Report of the Forward Calorimetry Task Force

B. Cox/R. Ruchti

1. Reminder of Charge
2. Task Force Organization
3. Report on Task Force Progress

New technologies (radiation hard)

- Crystals/Ceramics
- Photosensors
- Fiber Optics
- Dual Readout
- Precision Calorimetry Timing

Simulations

- Validation with test beam data
- Present Detector Configuration
- New Detector Configuration

Pileup up to 110 included when appropriate

Forward Calorimetry Task Force Charge I

- Work with sub-detector teams in HCAL and ECAL to:

- Ensure studies required for CMS to take decisions on its ultimate detector design are pursued including:

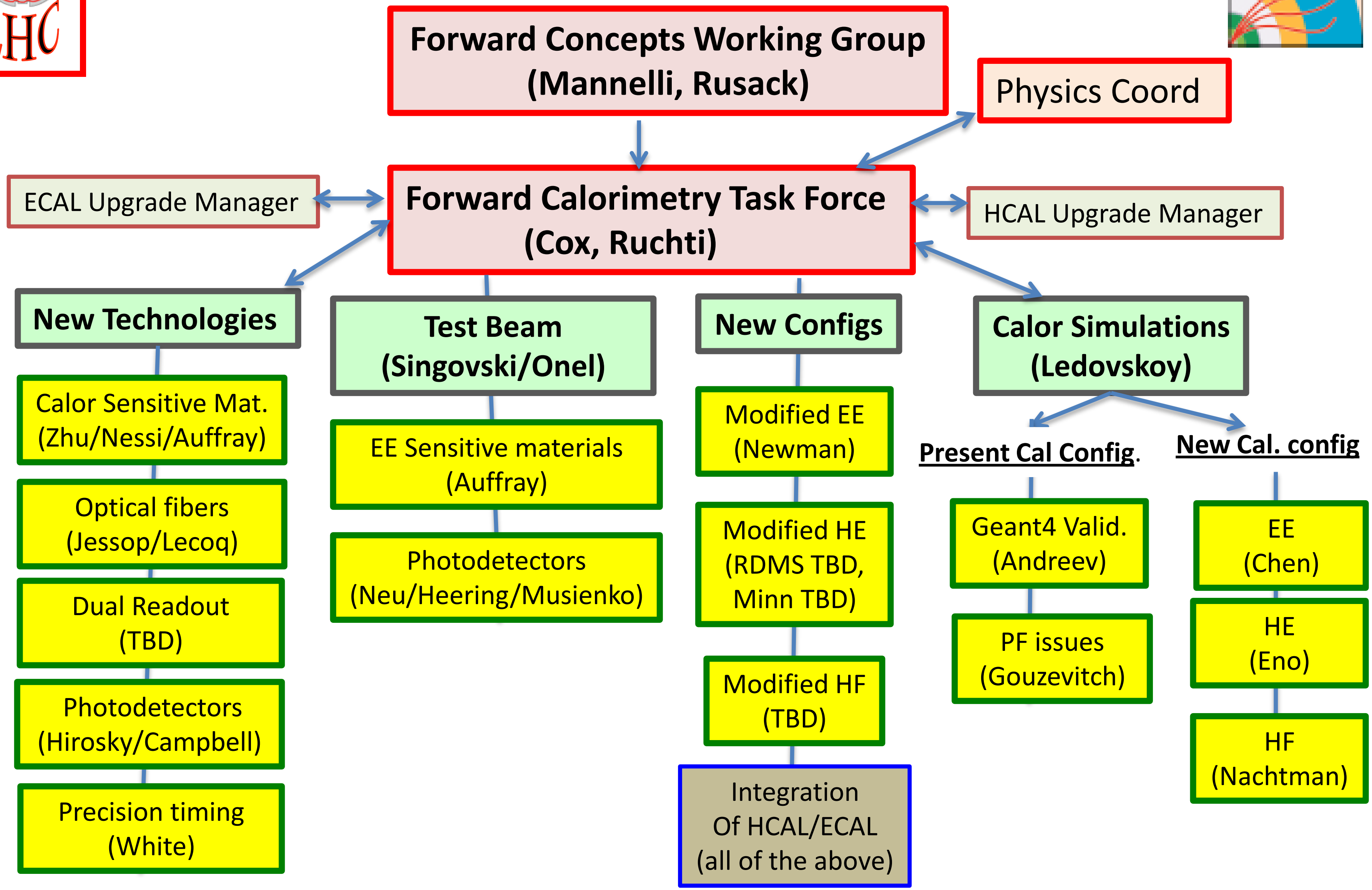
  Physics implications
  Simulation studies
  Candidate technology studies

- Use the results of these studies to analyze the impact of candidate designs on CMS level requirements and to understand the tensioning between alternative implementations

Forward Calorimetry Task Force Charge II

- Establish the requirements for calorimetry in the forward direction (eta > 1.5) for Phase II operation of CMS
  - a) Considering the likely physics opportunities for phase II and their requirements for forward calorimetry performance.
  - b) Estimating the radiation environment likely to be encountered during phase II, and its effect on the current calorimeter systems
- Consider potential replacement technologies for calorimetry in the forward direction
  - a) Determine what detector components would require replacement in order to meet the performance requirements
  - b) Explore potential replacement technologies
    1. Estimate cost/performance
    2. Consider required R/D
    3. Establish timeline for studies/decisions
  - c) Determine what detector components could be used during phase II Establish what modifications might be required for re-use, and what R/D is necessary

PHASE II/LS3 Forward Calorimetry Task Force



Forward Calorimetry Task Force
Institutional Participation

New Technologies

Calorimetry Sensitive Material – Caltech, CERN, ETH, Rome
Optical Fibers – Notre Dame, Iowa, CERN, Maryland
Rad Hard Photodetectors – Virginia, Minnesota, Notre Dame, Fermilab
Timing Techniques – Rockefeller
Dual Readout – Minnesota, Iowa, Carnegie-Mellon, Texas Tech

New EE/HE/HF Configurations

Caltech, Princeton, Iowa, Minnesota, Minsk,
CERN, Fermilab, Kolkata-Saha, RDMS

Simulations

Virginia, Florida State, IPNL Lyons, Minnesota, FIAN Moscow,
Notre Dame Maryland, Iowa, Minsk

https://twiki.cern.ch/twiki/bin/viewauth/CMS/ForwardCalorimetryTaskForce
https://twiki.cern.ch/twiki/bin/viewauth/CMS/FCALSimSLHC

Status of New Technologies Efforts

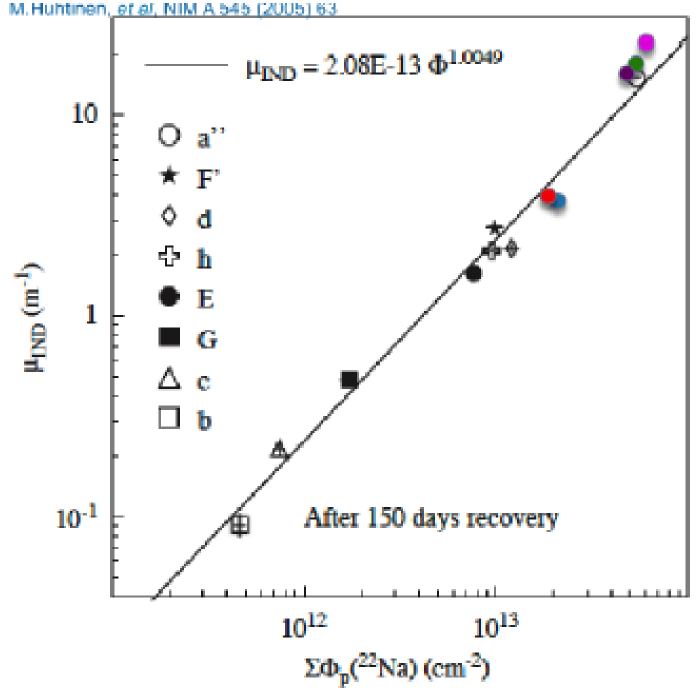
R&D for ECAL@HL-LHC Calorimetry
ETH Zürich

- I - Parametrization of Hadron Damage Effects in Crystals

→ The hadron effects measured in $PbWO_4$, combined with ECAL test beam and lab results, have been used to provide a fully data-driven estimate of the evolution of energy resolution due to changes in S/N and uniformity of light output

→ The measurement above agrees with energy resolution for hadron-irradiated crystals measured in CERN beam tests as determined by simulations

M. Huhtinen, et al, NIM A 545 (2005) 63



See F. N.-T., *“Crystal damage from hadrons: effects & expectations"*, ECAL workshop on Long-term performance, beam-tests & upgrades https://indico.cern.ch/conferenceDisplay.py?confId=1695562

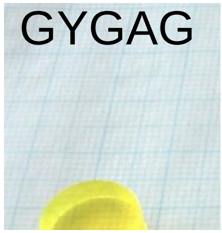
ETH Institute for Particle Physics

- II – γ irradiation tests of Ceramics and Crystals

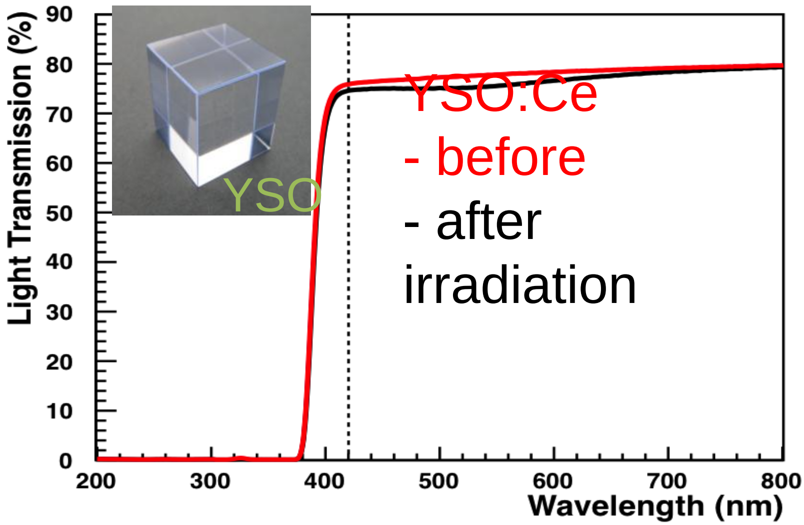
→ ^{60}Co dose rate was 0.58 kGy/h, the integrated dose 38 kGy

→ irradiation conditions are representative for the dose and dose rate present in proton irradiations, as well as for the dose rate in CMS for the worst HL-LHC running conditions

→ Samples studied were not optimized for calorimetry at HL-LHC:
ceramic LuAG:Ce, YAG:Ce, LuAG:Pr, LuYAG:Ce from SIC
ceramic GYGAG from LLNL
crystalline YSO:Ce from SIC



Modest transmission loss in crystalline YSO, that will be studied further and in GYGAG *(to be excluded due to the presence of* ^{157}*Gd, with thermal neutron capture cross-section of 259000 barn)*



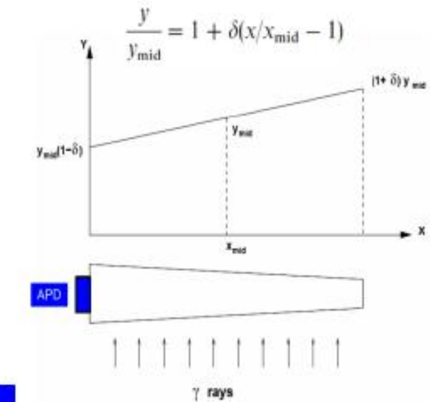
Caltech I

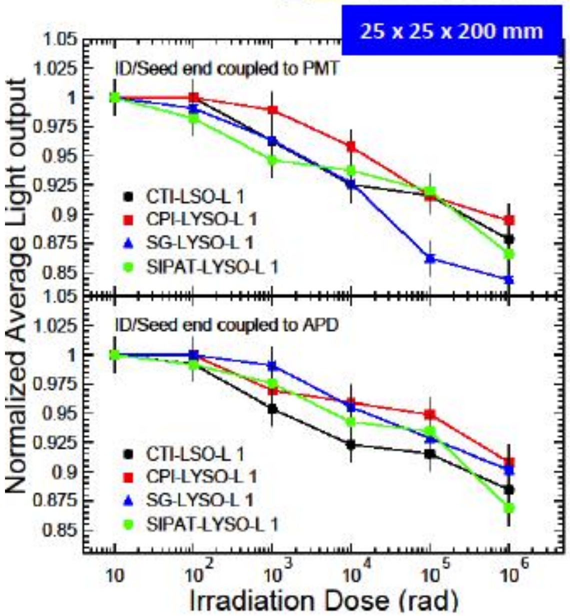
Progress on Characterizing Properties and Rad hardness of Crysatl Calorimetry Materials

