Physics of hadron shower development and the implications for calorimetric resolution

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Outline

- We want to understand the temporal development of hadronic showers, based on the basic physics processes involved. (instead of using pet theories to e.g. qualitatively fit observations in test beam, or using toy models that give you the result that you put in at the first place)
- We can learn a lot from simulation!!!!
- Asking the right questions in test beams (n need ot necessarily full prototypes). Calice will provide a lot of information.
- 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.
- This will be an ongoing process this is just the start.

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.

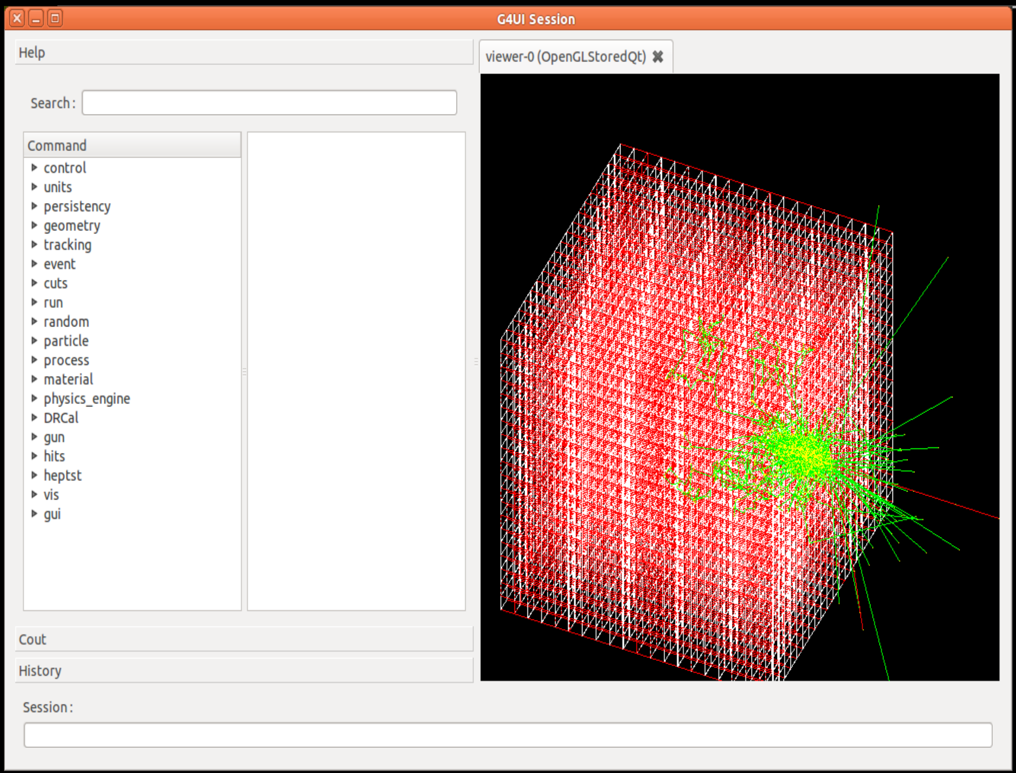
To be able to simulate Dual Read out calorimeters it provides special sensitive detectors and Hit classes that register both the energy deposit and the number of Cerenkov photons produced by particles above the Cerenkov threshold. Moving the calculation of produced Cerenkov photons into the sensitive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

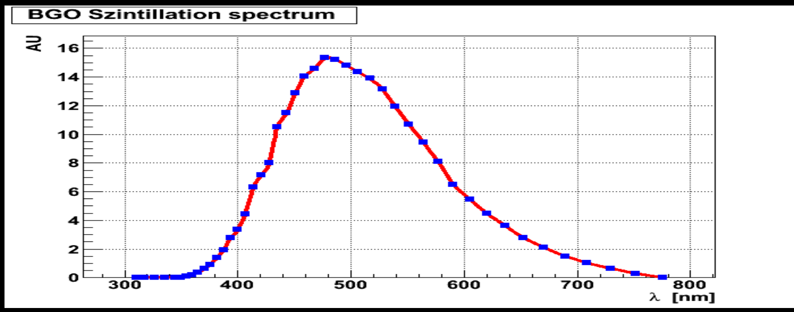
CaTS also allows the detailed study of single Calorimeter cells by enabling the tracing of optical photons, providing sensitive detectors that register optical photons and the gdml detector description allows to provide all relevant optical properties (refraction Index, Absorption length, Scintillation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

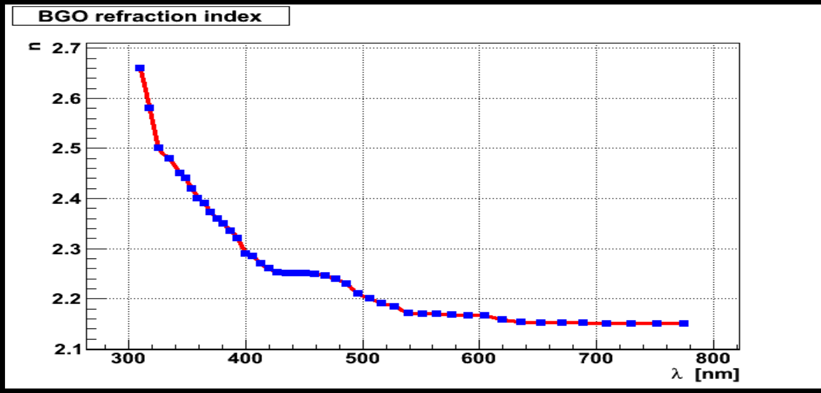
Elements of CaTS

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 Hit classes
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

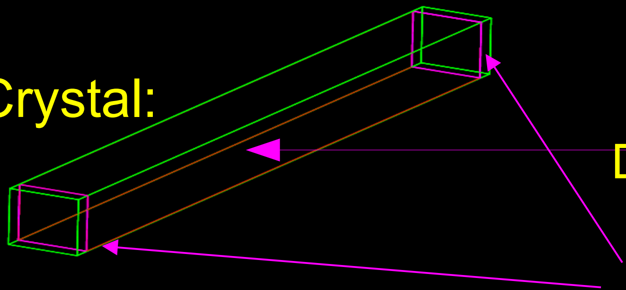
CaTS in Action







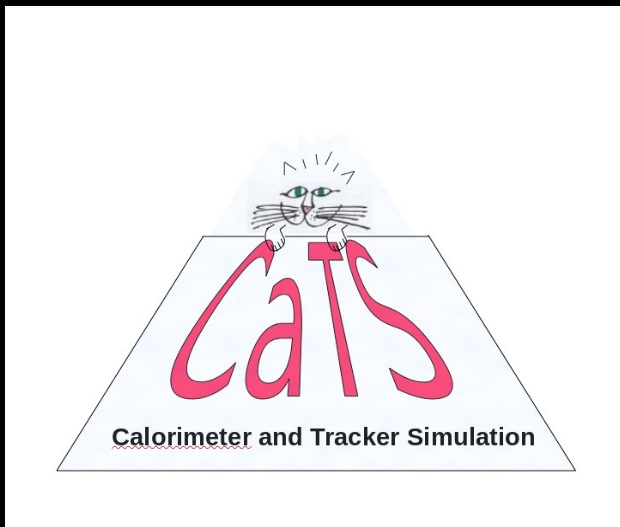
- Crystal:



DRCalorimeterSD

- PhotonSD

The CaTS Logo



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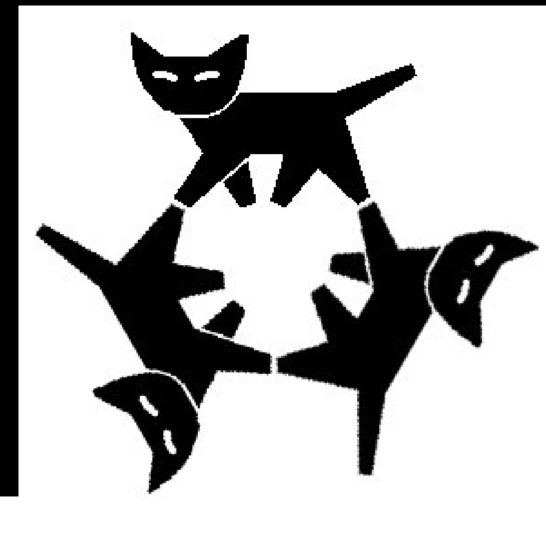
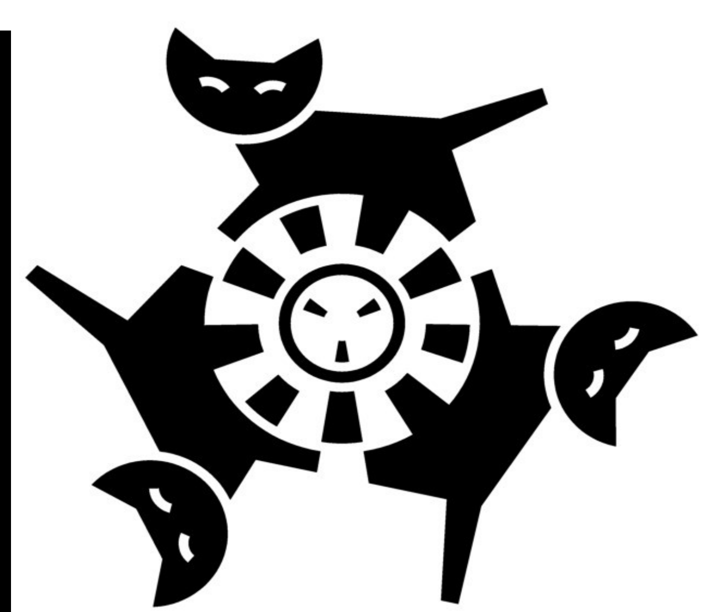
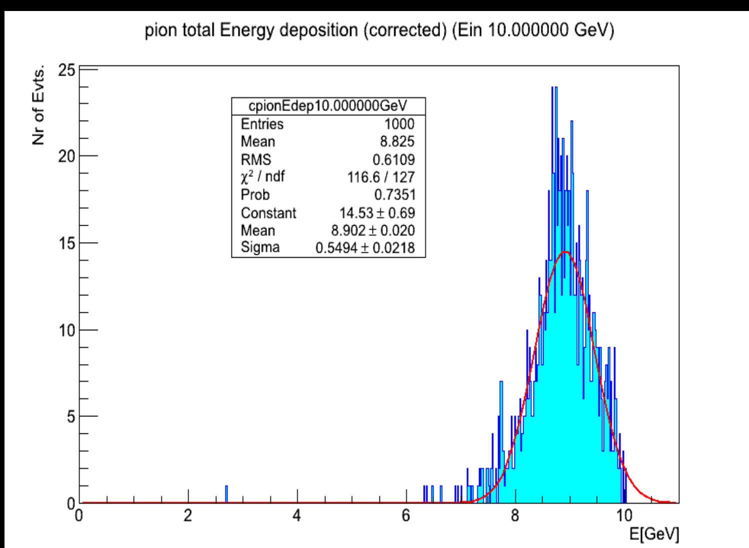
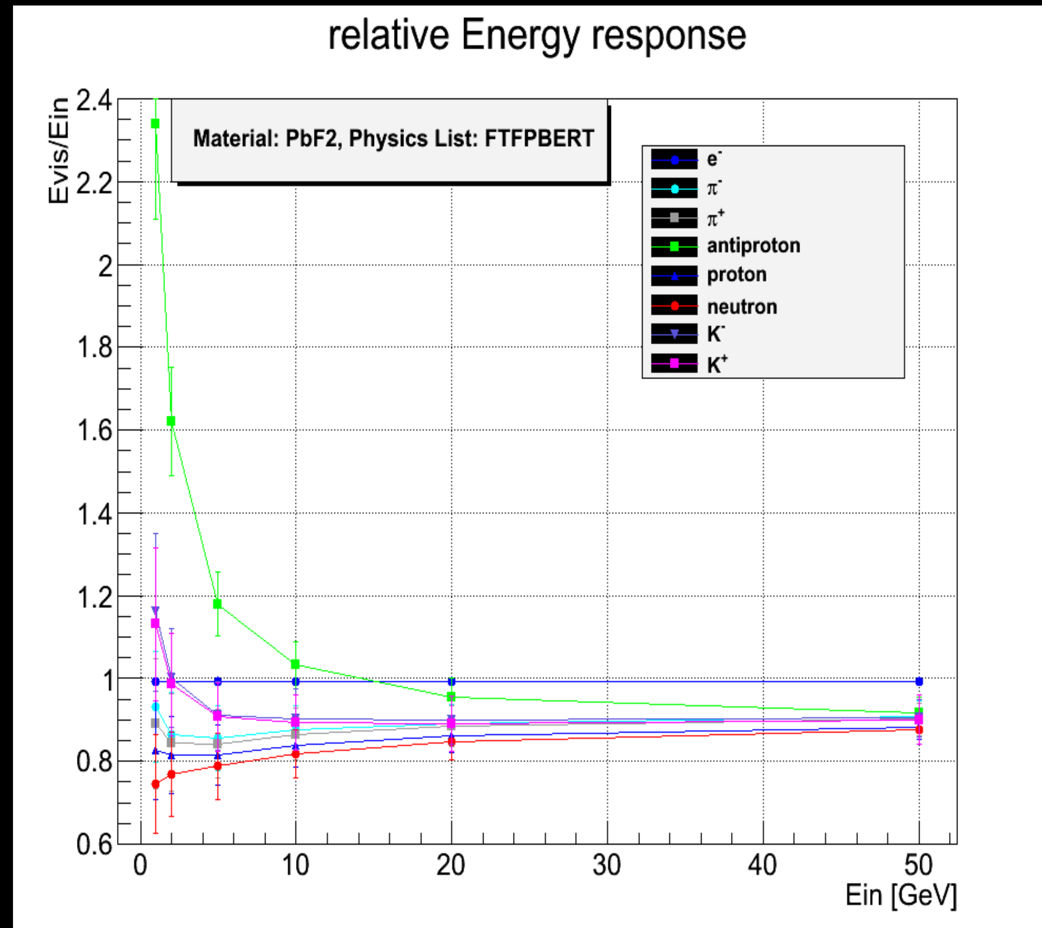




Response of non-compensating calorimeters

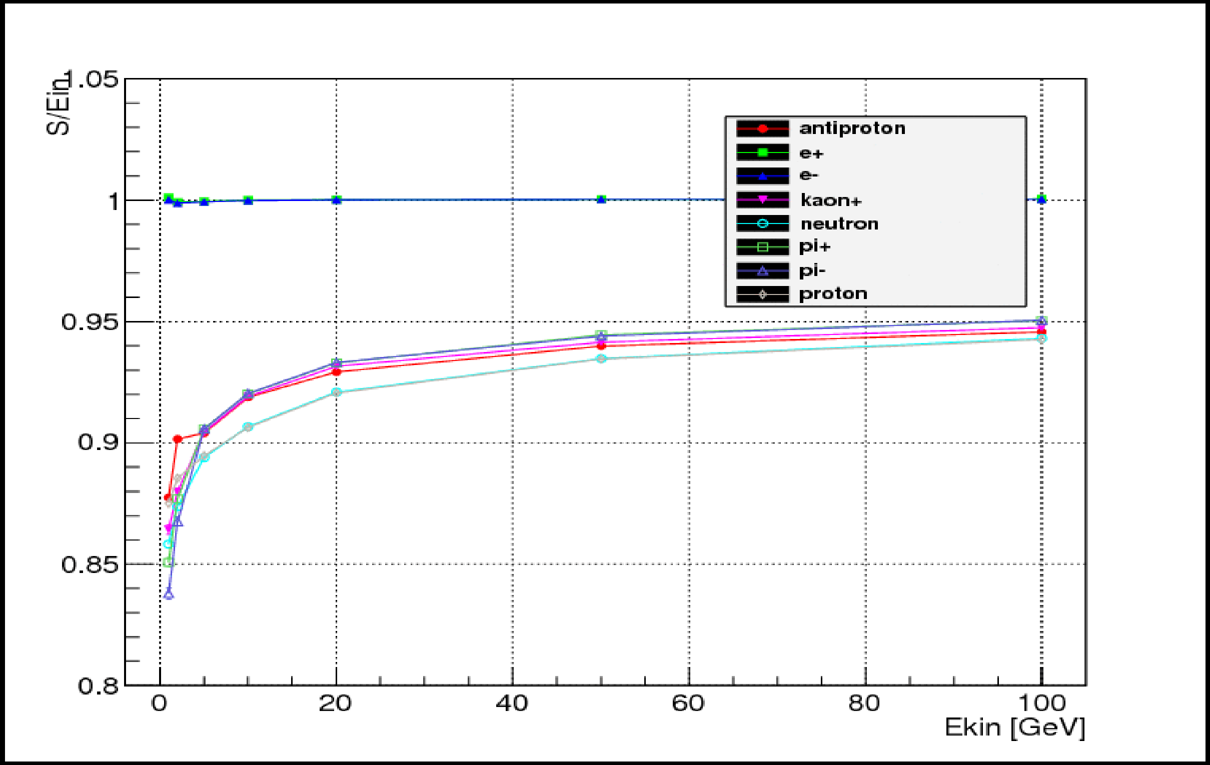
<u>Allegedly:</u>
non-linearity,
poor energy resolution,
non-Gaussian response function
Different response for different particles



