

# Recent Progress with Very Forward Calorimeters for Linear Colliders



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On behalf of the FCAL collaboration



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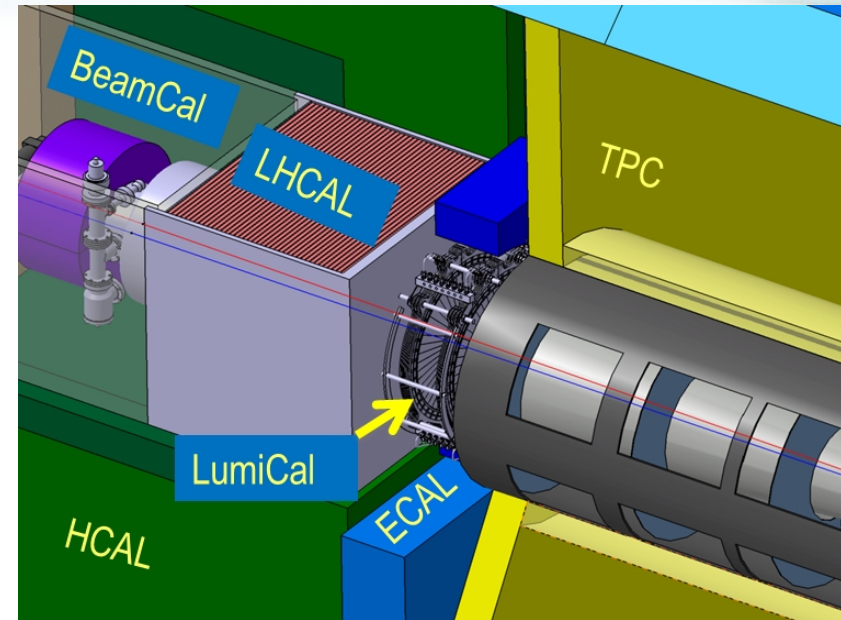
# Overview

- Instrumentation of the forward regions in linear collider experiments
- FCAL multi-plane detector prototypes:
  - LumiCal module and beam test infrastructure;
  - Thin LumiCal module design;
- BeamCal and LHCaL R&D
- Summary

# Instrumentation of the Forward Region

## Goals:

- Instant luminosity measurements;
- Provide information for beam tuning;
- Precise integrated luminosity measurements;
- Extend a calorimetric coverage to small polar angles. Important for physics analysis.



**LumiCal:**

- electromagnetic calorimeter;
- 30 layers of 3.5 mm thick tungsten plates with 1 mm gap for silicon sensors;
- symmetrically on both sides at  $\sim 2.5\text{m}$  from the interaction point.

**BeamCal:** similar construction, with tungsten absorber but radiation hard sensors (GaAs, CVD diamond).

**LHCAL:** extends the coverage of HCAL; design is being optimized in simulation studies.



# Luminosity Measurement with LumiCal

The luminosity can be measured by counting number  $N_B$  of Bhabha events in a certain polar angle ( $\theta$ ) range of the scattered electron.

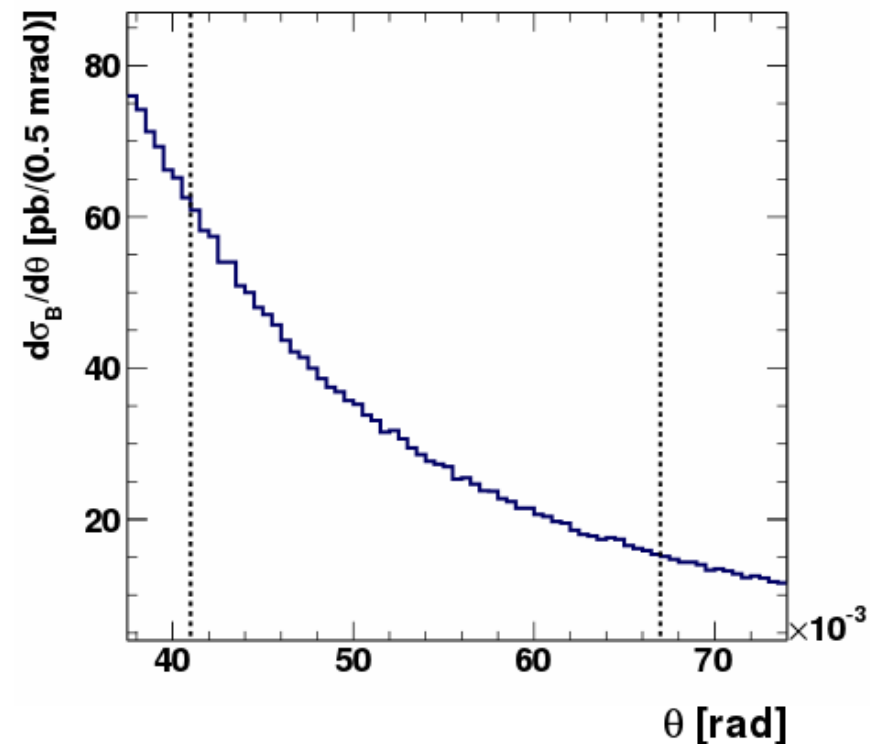
$$L = \frac{N_B}{\sigma_B} \quad \sigma_B - \text{integral of the differential cross section over the same } \theta \text{ range.}$$

The cross section of the Bhabha process can be precisely calculated.

In leading order:

$$\frac{d\sigma_B}{d\theta} = \frac{2\pi\alpha_{em}^2}{s} \frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{em}^2}{s} \frac{1}{\theta^3}, \quad \text{the approximation holds at small } \theta.$$

$\alpha$  is the fine-structure constant,  
 $s$  - center-of-mass energy squared.



