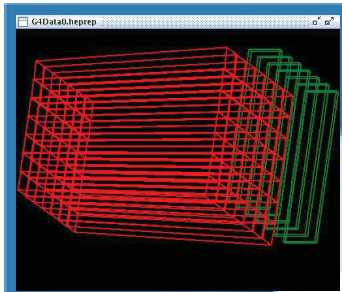


Simulation of total absorption dual readout calorimetry

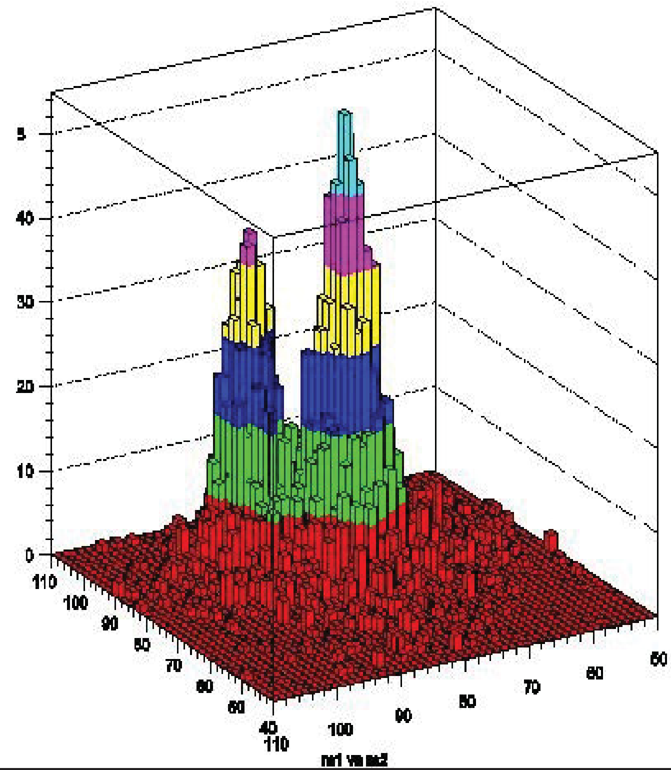
principles and performance

“14th International Conference on Calorimetry in High Energy Physics”, 10-14 May 2010

Hans Wenzel

Fermilab

11th May 2010



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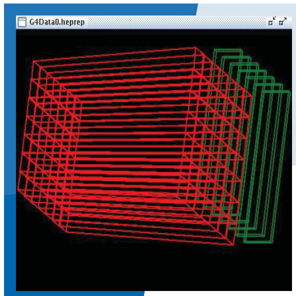
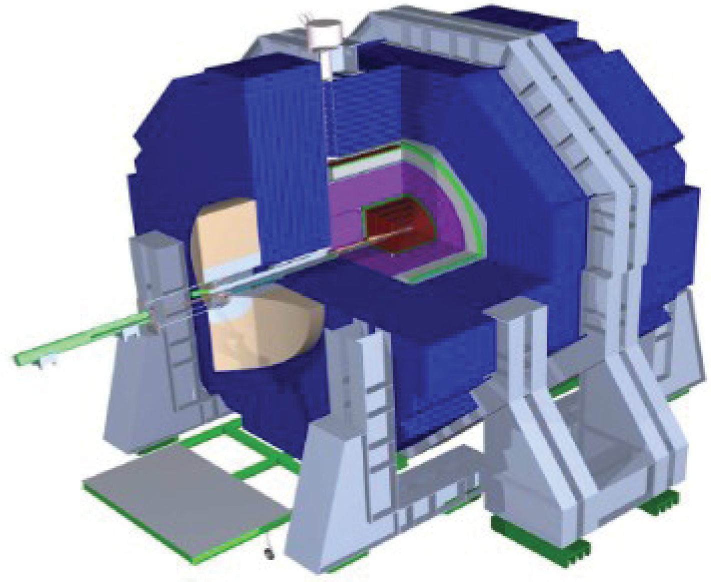
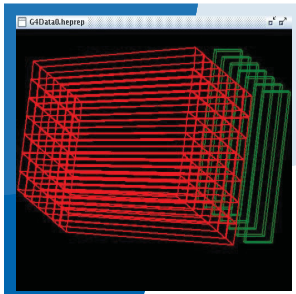


Outline

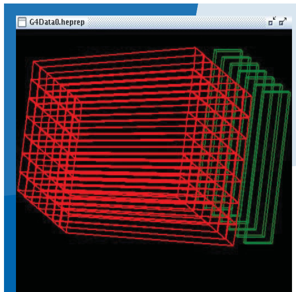


- Motivation
- Principle of a dual read out calorimeter
- The software environment:
  - SLIC
  - CrystalSim
- The ccal02 detector.
- Analysis:
  - Calibration using electrons.
  - Obtaining the dual read out correction.
  - Effects limiting the resolution
    - Modeling of hadronic showers (can we trust Geant4?)
    - Photon statistic (in progress)
    - leakage
    - energy dependence of dual read out correction
    - Birks attenuation
  - Resolution for single π^-
- Conclusions



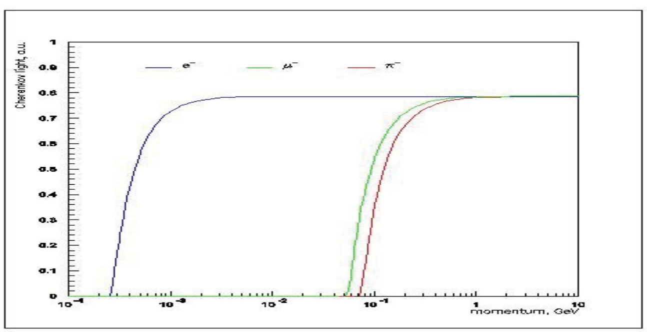
Motivation

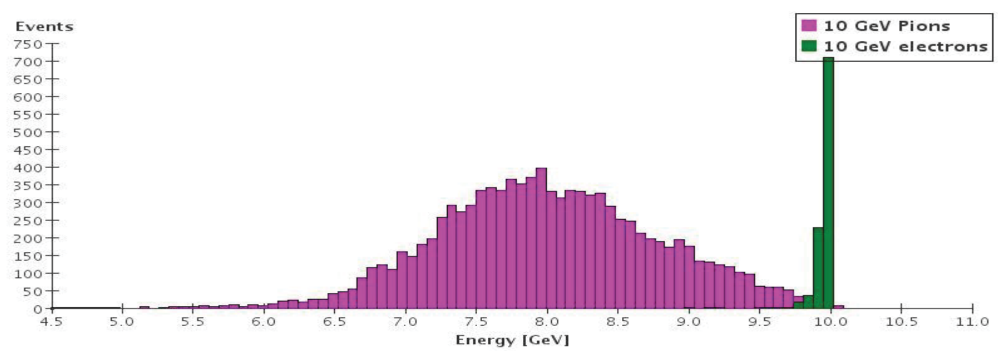
- Be ready for all potential physics scenarios we might encounter at a future lepton collider
- Totally active dual read out crystal calorimeter:
  - Excellent EM calorimeter.
  - Excellent hadron calorimeter:
    - Totally active, not a sampling calorimeter, even large sampling fraction induces significant stochastic term (dependent on particle type).
    - Dual read out.
  - Longitudinal segmentation helps to detect and correct for leakage.
  - While not a PFA calorimeter, segmentation is fine enough so that particle flow algorithms can be applied.
  - Dense scintillating crystals and new economical photo detector like SiPMT are what makes this possible.

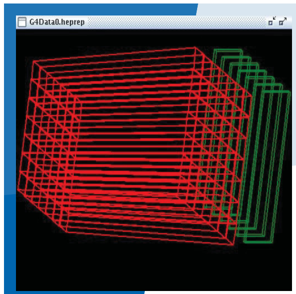


Principle of a dual read out calorimeter

- 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 (β>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.

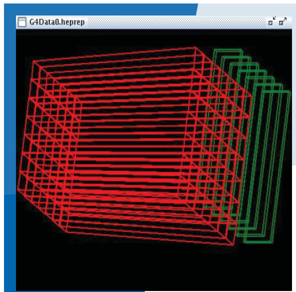






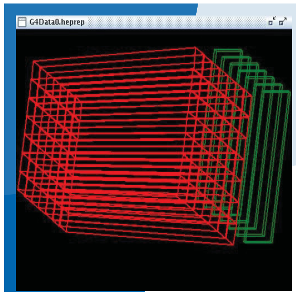
The software environment:

- **CCAL02:**
- **SLIC:** Geant 4 based framework for detector simulation.
- XML based detector description (geometry and sensitive detectors):
  - Easy to implement various detector variations: test beam/collider detector, materials, density, em and had segmentation, optical properties, …
  - Executing a simple script creates all files necessary for simulation and analysis.
  - Variety of physics lists.
  - **LCIO** event output
- Using **SLI C** allows us to make use of the entire SID framework:
  - **SLIC (C++), lcsim.org (netbeans), WIRED, JAS3, LCIO Event Browser (JAVA)** ….. → this allows us to study physics performance as part of a complete detector. (Very nice development environment.)
- If one prefers **ROOT** we have a **LCIO** to root converter for the relevant lcio classes.
- Easy to run SLIC on the grid → we have Grid scripts: make it easy to generate large data sets, takes care of names, random seeds etc., http://confluence.slac.stanford.edu/display/ilc/How+do+I+use+the+OSG+Grid
- Calibration and analysis is automated using the **lcsim.org**



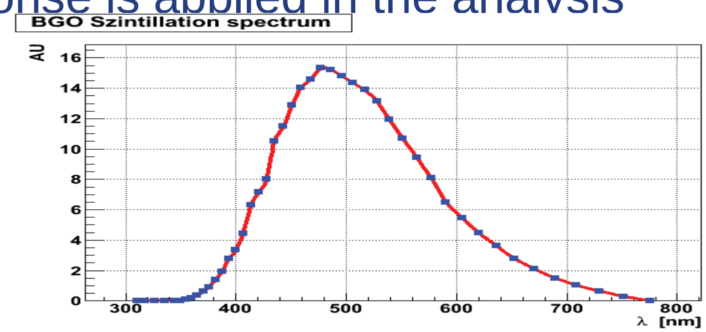
What needed to be done to simulate total absorption dual read out calorimeter in SLIC

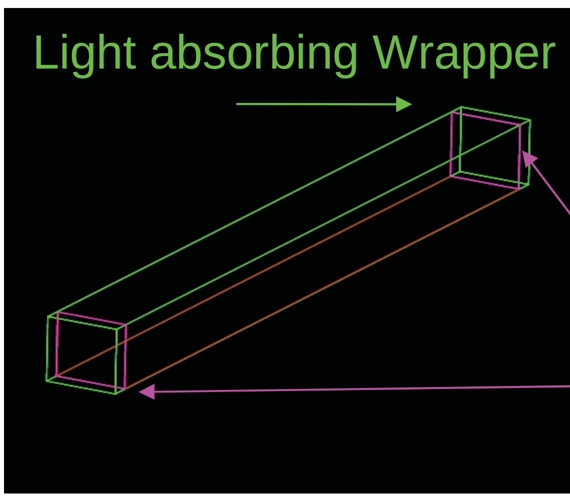
- Need to add optical physics (Cerenkov,Scintillation etc.,) → now can be used with any physics list.
- Need to be able to add optical properties to materials in the detector description e. g. refraction index/absorption as function of photon energy.
- Implement Birk's suppression
- Sensitive detector needs to be able to produce multiple hit Collections (Energy deposition, Cerenkov) → this is allowed in GEANT 4 but SLIC in its original form only allowed for one Hit collection per sensitive collector.
- Implement special optical calorimeter class:
  - Register energy deposition (Edep hits).
  - deal with optical photons. We don't track optical photons but kill them after the first step and add their energy to the Cerenkov hits.



CrystalSim: photon statistics and timing etc.

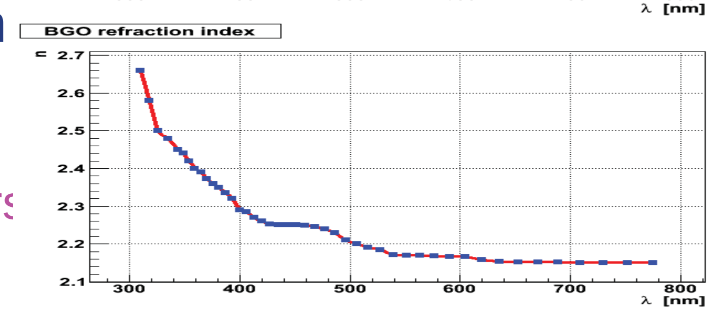
- Geant 4 based stand alone application
- tracks every optical photon from time of production until it's lost (absorbed) or detected at the photo-sensors.
- Input: rindex(λ), absorption length(λ), scintillation spectrum(λ,t), Birks suppression , crystal surface conditions.
- Since geant 4.9.3 LUT exist which describe various surface types (polished, painted, tyvek wrapped..) as measured by a group from LBNL.
- Quantum efficiency (λ) and electronic response is applied in the analysis step (ROOT).

