Hadronic Showers

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Outline

This talk gives the status of hadronic shower simulations in Geant4. Not yet available to us the latest comparisons with LHC collision data; some results from CALICE.

- Introduction
- Calorimeter test-beam and observables
- Some recent results from CALICE test-beam
- FTFP_BERT physics list
- Simplified calorimeters results
- Outlook

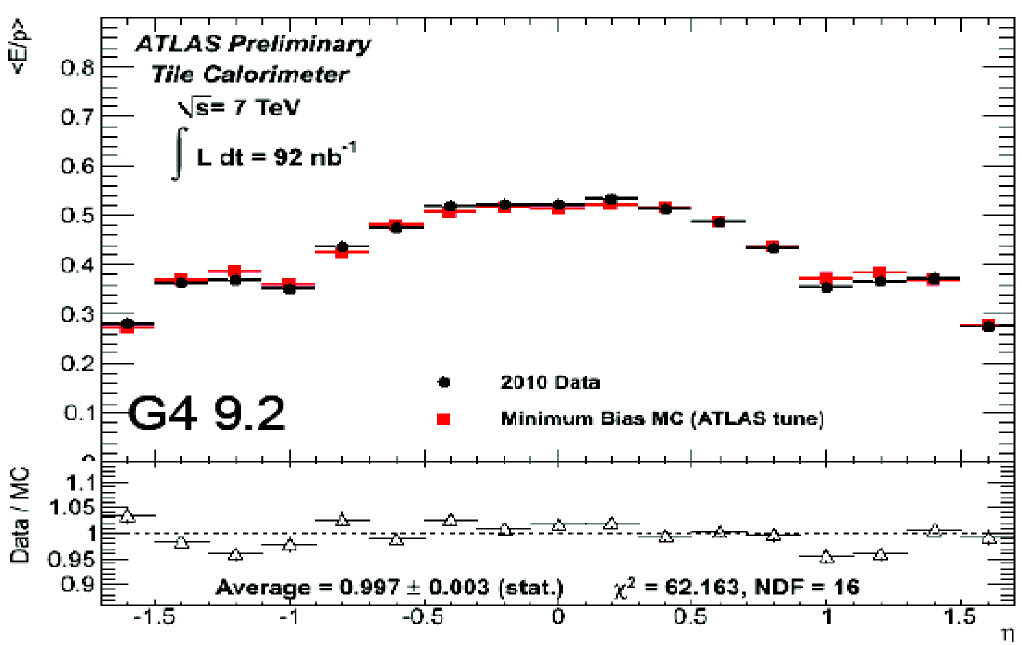
Introduction

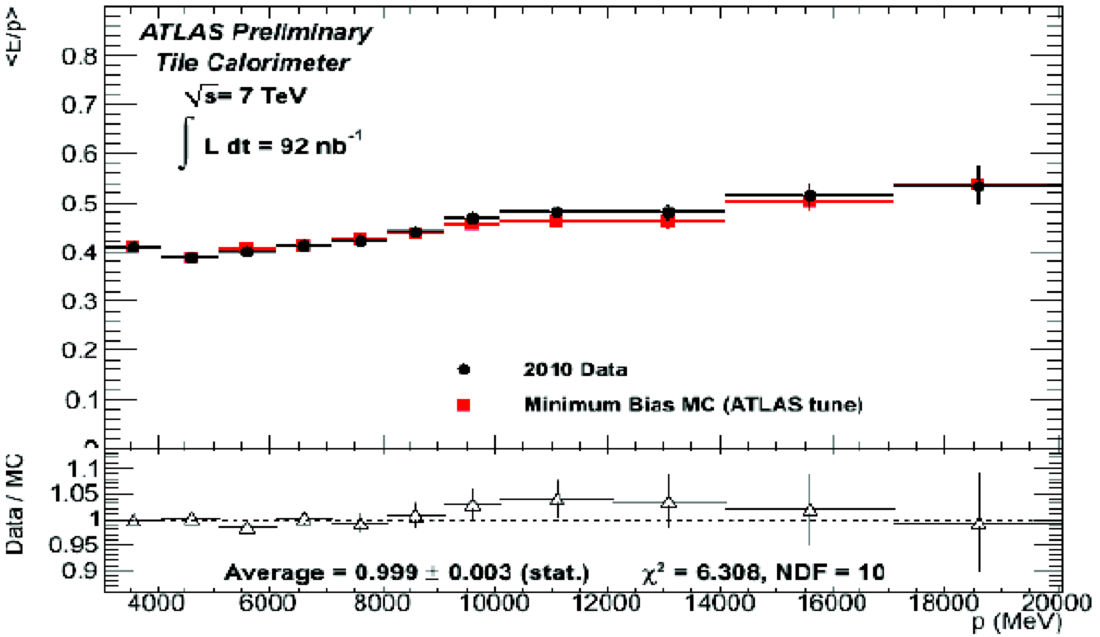
The simulation of hadronic showers (set of particles produced by a single hadron impinging on a block of matter, e.g. a calorimeter) is an important ingredient for the simulation of **jets**

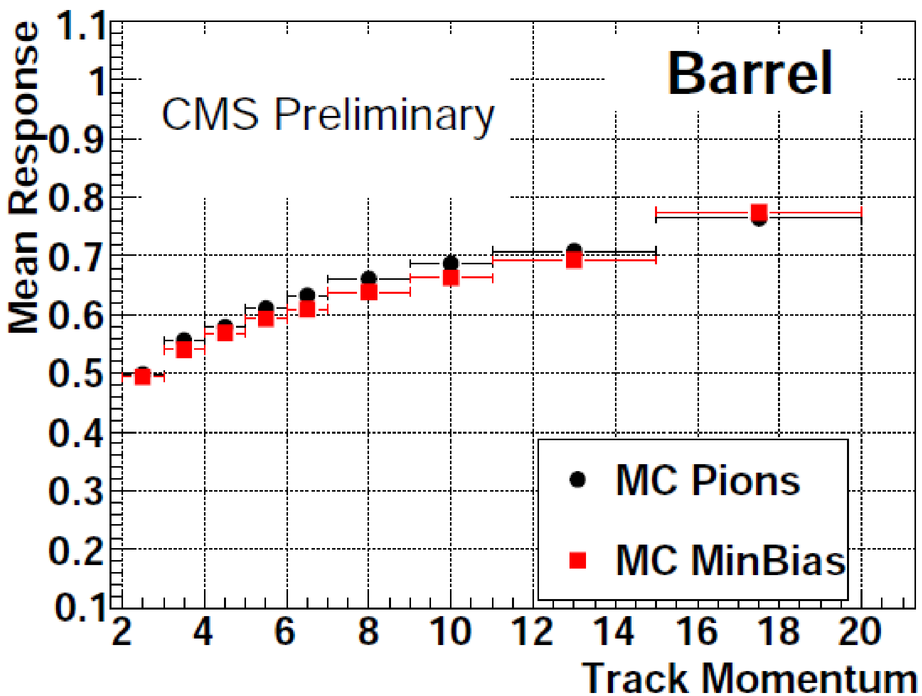
- The other ingredients are:
  - the Monte Carlo event generator
  - the experiment-specific aspects: geometry, digitization, pile-up
- Jets (collimated sprays of hadrons) are produced by strong (QCD) or electroweak (hadronic decays of τ / W / Z / H) interactions
- Jets can be part of the signal and/or the background
  - multi-jets in the same event is typical in hadron colliders as LHC, but it is also frequent in high-energy e+-e- linear colliders as ILC/CLIC
- For ILC/CLIC, the simulation of jets is essential for the optimal design of the detector (even more than traditionally because of the particle flow...)
- For ATLAS and CMS, the simulation of jets is now important for physics analysis

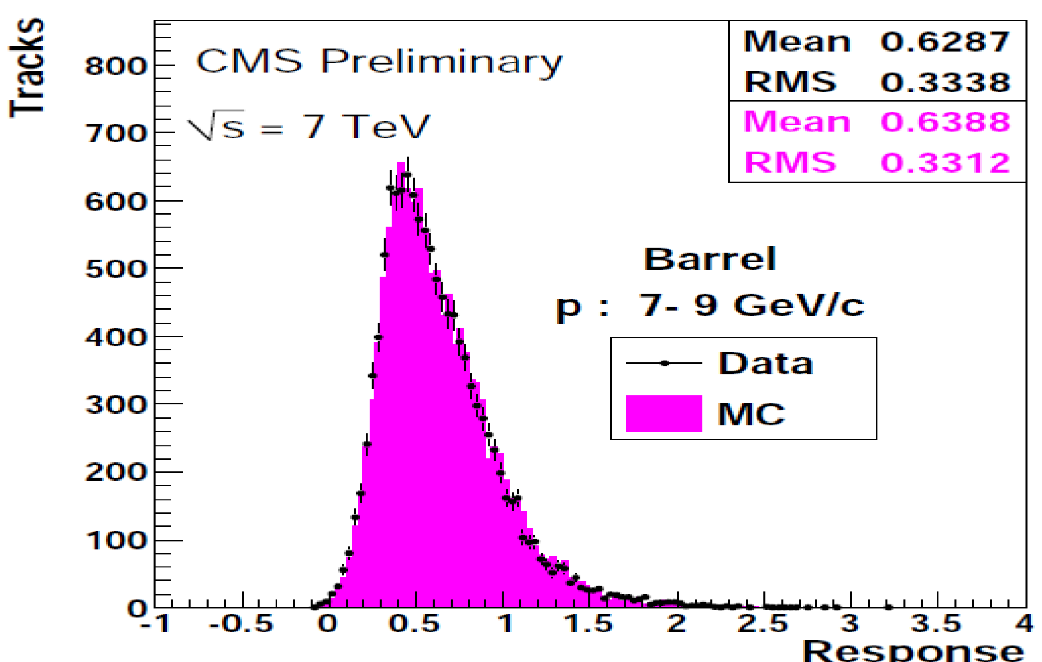
Simulations vs LHC collision data (1/2)

