Status of Hadronic String Models

Alberto Ribon , Vladimir Uzhinsky
CERN EP/SFT

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Outline

- FTF
- QGS
- Hadronic Showers
- String models for G4 10.6
- First look at very high energies

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 intra-nuclear 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
    - Light target materials (H & C) for NA61/SHINE and NA49
    - Variety of materials (Al, Cu, Pb, etc.) for HARP

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

Status of **FTF** model

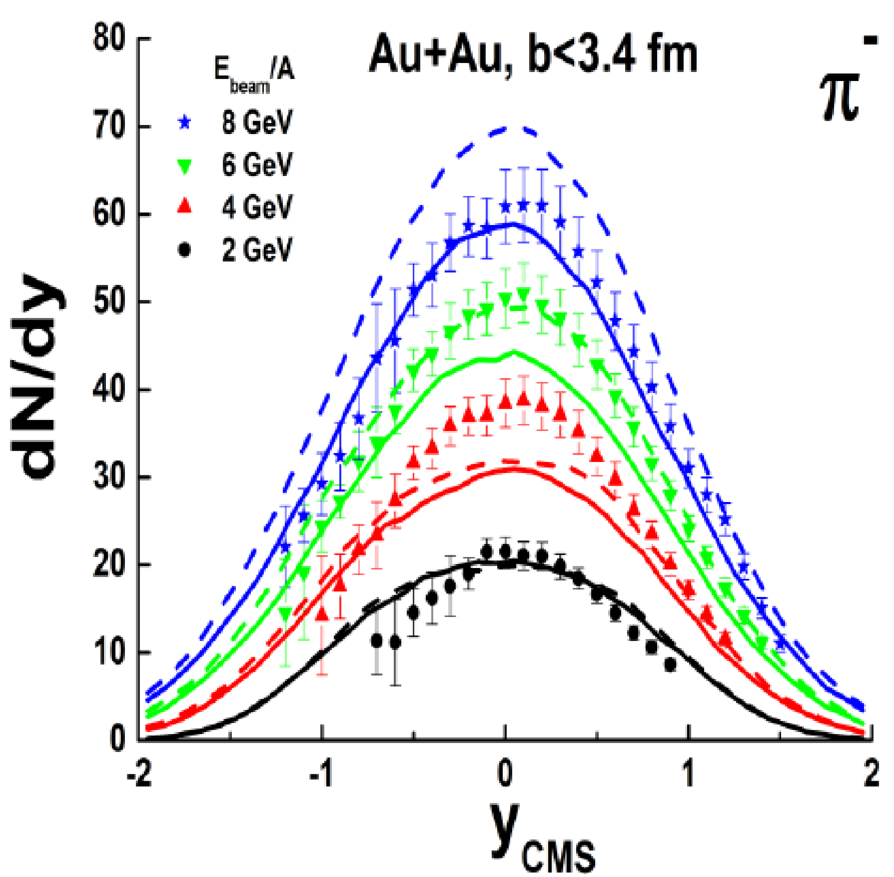
- FTF in G4 10.5
  - Decided to release the **development version**
  - Improved thin-target description and wider hadronic showers, while our suggested new treatment of Birks quenching (i.e. fitting the Birks parameter from e/π data) can cope with the increased visible energy
  - After the 2018 Collaboration meeting, retuning of the strange quark sector of the Lund string fragmentation

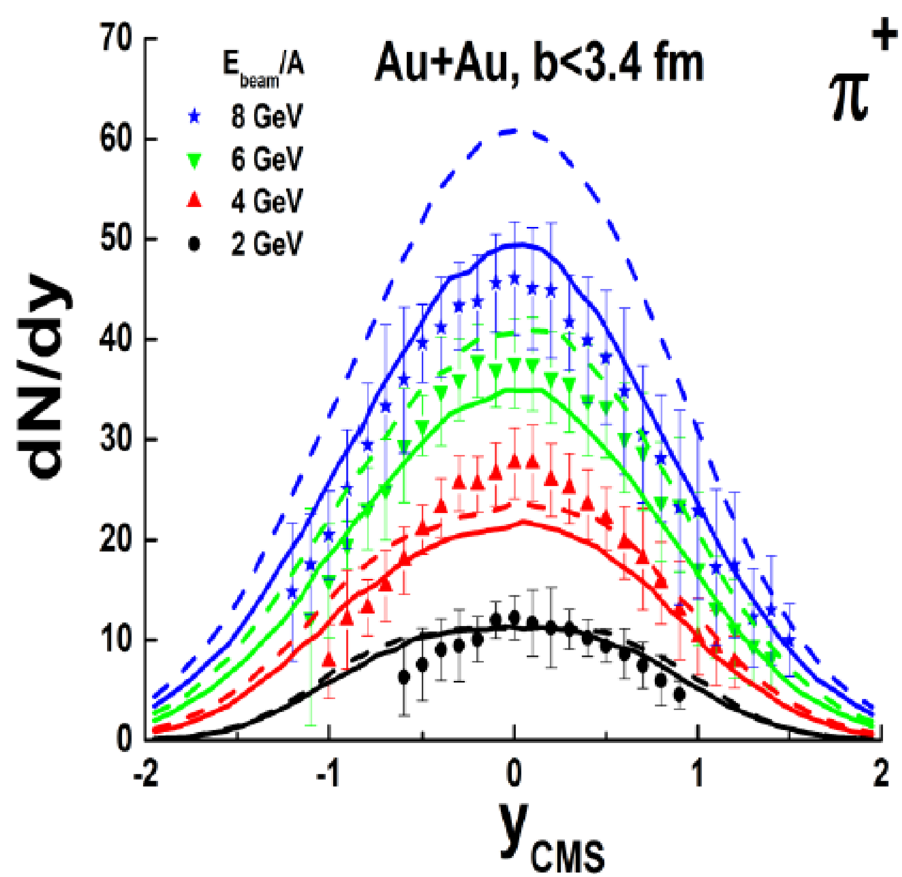
- Changes on FTF after G4 10.5
  - Validation and refinement of nucleus-nucleus interactions *(see an example in the next page)*
  - Improved annihilation at rest of antiprotons and light anti-ions
  - Extended configuration interface for pion projectile parameters
  - Fixed a memory leak

Results of the improvements for E895 exp.

J. L. Klay et al., Phys. Rev C 68, 054905 (2003)

Charged pion production in 2A to 8A GeV central Au+Au Collisions,





Dashed lines are previous calculations, solid ones – current results.

Results become better for high energies, T > 6 GeV.

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's improvements in the 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 multi-pomeron exchanges
  - 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, until 10.5

Status of **QGS** model

- QGS in G4 10.5
  - Decided to release the **development version**
  - Improved thin-target description, although narrower hadronic showers and increased visible energy
    - The increased visible energy can be compensated with our suggested new treatment of Birks quenching, i.e. fitting the Birks parameter from e/π
  - After the Collaboration meeting, improved the kaon treatment and performed further validation

- Changes on QGS after G4 10.5
  - Further validation
  - On-going code review
  - Fixed a bug in the computation of the transverse mass

FTF *vs.* QGS

- In Geant4 version 10.5, from thin-target data, we can generally conclude that QGS becomes **competitive** with FTF roughly above **~ 15 – 20 GeV** (lab. projectile E_{kin}) whereas below this energy FTF is better
  - In the QGS-based physics lists, the transition between FTF and QGS is currently in the region [12 , 25] GeV
- QGS model is more theory-based than FTF, therefore QGS is expected to be more reliable at high energies
  - Above about ~0.5 TeV, where there are no clean thin-target data
  - But both models cannot be valid above few TeV
    - Because of the lack of gluon-jet production
    - Likely acceptable for LHC experiments, but not for FCC...
- QGS hadronic showers are narrower and with higher energy response than those of FTF

  - FTF hadronic showers expected to agree better with test-beam data

Hadronic Showers

Pion- showers:

FTFP_BERT G4 10.5.ref08

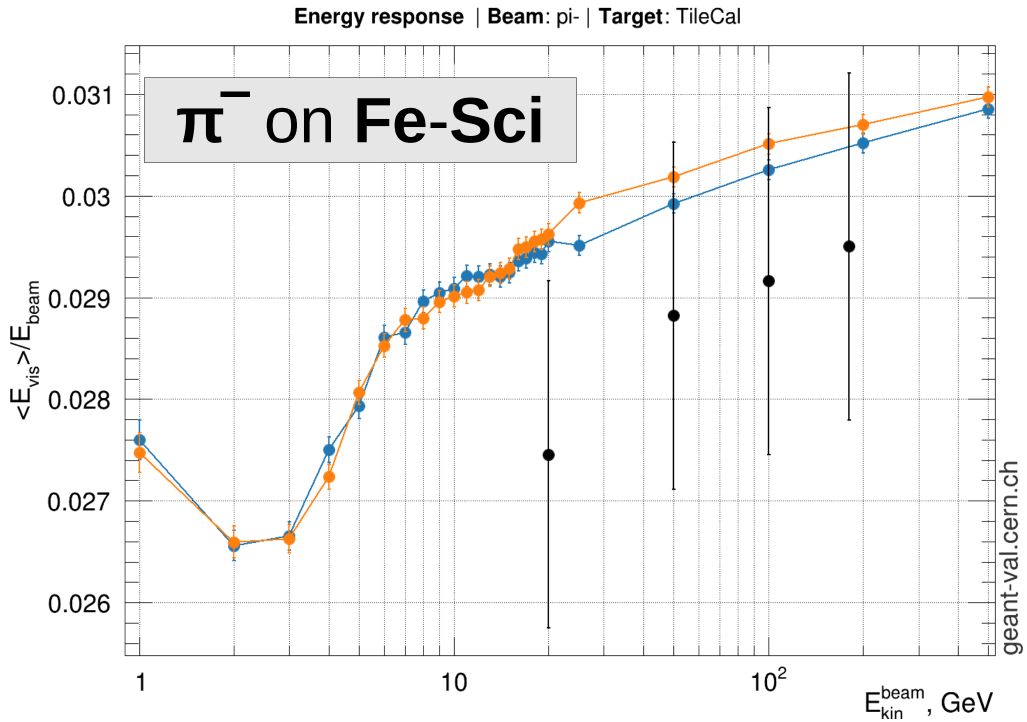
QGSP_FTFP_BERT G4 10.5.ref08

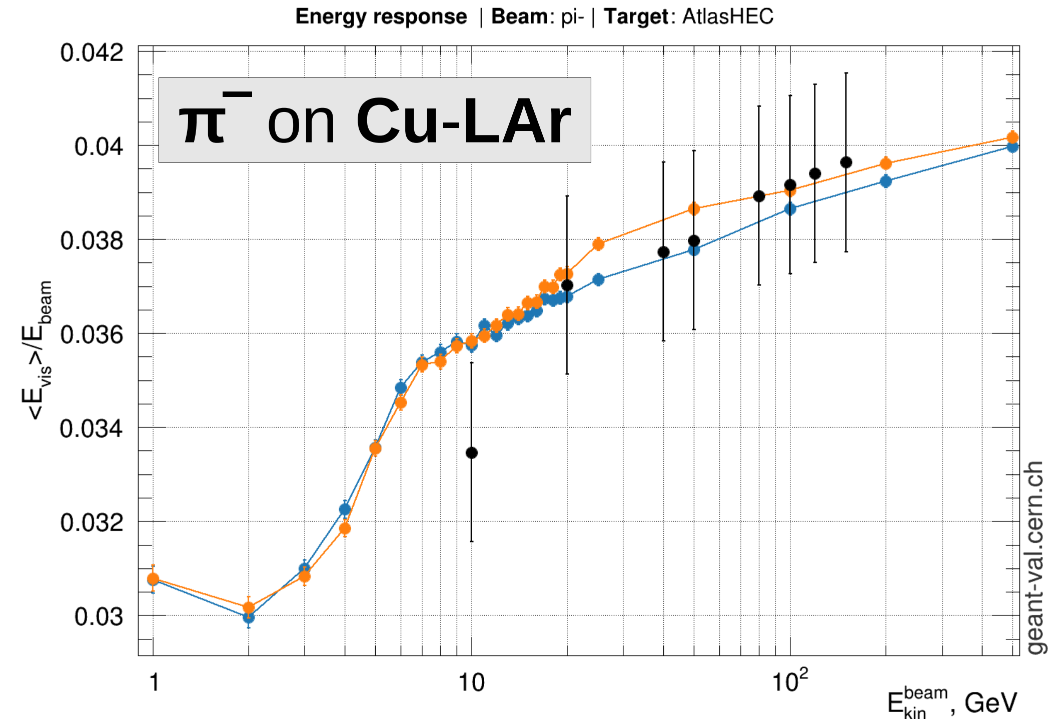
Note:

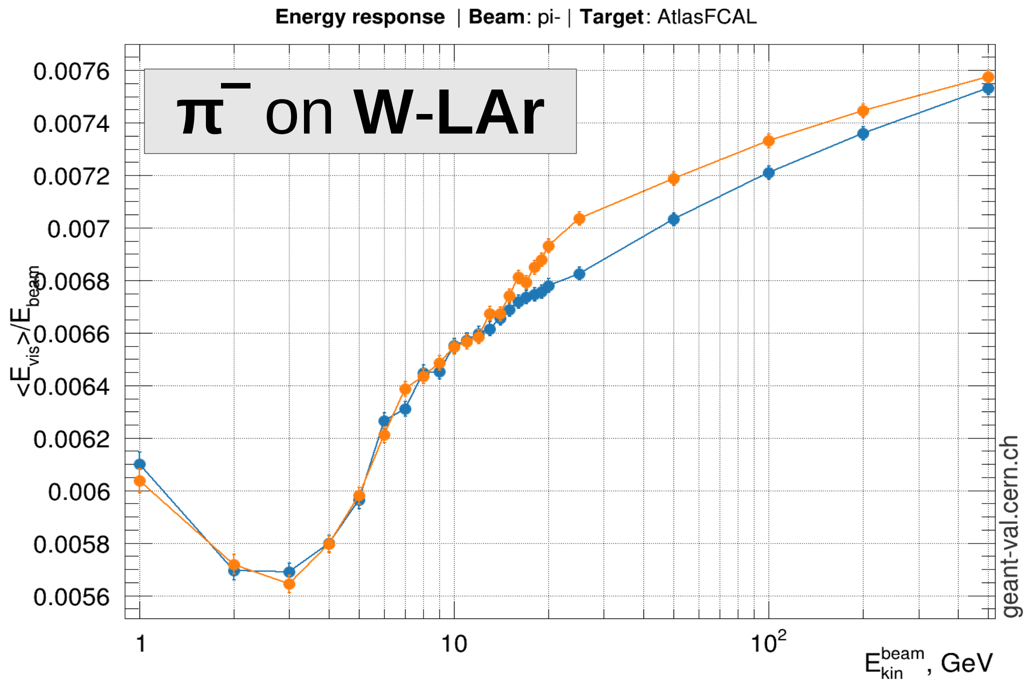
FTFP_BERT : [3, 6] GeV

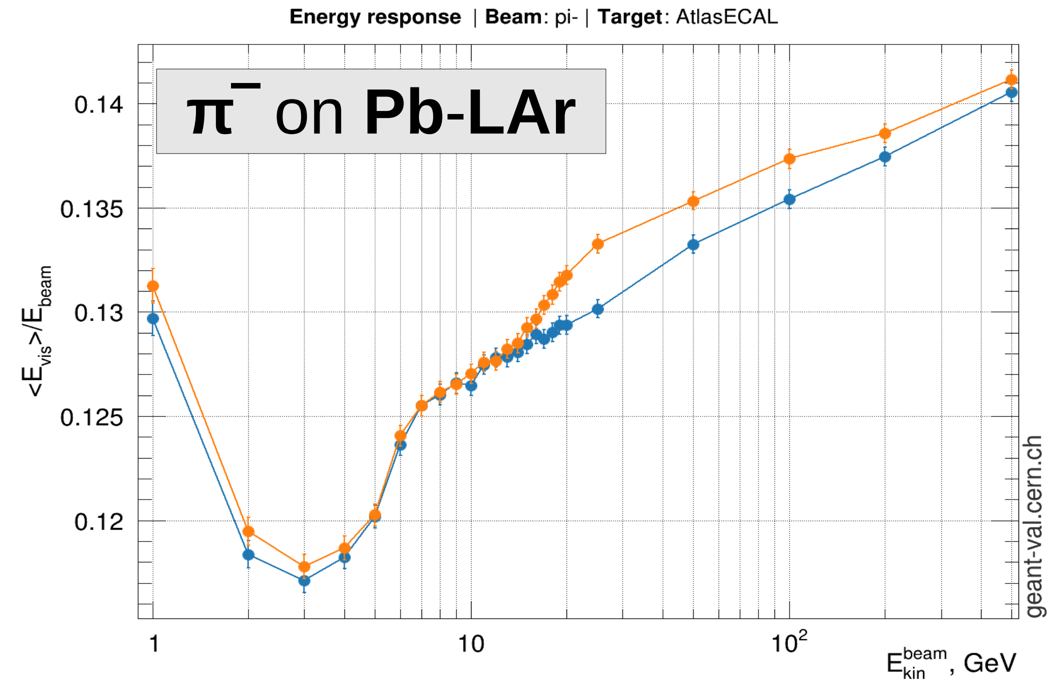
QGSP_FTFP_BERT : [3, 6] GeV ; [12, 25] GeV