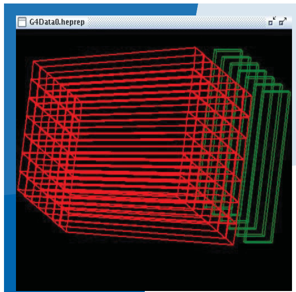




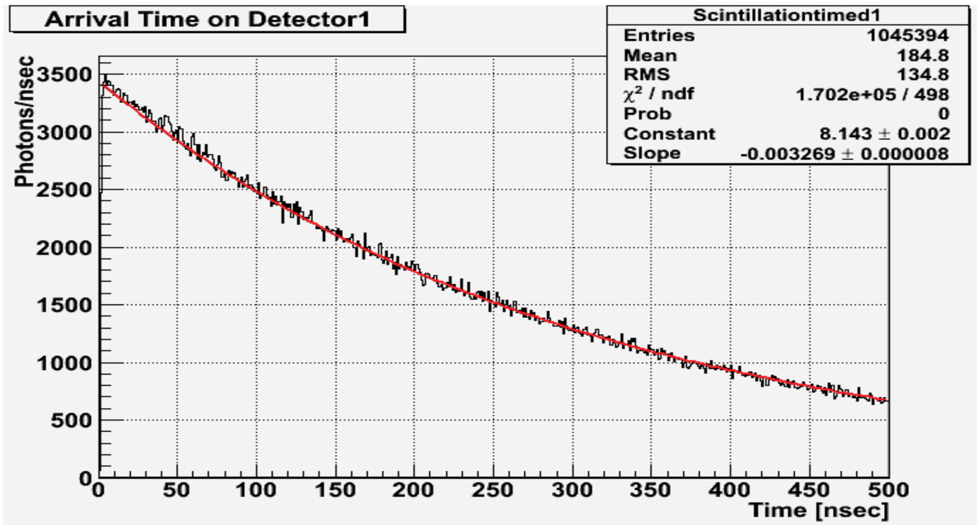
Crystal: 2x2x20 cm

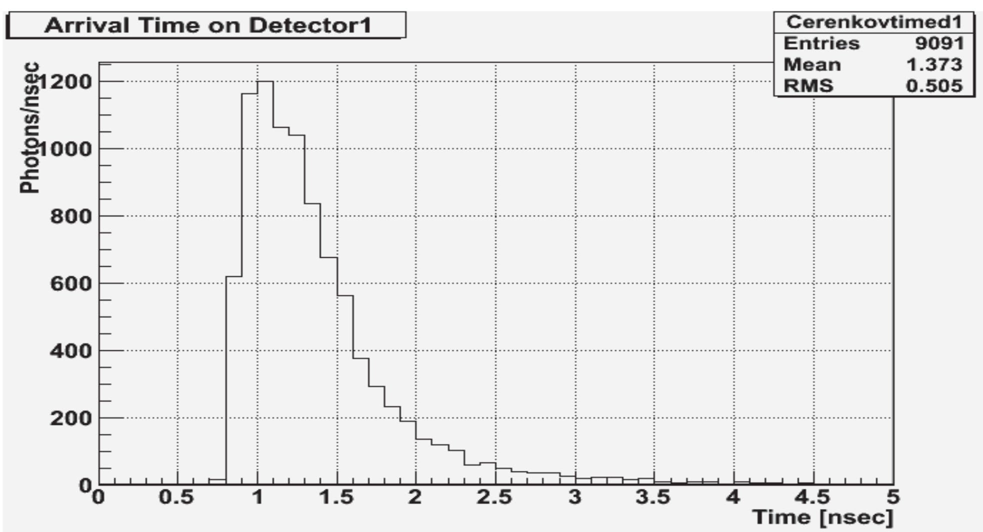
Ideal Photodetectors





CrystalSim: light at the photo detectors

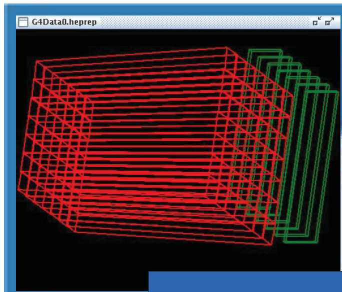




2 GeV Muons (2cm BGO):

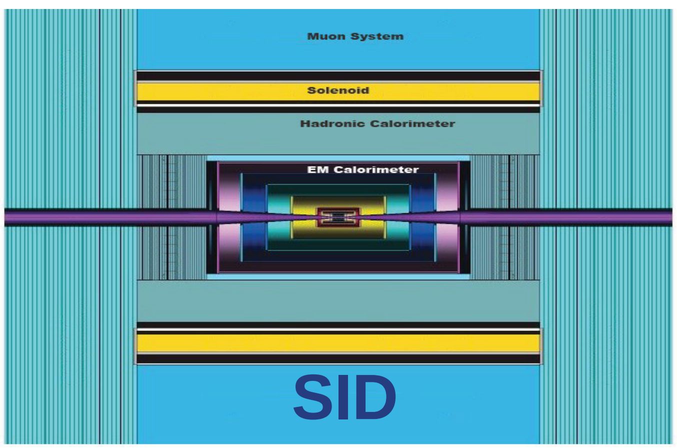
10500: Szintillation ph/sensor
90: Cerenkov ph/sensor

Will provide input to study effects of photostatistics, study how well we can separate cerenkov and scintilation light etc.....



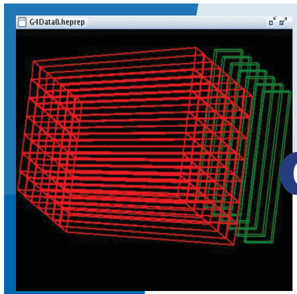
The CCAL02 detector
(Crystal Calorimetry version of SID)

				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



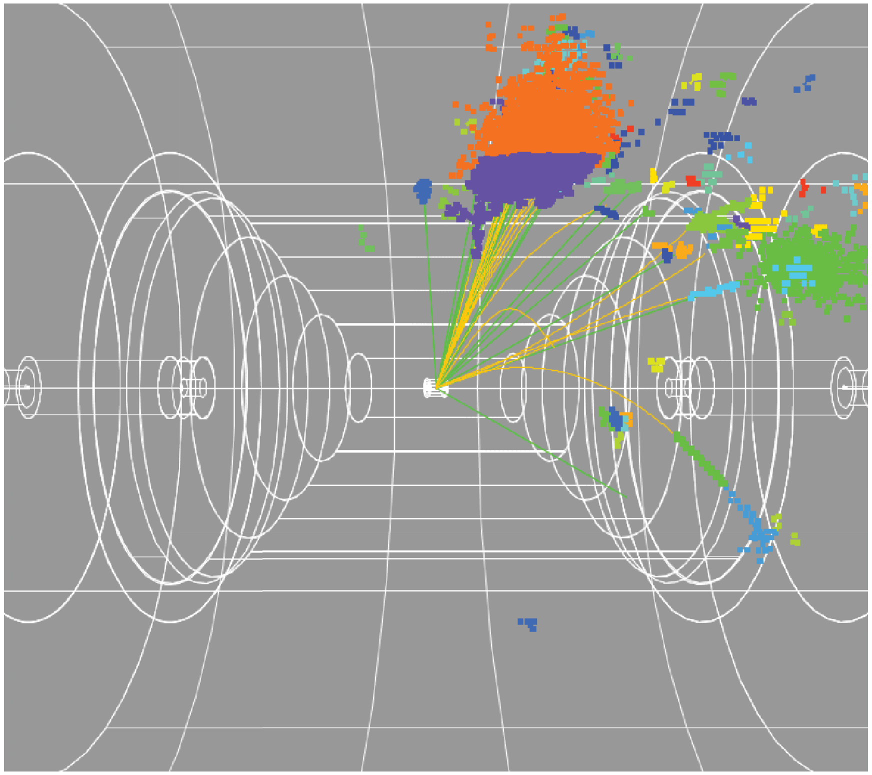
Material	Density	Rad. len. X0	IA len.
	[g/cm3]	[cm]	[cm]
BGO	7.13	1.12	21.88
PbWO4	8.3	0.9	18
SCG1-C	3.36	4.25	45.6

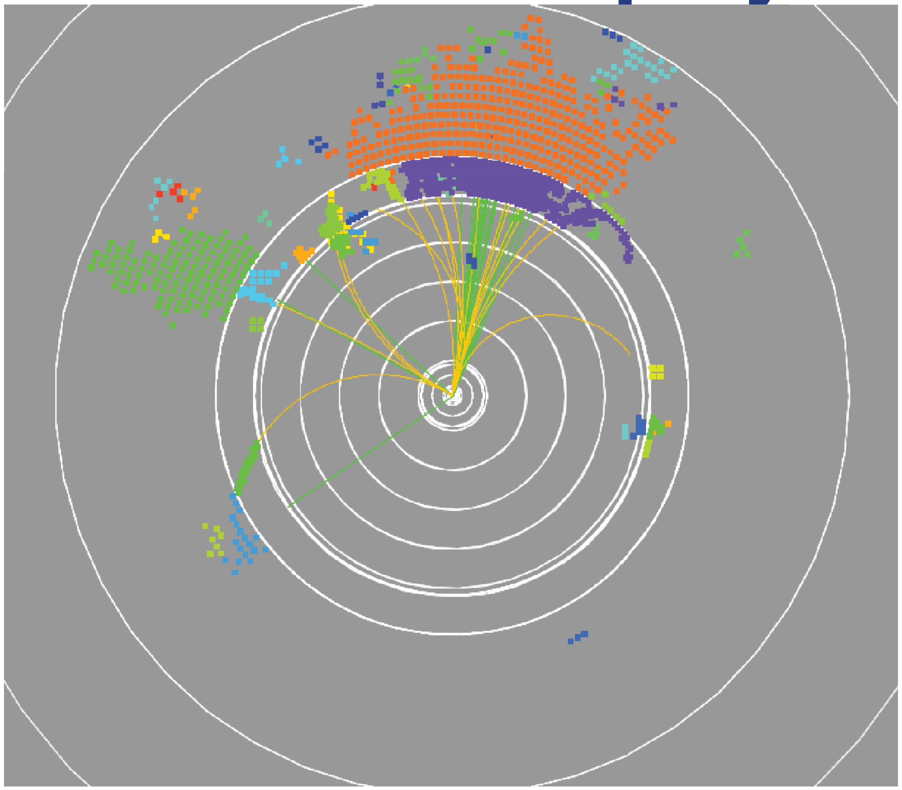
Monte Carlo: BGO with 15.0 g/cm^3



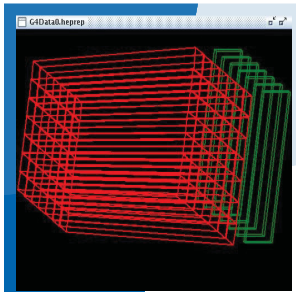
CCAL02 Scintillation response as displayed in the Wired event display

ZZ->qqνν

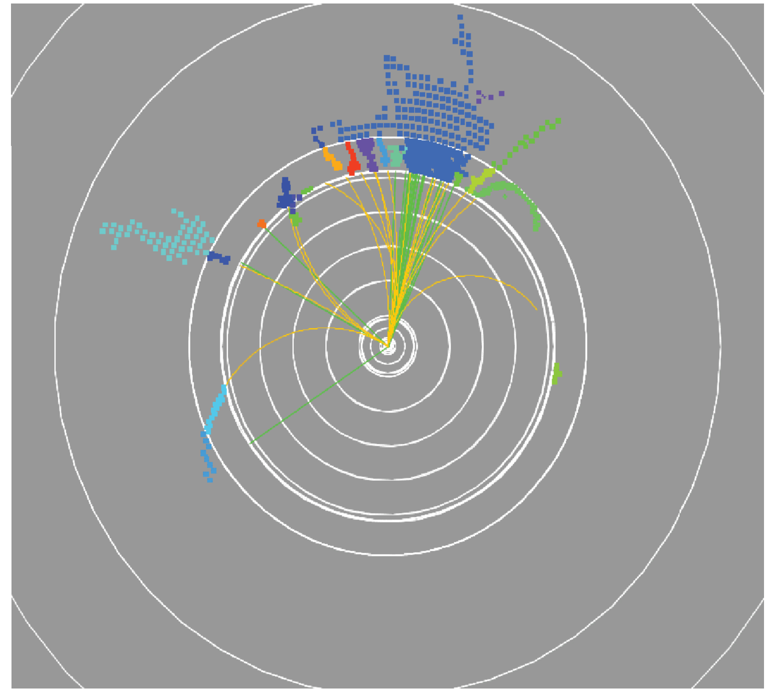




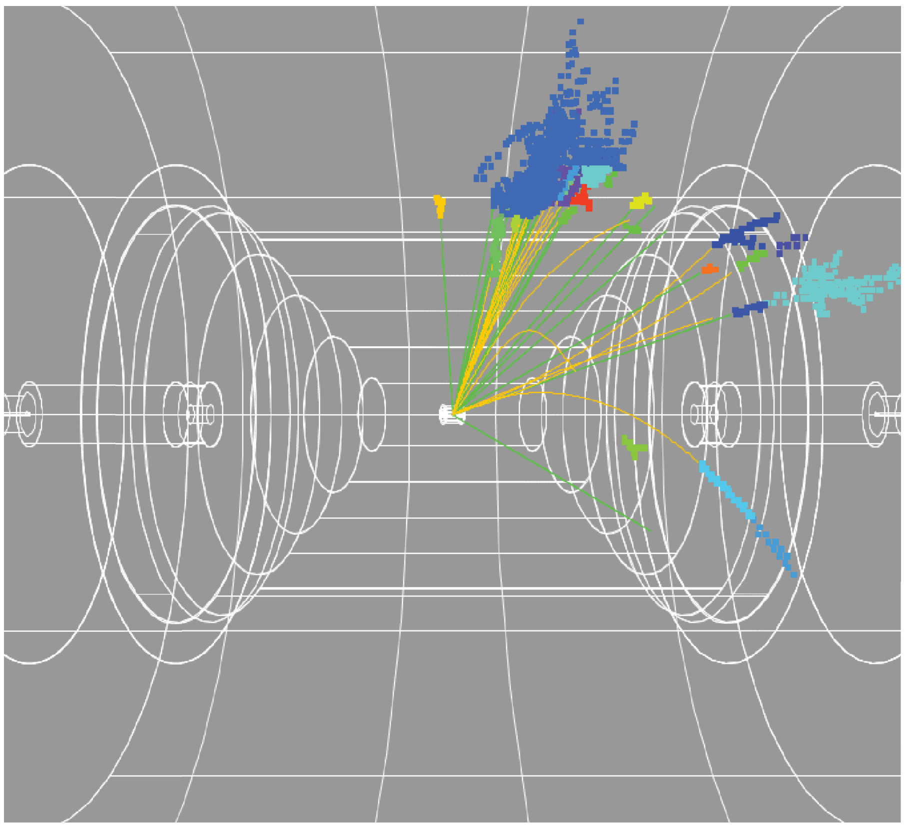
Digisim



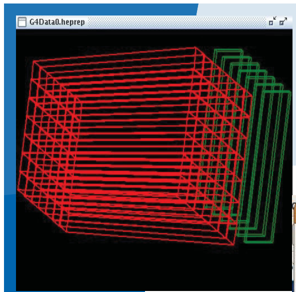
CCAL02 Cerenkov response as displayed in the Wired event display