# LumiCal Geometry

Uncertainty in luminosity measurement depends on the polar angle bias  $\Delta\theta$  and minimum polar angle  $\theta_{\min}$  as:

$$\left(\frac{\Delta L}{L}\right)_{\text{rec}} \approx 2 \frac{\Delta\theta}{\theta_{\min}}$$

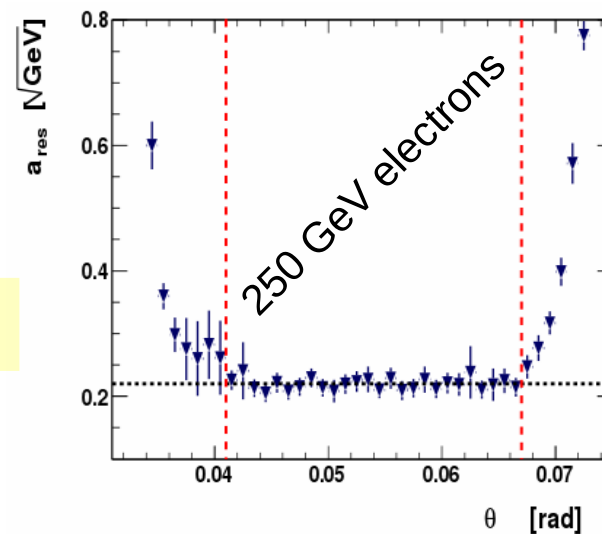
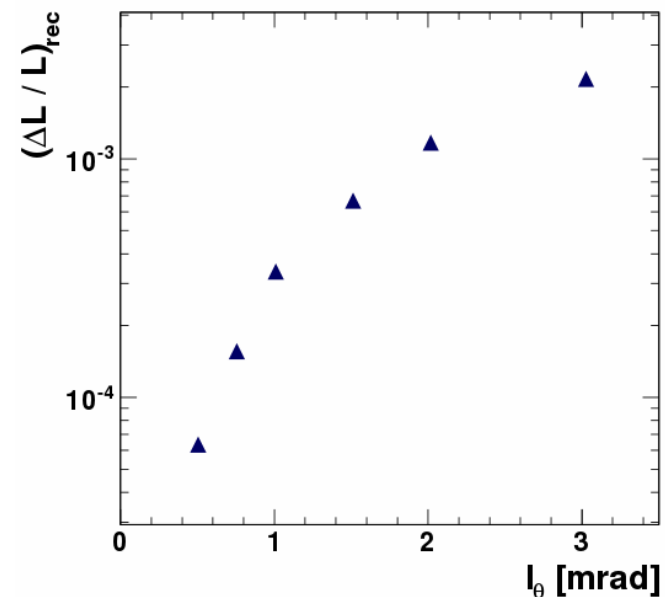
$\Delta\theta$  depends on polar angular pad size  $l_{\theta}$ .

For  $l_{\theta}=0.8$  mrad,  $\Delta L/L = 1.6 \cdot 10^{-4}$ .

Energy resolution: 
$$\frac{\sigma_E}{E} = \frac{a_{\text{res}}}{\sqrt{E_{\text{beam}} \text{ (GeV)}}}$$

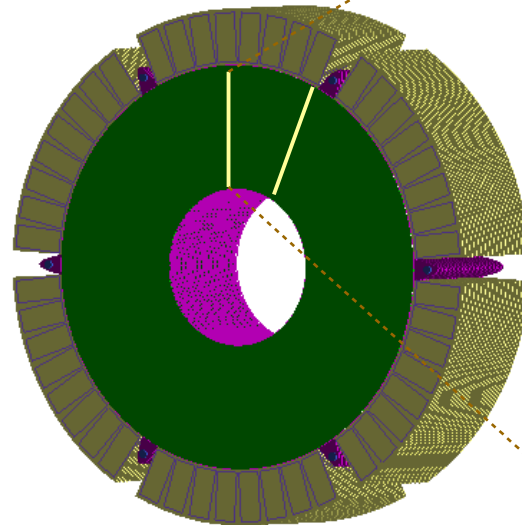
LumiCal fiducial volume:  $41 < \theta < 67$  mrad

$$a_{\text{res}} = (0.21 \pm 0.02) \sqrt{\text{GeV}}.$$

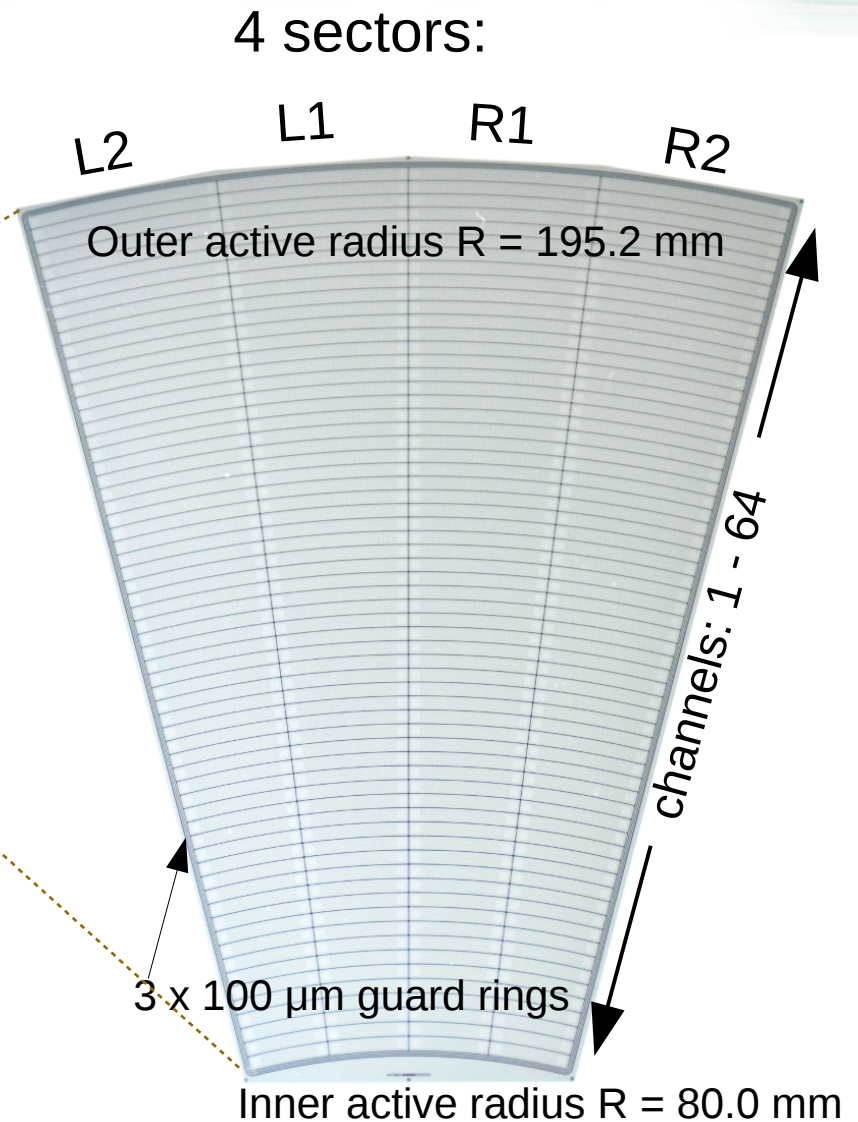


# LumiCal Design

- 12 tiles make full azimuthal coverage
- 4 azimuthal sectors in one tile,  $7.5^\circ$  each
- 64 radial pads, pitch 1.8 mm



