Summary of Geant4 Performance

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Outline

My first impressions aimed to summarize the Workshop and trigger a final discussion.

I'll concentrate mostly on physics performance of Geant4, but I start with few words on CPU performance.

- CPU performance
- Geant4 electromagnetic physics
- Geant4 hadronic physics
- Topics for discussion
  - Birks quenching
  - Test-beam data

Geant4 CPU performance

How to speed up Geant4 simulations (for users)?

- Explore EM options
  - Cuts per G4Region
  - “Simple” step limitation for multiple scattering
  - “ApplyCuts” for gamma processes

  You can gain a factor of ~2 max, not more
- Kill unwanted particles (neutrinos, low-energy stuff, etc.)
- Optimization of transportation in magnetic field
- Shower parameterizations or shower libraries in forward detectors
- Variance reduction (i.e. biasing) techniques
  - For low-energy neutrons, and maybe low-energy gammas

  Be extremely careful: it can compromise your results...
- Use (if you can) Geant4 static libraries
- Use multi-threading capability of Geant4

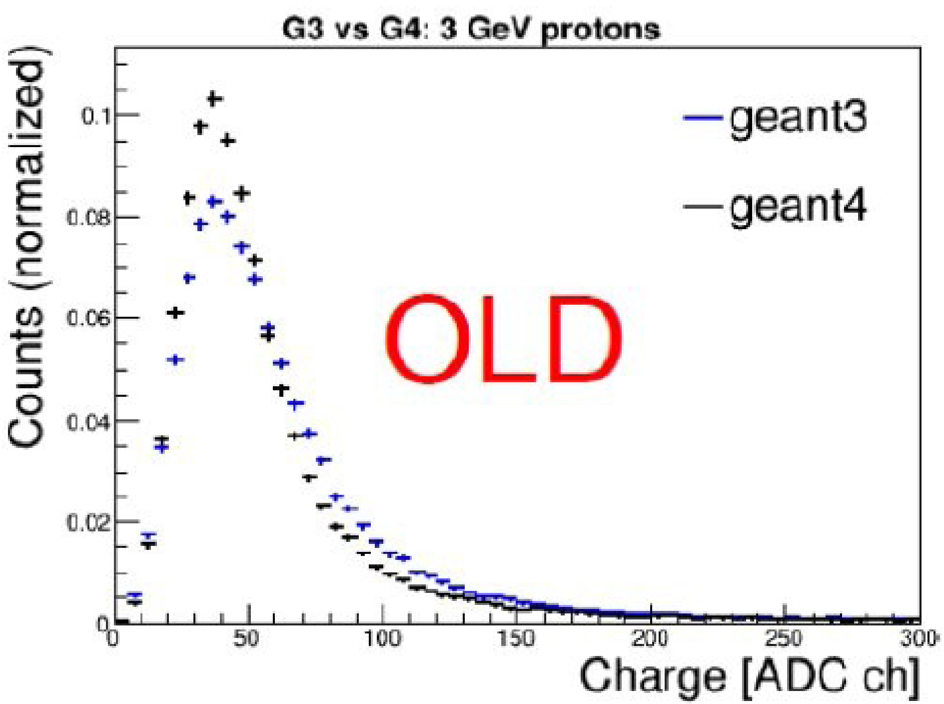
How to speed up Geant4 (for developers)?

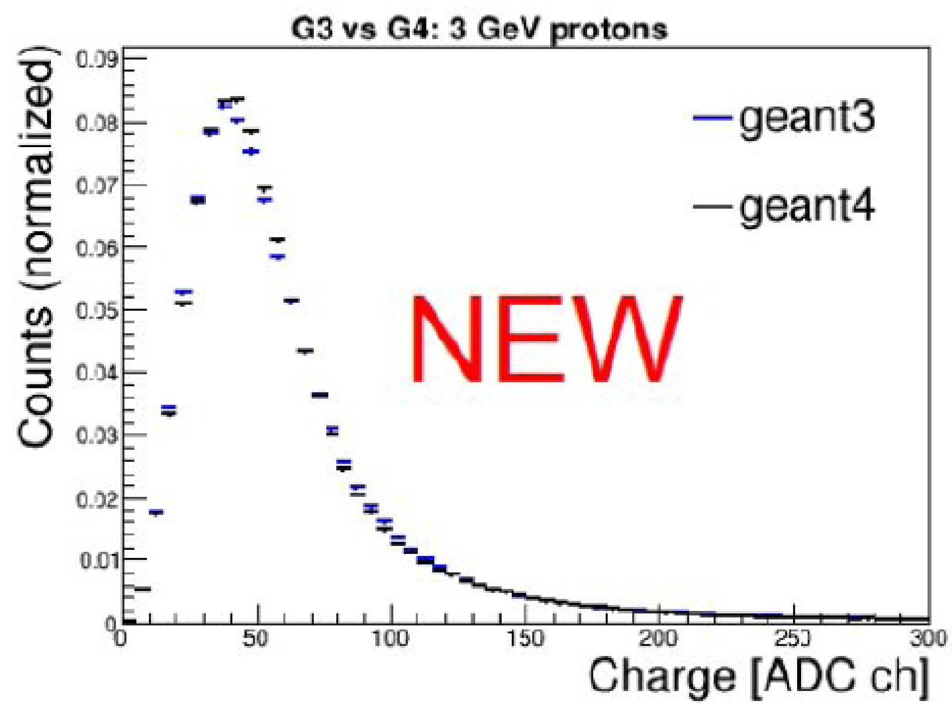
- We are well aware of the importance of CPU performance for detector simulation, so we consider the computing performance of Geant4 (mainly CPU, but also memory footprint and churn) with great care!
- Since a few years, we monitor regularly the Geant4 computing performance through a set of benchmarks, currently run for every reference (monthly) tag, patch, minor or major release
- Whenever a significant (>~ few %) deviation is detected, we investigate to understand its origin
- Hot-spot are detected with profiling, either directly from us or by the experiments
- Code review is an important way to make further progress (also in code quality)

Geant4 electromagnetic physics performance

Improvement in ALICE

- In 2013 solved the problem of the TPC response in G4 simulations
  - G3 uses a special ALICE/NA49 model which describes well the test beam data
  - The solution was to add additional fluctuations in the step where energy loss is converted to ionization using a tuned Gamma distribution on the ALICE side.

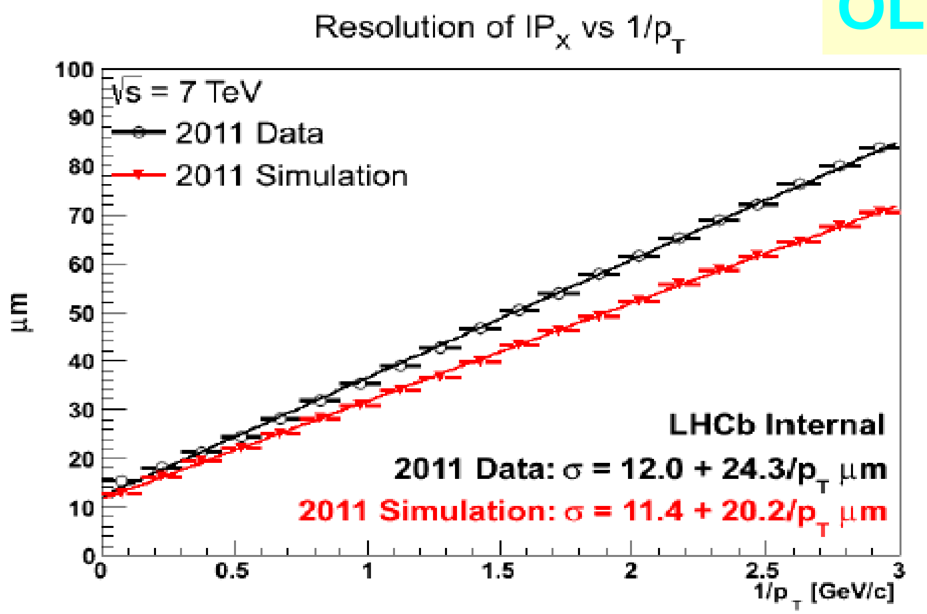


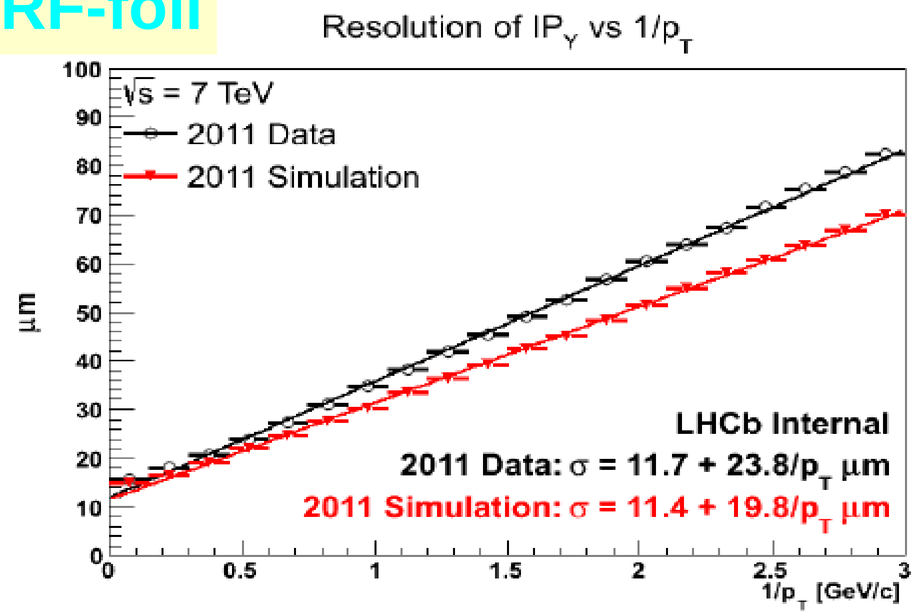


Default Geant4 fluctuation model (Urban) is enough!
No need of the more precise, but slower G4 PAI model

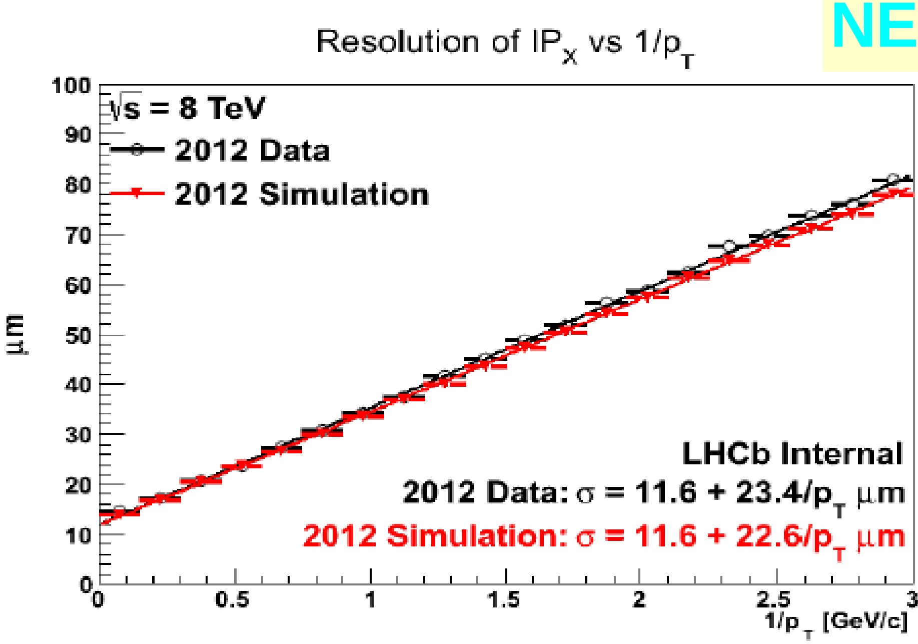
Improvement in LHCb

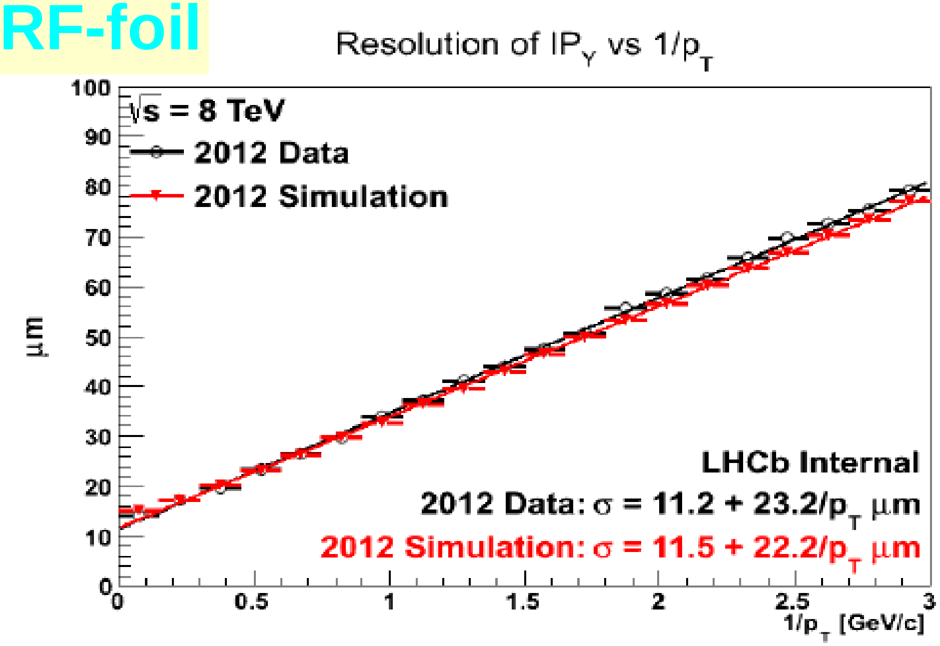
OLD RF-foil





NEW RF-foil

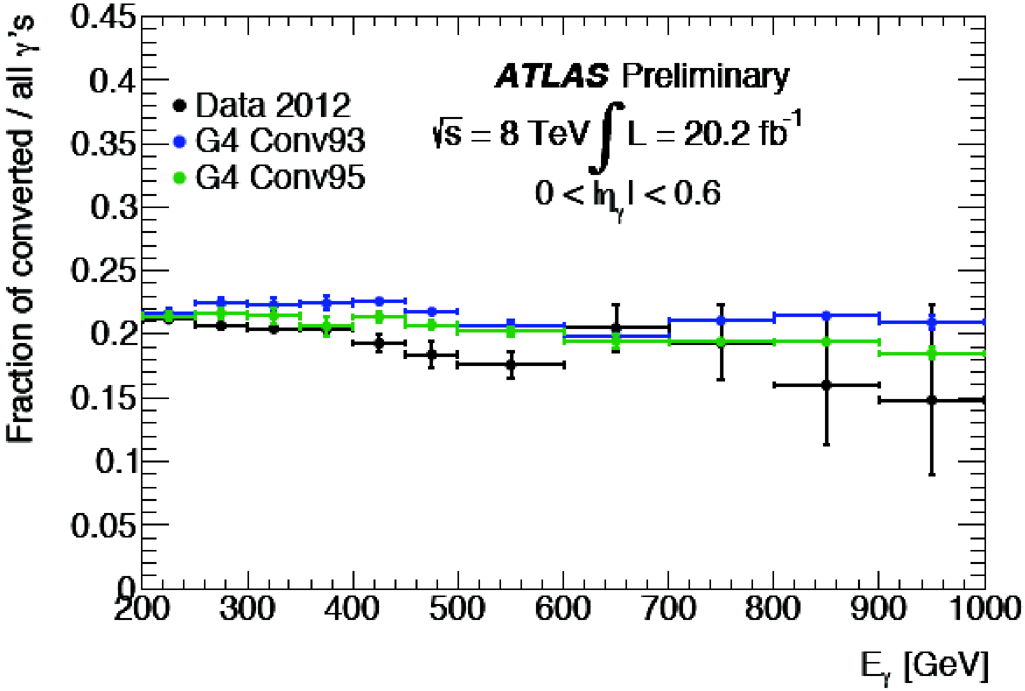


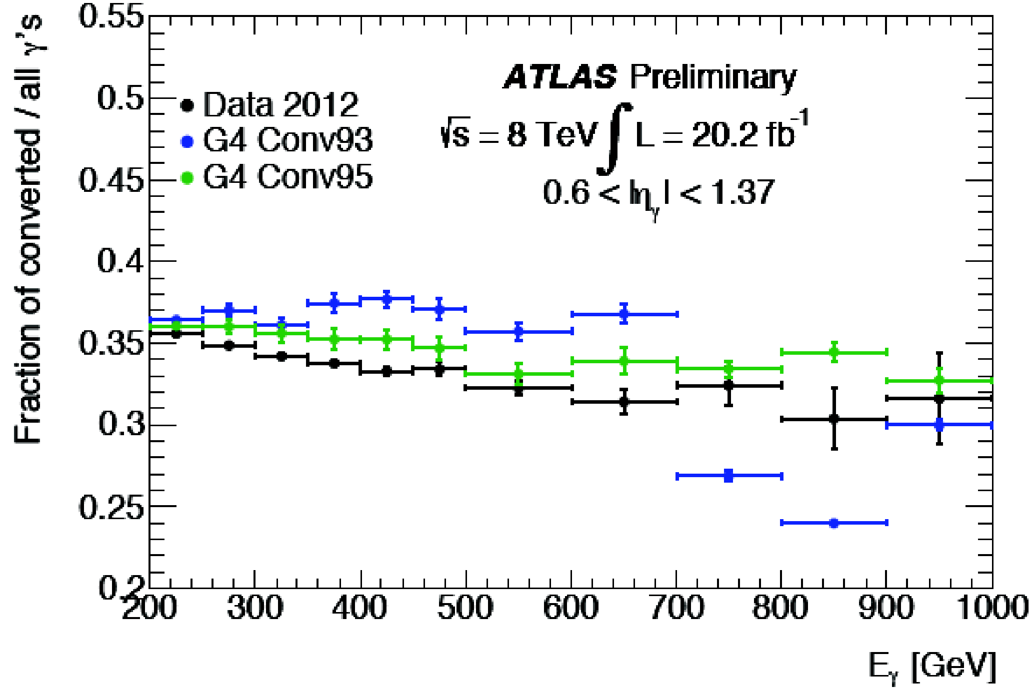


Improvement in ATLAS: photon conversions

- ✓ Conv93 *(known to overestimate probability of conversion in silicon tracker)*
- ✓ Conv95 *(accurate cross section above 100 GeV + ultra-relativistic conversion model accounting for LPM effect)*

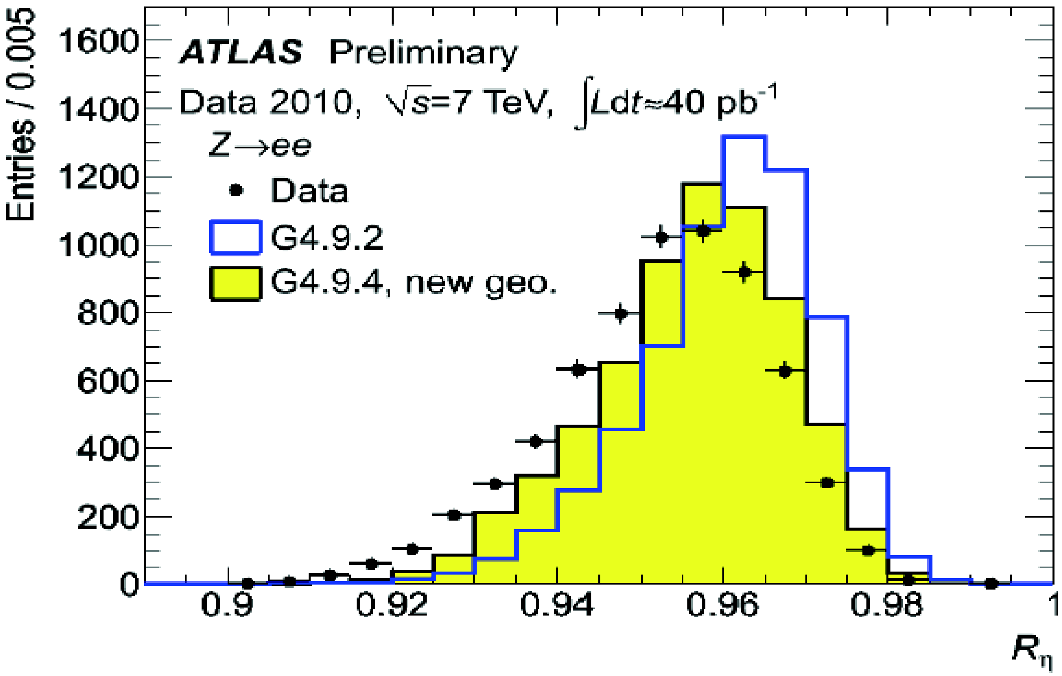
- **Fraction of reconstructed photon conversion vs. candidate energy**



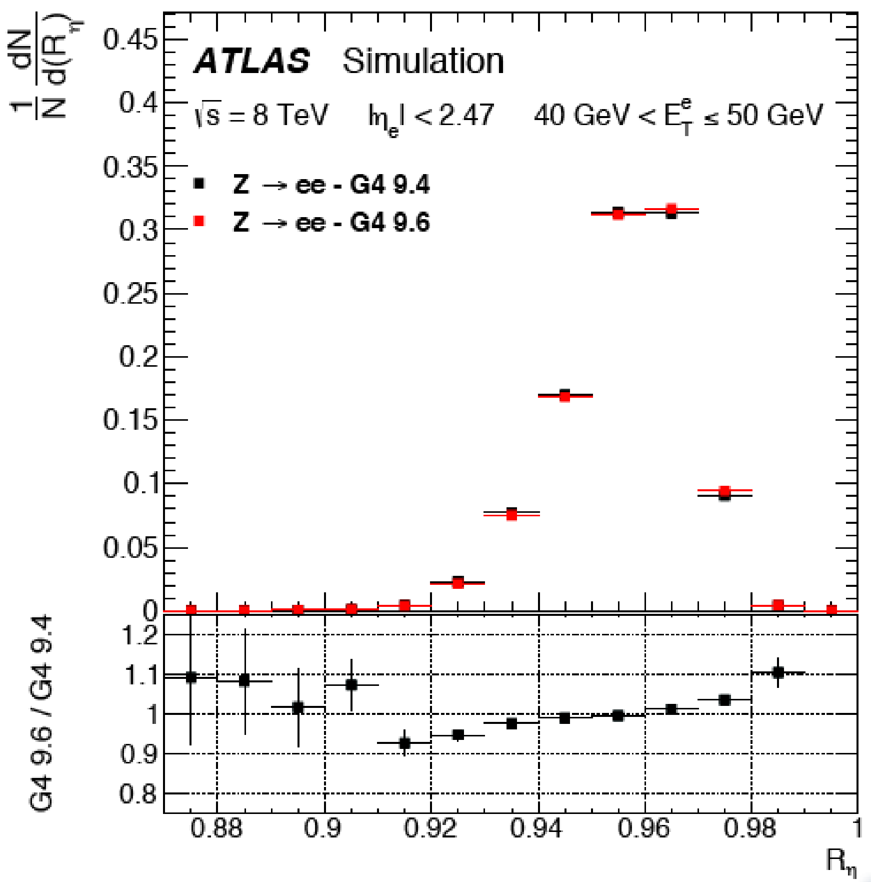


- **A qualitatively better agreement between data and MC is observed when the Conv95 conversion model is used**