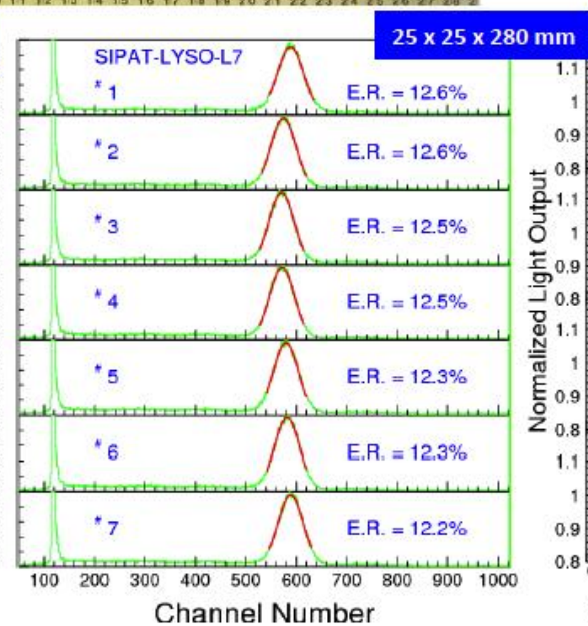
- **Measured LYSO plates of different thicknesses for consistency of optical and scintillation properties; good light response at few % level**
- **Excellent radiation hardness against gamma radiation at 10 Mrad**
- **Procured YSO and GSO plates and are preparing to test**
- **Planning underway to study other fast crystals such as BaF_2, CeF_3 and pure CsI as possible cost effective solutions**

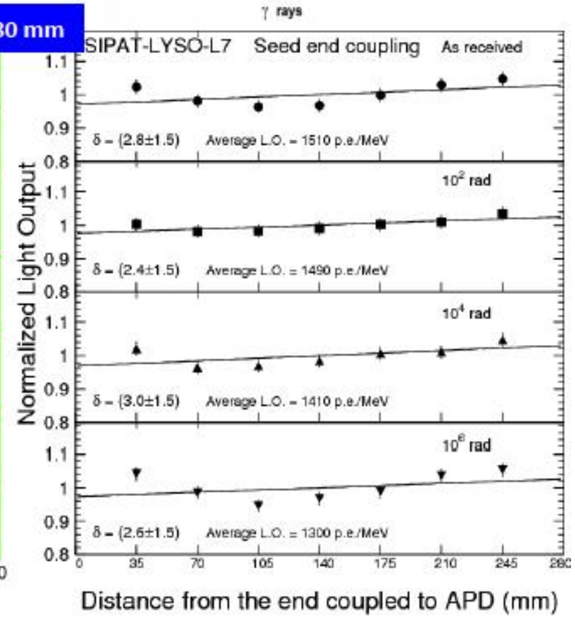
Caltech II

LYSO Studies









Minsk/CERN I

Activities in support of development of a Shashlik type configuration

- Optical elements and a custom made measuring setup has been prepared to measure light transport in the systems in a Shashlik style module. Plans are to measure the light output from crystal plates and high refractive glass wafers using different shape glass fibers (quartz).

- Initial stage of measurements will take place in Minsk and then to continue at CERN. Aim of measurements is to check correctness of simulations and to provide personnel who make simulation to compare with experimental results.

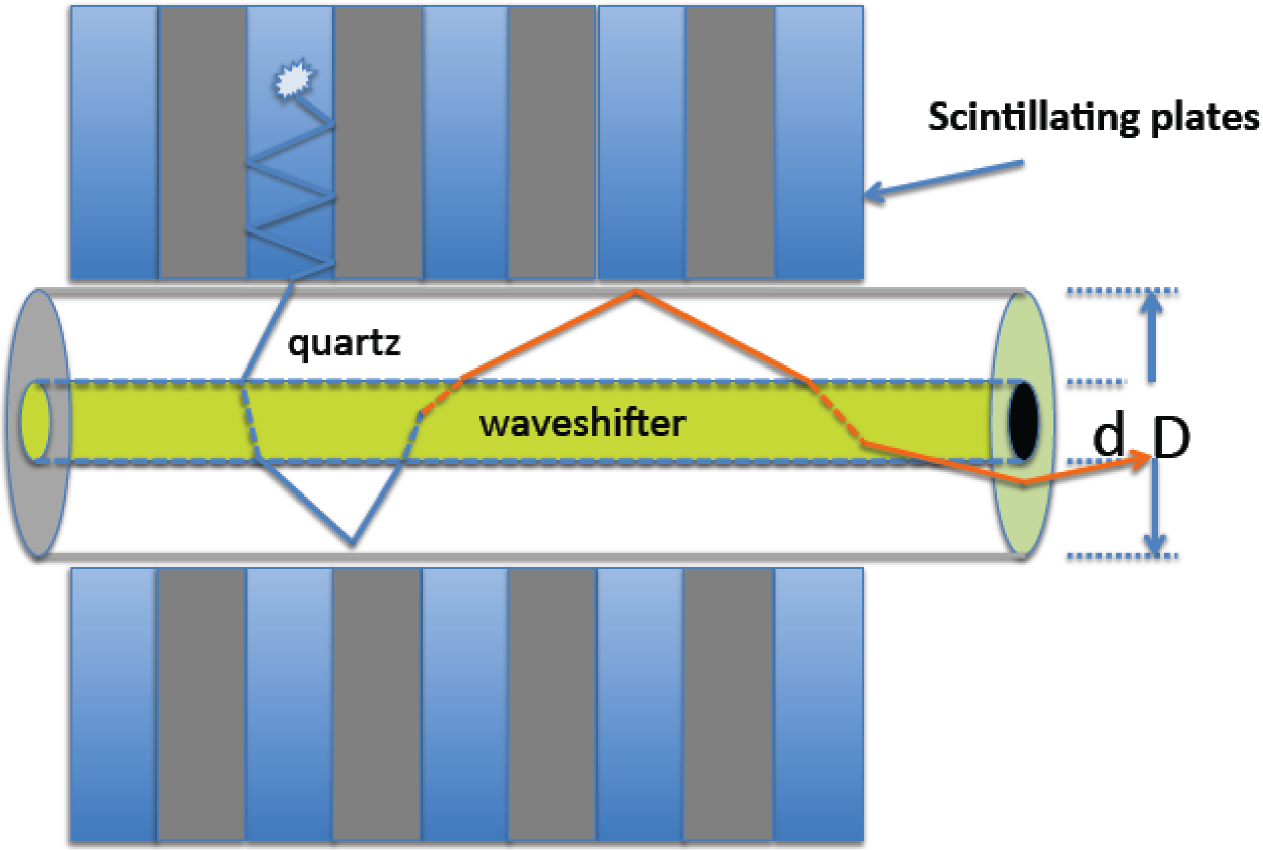
- In collaboration with CERN, do continued study of proton induced damage in heavy inorganic materials. This summer low Ce doped LSO and new YSO crystals have been irradiated in order to clarify a mechanism of the proton irradiation damage of LSO family crystals. Data and their analysis are coming in the fall.

- In collaboration with CERN, Minsk is doing irradiation with protons of some construction materials which may be used in further elements of calorimeters at high luminosity . Data will come by the end of the year.

Notre Dame/Maryland I
Rad Hard Fiber Optics for Shashlik Configuration
Embedded waveshifter element concept

Main idea is that the waveshifter is a light source but does not transport the light to the photosenser

The quartz performs that function



Schematic of light production, waveshifting and transfer (with apologies to Fresnel)

Notre Dame/Maryland II

Rad Hard Fiber Optics for Shashlik Configuration

Setups at Notre Dame and Maryland to test this idea. Additional setup for CERN.
Simulations are in progress at Maryland to guide the configuration

Materials:

WLS Fiber material: Kuraray MC fiber (940um diameter with end mirroring).
Chosen for convenience and comparison with what is currently used in CMS.
Capillary transport material: Quartz tubes, 30 cm length, 3mm OD.
Open core ID of 1mm. Presently studies do not include end mirroring.

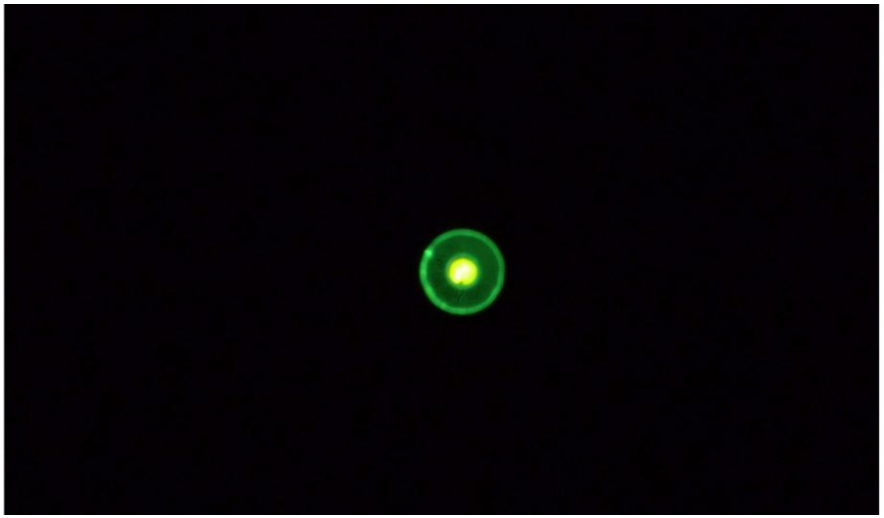
Irradiation: Materials are presently irradiated with ^{60}Co gammas up to 50 Mrad
Fibers are irradiated; Quartz tubes are not yet irradiated.
Light excitation: a blue violet LED to excite the Y11 shifter
Introduced through the sidewall of the fiber or capillary using.
Light sensor: Large area P/N diode.

Measurement Procedure

Move the LED along the fiber or capillary and measure signal from sensor
Currently covers the distance 0-30cm from sensor

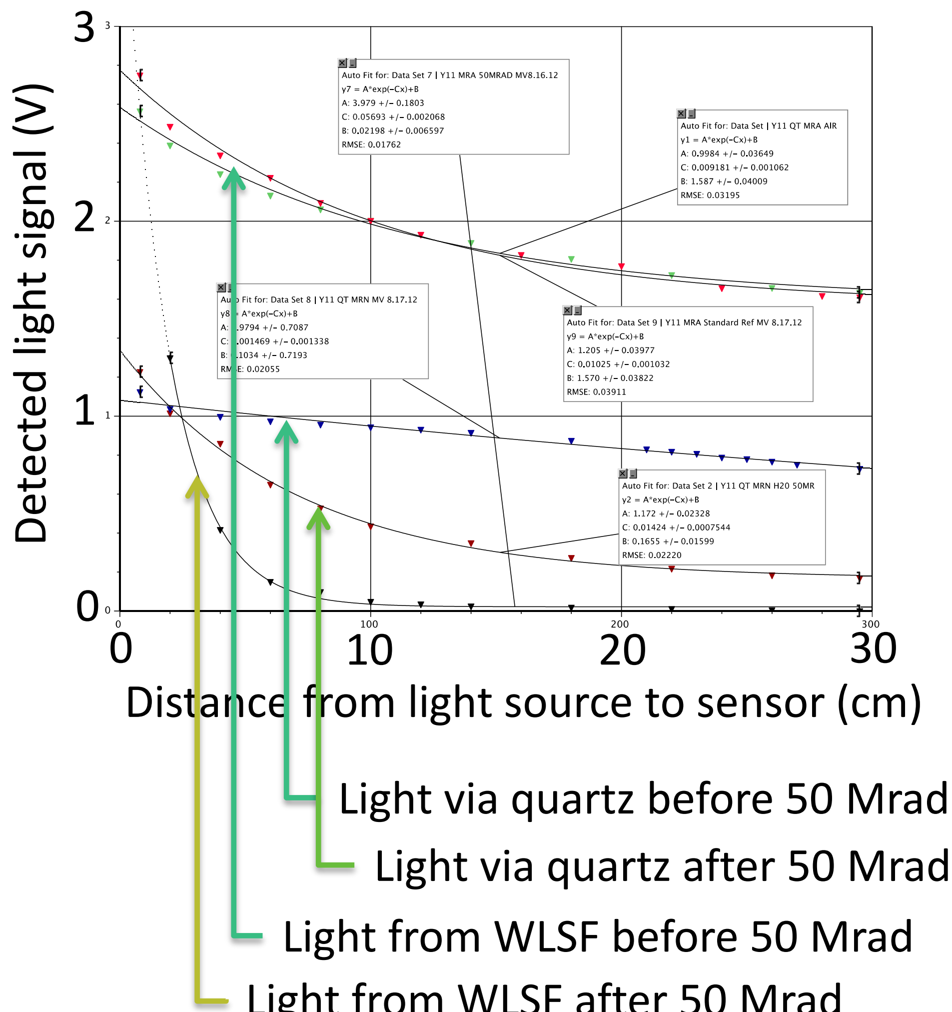
Notre Dame/Maryland III

Rad Hard Fiber Optics Technique for Shashlik Configuration



Irradiated Fiber inside un-irradiated Quartz capillary (50Mrad gammas)

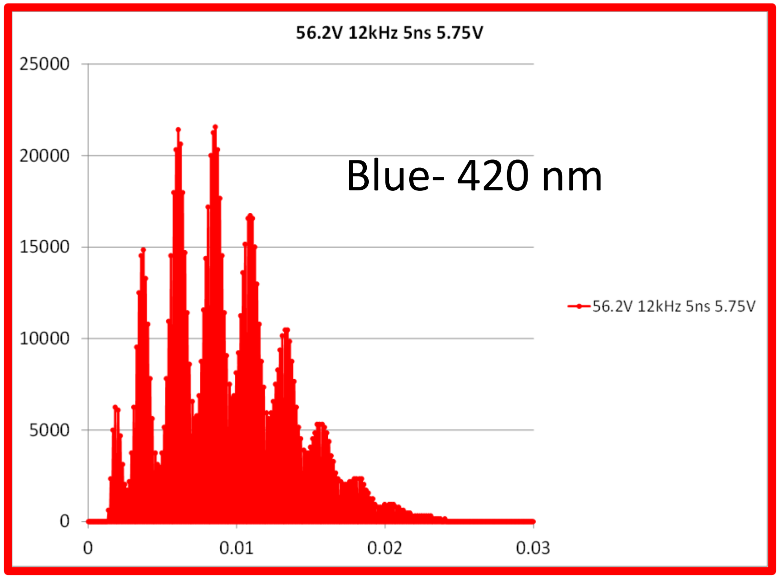
Note, little WLS light is transported by the WLSF (fiber) over 30 cm after irradiation; rather it is transported by the quartz capillary as planned

