Hadronic Physics Highlights of Geant4 11.2

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Particles

- Particle properties have been updated according to PDG-2023
  - Only a few charm and bottom hadrons, and some hadronic resonances, have either masses or lifetimes (widths) changed by more than 1% with respect to the previous set of values based on PDG-2017

Hadronic Data Sets

- Updated :
  - G4INCL**1.2**
    - Added new data files for at-rest and in-flight antiproton annihilation
  - G4ABLA**3.3**
    - Updated atomic masses and binding energies
- Unchanged :
  - G4PARTICLEXS**4.0** (mandatory for FTFP_BERT)
  - G4SAIDDATA**2.0** (mandatory for FTFP_BERT)
  - G4ENSDFSTATE**2.3** (mandatory for FTFP_BERT)
  - PhotonEvaporation**5.7** (mandatory for FTFP_BERT)
  - RadioactiveDecay**5.6**
  - G4NDL**4.7**
  - G4TENDL**1.4**

Hadronic Cross Sections

- Improved initialization of several cross section classes
  - Consistent way to fill static data

- New cross-section class, *G4ChargeExchangeXS*, for charge exchange process
  - $\pi^- p \rightarrow \pi^\circ/\eta^\circ n$, $\pi^+ n \rightarrow \pi^\circ/\eta^\circ p$
  - $K^- p \rightarrow K^\circ n$, $K^+ n \rightarrow K^\circ p$
  - Motivations: background for searching new physics in NA64 experiment (CERN); possible more accurate simulation of hadronic showers in calorimeters
  - Not yet used in any physics list

FTF (Fritiof) String model

- Introduced a new, alternative set of parameters for FTF, meant to overcome the problem of too optimistic (*i.e.* narrow) pion shower energy resolutions in ATLAS calorimeters with respect to test-beam data
  - This new FTF tune is enabled only in the reference physics list FTFP_BERT_ATL (used by ATLAS)
  - For all other reference physics lists, the default set of FTF parameters remain unchanged

Intra-nuclear Cascade models

- **BERT** (Bertini-like cascade)
  - Stable, no developments
    - The most used intra-nuclear cascade model in HEP
- **BIC** (Binary Cascade)
  - Stable, no developments
    - Used in medical physics, and sometimes in HEP for evaluating systematic errors
- **INCLXX** (Liege cascade)
  - **Extension to antiproton annihilations**
    - Both at-rest and in-flight. Used by default in all INCLXX-based physics lists
    - Great interest of the CERN AD/ELENA experiments and some astroparticle experiments (*e.g.* GAPS) for low-energy anti-baryon annihilations
    - Ph.D. work by Demid Zharenov (CEA Saclay)

Nuclear De-excitation models

- New, improved **Fermi Break-Up** model
  - Driven by the long standing issue #2263 (reported by Igor Pshenichnov)
    - Wrong distributions of fragments for light ion interactions (medical and space applications): in general, physically, one expects that the higher the excitation energy the wider the list of open decay channels, and, hence, the larger fragment multiplicity. This was indeed correctly observed in G4 9.2, but not any longer in more recent versions of Geant4 (*e.g.* 10.4).
  - Higher number of fragments are now handled
  - Many more reaction channels are now considered
    - 5421 (now) *vs.* 991 (before)
- Technical improvements
  - For initialization
  - For print-out
  - For modern C++, more robust code, clean up and better comments

Coupling ABLA with Cascade and String models

- ABLA is an alternative nuclear de-excitation model available in Geant4
  - With respect to the Precompound/de-excitation used everywhere
- Before G4 11.2, it was possible to use it only with INCLXX
  - But not by default: *G4INCLXXInterface::SetDeExcitation(new G4AblaInterface)*
- Now in G4 11.2, it is possible to use ABLA also with BERT, BIC, FTF, QGS
  - BERT : *G4CascadeInterface::useAblaDeexcitation()*
  - BIC : *G4BinaryCascade(new G4AblaInterface)*
  - FTF & QGS : *G4TheoFSGenerator::SetTransport(new G4GeneratorPrecompoundInterface(new G4AblaInterface))*
  - New “experimental” (*i.e.* meant only for developers for testing) physics list, *QBBC_ABLA ,* to exercise the ABLA nuclear de-excitation
    - Similar to QBBC, but for charged pions and nucleons projectiles, ABLA is coupled to BERT, BIC, FTF and QGS

