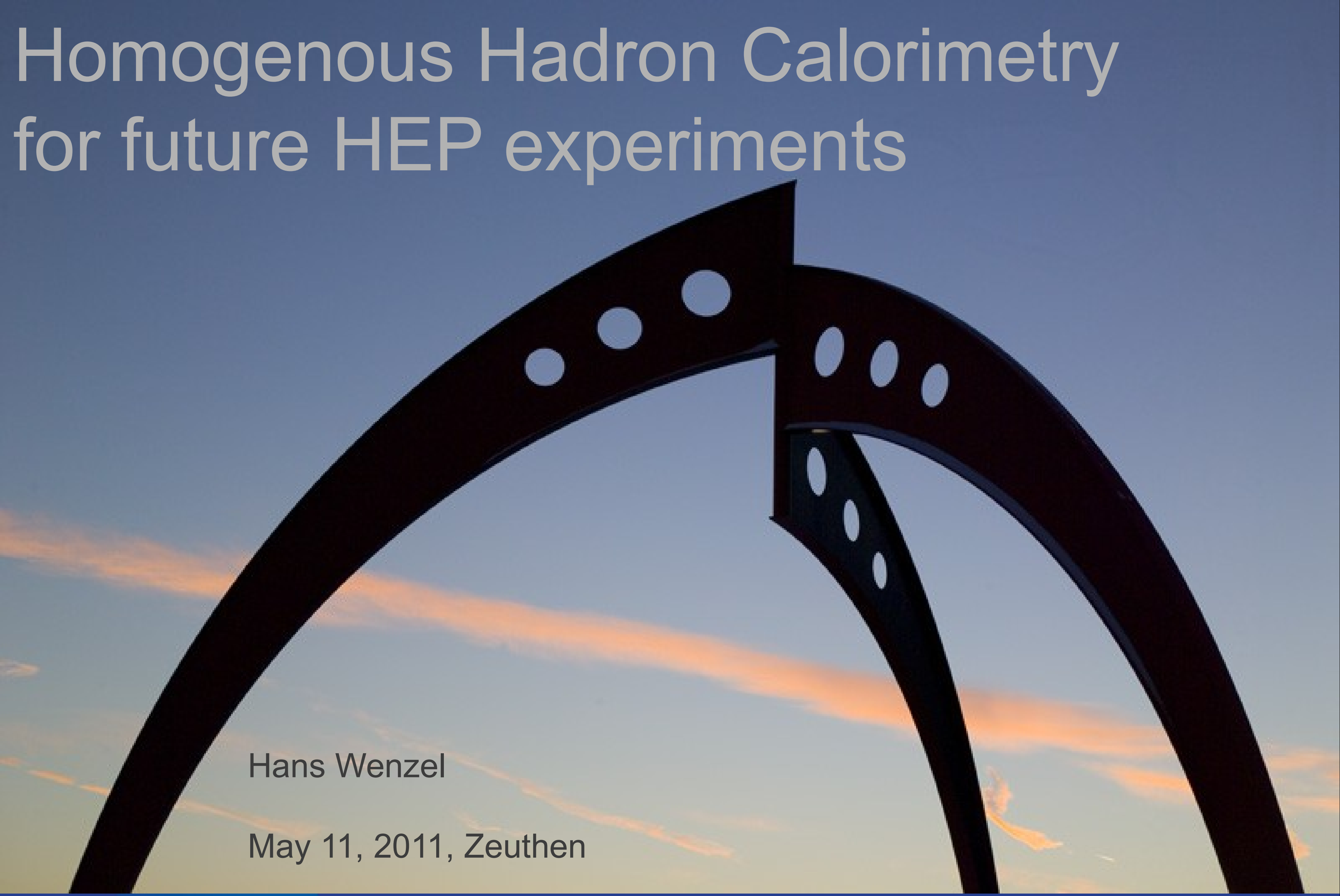


Homogenous Hadron Calorimetry for future HEP experiments

Hans Wenzel

May 11, 2011, Zeuthen

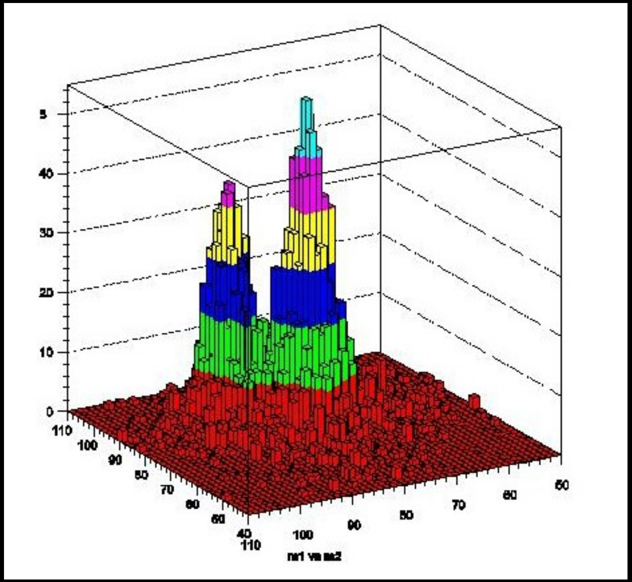
Outline

- Introduction/Motivation
- Simulation of a homogeneous Hadron Calorimeter
- Some effects limiting the Energy resolution
- Crystals in the Test Beam
- R&D to develop cost effective Crystals
- Conclusions

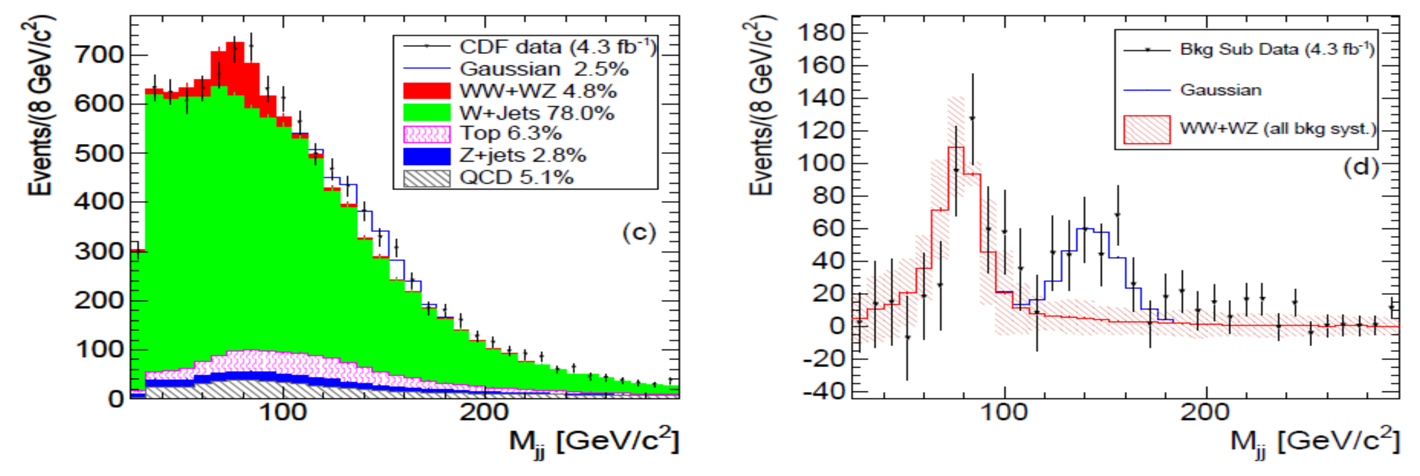
Introduction - General

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.

Why do you care!



Imagine a Possible Outcome of an Experiment



Importance of Resolution, linearity and equal response:

If you had $\Delta M/M \sim$ 2-3%:
- WW vs WZ: more physics
- W vs Z convincing demonstration of the calibration and other systematics

Mysterious bump on falling edge of W+jets background.

But:
- If you shift the background by one bin the effect is gone.
- How well did you model jets fragmentation functions?
- How do you know the correct fraction of quark vs gluon jets in your background?

→ If your calorimeter was linear and had the same response to all particles such questions would not be even raised..

Introduction (cont.)

R&D for future hep calorimetry : 3 different approaches

- particle flow approach (CALICE)
- dual readout calorimetry (DREAM)
- crystal/glass calorimetry (HHCAL Workshops)

particle flow paradigm:

highly granular EM and HADR calorimeters to allow very efficient pattern recognition for excellent shower separation and pid within jets to provide excellent jet reconstruction efficiency

dual readout calorimetry:

measurement of both the ionization/scintillation and the Cerenkov signals generated by a hadronic shower in order to determine on an event by event basis the electromagnetic fraction of the shower and so to cancel/correct for this source of fluctuation that degrades the energy resolution of the calorimeter

crystal/glass calorimetry:

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

Contributions to hadron energy resolution and non-linearity of response

The principal contributions include:

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

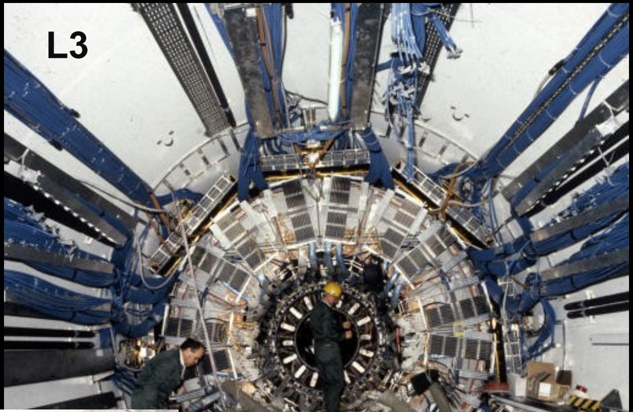
- Sampling fluctuations: fluctuations in the sharing of the shower energy between the active and passive materials (in sampling calorimeters) → homogeneous, totally active.

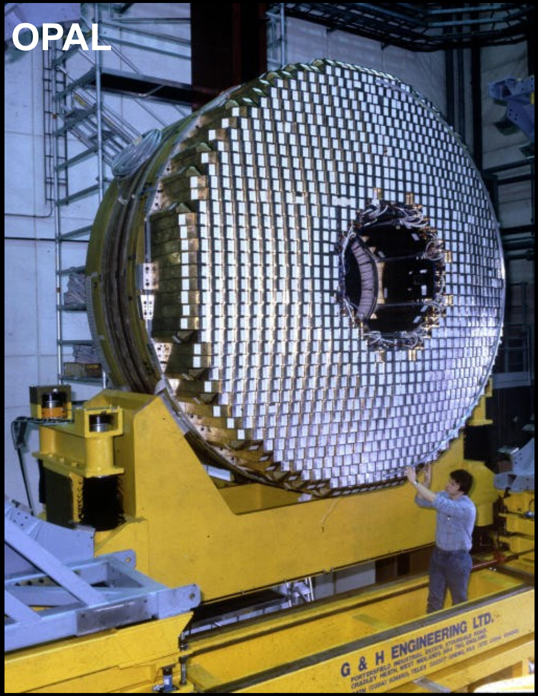
- Difference in the ’sampling fractions’ (i.e. ratio in the effective energy loss) between the different materials in the sampling calorimeters → homogeneous

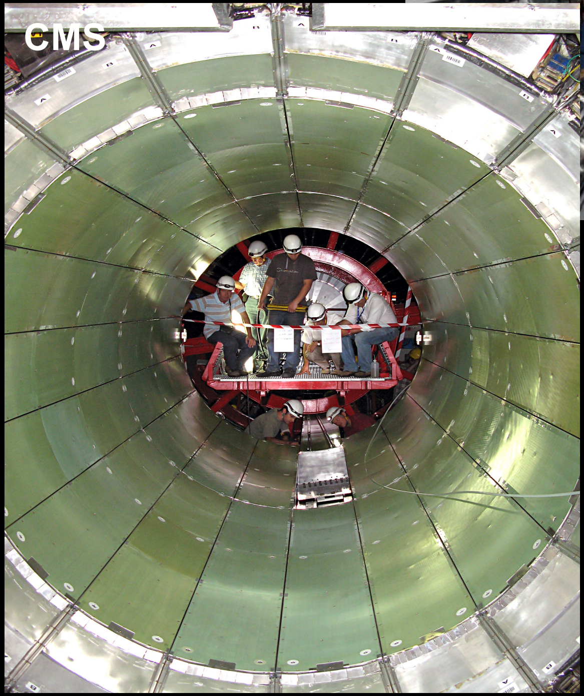
- Leakage fluctuations due to neutrinos, muons and tails of the hadronic shower escaping the detector volume → dense material

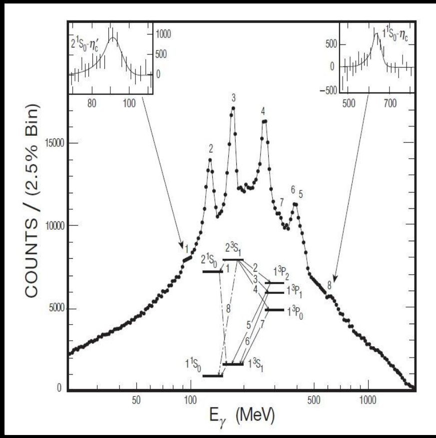
History

- 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









Principle of a dual read out calorimeter

Detect separately scintillation and Cerenkov light (same Volume)

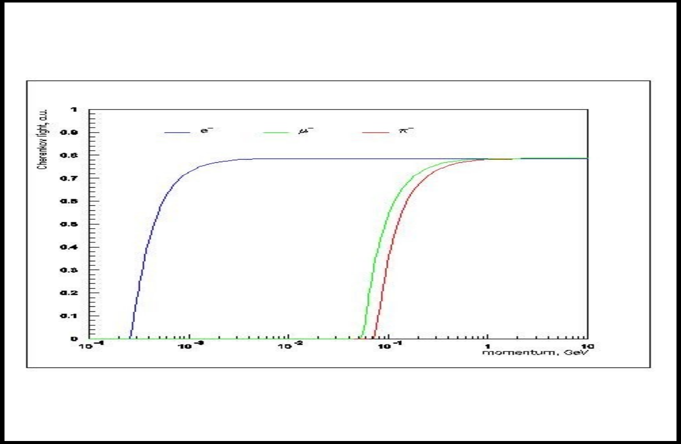
Scintillation light is a precise measure of the total energy released in the calorimeter (~total path length of the charged particles in a shower).

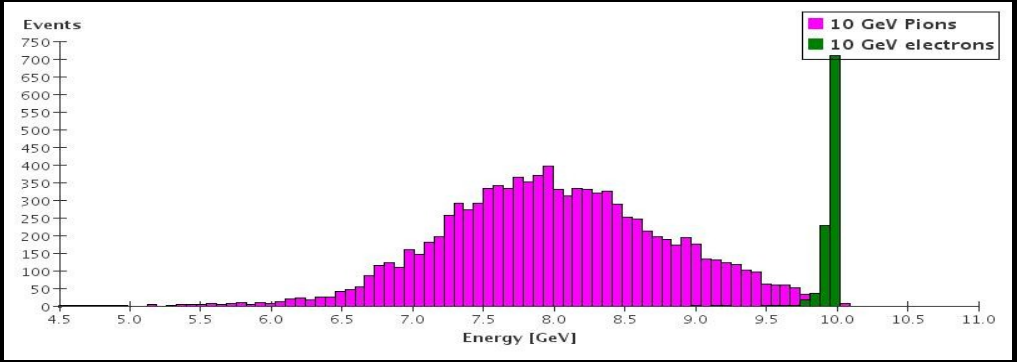
Cerenkov light is a precise measure of the total path length of the relativistic particles ($\beta>1/n$) in the shower.

Calibrate C=S for electron showers (spread of both signals very small)

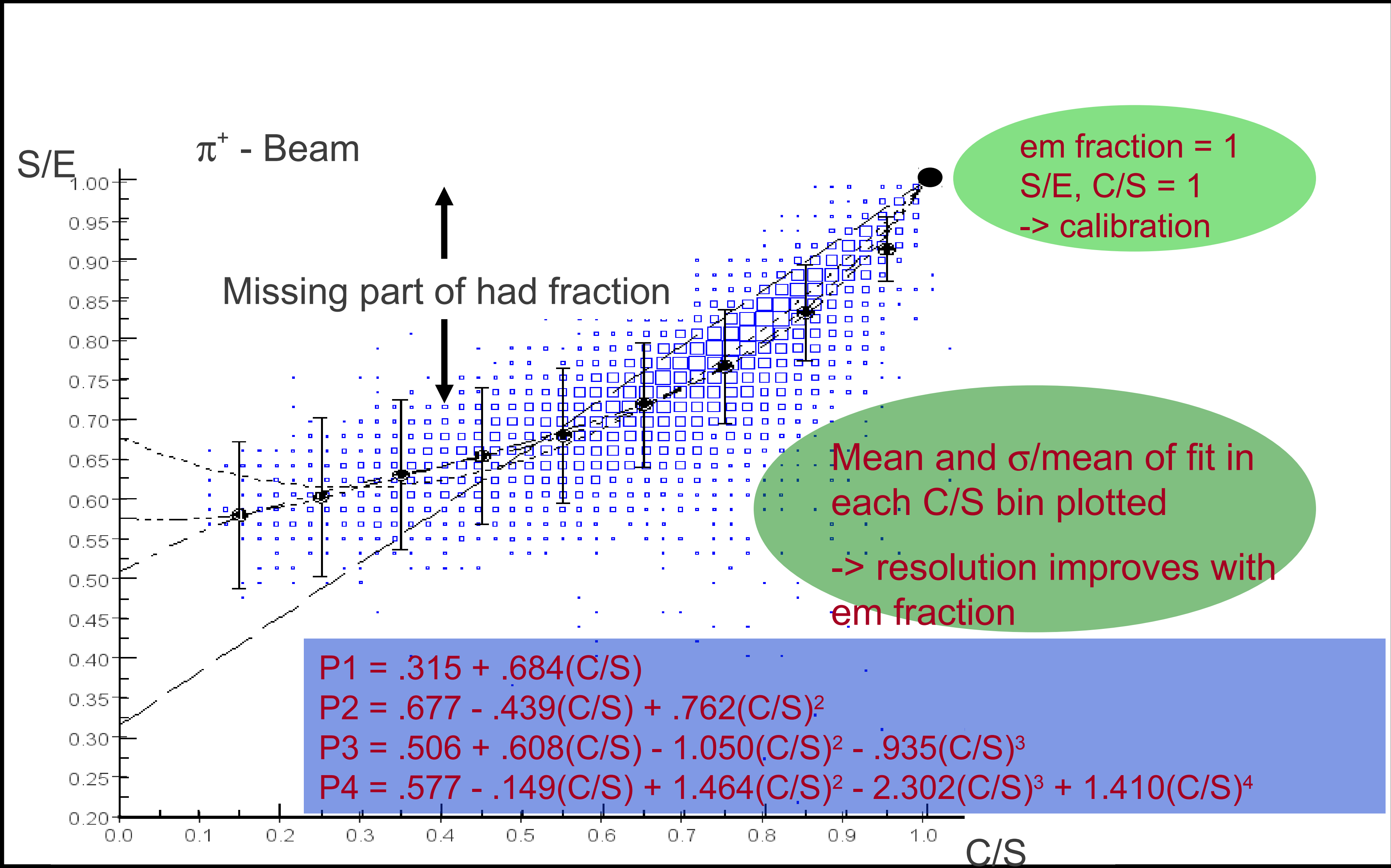
Hadron showers with large C/S → large electromagnetic component, small missing energy.

Hadron showers with low C/S → purely charged hadrons, large amount of missing energy.