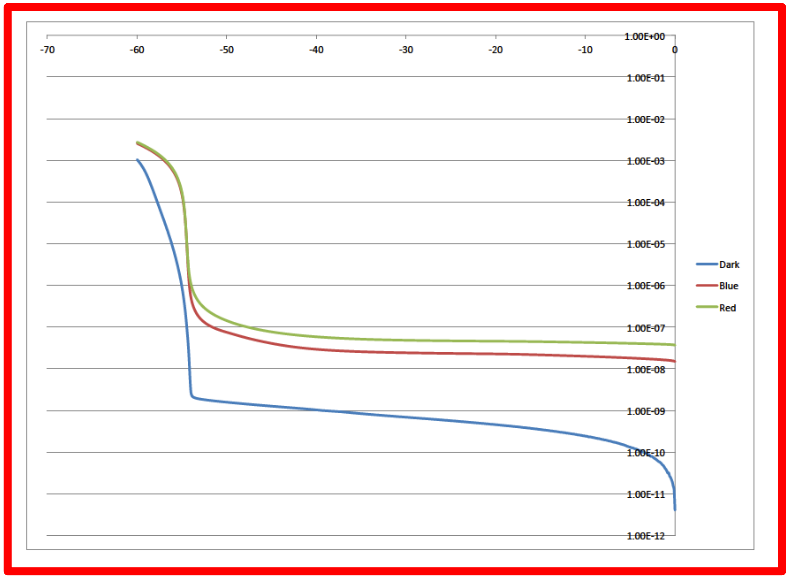


Virginia

GaAs/GaInP Geiger Mode Rad Hard Photodetector Progress

Some of the LightSpin characterizations of 2nd generation GaAs Photodetectors (0.5m x 1.5 mm arrays) **confirmed by Virginia**: dark and light IV curves, Geiger mode point, multipeak spectra from the multispad components of the available dice. More difficult measurements such as photodector efficiency underway.

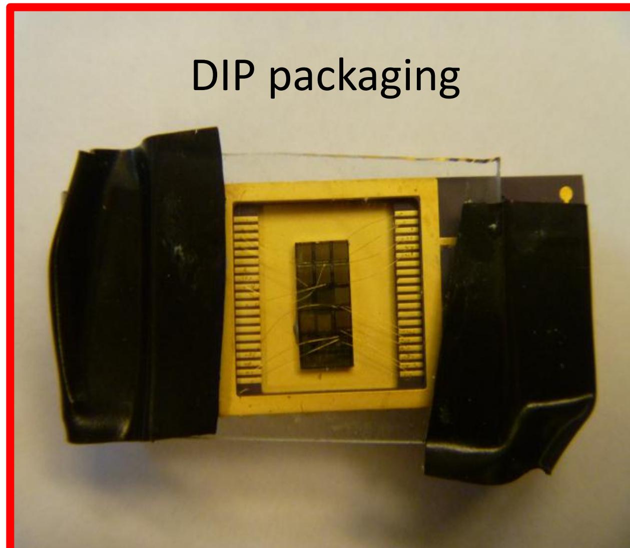




Virginia

GaAs/GaInP Rad Hard Photodetector Progress

- Focus is now on preparations for radiation testing in the PS of 2nd generation chips. 2nd generation is not expected to be as radiation hard as needed.
- Attention is given to packaging to minimize the activation of the photodetector support while providing adequate stability and robustness. Projection; ready for testing Nov. 1

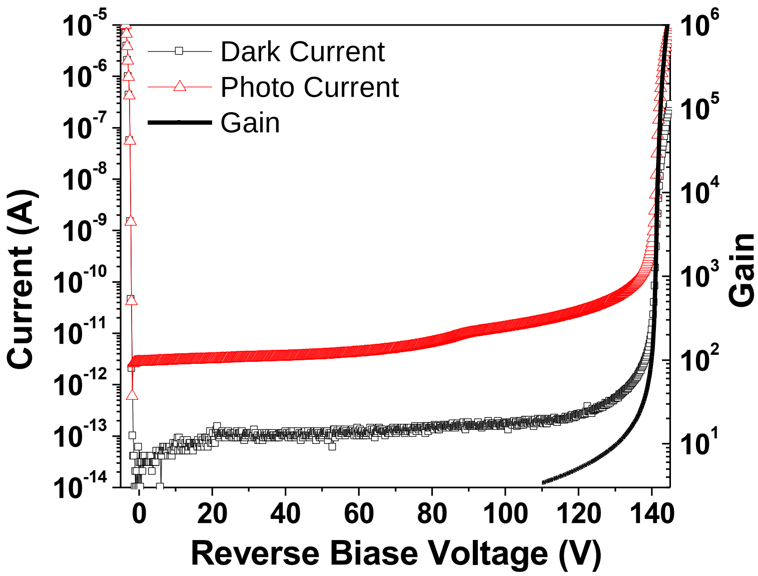


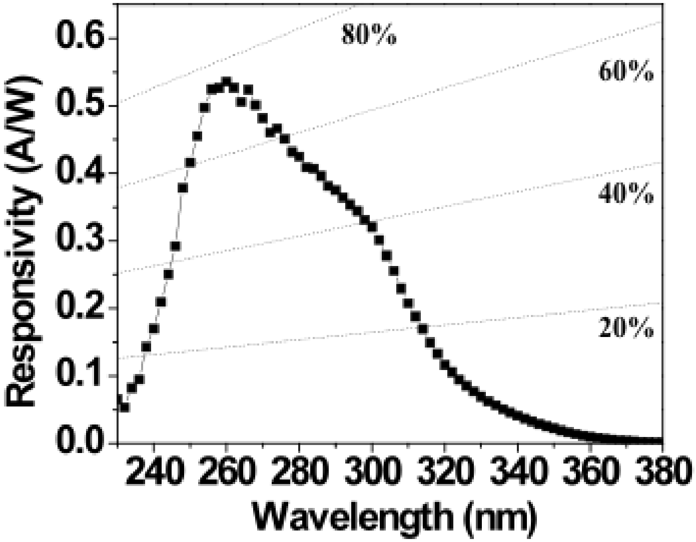
- Finally, iteration on 3rd generation photodetector underway. 3rd generation chips by the first of the year from LightSpin?

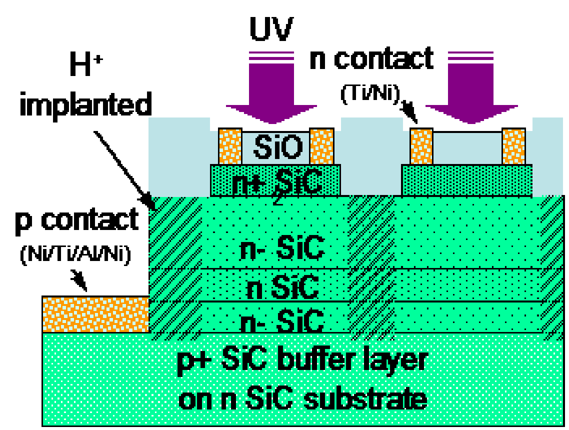
Minnesota/Virginia I

Toward Dual Readout Capability
SiC Photodetectors

Purpose is to detect Cerenkov light as distinct from scintillation light in the HE tiles by use of SiC APDs

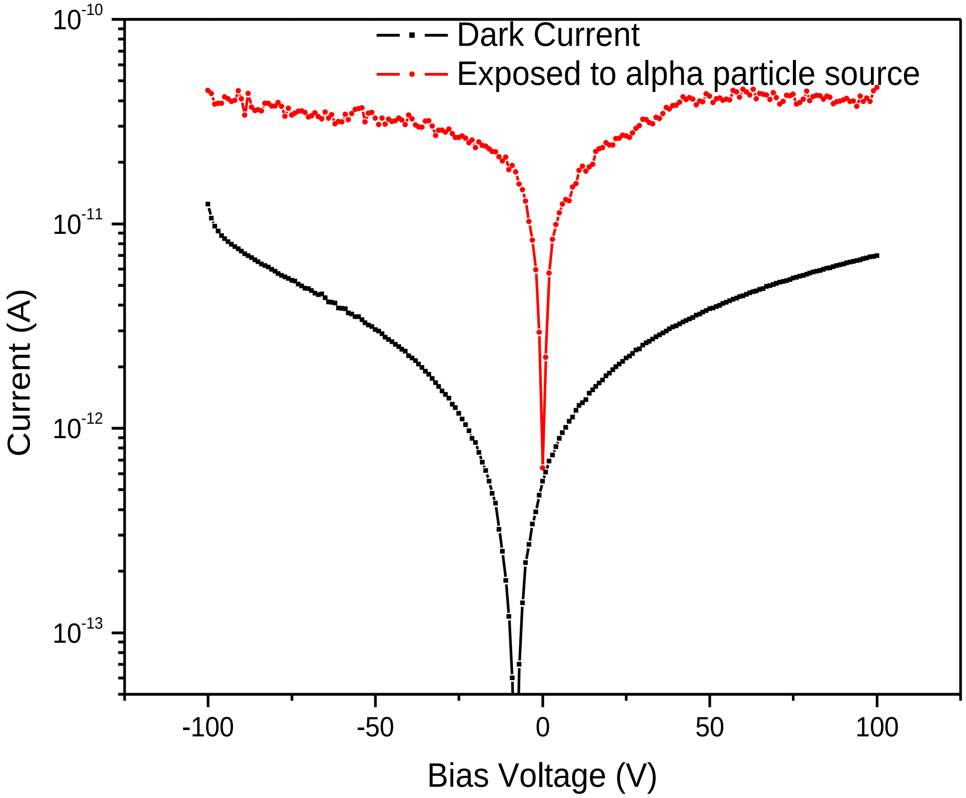






Minnesota/Virginia III

Alpha Particle Detection Test
First attempt to make aCustom SiC APD Photodetector



ECAL $PbWO_4$ Irradiation CERN PS Test Beam

- **Target – deliver information to the precise ECAL performance evaluation model to be used in simulation**
- **Source of information:**
  - current CMS data
  - PS: irradiation by protons up to high fluencies (≥ 2000fb^{-1} at η=2.2)
  - SPS : matrix performance with electron beam in 10-250 GeV energy range
  - Booster (Protvino): irradiation by high-energy (>30 MeV) neutrons up to $3x10^{13}$ n/cm^2
  - CMS: irradiation of EE crystals by hadrons at low rate
- **PS: 12 EE crystals irradiated to fluencies of ~$5x10^{13}$ p/cm^2 (~700fb^{-1} at η=2.2) – 9 crystals, and ~$2x10^{14}$ p/cm^2 (~2000fb^{-1} at η=2.2) – 3 crystals**
- **SPS:**
  - May: 5x5 matrix of the EE crystals evaluated before irradiation
  - July: 3x4 matrix of proton-irradiated crystals (2010-2011)
  - October: two 3x3 matrices based of PS-irradiated crystals
- **LHC: 4 EE crystals placed at the CASTOR position. Irradiation by LHC collisions at relatively low rate to ~(3-7)$x10^{13}$ particles/cm^2 during 6 months**
- **In-situ recovery evaluation setup: IR laser + oven. Built, calibrated, ready for tests (scheduled to October)**

Iowa I

Fermilab Test Beam Activities

- Focus on establishing a proof of concept for totally active hadron calorimetry.

- Evaluate the performance of:
  Different crystal and glass samples
  Different readout techniques

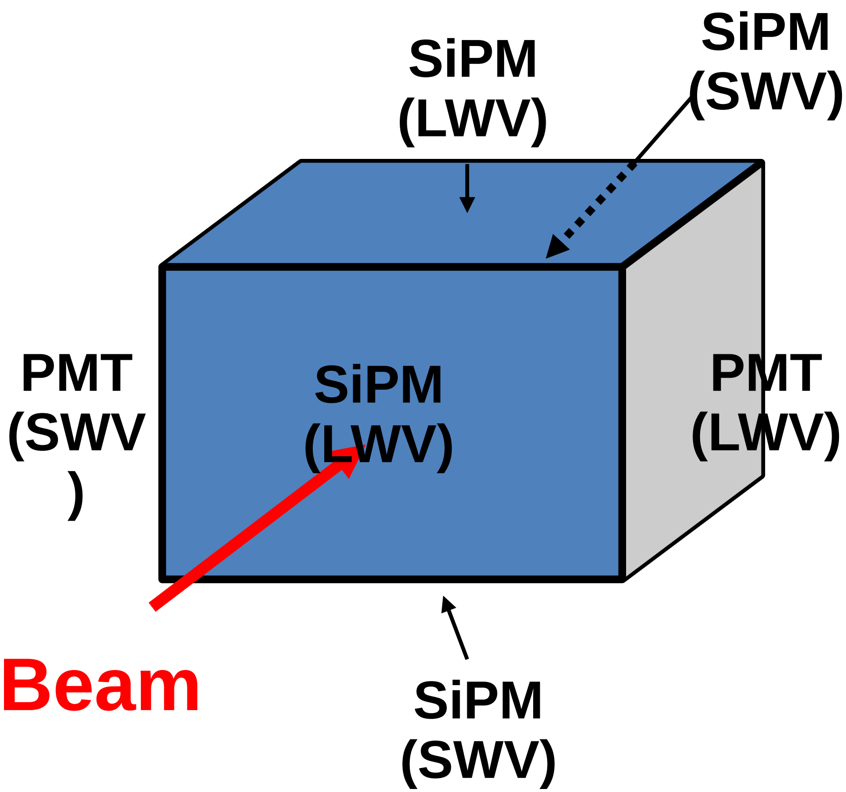
- Optimize the simultaneous collection of Čerenkov and scintillation light components
- for application of the Dual Readout technique to Total Absorption Calorimetry.