Energy Response



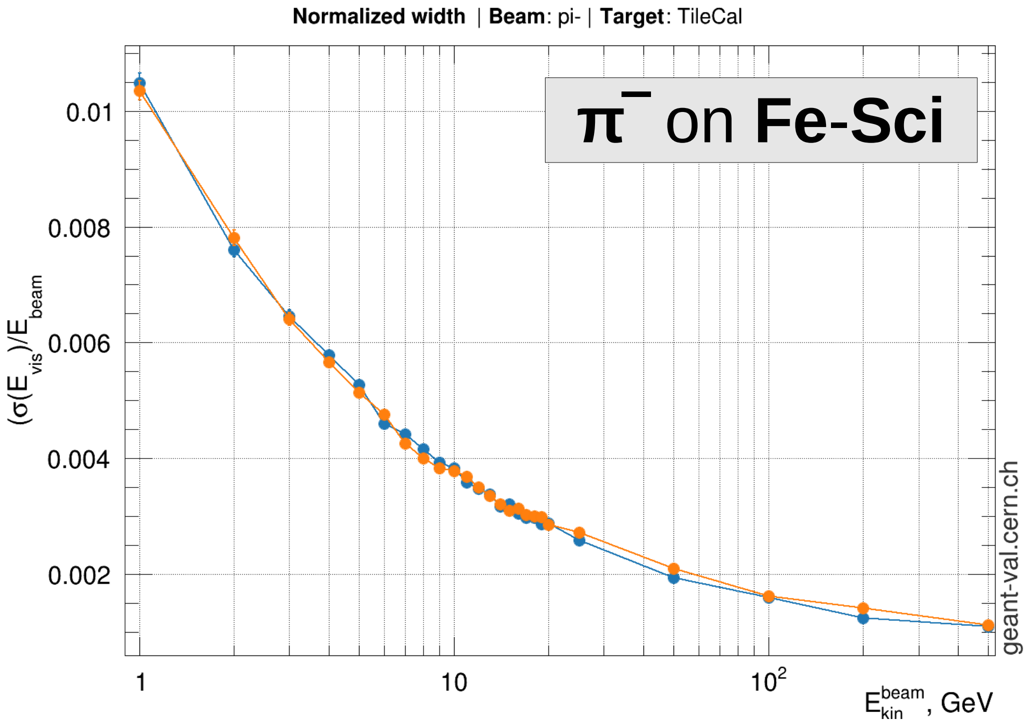


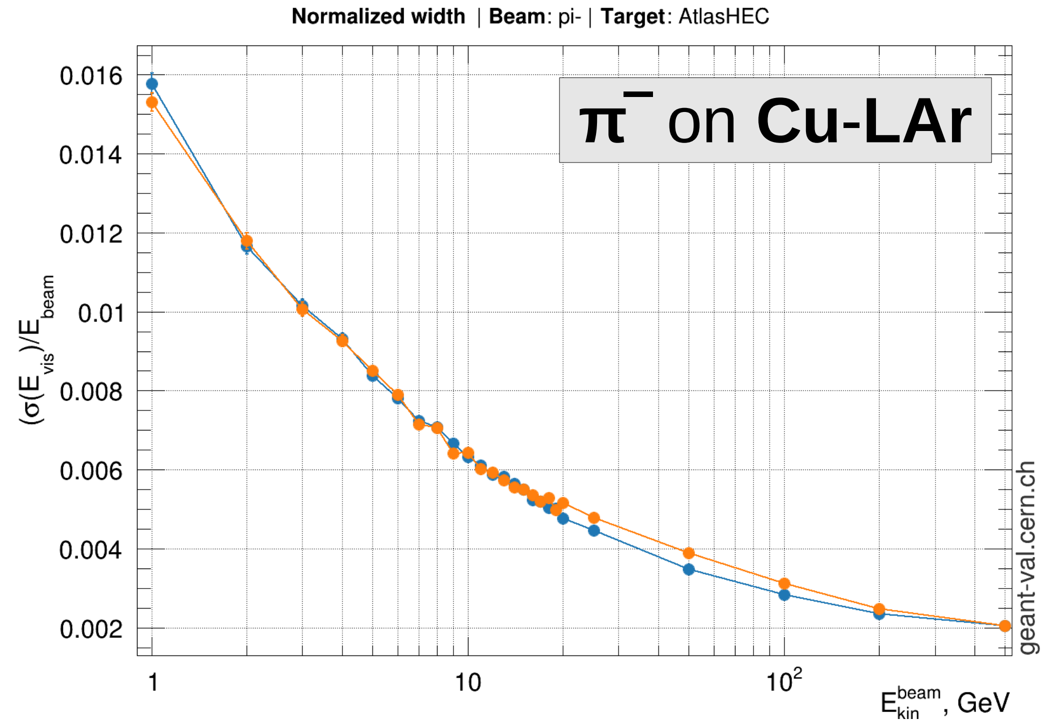


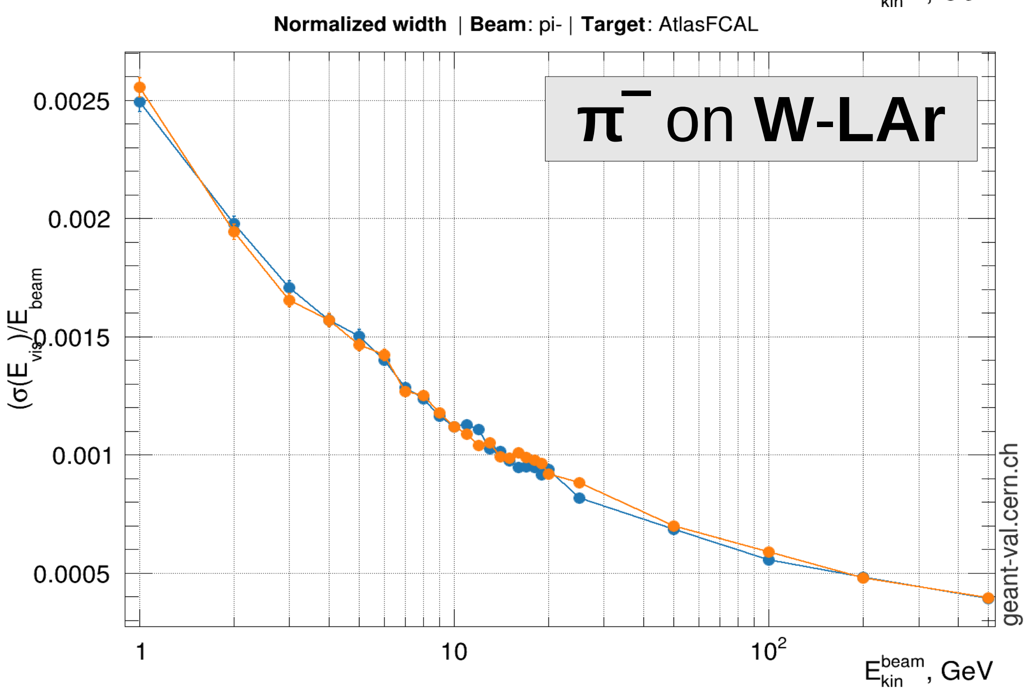


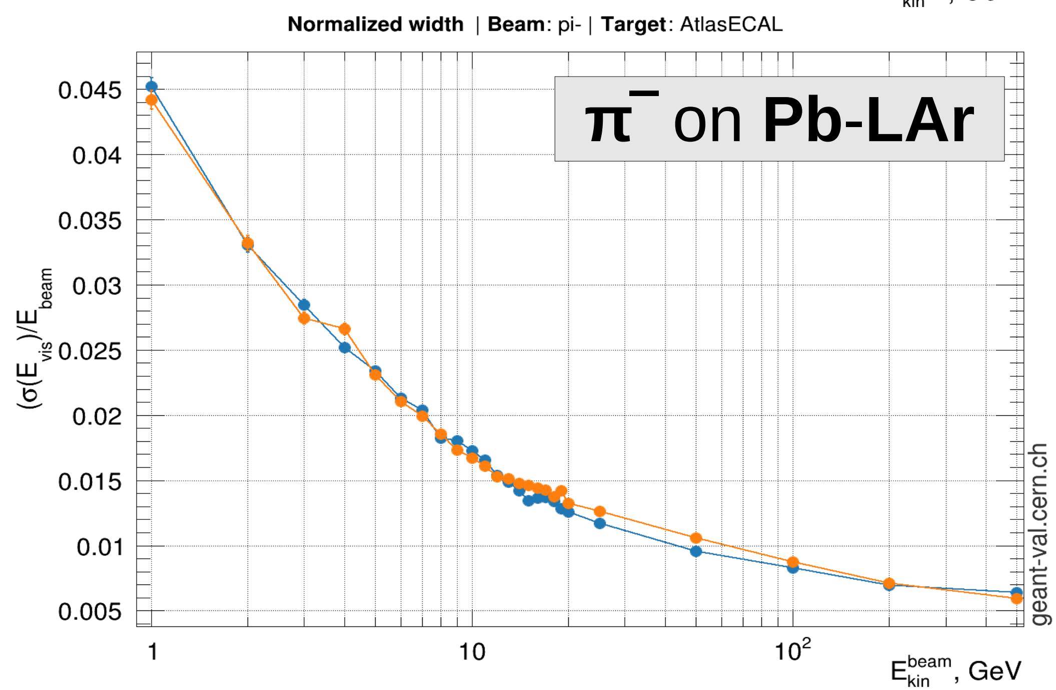
10.5.ref08 FTFP_BERT   10.5.ref08 QGSP_FTFP_BERT   10.5.ref08 FTFP_BERT   10.5.ref08 QGSP_FTFP_BERT