Isolated tracks (charged hadrons)





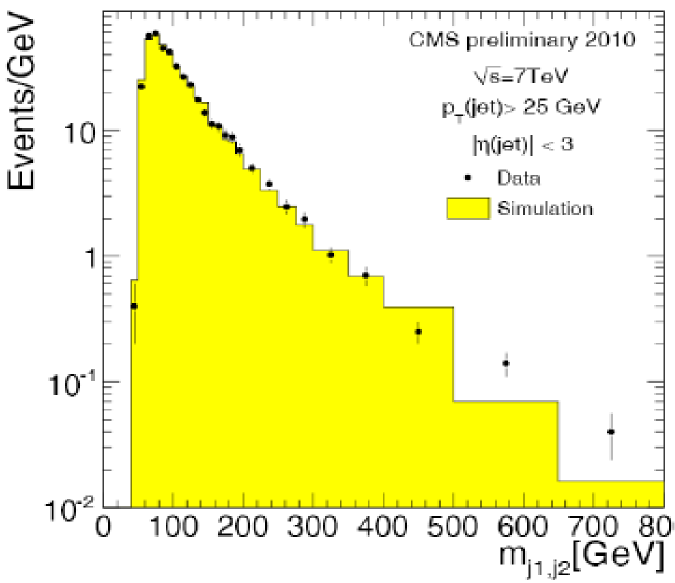


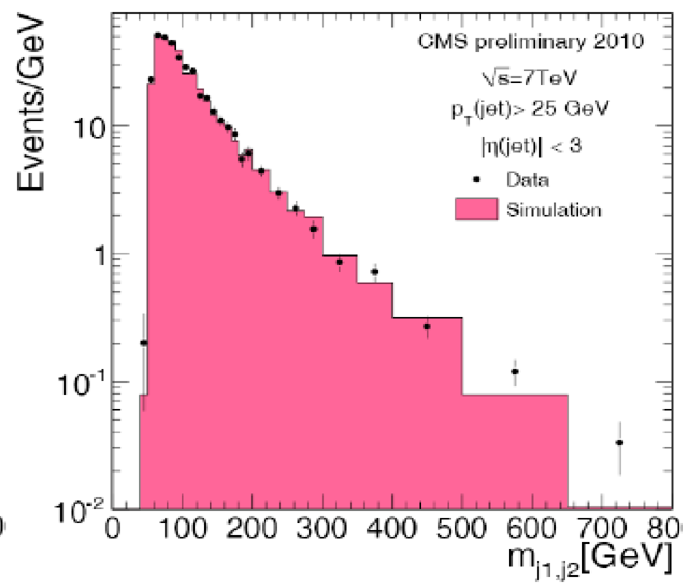


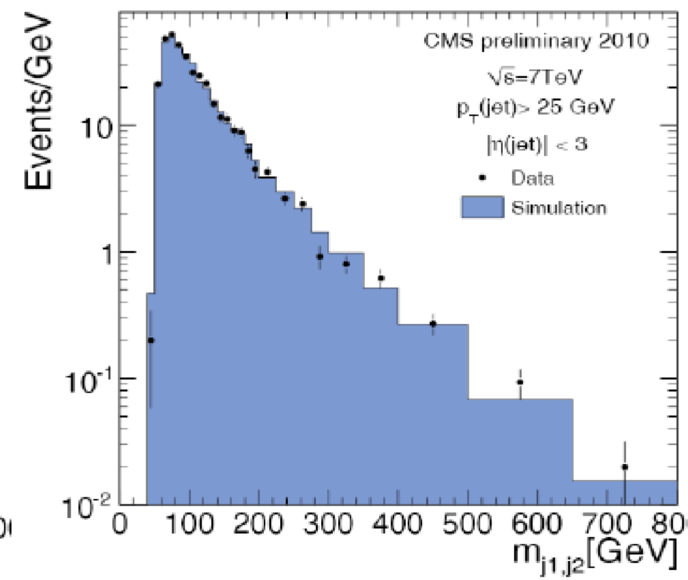
Simulations vs LHC collision data (2/2)

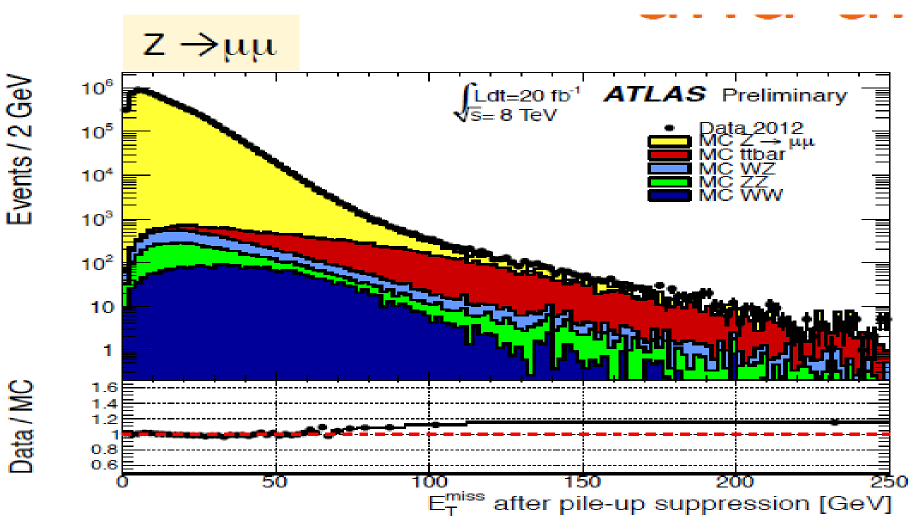
Jets and missing transverse energy

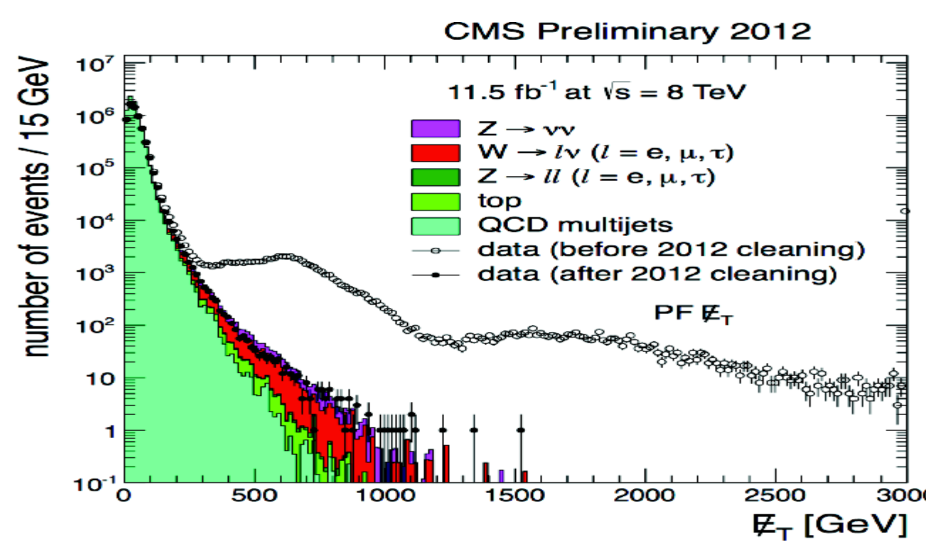
Calo jets **JPT jets** **PF jets**











Calorimeter test-beams

Up to now, the most challenging requirements for Geant4 hadronic physics were, and still are, all coming from calorimeter test-beams