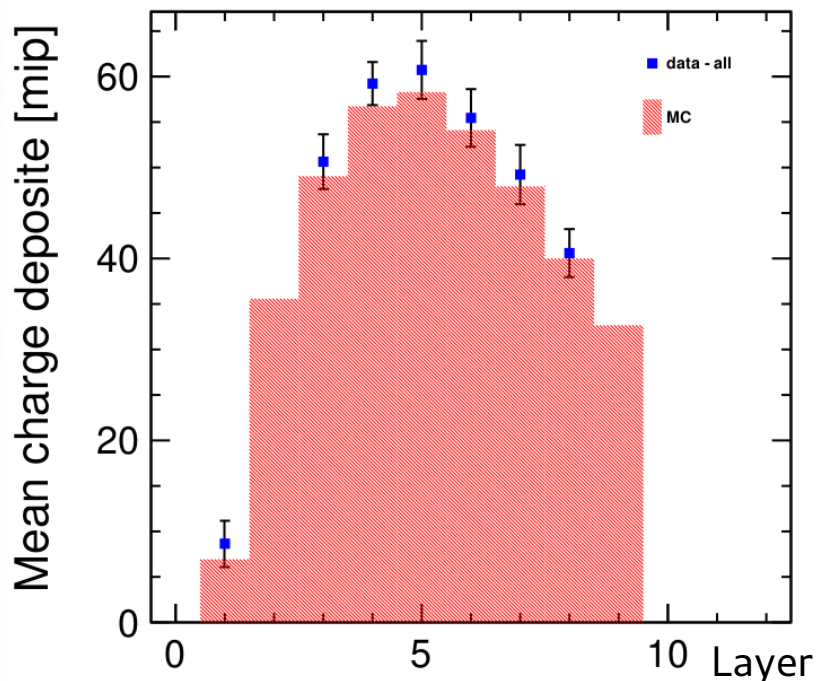
- Silicon sensor
- thickness  $320\ \mu\text{m}$
- DC coupled with read-out electronics
- $p^+$  implants in n-type bulk



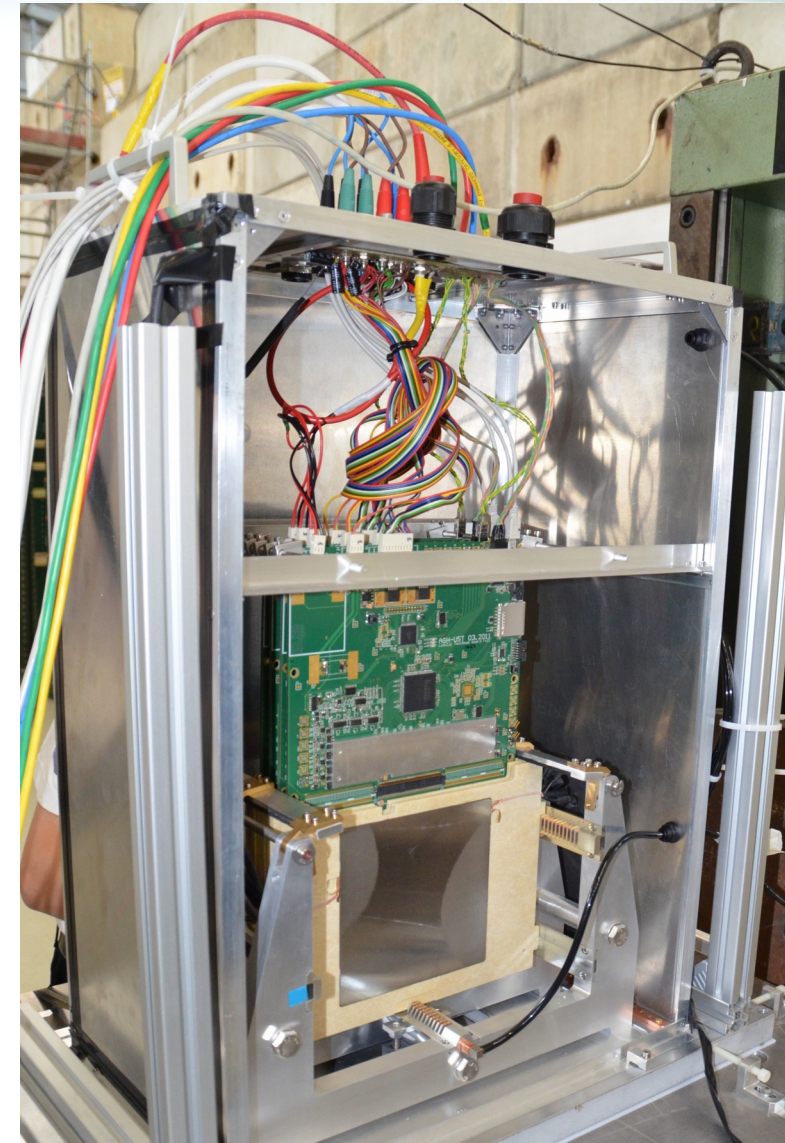


# Beam Test of LumiCal Multilayer Prototype

- CERN PS 5 GeV/c e<sup>-</sup> (muons, used for calibration);
- 4 LumiCal detector modules;
- 10 tungsten absorber plates in permaglas frames;
- Mechanical frame for precise ( $\pm 50\mu\text{m}$ ) positioning of absorber layers;
- 3 configurations for longitudinal scan of the electromagnetic shower.



