Development of a High-Resolution Crystal Calorimeter with Dual Readout of Scintillation and Cerenkov Light

Steve Magill

- Dual-Readout Crystal Calorimetry
- Crystal Development
- Readout Sensor Development
  - Scintillation Readout
  - Cerenkov Readout
- Summary

Motivation

Development of clear, dense (scintillating) crystals (BGO, PWO, PF, . . .)

-> total-absorption calorimeter ~same volume as current detectors

7-9 g/cc densities -> 5-6 λ_I total-absorption crystal calorimetry in, e.g., CDF calorimeter volume

-> Readout 2 sources of photons from 1 detector material

Cerenkov from fast, light particles -> $e^{\pm}$ from electromagnetic showers

Fast, UV light

Few photons -> sensors with high collection efficiency, large area, directionality?

Scintillation from all charged particles -> em and hadronic showers

Slower response, longer wavelength

Plentiful in current crystals -> small sensors

On-crystal photodetectors -> highly segmented and granular calorimeter

Dual-Readout Advantage :

-> C/S ratio ~represents the electromagnetic fraction of the visible energy

Large fluctuations in em fraction -> poor E resolution

Use C/S to correct total E response -> much improved E resolution

Dual Readout Calorimeter Detector Parameters

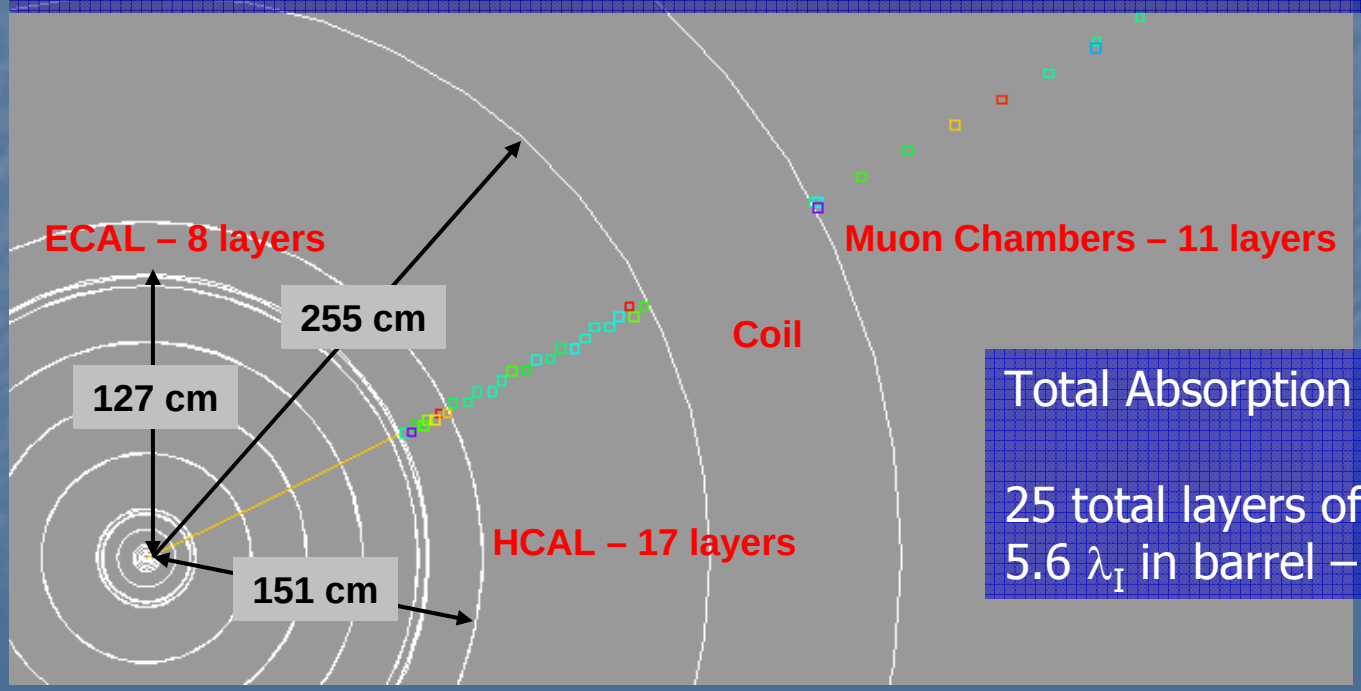
Dual Readout Calorimeter *in SiD02 Shell (Barrel and EC)*

