Physics of hadron shower development and the implications for calorimetric resolution

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Motivation for a Total Absorption Dual Readout Calorimeter

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

Outline

- We want 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?
- How can we contribute to the validation of Geant 4

CaTS: Calorimeter and Tracker Simulation

Hans Wenzel, Paul Russo, Peter Hansen

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

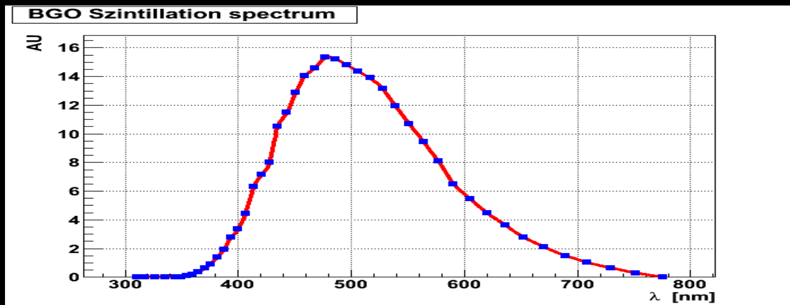
CaTS also allows the detailed study of single Calorimeter cells by enabling the tracing of optical photons, providing sensitive detectors that register optical photons and the gdml detector description allows to provide all relevant optical properties (refraction Index, Absorption length, Scintillation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

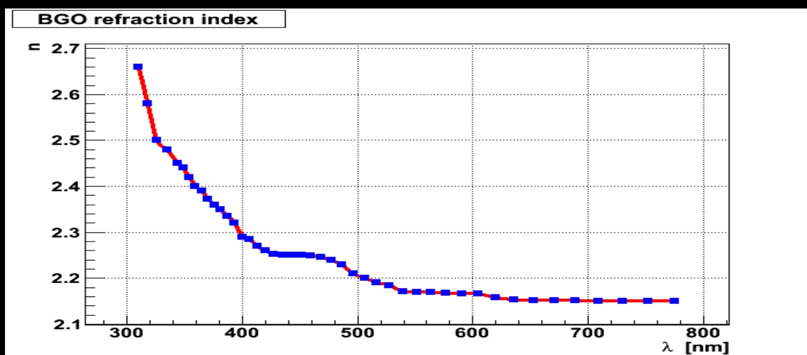
Elements of CaTS

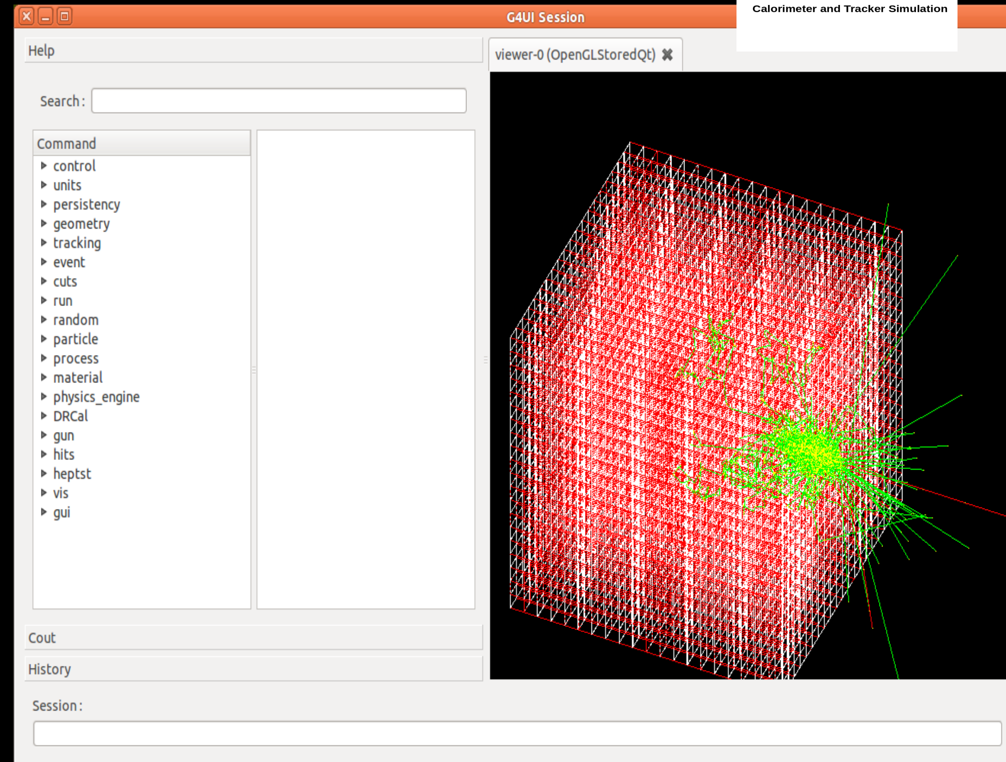
Calorimeter and Tracker Simulation

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

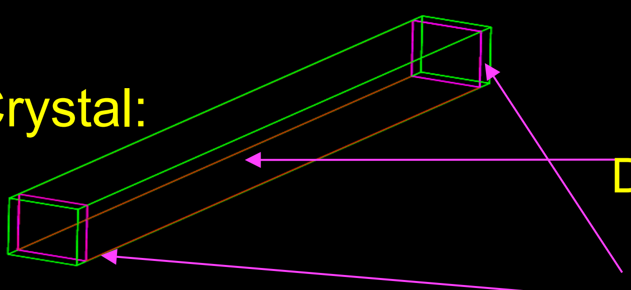
CaTS in Action: inputs and results





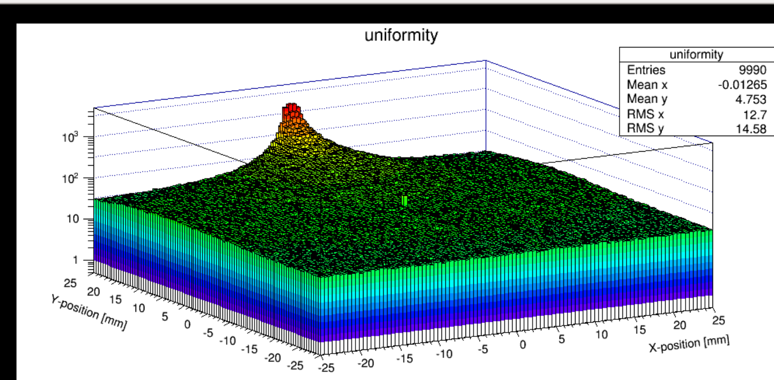


Crystal:



DRCalorimeterSD

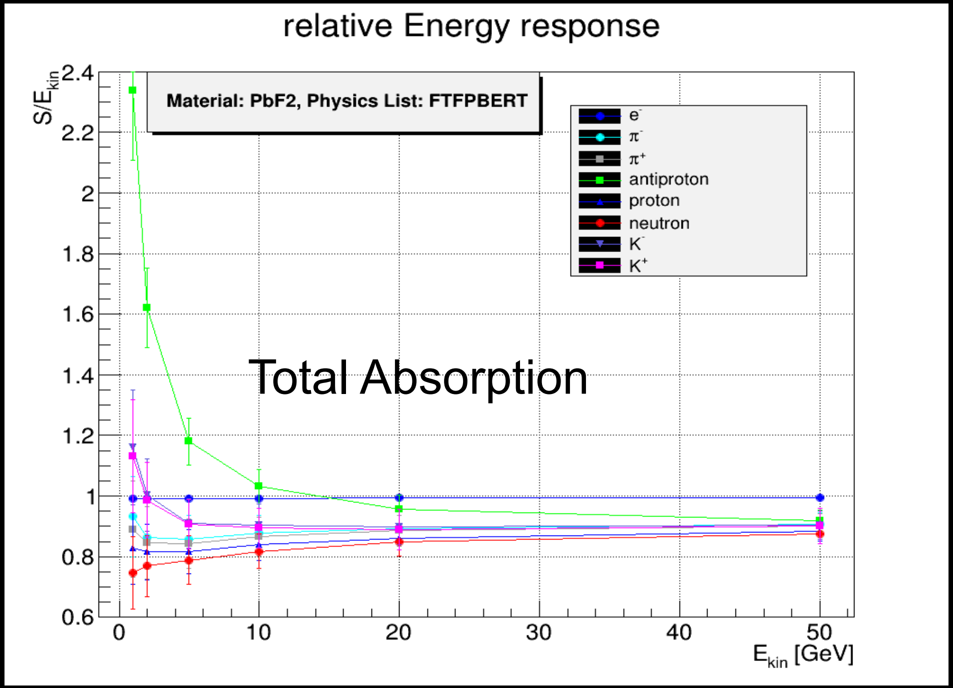
PhotonSD

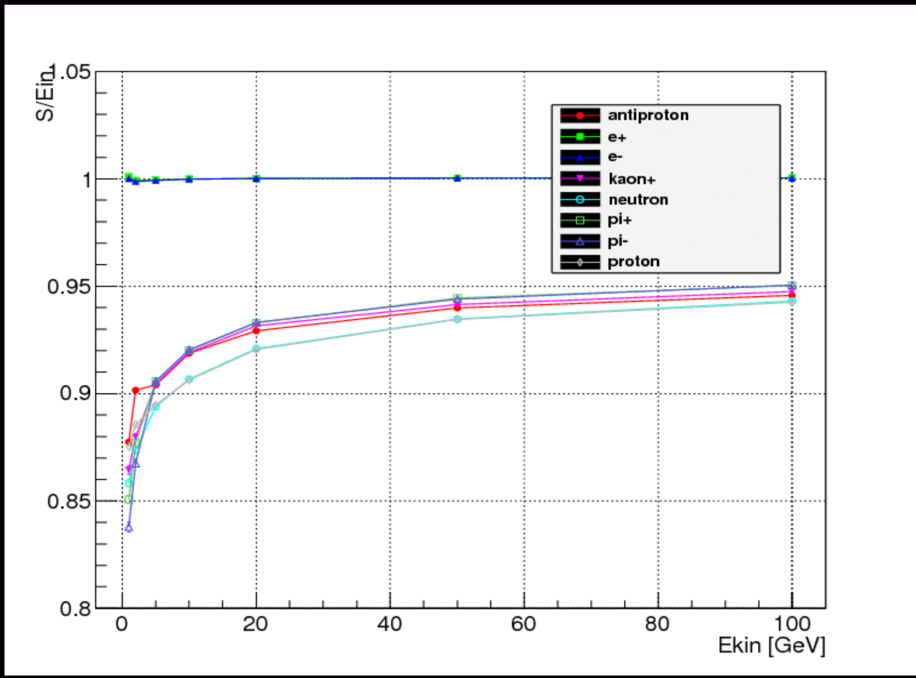


Response of non-compensating calorimeters

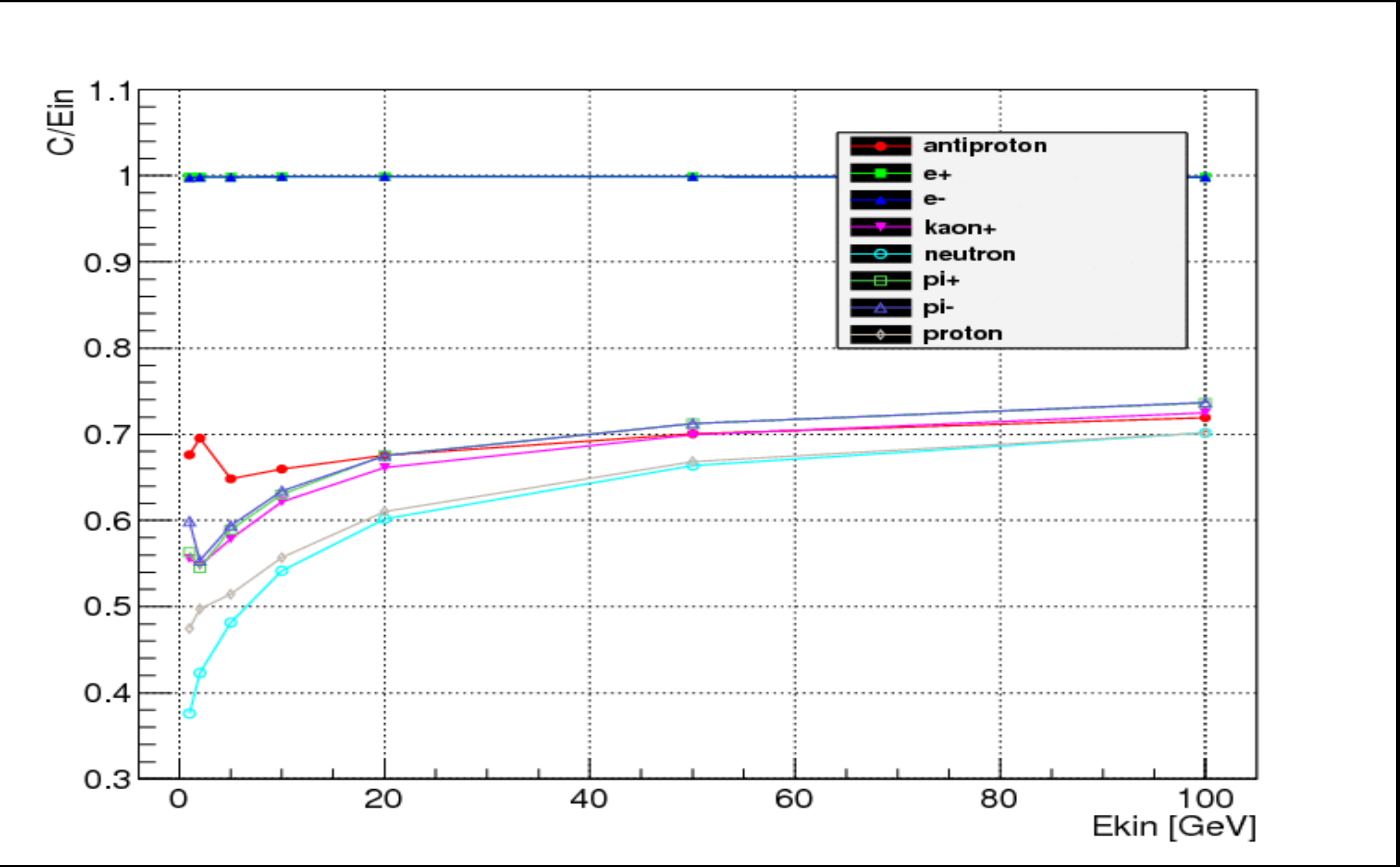
<u>Hadronic sampling calorimeters:</u>
non-linearity,
poor energy resolution,
non-Gaussian response function
Different response for different particles