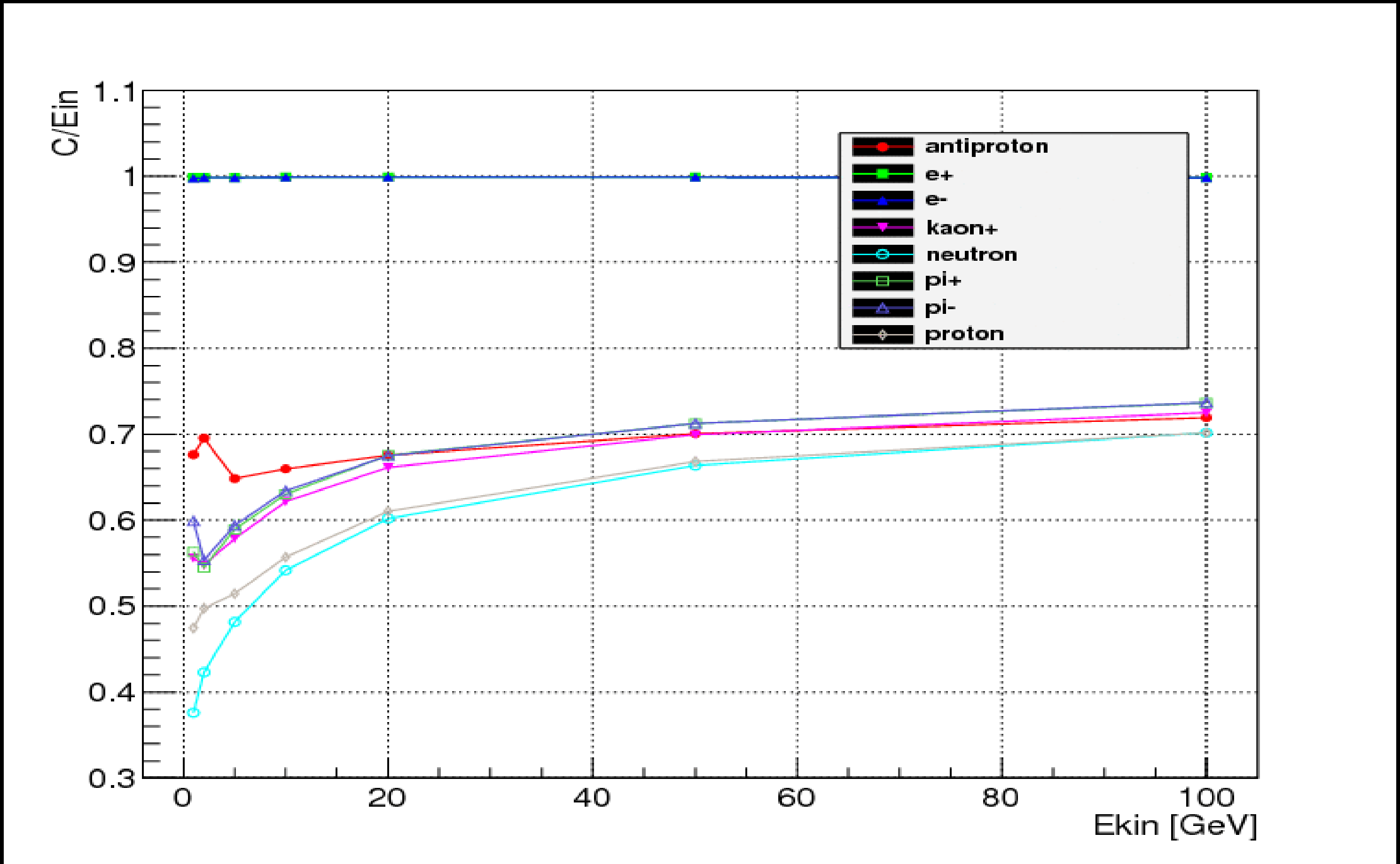


Different response?

