Status of Hadronic String Models

G. Folger, A. Ribon
CERN PH/SFT

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Outline

- FTF
- QGS
- Hadronic Showers
- String models for G4 10.5

FTF

Fritiof (FTF) Model

- Phenomenological hadronic string model, completely rewritten and extended at lower energies by V. Uzhinsky
  - It has allowed, for the first time in G4 **9.6**, to have full transition between a string model and Bertini intranuclear cascade, eliminating the need of Gheisha (then removed in G4 **10.0**)
- It is the production string model (via the physics list FTFP_BERT) used by LHC experiments in Run **2**
  - Replacing QGS (via the physics list QGSP_BERT) used in Run **1**
- Development of FTF has always been, and still is, driven by thin-target data
  - Mostly used data from NA61/SHINE, NA49, HARP
  - Dominated by light target materials (H & C in particular)

which then gave significant improvements in the simulation of hadronic showers up to version G4 **10.1**

FTF main developments in G4 10.{2,3,4}

- FTF in G4 10**.2**
  - Changed the preparation of the **excited nuclear remnant** to hand over to Precompound / de-excitation
  - Better thin-target (slow neutron production in ITEP), but worse hadronic showers: **higher energy response**
- FTF in G4 10**.3**
  - Improved treatment of Δ-isobars ; revised quark-exchange process ; improved Lund string hadronization ; re-tuning of model parameters
  - Worse hadronic showers: slightly higher energy and **narrower showers**
  - **Split** between **development version** (in reference tags & beta : better thin-target, worse hadronic showers) and **production/stable version** (in public releases: better hadronic showers, as in G4 10.1, but worse thin-target)
- FTF in G4 10**.4**
  - Introduction of **rotating strings** at the level of string fragmentation ; smearing of resonance masses (e.g. Δ and ρ); re-tuning of model parameters
  - Better thin-target at low energies (HARP data); worse hadronic showers (**smaller fluctuations** of energy response, but wider showers)
  - Kept the split between development and production/stable versions

FTF Status

- Changes on FTF after Wollongong and included in 10.5β
  - Corrected calculation of nuclear residual excitation energy
  - New tuning of the model parameters
  - Improved version and tuning of Lund string fragmentation
  - First implementation of alpha cluster structure of carbon nuclei (affecting only hadron – C12 interactions, for both FTF & QGS)
  - Fix on antiproton annihilation at rest to get flat *cos(θ)* and *φ*
  - Code improvements, without effects on the physics
    - Classes: G4FTFModel, G4DiffractiveExcitation, G4FTFAnnihilation
    - Changes in the random sequence only due to re-ordering of operations
  - Start trying to use Professor for tuning FTF parameters... (Julia)

==> Slightly better thin-target agreement, but small impact on hadronic showers: still higher energy response and smaller energy fluctuations *vs.* production/stable version of FTF

FTF dilemma: thin-target vs. showers

- Comparing FTF with:
  - Charged pions (projectile and/or production) thin-target data
  - Fluka simulations
  - Calorimeter test-beams
- And observing that using FTF together with better models:
  - Binary (instead of Bertini) cascade for nucleons below ~1.5 GeV
  - Better elastic scattering

  increases further the calorimeter energy response
- We suspect that the main problem is not the string model (FTF) but a **strong underestimation of Birks' quenching**
  - Not yet managed to show this from “first principles”, based on the available published data on quenching in scintillators...

QGS

QGS (Quark Gluon String) Model

- The QGS model of Geant4 has been successfully used in production for several years by ATLAS and CMS simulations
    - In particular for all Run 1 analyses, including the Higgs discovery
- After the improvements and low-energy extensions of FTF model made by V. Uzhinsky, FTF became the recommended string model in Geant4 for high-energy applications
    - It is used for Run 2 analyses by all LHC experiments
- Still, there are two main reasons to keep developing QGS

1. For evaluation of systematic errors, to compare against FTF
2. For its potential applicability up to slightly higher energy than FTF

    - QGS is more theoretically motivated than the phenomenological FTF model
    - Might be relevant for the increased LHC energy: 7-8 TeV --> 13-14 TeV, and even more for FCC @100 TeV
    - But QGS cannot be applied to much higher energies than few TeV : it does not included hard scattering (*i.e.* jet production) (the same applies for FTF as well)

QGS String Fragmentation

- In 2014, V. Uzhinsky made the first step in the revision of the Geant4 QGS model: the string fragmentation
  - The quark and diquark fragmentation functions (in G4 10.0) were significantly different with respect to Kaidalov's prescription
  - Kaidalov argued that the use of fragmentation functions extracted from e+ e- annihilation or in deep inelastic scattering is not justified in soft processes, and inconsistent with Reggeon theory
  - Vladimir changed the fragmentation functions of Geant4 QGS to bring them consistent with those recommended by Kaidalov
  - This development was included in G4 **10.1**
  - Although not driven by experimental data, the new QGS string fragmentation improved the description of some thin-target data
- Significant impact on hadronic showers
  - lower energy response, bigger (longer and wider) showers
  - closer to the hadronic showers of FTF model

QGS String Formation

- V. Uzhinsky improvements in formation of quark strings
  - Inclusion of the Reggeon Cascade, as in FTF
  - Rewriting of the sampling of parton momenta
  - Improvement of the Fermi motions of target nucleons
  - Inclusion of the multi-pomeron exchange
  - More accurate preparation of the excited nuclear remnant
  - Constituent quark masses have been introduced
  - Pomeron and reggeon parameters are set as prescribed by A. Kaidalov and M. Poghosyan
  - Interpretation of cutted (non-vacuum) reggeons as quark exchange processes
  - These developments have been included in reference tags & beta
  - All these improved the description of thin-target data, but for public releases we kept the production/stable version (equivalent to 10.1) to provide stable hadronic showers, as done for FTF