Light Ion QMD model

- New variant of the QMD (Quantum Molecular Dynamic) model, optimized for medical physics applications (*i.e.* light target nuclei and [30, 500] MeV/n)
  - Three lines of improvements:

    1. Updated Skyrme-type interaction
    2. Forming a realistic initial state of nuclei involved in the collision
       - Alpha-cluster structure : 12C − 3 alpha clusters ; 16O − 4 alpha clusters
    3. Tuned model parameters

  - Added an option in the ***Shielding*** physics list to use the new light ion QMD model, ***G4LightIonQMD***, instead of the default QMD model
    - *Shielding(true)*
    - Note: on-going validation and comparisons against the default QMD model for shielding-type of applications (*i.e.* heavy targets and projectile kinetic energies > 500 MeV/n)

DBRC (Doppler Broadening Rejection Correction)

- Improvement of ParticleHP : accurate modeling of neutron elastic resonant scattering in heavy nuclei by the use of DBRC algorithm
  - Relevant for the detailed simulation of nuclear reactors
    - Making Geant4 another step closer to MCNP and TRIPOLI
  - By default, it is switched off
  - It can be switched on, and its parameters can be set, via UI commands
    - */process/had/particle_hp/**use_DBRC***
    - */process/had/particle_hp/**SVT_E_max*** *value*
    - */process/had/particle_hp/**DBRC_A_min*** *value*
    - */process/had/particle_hp/**DBRC_E_min*** *value*
    - */process/had/particle_hp/**DBRC_E_max*** *value*

Code improvements of the ParticleHP package

- Major effort, started in G4 11.2, aimed to avoid duplications, improve and modernize the old C++ code, be consistent with what is done – *e.g.* for initialization and multi-threading – in other physics models.
  The goals are code maintainability and CPU performance.
  - For all HP-based reference physics lists, except for only one case, physics results remain unchanged
  - The only exception is QGSP_BERT_HP, where a few changes might affect the physics results
    - Different implementation of cross sections
    - On-the-fly Doppler broadening is not applied for neutrons with kinetic energies above 30 keV
    - Validation is still on-going
  - Renamed classes for capture from *G4ParticleHPCapture* to *G4NeutronHPCapture*. Removed unused *G4NeutronHP*.hh* headers
  - Revision of ParticleHP will continue in G4 11.3

Radioactive Decay

- Technical improvements to make it consistent with the implementation of both HP and nuclear de-excitation models
- The default value of the time threshold for radioactive decays of ions – above which these decays are ignored – has been changed
  - From 10^27 ns (corresponding to twice the age of the Universe) to **1 year**
    - To avoid surprising results (*e.g.* dependence on physics list and proton threshold) on energy depositions in thick targets, in the case that a time window is not explicitly set by users
  - For applications where radioactive decays of ions do play an important role, it is recommended to increase the default time threshold of these decays to a very high value, *e.g.* 1.0e+60 years
    - This can be done in one of the following equivalent three ways:

      1. */process/had/rdm/thresholdForVeryLongDecayTime 1.0e+60 year*
      2. *G4HadronicParameters::Instance()->SetTimeThresholdForRadioactiveDecay(1.0e+60*CLHEP::year)*
      3. *G4RadioactiveDecay("RadioactiveDecay", 1.0e+60*CLHEP::year)*

      In the examples, the first method is adopted.

Neutrino Physics

- Added new physics constructor for neutrino physics, *G4NeutrinoPhysics*, and its messenger
  - Neutrino physics can be activated on top of any reference physics list
- Introduced new process, *G4NuVacOscProcess*, for 3-flavor neutrino oscillation in vacuum
  - Oscillation in matter is planned for G4 11.3
- See “Physics Manual” for the UI commands and examples
  - Chapter 46, pages 439-441

Hadronic showers *(see plots in backup slides)*

- For all physics lists, hadronic showers in G4 **11.2** remain similar to those of 11.1
  - QGSP_BERT showers with respect to FTFP_BERT ones:
    - ~ 1-2% higher energy response
    - **~ 10% wider (*i.e.* less optimistic) energy resolution**
    - ~ 5% longer showers
    - ~ 7% narrower showers