DR ECAL

3 cm x 3 cm x 3 cm BGO
8 layers – 21.4 X_0 (1.1 λ_I)
127 cm IR – 151 cm OR
Scin/Ceren analog hits

DR HCAL

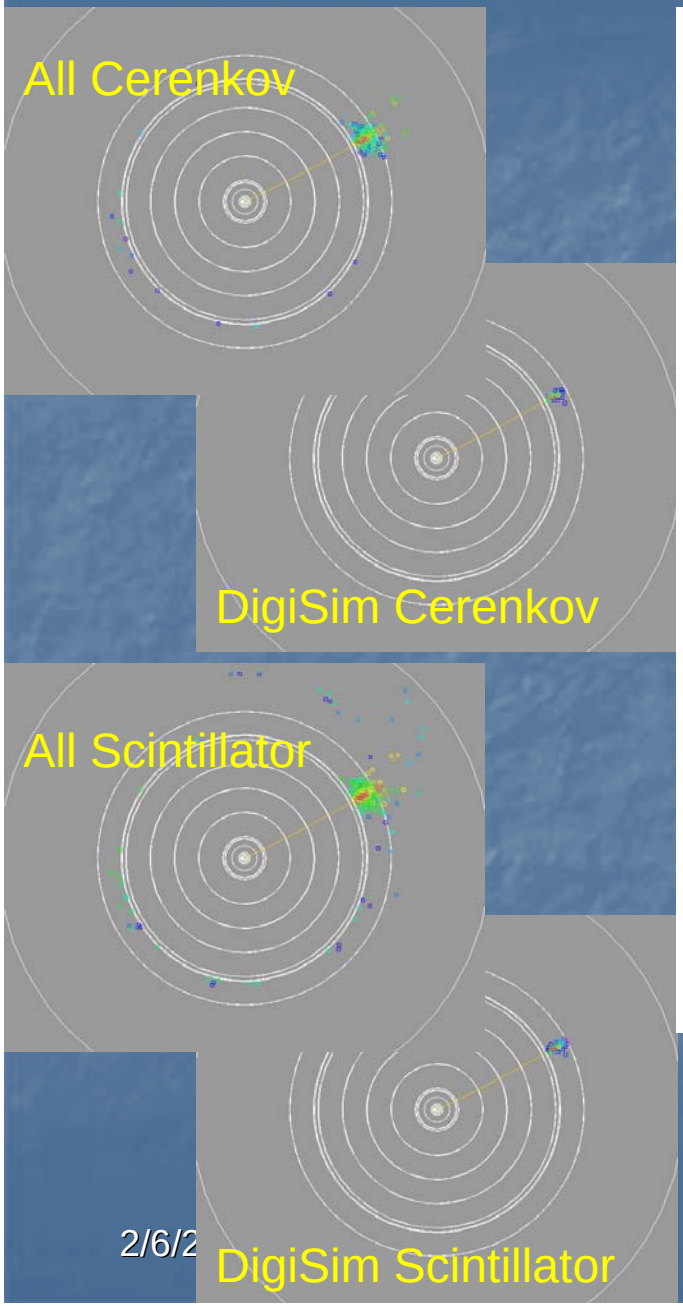
5 cm x 5 cm x 6 cm BGO
17 layers – 4.6 λ_I
151 cm IR – 253 cm OR
Scin/Ceren analog hits