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

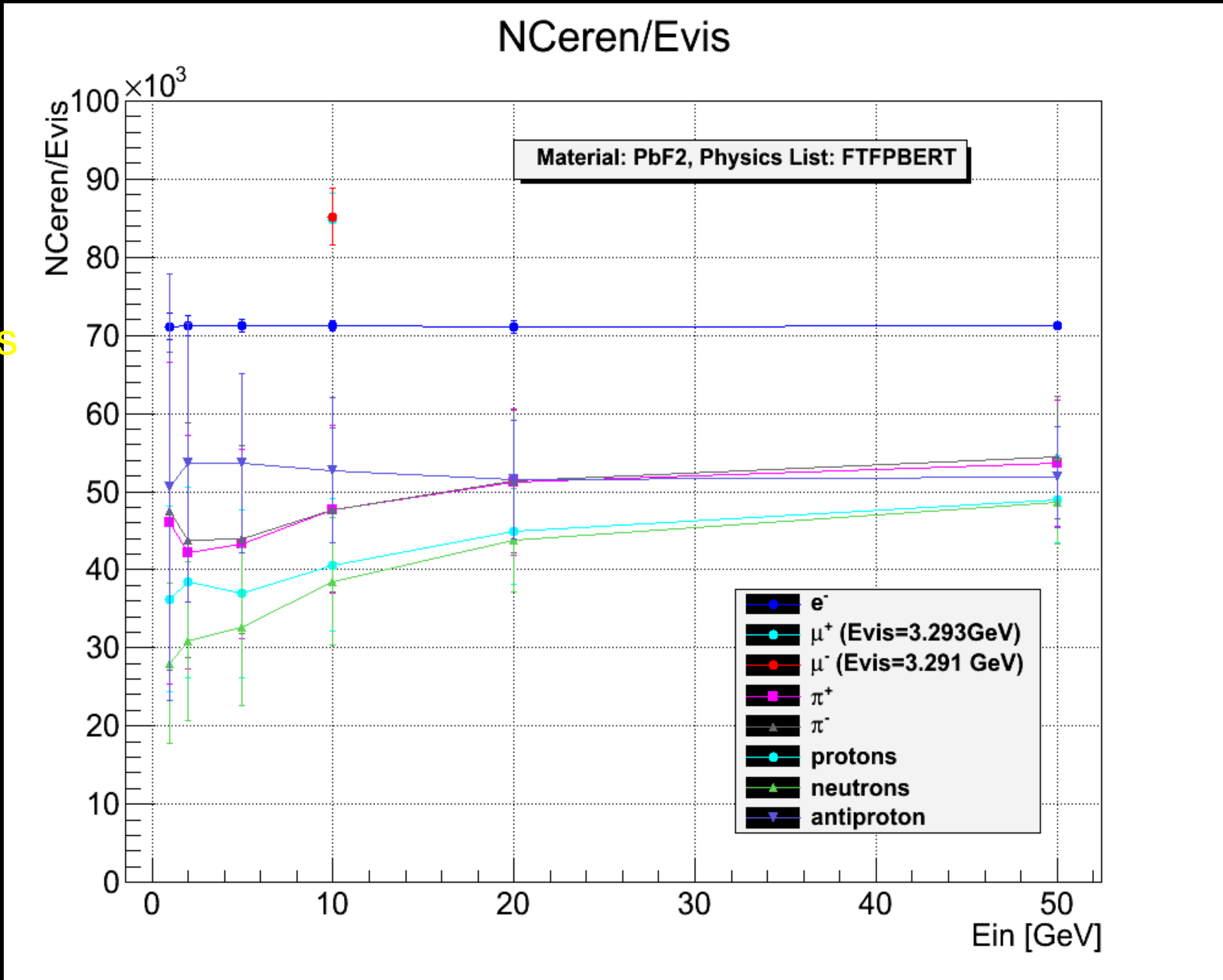


Cerenkov response



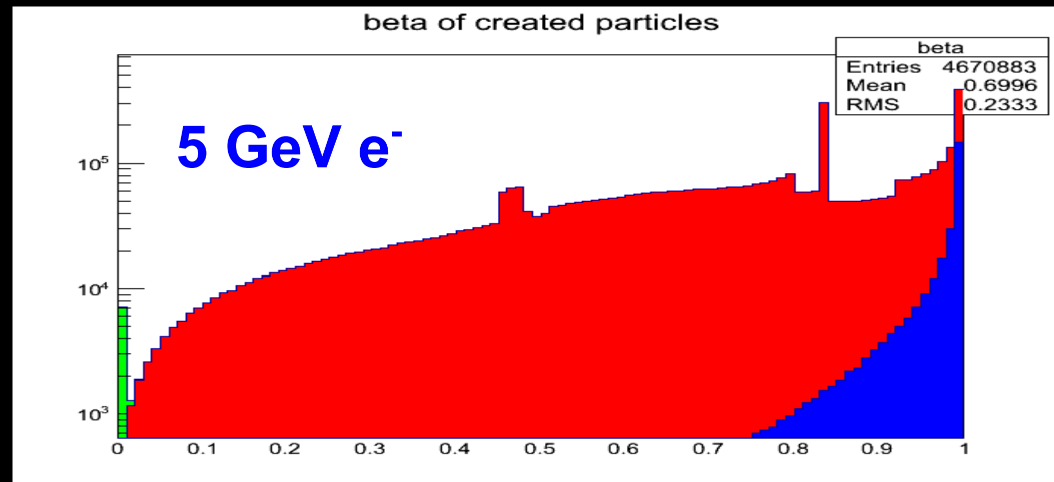
Ratio of Cerenkov/Scintillator (C/S) response

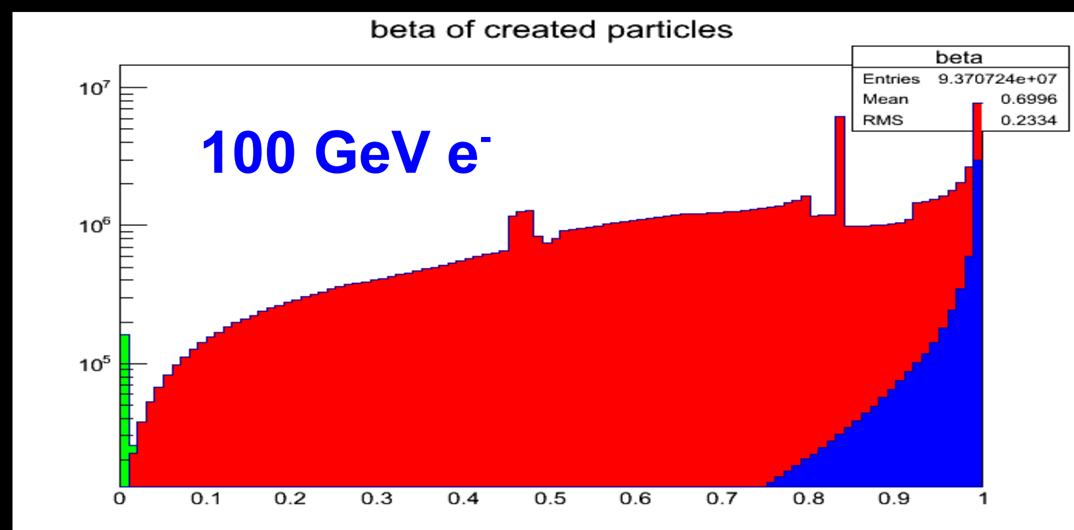
Electrons: not all charged particles in shower are relativistic C/S ratio const with energy → Cerenkov based EM Calorimeter Works.



β of charged particles produced in e^- showers

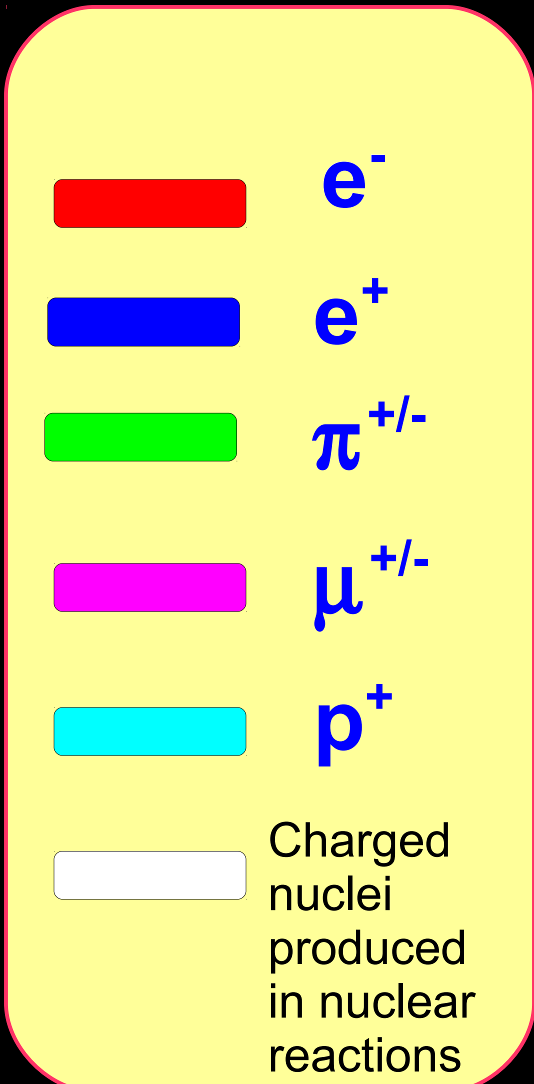
- Red: e^-
- Blue: e^+
- Green: Charged nuclei produced in nuclear Photo-production