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





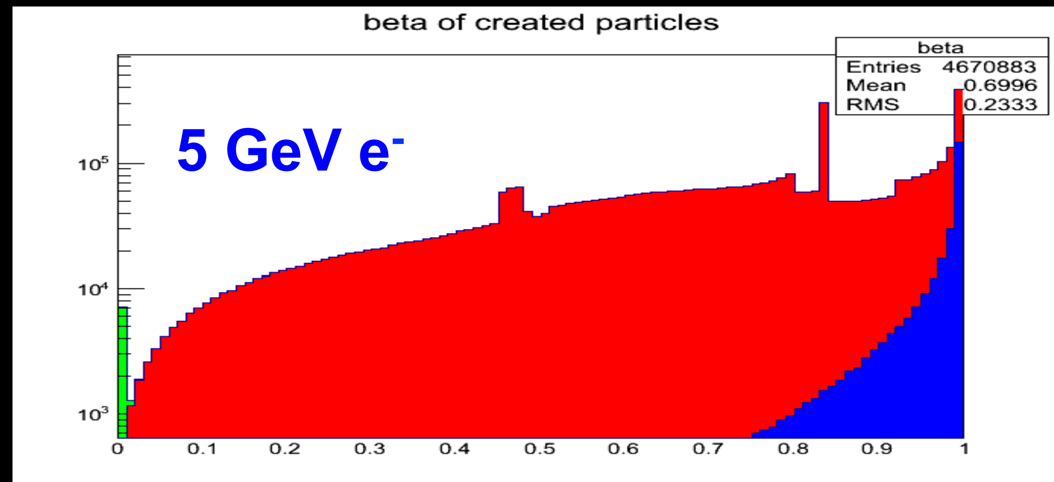
Cerenkov response

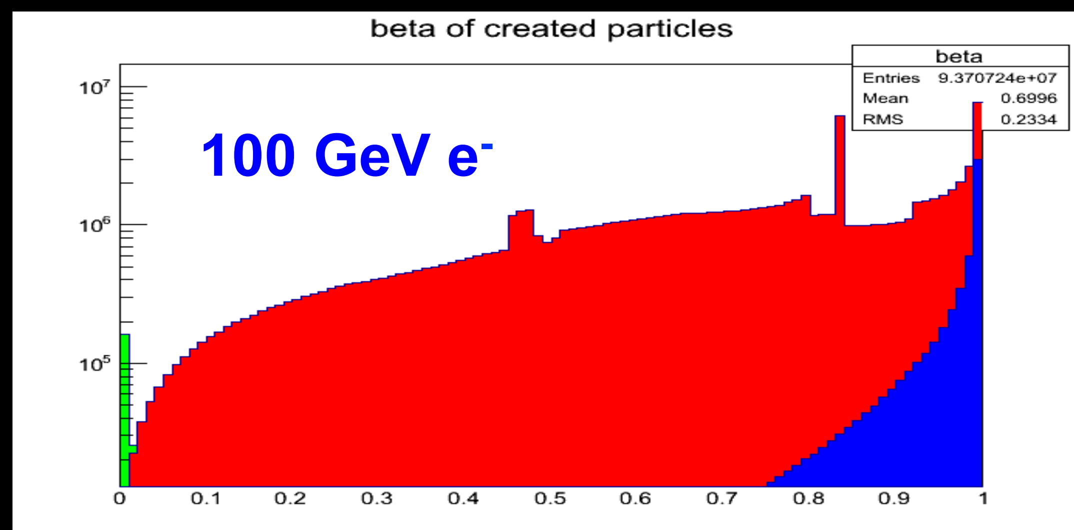


Cerenkov em Calorimeters work

β of charged particles produced in e^- showers

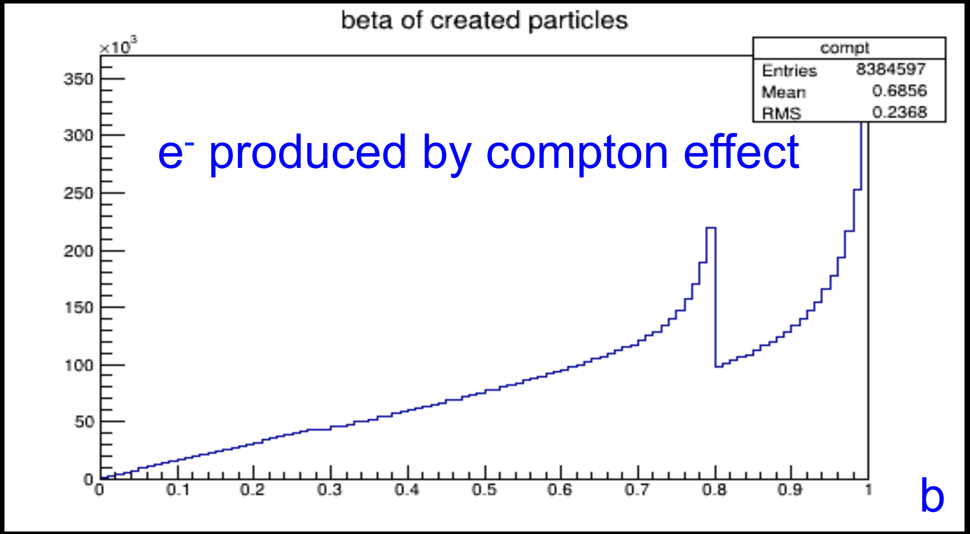
- Red: e^-
- Blue: e^+
- Green: Charged nuclei produced in nuclear Photo-production

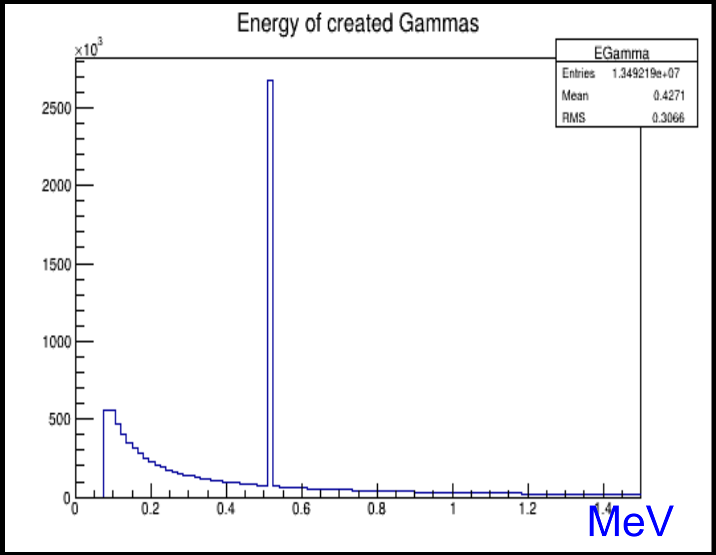




E_{in} (e^-) [GeV]	Mean β
5	0.6996
100	0.6996

Structure of β-spectrum





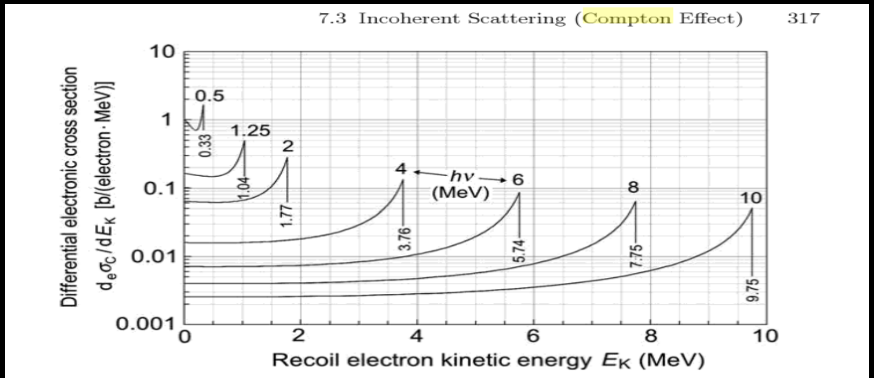
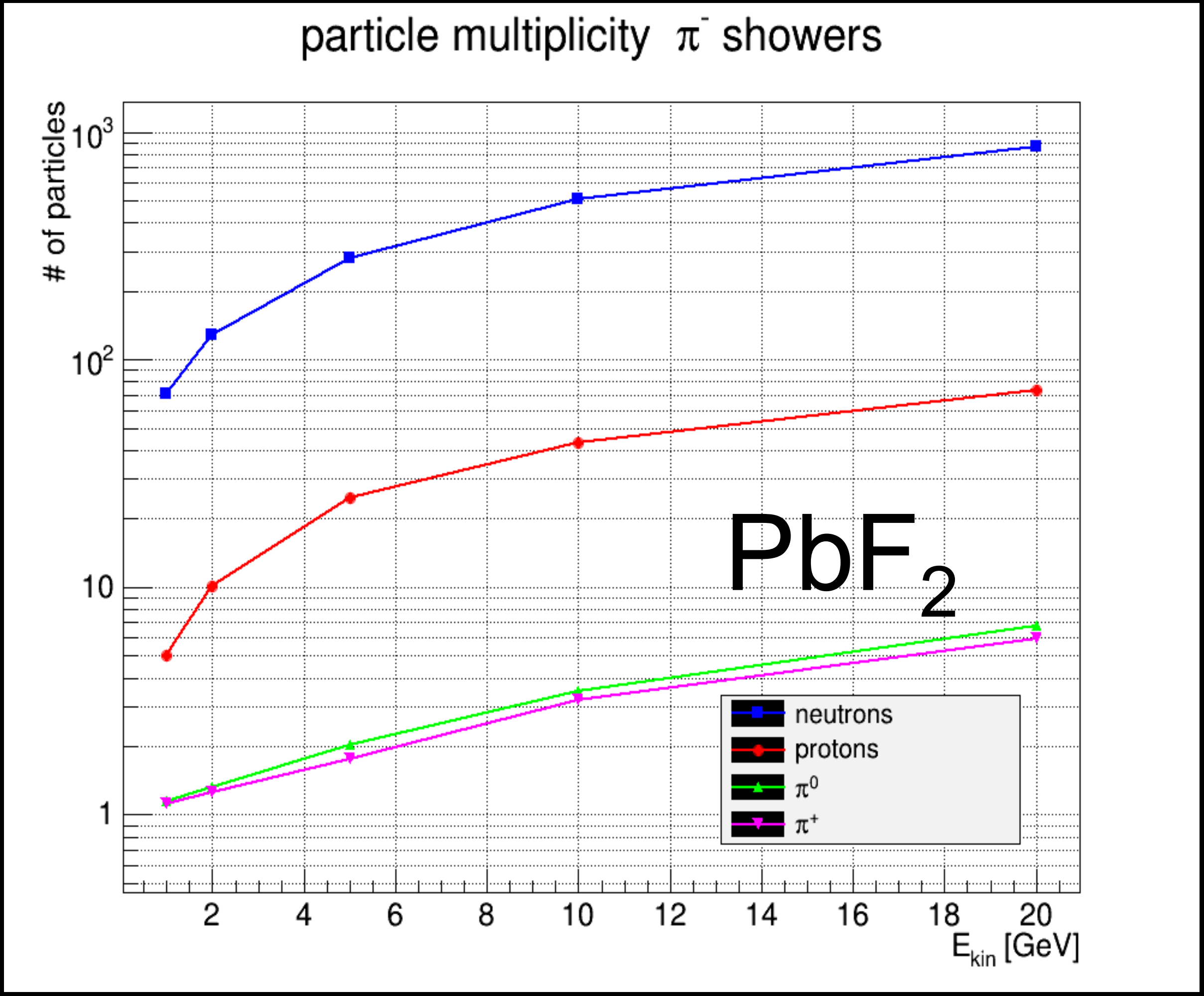


Fig. 7.16. Differential electronic Klein–Nishina cross section per unit kinetic energy $d_e\sigma_c^{KN}/dE_K$ calculated from (7.102) and plotted against the kinetic energy of the Compton recoil electron E_K^C for various incident photon energies $h\nu$ in the range from 0.5 MeV to 10 MeV. For a given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

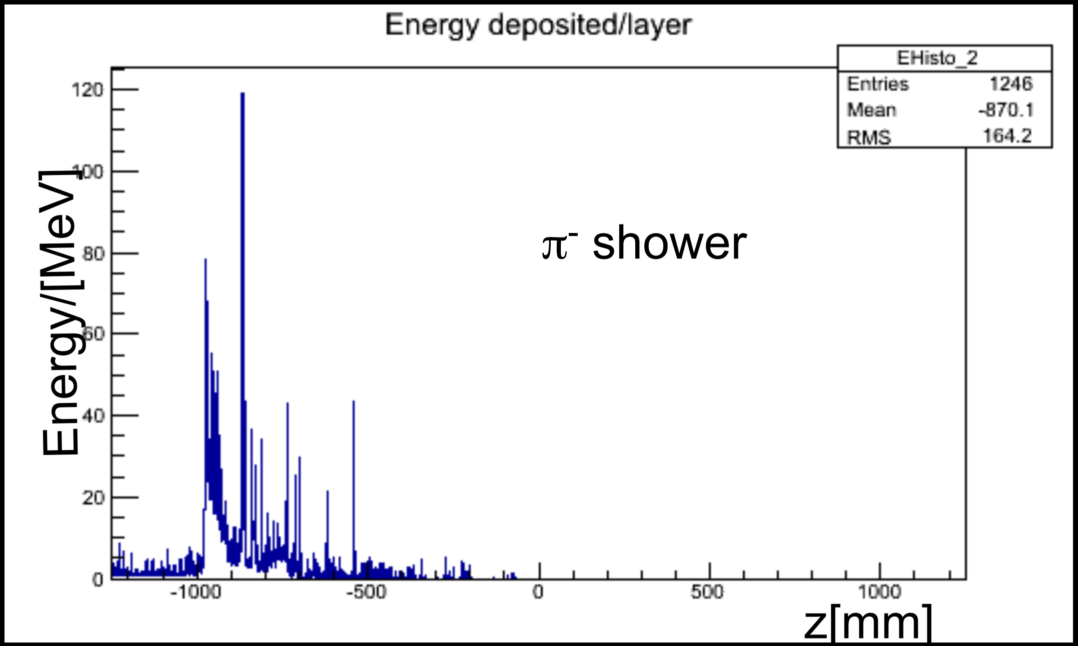
Particle multiplicity in π⁻ showers



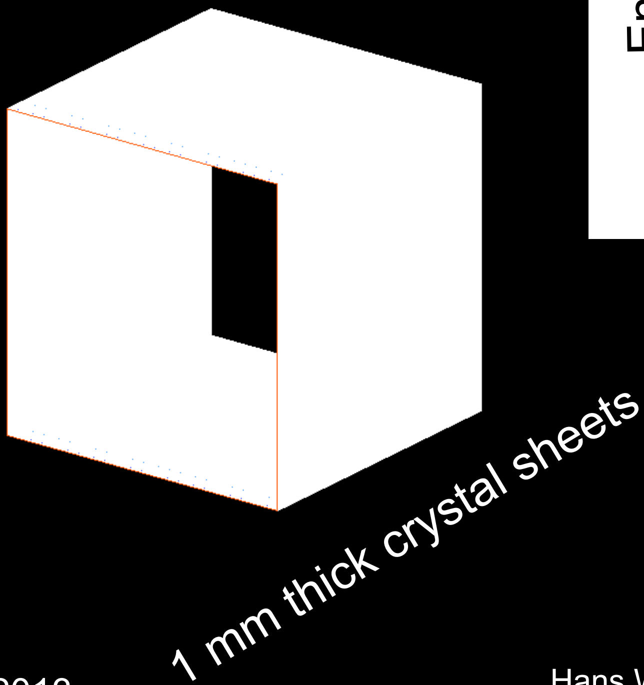
n/p ratio depends on material. Size of the Coulomb barrier