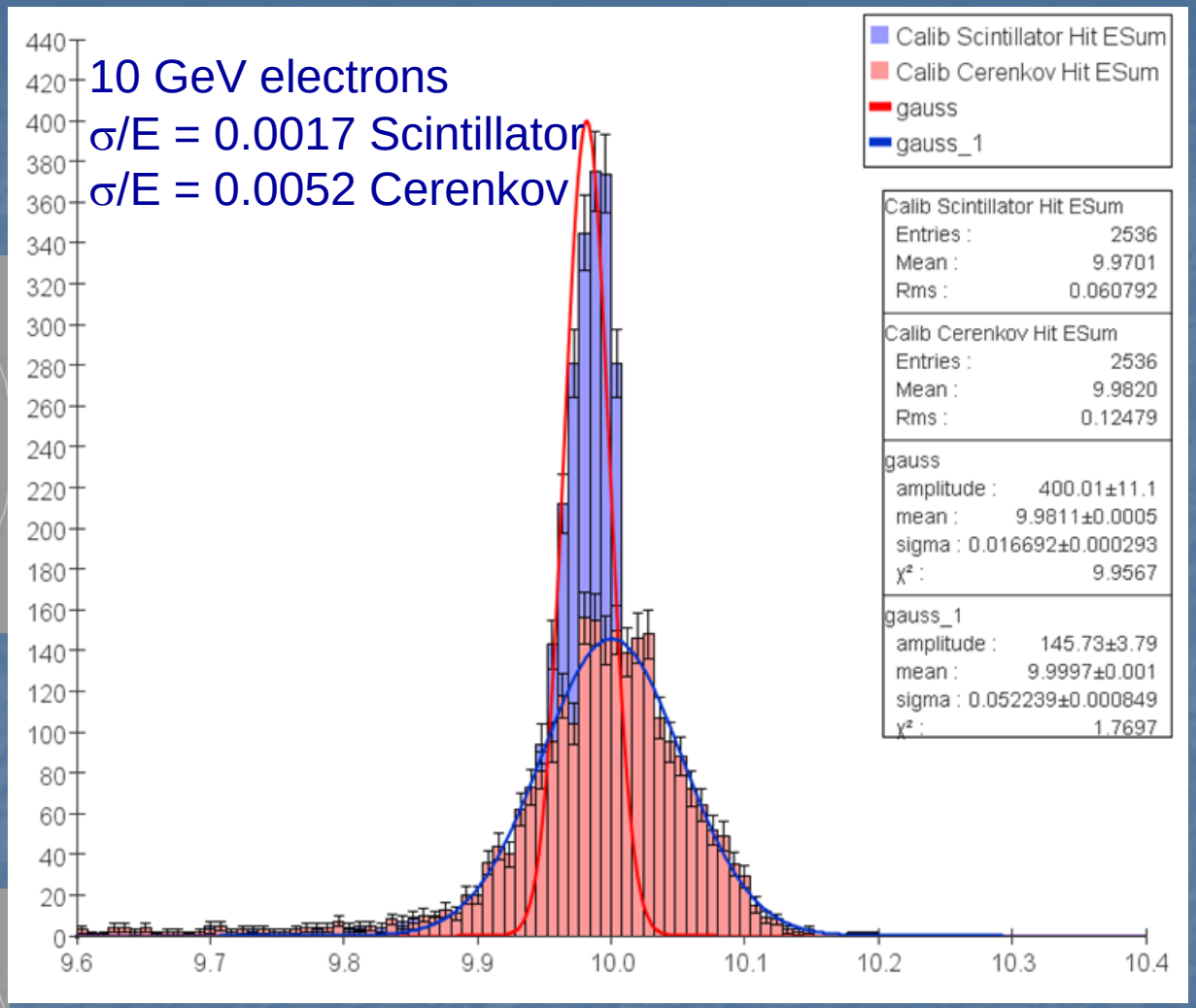


Total Absorption Crystal Calorimeter

25 total layers of BGO
5.6 λ_I in barrel – 2.5 m radius

Electron Calibration for Scintillator, Cerenkov