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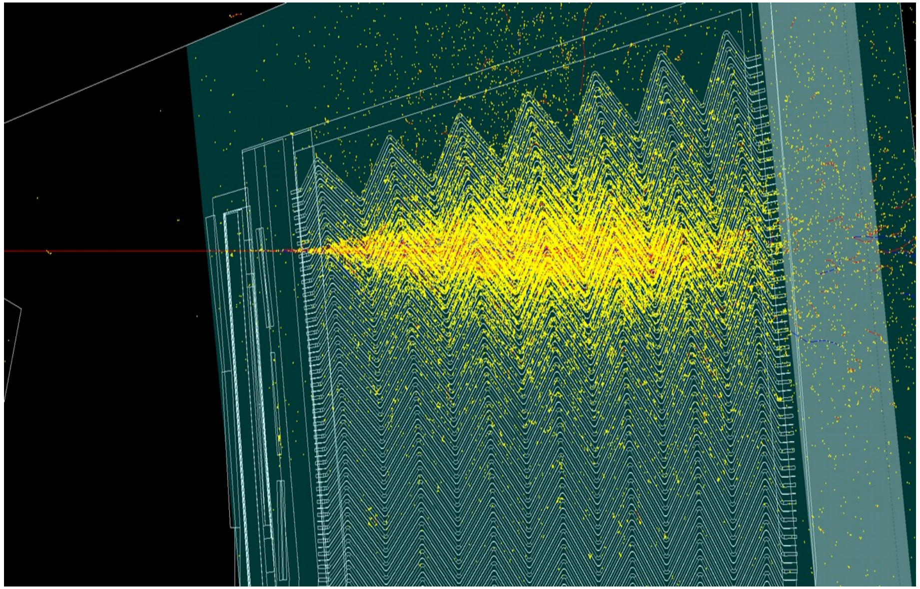
- The validation and testing suite of Geant4
- We rely heavily on it for all releases
  - For major, minor, patches and monthly development versions
- On-going work to extend its coverage
  - In particular, by importing calorimeter test-beams, *e.g.* **ATLAS HEC**, **ATLAS TileCal**, **CALICE SiW**, new **Dual-Readout** calorimeter, *etc.*
  - Added in 2023 also the ATLAS LAr barrel test, without data, useful for regression testing and for evaluating speeding-up solutions for EM physics



Examples related to Hadronic Physics

- ***FlukaCern***
  - New example showing how to get FLUKA hadron-nucleus inelastic physics – cross sections and final-states – from a Geant4 application, by using the new (Fortran) FLUKA.Cern interface to Geant4
    - *E.g.* it allows the comparison of hadronic showers between Geant4 and FLUKA

Backup slides

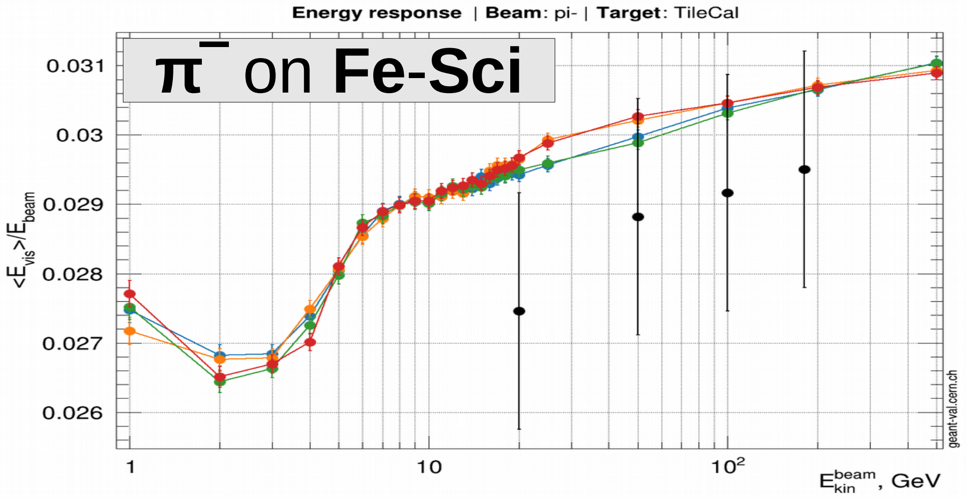
Pion– showers:

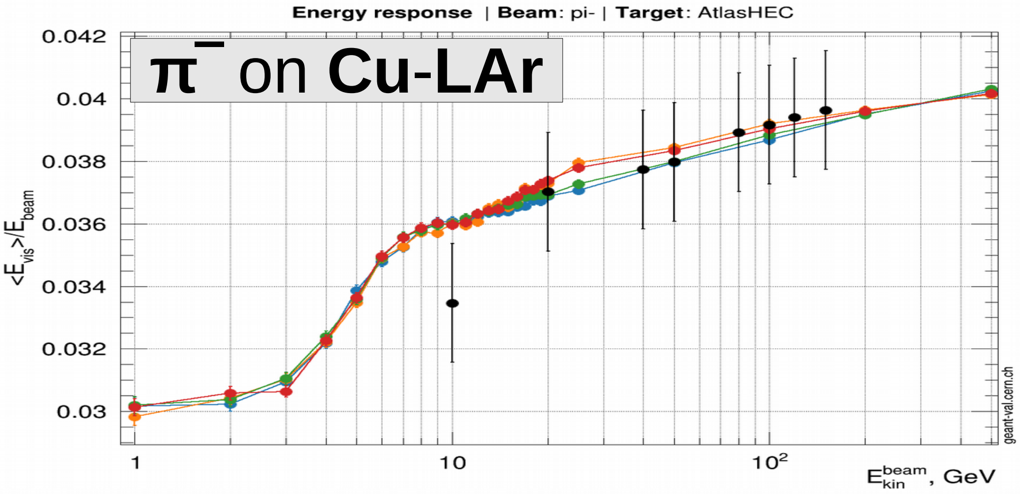
G4 11.2 FTFP_BERT
G4 11.1.p03 FTFP_BERT

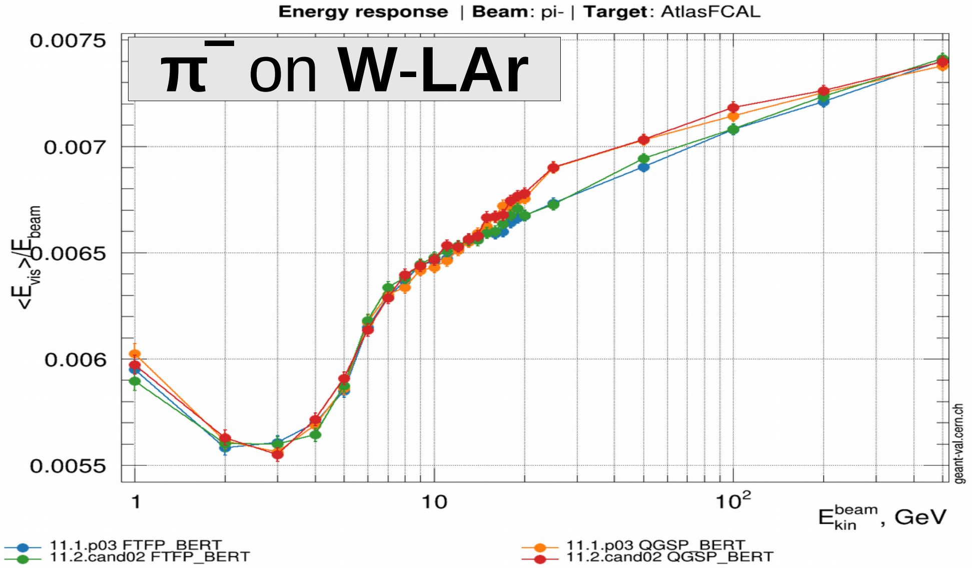
G4 11.2 QGSP_BERT
G4 11.1.p03 QGSP_BERT

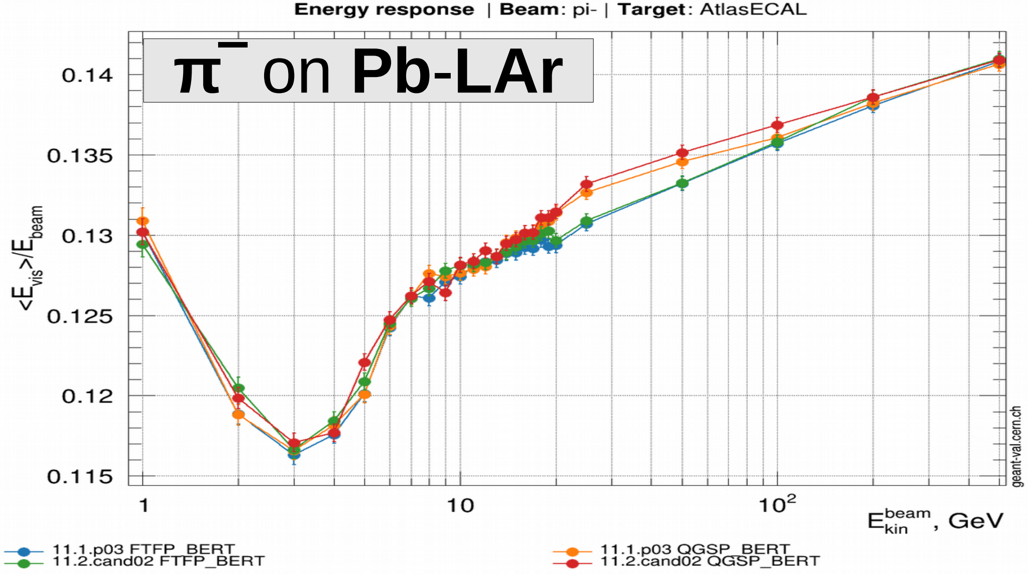
Note : conventional Birks treatment
(easier and no experimental h/e to fit !)