Polynomial Correction Functions: E=S/Pn



Missing part of had fraction

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

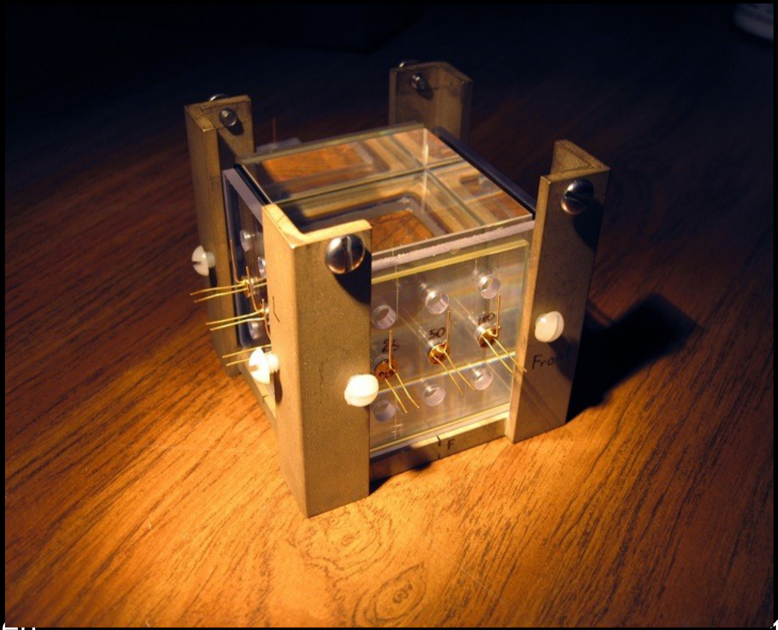
Mean and σ/mean of fit in each C/S bin plotted

-> resolution improves with em fraction

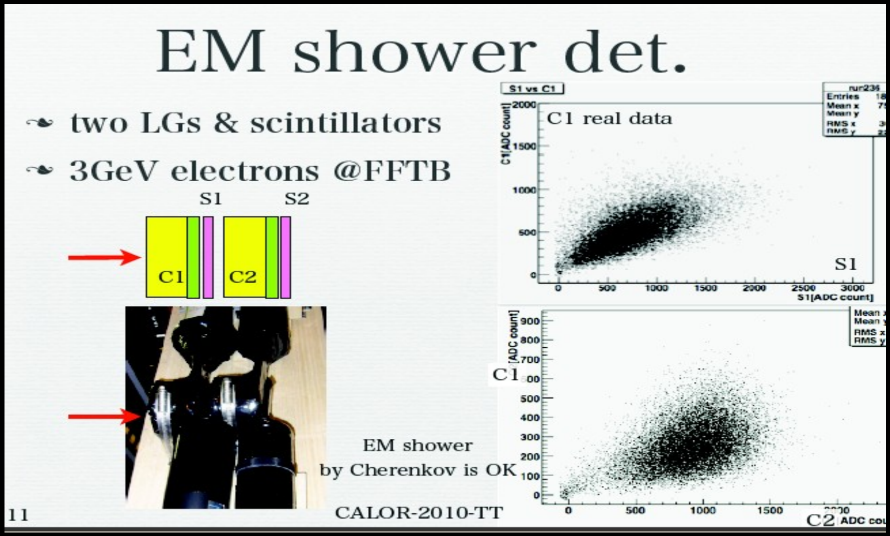
P1 = .315 + .684(C/S)
P2 = .677 - .439(C/S) + .762(C/S)²
P3 = .506 + .608(C/S) - 1.050(C/S)² - .935(C/S)³
P4 = .577 - .149(C/S) + 1.464(C/S)² - 2.302(C/S)³ + 1.410(C/S)⁴

Enabling technologies:

Major advances in the detectors technology/enabling technologies:
→ High density scintillating crystals/glasses (~20 cm)
→ „Silicon Photomultipliers“ ~ robust compact, inexpensive



Examples of other R&D projects

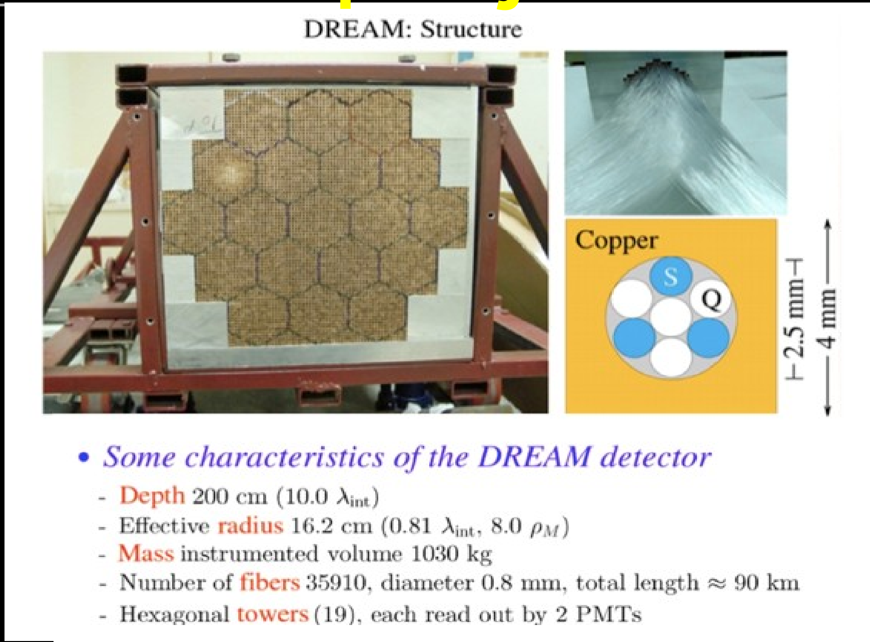


EM shower det.

- two LGs & scintillators
- 3GeV electrons @FFTB

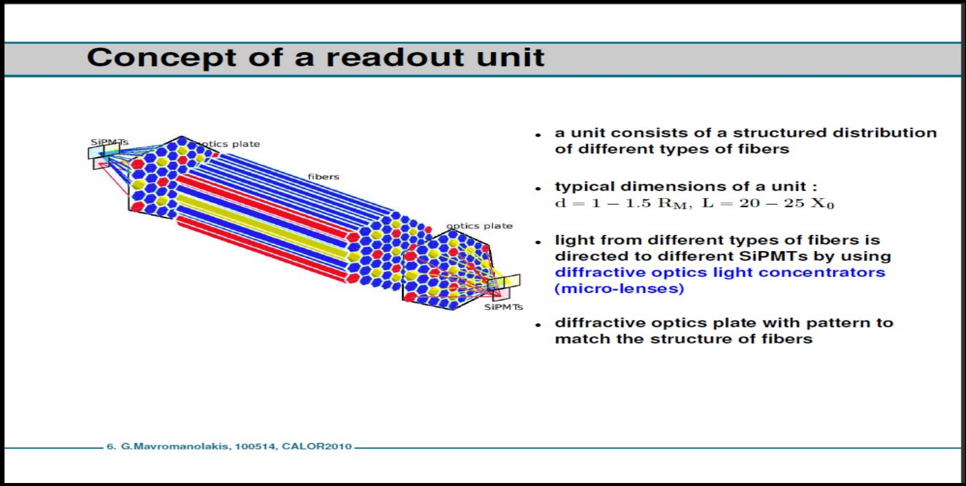
EM shower
by Cherenkov is OK

11 CALOR-2010-TT



DREAM: Structure

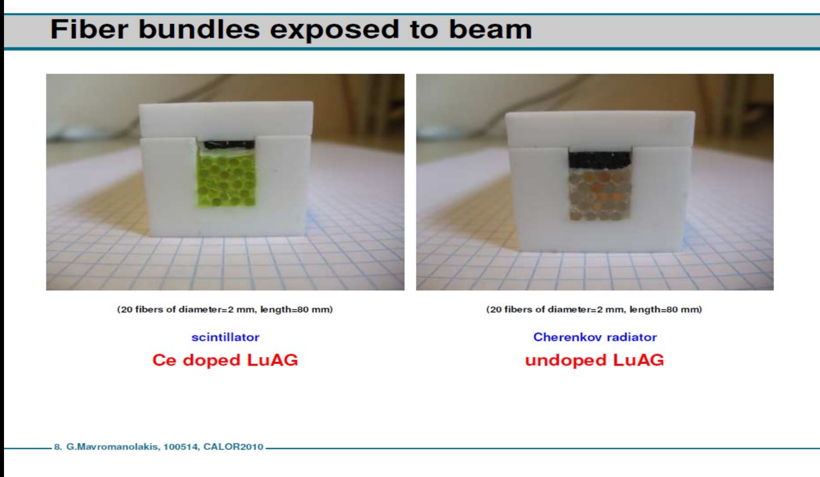
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs



Concept of a readout unit

- a unit consists of a structured distribution of different types of fibers
- typical dimensions of a unit : $d = 1 - 1.5\ \mathrm{R_M},\ \mathrm{L} = 20 - 25\ \mathrm{X_0}$
- light from different types of fibers is directed to different SiPMTs by using diffractive optics light concentrators (micro-lenses)
- diffractive optics plate with pattern to match the structure of fibers

6. G.Mavromanolakis, 100514, CALOR2010



Fiber bundles exposed to beam

(20 fibers of diameter=2 mm, length=80 mm)

scintillator

Ce doped LuAG

(20 fibers of diameter=2 mm, length=80 mm)

Cherenkov radiator

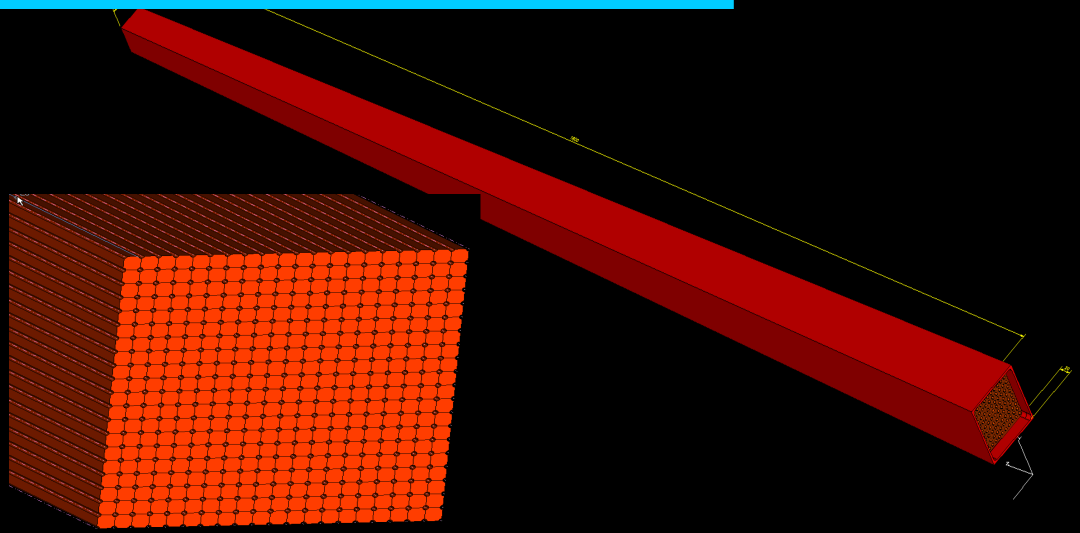
undoped LuAG

8. G.Mavromanolakis, 100514, CALOR2010

Examples of other R&D projects (cont.)

ADRIANO: A Dual-Readout Integrally Active Non-segmented Option

- Fully modular structure
- 2-D with longitudinal shower COG via Light division techniques



Cells dimensions: 4x4x180 cm^3

Absorber and Cerenkov radiator: SF57HHT

Cerenkov light collection: 8 BCF92 fiber/cell

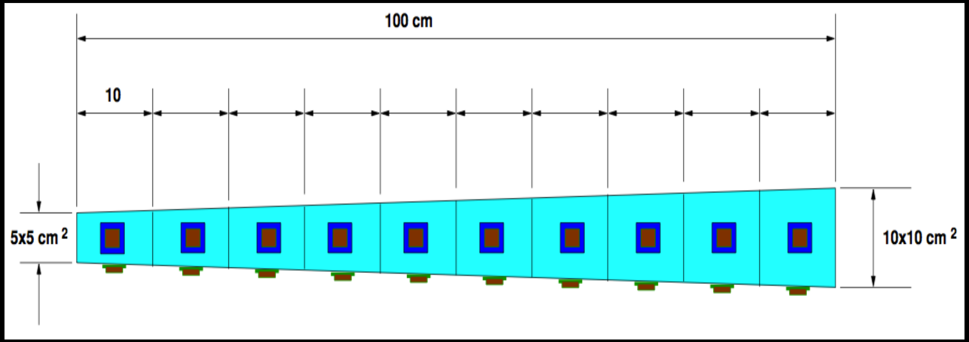
Scintillation region: SCSF81J fibers, dia. 1mm, pitch 4mm (total 100/cell) inside 100μm thin steel capillary

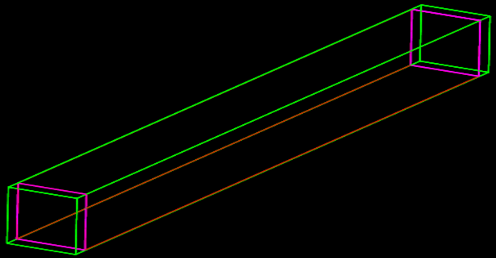
Particle ID: 4 BCF92 fiber/cell (black painted except for foremost 20 cm)

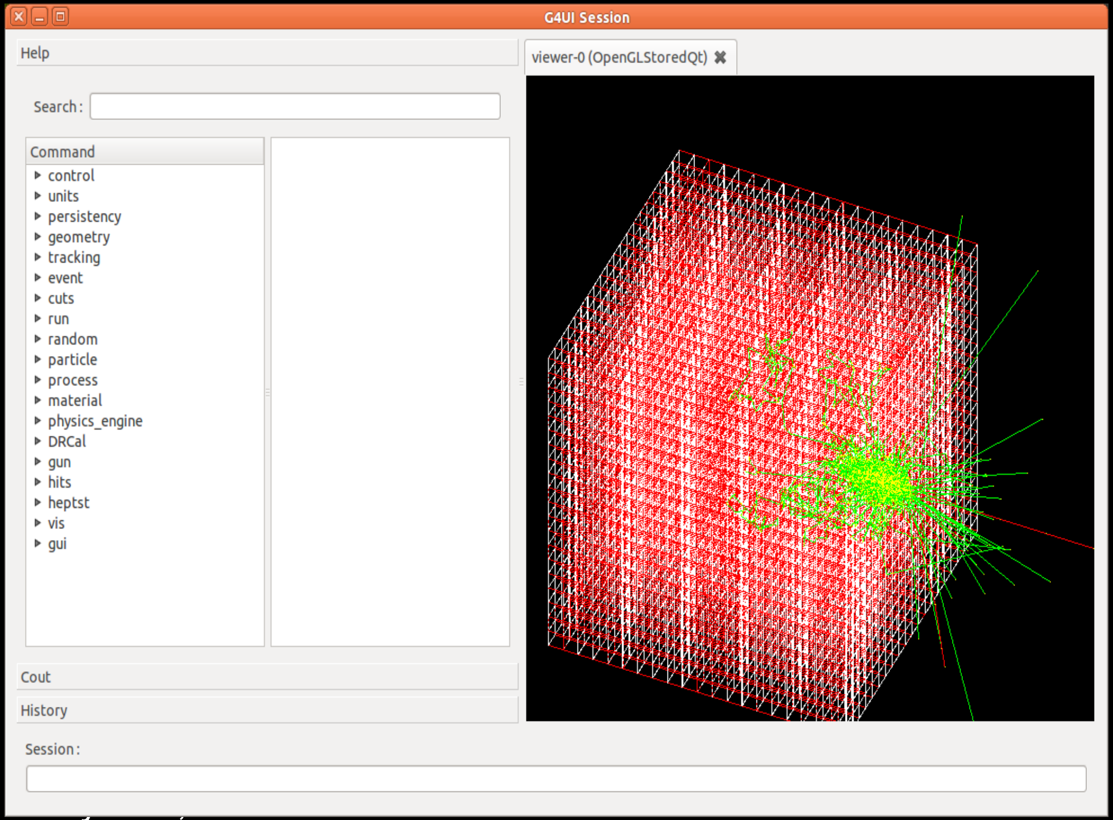
Readout: front and back SiPM

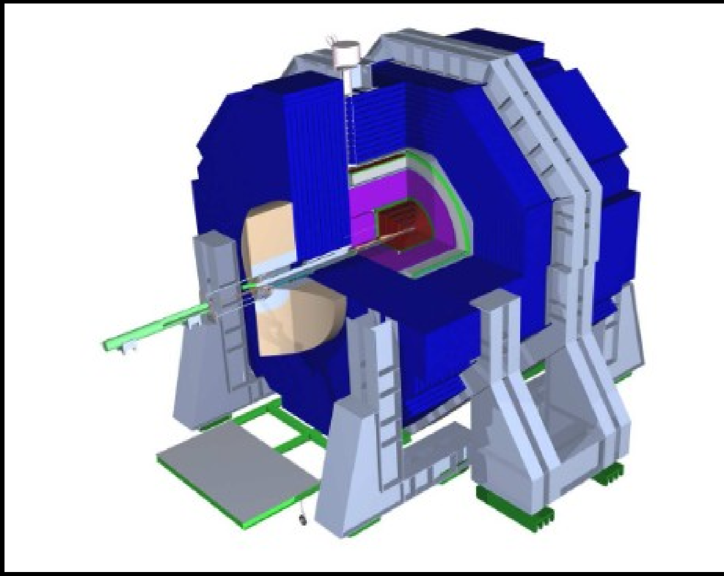
COG z-measurement: light division applied to SCSF81J fibers

Simulation from single Crystal to full detector





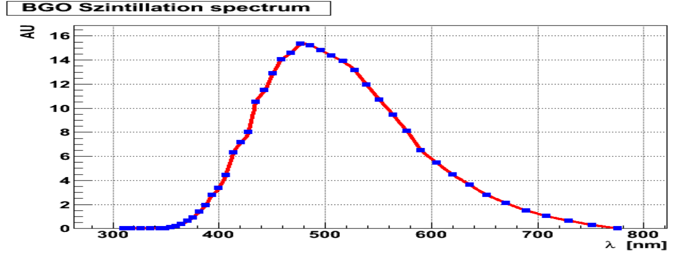




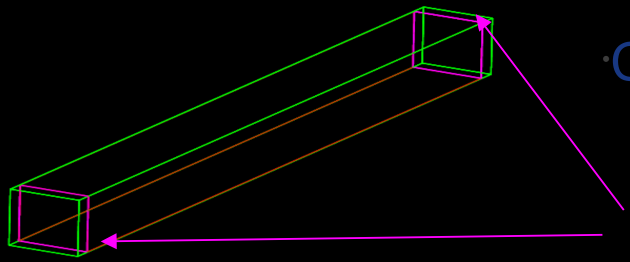
DRCal

- Geant 4 based stand alone application (optical photons).
  - - Assumes all deposited energy is converted to scintillation light.
  - Input:
  - - rindex(λ)
  - absorption length(λ)
  - scintillation spectrum(λ,t), light yield (photons/MeV)
  - Birks suppression
  - crystal surface conditions. (various models, LUT (LBNL))
- every optical photon is tracked from time of production until it's lost (absorbed) or detected at the photo-sensors.

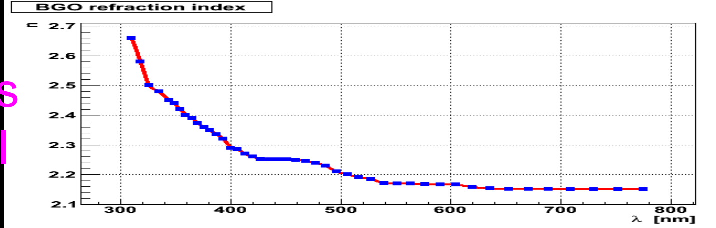
Quantum efficiency (λ) of photo detectors and electronic response is applied in the analysis step (ROOT).