QGS Status

- Changes on QGS after Wollongong and included in 10.5β
  - New tuning of the model parameters
  - Improved version and tuning of QGS string fragmentation
  - First implementation of alpha cluster structure of carbon nuclei (affecting only hadron – C12 interactions, for both FTF & QGS)
  - Fix rare crashes
  - Fixed event reproducibility problem in gamma-nuclear

==> Significant **better thin-target** agreement – vs. previous versions of QGS, and now comparable to the development version of FTF – but **worse showers** (higher energy response and narrower shape) with respect to the production/stable version of QGS, and both versions (development and production/stable) of FTF

Hadronic Showers

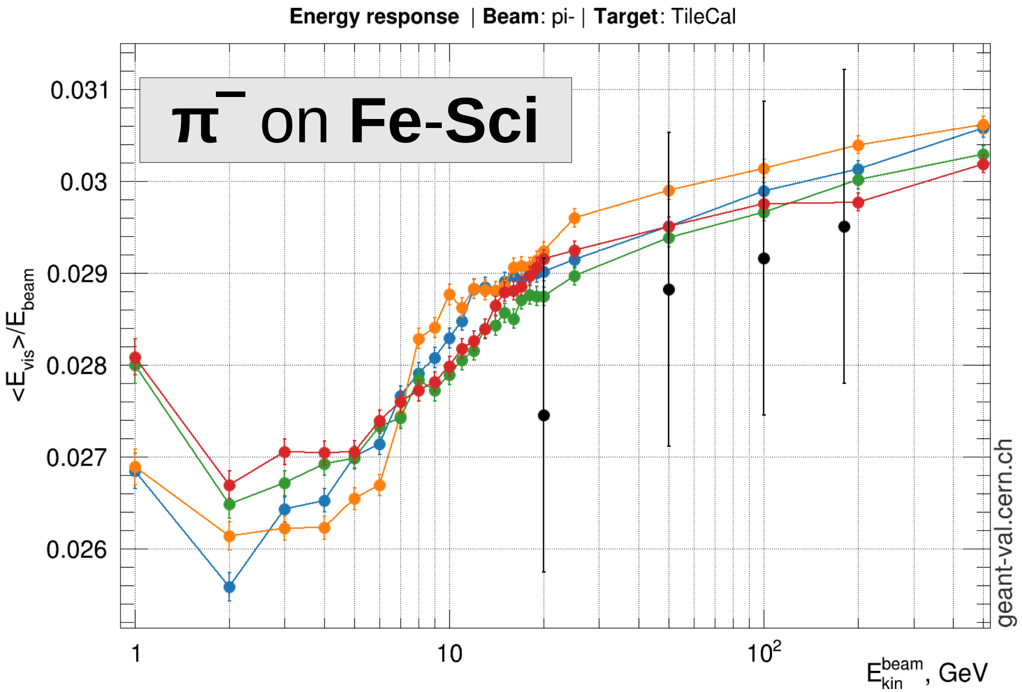
Pion- showers:

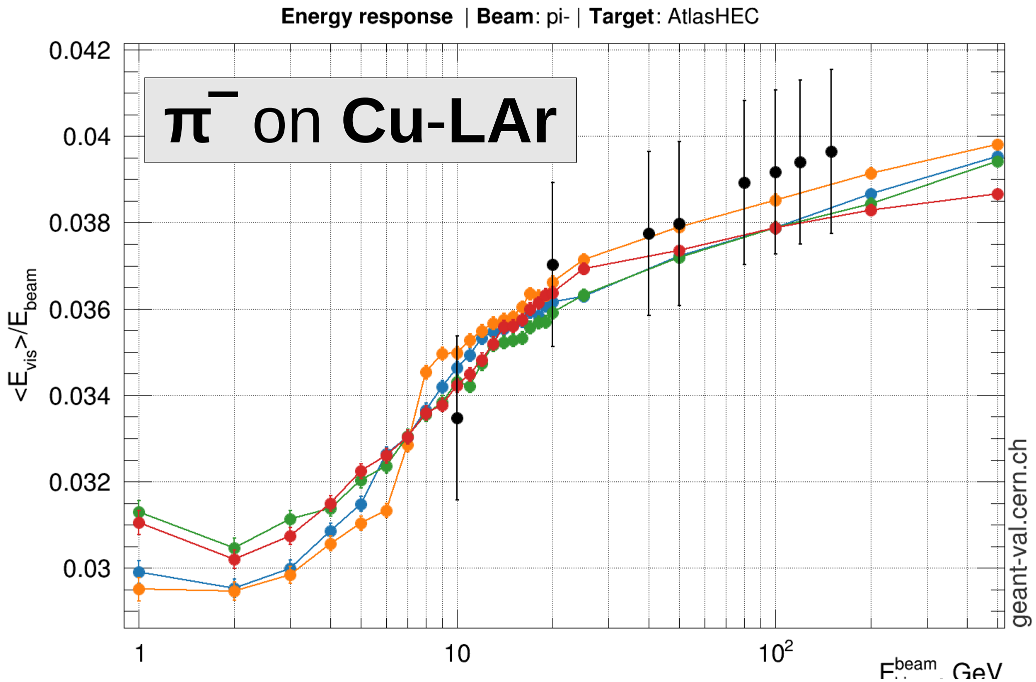
FTFP_BERT G4 10.5β
FTFP_BERT G4 10.4.p02