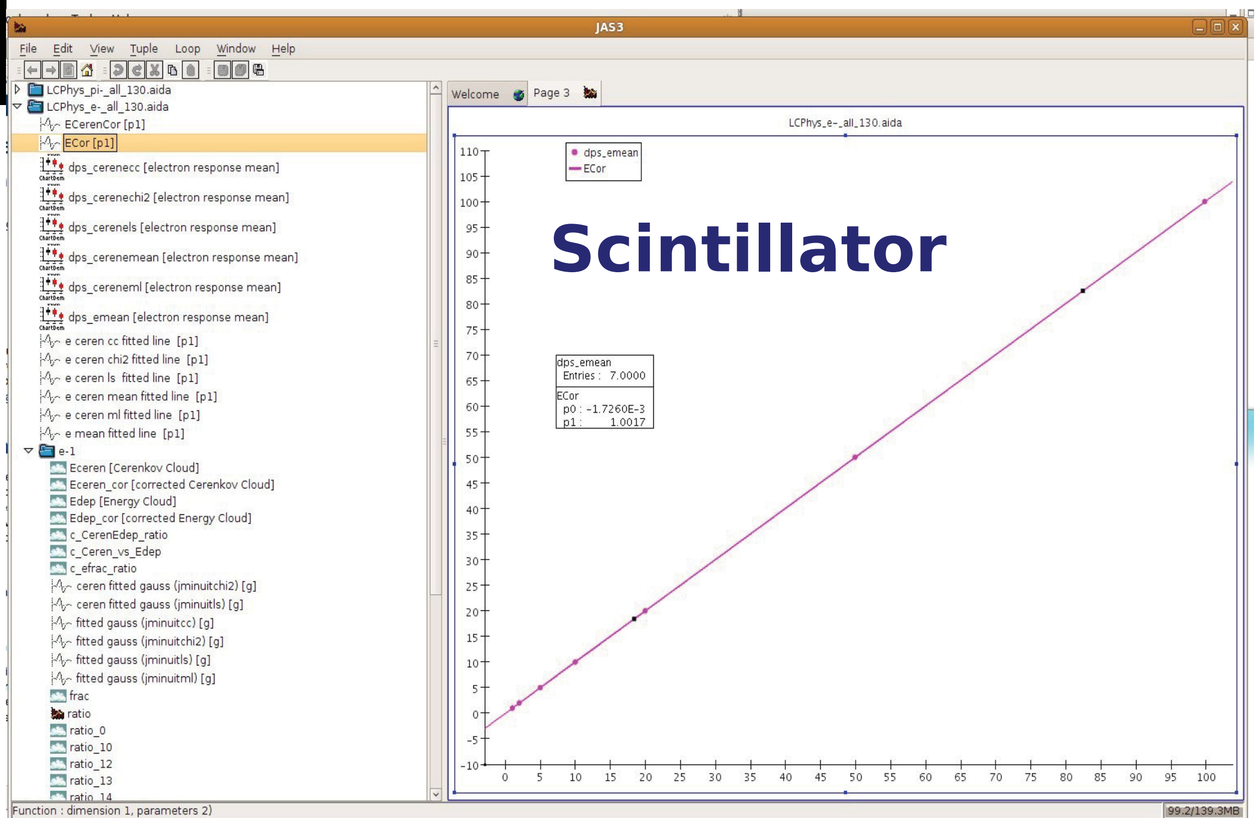


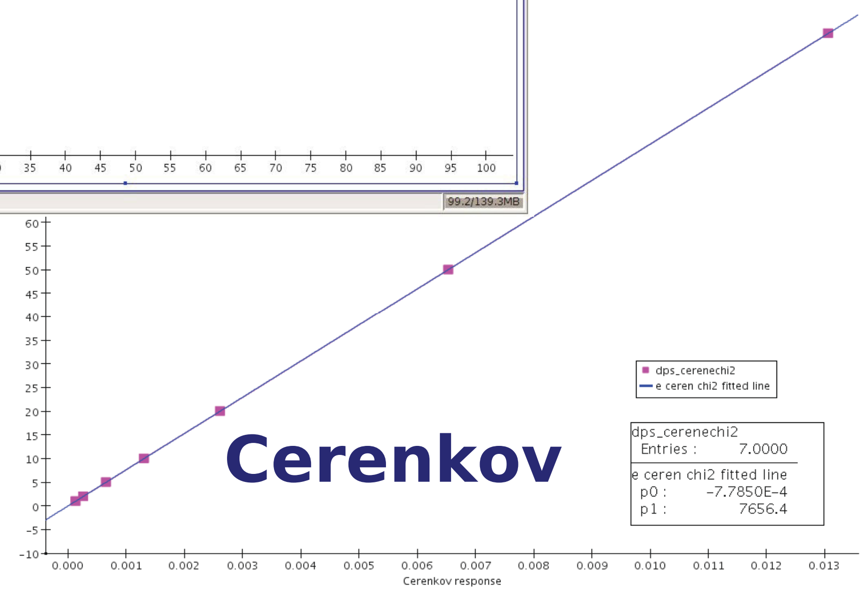
ZZ->qq$\nu\nu$



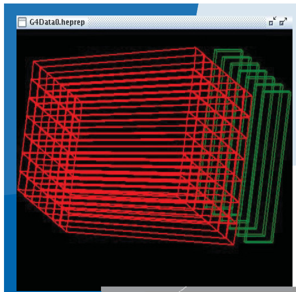
Electron Calibration for Scintillator, Cerenkov



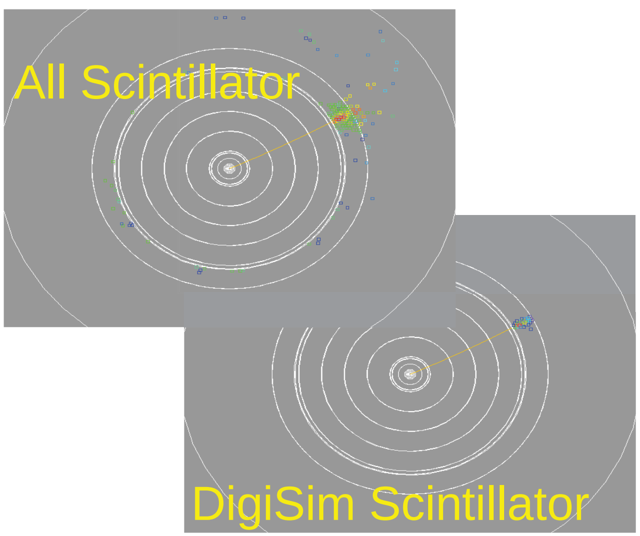


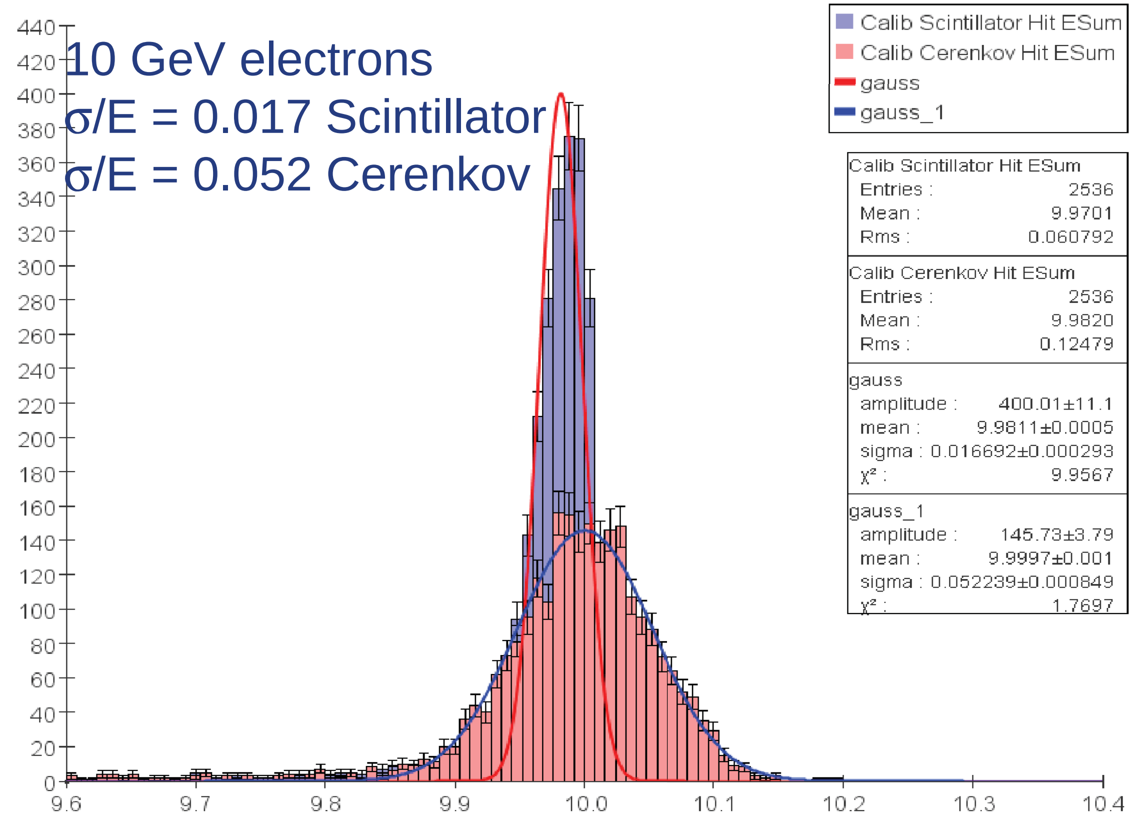


Use single electrons of
1.0, 2.0, 5.0, 10.0, 20.0, 50.0, 100.0 GeV
To estimate energy scale.

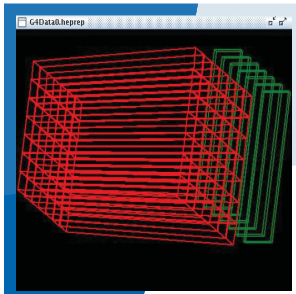


Analysis: Electron Calibration for Scintillator, Cerenkov

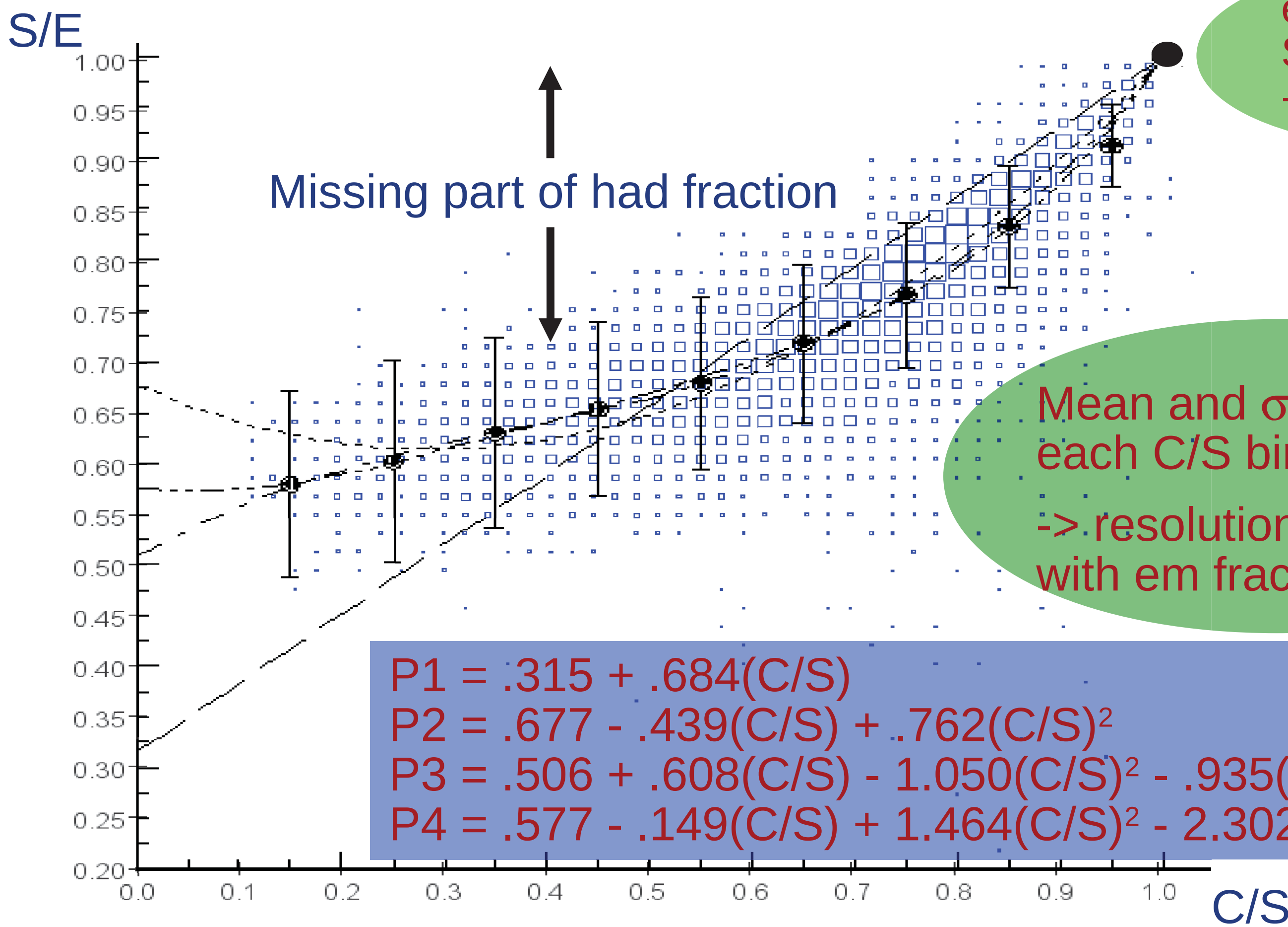




$S = 1.004 \times s_{raw}$ $C = 7692 \times c_{raw}$



Polynomial Correction Functions: E=S/Pn

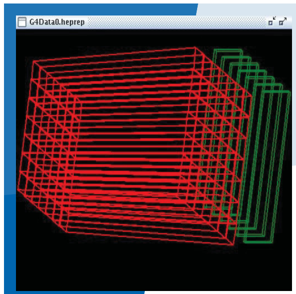


em fraction = 1
S/E, C/S = 1
-> calibration

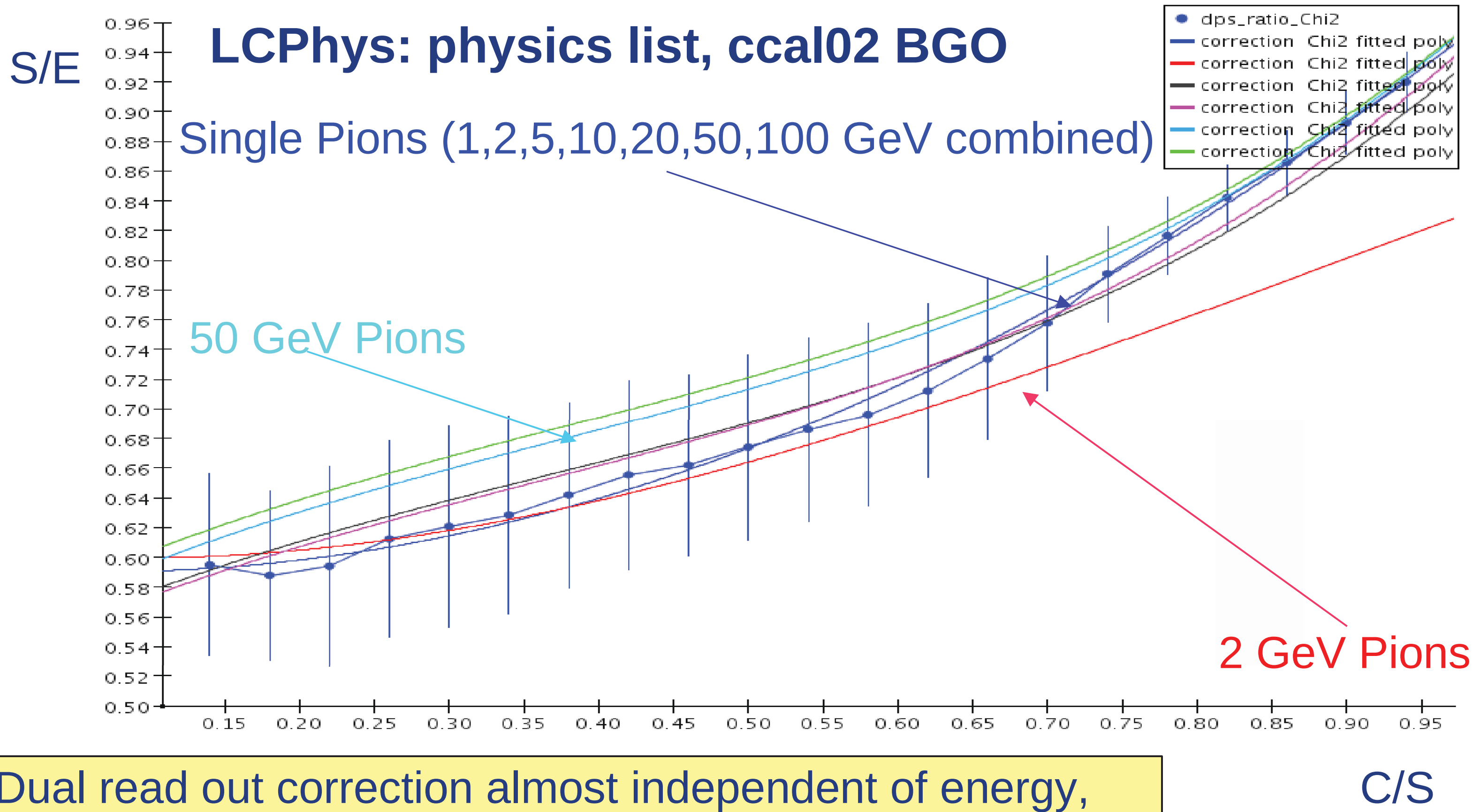
Mean and σ/mean of fit in each C/S bin plotted