Energy Response

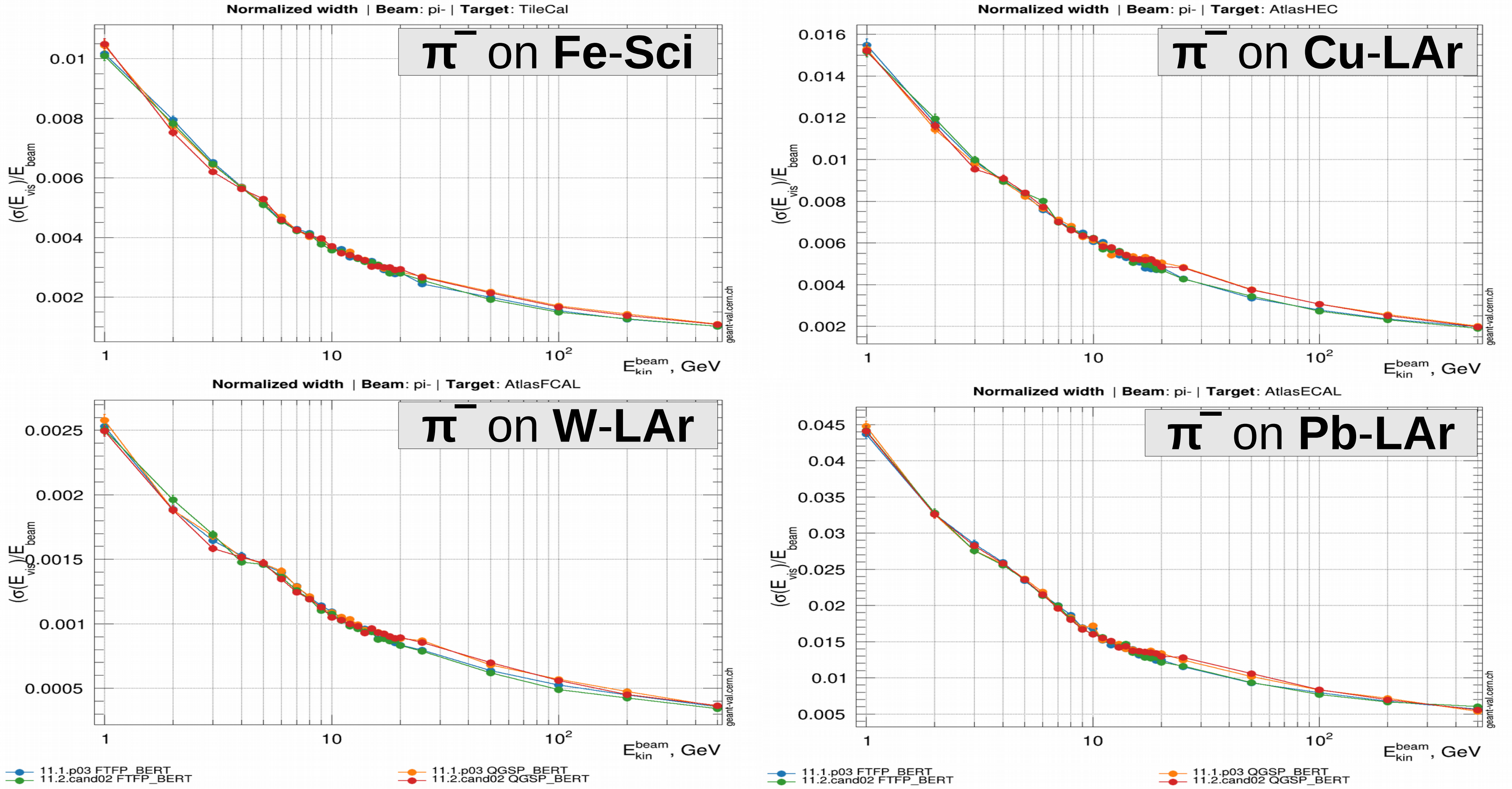




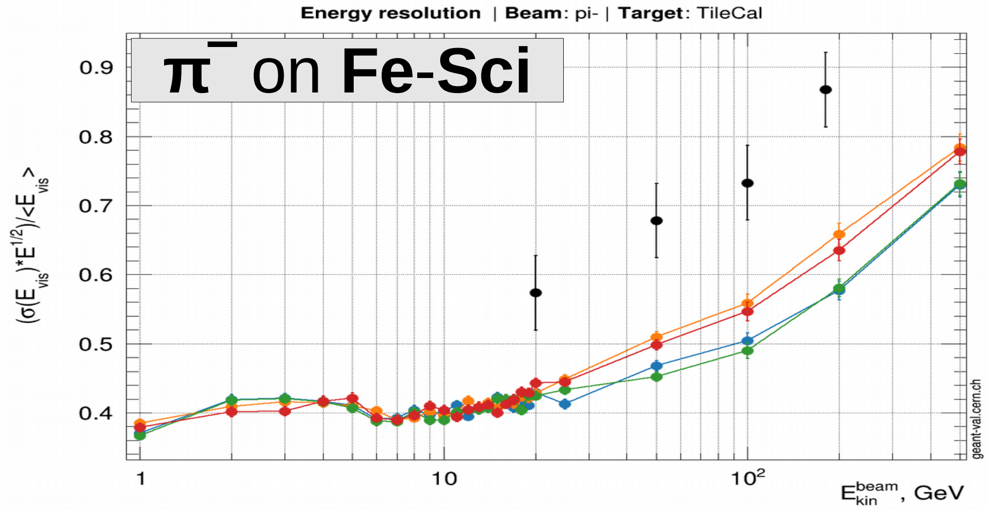