ATLAS: electron lateral shower shape



Improved simulation, but still narrower than data



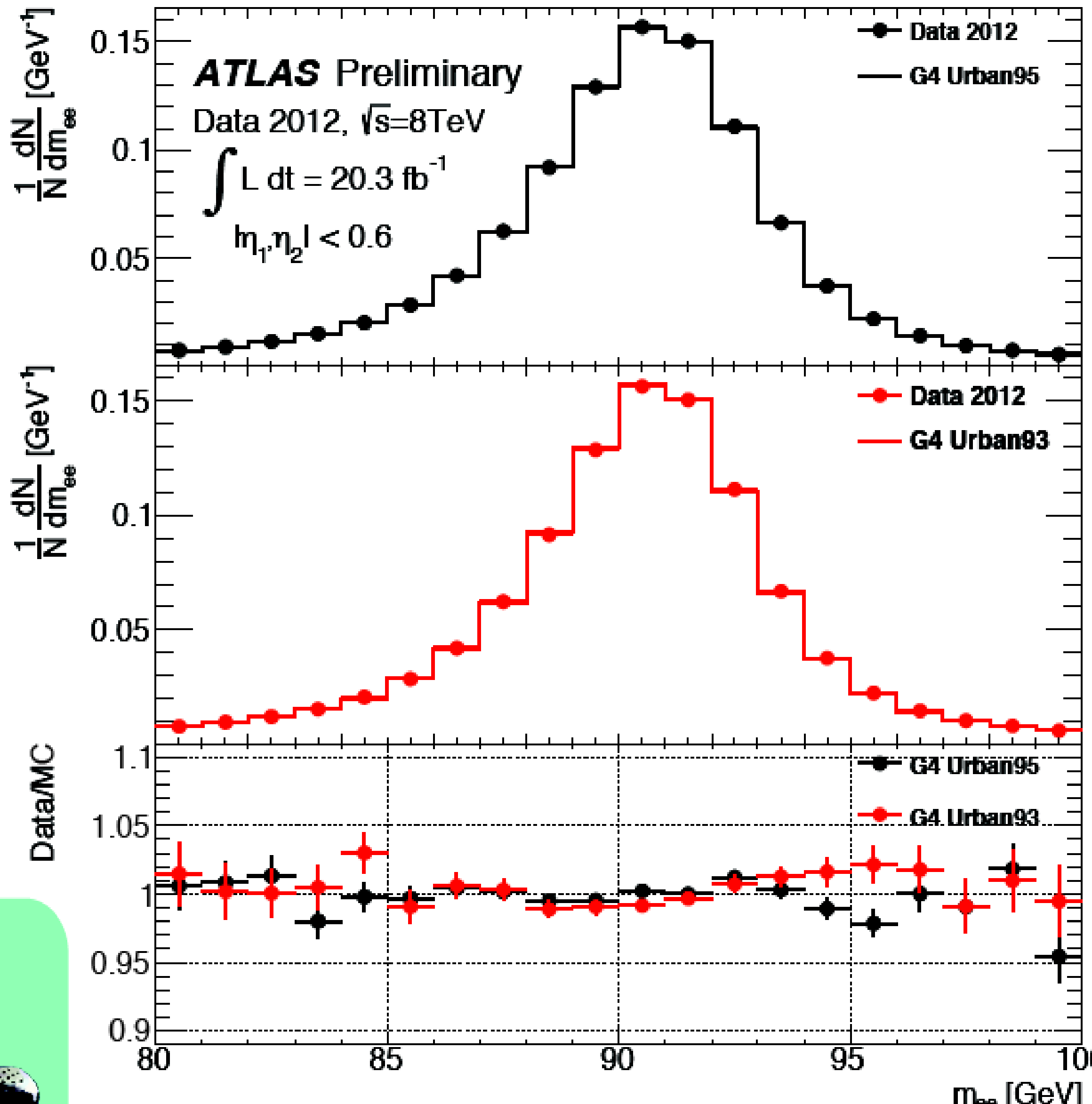
Not clear yet whether it is due to Geant4 physics...

Interesting to see results from CMS and CALICE

ATLAS: Z->ee line-shape

Understanding of Z->ee line-shape is fundamental for in-situ determination of the EM scale

Useful to monitor this very important observable in simplified calorimeters



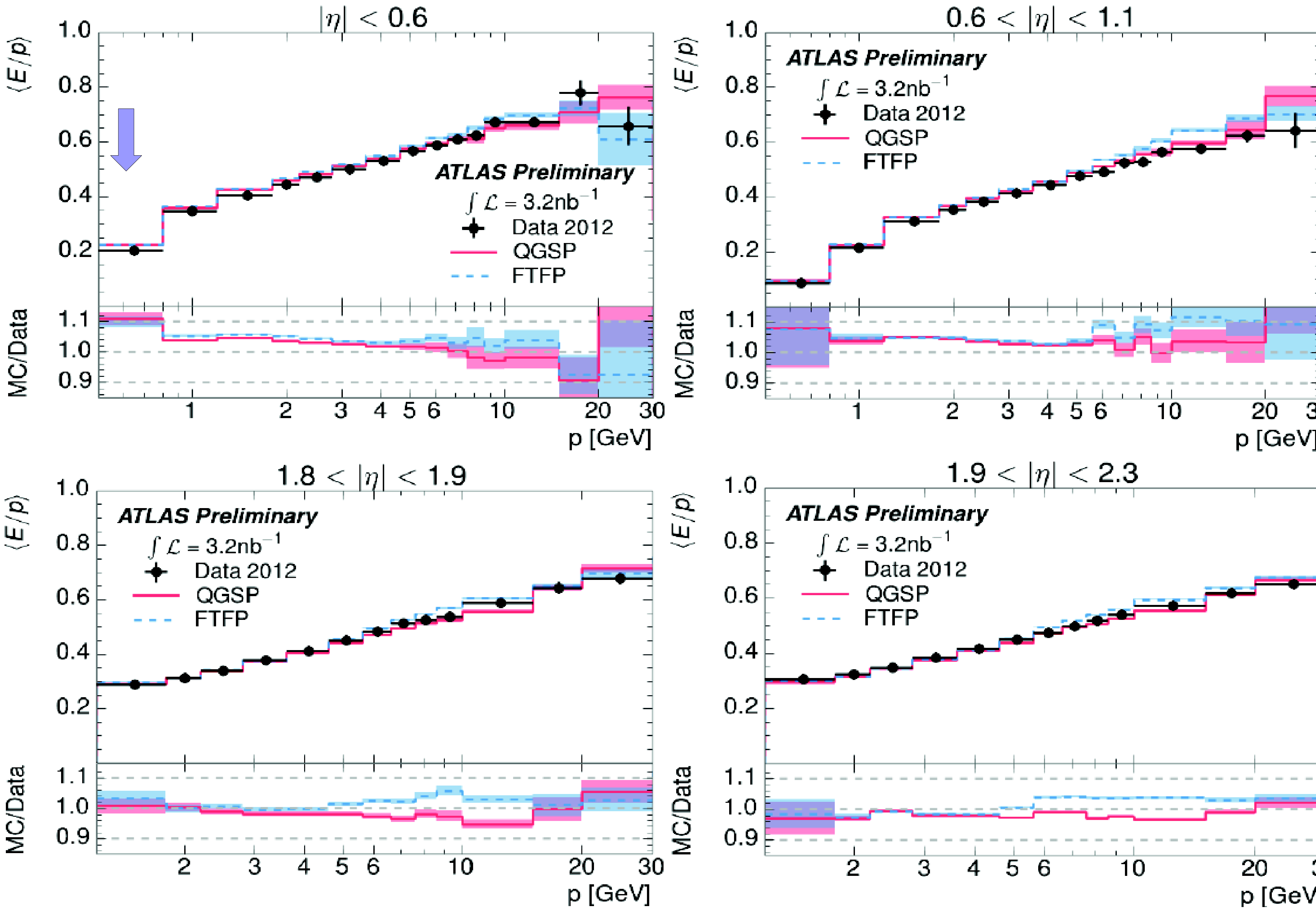
- Uncorrected Z→ee MC line-shapes agree < 1% in m_{ee} = 85-95 GeV, while **show systematic differences ~2-3% in *m_{ee}* tails.**

Status of G4 EM physics

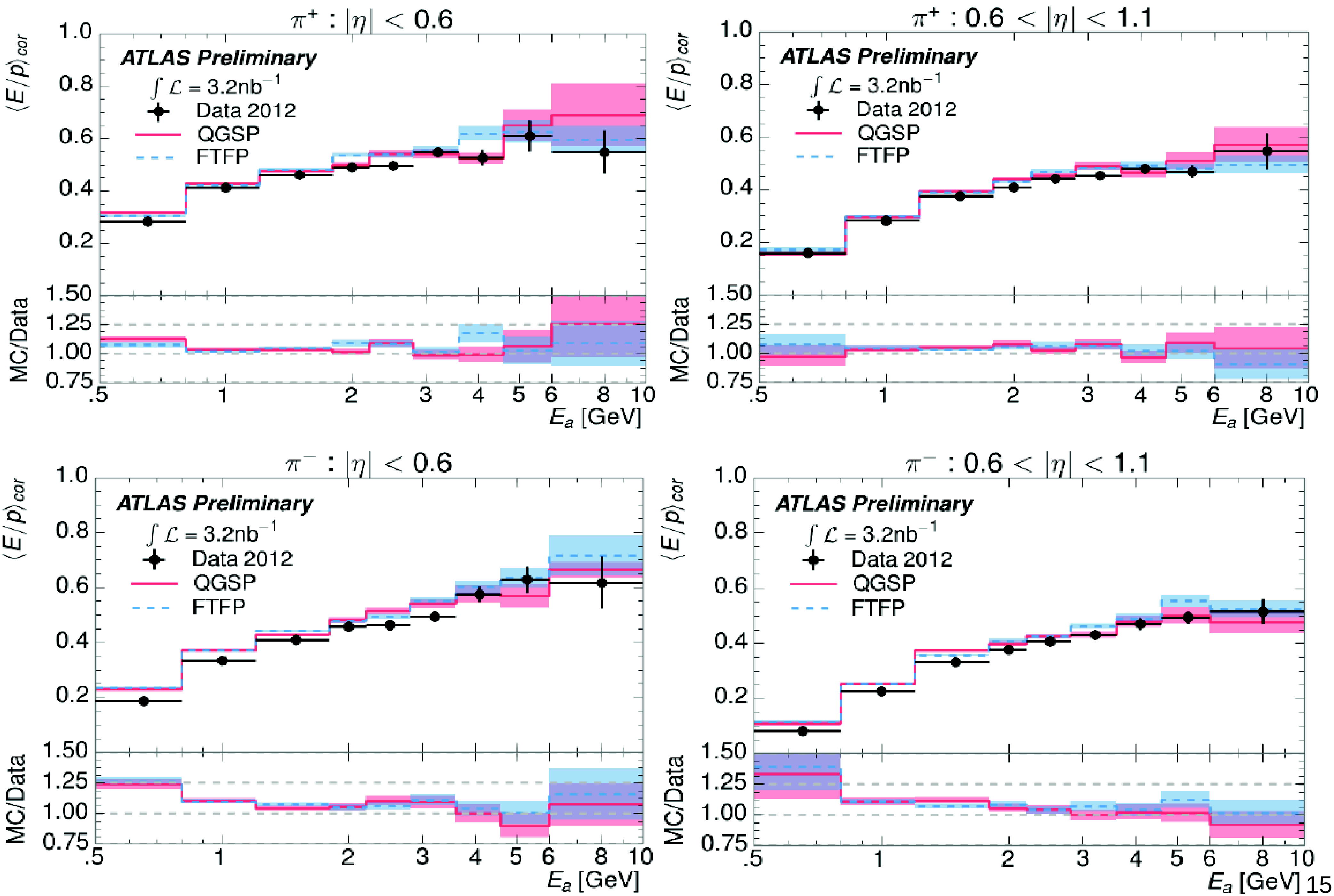
- Geant4 electromagnetic physics looks in "*pleine forme*"
  - As an healthy 20-year old guy is expected to be!
- Of course, the LHC data we got up to know is only the tip of the iceberg, so we have to be prepared for much tougher validation tests in coming years!
- We are continuing with our "normal" development work:
  - Reviewing and consolidating the EM processes
  - Extending the set of validation tests
  - Using regularly these tests, and striving to improve the agreement between simulation and data
- Important progress in recent years has been made on bremsstrahlung, gamma conversion, and multiple scattering
  - Feedback from the experiments has been essential
  - Monitor sensitive observables: Z->ee line-shape, shower shape

Geant4 hadronic physics performance

ATLAS: E/p for inclusive isolated tracks

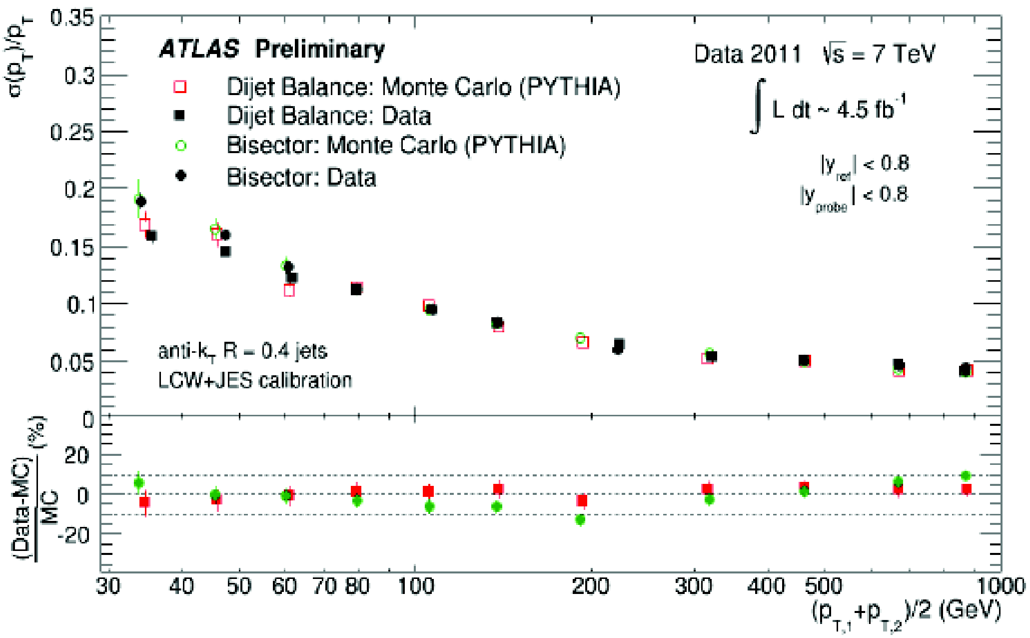


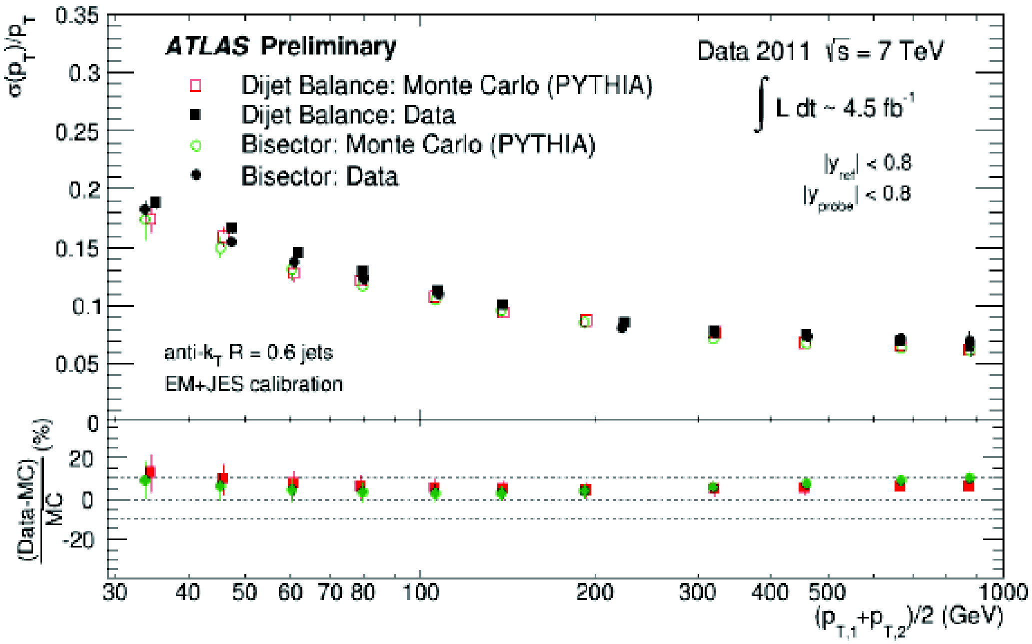
ATLAS: E/p for isolated π+ and π- (from K0s)



ATLAS: jet energy resolution

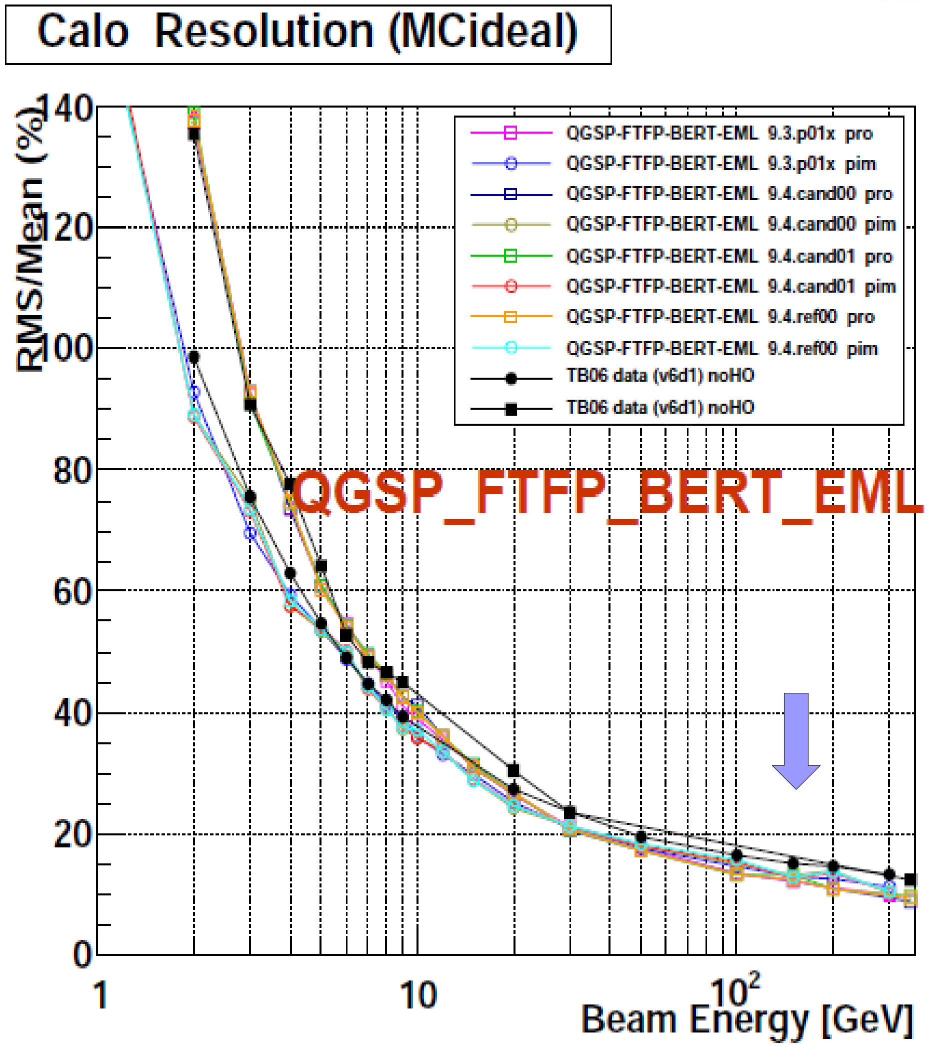
- Jet resolution looks much better in the full 2011 dataset (bottom) than we had feared at the last workshop
  - This is G4 9.4 with QGSP_BERT; picture might change with 9.6 / FTFP
- This doesn't mean that single particle resolution is a solved problem, of course, but it is not something we'll be able to get at from here
- Will revisit this issue with the full 2012 dataset soon, when we'll have more data to cover an even wider range of momenta