-> resolution improves with em fraction

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

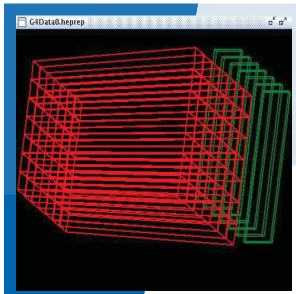


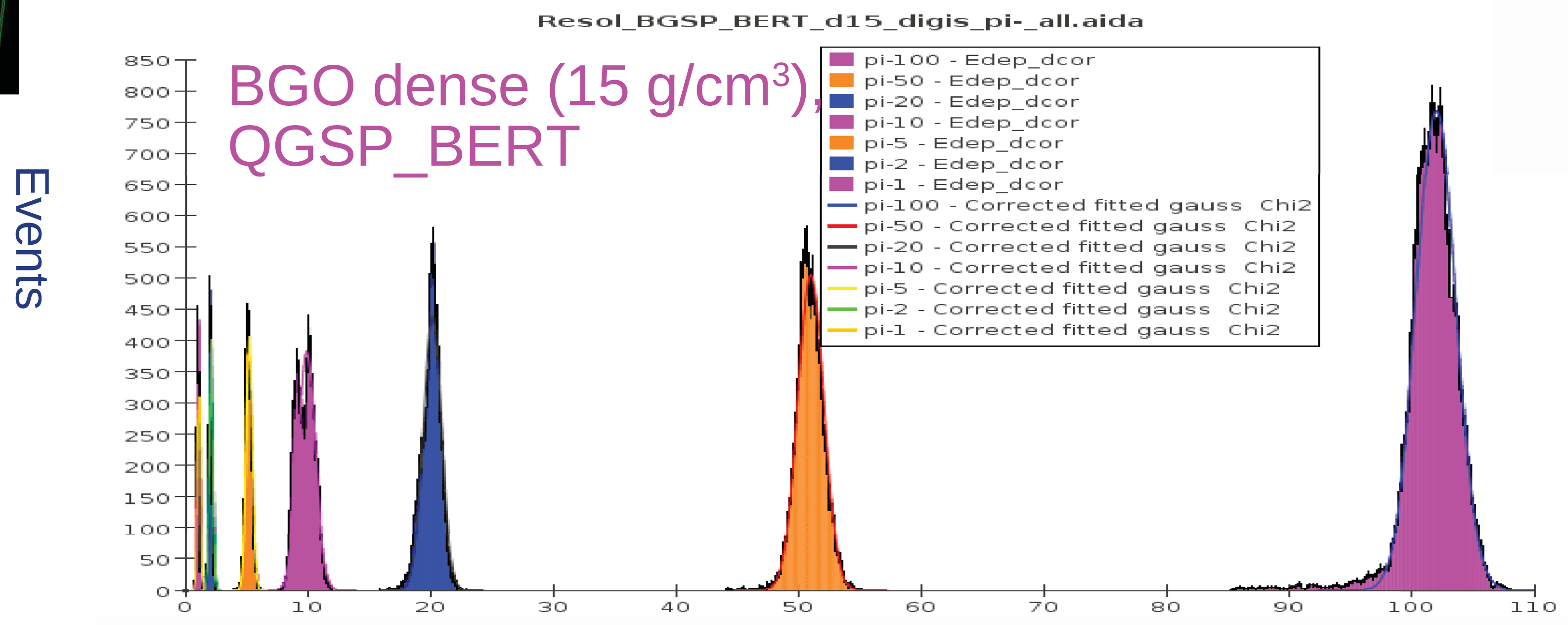
Correction function as function of energy

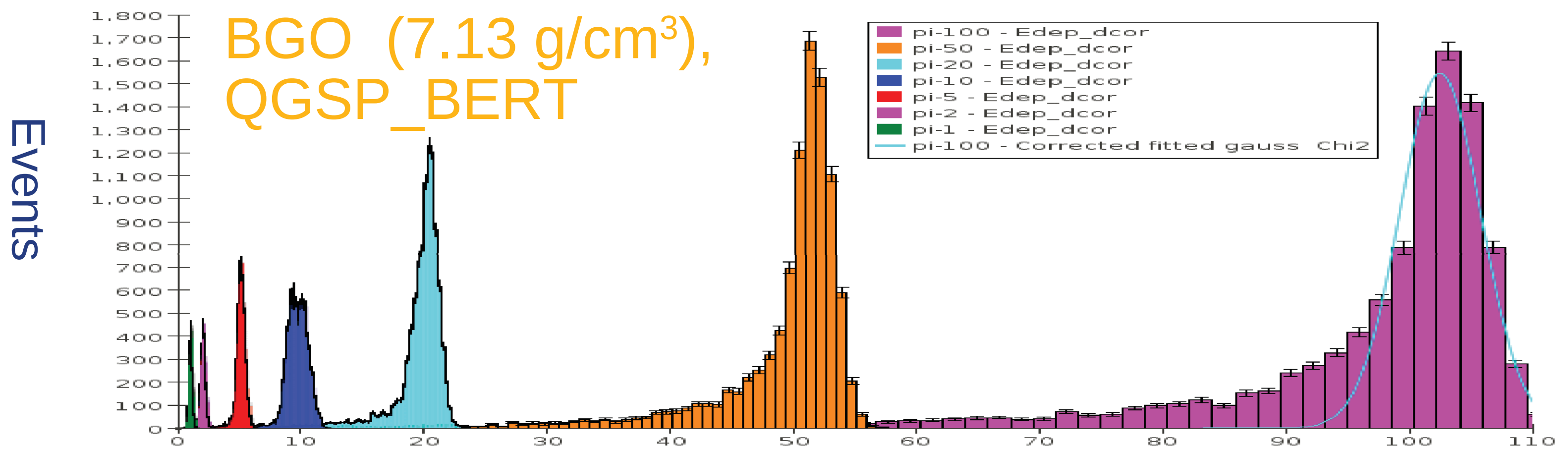


Note! Dual read out correction almost independent of energy, but it's worth exploring if we can improve energy resolution with energy dependent correction function

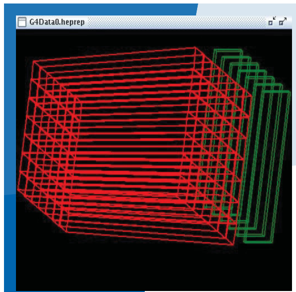
Corrected single π^- response



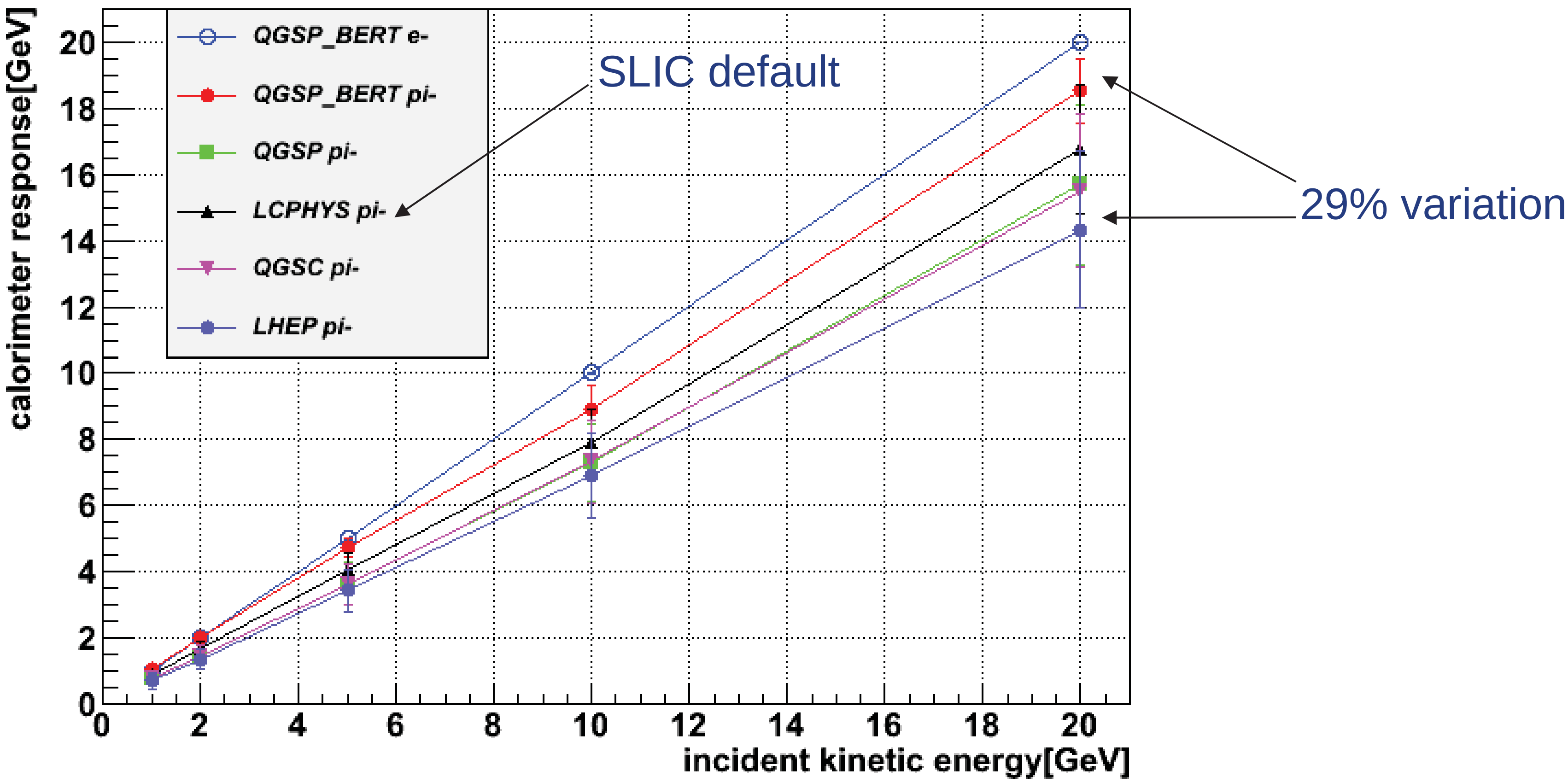




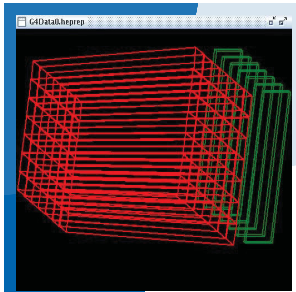
Energy in GeV after dual read out correction



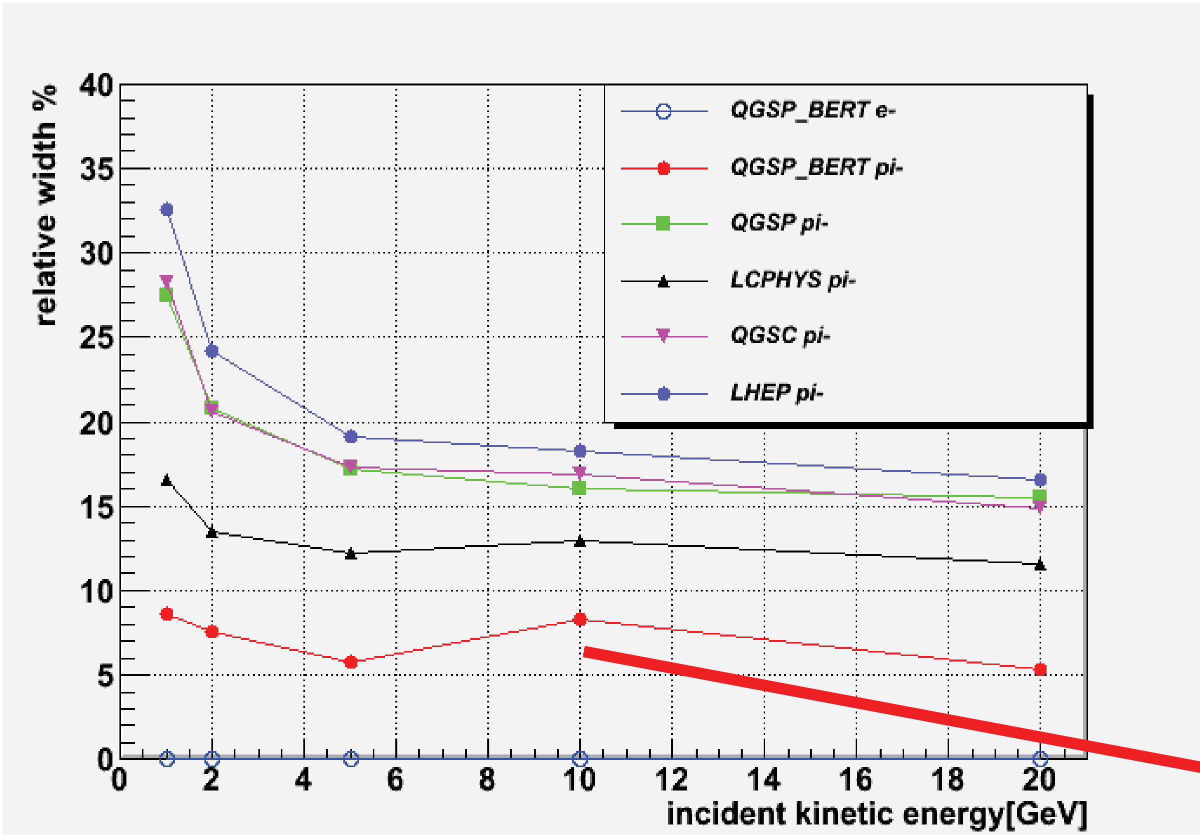
BGO Calorimeter response for different physics models