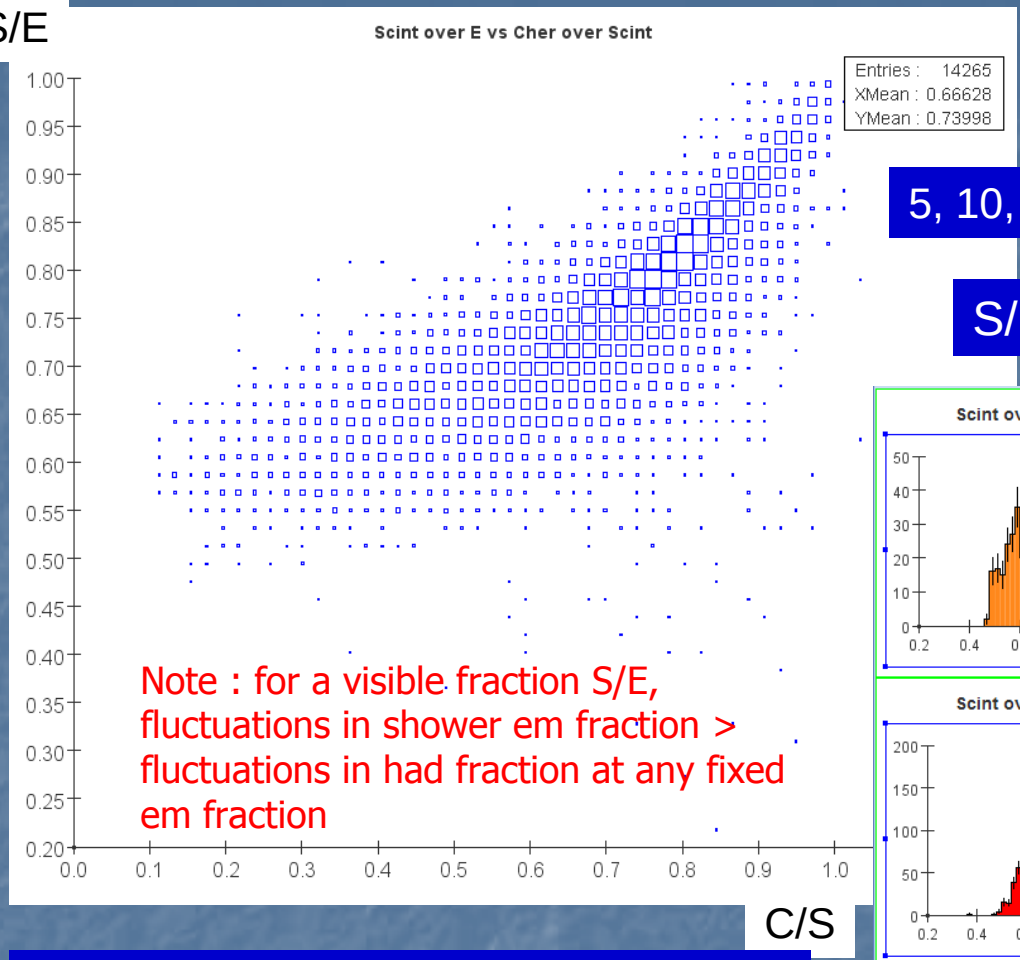




$S = 1.004 \times s_{raw}$

$C = 7692 \times c_{raw}$

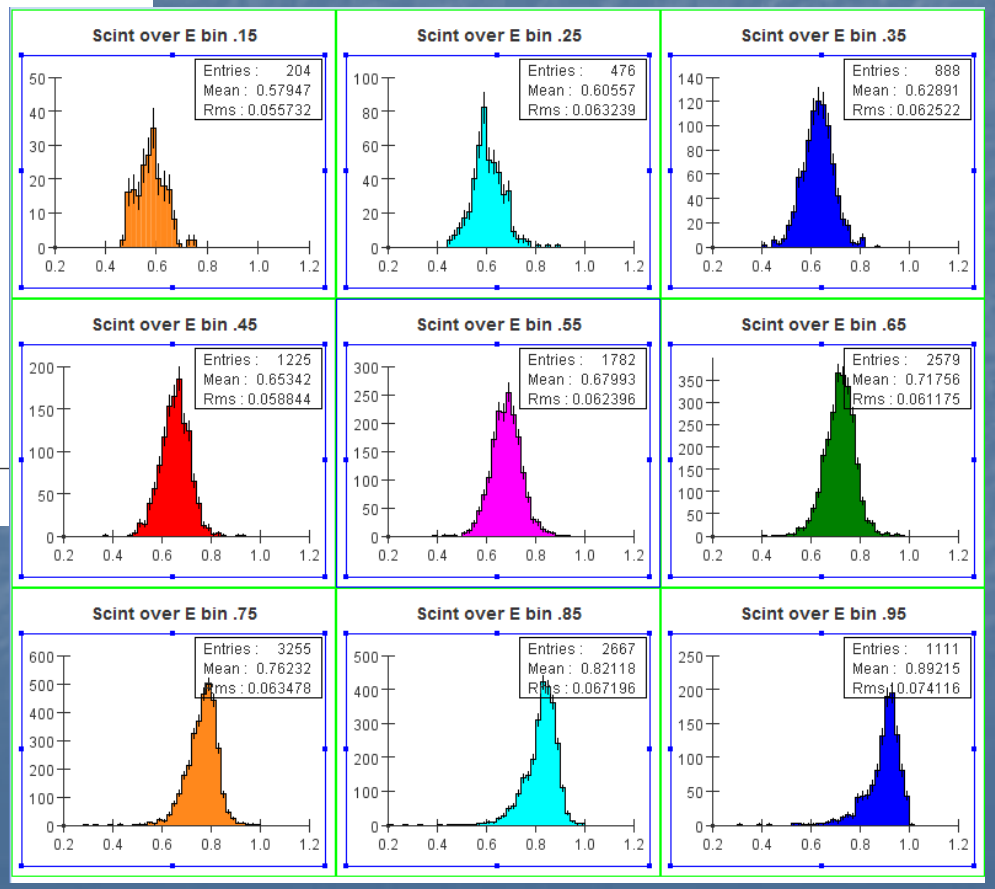
Cerenkov/Scintillator Correction for Hadrons



Note : for a visible fraction S/E, fluctuations in shower em fraction > fluctuations in had fraction at any fixed em fraction

