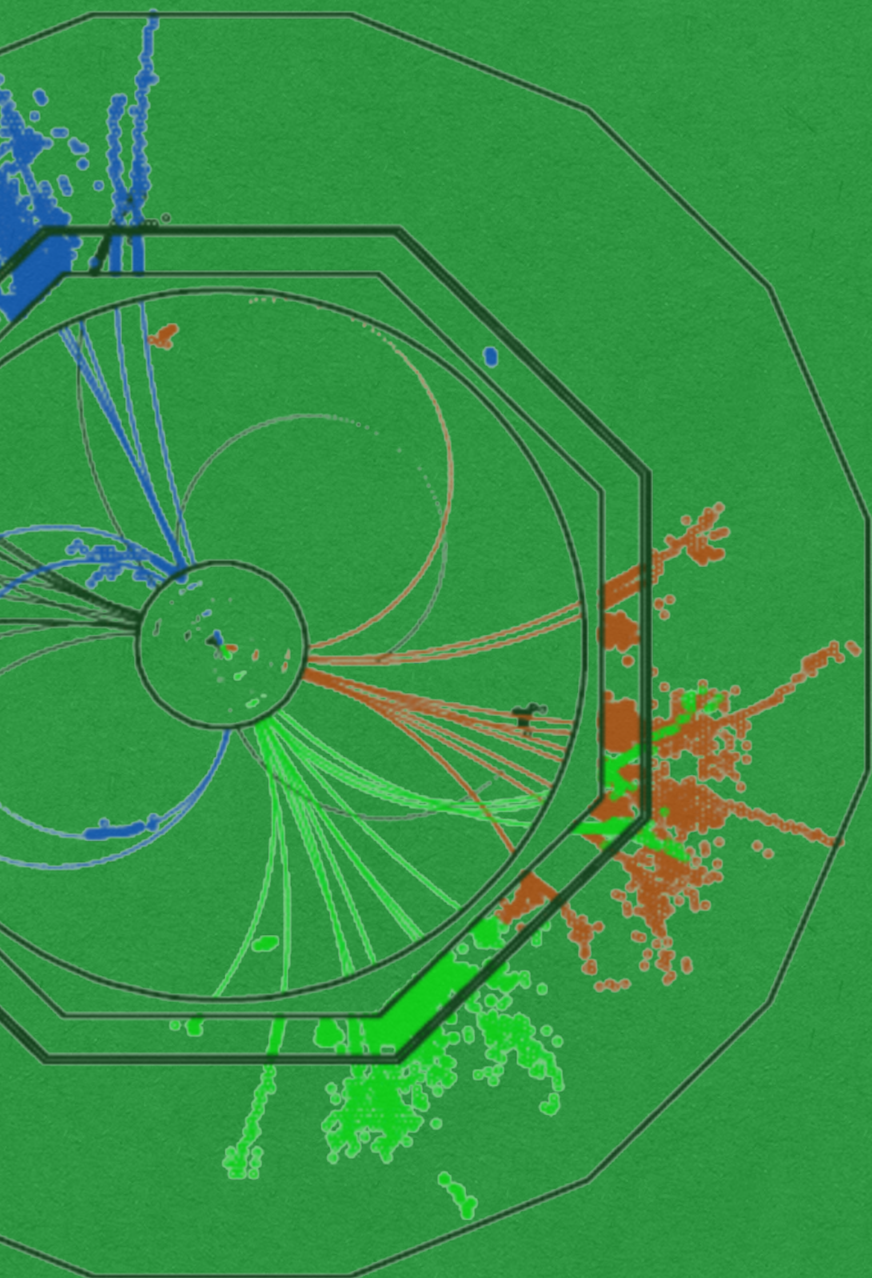
EUROPEAN PHYSICAL SOCIETY HEP2015



Detailed studies of hadronic showers and comparison to GEANT4 simulations with data from highly granular calorimeters

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on behalf of the CALICE Collaboration

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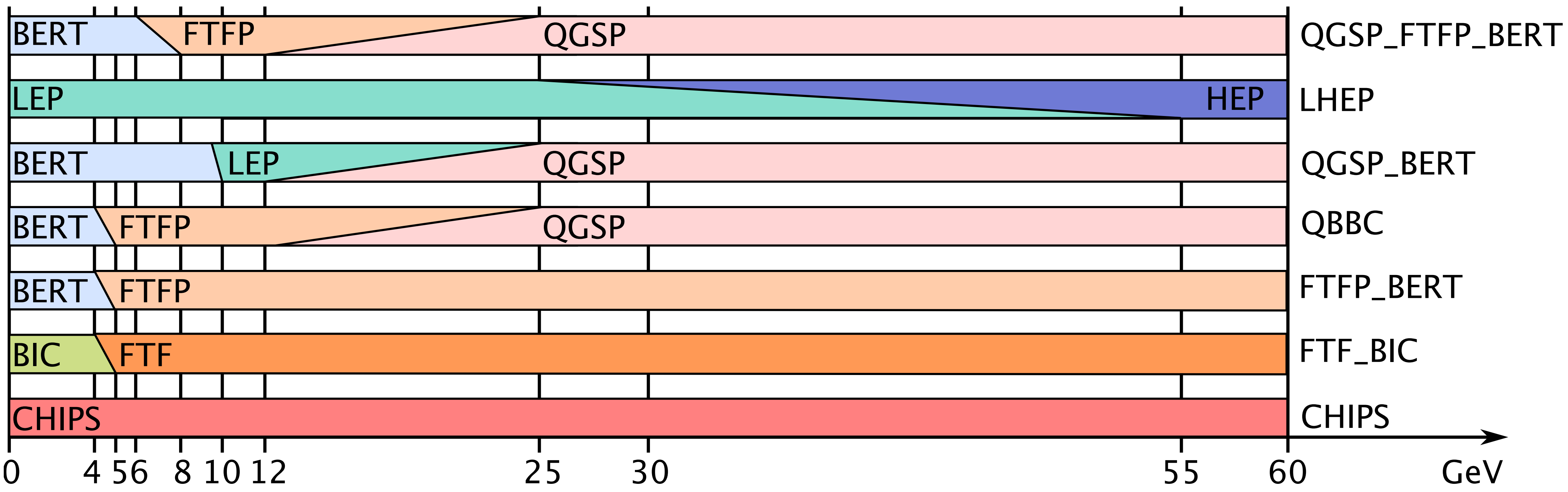
Studying hadronic showers

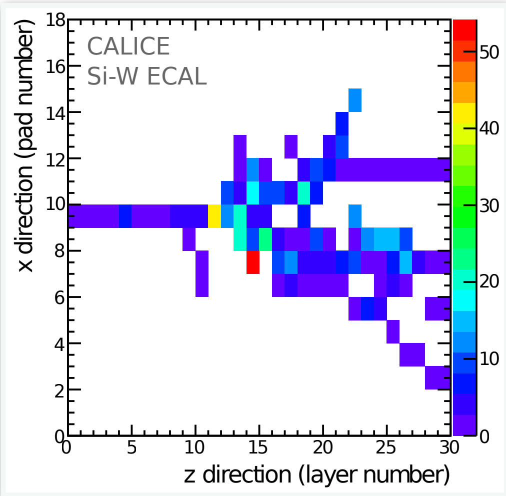
- Prototypes of highly granular calorimeters are built and tested by the CALICE collaboration to evaluate performance for future physics experiments (talk by V. Balagura), but their purpose is also to aid in better understanding hadronic showers
- A good understanding of hadronic showers is needed to efficiently develop Particle Flow Algorithms (PFA)
- Hadronic showers have a complex structure and are theoretically not as well understood as electromagnetic showers
- CALICE data, with its unprecedented granularity, provides a new level of information to improve modelling of showers in GEANT4
- CALICE prototypes have been operated in test beams at CERN, DESY and FNAL
- Characterize shower energy, shower shape, substructure and time structure of hadronic showers

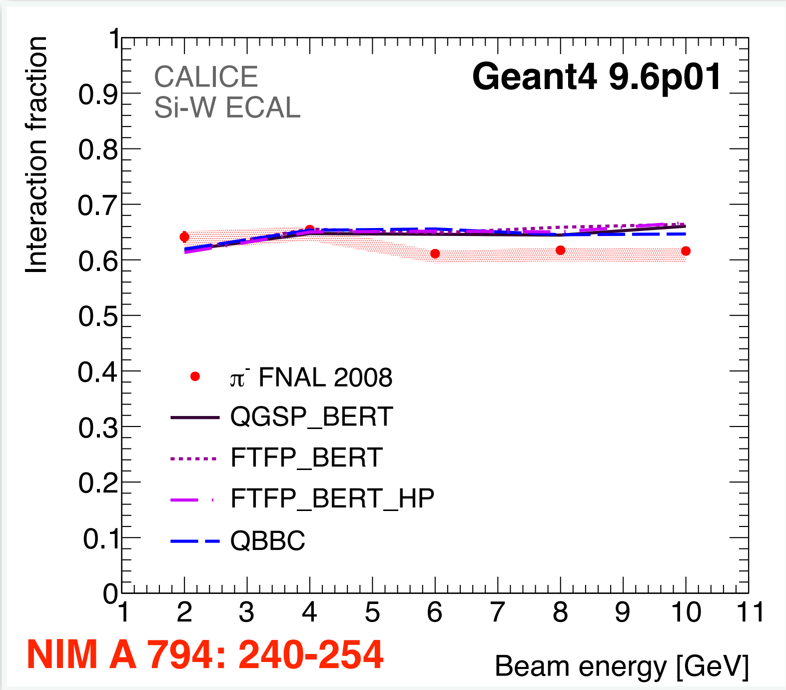
Geant4 Physics Lists

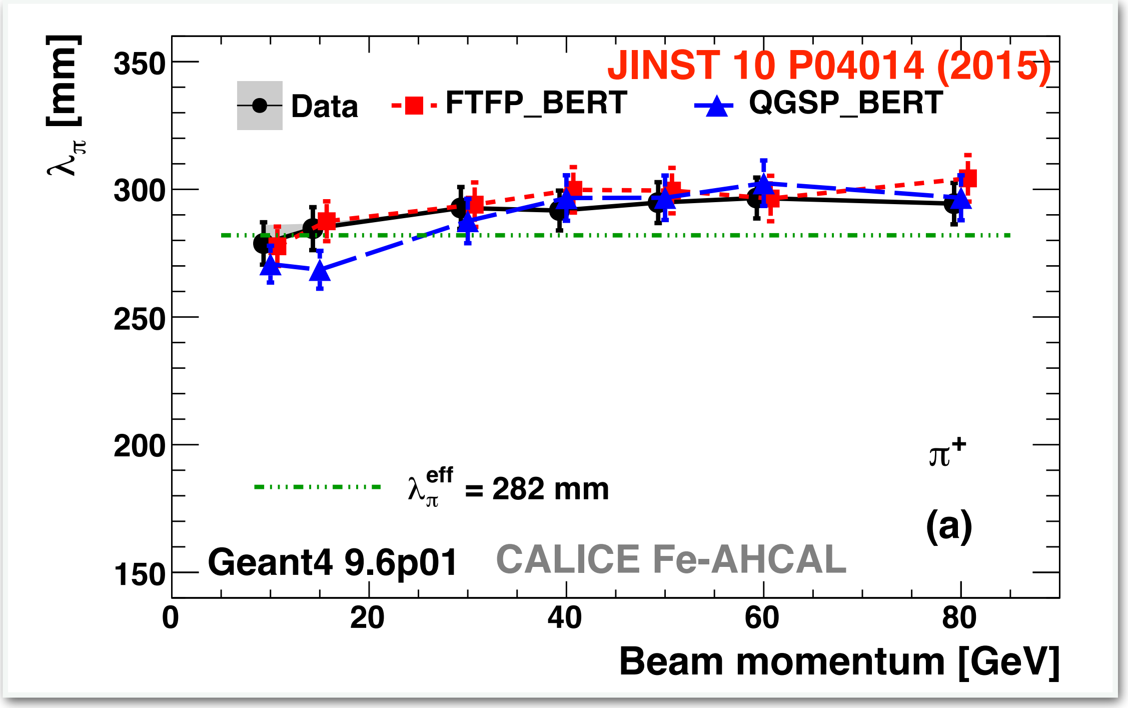
- Several theory-driven and phenomenological hadronic interaction models are available in Geant4
- Different hadronic interaction models are combined into *physics lists*
- Models are applied in a specific energy range
- Smooth transitions between models are achieved by randomly choosing one of the models on an event-by-event basis, with a probability that varies linearly with the energy in the transition interval
- FTFP_BERT is currently the recommended physics list for calorimetry simulations at the LHC