- Obtain a baseline for the detailed simulations of Čerenkov and scintillation light production in different crystals.

- Establish rigorous benchmarks for and characterizations of SiPMs

Iowa II

Setup of Single BGO Crystal fro Dual Readout Test Fermilab 120 GeV/c Proton Test Beam



All six sides instrumented With PMTs and SiPMs with long and short wavelength Filters as shown

Cerenkov and longer-wave visible light separated by filters and observed with SiPMs and PMTs in time spectrum

Precision Calorimeter Timing

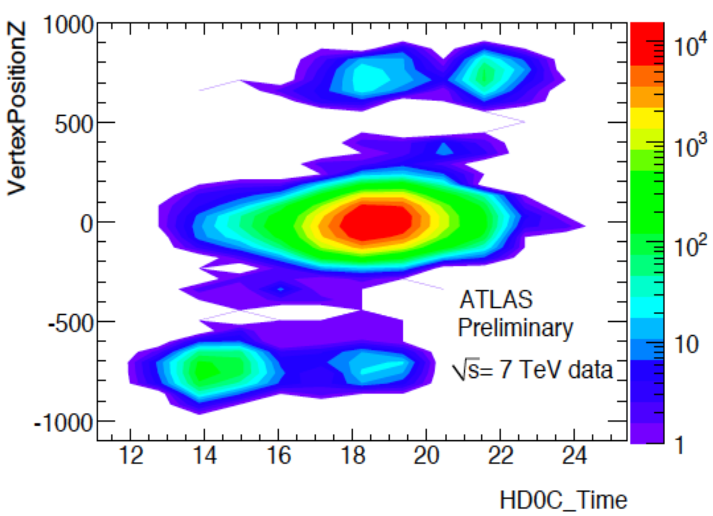
LHC bunch length sets a natural scale. ~7.5cm bunch, 55cm betastar
and 285 micro rad x-ing angle-> 170 picosec rms time spread, 4.5 cm rms vertex spread

Calorimeter(or track) time is a tool for resolving events in the 2-d space of event time and vertex position.

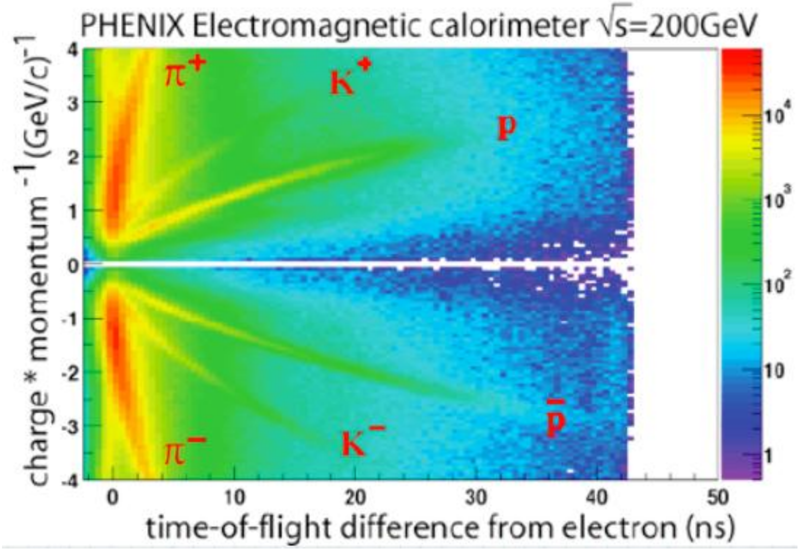
Existence proofs of calorimeters with <100 psec resolution

BNL-Yale built ATLAS ZDC timing (Quartz-Tungsten Shashlik) resolves 400 MHz (SPS) micro-bunch structure.

(Despite reduced bandwidth from low quality cable runs & 40 MSa/s sampling.)



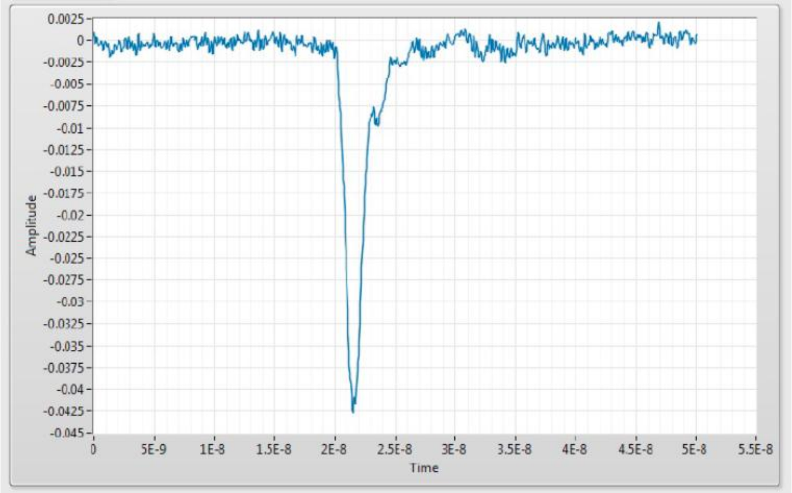
15,552 tower PHENIX shashlik also used for hadron id via TOF despite low energy deposit of ~0.5 GeV hadrons and TTS in un(longitudinally) segmented calorimeter



Potential options for CMS consideration
New technologies capable of better time resolution

A. Advanced Detector R&D Grant: Princeton, Rockefeller

1)New Hybrid Avalanche Photo Detector yielding 11 ps single photon rms response
2)Order of magnitude improvement over MCP-PMT lifetime
3)Deep-depleted APD for direct charged particle detection



Signal from 1 MIP crossing APD 0.5 ns rise time 6000 e-h pairs x200 APD gain eventual 10 ps rms TOF objective

->must demonstrate rad hardness
->battle test in a LHC (possibly ATLAS) environment before LS1
->explore application in upgraded CMS calorimetry designs

B. R&D multichannel plate arrays

Similar concerns as above

Status of Simulation Efforts

Test Beam Simulations

(good agreement with present test beam $PbWO_4$ radiation damage data; major accomplishment of the summer)

Simulation of Present Configuration

(close to having a Fastsim with both EE and HE radiation damage models up to date; simulation of physics such as Z->ee, forward jets, SUSY MET to be Repeated as a function of integrated luminosity

Simulations of New Configuration

(details of the possible new sampling calorimeter configurations such as light transmission from of individual elements are being simulated and appropriate radiation damage models being developed for the new technologies based on their radiation hardness test results)

Test Beam Simulations

Forward Calorimetry Task Force has developed a radiation damage model that incorporates test beam data from exposures of $PbW0_4$ to protons at the PS in order to develop a benchmarks and estimate when the present crystal detector will degrade for selected physics modes (Higgs->$\gamma\gamma$, SUSY MET measurements, jet position and energy resolution. This model will soon be incorporated in FastSim takes into account*

1. EM radiation damage the EB and EE crystals
2. Hadronic radiation damage to EE and EB
3. Hadronic radiation damage to HE
4. VPT degradation
5. Noise in EE VPTs
6. At present, no account yet taken of the error on the calibrations which will grow In magnitude as light is lost in the $PbWO_4$

These effects cause growth of the stochastic, noise, and constant terms in the present Detector resolution function. The model produces an induced absorption length as a function of η and integrated luminosity.

See Ledovskoy's talk from the June CMS week Forward Calorimetry Task Force meeting for the details of the model.

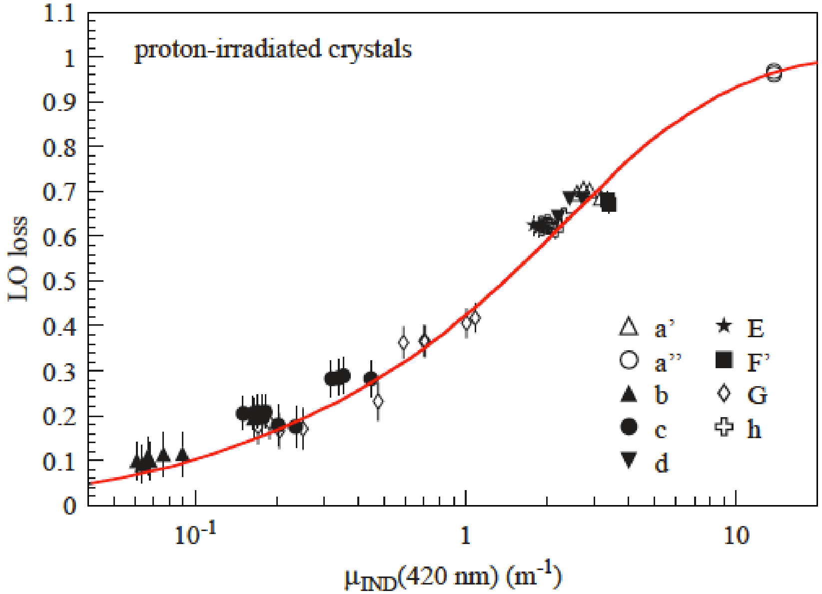
*

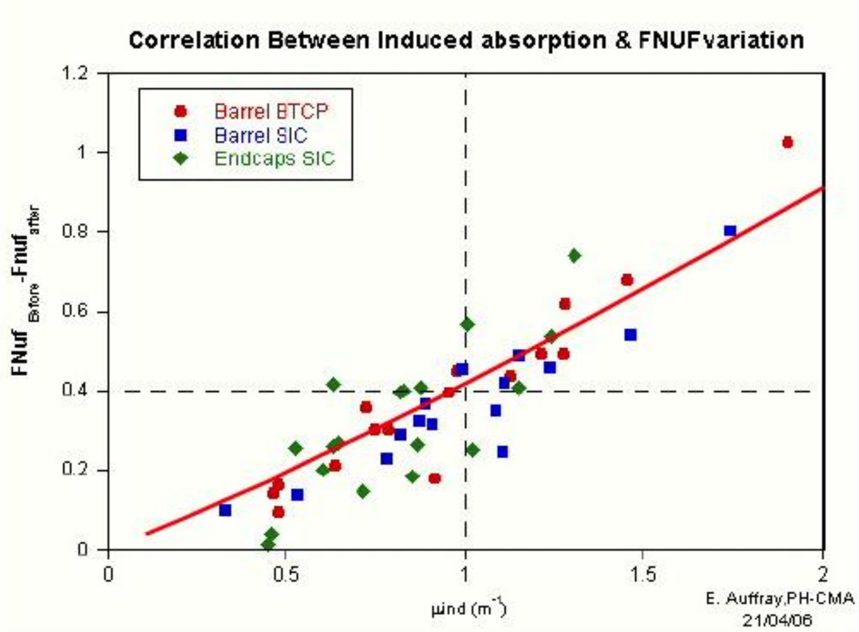
Induced Hadronic Radiation Damage (μ) as a Function of integrated Luminosity and η*

L(fb^{-1})/η–>	2.9	2.8	2.7	2.6	2.4	2.2	2.0	1.8	1.5
10	0.37	0.30	0.23	0.18	0.10	0.05	0.02	0.01	0.003
50	1.86	1.49	1.17	0.90	0.50	0.26	0.12	0.05	0.013
100	3.72	2.91	2.33	1.79	1.00	0.51	0.24	0.11	0.026
500	18.6	14.9	11.7	8.96	4.98	2.56	1.21	0.53	0.131
1000	37.2	29.7	23.3	17.9	9.96	5.11	2.42	1.06	0.262
2000	74.4	59.5	46.6	35.8	19.9	10.2	4.84	2.12	0.526
3000	111.5	89.2	70.0	53.8	29.9	15.3	7.26	3.17	0.788

1. Assumes the hadronic radiation damage plateaus such that it is uniform along the crystal
2. Uses Litrani to calculate light loss for a uniform μ along the crystal
3. Takes into account an additional EM radiation damage 0 to 2 μ that depends on instantaneous luminosity