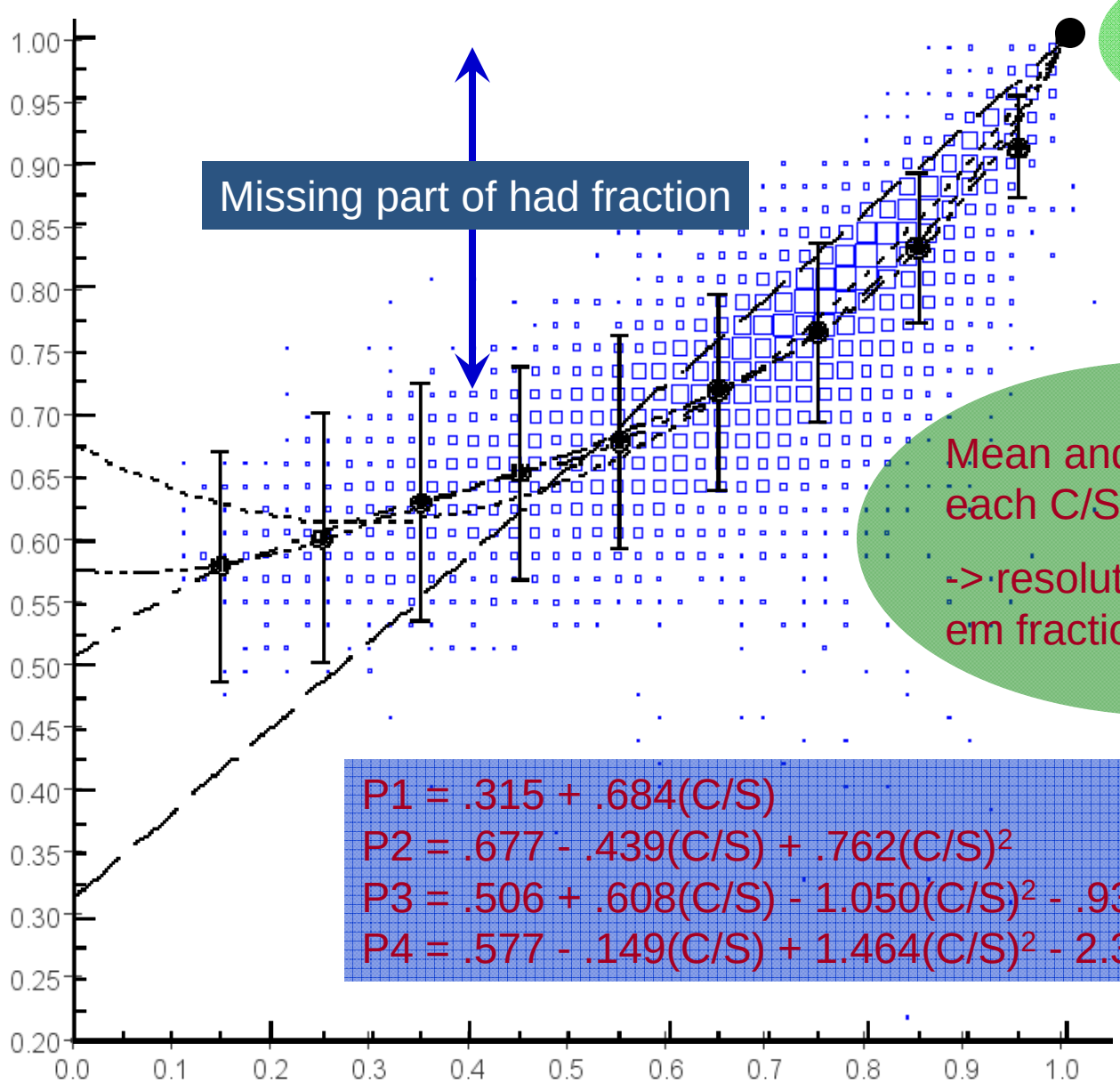
5, 10, 20, 50, 100 GeV pions

S/E slices in em fraction (C/S) bins



S (e calibrated scintillator response)
-> em and had visible energy
C (e calibrated cerenkov response)
-> ~em part of shower
C/S ~ em fraction of visible energy
S/E = total fraction of energy seen