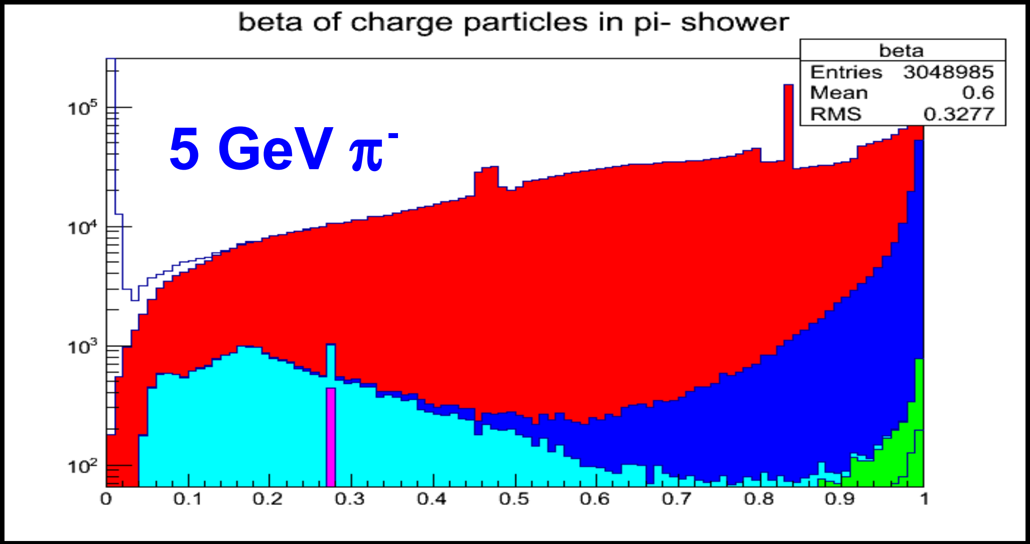


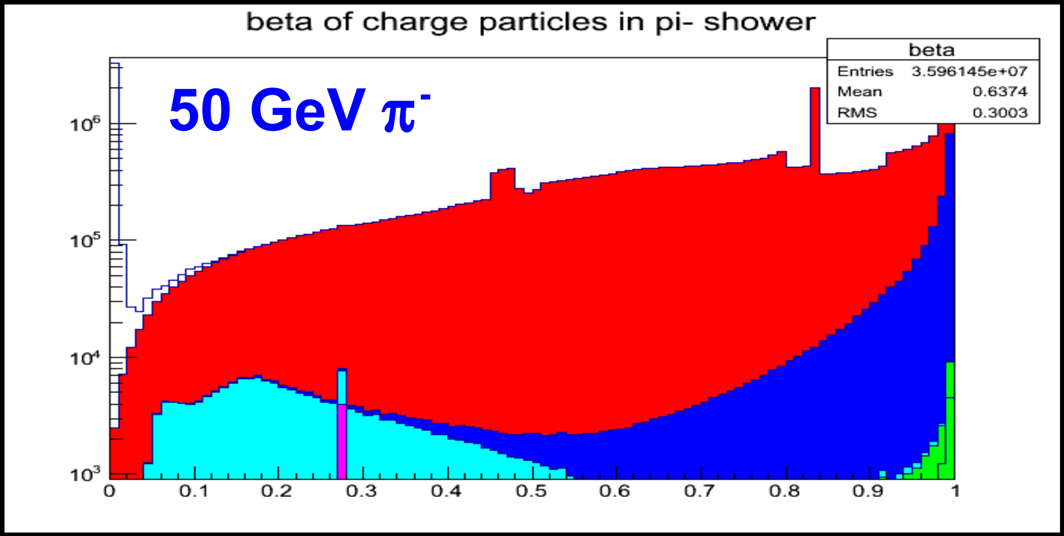


E_{in} (e^-) [GeV]	Mean β
5	0.6996
100	0.6996

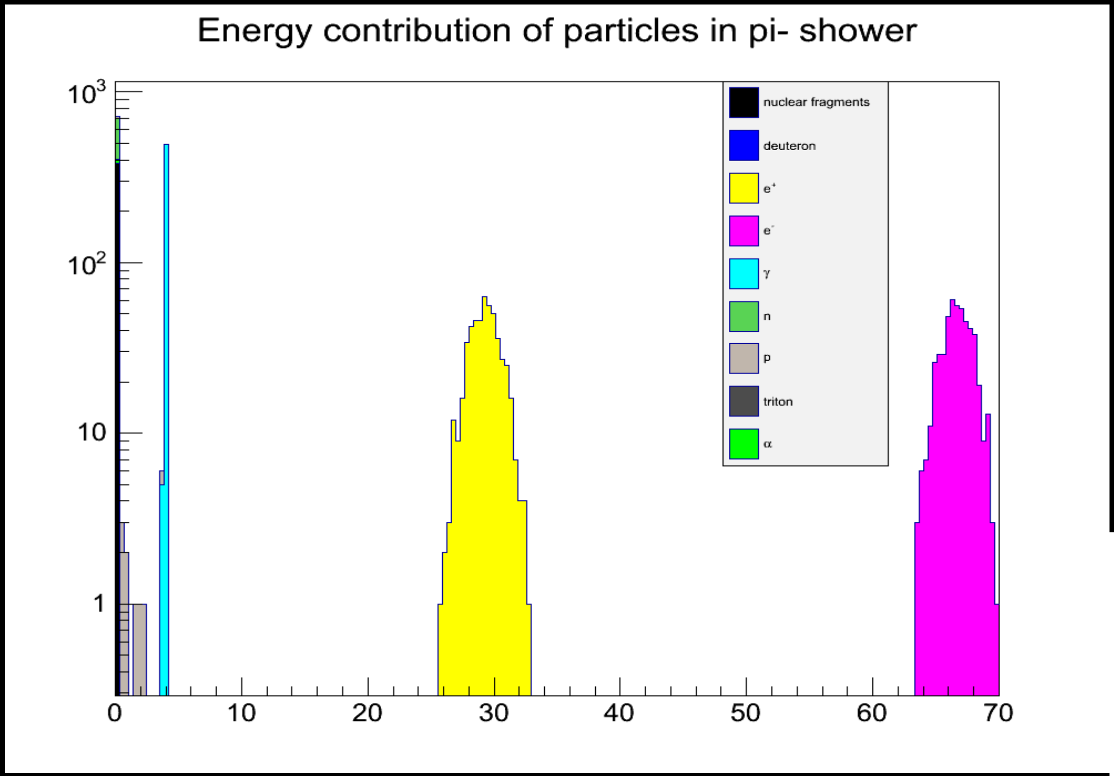
β of charged particles produced in π^- showers

