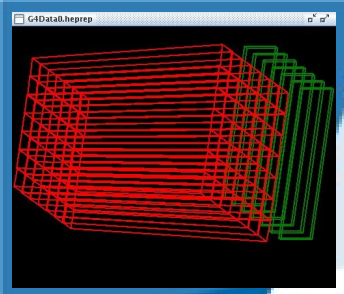


Simulation of total absorption dual readout calorimetry

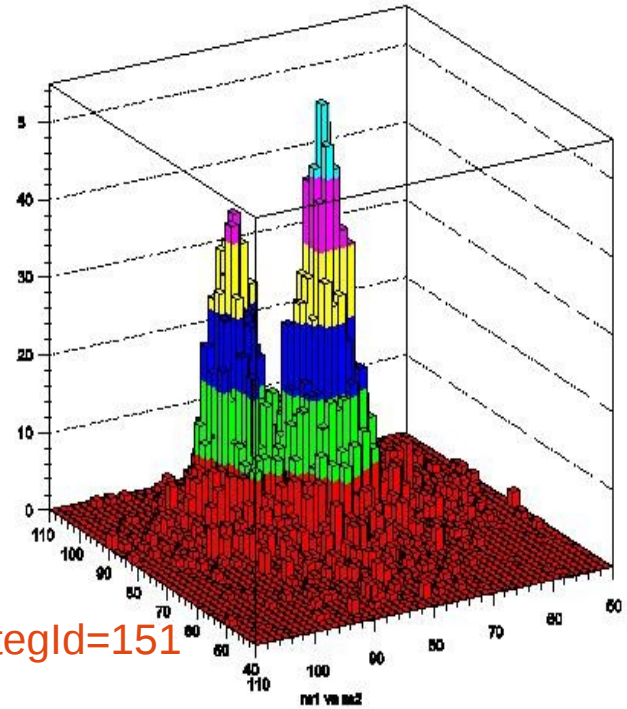
Review of dual readout calorimetry

2nd August 2010

Hans Wenzel

Fermilab

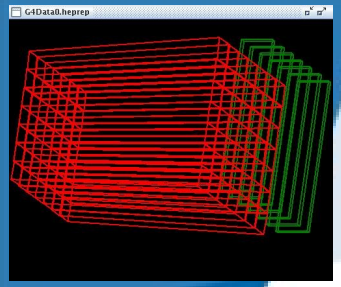
2nd August 2010



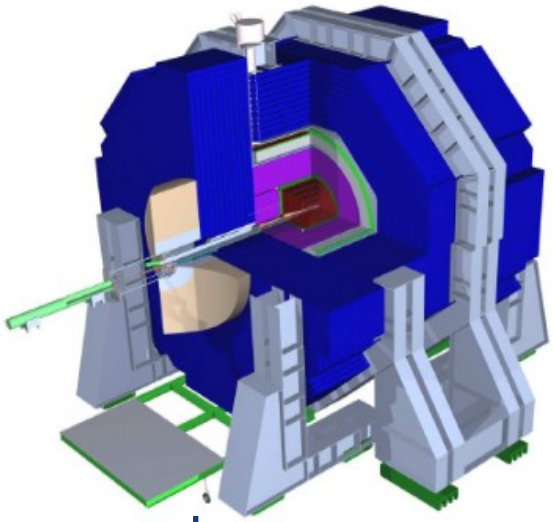
Weekly meetings, Agenda page:
http://ilcagenda.linearcollider.org/categoryDisplay.py?categId=151

CVS repository:

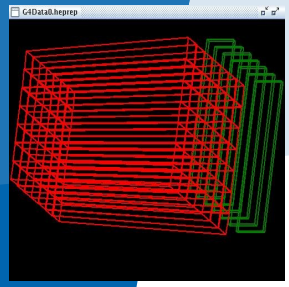
http://cdcvs.fnal.gov/cgi-bin/public-cvs/cvsweb-public.cgi/?hidenonreadable=1&f=h&logsort=date&sortby=file&hideattic=1&cvsroot=ilcdet



Outline



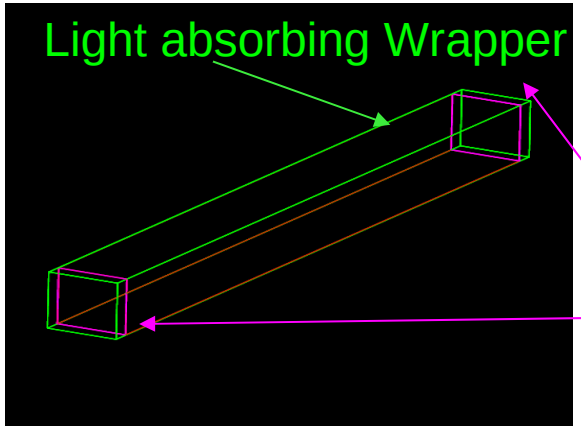
- Where we are:
  - The simulation software environment:
    - CrystalSim
    - The SID software framework
      - » The CCAL02 detector, the analysis chain, resolution
- Conclusion, Plans and future tasks



CrystalSim

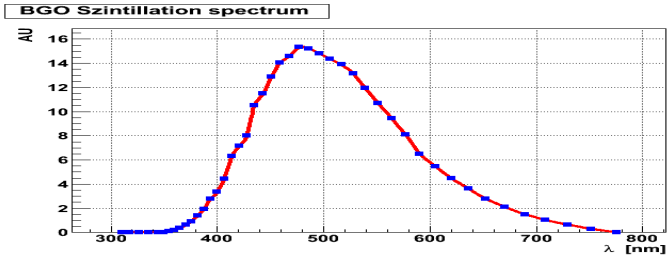
(Yannis Makris, Savvas Kyriacou from Cyprus, Students of Fotios Ptochos)

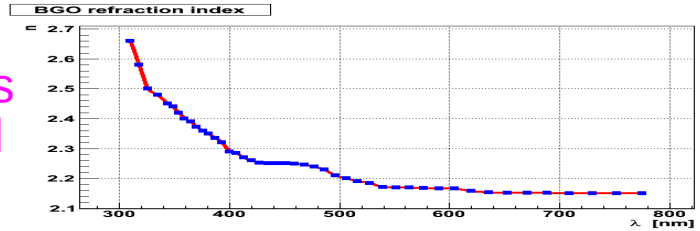
- Geant 4 based stand alone application (optical photons).
  - Assumes all deposited energy is converted to scintillation light.
  - Input:
    - rindex(λ)
    - absorption length(λ)
    - scintillation spectrum(λ,t), light yield (photons/MeV)
    - Birks suppression
    - crystal surface conditions. (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).

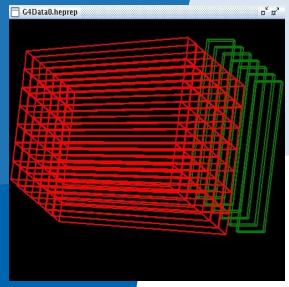


Crystal: 2x2x20 cm

Ideal Photodetectors (detect every optical photon)

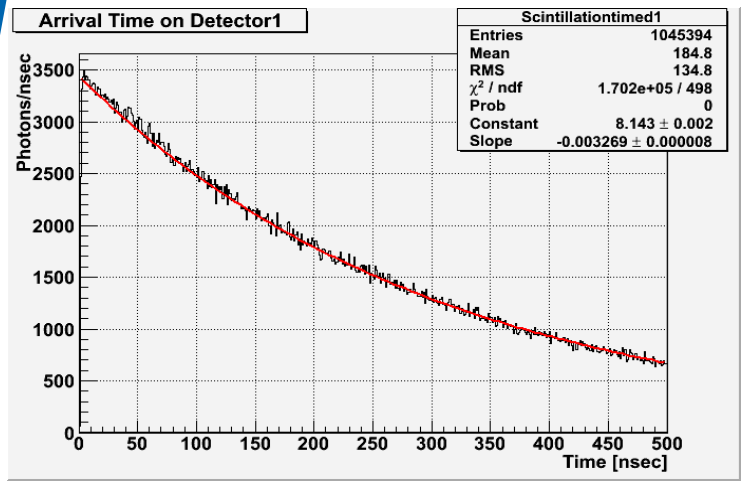


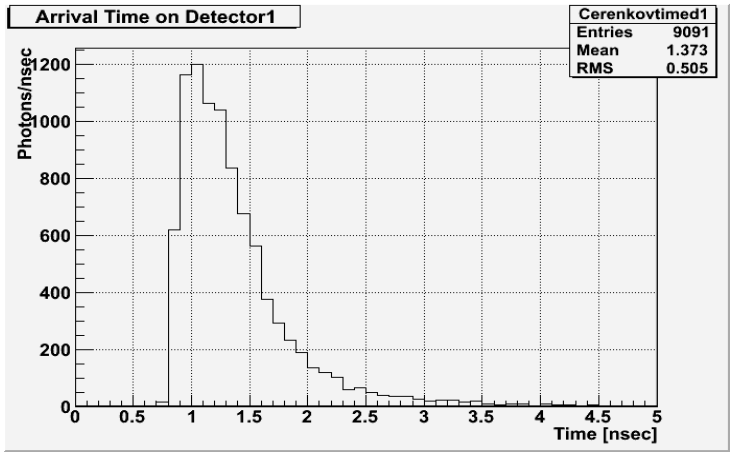




CrystalSim

CrystalSim can provide detailed studies of:



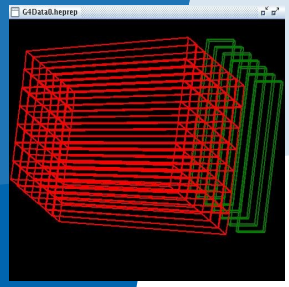


- Light yield (scintillation and Cherenkov)
- Light attenuation
- Crystal shapes
- Uniformity of the detector response
- Efficiency and purity of the Scintillation-Cherenkov separation by means of timing, wavelength
- Sizes and positions of the photodetectors
- Required properties of photodetectors

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

2 GeV Muons (2cm BGO):

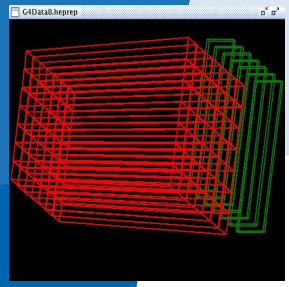
10500: Szintillation ph/sensor
90: Cerenkov ph/sensor



The SID software framework

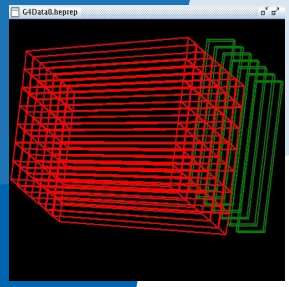
The software framework was developped for the SID ILC detector Concept. It's supported by SLAC, Norman Graf is the lead of the Project. Using the framework allows us to study physics performance as part of a complete Collider detector. The components of the Framework are:

- **SLIC:** Geant 4 (C++) 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 (common data format for ILC detector concepts), LCIO2 will use root io.
  - Easy to run SLIC on the Grid → makes it easy to generate large data sets. http://confluence.slac.stanford.edu/display/ilc/How+do+I+use+the+OSG+Grid
- **lcsim.org (netbeans):** analysis framework (JAVA) allows to automate calibration and analysis.
- **WIRED:** Event display (JAVA)
- **JAS3:** Interactive analysis program(JAVA).
- **LCIO Event Browser** (JAVA) .....
- **Confluence Wiki:** for documentation
  https://confluence.slac.stanford.edu/display/ilc/SLIC+Dual+Read+out+Tutorial



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

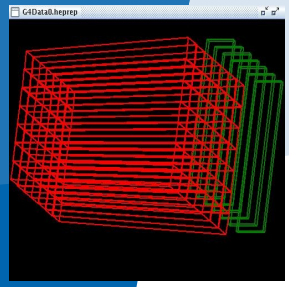
- Need to add optical physics (Cerenkov,Scintillation etc.,) → now can be used with any physics list.
- Need to be able to add optical properties to materials in the detector description e. g. refraction index/absorption as function of photon energy.
- Implement Birk's suppression
- Sensitive detector 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, no scintillation photons).
  - deal with optical photons from Cerenkov process. We don't track optical photons but kill them after the first step and add their energy to the Cerenkov hits.



SID Framework is used to study

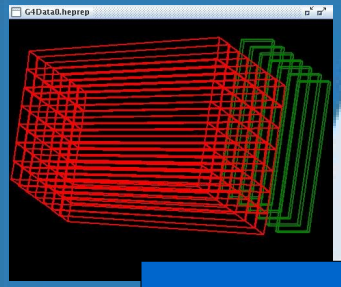
Summer student: Earle Wilson

- How energy resolution is affected by:
  - Geometry (segmentation)
  - Noise
  - Hit Thresholds
  - Non active areas
  - Calibration
  - Photon statistics (especially cerenkov)
  - Leakage
- Status of hadronic physics in Geant 4
- Best way to obtain Dual readout correction, energy dependence of correction, deconvolute DR correction and leakage effects.
- Effect of magnetic field on mass resolution, how to correct for it.
- Performance of calorimeter as part of collider detector (SID).
- Improving jet reconstruction and/or energy/mass resolution by combining the calorimetric and tracking information (PFA).
- various options and optimize the shape and the size of a full scale test beam prototype



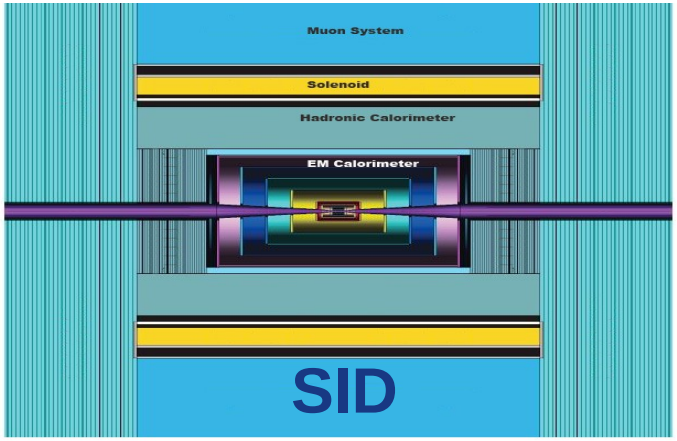
The CCAL02 detector, the analysis chain, resolution

- The CCAL02 detector
- The analysis chain
  - » Calibration using electrons.
  - » Obtaining the dual read out correction.
  - » Resolution for single π^-
  - » Physics analysis (e.g. ZZ $\rightarrow$ qqνν to reconstruct boosted Z's)
  - » PFA algorithmn
  - » Classifying clusters
  - » apply strict selection cuts when matching calorimeter clusters to tracks avoiding confusion term.
- Selected Effects limiting resolution
  - » Hadronic physics lists in Geant 4
  - » Leakage
  - » Birks suppression
  - » Many more not shown



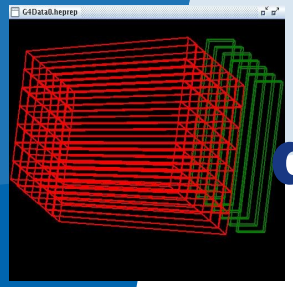
The CCAL02 detector
(Crystal Calorimetry version of SID)

				BGO		$PbWO_4$	
Name	Layers	Thickness/Layer	Segmentation	X_0	λ_I	X0	II
		[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