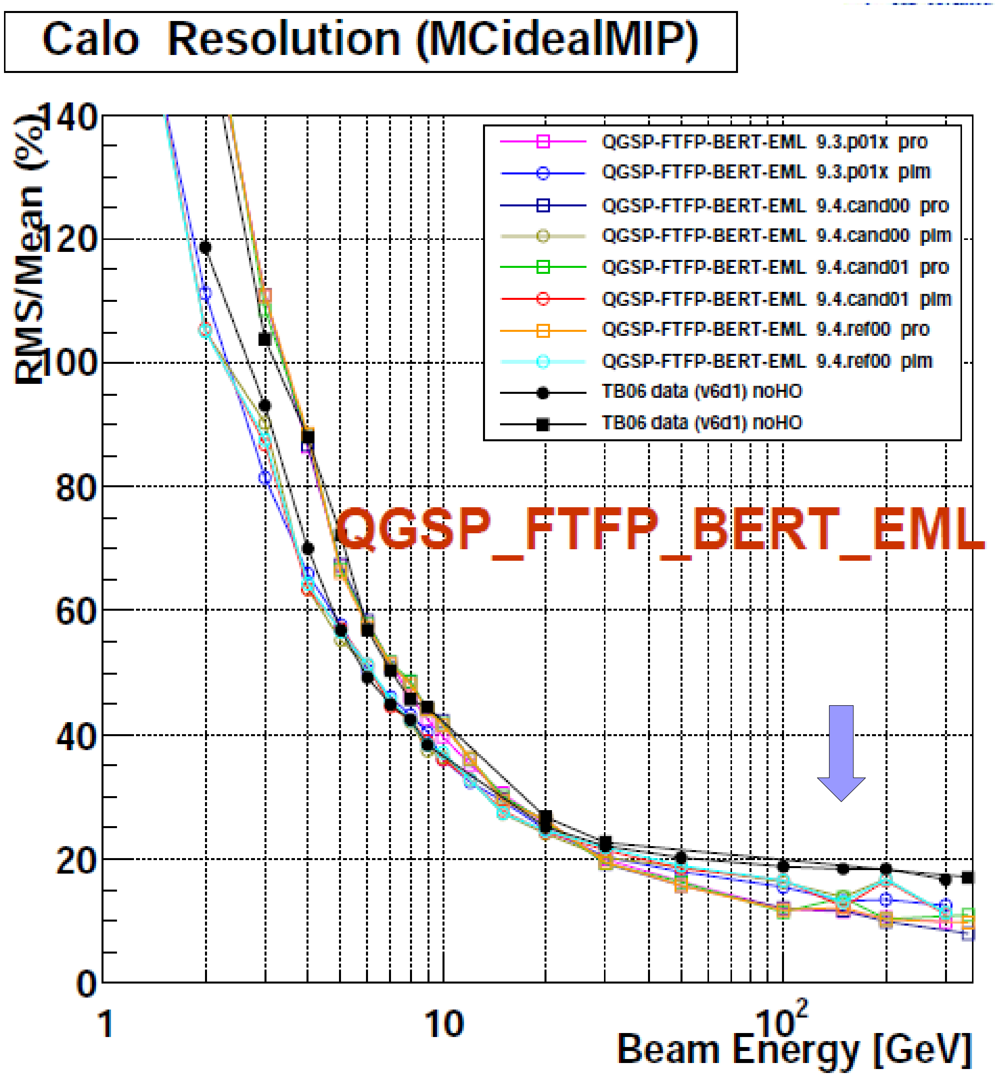


CMS : energy resolution

ECAL + HCAL



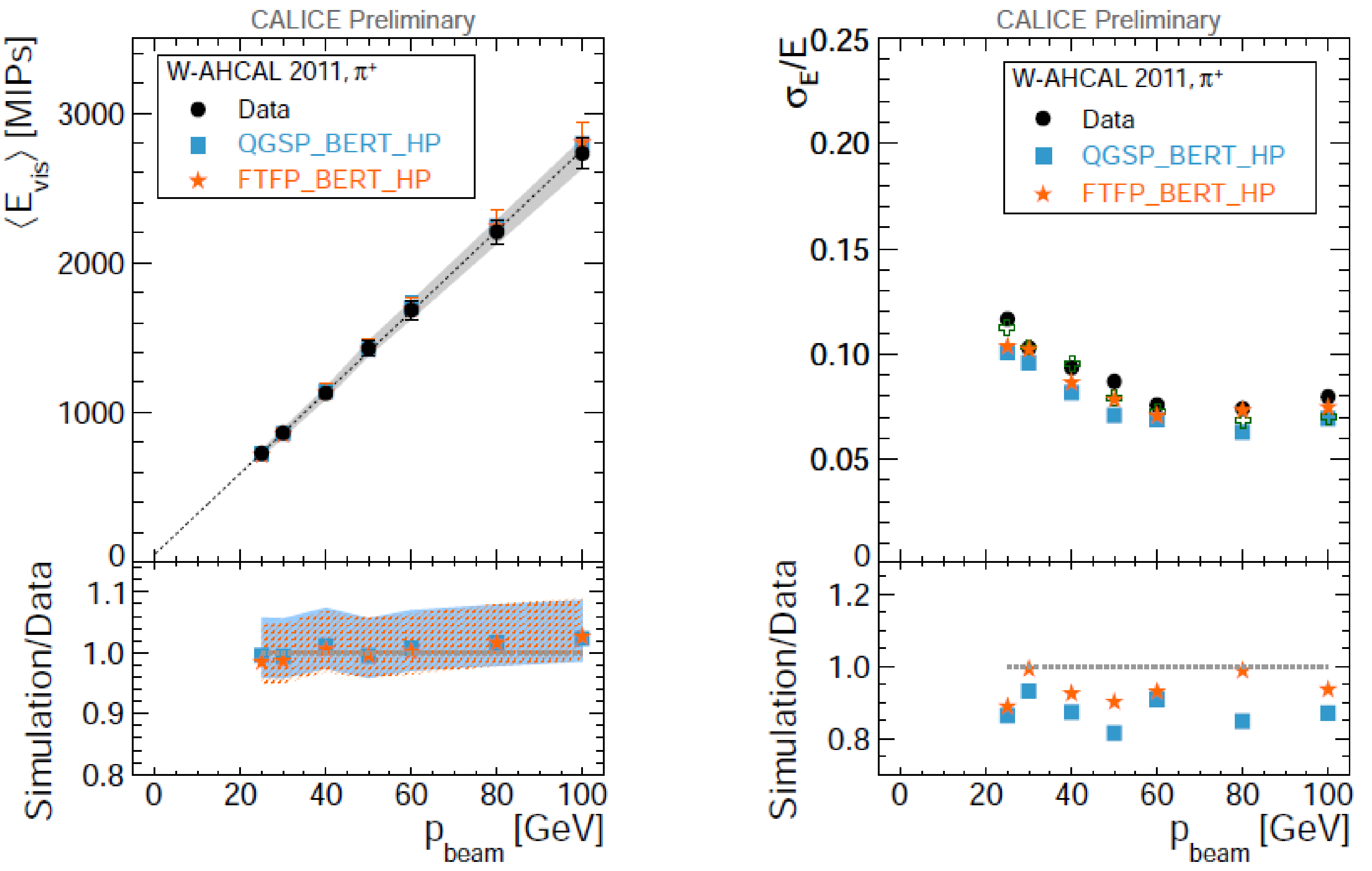
HCAL (mip in ECAL)



CALICE: energy resolution at high energies

Sc-W-AHCAL: Pion linearity and resolution 25-100 GeV

Geant4 version 9.5.p01

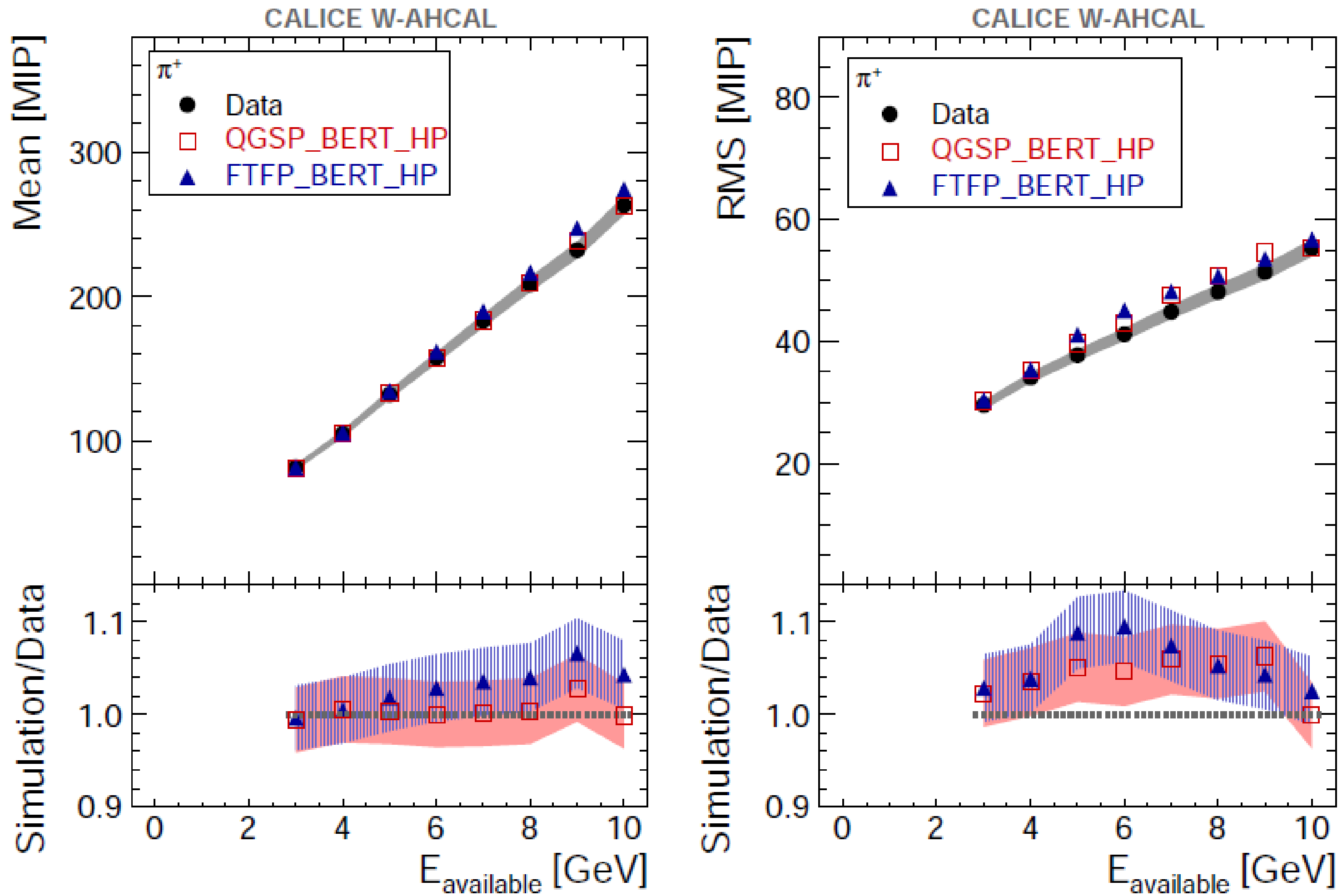


- Pions at 25-100 GeV ▸ CAN-044

CALICE: energy resolution at low energies

Sc-W-AHCAL: Pion linearity and resolution 3-10 GeV

Geant4 version 9.6.p02

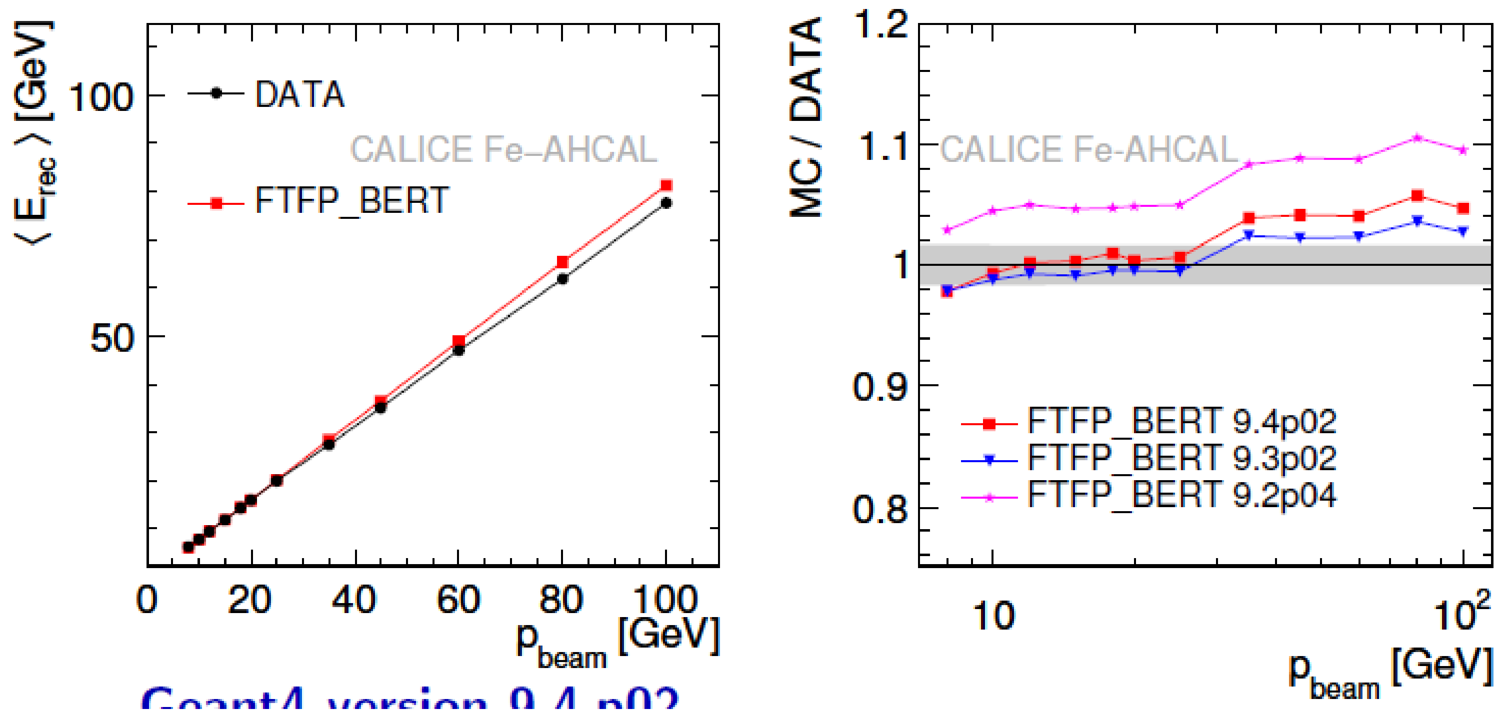


- Pions at 3-10 GeV JINST 9 2014 01004

CALICE: energy response

Sc-Fe-AHCAL: Mean energy of pions

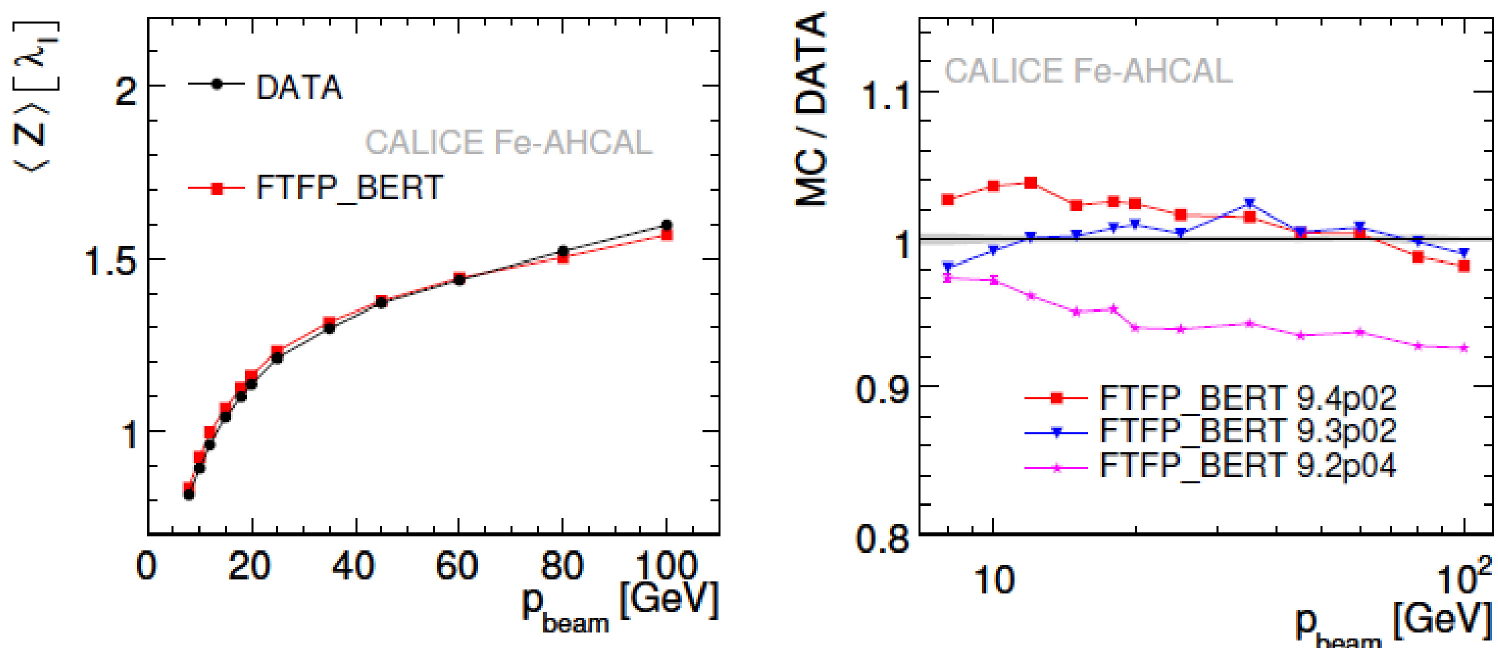
- Pions at 8-100 GeV ▸ 2013 JINST 8 P07005
- Combined test beam with Si-W-ECAL + Sc-Fe-AHCAL



CALICE: longitudinal shower shape

Sc-Fe-AHCAL: Pion longitudinal center of

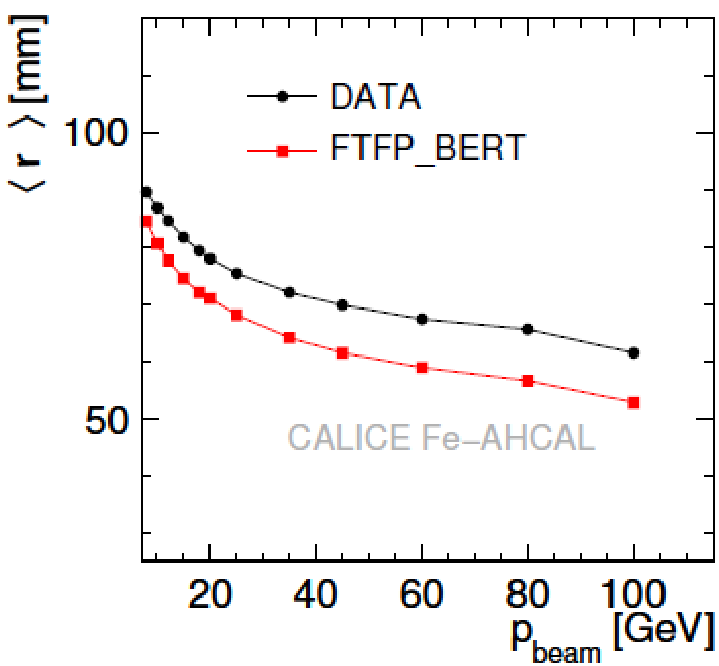
- Pions at 8-100 GeV ▸ 2013 JINST 8 P07005
- Combined test beam with Si-W-ECAL + Sc-Fe-AHCAL

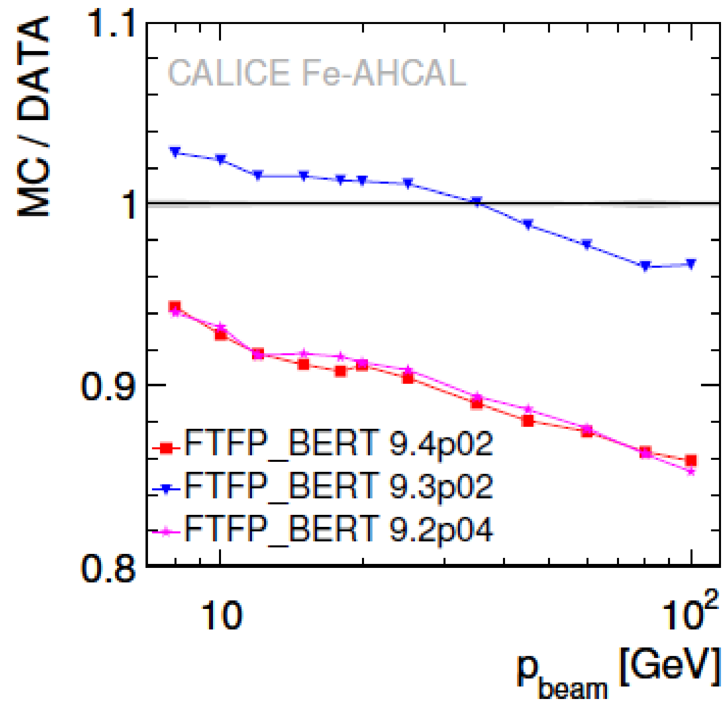


CALICE: lateral shower shape

Sc-Fe-AHCAL: Pion radial center of gravity

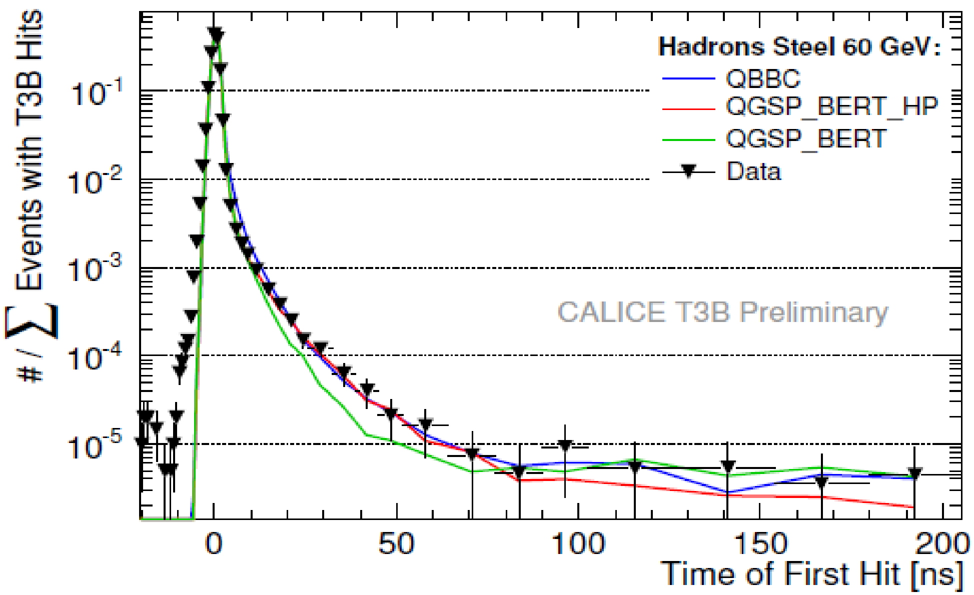
- Pions at 8-100 GeV 2013 JINST 8 P07005
- Combined test beam with Si-W-ECAL + Sc-Fe-AHCAL

