# Hadronic Highlights in G4 10.0

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# Fritiof (FTF) model

- Further improvements of hadron-nucleon diffraction dissociation
- Re-tuning of the model with an enlarged set of thin-target data
  - In particular, changed the probability of Δ-isobar production
    - From 5% to 10%
  - Switched off hadron-nucleus (target & projectile) diffraction
    - Favored by thin-target data
    - Possible destructive interference between the hadron-nucleon amplitudes...
- Extension to handle also **nucleus-nucleus** collisions
  - Above a few GeV per nucleon
  - Validation in progress

# Bertini-like (BERT) model

- Improved two-body final-state angular distributions for nucleon-nucleon and gamma-nucleon collisions
- Improved phase-space generation for multi-body final states
- Added capability to handle muon capture
- Several technical changes to adapt for multi-threading

# Isomer production

- Before G4 10, all excited nuclear fragments were forced to decay promptly
- Now, in G4 10, isomers (i.e. *long-lived meta-stable nuclides*) can be produced in hadronic interactions
  - Framework in place to create isomers, models are in charged to produce them (still under development and testing)
  - By default, only isomers with **$\tau_{1/2}$ > 1 μsec** are considered
  - Optionally, more excited nuclei can be produced by setting **G4ENSDFSTATEDATA** to point to the new data set of nuclei properties from the Evaluated Nuclear Structure Data File, G4ENSDFSTATE-1.0
  - The produced isomers are decayed only if **G4RadioactiveDecayPhysics** is activated
    - Not the case for most physics lists

# Photon Evaporation and Radioactive Decay

- Several changes and improvements in both **de_excitation** (in particular in photon_evaporation) and **radioactive_decay**
  - To allow the production of isomers
  - To be multi-threaded safe

- New libraries
  - G4PhotonEvaporation-3.0 (for all cases)
  - G4RadioactiveDecay-4.0 (if radioactive decay is used)

# NeutronHP

- It is now capable of reading compressed data files
  - Reduced significantly the size of the G4NDL library
    - From (G4 9.6) **G4NDL4.2** : **1.7 GB** (1.2 GB without ThermalScattering)
    - To (G4 10.0) **G4NDL4.4** : **0.5 GB** (including ThermalScattering)
- A new verbosity control allows the suppression of warning messages
- Introduced a new fission fragments generator
  - Developed by Brycen Wendt
  - Not yet used by default

# Removed models
## (declared obsolete in G4 9.6)

- **CHIPS** package
  - Kept a few components
    - Quasi-elastic, cross sections, electro-nuclear e -> γ* -> γ
  - Replaced by Fritiof + Bertini in physics lists
    - Nuclear capture of negatively charged hadrons
    - Gamma- and electron-nuclear

- Parameterized (Gheisha-like) **LEP/HEP** models
  - Replaced with Fritiof + Bertini in physics lists
    - Not needed for FTF-based physics lists
    - For QGS-based physics lists, this could become unnecessary if the QGS model will be extended to lower energies
    - Fission process has been removed
      - Except for the HP-based physics lists, where the parameterized model G4LFission is kept and used only above 19.9 MeV

# Neutron Capture

- Improved neutron capture simulation
  - Cross section: G4NeutronCaptureXS (instead of Gheisha)
  - Final-state model: G4NeutronRadCapture (instead of G4LCapture)

- Already used by QBBC and FTFP_BERT_TRV
- HP-based physics lists continue to use HP capture
- The main impact is for tungsten calorimeters
  - Because the neutron capture cross section is much bigger in tungsten than in iron, copper, lead

# Neutron inelastic cross sections

- Replaced the Barashenkov neutron inelastic cross section with "**NeutronXS**" below 20 MeV
  - "NeutronXS" is a fast approach based on neutronHP
    - "group-wise": average xsec per bin of neutron kinetic energy
  - Closer to data than Barashenkov

- Already used by QBBC and FTFP_BERT_TRV
- Of course, HP-based physics lists continue to use HP inelastic cross sections

# Physics lists

- New neutron capture, and low-energy neutron inelastic xsec
  - For non-HP physics lists
- Replaced LEP with FTFP + BERT in QGS-based P.L.
- All EM variants of the physics lists
  - _EMV , _EMX , _EMY , _EMZ , _LIV , _PEN

  available only through **G4PhysListFactory**
- New physics lists (based on INCL++):
  - QGSP_INCLXX_HP , FTFP_INCLXX , FTFP_INCLXX_HP
- Removed obsolete physics lists:
  CHIPS, CHIPS_HP , QGSC_BERT , QGSC_CHIPS , QGSP_BERT_CHIPS , LHEP , LHEP_EMV , QGSP , QGSP_QEL , QGSP_BERT_TRV , QGSP_BERT_95 , QGSP_BERT_95XS , QGSP_FTFP_BERT_95 , QGSP_FTFP_BERT_95XS

# Hadronic showers *(see plots in backup slides)*

- Hadronic showers in G4 **10.0** are similar to those in G4 9.6
  - Exception for **tungsten** calorimeters
    - Lower response and narrower lateral shape
    - Due to the improved neutron capture (xsec & final state)
    - Now closer to FTFP_BERT_HP
- **FTFP_BERT** our recommended HEP physics list
  - To consider also the variant **FTFP_BERT_TRV** and **QBBC**
    - Smoother (because of the wider transition region **3 – 12 GeV**)
    - For QBBC, also use of Binary Cascade (BIC) for protons and neutrons below 1.5 GeV

# Summary

Continued the **consolidation** of hadronic physics - **models**, **cross sections**, and **physics lists** - and adapted for multi-threading

- Improvements and extensions in BERT and FTF
- Enabled production of **isomers**
  - Revision of ions, de-excitation, and radioactive decay
- Removed CHIPS and LEP/HEP
- Improved neutron capture
- Improved low-energy neutron inelastic cross sections
- Expected improvements of FTFP_BERT hadronic showers in tungsten calorimeters

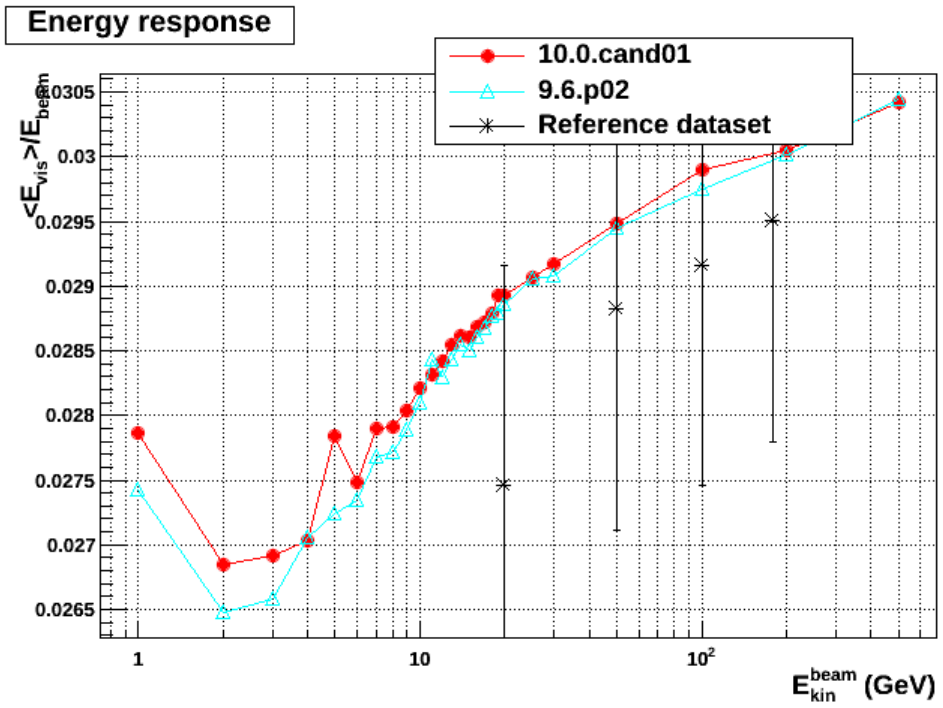
# Backup slides

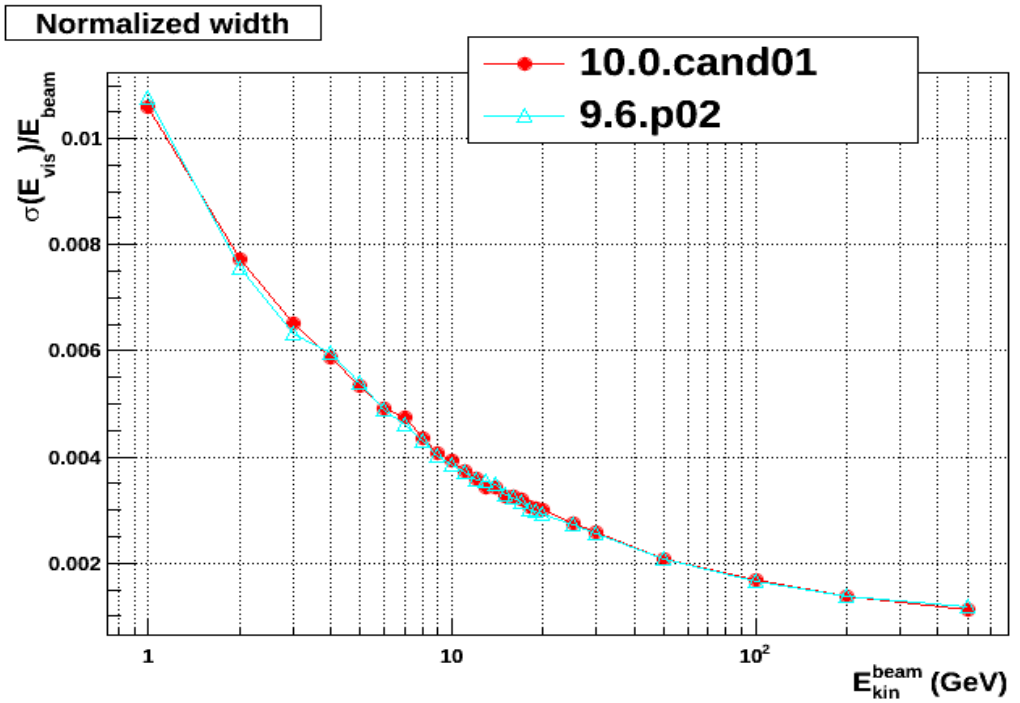
# Comparing G4 versions:

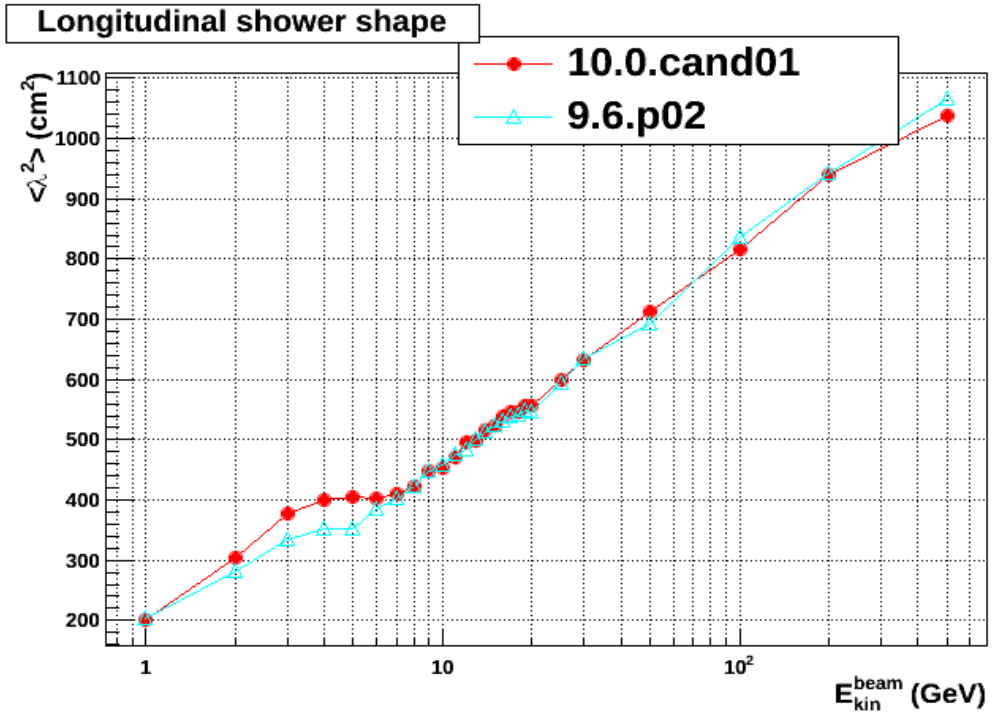
# 10.0 vs 9.6.p02

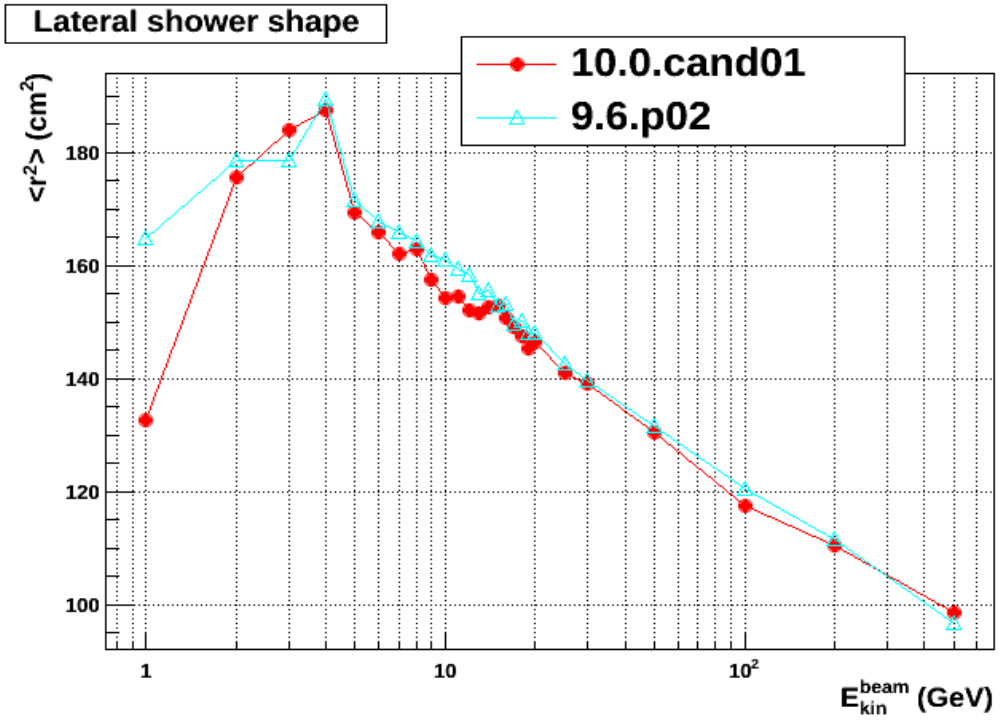
# FTFP_BERT

# $\pi^-$ on Fe-Sci



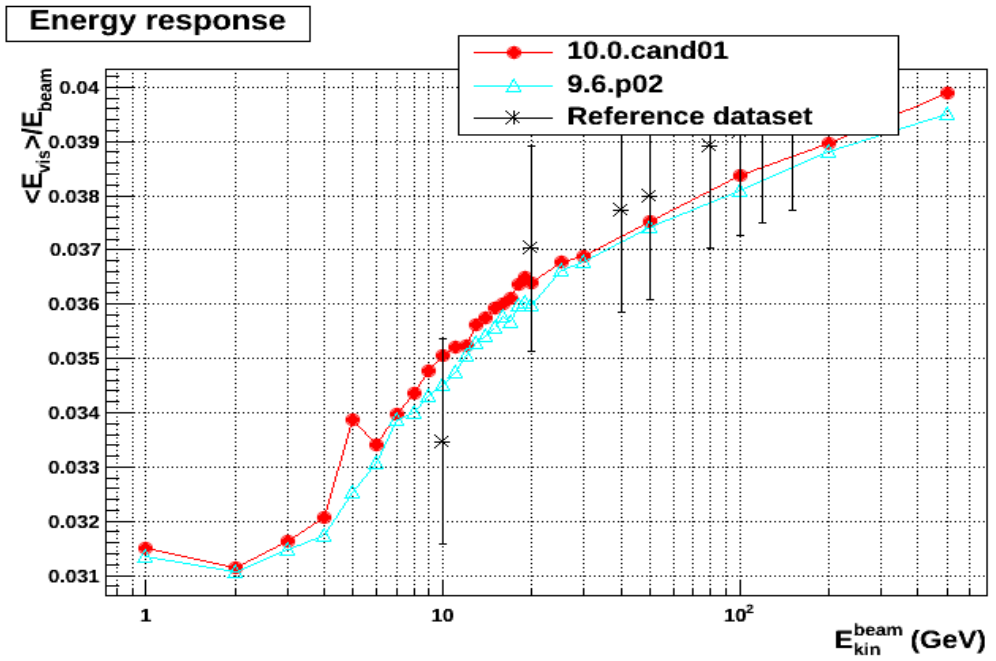



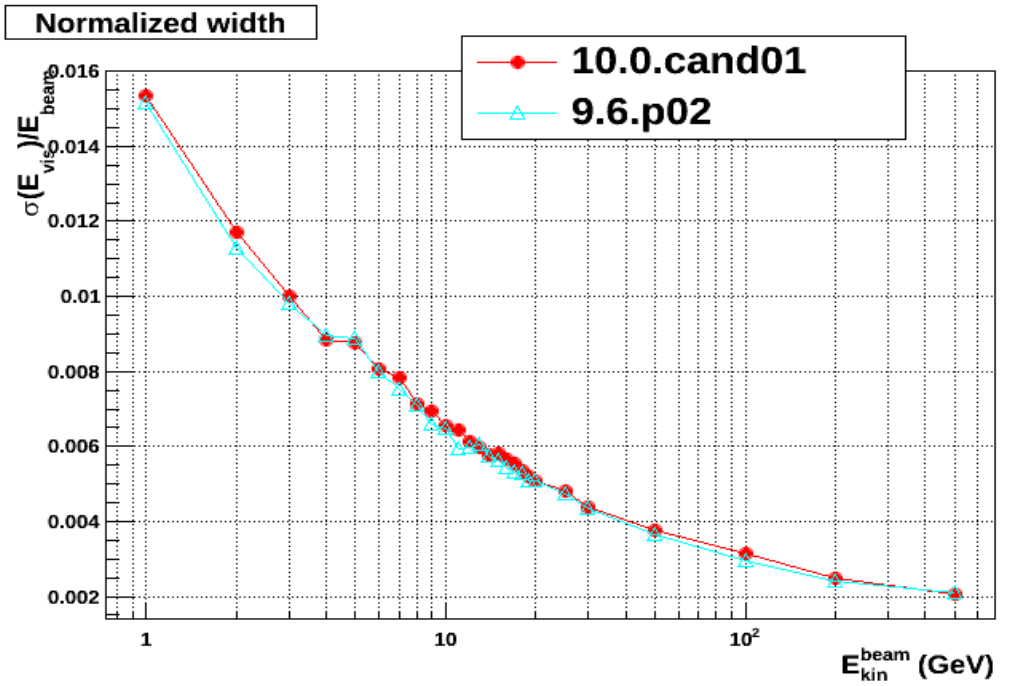



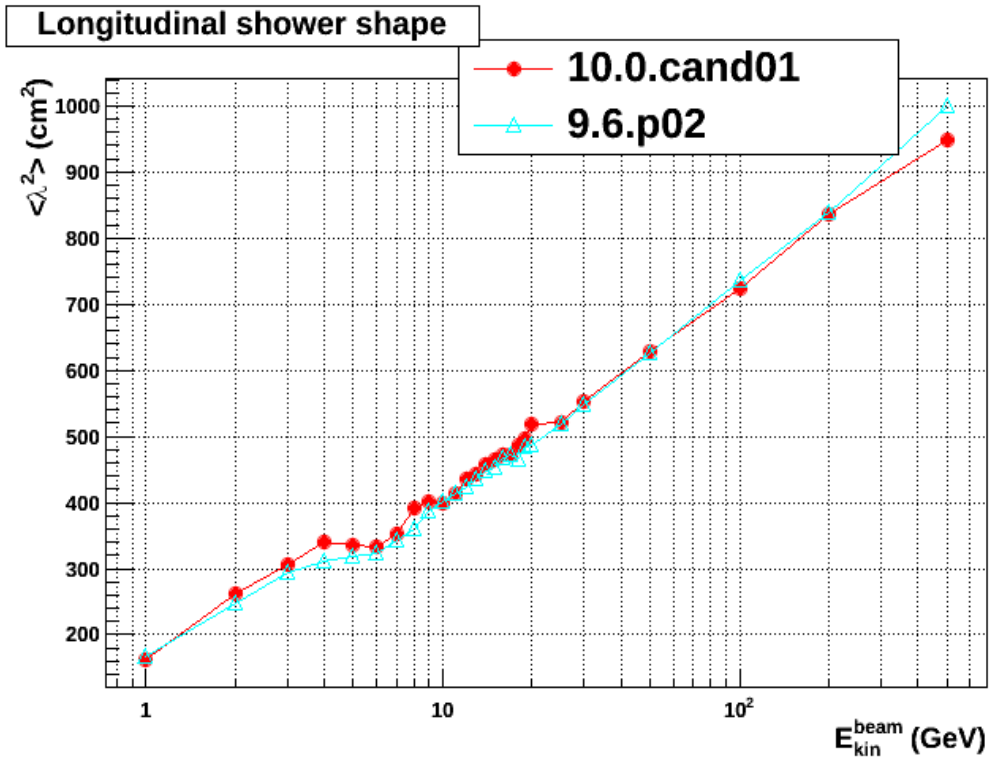



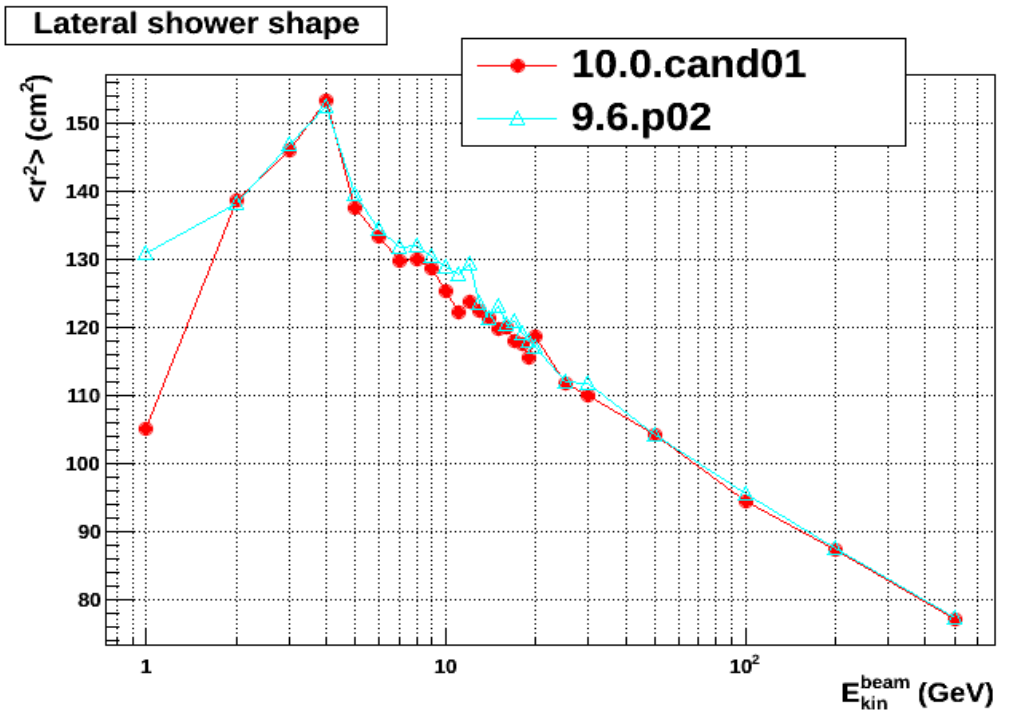
# FTFP_BERT

# $\pi^-$ on Cu-LAr



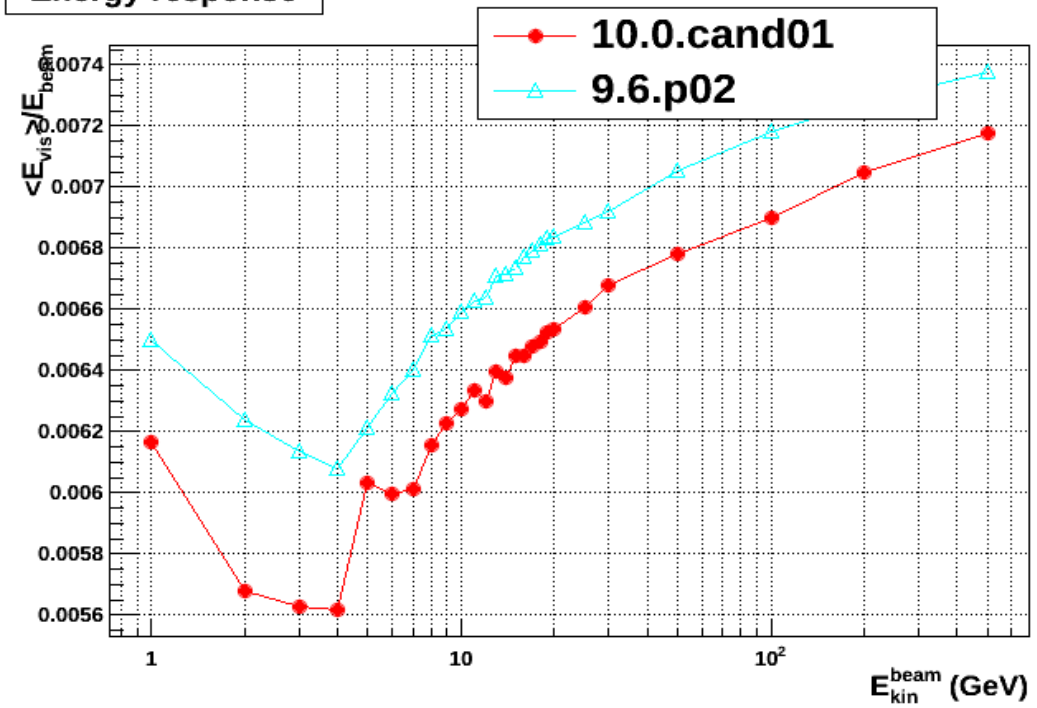



# FTFP_BERT

# $\pi^-$ on W-LAr

Energy response

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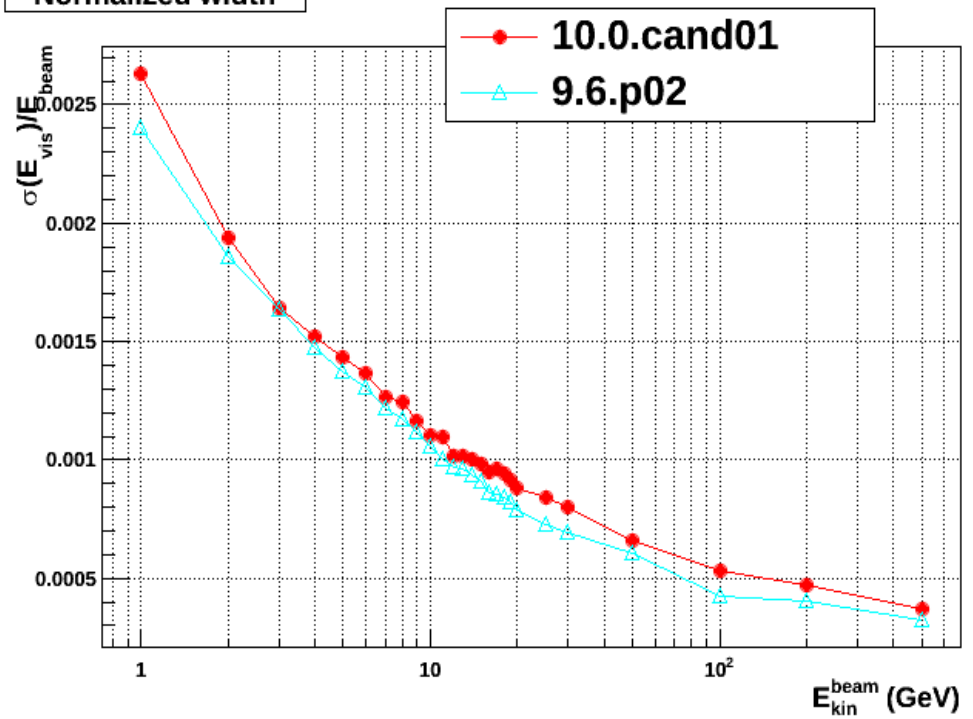
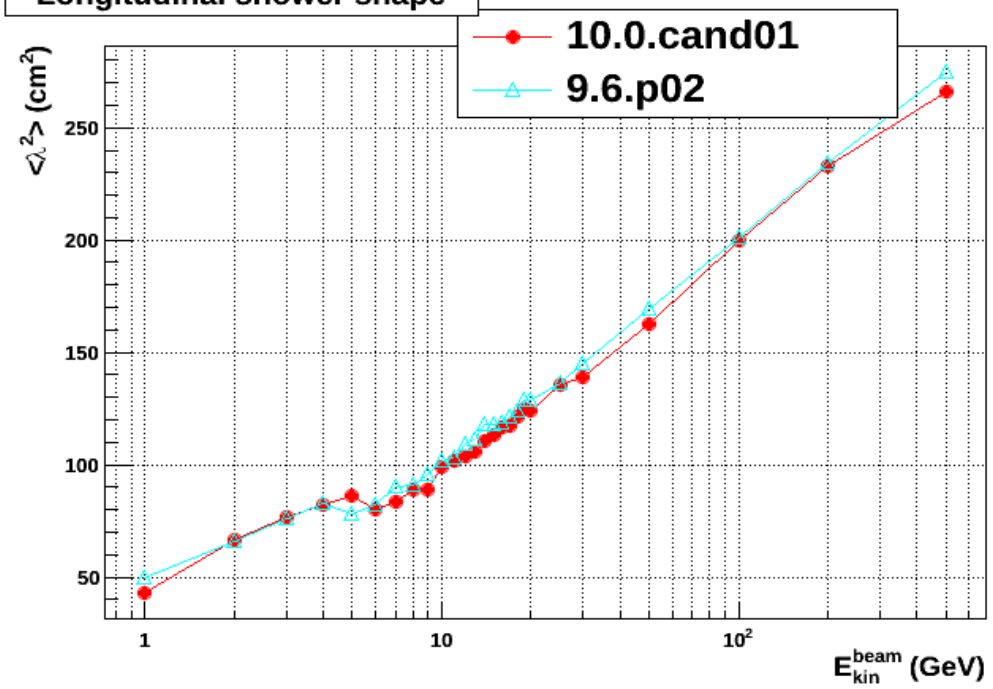
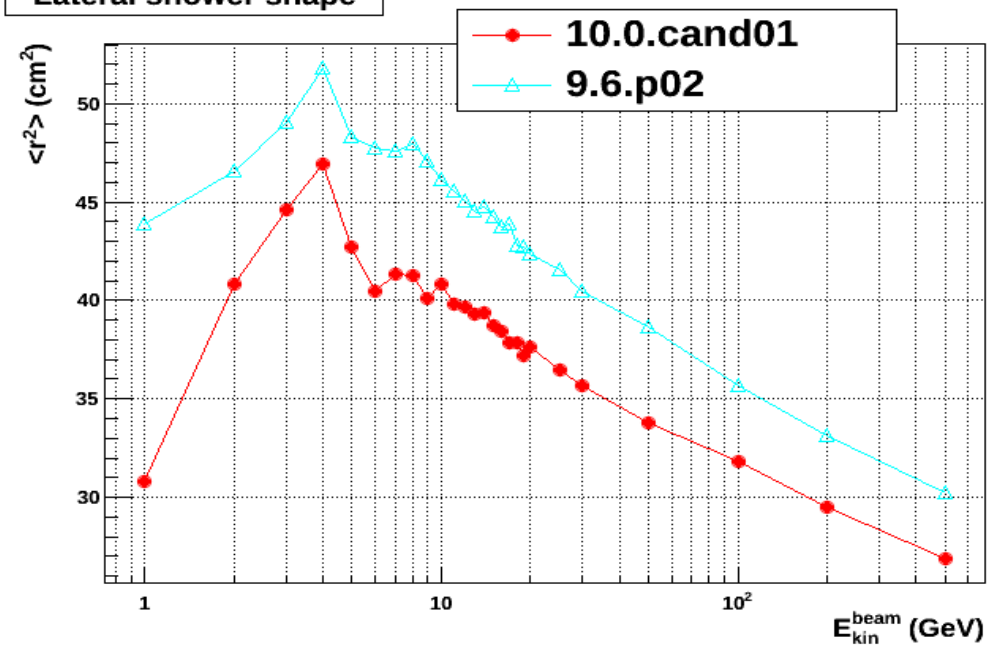