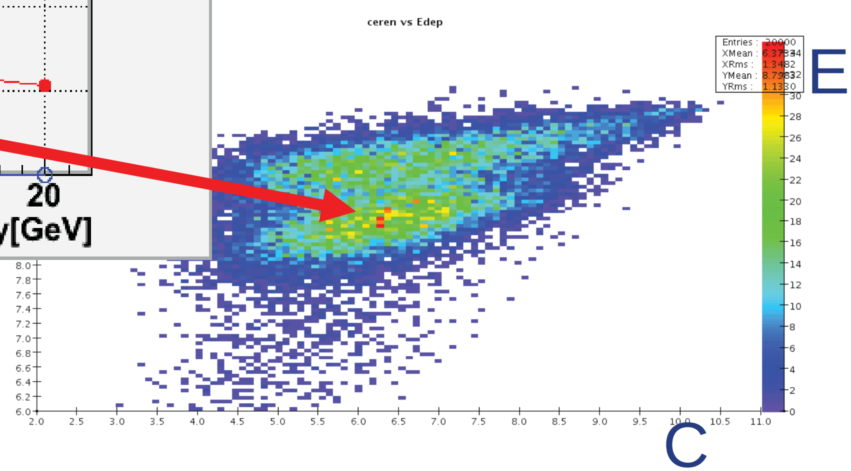


Particles produced within the calorimeter!
No threshold! → all energy deposition are added up

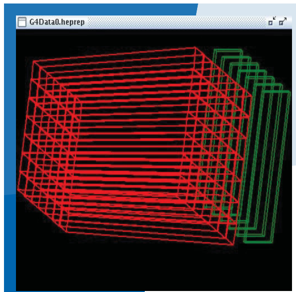


BGO relative width of energy response to charged pions for different physics lists





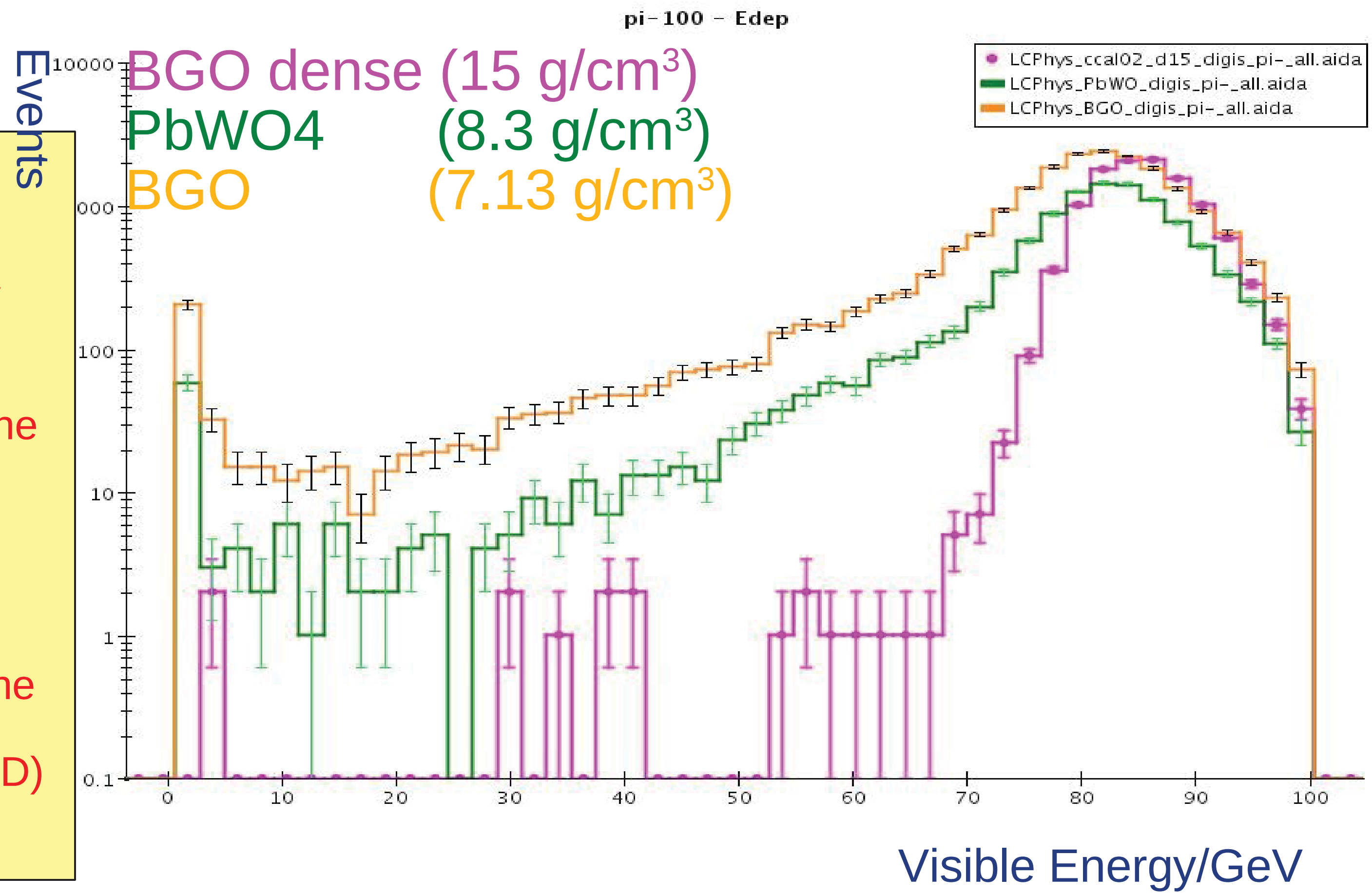
Geant 4 collaboration is aware of that!



100 GeV π leakage for BGO/PbWO4/ BGO dense

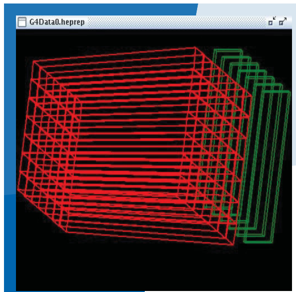
The leakage energy fluctuates and the fractional fluctuation increases with energy until it exceeds the stochastic term and sets the limit on the achievable energy resolution.

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



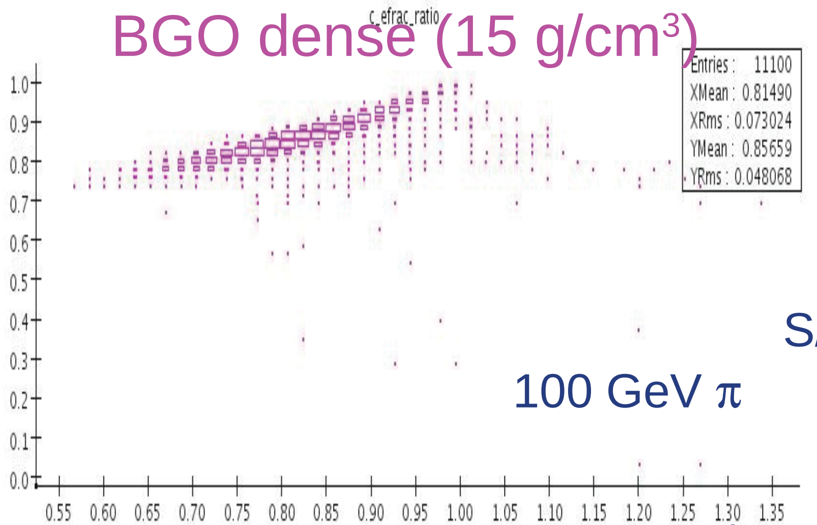
Leakage is of particular concern for compact detectors such as SID!

Leakage has to be considered when obtaining dual correction!



BGO dense (15 g/cm^3)

S/E

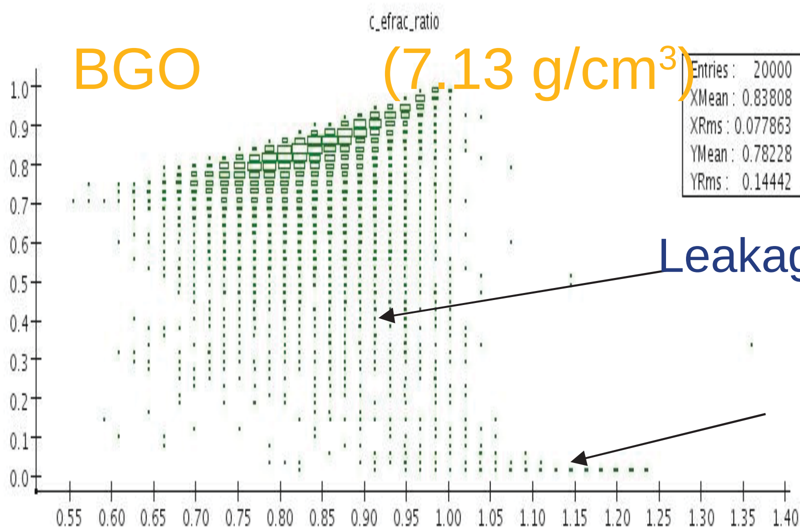


100 GeV π

C/S

BGO (7.13 g/cm^3)

S/E

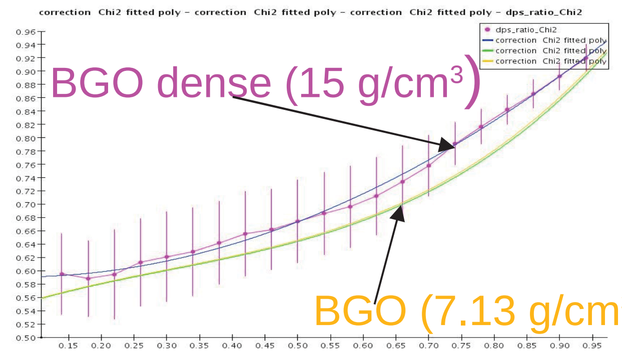


Leakage

Punch Through

C/S

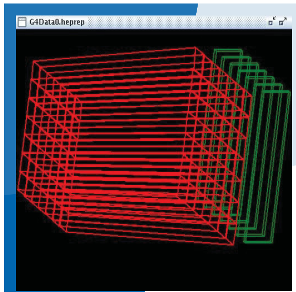
S/E



BGO dense (15 g/cm^3)

BGO (7.13 g/cm^3)

C/S



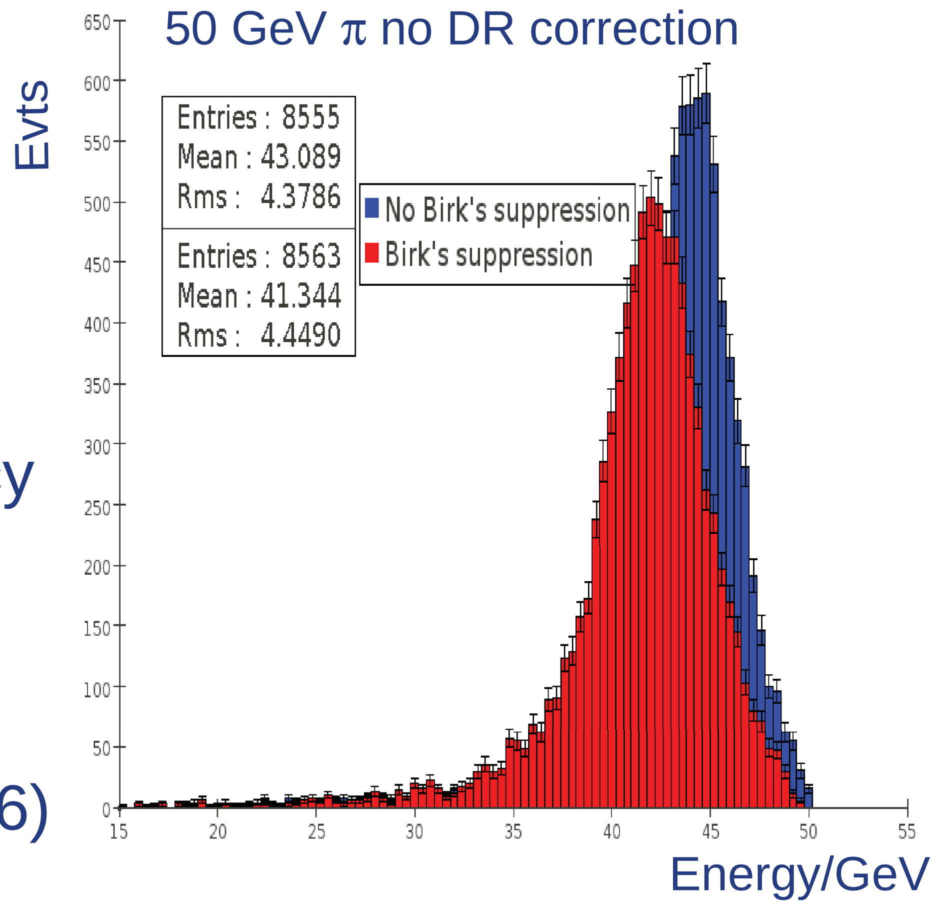
Birks attenuation

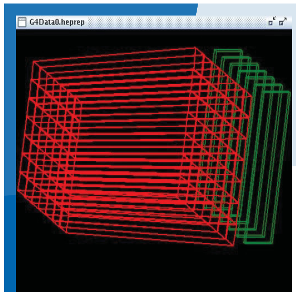
Implemented in SLIC,
Available in Geant 4 via Szintillation process