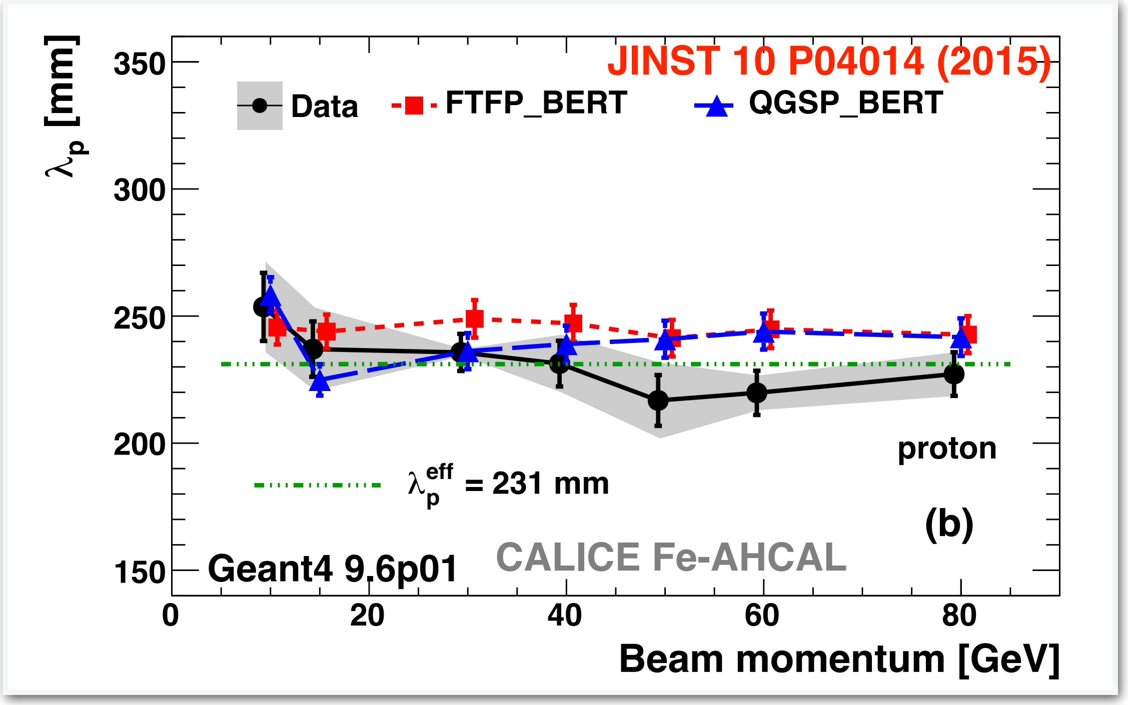


Interaction Length





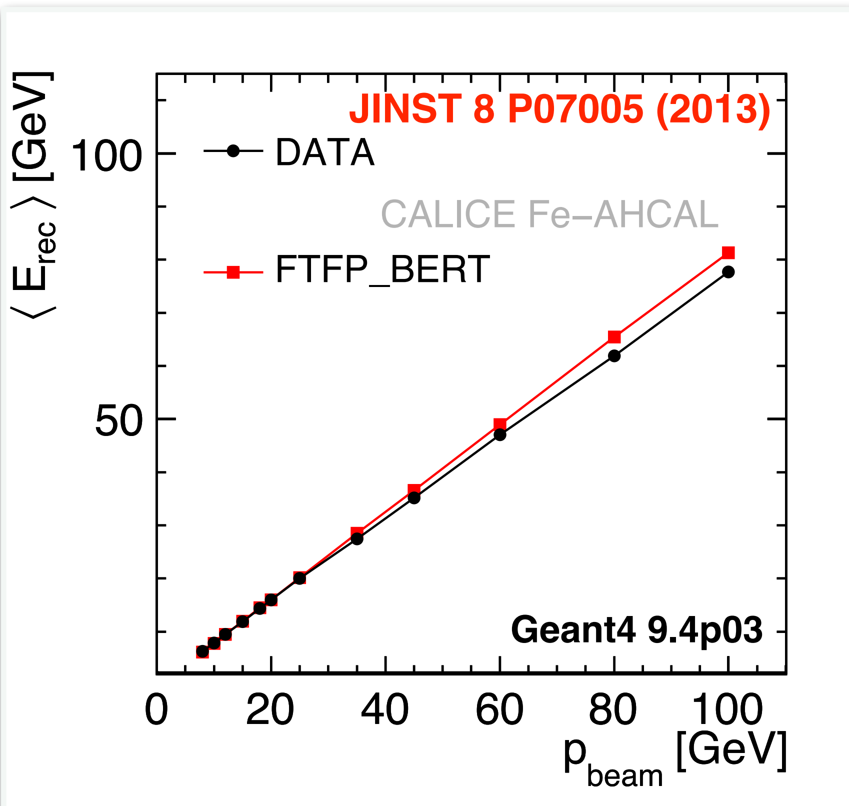


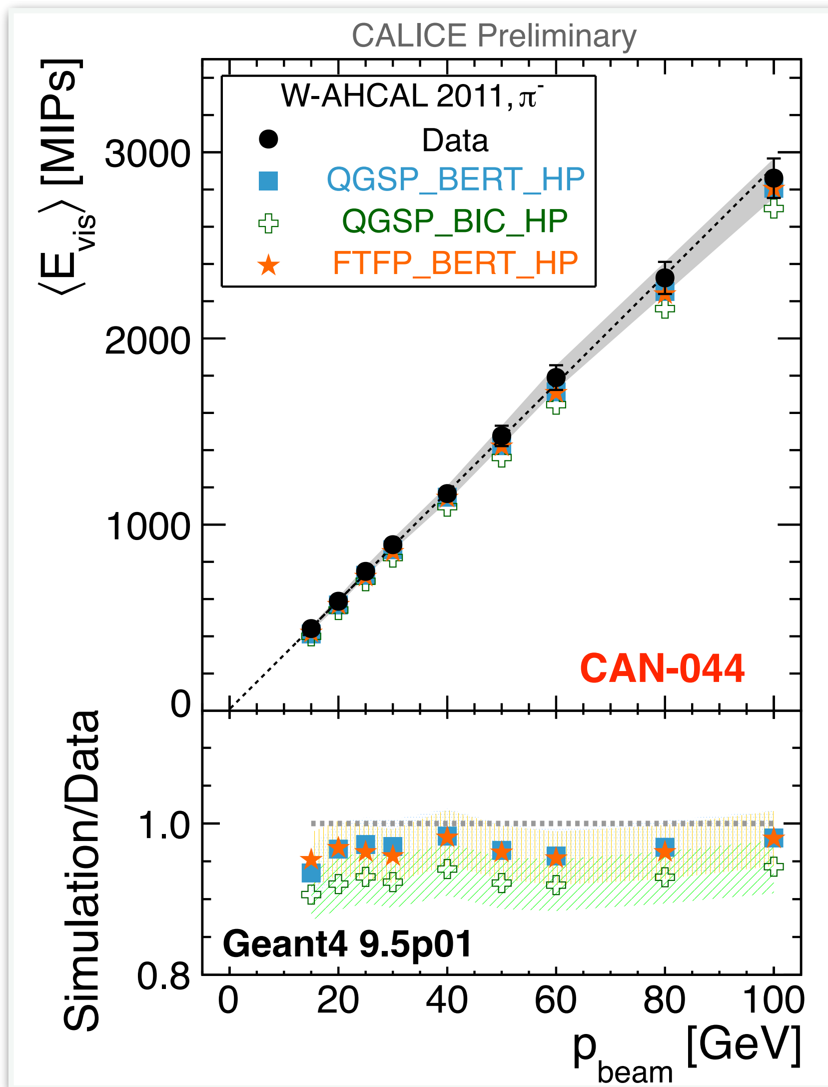


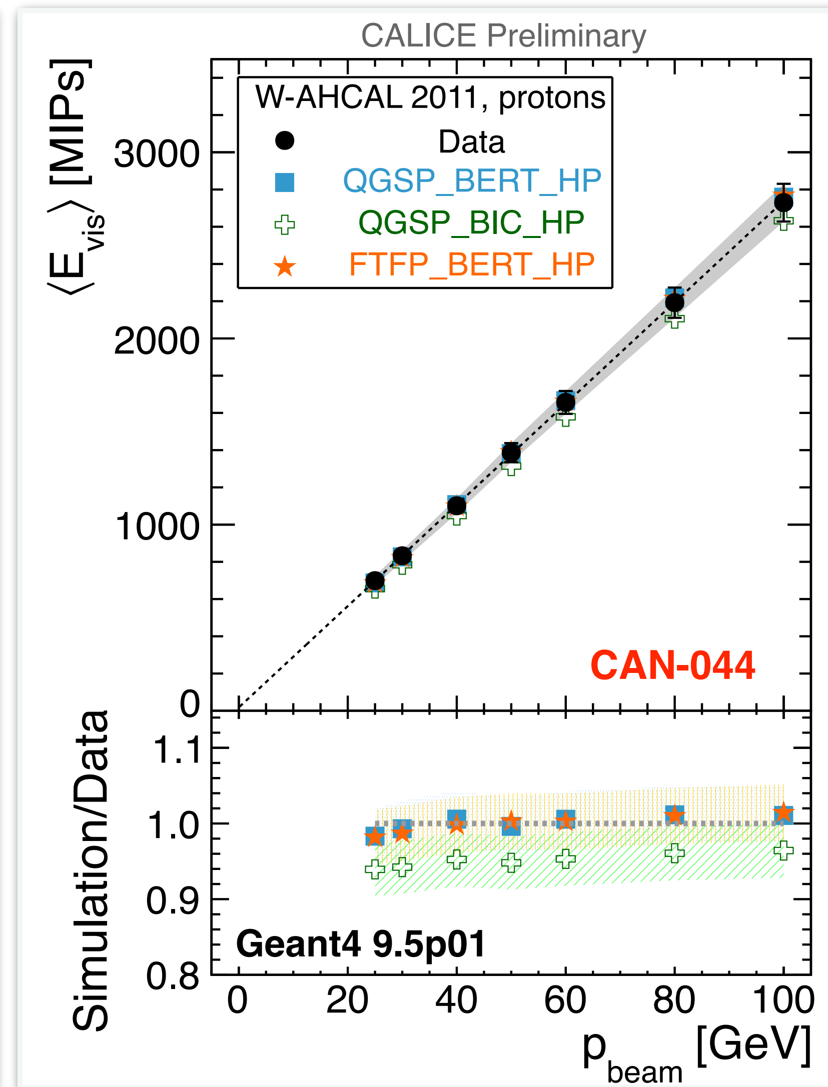
- Fraction of pions that interact and start a shower within ~1 interaction length (Si-W ECAL, 2 - 10 GeV)
- Pion and proton interaction length (Fe-AHCAL, 10 - 80 GeV) based on the distribution of the shower starting point
- Good agreement ~5% between data and simulation

