Using Geant4 to predict properties and performance of future high-precision hadron calorimeters

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Geant 4 collaboration meeting
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Introduction - General

The next generation of lepton collider detectors will emphasize precision for all sub-detector systems!
One benchmark: distinguish W and Z vector bosons in their hadronic decay mode.
→ This requires a di-jet mass resolution better the natural width of these bosons and hence a jet energy resolution better than 3%.
For hadron calorimetry this implies an energy resolution a factor of at least two better than previously achieved to date by any large-scale experiment.

→ Requires new ideas/concepts!

Introduction (cont.)

R&D for future hep calorimetry : 3 different approaches

- particle flow paradigm (CALICE):

Combine tracker and calorimeter information requires: highly granular EM and HADR calorimeters (digital or analog) to allow very efficient pattern recognition for excellent shower separation and particle id. within jets to provide excellent jet reconstruction efficiency

- dual readout calorimetry (DREAM):

measurement of both the ionization/scintillation and the Cerenkov signals generated by a hadronic shower in order to correct on an event by event basis

- crystal/glass calorimetry (HHCAL):

an approach that could combine the excellent energy resolution of crystals (homogeneous detector) with dual readout, where scintillation and Cerenkov Signals are separated and recorded, and with particle flow/imaging capabilities if the detector is segmented with high granularity

→ Simulation is absolutely crucial!! Full scale test beams are expensive

But not everyone in the Calorimeter community is convinced

What has been learned since 1990?

From Monte Carlo simulations:

NOTHING

(of meaningful importance)*

Just like in the past 30+ years, in the absence of reliable MC simulations, progress depends on experimental verification of new ideas

It's "only" MonteCarlo!

Motivation for a Total Absorption Dual Readout Calorimeter (HHCAL)

The principal contributions to hadron energy resolution and non-linearity include:

- fluctuations in Nuclear binding energy loss dominate the energy resolution, non-linear response, different response to charged and neutral pions → dual readout

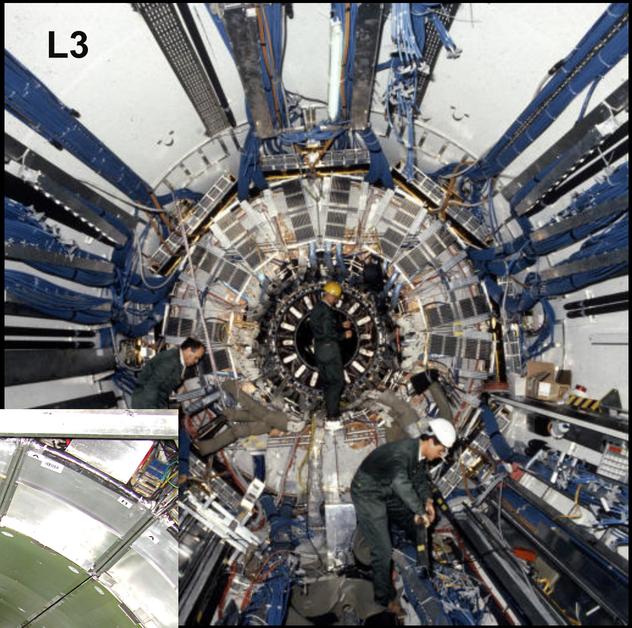
- Sampling fluctuations: fluctuations in the sharing of the shower energy between the active and passive materials (in sampling calorimeters) → homogeneous, totally active.

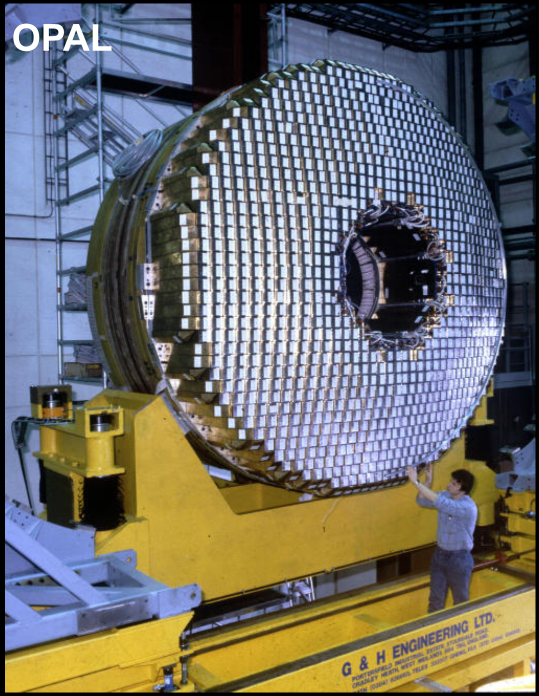
- Difference in the 'sampling fractions' (i.e. ratio in the effective energy loss) between the different materials in the sampling calorimeters → homogeneous

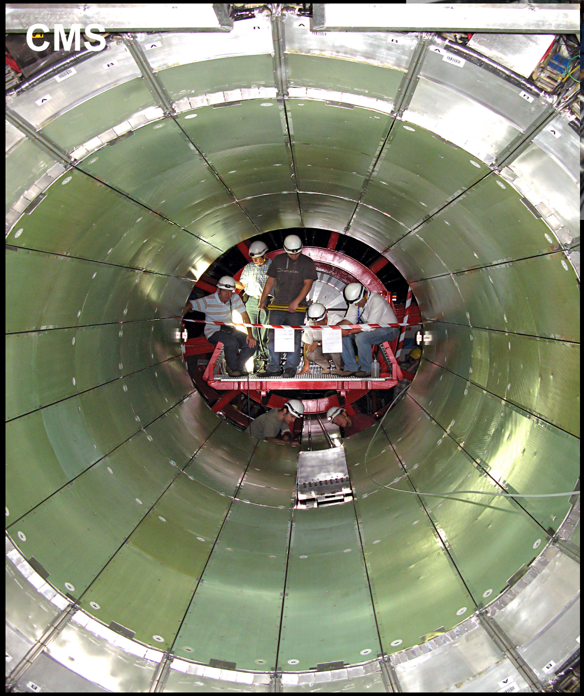
- Leakage fluctuations due to ~~neutrinos~~, muons and tails of the hadronic shower escaping the detector volume → dense material

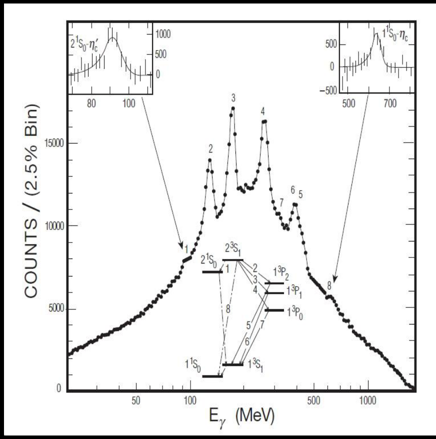
History

- Historical: e.g. Crystal Ball
- Some recent examples are:
  - OPAL: leadglass calorimeter
  - L3: BGO EM calorimeter
  - CMS: PbWO4 calorimeter (11 m^3)
- Dedicated efforts to develop the crystals









Enabling technologies:

Major advances in the detectors technology/enabling technologies:

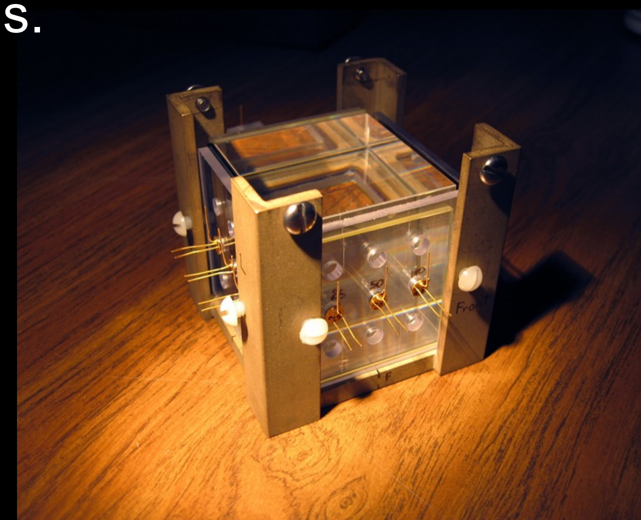
→ High density scintillating crystals/glasses (IA length ~20 cm)

→ „Silicon Photomultipliers" ~ robust compact, inexpensive, fast, not sensitive to ionizing particles in the shower, work in B-field, counting photons …

→ Allows for completely new layout/design options.

Table 2: Candidate Crystals for the HHCAL Detector Concept

Crystal	BGO	$PbWO_4$	PbF_2	BSO	PbFCl
Density (g/cm^3)	7.13	8.29	7.77	6.80	7.11
Radiation Length (cm)	1.12	0.89	0.93	1.15	1.05
Interaction Length (cm)	22.8	20.7	21.0	23.4	24.3
Hygroscopicity	No	No	No	No	No
Cut-Off Wavelength (nm)	300	350	260	295	280
Luminescence (nm)	480	420	?	470	420
Decay Time (ns)	300	30/10	?	100	25
Relative light Yield (%)	100	2	?	20	2
Melting Point (°C)	1050	1123	824	1030	608
Relative Raw Material Cost (%)	100	49	29	47	29



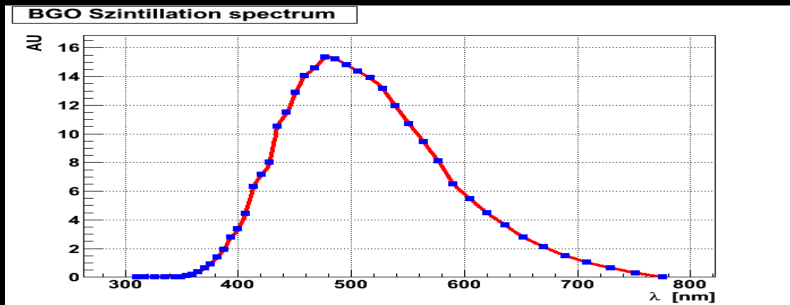
From simulation we want:

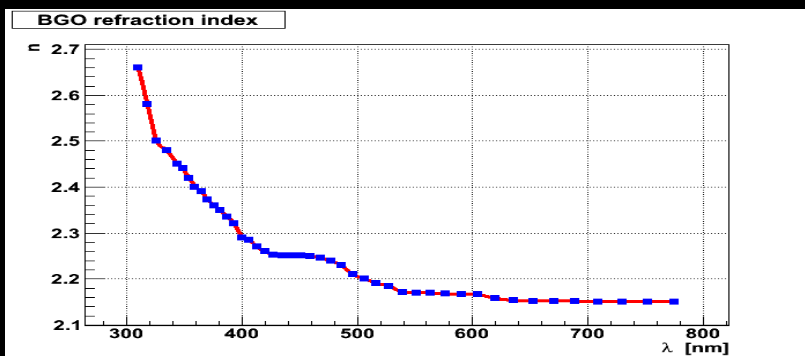
- to know if there are any show stoppers
- to understand the (temporal and spatial) development of hadronic showers.
  - what are the basic physics processes and particles as well as the fluctuations thereof that contribute to both the Cerenkov and ionization signal. In this presentation we concentrate on neutrons and protons!
  - what are the different components of the shower that Cerenkov and Ionization response are sensitive to.
    - e.g. neutrons are produced plentiful: in a Crystal→ neutron Capture → γ (all detected if integration time is long enough, might not be an option e.g. muon collider) ,
    - e.g. slow protons produced in inelastic hadronic interactions result in very localized energy deposit but not Birks suppressed. Seen in Crystal might get lost in absorber sampling calorimeter
    - e.g. role of heavy ionizing particles → Birks suppression could decrease response.
- How important is dual read out?
- Guidance to (small scale) testbeam experiments
- (and our students) to be educated (learn the physics involved)