Longitudinal shower shape

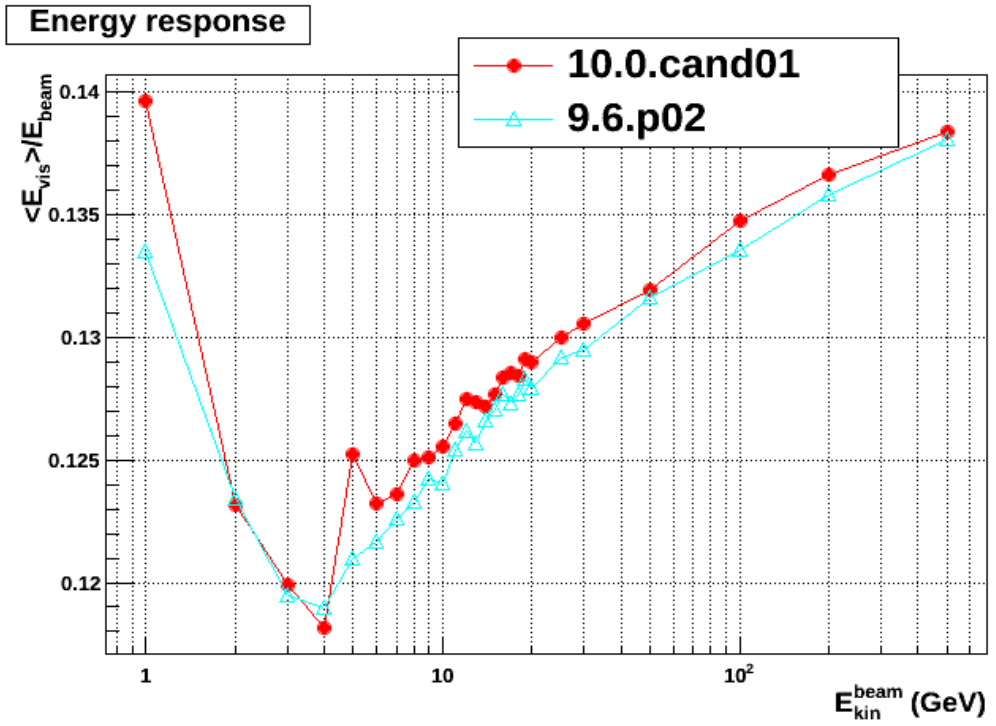


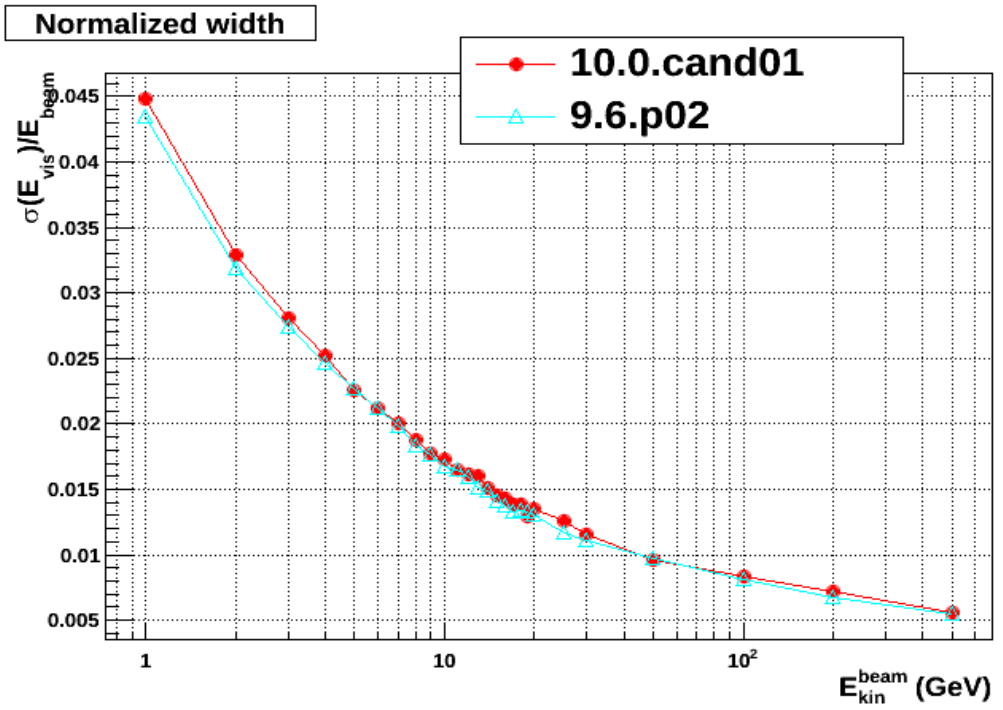

Lateral shower shape

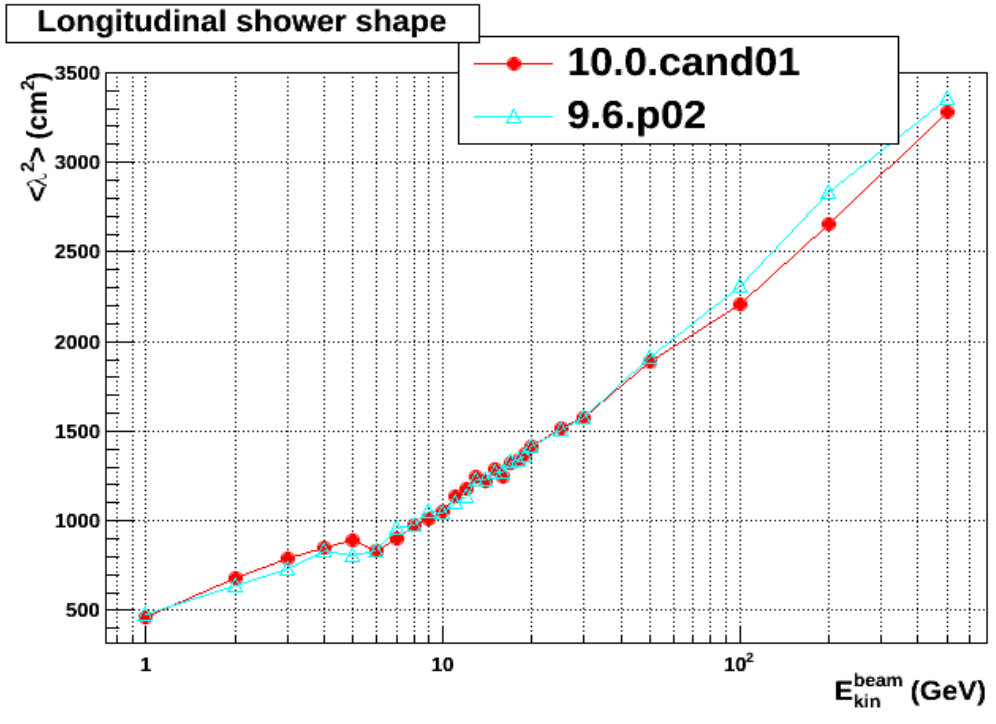


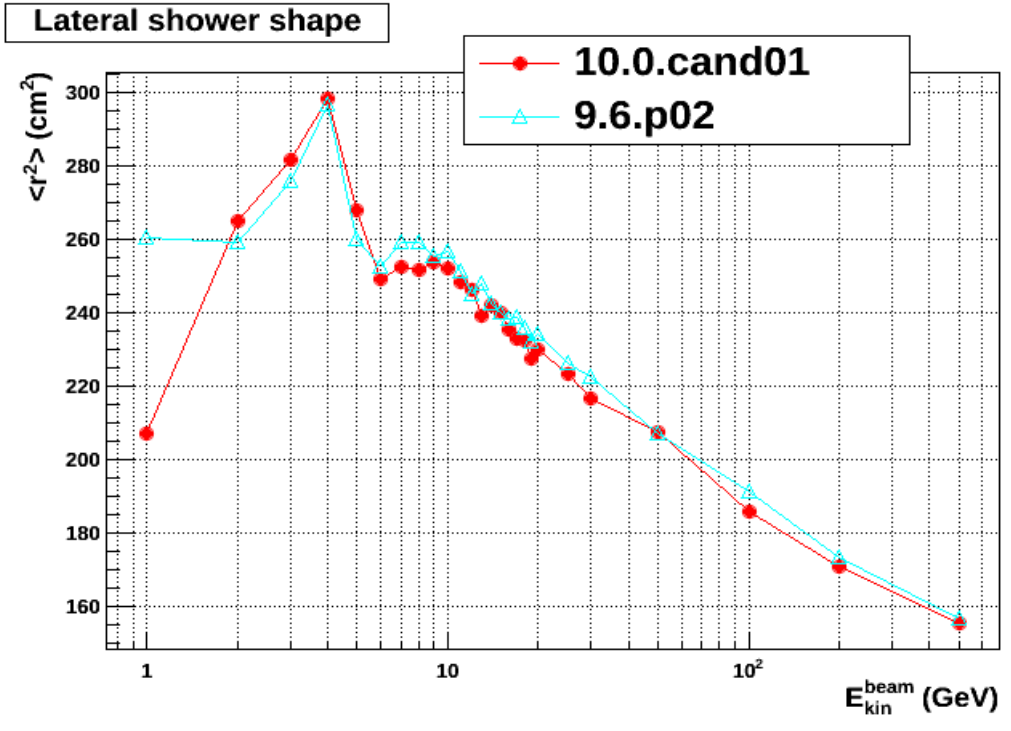
# FTFP_BERT

# $\pi^-$ on Pb-LAr



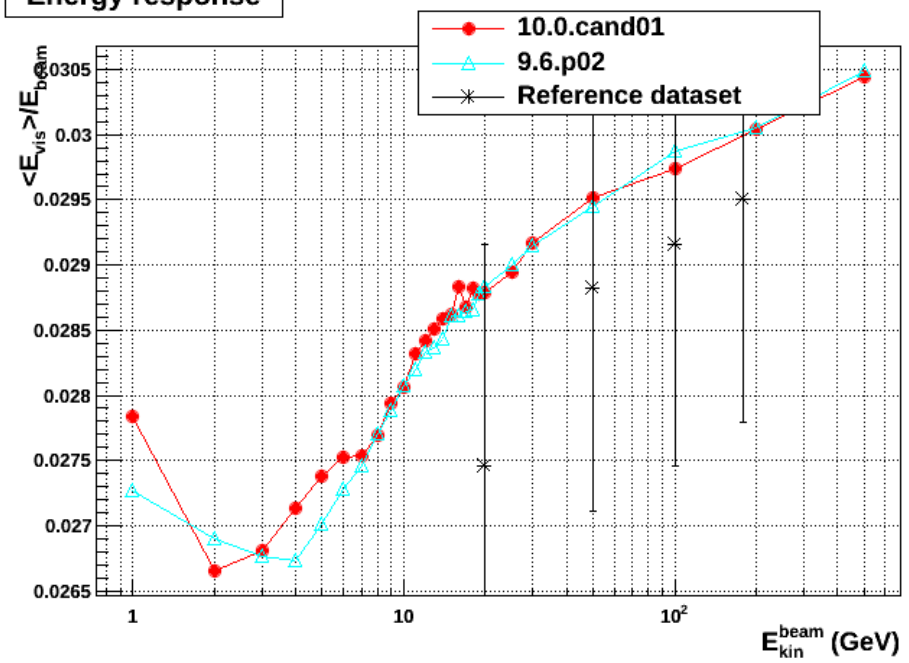



# FTFP_BERT_TRV

**$\pi^-$ on Fe-Sci**

**Energy response**

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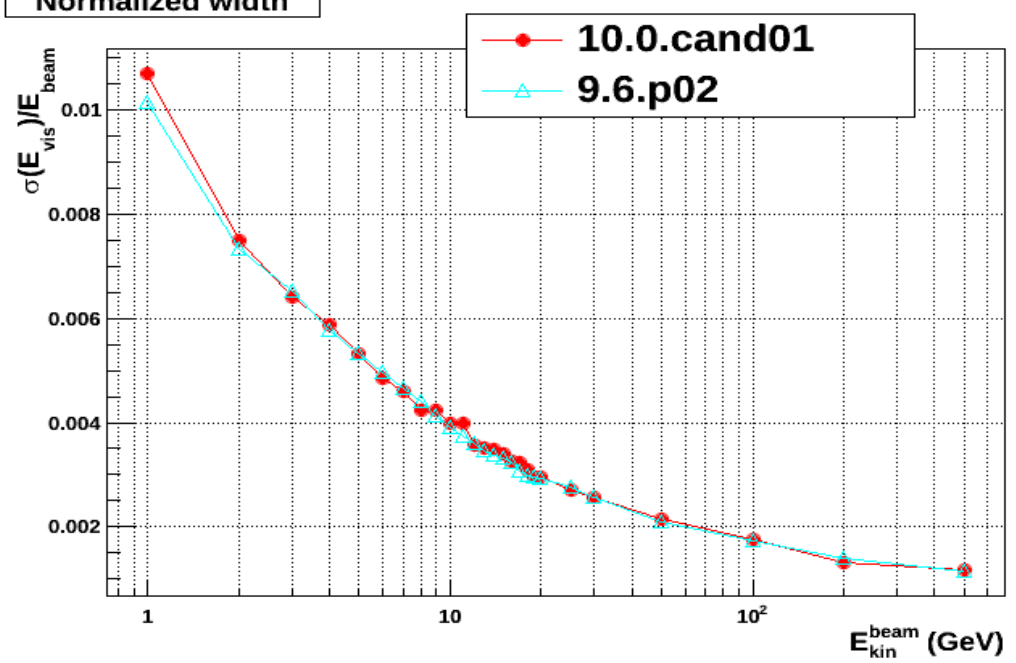
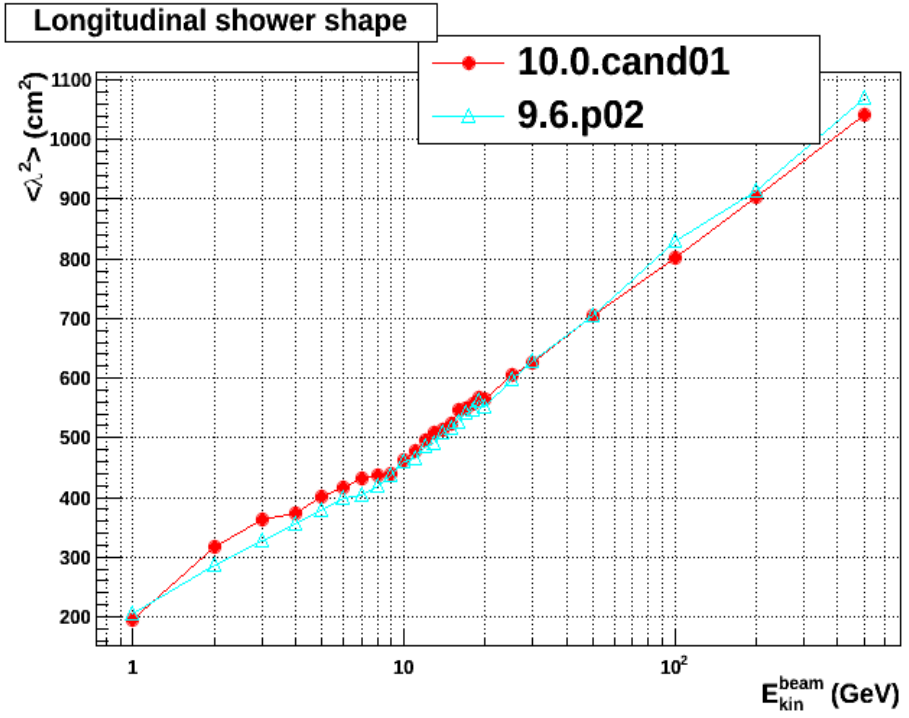
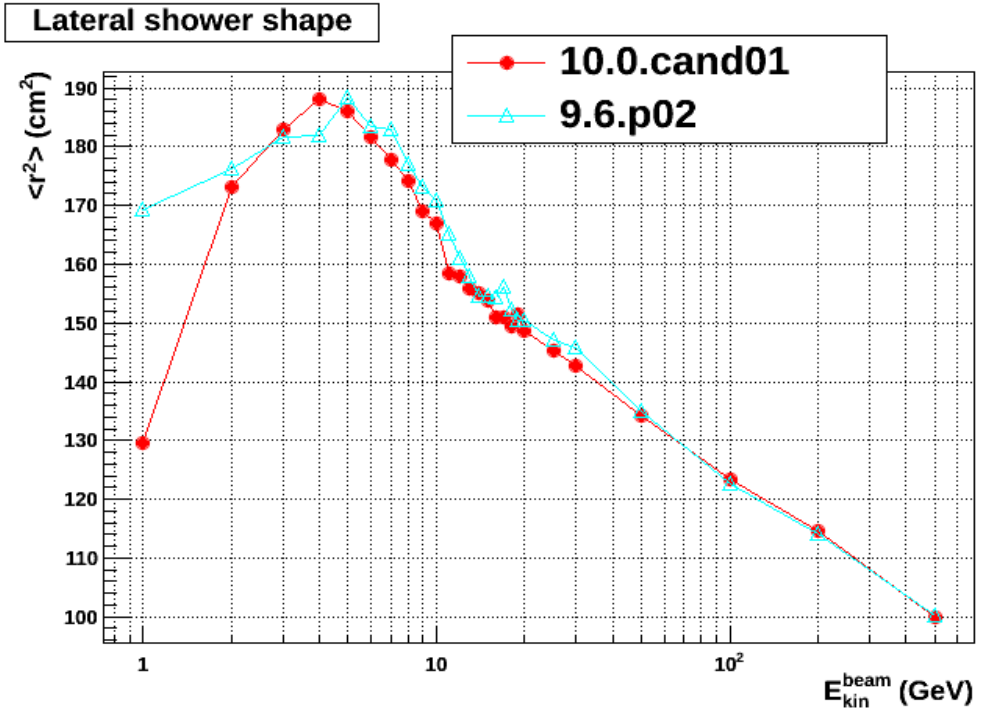



**Longitudinal shower shape**



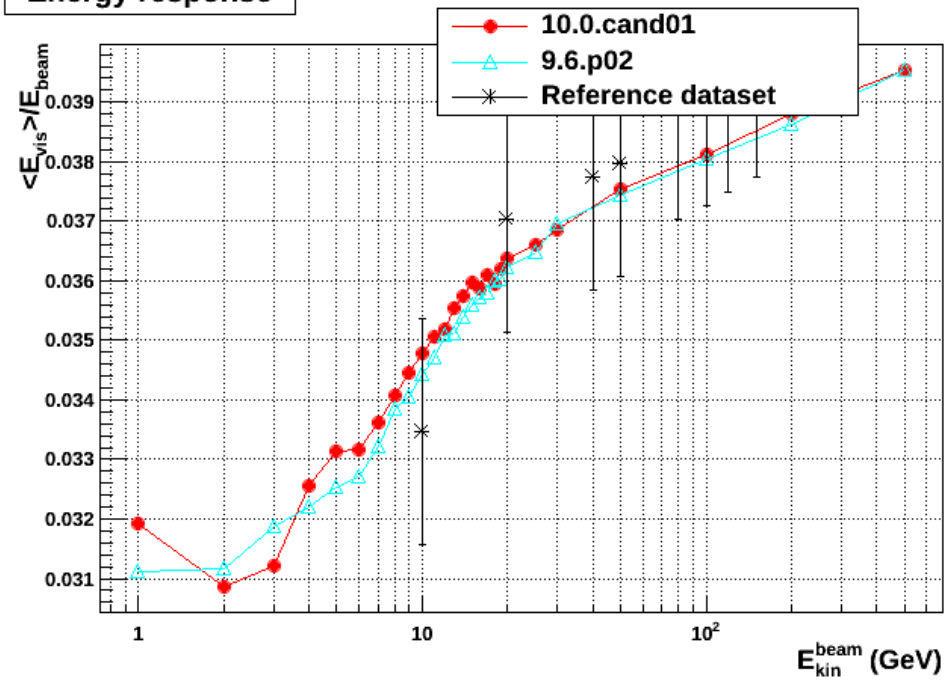

**Lateral shower shape**



# FTFP_BERT_TRV

**$\pi^-$ on Cu-LAr**

**Energy response**

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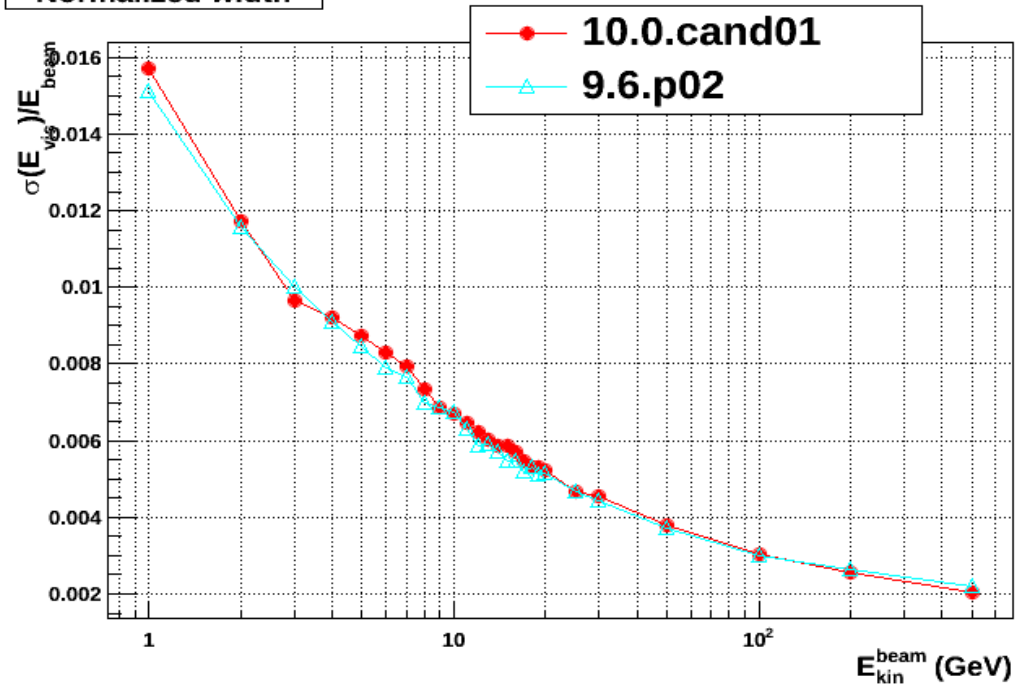