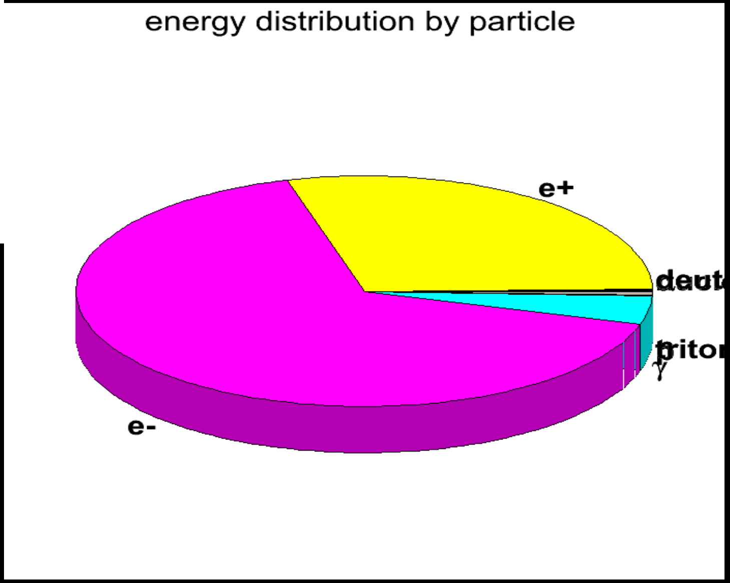




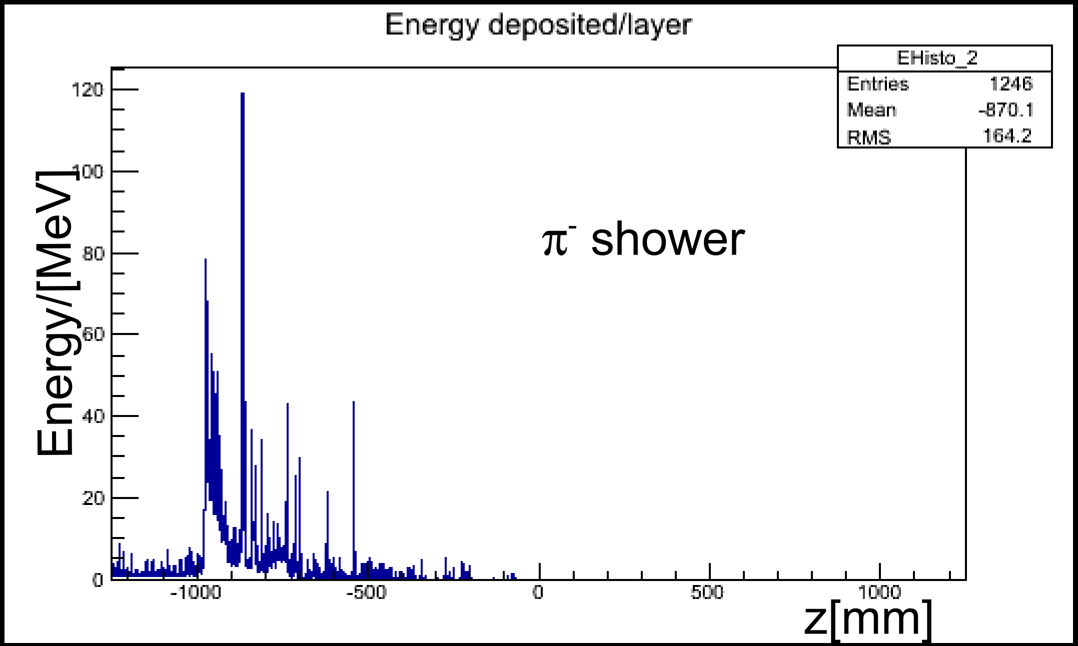


Energy contribution of particles in π^0 showers

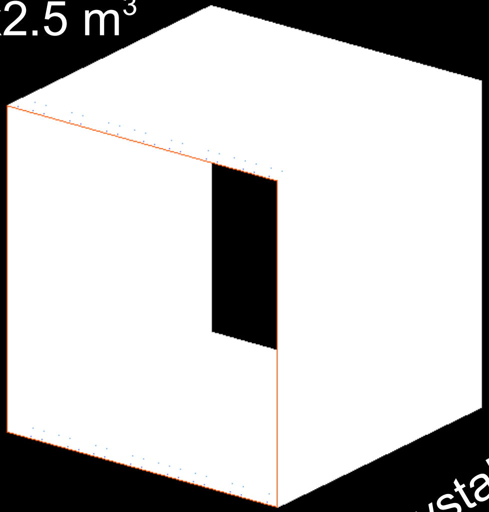




Spikes in the longitudinal shower profile



2.5x2.5x2.5 m^3



1 mm thick crystal sheets

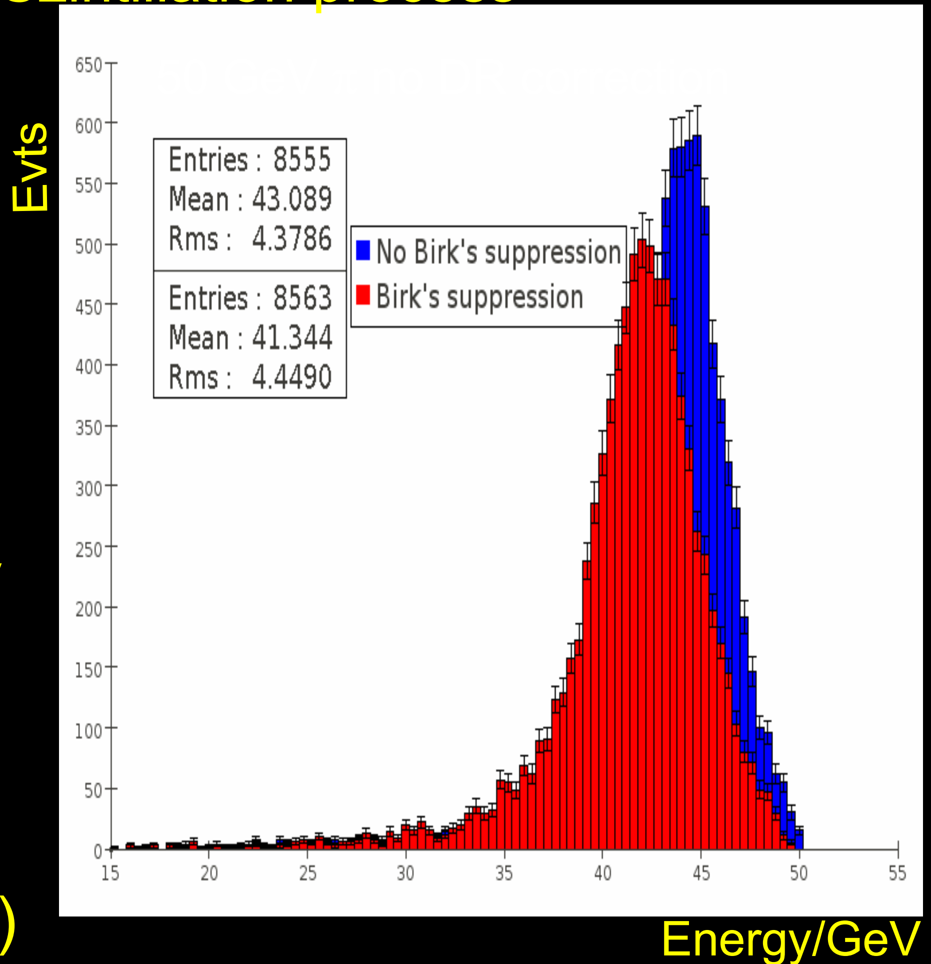
Consequences for sampling calorimeter with plastic scintillator as active medium (speculation! needs verification)

- 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

Birks attenuation

Implemented in SLIC,
Available in Geant 4 via Szintillation process

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

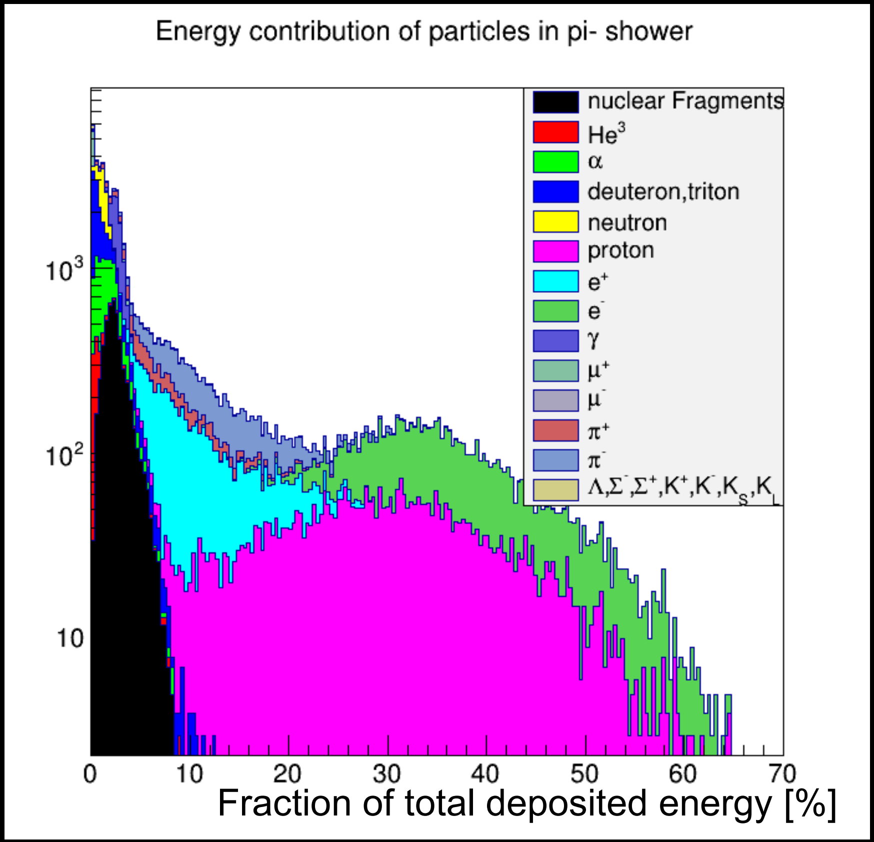


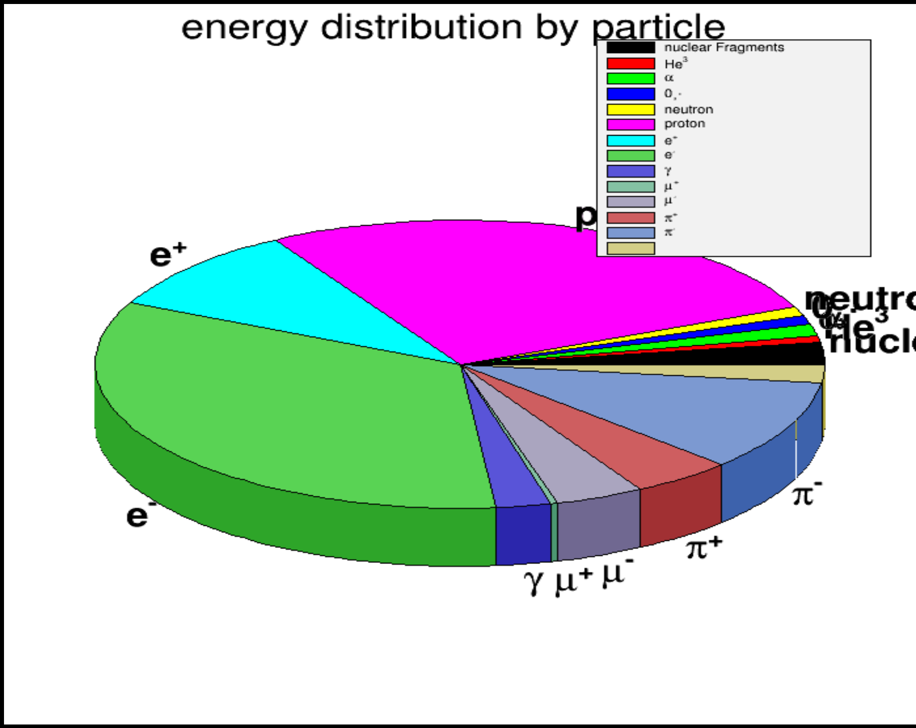
Where:
kB = Birks constant
S = Scintillation Efficiency