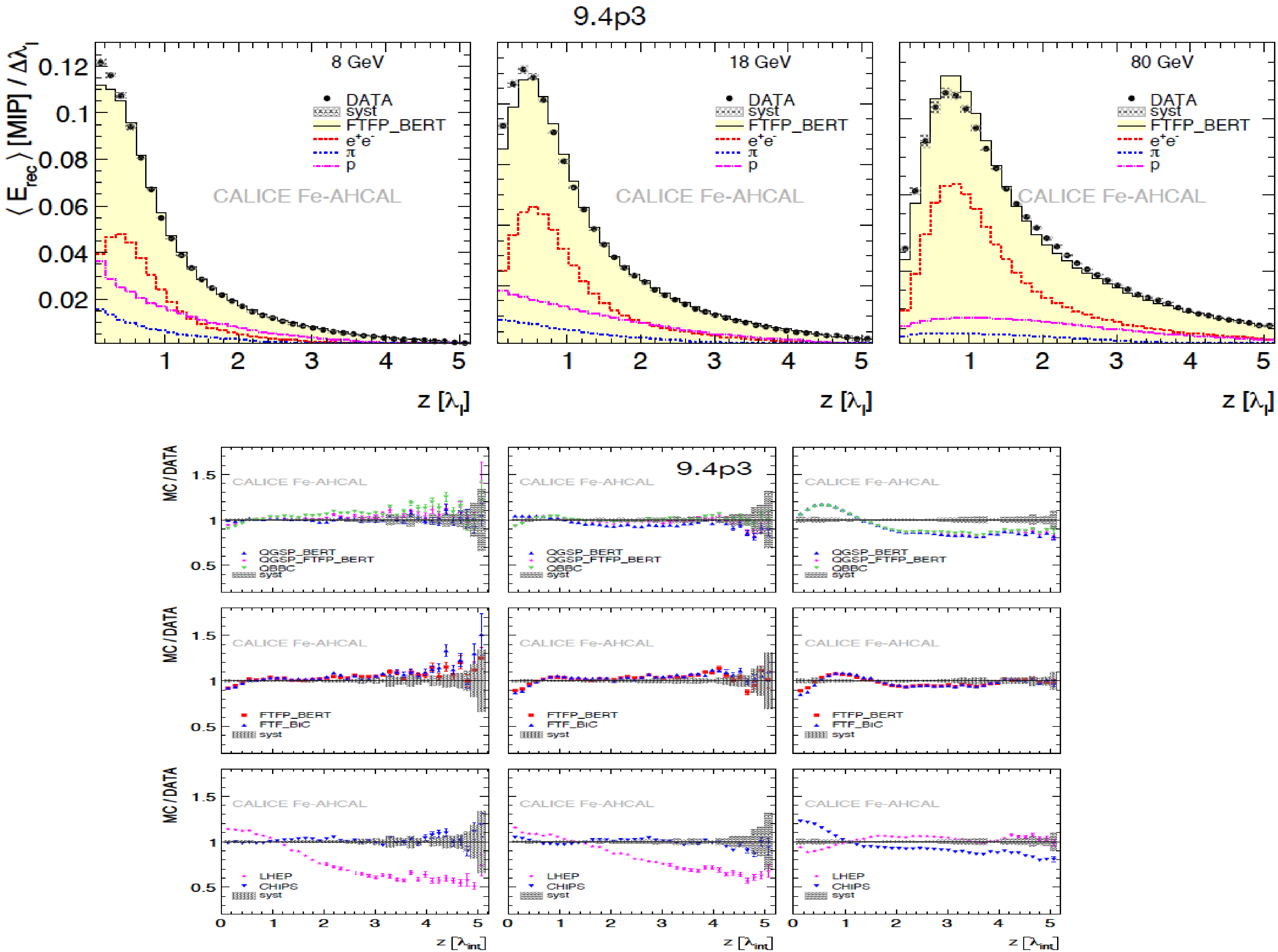
- Dominated by LHC test-beams in the last ~ 10 - 15 years
  - ATLAS TileCal (Fe-Sci), ATLAS HEC (Cu-LAr), ATLAS Combined (Pb-LAr + Fe-Sci)
  - CMS ECAL (PbWO4) + HCAL (Brass-Sci)
- Now being complemented and refined by the CALICE test-beams, which offer unprecedented details
  - Completed: Fe-Sci , W-Sci
  - On-going/planned: Fe-Gas , W-Gas

Most of the development in Geant4 hadronic physics has been & will be driven (not tuned: thin-target data is used for that!) by the need to improve the agreement between simulated hadronic showers and test-beam data

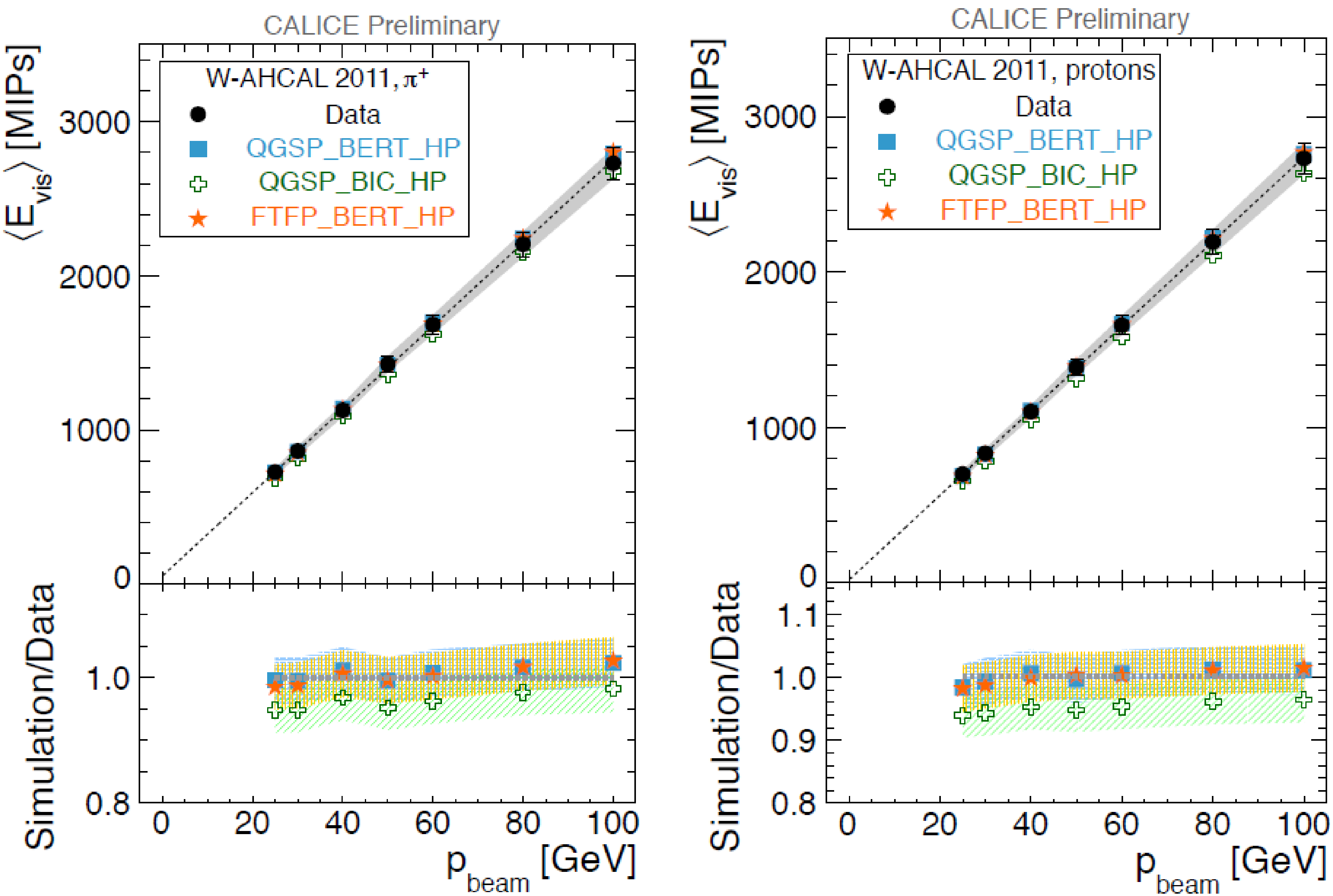
Calorimeter observables

- **Energy response**
  - **Very important for jet energy scale** for traditional calorimeter jets
  - Currently described with an accuracy of ~ few %
  - Sensitive to nearly all (string model, cascade, precompound/evaporation)
- **Energy resolution**
  - **Important for jet energy resolution and di-jet mass resolution** (e.g. hadronic decays of W, Z, H) for traditional calorimeter jets
  - Currently described with an accuracy of ~ 10 – 20 %
  - Sensitive to nearly all (string model, cascade, precompound/evaporation)
- **Lateral shower shape**
  - **Essential for the particle flow approach**
  - Relevant also in general for cluster identification, jet structure, isolation requirements, and jet overlaps
  - Currently described with an accuracy of ~ 10 – 20 %
  - Sensitive mostly to the intra-nuclear cascade, a bit less on the string model
- Longitudinal shower shape
  - Important for particle identification, jet-calibration, punch-through
  - Currently described with an accuracy of ~ 10 – 20 %
  - Sensitive mostly to forward physics (elastic, quasi-elastic, diffraction)