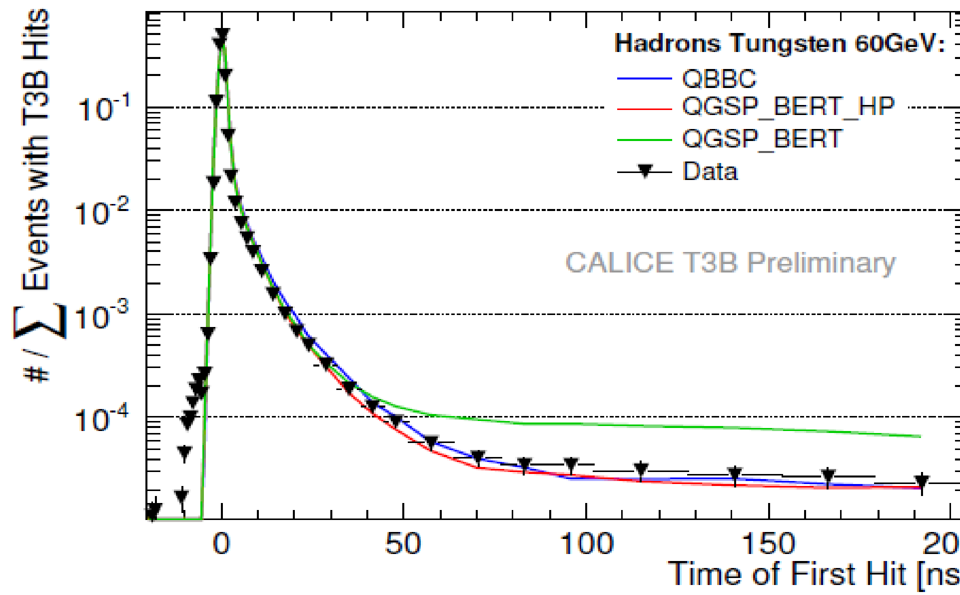




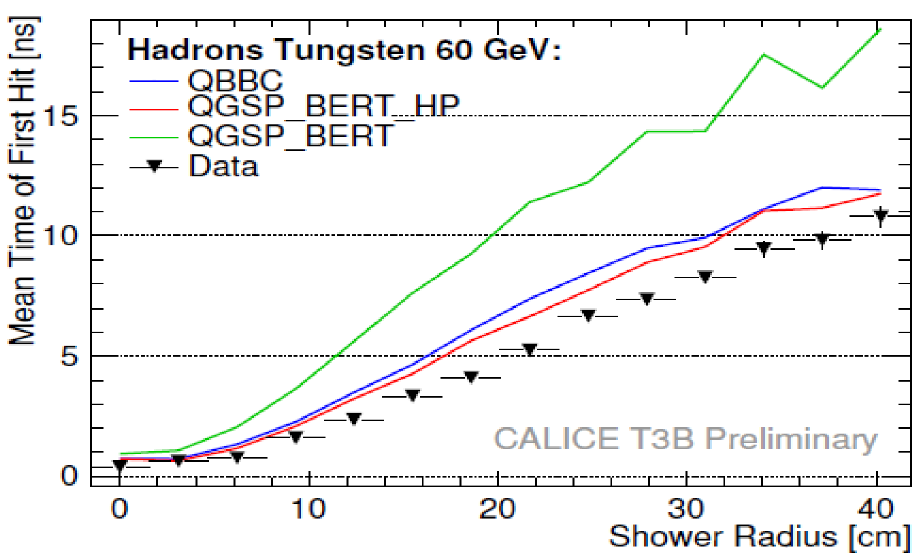
CALICE: shower evolution in time

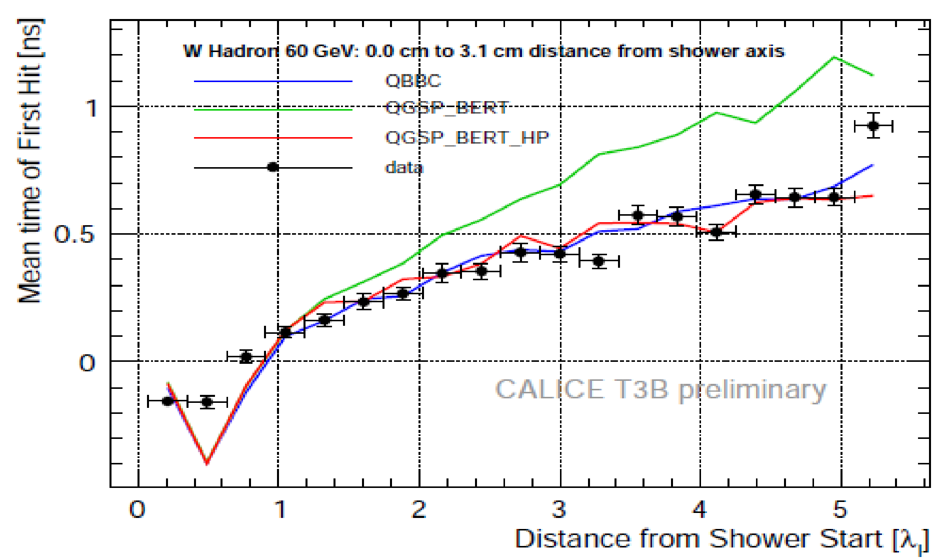
Geant4 version 9.4.p03





Geant4 version 9.4.p03





Status of G4 hadronic physics

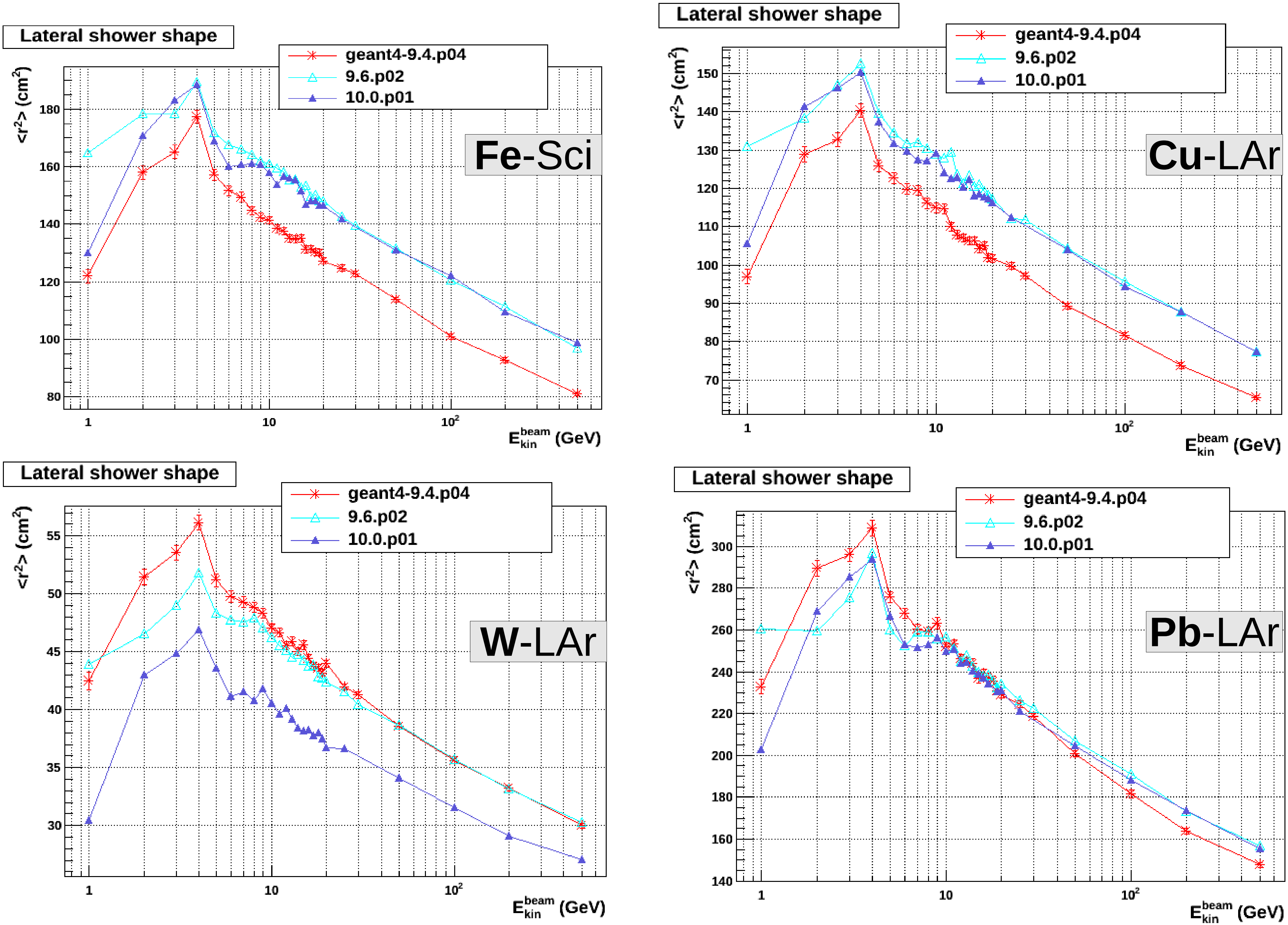
- General satisfaction has been expressed in this Workshop
- Of course, this is not because discrepancies are absent, but because of following two, independent reasons
  - In collider-data, it is difficult to distinguish between Geant4 aspects, event-generator effects, and experiment-specific issues (materials, digitization, pile-up)
  - For cleaner test-beam data, excellent agreement is not expected given the well-known complexity of hadronic physics!
- Since the last workshop, we have improved
  - Fritiof (FTF)
  - Bertini-like (BERT) model
  - Inelastic cross sections
  - Low-energy neutron treatment, in particular capture

The main effects on hadronic showers has been on lateral shower shapes

Hadronic shower lateral shape

- Main player is the intra-nuclear cascade model (BERT)
  - Revision of internal pion-nucleon and nucleon-nucleon cross sections
- Other players are:
  - Neutron-nucleus inelastic cross sections
  - Neutron capture, in particular for Tungsten
  - Meson (pi0) vs baryon production in the string model (FTF)
- Main changes (see pi- showers in simplified calorimeters in the next slide)
  - Wider showers in Fe and Cu
  - Narrower showers in W (similar to QBBC, therefore closer to _HP)
- We expect to have improved the simulation of the lateral shapes, but we need feedback from the experiments!

FTFP_BERT : Lateral shower shapes



Hadronic shower longitudinal shape

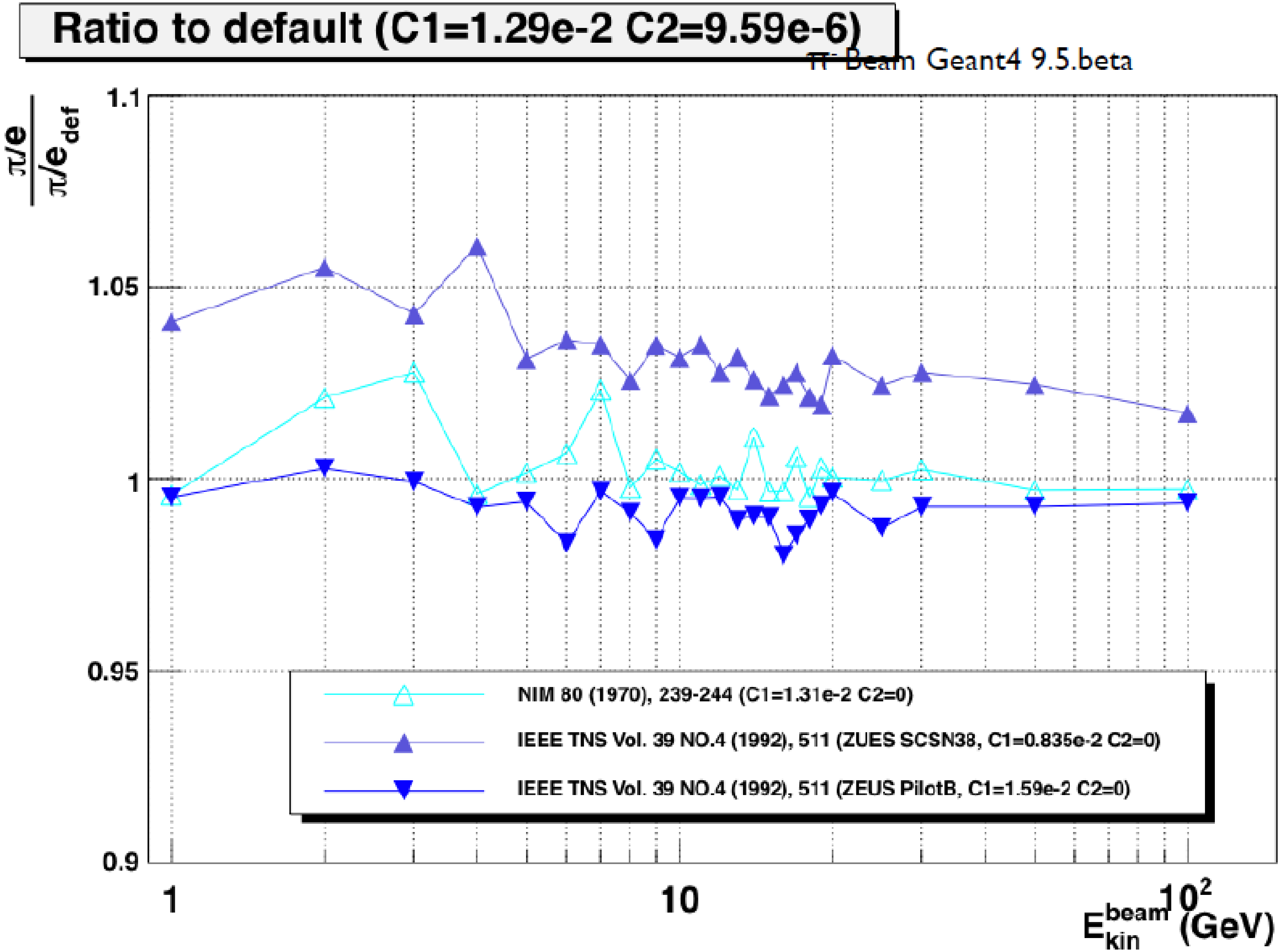
- Main players are:
  - Diffraction in the string model (FTF)
    - Major improvements in hadron-nucleon diffraction in FTF, but not clear what to do for hadron-nucleus...
  - Quasi-elastic
  - Elastic
  - Meson (pi0) vs baryon production in the string model (FTF)
- Small changes observed in simplified calorimeters
  - A little bit shorter
- We need feedback from the experiments!

Hadronic energy response

- All the models contribute:
  - Meson (pi0) vs baryon production in the string model (FTF)
  - Intra-nuclear cascade model
  - Precompound/de-excitation
- In simplified calorimeters
  - Big change (lower response) in Tungsten
    - Due to the improvement in neutron capture
  - Small changes observed for Iron and Copper
    - A little bit higher response at low energies
    - A little bit smaller response at high energies
- We need feedback from the experiments!
- Important issue: Birks quenching (see next slides)

Birks queching (1/2)

Scintillator based calorimeters



Max 4% differences depending on Birks' parameters choice

Slide from A. Dotti shown at the last workshop

Similarly to noise simulation is responsibility of experiment's frameworks

Birks quenching (2/2)

- So, the choice of the Birks coefficients can have a significant impact on energy response of hadrons in scintillator-based calorimeters
- As far as I know, both ATLAS and CMS use values published from an old paper with a different scintillator...
- CALICE has measured the Birks coefficients of their scintillator

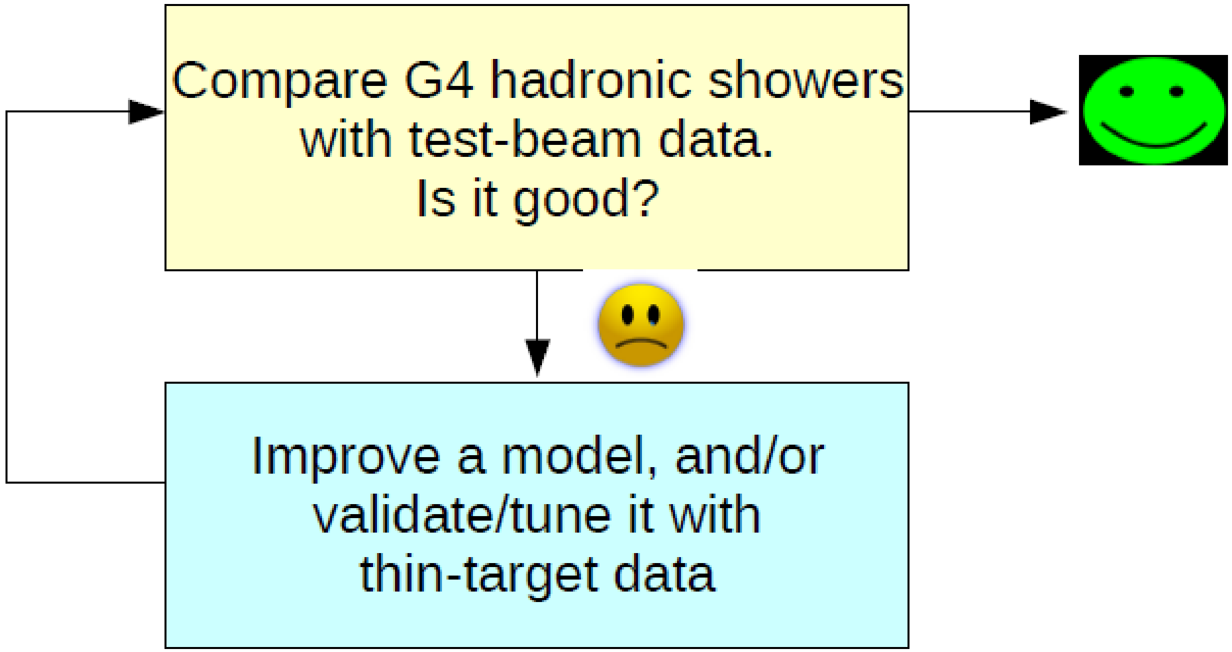
Would it be possible for ATLAS and CMS to measure these coefficients, in some way?

- There are subtleties on how to implement Birks quenching for gammas and neutrons...
- Birks can also be used for recombination effects in LAr...

Hadronic energy resolution

- All the models contribute:
  - Meson (pi0) vs baryon production in the string model (FTF)
  - Intra-nuclear cascade model
  - Precompound/de-excitation
- In simplified calorimeters
  - Small changes, a bit smaller fluctuations at high energies (so in the wrong direction with respect to the test-beam data!)
- We plan to concentrate on this observable
  - Re-scattering (BERT or BIC) in FTF
  - Re-tuning of BERT (with Precompound)
  - Try out also INCLXX and ABLA
- See next slide on the complication we have recently encountered on improving physics models, in particular BERT and FTF

A word of caution on our strategy



- It happened that physics-motivated improvements to a model produced worse thin-target data comparisons
  - For example Bertini: is this due to an old tuning?
- It happened that a new tuning of a model improved some thin-target data comparisons, but worsen others
  - For example latest Fritiof tuning: shall we look at the showers?

Test-beam data

Feedback to the Geant4 developers

- Most of the improvements in Geant4 physics have been driven by the calorimeter test-beams, in particular:
  - ATLAS **TileCal** , ATLAS **HEC**
  - CMS **ECAL+HCAL**
  - **CALICE**
- Before the LHC run, we got regular feedback from the LHC test-beams, typically once per public release
- Unfortunately, as seen clearly in this workshop, this is not the case any longer!
- What can we do about it?
  I think there 4 possible solutions, shown in the next slides in order of preference (and difficulty)

Test-beam validation: solution 1 (the best)

- Get regular feedback (~ once per year) directly from the people involved in the test-beam data, or new people of the same experiment, or even group
  - This would be ideal, because they know how to run the software, and all the details of the simulation
  - In my opinion (but I hope to be wrong!) very unlikely to happen
    - little time available
    - little interest to do this extra work

  The exception could be CALICE...

Test-beam validation: solution 2

- As solution 1, but executed by Geant4 people
  - Need either to extract the software to get a stand-alone application, or to have access to the experiment software, and then learn how to run it (porting from an old version could be likely needed...)
  - In my opinion, unlikely to happen
    - Need to have a dedicated Geant4 (SFT) fellow
    - Commitment of the experiment, and in particular the original authors of the test-beam, to help and guide him/her

Test-beam validation: solution 3

- Correct test-beam data for digitization and reconstruction, and export the geometry via GDML
  - Method proposed by Tancredi Carli (ATLAS) and I a few years ago
  - There are some complications to be studied
    - Beam spread
    - Using Geant4 to correct the data, and then using it to validate Geant4...
  - Good reactions from the people, but not concrete follow-up actions!
  - In my opinion, very unlikely to happen
    - it is too late, and the original authors of the test-beam are even busier than before to do the work

  The exception could be CALICE...

Test-beam validation: solution 4

- Put by hand the experimental test-beam data points (and error bars) on top of the simplified calorimeters, to reproduce the discrepancies reported by the experiments for a well-defined version of Geant4
  - Method introduced by Andrea Dotti
    - for the energy response of Fe-Sci (TileCal) and Cu-LAr (HEC)
  - In my opinion, the only realistic and reasonable solution
    - To be extended to other observables and test-beams (CALICE, CMS)

Conclusions

- Continued the **consolidation** of Geant4 physics - **cross sections**, **physics models**, and **physics lists** - and adapted for multi-threading.
  We plan to continue in this direction.

- G4 **9.6** is going to be the main production version for the Run 2 LHC simulations (at least ATLAS and LHCb), but G4 **10** could also be used (perhaps CMS, ALICE ?)
  - Of course, for us the best would be if all use G4 10 ...