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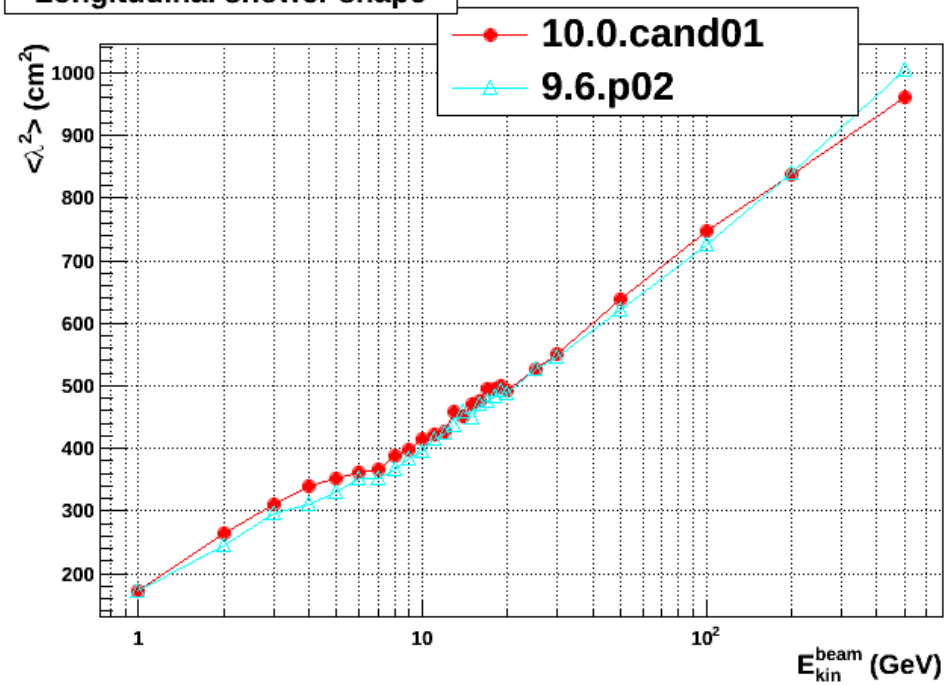
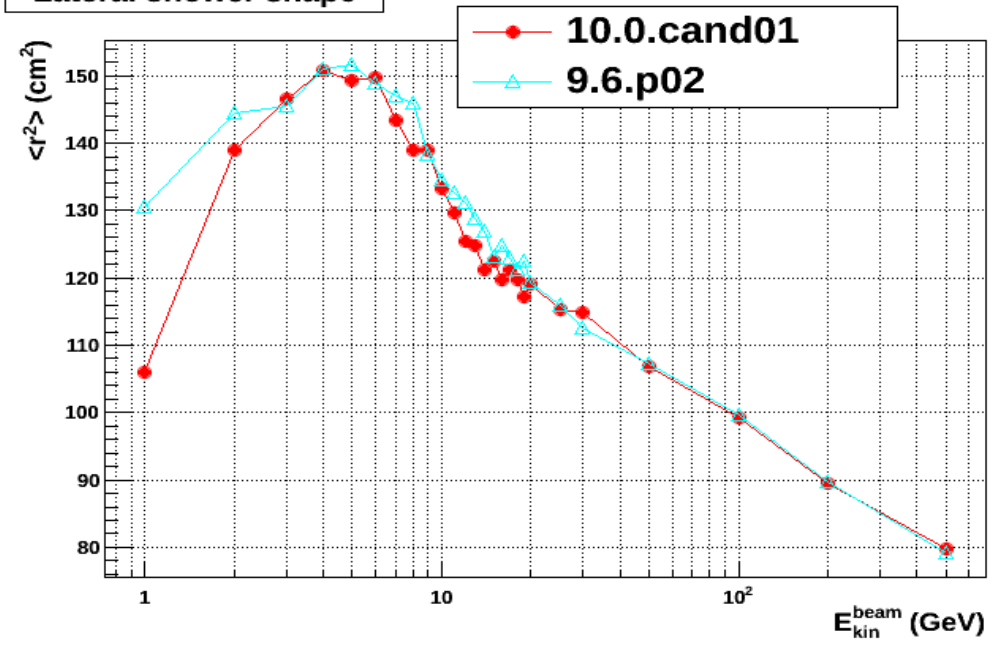


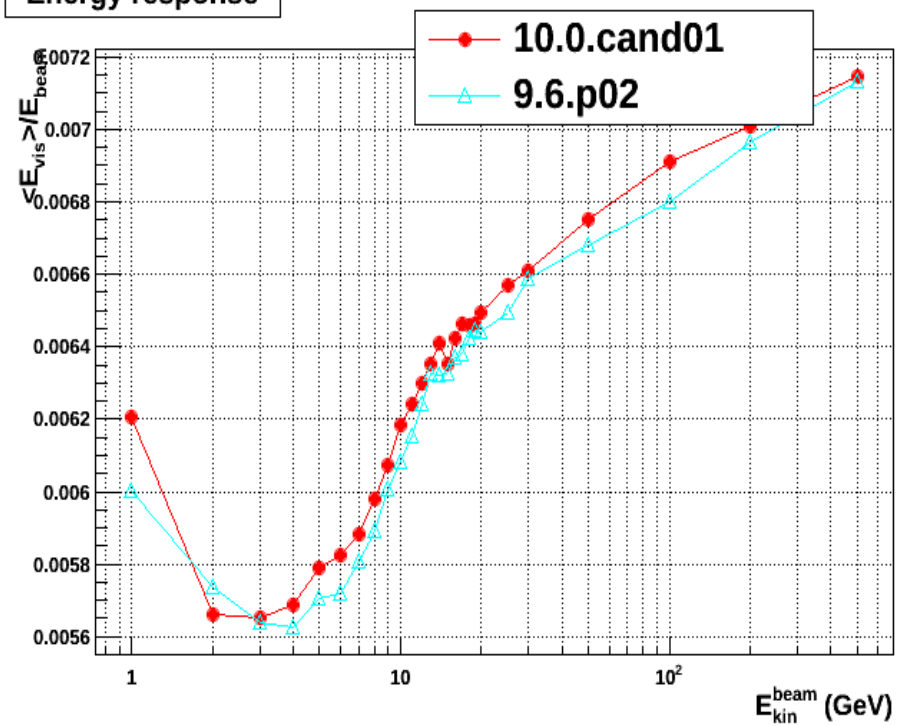

**Lateral shower shape**



# FTFP_BERT_TRV

**$\pi^-$ on W-LAr**

Energy response

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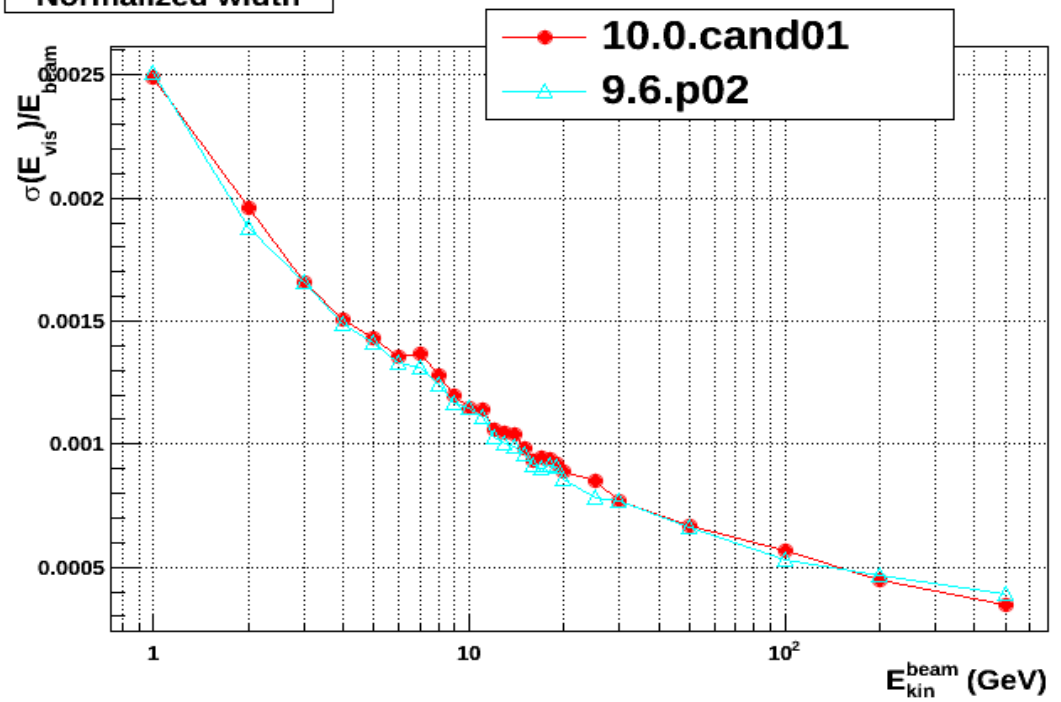
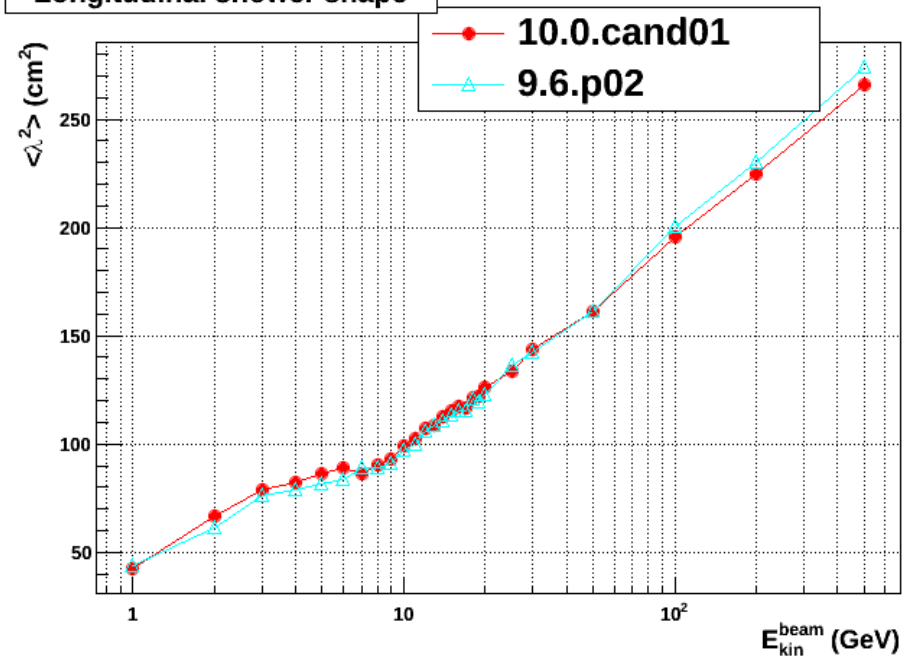
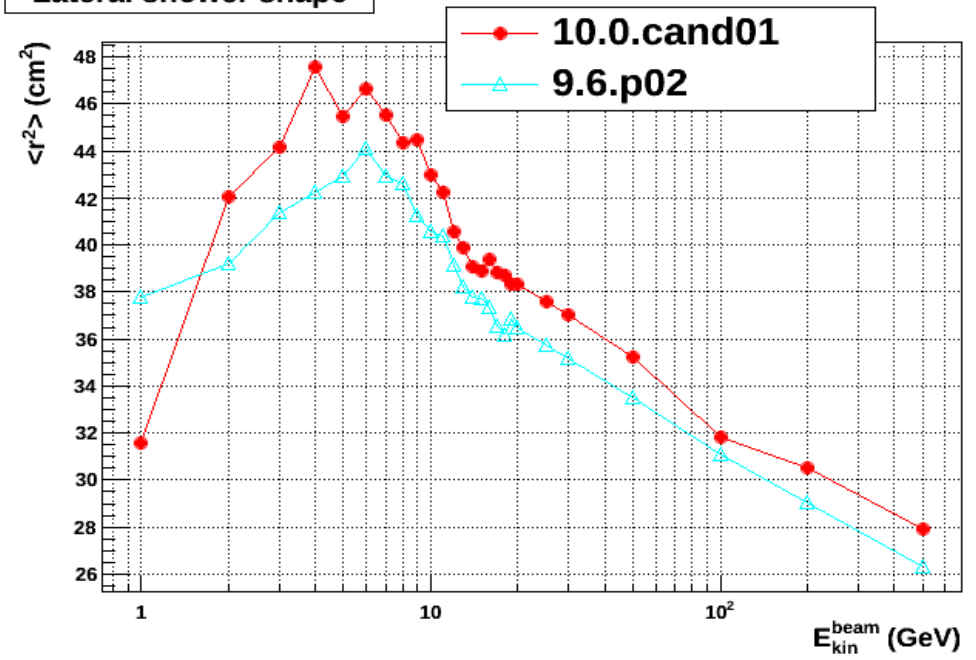