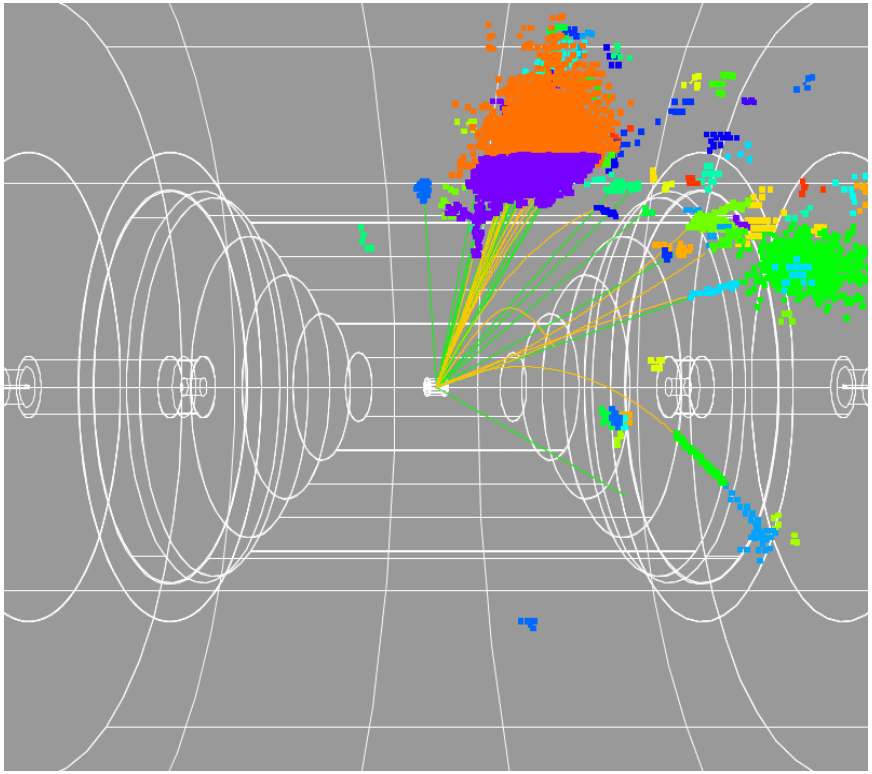
Material	Density	Rad. len. X0	IA len.
	[g/cm3]	[cm]	[cm]
BGO	7.13	1.12	21.88
PbWO4	8.3	0.9	18
SCG1-C	3.36	4.25	45.6

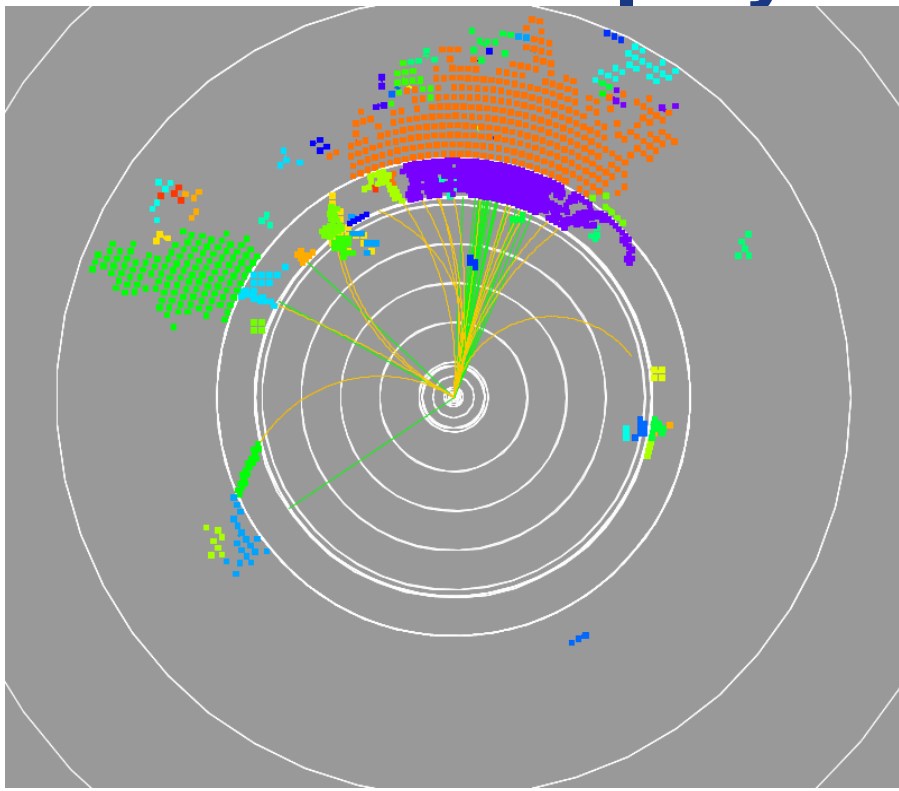
Monte Carlo: BGO with 15.0 g/cm^3



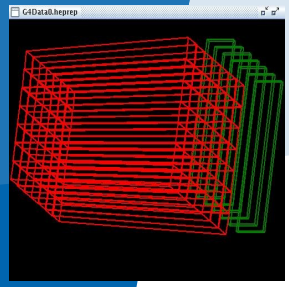
CCAL02 Scintillation response as displayed in the Wired event display