Reconstructed energy

- Reconstructed energy in the calorimeter (W-AHCAL and Fe-AHCAL) for pions and protons
- Good linearity and the MC agrees with data to better than 10%
- QGSP_BERT_HP gives the best prediction for the W-AHCAL

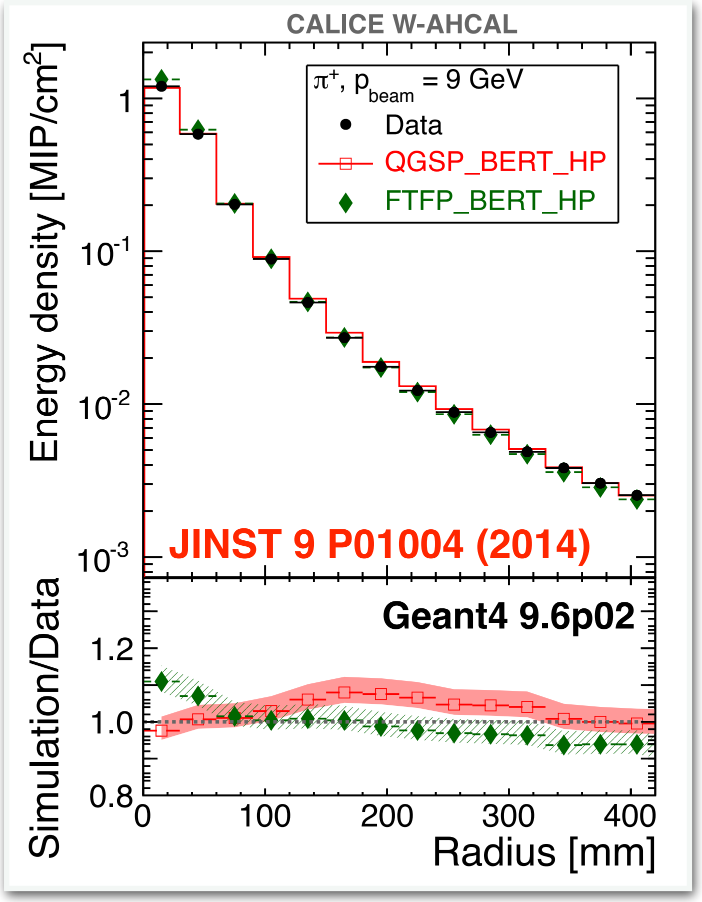






Radial distributions

- Radial energy distribution (radial profile) for pion showers (Si-W ECAL, W-AHCAL, Fe-AHCAL)
- Mean shower radius from radial profiles $R = \frac{\sum e_i r_i}{\sum e_i}$
- Sensitive to model transitions at low energy (Si-W ECAL)
- Radius decreases with energy (higher e.m. fraction)
- Similar results for proton showers (W-AHCAL, Fe-AHCAL)
- Simulations predict too dense showers (difference ~ 10%)
- Best agreement with FTFP_BERT for the Fe-AHCAL and FTFP_BERT_HP for the W-AHCAL



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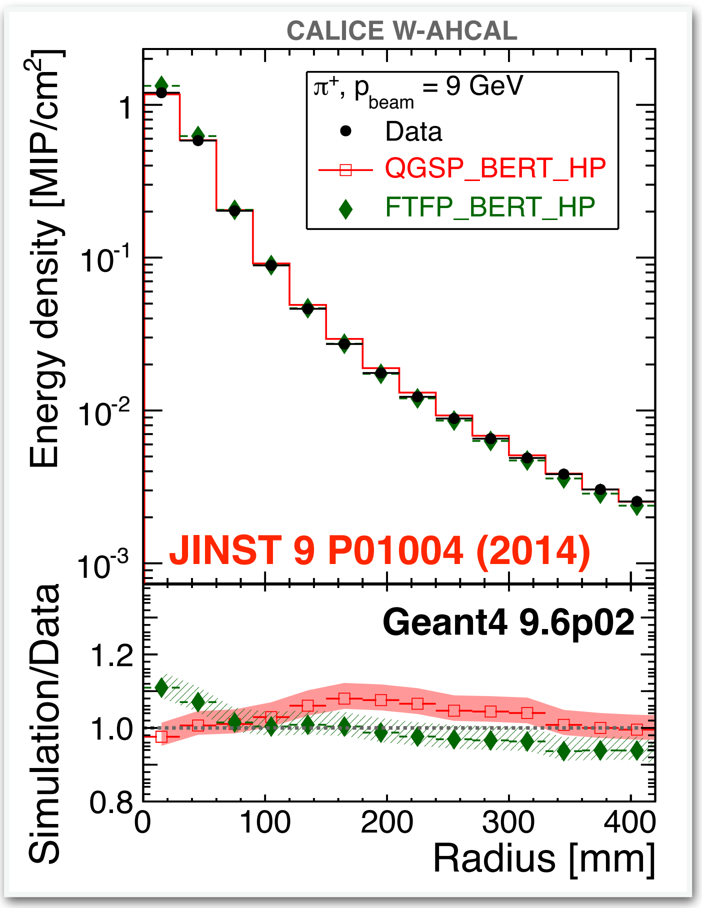

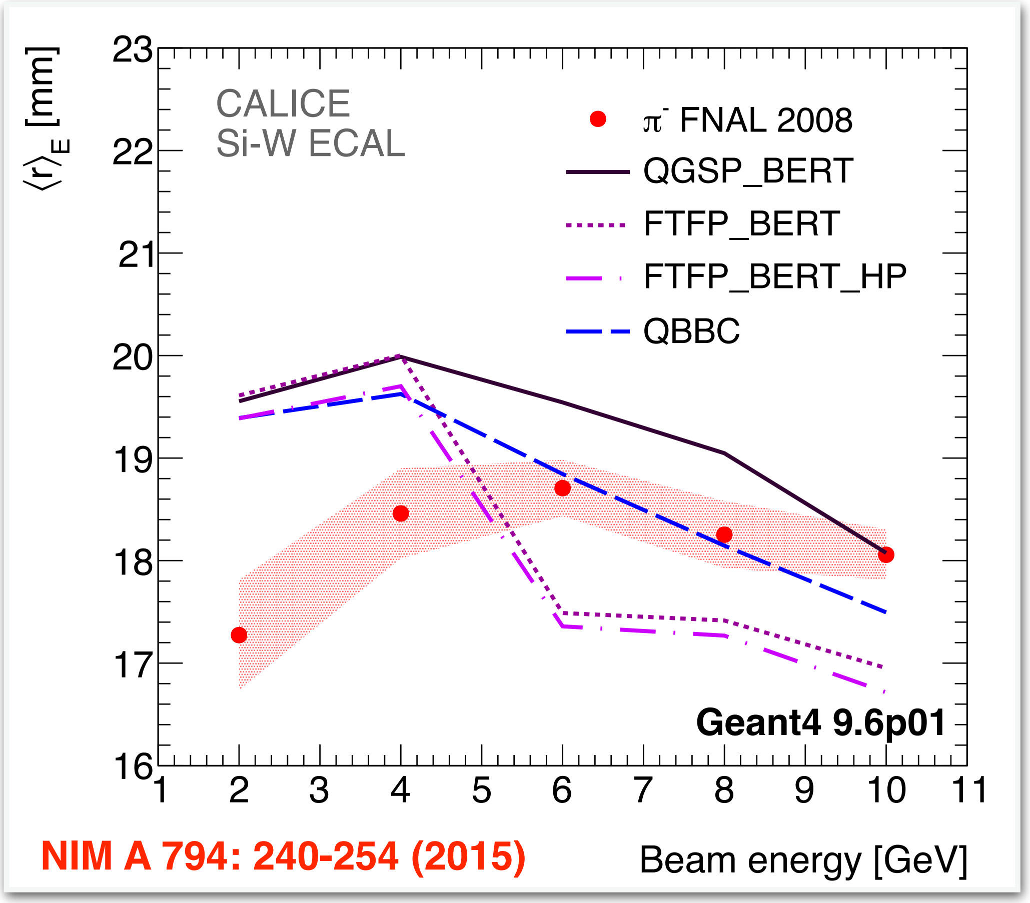

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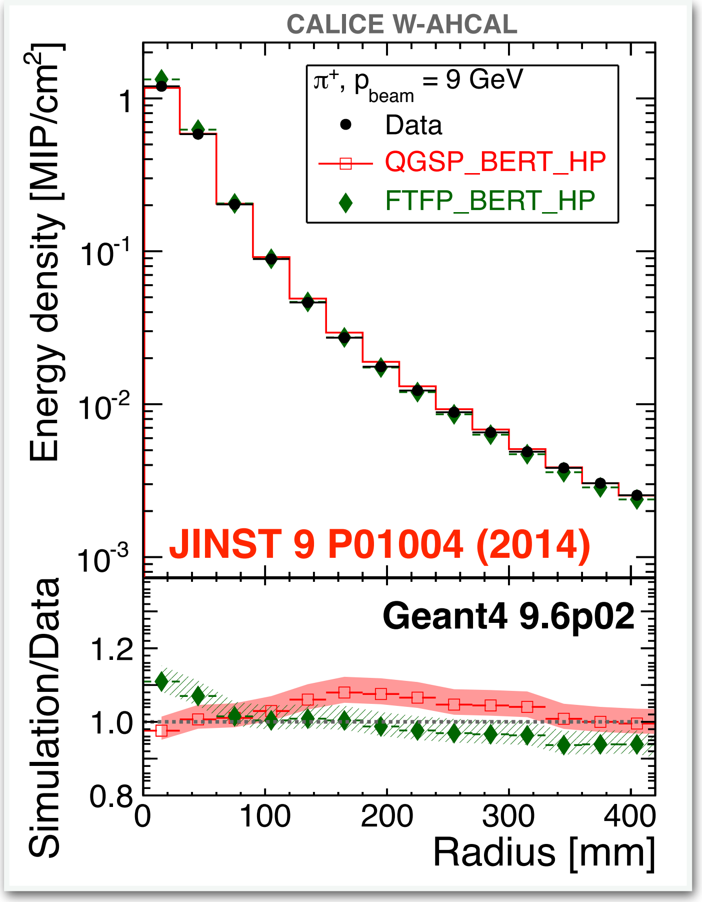