Longitudinal shower shape

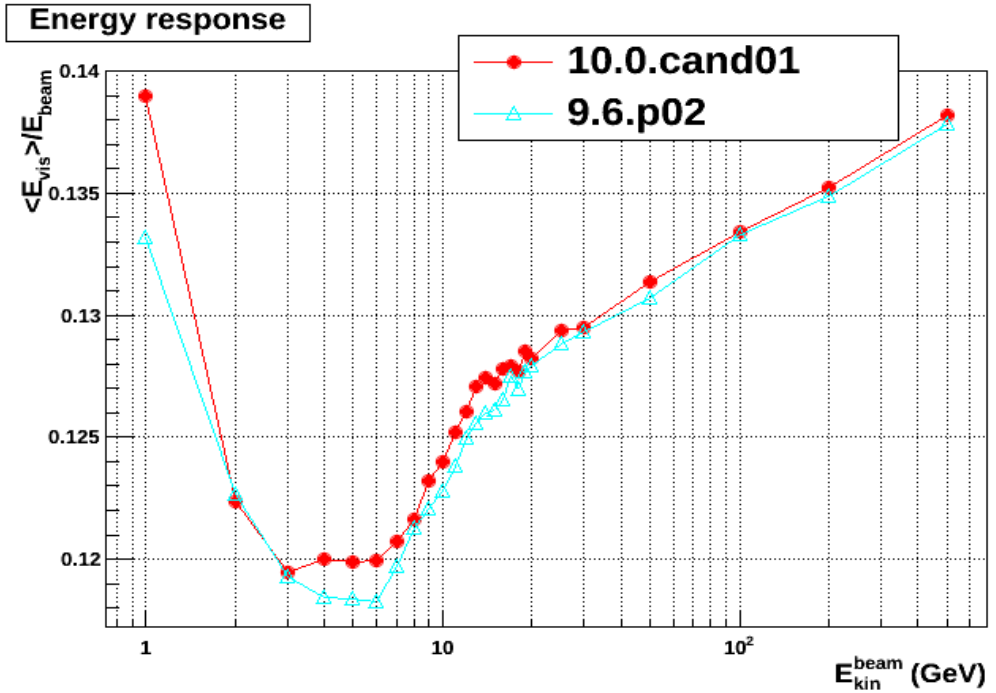


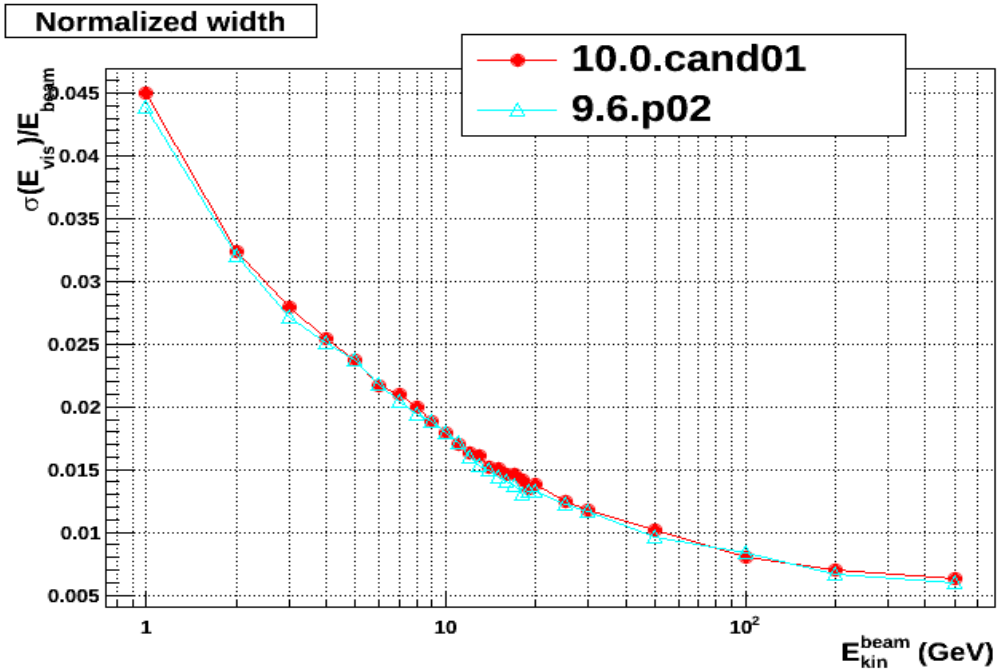

Lateral shower shape

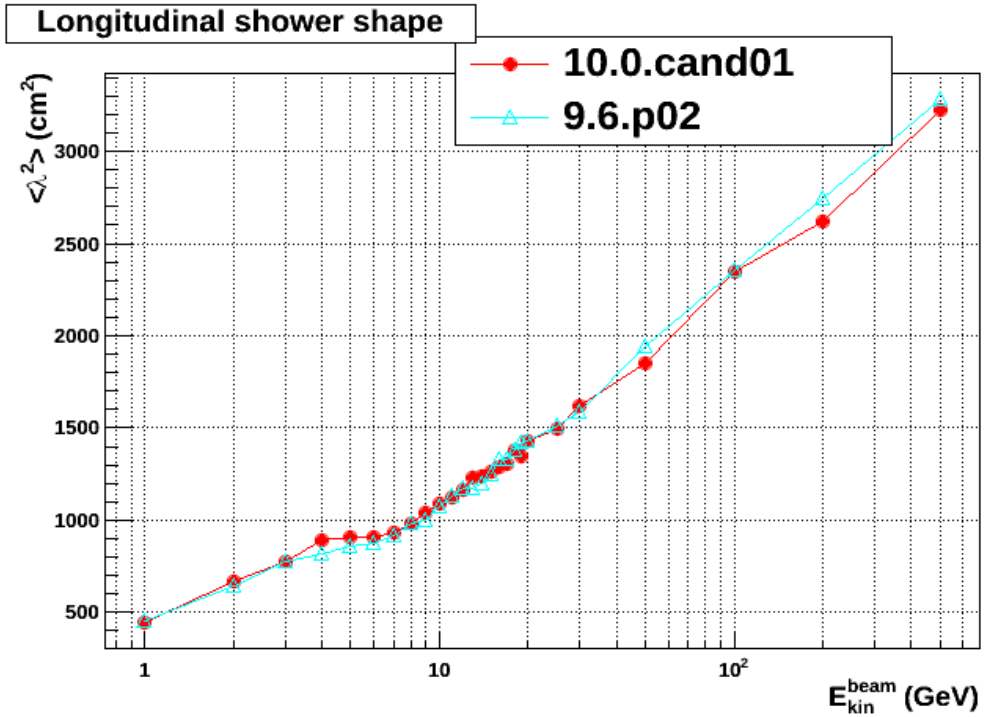


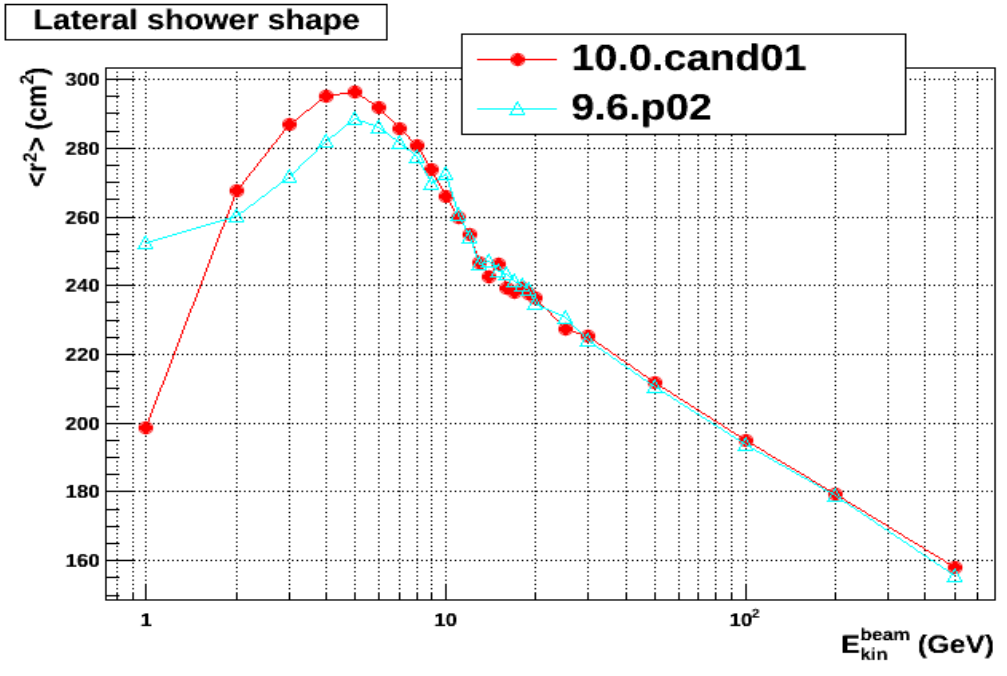
# FTFP_BERT_TRV

**$\pi^-$ on Pb-LAr**



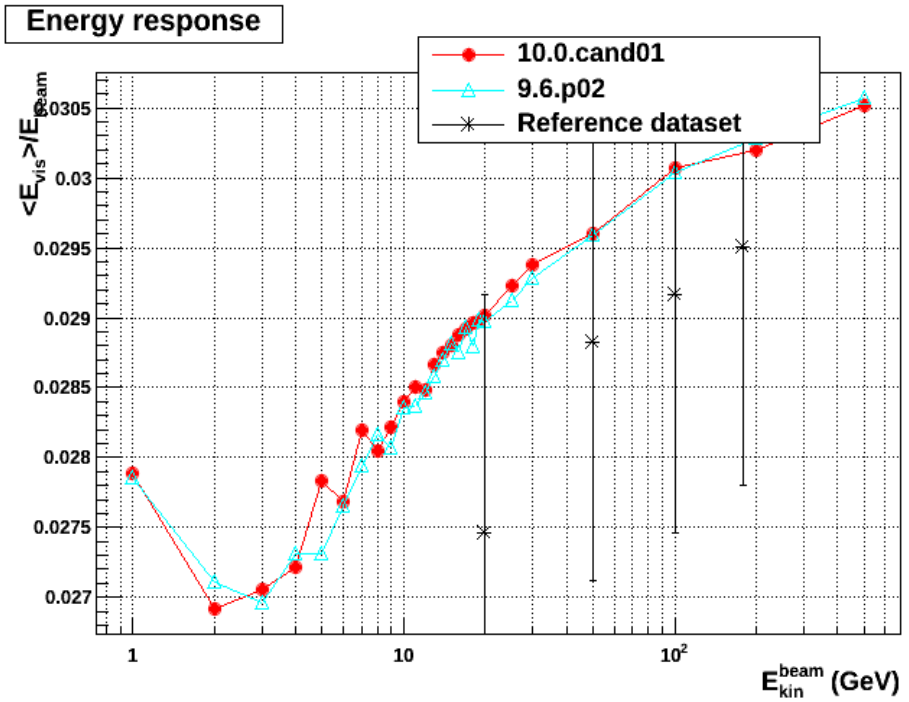



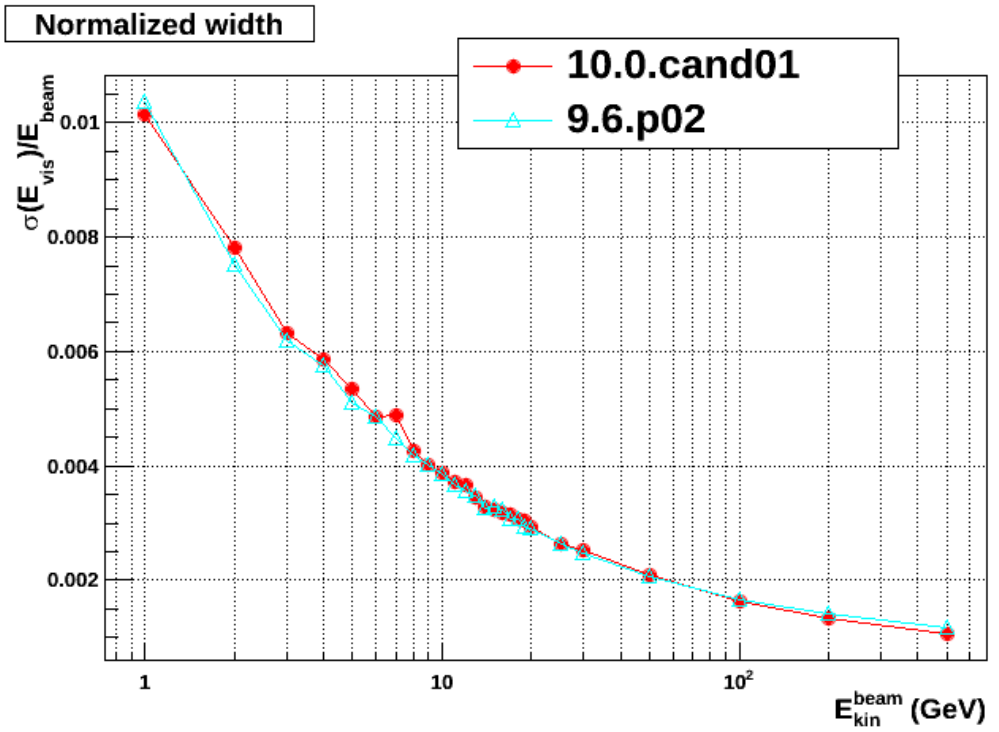



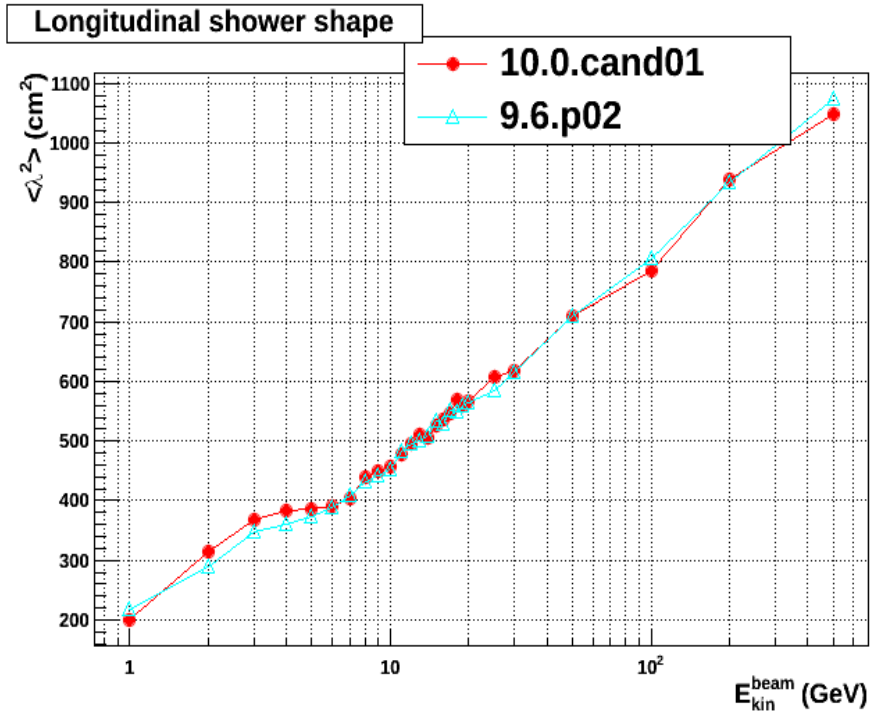



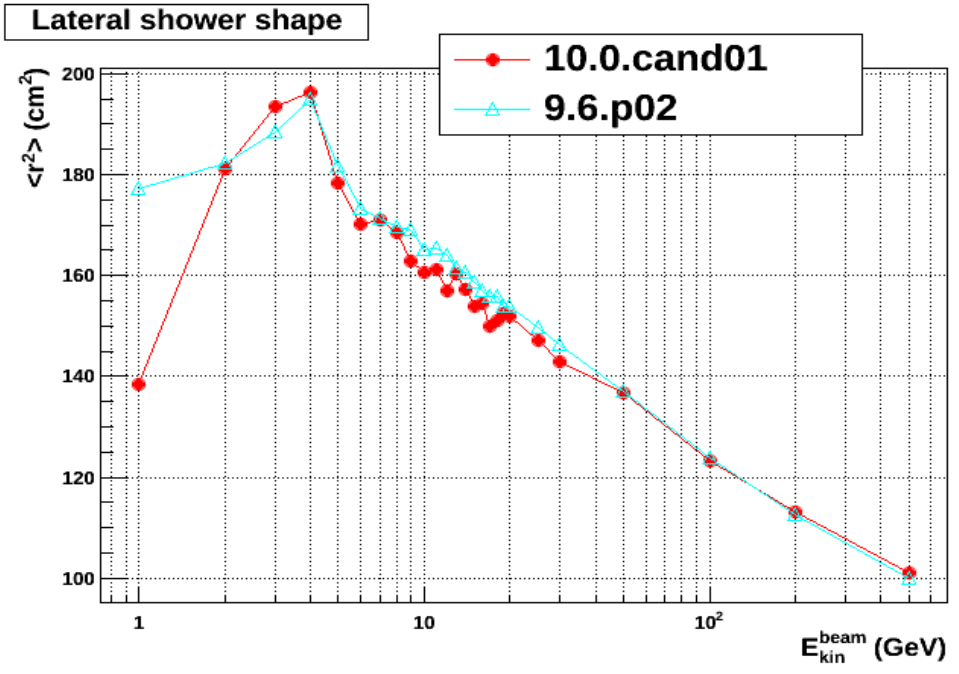
# FTFP_BERT_HP

## $\pi^-$ on Fe-Sci



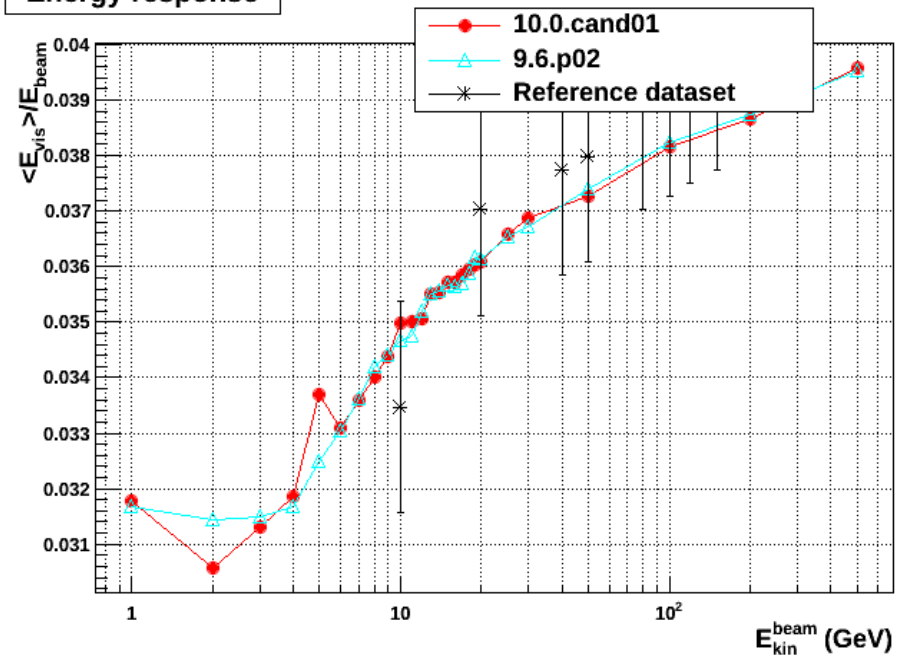



# FTFP_BERT_HP

## $\pi^-$ on Cu-LAr

**Energy response**

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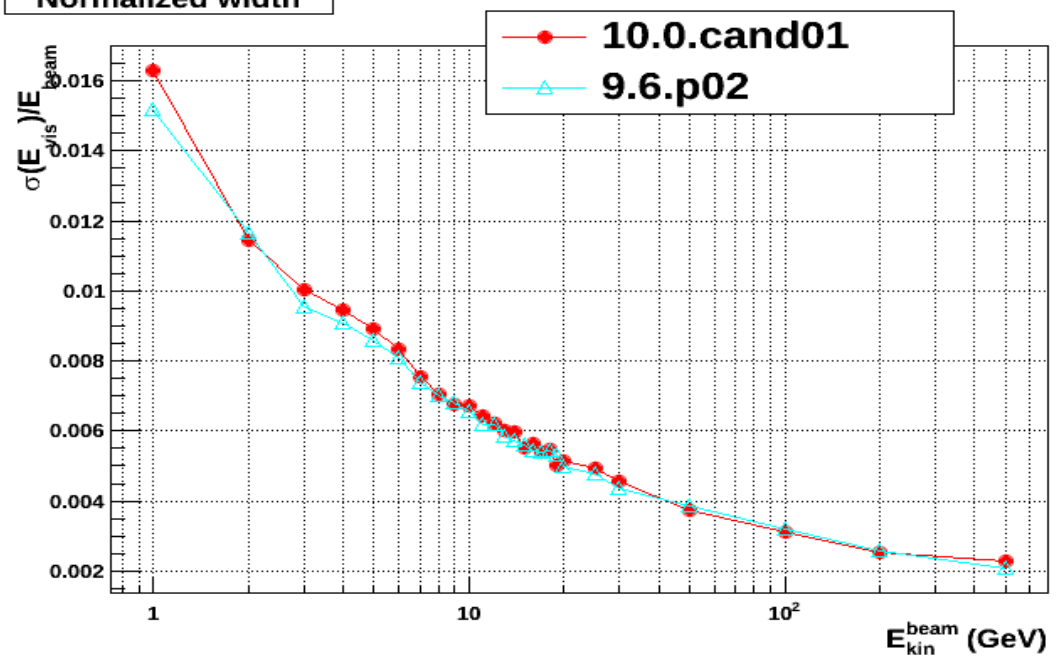