CALICE Fe-Sci : longitudinal shower profile



CALICE W-Sci : response to hadrons



G4 9.5p1

- CALICE WAHCAL: Tungsten/Scintillator - visible Energy

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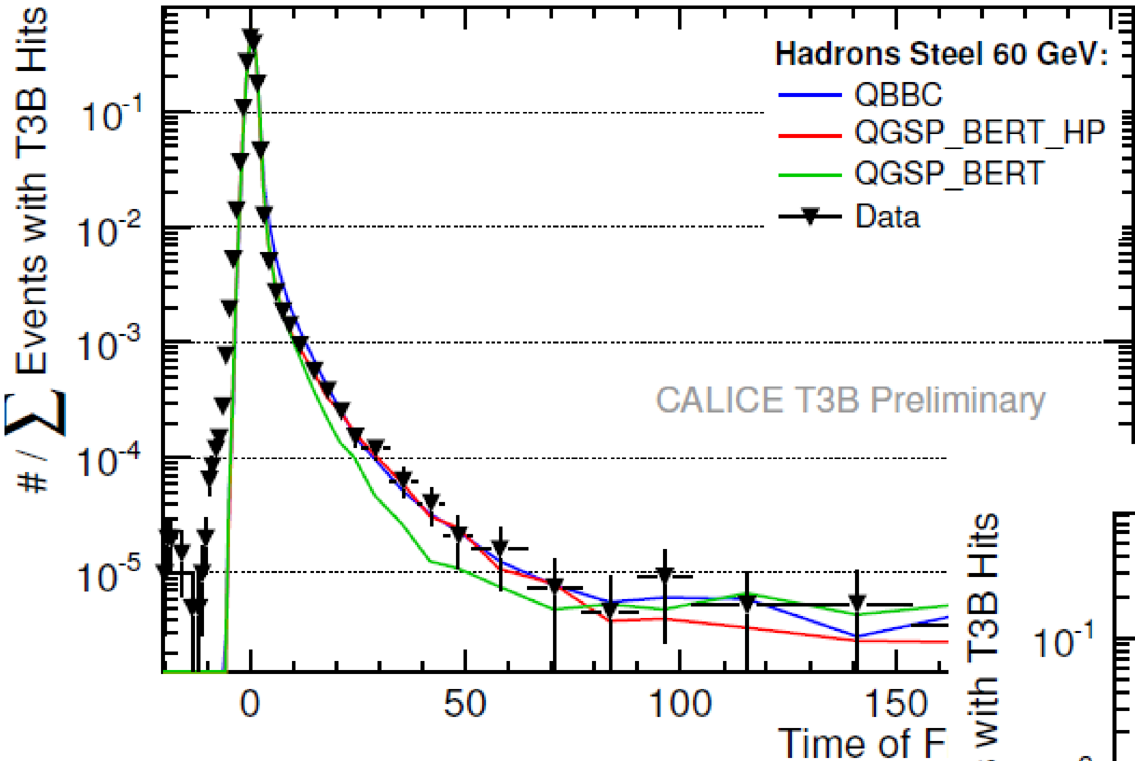
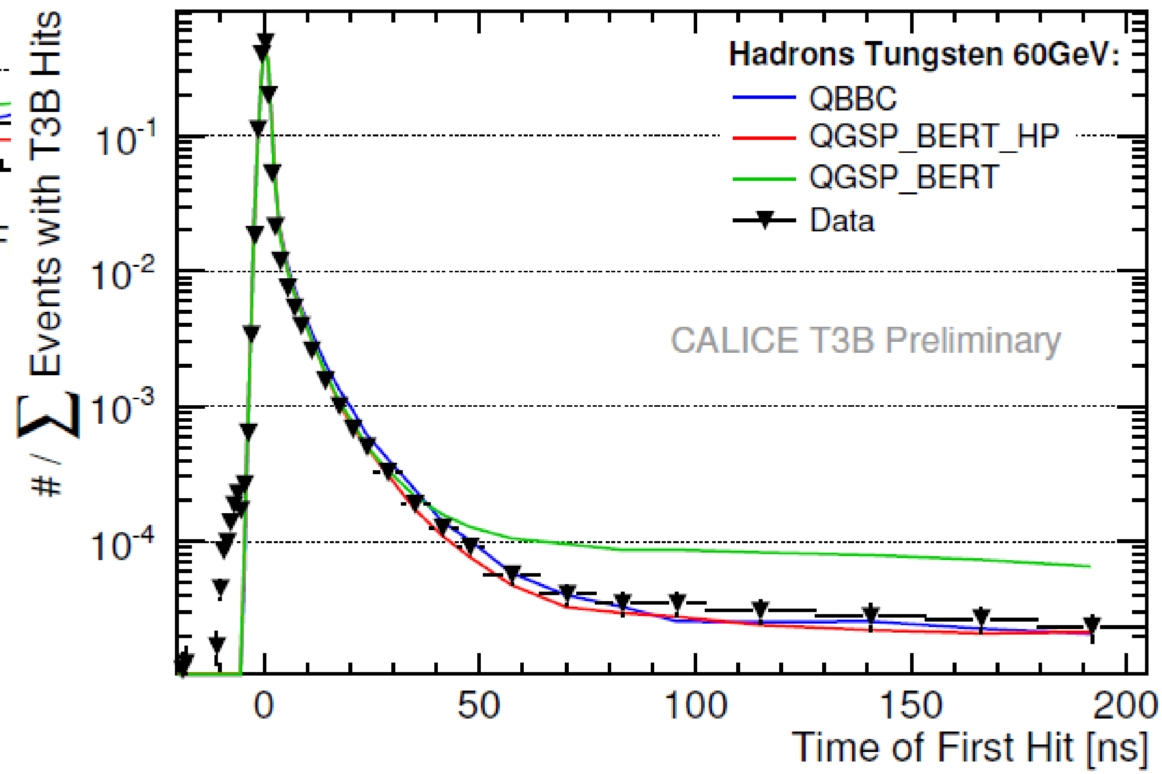
CALICE: Time Structure of Hadronic Showers (1/2)



- Sampling calorimeter with steel / tungsten absorber
- Active medium: Plastic scintillator & SiPM readout (only one layer at the back of the calorimeter)



- Simulations with GEANT4.9.4p3
- In general: Good reproduction of steel data by all models, tungsten requires HP or QBBC

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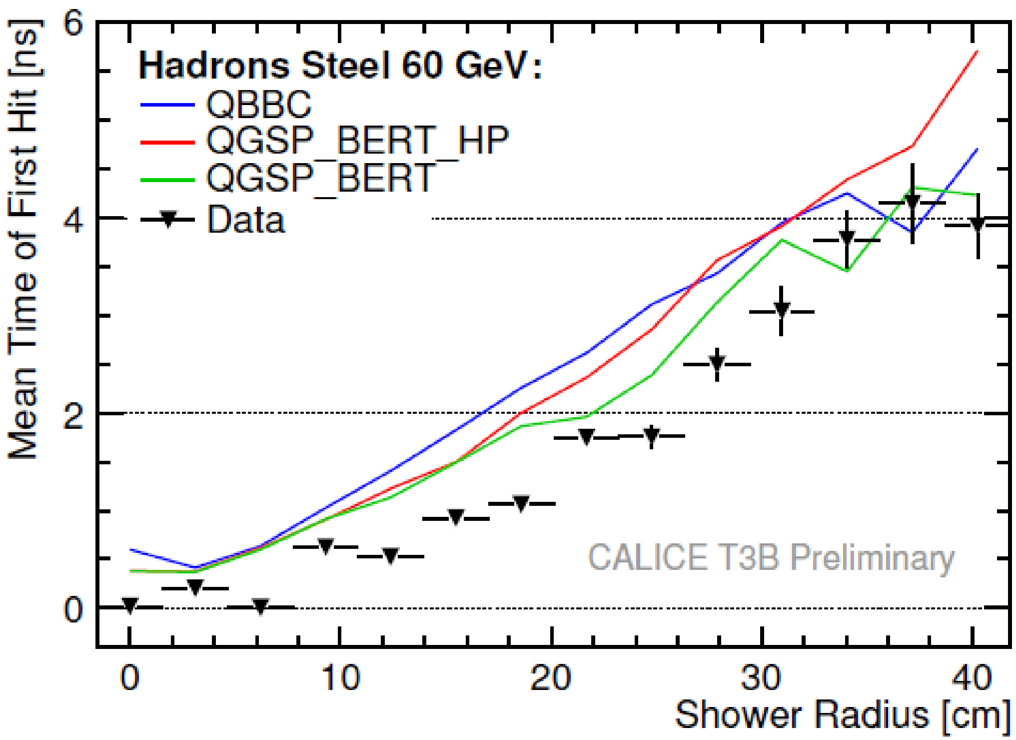
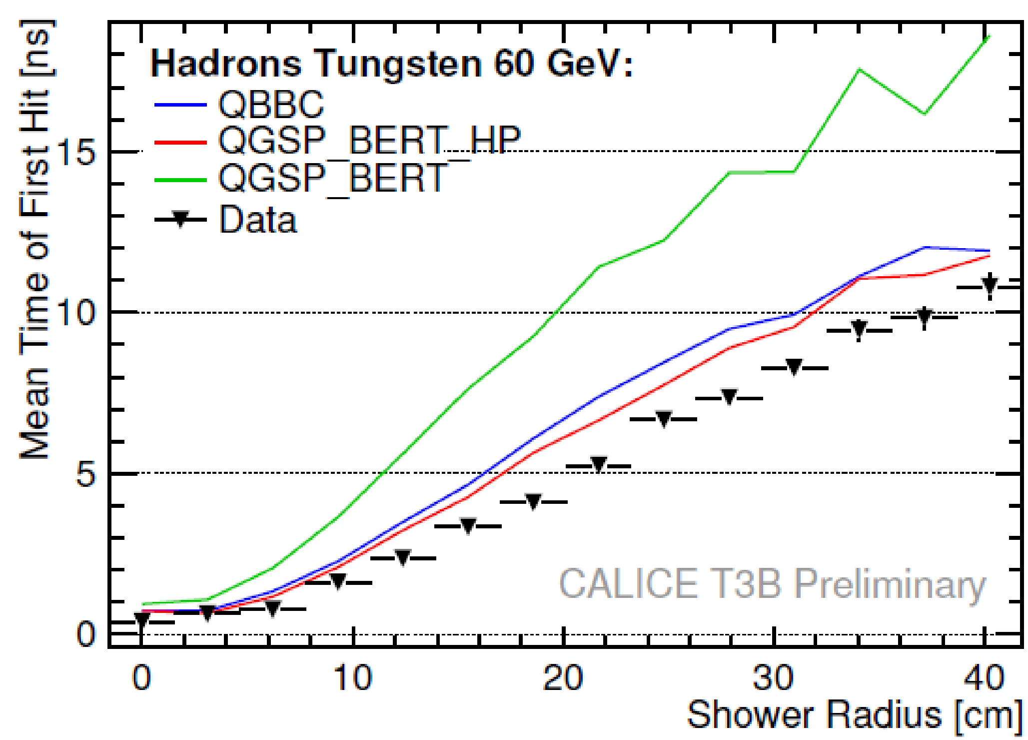
CALICE: Time Structure of Hadronic Showers (2/2)