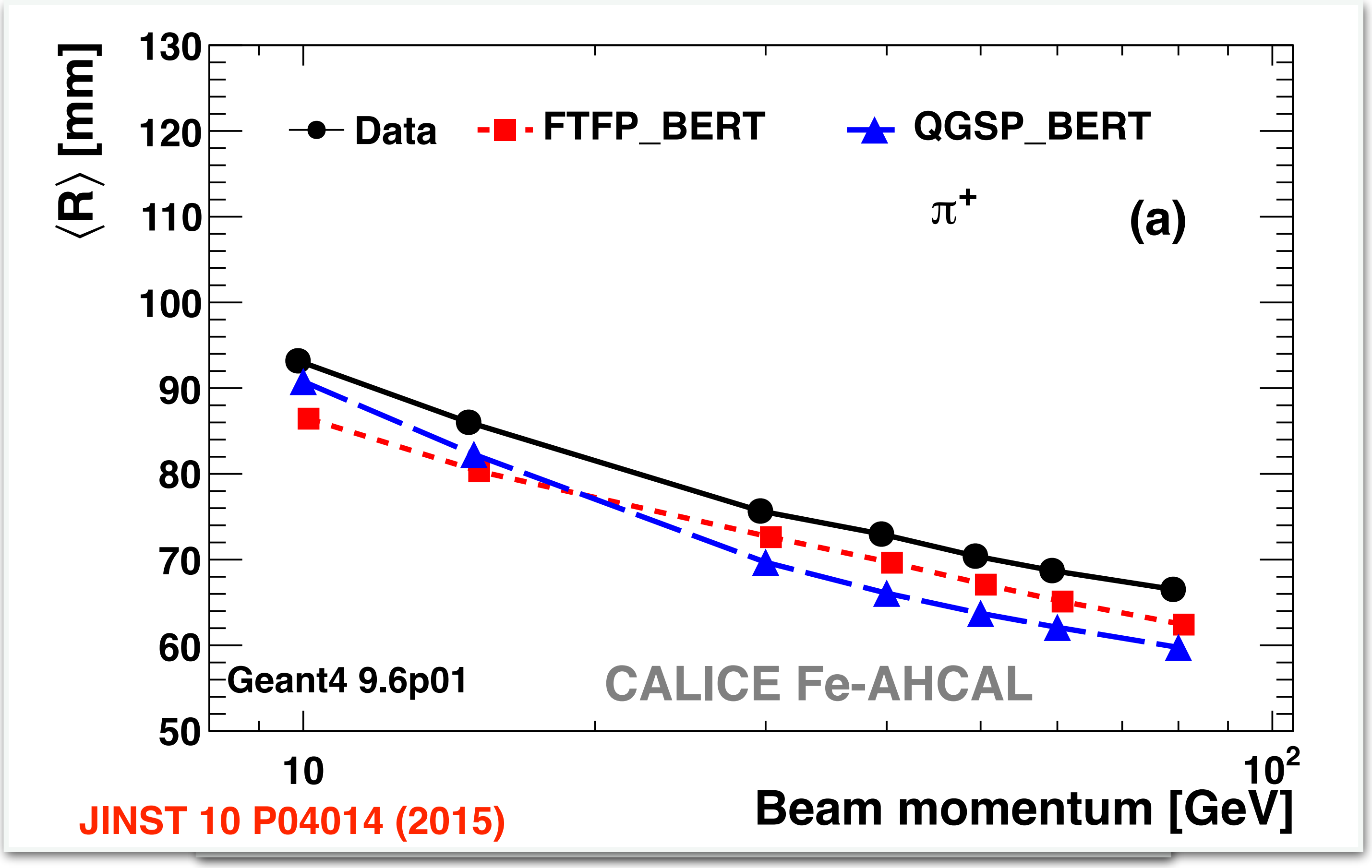

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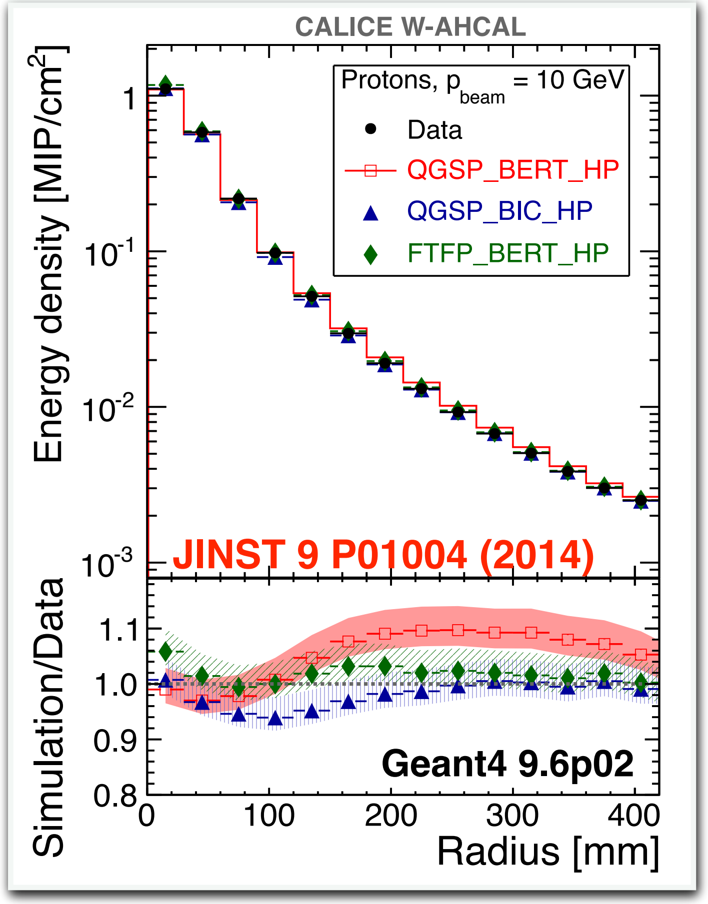
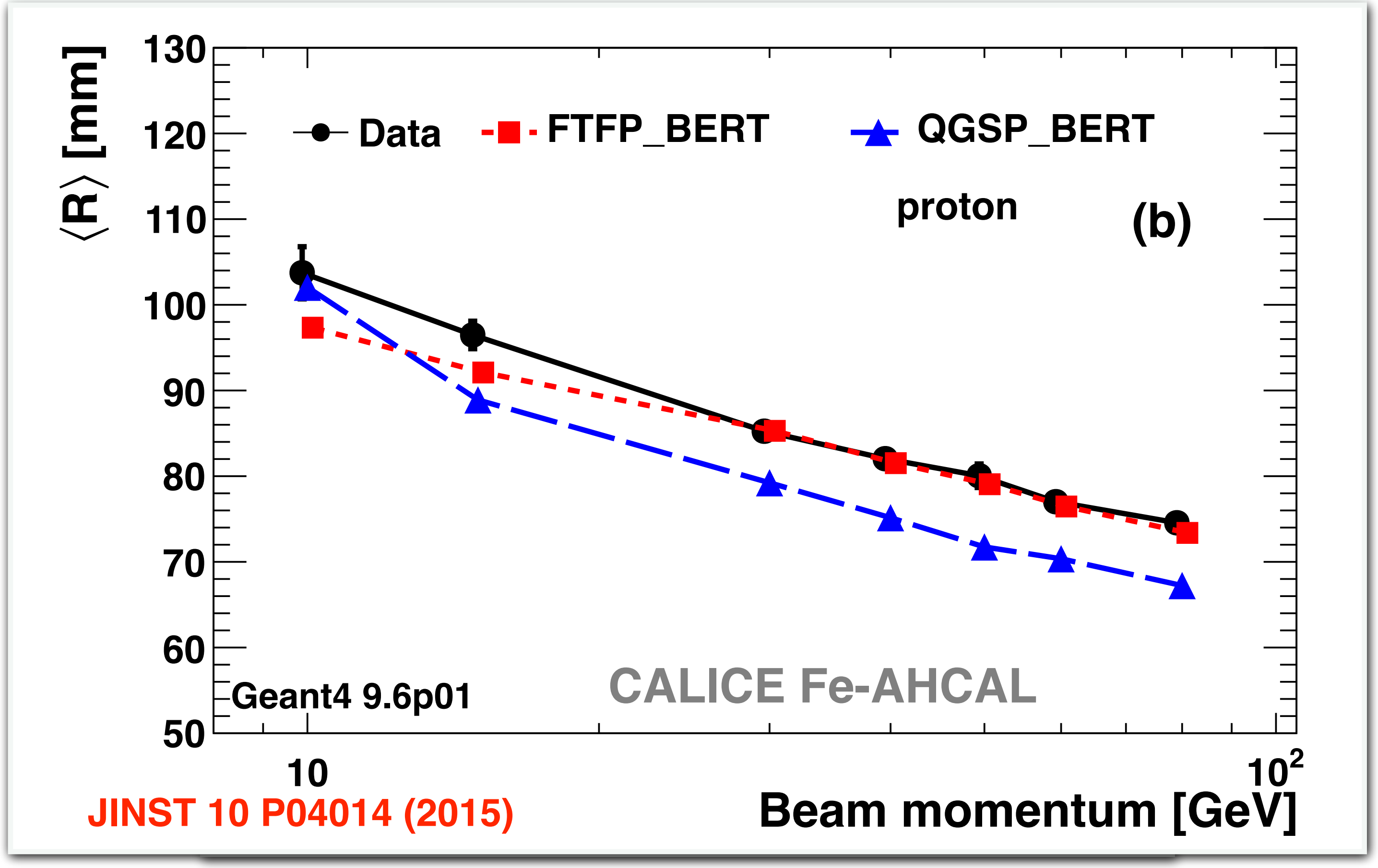
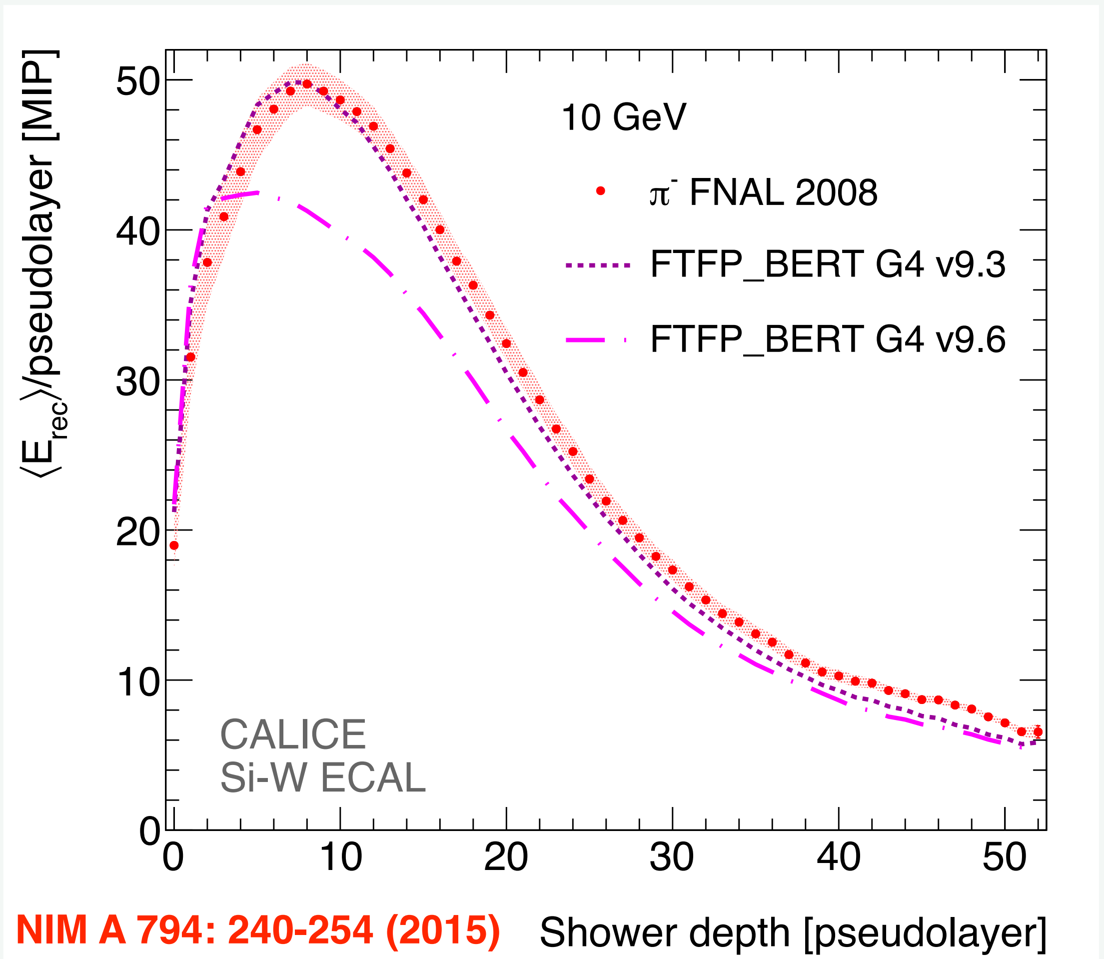


