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Geant4 studies in the context of Dual Readout Calorimetry simulations

Talk Outline

- Total absorption calorimetry and dual readout concept
- Detector geometries and compositions used
- Results and comparisons among various detector materials and physics lists used

Total Absorption and Dual Readout calorimetry concepts

- Total absorption calorimeter is defined here as a calorimeter which consist of homogenous and fully active medium to avoid/minimize problems inherent to inhomogeneous sampling calorimeters:
  - Sampling fluctuations - fluctuation of the energy deposit ratio in passive and active materials
  - Sampling fraction dependence on the particle type and momentum
  - Different Electro-Magnetic and Hadronic sections with usually different response characteristics
- Dual Readout means: collecting both energy deposited as scintillations (S) and Cerenkov light (C)

Simulation framework, detector parameters, assumptions

- Work done within SLIC framework, optical calorimeter option, using Geant4 versions 4.9.1,2
- Optical properties characterized by the refractive index n (relevant for Cherenkov radiation)
- Scintillation (S) == total ionization energy deposited. No Scintillation efficiency, light collection, Birks suppression
- Cherenkov (C) == total amount of energy radiated as Cherenkov radiation; No directionality, collection efficiency, fluctuations, Scintillation/Cherenkov separation
  - Total information about an event is usually reduced to two variables : S and C
- Scintillation and Cherenkov signals were calibrated using electron beam, so that S=C=Ebeam (for electrons)
- Beam energy is defined as the kinetic energy; the total beam energy which can deposited in the calorimeter is by .139 GeV (m_π) higher for pions . In the following we will be comparing the observed signals with the total energy which can be deposited in the calorimeter as defined above
- Still early stages of the analysis of the dual readout concept

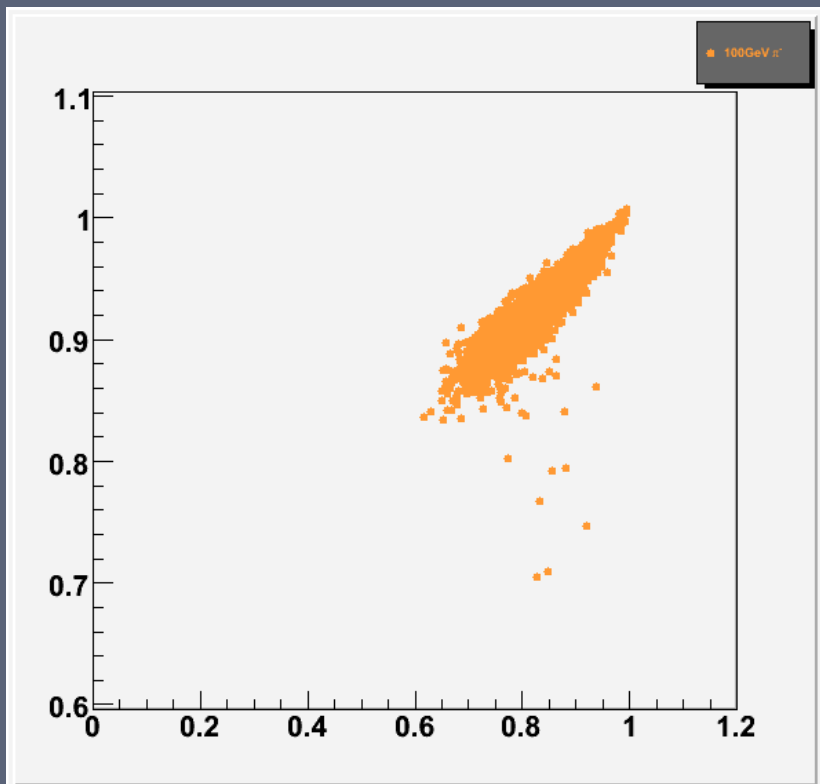
Detectors Simulated

- Very large rectangular "Test Beam/Optical" hypothetical calorimeter:
  - 3 x 3 x 3 m^3, segmented into 1 x 1 x 1 cm^3 "sub-modules", particles deposited 0.5 m inside the calorimeter (~no backscattering outside detector); density = 8 g/cm^3; "built" with different materials to explore impact of various parameters: dE/dx, radiation length, interaction length, nuclear effects…
  - H , n=1.65 (no nuclear effects)
  - Fe56, n=1.65 (tightest bound nucleus)
  - BGO, n=2.21 (perhaps a typical crystal material)
- SiD02 geometry detector, BGO crystals, n=1.65, D= 7.13 g/cm^3

Dual Readout Correction – the idea

Example distribution for 100 GeV pions,
QGSP-BERT physics list, Fe56, d=8.0 g/cm^3, n=1.65

Scintillation/Beam Energy
= fraction of energy detected



Cherenkov/Scintillation Energy

- The idea is to use the observed Cherenkov/Scintillation energy ratio to correct every event to the beam energy (B)

- Cherenkov & Scintillation response is scaled using calibration factors determined using electron distributions

(The resulting resolution is a function of the local width of the scatter plot)

Dual Readout Correction for 100GeV pions

QGSP_BERT physics list, Fe56, d=8.0 g/cm^3, n=1.65

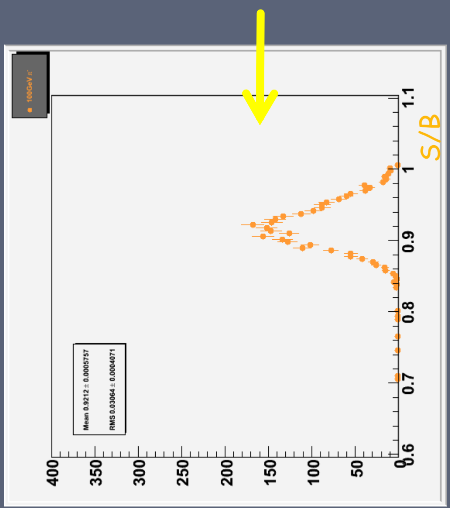
- 100 GeV π^-
- Raw (uncorrected) Scintillation/Beam Energy
- $\Delta E/E \sim 3.3\%$
- significant non-linearity, E~ 92 GeV

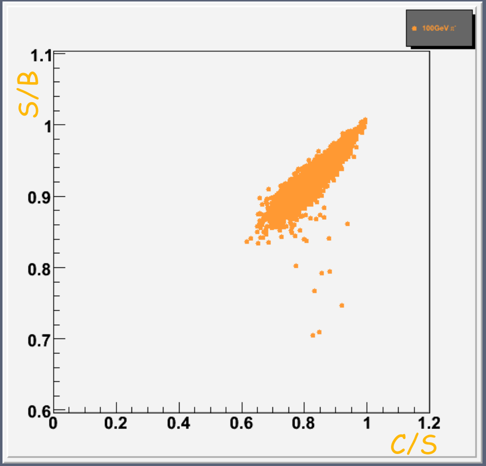
After dual readout correction, with the correction function (C/S) determined at the appropriate energy (here 100GeV):