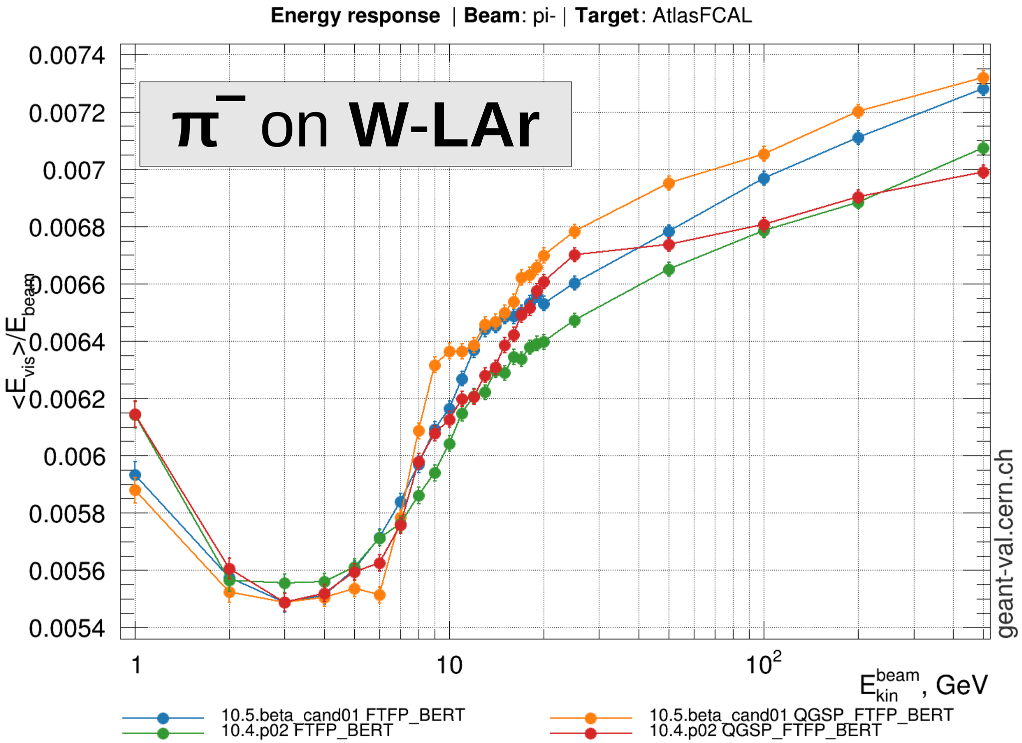
QGSP_FTFP_BERT G4 10.5β
QGSP_FTFP_BERT G4 10.4.p02

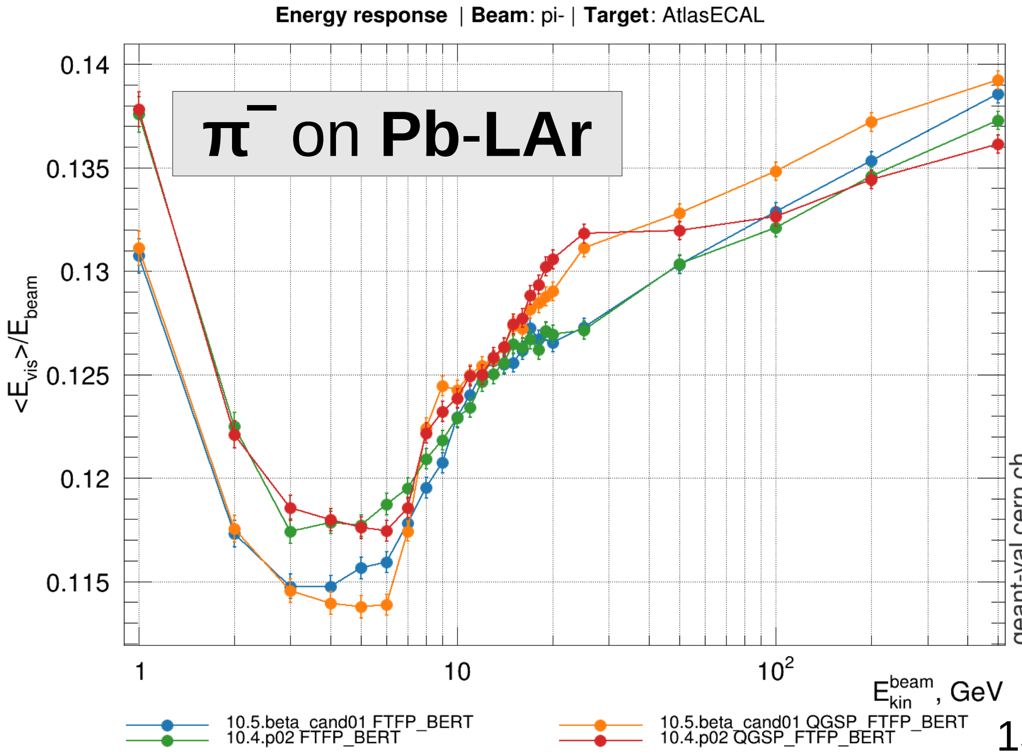
Note: FTFP_BERT : BERT > 3 GeV
FTFP < 12 GeV
QGSP_FTFP_BERT : BERT < 8 GeV
FTFP [6, 25] GeV
QGSP > 12 GeV