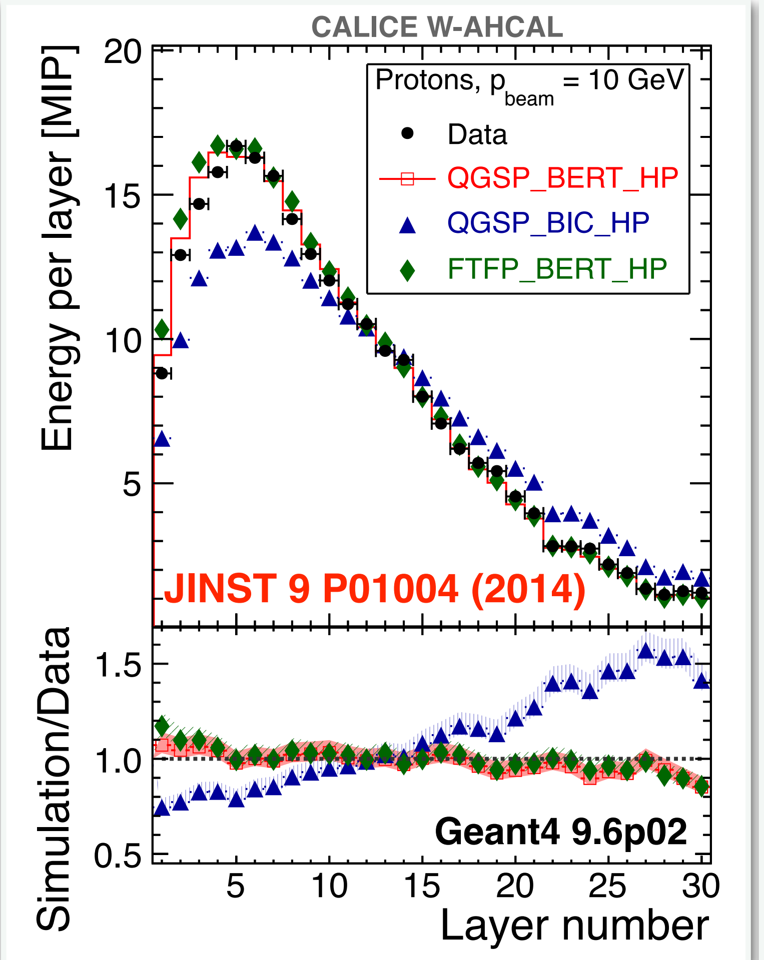


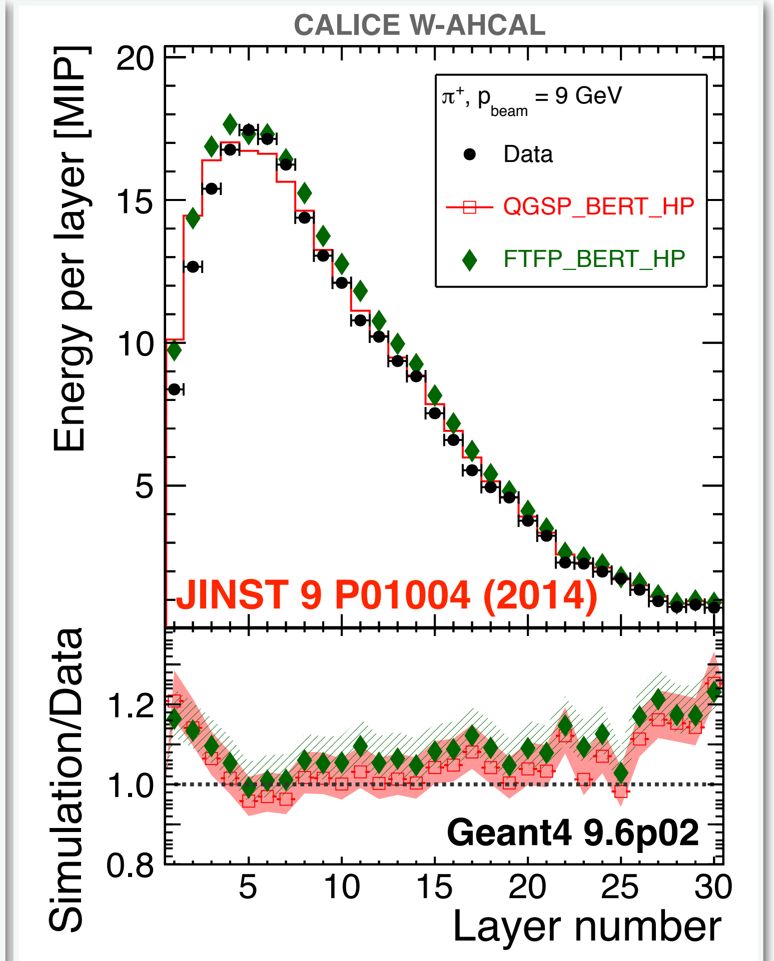
Longitudinal distributions

- Longitudinal shower distributions for pions at low energy (Si-W ECAL) and for pions and protons in the W-AHCAL
- The profile is measured from the start of the shower to take out smearing from the exponential distribution of the first interaction
- The accuracy of MC predictions varies with the physics list and version of Geant4
- The overall level of agreement is 10% - 20%
- The longitudinal centre of gravity (Z0) for pions and protons (Fe-AHCAL) is best modelled by FTFP_BERT, to better than 2% for pions and 3% for protons above 15 GeV