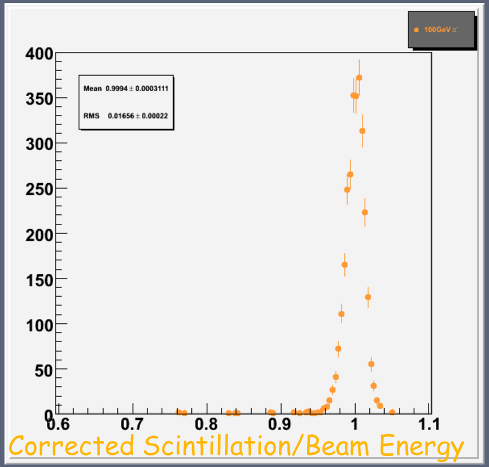
$\Delta E/E \sim 1.7\%$

Scintillation/Beam Energy ~1

Significant improvement in energy resolution and correctness of the energy response



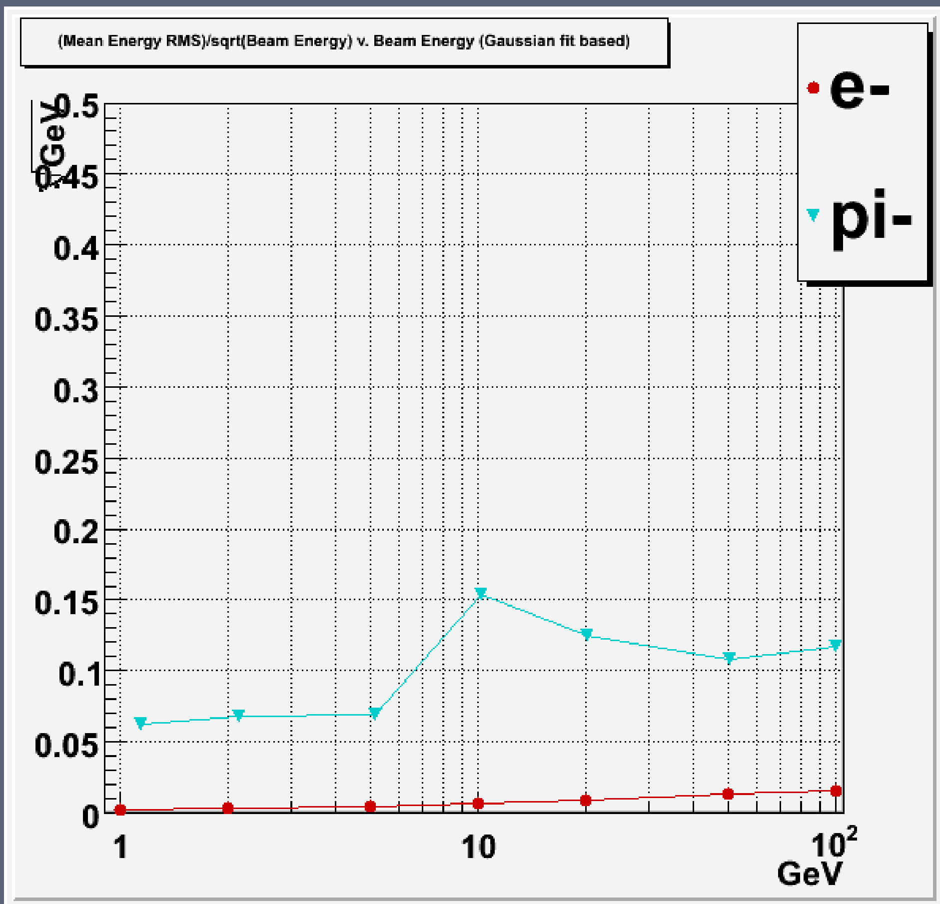




Dual Readout Calorimeter performance as a function of beam energy

$\Delta E/\sqrt{E}$ vs. E

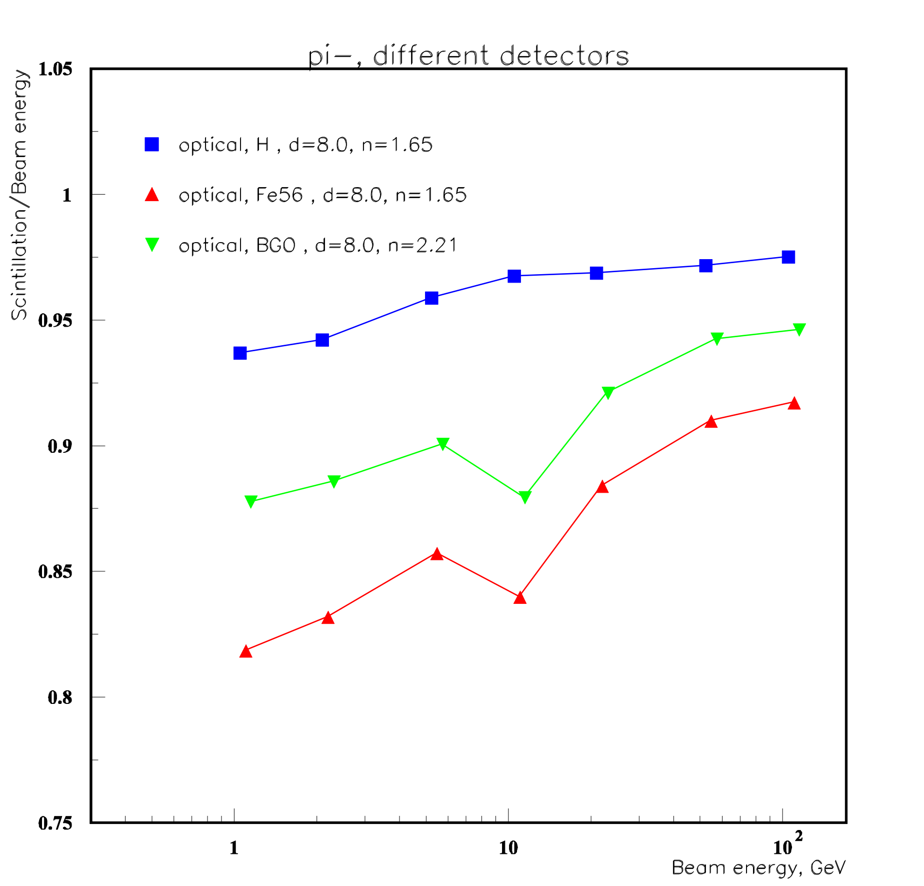
QGSP-BERT physics list, Fe56, d=8.0 g/cm^3, n=1.65



- Dual correction done using global (not energy specific) correction function
- pion energy resolution scales like $\Delta E/E =\sim \alpha/\sqrt{E}$ with $\alpha =\sim 0.07-0.15$
- Note a surprising degradation of the energy resolution in the energy range in vicinity of 10GeV