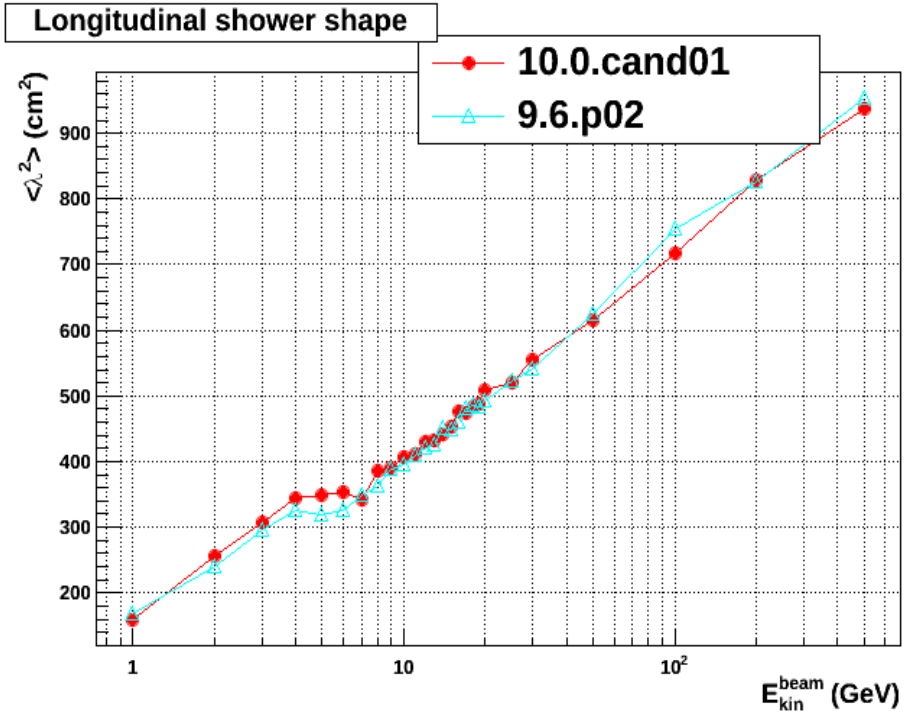
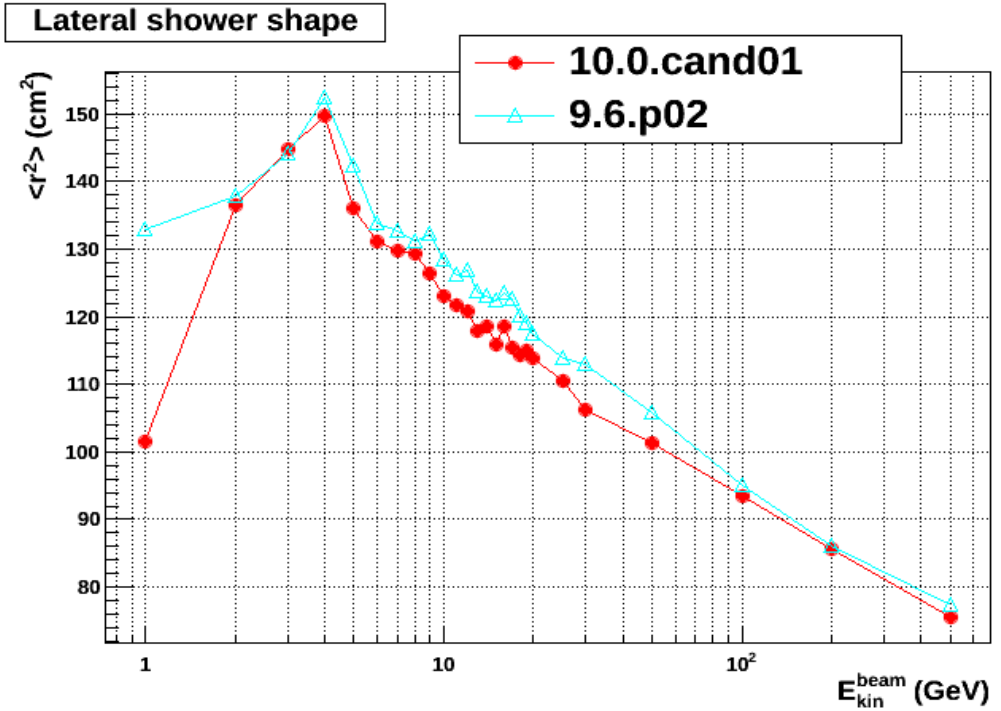



**Longitudinal shower shape**



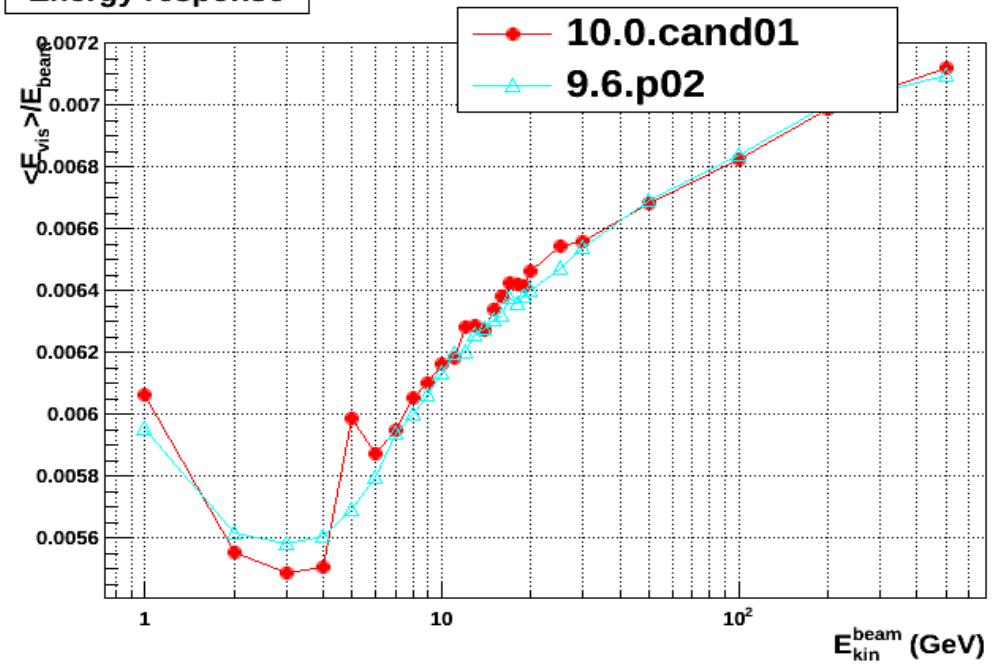

**Lateral shower shape**



# FTFP_BERT_HP

## $\pi^-$ on W-LAr

**Energy response**

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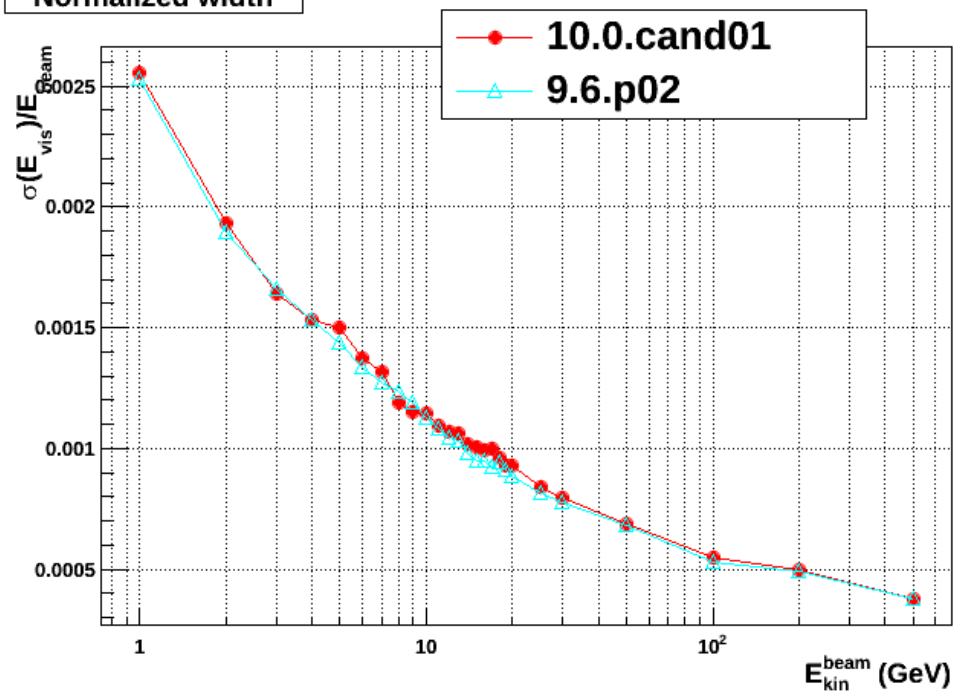


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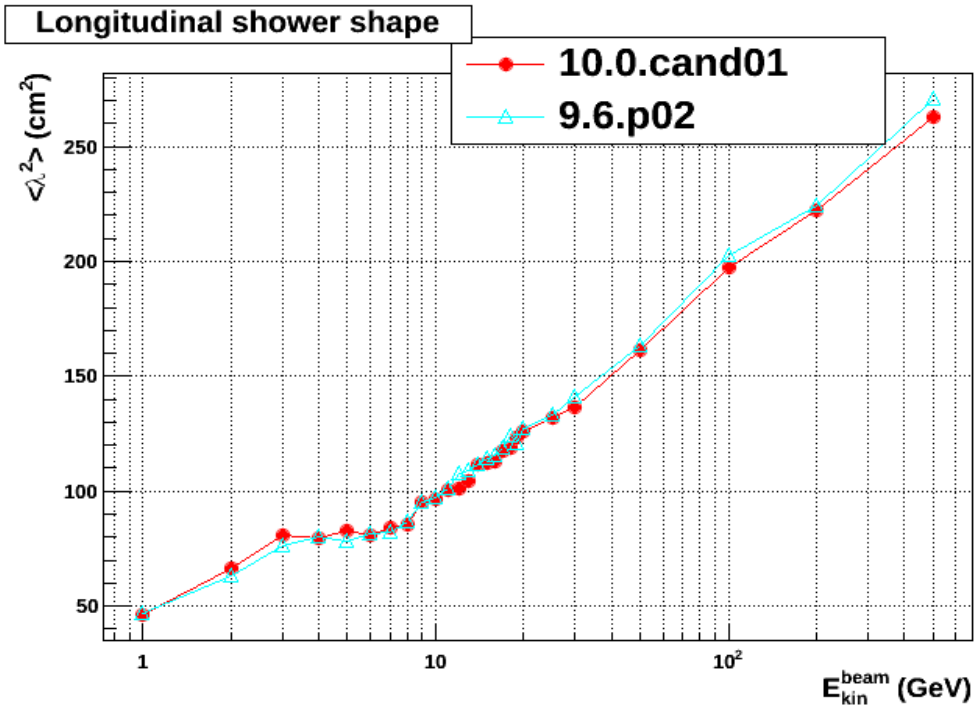


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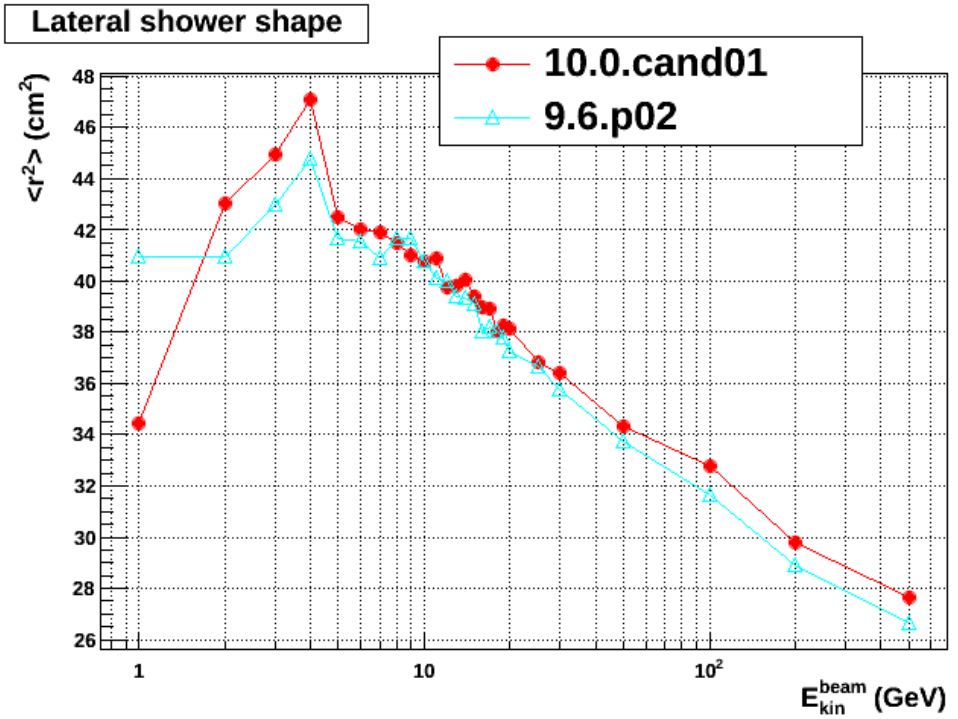
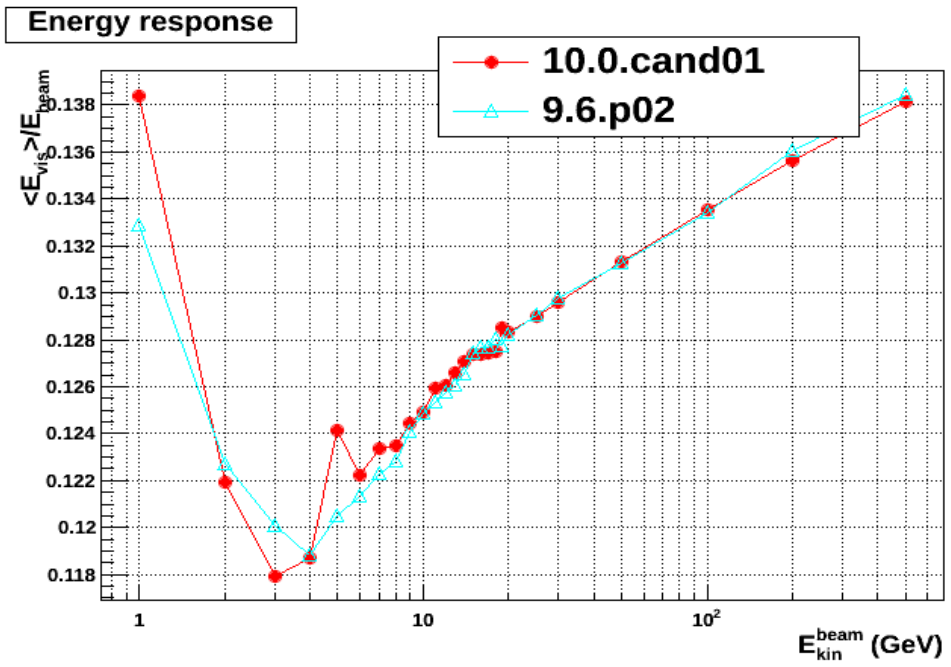
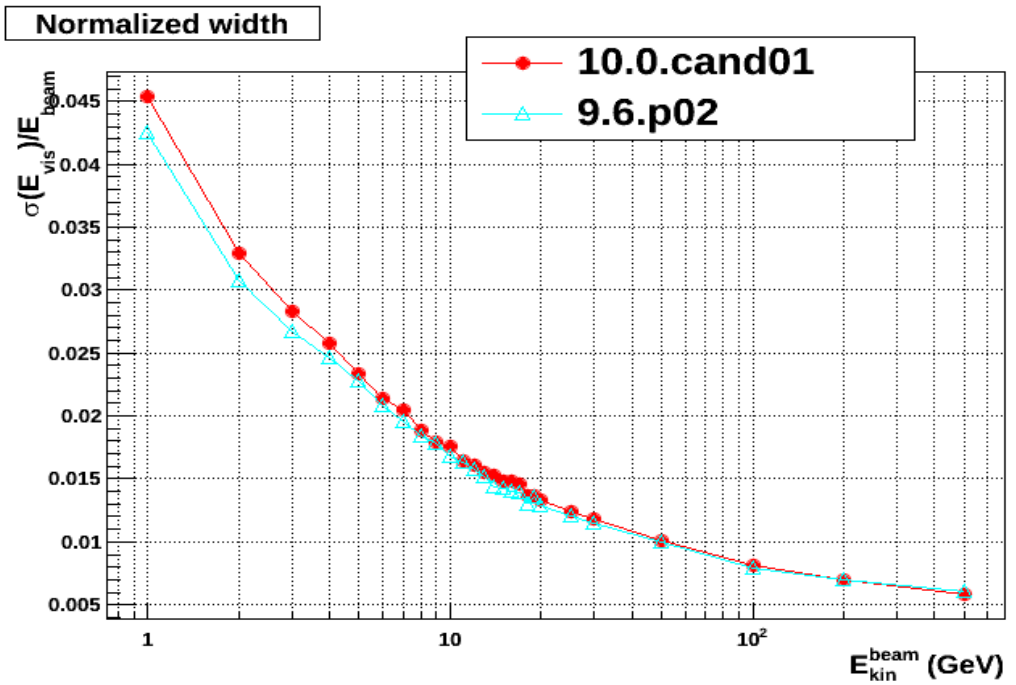
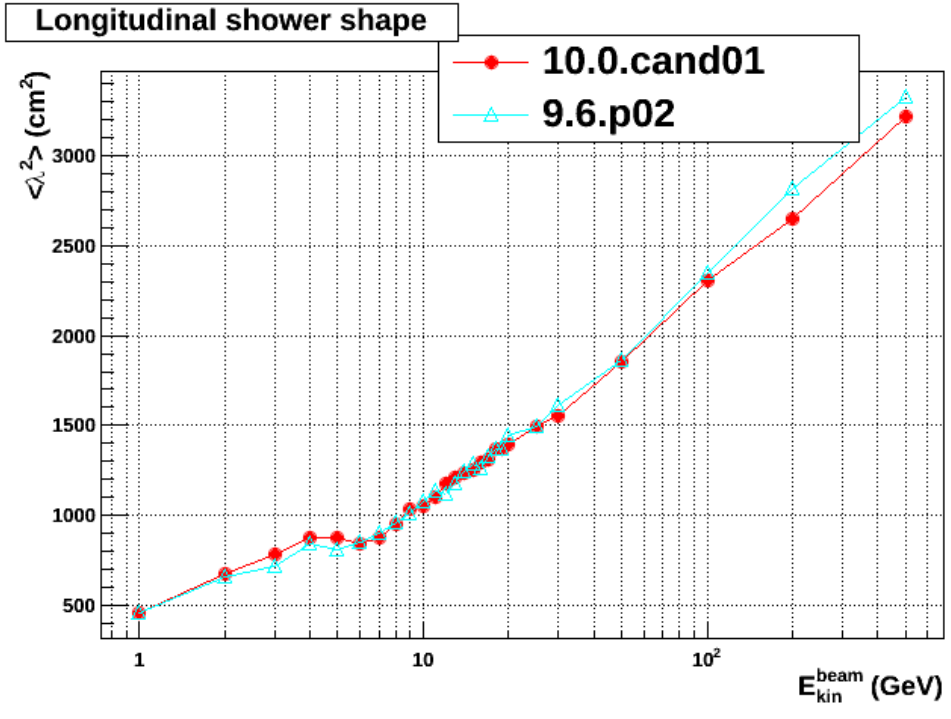