Longitudinal shower development



Four LumiCal modules in stack

# Shower Study in Transverse Plane

Transverse shower profile is approximated as

$$F_{E(r)} = (A_C)e^{-\left(\frac{r}{R_C}\right)^2} + (A_T)\frac{2rR_T^2}{(r^2 + R_T^2)^2}$$

$r$  – the distance from the shower center;  
 $A_C, A_T, R_C, R_T$  – fit parameters.

Moliere radius  $R_M$  can be found from the equation:

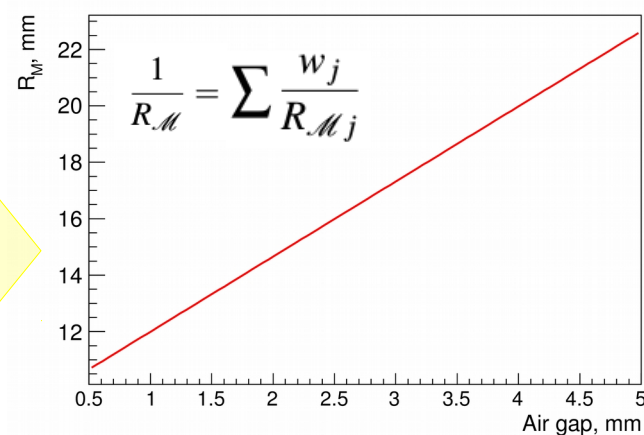
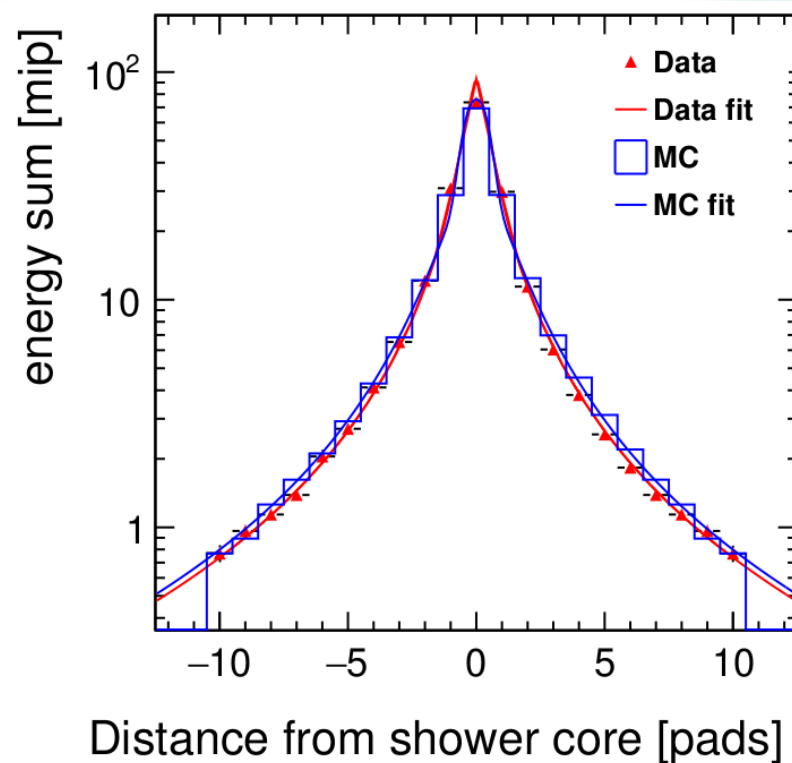
$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_M} F_E(r) r dr$$

For the configuration with four detectors at  $3X_0, 5X_0, 7X_0$  and  $9X_0$ , preliminary result gives  $R_M = 1.6 \pm 0.2$  cm for the data;

Analysis in progress...

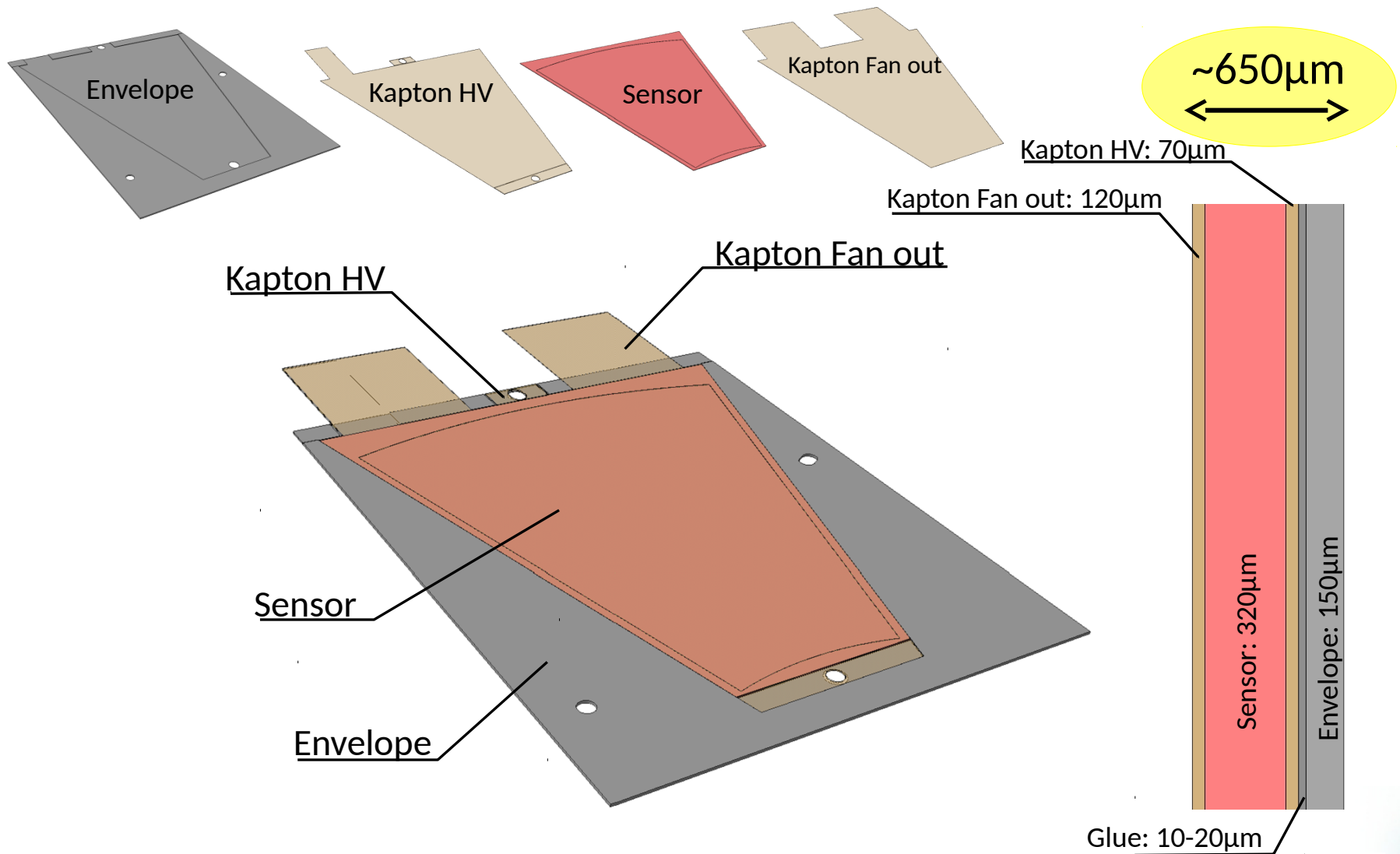
$R_M$  as function of the air gap between 3.5 mm thick tungsten plates