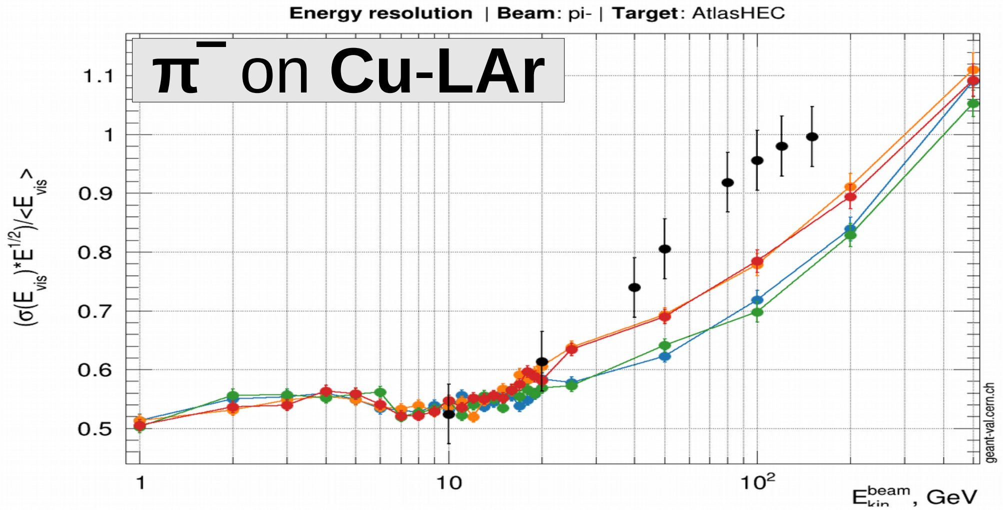


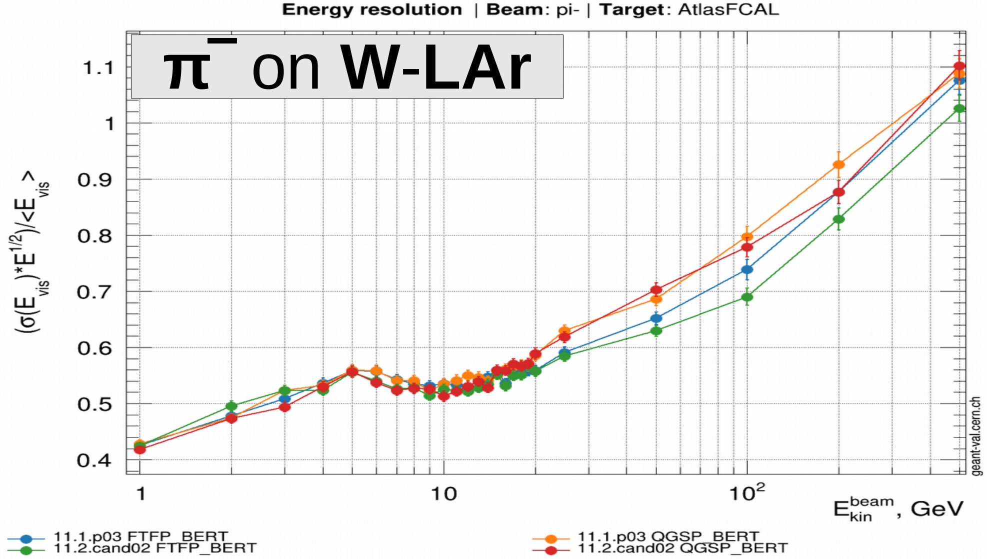