ZZ->qqνν



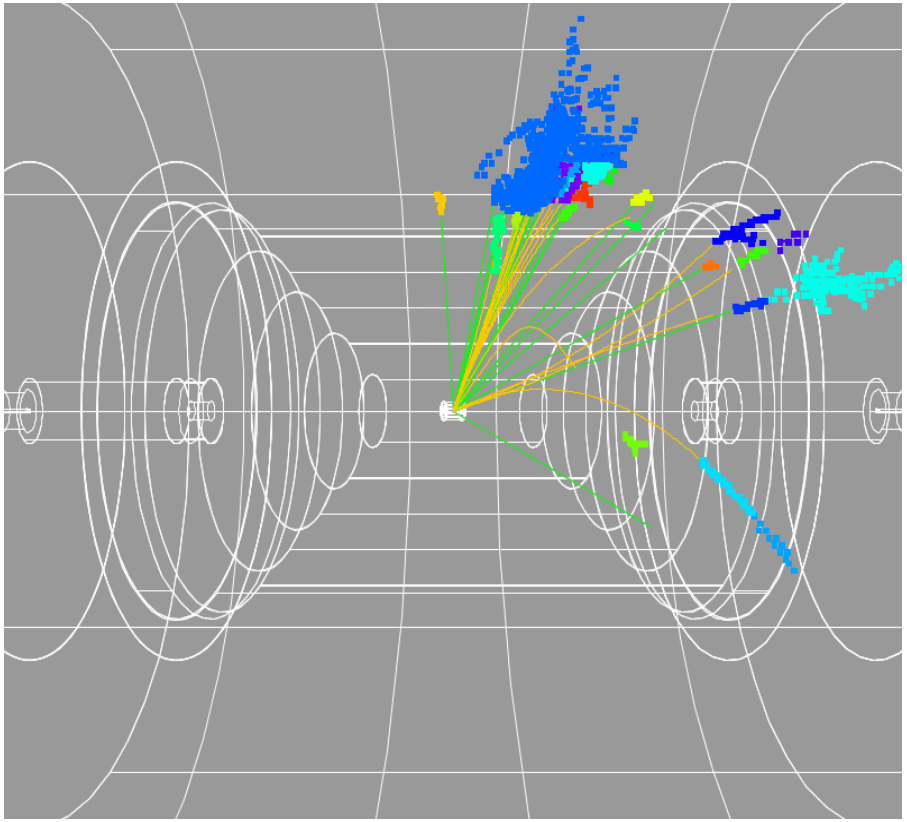


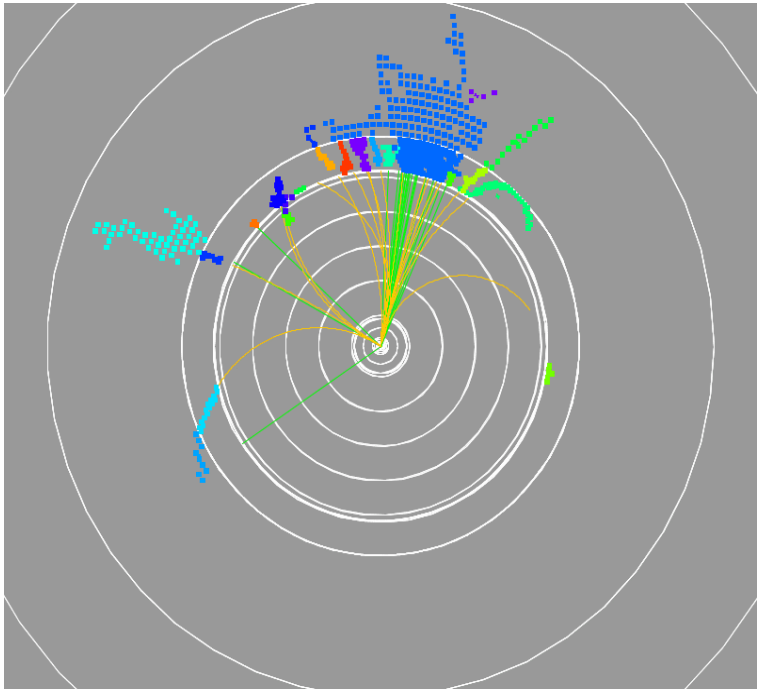
Digisim,
threshold 1/50 of a mip

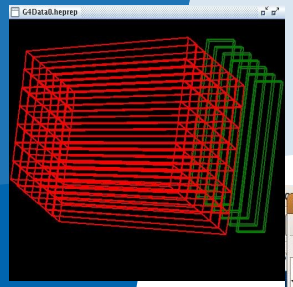


CCAL02 Cerenkov response as displayed in the Wired event display

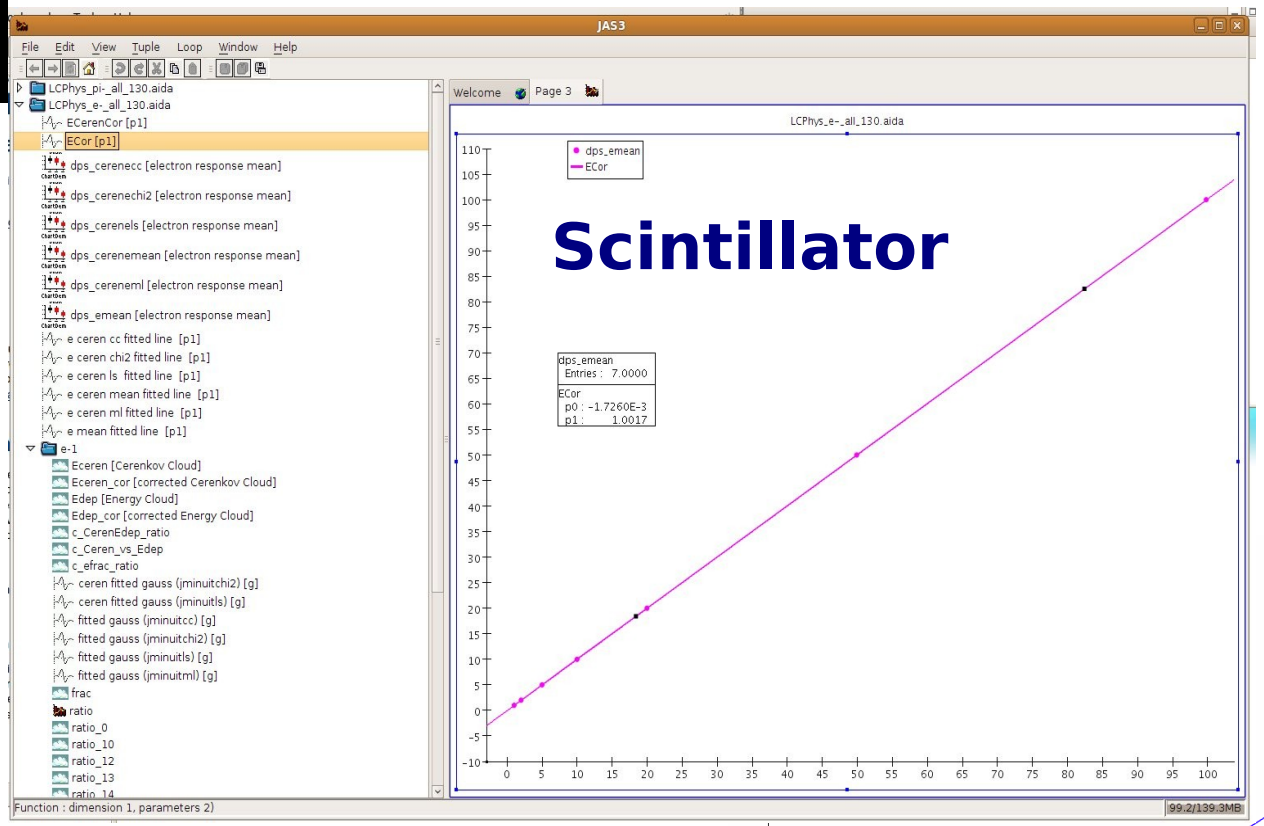
ZZ->qqνν



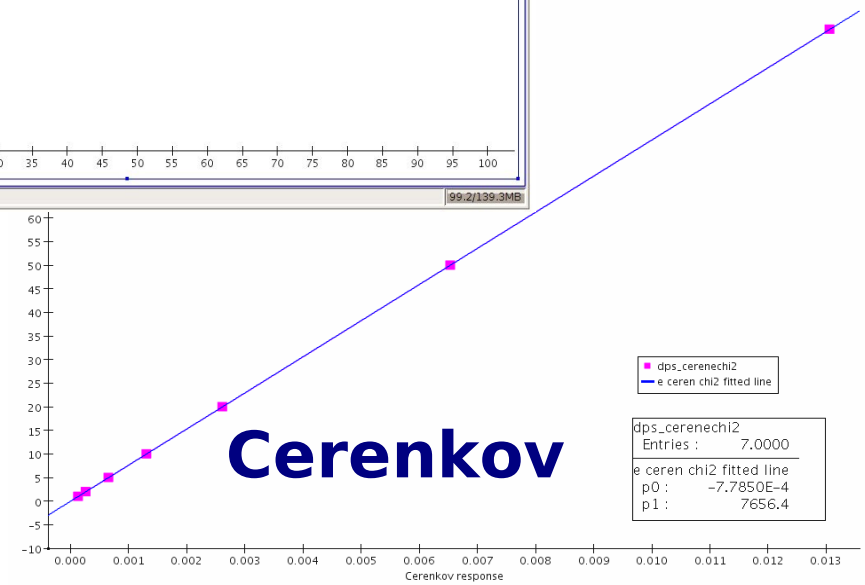


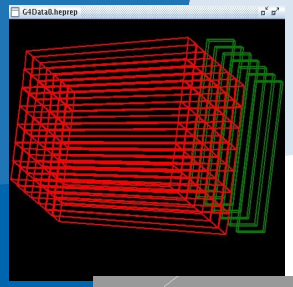


Electron Calibration for Scintillator, Cerenkov

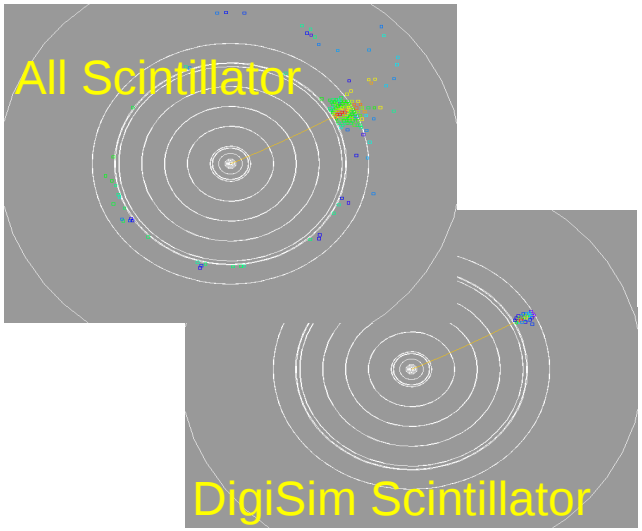


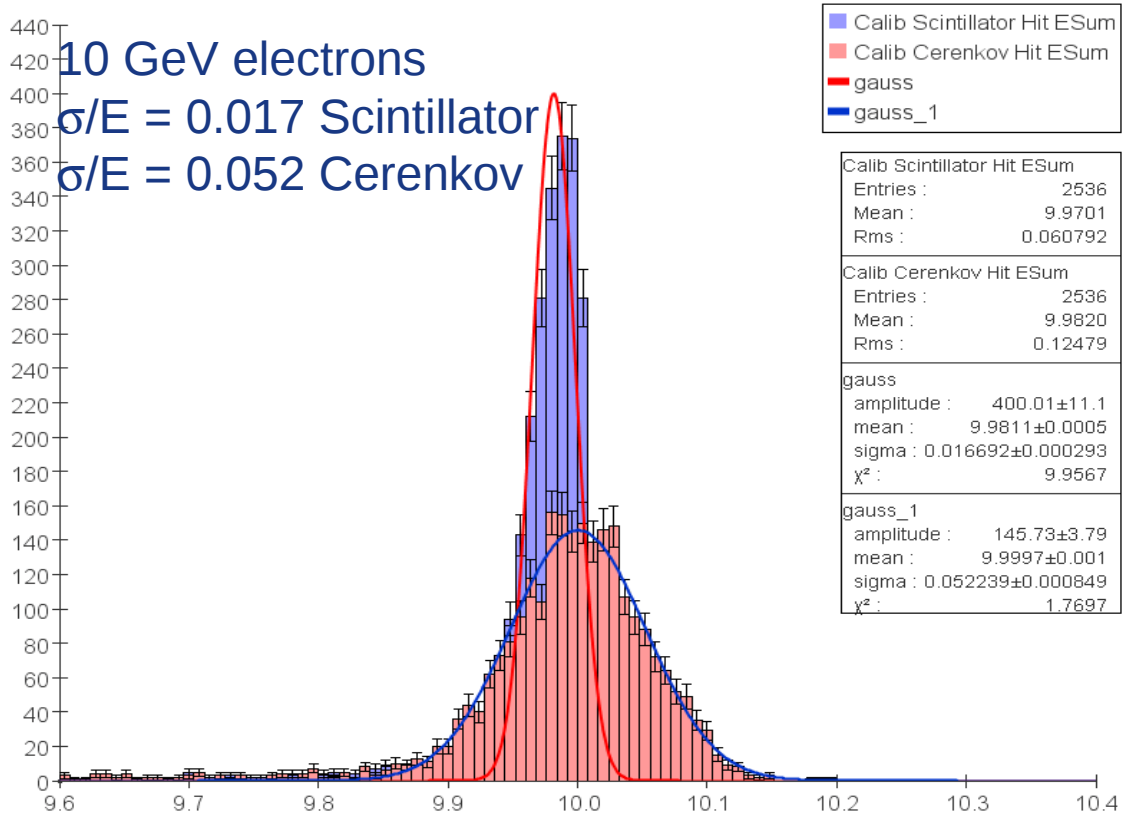
Use single electrons of
1.0, 2.0, 5.0, 10.0, 20.0, 50.0, 100.0 GeV
To estimate energy scale.



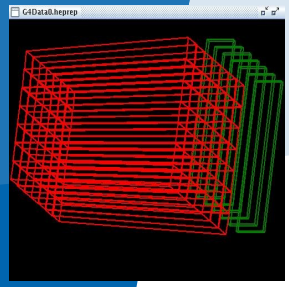


Analysis: Electron Calibration for Scintillator, Cerenkov

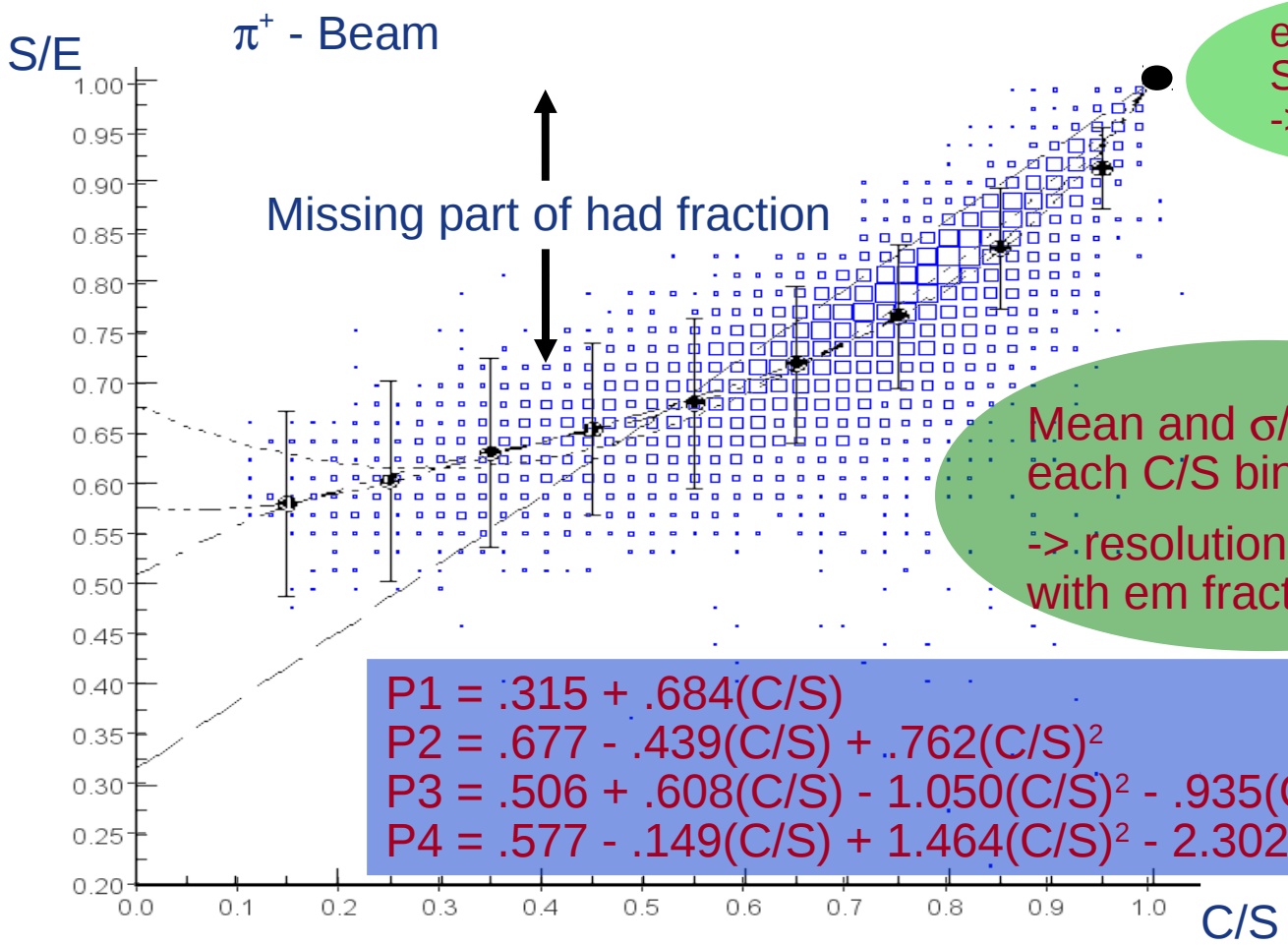




$S = 1.004 \times s_{raw}$ $C = 7692 \times c_{raw}$



Polynomial Correction Functions: E=S/Pn

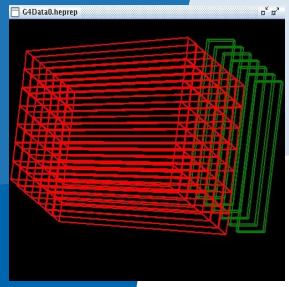


em fraction = 1
S/E, C/S = 1
-> calibration

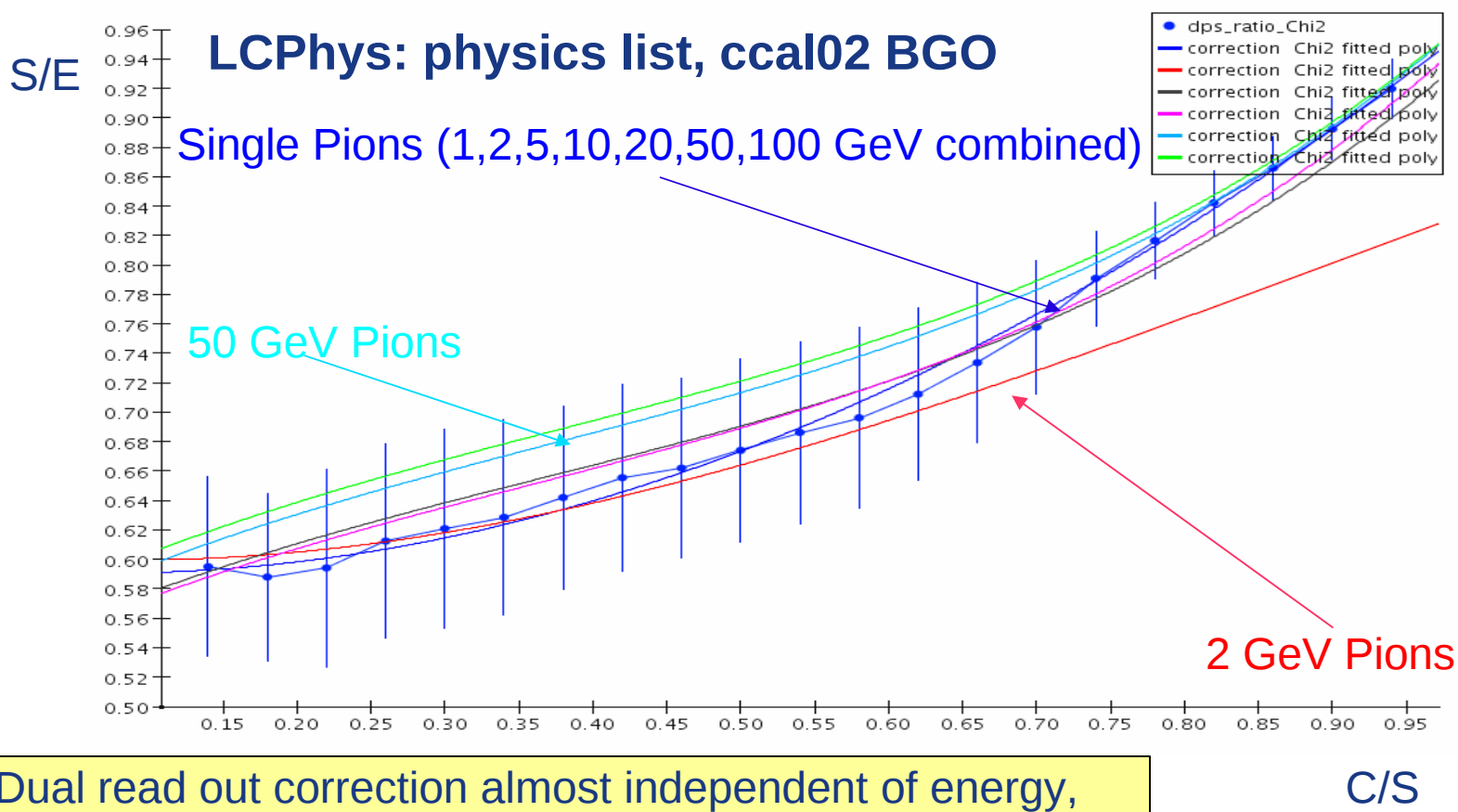
Mean and σ/mean of fit in each C/S bin plotted

-> resolution improves with em fraction

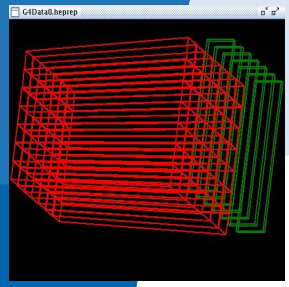
$P1 = .315 + .684(C/S)$
$P2 = .677 - .439(C/S) + .762(C/S)^2$
$P3 = .506 + .608(C/S) - 1.050(C/S)^2 - .935(C/S)^3$
$P4 = .577 - .149(C/S) + 1.464(C/S)^2 - 2.302(C/S)^3 + 1.410(C/S)^4$



Correction function as function of energy



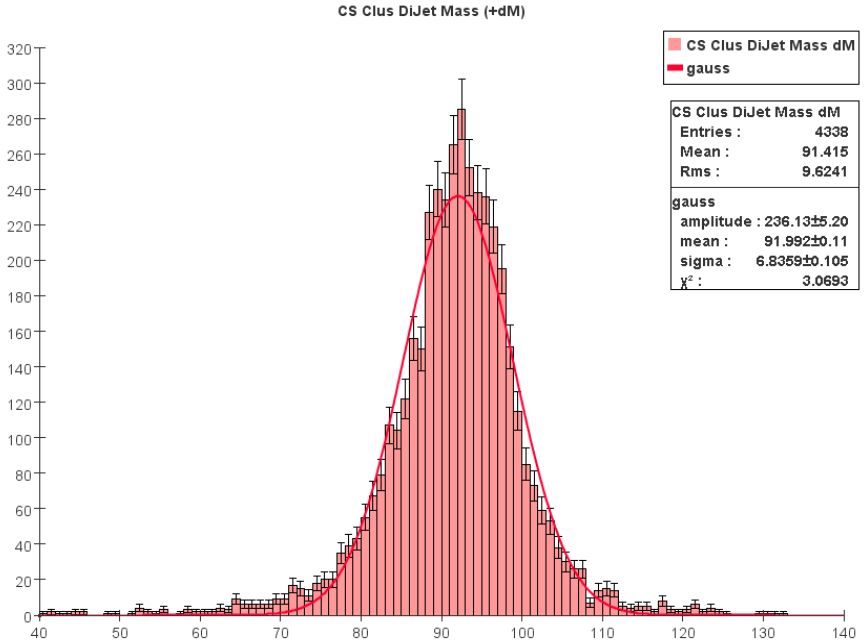
Note! Dual read out correction almost independent of energy, but it's worth exploring if we can improve energy resolution with energy dependent correction function

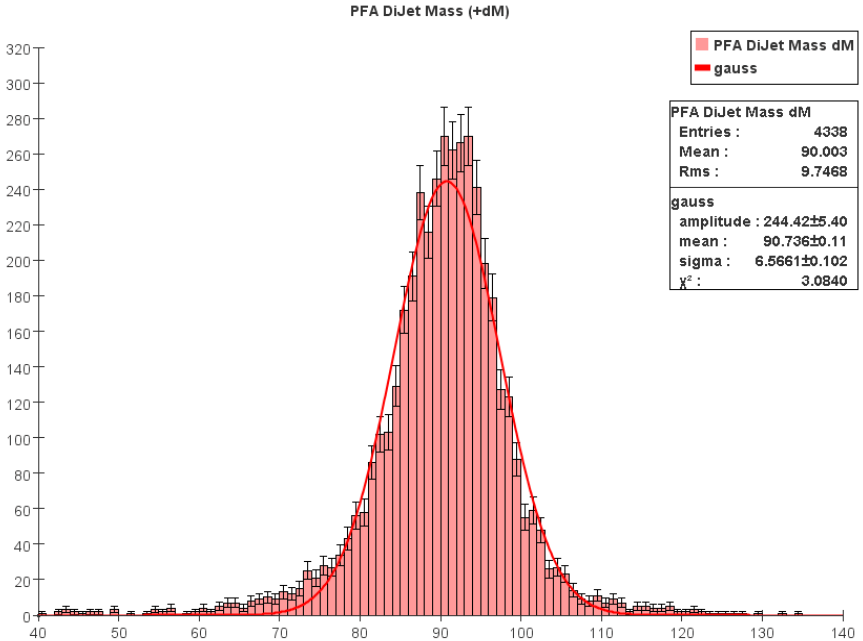


Improving massresolution by combining the calorimetric and tracking information (PFA).

