5 (2018). Stable since then.



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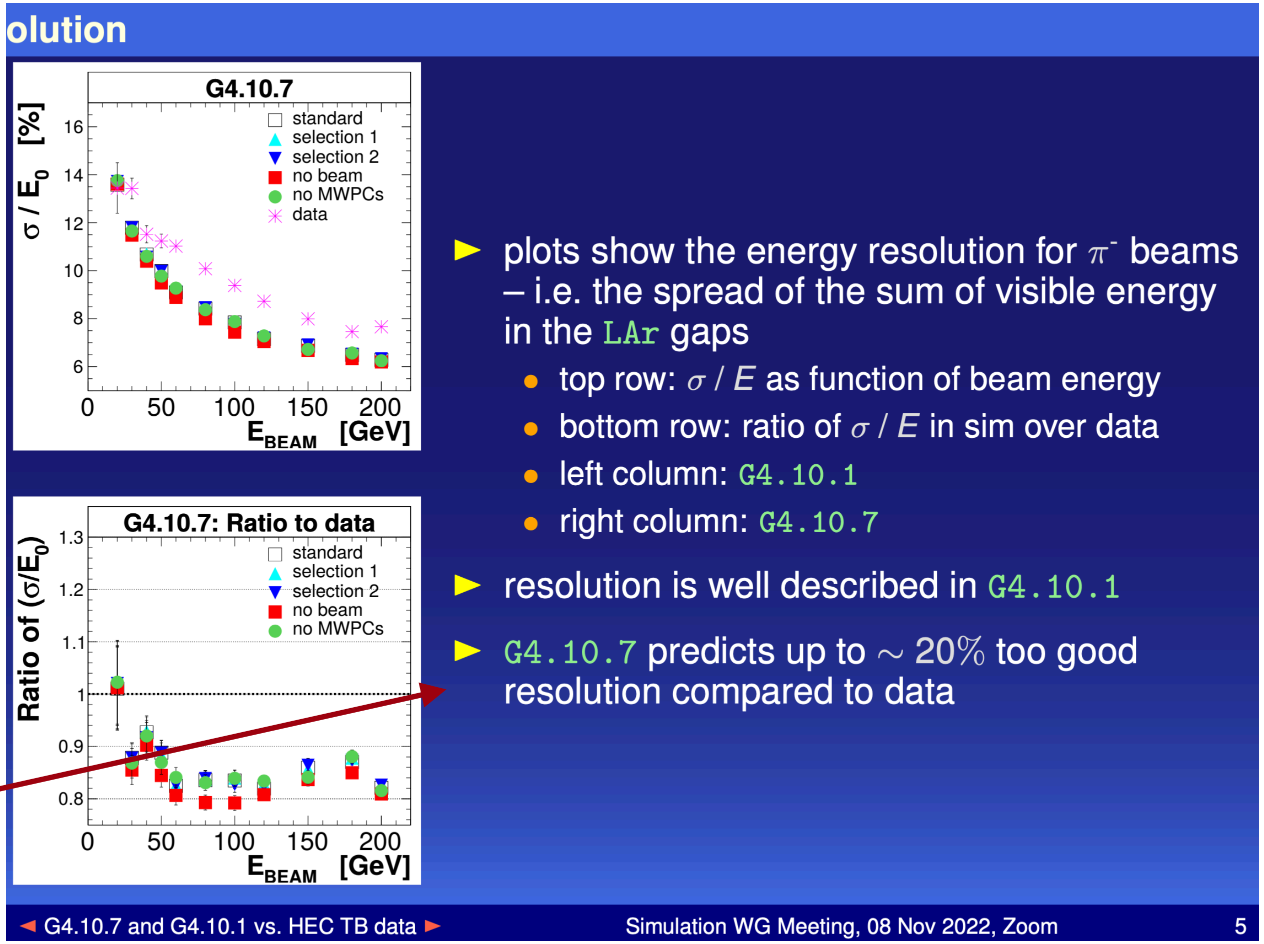
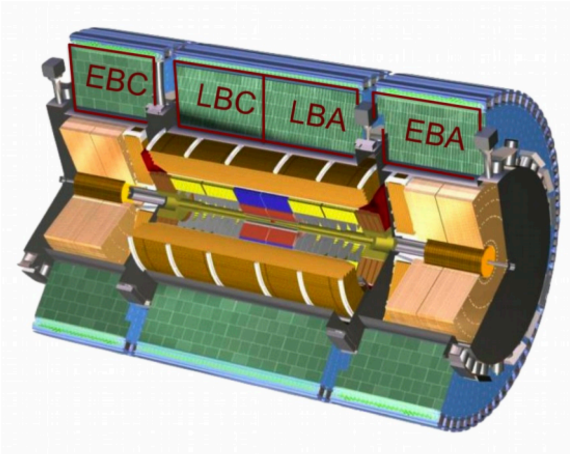
- A little history about this problem:
  - Reported to ATLAS by G4 for the first time on 6/6/2021 (hec-slides) and again on 20/9/2022 (tilecal-slides)
  - Confirmed by ATLAS (HEC Group) on 8/11/2022 (slides)

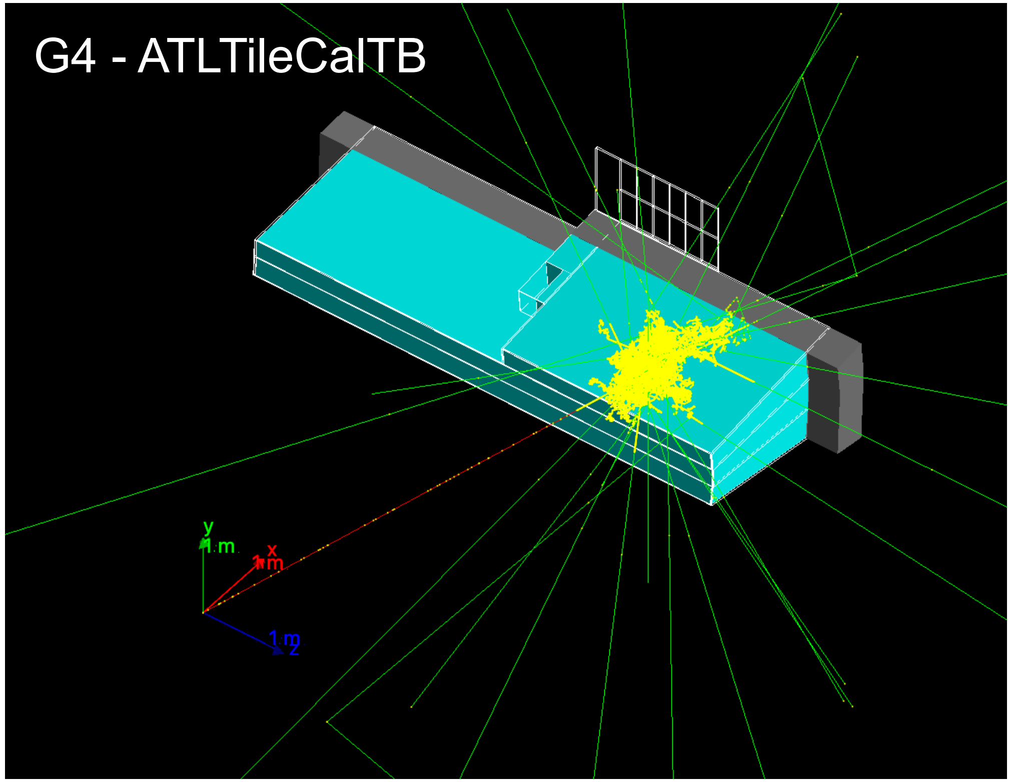
From ATLAS talk



Recap: ATLAS TileCal

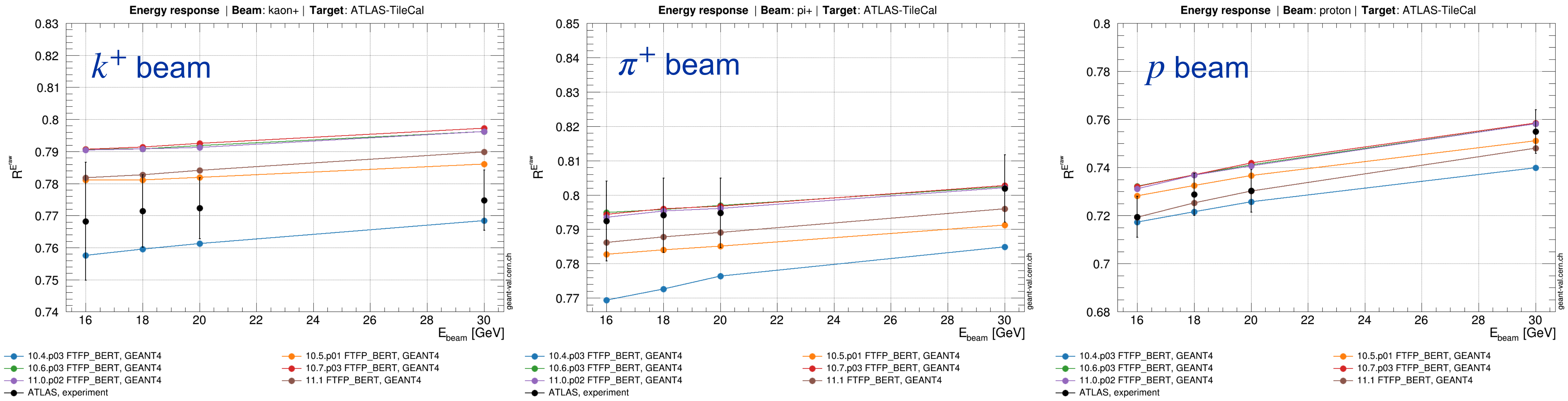


- Mostly used to reconstruct hadronic jets in the range $|\eta| < 1.7$ thanks to 3 cylinders containing 64 modules each.
- Measures light in scintillating tiles brought to PMTs by WLS fibers. Readout is grouped in pseudo projective cells with each layer readout by two PMTs.
- 2 Long Barrel Modules and 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 (Eur. Phys. J. C (2021) 81:549)
- Cherenkov auxiliaries used to tag π^+, p and k^+.
- In the following only the FTFP_BERT PL is considered, results for other PLs available on geant-val.cern.ch
- Results as on geant-val on August 2023, i.e. ATLTileCalTB v1.0 and v1.1 (data tag 1.0 and 1.1_1).



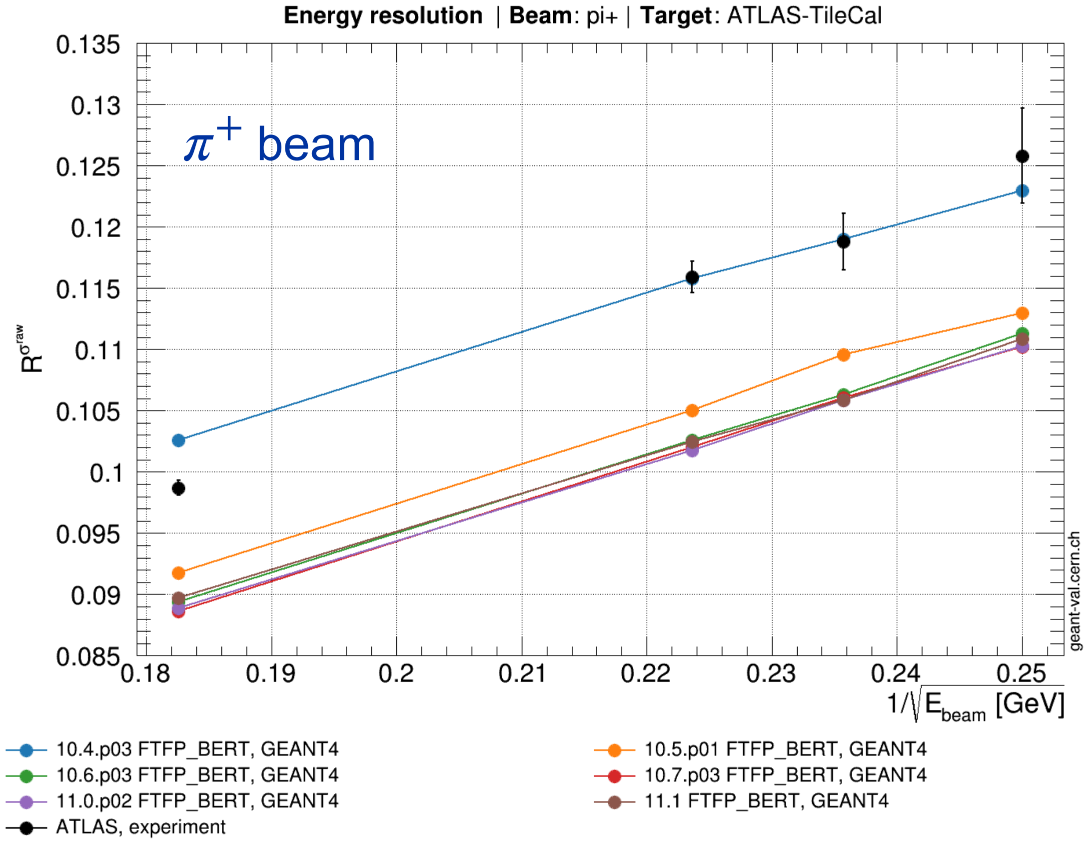
Recap: ATLAS TileCal response

- 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.