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

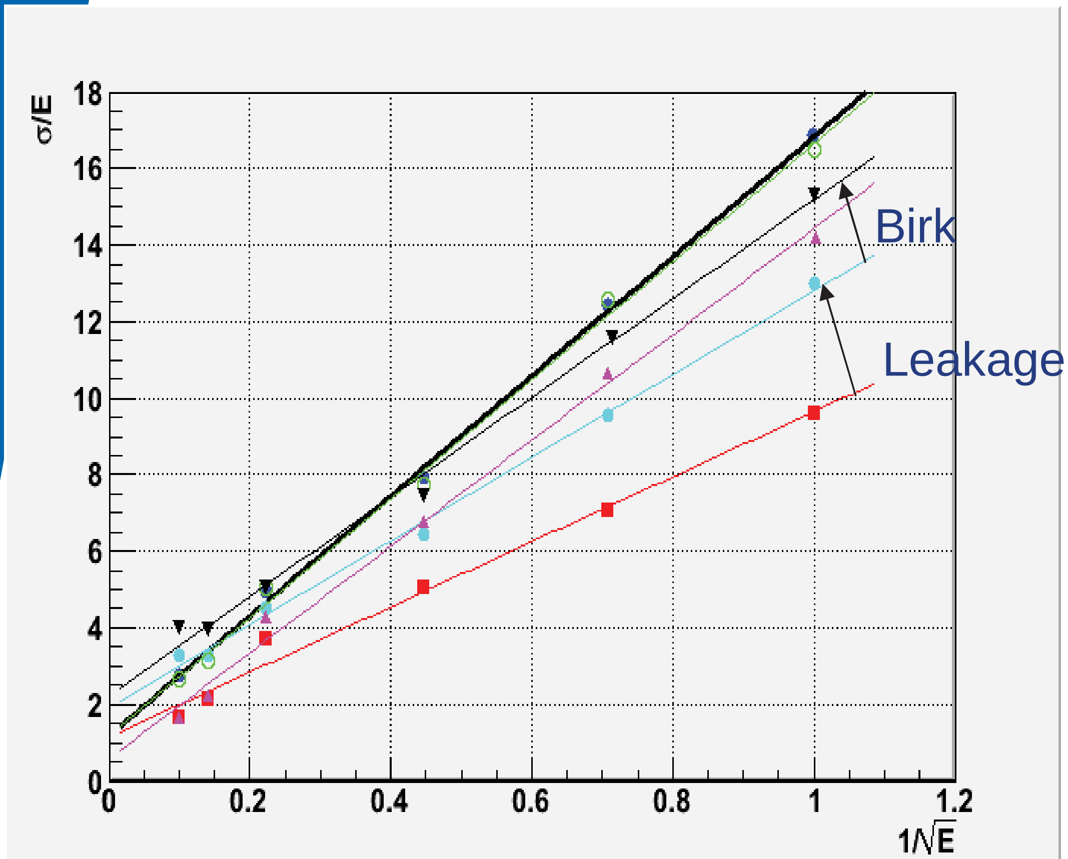
Where:
kB = Birks constant
S = Scintillation Efficiency
$\frac{dL}{dx}$ = Light Output

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





Single π^- resolution for different detector configurations



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

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

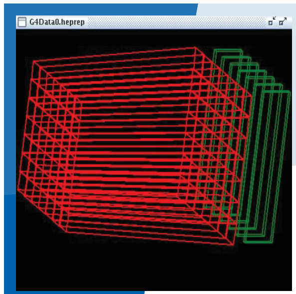
BGO, QGSP_BERT , Birk supr.:
$\sigma(E)/E=2.23 + 13.0/\mathrm{sqrt}(E)$ %

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.



Conclusions

- We have developed a flexible and robust set of tools for simulation of dual readout hadron calorimeters with various geometries, from test-beam to collider detectors.
- We have studied in detail the performance of a total absorption dual readout calorimeter, using the Cherenkov-scintillation correlation to correct for the energy depositions undetected or under-detected via scintillation light
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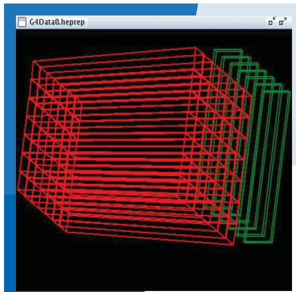
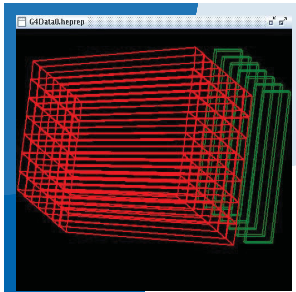


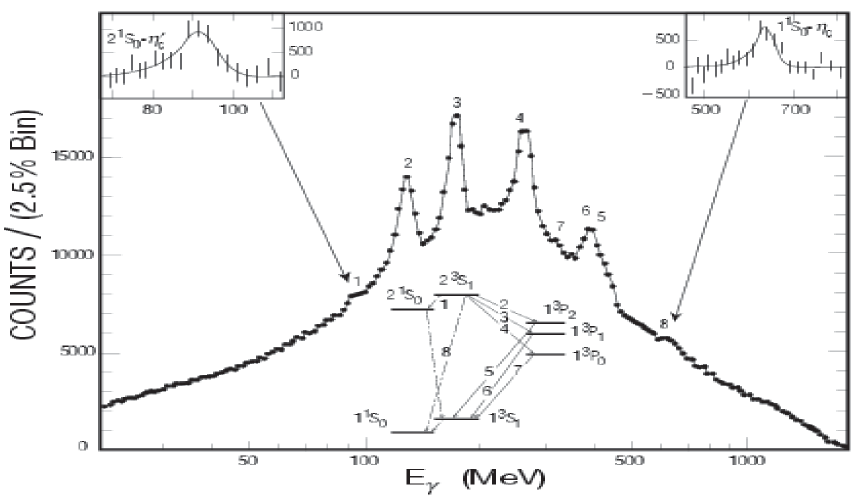
Backup slides



Motivation

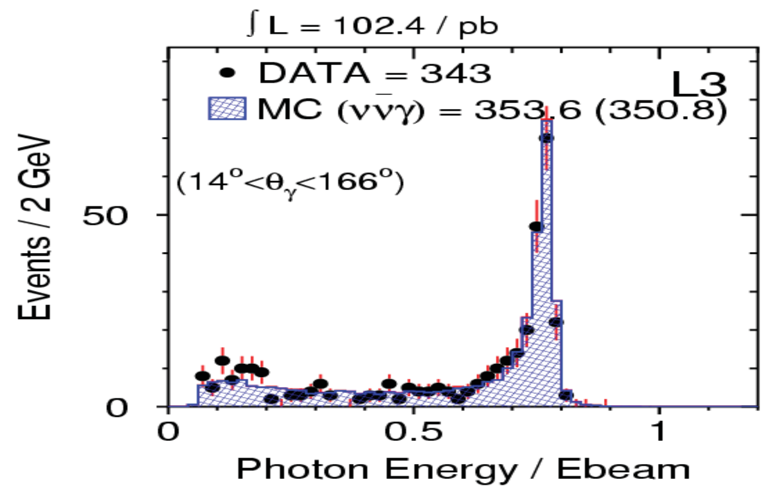
- Lepton Colliders provide a clean environment and aim for high precision measurements complementing discovery machines like the LHC. We don't know what physics scenarios we will finally encounter. We should be ready for all scenarios and aim to build the best possible detector/calorimeter.

Charmonium System Observed Through Inclusive Photons: CB

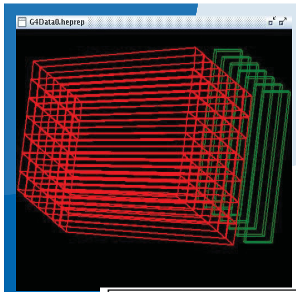


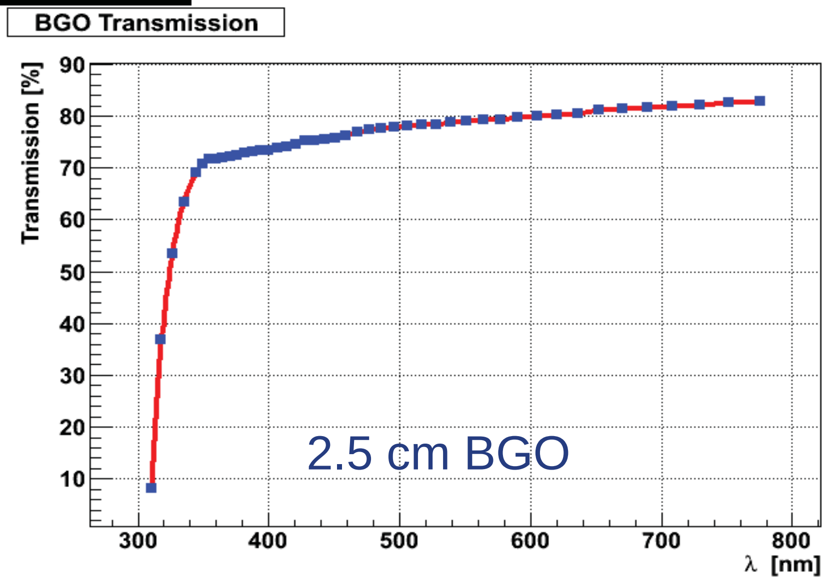
SUSY Breaking with Gravitino

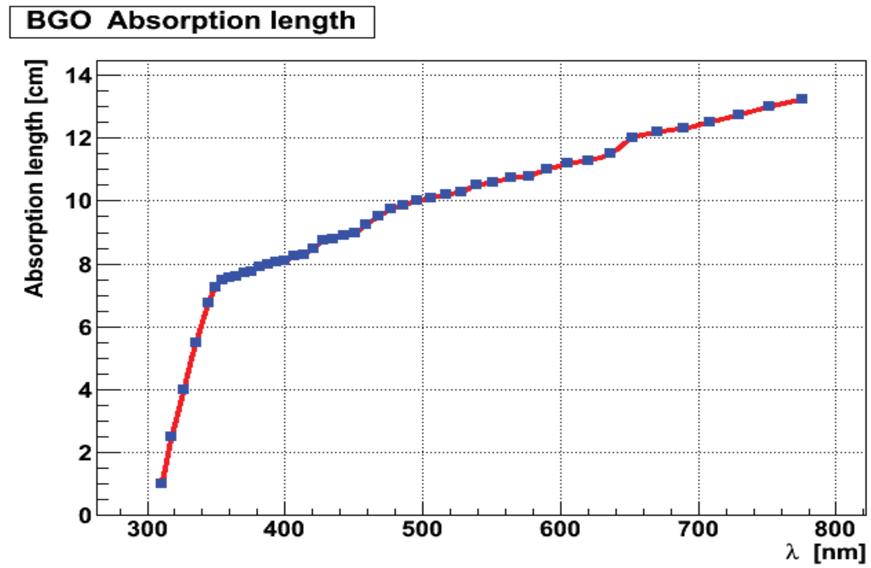
$$e^+ e^- \longrightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \longrightarrow \gamma\gamma \tilde{G}\tilde{G}$$

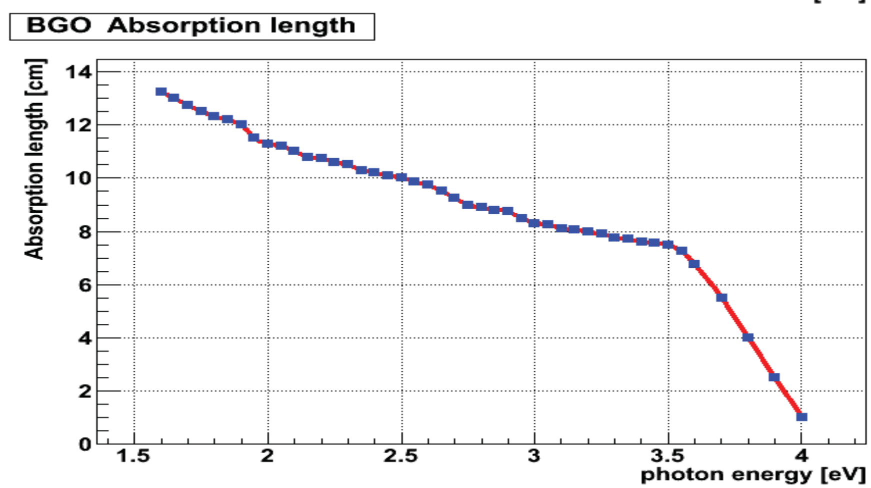


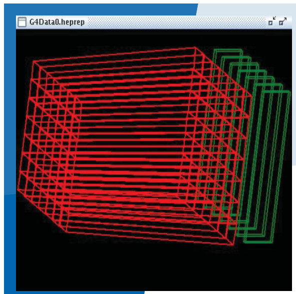
BGO optical properties (II)



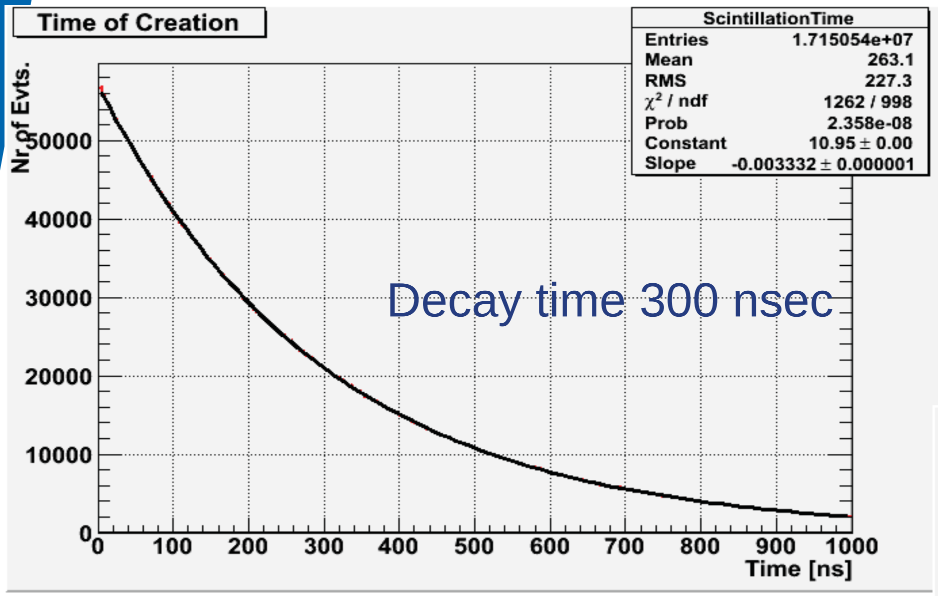




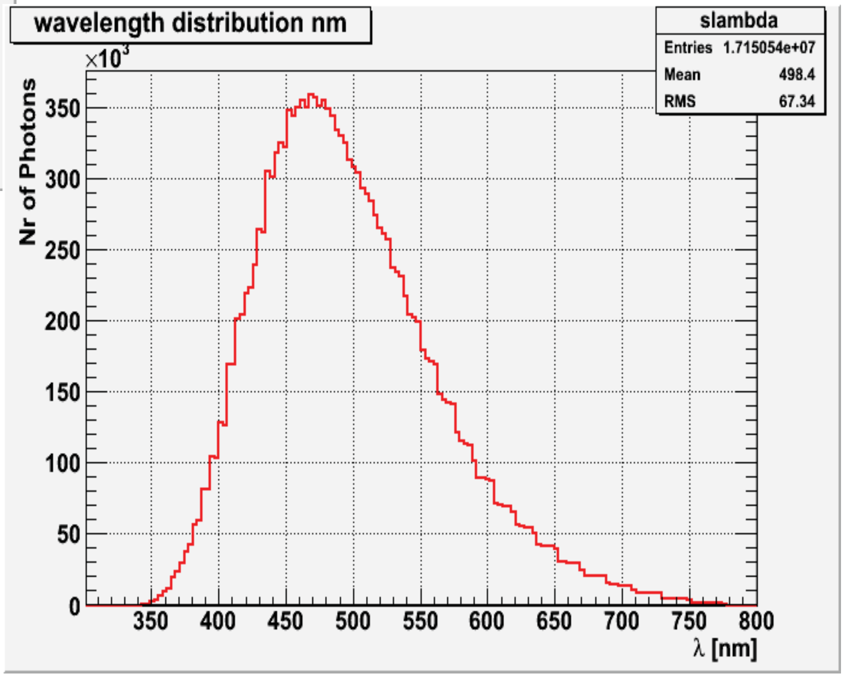


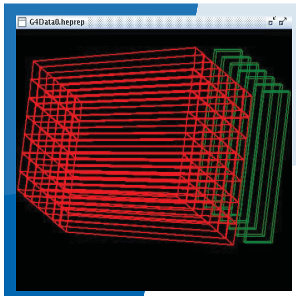


Geant 4: produced Scintillation light



2 GeV Muons (2cm BGO):
171500 Scintillation photons/evt.

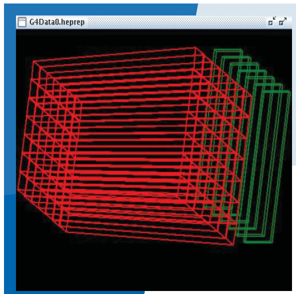




LUT (Reflectivity)