Reducing air gap from 4.5 mm to 1 mm gives RM: 21 mm -> 12 mm.





# Design of the Thin LumiCal Module

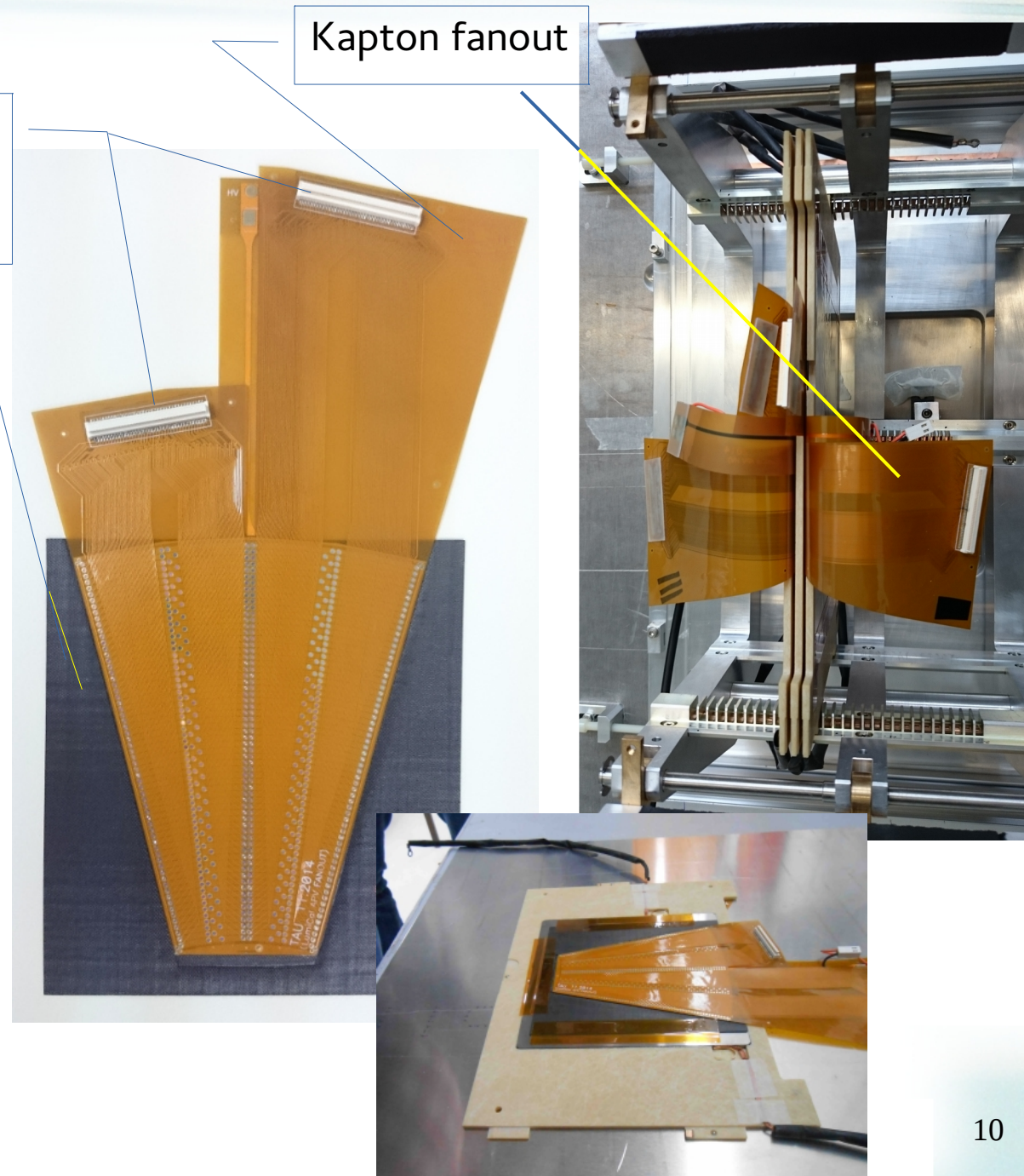


# Thin LumiCal Module in Mechanical Frame

130 pin Panasonic connectors provides interface to APV-25 hybrid and SRS DAQ system.

Carbon fiber supporting structure ("envelope") provides mechanical stability and easy stack assembly.

- 4 modules were successfully tested with e- beam at DESY in October 2015. Data analysis is in progress.
- 4 additional modules are in preparation for beam test in August 2016 including one assembled with TAB bonding technology.