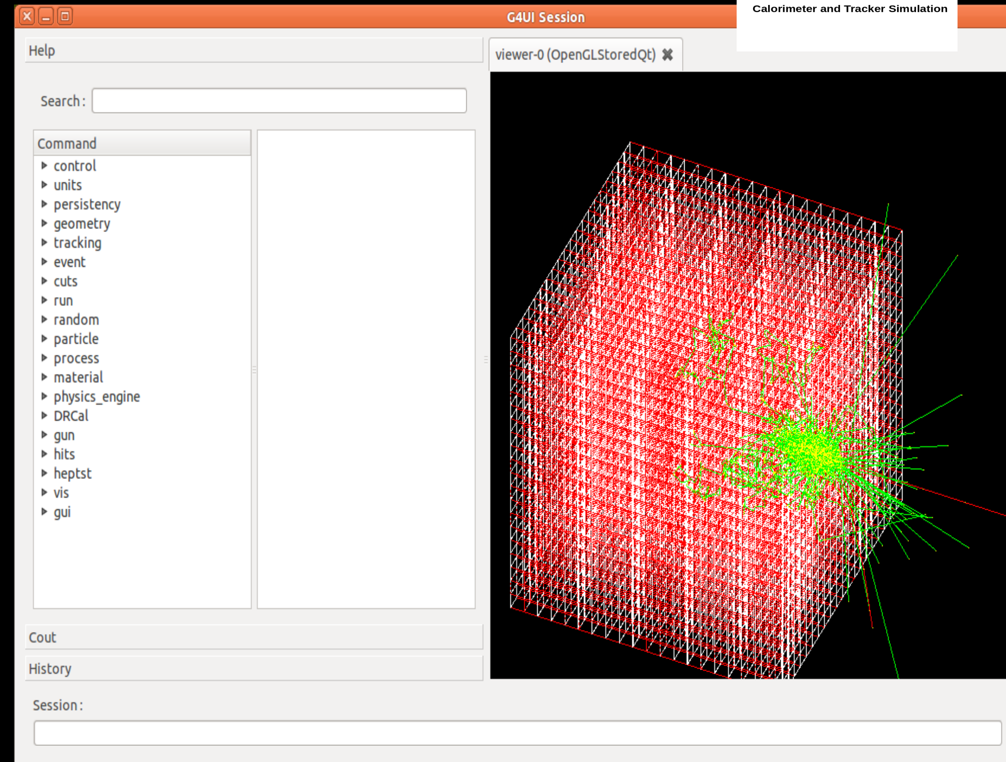
Elements of CaTS: (Calorimeter and Tracker Simulation)

Detector Description:	Xml based gdml input file (e.g. crystalcal.gdml) (Geometry, Materials, optical properties, sensitive detector), we provide working examples
Persistency	uses Root reflexion (gccxml) to automatically, create dictionaries for all classes we want to write out (e.g. Hits)
Input modules:	GPS, Particle Gun, HEPMC (Pythia)
Physics Lists:	choice of all Reference Physics Lists which can be extended to include optical physics processes (Cerenkov, Rayleigh, Scintillation etc.)
Sensitive Detectors and Hits:	TrackerSD, CalorimeterSD, DRCalorimeterSD (also registers Cerenkov photons), DRTSCalorimeterSD (time slices), StoppingCalorimeterSD, PhotonSD: sensitive detector that registers optical photons.
User Actions:	examples of user actions (EventAction, RunAction, StackingAction,SteppingAction...) are provided
CVS Code repository & Instructions:	http://cdcvs.fnal.gov/cgi-bin/public-cvs/cvsweb-public.cgi/?hidenonreadable=1&f=h&logsort=date&sortby=file&hideattic=1&cvsroot=ilcdet http://home.fnal.gov/~wenzel/cvs.html#Optical

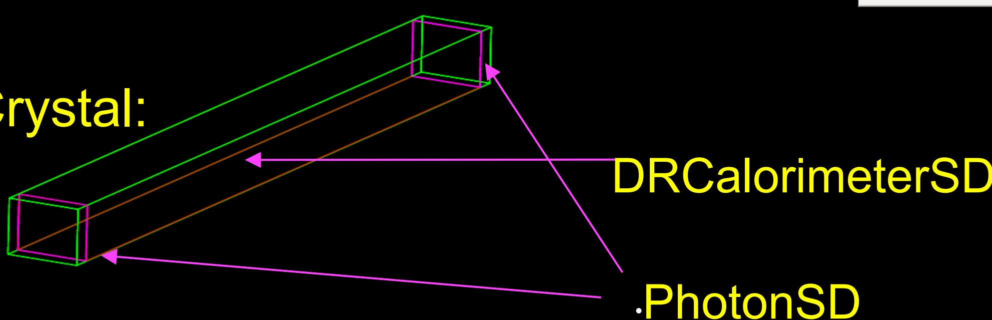
CaTS in Action: inputs and results

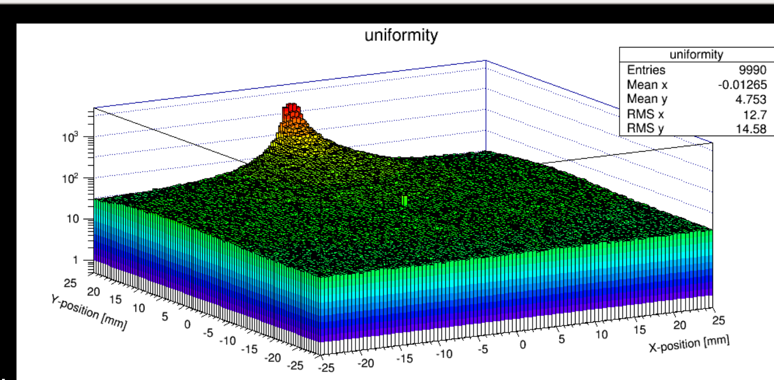






Crystal:





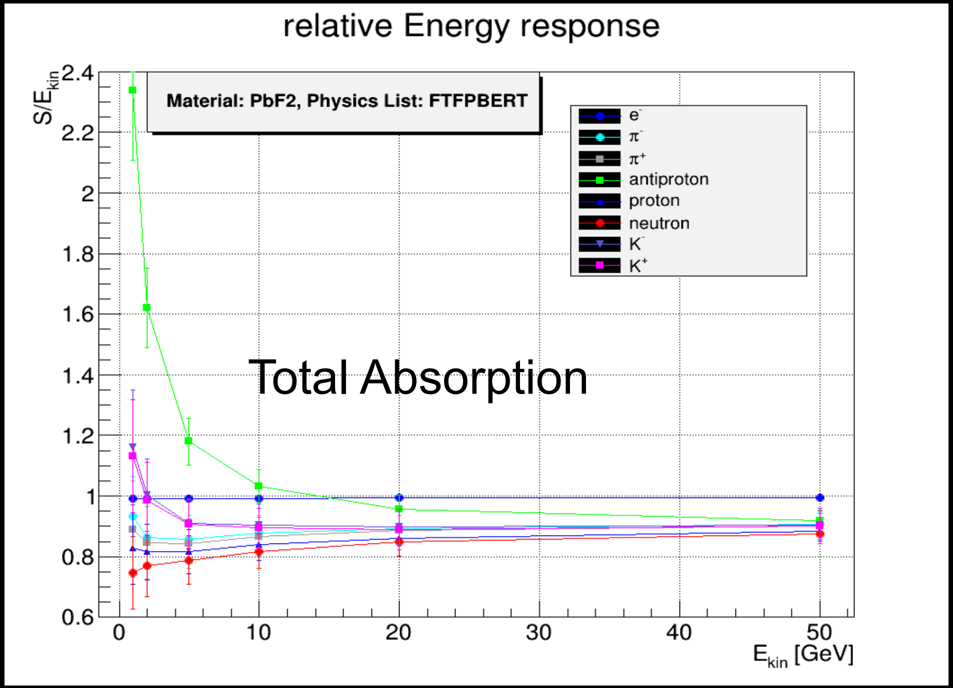
In the process of making CaTS part of ctest/cdash system →
need to decide on best example

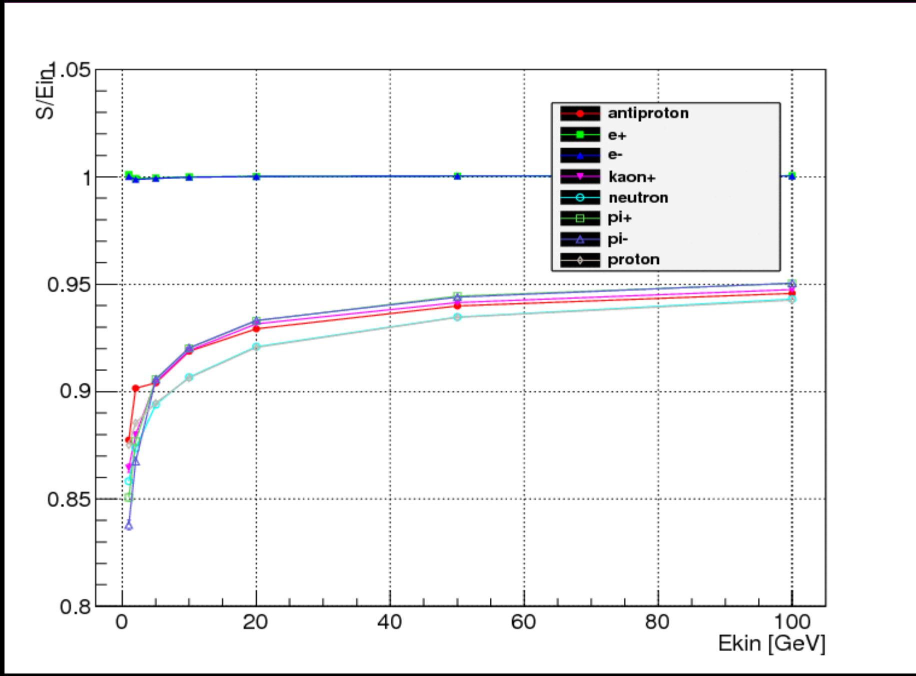
Needed to implement fast calculation of # cerenkov photons
in sensitive detector discuss with Peter if this could be standard
in geant 4.