Derived from measurements At LBL:
M. Janecek, W. Moses IEEE Transactions on Nuclear Science
Now part of regulare geant 4 distribution as of 4.9.3

- polishedlumirrorair, // mechanically polished surface, with lumirror
- polishedlumirrorglue, // mechanically polished surface, with lumirror & meltmount
- polishedair, // mechanically polished surface
- polishedteflonair, // mechanically polished surface, with teflon
- polishedtioair, // mechanically polished surface, with tio paint
- polishedtyvekair, // mechanically polished surface, with tyvek
- polishedvm2000air, // mechanically polished surface, with esr film
- polishedvm2000glue, // mechanically polished surface, with esr film & meltmount
- etchedlumirrorair, // chemically etched surface, with lumirror
- etchedlumirrorglue, // chemically etched surface, with lumirror & meltmount
- etchedair, // chemically etched surface
- etchedteflonair, // chemically etched surface, with teflon
- etchedtioair, // chemically etched surface, with tio paint
- etchedtyvekair, // chemically etched surface, with tyvek
- etchedvm2000air, // chemically etched surface, with esr film
- etchedvm2000glue, // chemically etched surface, with esr film & meltmount
- groundlumirrorair, // rough-cut surface, with lumirror
- groundlumirrorglue, // rough-cut surface, with lumirror & meltmount
- groundair, // rough-cut surface
- groundteflonair, // rough-cut surface, with teflon
- groundtioair, // rough-cut surface, with tio paint
- groundtyvekair, // rough-cut surface, with tyvek
- groundvm2000air, // rough-cut surface, with esr film
- groundvm2000glue // rough-cut surface, with esr film & meltmount

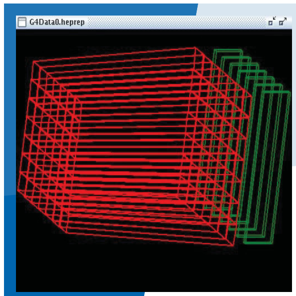


How to use the LUT

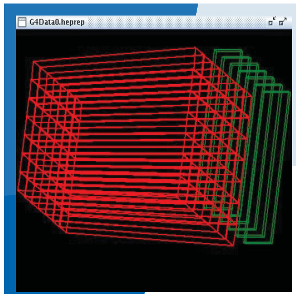
set an environment variable,
G4REALSURFACEDATA,
to the directory of geant4/data/RealSurface1.0.

```
// ------------- Surfaces --------------
//
// Quartz Bar/Air
//
G4OpticalSurface* OpBGOSurface = new G4OpticalSurface("BGOSurface");
OpBGOSurface->SetType(dielectric_LUT);
OpBGOSurface->SetModel(LUT);
OpBGOSurface->SetFinish(polishedtyvekair);

G4LogicalBorderSurface* BGOSurface =
        new G4LogicalBorderSurface("BGOSurface",
        BGOBar_phys, expHall_phys, OpBGOSurface);
```



Can we trust the Monte Carlo?



Conclusions

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- We have studied in details the performance of a total absorption dual readout calorimeter, using the Cherenkov-scintillation correlation to correct for the energy depositions undetected or under-detected via scintillation light
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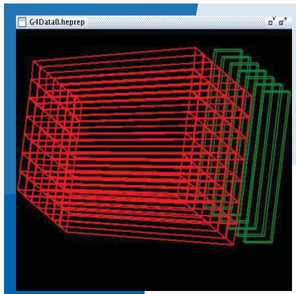
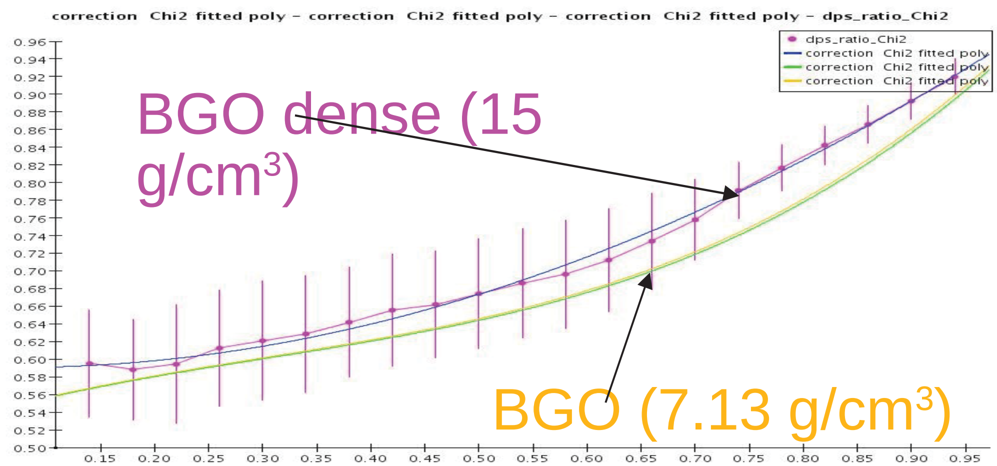
- This correction has very slight energy dependence. Even its energy-independent implementation indicate that the energy resolution in the range 10-15%/sqrt(E) should be achievable.
- The correction determined for single particles works well for collection of particles
- Whereas the actual magnitude of the DR correction depends very strongly on the GEANT4 physics model, the predicted performance of the calorimeter is independent of the simulation model
- The energy resolution predicted by the full GEANT4 simulation is limited by the modeling imperfections due to transition between the models, and not by the simulated fluctuations of the observed signals in the models themselves



Deconvolute Dual read out from leakage

Leakage must be considered when obtaining the dual read out correction by e.g. requiring the π shower to be fully contained.
If this is not done correctly leads to overcorrection!

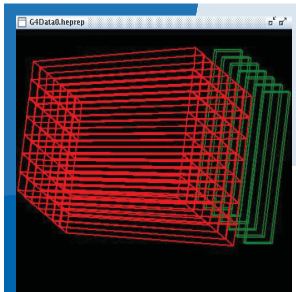
S/E



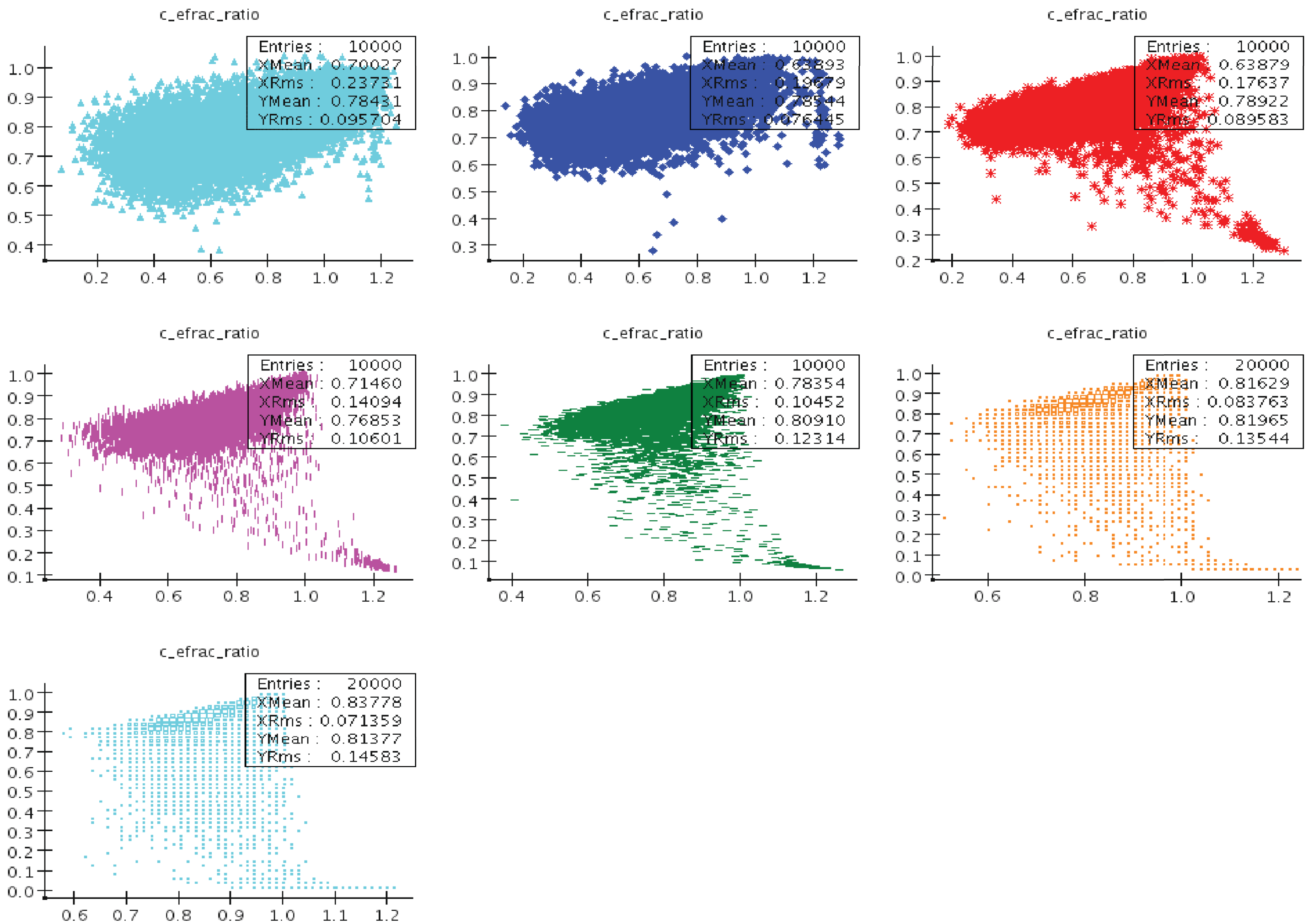
c/s

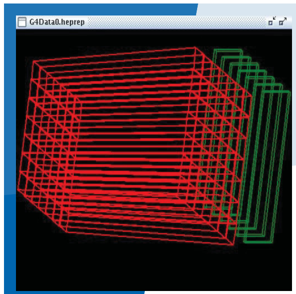
Segmentation can be used to correct for leakage:

Giovanni Pauletta and Anna Driutti have developed an Algorithm to correct for leakage



DualCorrection:S/E vs C/S all energies combined

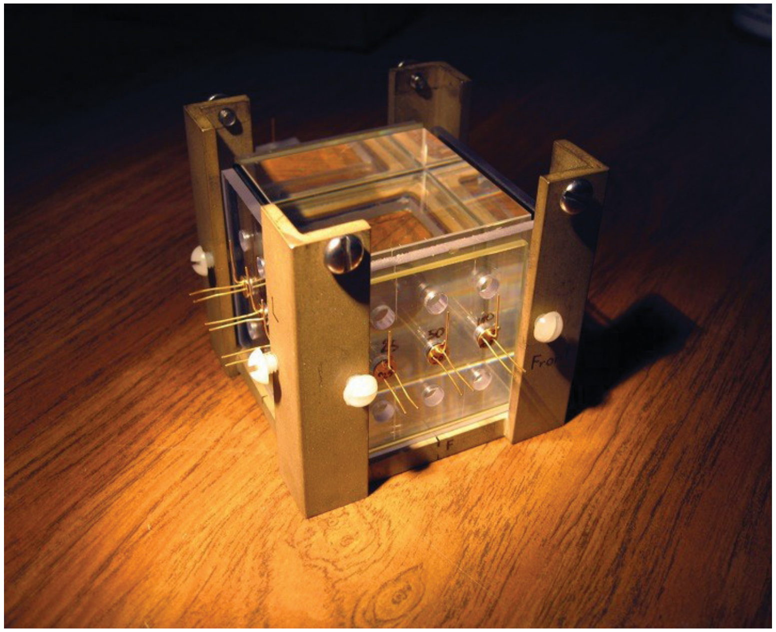


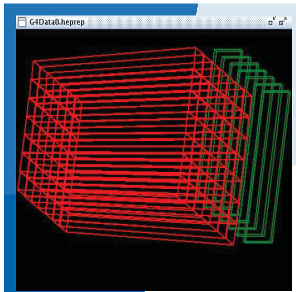


Crystals in a Test Beam

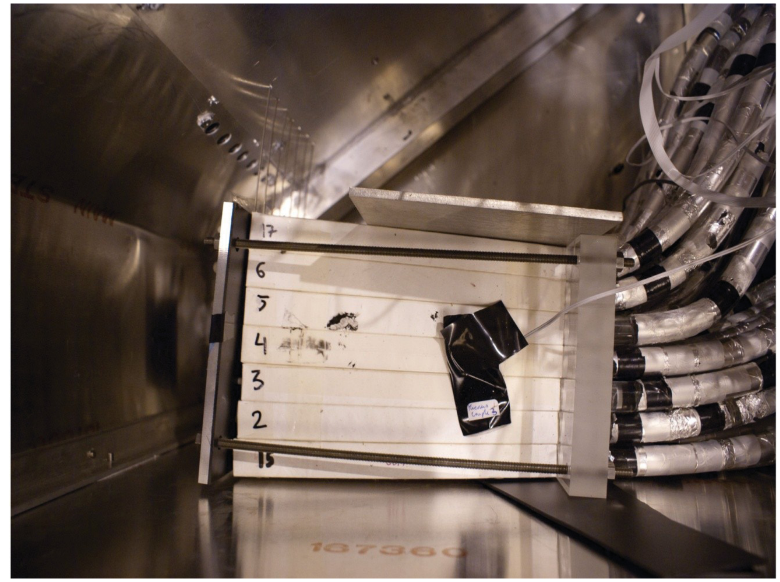
Single crystal studies:

- Scintillation and Cerenkov light yield
- With different filters
- With different photo detectors
- Position dependence
- Angular dependence
- Angular distribution of Cerenkov light in a shower
- Time profiles
- Compare with detailed Geant 4 simulations.