Pions: Overall Response

1,2,5,10,20,50 GeV pions, QGSP-BERT physics list, d=8.0 g/cm³, H,Fe56,BGO



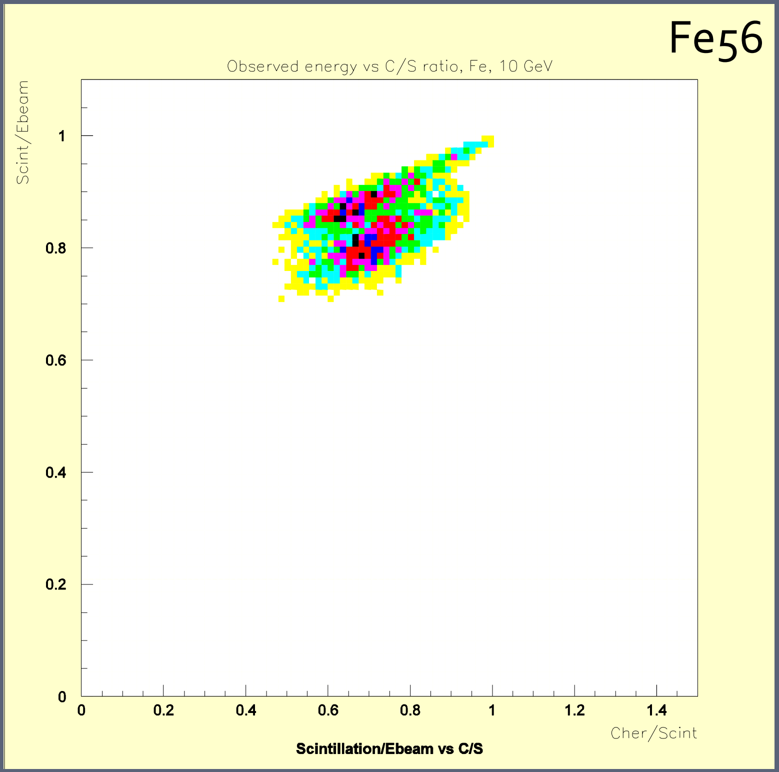
- Note the significant dip in the response around ~10 GeV beam in case of heavy nuclear targets (not Hydrogen) - Why?

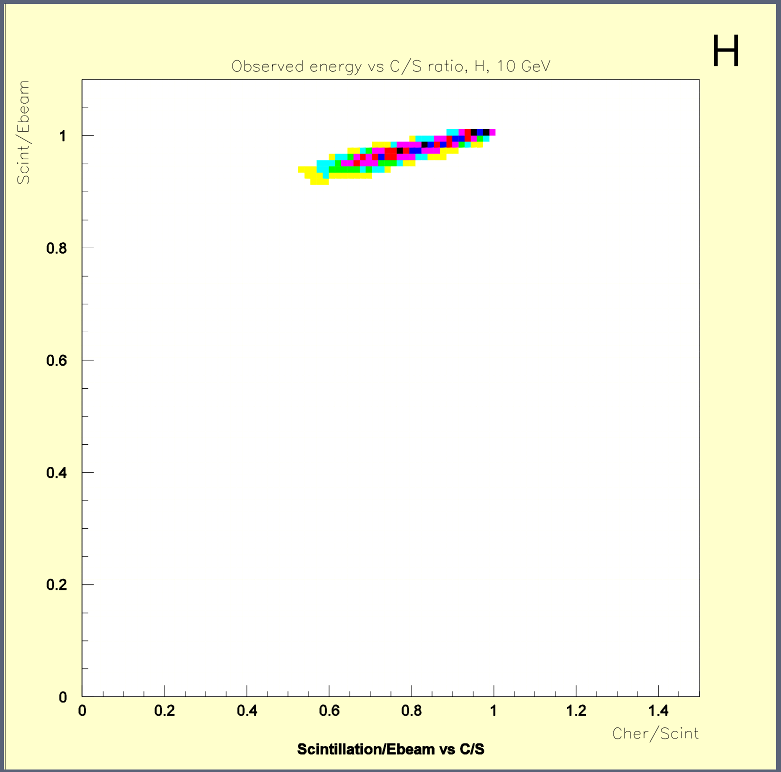
Closer look at the dual readout distributions for 10 GeV pions in case of Fe56 & H detectors

Scintillation/Beam Energy vs. Cherenkov/Scintillation Energy

QGSP-BERT physics list, Fe56 & H d=8.0 g/cm^3, n=1.65; 10 GeV pions

Note the two peaks in the Scintillation/Beam Energy distribution in case of Fe56 (but not H)

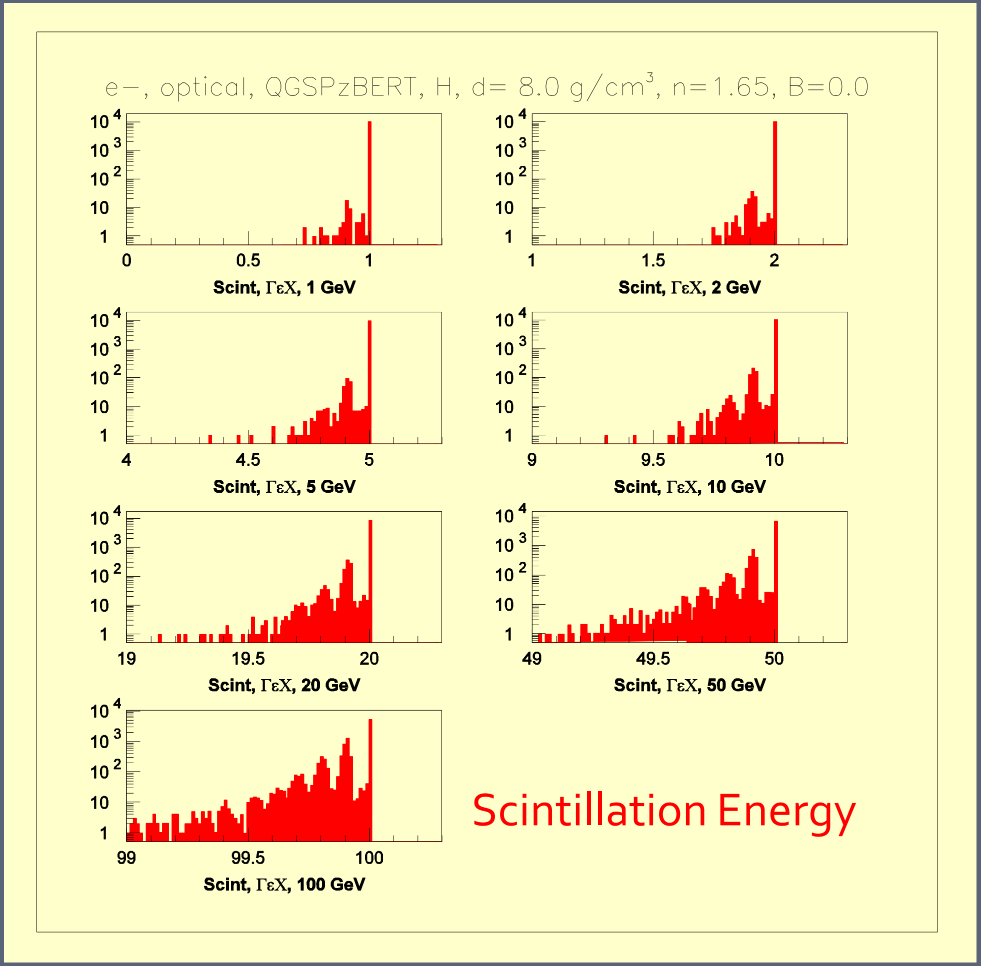




Calorimeter response for various combinations of beams and targets - occasional "excess energy" aspect in case of BGO targets