dL/dx= Light Output

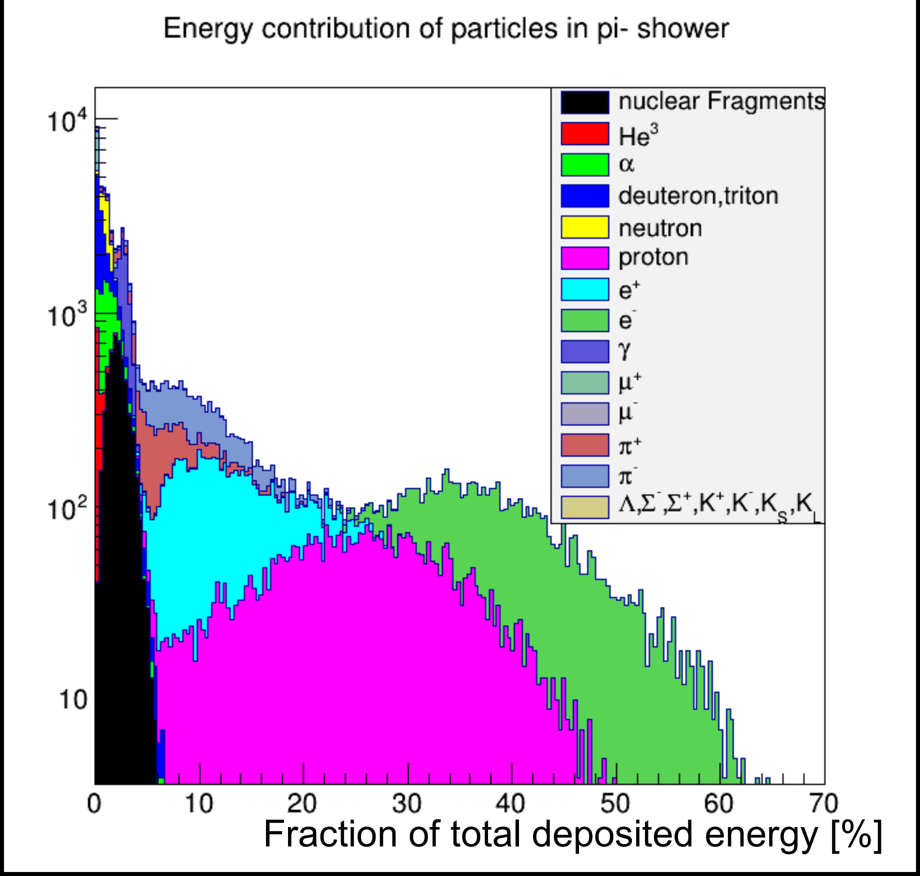
BGO: kB = 6.5 μm/MeV
(NIM A439 (2000) 158-166)

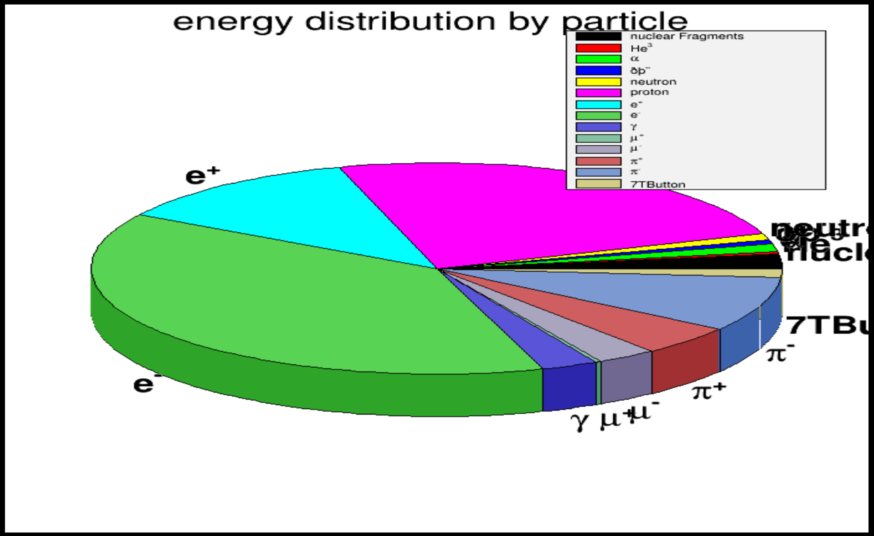
Energy deposition by particle in 5GeV π^- showers





Energy deposition by particle in 10 GeV π^- showers





Conclusion and plan

- Just started → no show stoppers.
- Will simulate sampling calorimeter and e.g. study the importance of neutrons.
- Instrument CaTS to extract more details.
- Ultimately finally write it all up

Backup

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

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

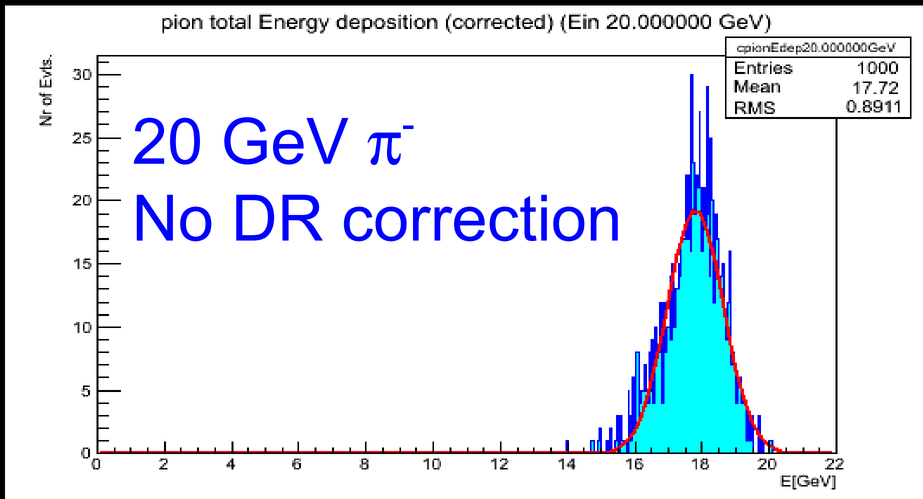
Cerenkov Response: $C/E_{in} = f_{em} + (1 - f_{em})\, h_C$

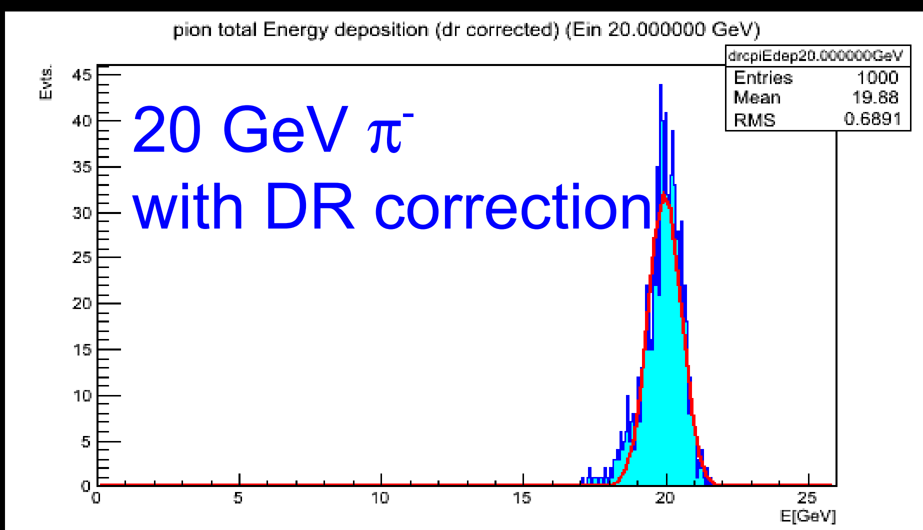
$$E = S\left[\frac{(1-hc) - C/S\,(1-hs)}{hs - hc}\right]$$