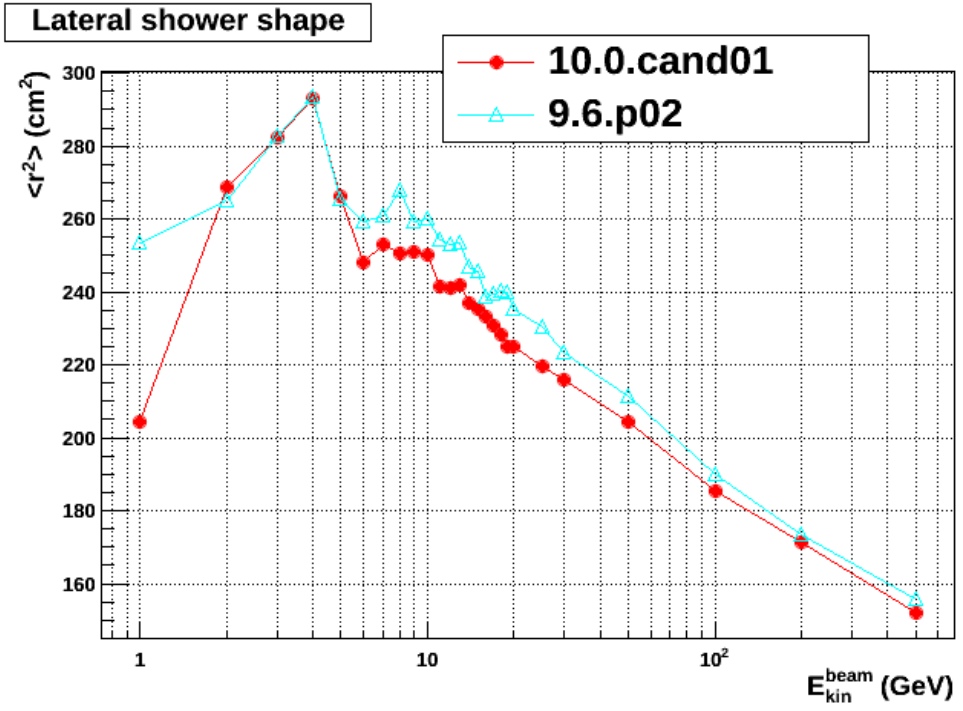
# FTFP_BERT_HP

**$\pi^-$ on Pb-LAr**



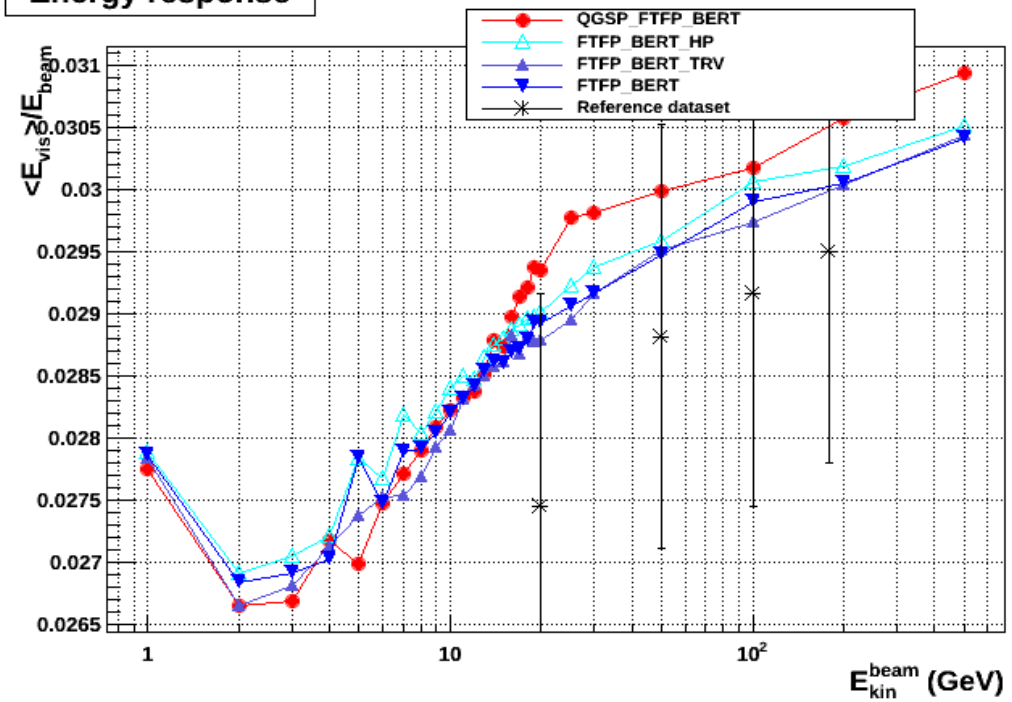



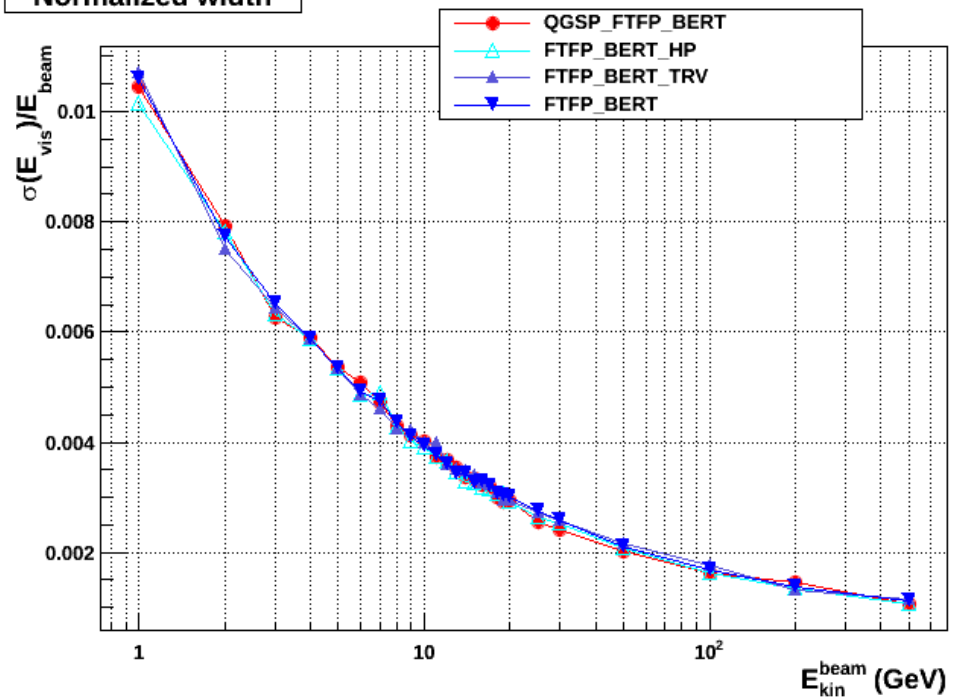
# Comparing Physics Lists in G4 10.0

# $\pi^-$ on Fe-Sci

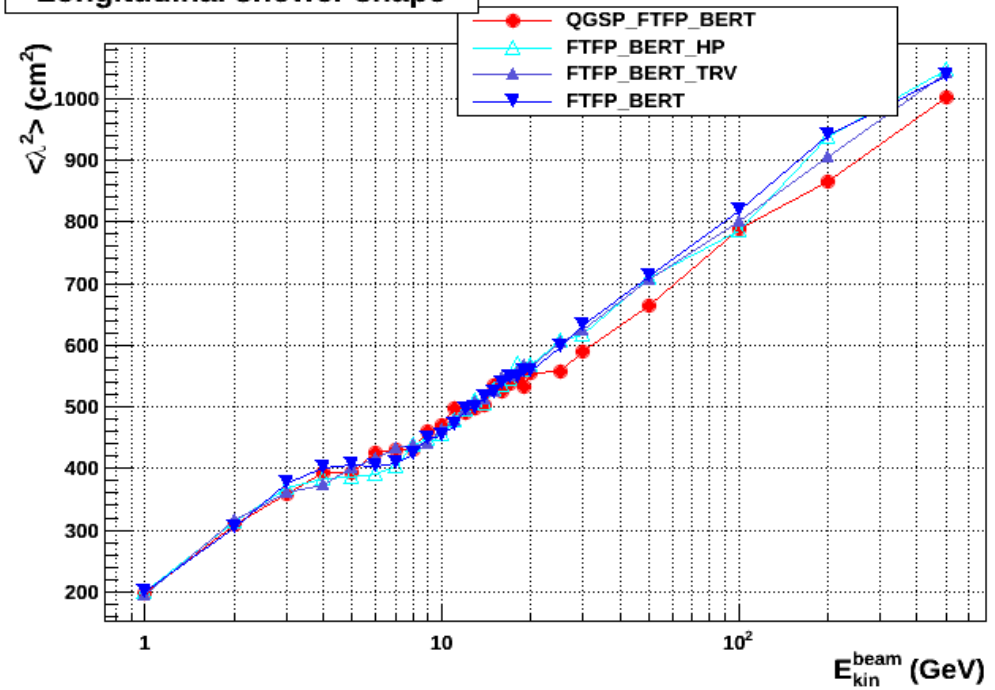
## Energy response



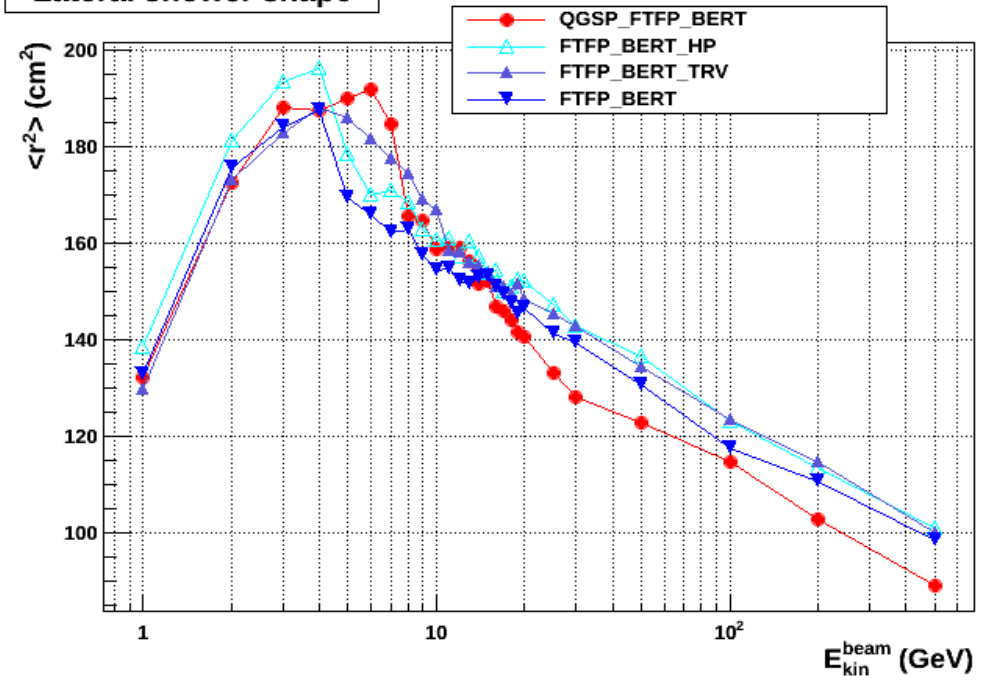

## Normalized width




## Longitudinal shower shape

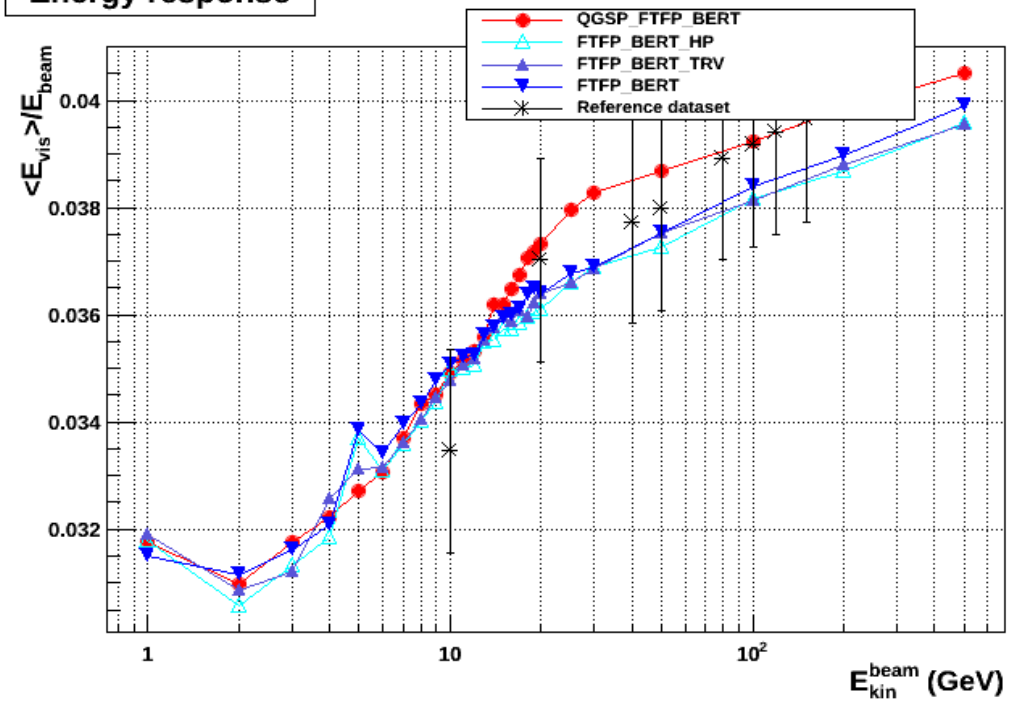



## Lateral shower shape

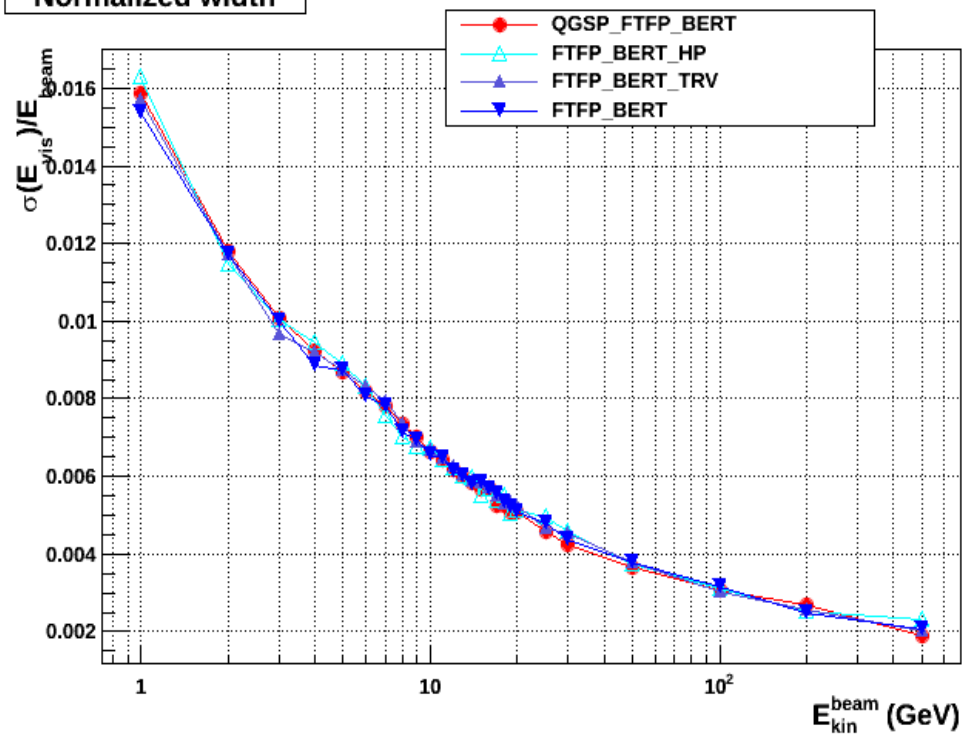


# $\pi^-$ on Cu-LAr

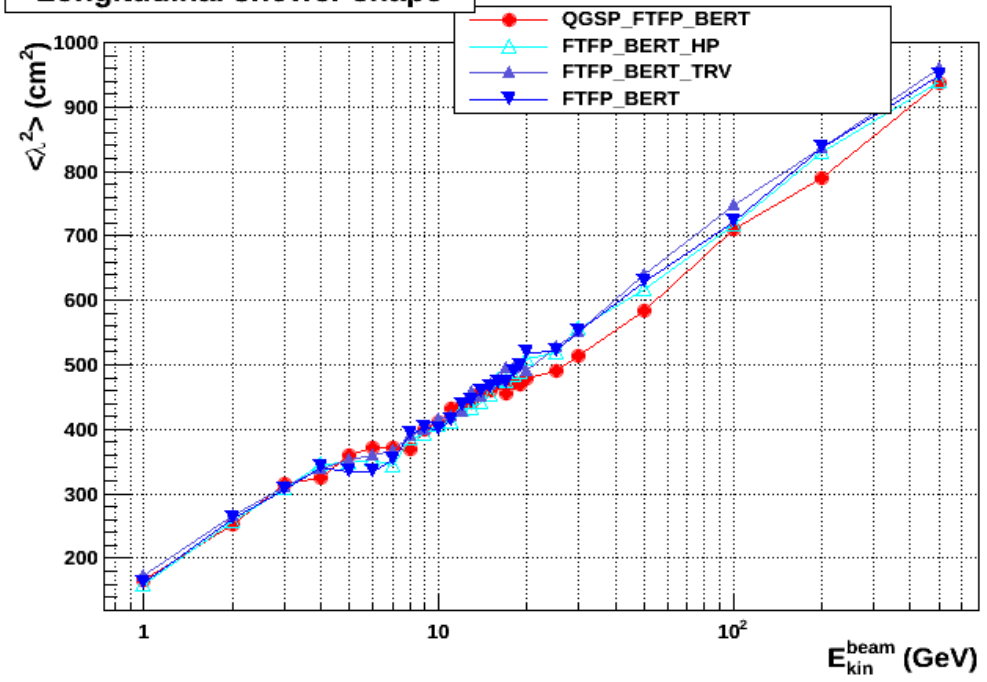
## Energy response



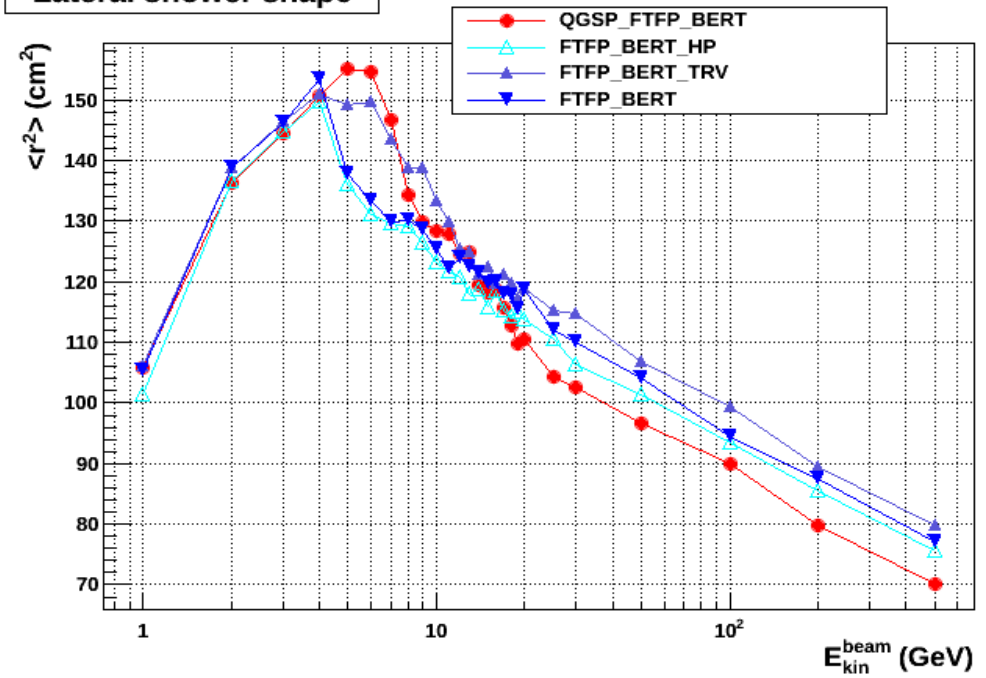