Electrons on Hydrogen: Deposited Energy Distributions

1,2,5,10,20,50 GeV electrons, QGSP-BERT physics list, H, d=8.0 g/cm^3, n=1.65

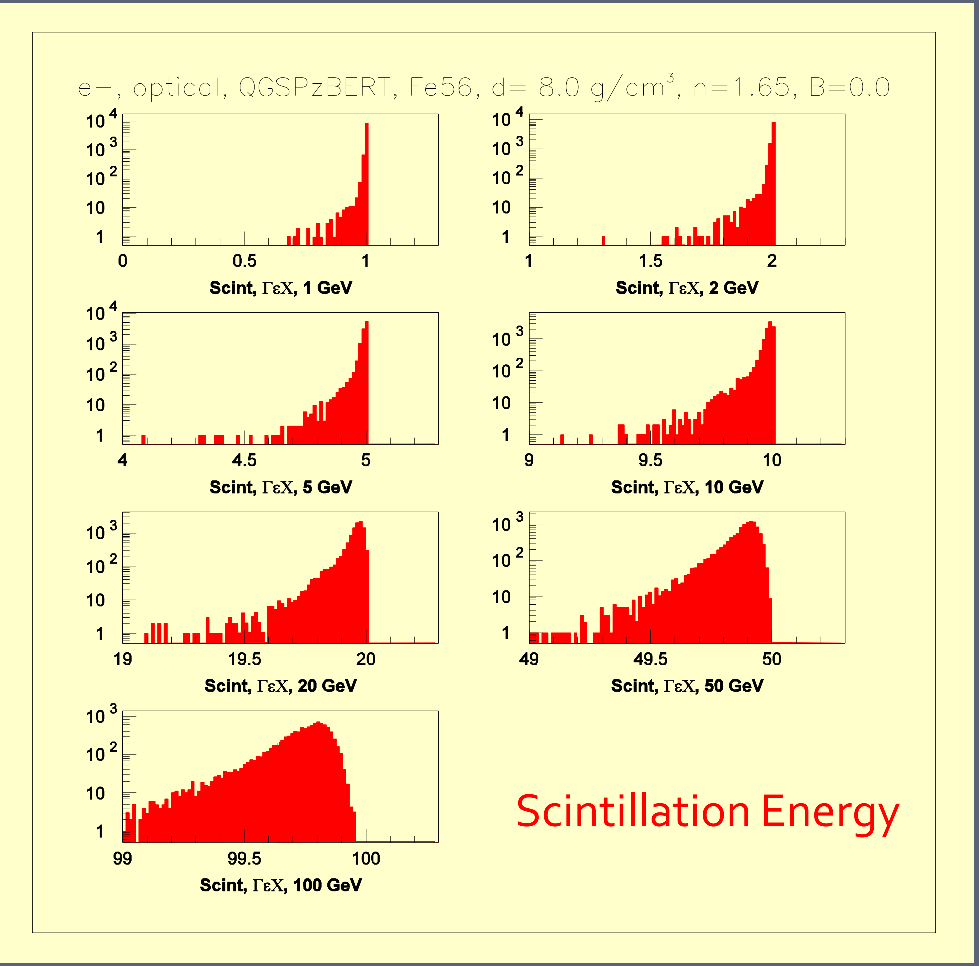


- Scintillation Energy is never bigger than the beam energy

- But sometimes it is smaller, and it shows distinct peaks
- Is it one, two, three etc... pion production in deep inelastic e-H scattering? neutrinos carry away ~ 100 MeV per decaying pion

Electrons on Iron: Deposited Energy Distributions

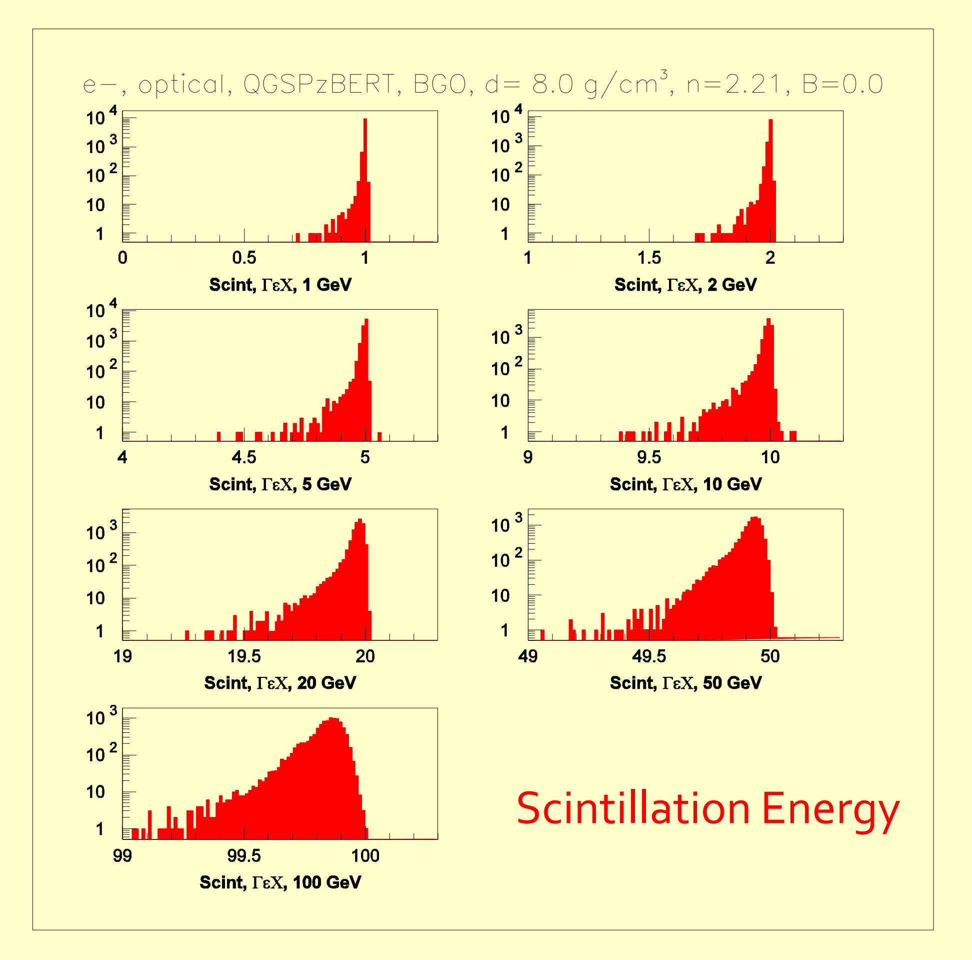
1,2,5,10,20,50 GeV electrons, QGSP-BERT physics list, Fe56, d=8.0 g/cm^3, n=1.65



- Energy is never bigger than the beam energy
- Energy loss in nuclei smear the pions production peaks seen in hydrogen?