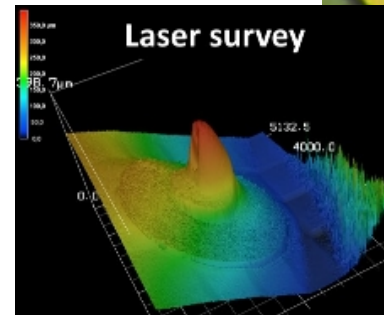
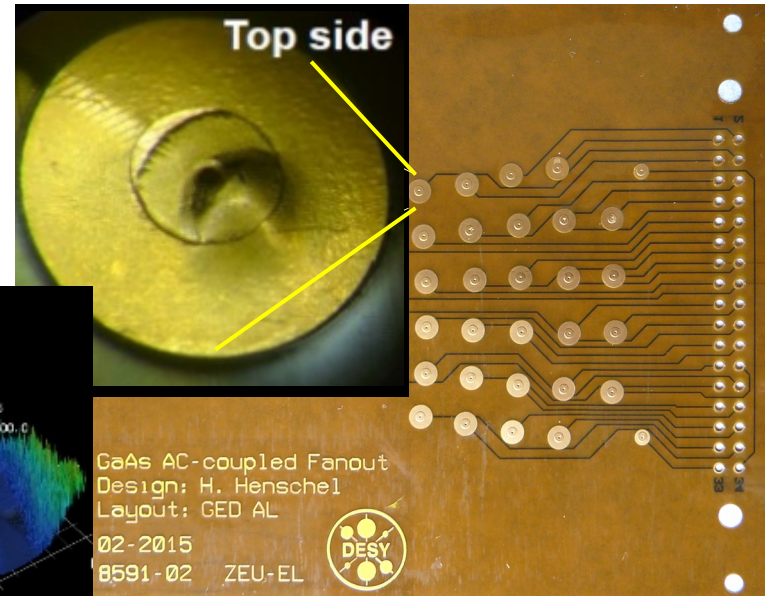
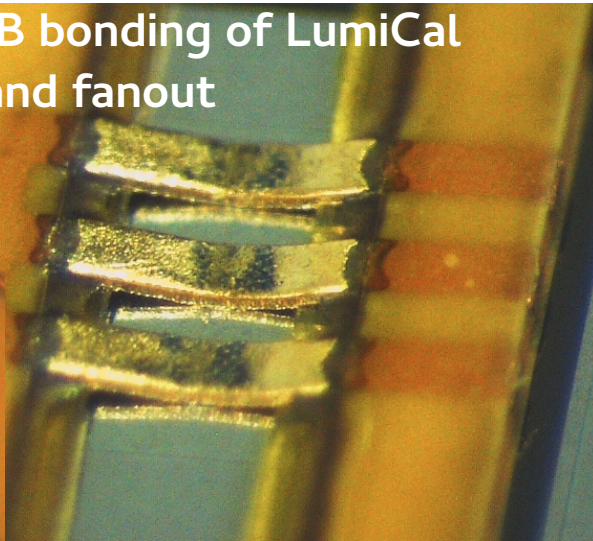


# Front-end Contact Technologies

Search for long-term stable contact between sensor and readout electronics which meets LumiCal and BeamCal geometrical (compactness) requirement

Test TAB bonding of LumiCal sensor and fanout

wire bonding



GaAs AC-coupled Fanout  
Design: H. Henschel  
Layout: GED AL  
02-2015  
0591-02 ZEU-EL



## Single point Tape Automated Bonding (TAB):

- No wire loop, the bond can be covered by the glue for better protection;
- One LumiCal module is being assembled and tested using TAB technology.

## Spring Loaded Contact:

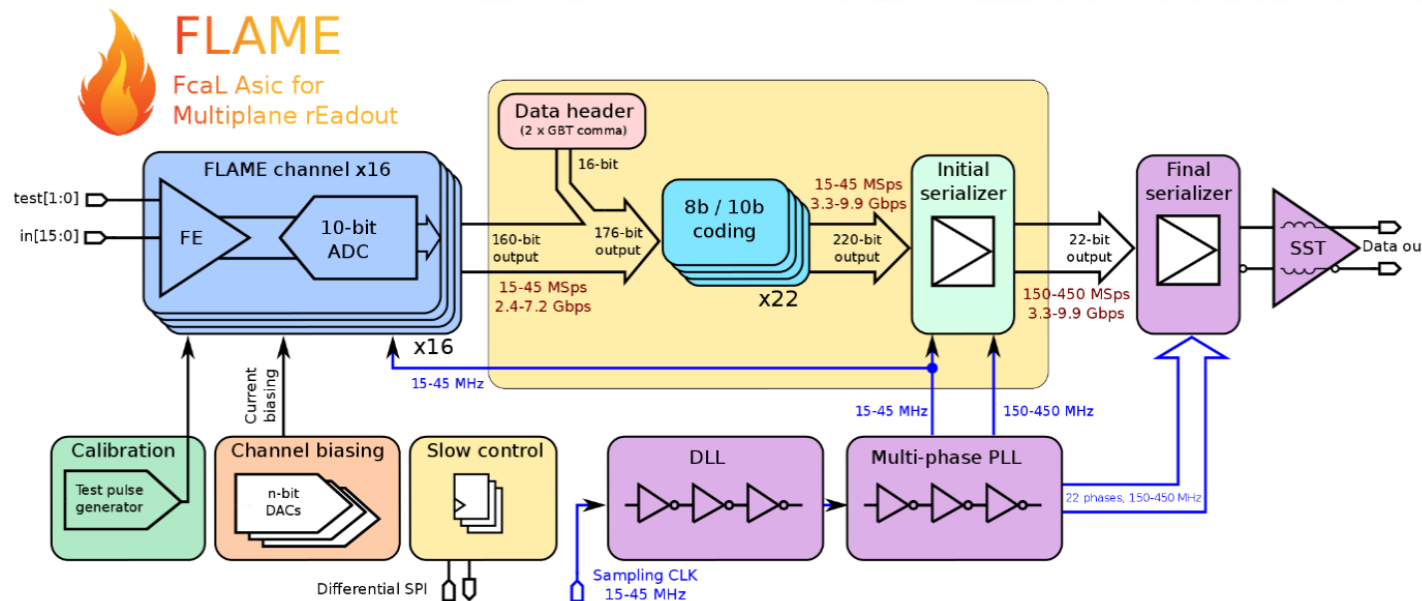
- Bumped fanout has been produced;
- It demonstrates good contact at certain pressure ( $\sim 7.2\text{kPa}$ );
- Ongoing tests with GaAs sensor.



# New LumiCal Readout ASIC

## FLAME – FcaL Asic for Multiplane rEadout

16-channel ultra-low power readout ASIC in CMOS 130 nm, FE&ADC in each channel, fast serialization and data transmission, all functionalities in single ASIC.