GEANT4.9.4p3

- Radial dependence of mean time of hits:
  - Good agreement for steel (a few 100 ps, which is comparable to systematics)
  - For tungsten: HP / QBBC necessary, QGSP_BERT overestimates late contributions, which matter most at larger radii (extended "neutron cloud" vs rather collimated em-subshowers and relativistic hadrons)

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Geant4 simulation of hadronic showers

History of production physics lists used by ATLAS and CMS

- **LHEP** : the first available, fast but very rough.
  Still used by LHCb for LHC data analysis up to now
- **QGSP** : better energy response and resolution; but too compact showers (for the longitudinal shape, worse than LHEP)
- **QGSP_BERT** : even better energy response and resolution, and wider showers; longitudinal showers improved by including quasi-elastic; but unphysical kinks due to the transition between models (BERT & LEP).
  Used by ATLAS for LHC data analysis up to now
- **QGSP_FTFP_BERT** : smoother transition, replacing LEP with FTFP in the intermediate region.
  Used by CMS for LHC data analysis up to now
- **FTFP_BERT** : our current recommended physics list; not yet used for large productions up to now

Evolution of FTFP_BERT between G4 9.4 - 9.6

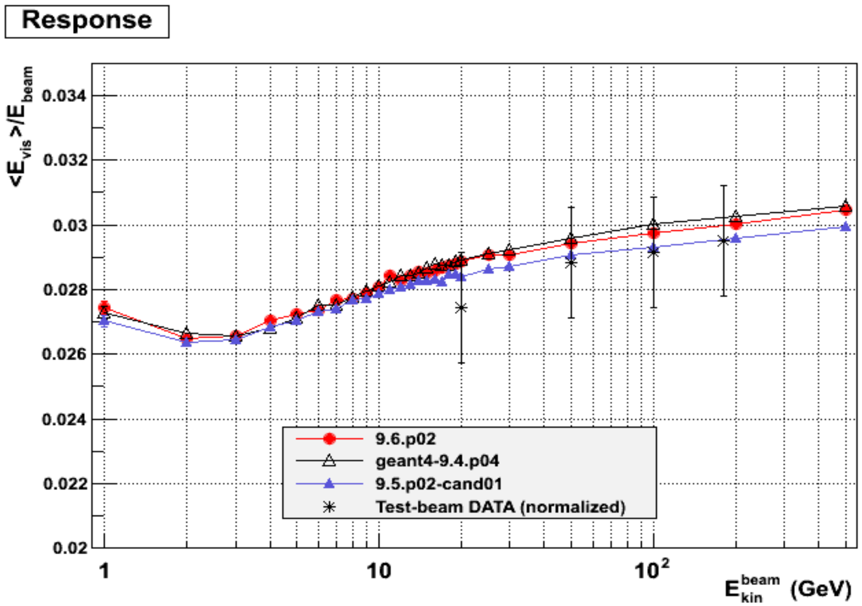
- **FTF** improved (new tuning + diffraction : in G4 9.6) and extended (anti-baryons - nucleus interactions : in G4 9.5)
- **BERT** improved (internal nucleon-nucleon cross sections in G4 9.6 ; angular distributions in G4 9.5) and extended (gamma-nucleon + nuclear capture at rest : in G4 9.6)
- Improved nucleon-nucleus inelastic cross sections (replaced Wellisch xsec with Barashenkov-Glauber xsec : in G4 9.6)
- New nuclear capture at rest and lepton-nuclear (replaced CHIPS with FTF/Preco + BERT)
- New treatment of hyperons, anti-hyperons, anti-protons, light-ions and light anti-ions (replaced CHIPS or LEP with FTF/Preco (+BERT for hyperons, or +BIC for light ions); kept CHIPS xsec for hyperons and anti-hyperons)

Pion showers in simplified calorimeters

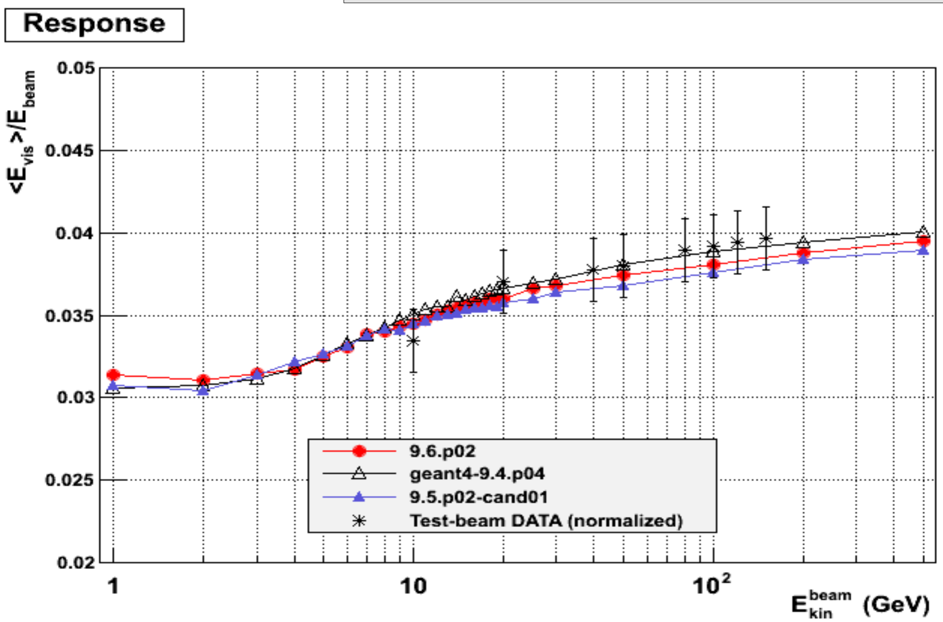
Note: when data is shown, these are rescaled ATLAS test-beam data (obtained with an old version of Geant4, before G4 9.4)