Energy Width

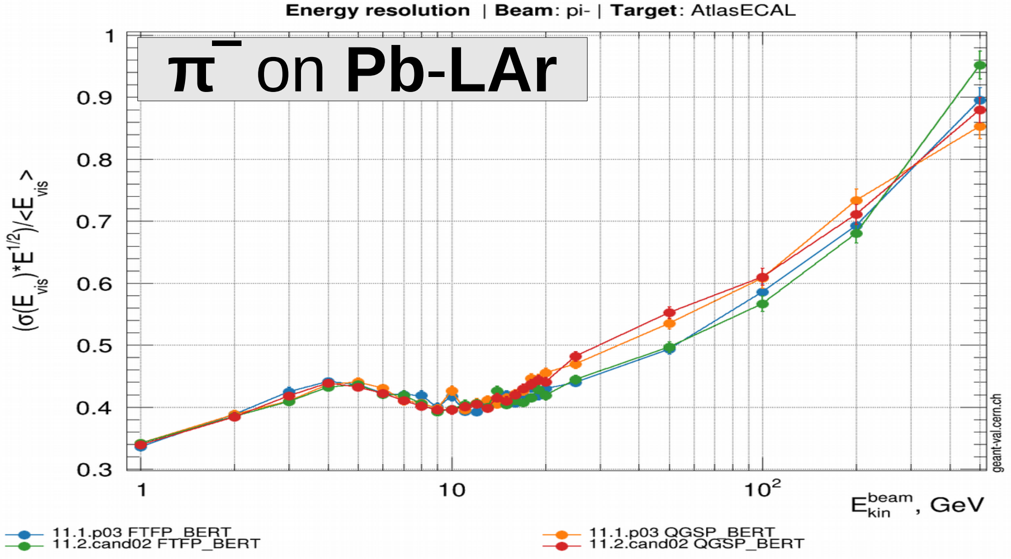


Energy Resolution