Response of non-compensating calorimeters

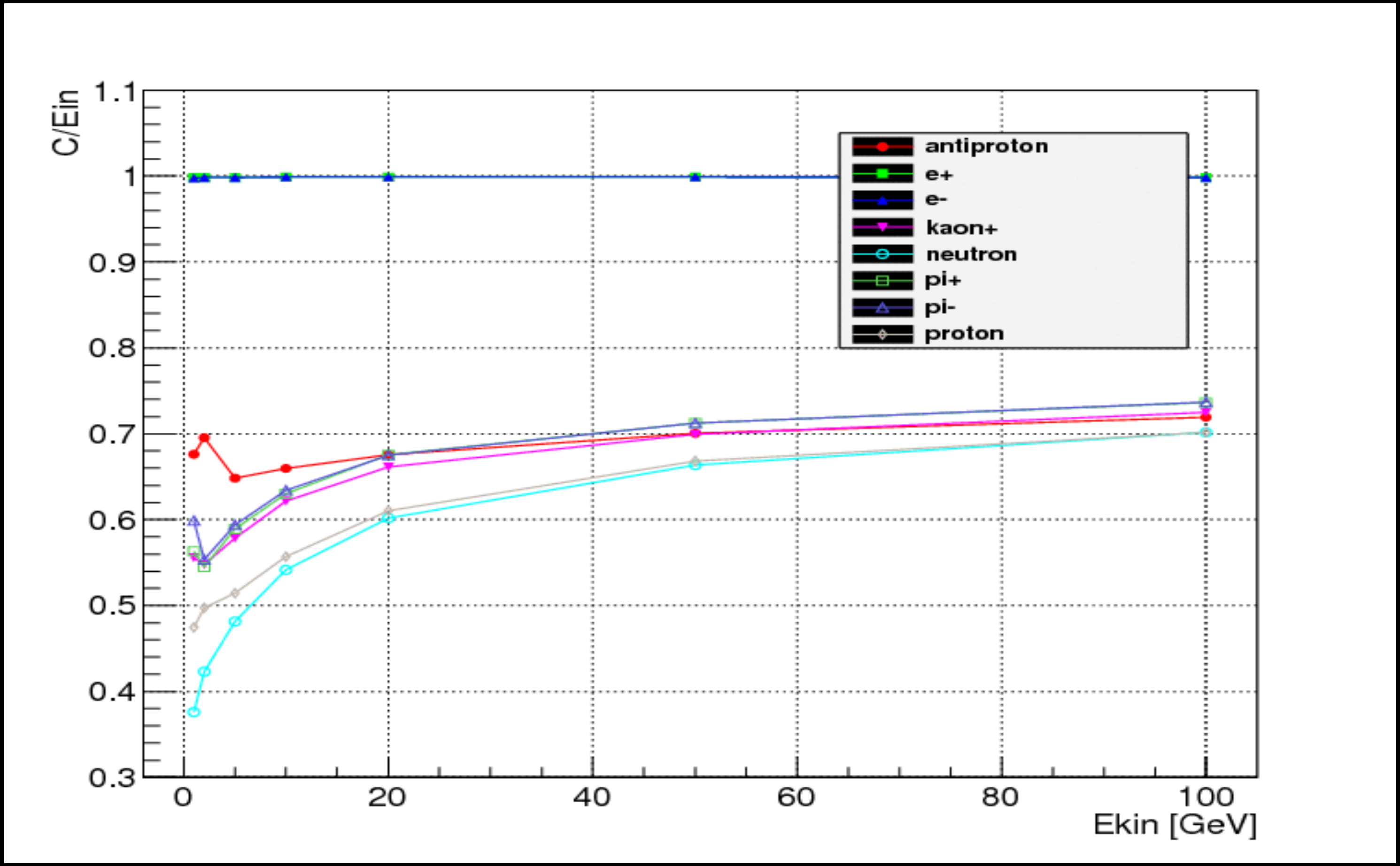
<u>Hadronic sampling calorimeters:</u>
non-linearity,
poor energy resolution,
non-Gaussian response function
Different response for different particles

Depending on particle:
$E_{in} = E_{kin}$
$E_{in} = E_{kin} + E_{Decay}$
$E_{in} = E_{kin} + E_{Annihilation}$





Cerenkov response

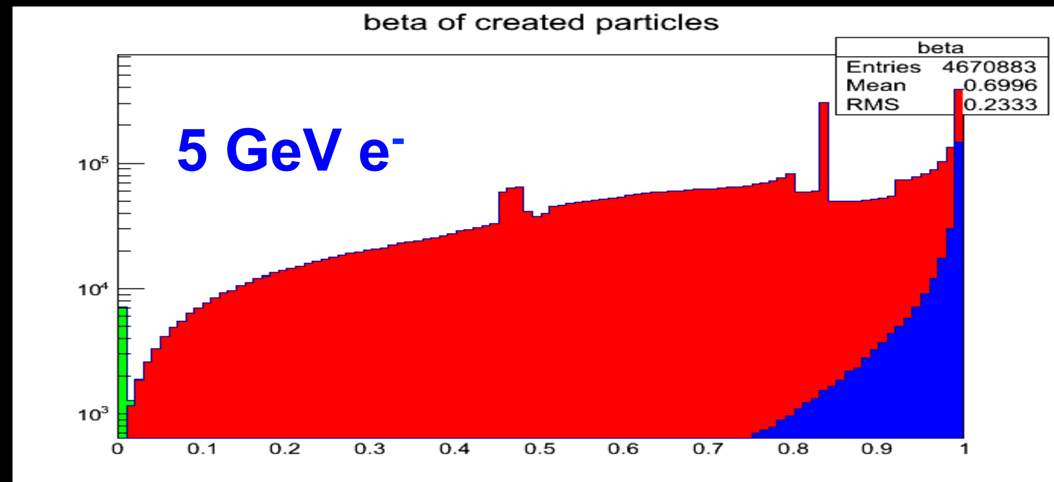


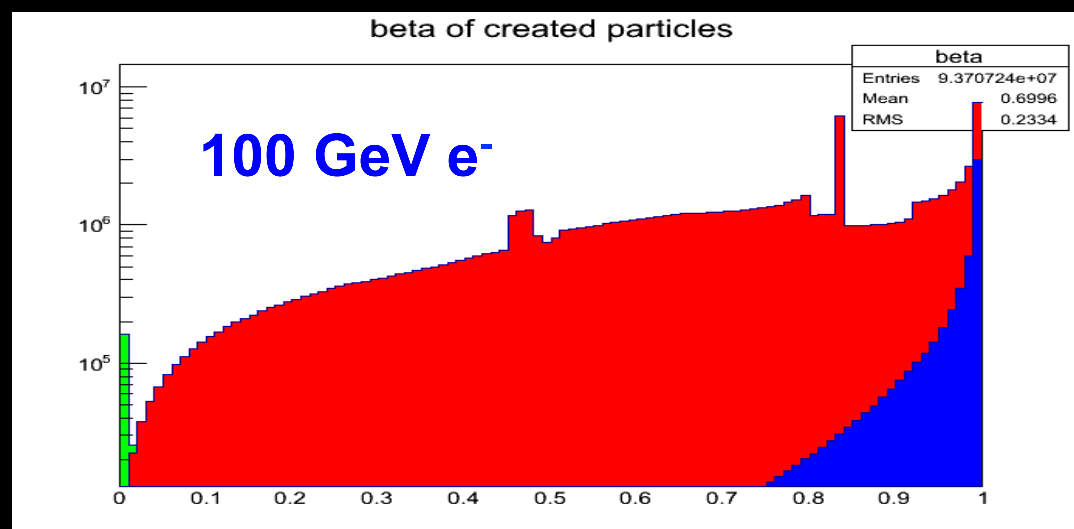
Cerenkov em Calorimeters work

β of charged particles produced in e^- showers

- Red: e^-
- Blue: e^+
- Green: Charged nuclei produced in nuclear Photo-production

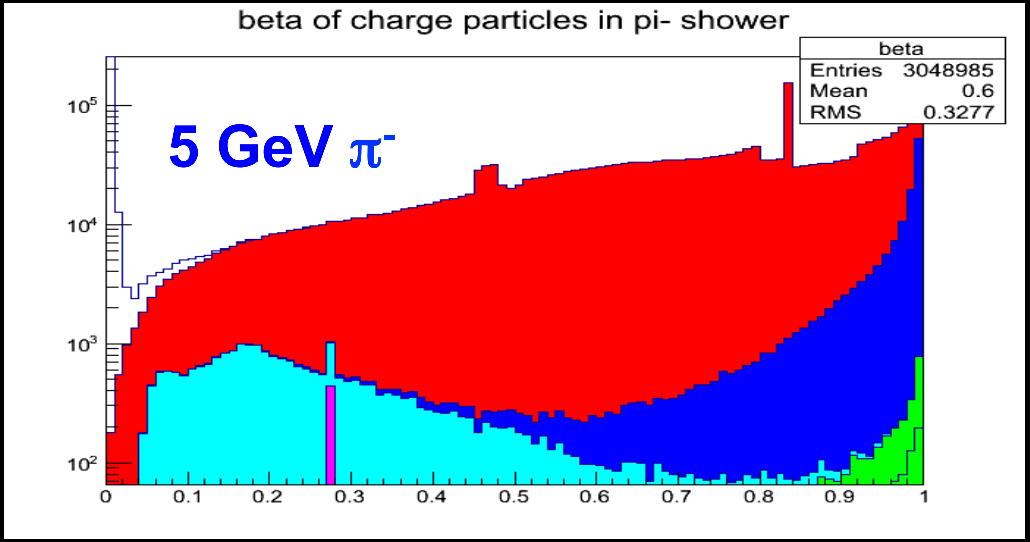
E_{in} (e^-) [GeV]	Mean β
5	0.6996
100	0.6996