Two components of the FLAME were designed and produced:

Prototype ASIC comprising 8 FLAME channels:

- Front-end with variable gain, differential CR-RC shaper,  $T_{peak} = 50\text{ns}$ ,  $ENC \sim 900\text{el}@20\text{pF}$
- 10-bit multichannel SAR ADC
- Power (FE+ADC)  $< 2\text{mW/channel}$

Fast (3.3 – 9.9 Gbps) serializer with SST driver

- Simulated power consumption  $\sim 15\text{ mW}$

Tests will start soon.

# Beam Parameters Reconstruction in BeamCal

Energy depositions in BeamCal from  $e^+ e^-$  pairs, produced by beamstrahlung photons, can be used for fast beam parameter reconstruction and instant luminosity measurements.

- Use GuneaPig to simulate the beam with modified parameters:
  - Increase beam envelope at origin;
  - Move waist of electron and positron beam;
  - Change targeting angle of electron and positron beam.
- Study parameters (observables) of 3D energy deposition distribution in BeamCal:
  - Deposited energy,
  - mean depth of shower,
  - L/R and up/down asymmetries,
  - thrust (relative to barycenter) value.
- find the dependence between BeamCal observables and beam parameters.

Previous study assumed linear dependence between BeamCal observables and beam parameters and used Moore-Penrose inverse of the Taylor matrix to calculate the parameters of the beam.

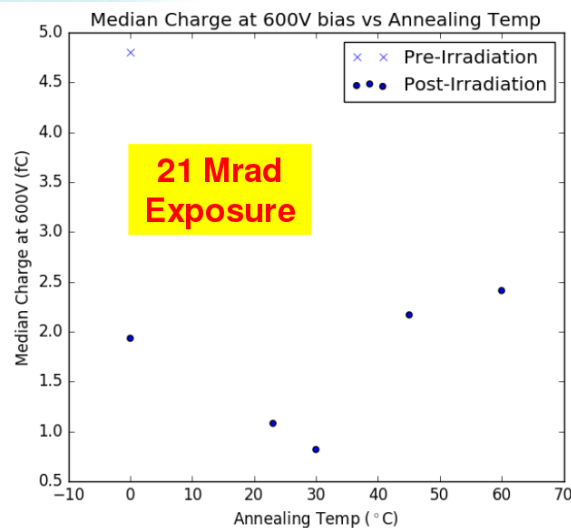
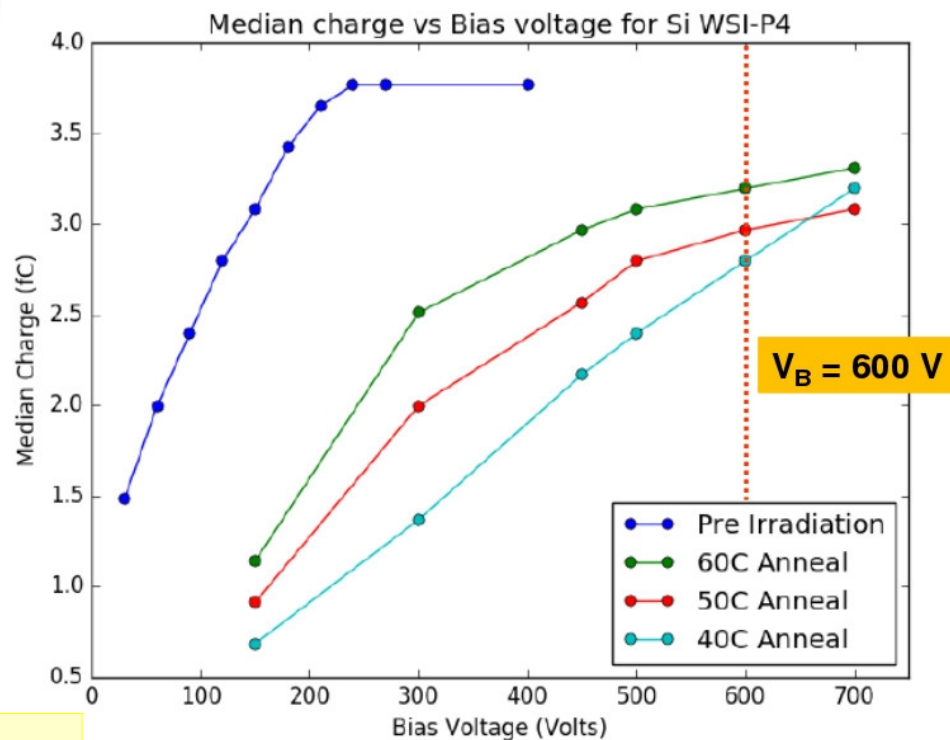
# BeamCal Sensors Radiation Studies

Electromagnetically-induced showers irradiation at 3°C

Sensor Type	Notable Exposures (Mrad)
GaAs	<b>20</b>
SiC	<b>80</b>
Si PF	<b>270, 570</b>
Si NF	<b>300</b>
Si PC	<b>300</b>
Si NC	<b>290</b>

Si sensors legend:

- P – p-type bulk;
- N – n-type bulk;
- F – float zone;
- C – Czochralski



Mean collected charge in GaAs sensor after 21 Mrad for different annealing temperature

~20% loss at 600V and 60°C anneal for silicon detectors.

GaAs sensor shows better performance compared to the e- irradiation w/o e-m shower.

- GaAs is the default option with many prototypes fabricated and studied.
- Very promising results have been obtained recently with rad-hard silicon sensors.
- Other materials are studied (SiC, CVD).