Protons

“Spikes” in the longitudinal shower profile

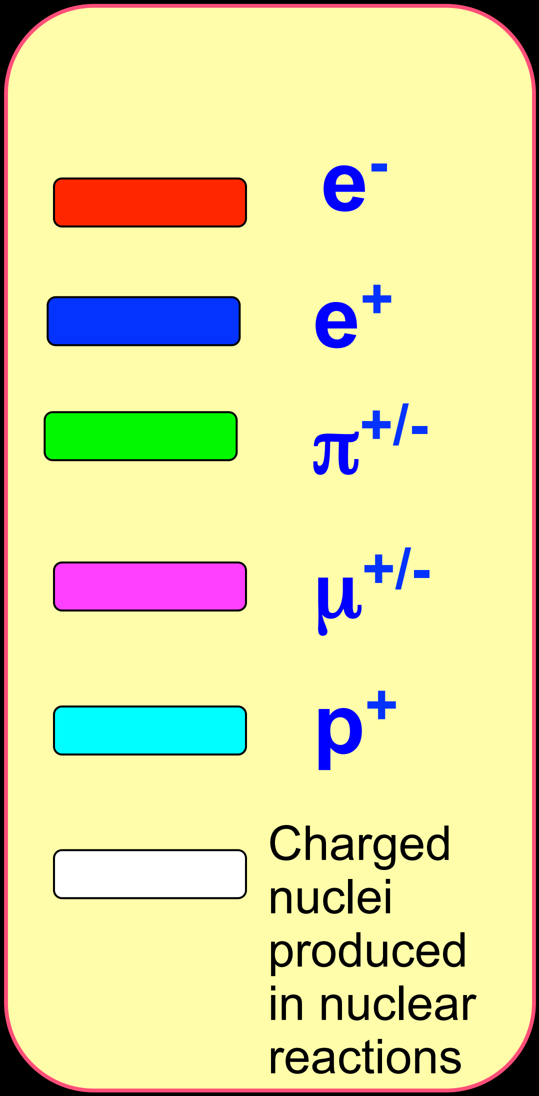


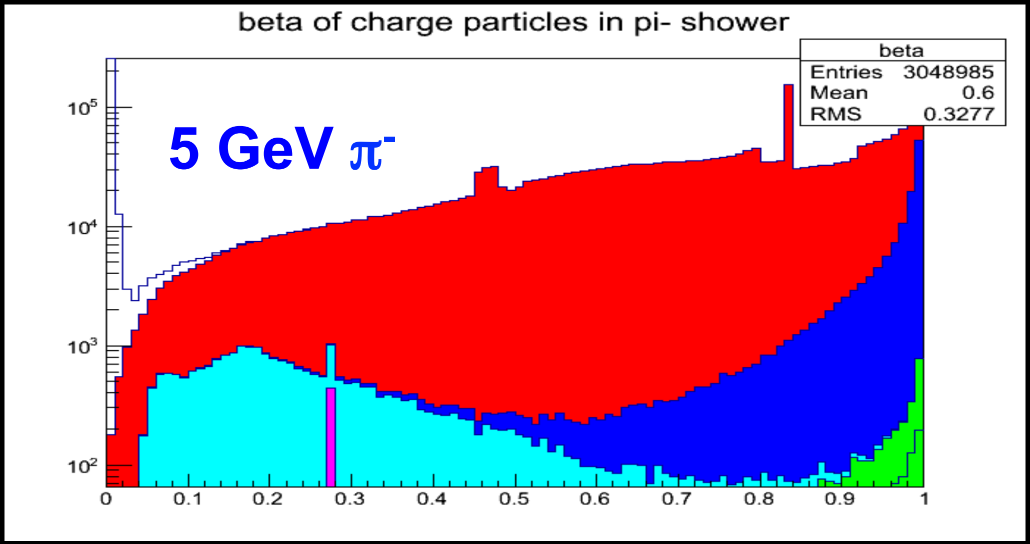
PbF2
2.5x2.5x2.5 m^3

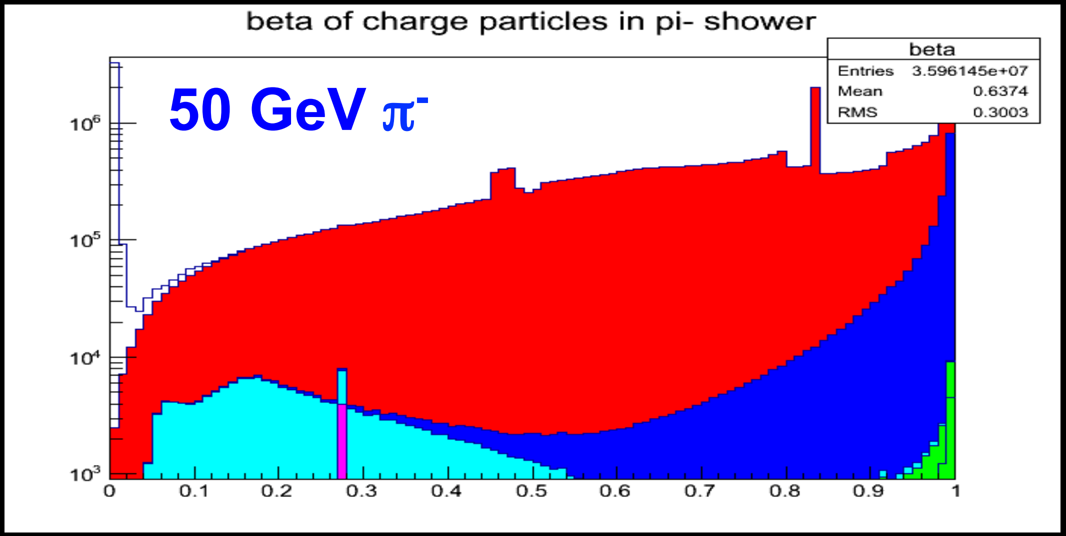


“Spikes” are due to spallation protons produced in inelastic hadron-nucleus interactions

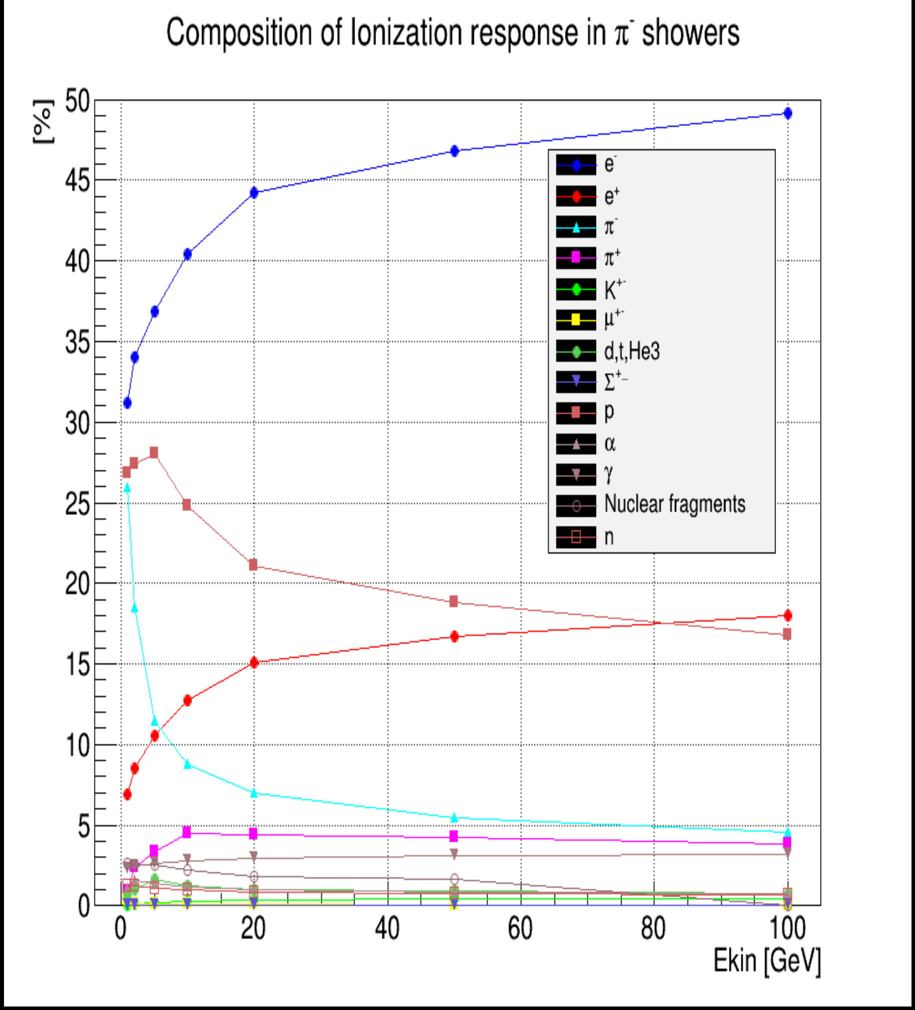
β of charged particles produced in π^- showers

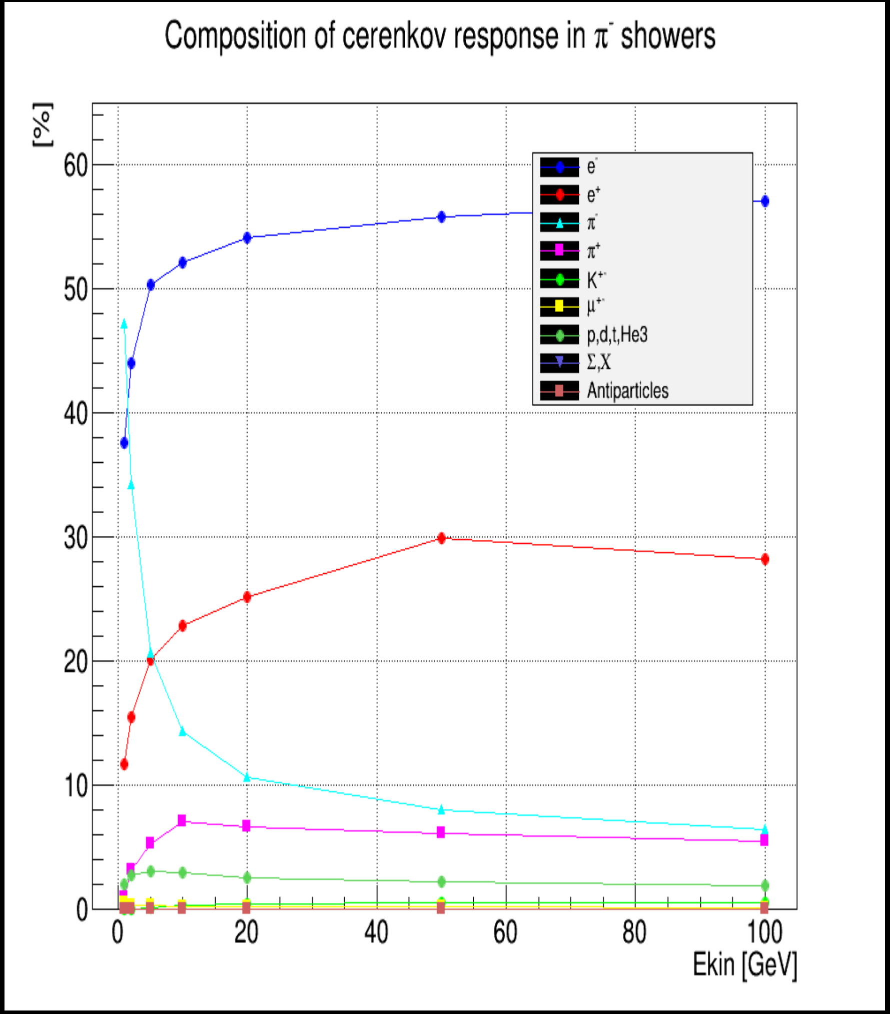






Composition of Ionization and Cerenkov response in π^- showers





Implications of Spallation Protons for Calorimetry

- Range of spallation protons is very short (~ 1 mm).
- In a sampling calorimeter these energies are not observable (part of the ‘nuclear effects’).
- In a total absorption calorimeter these protons contribute significantly to the observed ionization signal.
- These protons don’t contribute to Cerenkov signal.