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

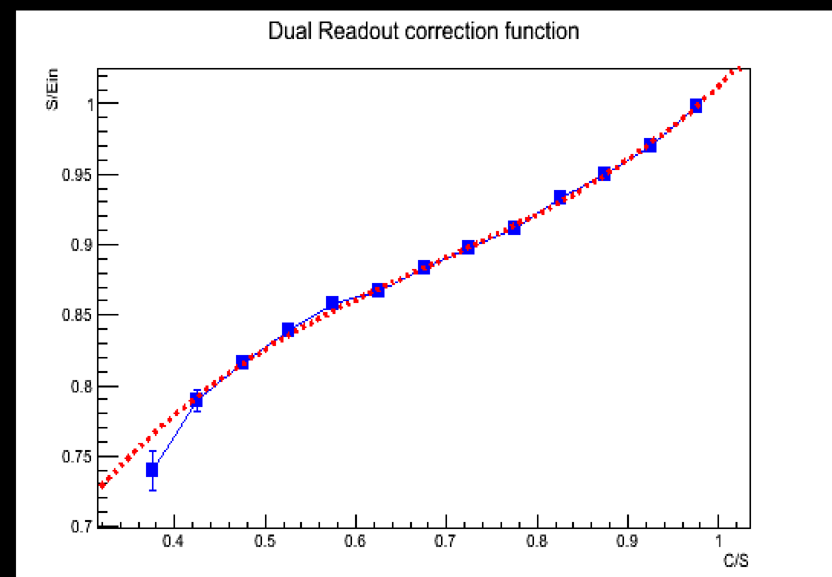
Effect of dual read out correction





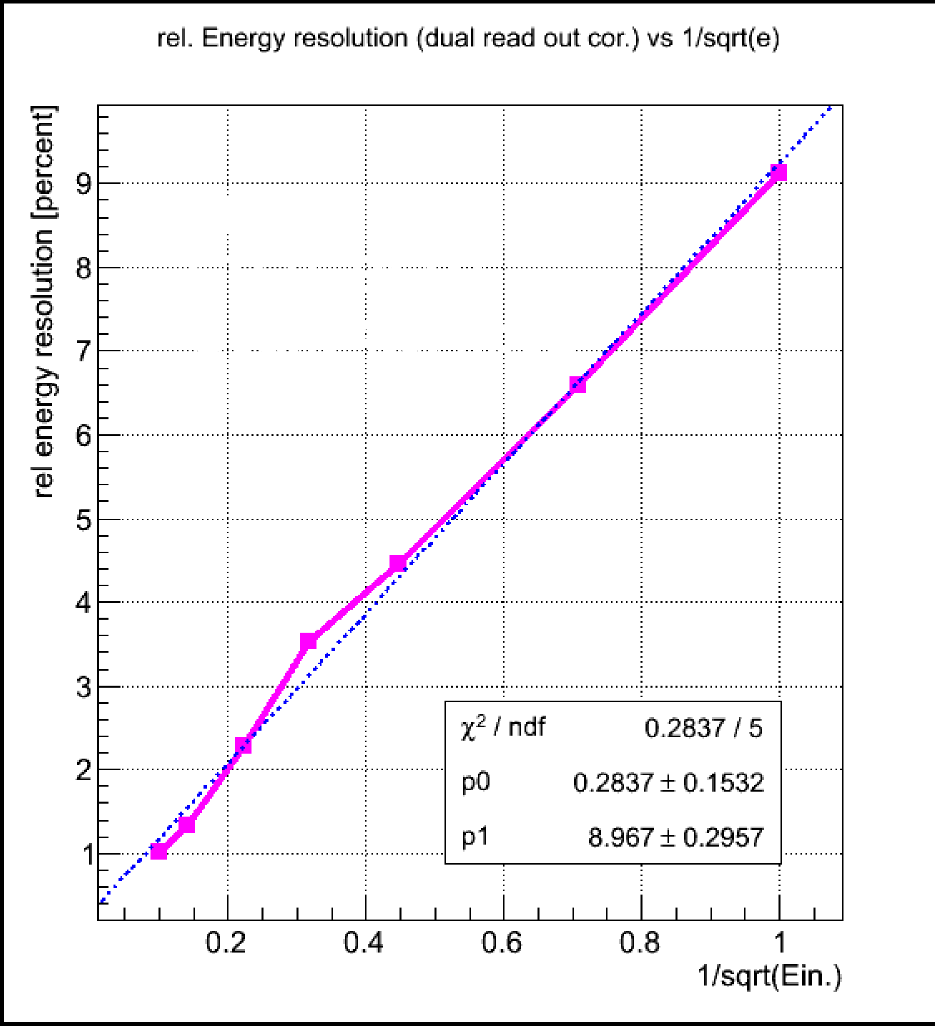
Before Dual Read out correction:
Mean: 17.8
σ: 0.83

After DR correction:
Mean: 20.
σ: 0.58



Energy Resolution for single π^-

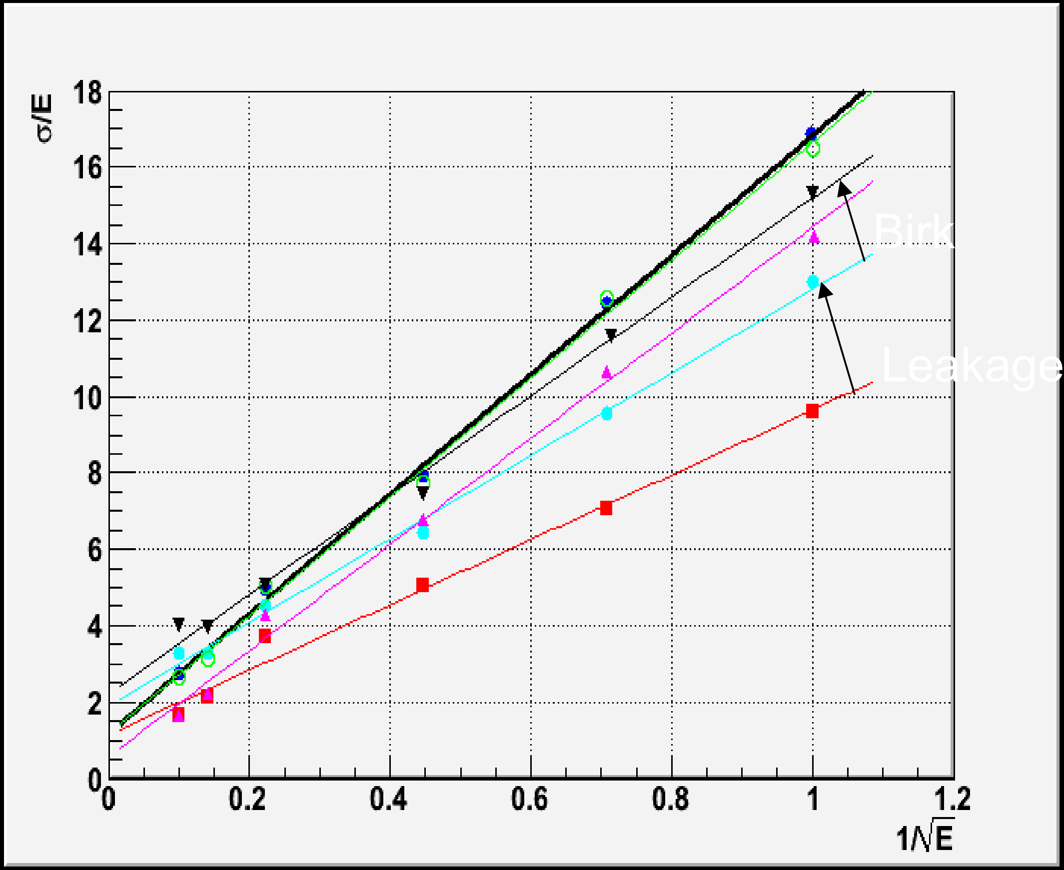
Relative Energy resolution in Ideal case:
$\sigma E/E = 0.3 + 9. /\mathrm{Sqrt}(E)$ %



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.

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

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)
Enabling technologies:
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

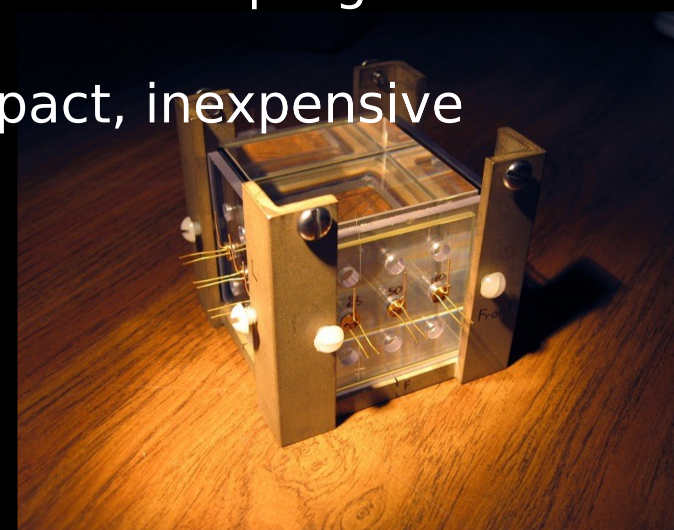


Table 2: Candidate Crystals for the HHCAL Detector Concept

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