- It would be very useful for us to get regular feedback from the experiments, in particular for the old, but vital, test-beams, for at least each new Geant4 public versions (i.e. once per year)

- When to hold the next (3^{rd}) LPCC Detector Workshop ?
  After the Run 2 ?

Backup slides

Pion showers in simplified calorimeters

Note: when data is shown, these are rescaled ATLAS test-beam data (obtained with an old version of Geant4, before G4 9.4)

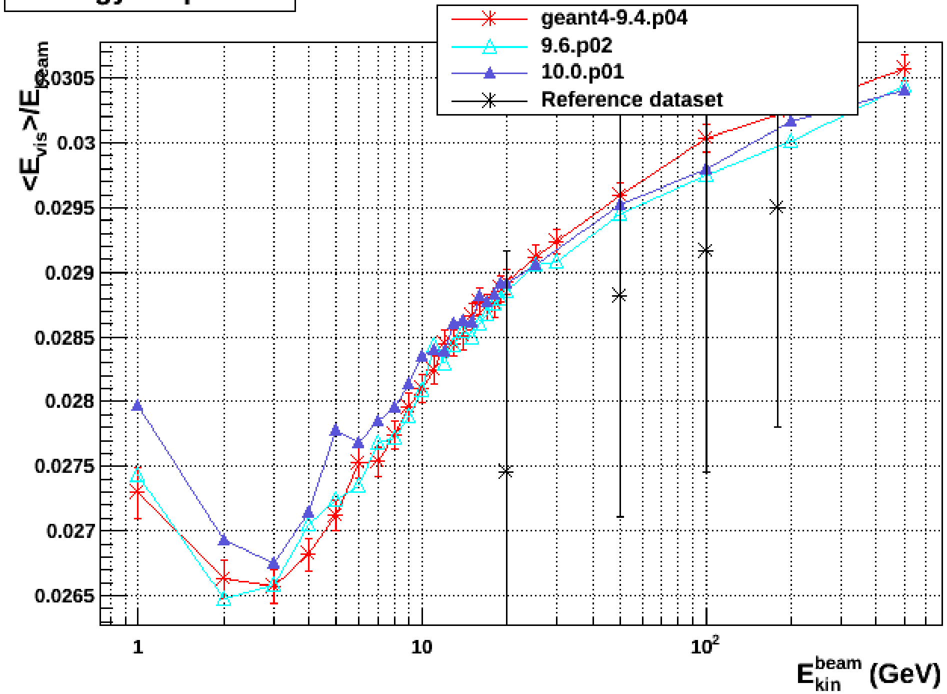
Comparing G4 versions:

9.4.p04 , **9.6**.p02 , **10.0**.p01

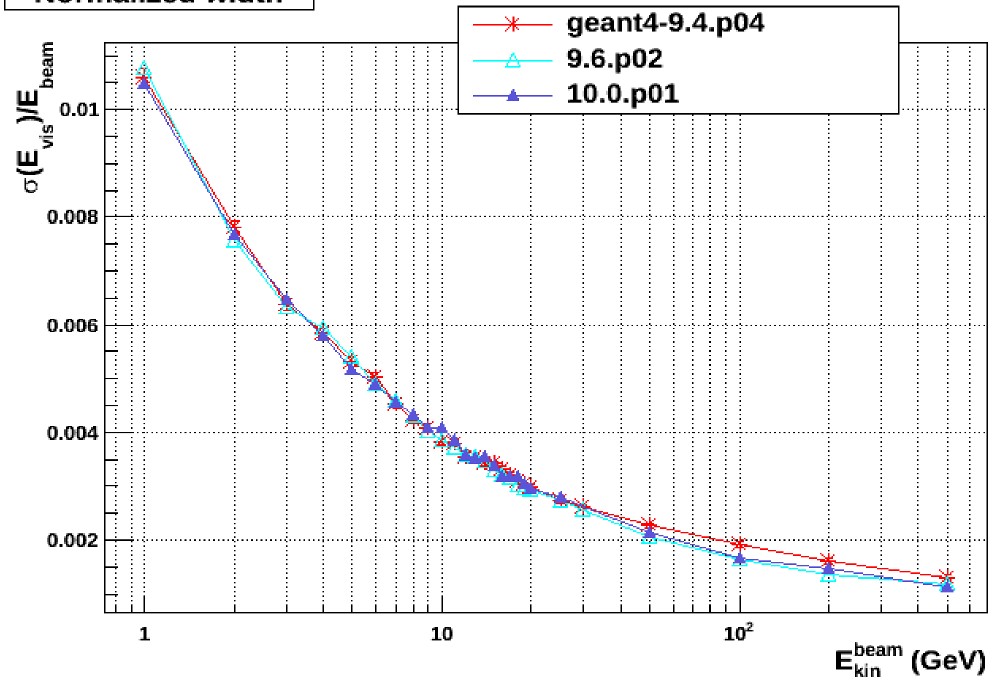
FTFP_BERT

π^- on Fe-Sci

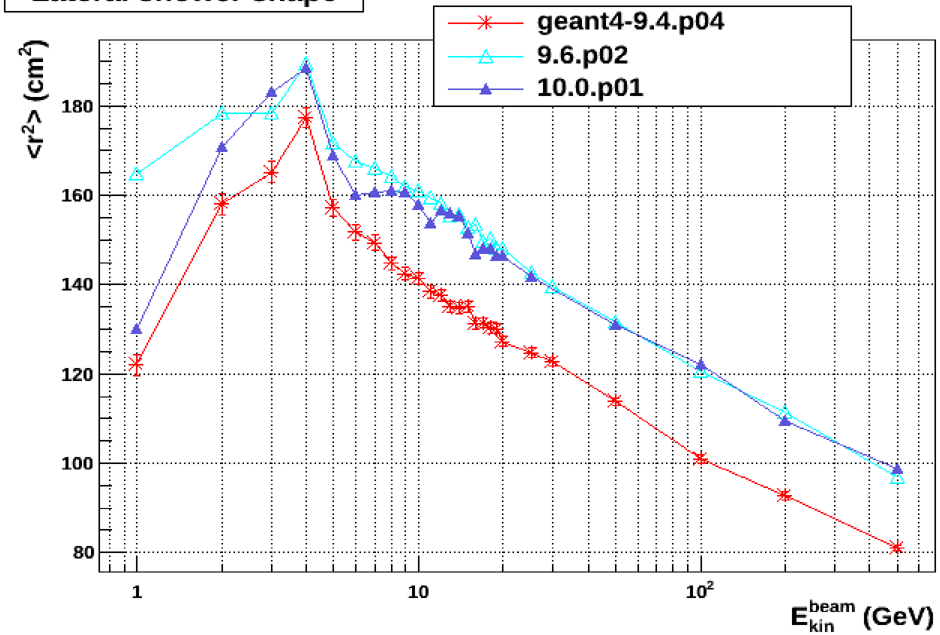
Energy response



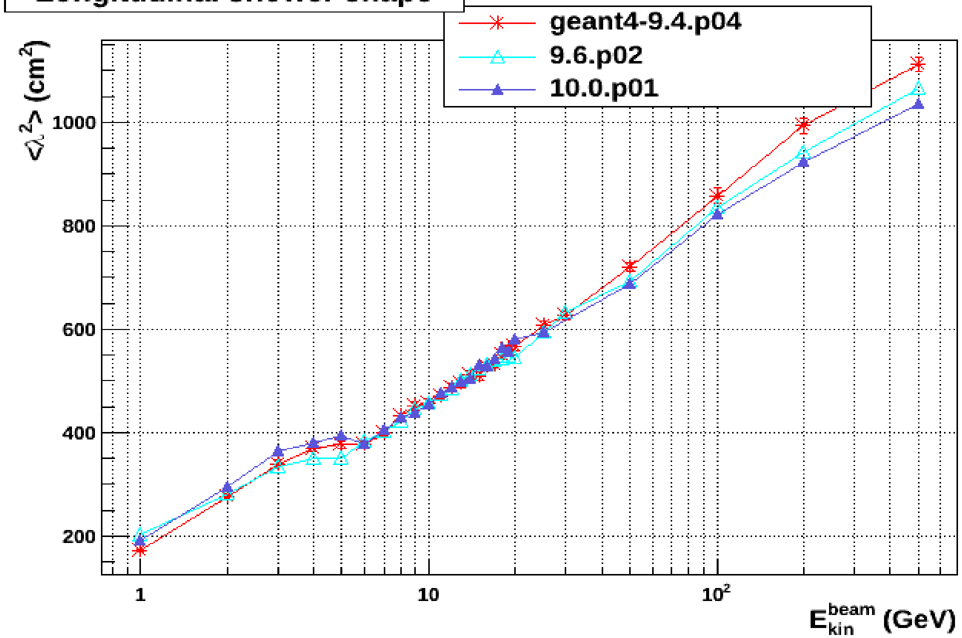
Normalized width



Lateral shower shape



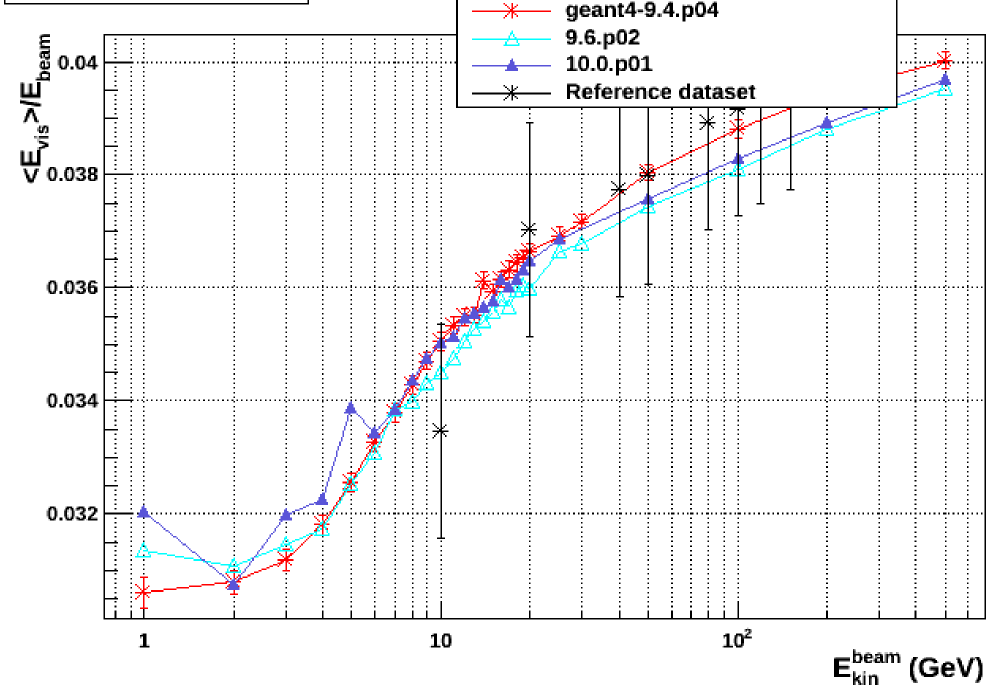
Longitudinal shower shape



FTFP_BERT

π^- on Cu-LAr

Energy response



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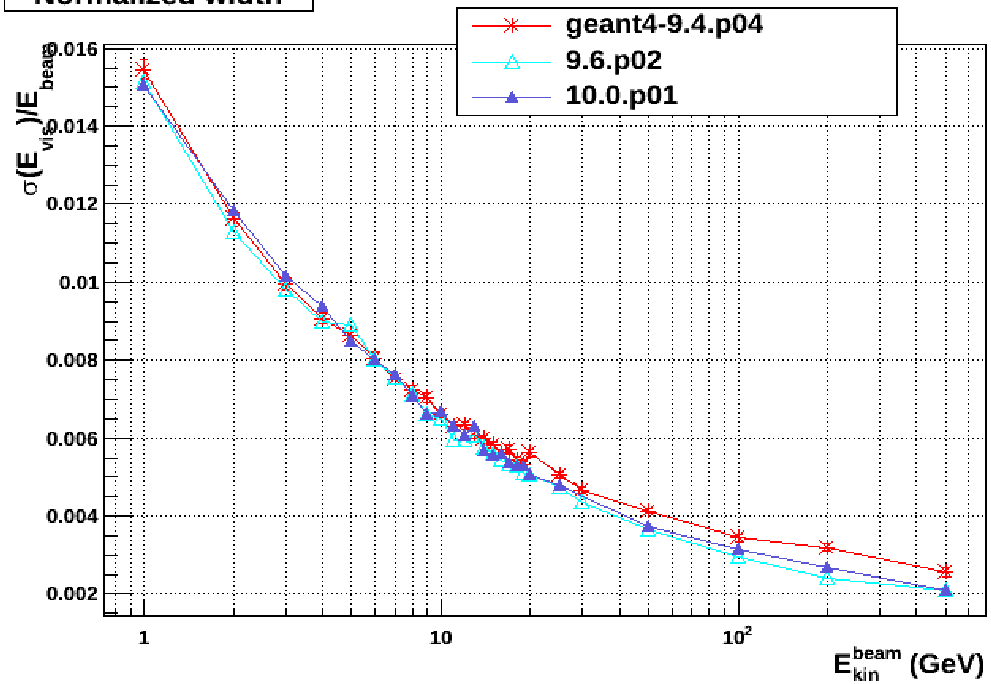
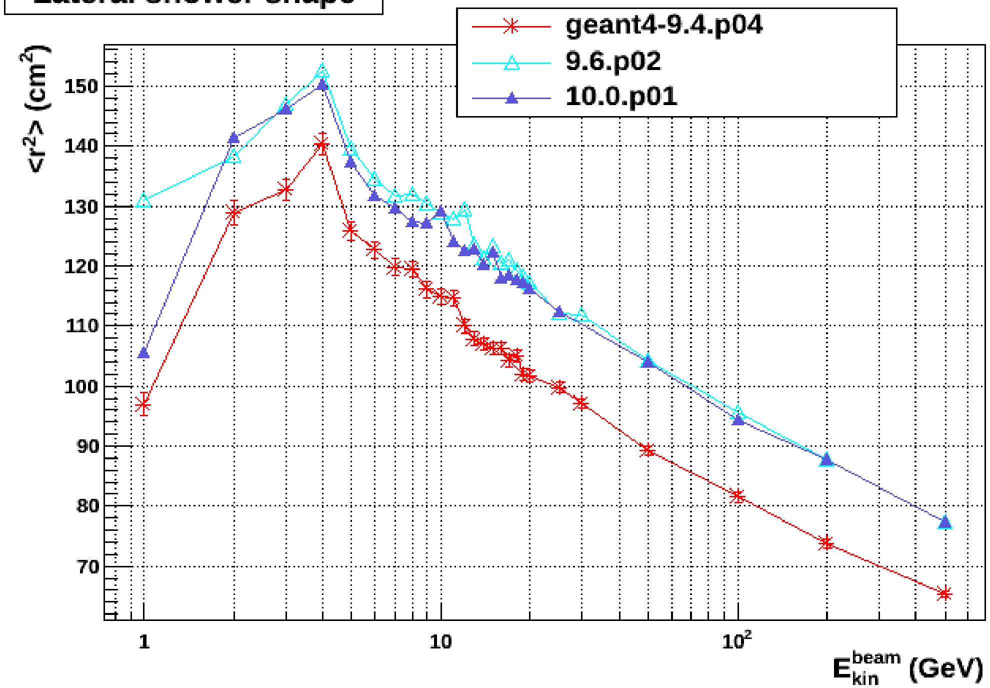
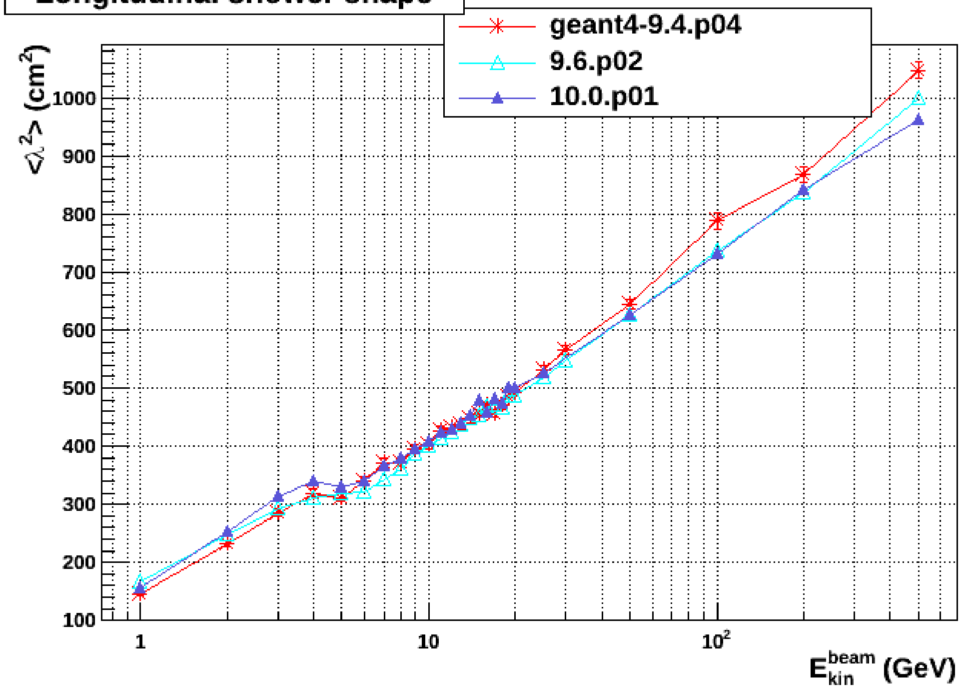