Stephen Magill-ANL
Calor 2010, ALCPG 2009

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





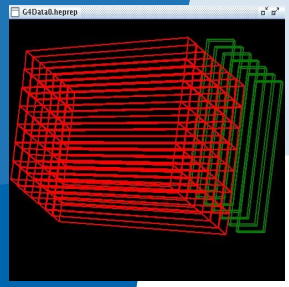
C/S-corrected Clusters

$\sigma/M = 0.075$

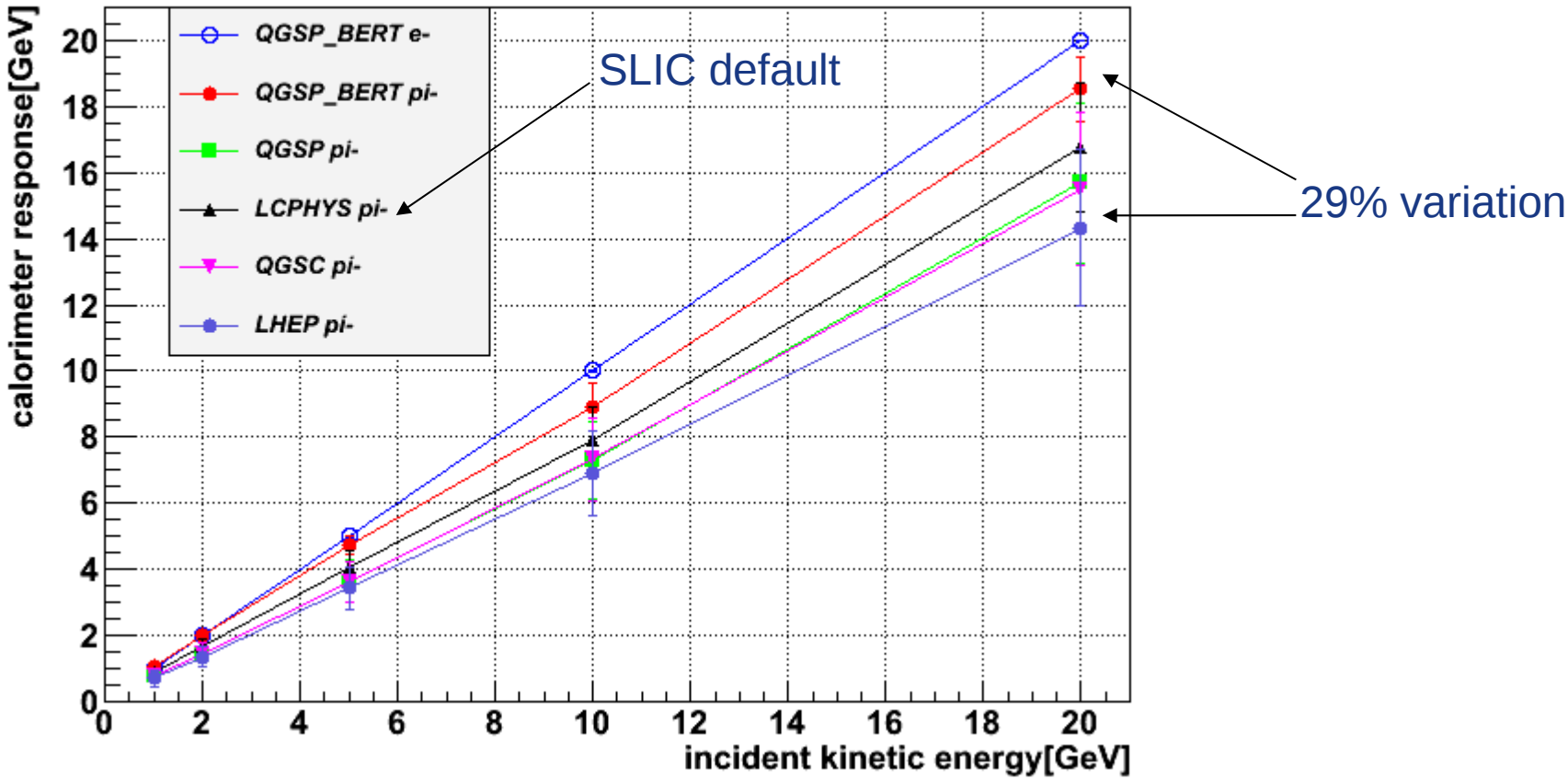
PFA-enhanced Clusters

$\sigma/M = 0.061$

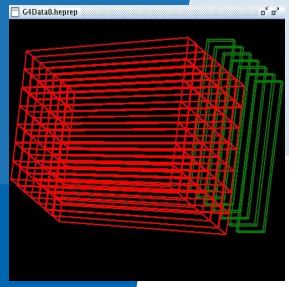
19% improvement



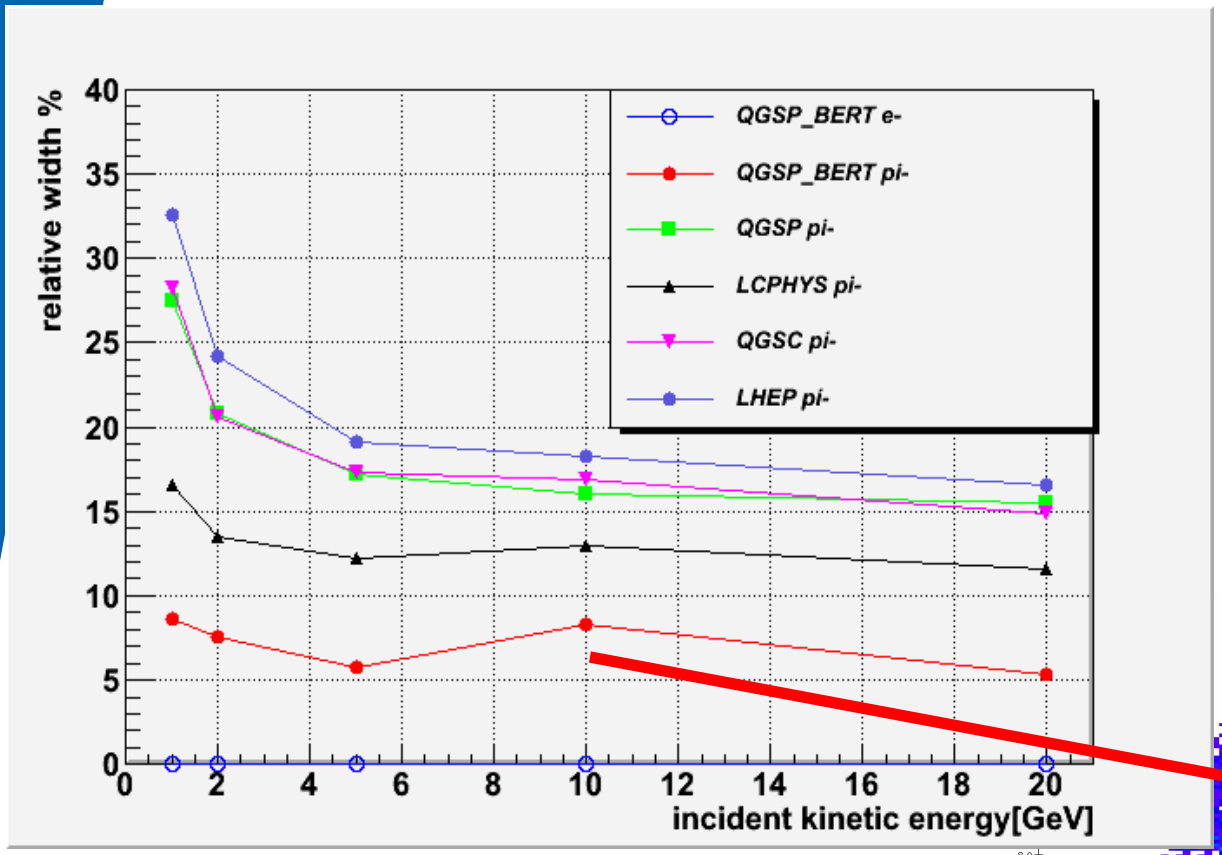
BGO Calorimeter response for different physics models

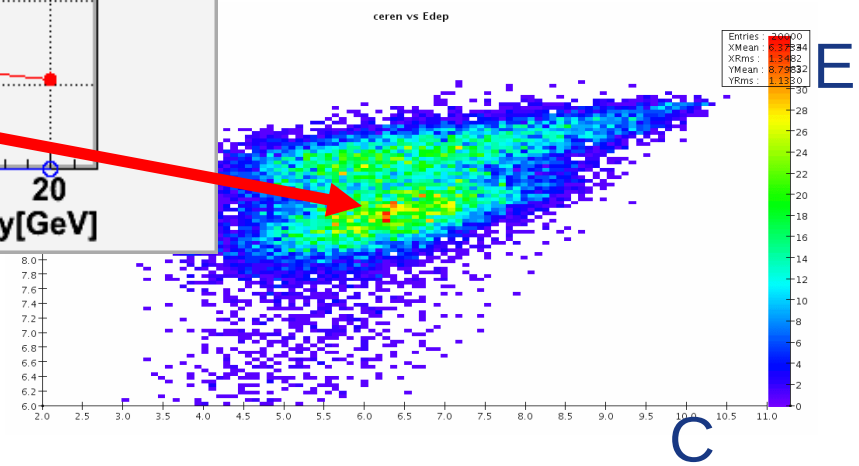


Particles produced within the calorimeter!
No threshold! → all energy deposition are added up

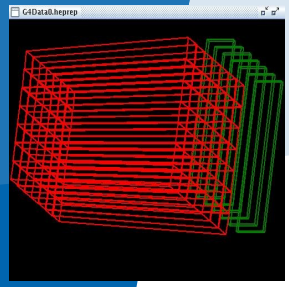


BGO relative width of energy response to charged pions for different physics lists



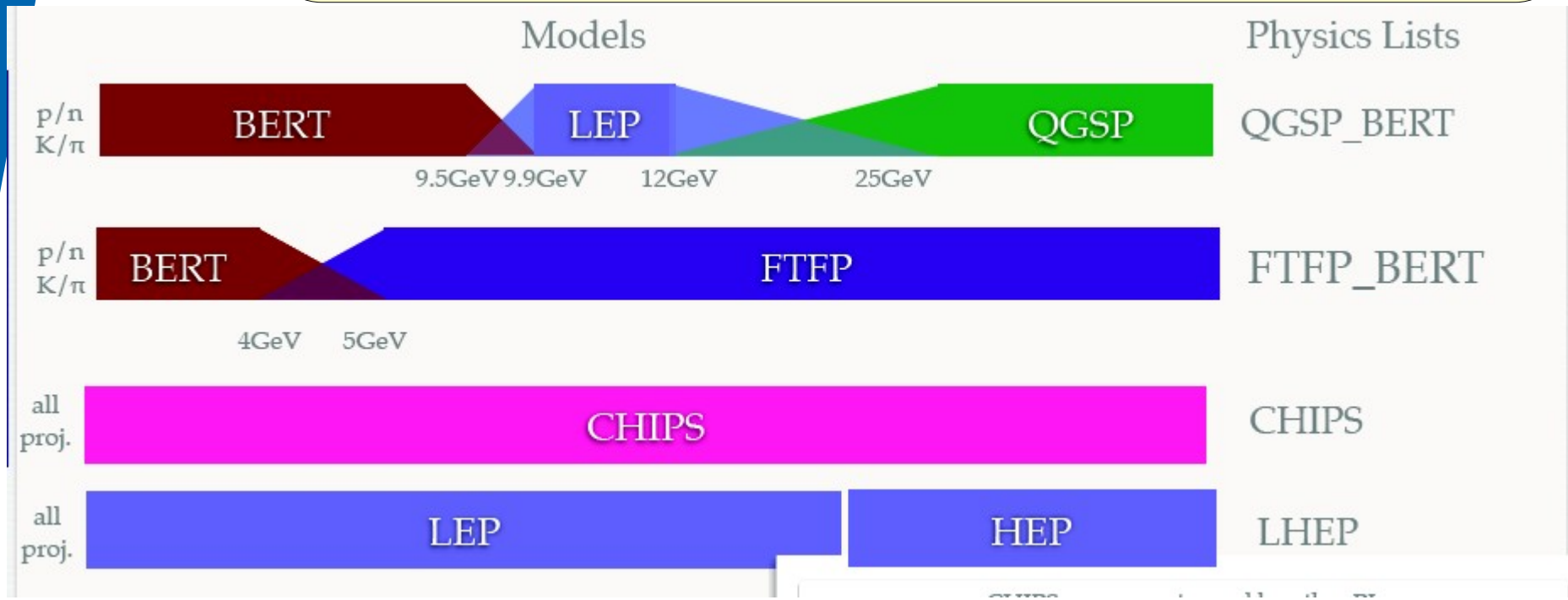


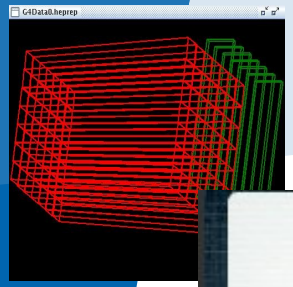
Geant 4 collaboration is aware of that!



Why are there kinks in the energy response?

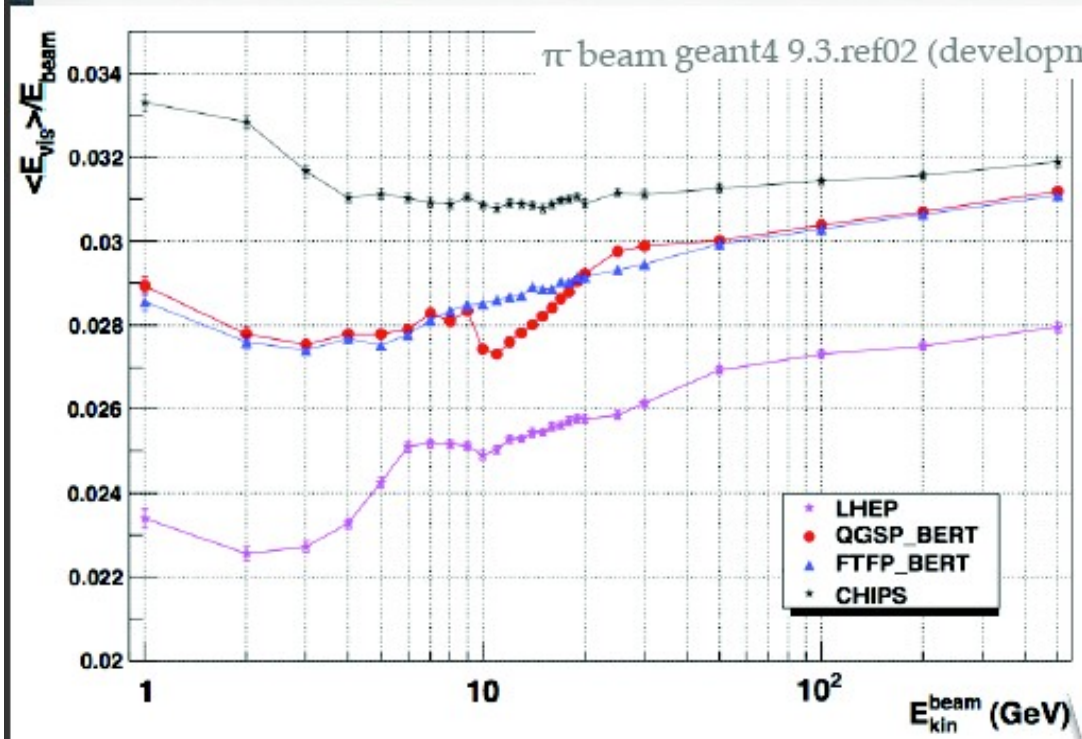
- Physics Lists use different hadronic models for different energy ranges
  - No smooth transition in energy response
  - Resolution is sum of two distinct distributions and therefore too wide
  - What about other observables?
- Improving hadronic modelling is priority of Geant 4 Collaboration.