Energy Width



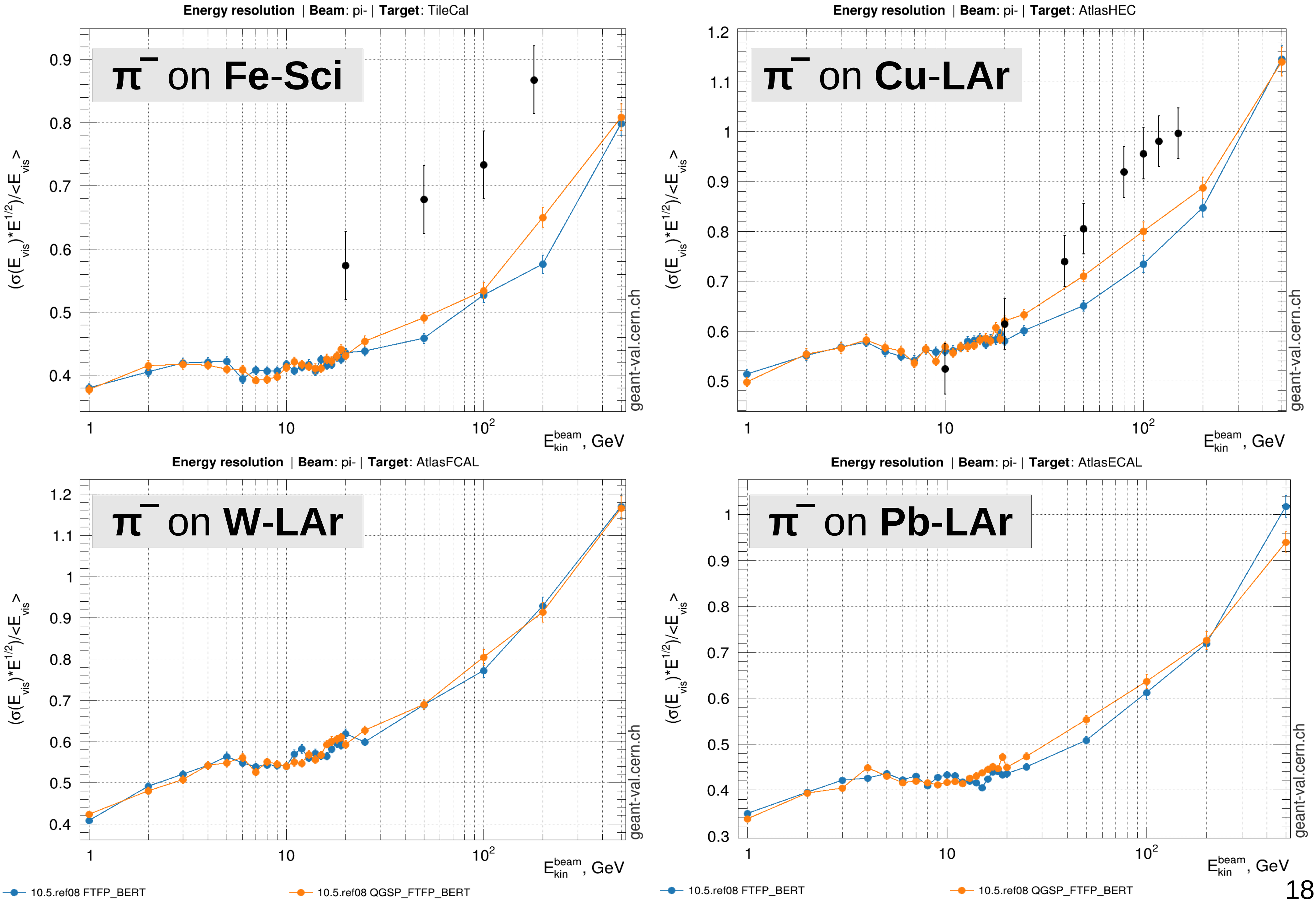




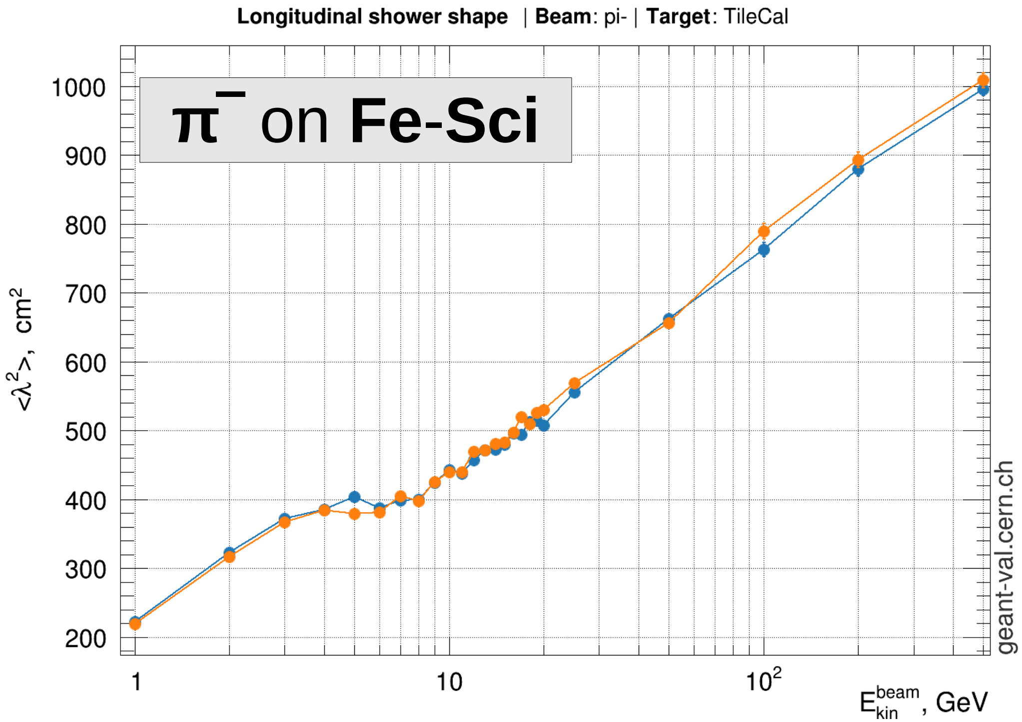


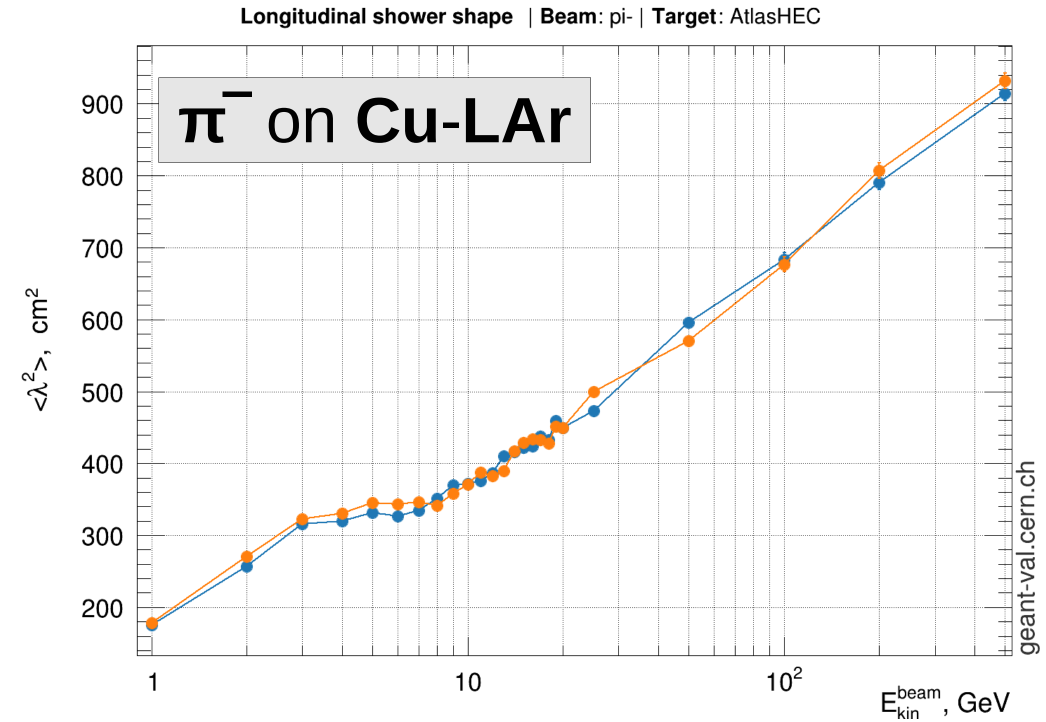
10.5.ref08 FTFP_BERT   10.5.ref08 QGSP_FTFP_BERT   10.5.ref08 FTFP_BERT   10.5.ref08 QGSP_FTFP_BERT