Lateral shower shape

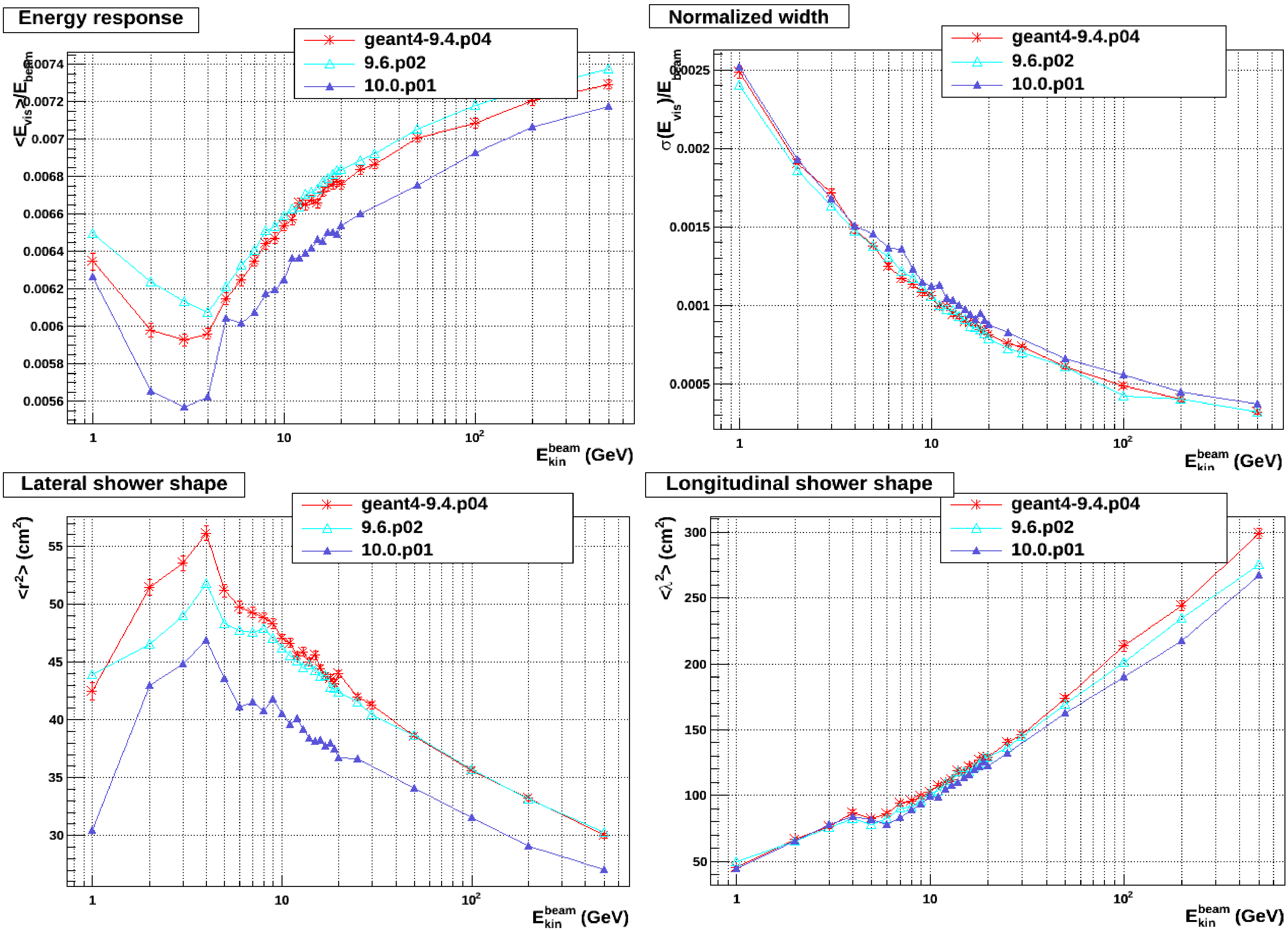


Longitudinal shower shape



FTFP_BERT

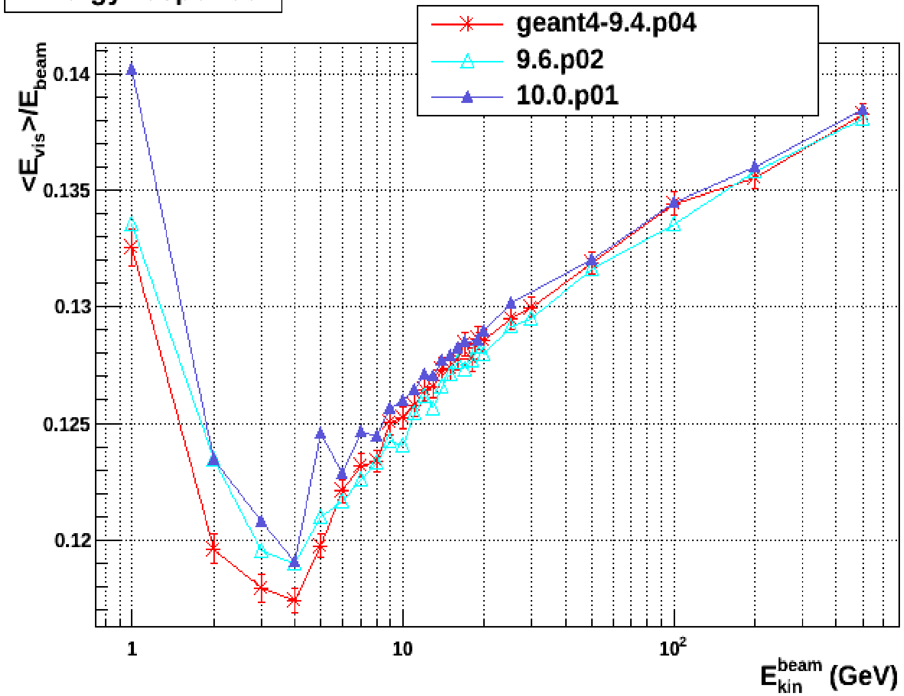
π⁻ on W-LAr



FTFP_BERT

π^- on Pb-LAr

Energy response



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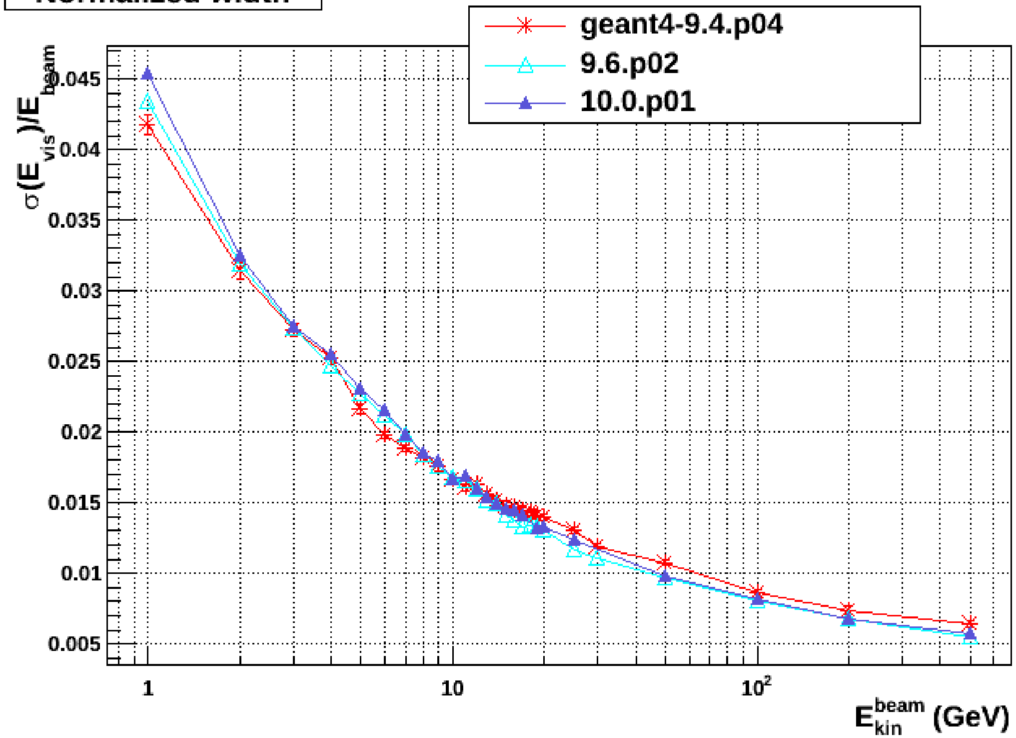
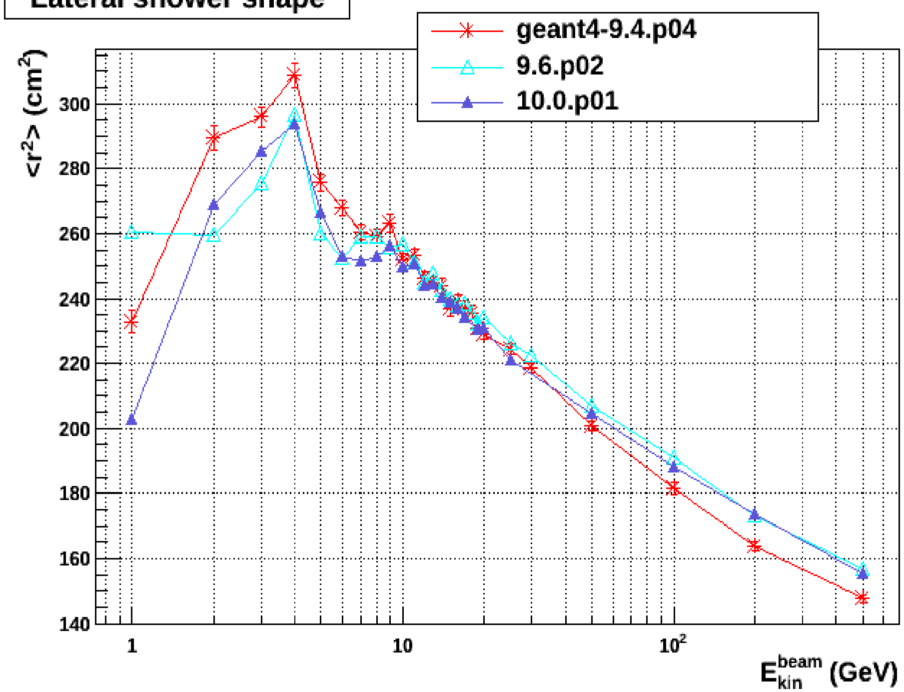
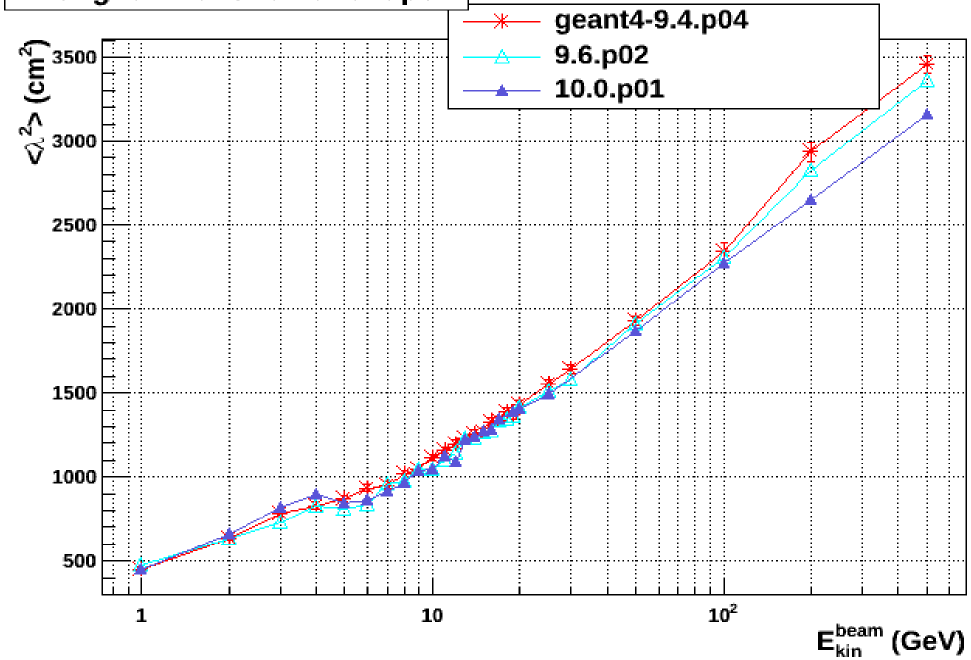