Electrons on BGO: Deposited Energy Distributions

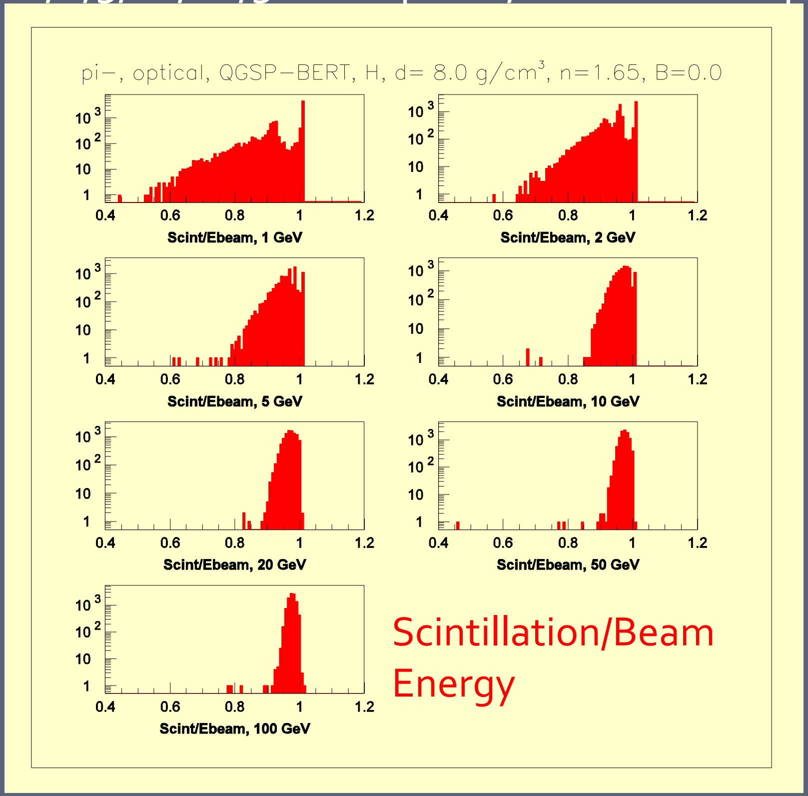
1,2,5,10,20,50 GeV electrons, QGSP-BERT physics list, BGO, d=8.0 g/cm^3, n=1.65

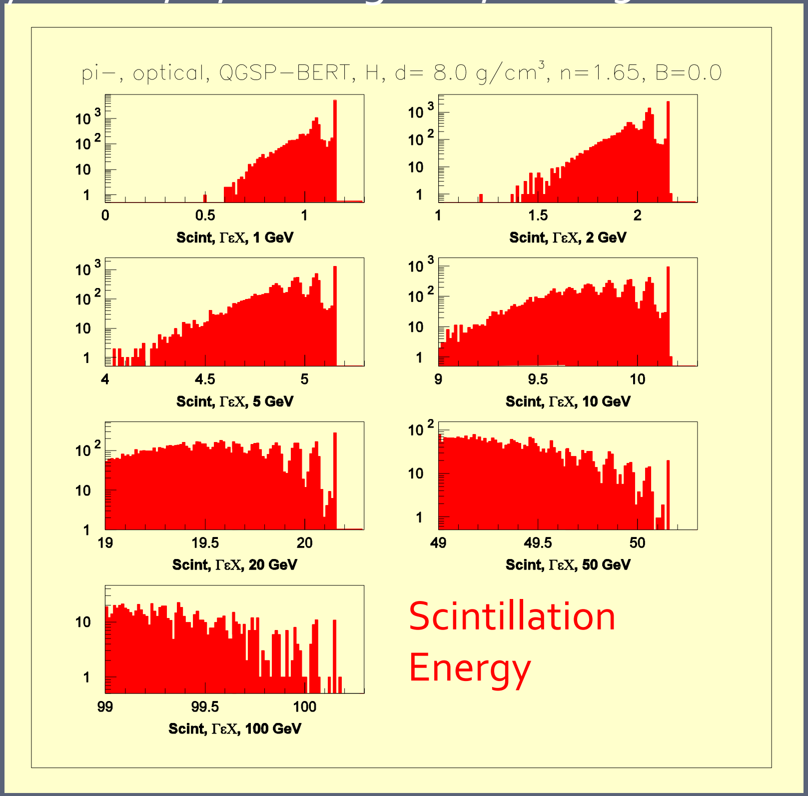


- BGO is similar to the Iron case
- However occasional examples of energy deposited exceeding the beam energy – Why? Is it Fission?
- The tails to the left (nuclear binding energy related loss?) slightly smaller (energy losses smaller) than in the Fe case (binding energy difference?)