Recap: ATLAS TileCal energy resolution

- Pion data:
  - FTFP_BERT regression testing for the π^+ response fluctuations shows good agreement with data for G4 10.4 (2017).
  - We observe a constant reduction of the response fluctuations from 10.4 to 10.5 to 10.6. Currently FTFP_BERT is $\simeq 15\% - 20\,\%$ off w.r.t. ATLAS. Similarly to the HEC case.



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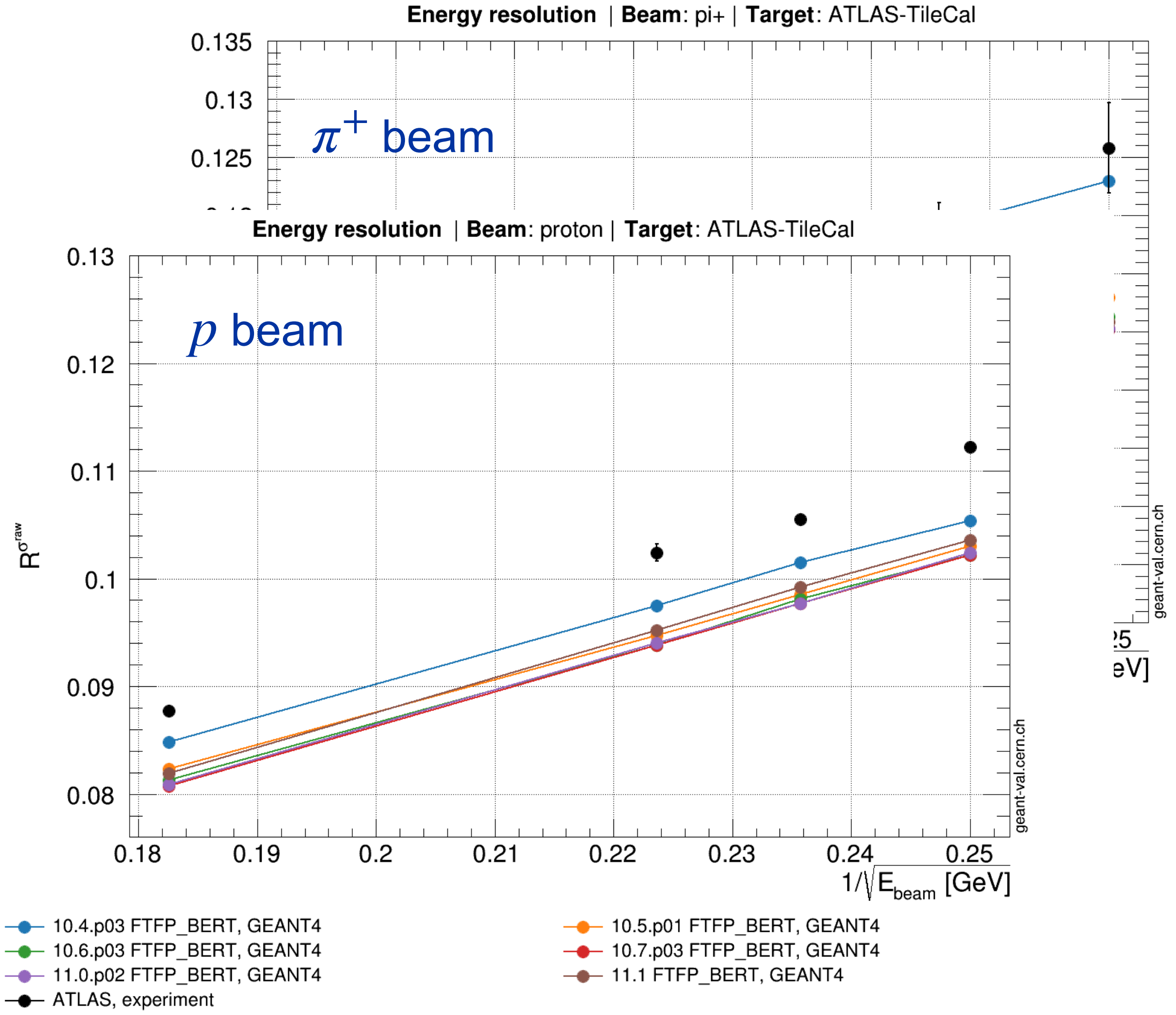
- Proton data:
  - FTFP_BERT regression testing on p data indicates a better agreement with a reduction of the response fluctuations from 10.4 to 10.5 of $\simeq 4\,\%$ and the current agreement is $\simeq 6\,\%$ off w.r.t. ATLAS.



Fixing the problem

These investigations indicate that recent Geant4 releases predicts hadronic showers in ATLAS calorimeters with too narrow signal fluctuations.

Our approach to further study the problem was twofold:

Customize the FTFP_BERT Physics List with the (very new) Geant4-to-FLUKA.CERN interface included in Geant4-11.1.ref05 by Gabrielle Hugo.

Study the ATLAS simulation when the Hadron Inelastic Process is modeled by FLUKA.CERN.

Customize the FTF model parameters in order to adjust the large discrepancy in the hadronic signal fluctuations.

Provide this new configuration to ATLAS as a new FTF tune selectable via UI.

Geant4/FLUKA.CERN comparison

Results in the following obtained with Geant4-11.1.ref05 and FLUKA4-3.3.
Tests releases are ATLHECTB-2.6 (data tag 2.6_1) and ATLTileCalTB-1.2 (data tag 1.2_1).

The FLUKA.CERN interface

- Our steps (see documentation) for a customized FTFP_BERT Physics Lists that uses the FLUKA.CERN Hadron Inelastic model:
  - Register to the FLUKA.CERN website with CERN credentials and accept the LICENSE
  - Download the Fluka4-3.3 source code and install (used gfortan compiler from gcc10.1.0)
  - Compile the FLUKA.CERN interface
  - Build our tests with CMake option -DG4_USE_FLUKA=1, it adds a compiler definition -DG4_USE_FLUKA
  - Run the simulation in single-threaded mode

- Added a new FTFP_BERT Physics List that replaces the G4HadronPhysicsFTFP_BERT constructor with a new one that exploits the FLUKA.CERN interface.

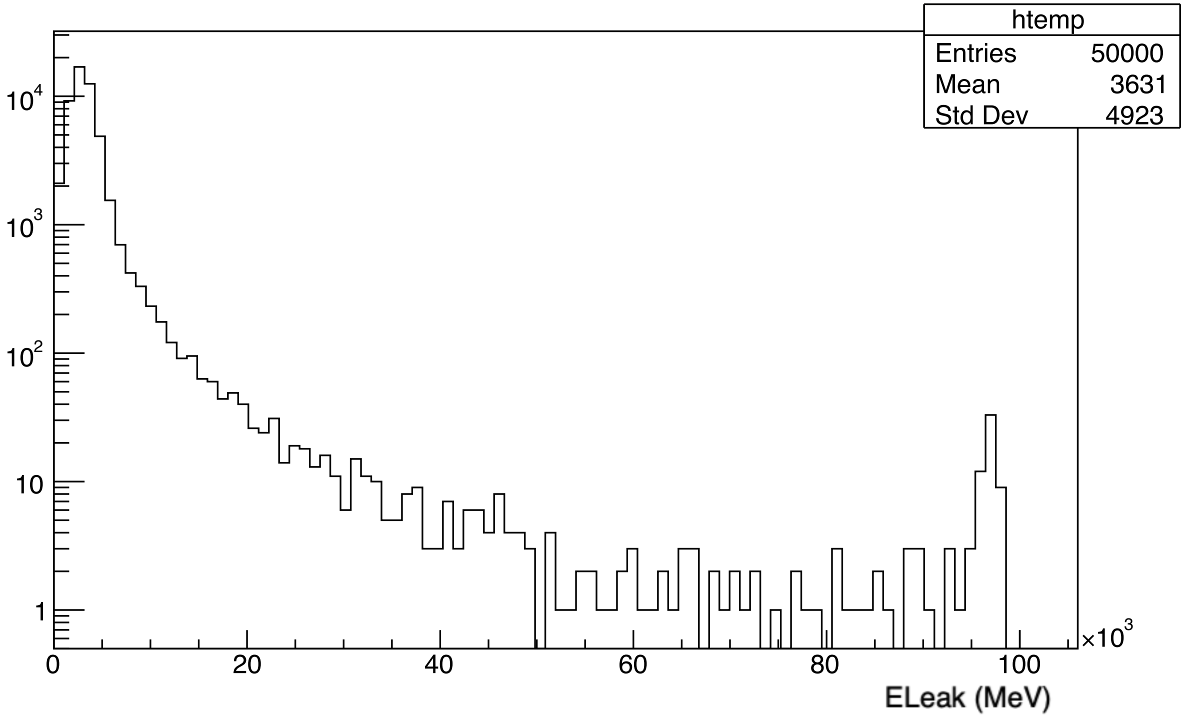
FLUKAHadronInelasticPhysics.cc

```
void FLUKAHadronInelasticPhysics::ConstructProcess() {
  //...

  const auto helper =
          G4PhysicsListHelper::GetPhysicsListHelper();

  // FLUKA hadron - nucleus inelastic XS
  const auto flukaInelasticScatteringXS =
                     new FLUKAInelasticScatteringXS();

  // FLUKA hadron - nucleus model
  const auto flukaModel =
                     new FLUKANuclearInelasticModel();

  // PROTON
  build_G4_process_helpers::buildInelasticProcess(
                                G4Proton::Proton(),
                                helper,
                            flukaInelasticScatteringXS,
                                flukaModel);


  //...
}
```

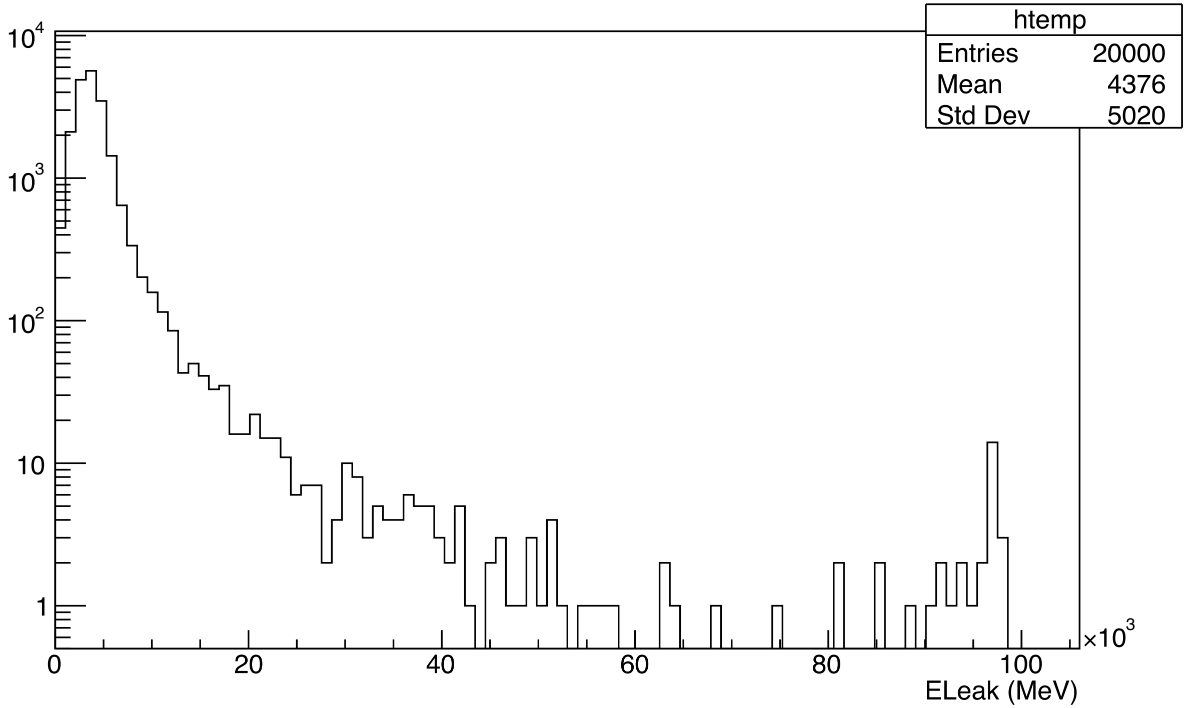
ATLAS HEC G4 *vs.* FLUKA: health checks

- FLUKA predicts an (out-of-world) leakage that is on average $\simeq 20\,\%$ larger than the Geant4 one.
- However, it does not affect heavily the signal distributions → the same data analysis is run over Geant4 and FLUKA data.