Comparison of energy response for different physics lists

Simplified Fe/Sci Calorimeter



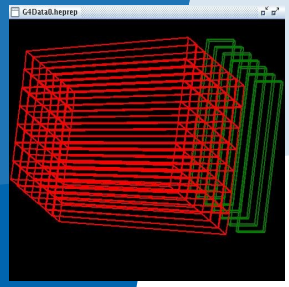
- QGSP_BERT stable since G4 8.3 (May 2007)
- FTFP_BERT smooth response (improved in G4 9.3)
- CHIPS (new in G4 9.3) higher response

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)?

Andrea Dotti : CALOR2010)



DRImageDB

Perform detailed studies of hadronic physics in Geant 4 (what reactions contribute, particle produced …).
Result stored in database, browsable with web application

File Edit

http://localhost:8080/DRImageDB/DisplayImage.jsp?param1=100&param1=Display+Image+ar

Most Visited ▾ Getting Started Latest Headlines ▾ Smart Bookmarks ▾ Personal ▾ ILC ▾ CMS ▾ Fermilab ▾ CERN ▾ Search ▾ C++ ▾

Fermilab Redmine | Condor Manuals | 3.12 Quill | {3} Active Tickets by Mi... | Image –Image

DRImageDB

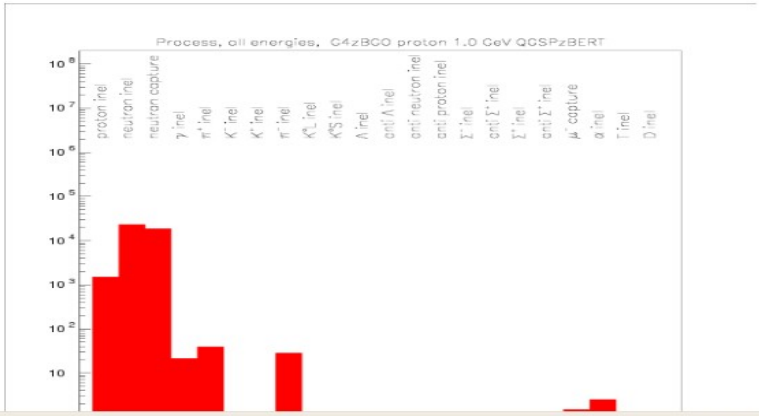
HOME | Select | Upload Images | test | Login

Display Menu

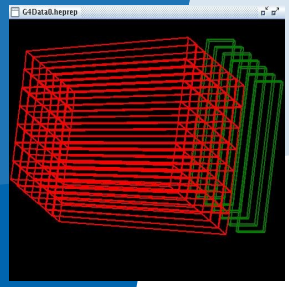
- Item 1
- Item 2

Image ID: 100

Name	Value
Particle	proton
Energy	1.0
Material	G4_BGO
Physics List	QGSP_BERT
Description	Process, all energies



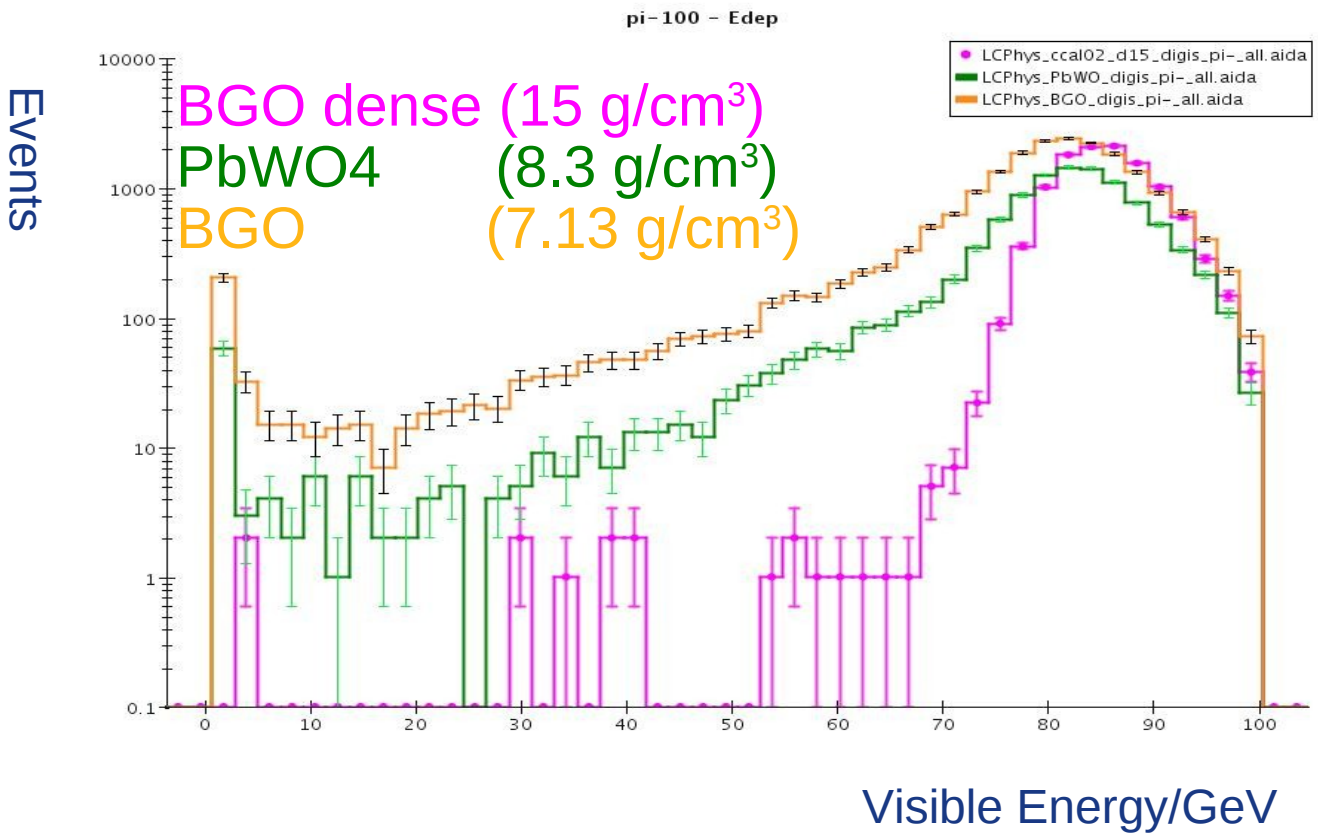
Done 71.4°F



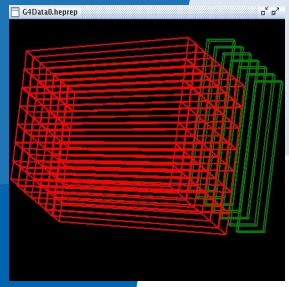
100 GeV π leakage for BGO/PbWO4/ BGO dense

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.

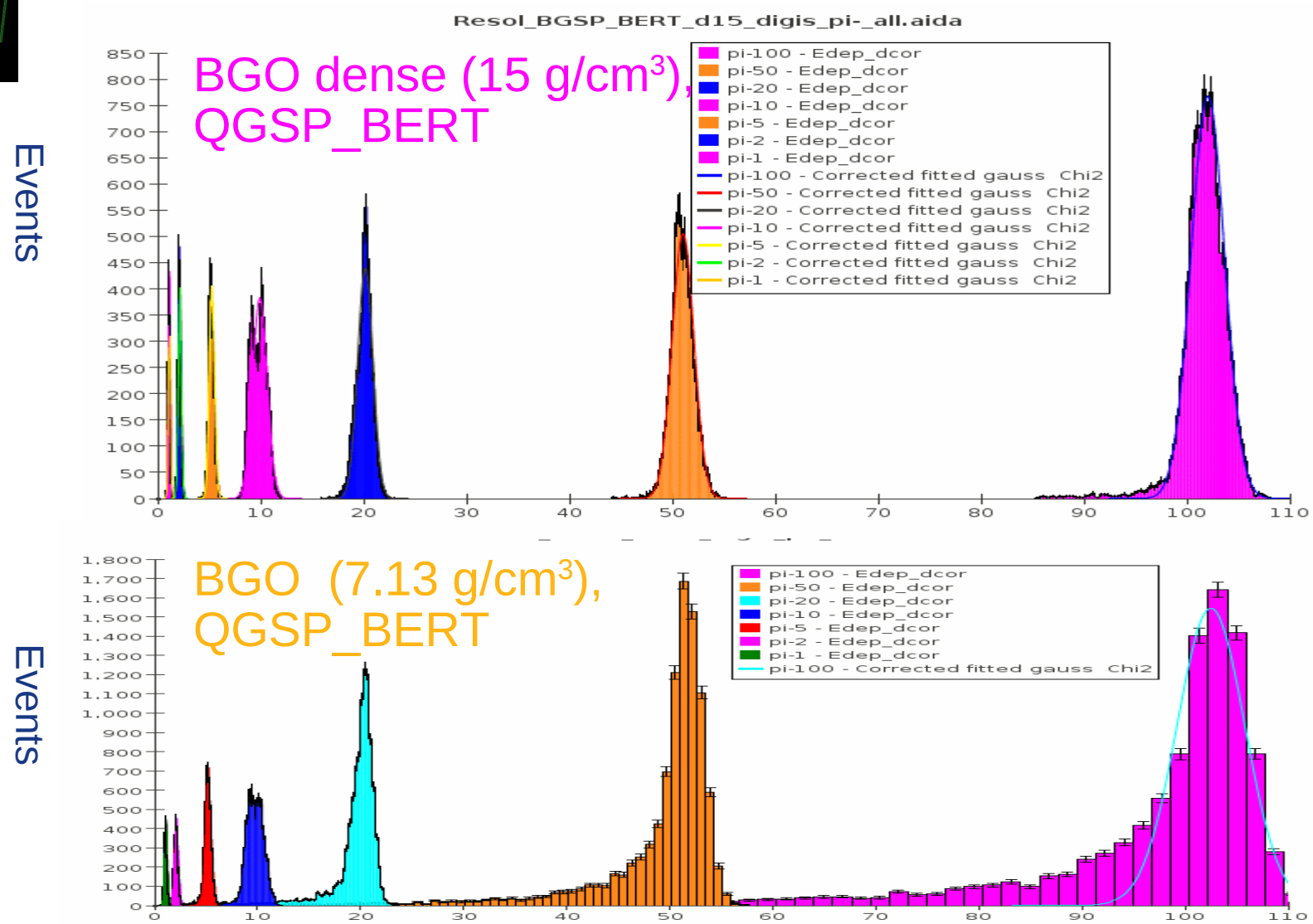
Leakage fluctuations depend on:
-the starting point of the hadron shower (Interaction Depth or ID)
-the extension of the shower



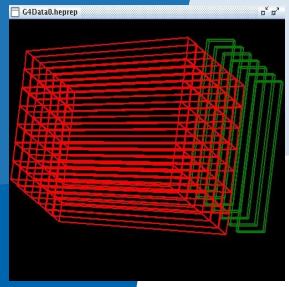
Leakage is of particular concern for compact detectors such as SID!
Giovanni Pauletta and Anna Driutti (Udine) are evaluating possible techniques to improve the energy resolution in the presence of leakage (requires longitudinal Segmentation!). See presentations at Calor 2010 and ALCPG 2009.



Corrected single π^- response



Energy in GeV after dual read out correction



Birks attenuation

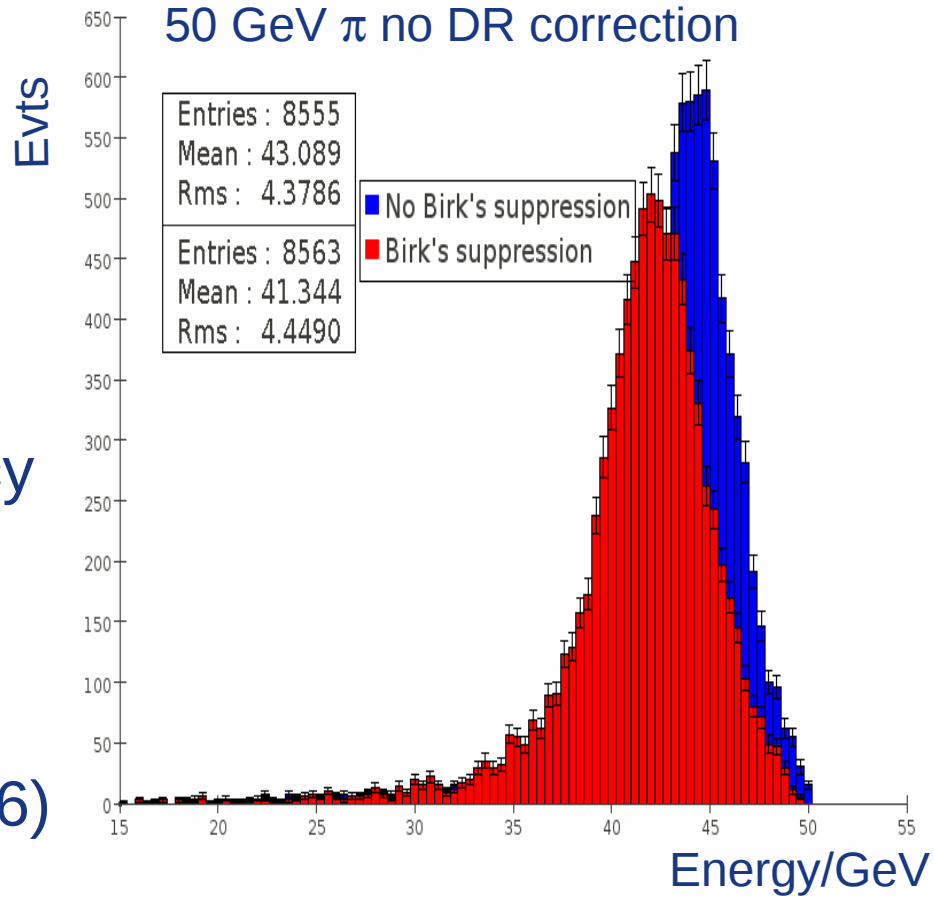
Implemented in SLIC,
Available in Geant 4 via Szintillation process

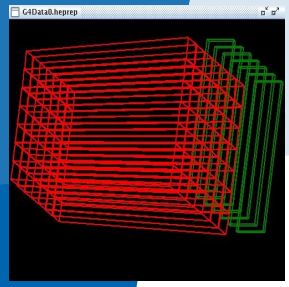
$$\frac{dL}{dx} = \frac{S \cdot \frac{dE}{dx}}{1 + kB \cdot \frac{dE}{dx}}$$