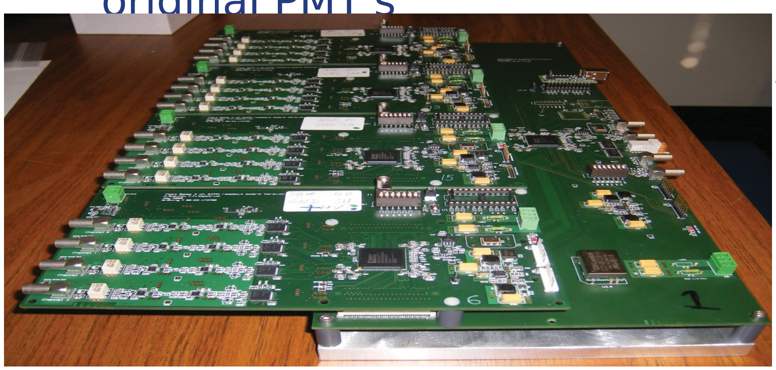




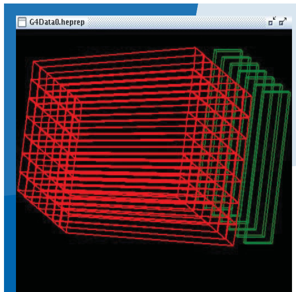
Crystals in a Test Beam



- CMS EM test module (University of Iowa)
- 49 PbWO4 crystals, photomultipliers,light guides
- Sent over from CERN
- Support structure under construction
- (Short term) plan:
  - Re-assemble the test beam module
  - Establish the performance (resolution) for electrons using the original PMT's



, direct



compact.xml/ccal02.xml

GeomConverter

Lcdd file

Edit by lcdd by hand

Lcdd file with:
- optical properties added
  (refraction index)
- calorimeter tag replaced with optical_calorimeter where necessary
- proper input for slic (needs optical physics enabled)

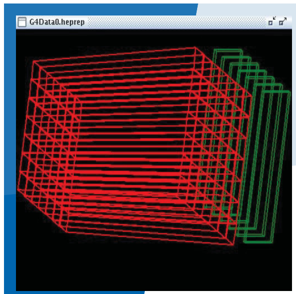
SLIC/Simulation

Analysis/Event Display

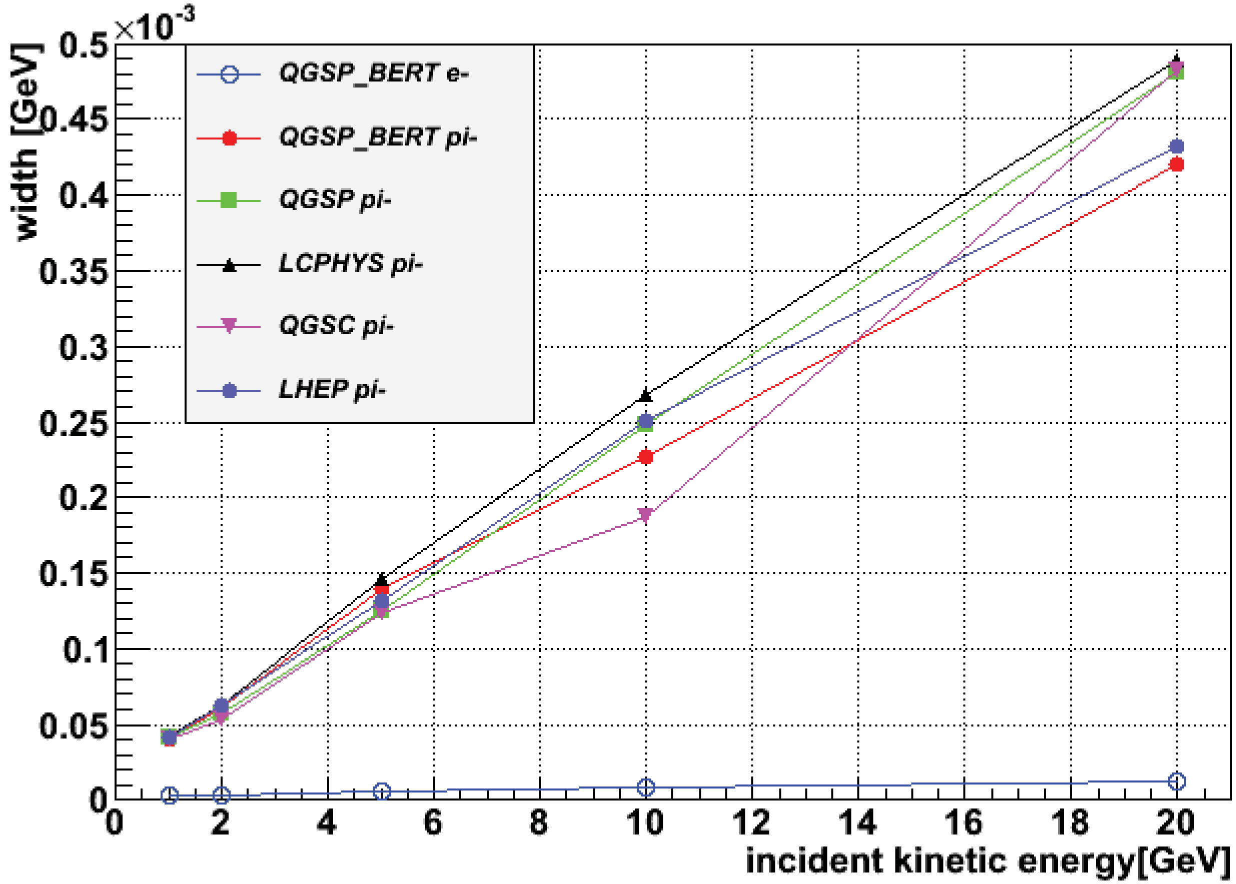
Edit by compact by hand

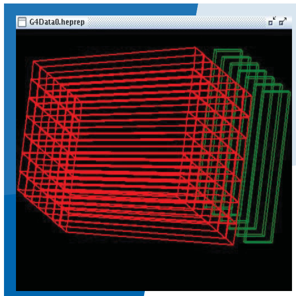
Compact with Edep_ and Ceren_ calorimeter hit collections

Hans Wenzel

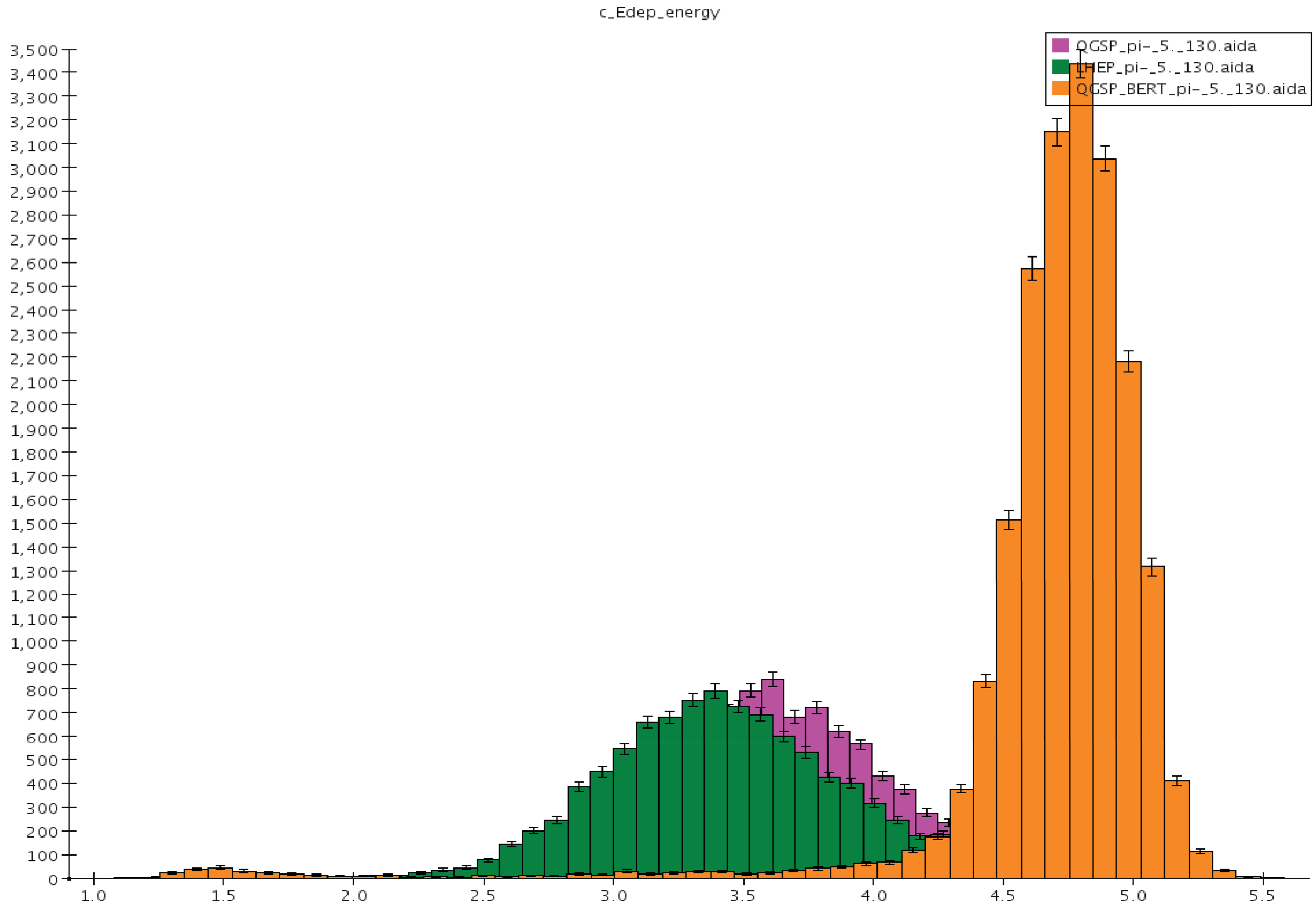


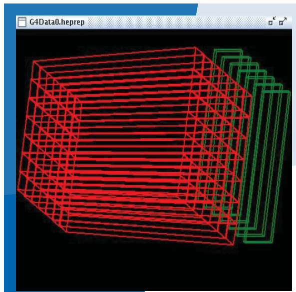
Width of cerenkov distribution





Calorimeter response for different physics models





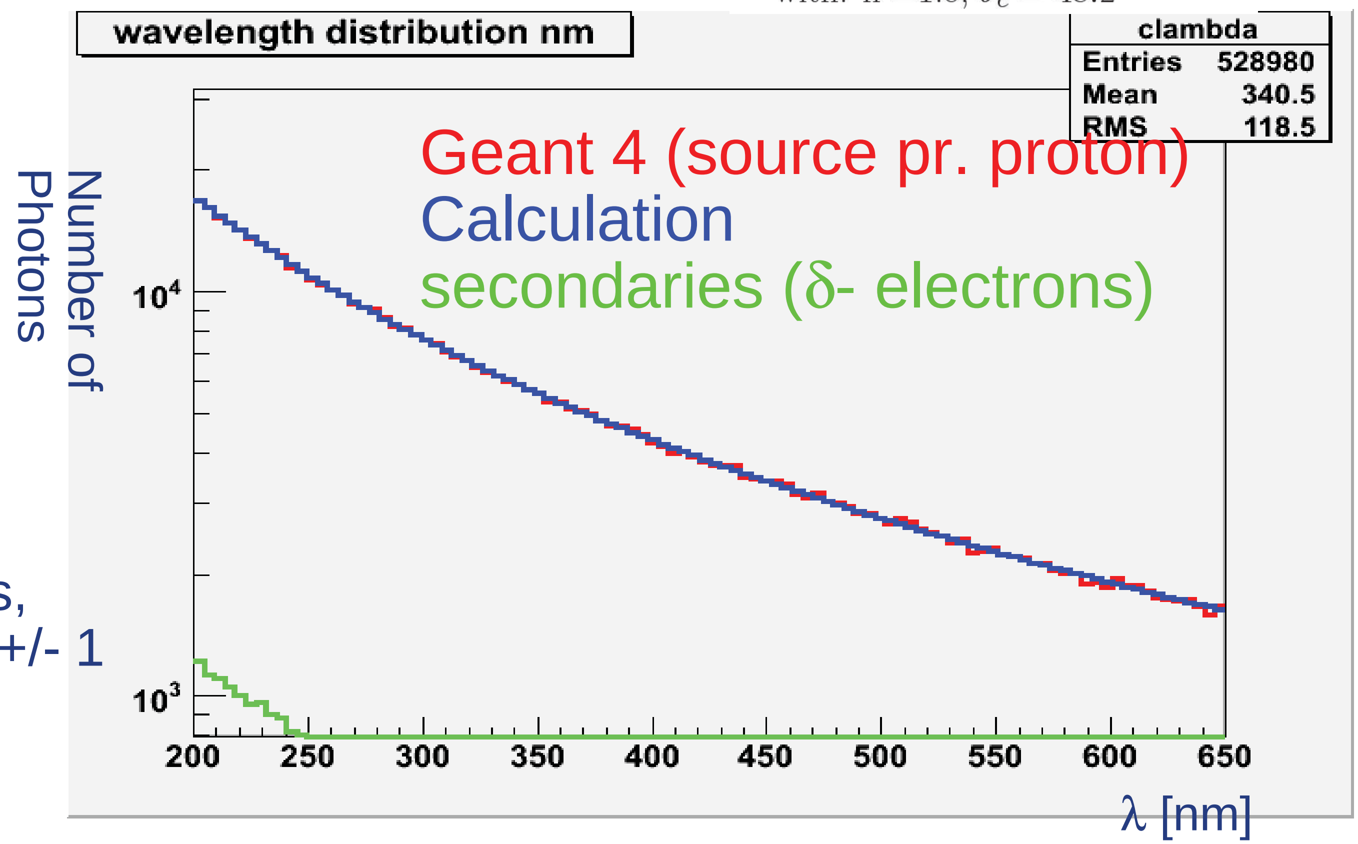
Spectrum of Cerenkov photons

$$n_{photons} = 2\pi\alpha \sin^2\theta_c \cdot \int_{\lambda_2}^{\lambda_1} \frac{1}{\lambda^2} d\lambda$$

where

$$\cos\theta_c = \frac{1}{\beta n}$$

with: n $=1.5$, $\theta_c = 48.2^0$



expect ~ 526 photons,
Geant 4 predicts 528+/- 1