- Crystal: 2x2x20 cm

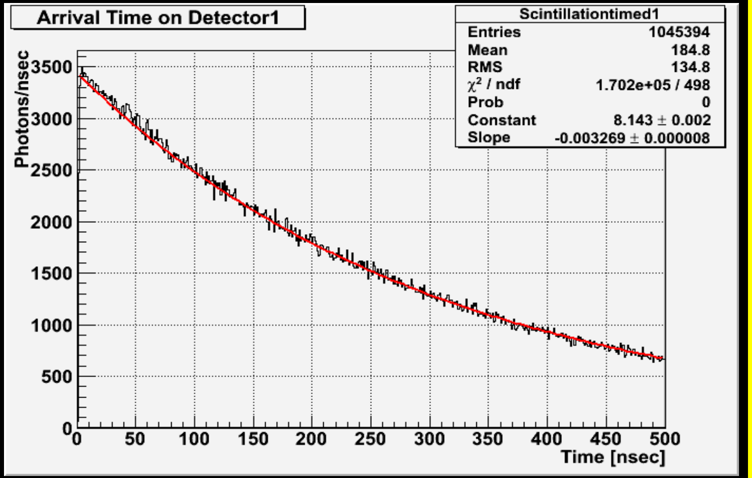


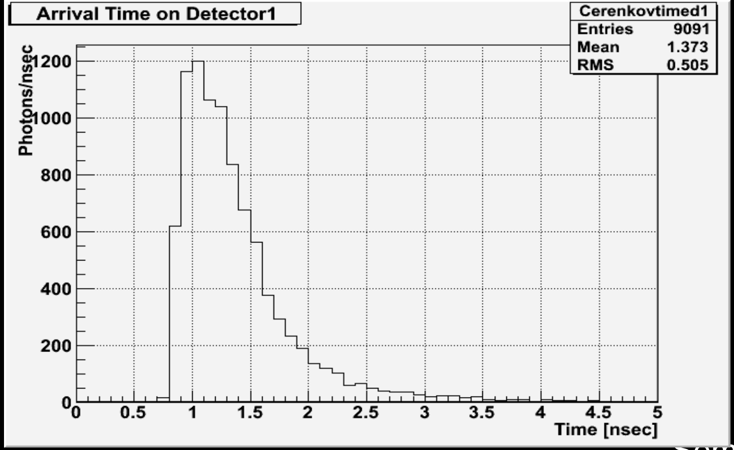
- Ideal Photodetectors
- (detect every optical
- photon)



DRCal

DRCal can provide detailed studies of:





- Light yield (scintillation and Cherenkov)
- Light attenuation
- Crystal shapes
- Uniformity of the detector response
- Efficiency and purity of the Scintillation-Cherenkov separation by means of timing, wavelength
- Sizes and positions of the photodetectors
- Required properties of photodetectors

This can then be applied in full detector Simulation (SLIC)

2 GeV Muons (2cm BGO):

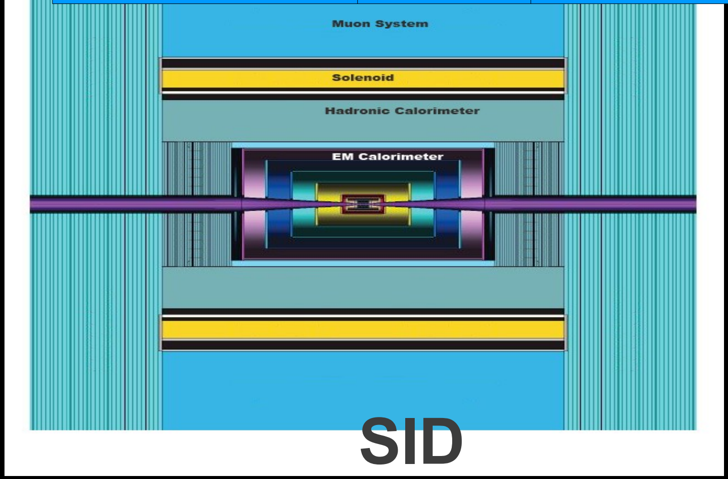
10500: Szintillation ph/sensor

90: Cerenkov ph/sensor

The CCAL02 detector

(Crystal Calorimetry version of SID)

				BGO		$PbWO_4$	
Name	Layers	Thickness/Layer	Segmentation	X_0	λ_I	X0	ll
		[cm]	[cm x cm]				
ECAL Barrel	8	3	3 x 3	21.4	1.1	27	1.3
HCAL Barrel	17	6	5 x 5		4.7		5.7
Total Barrel	25				5.8		7
ECAL Endcap	8	3	3 x 3	21.4	1.1		1.3
HCAL Endcap	17	6	5 x 5		4.7		5.7
Total Endcap	25				5.8		7

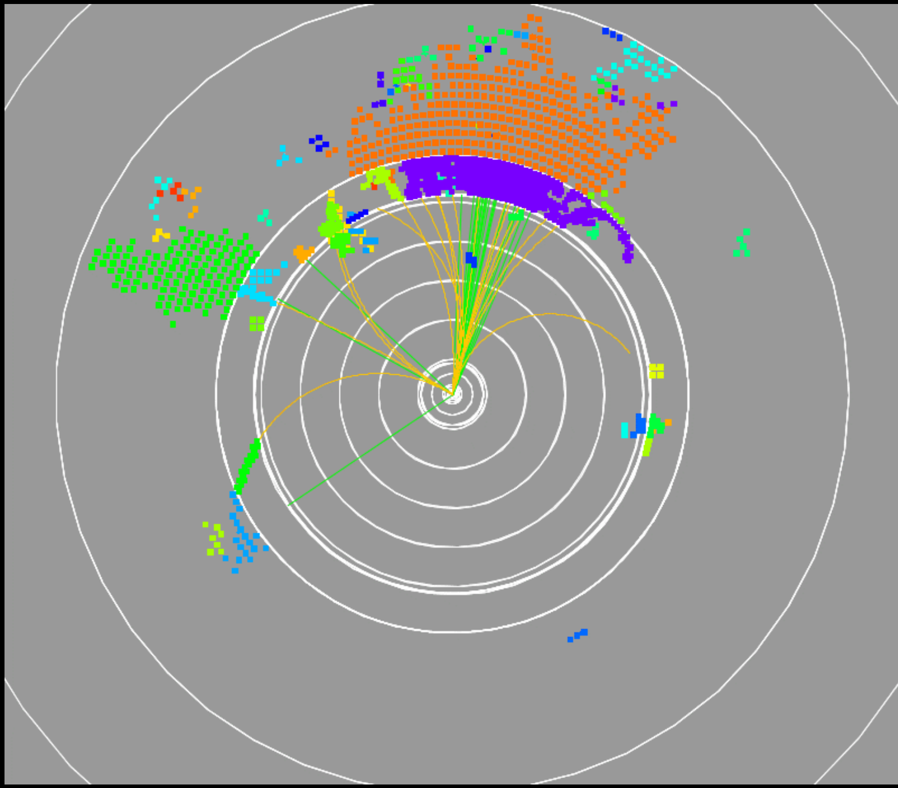


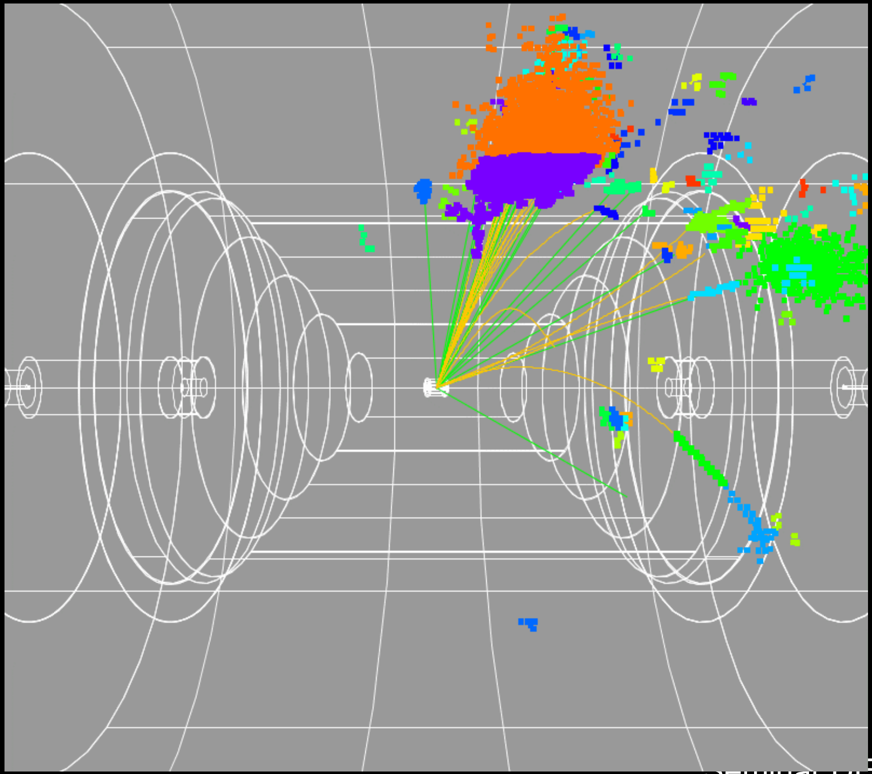
Material	Density	Rad. len. X0	IA len.
	[g/cm3]	[cm]	[cm]
BGO	7.13	1.12	21.88
PbWO4	8.3	0.9	18
SCG1-C	3.36	4.25	45.6

Monte Carlo: BGO with 15.0 g/cm

CCAL02 Scintillation response

ZZ->qqνν

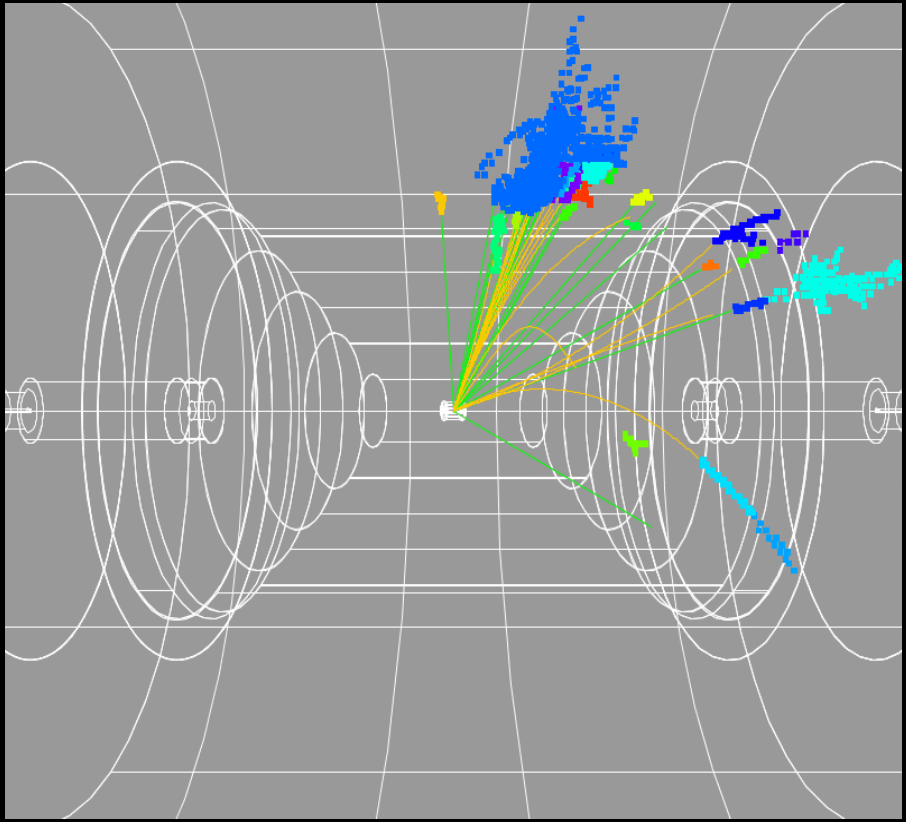


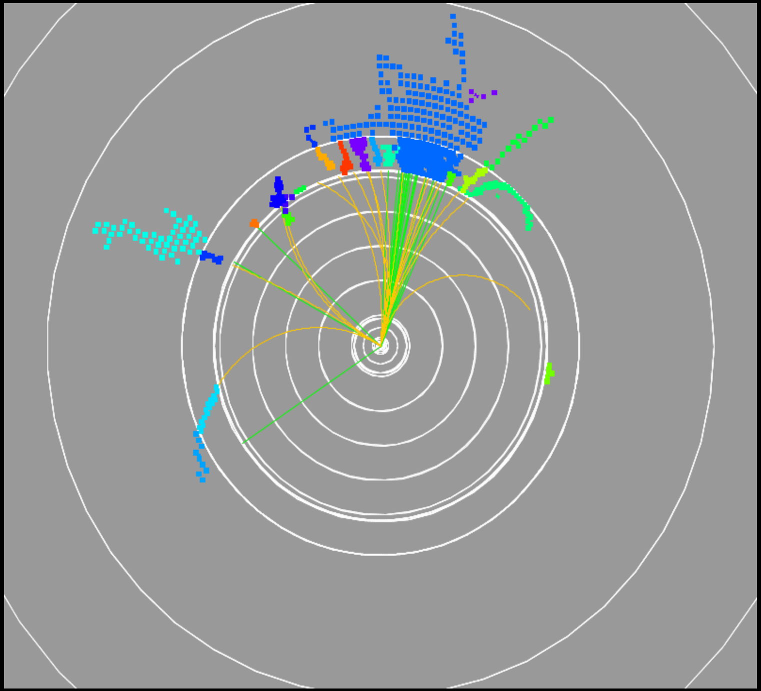


- Digisim,
- Threshold 1/50 of a mip

CCAL02: Cerenkov response

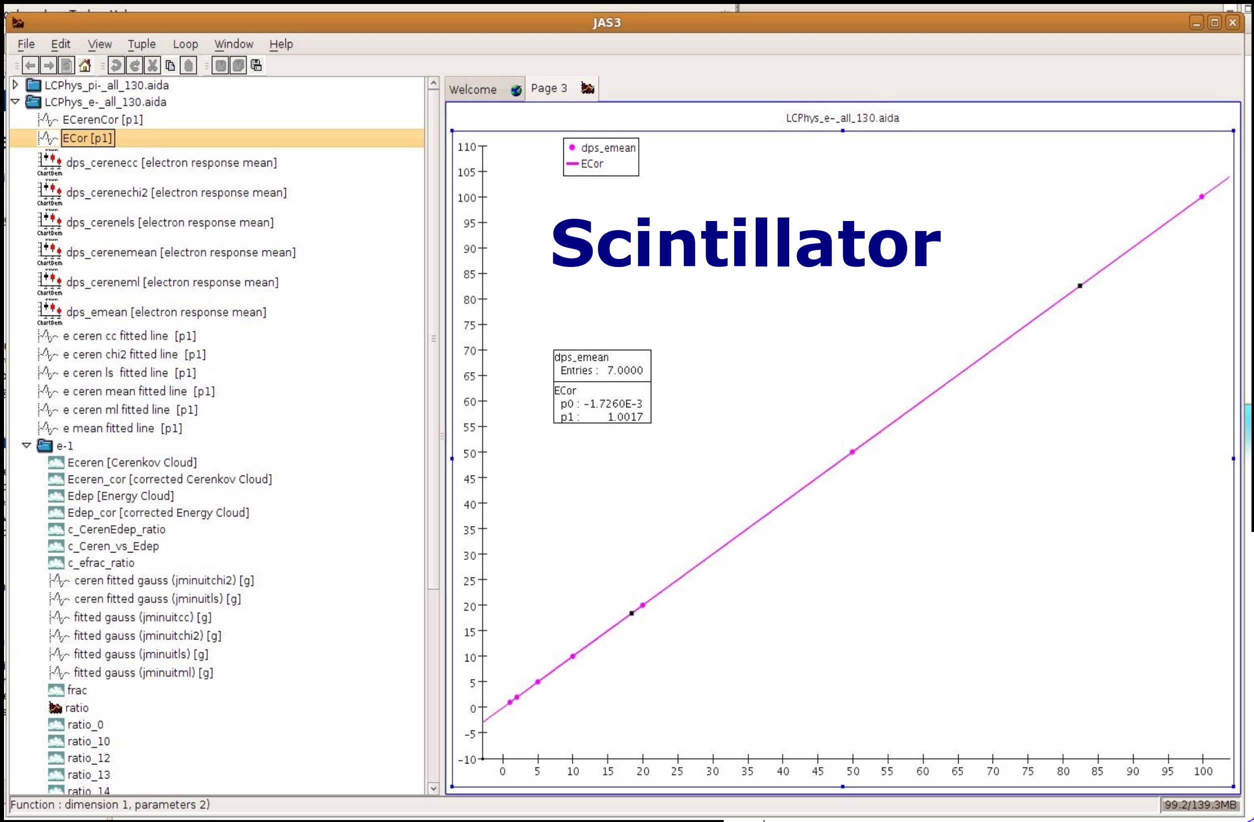
- ZZ->qq$\nu\nu$





Simulation registers the enrgy of all the Cerenkov photons that are produced → No inefficiencies absorption etc.