Lateral shower shape

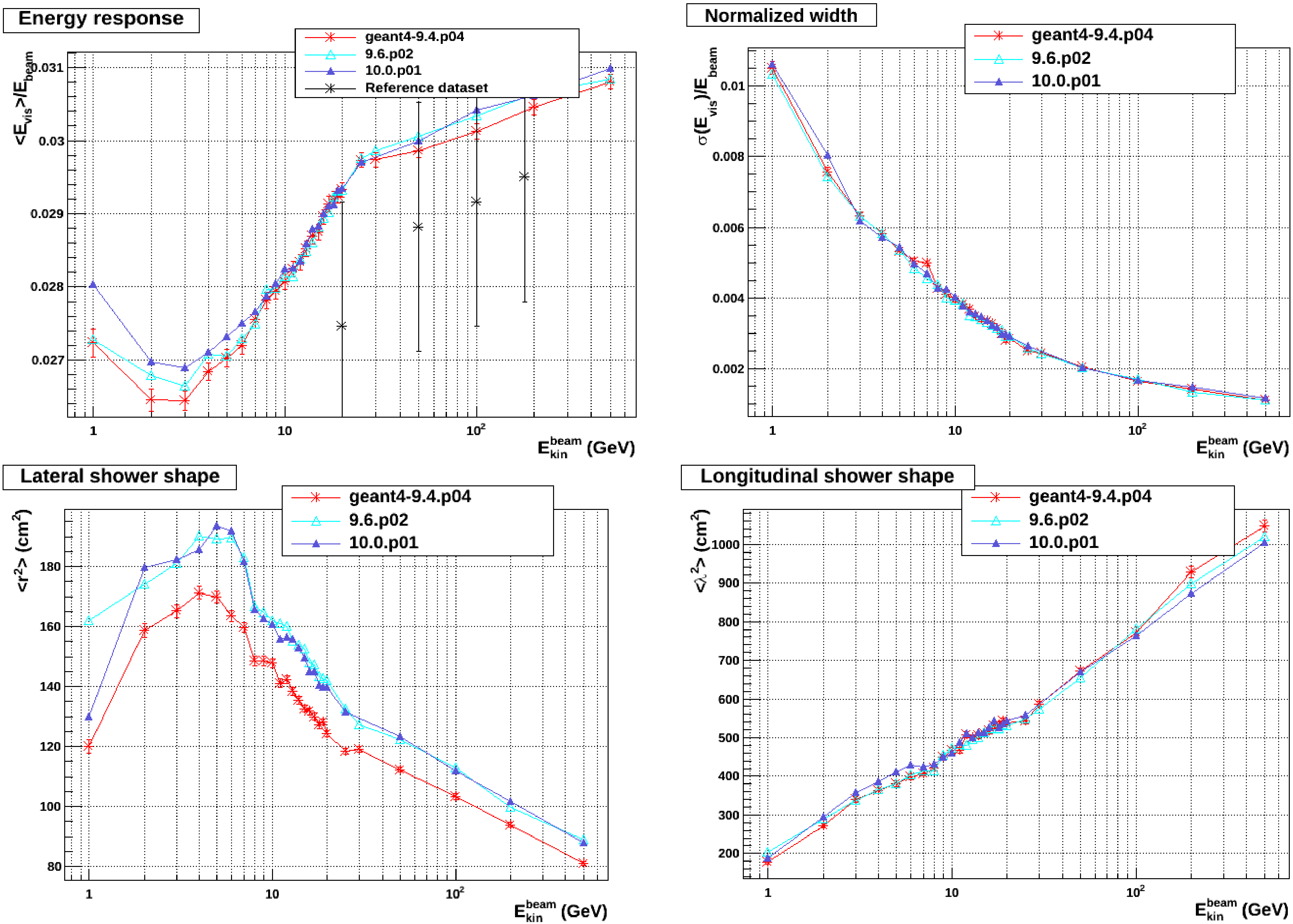


Longitudinal shower shape



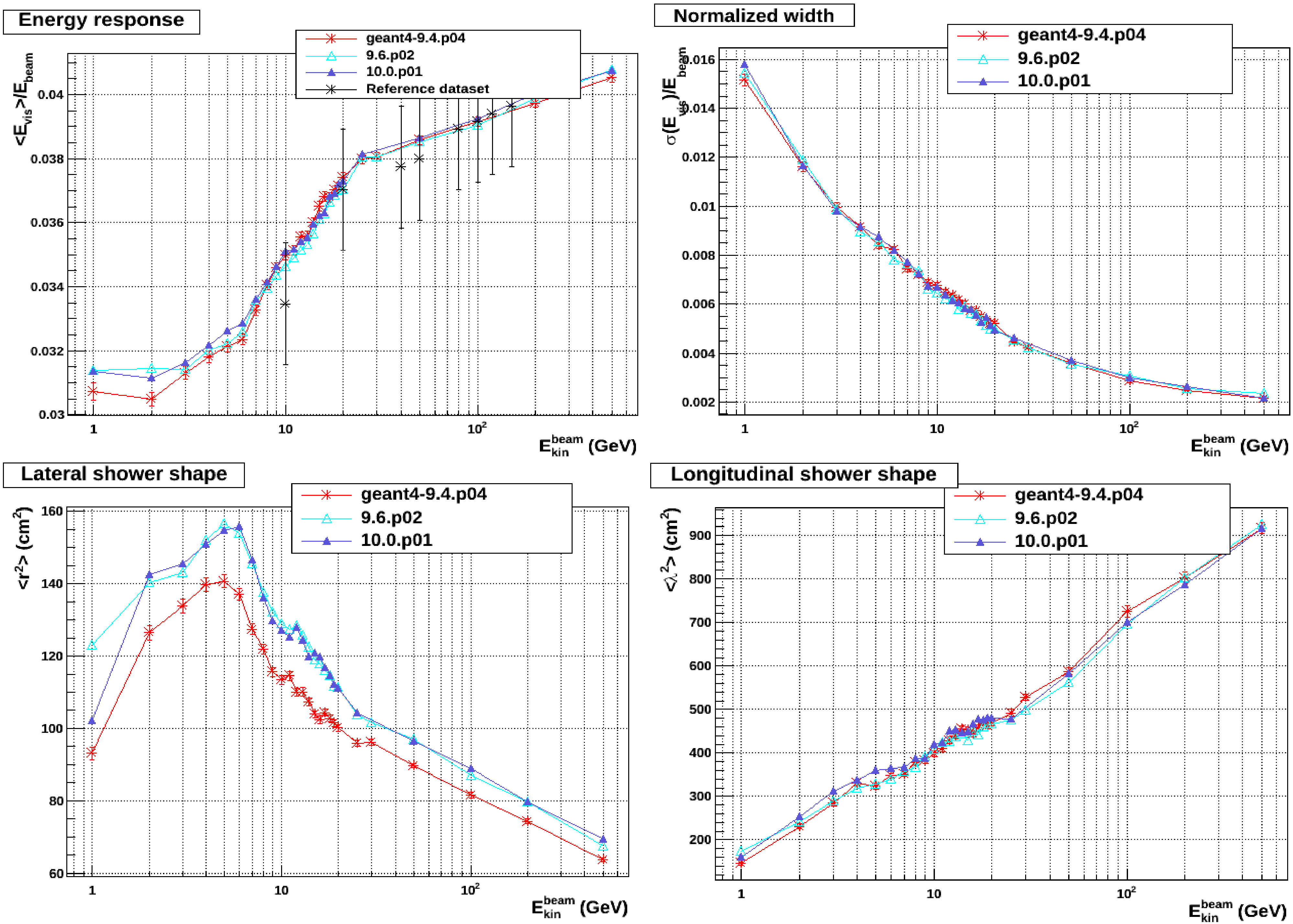
QGSP_FTFP_BERT

π⁻ on Fe-Sci



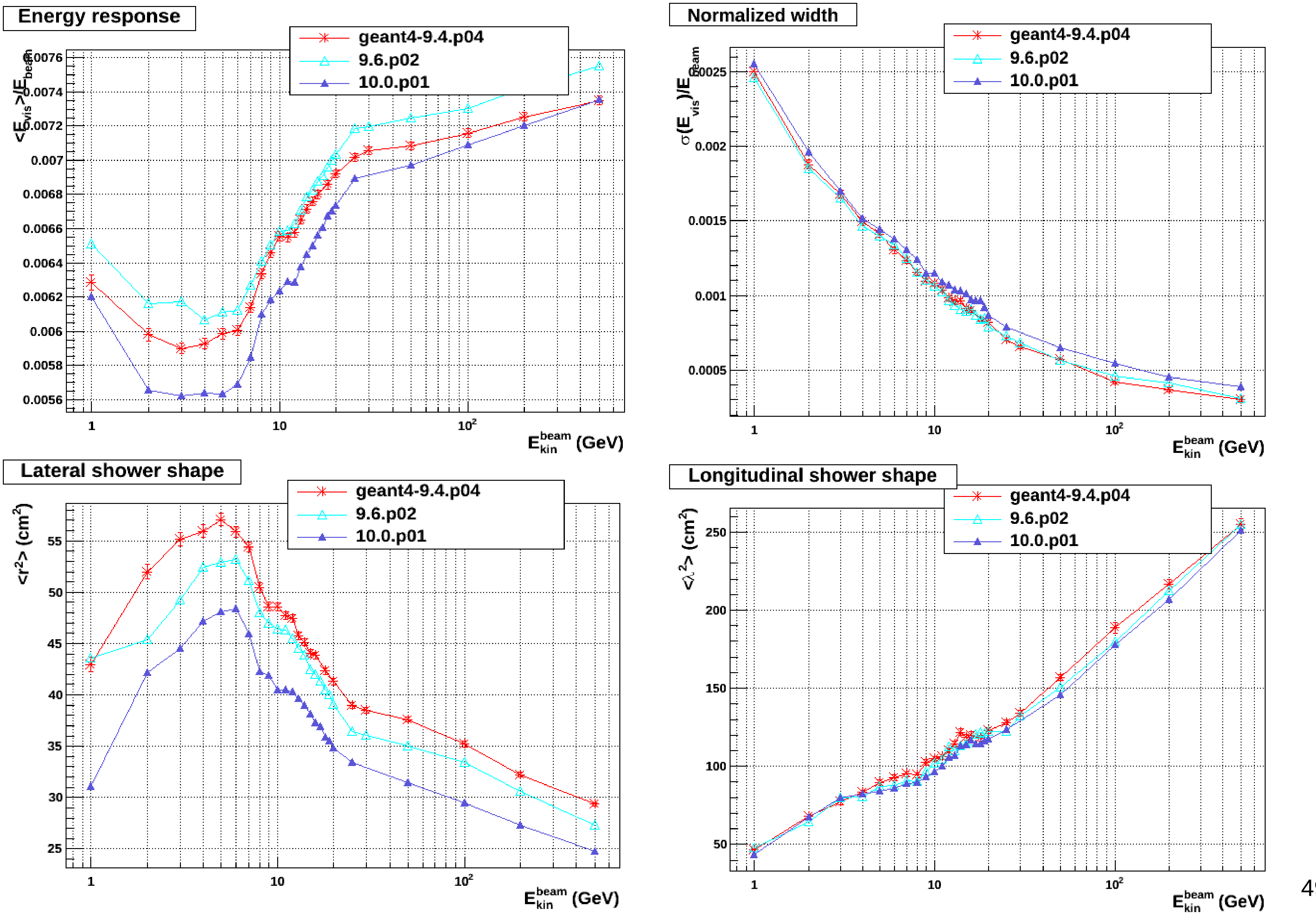
QGSP_FTFP_BERT

π^- on Cu-LAr



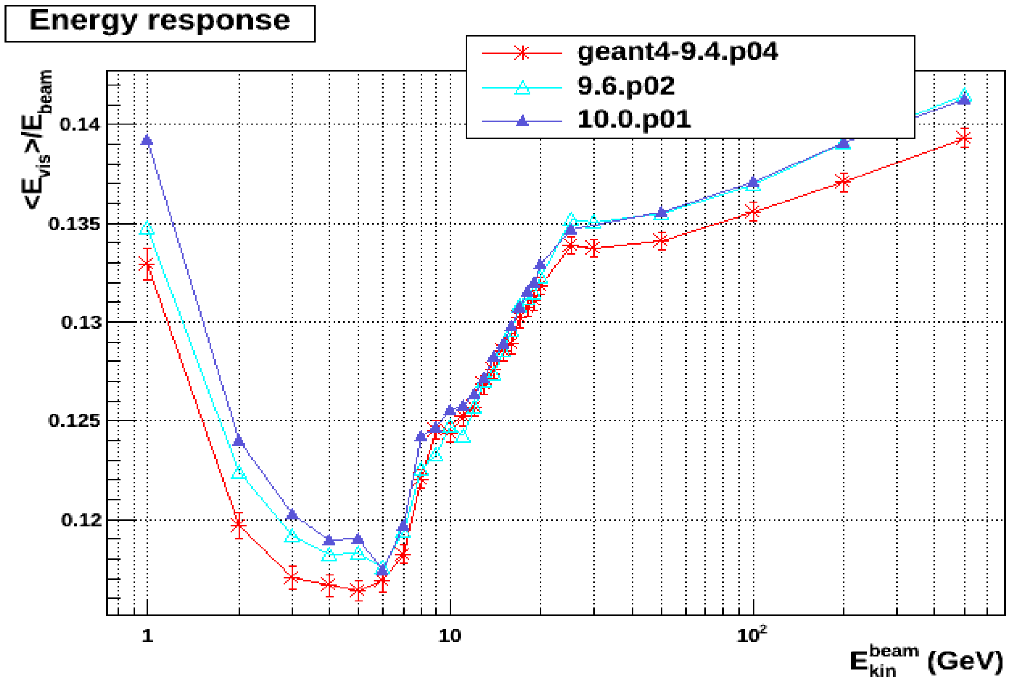
QGSP_FTFP_BERT

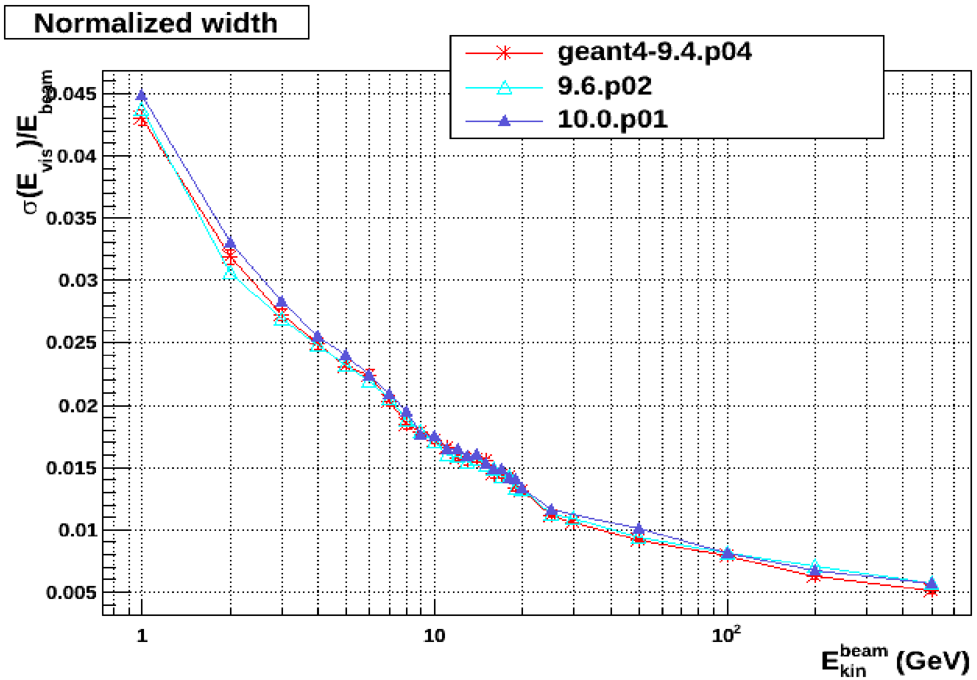
π^- on W-LAr

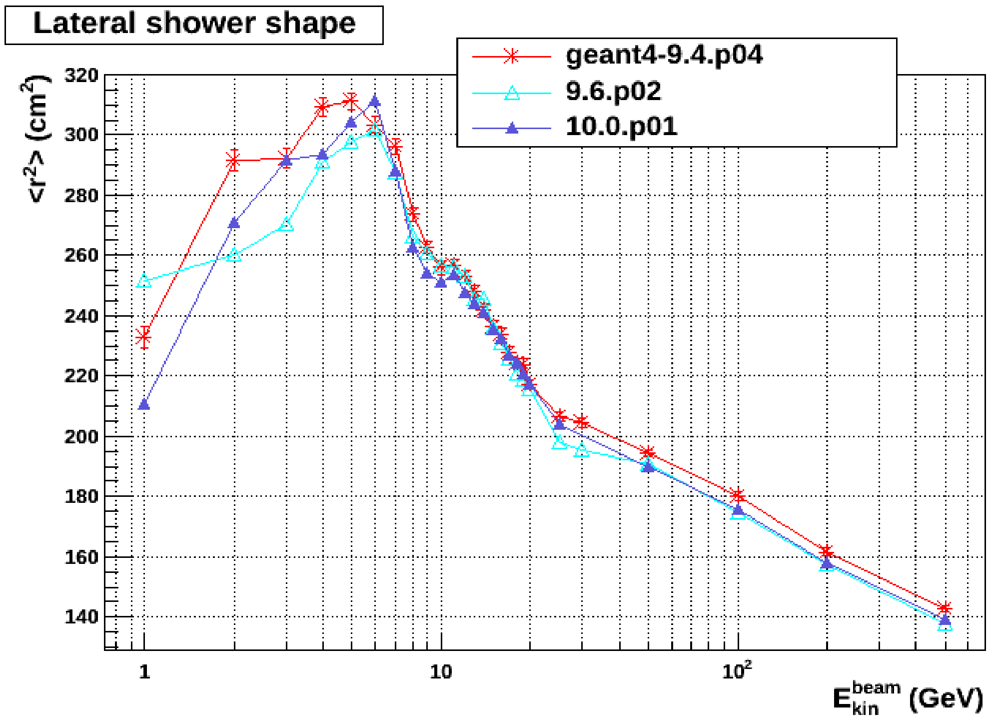


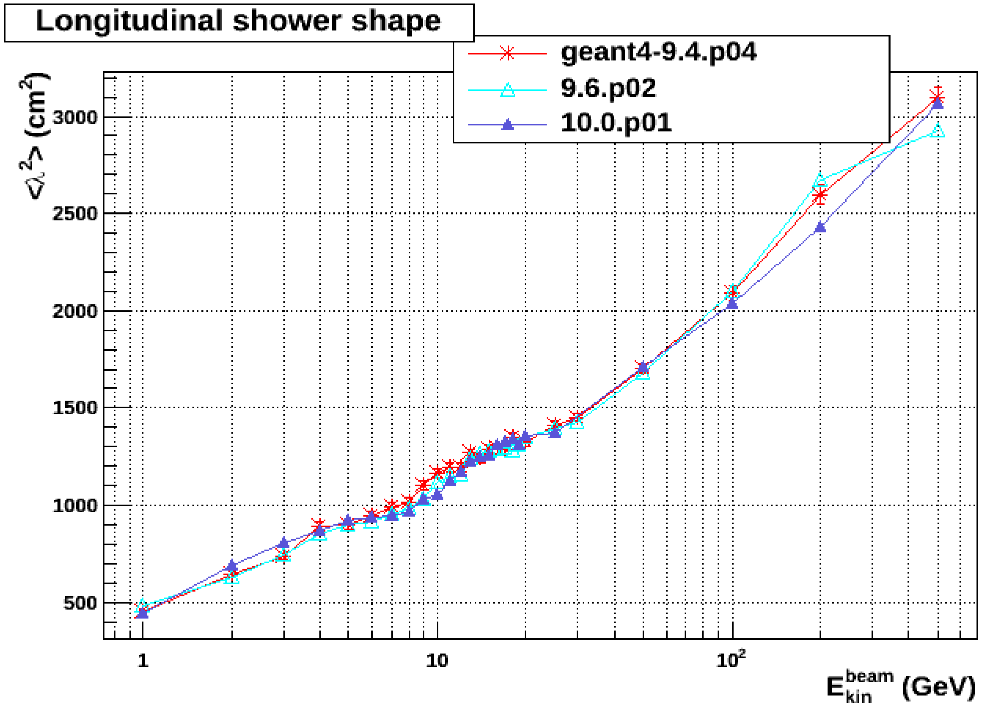
QGSP_FTFP_BERT

π^- on Pb-LAr









Comparing Physics Lists for G4 **9.6.p02** :