Predictions of the Light Loss Model (red) for Test Beam Irradiation Data

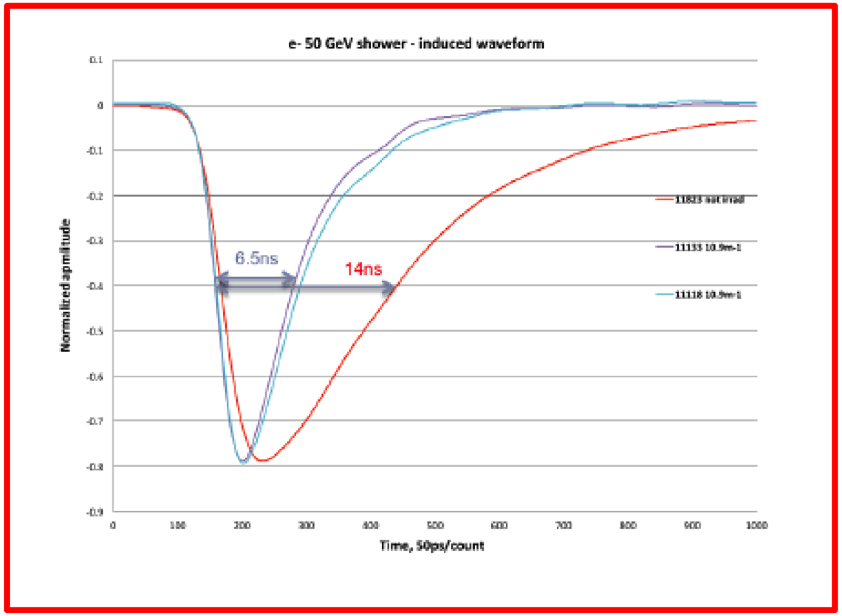




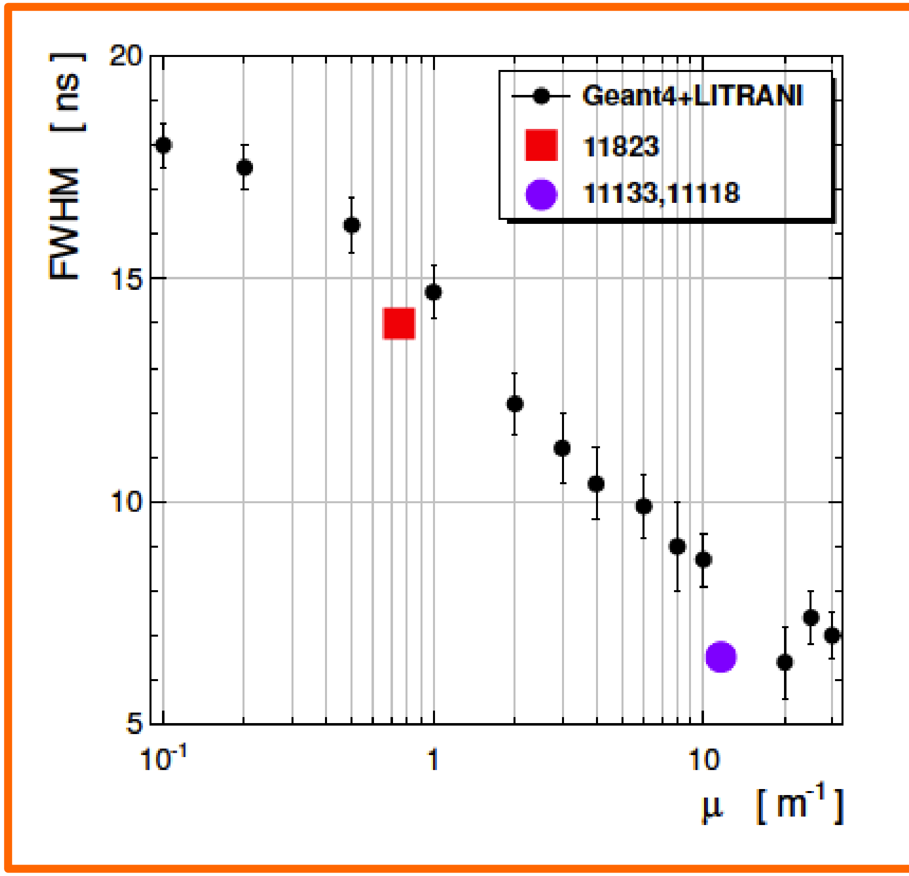
Light loss vs μ induced absorption from cosmic muons In radiation damaged crystals

Prediction of change of FNUF with μ

Change in Shape of the $PbWO_4$ Pulses due to radiation Damage

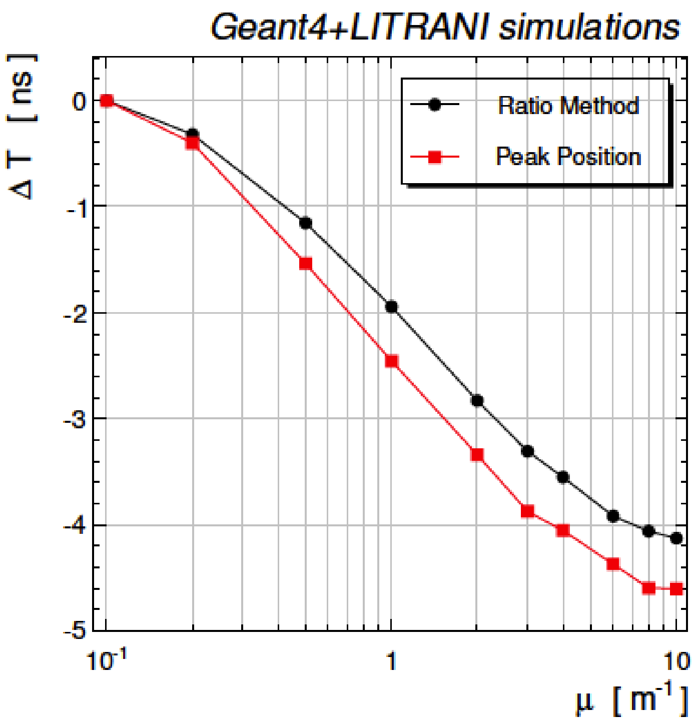


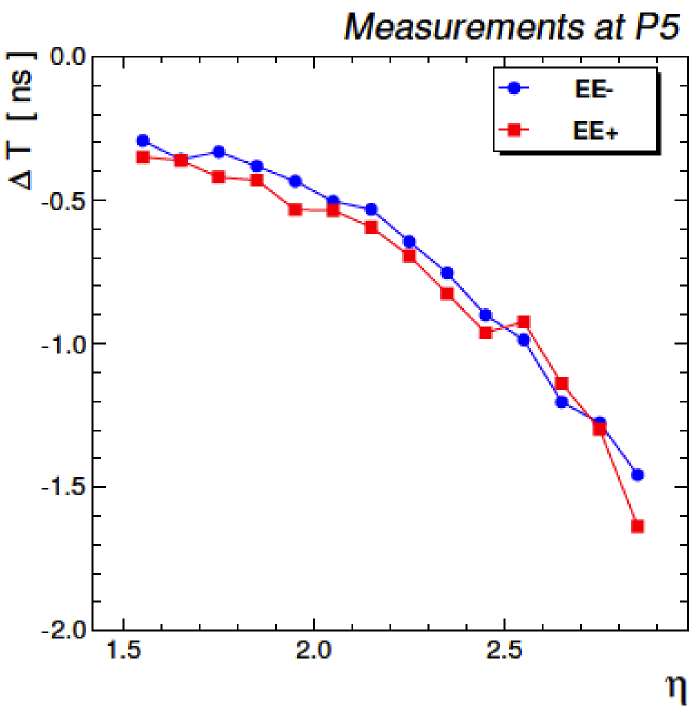
Observed change of pulse shape due to radiation damage; FWHM decreases from 14ns to 6.5ns



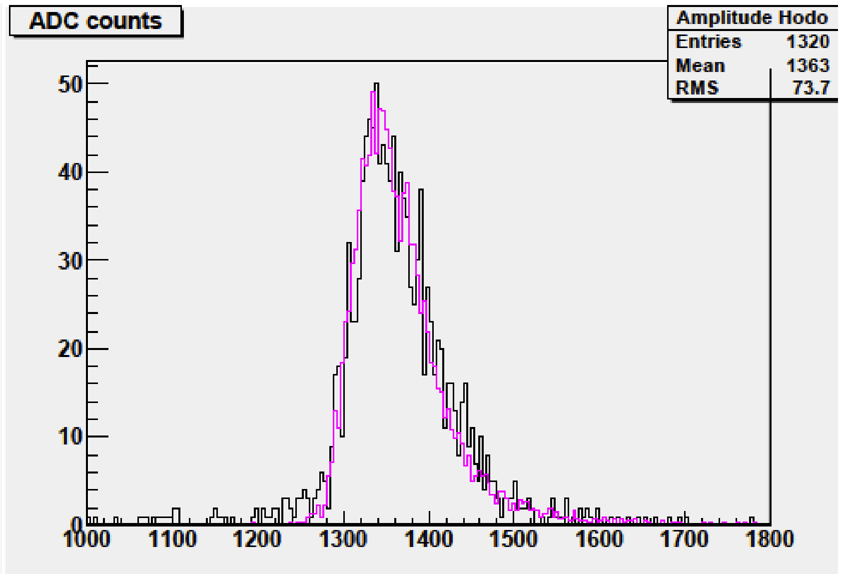
Prediction of the light loss model

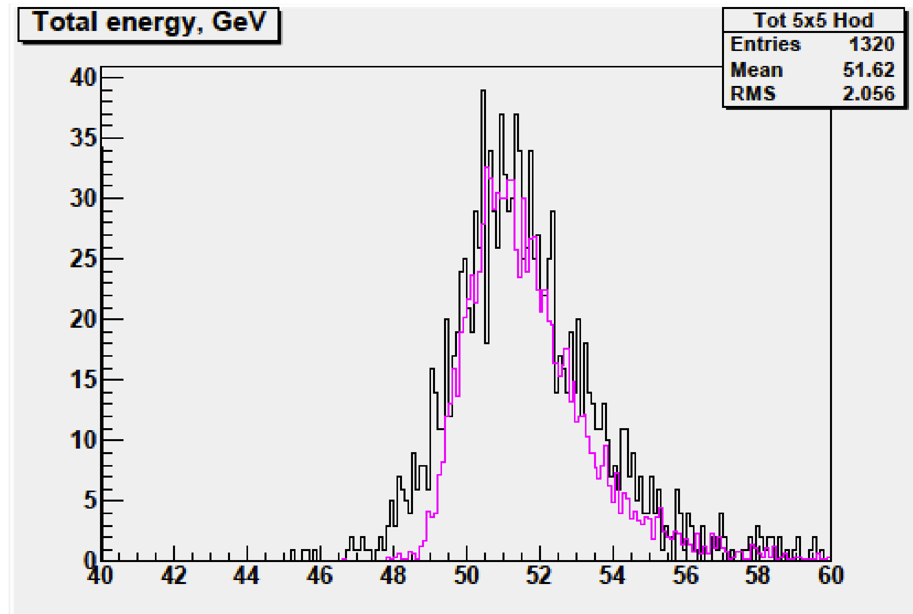
Timing Drift with Radiation Damage in CMS Predicted by Light Loss Model and Observed at P5





Prediction of Energy Distributions In Damaged Single Crystals and Arrays





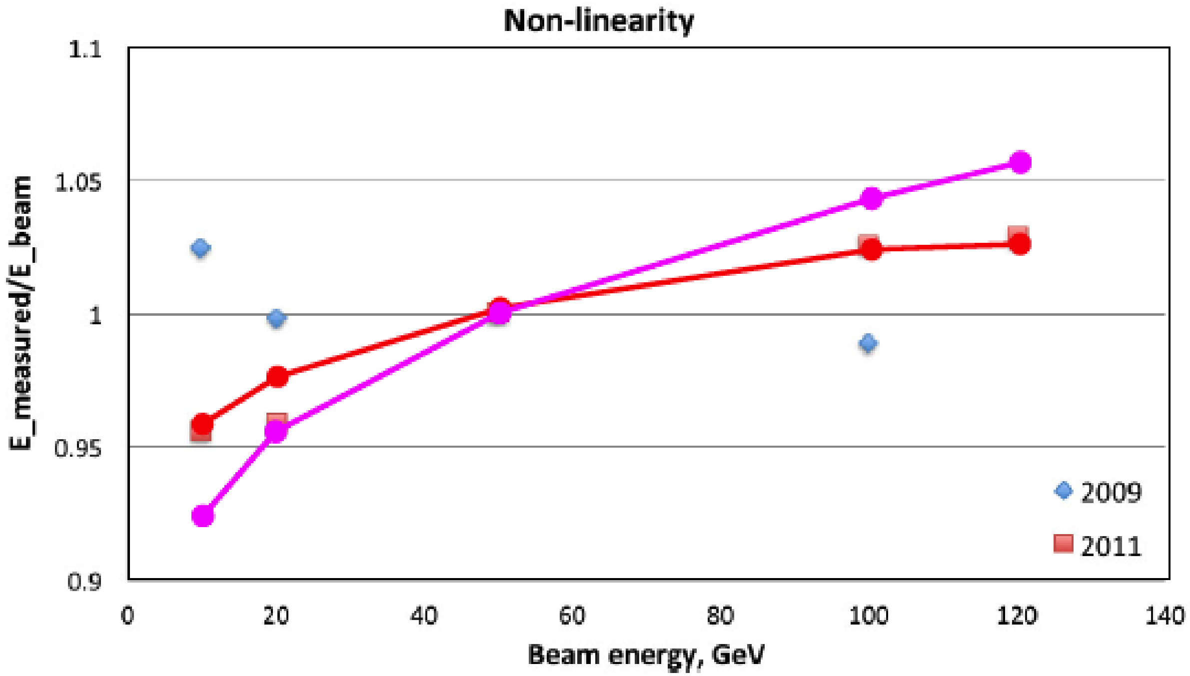
Energy Distribution
Single Crystal $\mu=10.6\ m^{-1}$