100 GeV π^- Geant4 - Out-of-world leakage

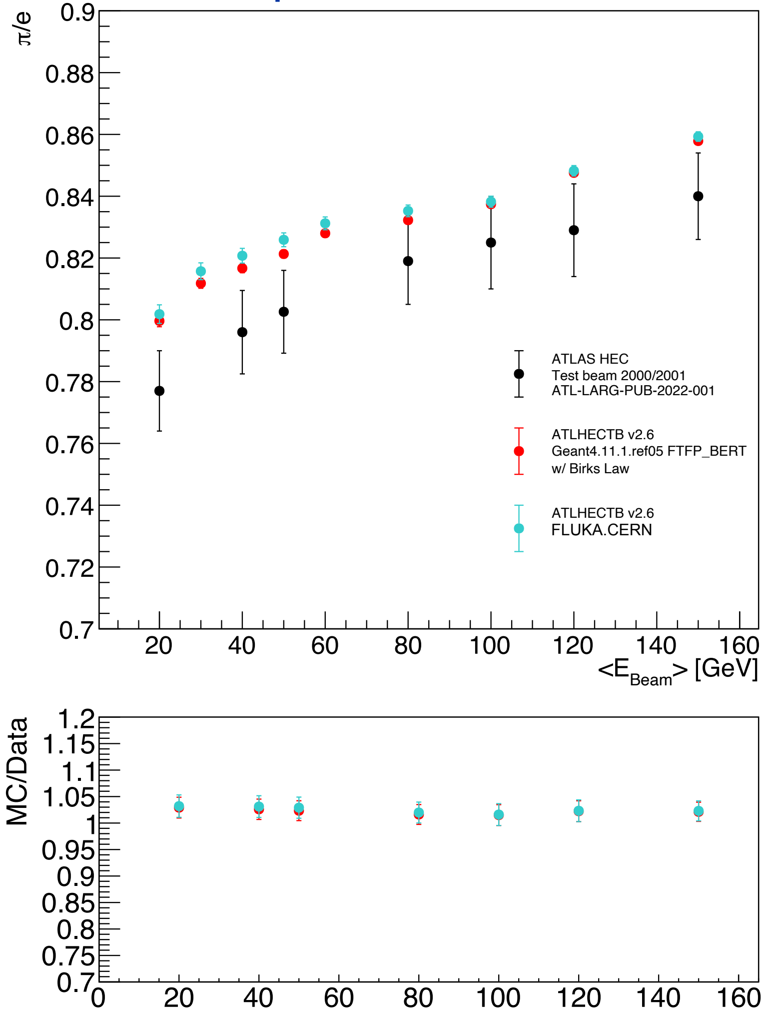


100 GeV π^- FLUKA - Out-of-world leakage

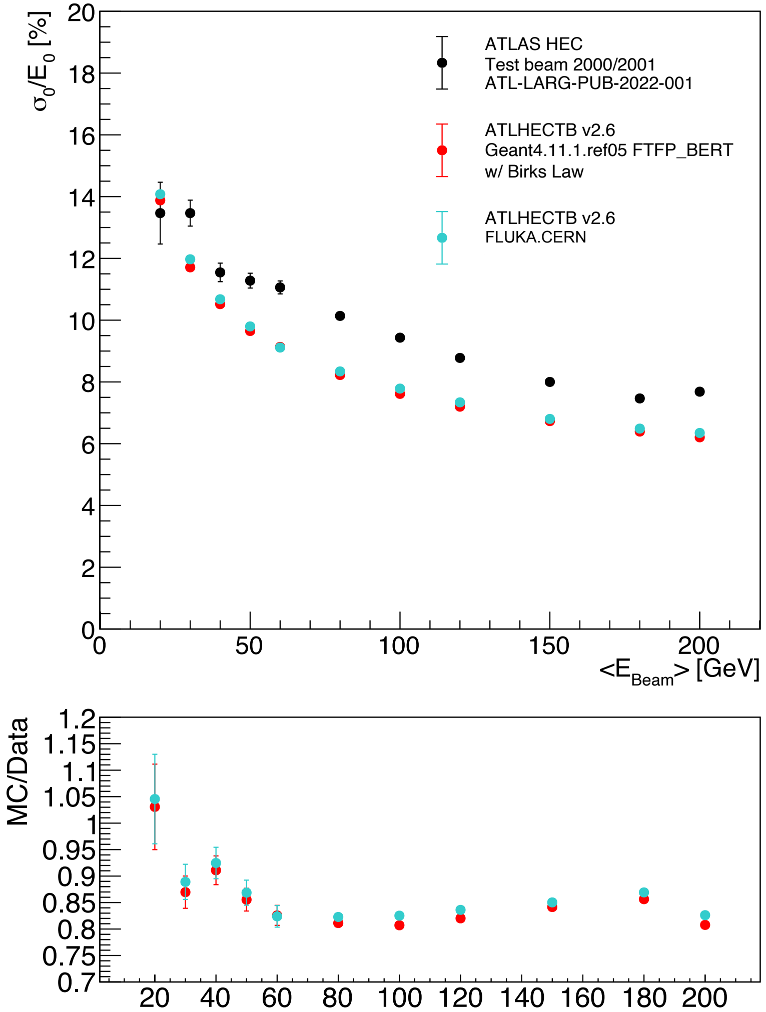


ATLAS HEC G4 *vs.* FLUKA: response and resolution

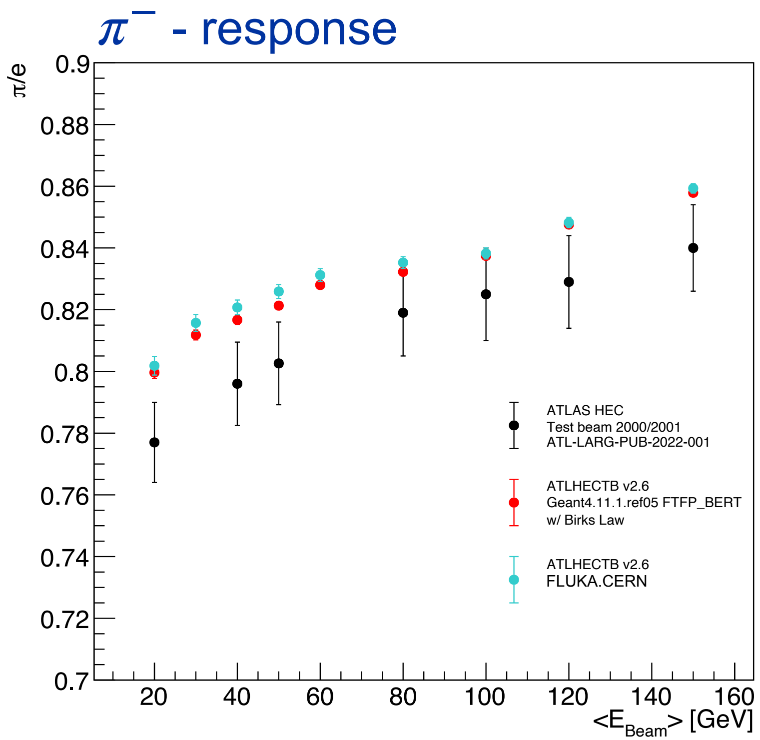
π^- - response

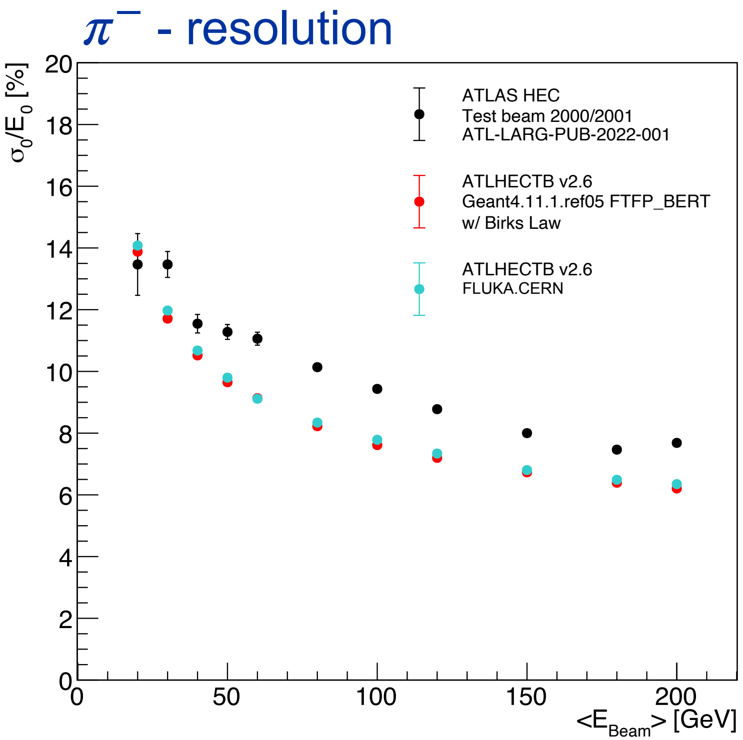


π^- - resolution



ATLAS HEC G4 *vs.* FLUKA: response and resolution

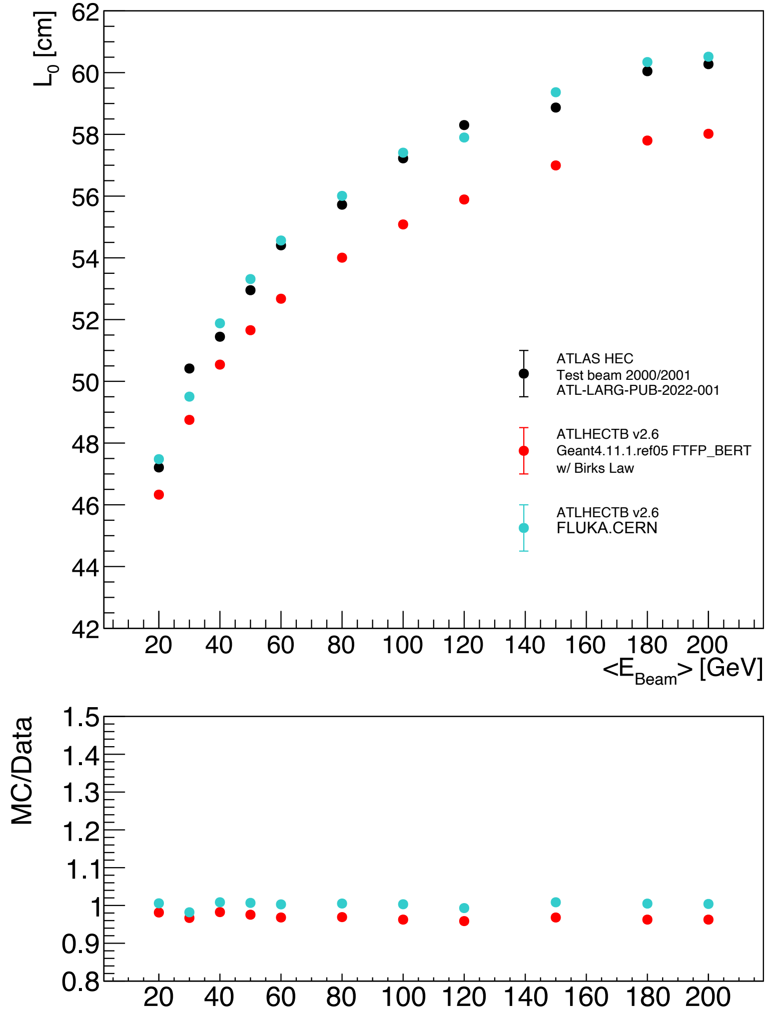




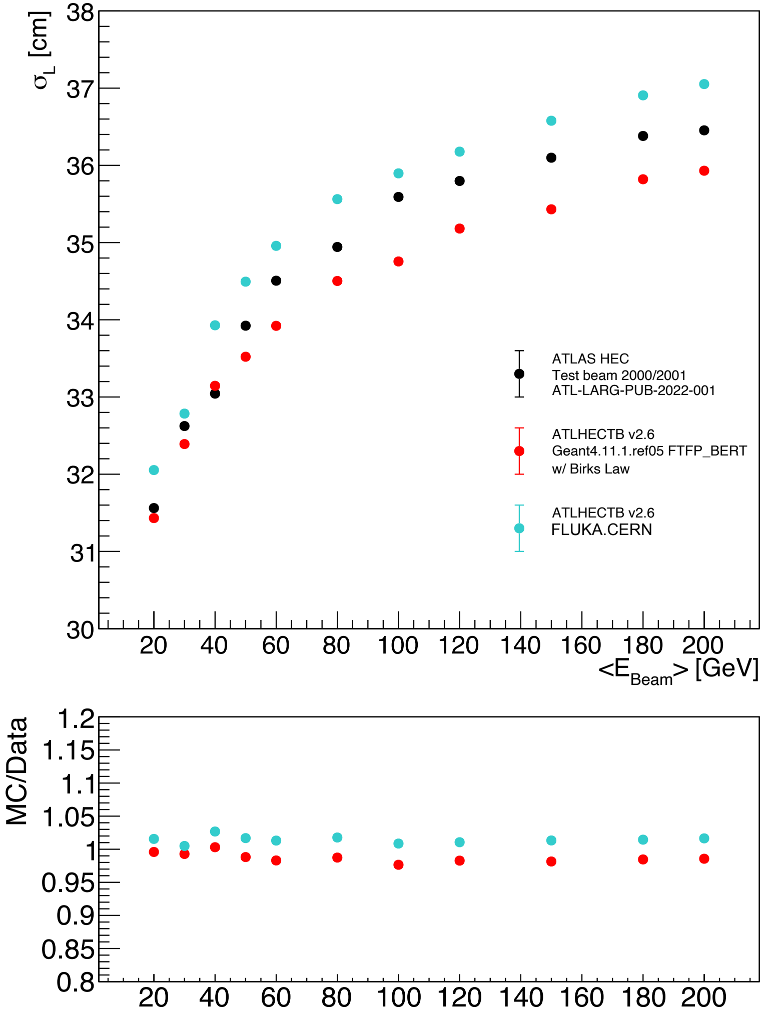
- FLUKA and Geant4 are very close both in (average) response and signal fluctuations (resolution). Currently they both underestimates the HEC resolution by $\simeq 15\% - 20\,\%$.
- The scaling with E_{beam} is in good agreement with the ATLAS one for both Monte Carlos.