$$Z0 = \frac{\sum e_i z_i}{\sum e_i}$$







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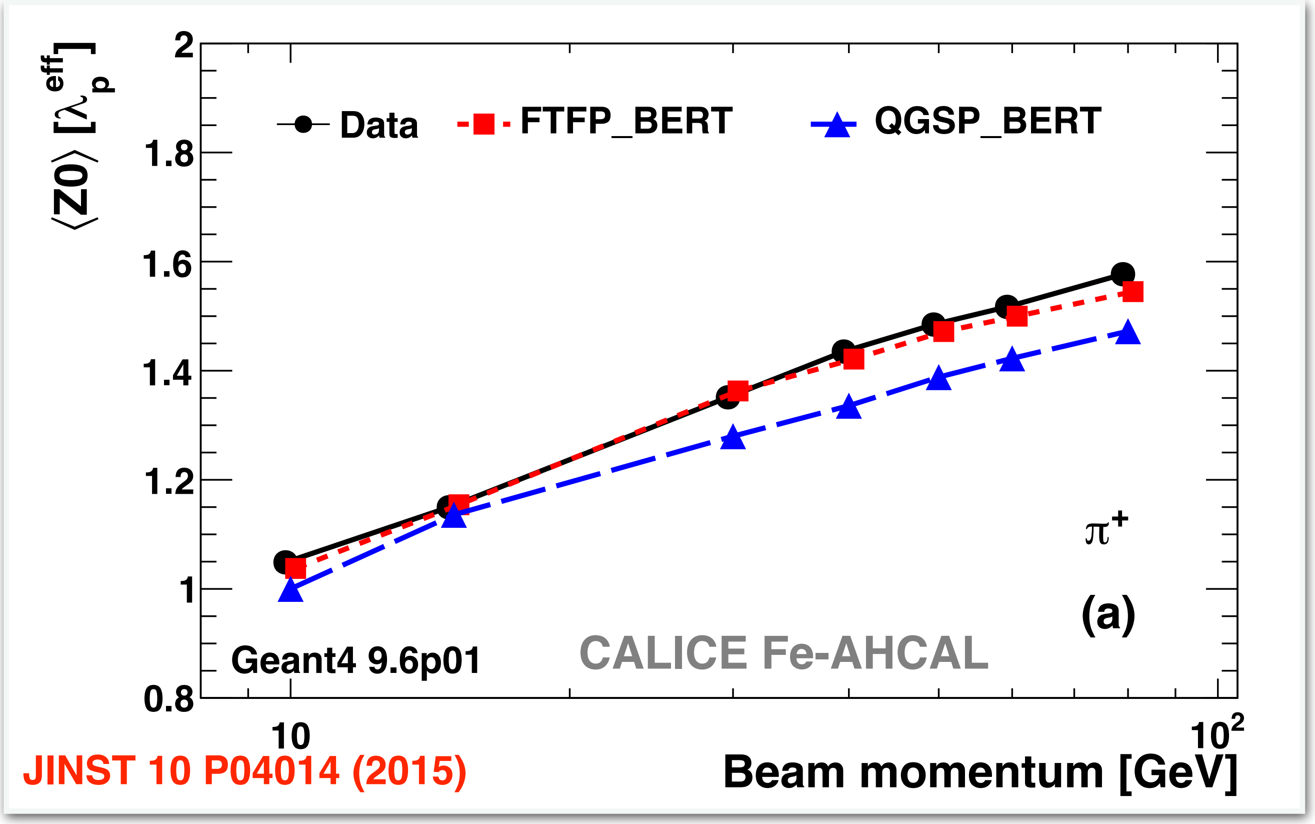
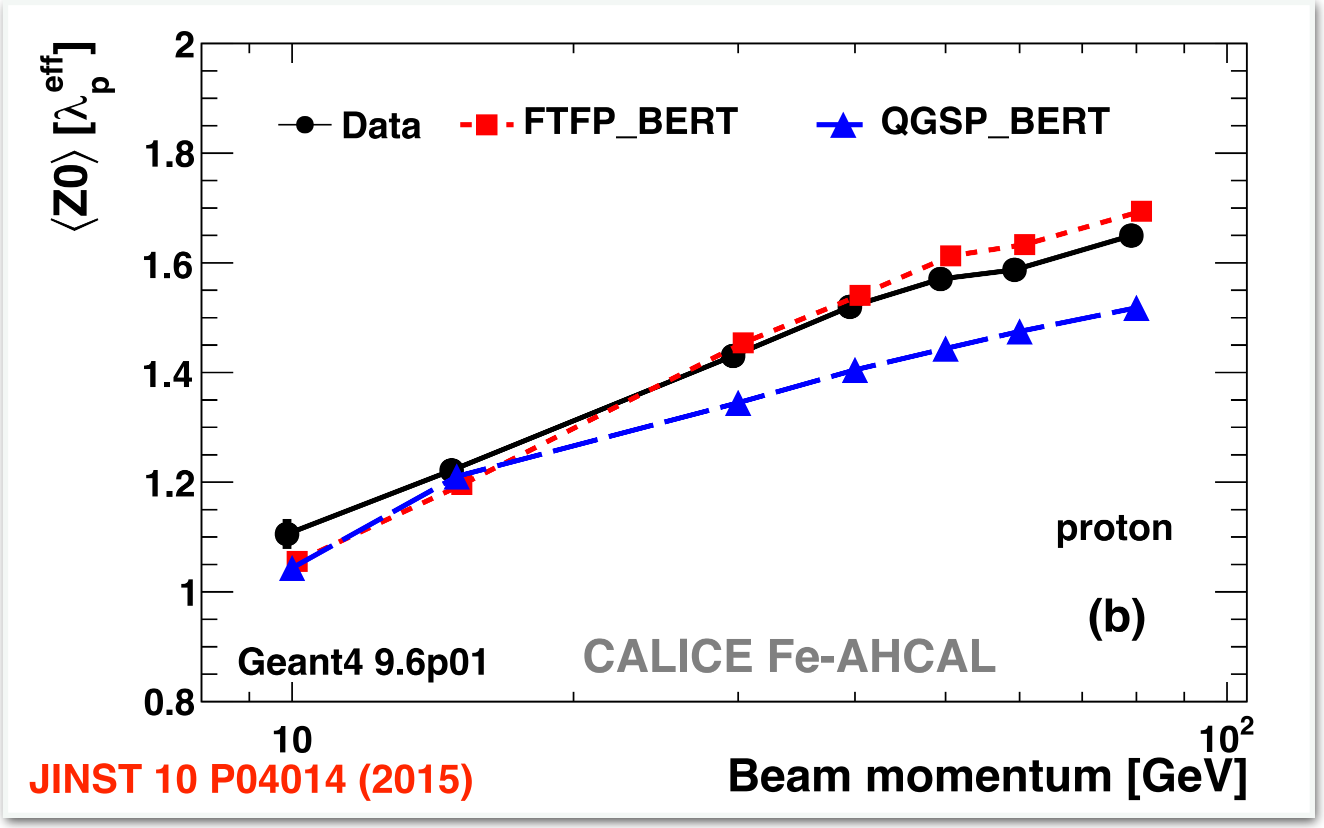
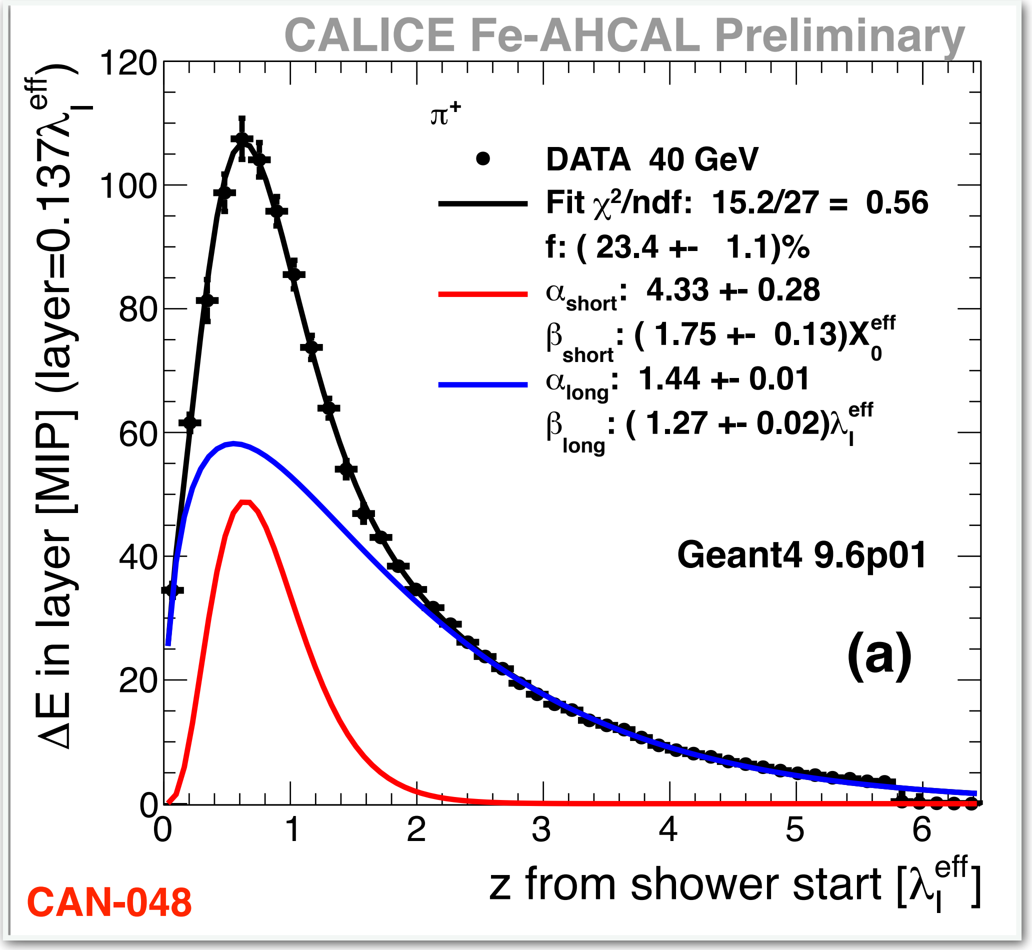
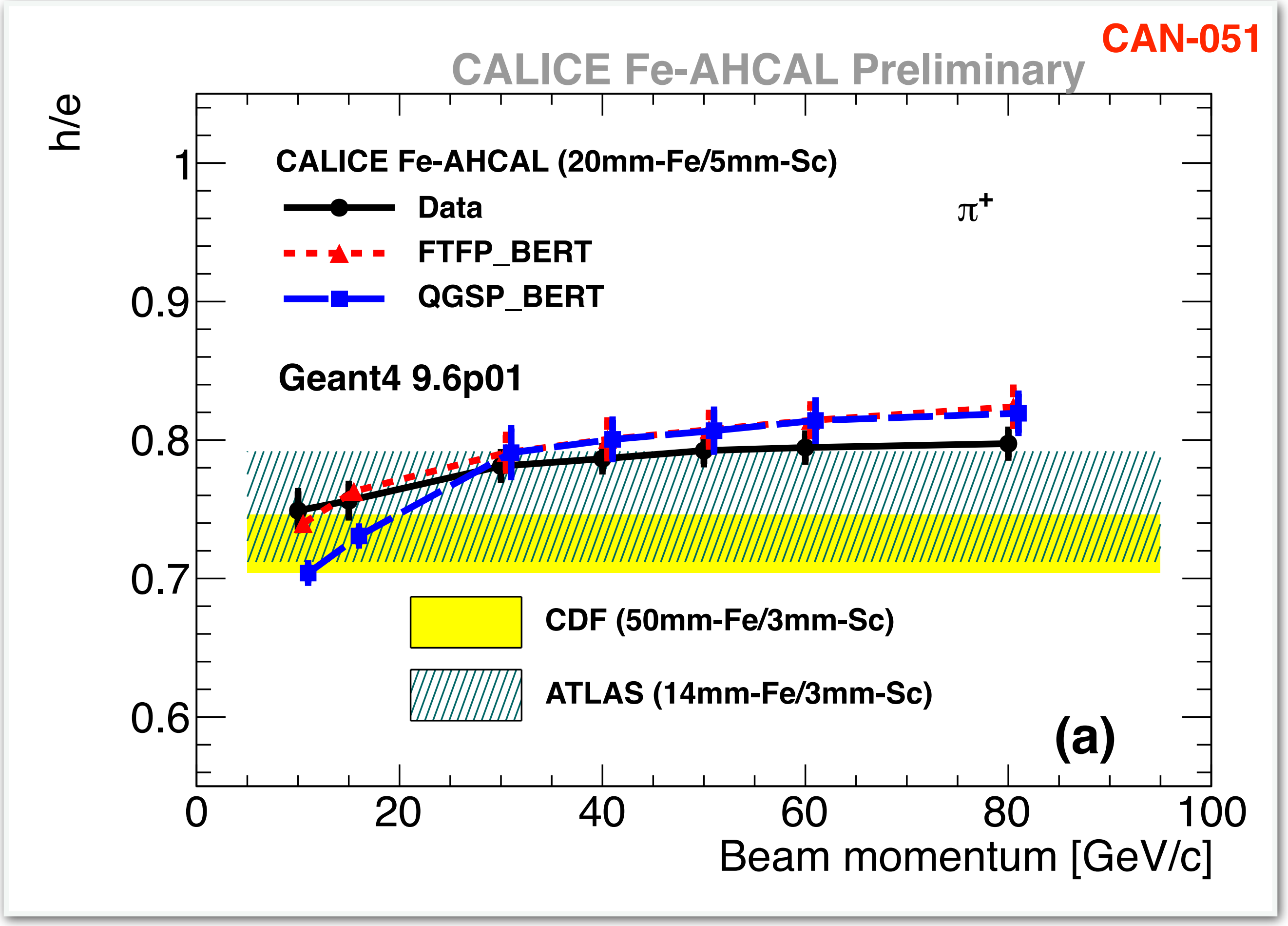




H/E RATIO

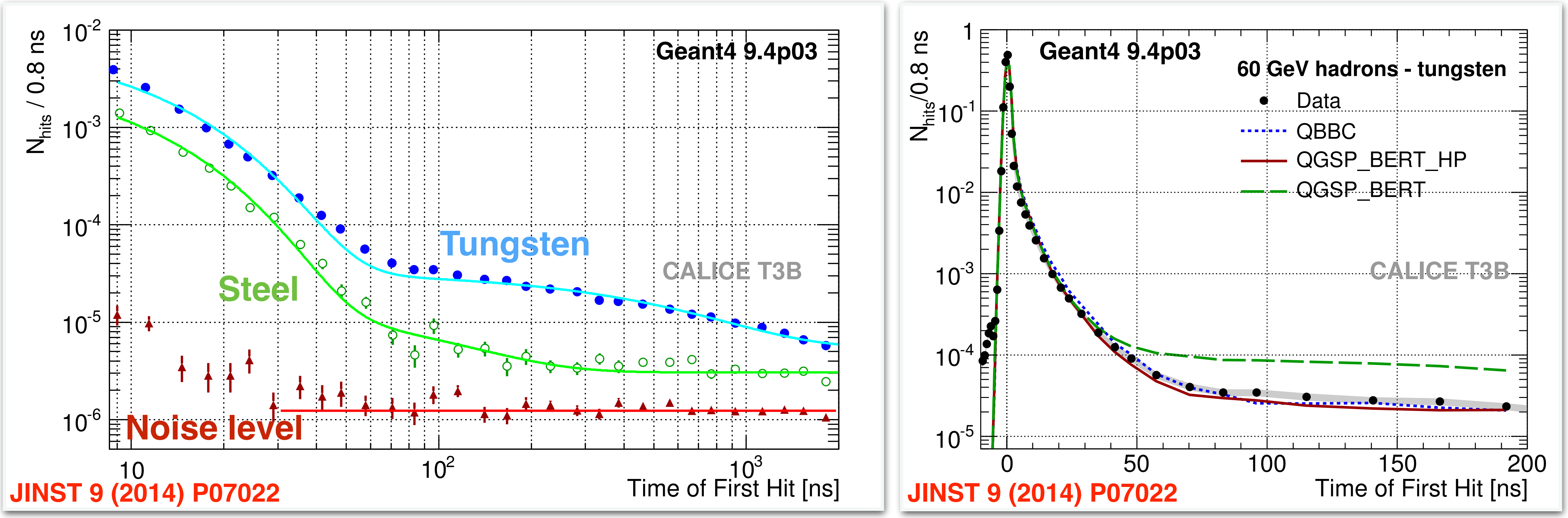
- Hadron showers can be parametrised with a two component function;
  - a *short* component, closely related to X_0; the electromagnetic content of the shower
  - a *long* component, closely related to λ_I; the pure hadronic content of the shower
- Ratio of the response to the hadronic and electromagnetic component, h/e, can be estimated from fitting with this function (Fe-AHCAL).