Where:
kB = Birks constant
S = Scintillation Efficiency

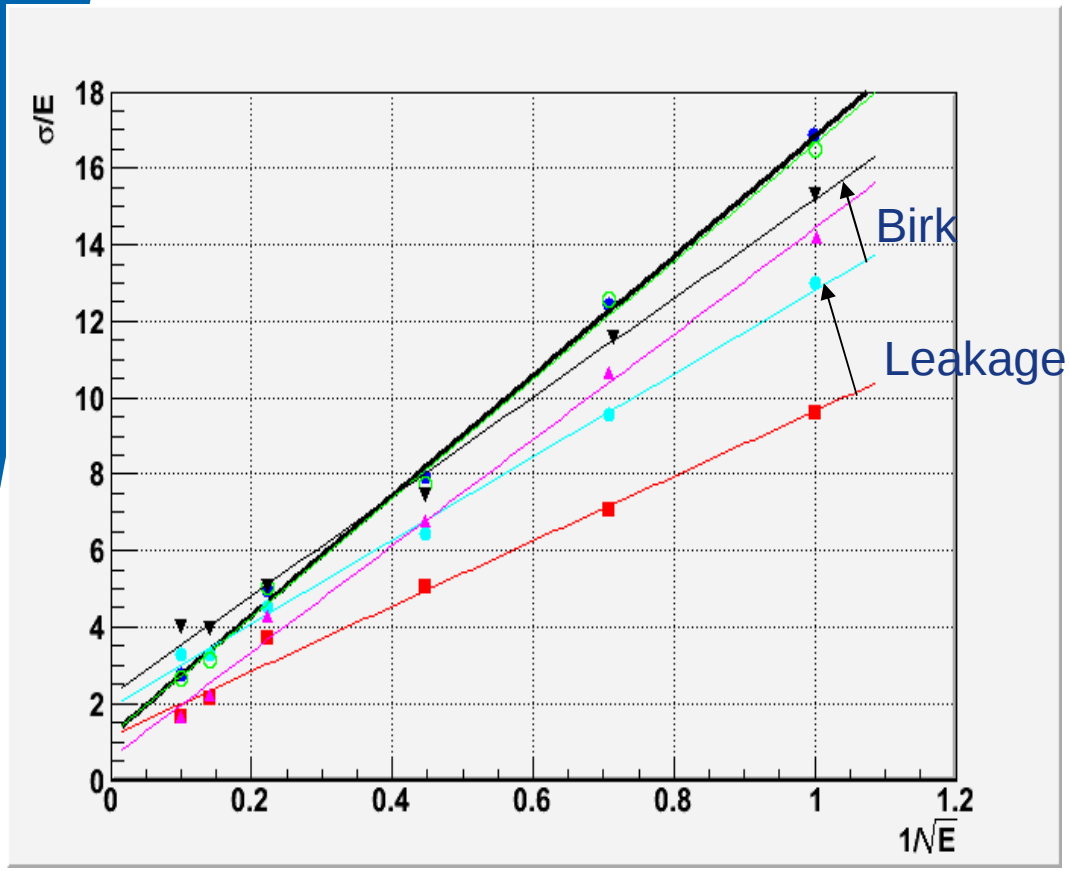
$\frac{dL}{dx}$ = Light Output

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





Single π^- resolution for different detector configurations



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

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

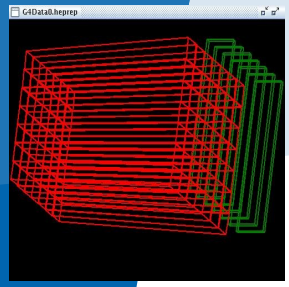
BGO, QGSP_BERT , Birk supr.:
σ(E)/E=2.23 + 13.0/sqrt(E) %

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

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

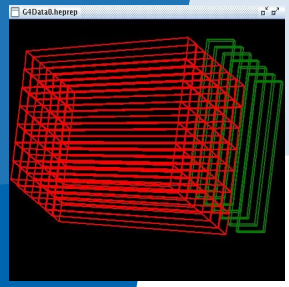
PbWO4, LCPhys:
σ(E)/E=1.2 + 15.5/sqrt(E) %

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



Conclusions

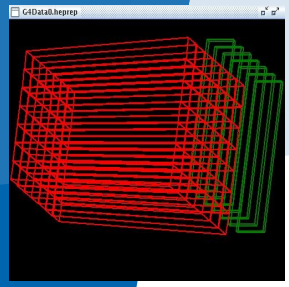
- We have developed a comprehensive set of tools: from the simulation of single crystals, light production,propagation and detection, test-beam prototypes (with variable materials, geometry, physics models) to a complete colliding beam detector
- We have studied the performance of a total absorption calorimeter for single particles (of all kinds) and for jets as a function of energies, materials and their optical properties. Results indicate that an energy resolution in the range 10-15%/sqrt(E) should be achievable.
- We have started the detailed examination of the physics content of the hadron shower simulation codes and we communicate our finding to the code developers (talks at the GEANT Users meeting, CALOR2010, ALCPG09, Muon Collider workshop)
- We have performed complete physics analysis to demonstrate the performance as part of a collider detector.



Simulation Software Collaborations

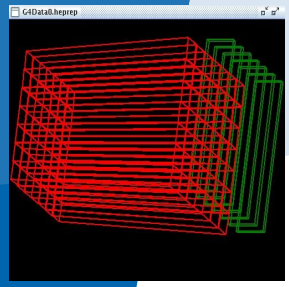
Collaborations that should be maintained or actively pursued are:

- Collaborate with SLAC/SID e. g. enhancing SLIC and framework
- Collaborate with Geant 4 collaboration
  - Validating hadronic physics lists (we are part of the geant 4 hadronic physics group and also collaborate with Desy Zeuthen on hadronic validation framework).
  - Might have to enhance the capabilities of optical processes in Geant 4. (e.g. simple exponential curve might not be sufficient to describe the time of scintillation photons).
- Collaborate with future lepton collider (muon collider, CLIC, ILC) detector collaborations to demonstrate physics performance and to establish DR-calorimeter as a viable option.
- Collaborate with other calorimeter R&D collaborations e.g. proper simulation of hadronic physics in Geant 4 is also an important topic for PFA -type calorimeters (Calice).



Software + Simulation Tasks

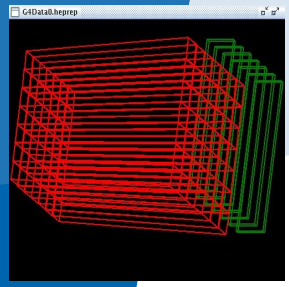
- **Minimum: retain current capabilities:**
  - Keep software available and up to date (man power, diskspace)
  - Keep capability to store data samples on disk (few TB of disk space)
  - Keep capability to produce large data samples on the GRID (300 slot + opportunistic resources, CPU)
  - Keep supporting (summer) students (manpower)
  - Keep CVS software repository (move to subversion at some point)
  - Provide and document examples



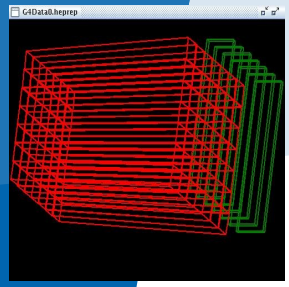
Software + Simulation Tasks (cont.)

- **Enhancements:**
  - Write up → NIM?
  - Continue improving CrystalSim, e.g. use gdml to easily descibe and change detector geometries. (man power)
  - examine various options and optimize the shape and the size of a full scale test beam prototype
  - Continue improving SLIC, e. g. extend lcdd to describe optical properties and birk suppression factor used by Geant 4, evaluate the new version of lcio. (man power)
  - Continue the evaluation and comparisons of physics models, in particular we want to compare the various GEANT simulations with e.g. the MCNPX code (man power, license costs)
  - Continue the studies of the possible techniques to improve the energy resolution in the presence of leakage (man power).
  - continue the studies of jet reconstruction, in particular as a function of the detector granularity
  - Develop strategies to intercalibrate the calorimeter cells.
  - continue the studies of the possible improvements in the jet reconstruction and/or energy resolution by combining the calorimetric and tracking information (PFA)
  - Create, host and maintain database containing the characteristics of different Crystal materials like density, composition, optical properties, surface properties etc... Provide tools to easily access this measurements and best translate them into the format used by Geant 4 (currently BGO, $PbWO_4$). (manpower, diskspace, server)
  - Dito for photodetector characteristics.
  - Make data sets easily available to collaborators outside of Fermilab (HTTP, FTP ?) (manpower, diskspace, server)
  - Host DRImage database and webapplication. Continue improving the application (manpower, diskspace, server)

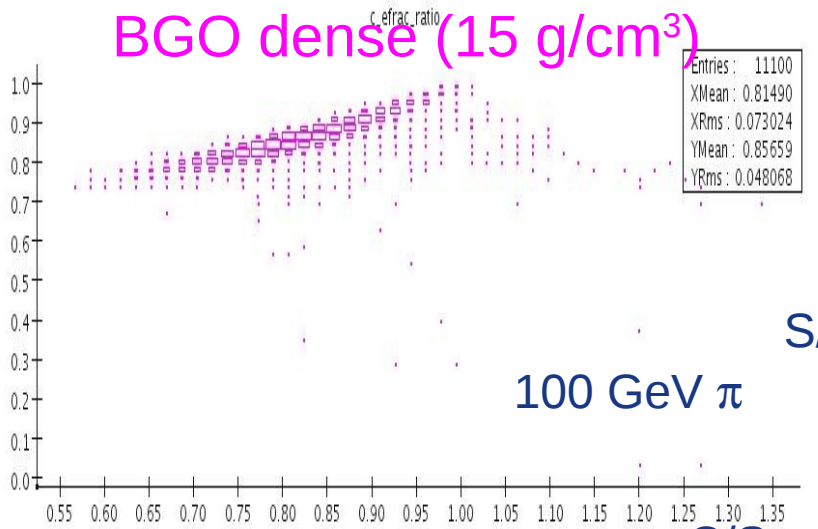
→ Adding up the tasks obvious that we can't do it with fractions of FTE's

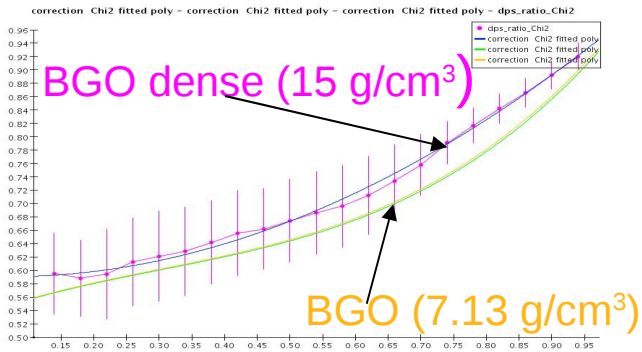


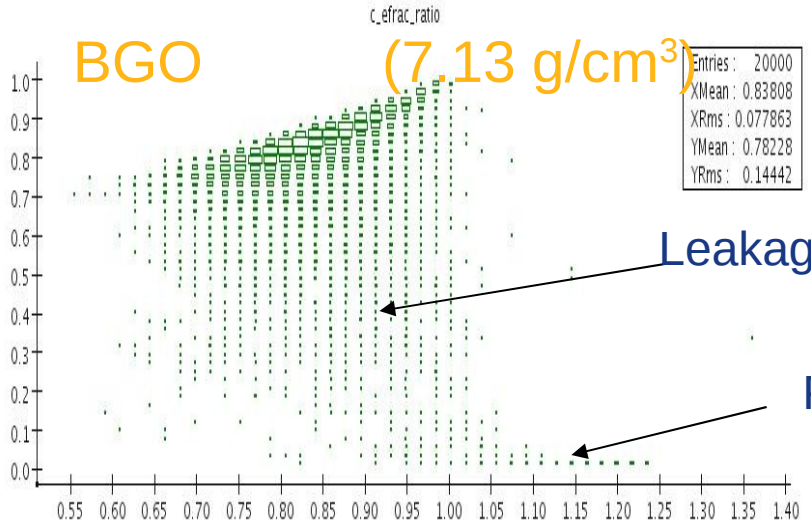
Backup slides

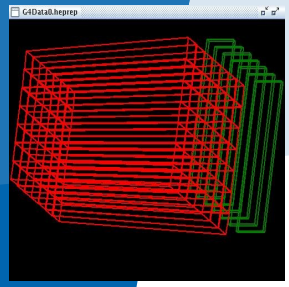


Leakage has to be considered when obtaining dual correction!





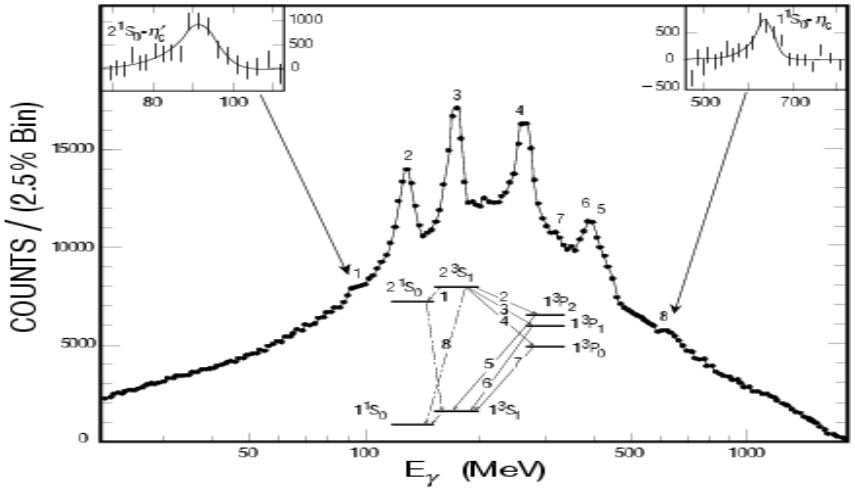




Motivation

- 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.

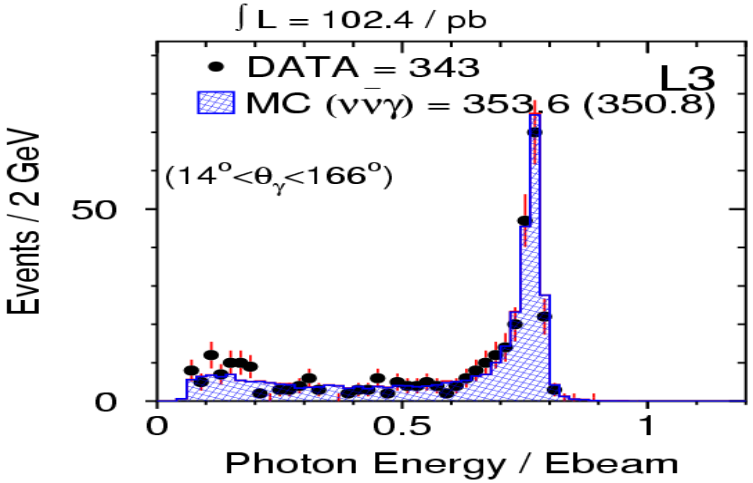
Charmonium System Observed Through Inclusive Photons: CB