Electron Calibration for Scintillator, Cerenkov



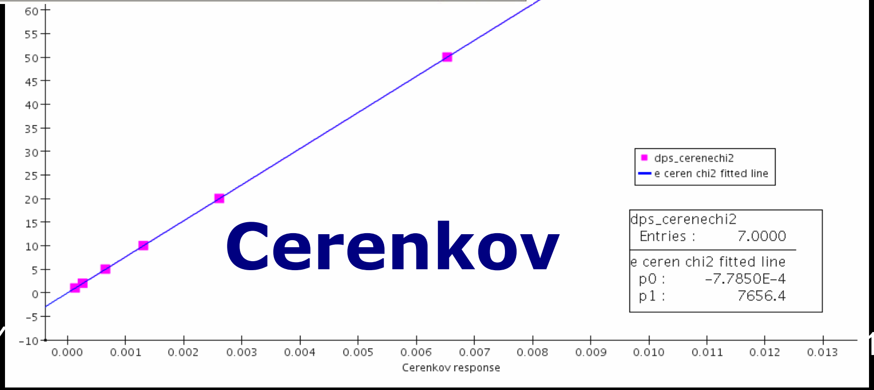
- LCPhys_pi-_all_130.aida
- LCPhys_e-_all_130.aida
  - ECerenCor [p1]
  - ECor [p1]
  - dps_cerenecc [electron response mean]
  - dps_cerenechi2 [electron response mean]
  - dps_cerenels [electron response mean]
  - dps_cerenemean [electron response mean]
  - dps_cerenemI [electron response mean]
  - dps_emean [electron response mean]
  - e ceren cc fitted line [p1]
  - e ceren chi2 fitted line [p1]
  - e ceren ls fitted line [p1]
  - e ceren mean fitted line [p1]
  - e ceren ml fitted line [p1]
  - e mean fitted line [p1]
  - e-1
    - Eceren [Cerenkov Cloud]
    - Eceren_cor [corrected Cerenkov Cloud]
    - Edep [Energy Cloud]
    - Edep_cor [corrected Energy Cloud]
    - c_CerenEdep_ratio
    - c_Ceren_vs_Edep
    - c_efrac_ratio
    - ceren fitted gauss (jminuitchi2) [g]
    - ceren fitted gauss (jminuitls) [g]
    - fitted gauss (jminuitcc) [g]
    - fitted gauss (jminuitchi2) [g]
    - fitted gauss (jminuitls) [g]
    - fitted gauss (jminuitml) [g]
    - frac
    - ratio
    - ratio_0
    - ratio_10
    - ratio_12
    - ratio_13
    - ratio_14

Function : dimension 1, parameters 2)

dps_emean
Entries : 7.0000

ECor
p0 : -1.7260E-3
p1 : 1.0017

Scintillator



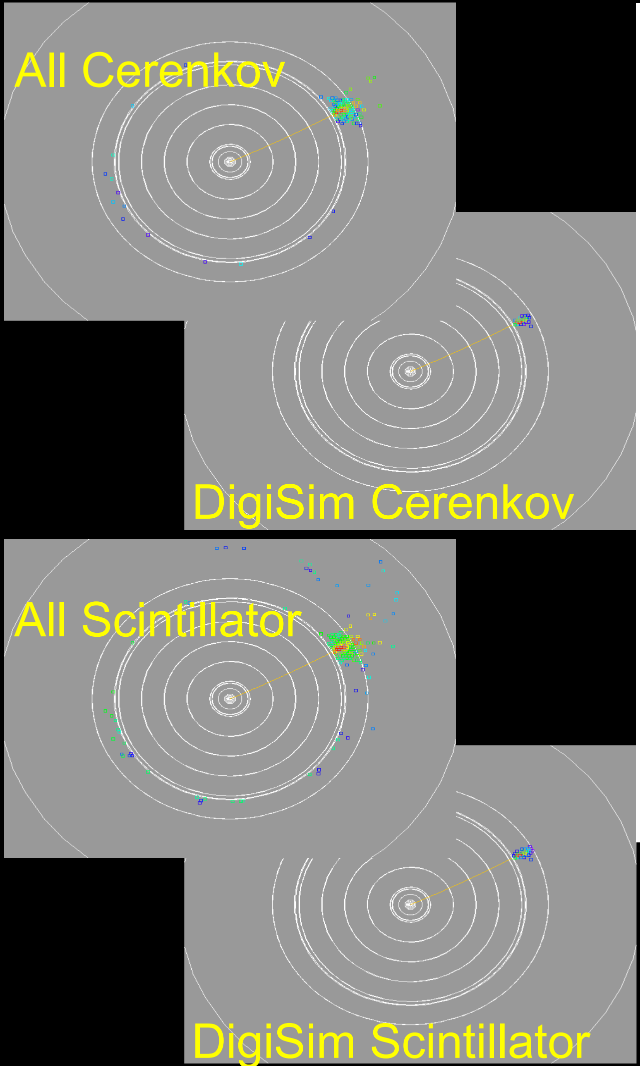
dps_cerenechi2
Entries : 7.0000

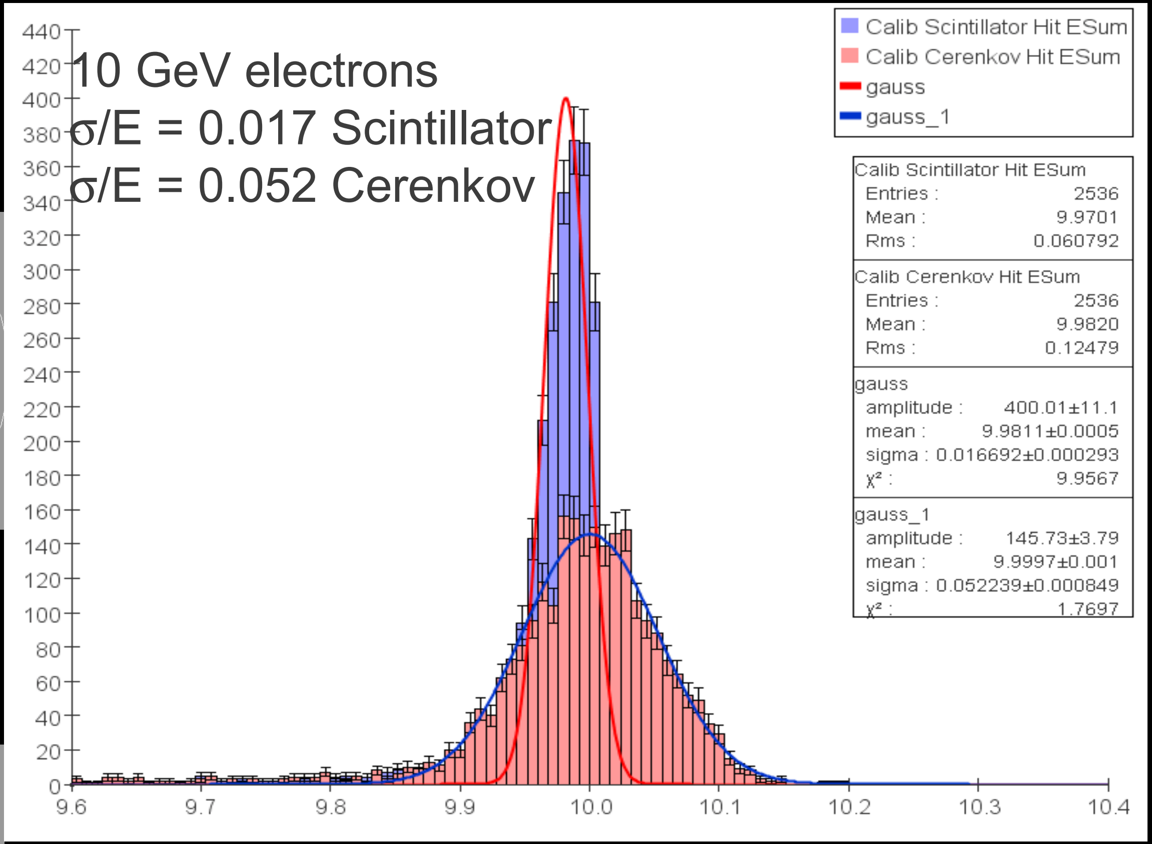
e ceren chi2 fitted line
p0 : -7.7850E-4
p1 : 7656.4

Cerenkov

Use single electrons of
1.0, 2.0, 5.0, 10.0, 20.0, 50.0, 100.0 GeV
To estimate energy scale.

Analysis: Electron Calibration for Scintillator, Cerenkov



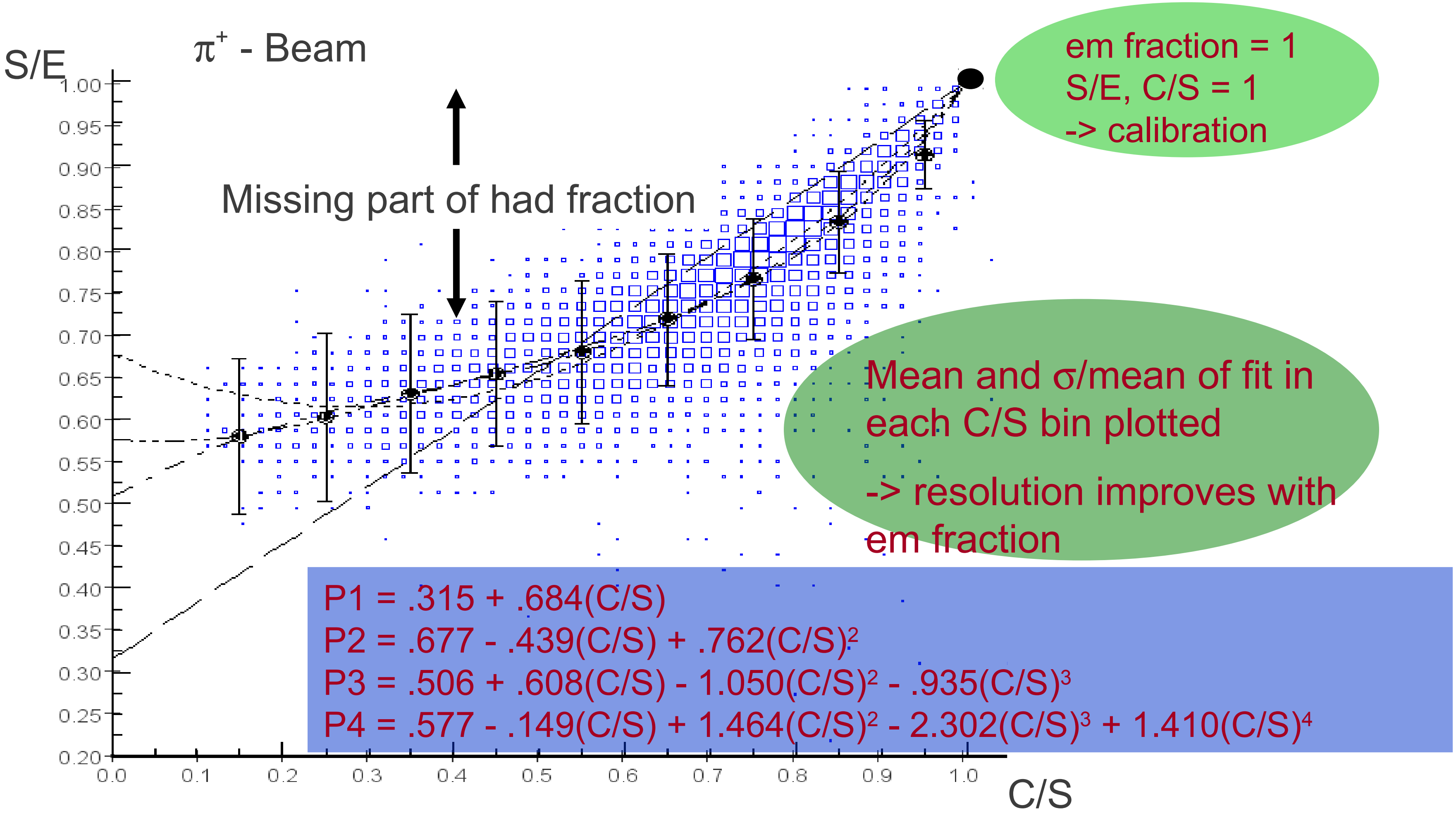

10 GeV electrons

σ/E = 0.017 Scintillator

σ/E = 0.052 Cerenkov

$S = 1.004 \times s_{raw}$ $\qquad$ $C = 7692 \times c_{raw}$

Polynomial Correction Functions: E=S/Pn



Missing part of had fraction

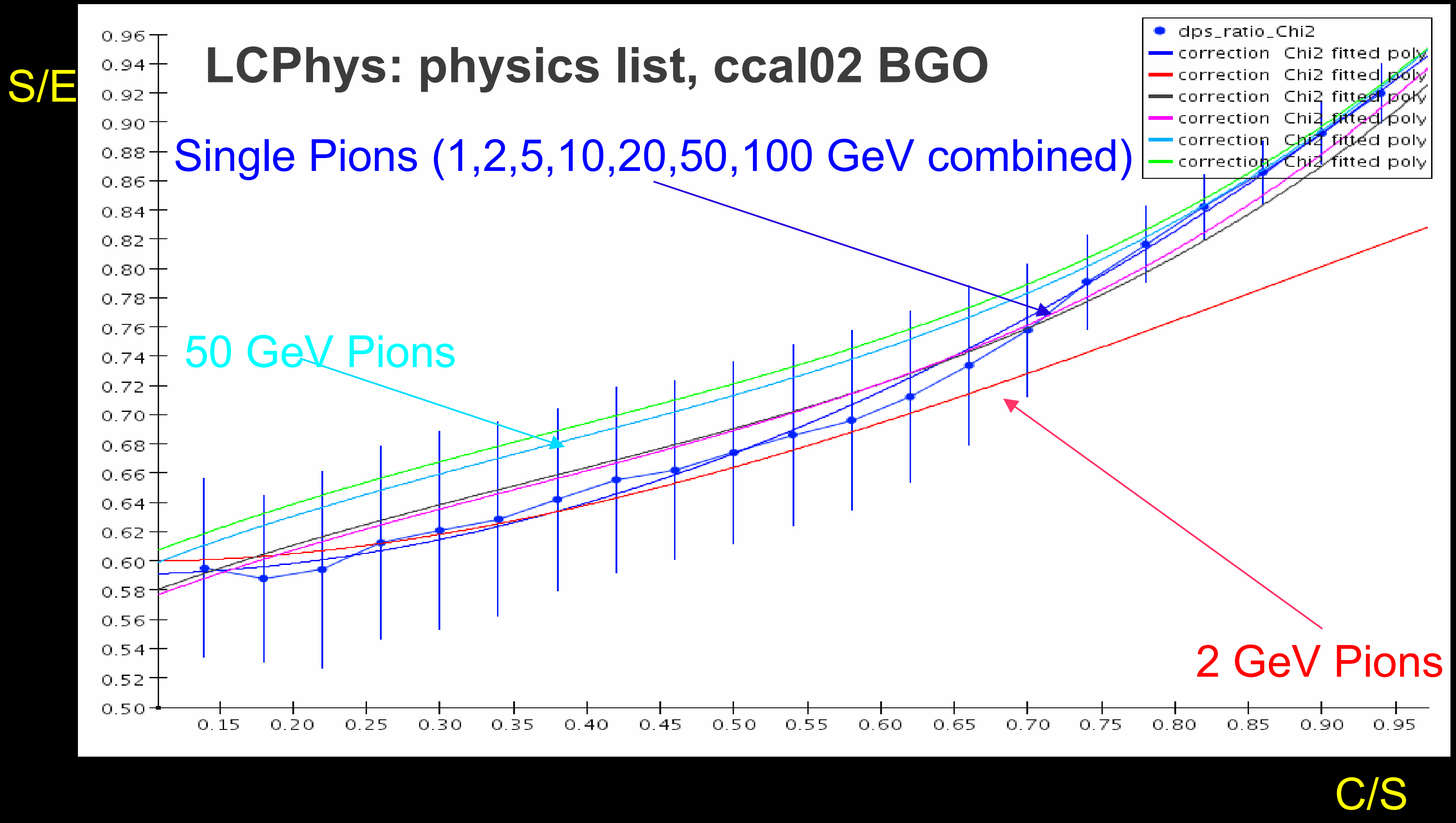
em fraction = 1
S/E, C/S = 1
-> calibration

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

-> resolution improves with em fraction

$P1 = .315 + .684(C/S)$
$P2 = .677 - .439(C/S) + .762(C/S)^2$
$P3 = .506 + .608(C/S) - 1.050(C/S)^2 - .935(C/S)^3$
$P4 = .577 - .149(C/S) + 1.464(C/S)^2 - 2.302(C/S)^3 + 1.410(C/S)^4$

Correction function as function of energy



LCPhys: physics list, ccal02 BGO

Single Pions (1,2,5,10,20,50,100 GeV combined)

50 GeV Pions

2 GeV Pions

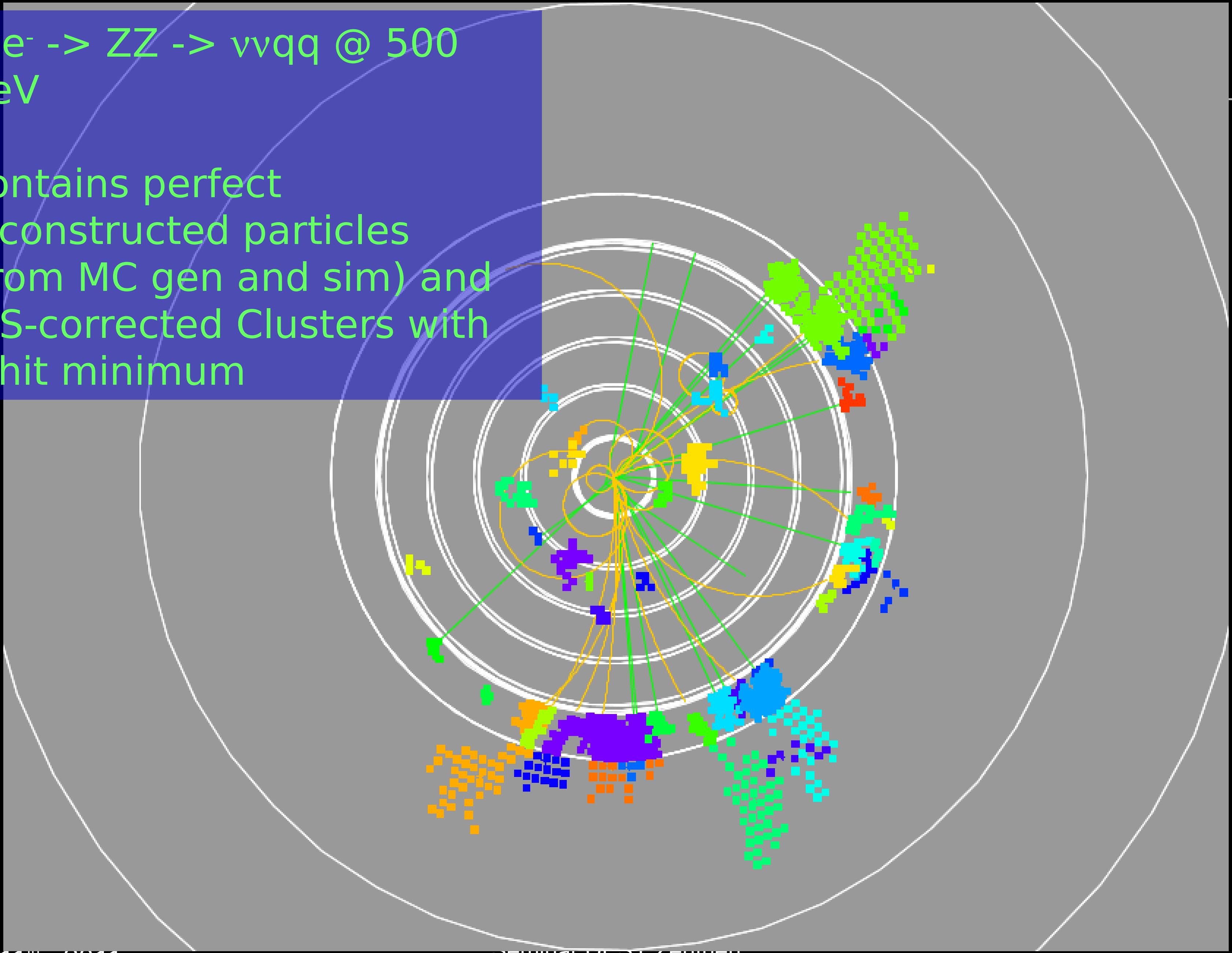
Note! Dual read out correction almost independent of energy, but it's worth exploring if we can improve energy resolution with energy dependent correction function