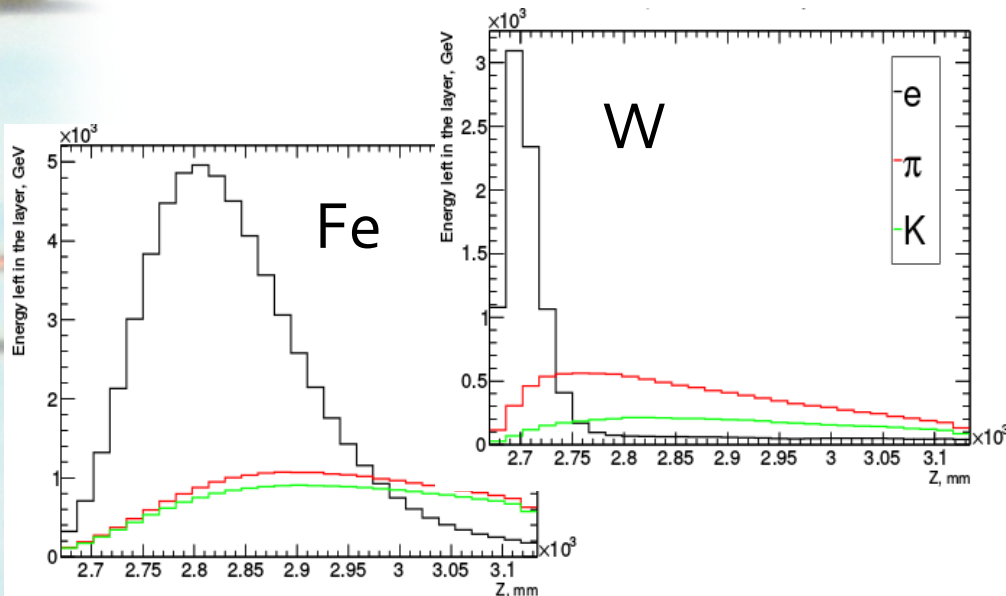
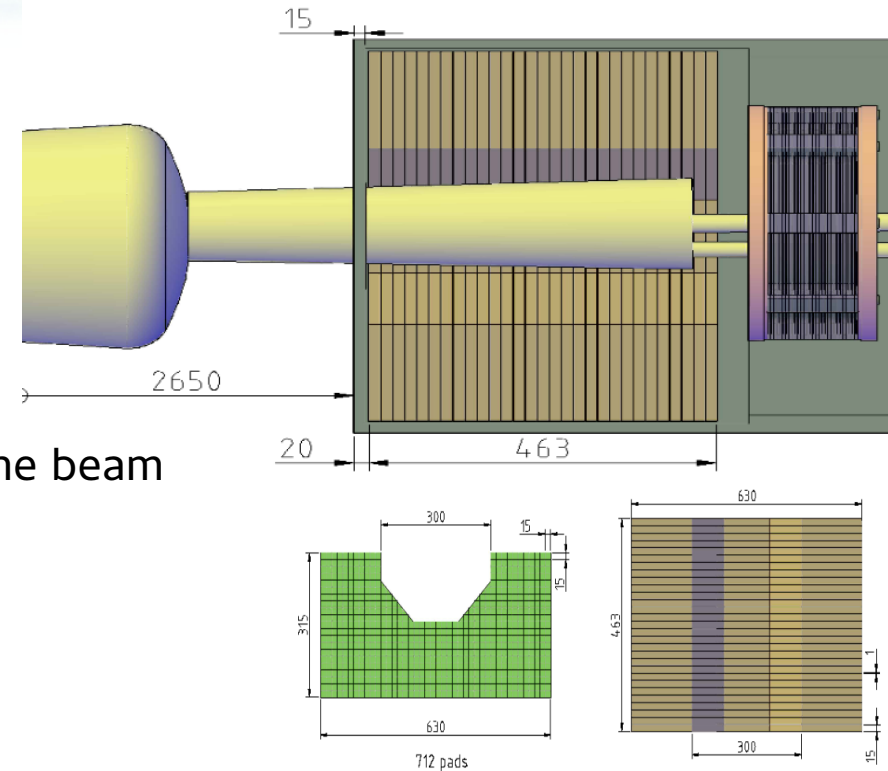


# LHCal Study

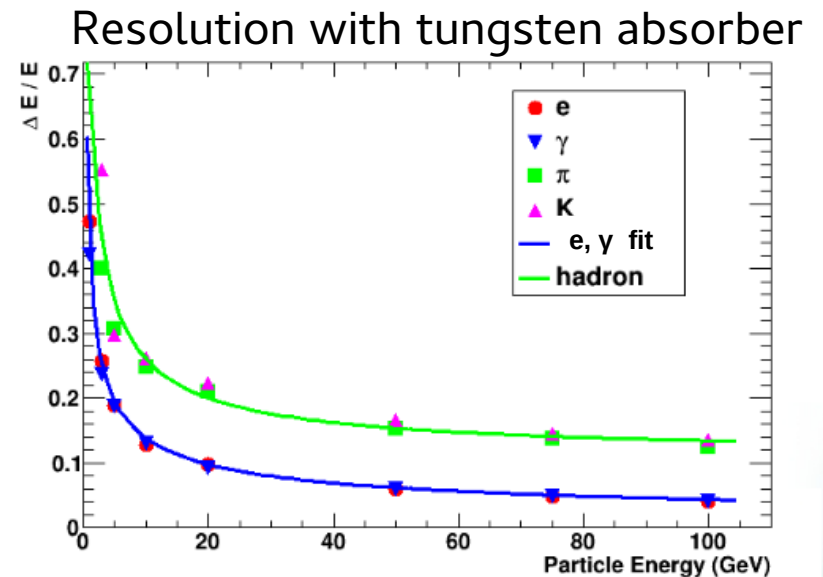
- LHCal is a sampling hadronic calorimeter;
- Covers the gap between LumiCal and BeamCal;
- Provides lepton – hadron identification;

Optimized geometry and performance is studied in simulation:

- External dimensions are constrained by the beam pipe, LumiCal and BeamCal positions;
- Fe vs. W absorbers;
- Implemented in DD4Hep.



Energy deposition per layer



# Summary

- Electromagnetic shower development in LumiCal 4-module prototype was studied using the beam test data. The paper is in final stage of preparation.
- Thin LumiCal modules with submillimeter thickness were developed and successfully produced. The LumiCal prototype with the thin modules and existing mechanical structure was assembled and tested with beam. Data analysis is in progress.
- Spring Loaded Contact and TAB technologies are investigated as a possible solution to connect fanout to LumiCal and BeamCal sensors.
- Prototypes of new fast, ultra-low power SoC type readout ASIC were produced and will be tested soon.
- Studies of the LC beam parameter reconstruction using BeamCal observables and possible BeamCal sensor materials Si, GaAs, SiC continue.
- LHCAL design optimization study in simulation is underway.

Thank you for your attention!