Energy Distribution Array

11962 **7.8**	12014 **4.7**	11845 **2.5**
11118 **10.9**	11133 **10.6**	11856 **3.2**
7022 **11.4**	11830 **2.5**	11832 **0**

Each distribution requires a scale factor of 0.7 applied to μ to get agreement because the test beam radiation damage in a crystal is NOT equivalent to the radiation damage of a crystal. The test beam only damages the center of the crystal

Prediction of Non-Linearity In Test Beam Data



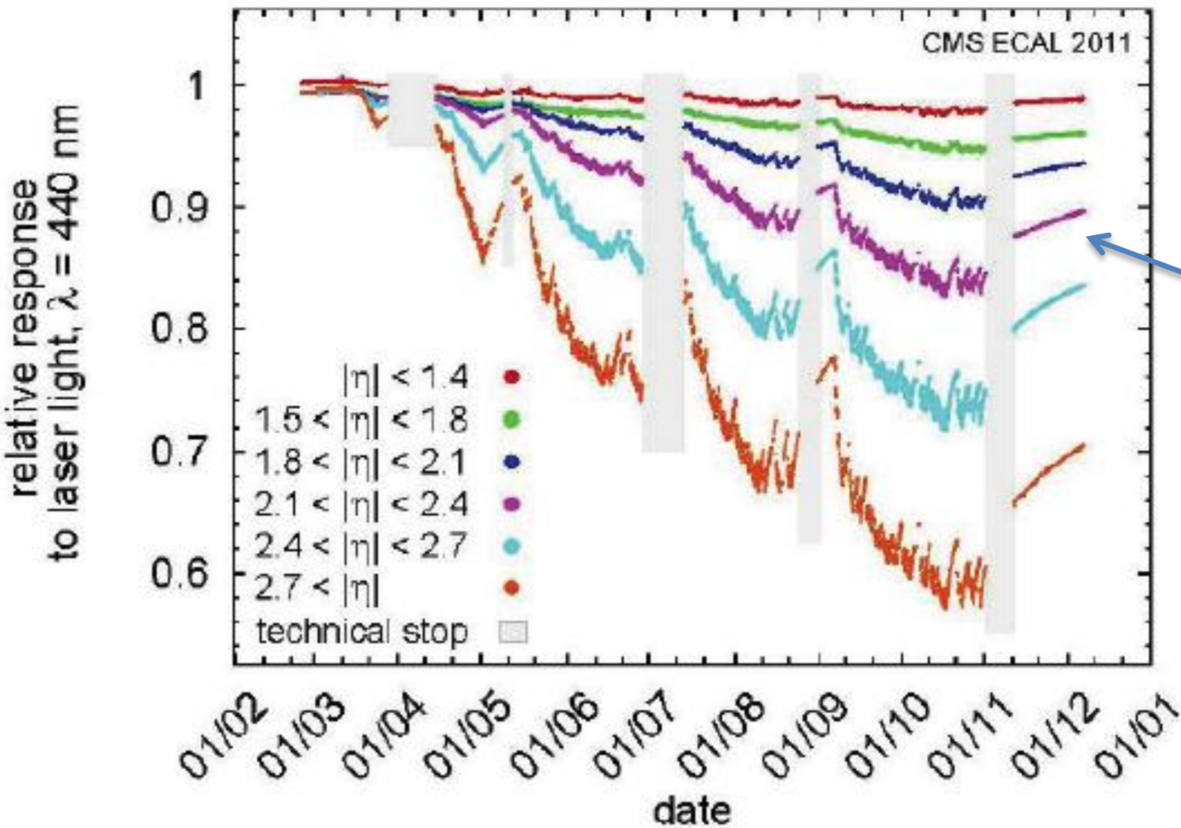
Red dots are measurements of non-linearity for a single crystal in test beam (red line is simulations using μ (10.7) x 0.7 for crystal

Magenta is prediction for the 3x3 array in the CMS detector with μ=10.7 for all crystals

State of Response Loss
In the CMS Endcap in the 2011 run ~ 5 fb^{-1}
Still in the EM Damage Era

Hadronic D\damage does not seem to self anneal according to tests

Hadronic Damage is expected begin to dominate at 500 fb^{-1}



Dominated at moment by EM rad damage

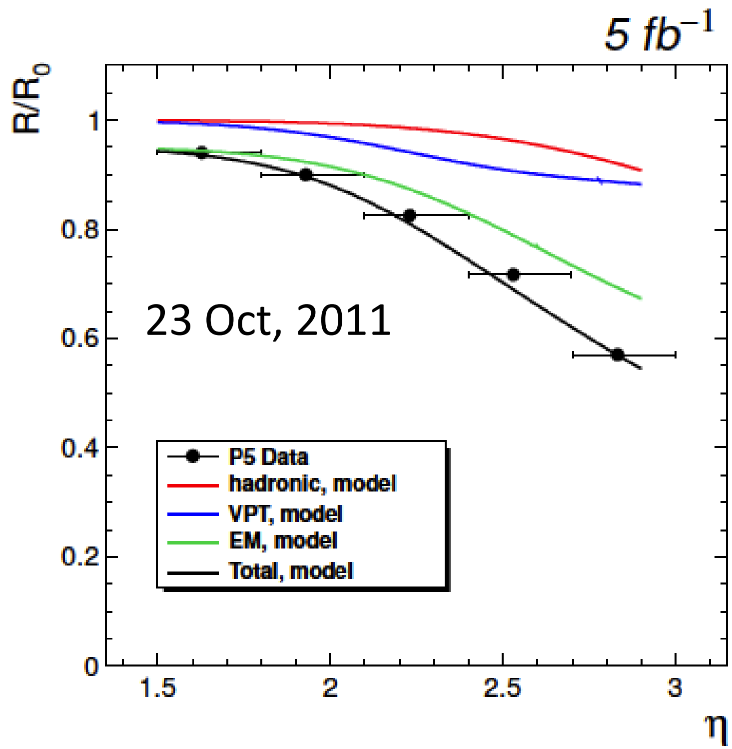
Note the recovery due to self annealing

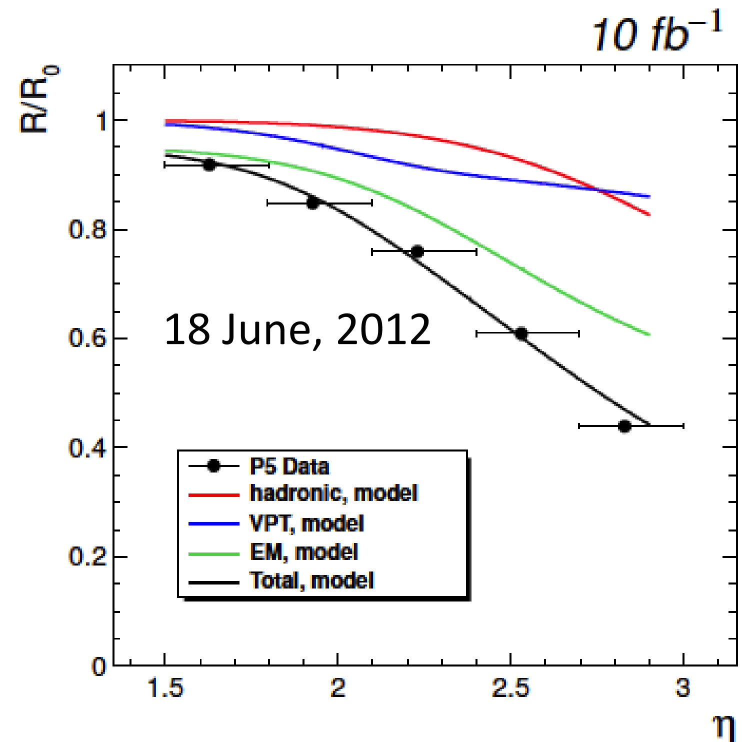
Color center saturation is expected to lead to EM damage saturation with loss of ~60% of light

- **Includes other effects (VPT aging, etc.)**
- **Still correctable but with loss of resolution**

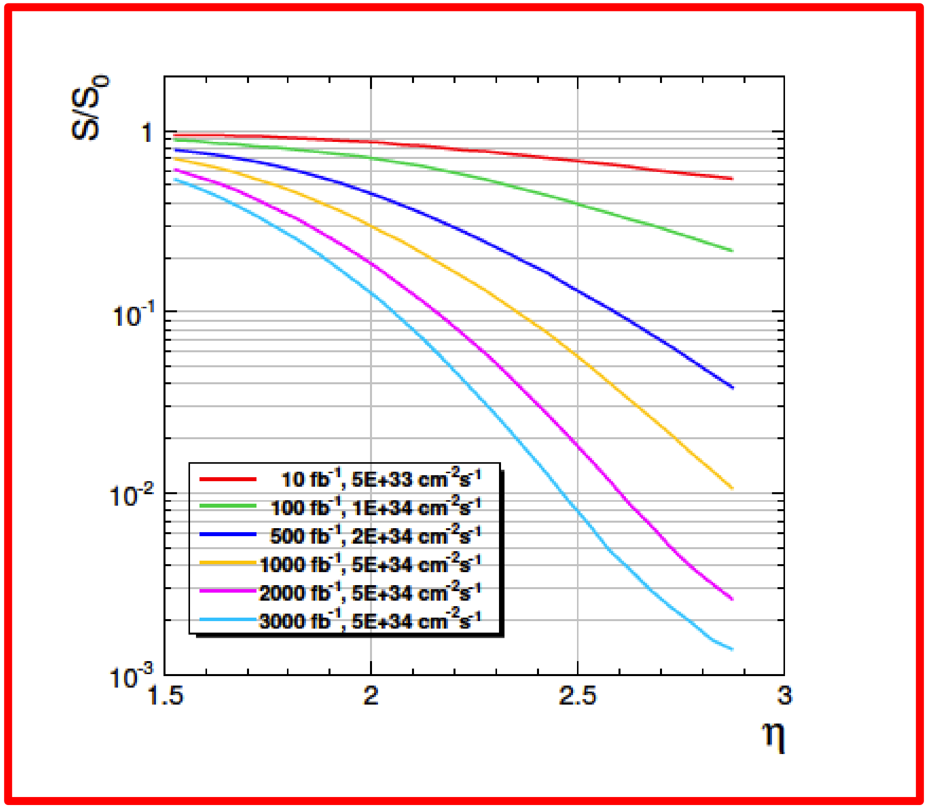
Prediction of the Model
For Recent CMS Operation

- Assumes EM damage reaches equilibrium during stable LHC operations
- EM radiation damage is at maximum of $\mu=2\ m^{-1}$
- Average VPT aging based on 11 VPTs

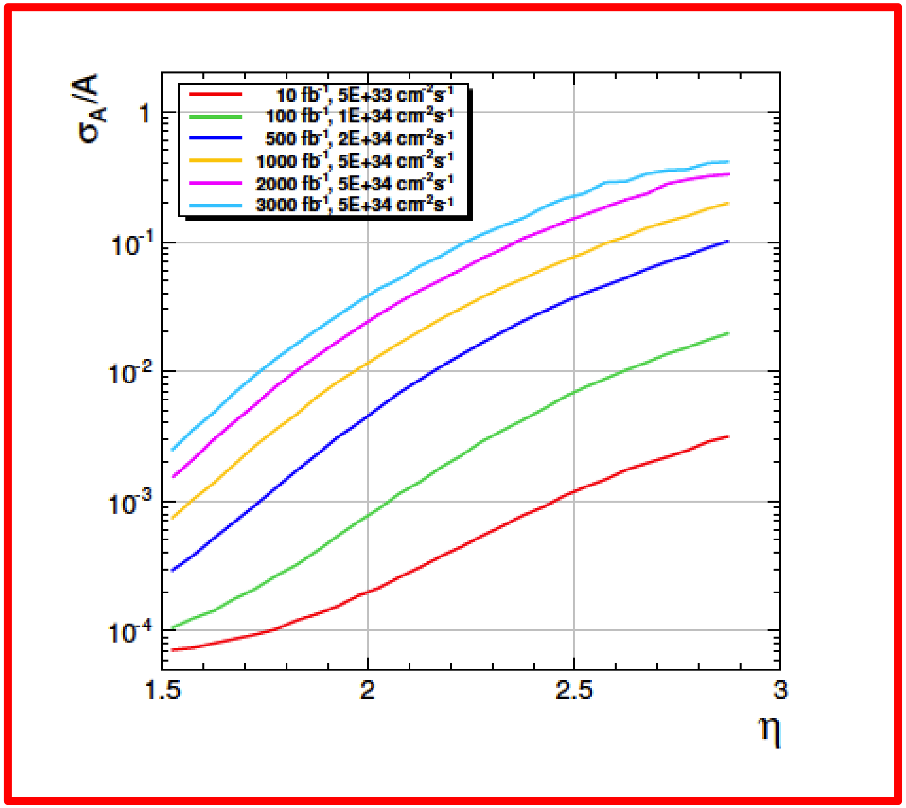




What about the Future (out to 3000 fb^{-1})