FTFP_BERT response

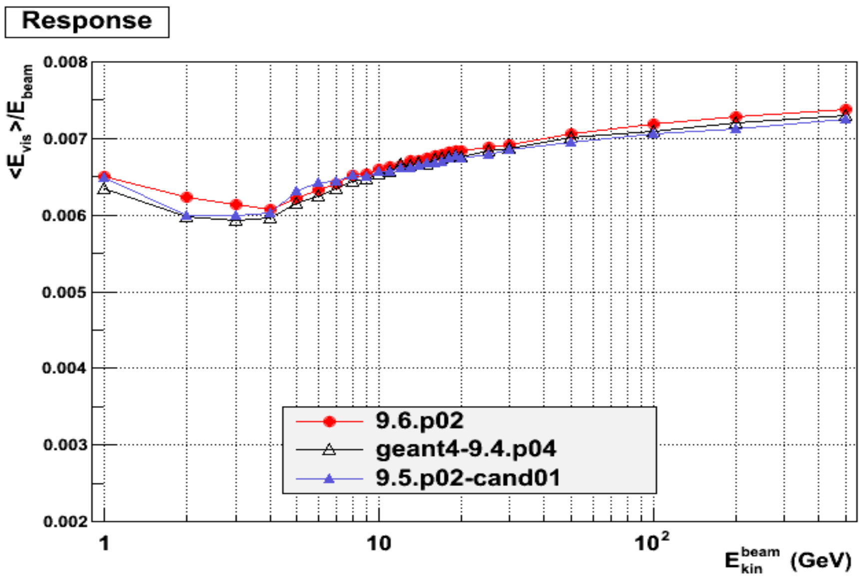
π⁻ on Fe-Sci



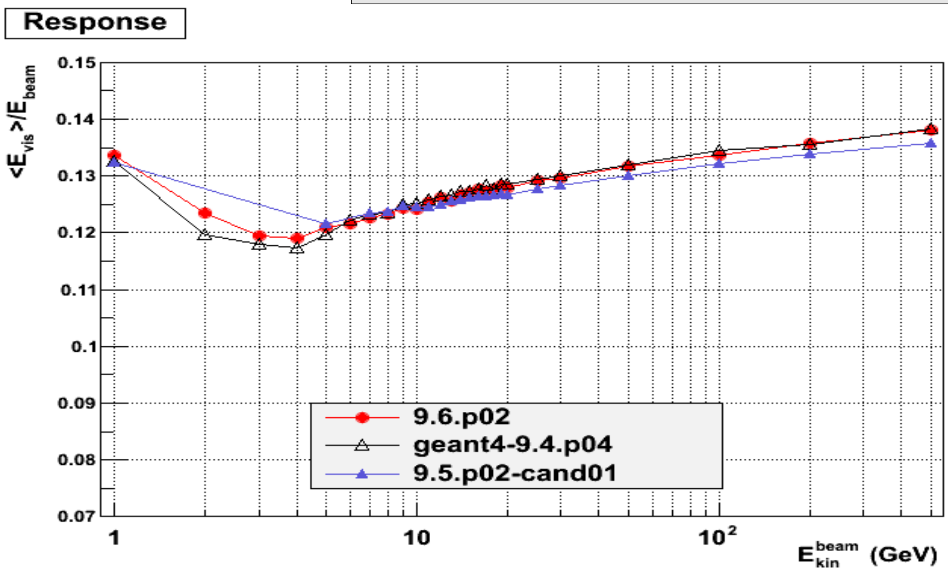
π⁻ on Cu-LAr



π⁻ on W-LAr

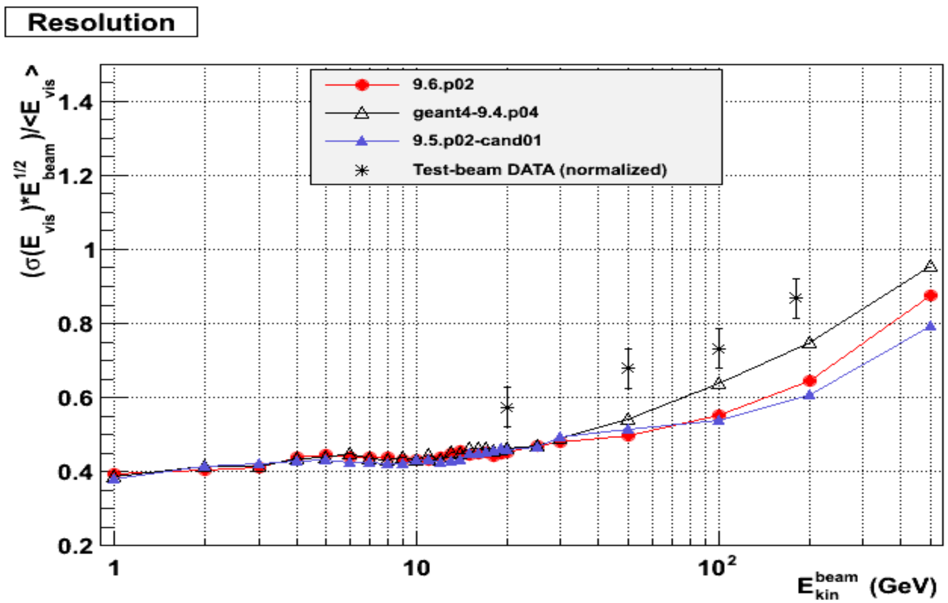


π⁻ on Pb-LAr

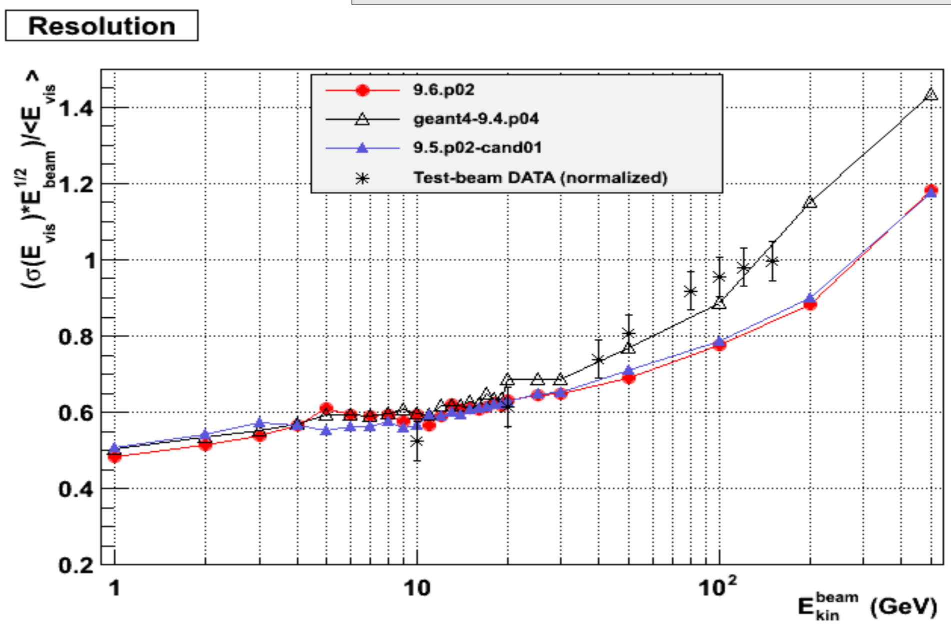


FTFP_BERT energy resolution

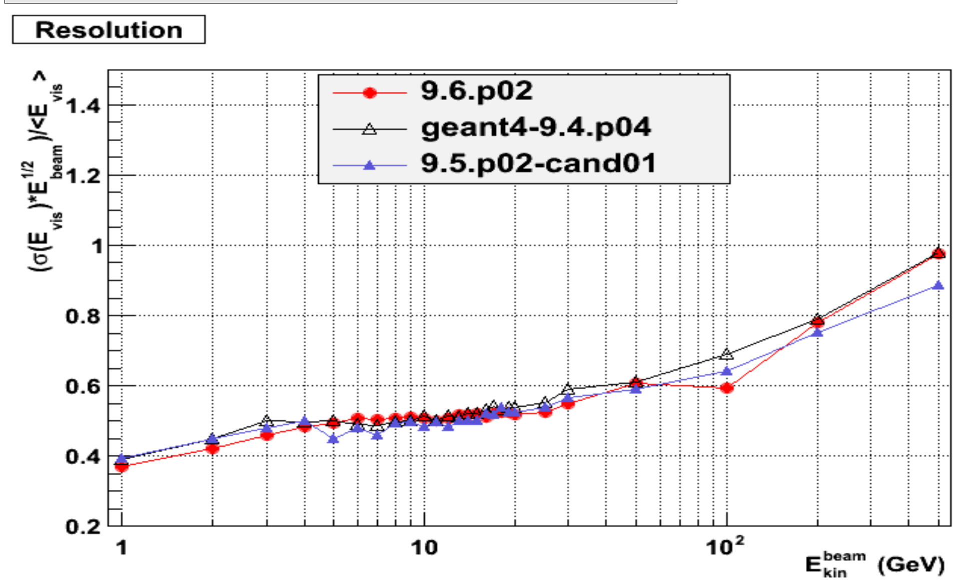
π^- on **Fe-Sci**



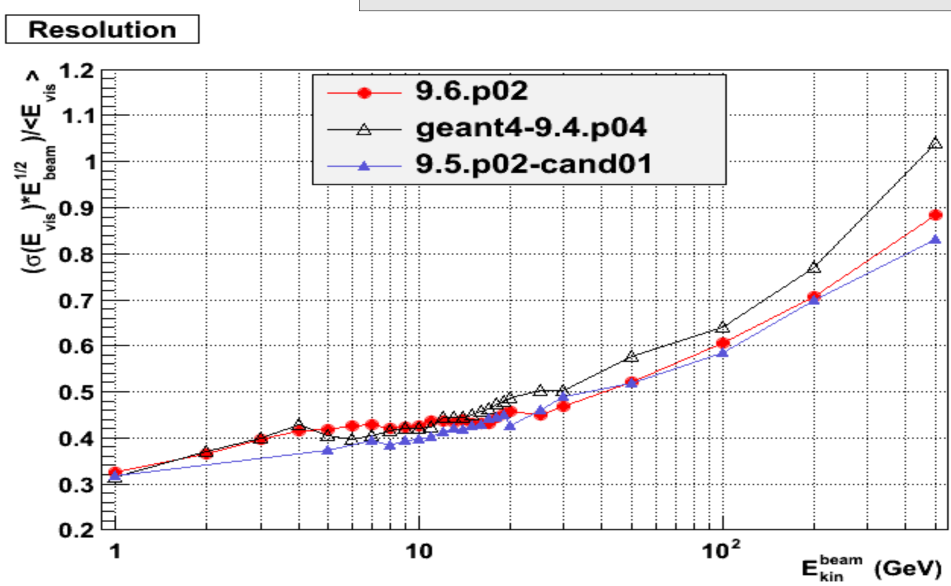
π^- on **Cu-LAr**



π^- on **W-LAr**

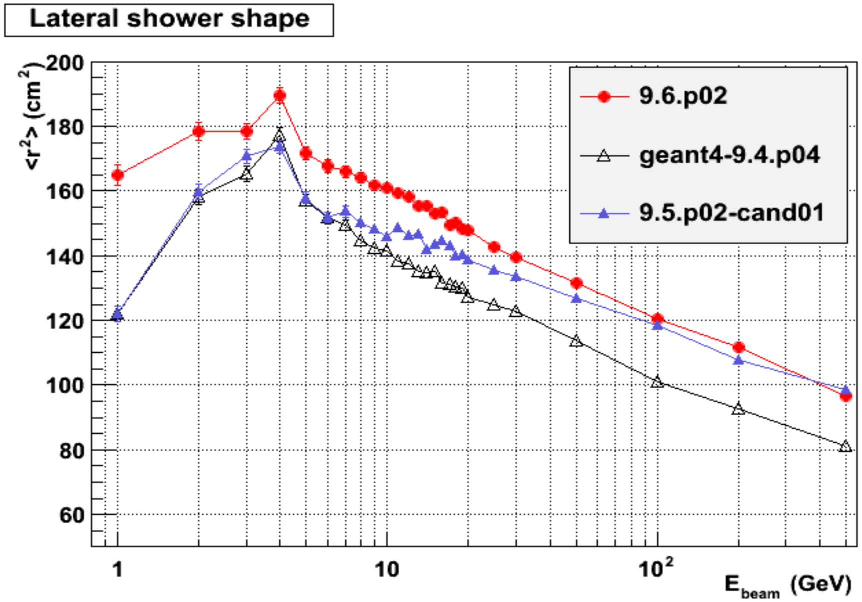


π^- on **Pb-LAr**

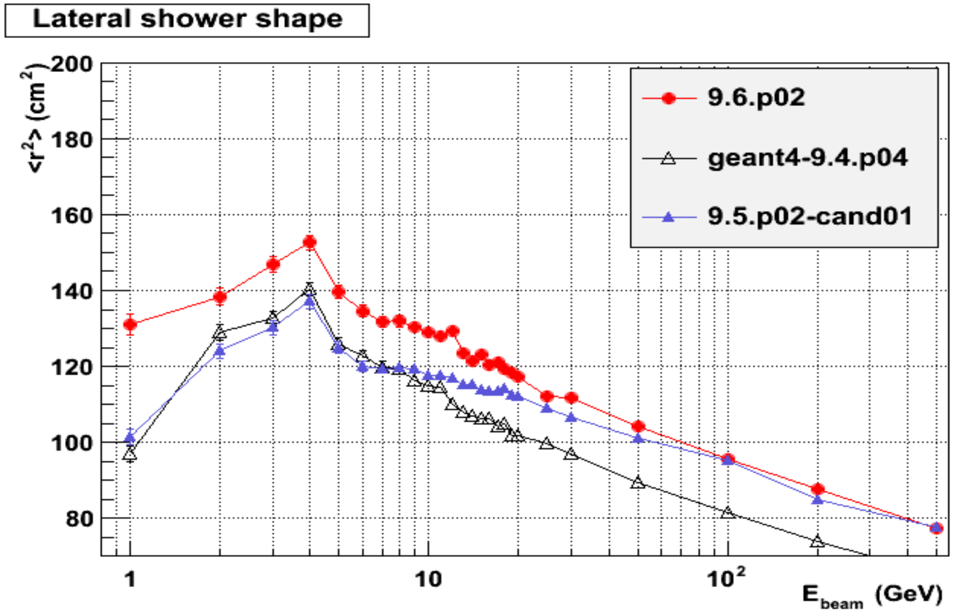


FTFP_BERT lateral shower shape

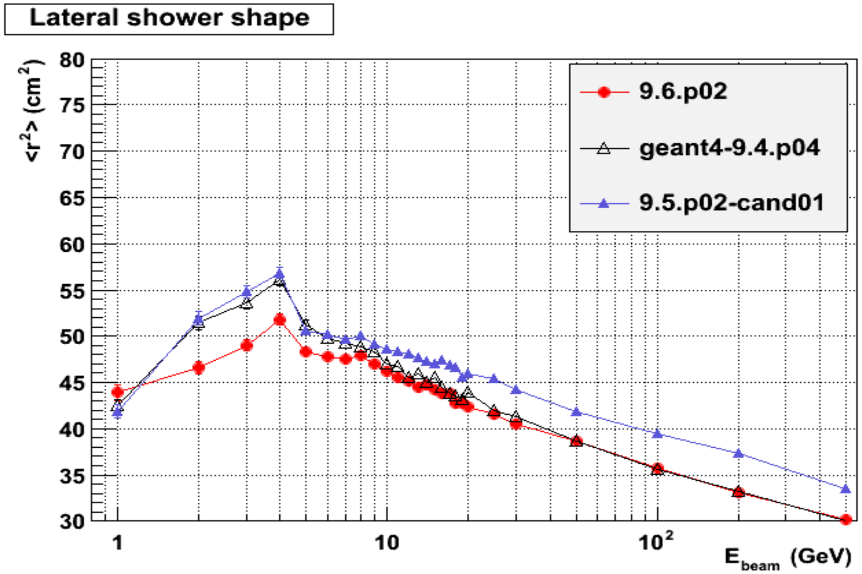
π⁻ on Fe-Sci



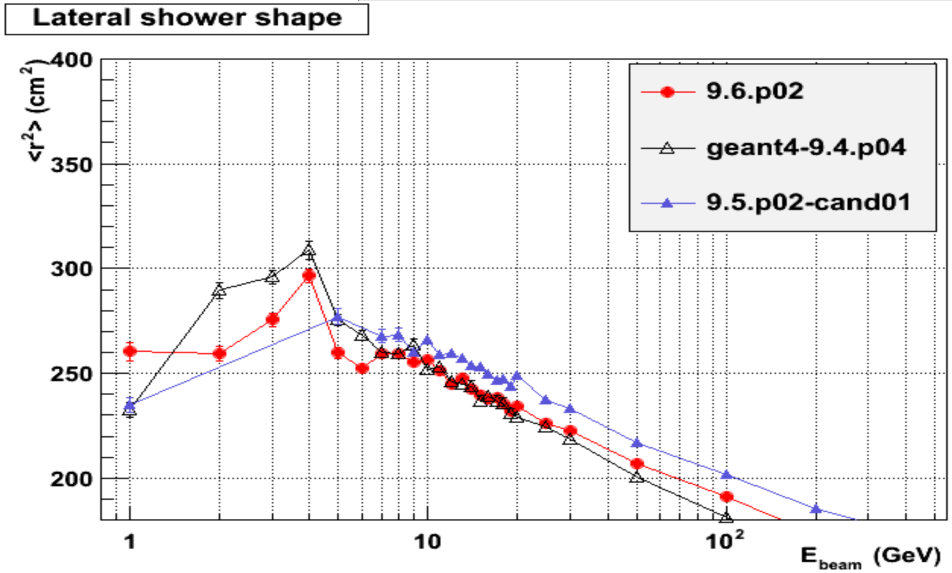
π⁻ on Cu-LAr



π⁻ on W-LAr

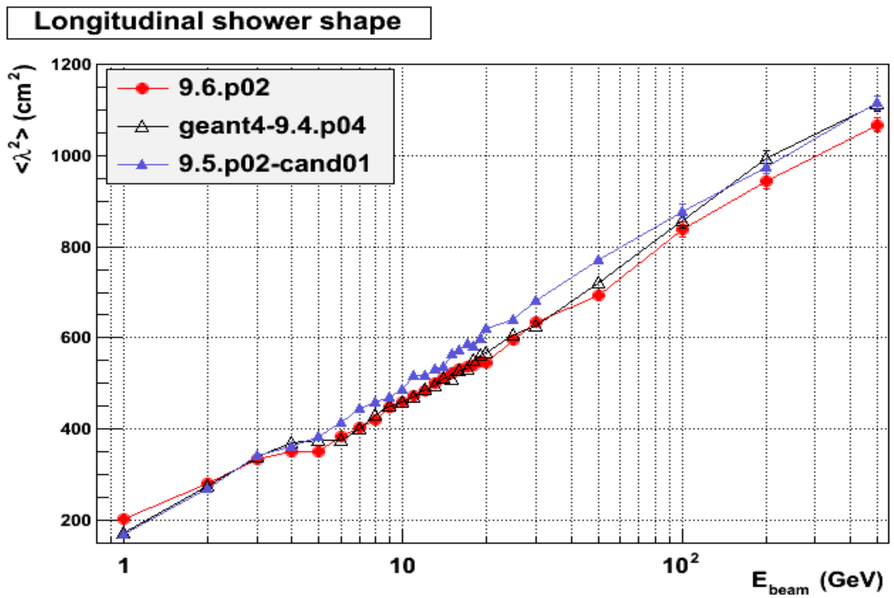


π⁻ on Pb-LAr

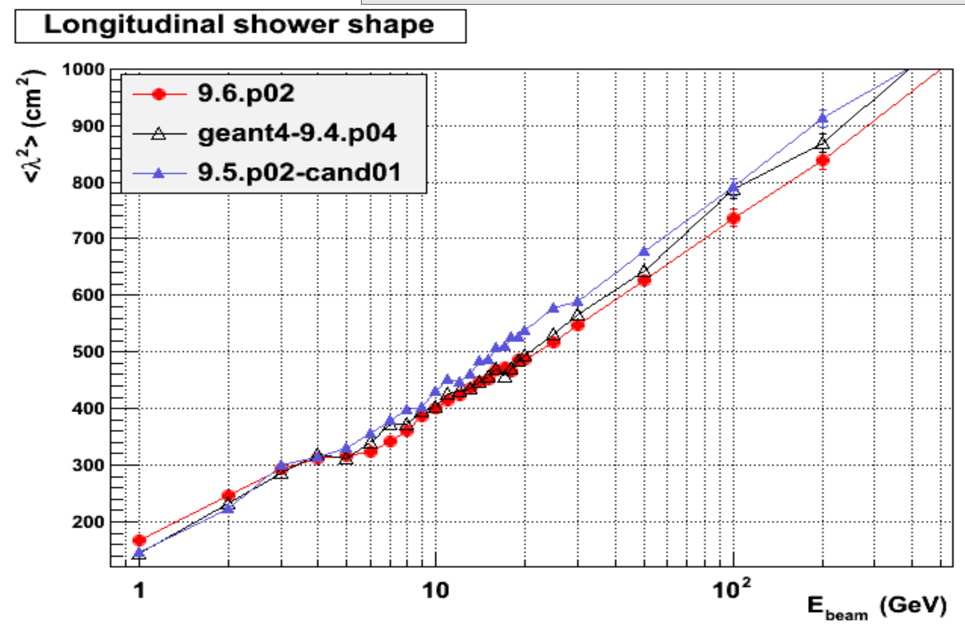


FTFP_BERT longitudinal shower shape

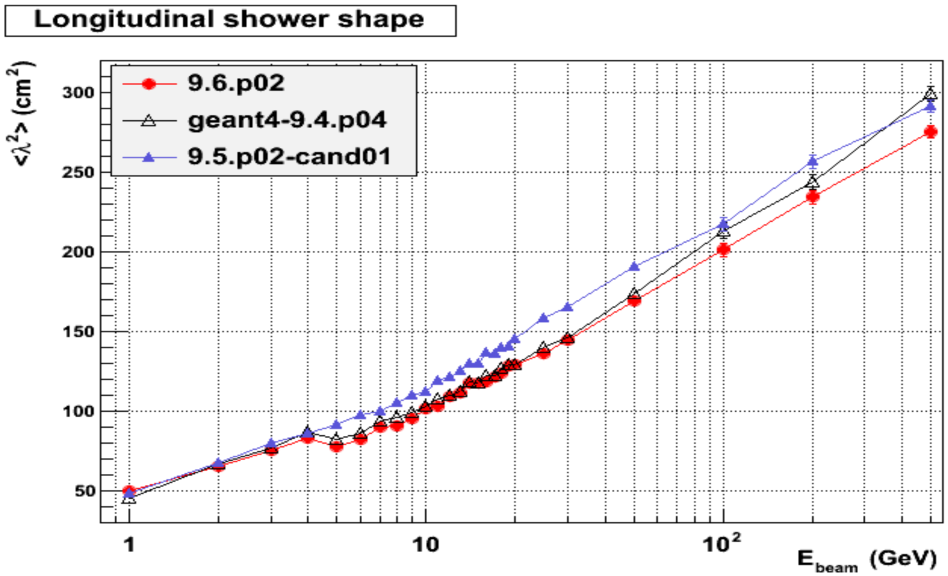