ATLAS HEC G4 *vs.* FLUKA: shower shape

π^- - barycenter longitudinal position



π^- - shower length



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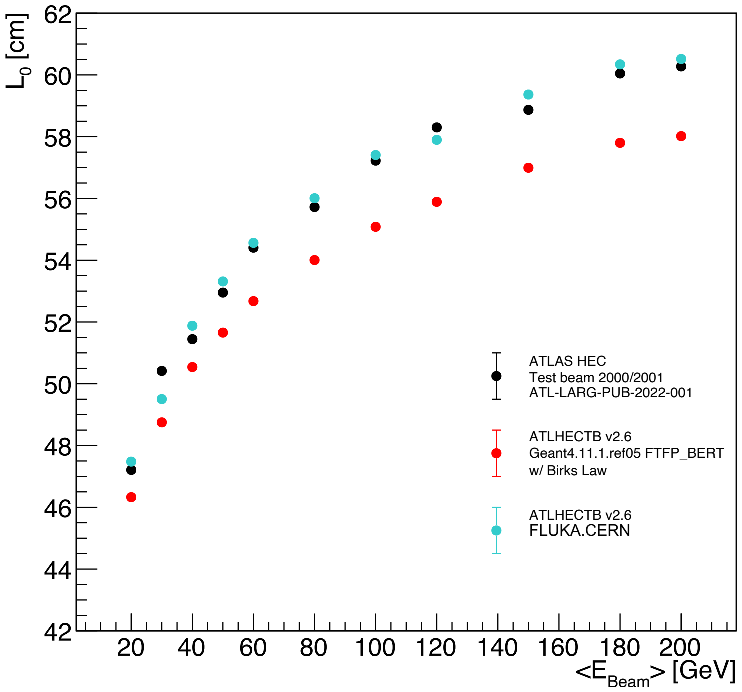
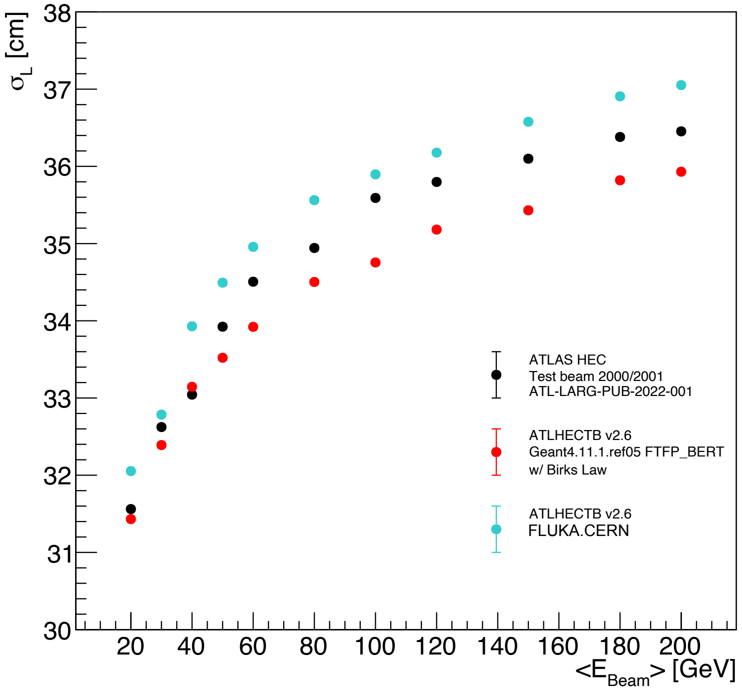


π^- - shower length

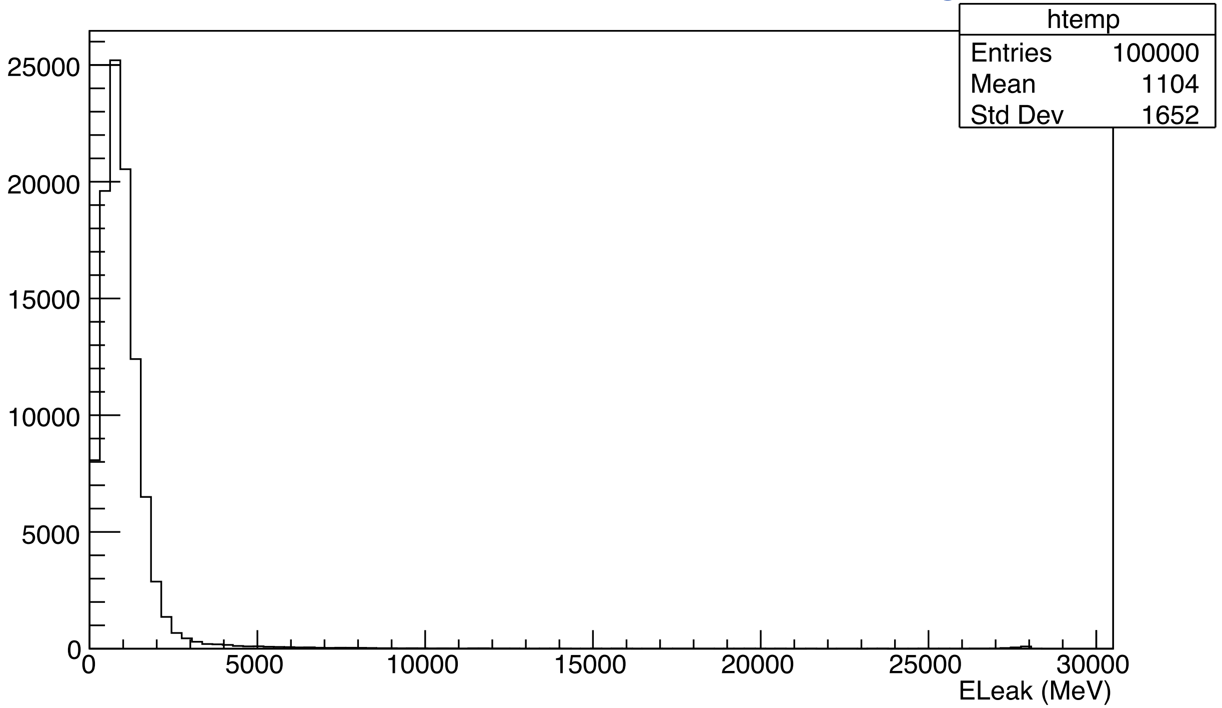


- FLUKA reproduces very well the hadronic shower longitudinal barycenter position. Geant4 is $\simeq 1\% - 3\,\%$ off and its scaling with E_{beam} deviates from the ATLAS one.
- FLUKA overestimates the shower length by $\simeq 1\% - 2\,\%$ while Geant4 underestimates it by $\simeq 1\% - 2\,\%$.

ATLAS TileCal G4 *vs.* FLUKA: health checks

- FLUKA introduces a much larger (out-of-world) leakage average values and event-by-event fluctuations w.r.t. Geant4 (this discrepancy is bigger than the HEC one and it should be studied).

30 GeV π^+ Geant4 - Out-of-world leakage



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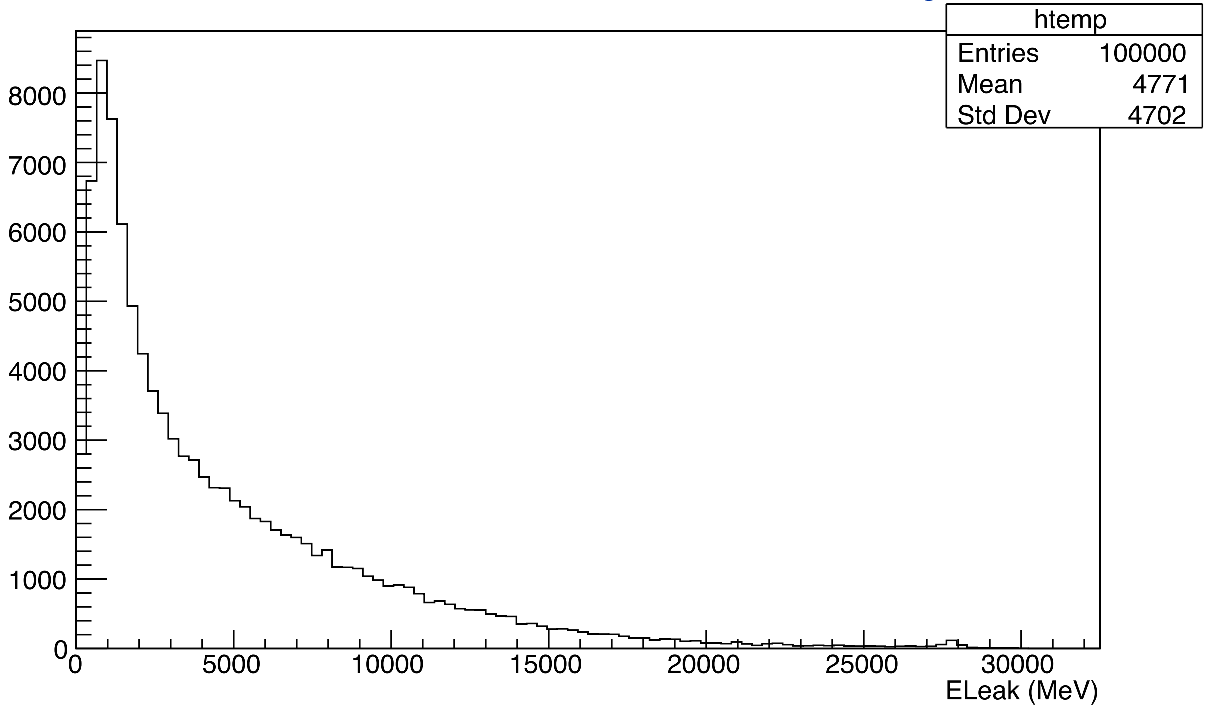
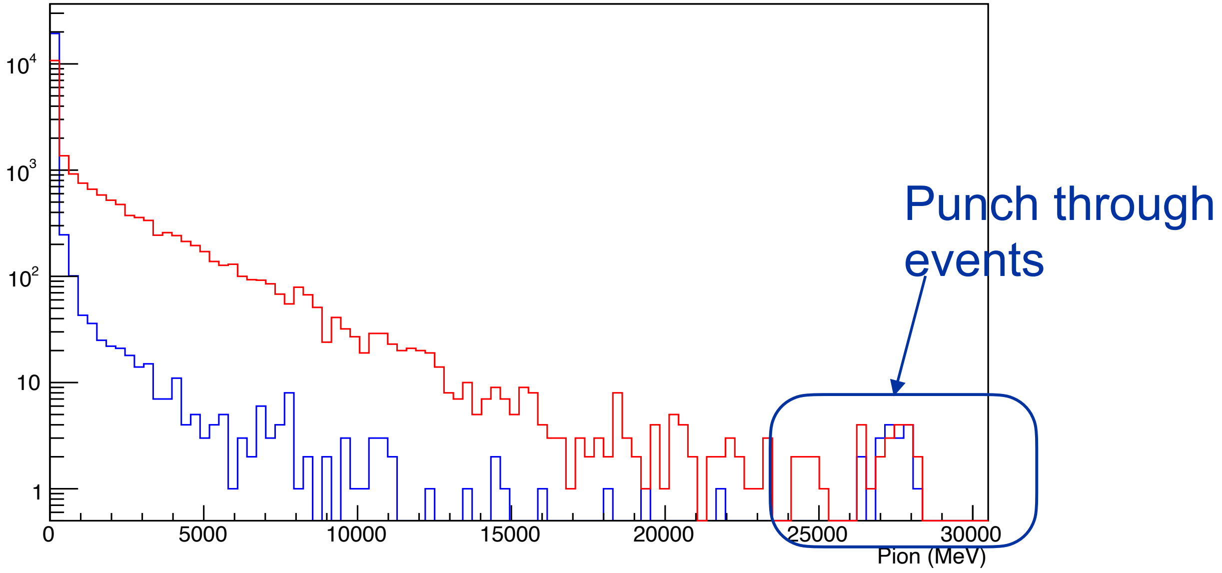


ATLAS TileCal G4 *vs.* FLUKA: health checks

- FLUKA introduces a much larger (out-of-world) leakage average values and event-by-event fluctuations w.r.t. Geant4 (this discrepancy is bigger than the HEC one and it should be studied).
- Preliminary studies on the particles leakage spectrum indicate that for every hadron leakage fluctuations are larger using the FLUKA hadronic model.