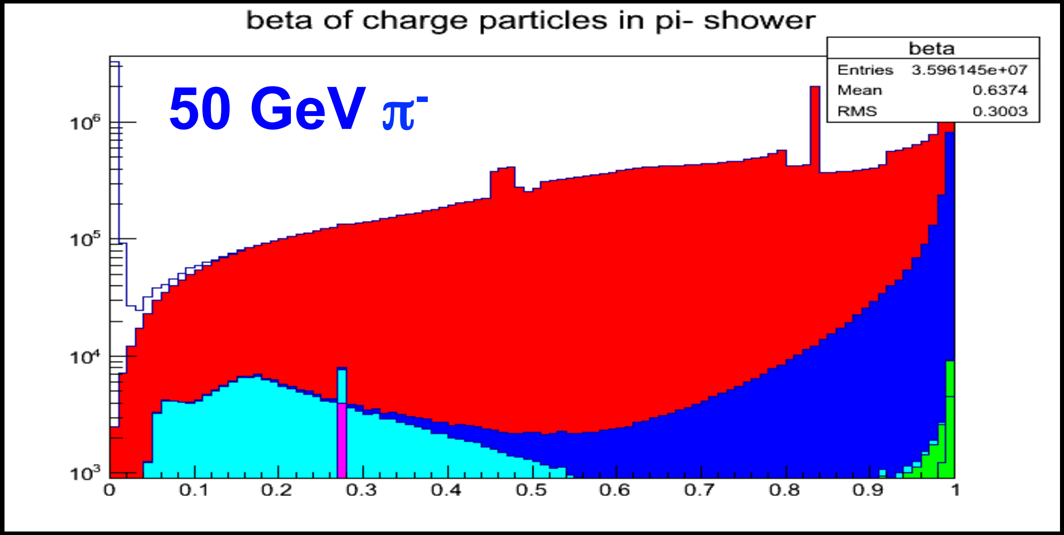




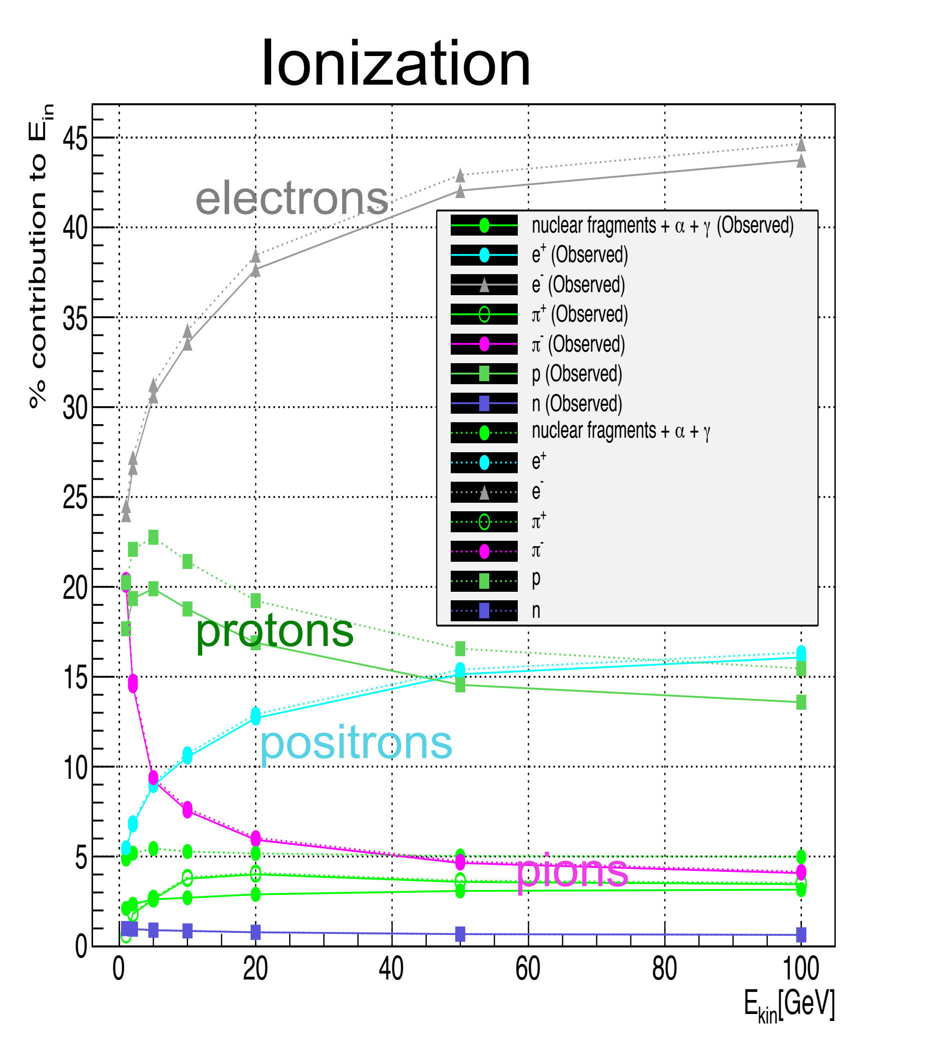
β of charged particles produced in π^- showers

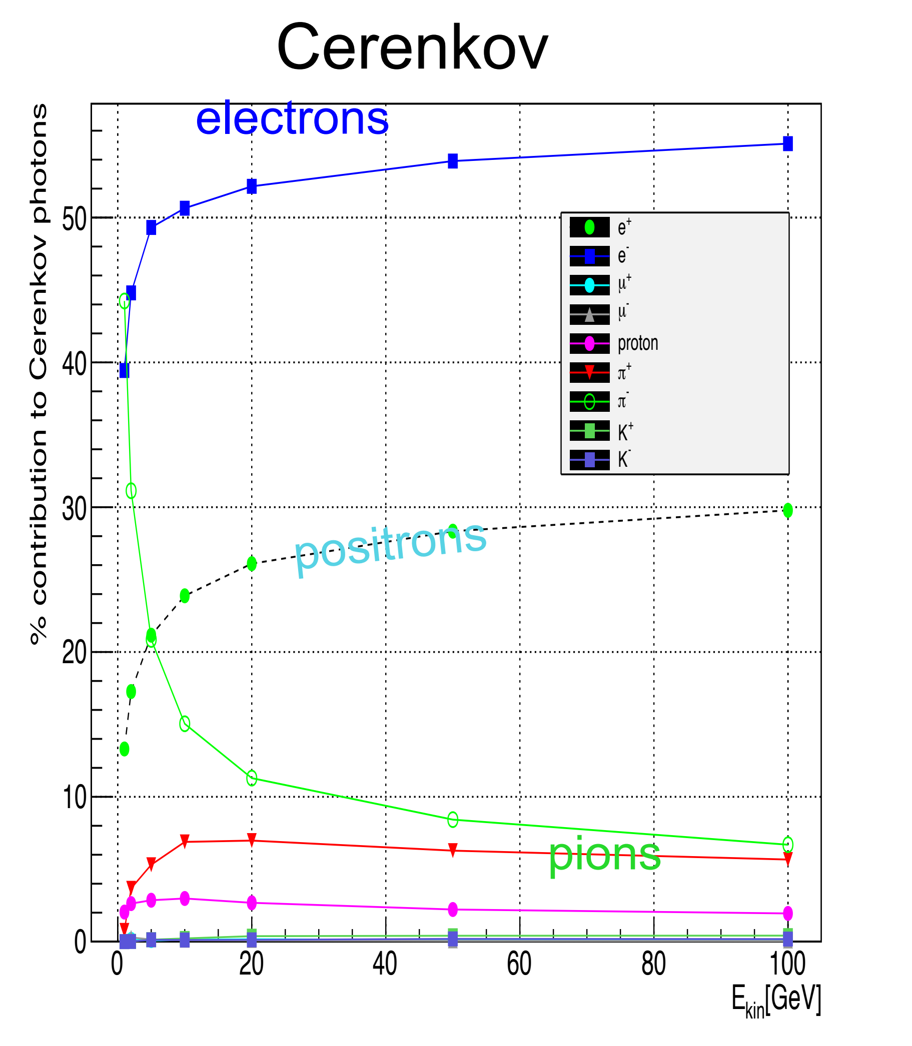
- e^-
- e^+
- $\pi^{+/-}$
- $\mu^{+/-}$
- p^+
- Charged nuclei produced in nuclear reactions



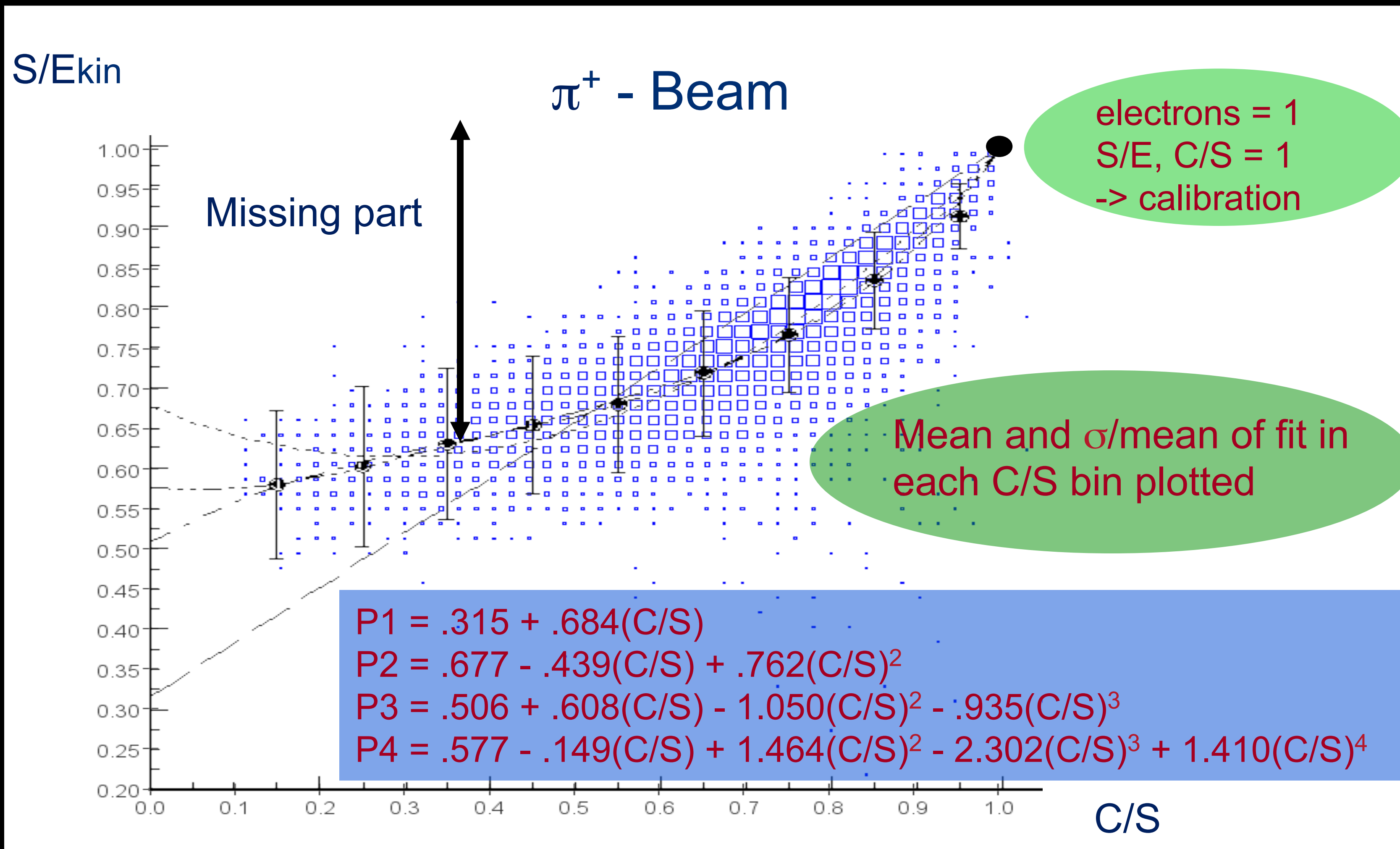


Composition of Ionization(before/and after and Cerenkov response in π^- showers





Polynomial Correction Functions: E=S/Pn



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

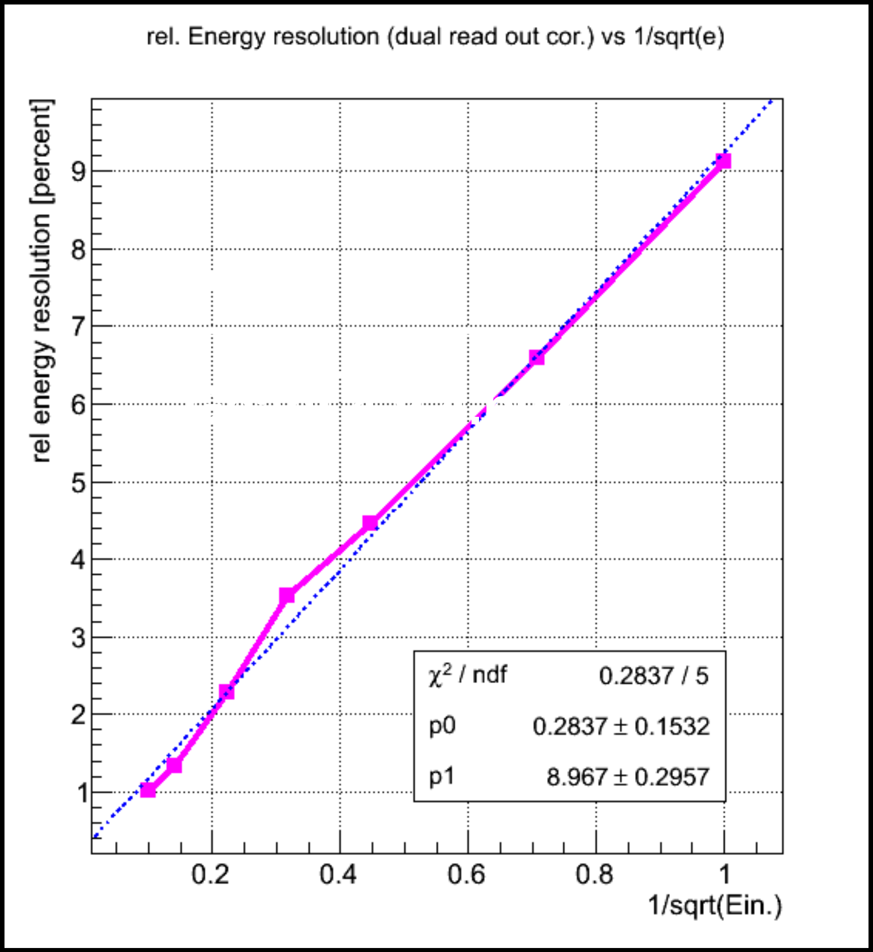
$P2 = .677 - .439(C/S) + .762(C/S)^2$

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

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

Energy Resolution for single π^-

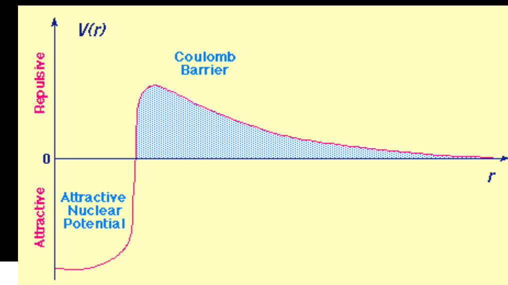
Relative Energy resolution in Ideal case:
$\sigma E/E = 0.3 + 9. /Sqrt(E)$ %