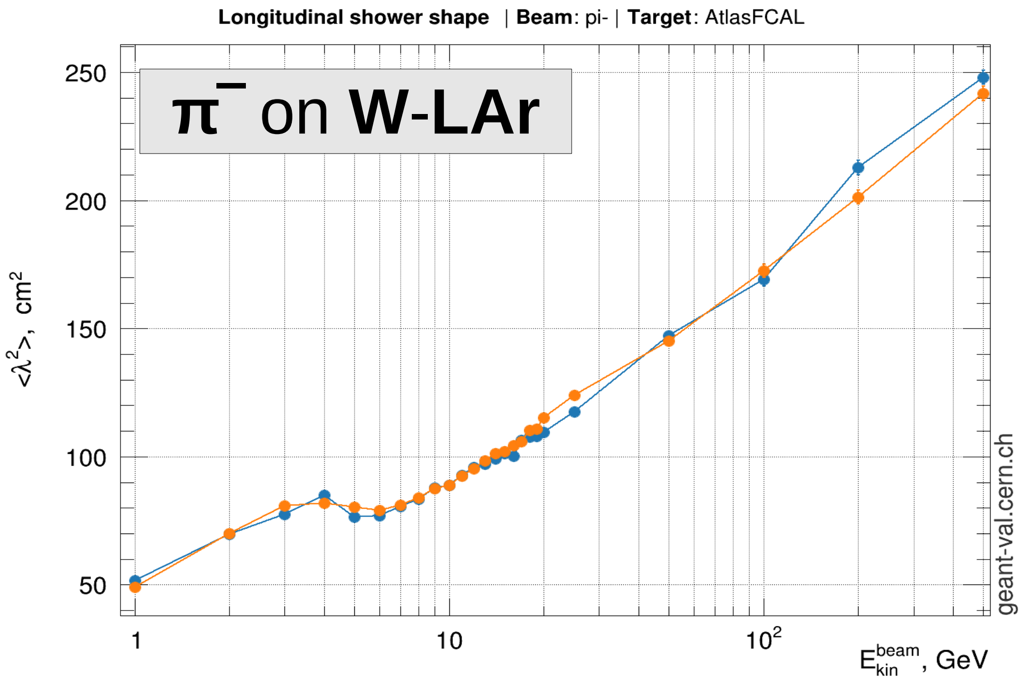
Energy Resolution

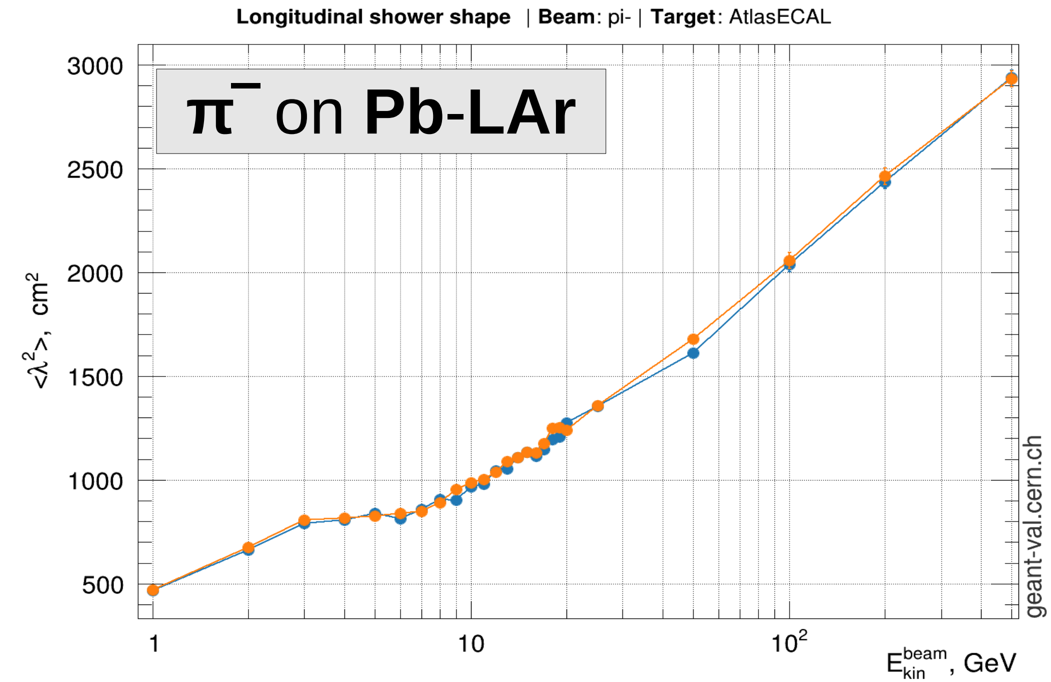


Longitudinal Shape





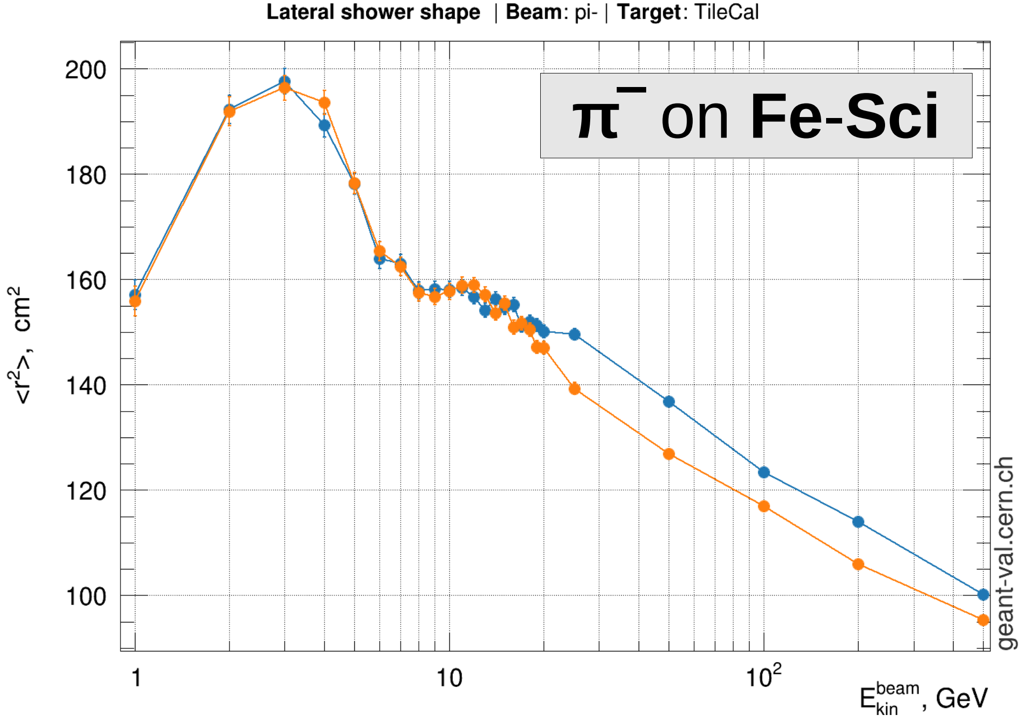


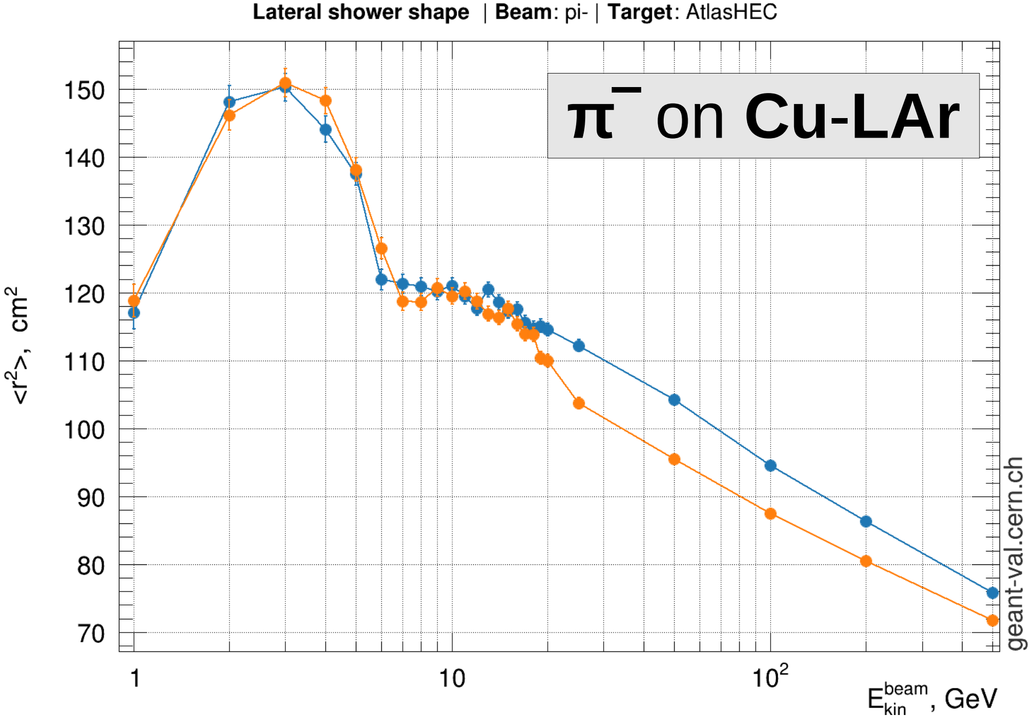


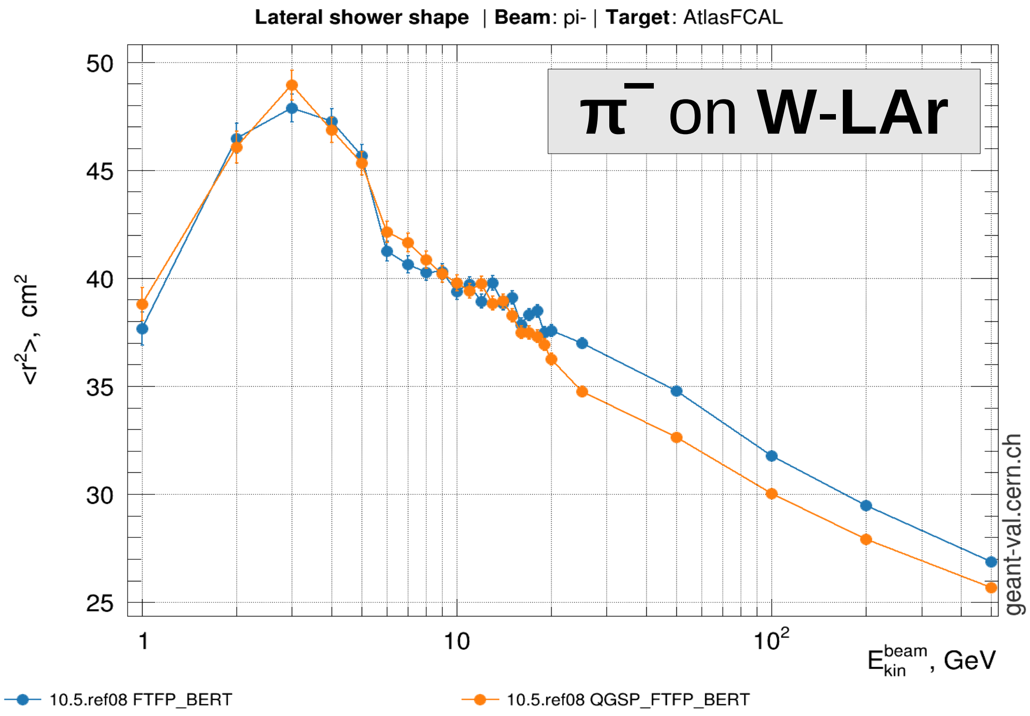
10.5.ref08 FTFP_BERT 10.5.ref08 QGSP_FTFP_BERT

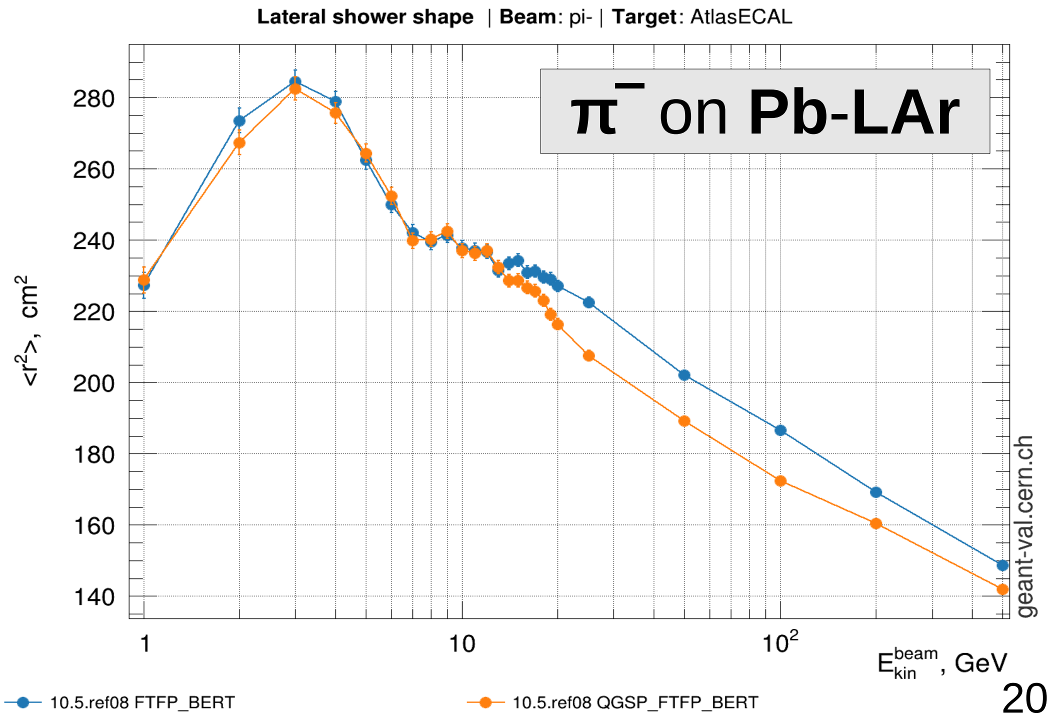
10.5.ref08 FTFP_BERT 10.5.ref08 QGSP_FTFP_BERT

Lateral Shape









String models for G4 10.6

String models for G4 10.6

- V. Uzhinsky is now working at CERN – since 1st August, for 4 months – on the string models. His current main task is to **extend the string models to charm and bottom hadrons** i.e. transporting and/or producing heavy hadrons
  - Interest in FCC (as well as LHC) experiments to simulate hadronic interactions of highly boosted charmed and bottom hadrons in the beam pipe and first layers of the silicon tracker
  - Grichine's Glauber-Gribov nuclear cross sections for heavy hadrons will be available in the coming release G4 10.6
    - Unfortunately, no experimental data is available !
- This extension will be common for FTF and QGS for the **string fragmentation** part, whereas the **string formation** part will be done separately for FTF and QGS
  - Starting first with FTF ; not yet clear how much will go in G4 10.6
  - Aida Galoyan will collect experimental data on charm production

First Look at
Very High Energies

Set-up

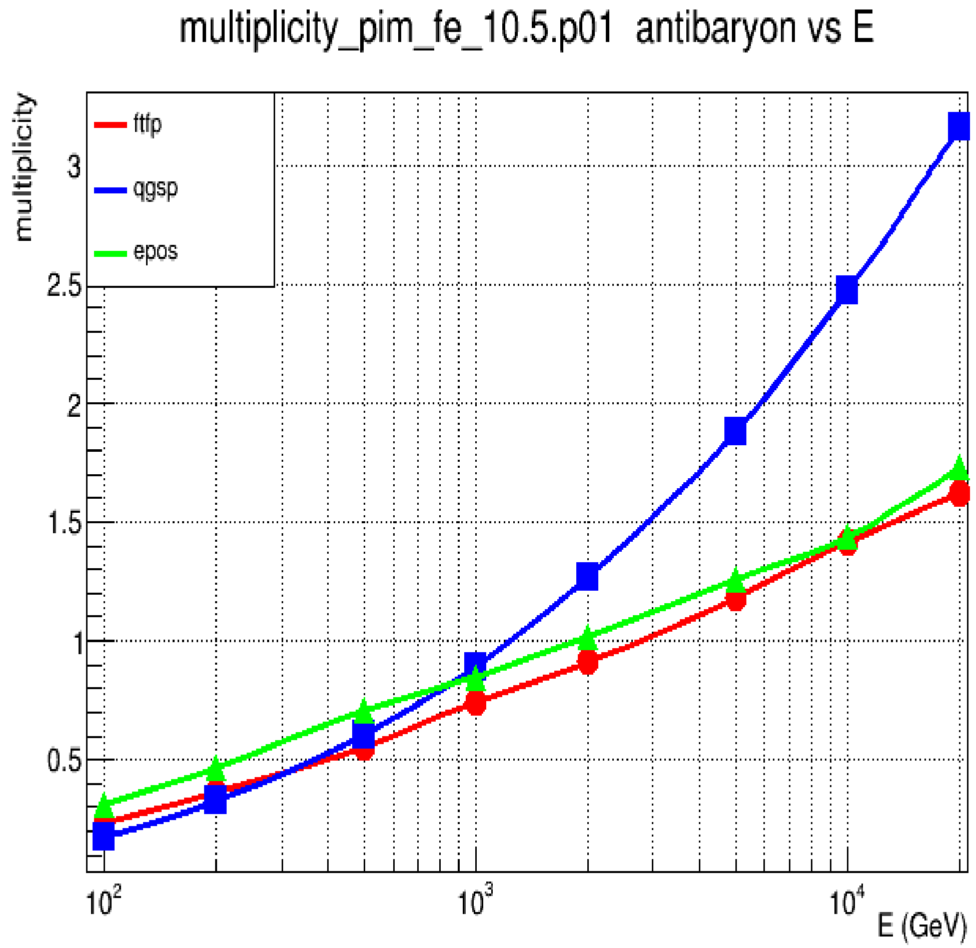
- Model-level test of hadron-nucleus interactions with
  - FTFP and QGSP from G4 10.5.p01
  - EPOS-LHC (via CRMC interface in Hadr02 in G4 10.5.p01)
    - Cosmic Ray Monte Carlo : *https://web.ikp.kit.edu/rulrich/crmc.html*
  - 10'000 collisions for each configuration
- Hadron projectile kinetic energies (lab frame):
  - 0.1 , 0.2 , 0.5 , 1 , 2 , 5 , 10 , 20 TeV
- Hadron projectile types:
  - Charged pions, kaons, nucleons, anti-nucleons
- Target nuclei:
  - Si, Fe, Cu, W, Pb
- Observables:
  - Multiplicity and energy flow for different categories of secondaries
    - For all angles and energies