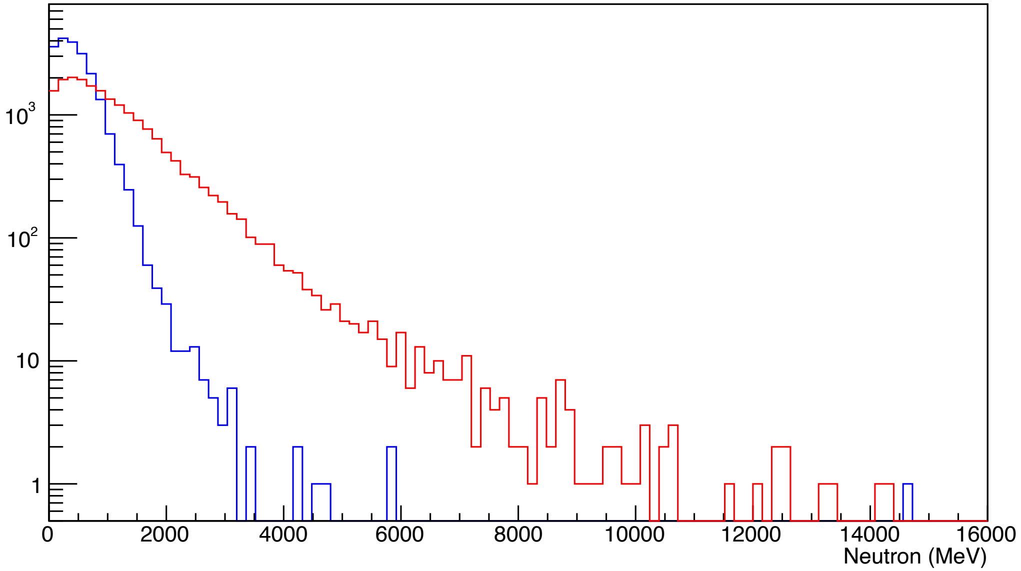
30 GeV π^+: Geant4 vs. FLUKA.CERN

Kinetic Energy of leaking π^+



30 GeV π^+: Geant4 vs. FLUKA.CERN

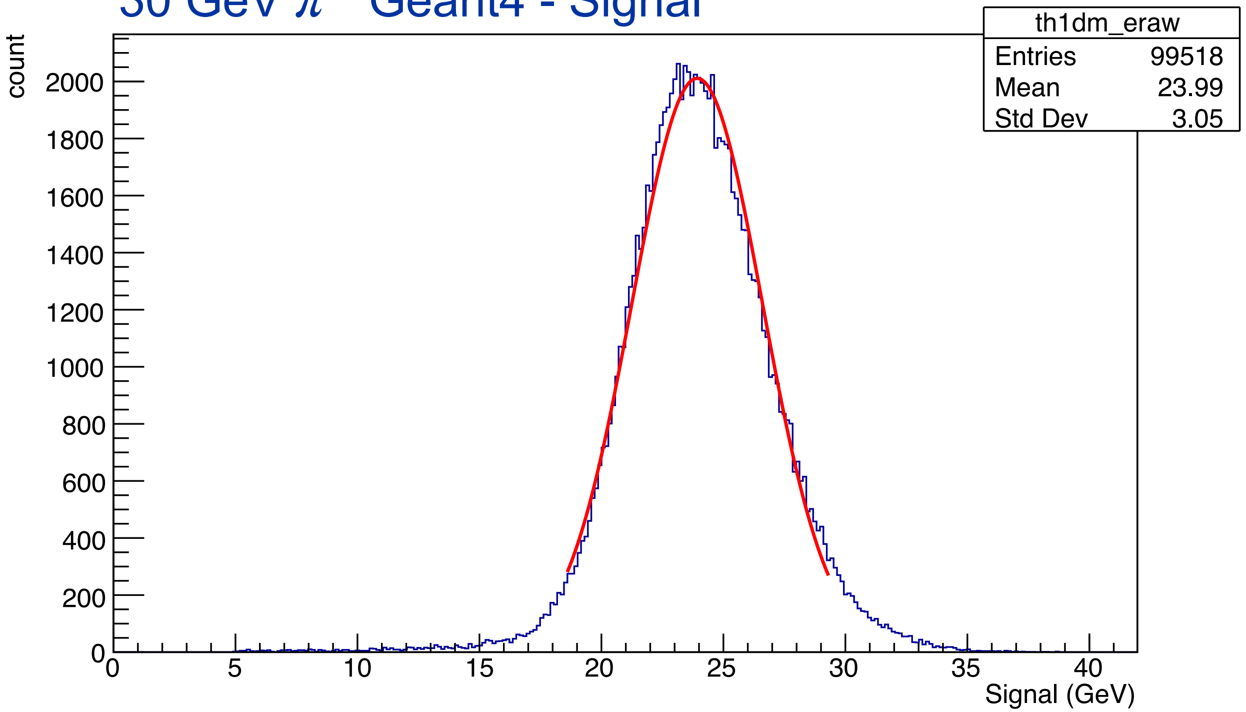
Kinetic Energy of leaking neutrons



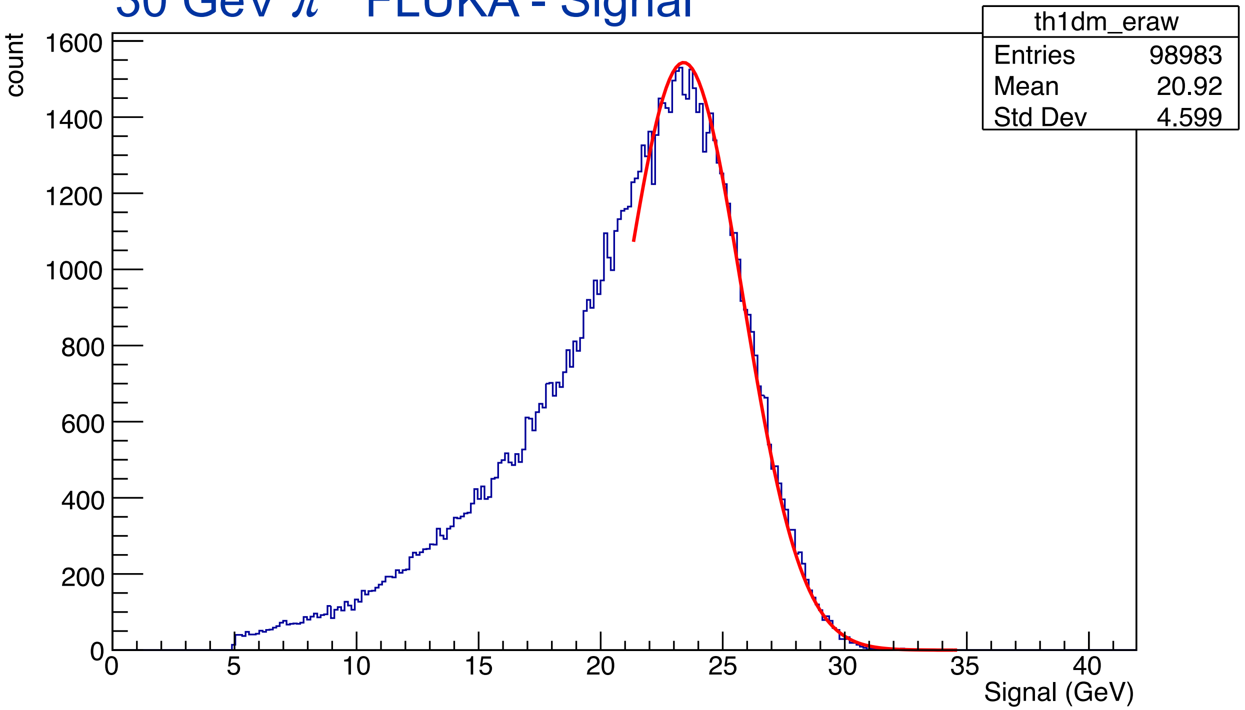
ATLAS TileCal G4 *vs.* FLUKA: health checks

- FLUKA introduces a much larger (out-of-world) leakage average values and event-by-event fluctuations w.r.t. Geant4 (this discrepancy is bigger than the HEC one and it should be studied).
- It heavily affects the calorimeter signals distributions. To only take into account the gaussian part, mean and sigma values are extracted from a right-side-only fit to data for the FLUKA case.