PFA-enhanced Dual Readout Procedure

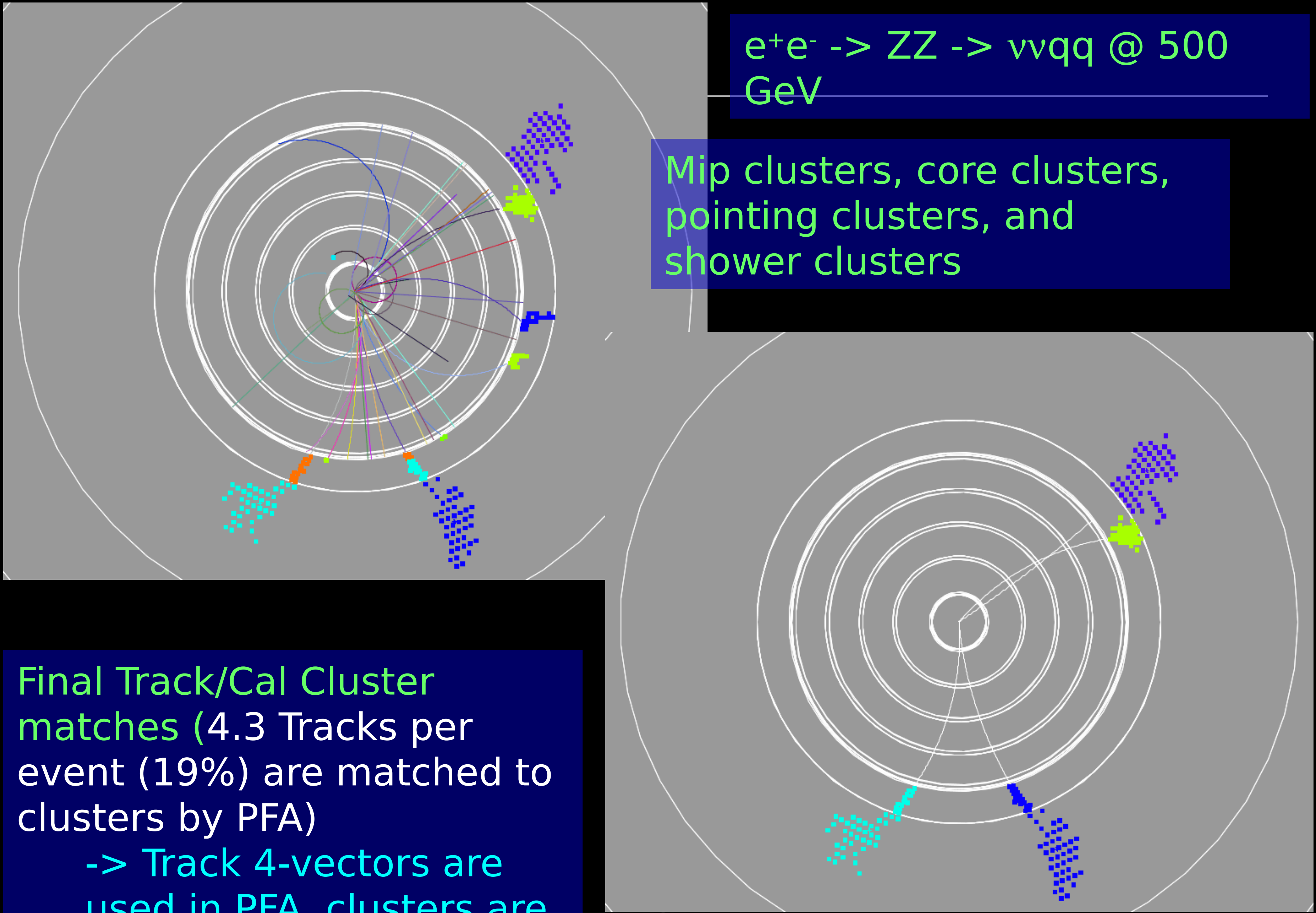
- Apply threshold, timing cuts to both scintillator and cerenkov hit cells
- Extrapolate charged particle tracks to calorimeter and use cerenkov hits to define a “mip” cluster and spacepoint at start of shower
- Cluster remaining cells using Nearest-Neighbor cluster algorithm
- Correct each cluster using C/S ratio (+ corrections for clustering, thresholds)
- Apply PFAs to match clusters with tracks
  - -> Core cluster algorithm
  - -> Cluster pointing algorithm
  - -> Track/Shower cluster algorithm
- Find jets from Tracks, Clusters, PFA Particles
- Link track jets to Cluster, PFA jets
- Make ΔM corrections to Cluster, PFA jets using linked tracks
- Determine DiJet mass from jets

e^+e^- -> ZZ -> ννqq @ 500 GeV

Contains perfect reconstructed particles (from MC gen and sim) and C/S-corrected Clusters with 4-hit minimum



e^+e^- -> ZZ -> ννqq @ 500 GeV



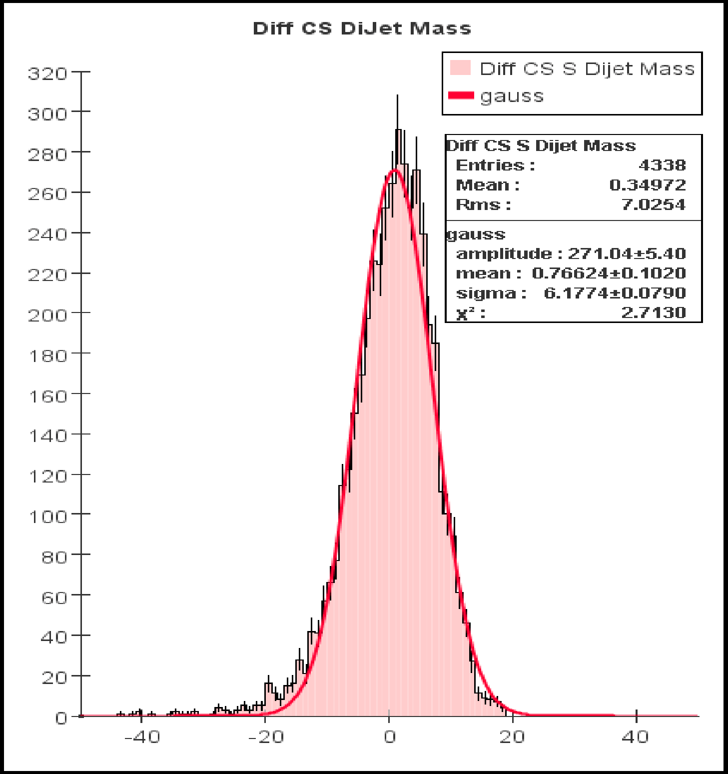
Mip clusters, core clusters, pointing clusters, and shower clusters

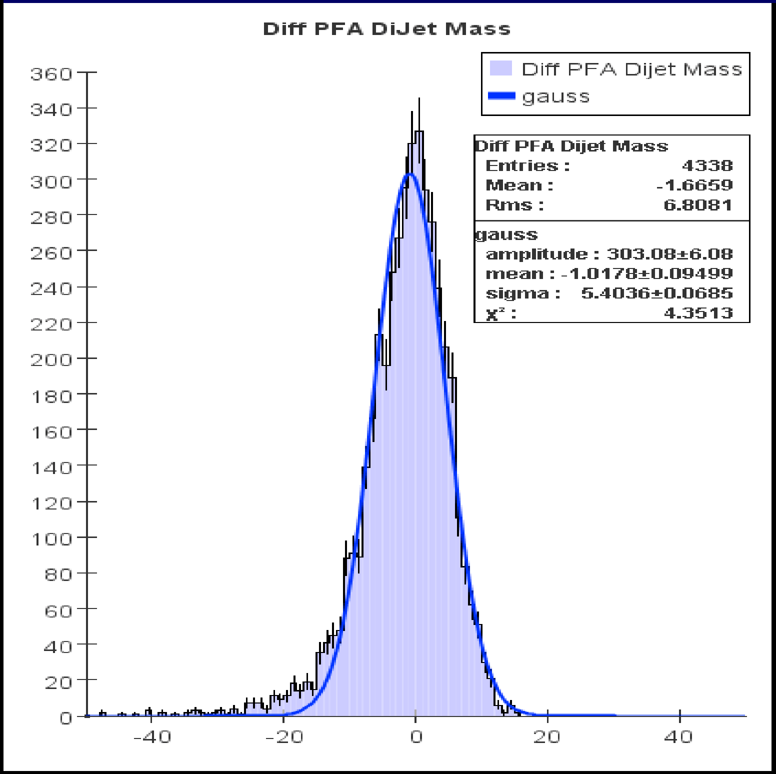
Final Track/Cal Cluster matches (4.3 Tracks per event (19%) are matched to clusters by PFA)

-> Track 4-vectors are used in PFA, clusters are removed

Difference -> DiJet Mass – qq Mass

$e^+e^- \rightarrow ZZ \rightarrow \nu\nu qq$ @ 500 GeV





C/S-corrected Clusters

σ/M = 0.068

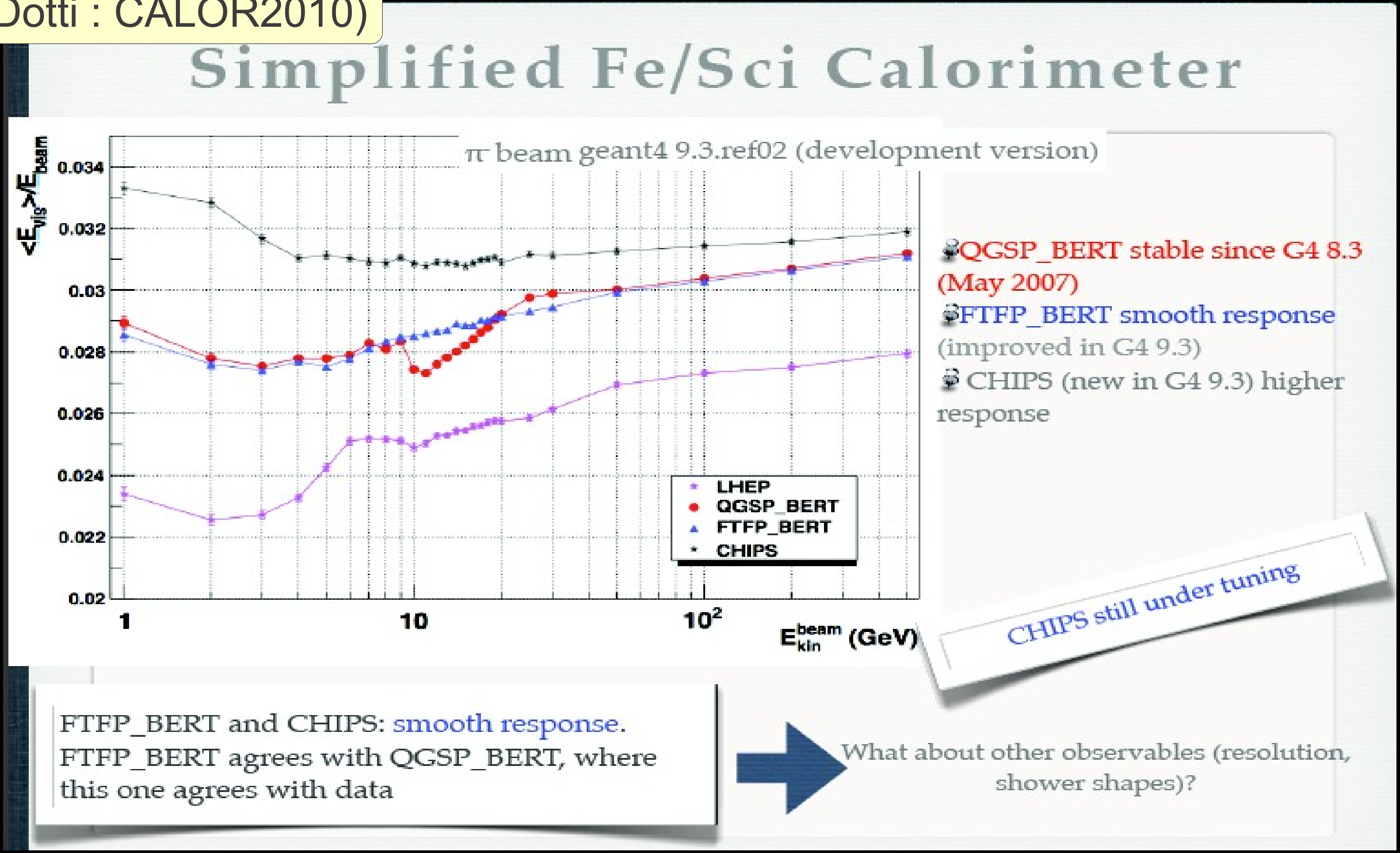
PFA-enhanced Clusters

σ/M = 0.059

But Can we trust the MonteCarlo?

Comparison of energy response for different physics lists

Andrea Dotti : CALOR2010)



Simplified Fe/Sci Calorimeter

π beam geant4 9.3.ref02 (development version)

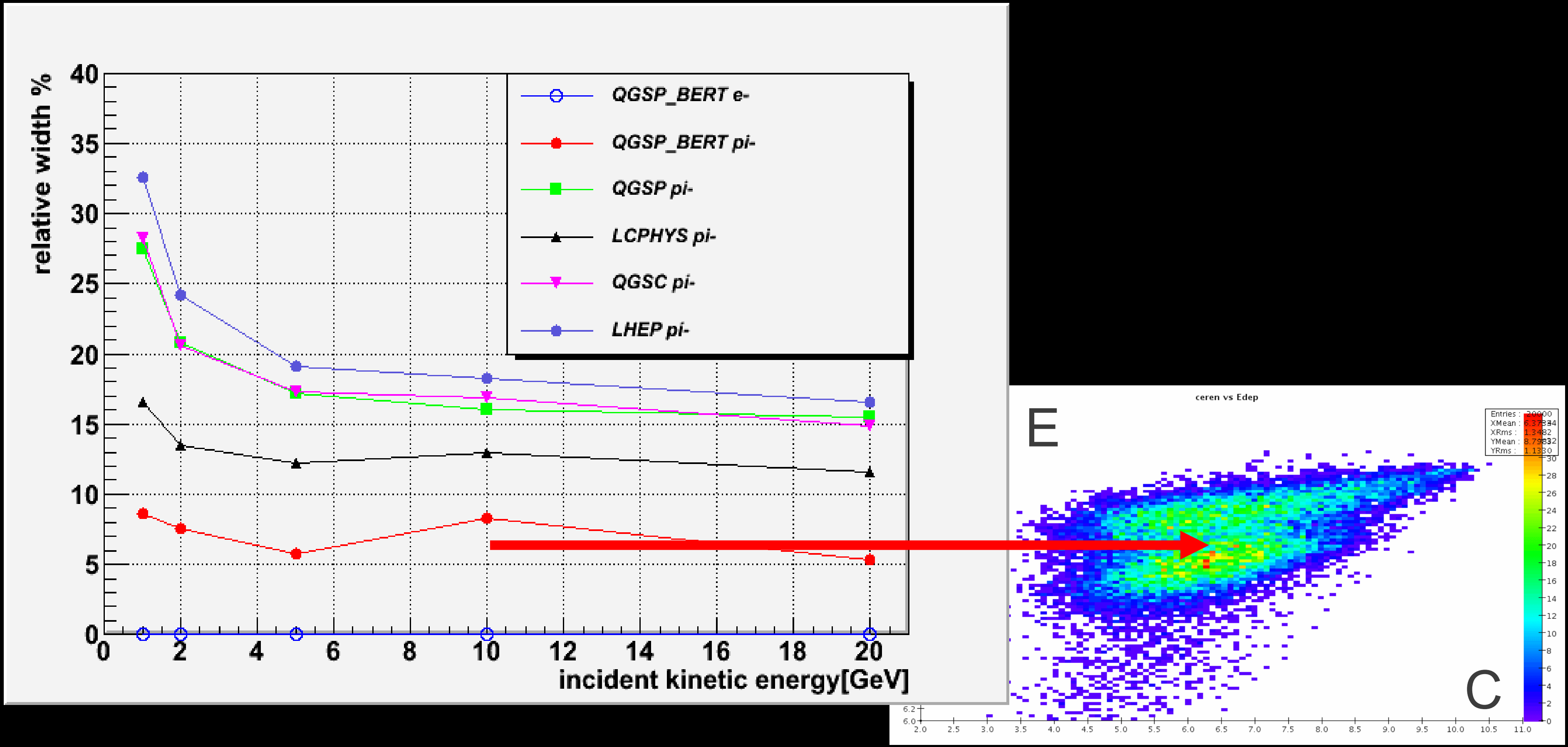
- QGSP_BERT stable since G4 8.3 (May 2007)
- FTFP_BERT smooth response (improved in G4 9.3)
- CHIPS (new in G4 9.3) higher response

CHIPS still under tuning

FTFP_BERT and CHIPS: smooth response.
FTFP_BERT agrees with QGSP_BERT, where this one agrees with data

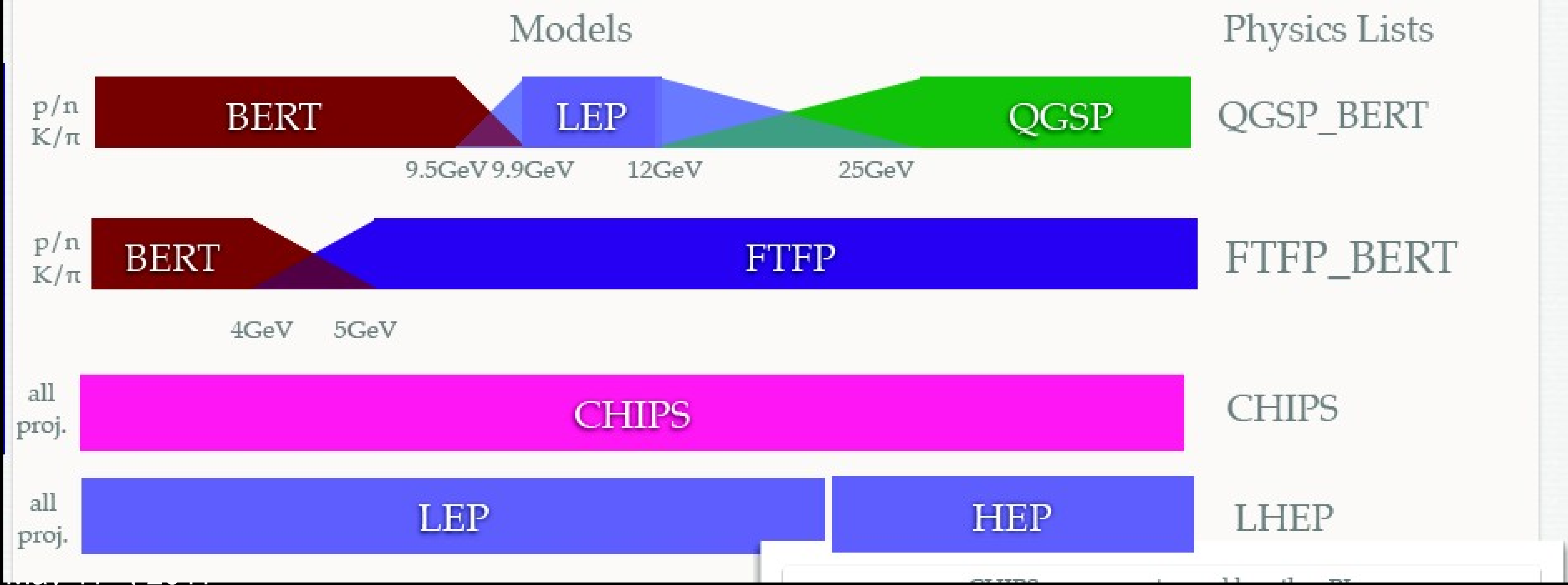
What about other observables (resolution, shower shapes)?

BGO relative width of energy response to charged pions for different physics lists



Why are there kinks in the energy response?

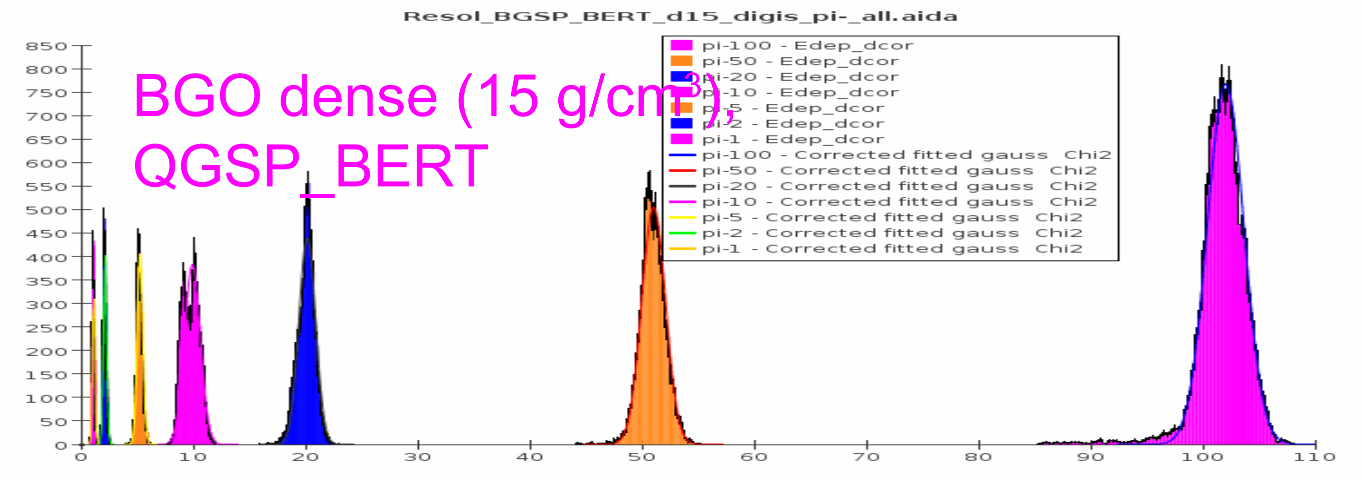
- Physics Lists use different hadronic models for different energy ranges
  - Not always smooth transition in energy response
  - Resolution is sum of two distinct distributions and therefore too wide
  - What about other observables?
- Improving hadronic modelling is priority of Geant 4 Collaboration.