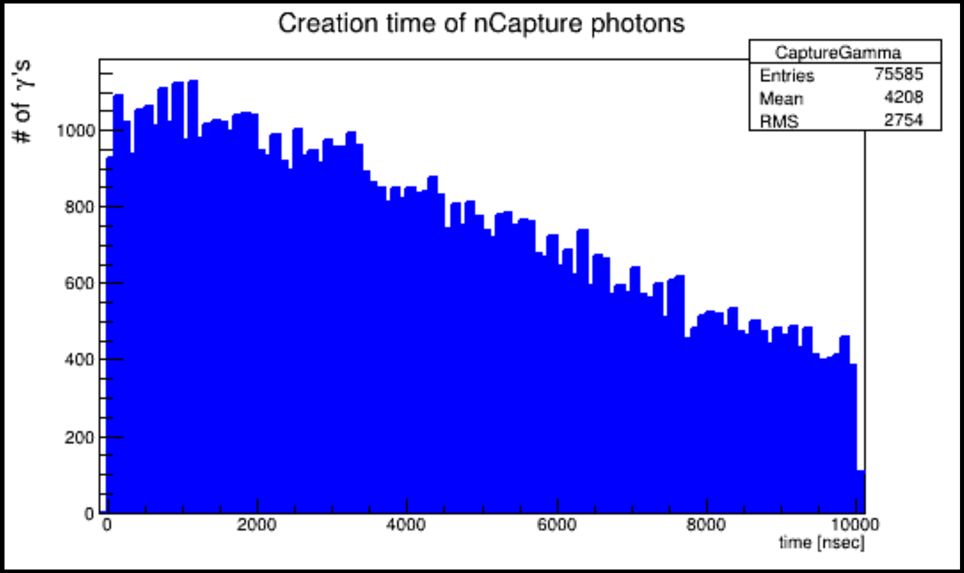
Neutrons

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

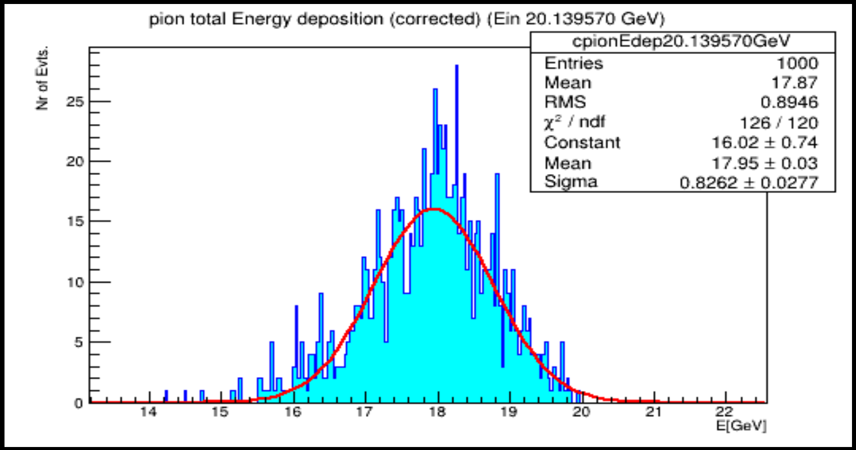
Response		Response due to nCapture		Fractional nCapture Response	
Ionization [GeV]	Cerenkov [# C phot.]	Ionization [GeV]	Cerenkov [# C phot.]	Ionization [%]	Cerenkov [%]
4.322	1.977E5	0.734	0.456E5	17	23

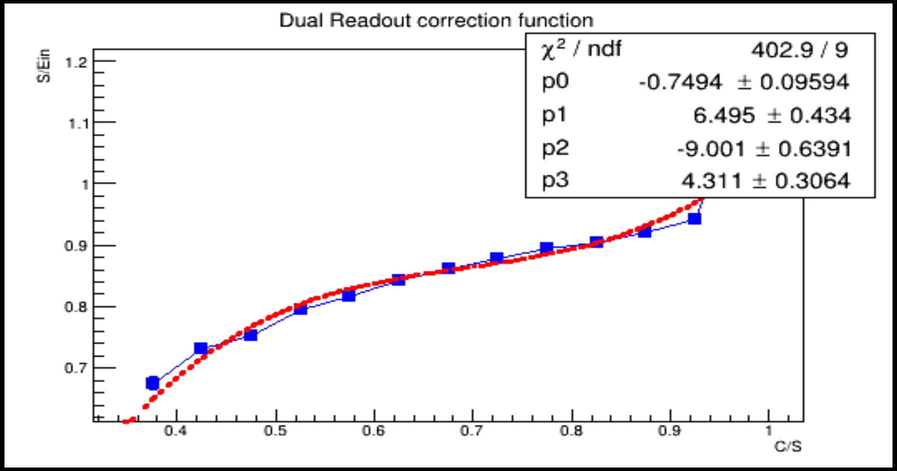
n→ thermalize → neutron Capture → γ → visible Energy

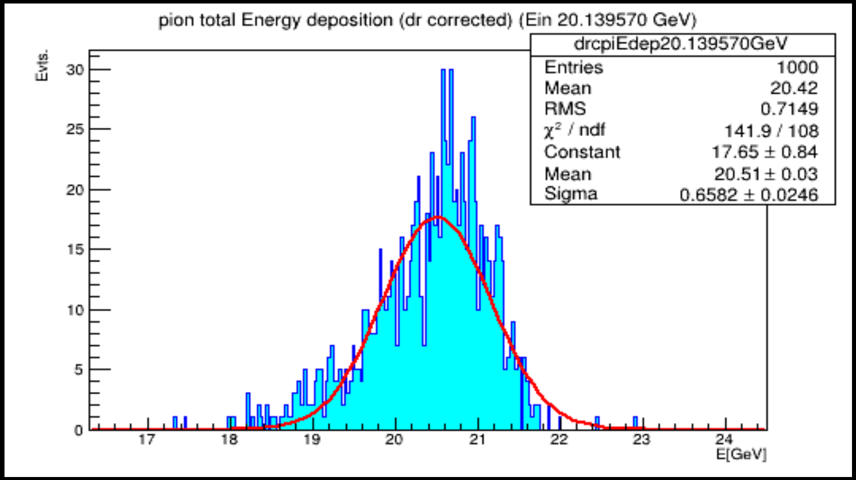
(mean Time: 4.2 μ sec)



Effect of dual read out correction: all contributions no gate



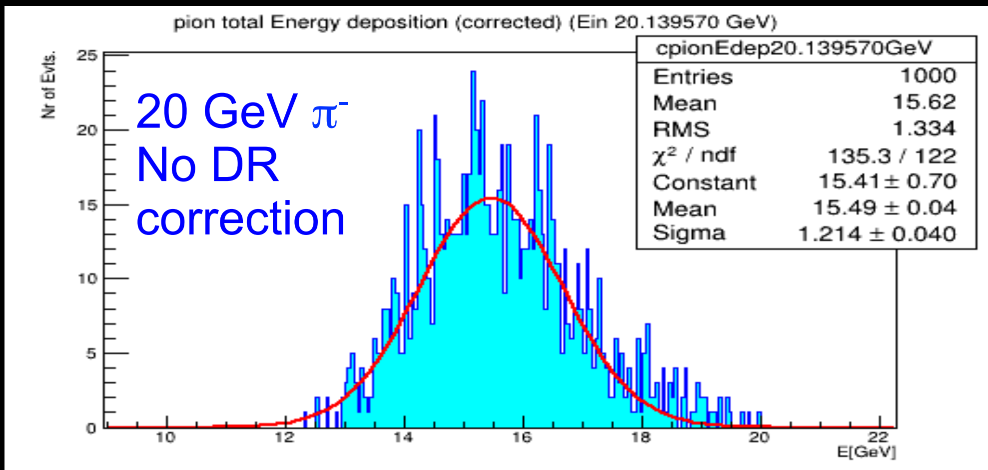


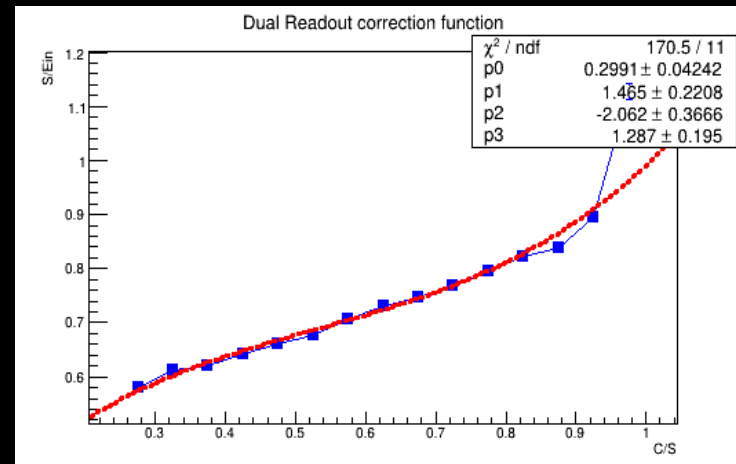


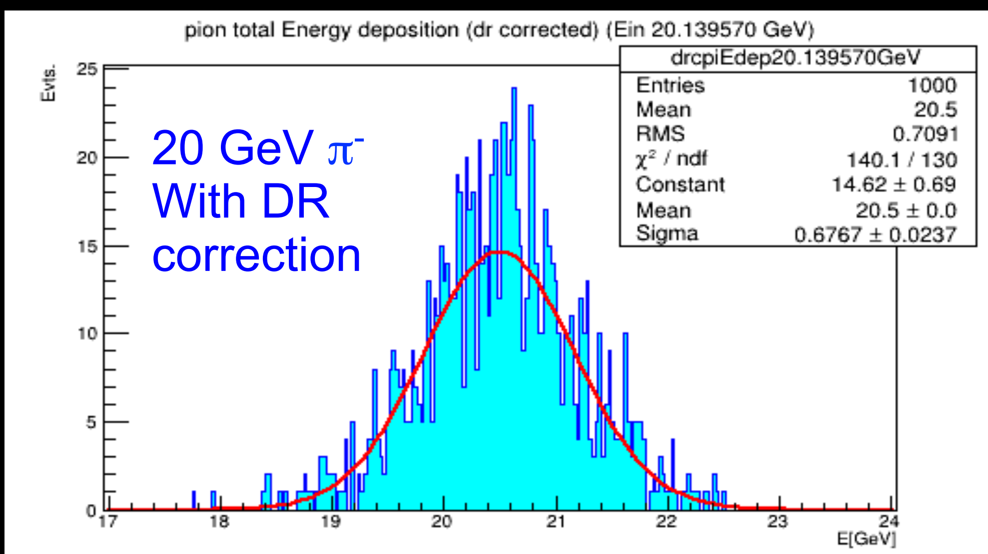
Before Dual Read out correction:
Mean: 17.95 GeV
σ: 0.826 +/-0.03GeV

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 hadron shower there are ~20 neutrons ‘evaporated’ per GeV of a shower from nuclei with typical energies of 1-2 MeV, thus consuming ~15-20% of a hadron shower energy.
- In a sampling calorimeter with hydrogenous active medium these neutrons are observed via elastic n-p reaction, thus recovering 1-2% of the total energy.
- 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

- We created a flexible, easy to use simulation framework (CaTS). Allows detailed studies of single Crystals and full detector setups.
- We have instrumented CaTS (GEANT 4.9.6.p01) to extract more information for detailed studies of the modeling of physics processes.
- Presented here how protons and neutrons contribute to the Scintillation and Cerenkov response in a crystal total absorption calorimeter.
- Work in progress