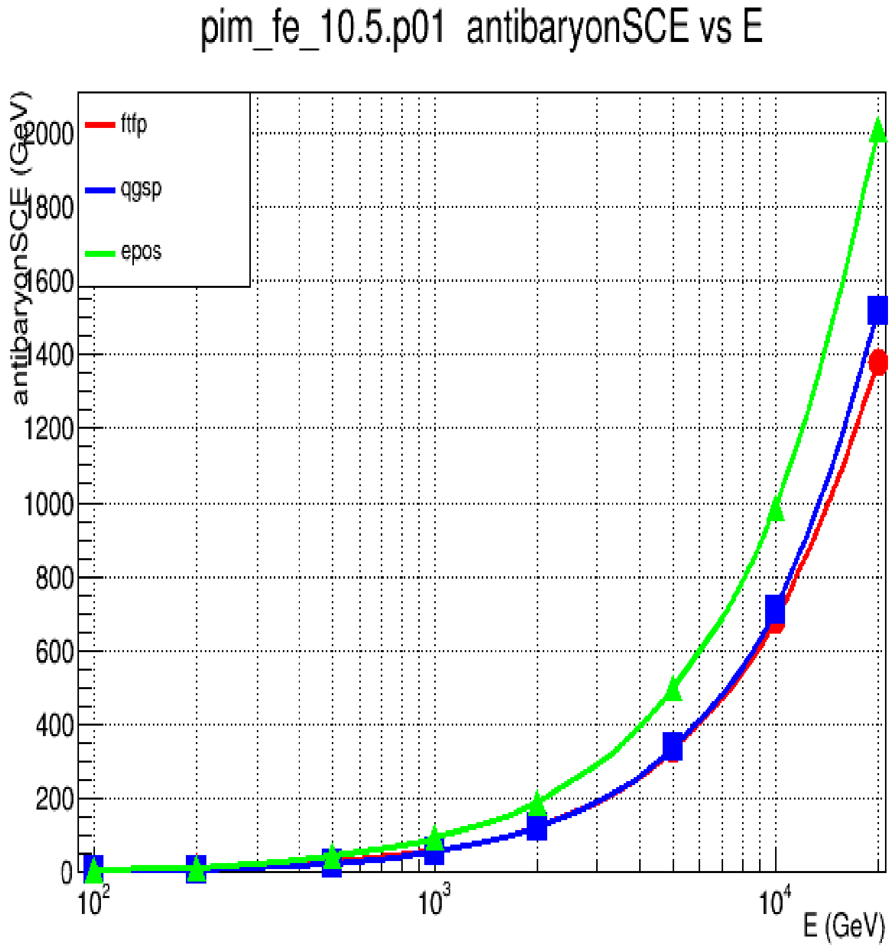
Antibaryon production

Multiplicity

π^- on **Fe**

Energy Flow



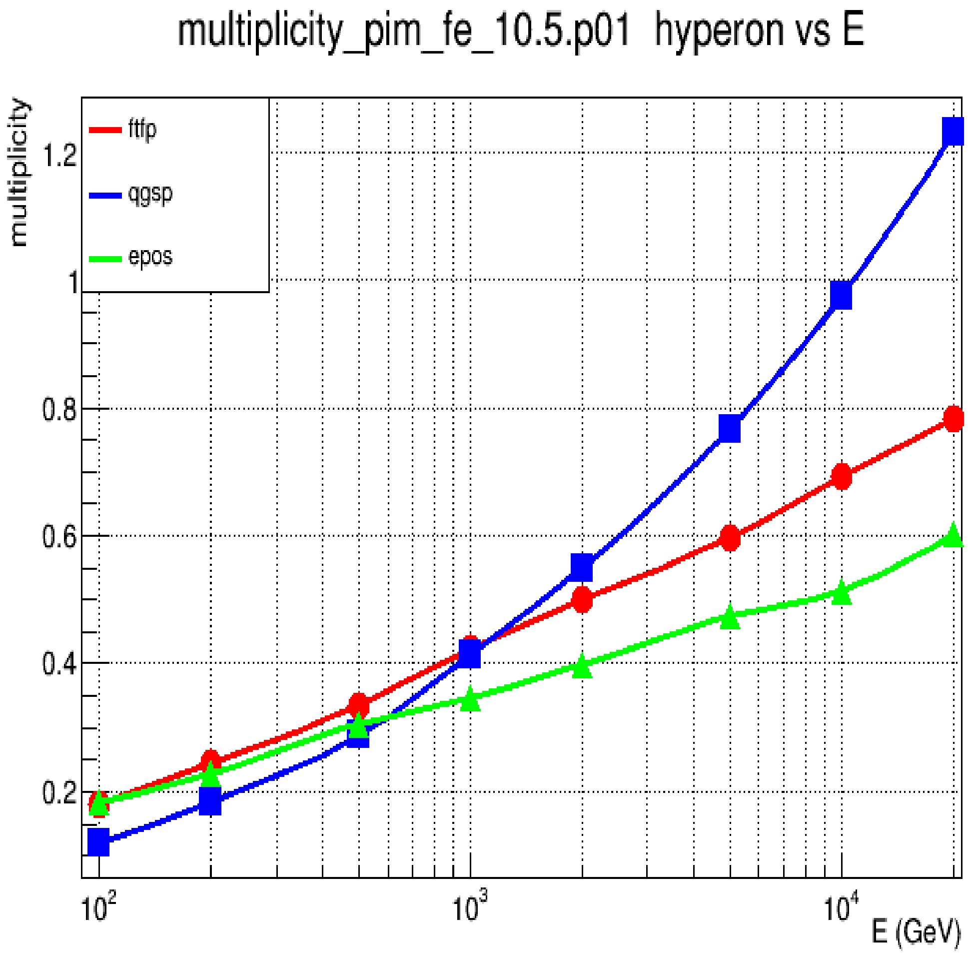


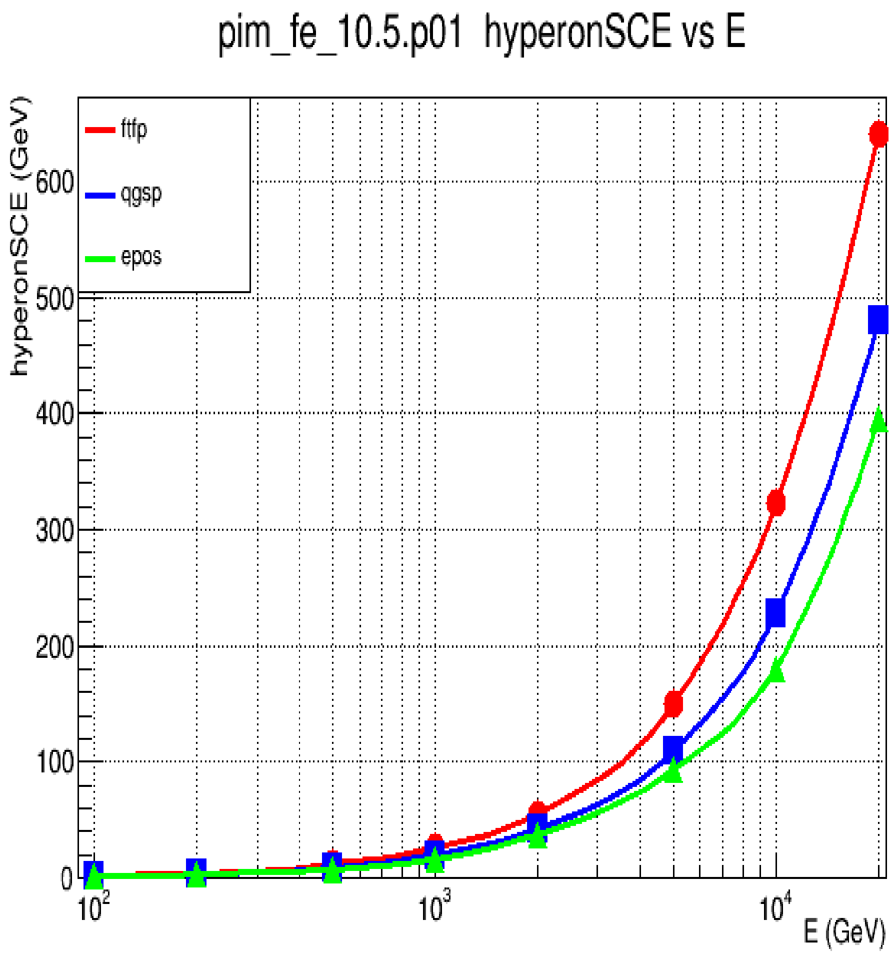
Hyperon production

Multiplicity

π^- on **Fe**

Energy Flow



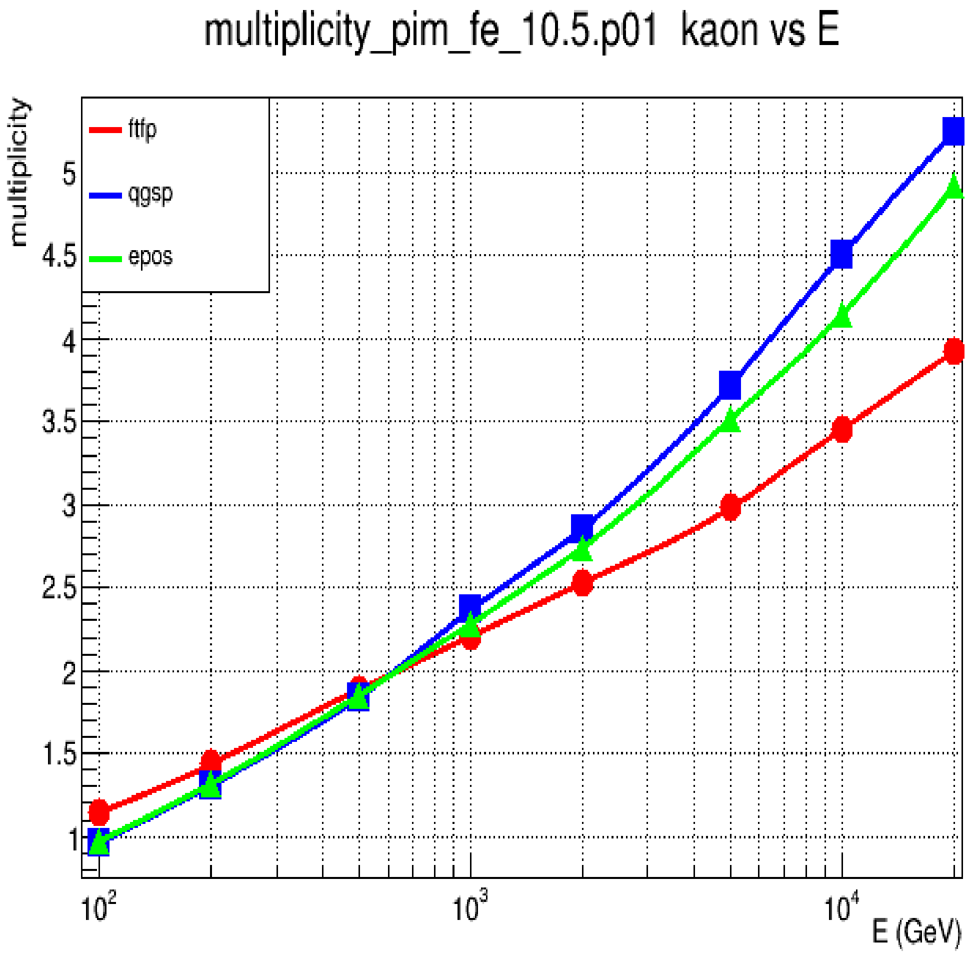