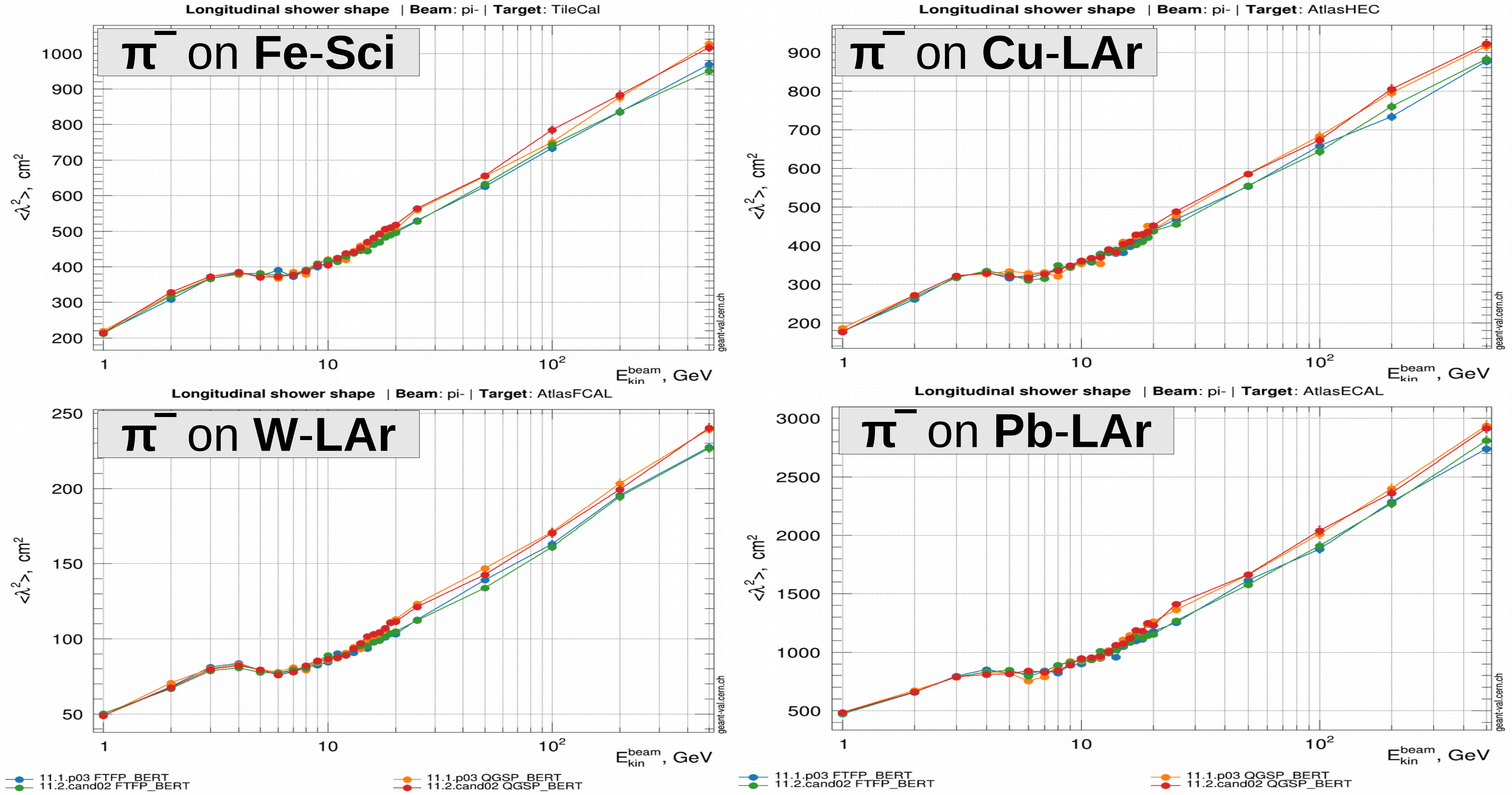








Longitudinal Shape



Lateral Shape