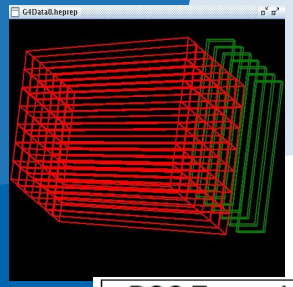


SUSY Breaking with Gravitino

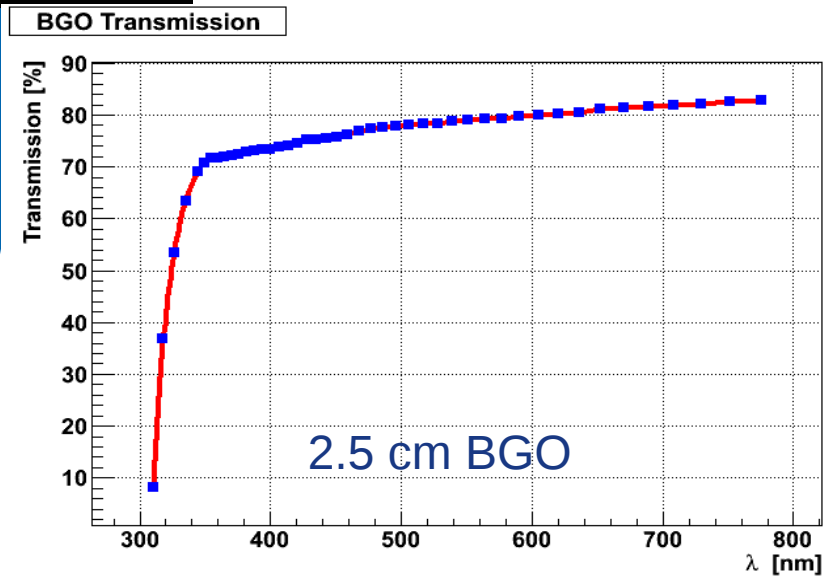
$\tilde{G}\tilde{G}$

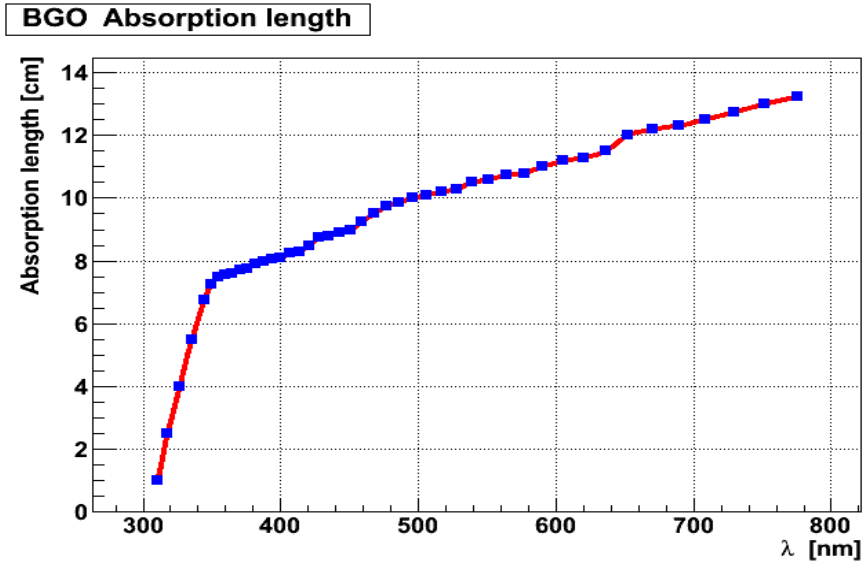
$e^+ e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma\gamma$

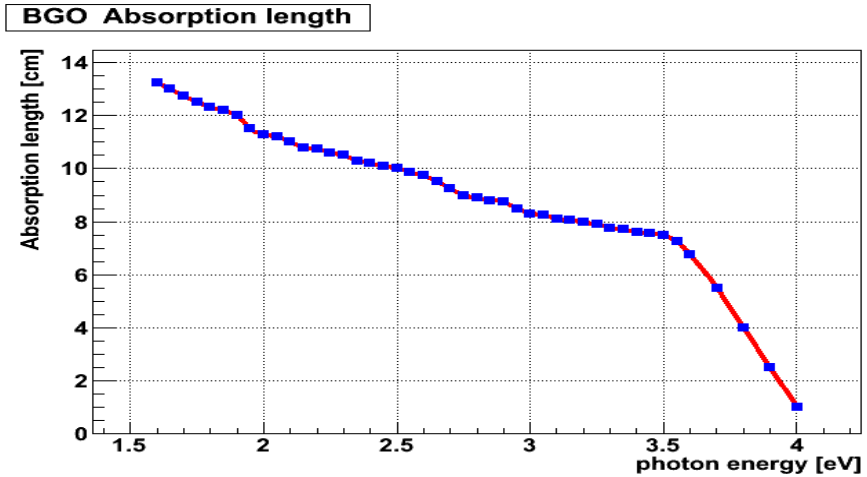


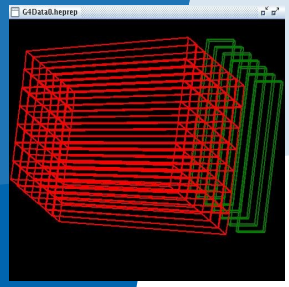


BGO optical properties (II)

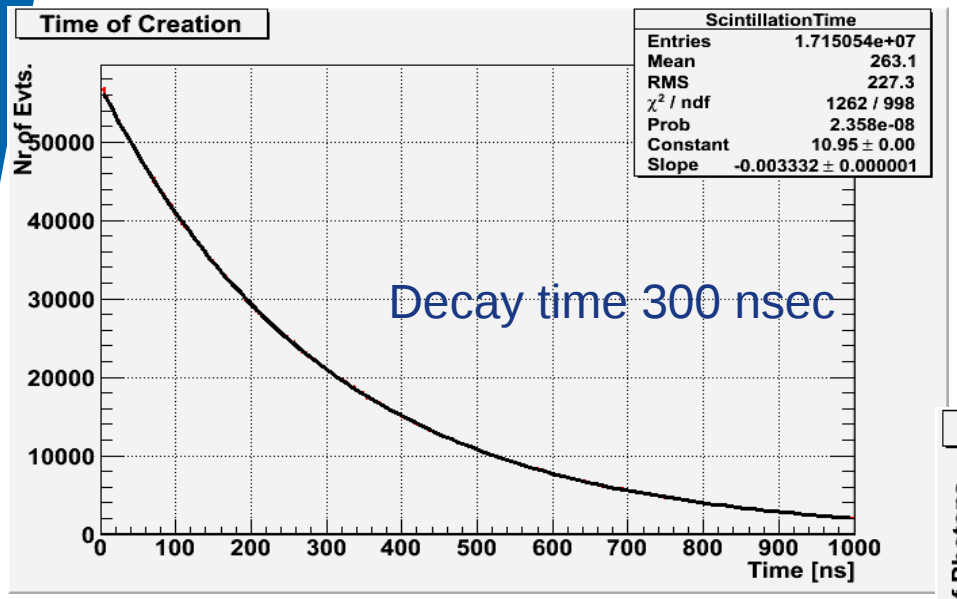




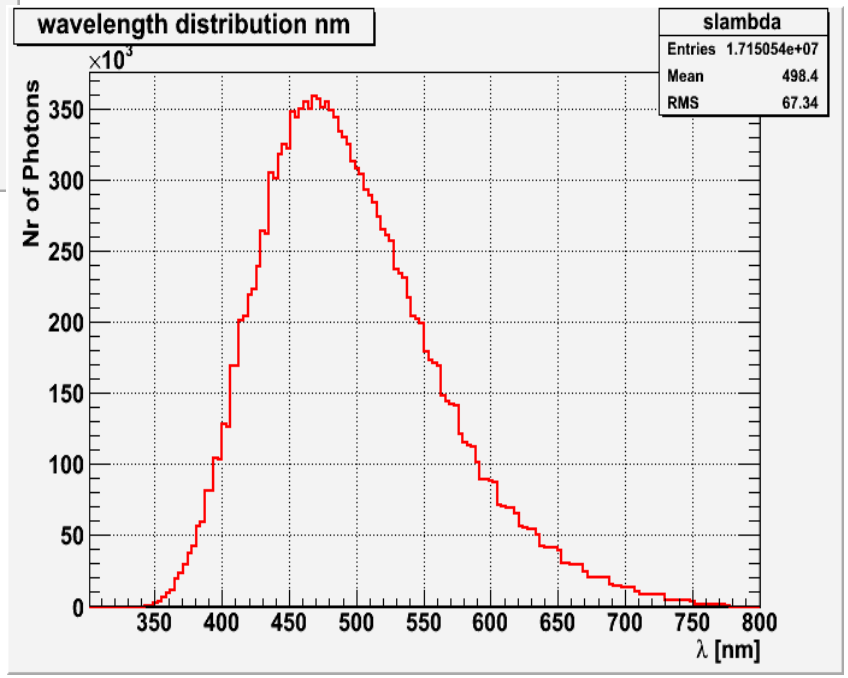


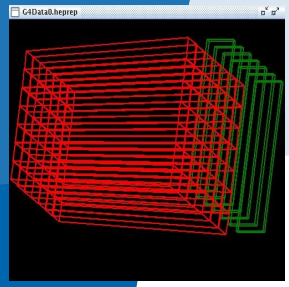


Geant 4: produced Scintillation light



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

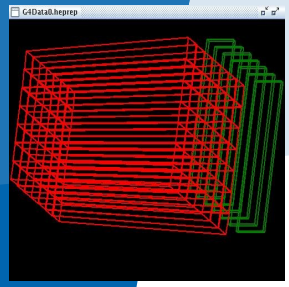




LUT (Reflectivity)