Pions on Hydrogen: Deposited Energy Distributions

1,2,5,10,20,50 GeV pions, QGSP-BERT physics list, H, d=8.0 g/cm^3, n=1.65

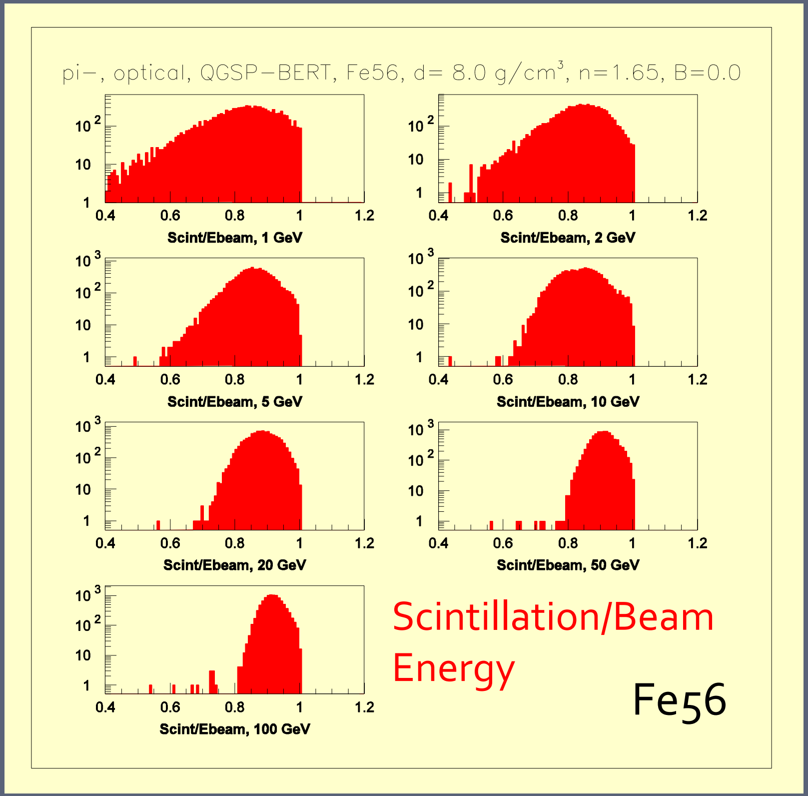


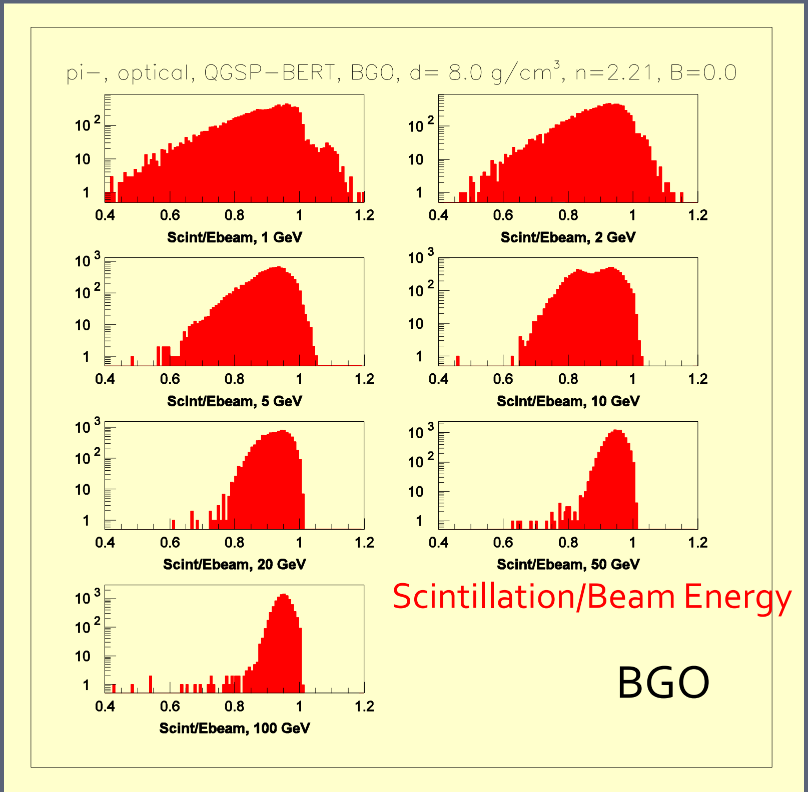


- No energy greater than beam energy ($E_{kinetic}+m_{\pi}$)
- Observed energy deficit and its fluctuations consistent with possible fluctuations of multiplicity of charged particles production

Pions on Iron and BGO: Deposited Energy Distributions

1,2,5,10,20,50 GeV pions, QGSP-BERT physics list, Fe56, BGO, d=8.0 g/cm^3, n=1.65





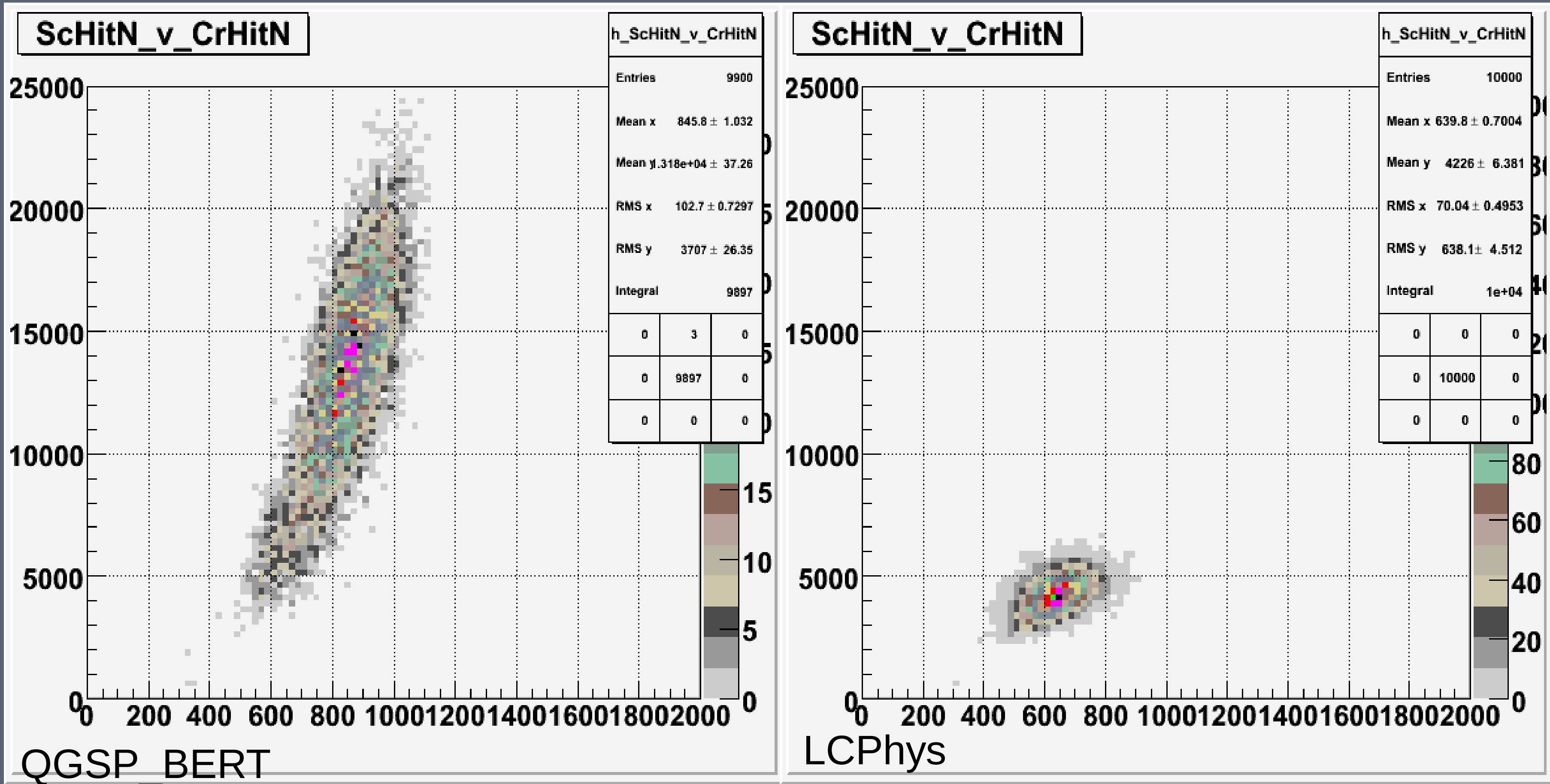
- Nuclear binding energy related losses smaller (higher response) in BGO vs. Iron
- No observed energy greater than beam energy ($E_{kinetic}+m_{\pi}$) for Iron
- Occasional 'surplus' energy in BGO - Why? Fission?