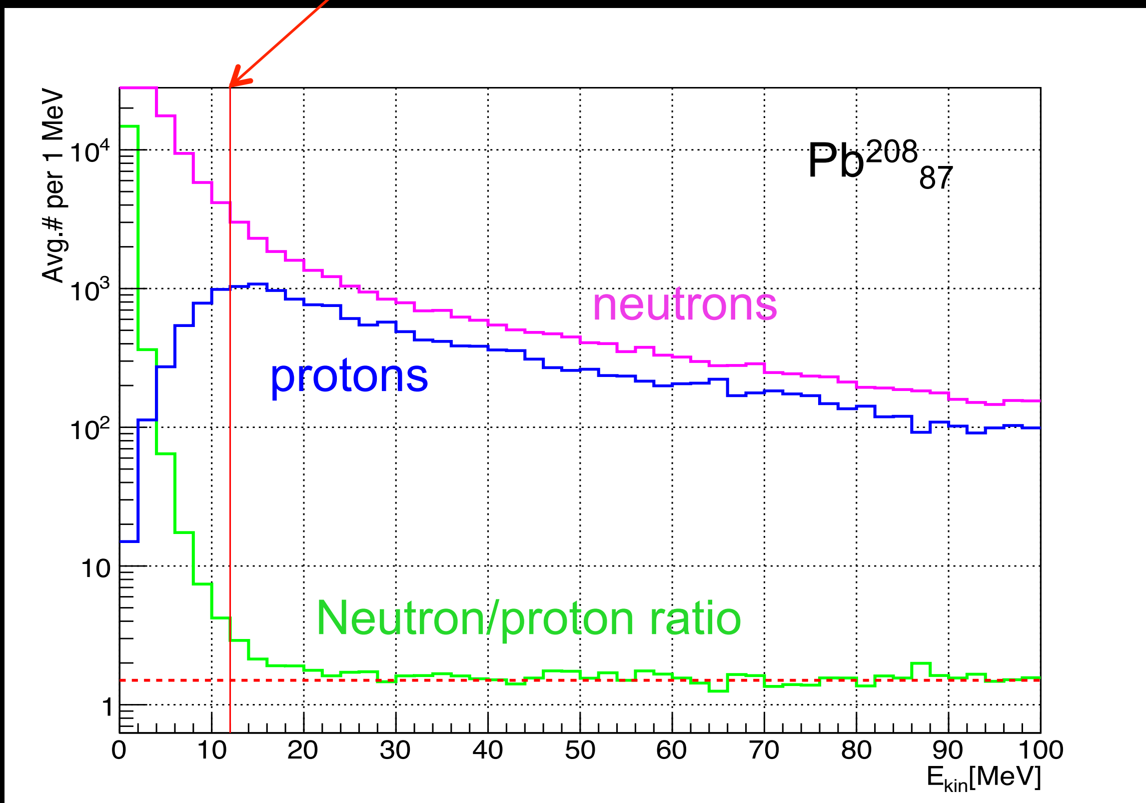


<u>Before Detector effects:</u>
- Noise
- threshold cuts
- calibration
- detection efficiency
- perfect separation of C/S
- Birks suppression (small effect)

Spallation: Proton and neutron spectrum

Coulomb barrier: $\frac{z_1 z_2 e^2}{4\pi\varepsilon_0 r}$ ~12MeV



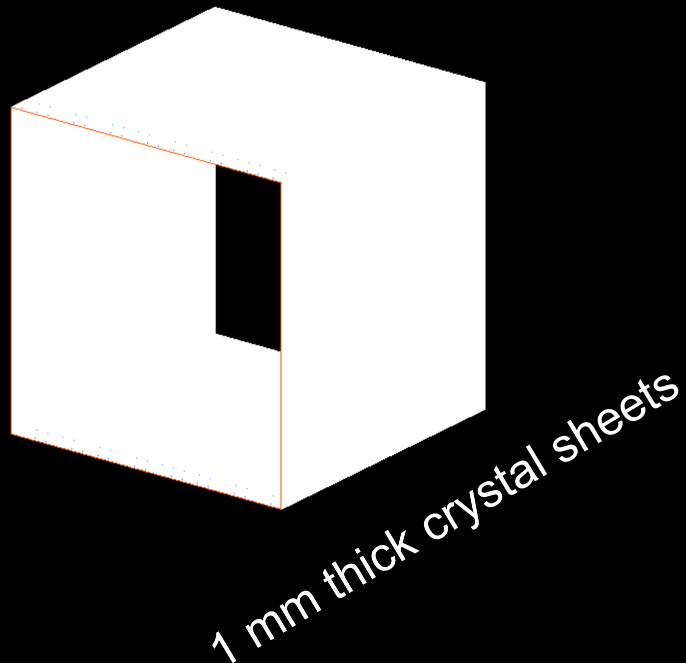


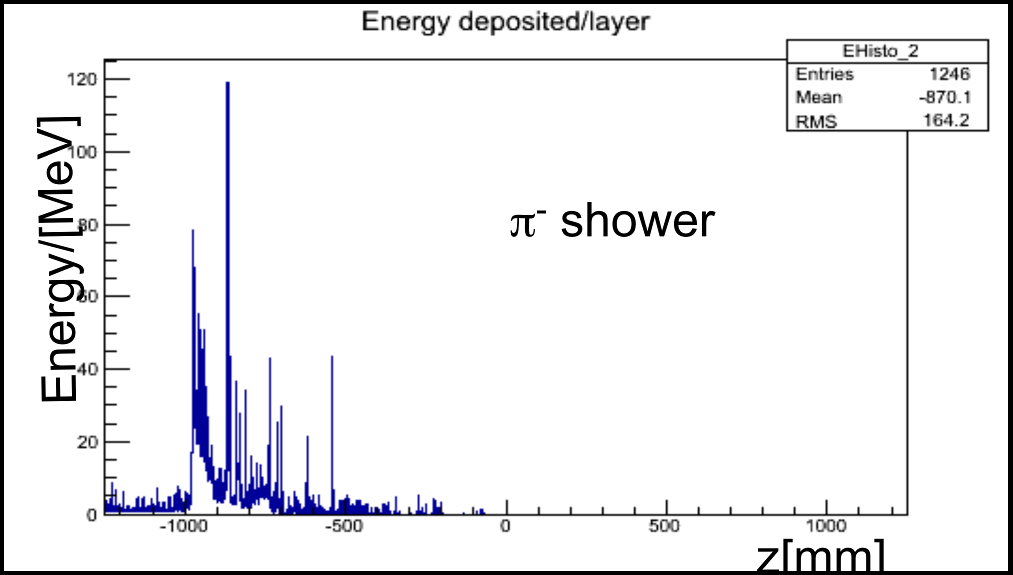
In the fast cascade stage, protons and neutrons are emitted in the ratio in which they are present in the target nucleus. ~1.39

Protons

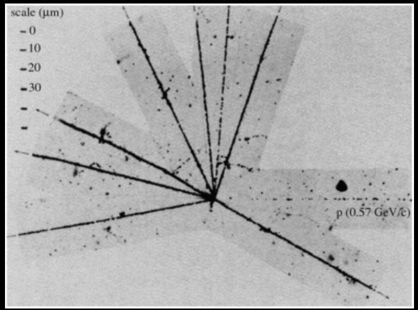
“Spikes” in the longitudinal shower profile

PbF2
2.5x2.5x2.5 m^3





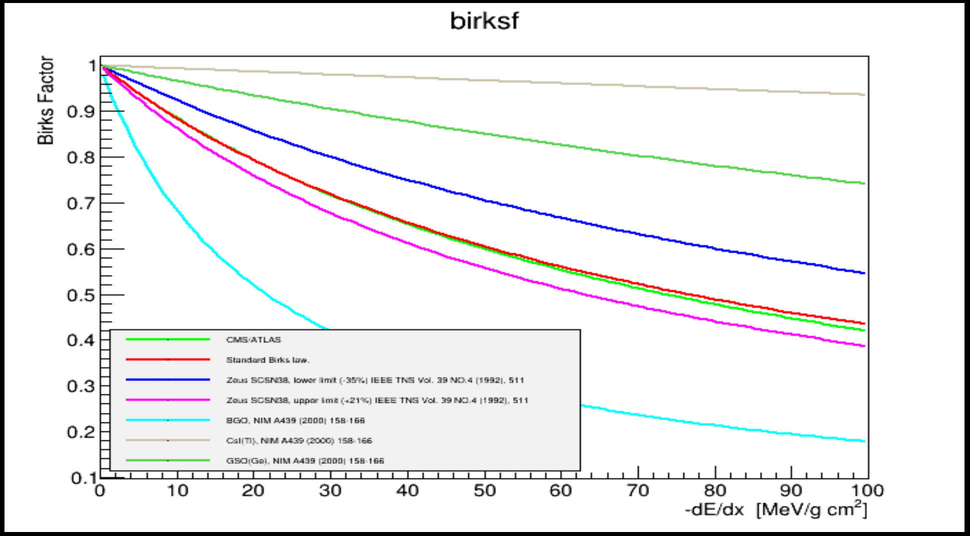
“Spikes” are due to spallation protons/alphas produced in inelastic hadron-nucleus interactions

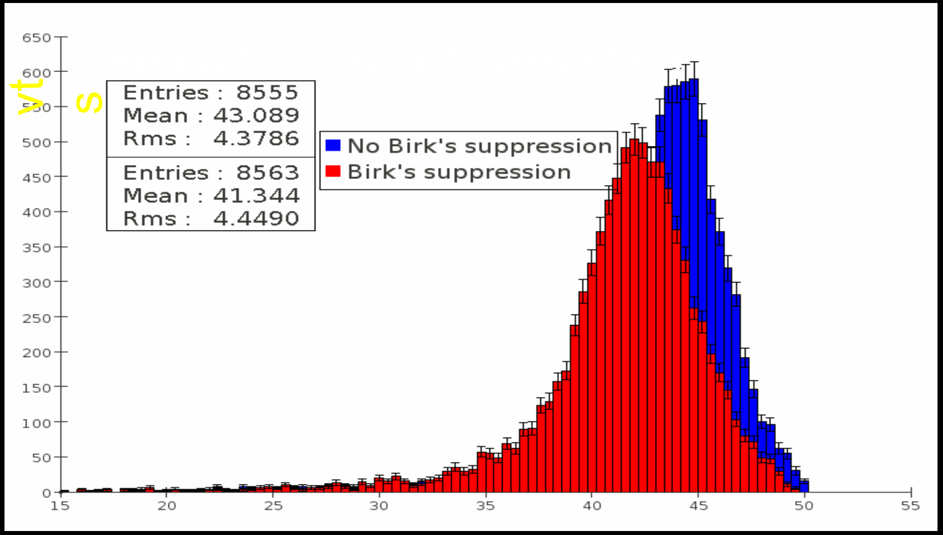


Birks saturation

Implemented in CaTS:

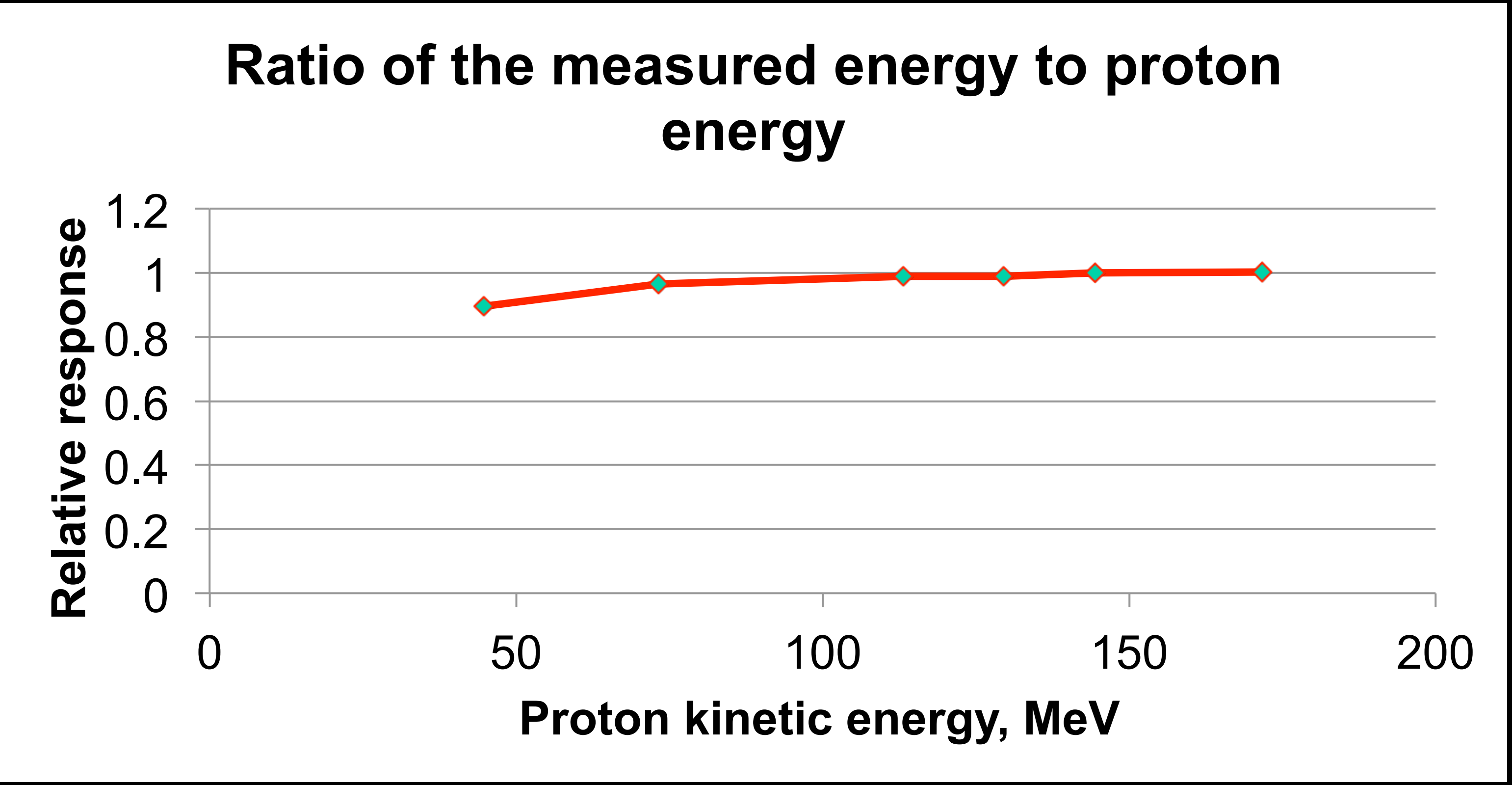
$$\frac{dL}{dr} = \frac{S \cdot {dE}/{dr}}{1 + c_1 \cdot {dE}/{dr} + c_2 \cdot ({dE}/{dr})^2}$$





Response of crystals to low energy protons

The only experimental plot in the presentation



Implications of Spallation Protons for Calorimetry

- Range of spallation protons is very short (~ 1 mm).
- In a sampling calorimeter these energies might not observable (part of the ‘nuclear effects’). Fluctuations contribute to resolution
- In a total absorption calorimeter these protons contribute significantly to the observed ionization signal. Need to overcome Coulomb barrier so enough kinetic energy to be only slightly affected by saturation effects (Birks).
- These protons don’t contribute to Cerenkov signal. (not relativistic)

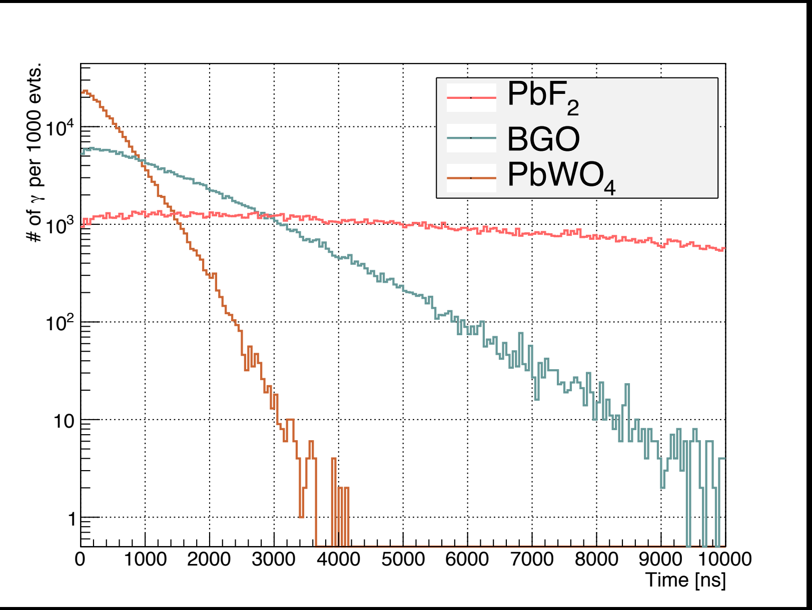
Neutrons

Contribution of neutron Capture process in 5 GeV π^- showers

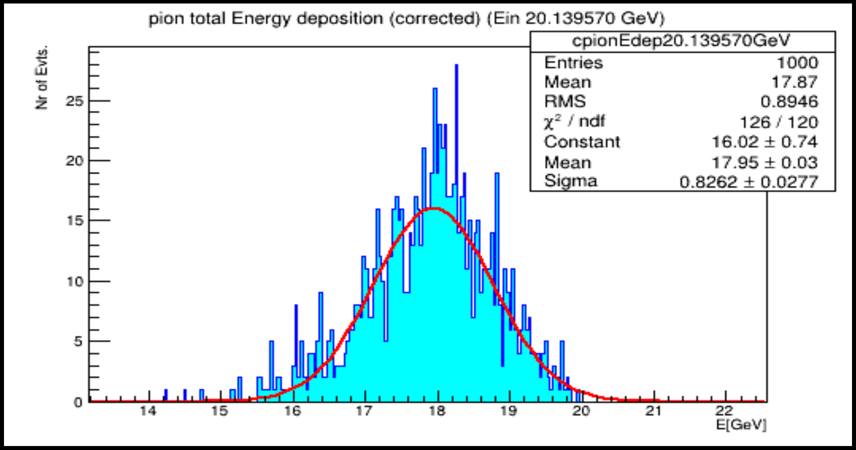
Response (PbF_2)		Response due to nCapture		Fractional nCapture Response	
Ionization [GeV]	Cerenkov [# C phot.]	Ionization [GeV]	Cerenkov [# C phot.]	Ionization [%]	Cerenkov [%]
4.322	1.977E5	0.734	0.456E5	17	23

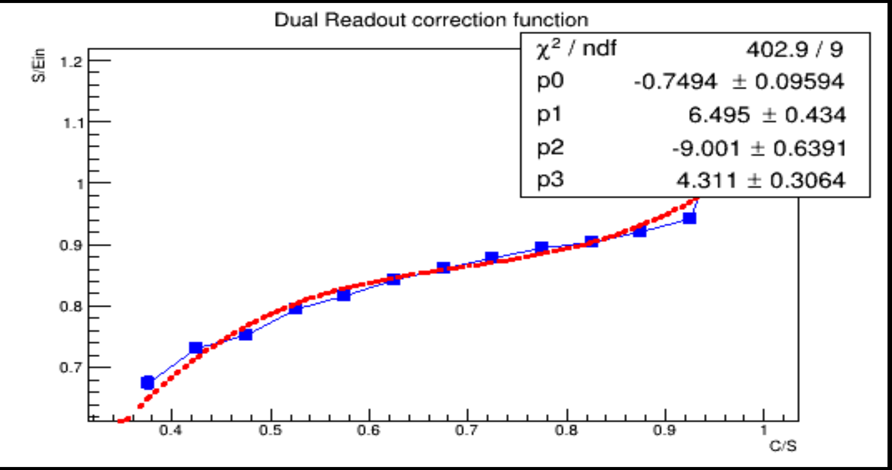
n→ thermalize → neutron Capture → γ → visible Energy

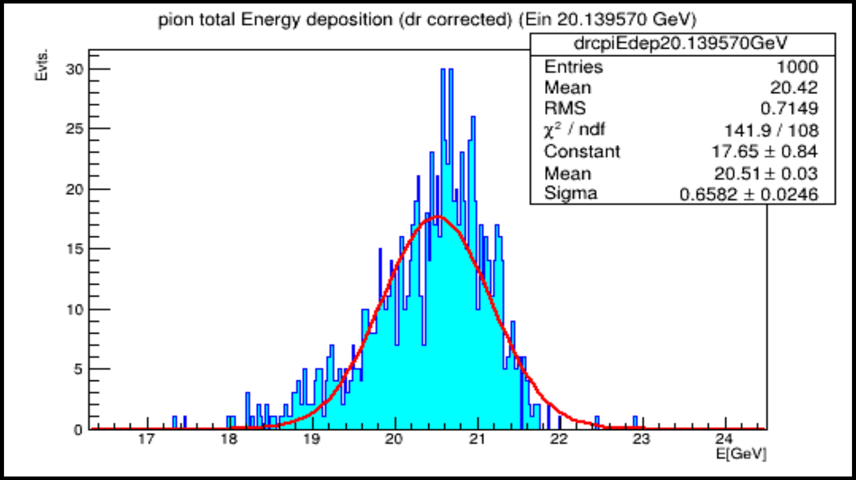
(mean Time: >4.2 μ sec (PbF_2))