Polynomial Correction Functions : E = S/Pn



em fraction = 1
S/E, C/S = 1
-> calibration

Mean and σ/mean of fit in each C/S bin plotted

-> resolution improves with em fraction

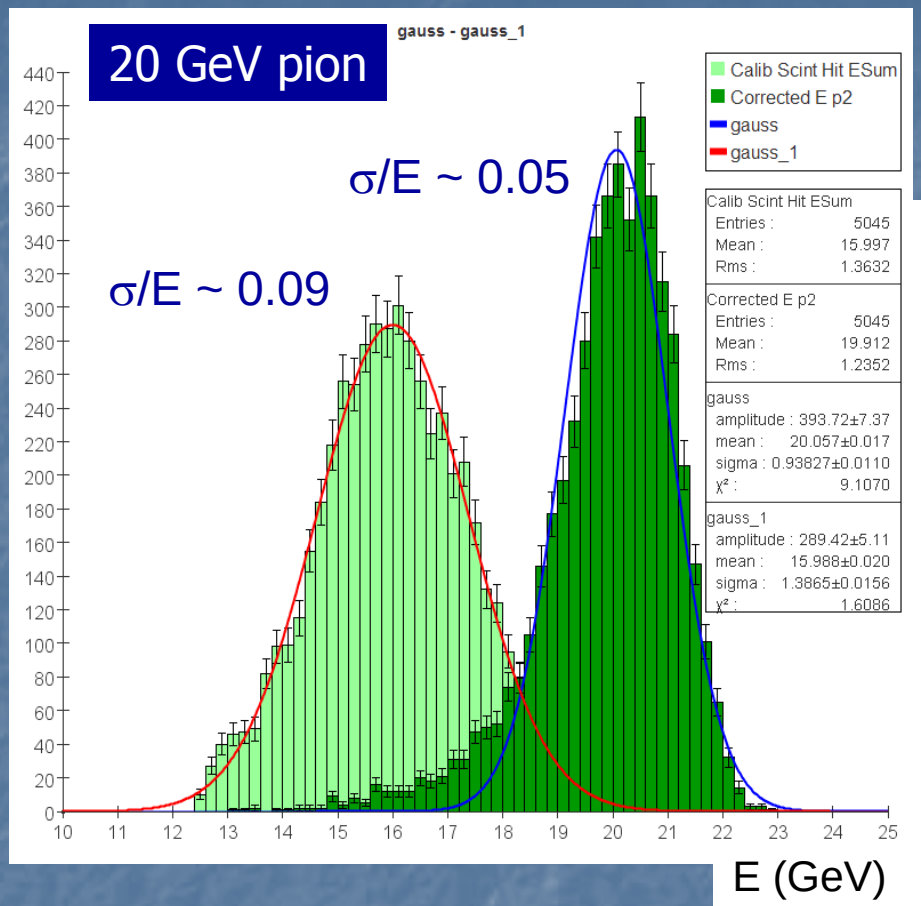
$P1 = .315 + .684(C/S)$

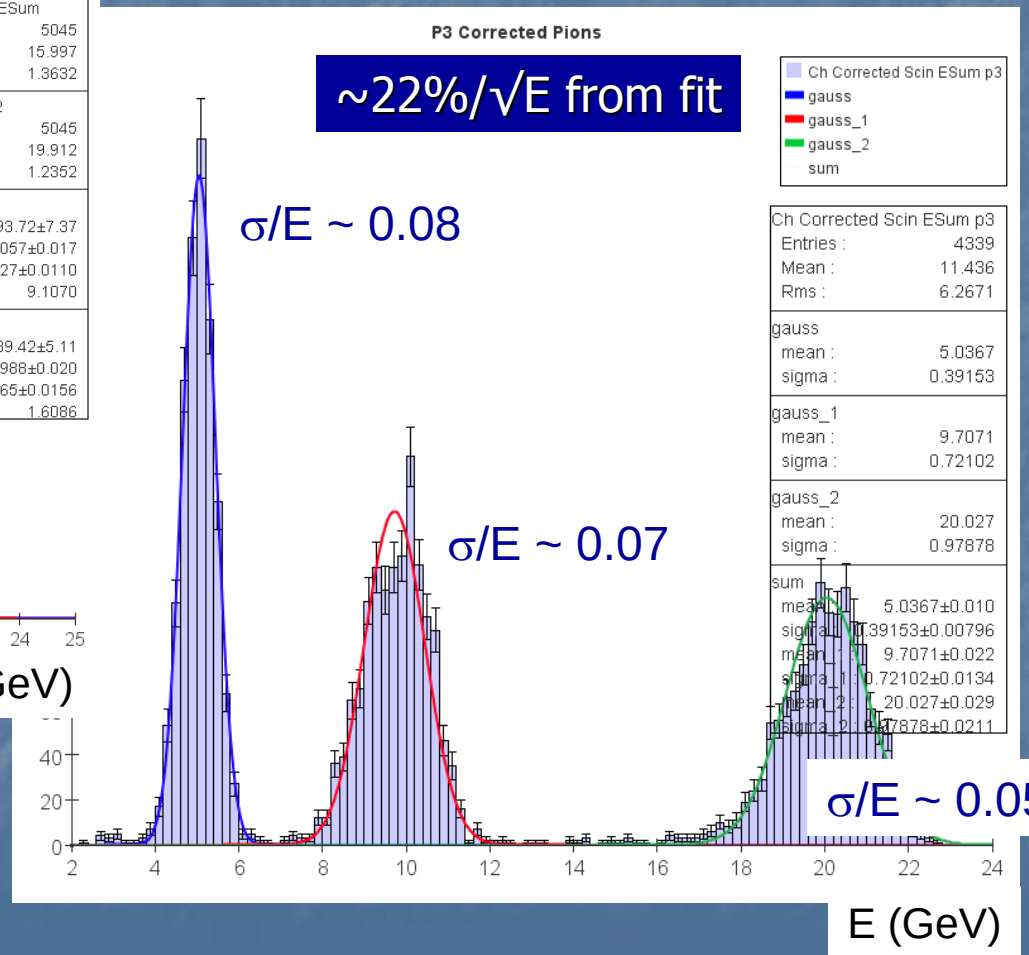
$P2 = .677 - .439(C/S) + .762(C/S)^2$

$P3 = .506 + .608(C/S) - 1.050(C/S)^2 - .935(C/S)^3$

$P4 = .577 - .149(C/S) + 1.464(C/S)^2 - 2.302(C/S)^3 + 1.410(C/S)^4$

Corrected Pion Scintillator signal using Polynomials





Using C/S correction
-> 40%/√E to ~22%/√E

Crystal Development R&D

R&D Focus : Discovering a crystal that can produce both scintillation and cerenkov light from particle showers and that is dense enough to contain hadron showers in a reasonable volume

PWO crystals dense (8.3 g/cc), but
-> oxides have a low E band gap, so propagate little cerenkov light
PF crystals dense (7.7 g/cc), but
-> fluorides have a higher E band gap more suitable for cerenkov propagation, but don't scintillate!
Add dopant to make PF scintillate? (literature on this)
What about UF (~9 g/cc)?

Needs :
ANLHEP partnership with a crystal grower to obtain samples for testing?
Extensive use of test beams – probably only needs electron beam for single crystal studies, pions later for larger prototyping with multiple crystal sets

Readout Detector Development R&D

R&D Focus : Optimal readout technologies for scintillation and cerenkov signals – includes minimization of material between crystals to maximize sampling fraction

Scintillation Sensor R&D

- Present scintillating crystals produce plenty of scintillation light
  - -> readout candidates – mm^2 SiPM, small sensors
  - -> want non-prompt, long wavelength light, so timing cuts, filtering means larger sensors?
- HEP doesn't normally require "medical grade" (~100k γ/MeV) crystals
- Readout candidates depending on final realization of scintillation γ/MeV from material, filtering, timing compromises
  - -> many-mm^2 SiPMs, APD?
  - -> mounts on 1 face of crystal?

Needs :

- Optimization of filters, timing cuts for good scintillator crystal – PWO using test beam
- Extension to samples of new crystal materials