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

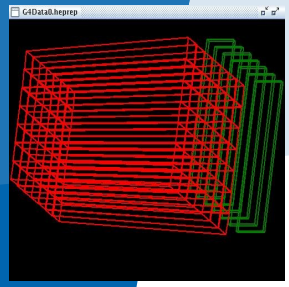


How to use the LUT

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);
```

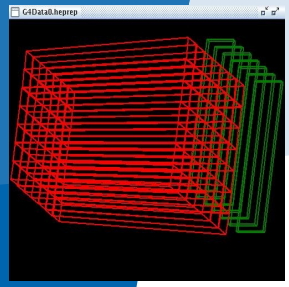


Deconvolute Dual read out from leakage

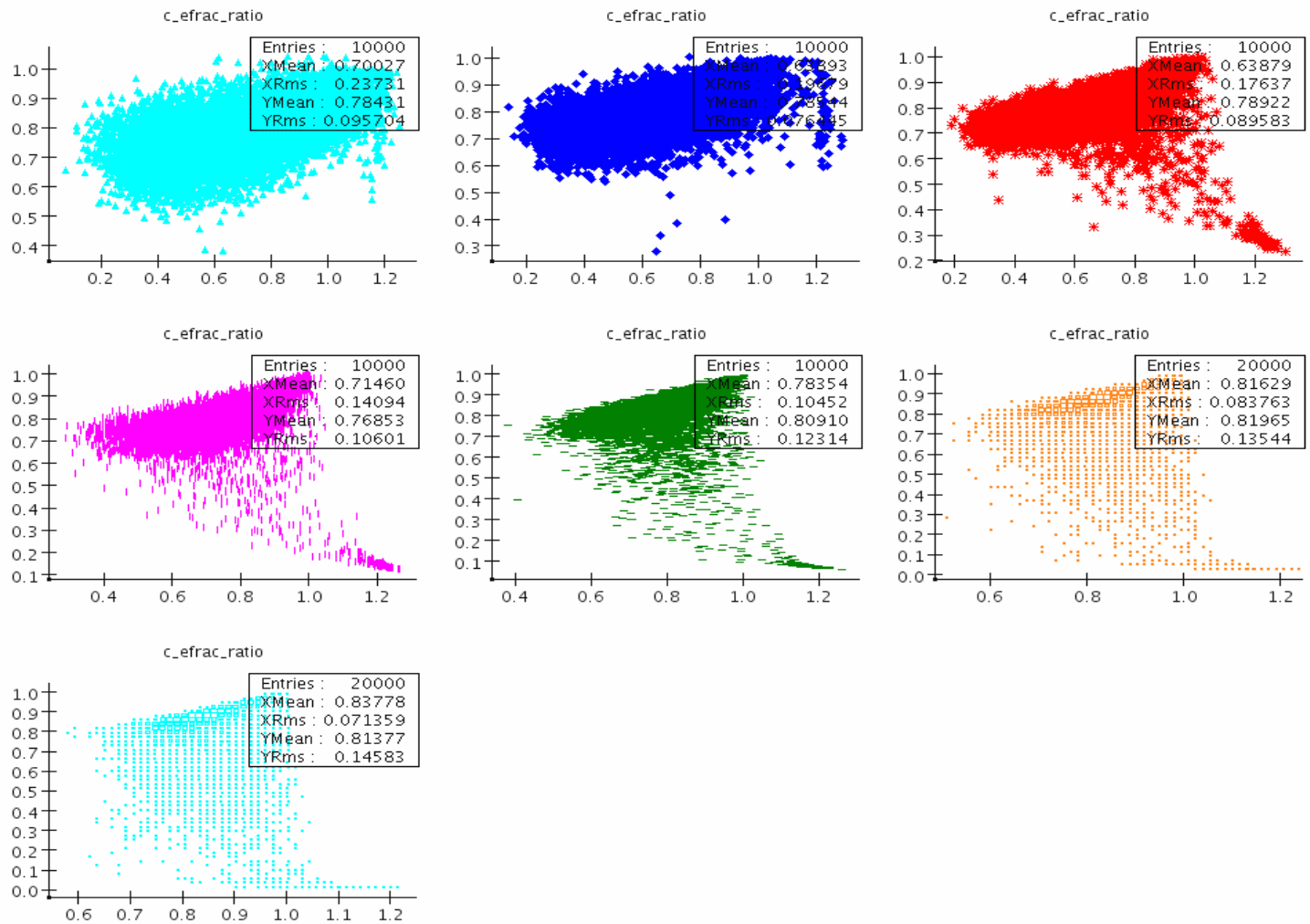
Leakage must be considered when obtaining the dual read out correction by e.g. requiring the π shower to be fully contained.
If this is not done correctly leads to overcorrection!

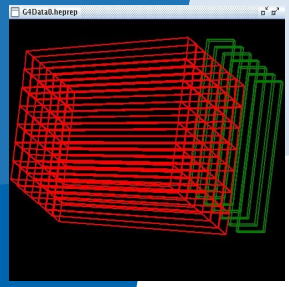
Segmentation can be used to correct for leakage:

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



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

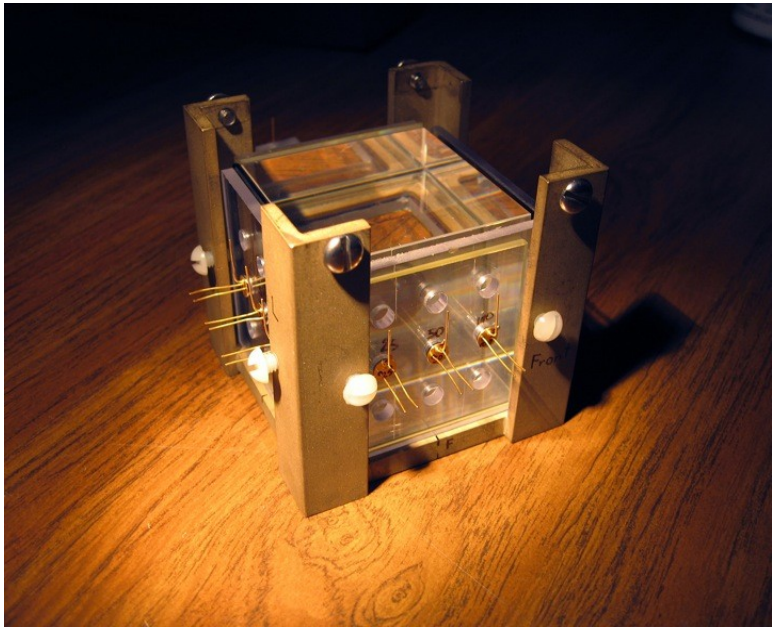


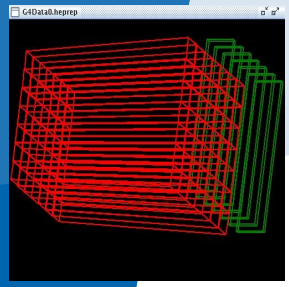


Crystals in a Test Beam

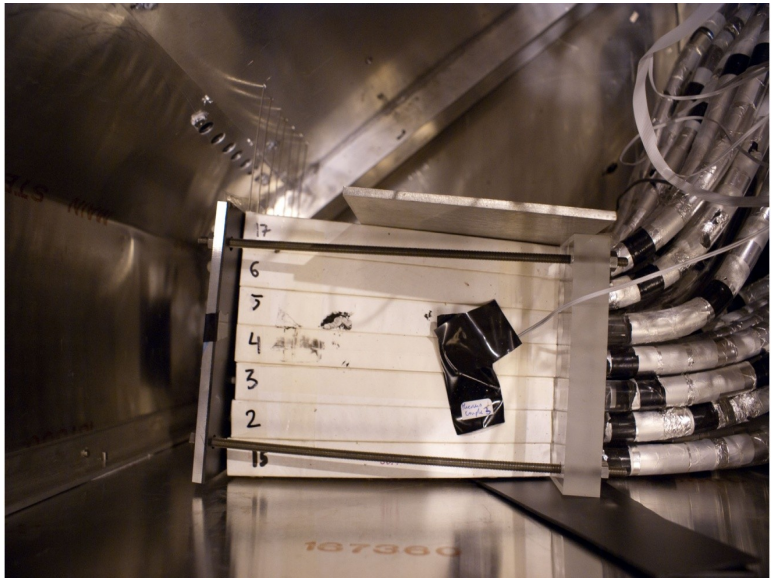
Single crystal studies:

- 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.

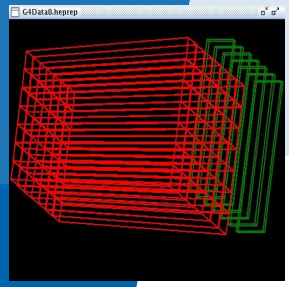




Crystals in a Test Beam



- 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)

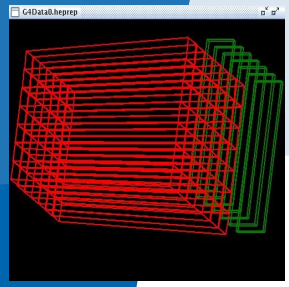
SLIC/Simulation

Analysis/Event Display

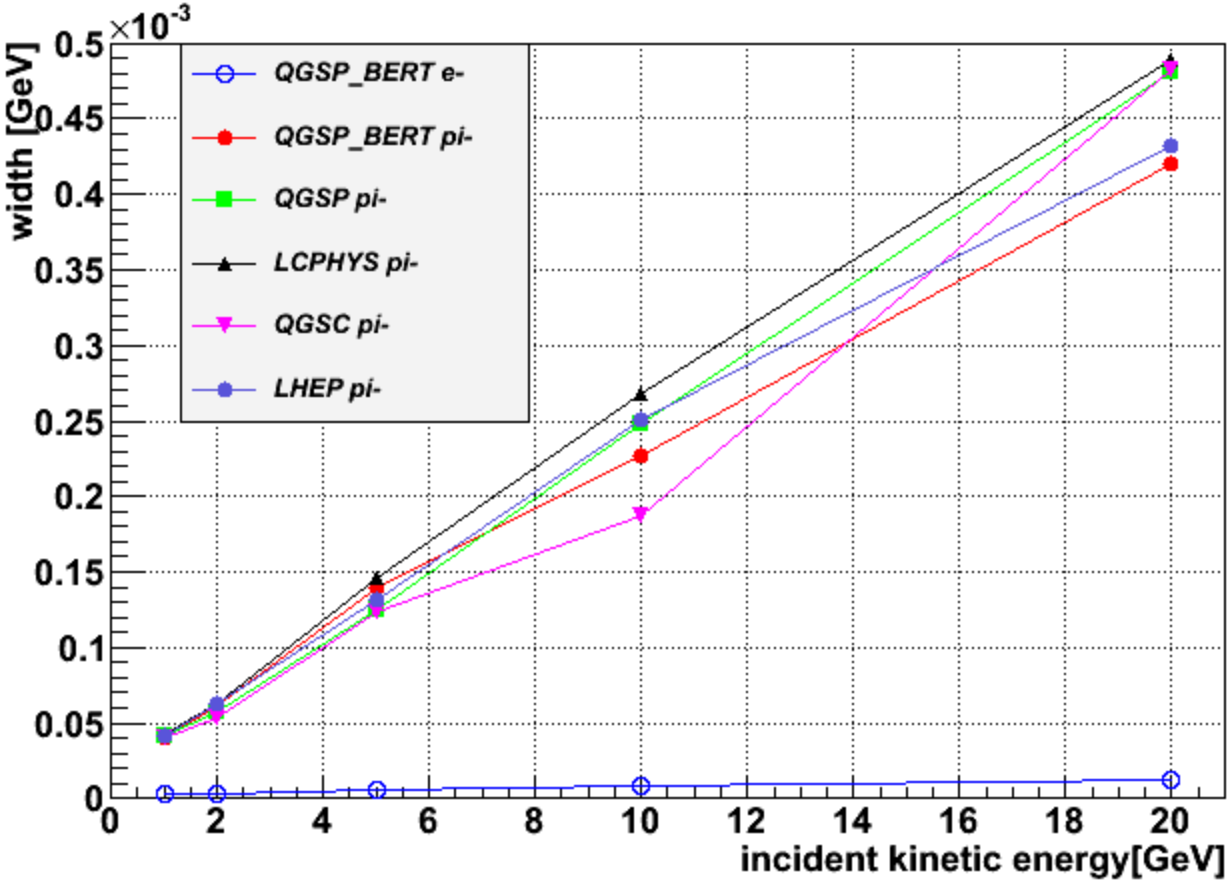
Edit by compact by hand

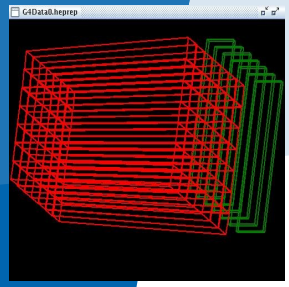
Compact with Edep_ and Ceren_ calorimeter hit collections

Hans Wenzel

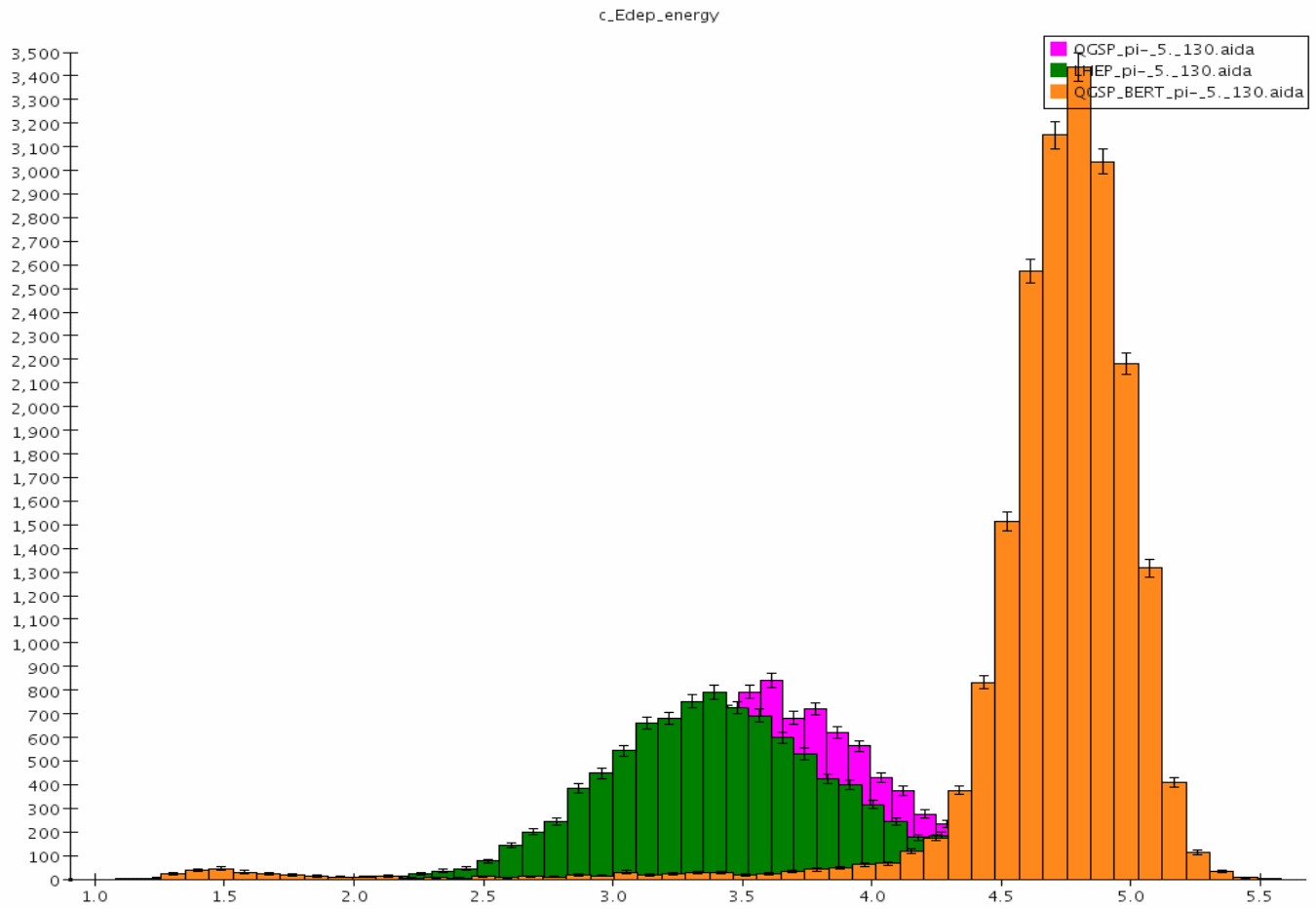


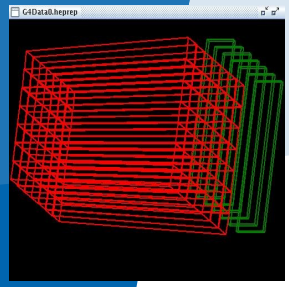
Width of cerenkov distribution





Calorimeter response for different physics models





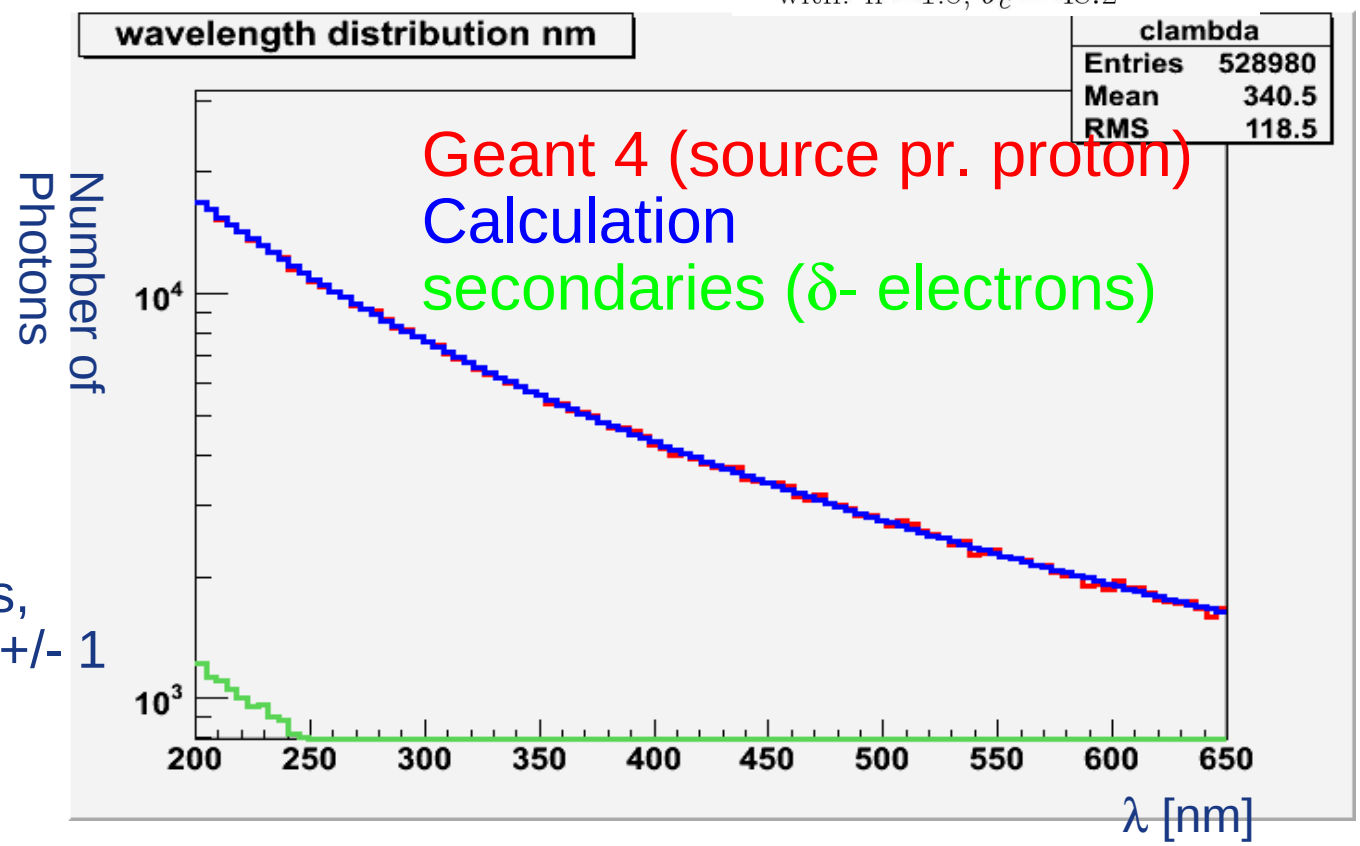
Spectrum of Cerenkov photons

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

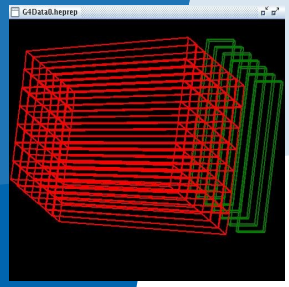
where

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

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

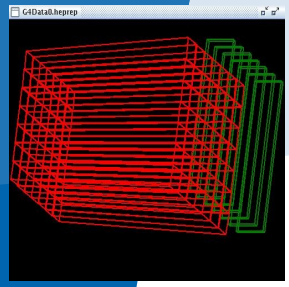


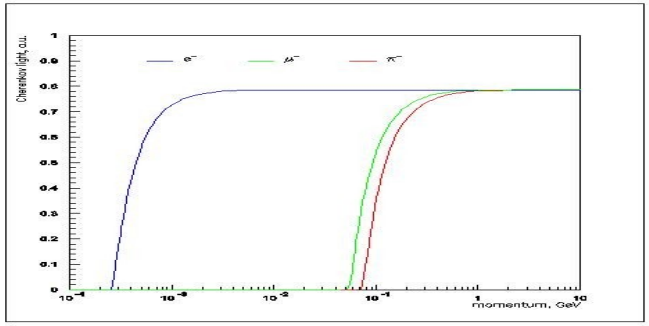
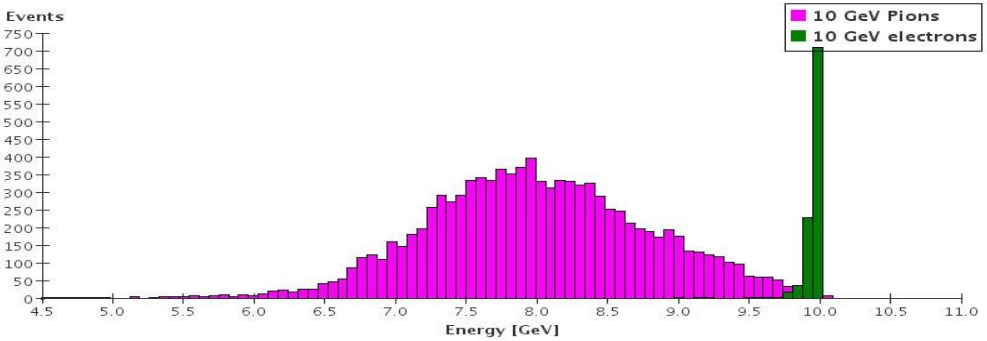
expect ~ 526 photons,
Geant 4 predicts 528+/- 1



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.