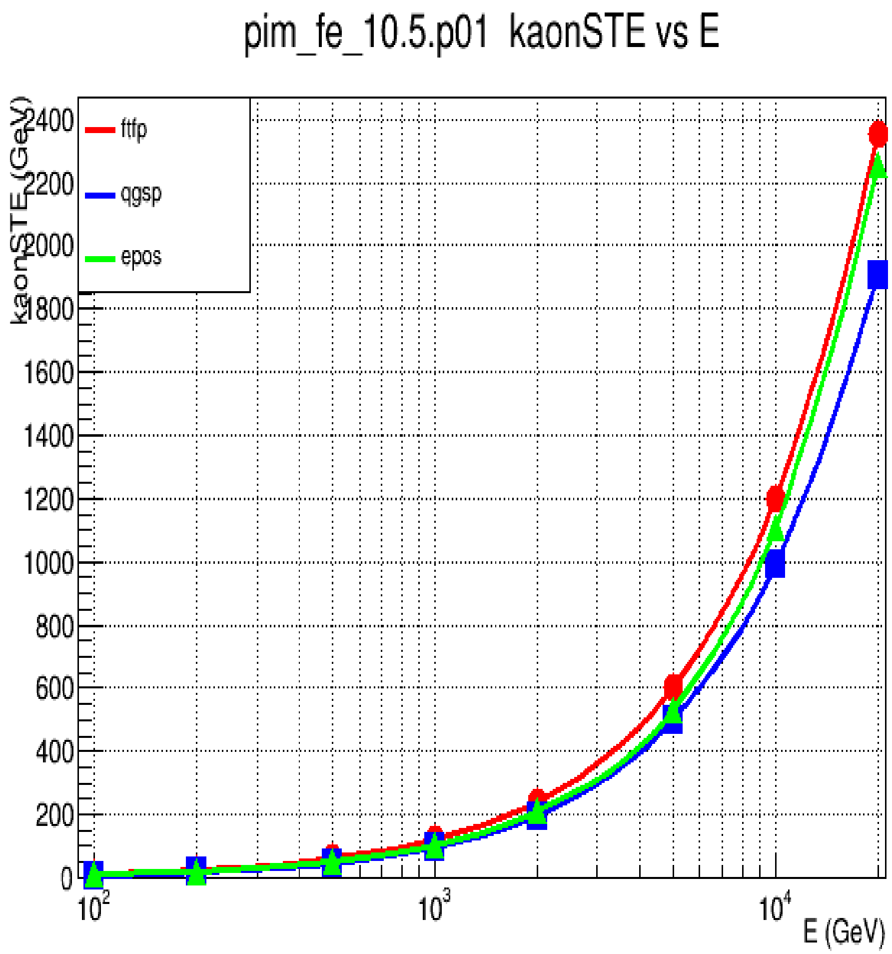
Kaon production

Multiplicity

π^- on **Fe**

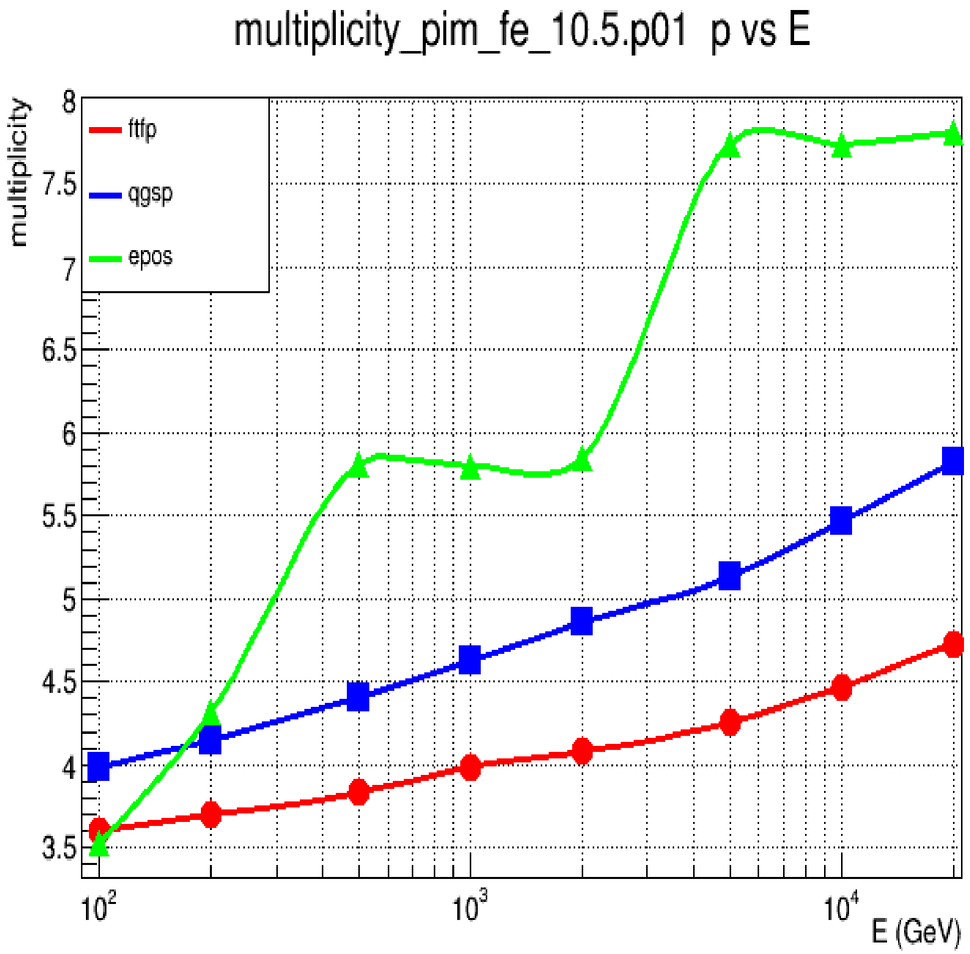
Energy Flow

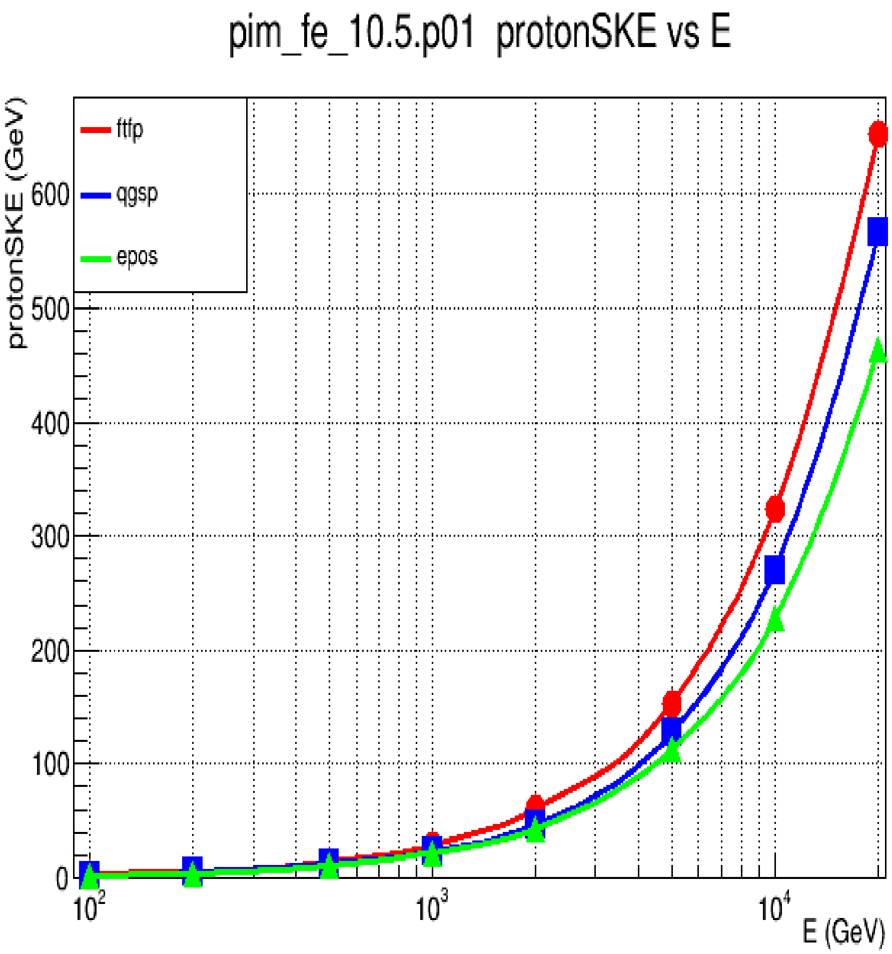




Proton production

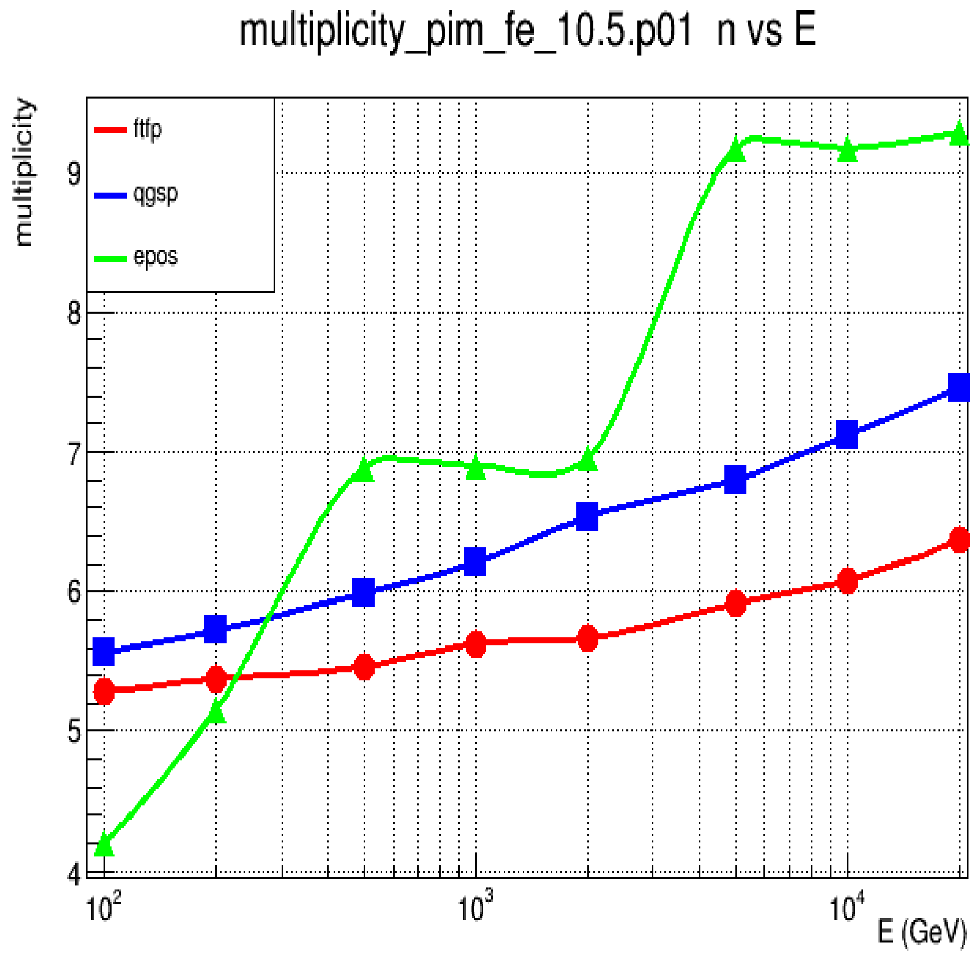
Multiplicity | π^- **on Fe** | **Energy Flow**

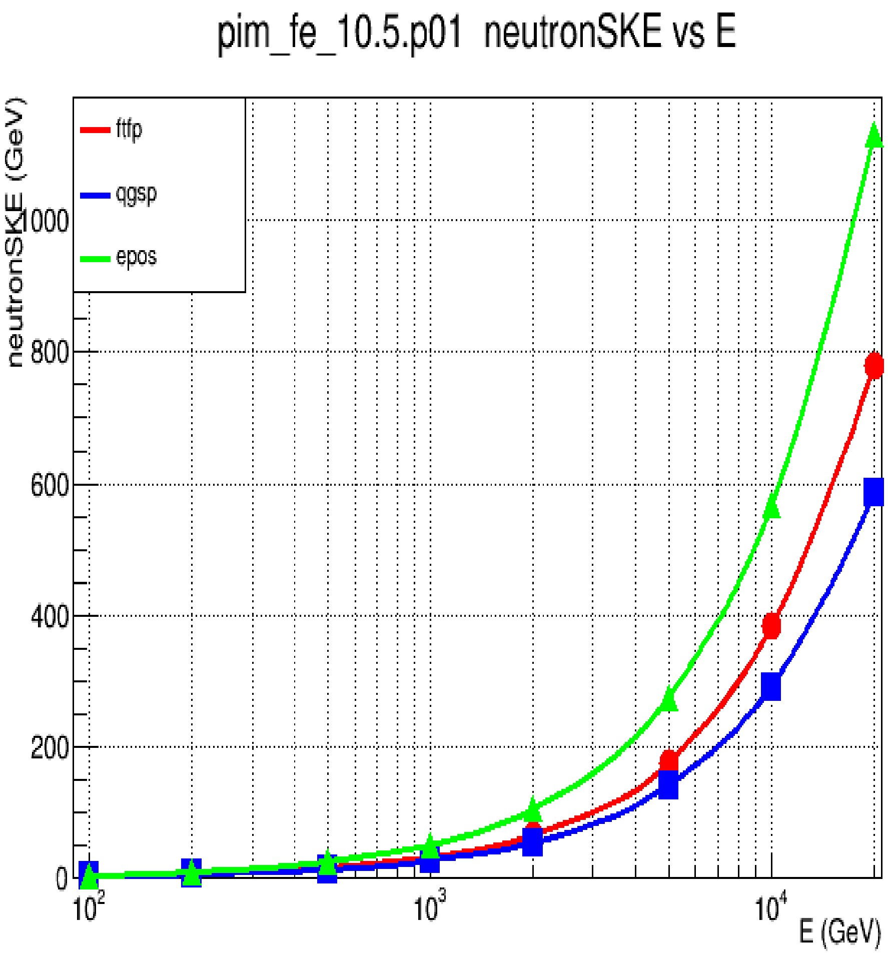