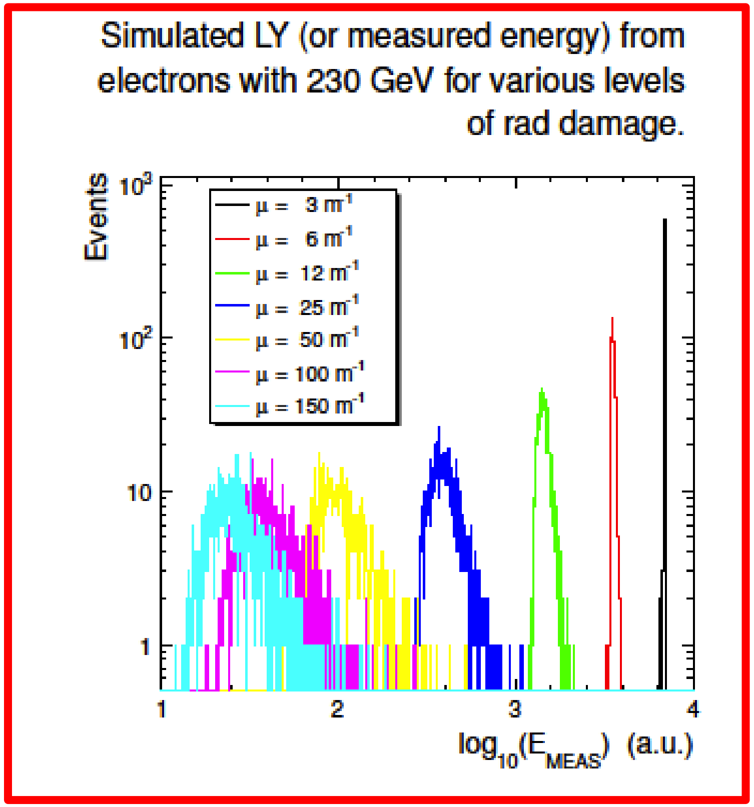
50 GeV Electron Signal Loss



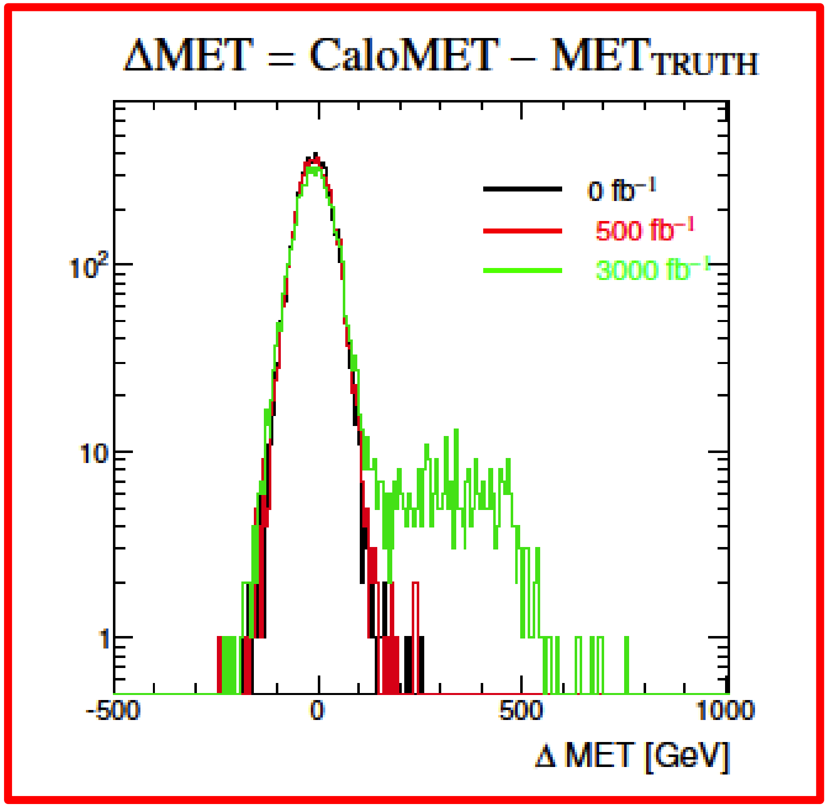
50 GeV Electron Constant Term

Effects on Physics
Earlier Calculations
Some effects not yet included
No HCAL or HF damage- only EE

Stay tuned For more up to date simulations



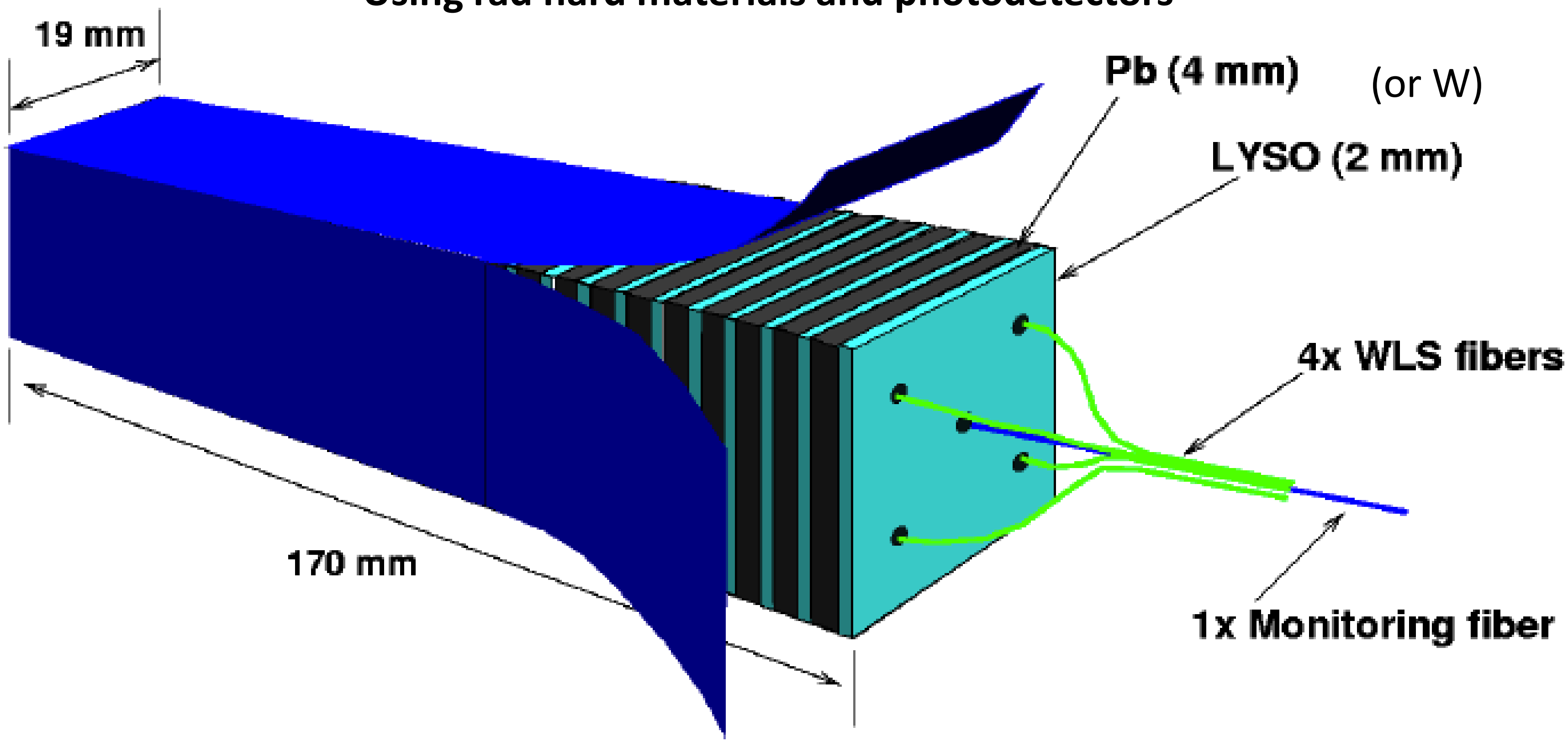
Electron Energy Loss



SUSY MET

New Possible Radiation Hard Shashlik EE module*

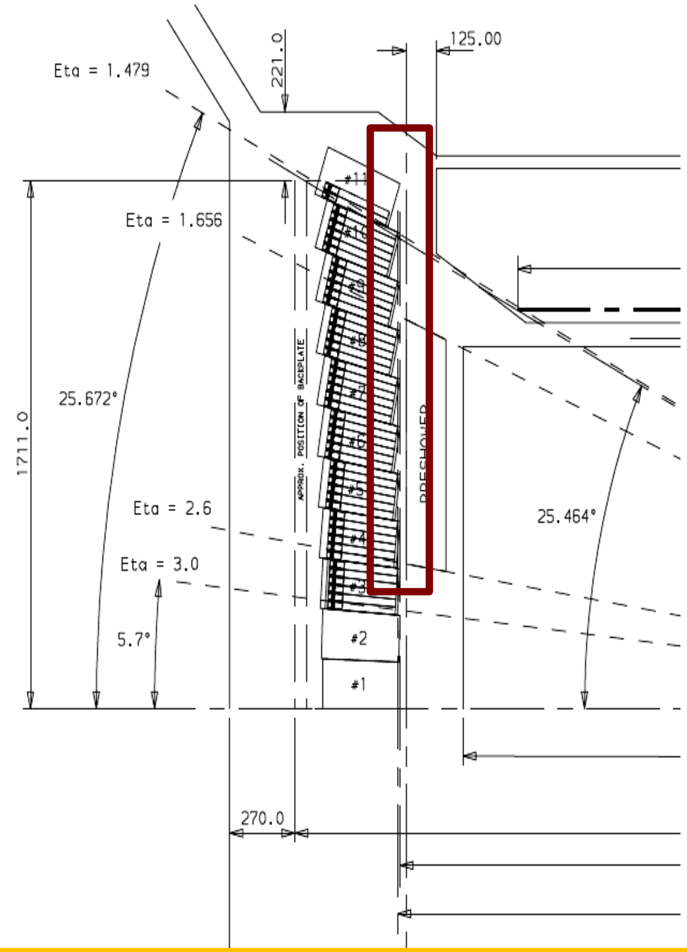
Using rad hard materials and photodetectors



- A homogeneous detector is a possible configuration but probably too expensive if based on LYSO

Possible Model of W-LYSO Shashlik ECAL

- W is available as machinable alloys or sintered material: 16.5 – 18.5 g/cc
- Pure W: X_0 = 0.350 cm, λ_{Int} = 9.95 cm, R_M = 0.93 cm [Compare Pb: X_0 = 0.561 cm, λ_{Int} = 17.6 cm, R_M = 1.60 cm]
- Cover η = 1.48-3.0; 5.6 m²/endcap R_{in} = 31.4 cm; R_{out} = 150 cm
- Total 14648 Towers of 26 X_0 (Or 552 + 72 Partial Full Supertowers)
- **2.85 X 2.85** X 12 cm³ per Tower; ~1.5Kg 14.3 X 14.3 X 12 cm³ per Supertower
- 20 Cells Each 4 mm W + 2 mm LYSO (26 X_0): Sampling term ~12 - 15%/√E
- ➡ Total W: 1.0 m³ = 19 Ton
- ➡ Total LYSO: 0.45 m³ ~ $ 11 M at $ 25/cc



- **Think about proper tower size (γ/π⁰).** Present EE: larger than ECAL TDR

Summary

New Technologies

As far as possible with existing funding the most significant problems under investigation.

Simulations of present detector

What is implemented for EE

Degradation of signal in each ECAL channel
- Average loss of amplitude due to EM and Hadronic damages
- Energy non-linearity due to non-uniformity of LY
- Additional smearing due to non-uniformity of LY
- Degradation of VPT response

Energy deposition from real particles are smeared...
- according to photo-statistics (Degraded)
- according to non-uniformity contribution (Degraded)
- according to noise in energy equivalent (Degraded)

Noise in each channel same in ADC, increased in energy equivalent

Readout thresholds same in ADC, increased in energy equivalent

What is implemented for HE

A radiation damage model built on empirical radiation damage data

What is implemented for HF

Not much attention yet given to this; just beginning to consider

Simulations of parts of new configuration underway in parallel

Time Scale

Choice of baseline options for detectors elements, photodetectors and other equipment. R&D continues (price, commercial availability, and applicability)	End-2013
Completion of choice of configuration for Forward Calorimetry (based on data/simulations)	Mid 2014
Technical Proposal ★	End 2014
Technical design report	Mid 2015
Start of funding request process.	End 2015
Construction of upgrade elements	2016 - 2022
Installation	2022-2023

Additional Information

ETH Institute for Particle Physics

- III - Hadron irradiation tests of ECAL-upgrade candidate scintillators

→ Proton irradiations of YSO and possibly other samples will be performed later in 2012, up to 10^{14} p/cm^2

→ Results on the visualization of damage in Lead Tungstate were just published in NIM A684 (2012) 57-62.