Calorimeter and Tracker Simulation

Toward happy
Little by little
Let’s progress

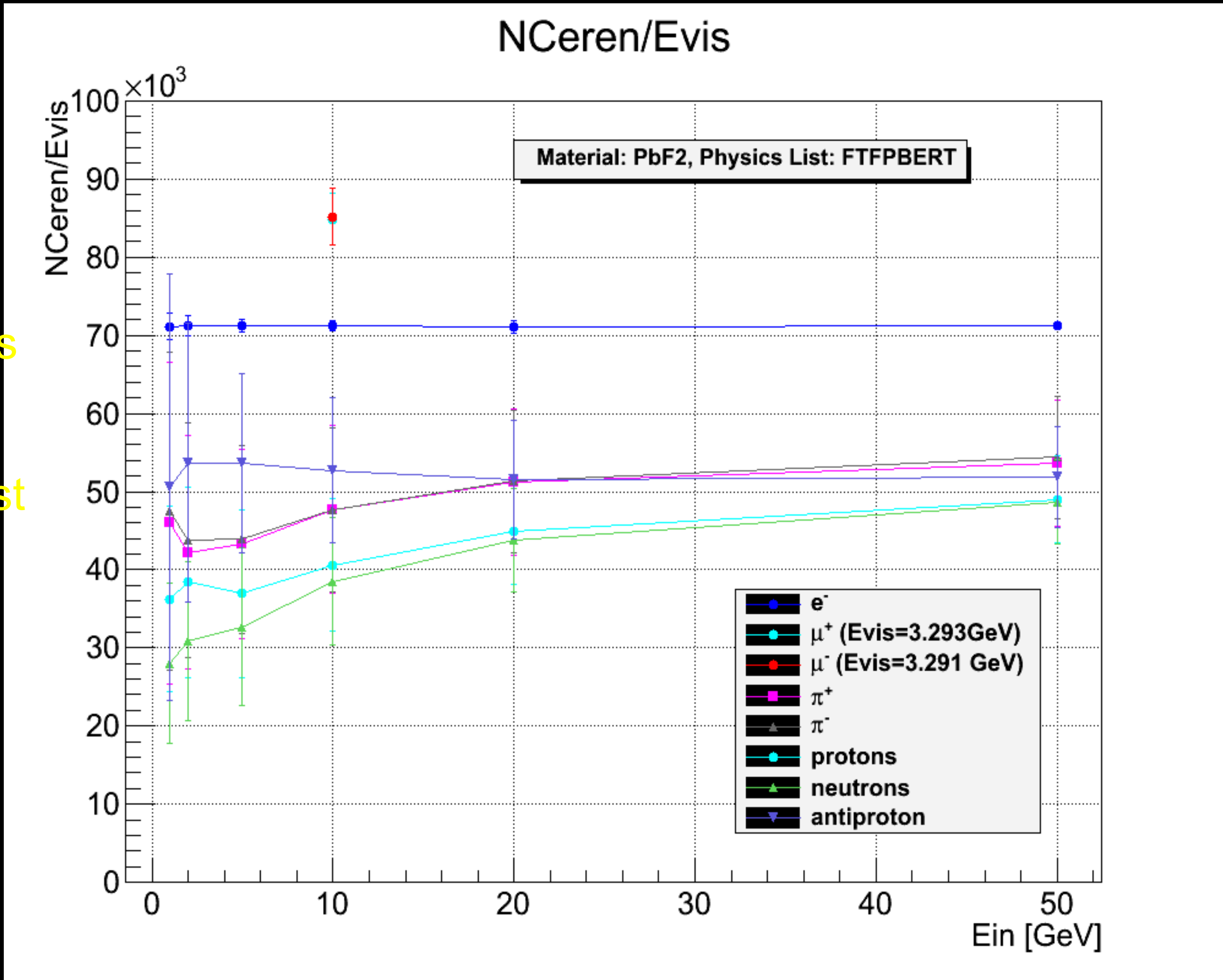
Backup

Ratio of Cerenkov/Scintillator (C/S) response

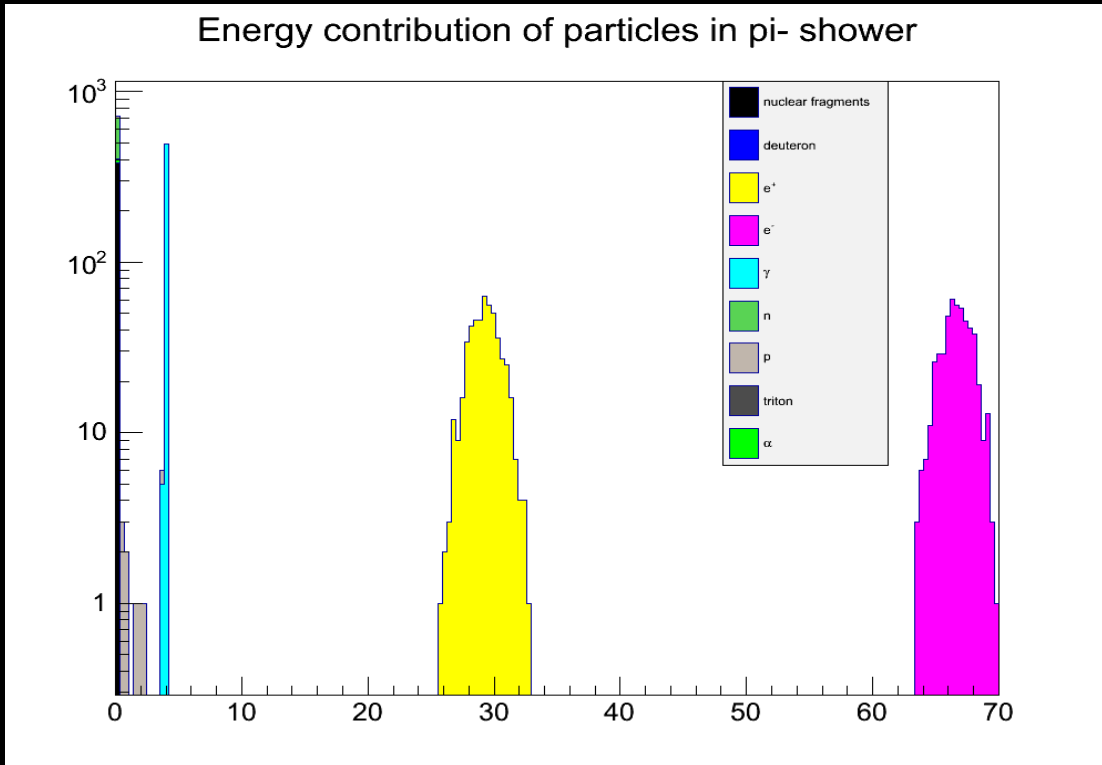
Electrons: not all charged particles in shower are relativistic

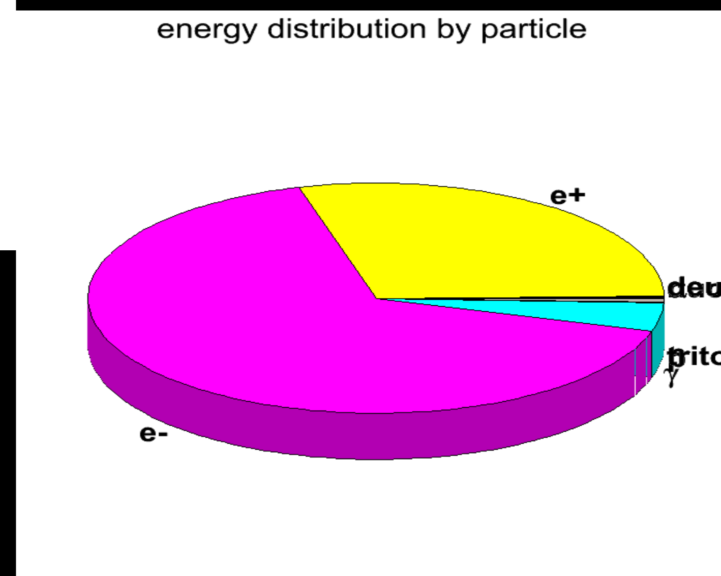
C/S ratio const with energy

→ Cerenkov based EM Calorimeter Works.



Energy contribution of particles in p^0 showers





Obtaining f_{em}, h_c,h_s from Monte Carlo

Scintillation Response: $S/E_{in} = f_{em} + (1 - f_{em})\, h_s$

Cerenkov Response: $C/E_{in} = f_{em} + (1 - f_{em})\, h_C$

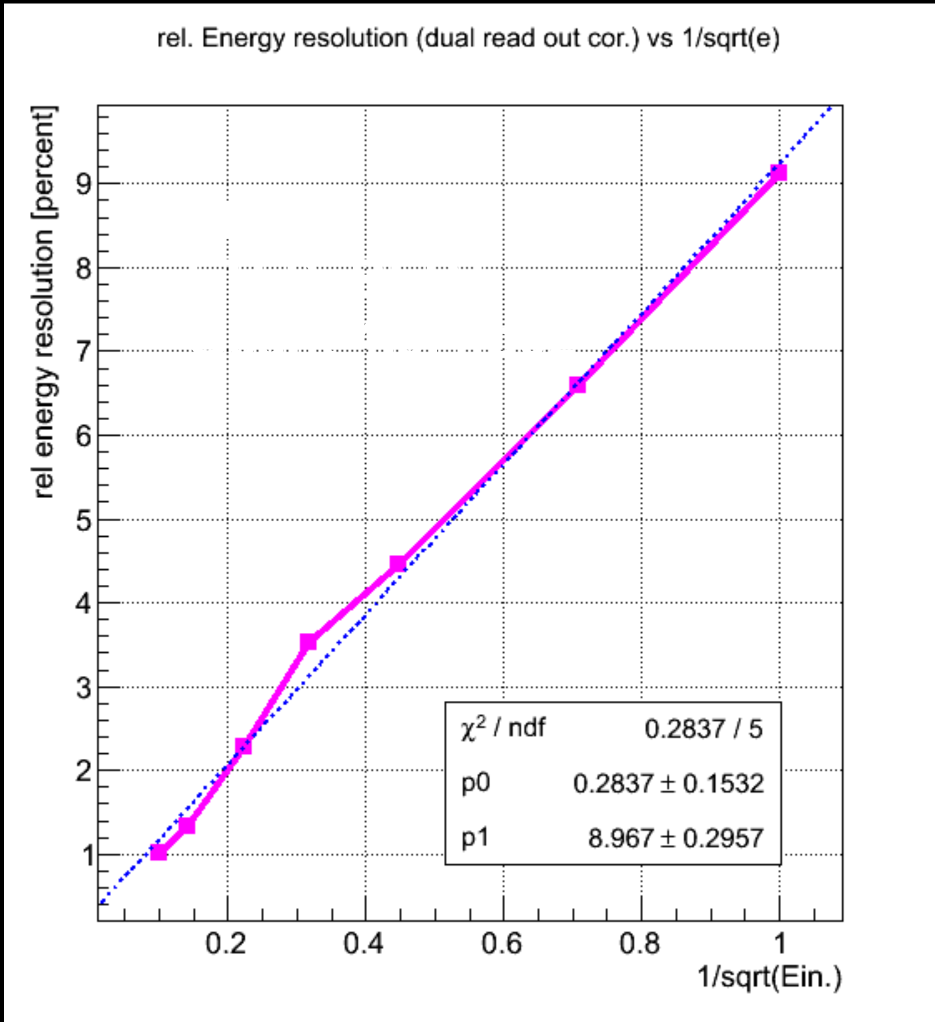
$$E = S\left[\frac{(1-hc) - C/S(1-hs)}{hs - hc}\right]$$

Where: $h_s > h_c$

E_{in}	E_{sz}	E_c	E_{em}	f_{em}	h_s	h_c
2	1.727	1.062	0.7257	0.363	0.79+/-0.02	0.26+/-0.001
5	4.283	2.656	2.11	0.422	0.75+/-0.02	0.19+/-0.001
10	8.767	5.912	4.89	0.489	0.76+/-0.02	0.2+/-0.001
20	17.83	12.93	11.13	0.555	0.76+/-0.02	0.2+/-0.001
50	45.35	34.87	31.	0.62	0.76+/-0.02	0.2+/-0.001
100	91.87	73.36	66.5	0.665	0.76+/-0.02	0.2+/-0.001

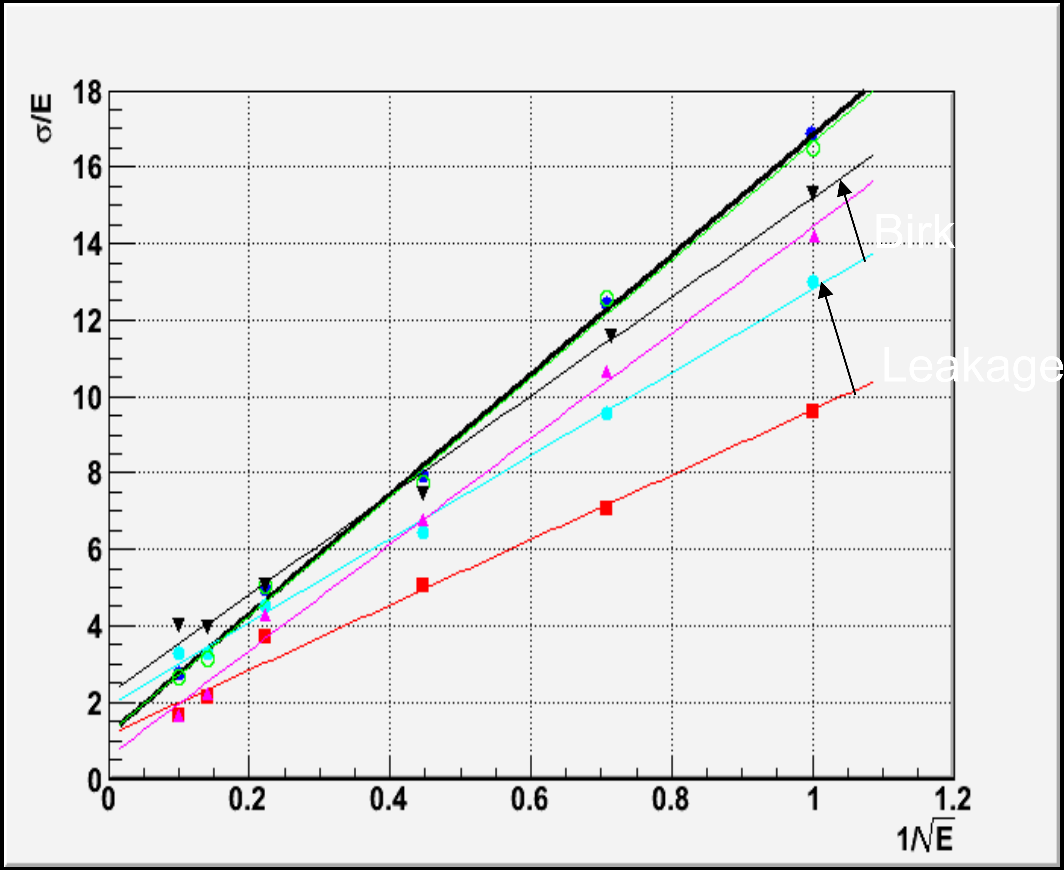
Energy Resolution for single π^-

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



Before Detector effects:
- Noise
- threshold cuts
- calibration
- detection efficiency
- perfect separation of C/S
- Birks suppression

Single π^- resolution for different detector configurations



BGO(dense), QGSP_BERT:
$\sigma(E)/E = 1.1 + 8.5/\mathrm{sqrt}(E)$ %

BGO, QGSP_BERT:
$\sigma(E)/E = 1.9 + 10.9/\mathrm{sqrt}(E)$ %

BGO, QGSP_BERT , Birk supr.:
$\sigma(E)/E = 2.23 + 13.0/\mathrm{sqrt}(E)$ %

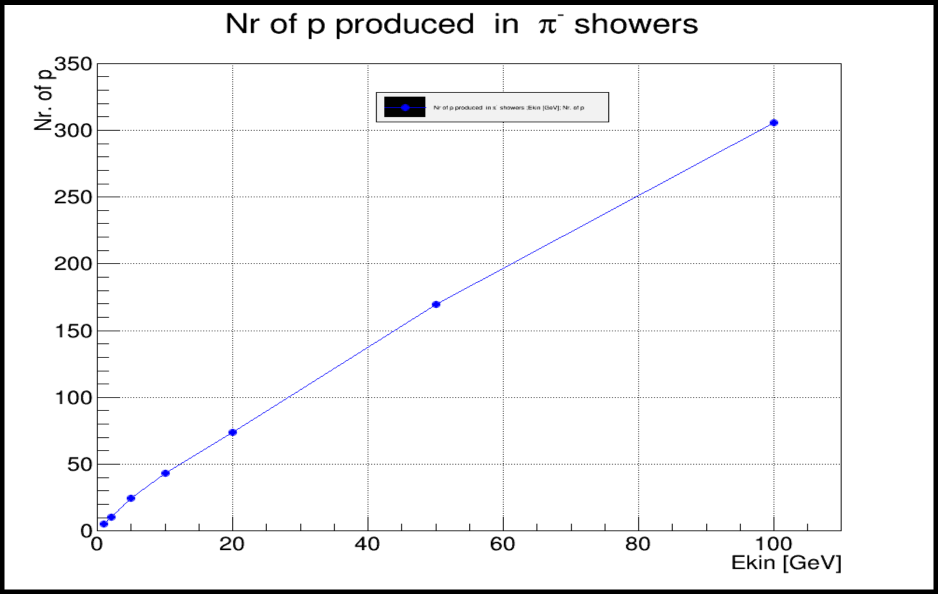
BGO(dense), LCPhys:
$\sigma(E)/E = 0.6 + 13.8/\mathrm{sqrt}(E)$ %