Effect of dual read out correction: all contributions no gate



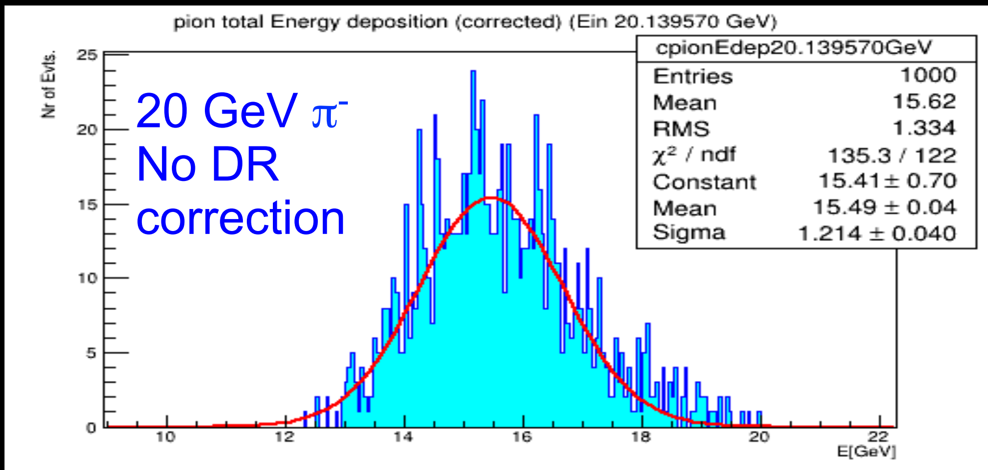


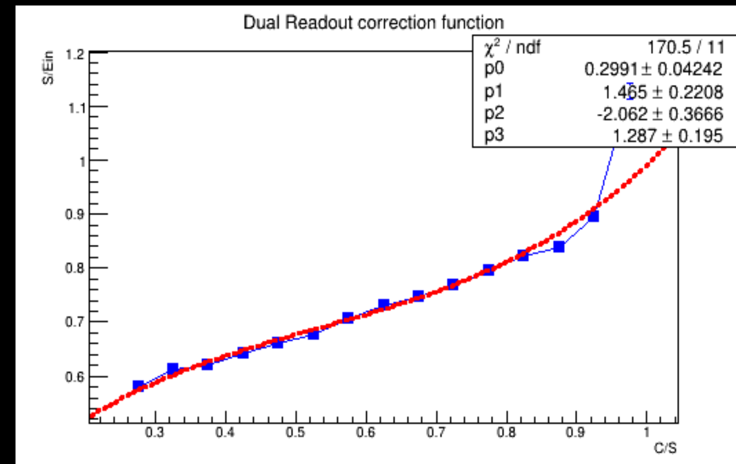


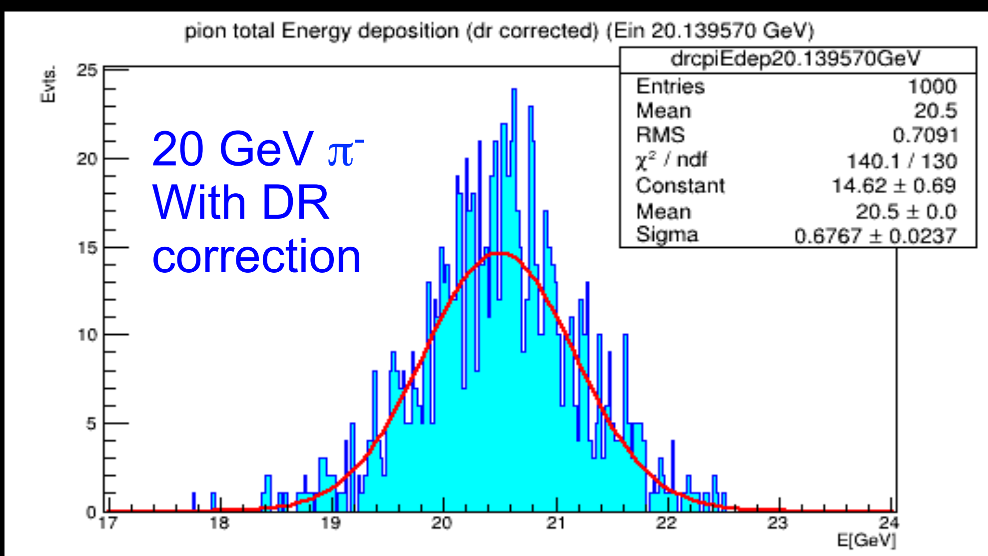
Before Dual Read out correction:
Mean: 17.95 GeV
σ: 0.826 +/-0.03GeV

After DR correction:
Mean: 20.5 GeV
σ: 0.66+/-0.02 GeV

Effect of dual read out correction: γ 's from neutron Capture discarded







Before Dual Read out correction:
Mean: 15.5 GeV
(reduced by 13.6 %)
σ: 1.21+/-0.04 GeV

After DR correction:
Mean: 20.5 GeV
σ: 0.68+/-0.02 GeV

“Neutrons”

- In a “sampling” calorimeter with hydrogenous active medium these neutrons are observed via elastic n-p reaction. The kicked protons are very soft and highly ionizing → Birks suppression plays an important role in explaining the observed signal in Sz. Plastic also serves as moderator.
- In a total absorption Crystal calorimeter these neutrons are thermalized and captured (on a microsecond timescale) and they ‘return’ all of their energy to the observed ionization signal (γ’s).
- These γ‘s from neutron capture also contribute significantly to the Cerenkov signal.
- Total observed energy and Nr. Of Cerenkov photons depends on the integration time and material.
- The magnitude of the dual readout correction depends on the gate. Resolution does not (after the correction)!

Conclusion

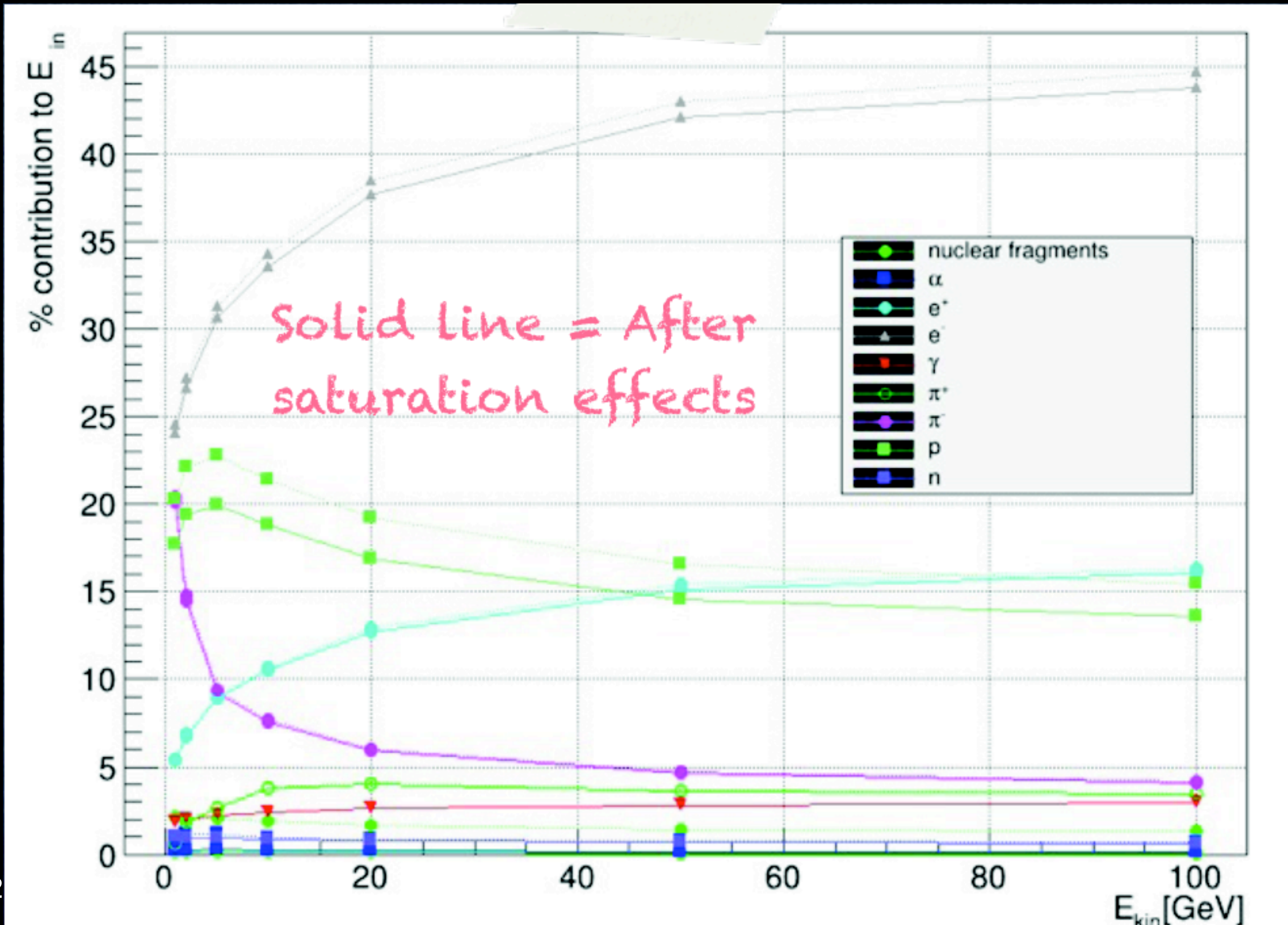
- Demonstrated the performance of a dual read out crystal calorimeter.
- Could reproduce behavior of sampling calorimeters (not shown in this presentation) and understand compensation.
- We created a flexible, easy to use simulation framework (CaTS). Allows detailed studies of single Crystals and full detector setups.
- Presented here how protons and neutrons contribute to the Scintillation and Cerenkov response in a crystal total absorption calorimeter.
- Simulation provides guidance for small

  scale test beam studies.
- Work in progress

Calorimeter and Tracker Simulation

Backup

Toward happy
Little by little
Let’s progress


% contribution to E_in
E_kin[GeV]
nuclear fragments
α
e+
e-
γ
π+
π-
p
n
Solid line = After saturation effects