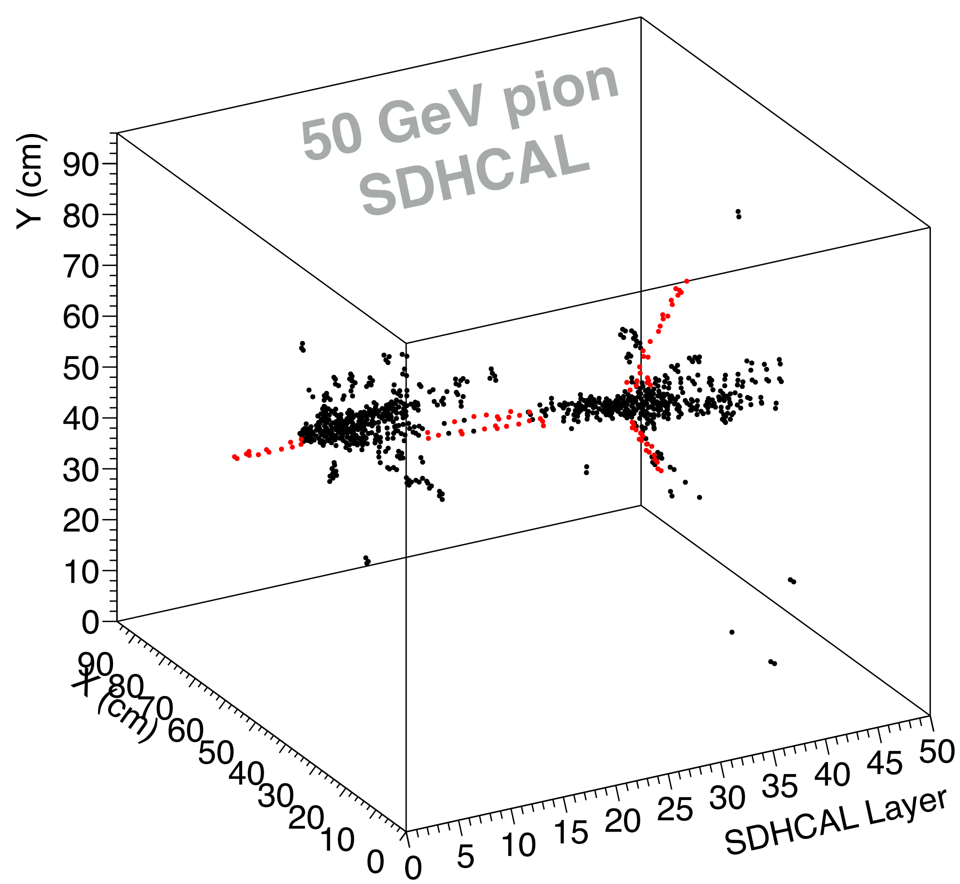
Time structure of showers

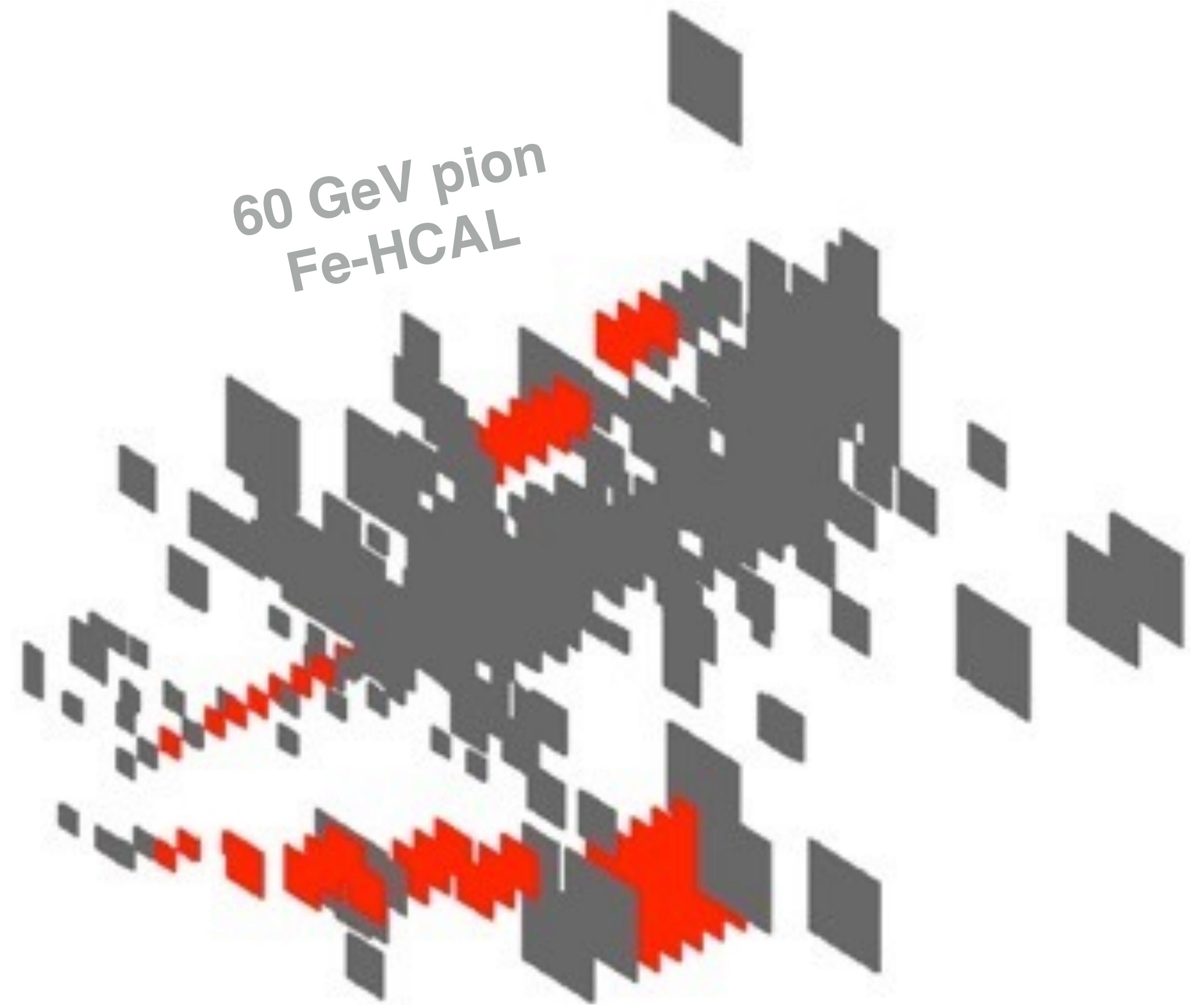
- Tungsten Timing Test beam (T3B) operated together with the W-AHCAL (Tungsten absorber) and SDHCAL (steel absorber)
- Strip of 15 scintillator tiles and SiPM readout
- Record arrival times of signal; time of first hit
- Hadron showers show delayed components due to neutron induced processes; more in tungsten than in steel
- Monte Carlo models reproduce measurements in steel well, but need a dedicated treatment for low energy neutrons for Tungsten (QGSP_BERT_HP, QBBC)



Tracks in hadron showers

- Hadronic showers are tree-like structures with MIP-like hadrons connecting regions of denser activity
- Reconstruct MIP like tracks within the hadron shower
- Pions (10 - 80 GeV) in the SDHCAL and Fe-AHCAL
- Best agreement in the number of reconstructed tracks between data and QGSP_BERT for the Fe-AHCAL and QGSP_BERT_HP for the SDHCAL
- This high level of detail in shower modelling aids particle separation in PFA (shown in talk by V. Balagura)





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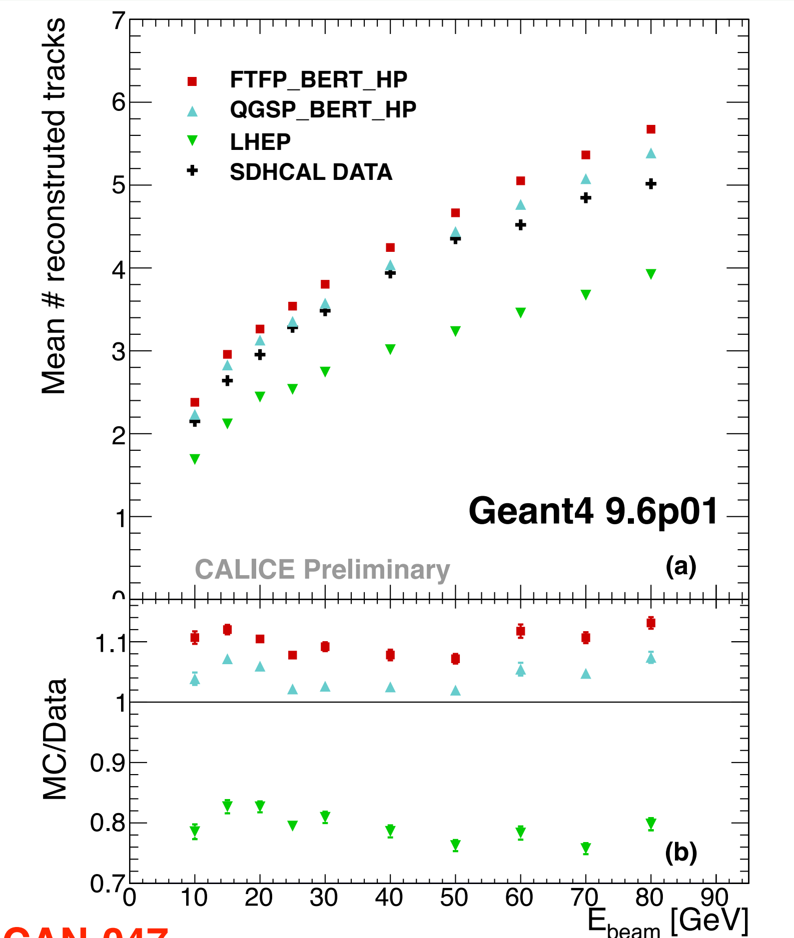