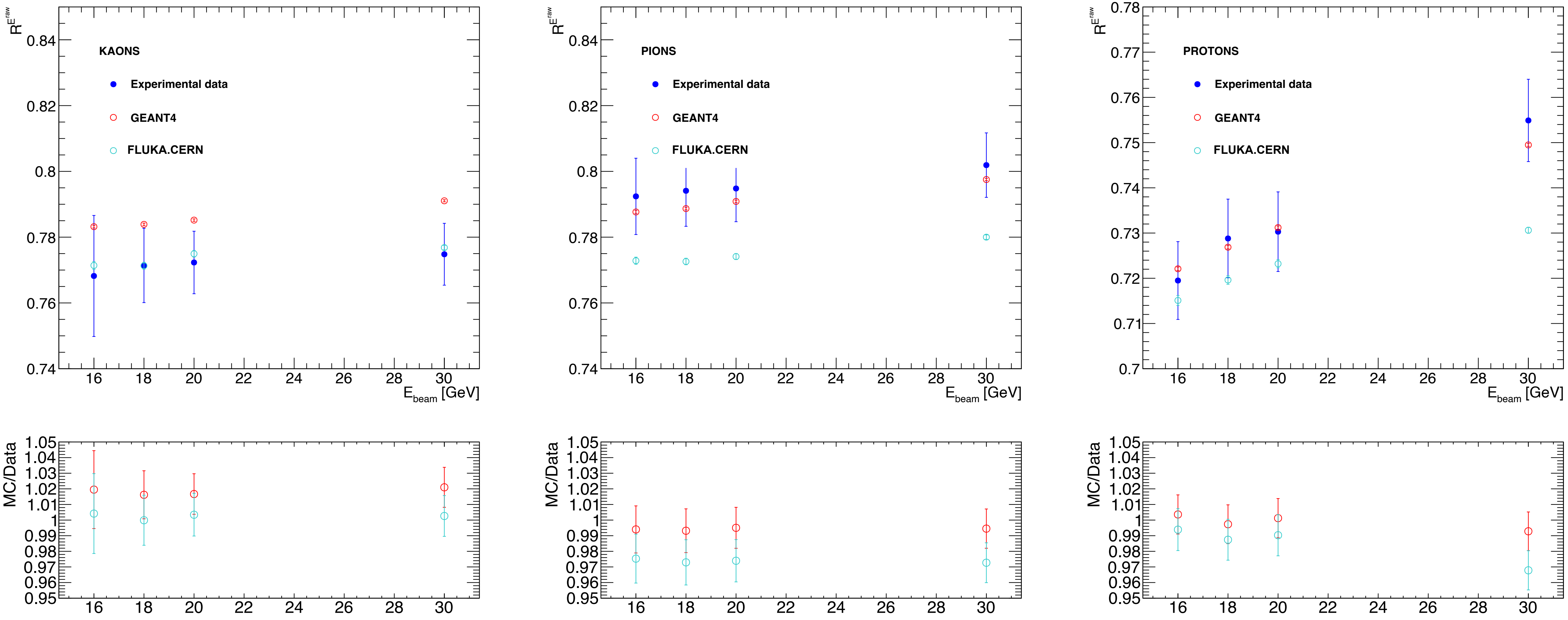
30 GeV π^+ Geant4 - Signal



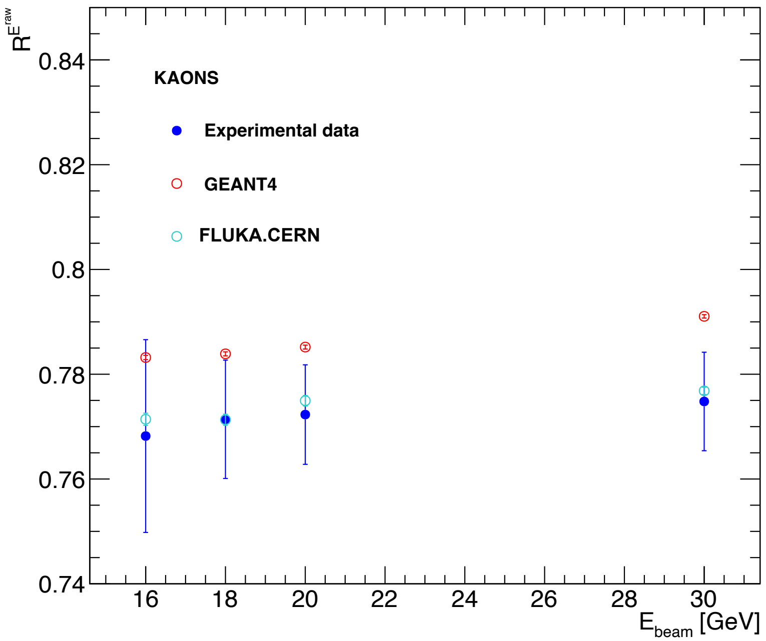
30 GeV π^+ FLUKA - Signal

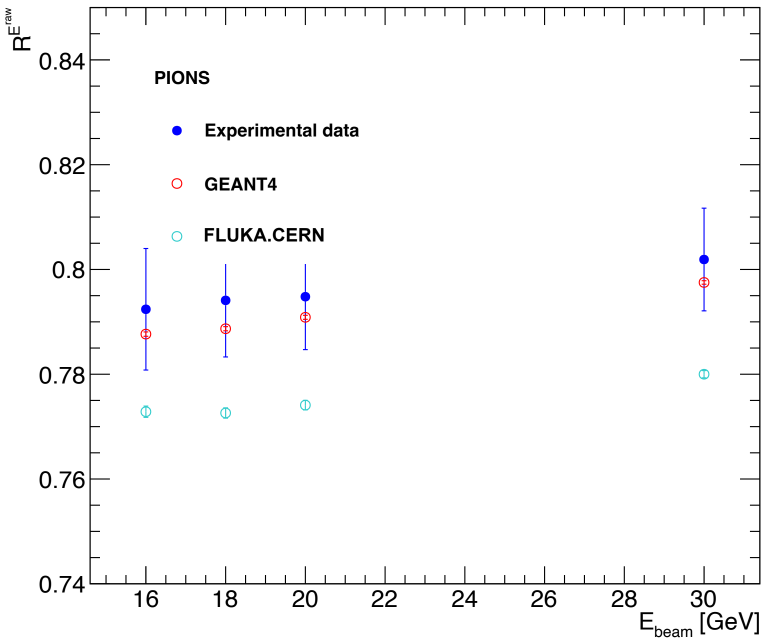


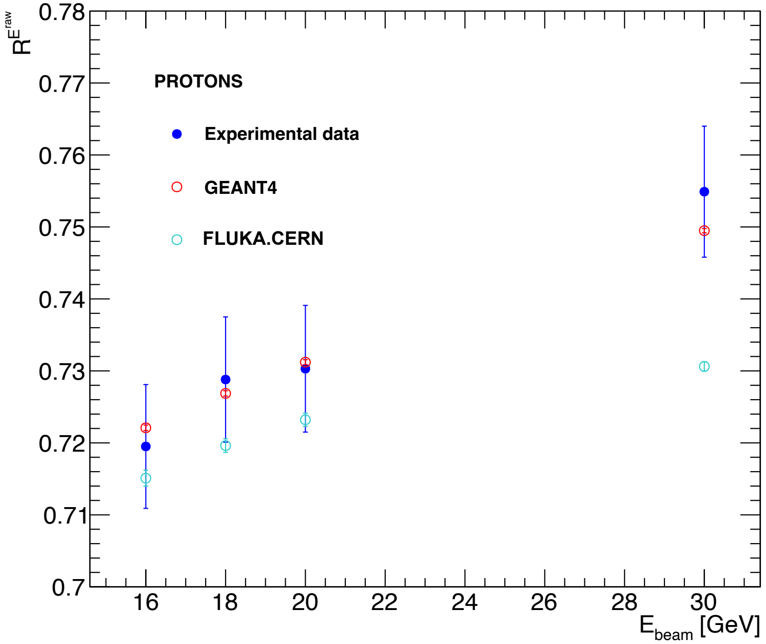
ATLAS TileCal G4 vs. FLUKA: response



ATLAS TileCal G4 vs. FLUKA: response

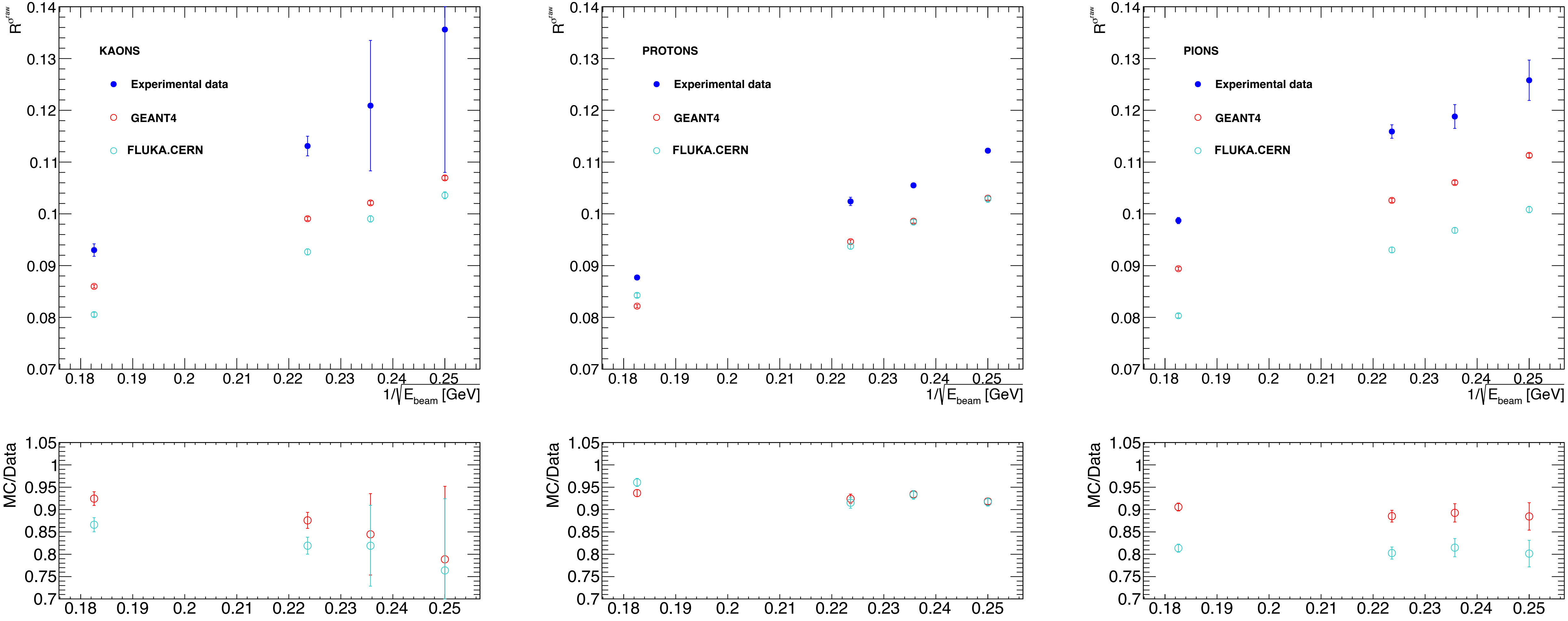




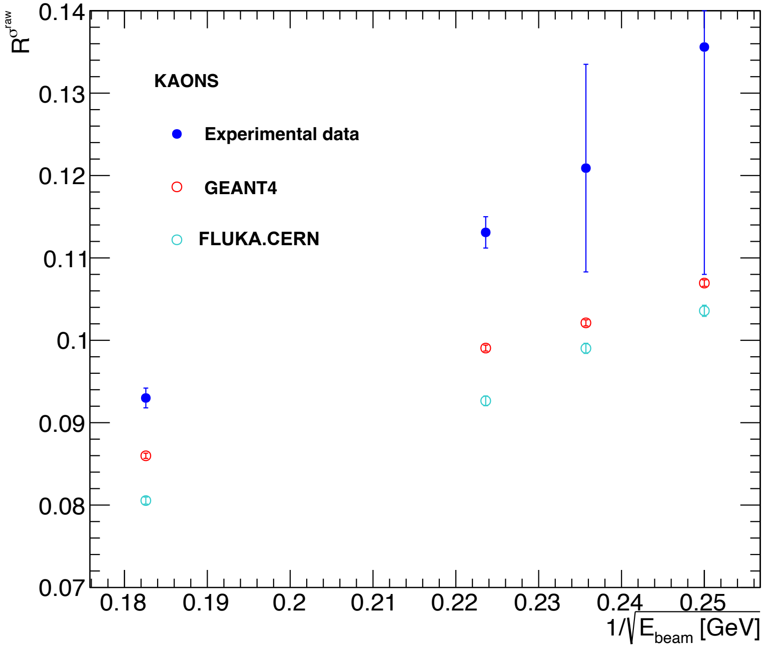


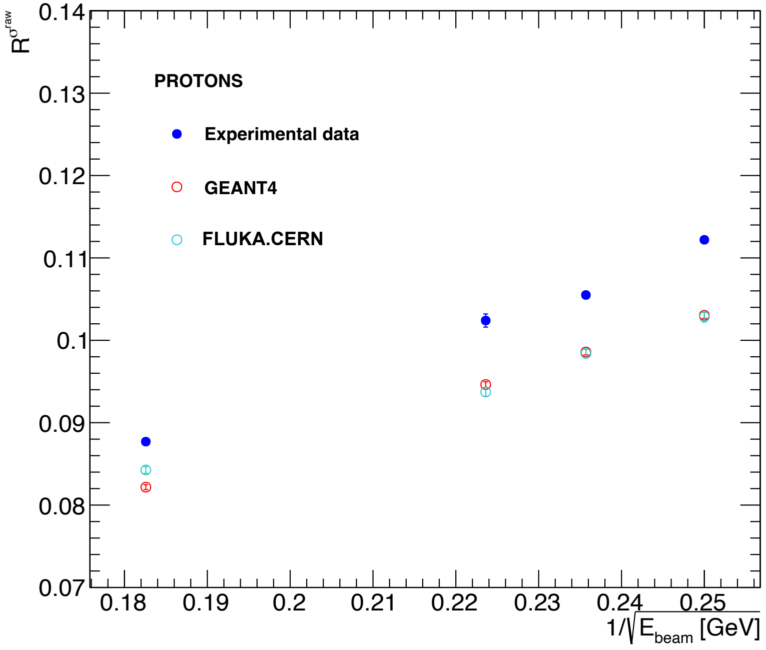
- The FLUKA response is $\simeq 1-3\,\%$ lower than the the Geant4 one.
- The response scaling with E_{beam} is well reproduced both by Geant4 and FLUKA $\rightarrow$ likely it means that the π^0 production is well modeled by both Monte Carlos.

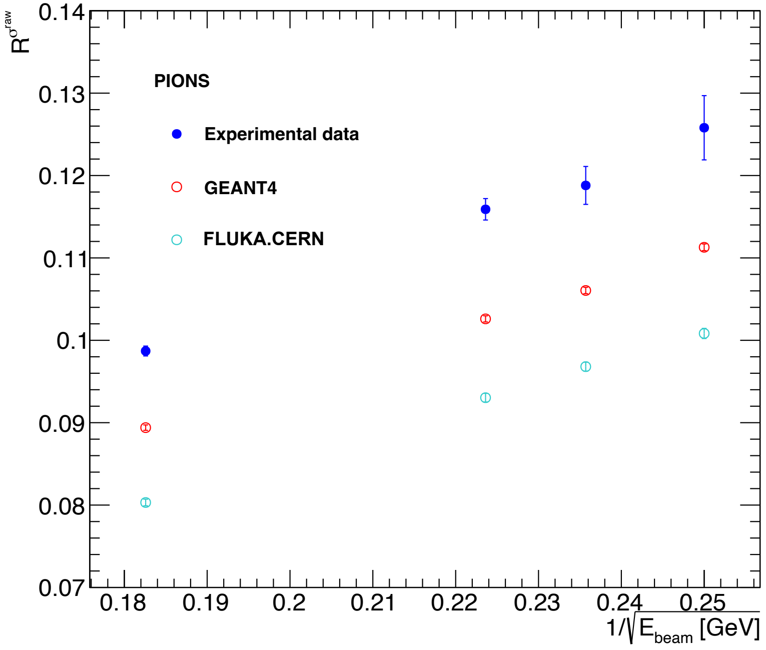
ATLAS TileCal G4 vs. FLUKA: energy resolution



ATLAS TileCal G4 vs. FLUKA: energy resolution







- Caveat: The different fitting technique on FLUKA distributions might have an impact on the σ used.
- The FLUKA resolution is very close to Geant4 for p events, and between $7\ \%$ and $12\ \%$ lower than Geant4 for π^+ and k^+ events. The scaling with E_{beam} is close to the Geant4 one.