Energy Response

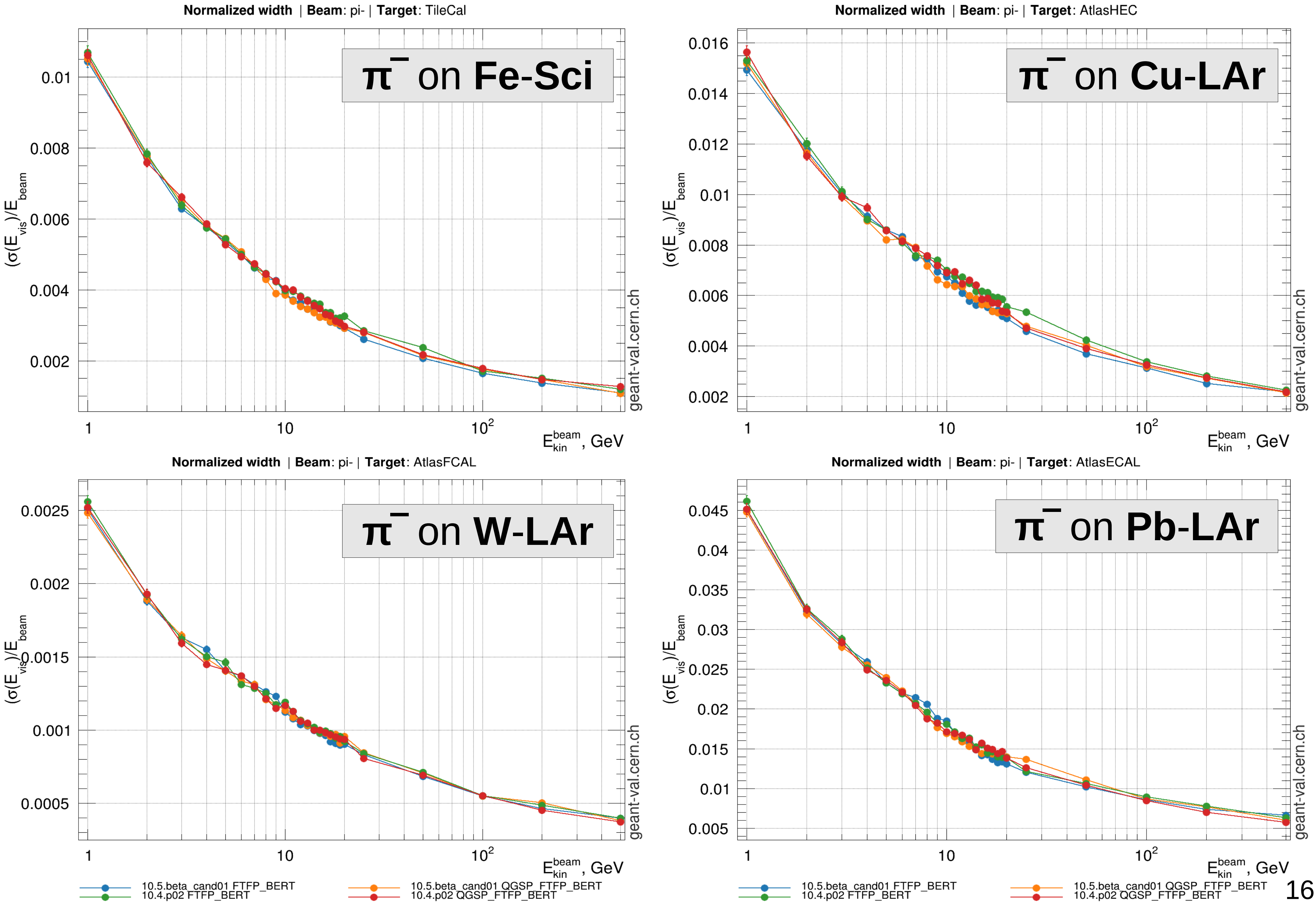




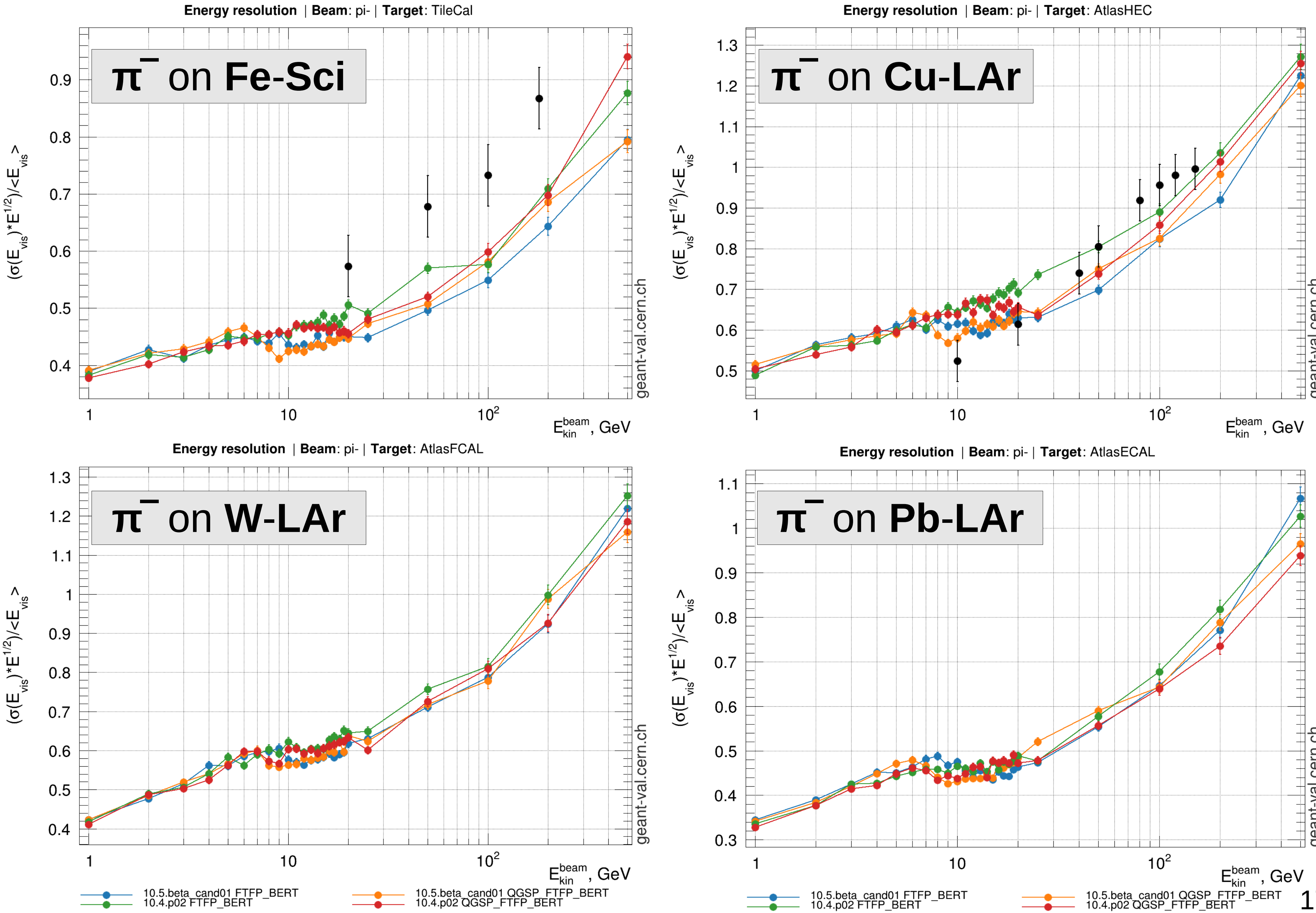




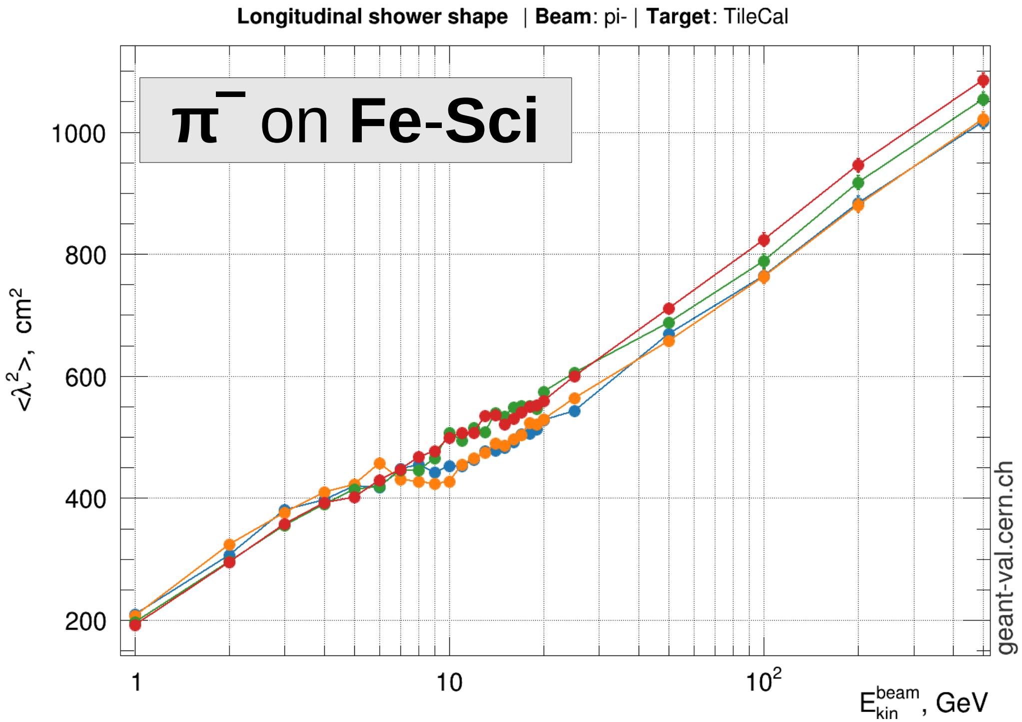
Energy Width

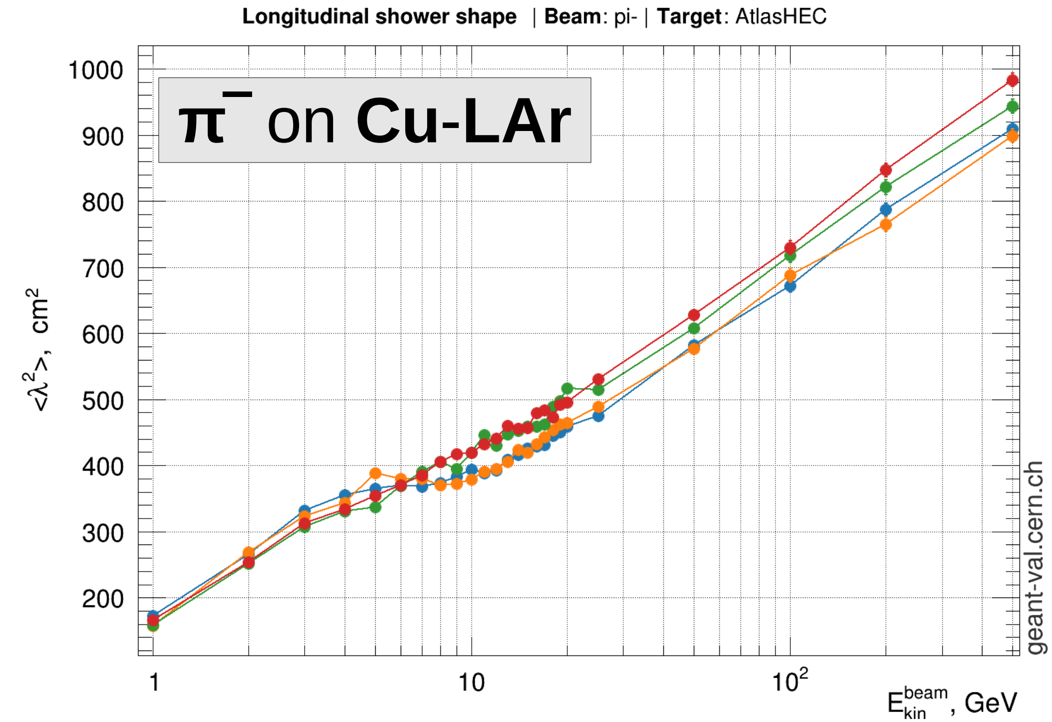


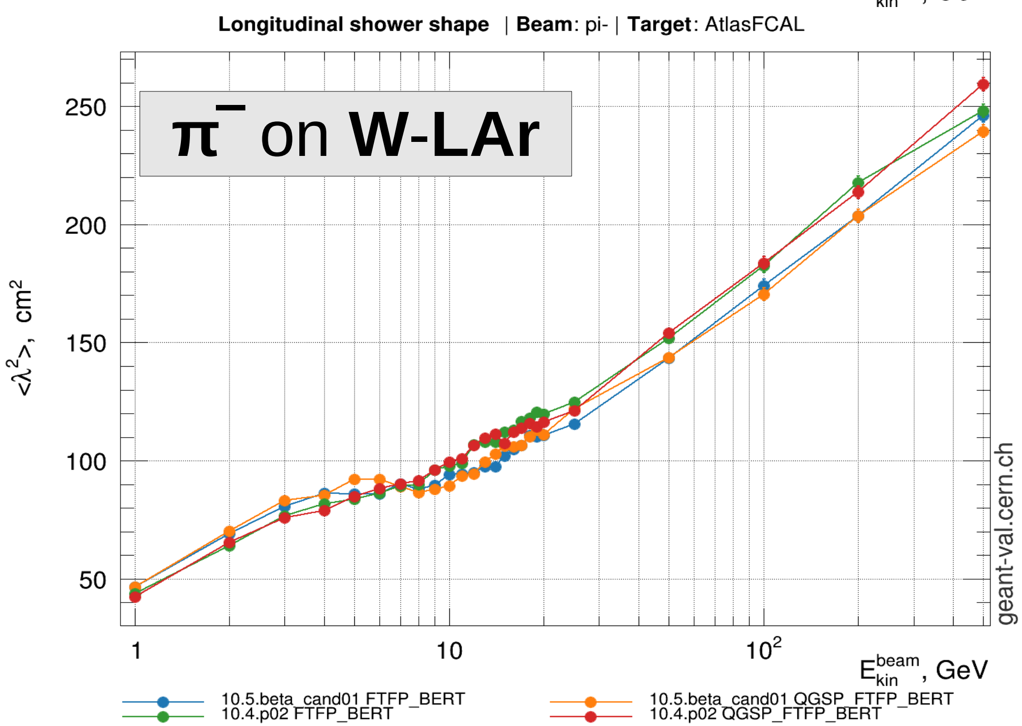
Energy Resolution

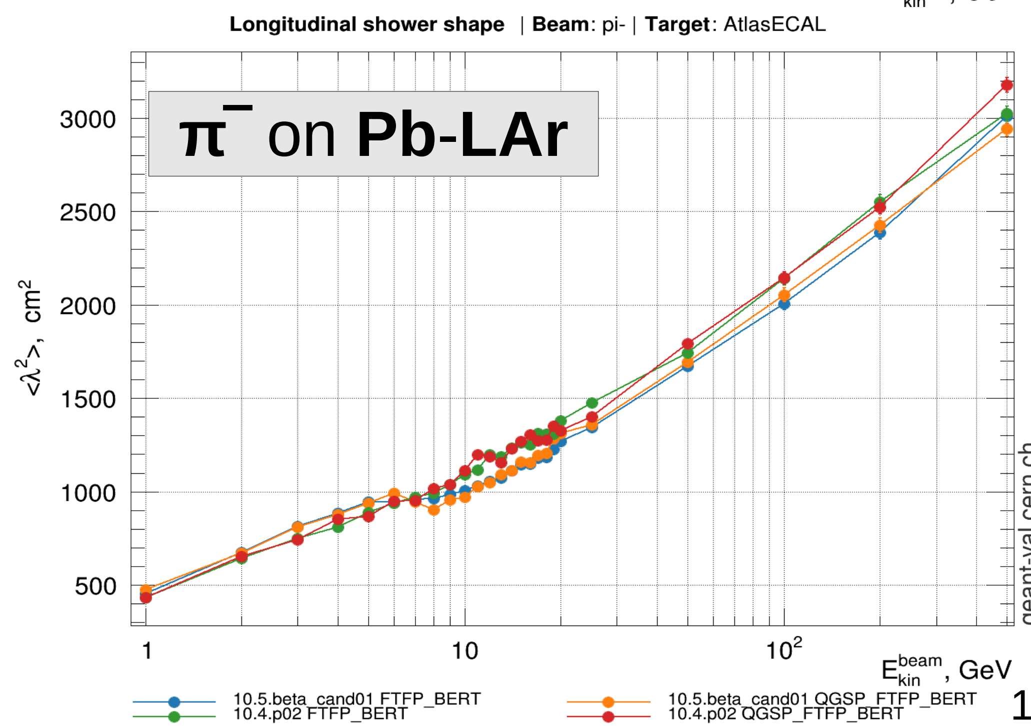