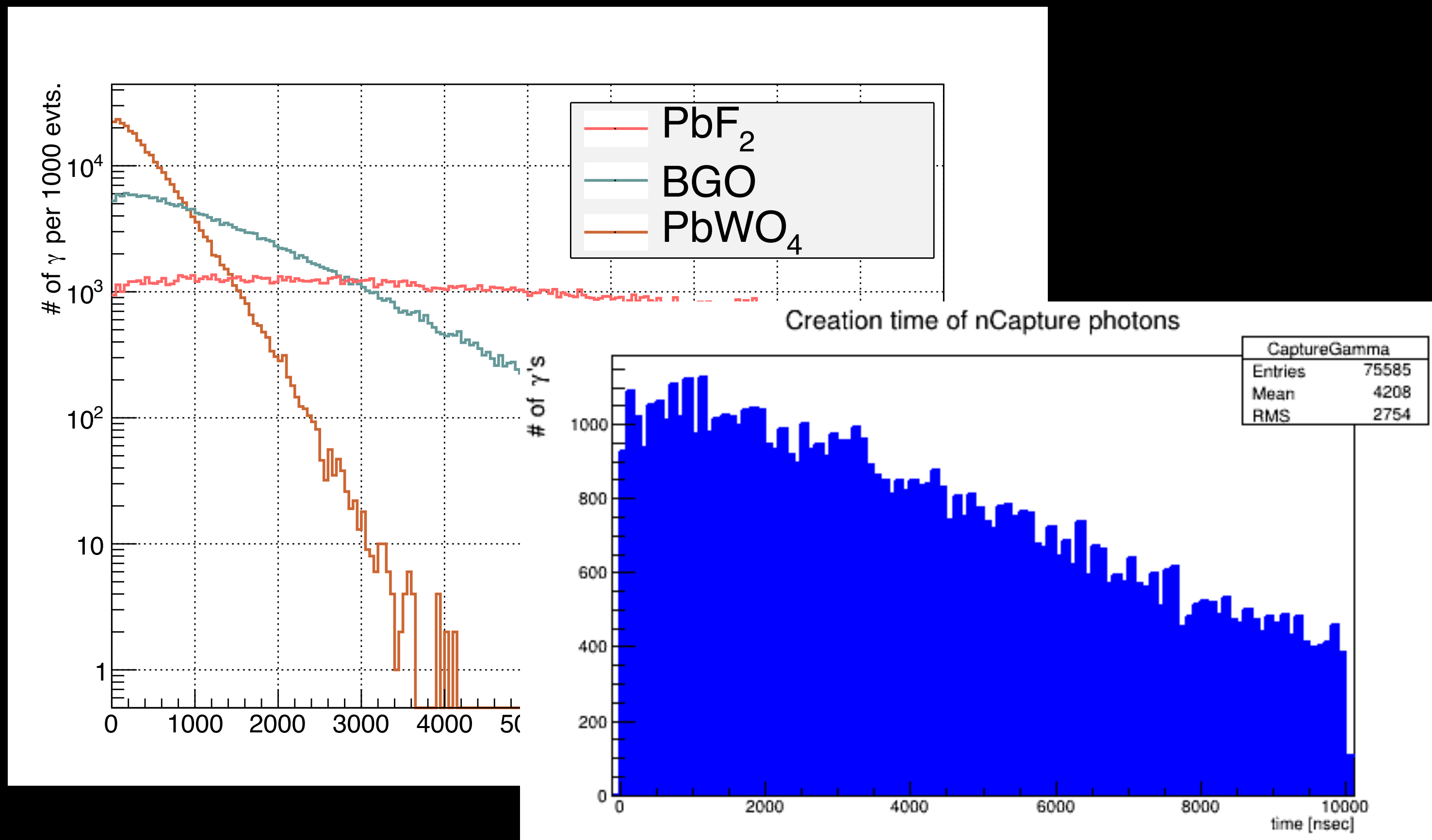
CaTS: Calorimeter and Tracker Simulation

Hans Wenzel, Paul Russo, Peter Hansen
http://home.fnal.gov/~wenzel/CaTS.html

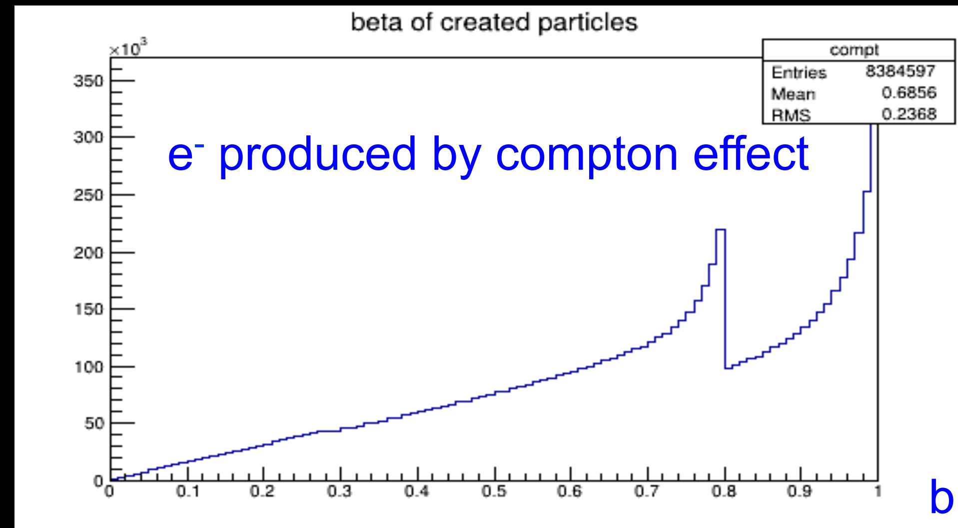
CaTS is a flexible and extend-able framework (based on geant4 and ROOT) for the general simulation of calorimeter and tracking detectors.

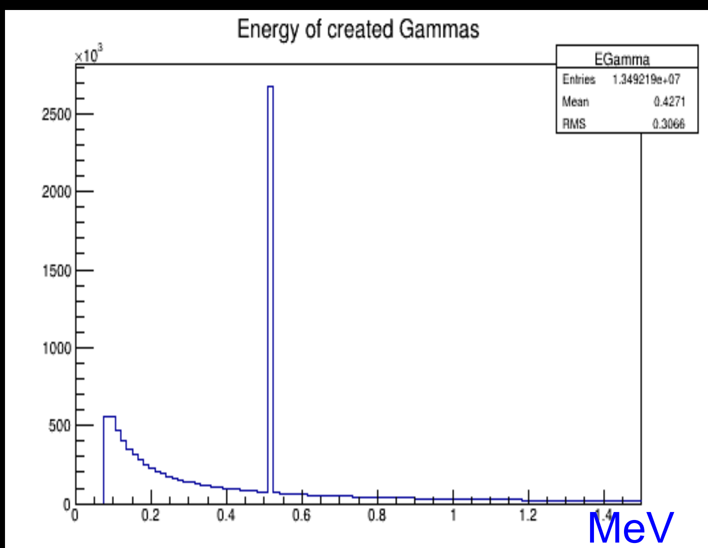
To be able to simulate Dual Read out calorimeters it provides special sensitive detectors and Hit classes that register both the energy deposit and the number of Cerenkov photons produced by particles above the Cerenkov threshold. Moving the calculation of produced Cerenkov photons into the sensitive detector results in significant speed up (10X) and reduces memory use

CaTS also allows the detailed study of single Calorimeter cells by enabling the tracing of optical photons, providing sensitive detectors that register optical photons and the gdml detector description allows to provide all relevant optical properties (refraction Index, Absorption length, Scintillation Yield, Rayleigh scattering length, Surface properties (e.g. Reflectivity)....)


PbF2
BGO
PbWO4
# of γ per 1000 evts.
10^4
10^3
10^2
10
1
0
1000
2000
3000
4000
Creation time of nCapture photons
CaptureGamma
Entries 75585
Mean 4208
RMS 2754
# of γ's
1000
800
600
400
200
0
2000
4000
6000
8000
10000
time [nsec]

Structure of β-spectrum





7.3 Incoherent Scattering (Compton Effect) 317

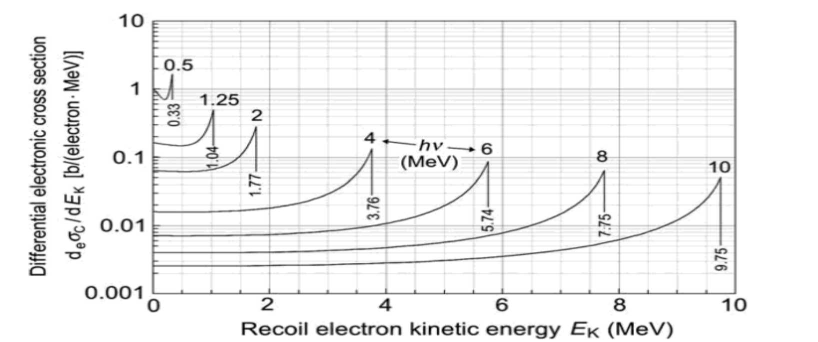
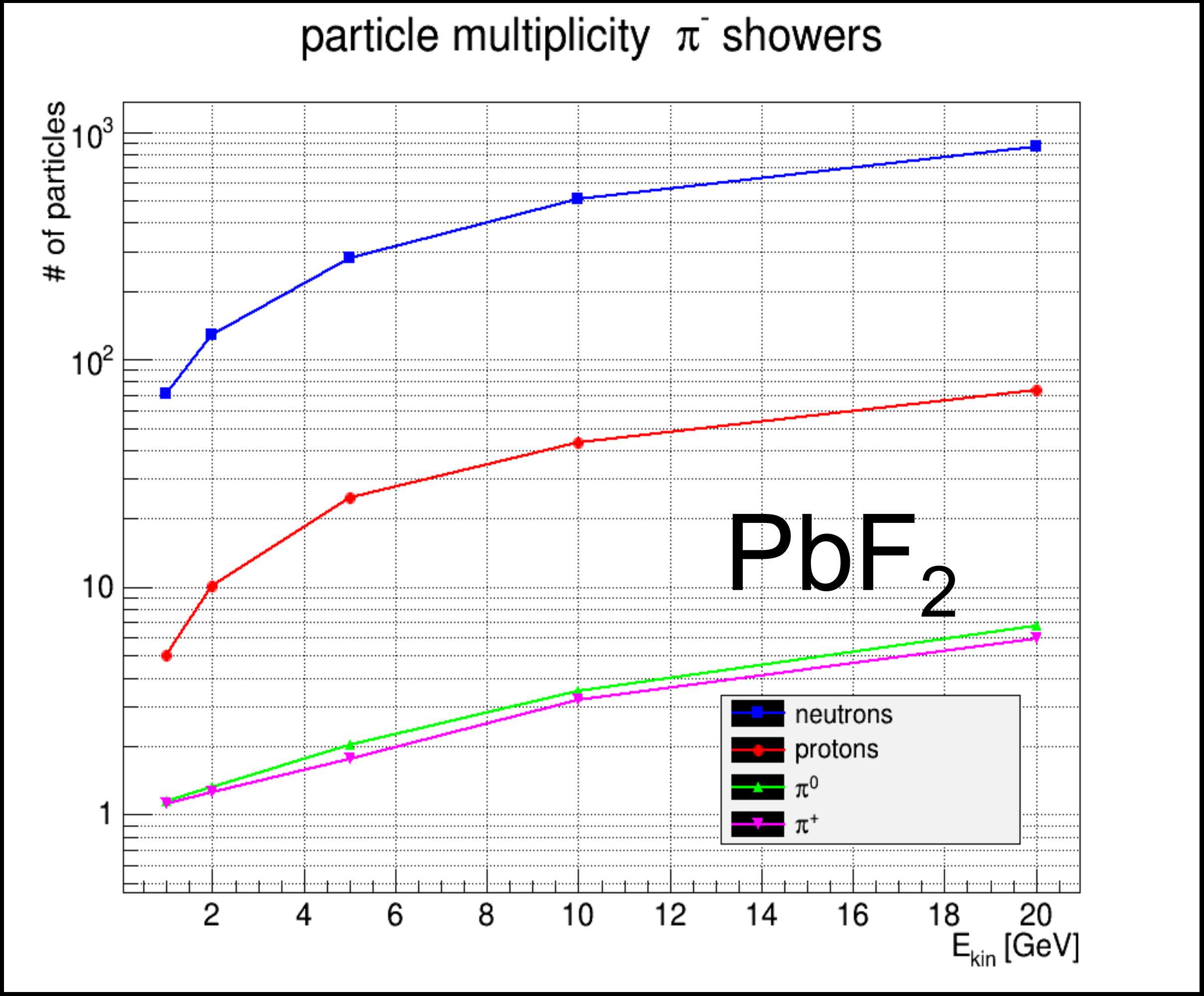


Fig. 7.16. Differential electronic Klein–Nishina cross section per unit kinetic energy $d_e\sigma_c^{KN}/dE_K$ calculated from (7.102) and plotted against the kinetic energy of the Compton recoil electron E_K^C for various incident photon energies $h\nu$ in the range from 0.5 MeV to 10 MeV. For a given photon energy the maximum kinetic energy of the recoil electron in MeV, calculated from (7.81), is indicated on the graph

Multiplicity of selected particles in π^- showers



n/p ratio depends on material. Size of the Coulomb barrier