Calorimeter response for various physics lists

- Next three transparencies show comparison between QGSP_BERT and LCPhys physics lists for Fe56, d=8.0 g/cm^3, n=1.65, here the energy information is not summed up per event, but rather the energy (scaled) from 1cm^3 cubes ("hits") is plotted

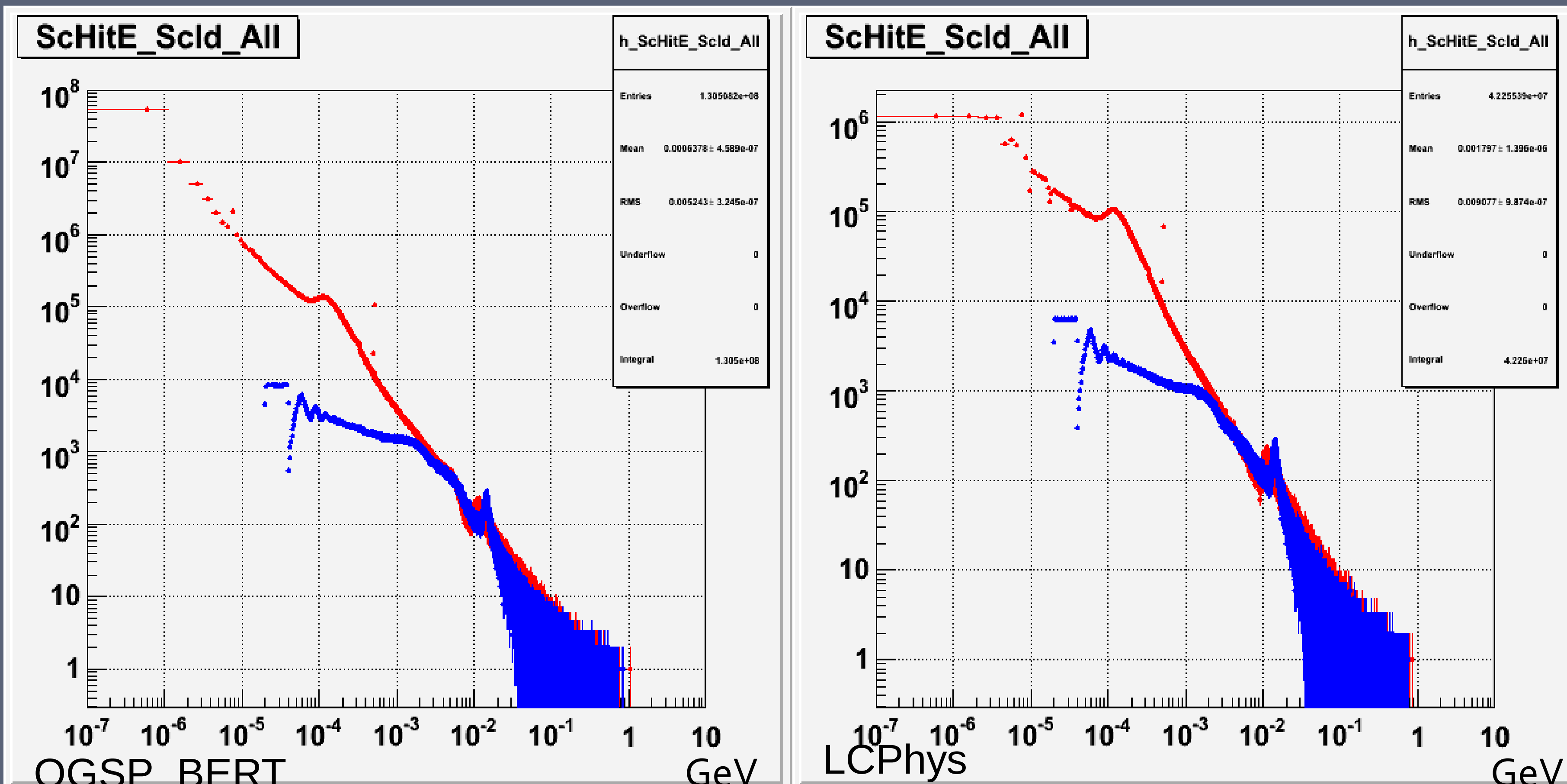
QGSP_BERT vs. LCPhys physics lists
Number of Scintillation vs. Cherenkov hits

One entry per event; Note the lower number of Scintillation (~3) hits and Cherenkov (~0.3) hits in LCPhys type simulation



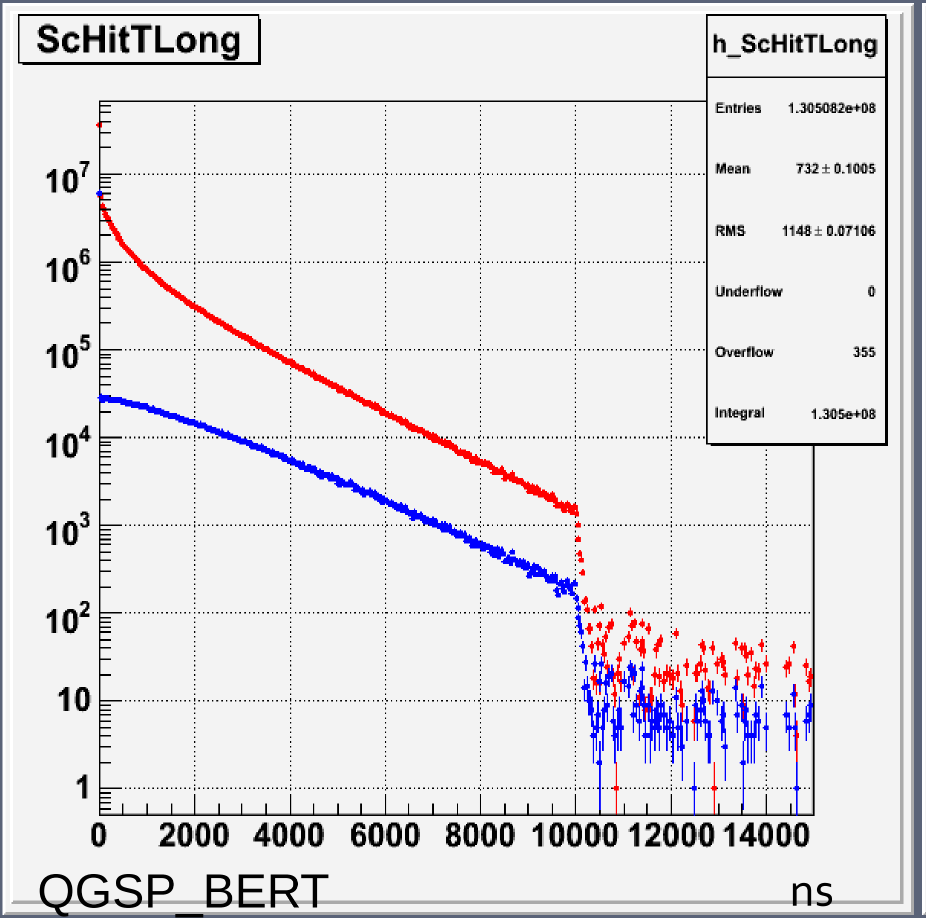
QGSP_BERT vs. LCPhys physics lists Scintillation and Cherenkov hit energy distributions