Longitudinal Shape

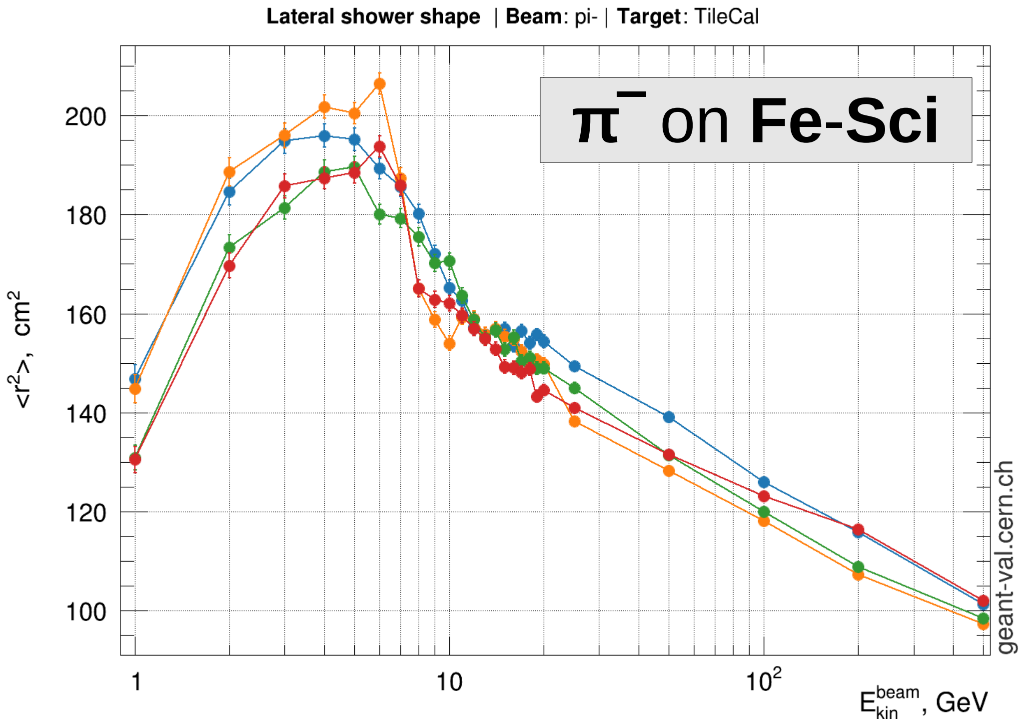


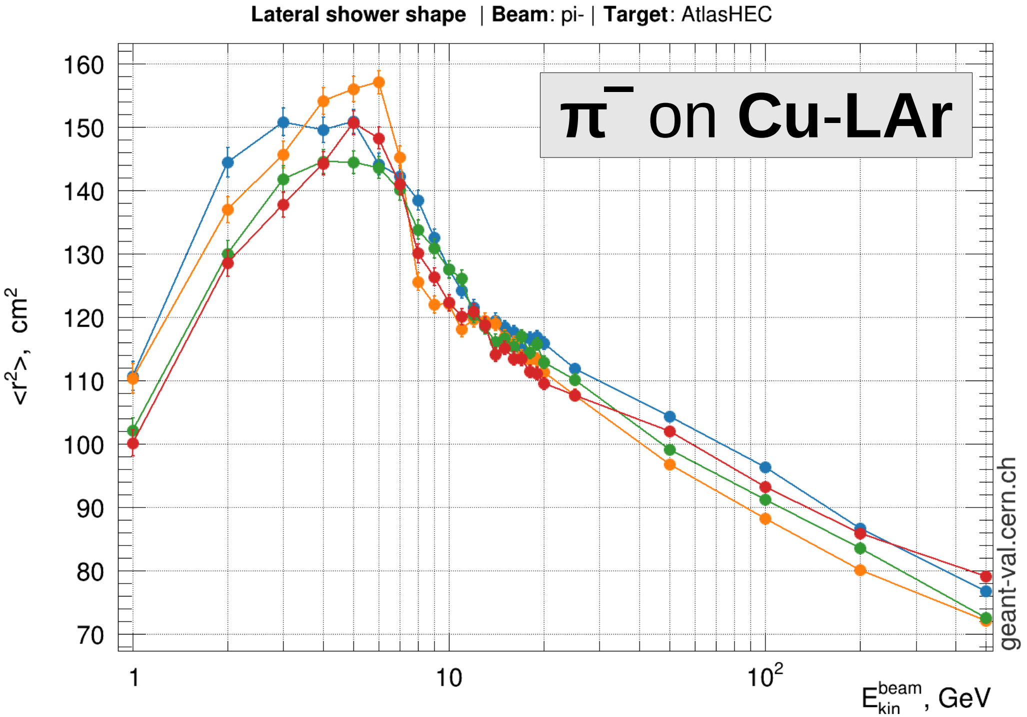


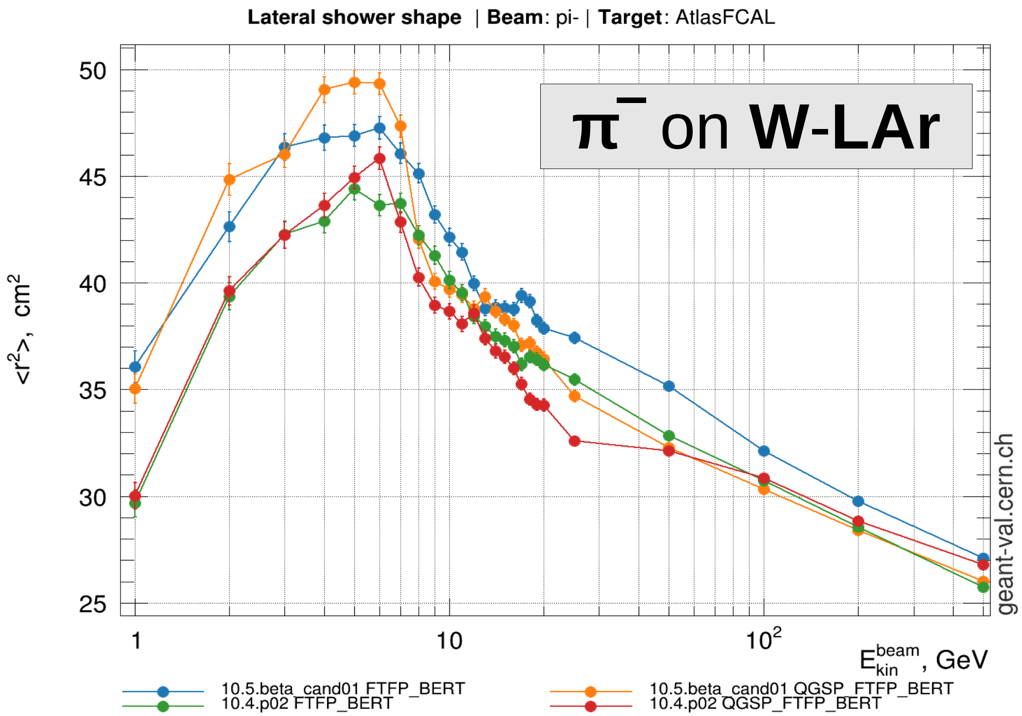


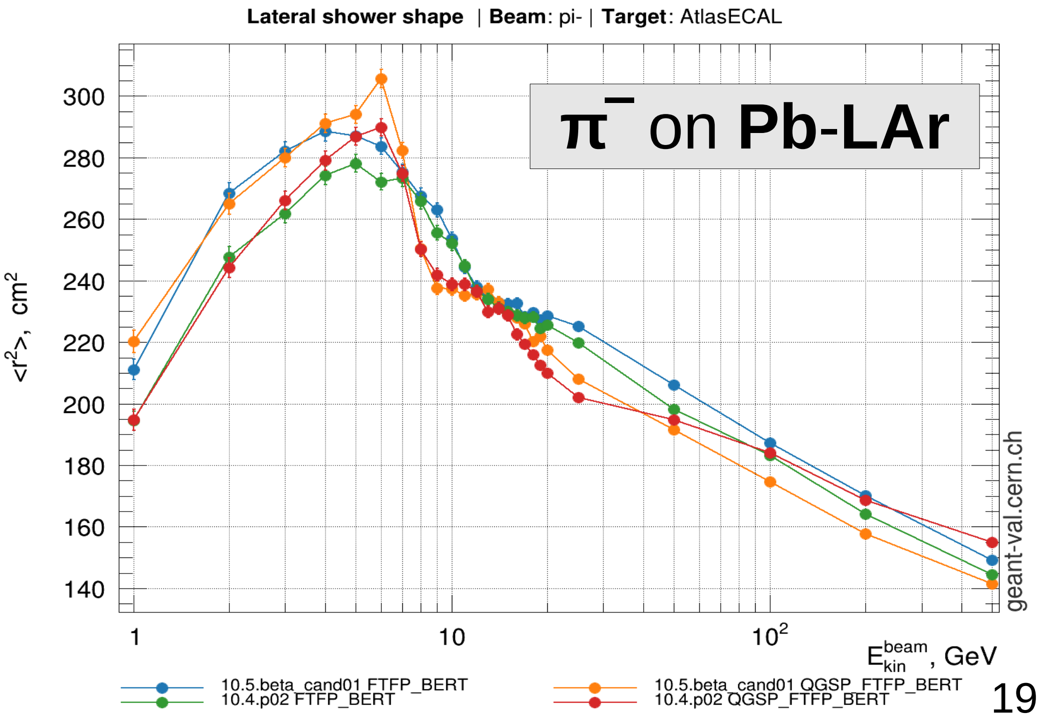


Lateral Shape









String Models for G4 10.5

String Models for G4 10.5

- V. Uzhinsky is starting this year only on 1st September to work at CERN. His main task will be to improve the QGS model, but some developments in FTF could be possible...
- We don't expect major changes, so for December release G4 **10.5** we are facing to the "usual" dilemma: *do we want to release the latest **development version** of the string models – which gives better description of **thin-target data** – or the **production/stable version** – which gives better description of **hadronic showers** in calorimeters ?*
- The conservative, safer option is the second, as we did already for G4 **10.3** & **10.4** (as well as **10.2** for QGS)
- We prefer the first one – together with using BIC (instead of BERT) for nucleons below 1.5 GeV, and with the new elastic – pushing the experiments (during the pause at the end of Run 2) to apply a **stronger Birks' quenching**... Alternative: wait for G4 **11.0**