Trying to retrieve ATLAS energy resolutions of G4-10.1 with recent versions

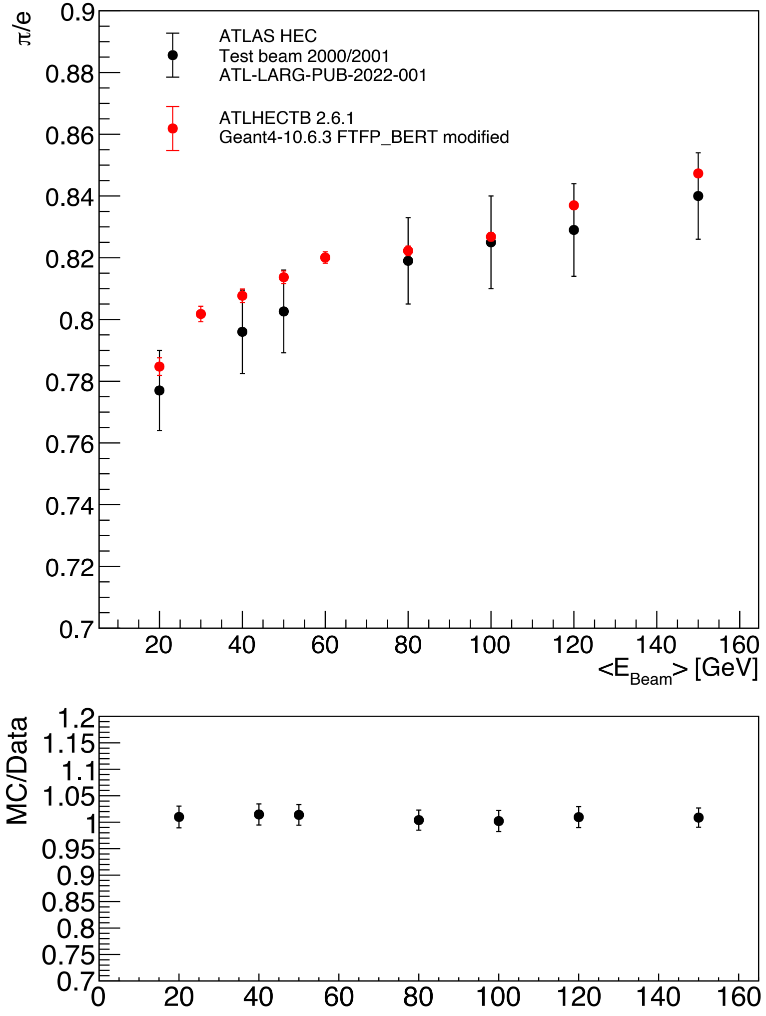
Results in the following obtained with Geant4-10.6.3 (modified FTFP_BERT), ATLHECTB-2.6.1 (data tag 2.6.1_1 - 2.6.1_2) and ATLTileCalTB-1.2 (data tag 1.2_2 - 1.2_3).

Changing FTF parameters

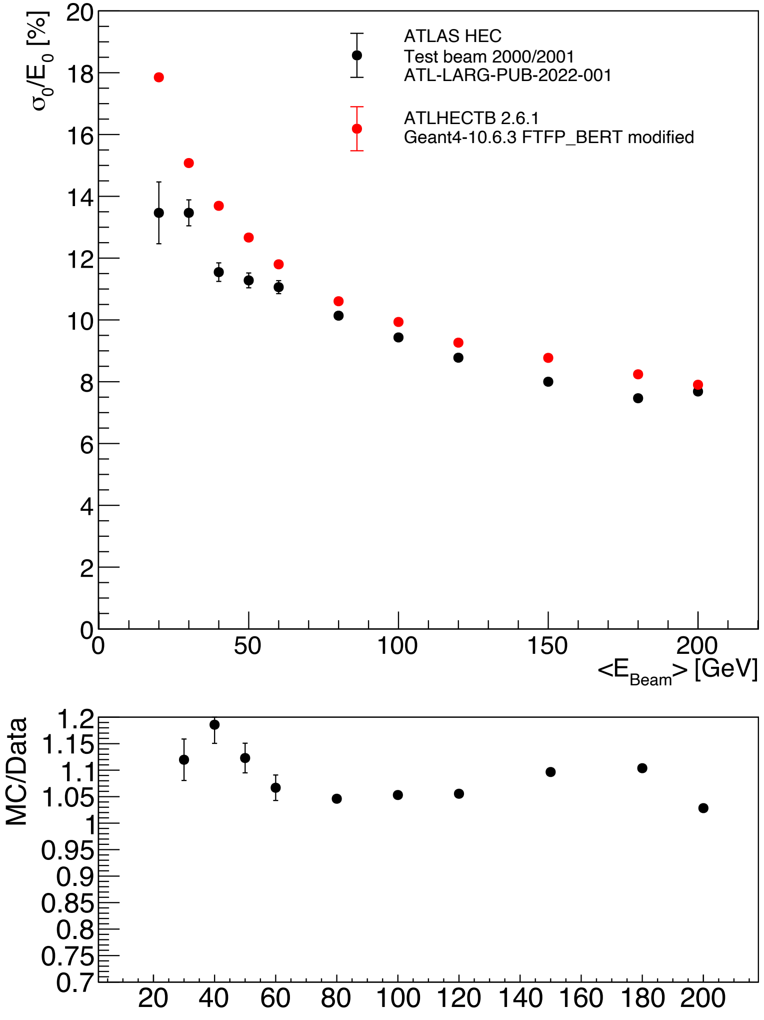
- ATLAS moved from Geant4-10.1 to Geant4-10.6 for the Run3 MC campaign → we need to improve the (too) narrow signal fluctuations.
- We tried to achieve it by changing the FTF parameters (`G4FTFParameters.cc`) affecting the charge-exchange string-formation process and the nuclear destruction. First attempt using values from G4-10.1.
- These changes:
  - increase the probability of having a charge-exchange process during the string formation
  - increase the probability of involving a neighboring nucleon during the Reggeon cascade
  - increase the excitation energy per wounded nucleon
- These changes only affect $\pi^{\pm}$-induced showers.
- We studied their effect on ATLAS calorimeters using Geant4-10.6.p03 (labelled as FTFP-BERT modified).
- If ATLAS wants, we can add the new parameters as a new FTF tune selectable via UI, or make them the default ones for the ATLAS PL (FTFP_BERT_ATL).