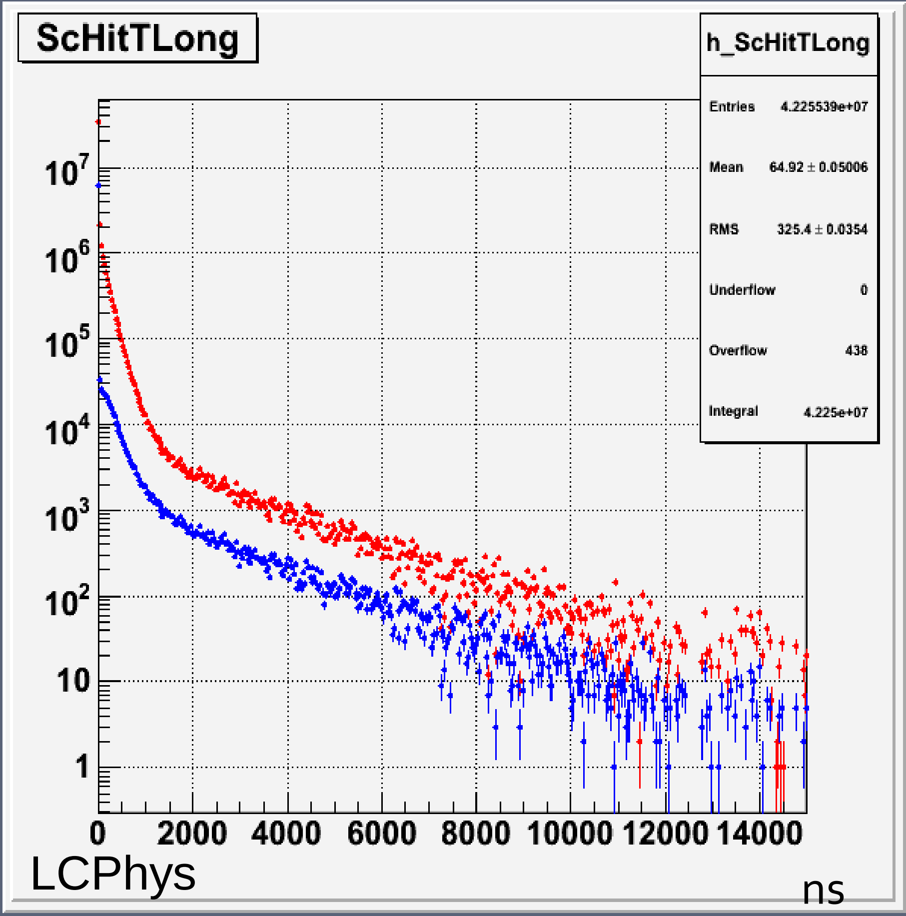
Scintillation (red) and Cherenkov (blue) hit energy distributions; Note the much lower number of low energy scintillation hits in LCPhys type simulation



QGSP_BERT vs. LCPhys physics lists
Scintillation and Cherenkov hit timing distributions

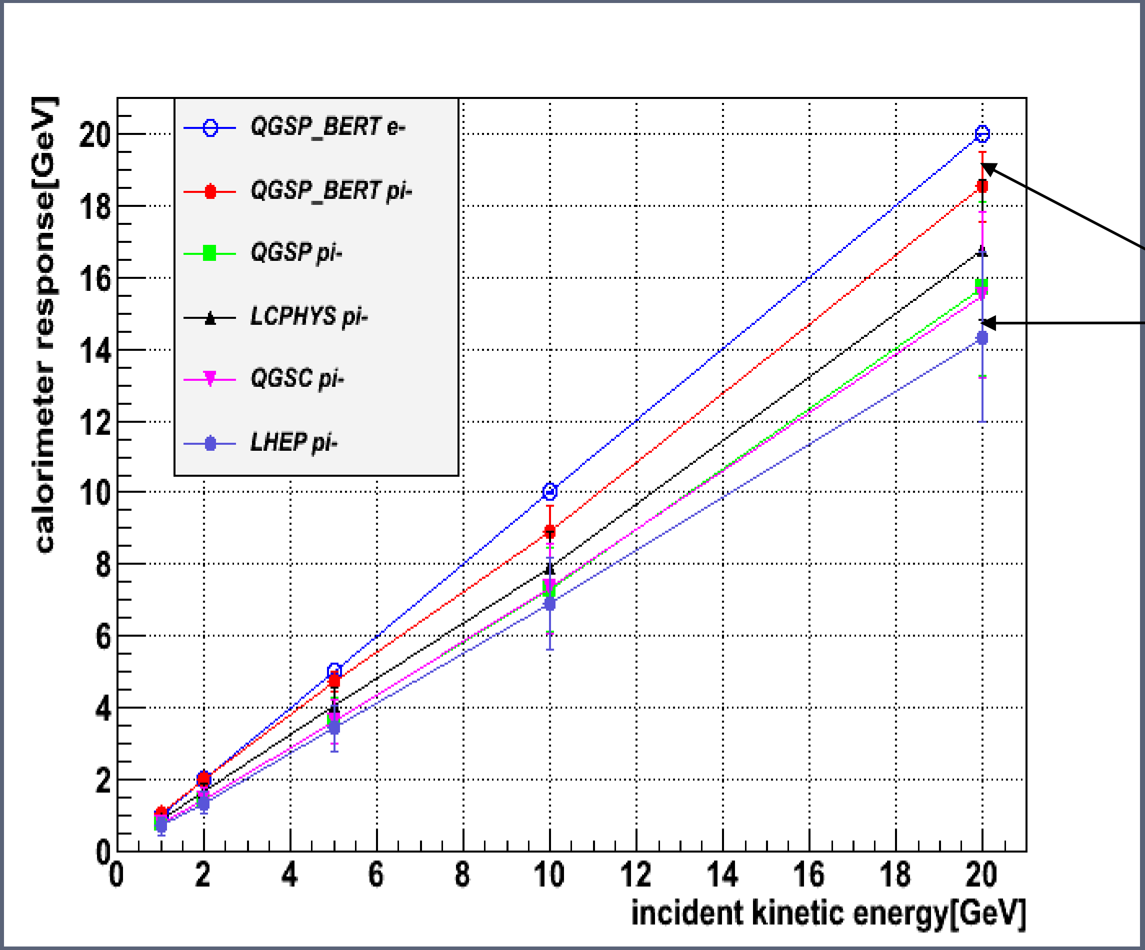
Scintillation (red) and Cherenkov (blue) hit timing distributions; Note the very large number of entries in the very first bins and the very different nature of distributions





BGO Calorimeter response for different physics models

SiDo2 geometry detector, electrons, pions, BGO crystals, n=1.65,



~29% variation in energy response

again, a nonlinearity around 10GeV esp. for QGSP_BERT

Which model is “correct”?

Summary

- Total absorption dual readout calorimeter is a sensitive tool to study Geant4 properties
- We observe the following Geant4 features while investigating the above calorimeter:
  - There is an effect in the simulation of hadronic cascades, in the region around 10 GeV beam energy, where the scintillation energy distributions exhibit two distinct peaks and the energy response deviates from the "expected" curve based on other energies; This effect dominates over the detector resolution effects and contributes to the nonlinearity of the energy response – What is it? Can it be avoided?
  - An excess of detected energy in detectors made out of heavy nuclei (above Iron) targets - Is it correct? Is it fission?
  - Using various physics lists lead to generation of very different results in – which one is the best one ?
- Total absorption dual readout calorimetry depends on Geant4 simulation for calculating detector parameters
  - We thank the Geant4 collaboration for continuing to develop a sophisticated tool