Neutron production

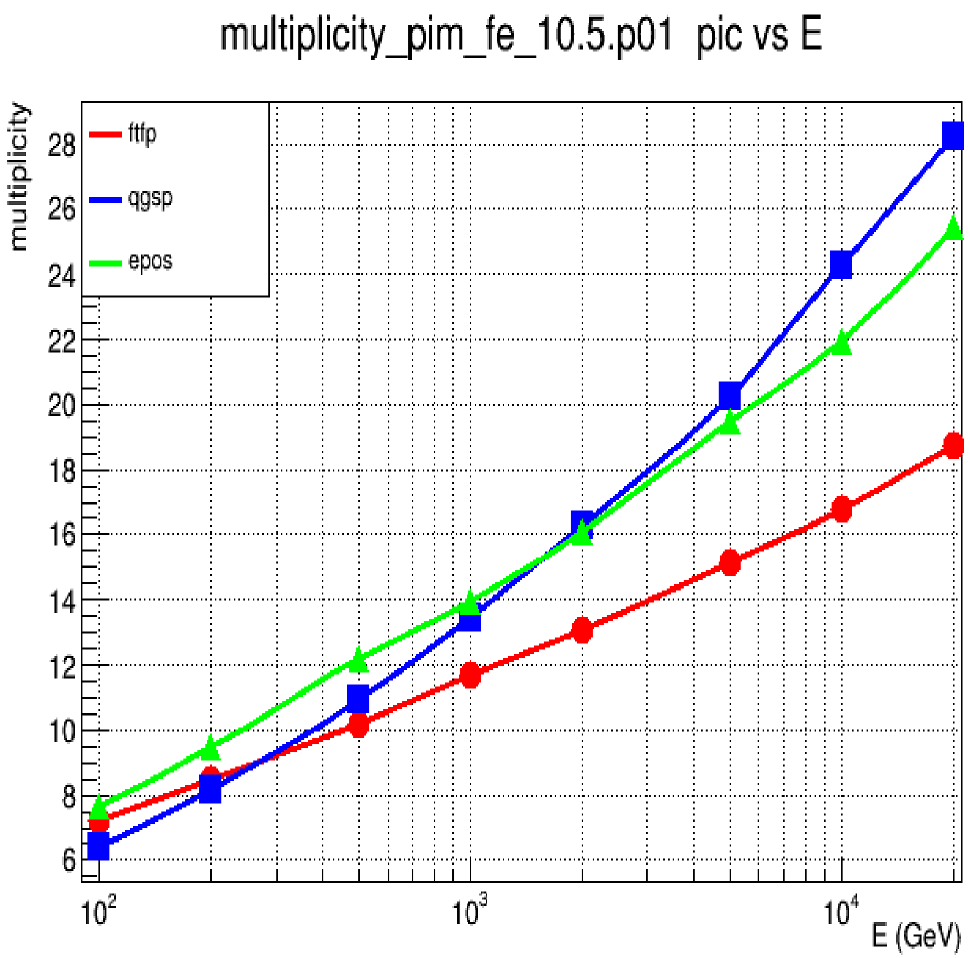
Multiplicity | π^- on **Fe** | **Energy Flow**

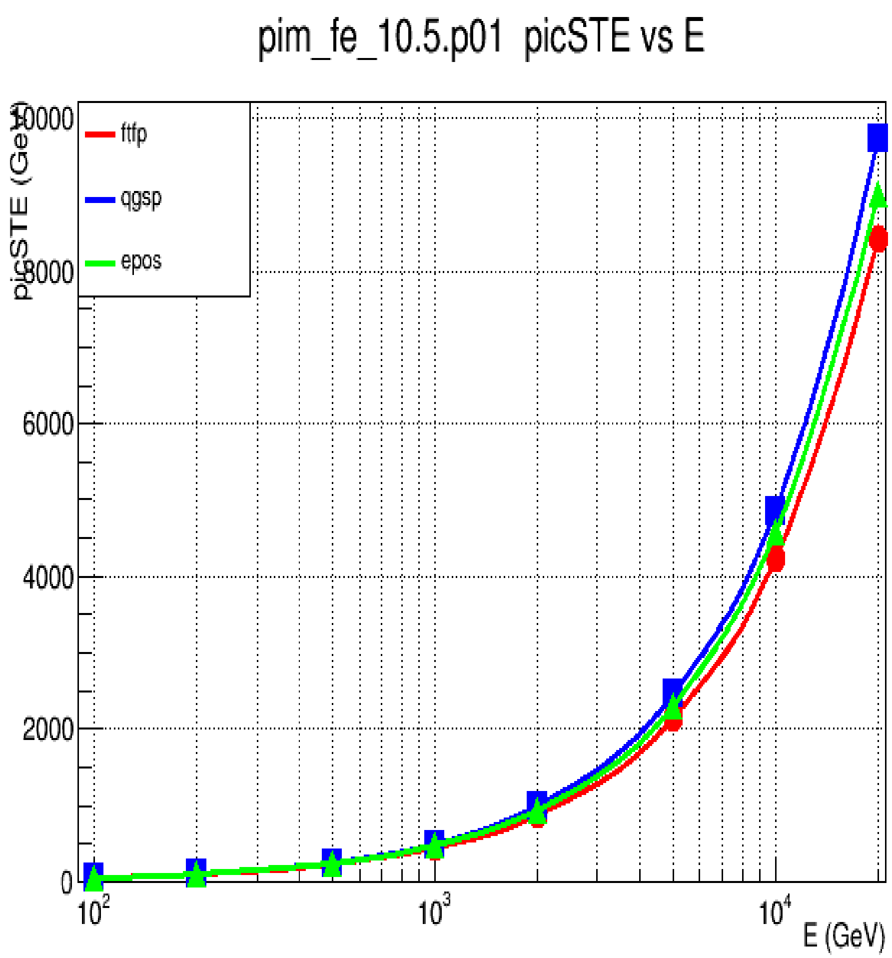




Charged Pion production

Multiplicity | **π^- on Fe** | **Energy Flow**





π° + η + η' + γ production

Multiplicity

π⁻ on Fe

Energy Flow