Effects limiting the Energy resolution

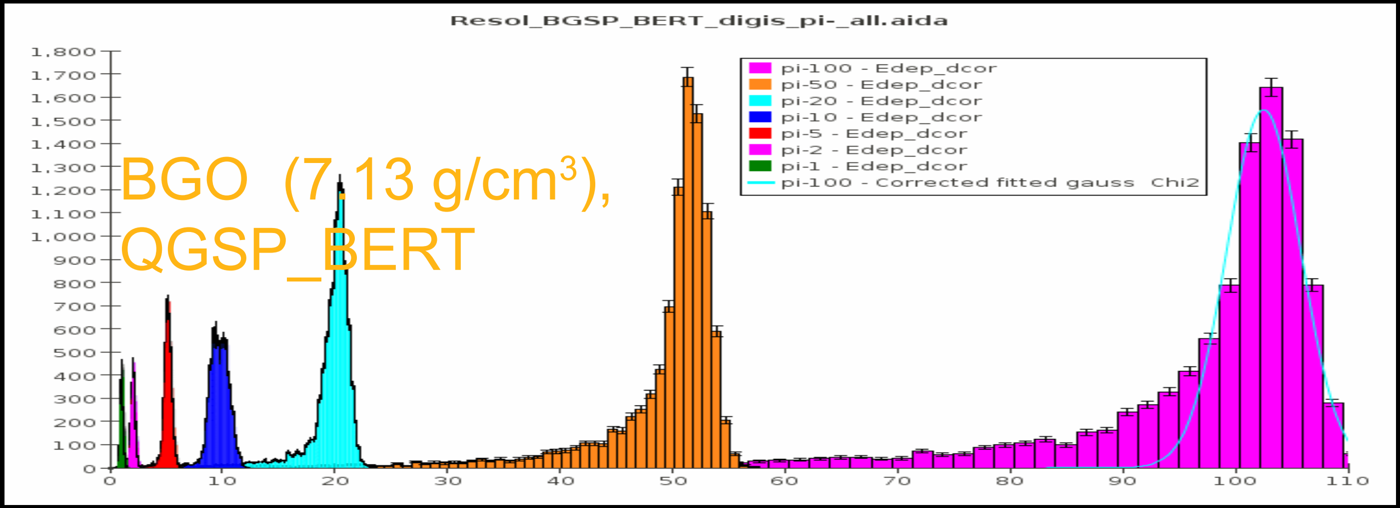
Corrected single π^- response

Events



BGO dense (15 g/cm^3),
QGSP_BERT

Events



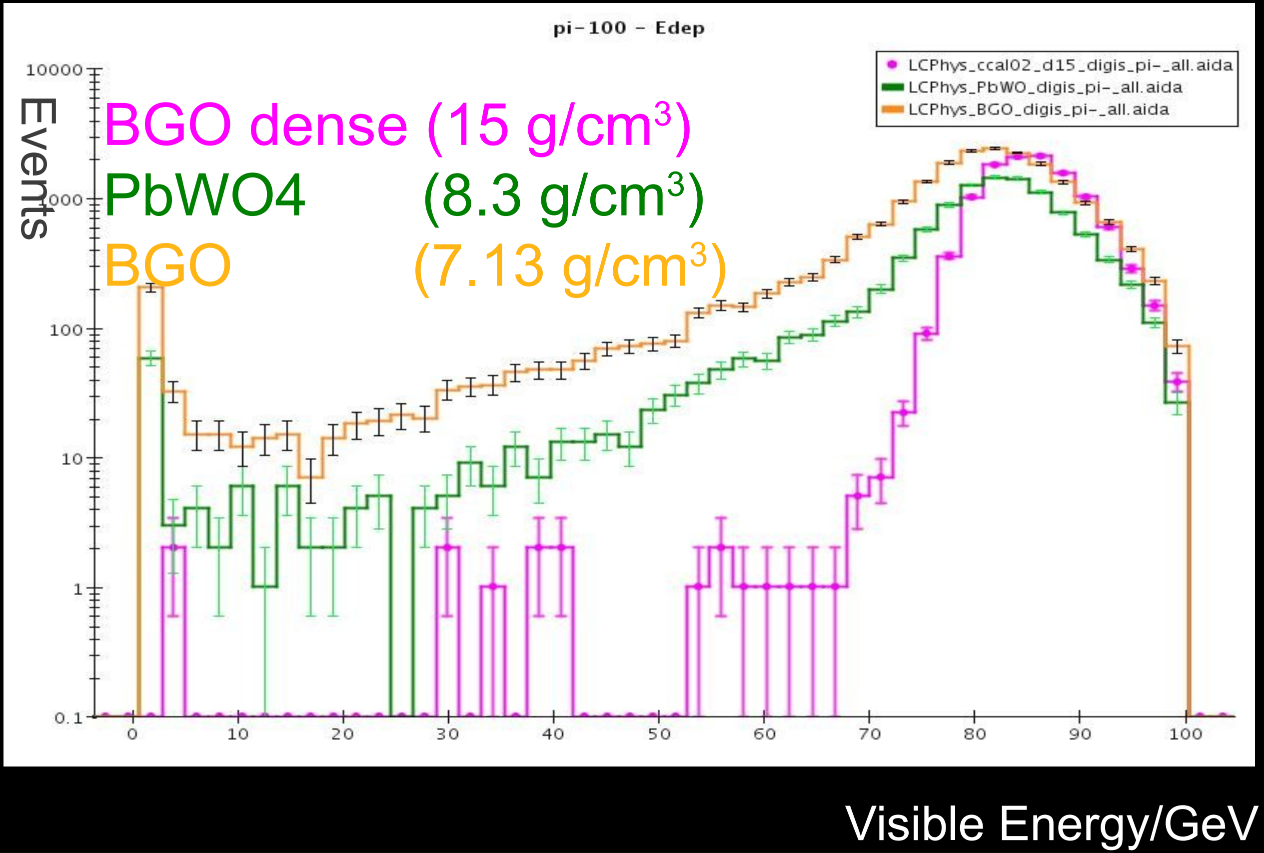
BGO (7.13 g/cm^3),
QGSP_BERT

Energy in GeV after dual read out correction

100 GeV π leakage for BGO/PbWO4/ BGO dense

The leakage energy fluctuates and the fractional fluctuation
increases with energy
until it exceeds the stochastic term
and sets the limit on the achievable energy resolution.

Leakage fluctuations depend on:
-the starting point of the hadron shower
(Interaction Depth or ID)
-the extension of the shower



Leakage is of particular concern for compact detectors such as SID!
But we are evaluating possible techniques
to improve the energy resolution in the presence of leakage (requires longitudinal Segmentation!). See presentations at Calor 2010

Birks attenuation

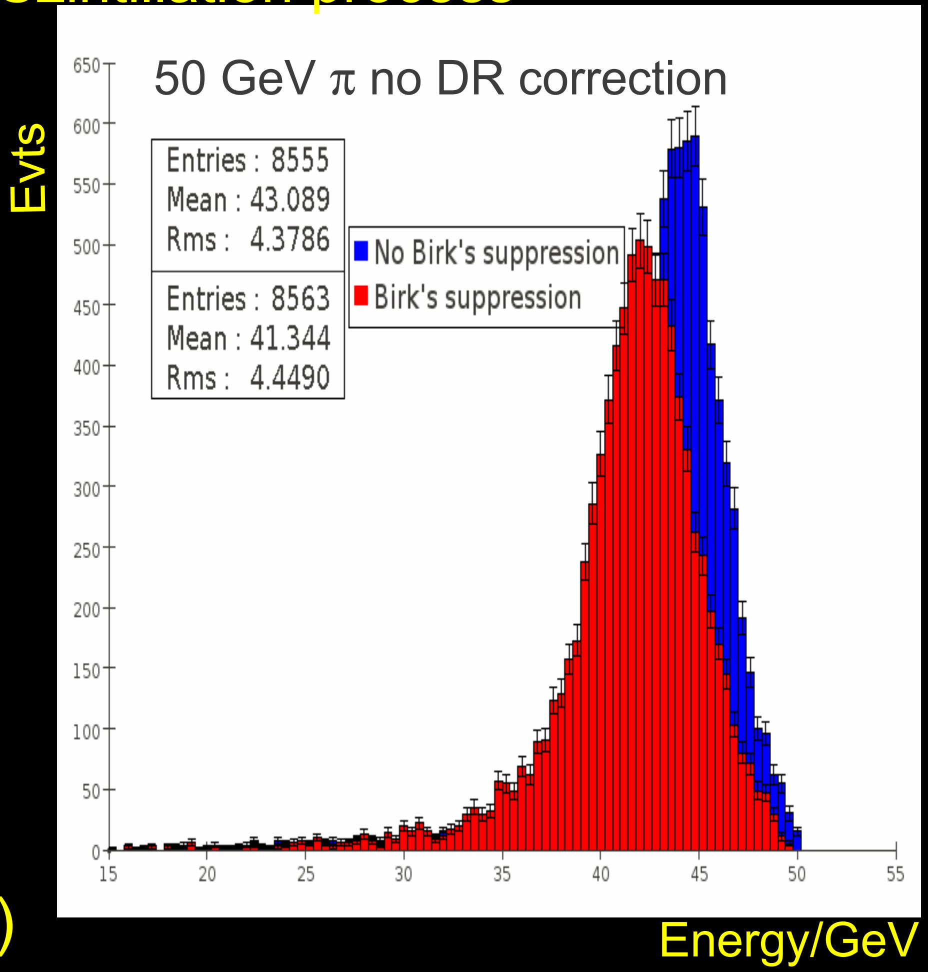
Implemented in SLIC,
Available in Geant 4 via Szintillation process

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

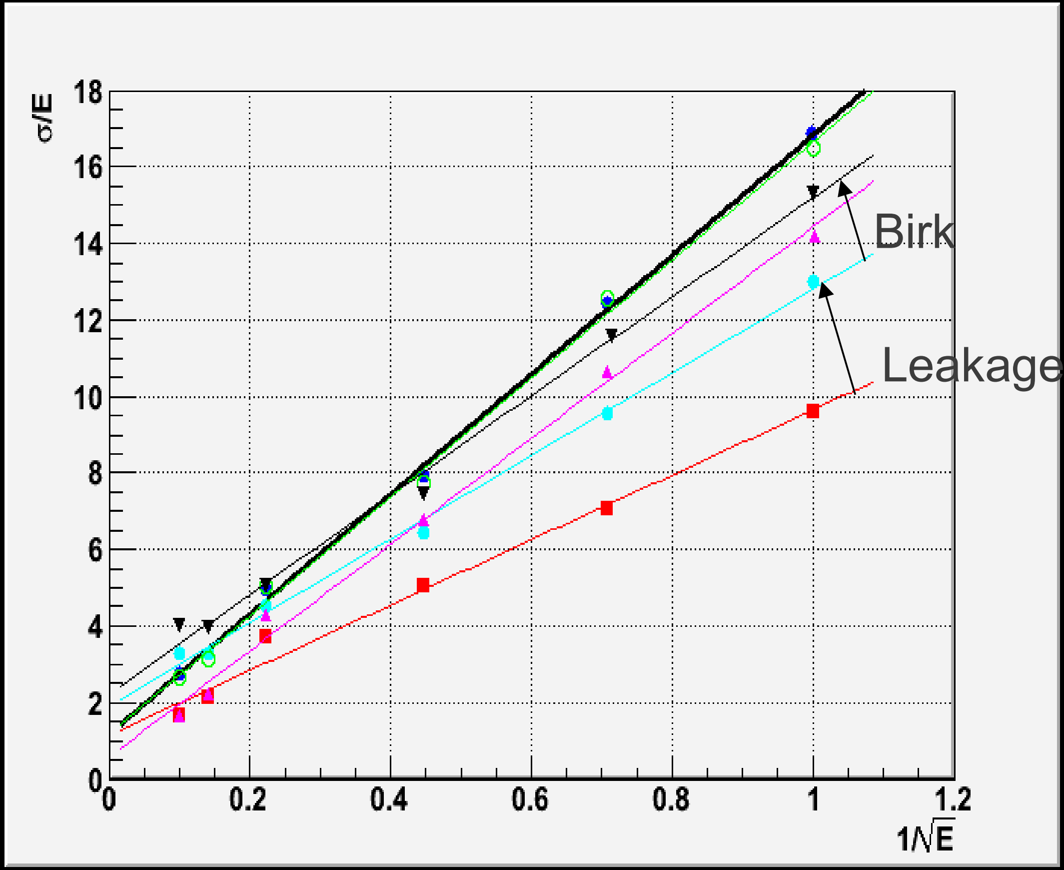
Where:
kB = Birks constant
S = Scintillation Efficiency

dL/dx= Light Output

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



Single π^- resolution for different detector configurations



BGO(dense), QGSP_BERT:
σ(E)/E=1.1 + 8.5/sqrt(E) %

BGO, QGSP_BERT:
σ(E)/E=1.9 + 10.9/sqrt(E) %

BGO, QGSP_BERT , Birk supr.:
σ(E)/E=2.23 + 13.0/sqrt(E) %

BGO(dense), LCPhys:
σ(E)/E=0.6 + 13.8/sqrt(E) %

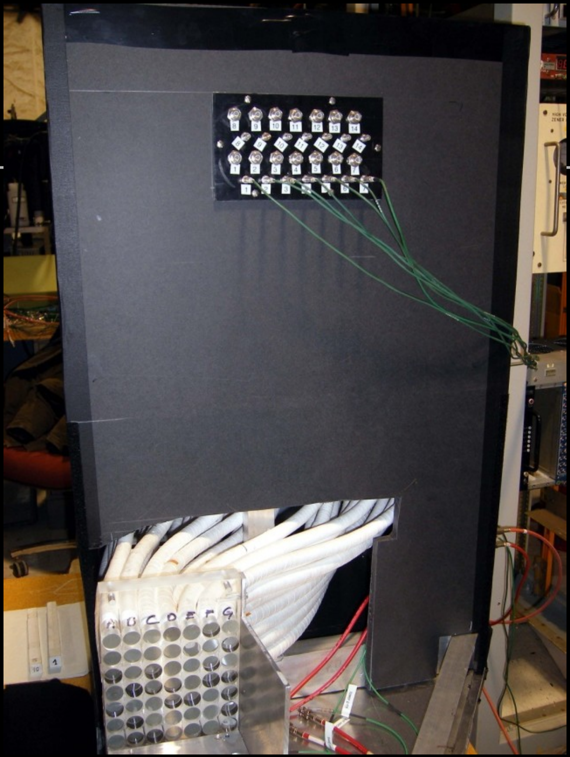
BGO, LCPhys: (nominal)
σ(E)/E=1.2 + 15.6/sqrt(E) %

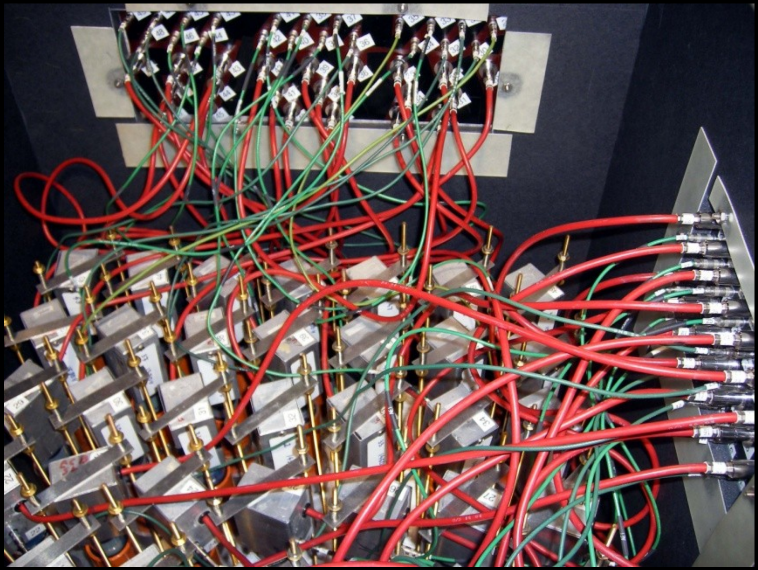
PbWO4, LCPhys:
σ(E)/E=1.2 + 15.5/sqrt(E) %

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

From Simulation to Reality
Crystals in the testbeam


A B C D E F G
1
2
3
4
5
6
7


A B C D E F G



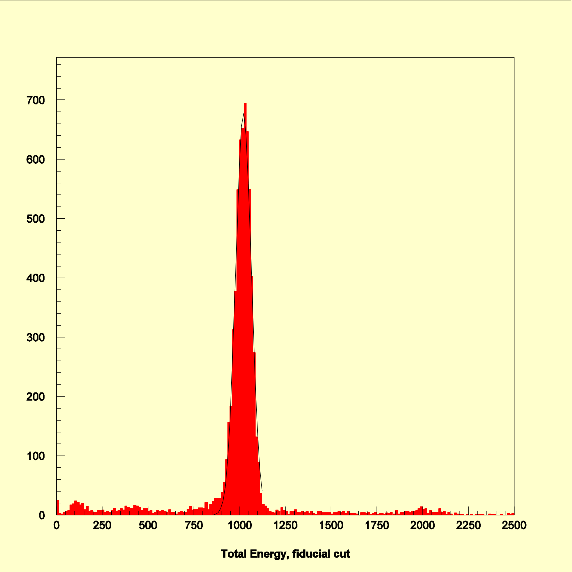

13
14
15
16


21
22
23
24

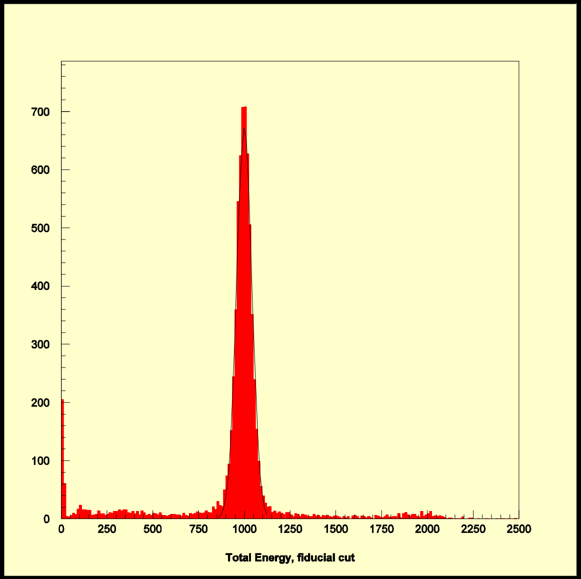

29
30
31
32


46
47
48
49

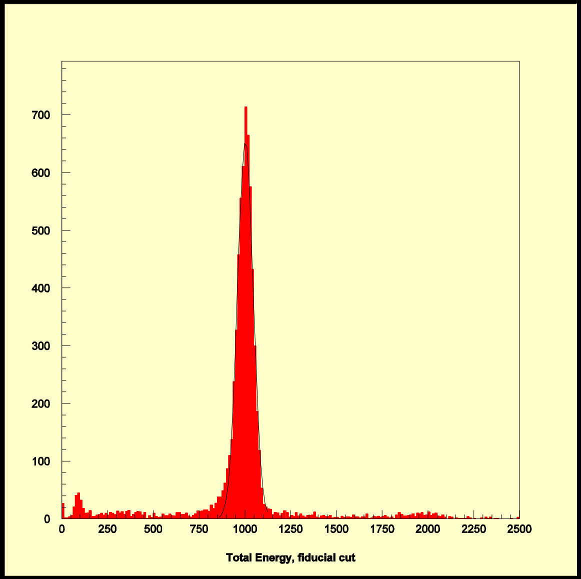
Electron calibration (an example)