## Normalized width




## Longitudinal shower shape

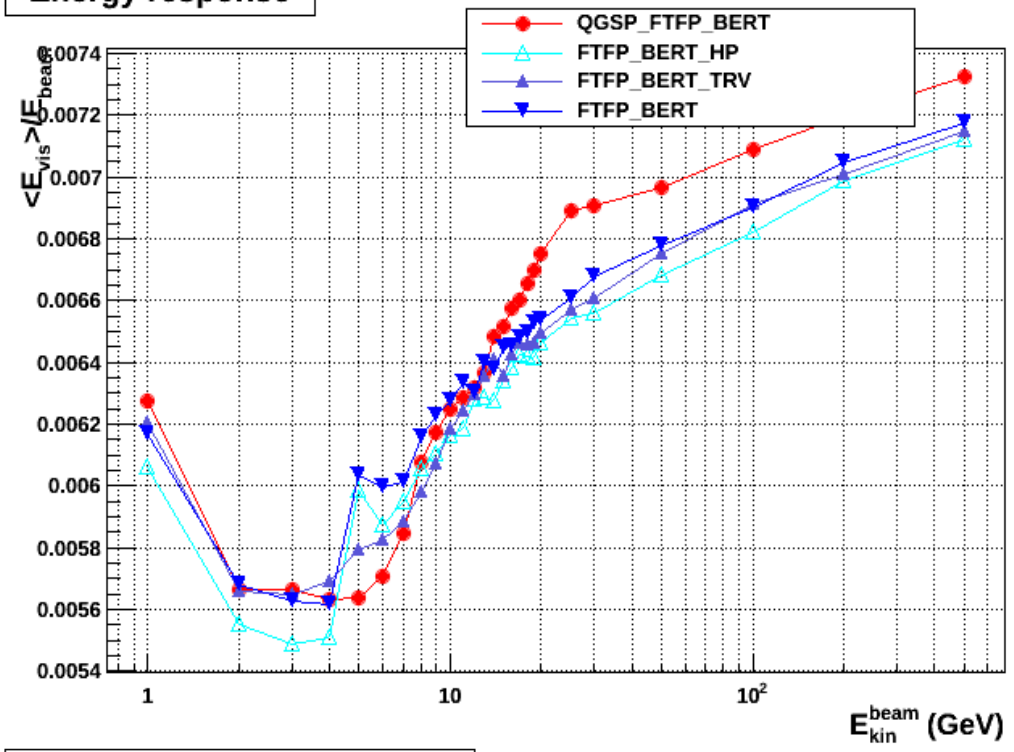



## Lateral shower shape

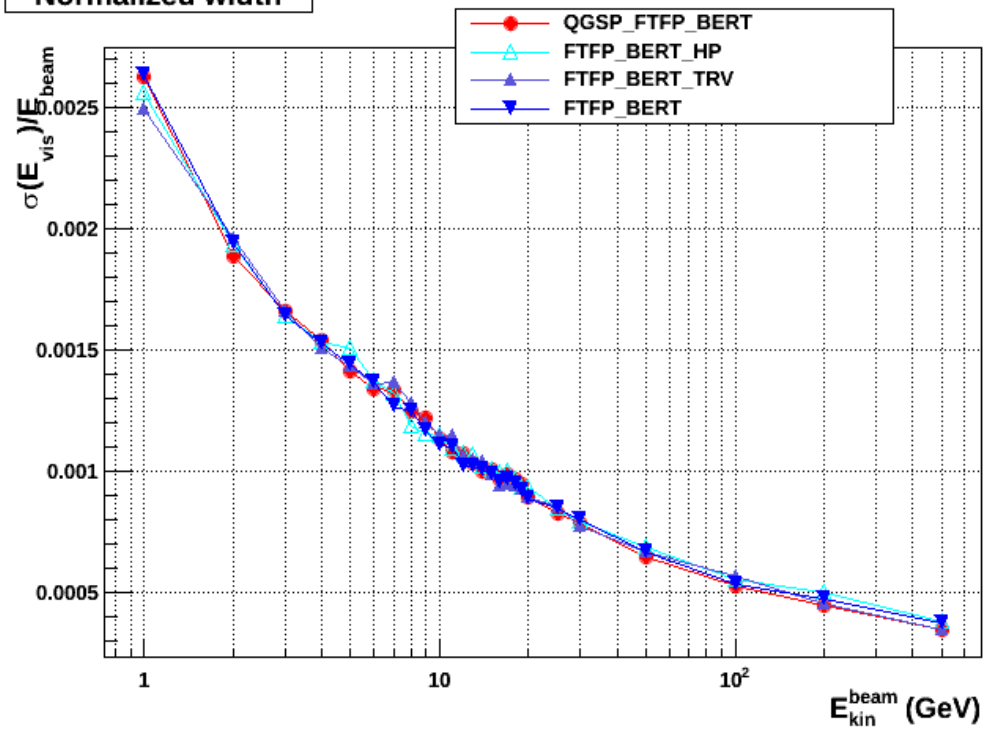


# $\pi^-$ on W-LAr

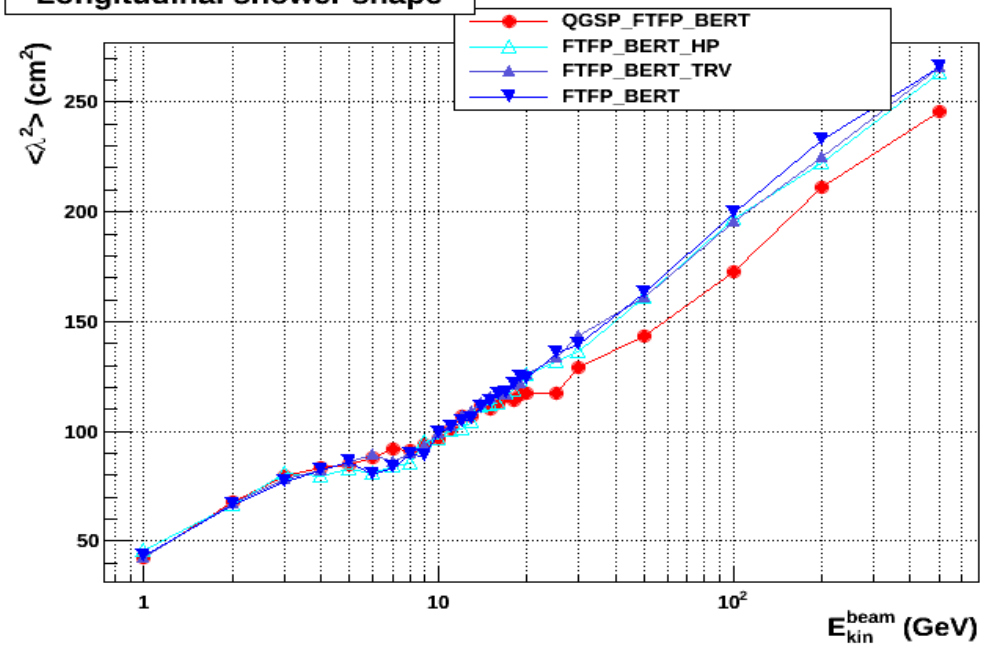
## Energy response



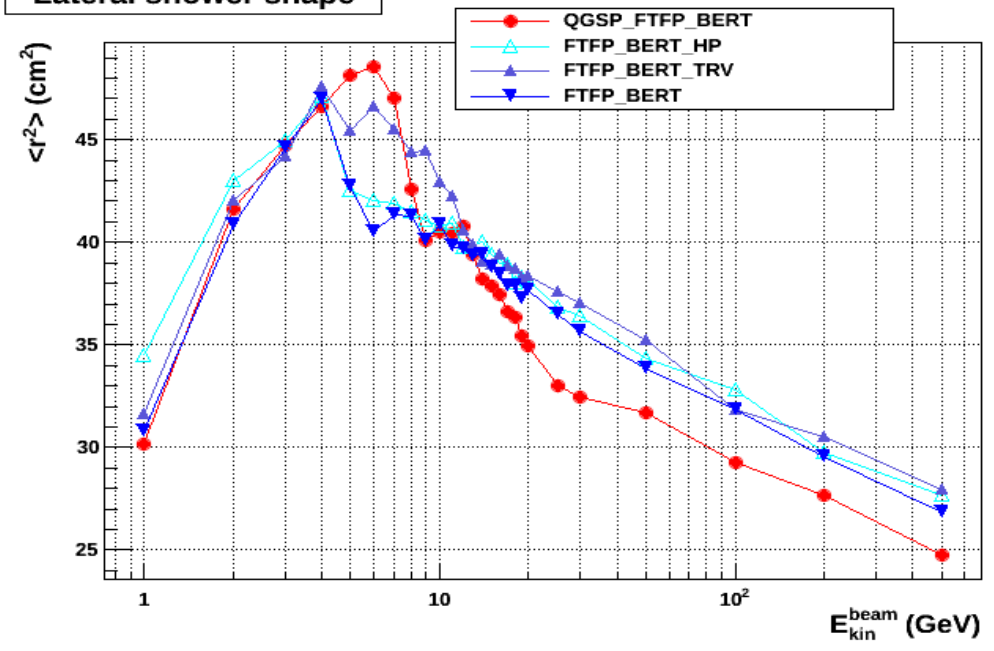

## Normalized width




## Longitudinal shower shape

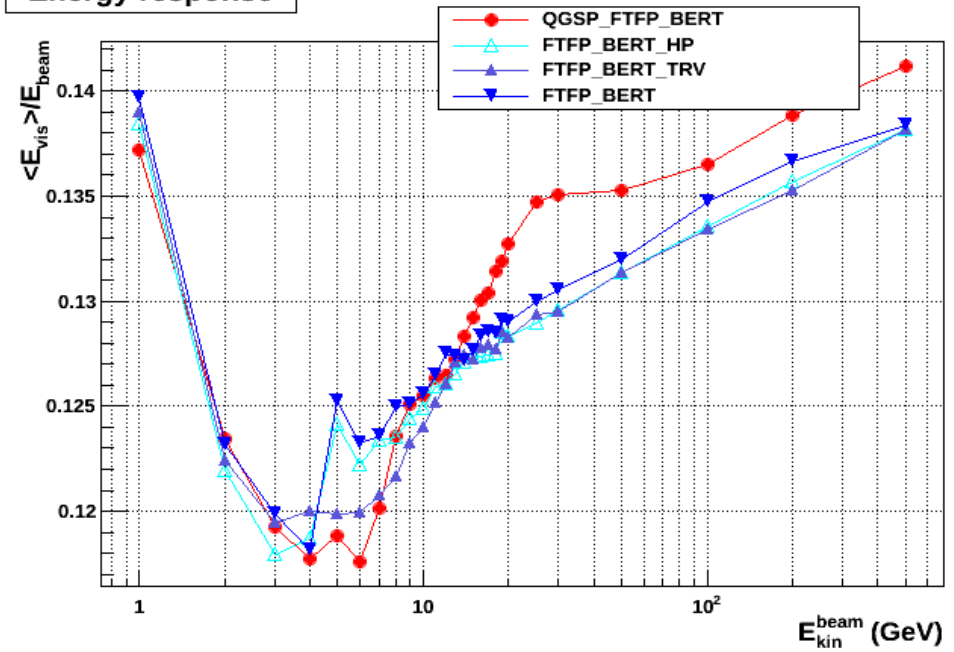



## Lateral shower shape

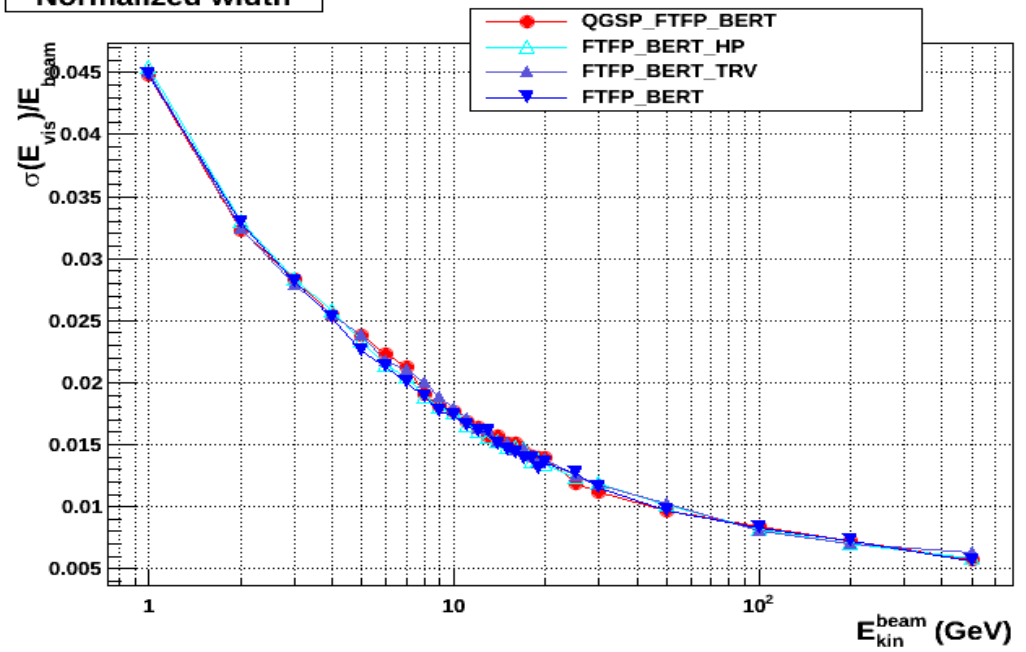


# $\pi^-$ on Pb-LAr

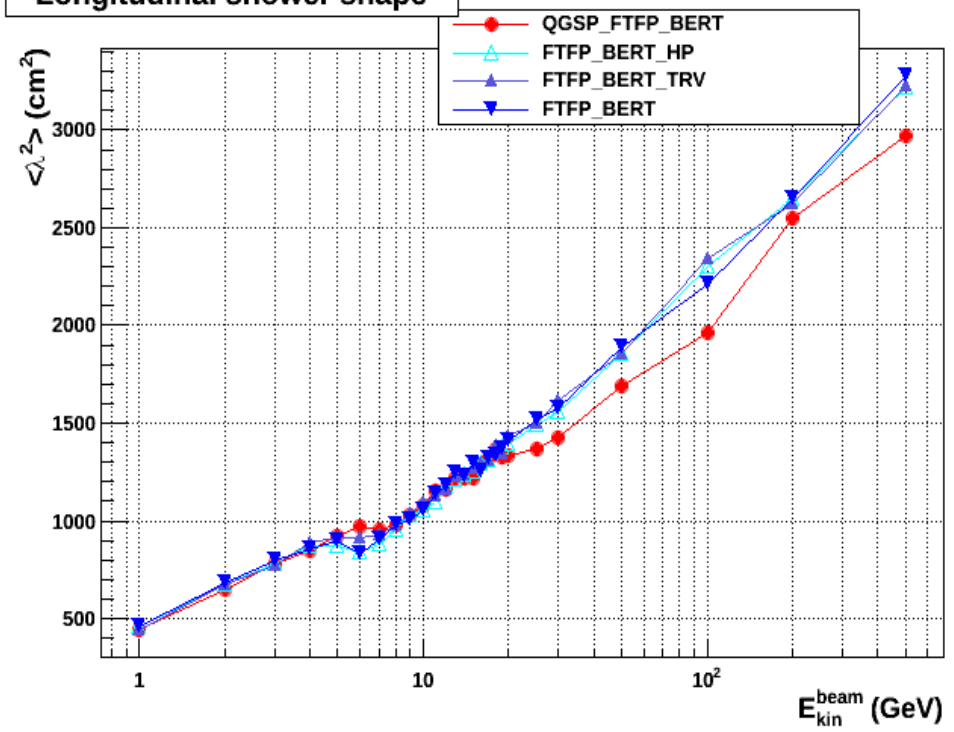
## Energy response




## Normalized width




## Longitudinal shower shape




## Lateral shower shape