These results provide a direct, visual evidence to the mechanism of hadron damage in Lead Tungstate:

☑ the highly ionizing fragments of Pb and W, from fission induced by energetic hadrons, produce permanent local damage, that scatters light

☑ crystals made out of non-fissionable elements are a more sensible choice for an ECAL upgrade

Nuclear Instruments and Methods in Physics Research A 684 (2012) 57–62

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

A visualization of the damage in Lead Tungstate calorimeter crystals after exposure to high-energy hadrons

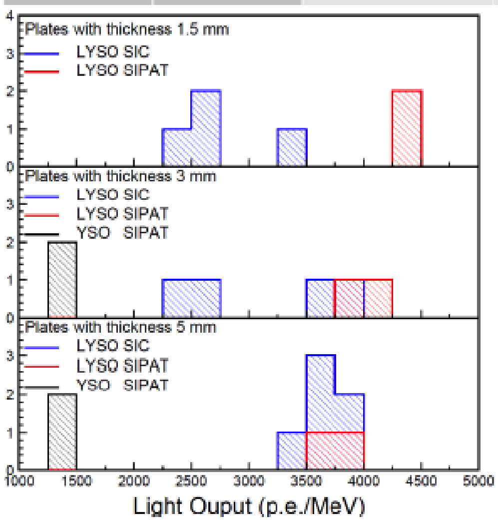
G. Dissertori [a], D. Luckey [a,1], F. Nessi-Tedaldi [a,*], F. Pauss [a,2], R. Wallny [a], R. Spikings [b], R. Van der Lelij [b], G. Arnau Izquierdo [c]

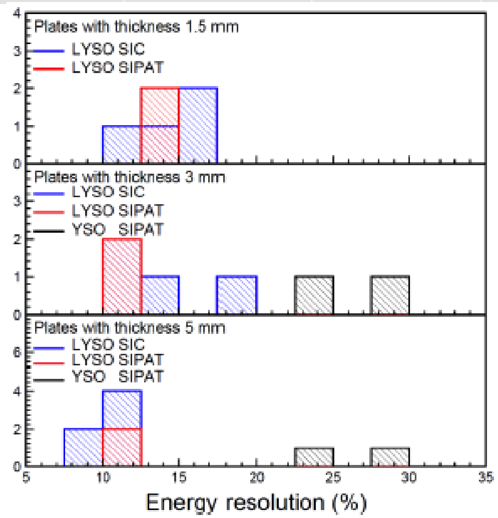
[a] Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland
[b] Department of Mineralogy, University of Geneva, 1205 Geneva 4, Switzerland
[c] CERN—EN Department, 1211 Geneva 23, Switzerland

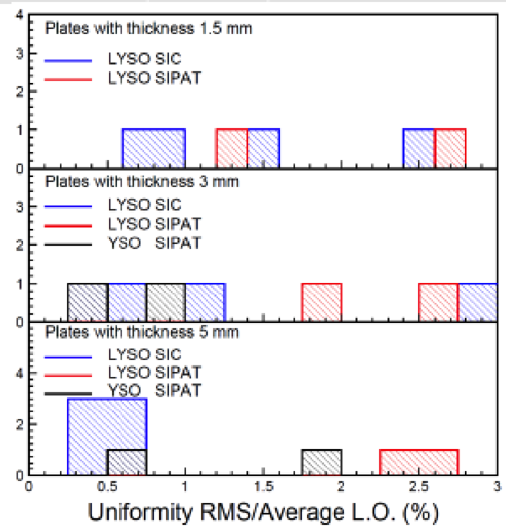
Caltech III

LYSO/YSO Plates
Uniformity of light response

Vender	Crystal	Thickness (mm)	Ave. Cutoff (nm)	Ave. EWLT (%)	Ave. τ (ns)	Ave. LO (p.e./MeV)	Ave. E.R. (%)	Ave.Uniformity RMS/L.O. (%)
SIC	LYSO	1.5	376.2	78.7	36.9	2776.2	14.0	1.38
		3.0	379.0	77.9	38.2	3117.1	13.2	1.25
		5.0	381.0	75.8	39.8	3669.7	9.9	0.44
SIPAT	LYSO	1.5	375.1	80.3	40.4	4363.5	13.8	2.02
		3.0	377.9	79.3	43.1	4009.4	11.7	2.32
		5.0	380.5	78.1	43.5	3734.2	11.5	2.52
SIPAT	YSO	3.0	380.5	79.2	42.7	1440.0	27.0	0.59
		5.0	383.3	78.1	44.0	1363.0	26.7	1.28







Minsk/CERN I

Activities in support of Development of a Sashlik type configuration

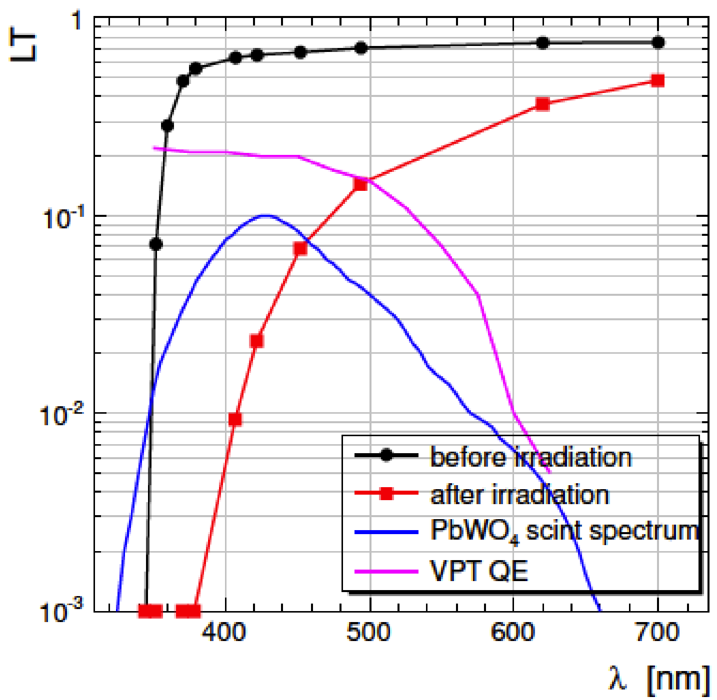
Fibers

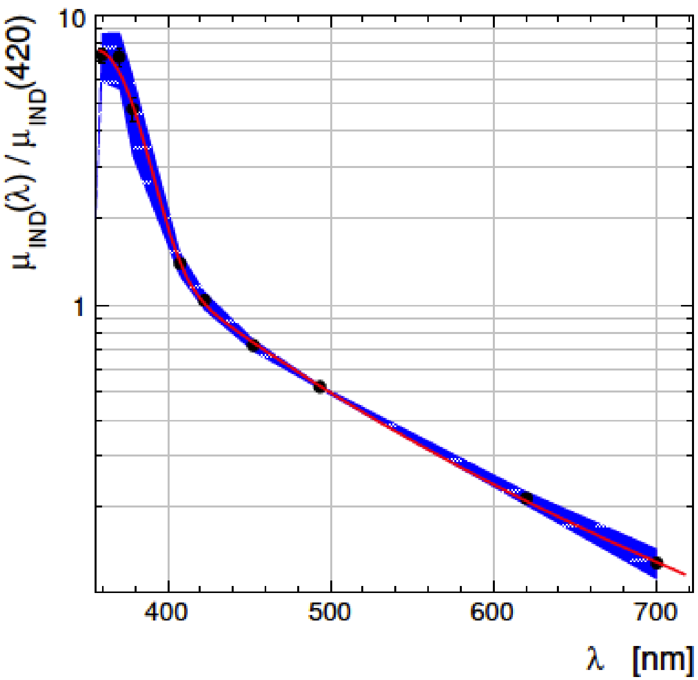
Plates

Measurement Setup at Minsk

Simulation/Use of $PbWO_4$ Test Beam Results

Wavelength dependence must be taken into account to determine induced absorption as a function of wavelength λ





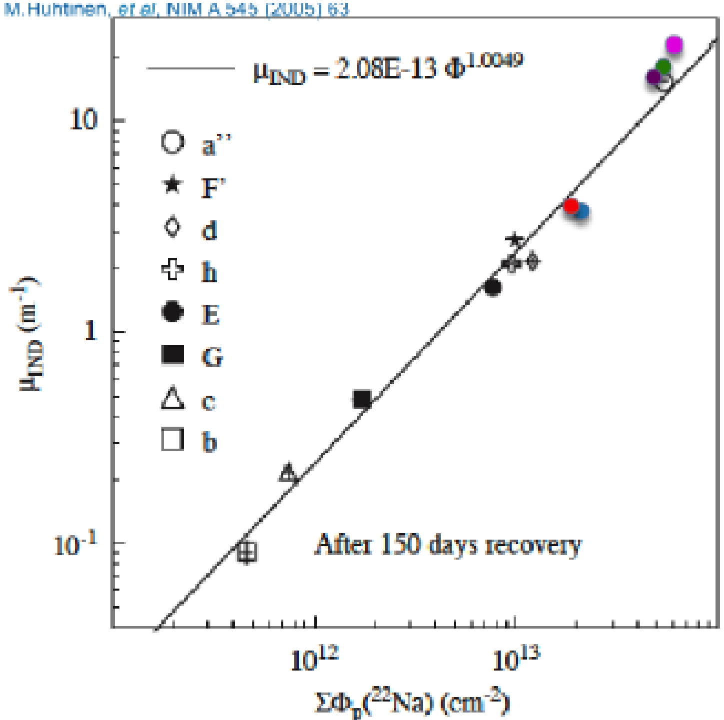
- Radiation damage effects
- Scintillation spectrum
- Refractive index of $PbWO_4$

taken into account

Irradiation of several crystals was performed and $\mu(\lambda)/\mu(420\text{ nm})$ was determined. The variation crustal to crystal is the blue envelope. Above 420 nm, the curve is consistent with Rayleigh $(1/\lambda^4)$ scattering

Inputs to induced Hadronic Radiation Model

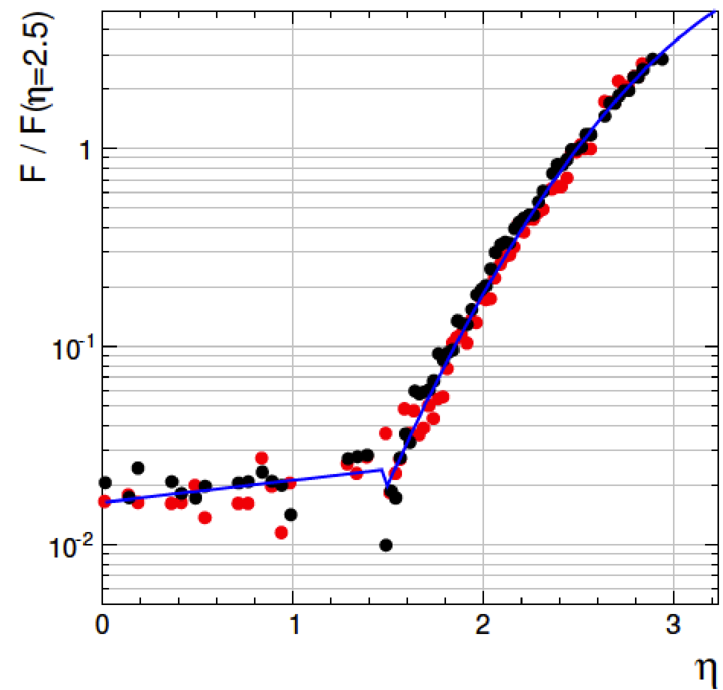
M.Huhtinen, *et al*, NIM A 545 (2005) 63



Crystals irradiated at PS in 2010 and 2011

- 11845
- 11830
- 11118
- 11133
- 11162

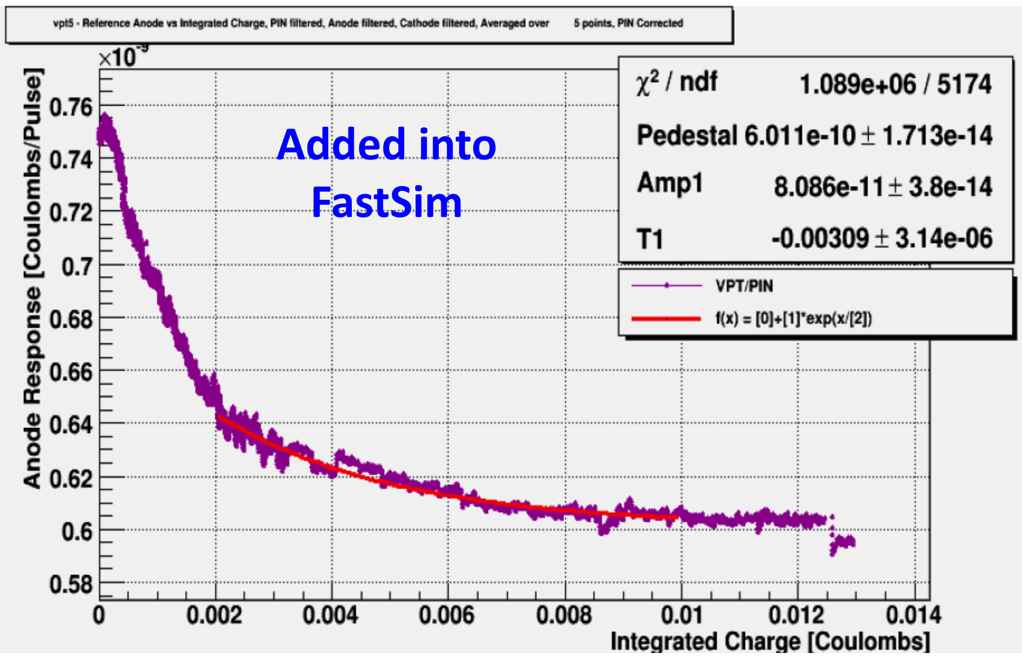
Induced absorption length
As a function of fluence



Eta dependence of fluence
(EM= red, Hadronic=black)
Normalized to η=2.5

Using the Light Loss Model

- The Light loss model is becoming more and more complete and believable
- It can be introduced into FastSIM and used to as a tool to predict the evolution of the present detector
- Should include other effects such as aging of the VPTs due to the number of Coulombs that pass through the tubes



VPT Aging