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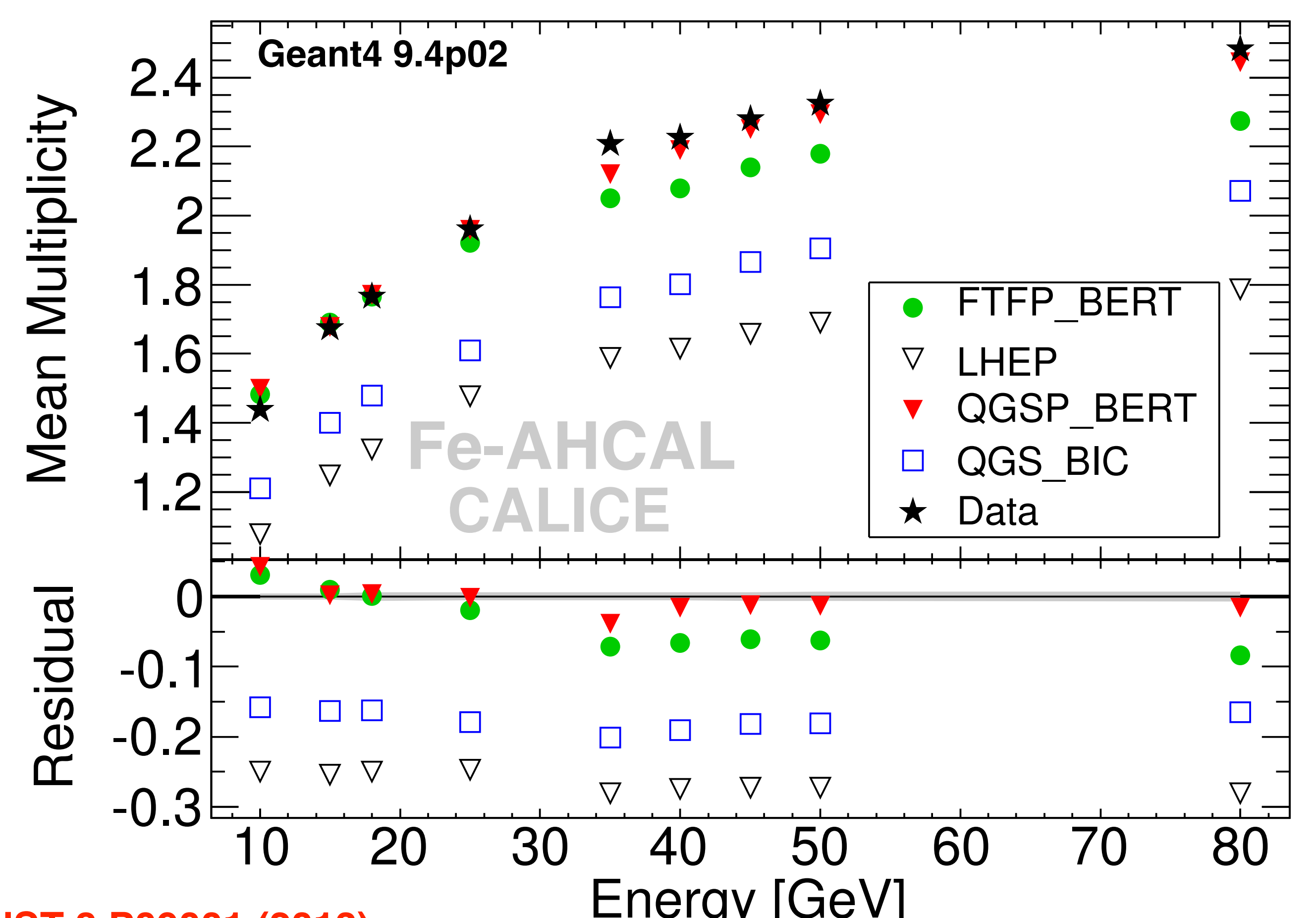

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Summary and Conclusions

- Test beam experiments with CALICE ECAL and HCAL prototypes
  - Test of novel technologies in large scale calorimeters
  - Characterize prototype performance
  - **Detailed measurements of hadronic showers**

- Comparison to data helps to improve hadronic interaction models
  - Geant4 models reproduce hadronic data within 5 - 20 %
  - Level of agreement depends on the model and version of Geant4
  - Generally QGSP_BERT and FTFP_BERT describe the test beam data best
  - High precision neutron tracking needed for tungsten simulation (HCAL)
  - These detailed results support the theory driven approach of modern shower simulations
- More detailed studies to come…

Backup

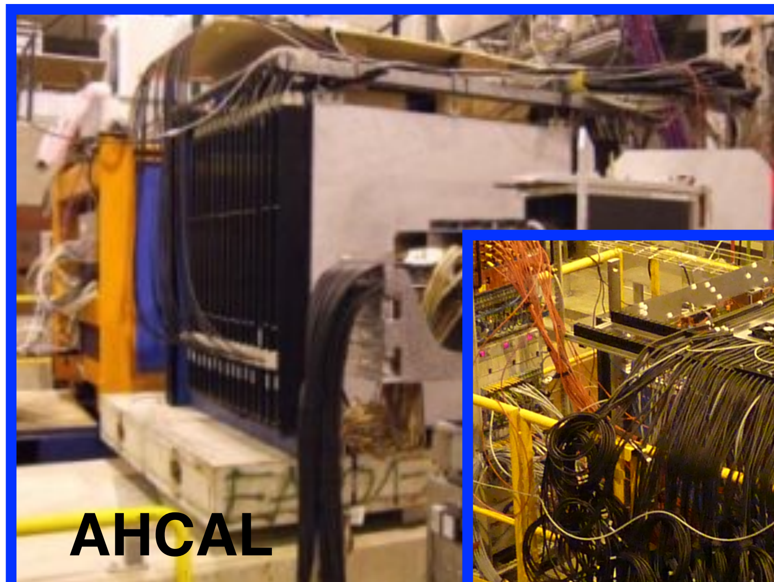
CALICE COLLABORATION

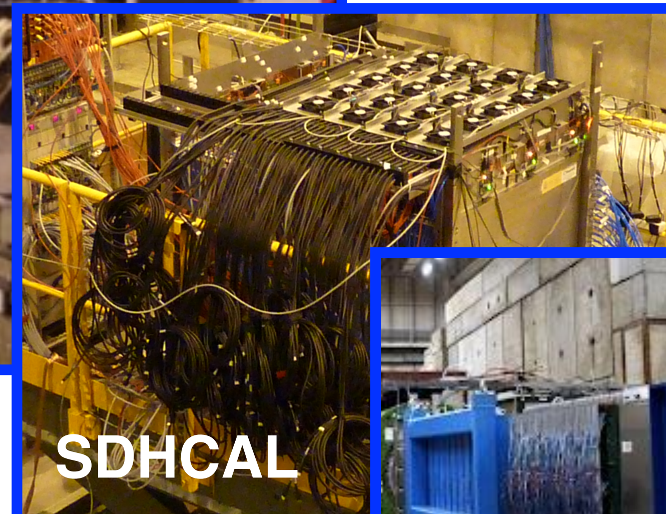
- **CA**lorimetry for **LI**near **C**ollider **E**xperiments
- International R&D collaboration ~330 members
- Development of imaging calorimeters for experiments at high-energy electron-positron colliders
  - Build and test calorimeter prototypes
  - Demonstrate that the required performance of the calorimeter system can be achieved
  - Compare test beam results to MC predictions and assist in improving simulation models

CALICE PROTOTYPES

- **Si-W ECAL**
  Silicon pixels
  10x10x0.5 mm3
  Tungsten absorber
- **Sc ECAL**
  scintillator strips with SiPM readout
  45x5x3 mm3
  Tungsten absorber

- **Analogue HCAL**
  scintillator tiles with SiPM readout
  30x30x5 mm3
  Steel or tungsten absorber
- **Semi-digital HCAL**
  GRPCs (microMegas)
  10x10x1.2 mm3
  Steel absorber
- **Digital HCAL**
  RPCs (GEMs)
  10x10x1.15 mm3
  Steel or tungsten absorber





Highly granular calorimeters

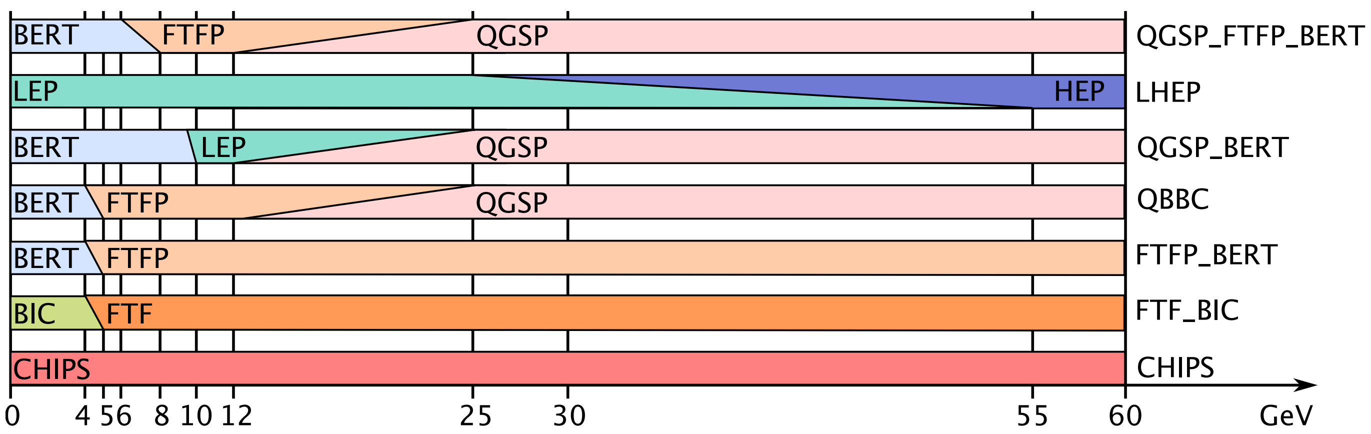
- The ideal event reconstruction is possible with **particle flow** algorithms
- Particle flow combines tracking and calorimetry information to reconstruct the 4-vector of each individual final-state particle
- Use the information from the best sub detector for each particle type
  - *Charged particles* -> tracker
  - *photons* -> ECAL
  - *neutral hadrons* -> HCAL
- Requires highly granular calorimeters to separate the energy deposition from close by particles
- Jet energy resolution goal 5 - 3.5% for 50 GeV - 1TeV jets
- Limited by confusion; wrongly assigned energy deposits

Detector simulations

- Geant4 detector simulation
  - Full test beam setup including beam instrumentation
  - Particle generation using particle gun
  - Beam position, direction and spread corresponding to the data runs
- Digitization
  - Realistic detector granularity
  - Detector effects, e.g. optical cross talk between neighbouring scintillator tiles for the AHCAL
  - Birk's law for scintillators (AHCAL)
  - Simulated readout electronics; signal shaping time, noise
  - Saturation effects

Geant4 Physics Lists

- Physics lists combine several hadronic models in specific energy ranges
- At higher energies theory-driven models are available (FTF, QGS) while for lower energies more approximate models are used (BERT, BIC)
- A number of reference physics lists are available in Geant4 with different tradeoffs between physics precision and speed
- Physics lists can use different models for different hadrons, the model used for pions dominates because the majority of secondary particles in a hadronic shower are pions



- **BERT** - Bertini cascade model
- **BIC** - Binary cascade model
- **FTF(P)** - Fritiof string model
- **QGS(P)** - Quark gluon string model
- **LEP/HEP** - Low/High energy parametrised (based on fits to data, *discontinued, replaced by BERT, FTF, QCD*)
- **CHIPS** - Chiral invariant phase space (*discontinued, replaced by BERT, FTF*)

Studied observables

- **Interaction length**: The probability P_I of having an inelastic hadron-nucleus interaction before a distance x: $$P_I = 1 - e^{-x/\lambda_\pi}$$
- **Z0**: The longitudinal centre of gravity is defined as the energy weighted mean of the hit longitudinal coordinate along the shower axis: $$Z0 = \frac{\sum e_i z_i}{\sum e_i}$$
- **r**: radial distance: $r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$
- **x0, y0**: energy weighted shower centre: $x_0 = \frac{\sum e_i x_i}{\sum e_i}$ $y_0 = \frac{\sum e_i y_i}{\sum e_i}$
- **R**: shower radius: $R = \frac{\sum e_i r_i}{\sum e_i}$