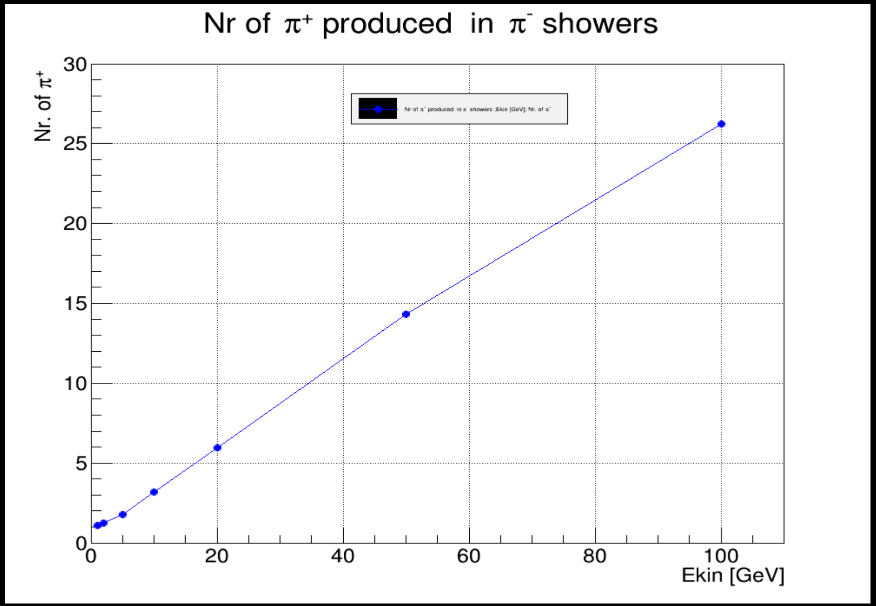
BGO, LCPhys: (nominal)
$\sigma(E)/E = 1.2 + 15.6/\mathrm{sqrt}(E)$ %

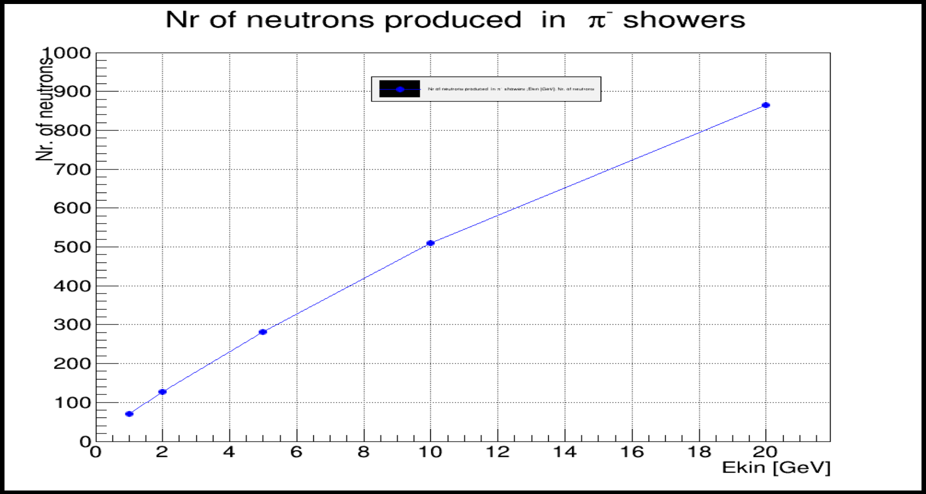
PbWO4, LCPhys:
$\sigma(E)/E = 1.2 + 15.5/\mathrm{sqrt}(E)$ %

Using global dual read out correction → can be Improved using energy dependent correction.

Nr of particles produced







Motivation for a Total Absorption Dual Readout Calorimeter (cont.)

Cerenkov light is prompt and might provide a fast signal when timing is critical (e.g. muon collider).
Segmentation will allow for the application of Particle flow algorithmns (PFA)
<u>Enabling technologies:</u>
Major advances in the detectors technology/enabling technologies:
→ High density scintillating crystals/glasses → R&D program to find affordable Crystals
→ „Silicon Photomultipliers" ~ robust compact, inexpensive

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

The CaTS Logo

CaTS
Calorimeter and Tracker Simulation

?

Birks attenuation

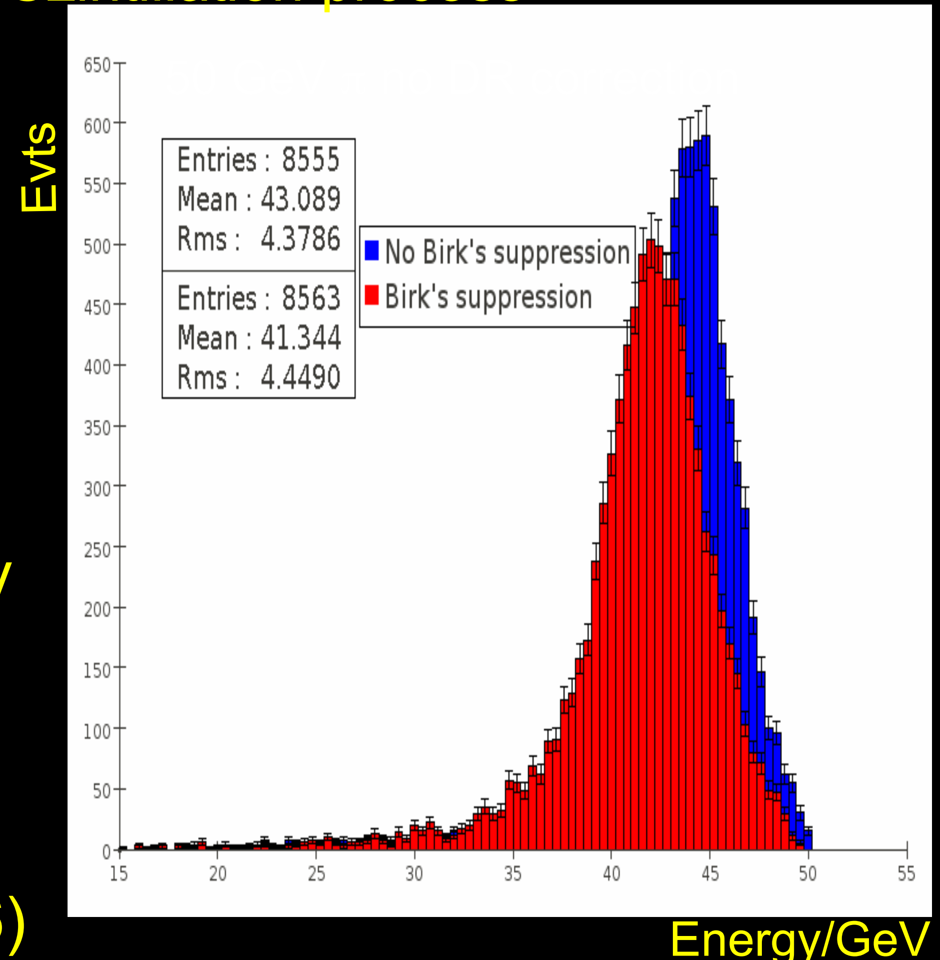
Implemented in SLIC,
Available in Geant 4 via Szintillation process

$$\frac{dL}{dx} = \frac{S \cdot \frac{dE}{dx}}{1 + kB \cdot \frac{dE}{dx}}$$

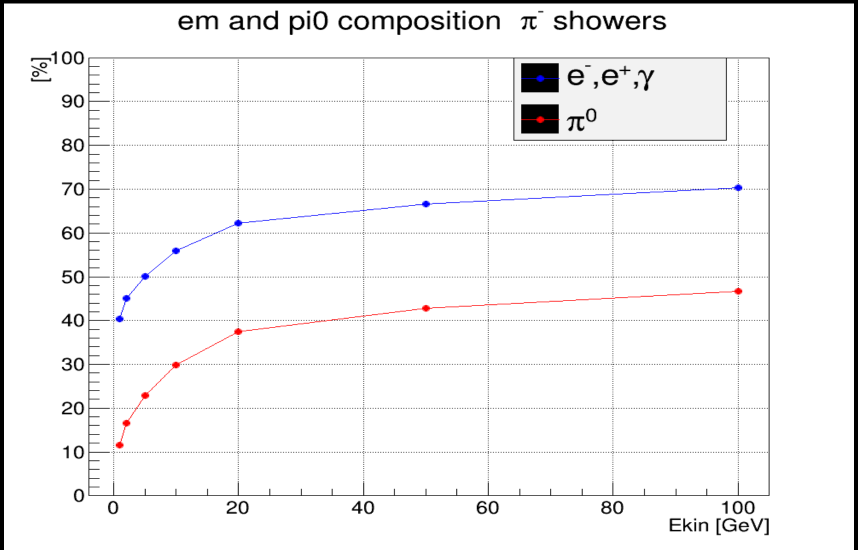
Where:
kB = Birks constant
S = Scintillation Efficiency

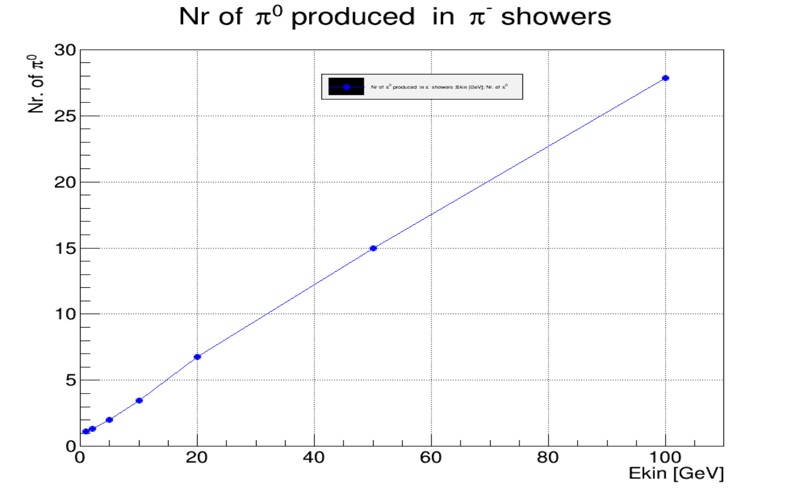
dL/dx= Light Output

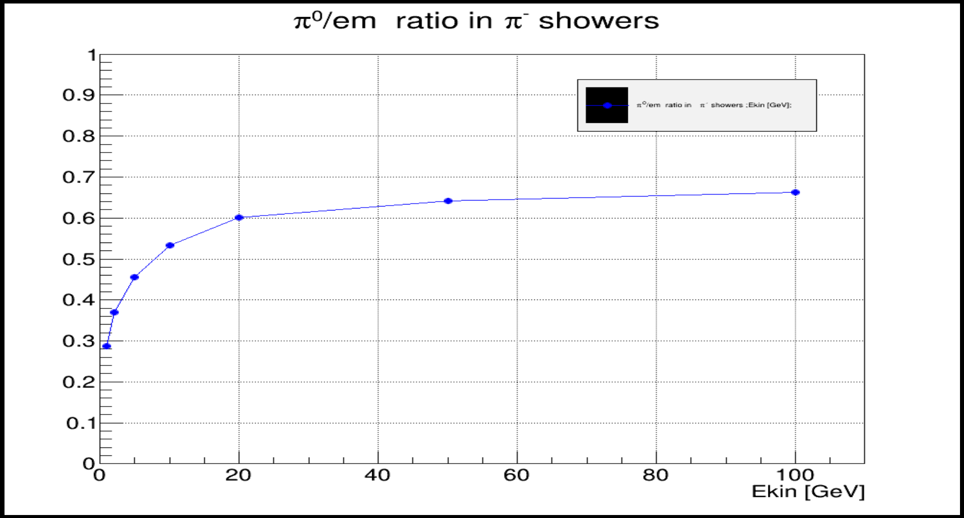
BGO: kB = 6.5 μm/MeV
(NIM A439 (2000) 158-166)