FTFP_BERT

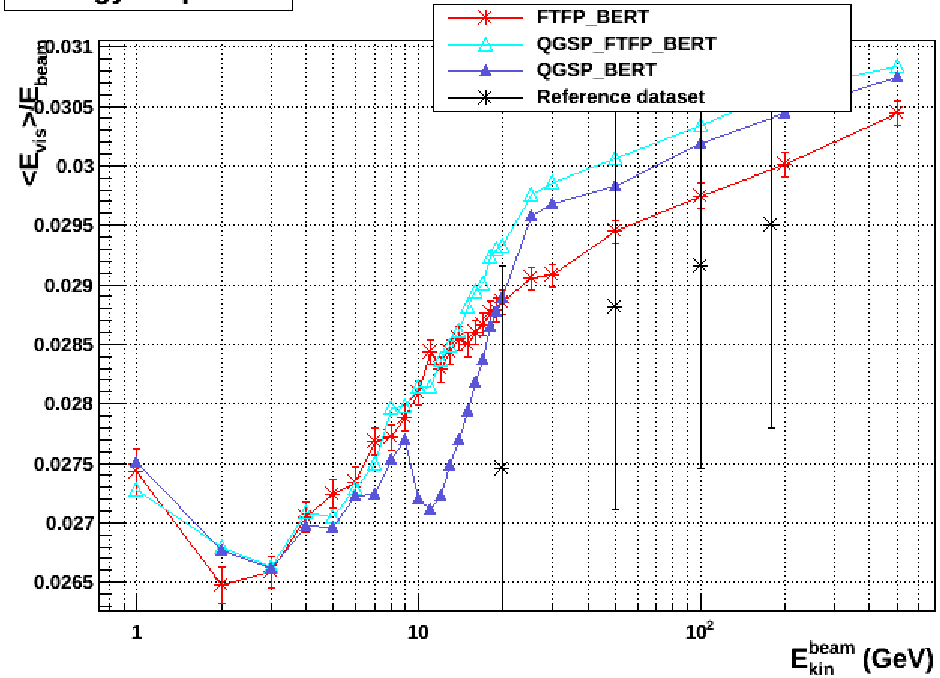
QGSP_FTFP_BERT

QGSP_BERT

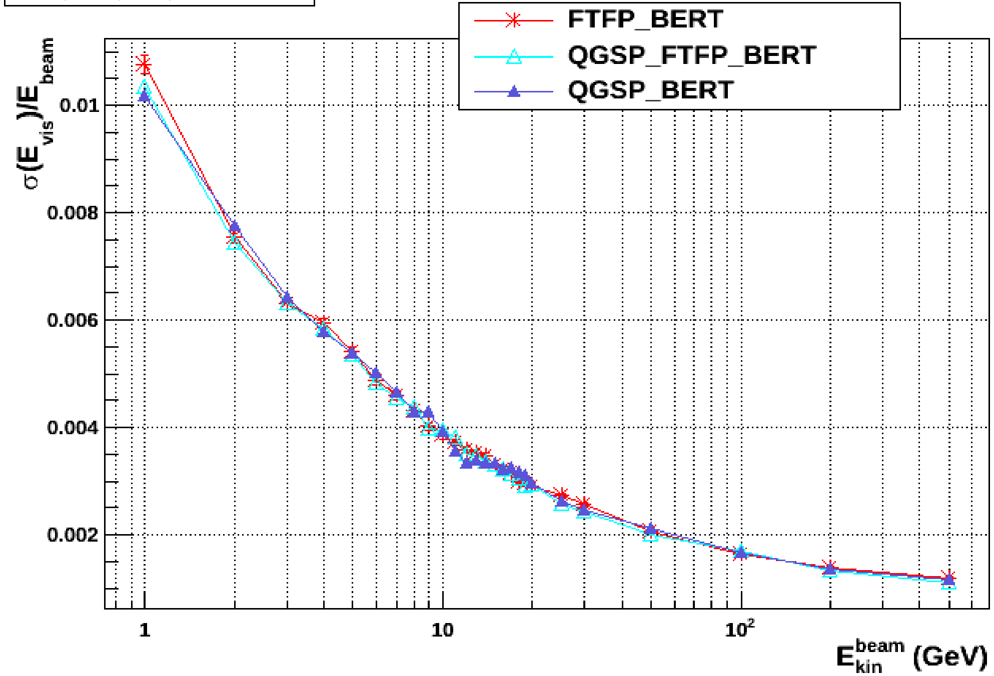
G4 9.6.p02

π^- on Fe-Sci

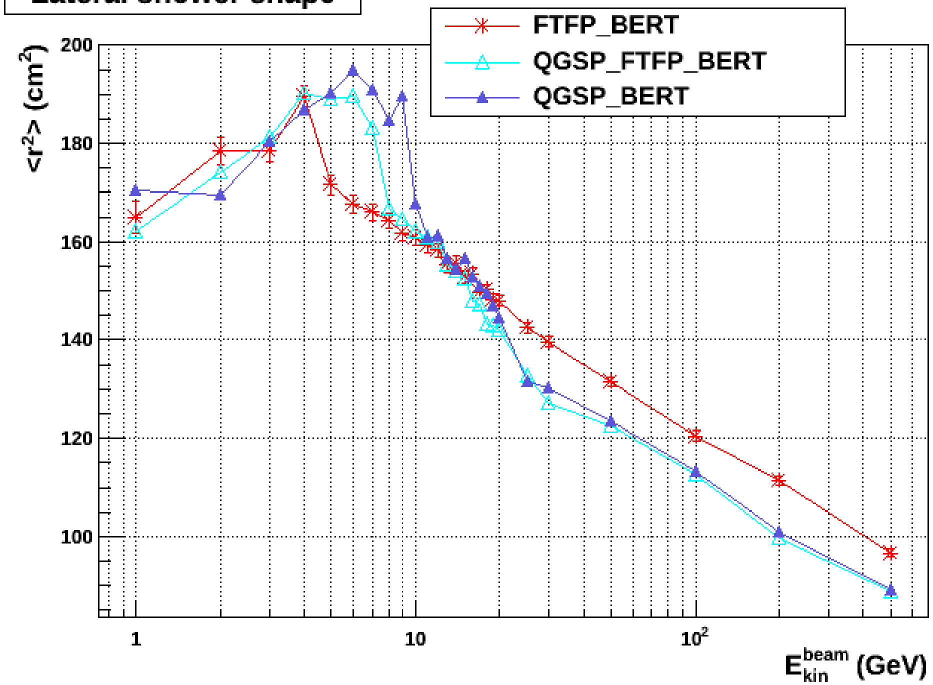
Energy response



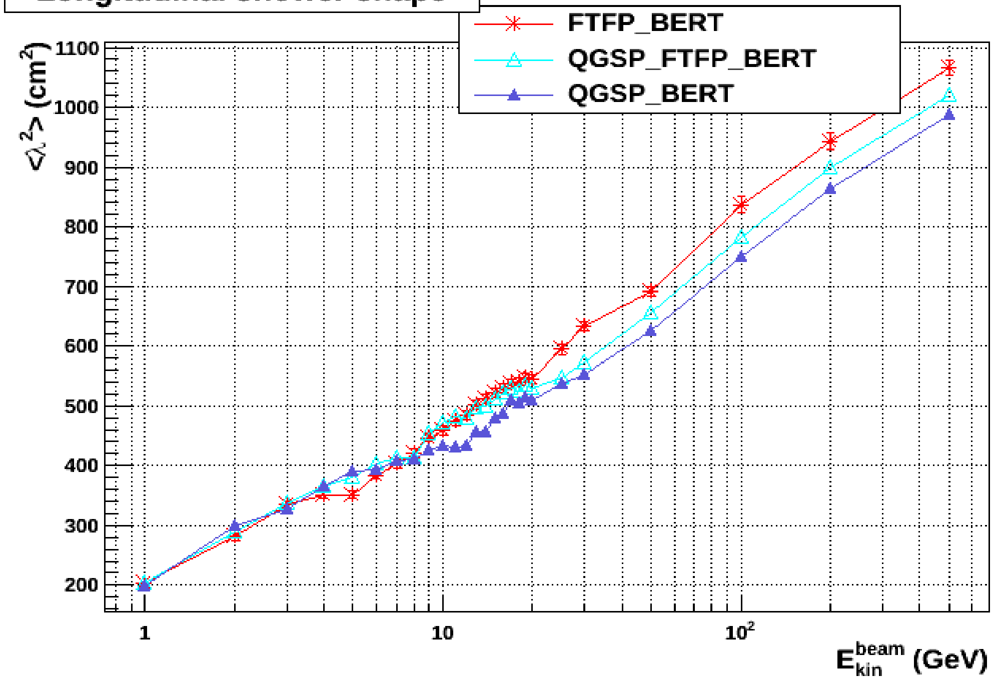
Normalized width



Lateral shower shape



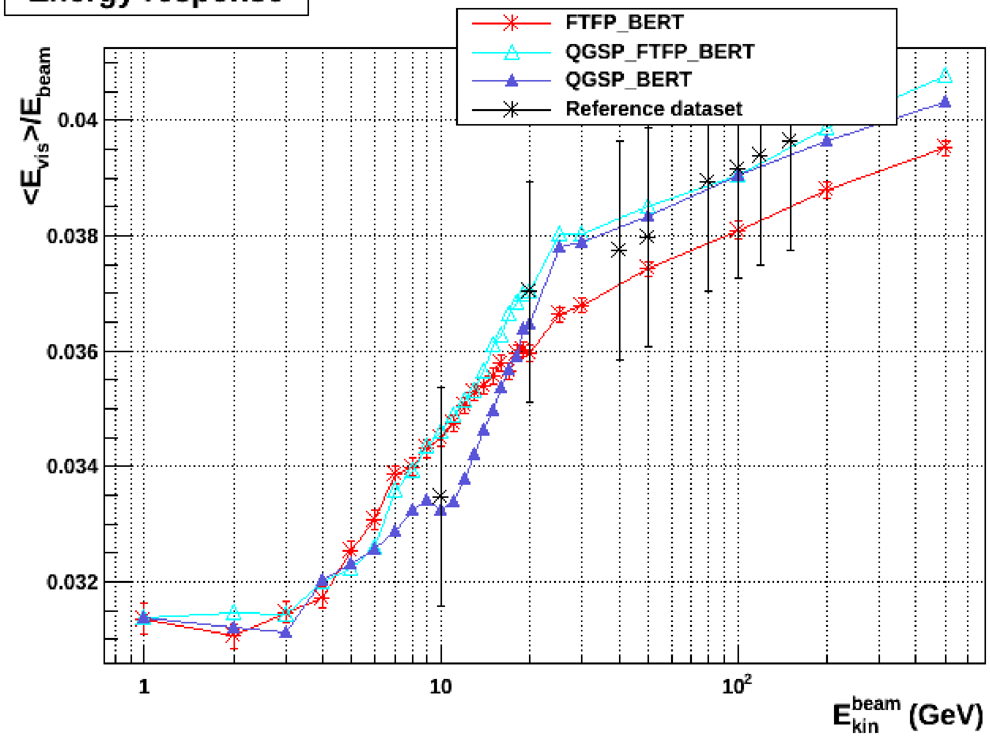
Longitudinal shower shape



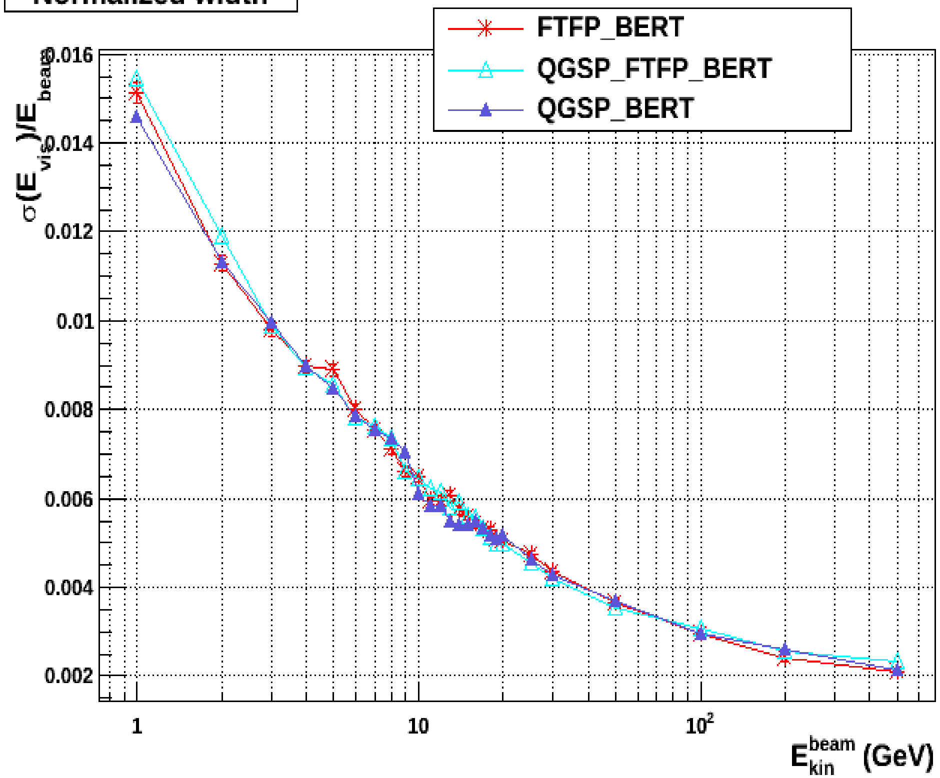
G4 9.6.p02

π^- on Cu-LAr

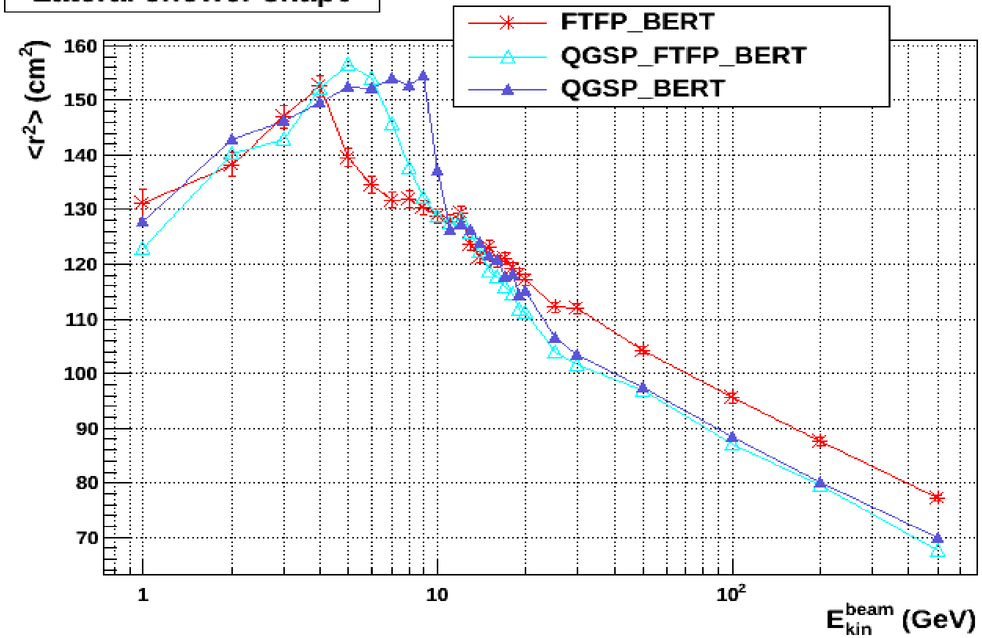
Energy response



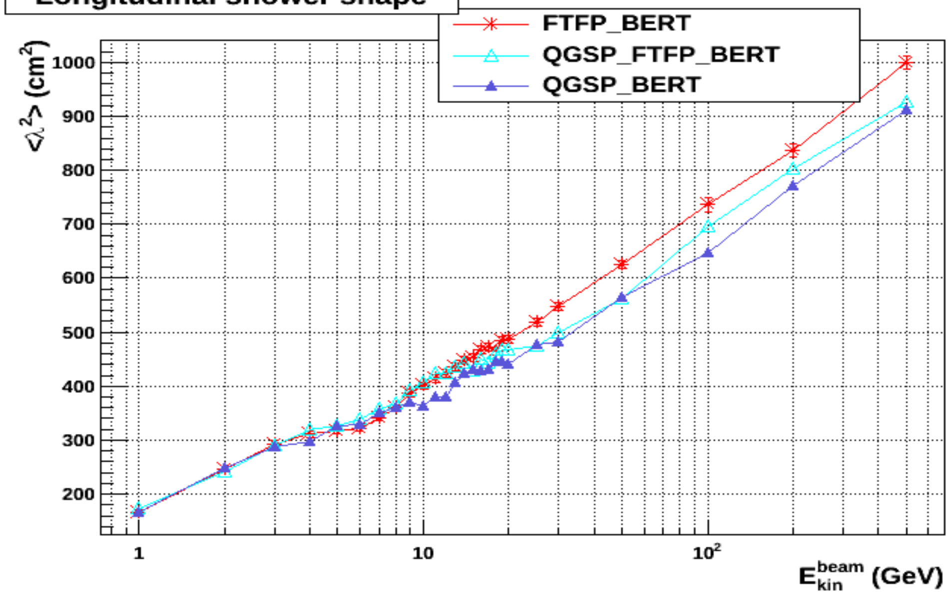
Normalized width



Lateral shower shape



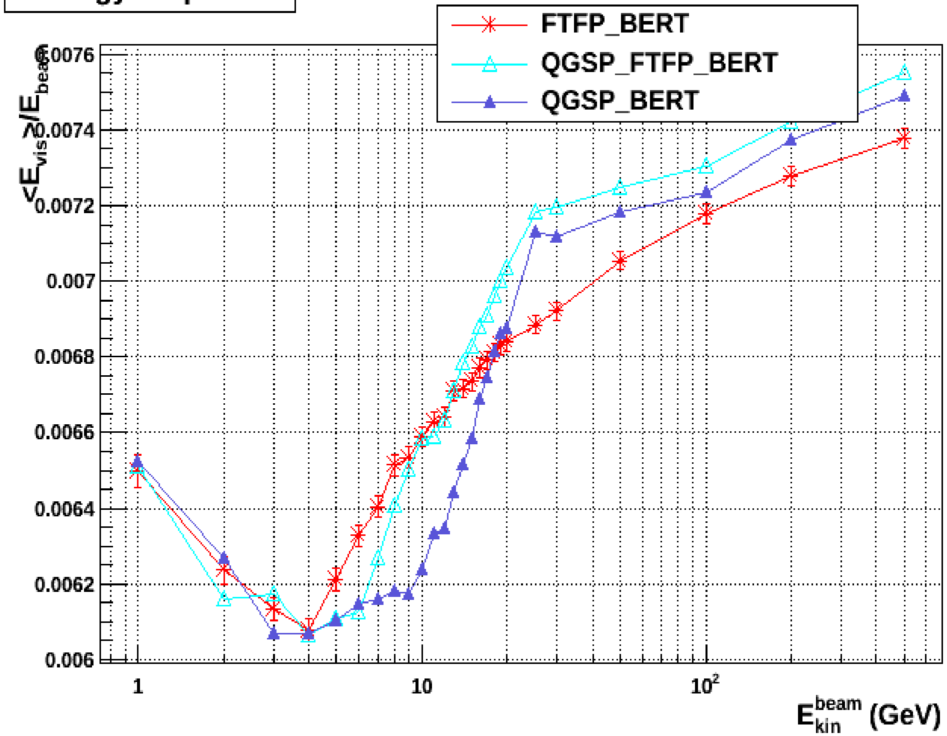
Longitudinal shower shape



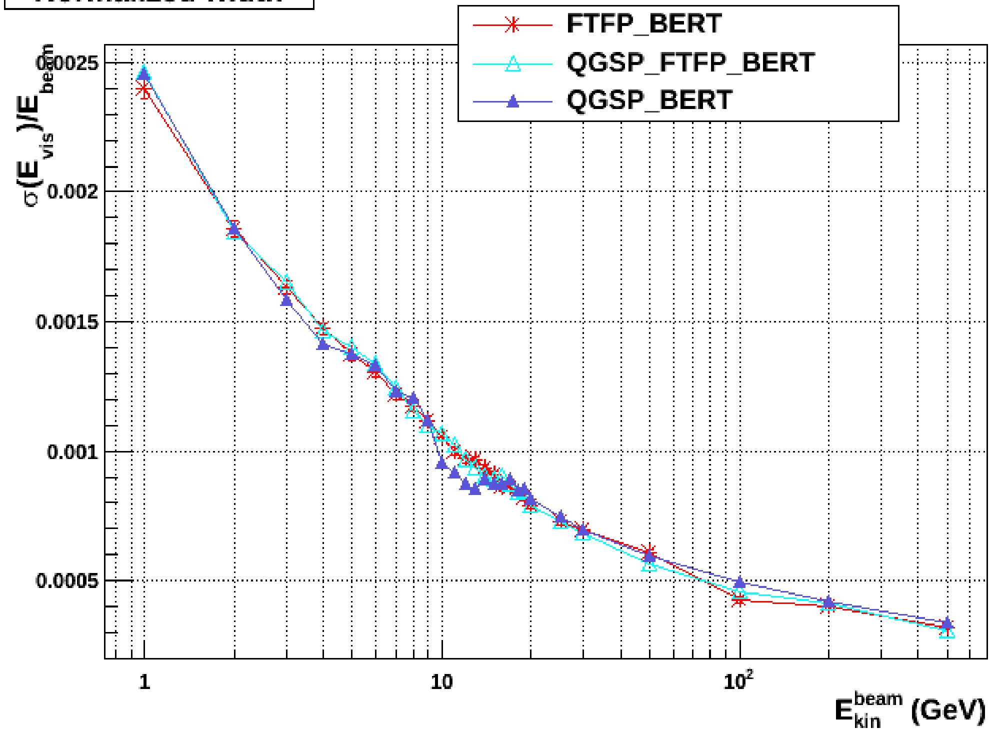
G4 9.6.p02

π^- on W-LAr

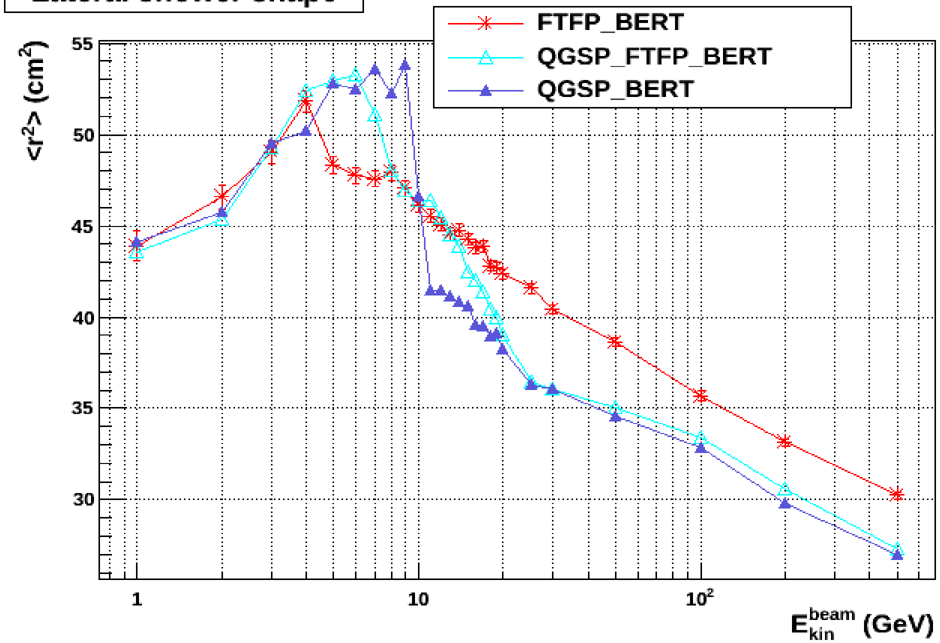
Energy response



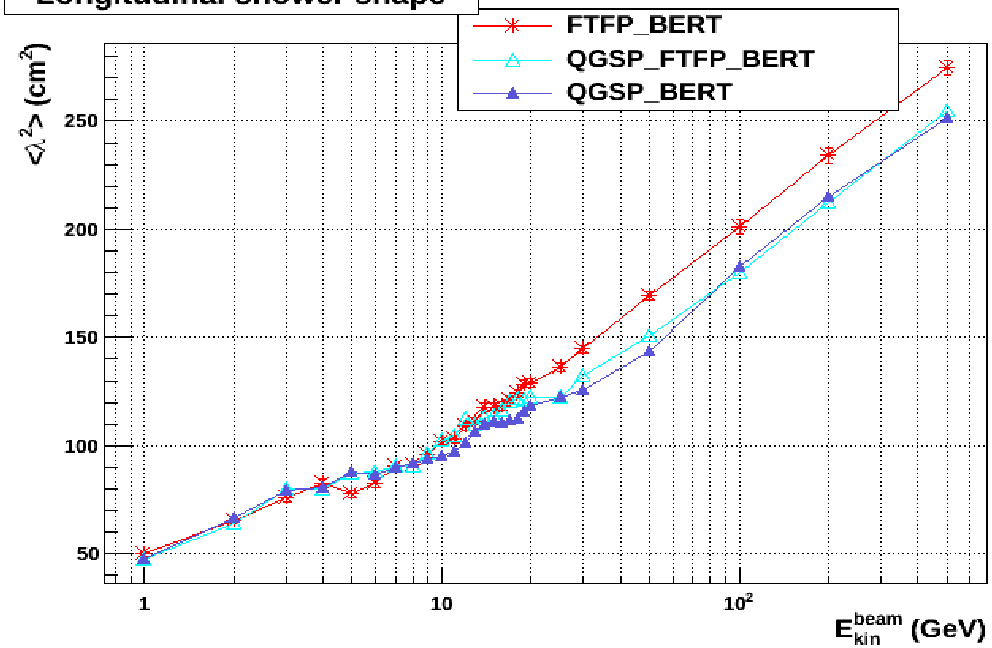
Normalized width



Lateral shower shape



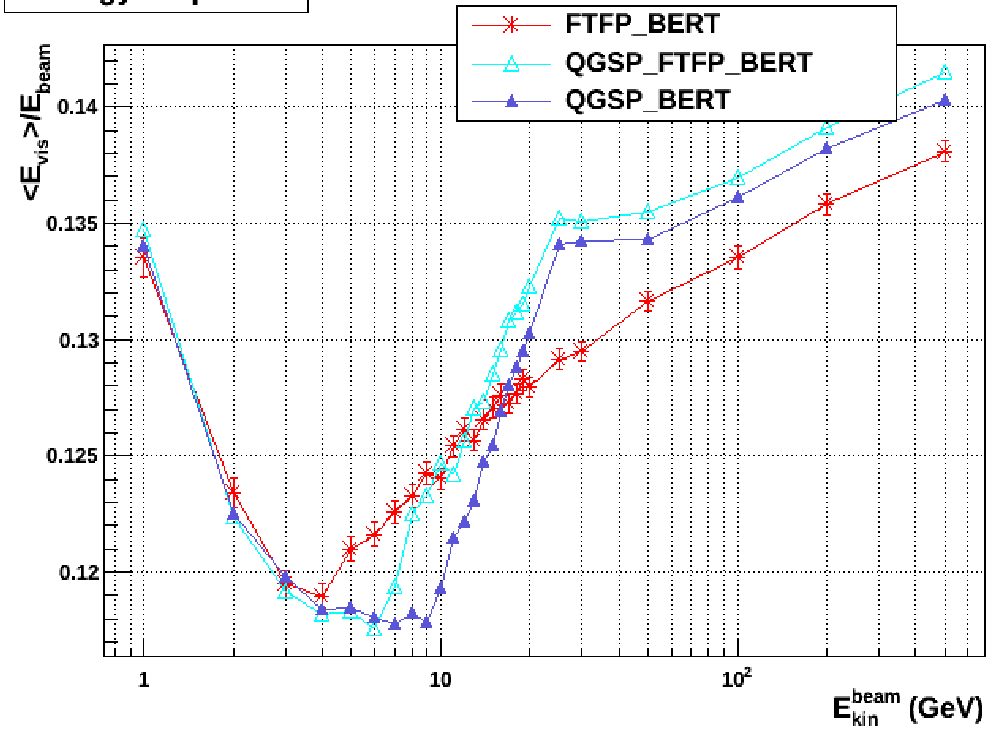
Longitudinal shower shape



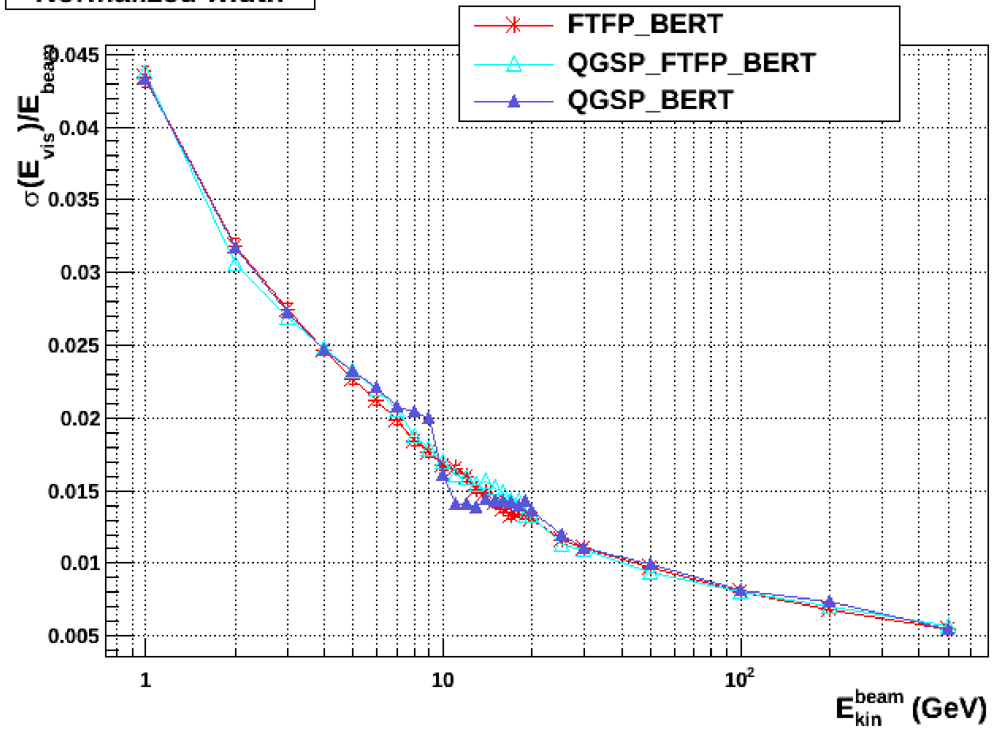
G4 9.6.p02

π^- on Pb-LAr

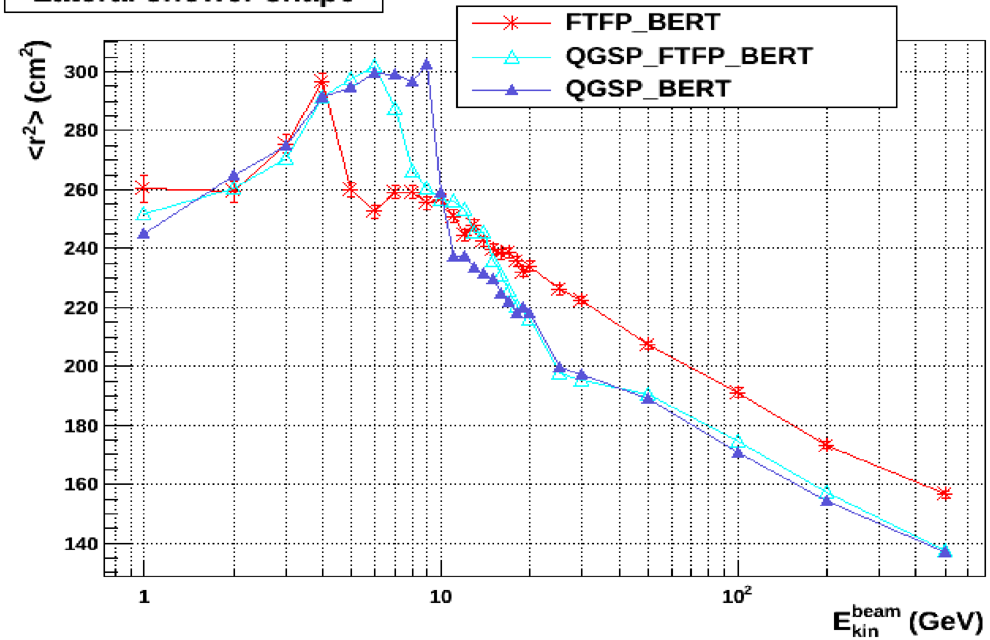
Energy response



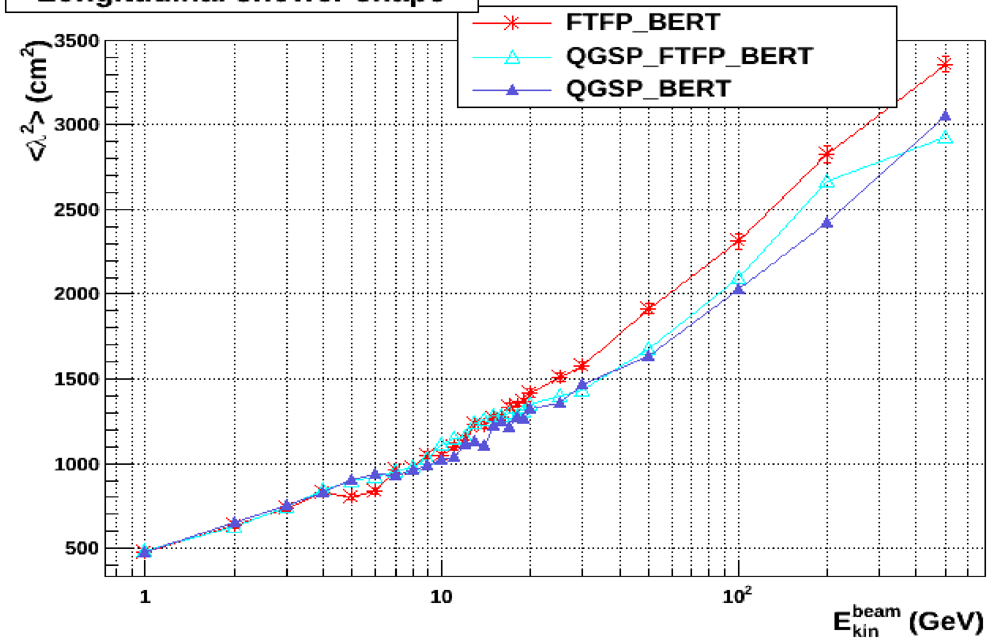
Normalized width



Lateral shower shape



Longitudinal shower shape



Electromagnetic Physics

Main Changes from G4 9.4 to 9.6 in Electromagnetic Physics

- Improved bremsstrahlung model
  - G4SeltzerBergerModel used in the range 1 keV – 1 GeV
  - Introduced in G4 9.5;
    improved in G4 9.6: more detailed grid of differential cross sections
- Improved gamma conversion model
  - relativistic model and LPM effect at high energy
- Improved ionization model
- Improved multiple scattering model
  - electrons & positrons *: G4UrbanMscModel95 < 100 MeV,*
    G4WentzelVIModel > 100 MeV
  - muons, pions, kaons, protons *: G4WentzelVIModel*
  - others (hyperons, ions) *: G4UrbanMscModel95*
  - Sampling of MSC now AlongStep *(before sampling energy loss)*

Main Changes from G4 9.6 to 10.0 in Electromagnetic Physics

- Consolidated multiple scattering
  - Only one version **G4UrbanMscModel** is available
- Improved e+/e- pair-production by muons and hadrons
- Improved ionisation models

Main 2014 Work-Plan for G4 10.1 in Electromagnetic Physics

- Further development of multiple & single scattering:
  - finalize multiple scattering to AlongStep
  - add lateral displacement option at boundary
  - add next order corrections to the WentzelVI model
  - review of the Goudsmit-Saunderson model
- Further update of ionization processes:
  - improve Urban fluctuation model
  - perform study on alternative fluctuation models
  - refine treatment of Birks effects
  - refine approach of effective ion charge
  - alternative ion-ionization models for moderate energies
- Further update of bremsstrahlung & gamma models:
  - improve parameterisation for positron cross section
  - update Compton scattering model adding radiative corrections
  - update gamma-conversion model below 10 MeV
  - study new model for e+/e- pair-production by electrons & positrons

Hadronic Physics

Main Changes from G4 9.4 to 9.6 in Hadronic Physics

- Fritiof (FTF): improved diffraction and tuning;
  extended to anti-baryons – nucleus interactions
- Bertini (BERT): improved internal nucleon-nucleon xsections
  and angular distributions:
  - *wider lateral hadronic showers in Iron & Copper*

  extended to gamma- and electro-nuclear, and
  to nuclear capture at rest
- Physics List improvements:
  - Nucleon – nucleus inelastic cross sections *(Wellisch -> BGG)*
  - Nuclear capture at rest *(CHIPS -> FTFP + BERT)*
  - Gamma- and electro-nuclear *(CHIPS -> FTFP + BERT)*
  - Hyperon – nucleus *(CHIPS -> FTFP + BERT)*
  - Anti-baryon – nucleus *(CHIPS or LEP -> FTFP)*
  - Light ion – nucleus *(LEP -> FTFP + BIC)*
  - Light anti-ion – nucleus *(/ -> FTFP)*

Main Changes from G4 9.6 to 10.0 in Hadronic Physics

- Fritiof (FTF): further improved diffraction and tuning;
  extended to nucleus – nucleus interactions
- Bertini (BERT): improved 2-body angular distributions and
  multi-body phase-space;
  extended to muon-capture
- Enabled production of isomers: revision of ions, de-excitation,
  radioactive decay
- Improved neutron-capture simulation
  - *improved simulation of hadronic showers in Tungsten*
- Improved low-energy neutron inelastic cross sections
- Removed **CHIPS** and **LEP**/**HEP** (Gheisha models in G4)

Main 2014 Work-Plan for G4 10.1 in Hadronic Physics

- String models
  - Consolidation (code & parameters) of FTF
  - Re-scattering in FTF with BERT or BIC
  - Extension to lower energies and revision of QGS
- Cascade models
  - Making BERT more physically realistic
    - Re-tuning of BERT (with Precompound), major effort
  - BIC : add coalescence; study gamma-nuclear and capture-at-rest
  - High-energy extension of INCL++ (up to 12 GeV)
- Revision of hadron elastic
- Extension of the validation for models and cross sections