Readout Detector Development R&D (cont.)

R&D Focus : Optimal readout technologies for scintillation and cerenkov signals – includes minimization of material between crystals to maximize sampling fraction

Cerenkov Sensor R&D

- Cerenkov angle ~60° (index of refraction at these densities)
  - -> use all faces of the crystal
- Optimizing crystal material for maximum cerenkov yield
  - -> still probably requires few cm^2 sensors on several faces of the crystal
  - -> thin profile to minimize material in between crystals

Needs : much R&D, potential use elsewhere?

- An extension of MCP work currently ongoing at ANLHEP?
- MCP -> NCP (Nano-Channel Plate)?
  - -> Could leverage existing test facilities, lab space, testing tools, etc.
- Thin Film Silicon Nanoparticle UV Photodetector (U of I U-C)
  - -> depositing silicon nanoparticles on a silicon wafer turns silicon from visible to UV detector (200-400 nm light)

Summary

Promising technology for future high-resolution calorimetry using dual-readout of a ~total-absorption crystal detector

Crystal Materials R&D

Must "discover" a new clear, dense crystal which can produce and propagate adequate numbers of γ/MeV of both scintillation and cerenkov light

Readout Sensor R&D

Must develop readout sensors for each of these responses maximizing detection efficiency as a function of time and wavelength while minimizing the amount of material in the sensor

More Challenges/Opportunities

With sensors mounted directly on the crystals, can imagine an imaging calorimeter with crystal "pixel" construction

-> particle reconstruction techniques (PFA?)

-> enhanced performance utilizing dual-readout corrections with individual particle reconstruction

-> natural progression to higher energies – less emphasis on PFA, more on cerenkov correction

Calorimeter Calibration

-> how to calibrate each crystal for its em response without putting tens of thousands of crystals in test beam?

-> method using CR muons? – relate to em response?

Engineering challenges for Calorimeter Support

-> how to support crystals while minimizing material?

-> Barrel Cal example – upwards of 800 tons to support