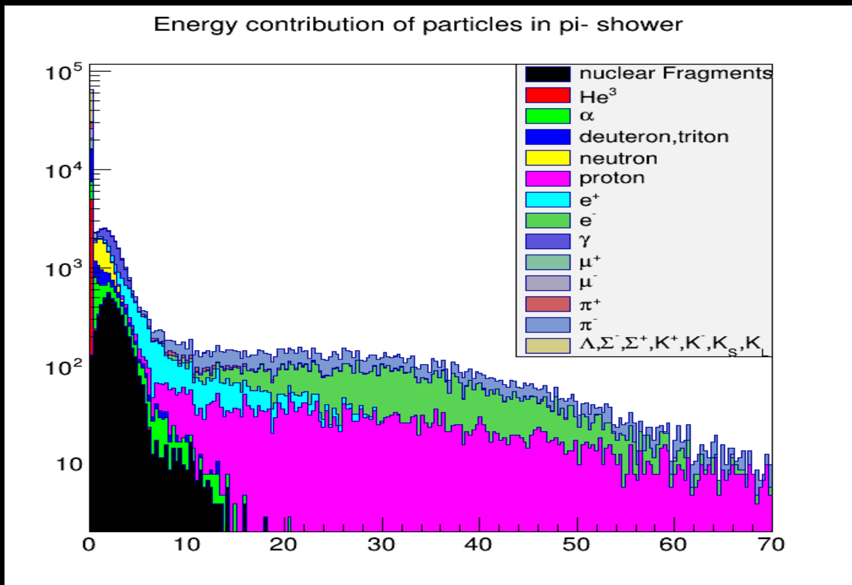
em-fraction in p$^-$ showers

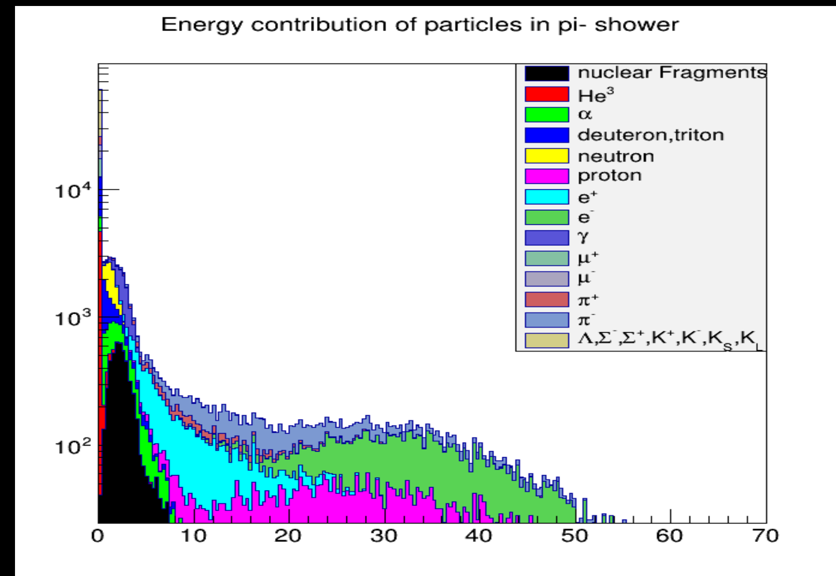


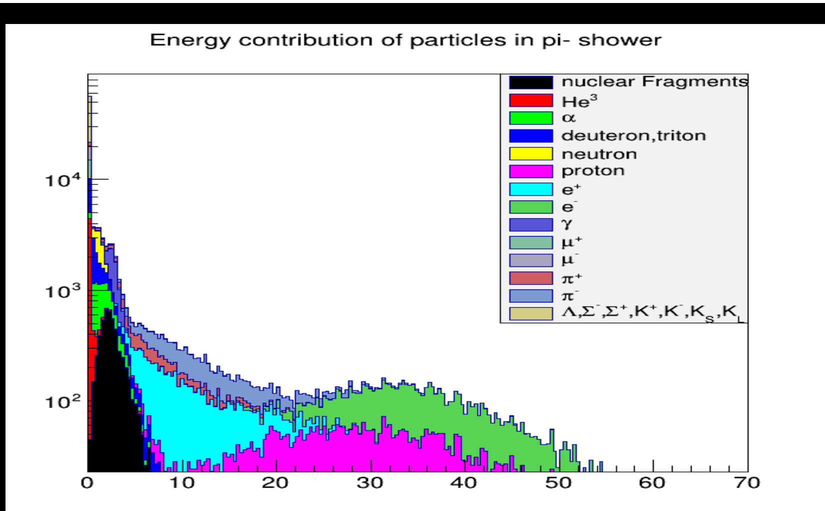


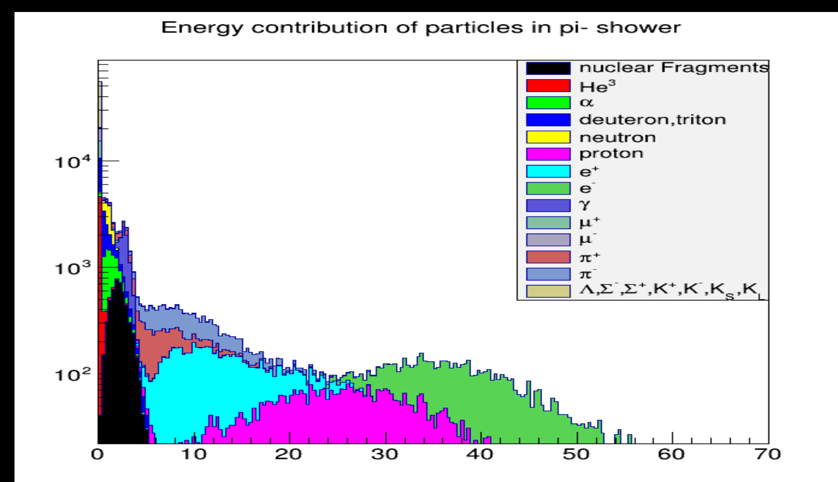


Energy deposition by particle in p^- showers

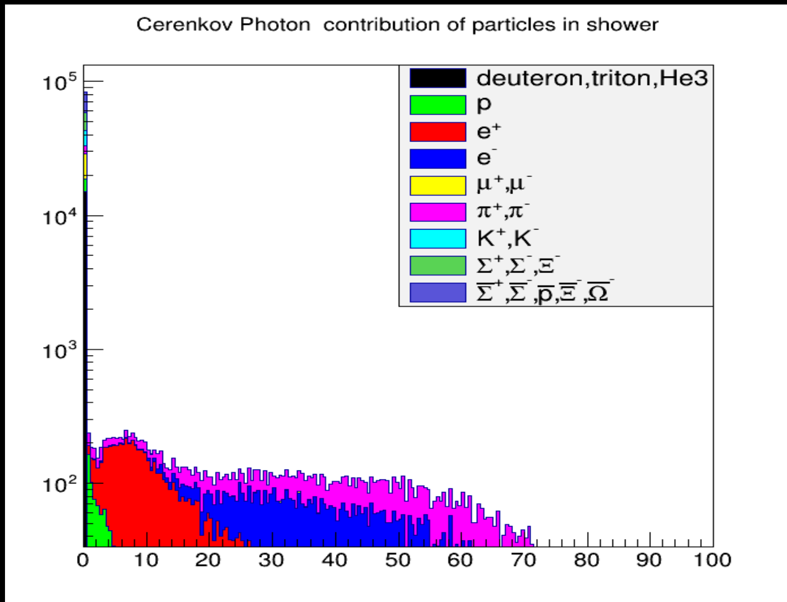


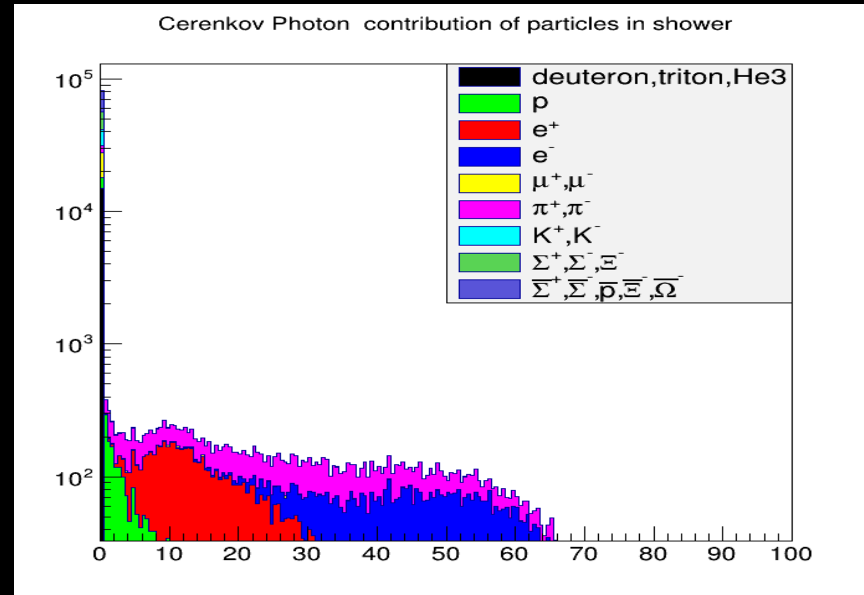


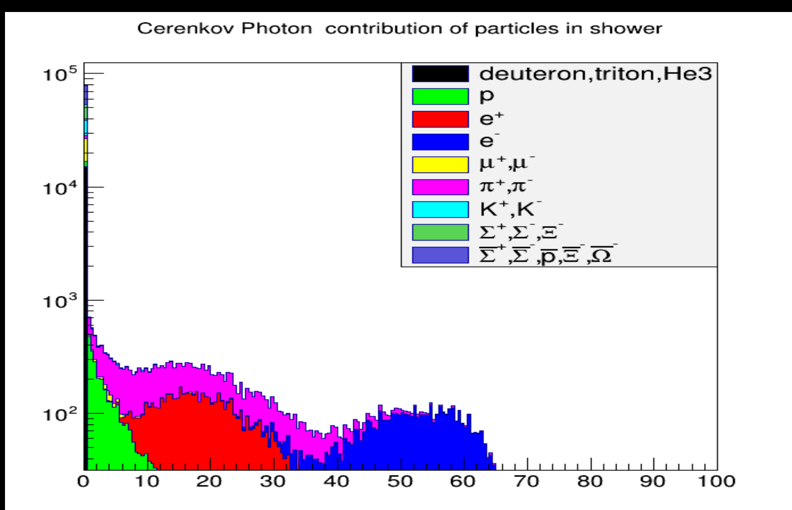


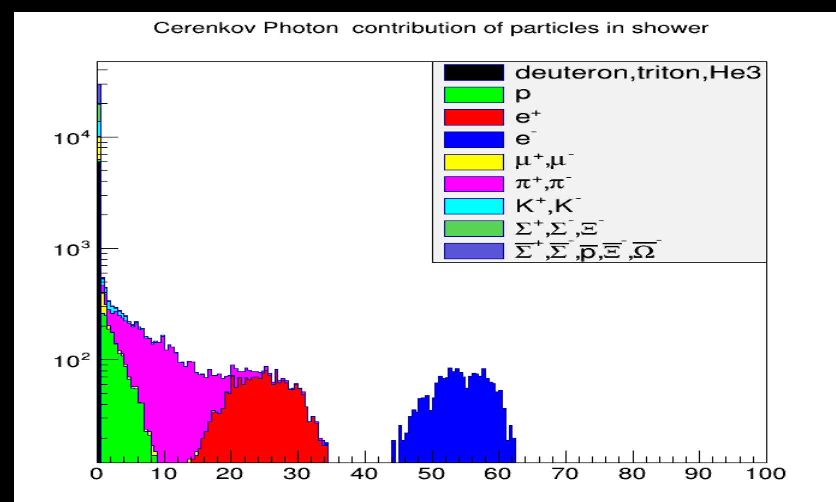


Cerenkov photons by particle in p^- showers









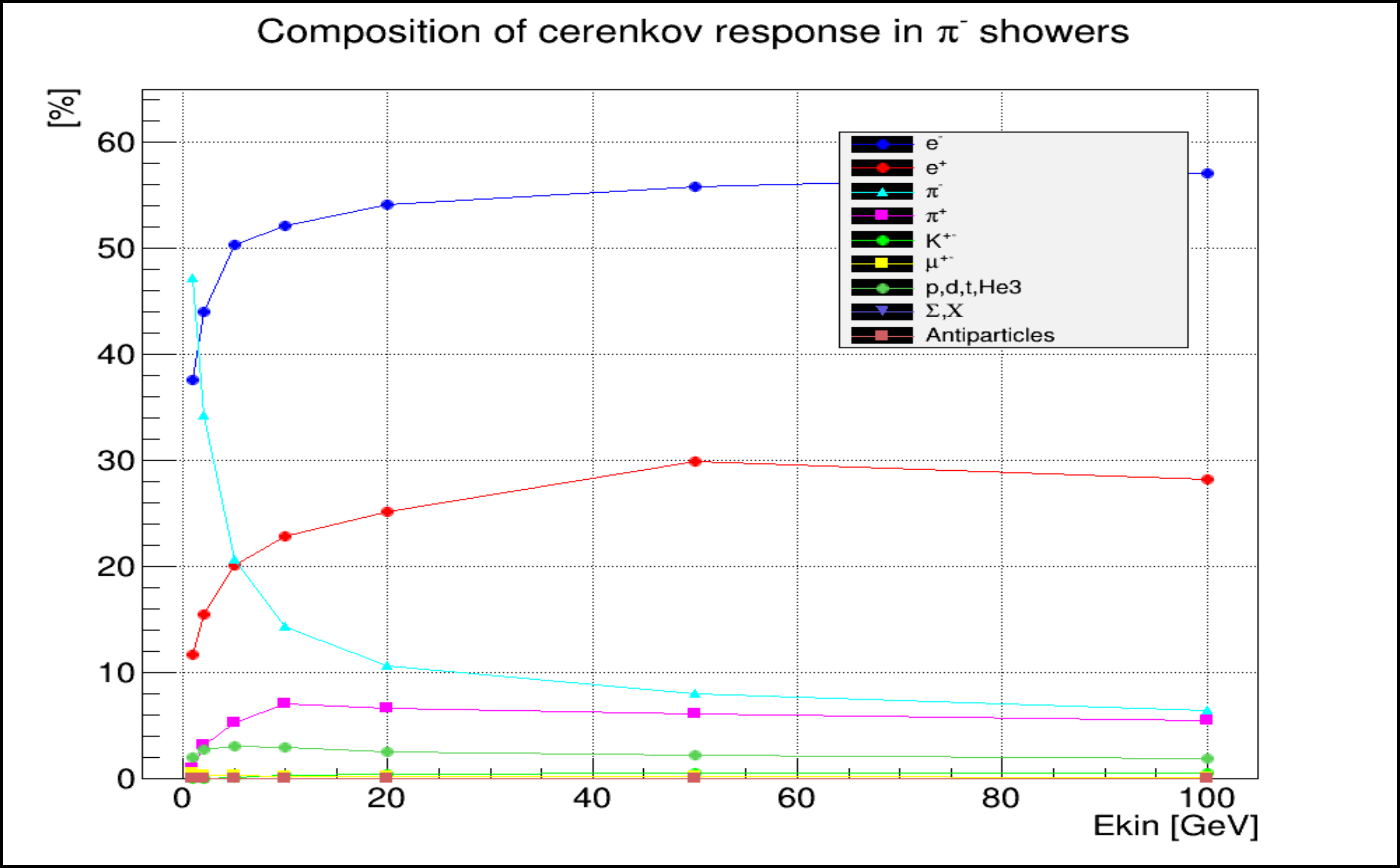
Consequences for sampling calorimeter with plastic scintillator as active medium (speculation! needs verification)

- Nuclear break up doesn't happen in plastic, only in the high Z absorber. Particles coming from the interaction might be short ranged and therefore deposit their entire energy in the absorber. (spike is invisible → nuclear break up don't contribute in homogeneous calorimeter)
- Even if energy is deposited high energy density → response might be Birks suppressed (high in plastic, low in crystals)
- Both effects → sampling fractions much lower than expected → hadronic response seems suppressed → fluctuations contribute to energy resolution.
- But sensitive to neutrons → neutron response is amplified (most neutrons end up in the plastic) → compensation

Outline (cont.)