π^- on Fe-Sci



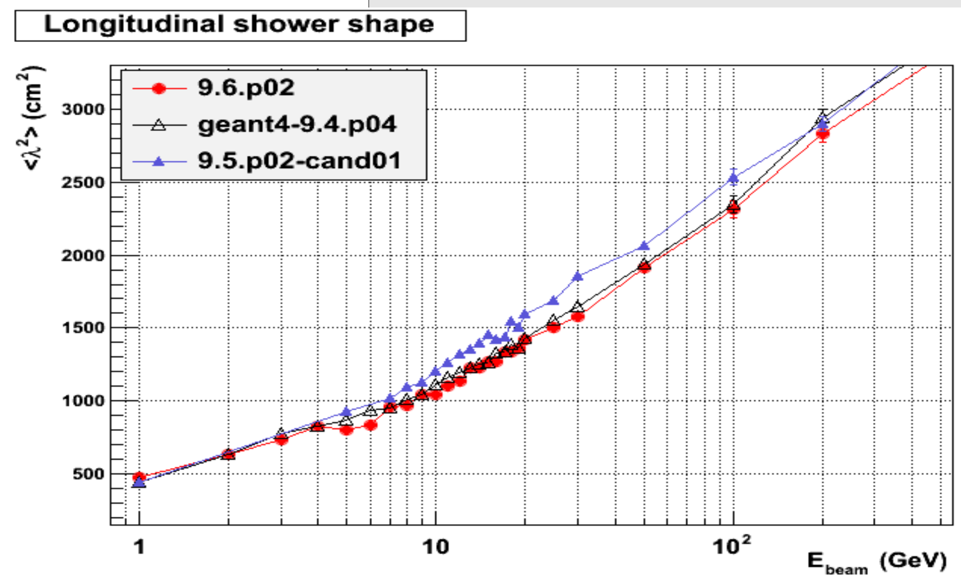
π^- on Cu-LAr



π^- on W-LAr



π^- on Pb-LAr



FTFP_BERT after G4 9.6

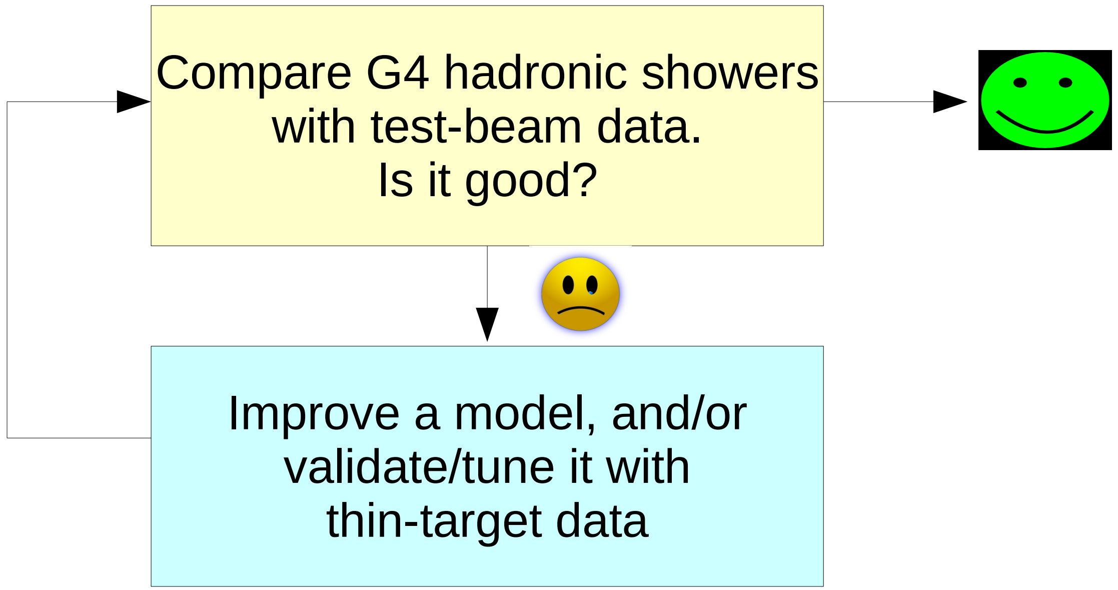
- Latest tuning of FTF (included in G4 9.6.ref07)
  - Increased significantly the probability to produce delta-isobars
  - Switched off hadron-nucleus and nucleus-nucleus diffraction

has a significant impact on hadronic showers;
still evaluating its thin-target motivations...

- Future developments
  - Fritiof re-scattering with Bertini (vs. Binary)
  - Fritiof code revision & consolidation
  - Bertini coupled with G4 Precompound/evaporation
  - Making Bertini more physically realistic
  - Revision of the transition energy interval between FTFP and BERT
  - Try to use Binary Cascade for low-energy (< ~1-2 GeV) nucleons

Most of this is ready, but likely needs careful re-tuning...

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?

Summary and Outlook

- The most important use of Geant4 hadronic physics in HEP is the simulation of hadronic showers, needed to simulate jets
- Significant progress in the simulation of hadronic showers over the years, driven mainly by calorimeter test-beams
- **FTFP_BERT** the current recommended physics list
  - Recent improvements in lateral hadronic shower shapes
    - Wider showers in **Fe** and **Cu**
  - **Energy resolution too optimistic** (at least at high energies)
  - Stable energy response and longitudinal shower shapes
    - Need new comparisons with (LHC & CALICE) test-beam data
- Looking forward to the next LPCC Detector Simulation Workshop (early 2014)
  - Latest comparisons of simulations with LHC data
  - Simulations with FTFP_BERT and recent versions of Geant4