Tower 25
Mean = 1021.2
σ = 43.25



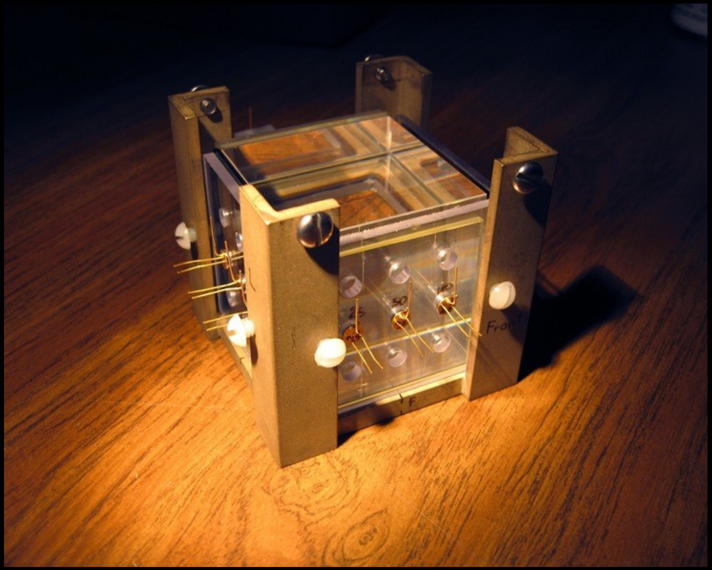
Tower 32
Mean = 999.40
σ = 41.81

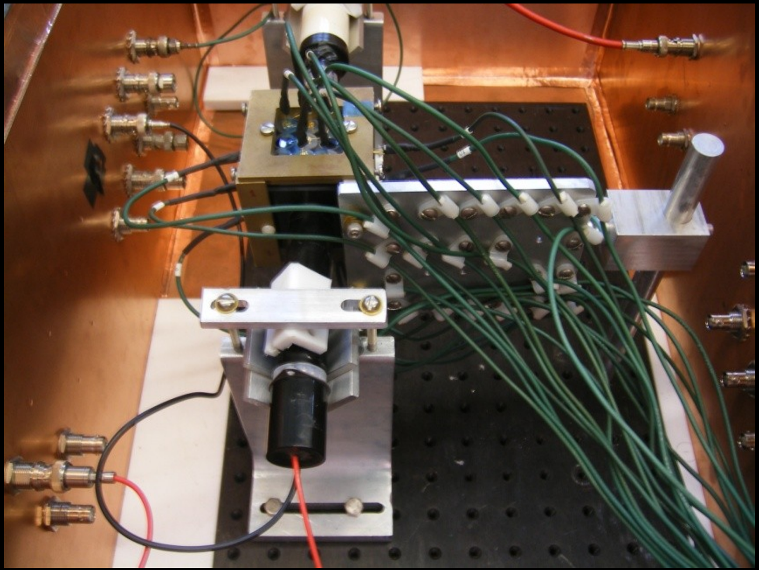


Tower 18
Mean = 1002.6
σ = 43.02

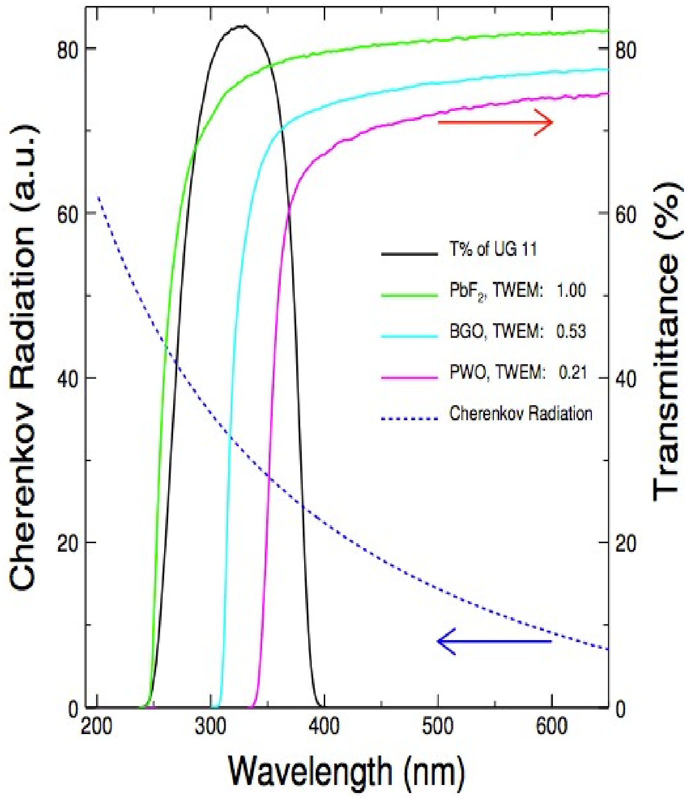
Relative cross-calibration good to ~ 1%. Energy resolution at 4 GeV is ~ 4.3% (probably dominated by the beam spread).

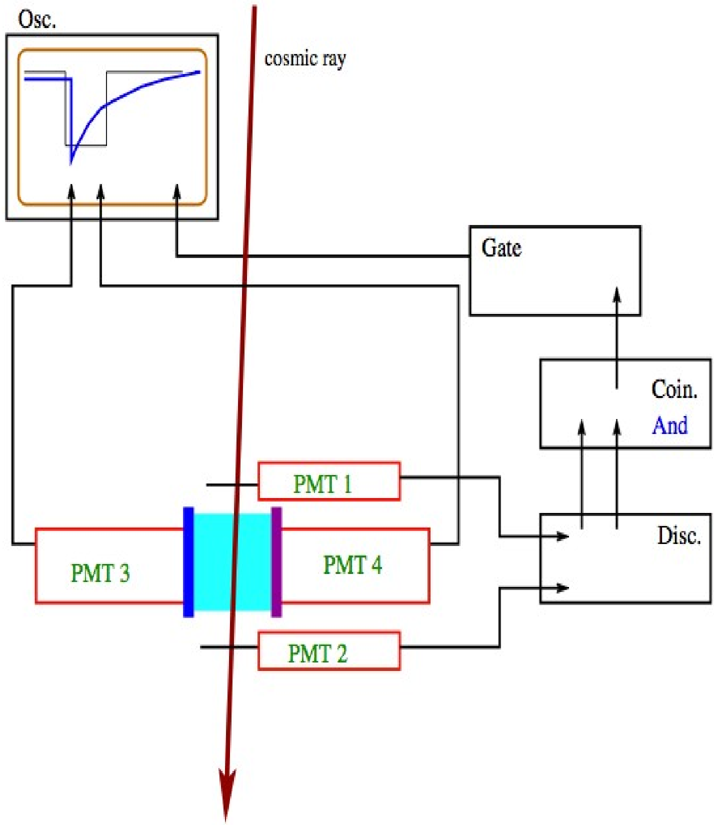
Single Crystal Setup





- BGO crystal (from Caltech)
- visible and UV filters
- two PMT's
- 20 Hamamatsu SiPM's
- TB4 readout boards (P. Rubinov)

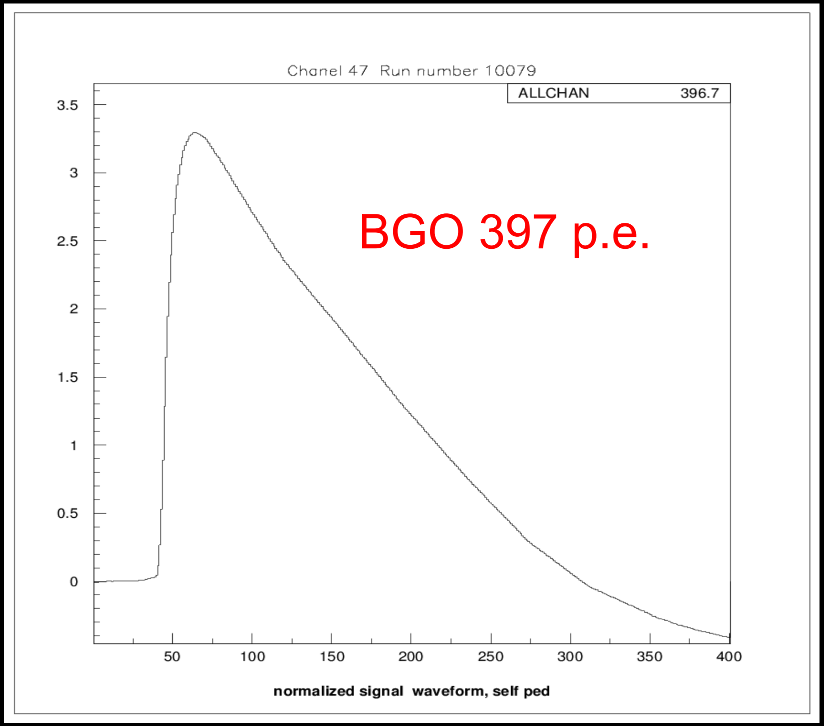

Cherenkov Radiation (a.u.)
Transmittance (%)
Wavelength (nm)
0
20
40
60
80
200
300
400
500
600
T% of UG 11
PbF2, TWEM: 1.00
BGO, TWEM: 0.53
PWO, TWEM: 0.21
Cherenkov Radiation


Osc.
cosmic ray
Gate
Coin.
And
Disc.
PMT 1
PMT 3
PMT 4
PMT 2

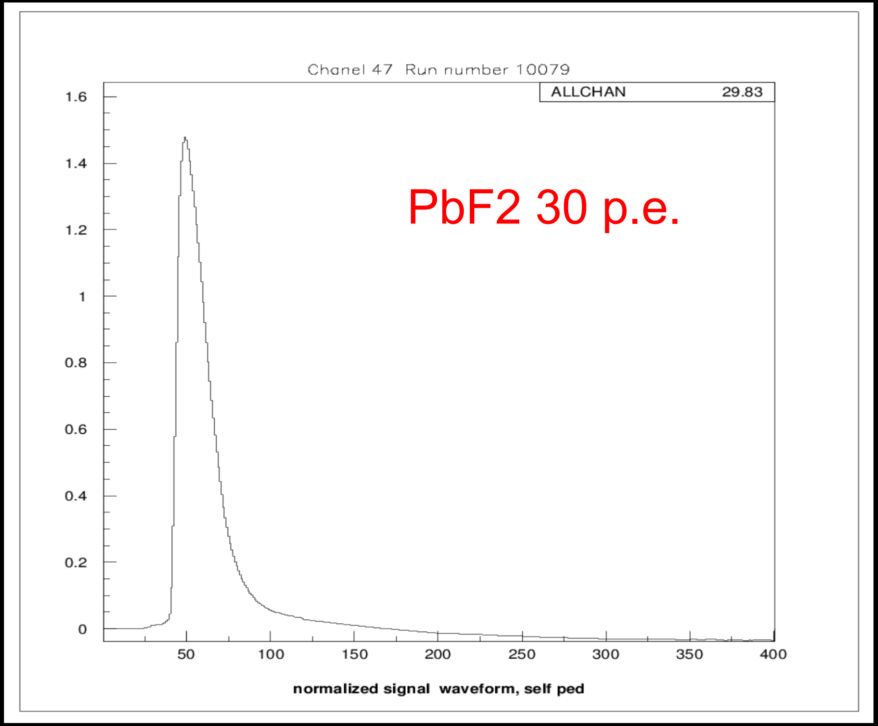
Single Crystal results

Signals from PbF2 and BGO crystals exposed to 120 GeV proton beam . Crystals are 4x4x5 cm,

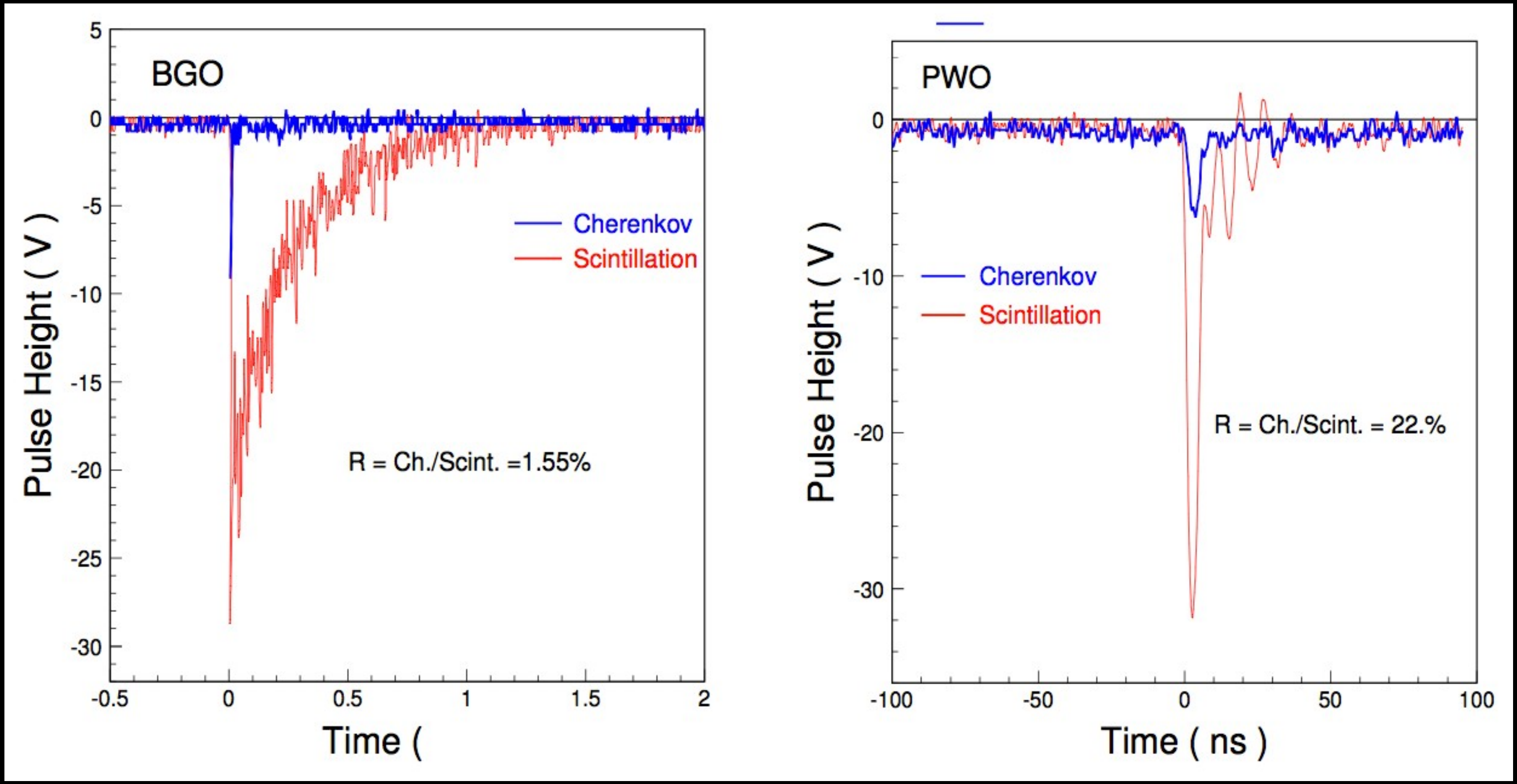
The scale is in number of photoelectrons as read out by Hamamatsu 3x3 mm SiPM.



BGO 397 p.e.



PbF2 30 p.e.


BGO
Cherenkov
Scintillation
R = Ch./Scint. =1.55%
Pulse Height (V)
Time (
5
0
-5
-10
-15
-20
-25
-30
-0.5
0
0.5
1
1.5
2
PWO
Cherenkov
Scintillation
R = Ch./Scint. = 22.%
Pulse Height (V)
Time (ns)
0
-10
-20
-30
-100
-50
0
50
100

R&D to develop cost effective Crystals

- HH-calorimetry needs the development of new materials
  - It appears that there are no fundamental limits to count Cerenkov and scintillation photons
  - There are many potential candidates, but systematic studies are absent

- The expected time scale for application is enough to develop new sensor material

- Affordable cost of detectors is a key problem for crystal technology and production

- Systematic collaborative R&D is of critical importance !