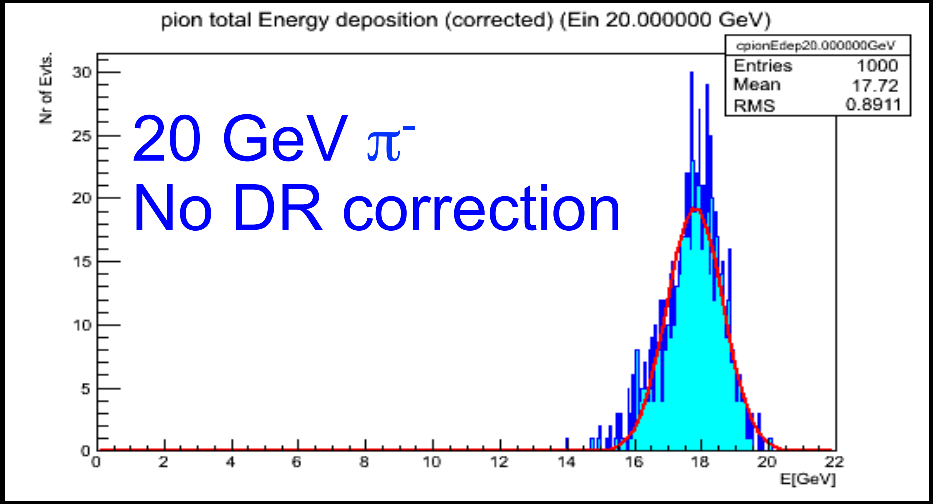
- We can learn a lot from simulation!
- Asking the right questions in test beams (no need for full prototypes).
- Want to know: what processes and particles in the shower are important and how they contribute to energy deposit and fluctuation
- Gain confidence in simulation by e.g. demonstrating how compensating sampling calorimeters work, comparison to test beams etc.
- how important is the dual read out?
- finally validate Geant 4.

Composition of Cerenkov response in p- showers



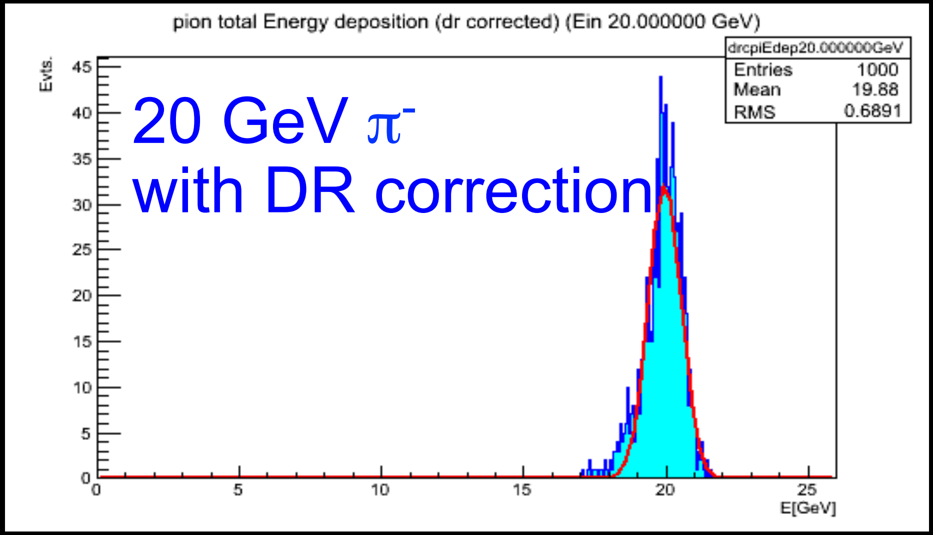
Hans Wenzel, Adam Para

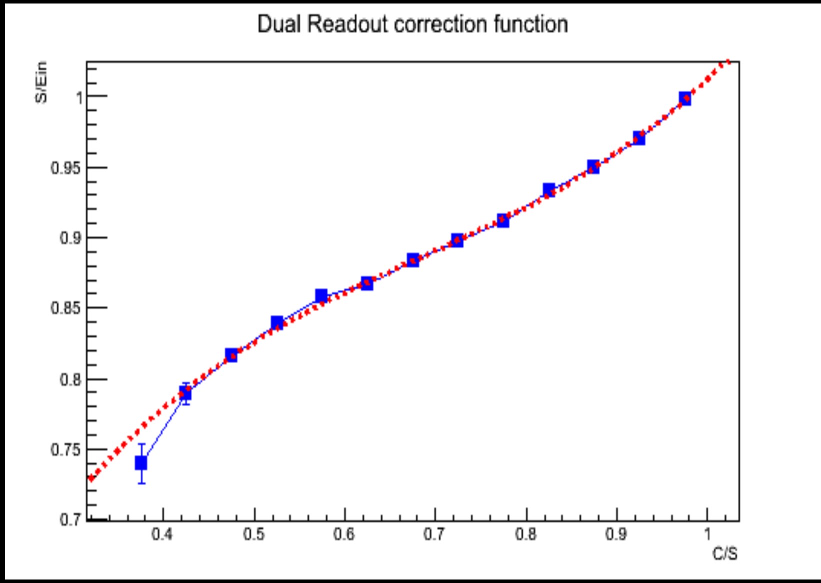
Effect of dual read out correction



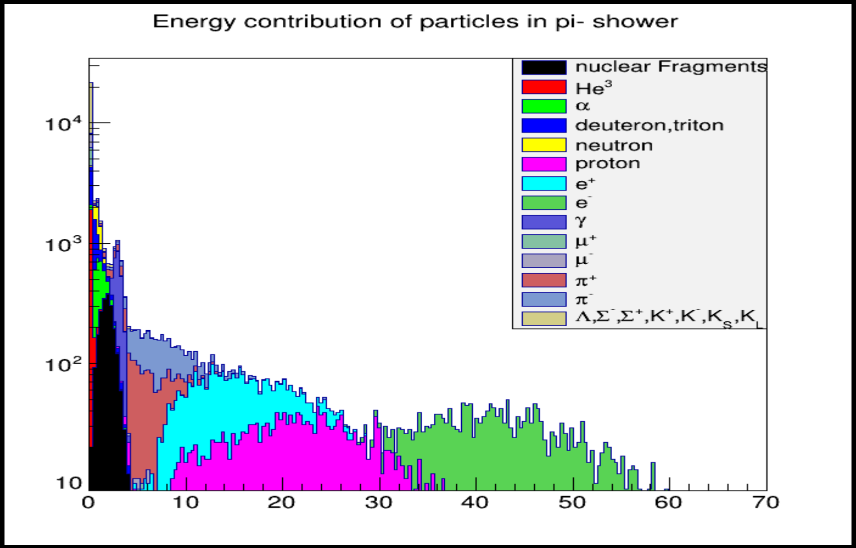
Before Dual Read out correction:
Mean: 17.8
σ: 0.83

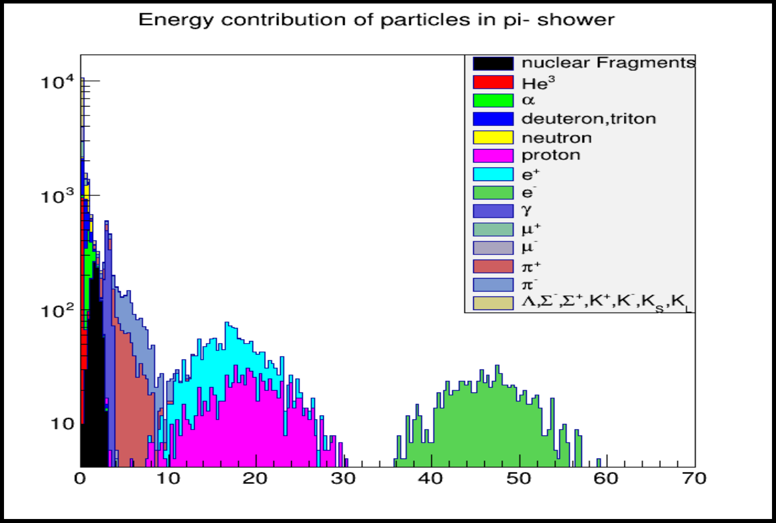
After DR correction:
Mean: 20.
σ: 0.58

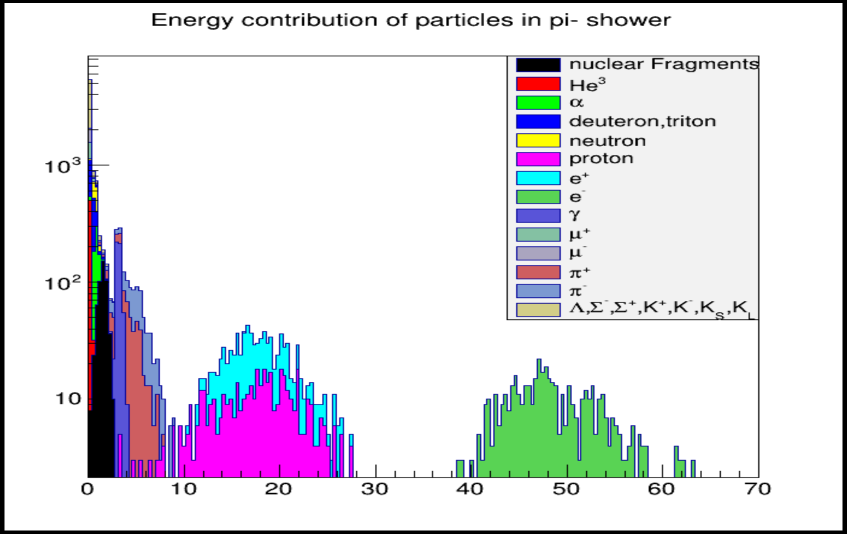




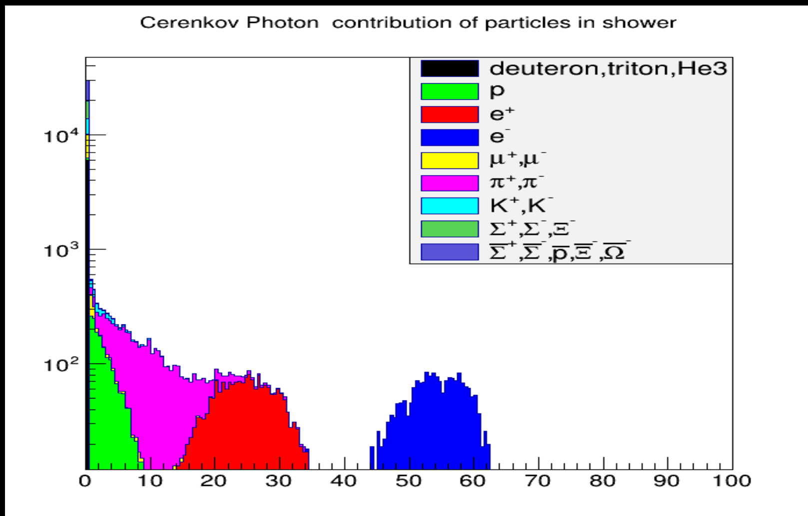
Energy deposition by particle in π^- showers

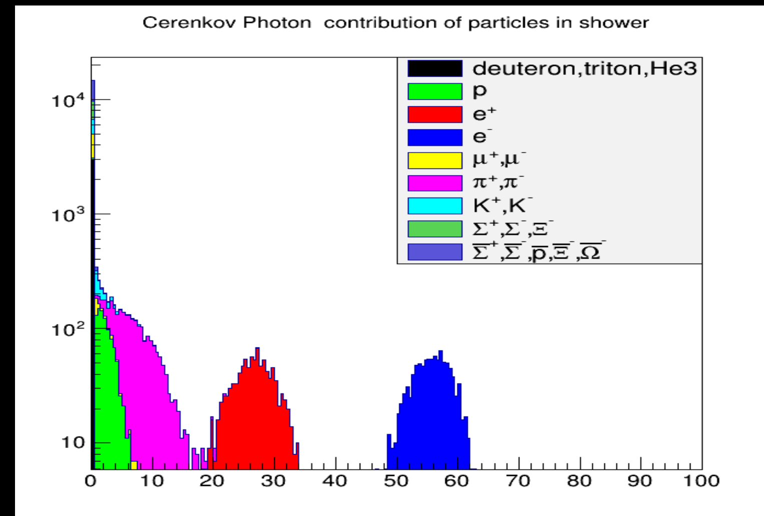


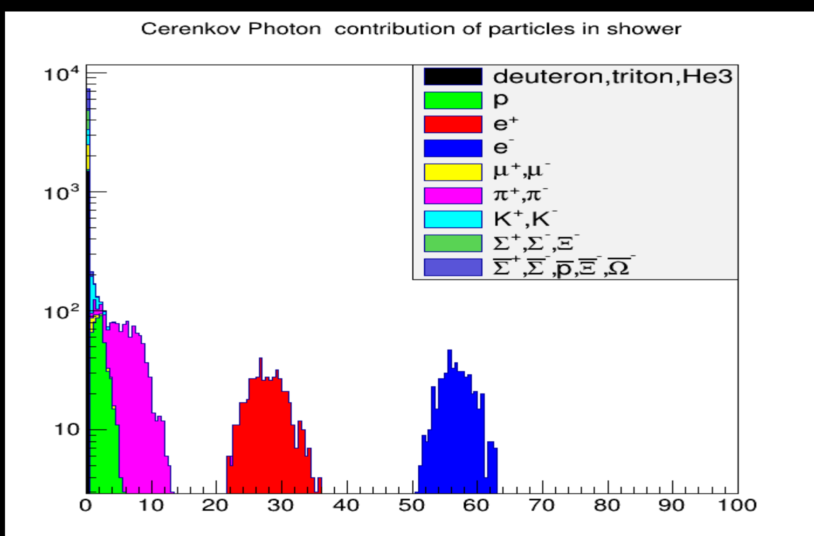




Cerenkov photons by particle in p^- showers







Different response?

non-linearity,
poor energy resolution,
non-Gaussian response function
Different response for different particles