HEC FTFP_BERT modified: response and resolution

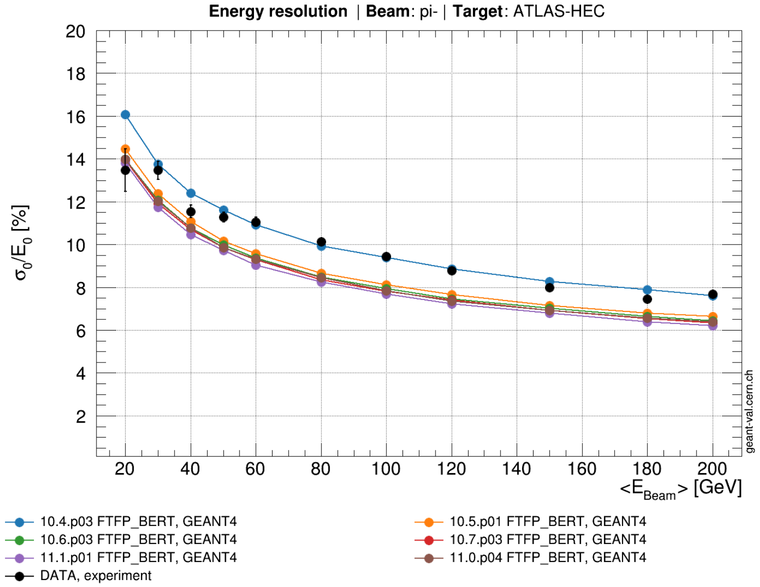
π^- - response G4 modified



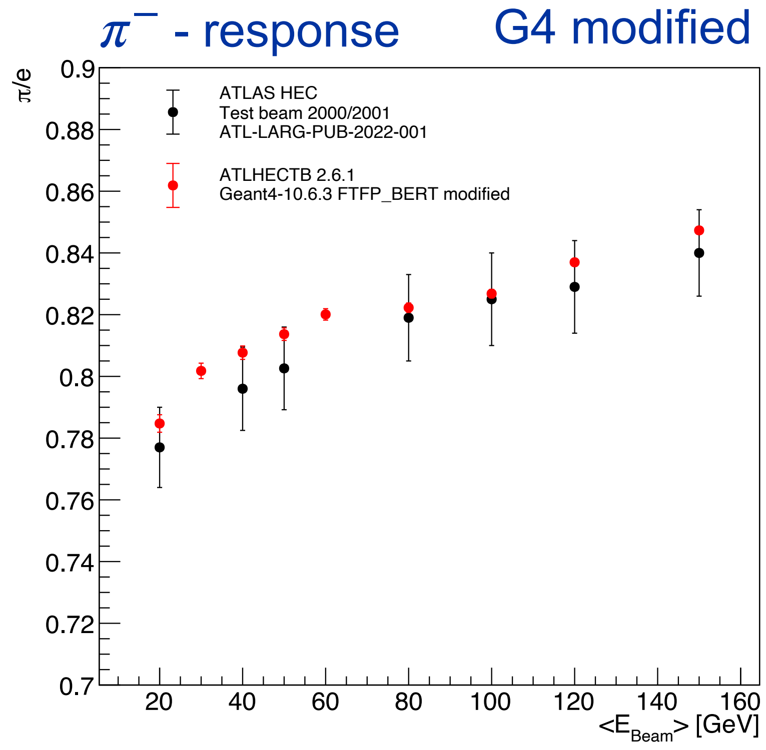
π^- - resolution G4 modified

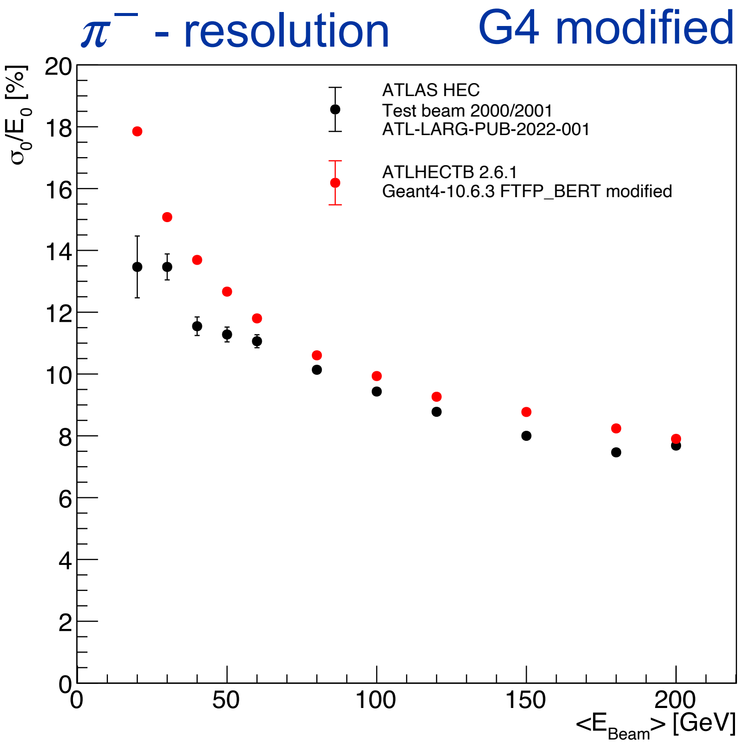


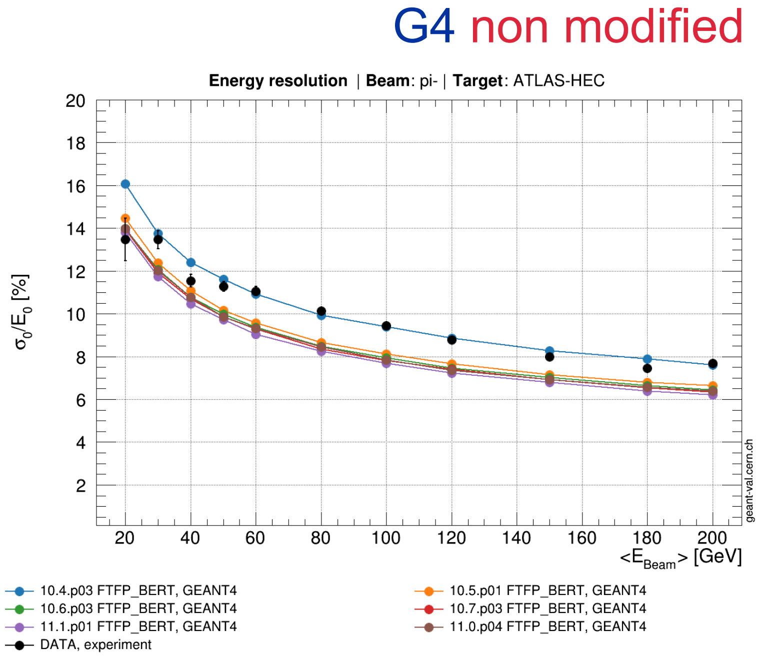
G4 non modified



HEC FTFP_BERT modified: response and resolution



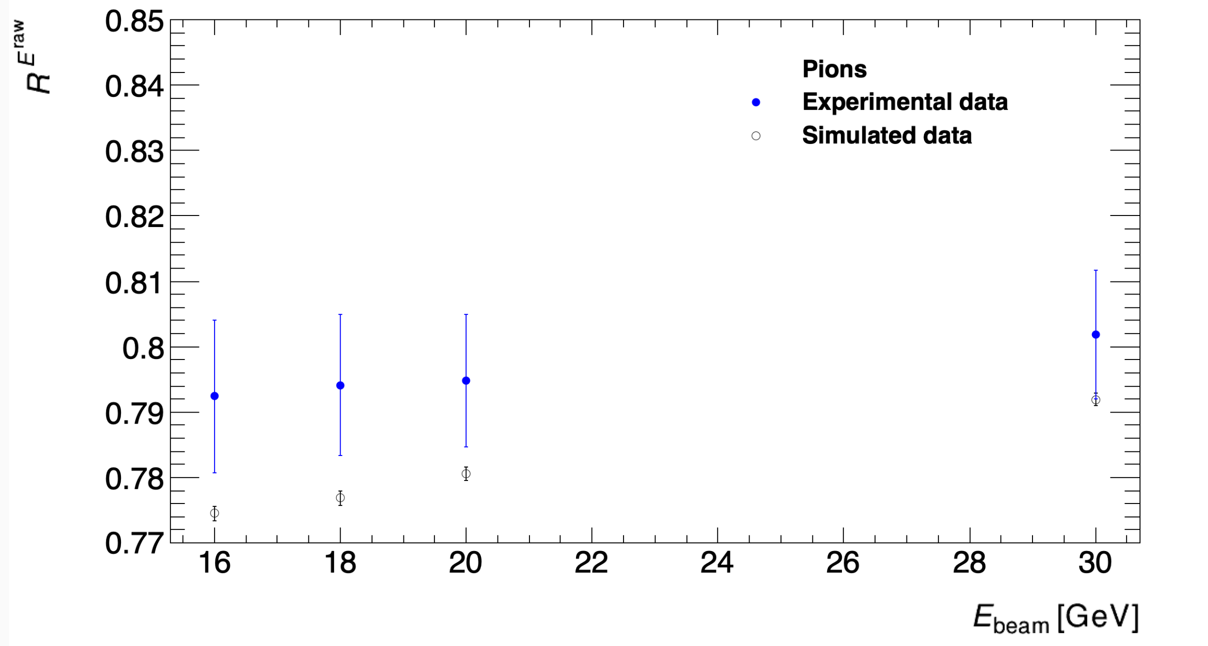




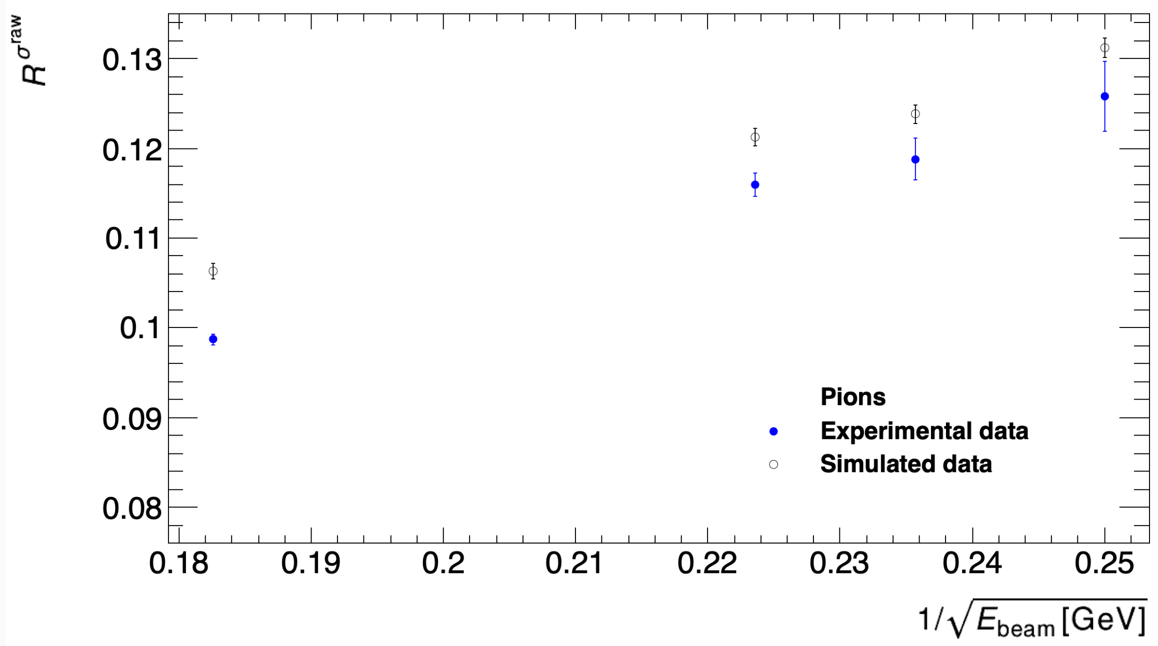
- The modified FTFParameters leads to a better agreement in the response (π/e), now within ATLAS error bars.
- They also increase response fluctuations heavily, now $\simeq 5\,\%$ larger than the ATLAS one above 50 GeV.

TileCal FTFP_BERT mod: response and resolution

π^+ - response



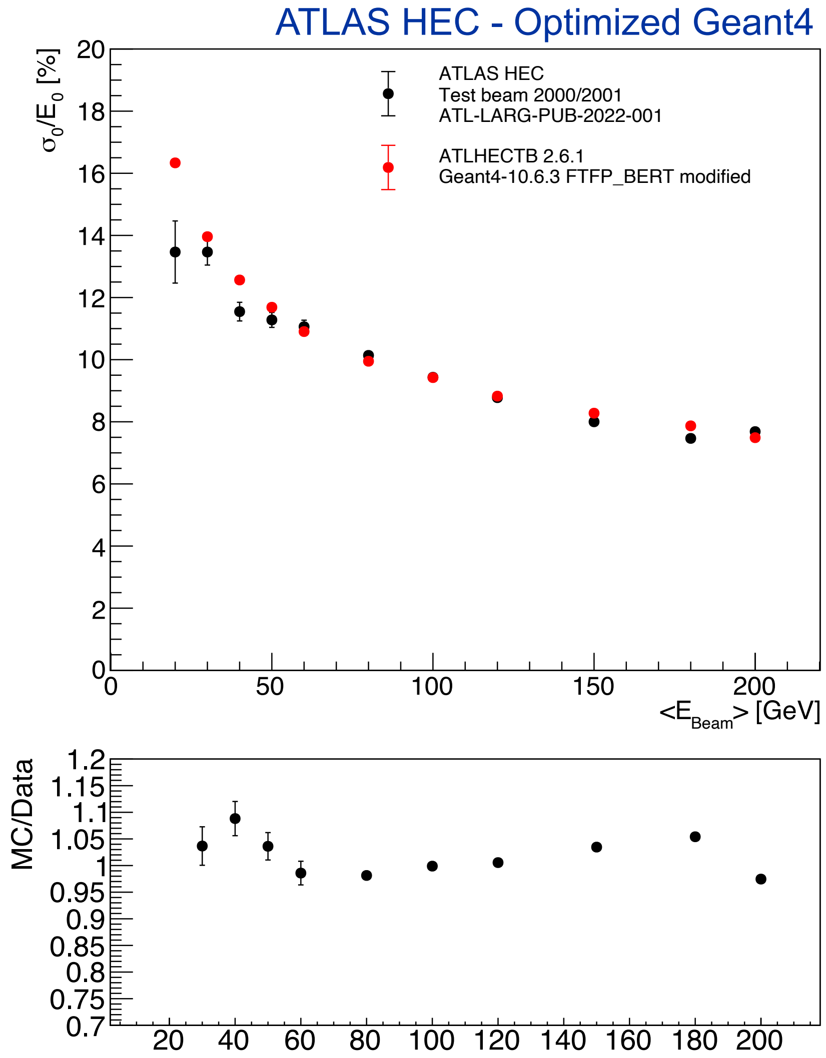
π^+ - resolution



- The modified FTFParameters leads to a good agreement in the response (π/e), now $\simeq 2\,\%$ lower than the ATLAS one.
- Enlarge response fluctuations heavily, now $\simeq 6\,\%$ larger than the ATLAS one (standard Geant4 is $\simeq 15\% - 20\,\%$ narrower).

Further model tuning on ATLAS data

- ✦ Using G4-10.1 FTF parameters in G4-10.6 leads to a better agreement in signal fluctuations for both the HEC and the TileCal.
- ✦ It is still possible to further improve the agreement with ATLAS by a fine tune on data.
  - We believe the best/safer parameter to be fitted over the ATLAS response fluctuations is the `ExcitationEnergyPerWoundedNucleon`. A simple binary search found that 50 MeV further improves the agreement.
    - Agreement within $\simeq 2\,\%$ at most beam energies for the ATLAS HEC.



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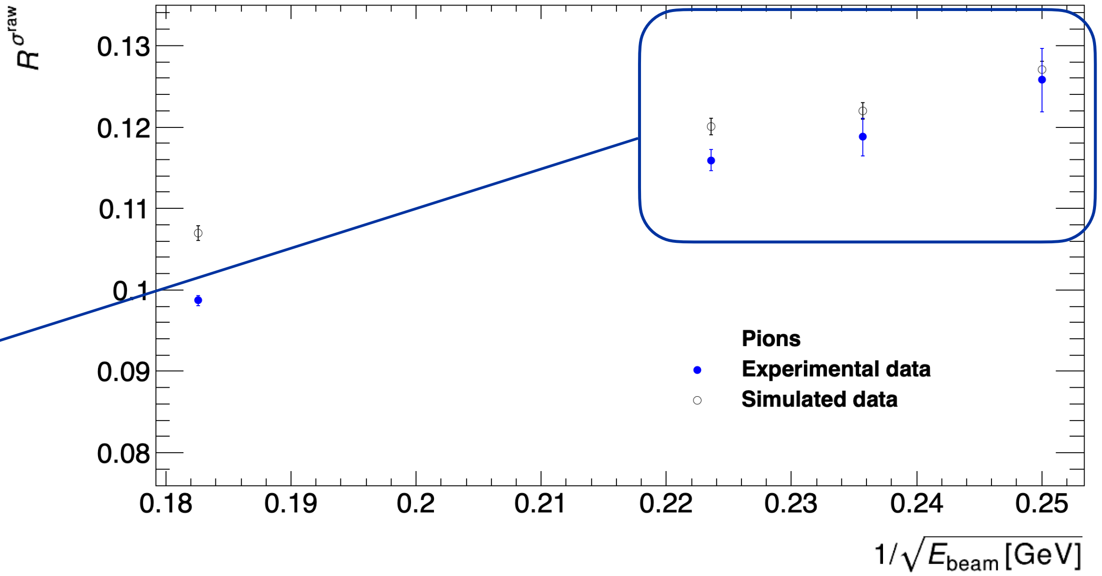
  - We believe the best/safer parameter to be fitted over the ATLAS response fluctuations is the `ExcitationEnergyPerWoundedNucleon`. A simple binary search found that 50 MeV further improves the agreement.
    - Agreement within $\simeq 2\,\%$ at most beam energies for the ATLAS HEC.
    - Within statistical error bars in the energy range 16-20 GeV for the ATLAS TileCal.
      - The resolution at 30 GeV is still off, we might want to test it with newer TileCal beam tests.

ATLAS TileCal - Optimized Geant4



Conclusion

- We developed standalone tests of the ATLAS hadronic calorimeters beam tests for internal testing of Geant4 releases.
- Regression testing shows a large difference in hadronic performance arising mostly between Geant4-10.4 and Geant4-10.5.
  - Responses kept increasing and signal fluctuations kept decreasing.
  - The average response is still in good agreement with ATLAS data and can be fixed with an overall scaling factor or with Birks tuning. On the other hand, the fluctuations are $\simeq 20\,\%$ narrower w.r.t. ATLAS and harder to fix offline (an event-by-event correction that preserves momentum conservation is needed!).
- On energy resolution, Geant4-11.1.ref05 and FLUKA.CERN (4.3.3) are in good agreement and therefore narrower than ATLAS data: are we missing something in our simulations?
  - The FLUKA.CERN hadronic model introduces considerably larger leakage (to be studied).
- It is possible to retrieve ATLAS-like signal fluctuations (for $\pi^{\pm}$ events) by changing the FTF parameters.
  - ATLAS might use it as a UI-selectable FTF-tune, or via (a new) FTFP_BERT_ATL Physics List.