Requirements

- Goal: obtain high energy resolution through total absorption
- Requirements: simultaneous detection of Cherenkov and scintillation through wavelength and timing cut

- Specifications:
  1. Clean separation of scintillation/Cherenkov light
  2. High transmittance down to UV (300nm)
  3. Scintillation at longer wavelength, ~500nm
  4. Relatively slow decay, ~100ns
  5. No short wave and fast decay scintillation
  6. High density for short interaction length
  7. Good Cherenkov light yield, 10pe/GeV
  8. Modest scintillation light yield, 1000pe/GeV
  9. Stable properties
  10. Low cost

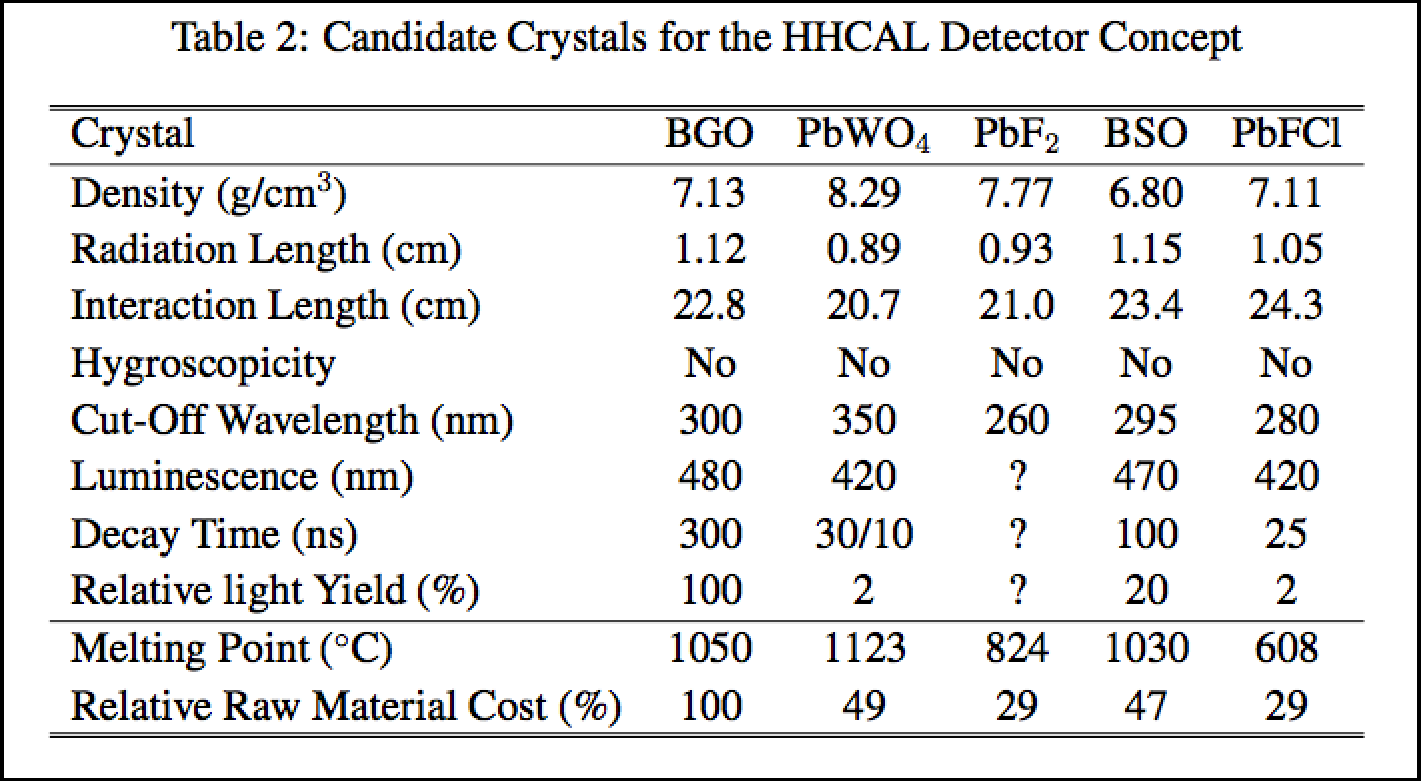


Table 2: Candidate Crystals for the HHCAL Detector Concept

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

Workshops

- To date, workshops on HH-calorimetry organized:
  - Shanghai, February 19, 2008
  - Exploratory discussions with companies and universities
  - Beijing, May 9, 2010
  - Satellite meeting at the CALOR 2010 workshop
  - http://indico.ihep.ac.cn/conferenceTimeTable.py?confId=1470
  - Twelve detailed presentations on the subject

  satellite meeting at the IEEE meeting in Knoxville, TN, October 31, 2010

  Conveners of the 3rd HHCAL workshop:

  Paul Lecoq (CERN)
  Stephen E. Derenzo (LBL)
  Marvin J. Weber (LBL)

Given the traction and interest of the community, an international organization committee to pursue the development of materials for HH-calorimetry has been formed before the 2nd workshop:

- Marcel Demarteau, Steve Derenzo, Etiennette Auffray, Jun Fang,
  - Alexander Gektin, Paul Lecoq, Michele Livan, William Moses, Adam Para, Yifang Wang, Marvin Weber, Tianchi Zhao, Ren-yuan Zhu

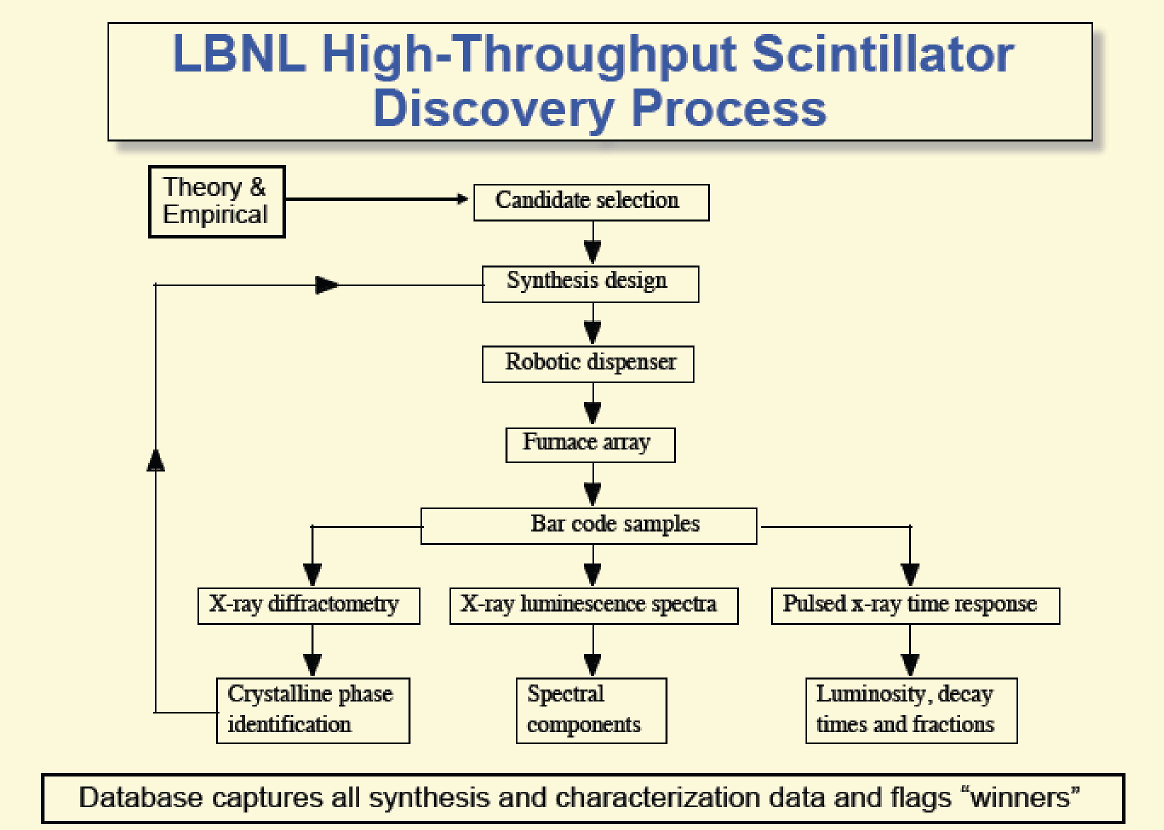
Consortium

- Formation of an HH-cal consortium
  - BGRI (Beijing Glass Research Institute)
  - Caltech
  - CERN
  - Fermilab
  - IHEP (Beijing)
  - Institute for Scintillation Materials (Kharkov)
  - LBL (HEP and Materials Science)
  - NingBo University
  - SICCAS (Shanghai Institute of Ceramics, Chinese Academy of Science)
  - University of Washington

- All interested in collaborative R&D, each bringing specific expertise

LBNL

- For example, LBNL High-Throughput Facility for Scintillator Material Discovery
  - High-Throughput Screening of Crystalline Powder and Solid Samples (Stephen Derenzo)
  - LBNL Crystal Growth Facility (Edith Bourret-Courchesne)



LBNL High-Throughput Scintillator Discovery Process

Database captures all synthesis and characterization data and flags “winners”

LBNL

- High-Throughput measurements:
  - 8 keV monochromatic X-ray beam
  - diffractometry for synthesis
  - verification
  - 50 keVp white X-ray beam
  - luminescence spectra
  - scintillation luminosities
  - 200-1000 nm optical excitation
  - excitation and emission spectra
  - quantum efficiencies
  - 200-1000 nm reflectance
  - band gaps (1.5 to 5 eV)
  - 80 ps, 40 keVp pulsed X-rays
  - decay times
  - scintillation luminosities
  - filters for wavelength selected decay times

Furnace Array

- All with computer-controlled sample changers, bar code readers, and automatic data upload to a real-time database

Conclusion

- HH-calorimetry portends to be extremely powerful

- Next generation experiments demand the ultimate in precision and background rejection

- Total absorption hadron calorimetry is well positioned to significantly enhance the physics reach of future experiments

- But, significant R&D is needed to develop the right medium and photodetector that meets the physics requirements

- But Simulation needs to be improved to make sure that energy resolution is not dominated by Simulation artefacts (e.g. sum of two distinct distributions dominate the distribution)

- The timescale of new experiments seems well matched with carrying out a well focused R&D program on the development of these new materials and sensors

BACKUP

Summary

- The development of new materials for total absorption hadron calorimetry is a necessity

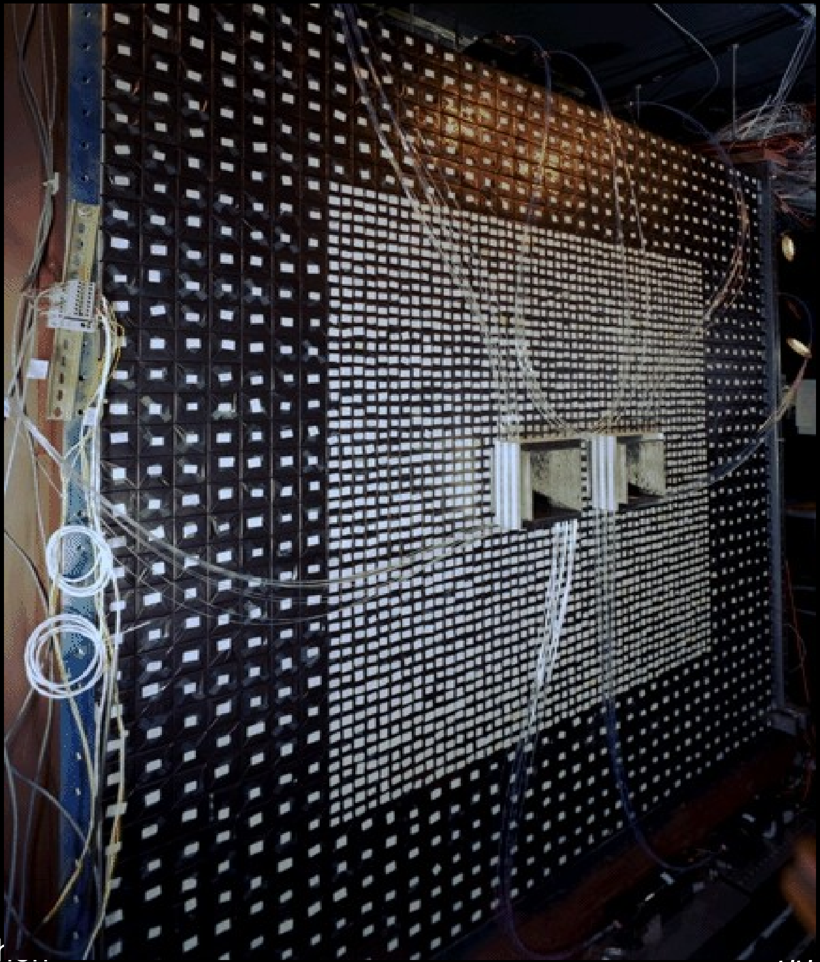
- Fermilab will not and cannot develop these materials

- Industry and other research institutions are very interested in carrying out the R&D for this development, as witnessed by the growing interest in this effort

- Fermilab is in the unique position to take scientific leadership, but requires us to demonstrate unambiguously that we are committed to developing the technology

History

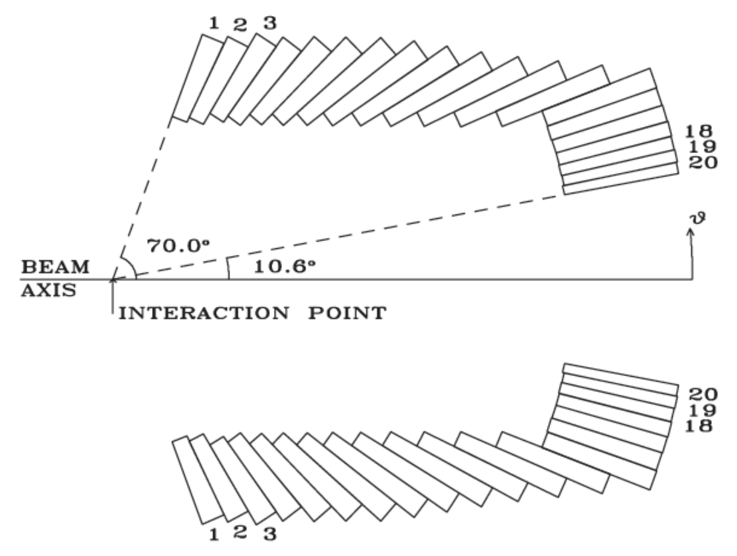
- Investing in new calorimetry techniques has been done in the past
- KTeV: high-speed , high-resolution CsI EM calorimeter (1996)
  - 3100 crystals, covering 2m x 2m
  - 27 X0 deep (50cm)
  - Three crystal vendors:
- Horiba, Crismatec and Bicron
- Only Horiba was able to grow 50cm
- long crystals. Crismatec and Bicron
- has 25 cm long crystals that were
  - glued together
  - Tight mechanical tolerances were
  - difficult to achieve simultaneously
  - with the uniformity requirements
  - Uniformity often required polishing
  - and too much polishing would take the
  - crystal out of mechanical spec.

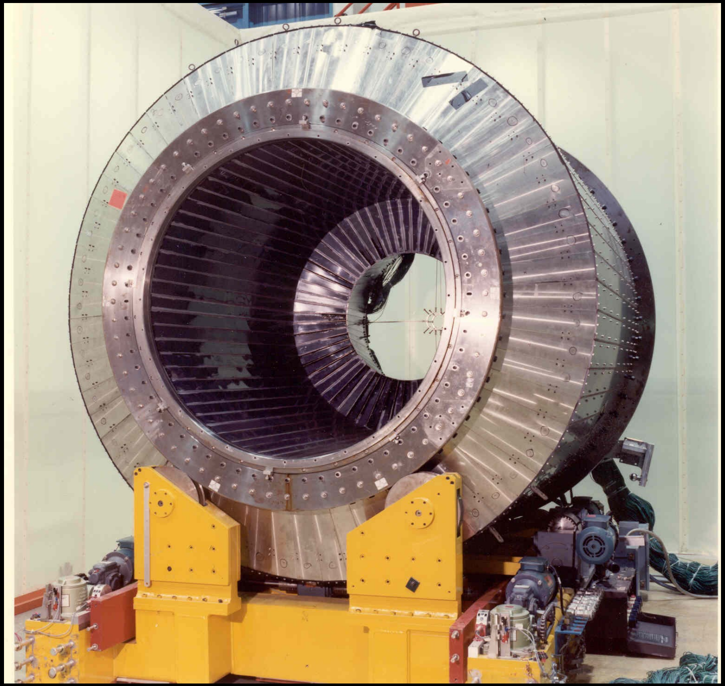


E760 / E835 Calorimeter

- Experiment to explore charmonium states through p-pbar annihilation
- Calorimeter was composed of 1280
- lead-glass Čerenkov counters read out
- with photomultiplier tubes
    - Spatial resolution of 9 mm obtained
    - Energy resolution of 3.0%/√E + 1.5%

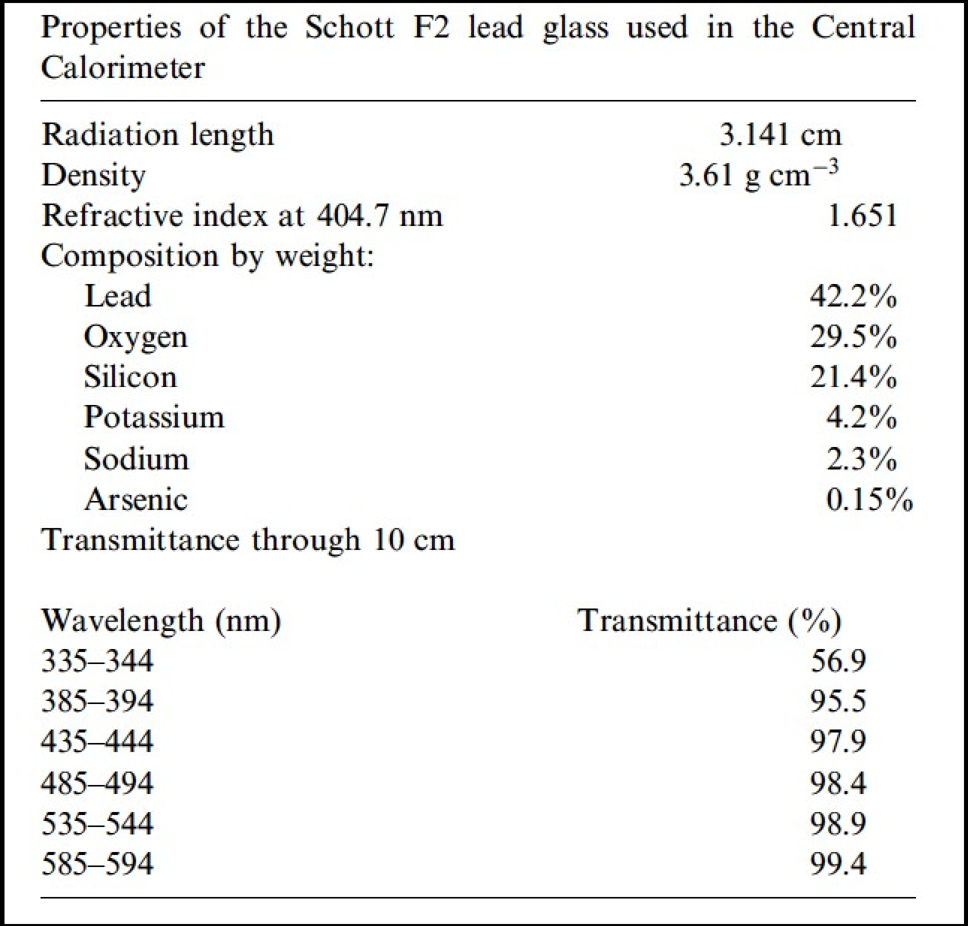
Fermilab Pub 90/190-E
NIM A 519 (2004) 558–609





E760 / E835 Calorimeter

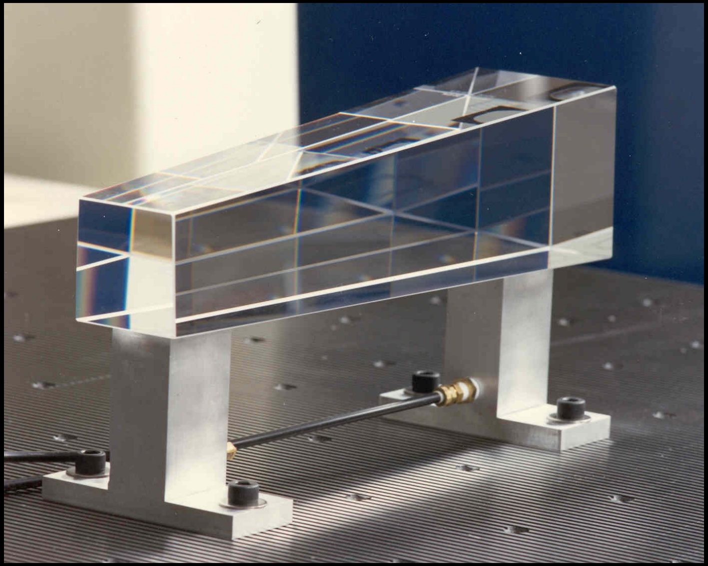
- Crystals were manufactured by Schott Glass Technologies, Inc. Duryea, Pennsylvania



Properties of the Schott F2 lead glass used in the Central Calorimeter

Radiation length	3.141 cm
Density	3.61 g cm^{-3}
Refractive index at 404.7 nm	1.651
Composition by weight:	
Lead	42.2%
Oxygen	29.5%
Silicon	21.4%
Potassium	4.2%
Sodium	2.3%
Arsenic	0.15%
Transmittance through 10 cm	

Wavelength (nm)	Transmittance (%)
335–344	56.9
385–394	95.5
435–444	97.9
485–494	98.4
535–544	98.9
585–594	99.4



A novel approach to achieving superior hadronic energy resolution is based on a homogeneous hadronic calorimetry (HHCAL) detector concept,

- includes both electromagnetic and hadronic parts,
- has separate readout of the Cerenkov and scintillation light → uses their correlation to obtain superior hadronic energy resolution.
- This HHCAL detector has a total absorption nature → energy resolution is not limited by the sampling fluctuations.
- no structural boundary between the ECAL and HCAL → no dead material in the middle of hadronic showers.