Recent developments in Linear Collider Calorimeter R&D

a brief and incomplete overview;
many more details in the calorimeter sessions

Daniel Jeans, The University of Tokyo
LCWS 2015, Whistler

Calorimetry for Linear (Lepton) Colliders

maximise the physics potential of
hadronic final states
which dominate the decays of W, Z, H

make a hadronic jet as useful as a lepton when
probing electro-weak processes
→ maximise profit from leptonic initial state,
& resulting “triggerless” operation

benchmark:
distinguish di-jet final states of W and Z
→ jet energy resolution ~3%
~ 2x better than existing systems
→ needs improved or new devices

average hadronic jet energy

dominated by charged hadrons ~65%

photons ~25%, neutral hadrons ~10%

Typical hadronic calorimeters have precisions of ~10s of % at

typical LC particle energies 1 ~ 10 GeV

Two approaches to improved resolution being investigated:

– minimise use of calorimeters:

use tracker momentum measurement whenever possible

“Particle Flow”

→ highly granular particle flow calorimeters

→ also allows detailed reconstruction of e.g. hadronic tau decays

– improve intrinsic hadronic calorimeter performance

→ *e.g.* dual readout, shower-by-shower compensation

calorimeters in the forward region have additional roles

luminosity via small angle Bhabha scattering

beam size via beamstrahlung remnants ← fast feedback to machine

in a relatively high radiation environment

Technologies

Large sensitive volumes/areas are required
→ cost becomes important factor
A variety of technological approaches are being developed

Dual readout
heavy glasses and scintillating fibers

High granularity ~ O(1 cm^3)
scintillator
strips or cells, read out by SiPMs

semi-conductor diodes
(silicon, GaAs for radiation hardness)

gas
glass RPC,
MPGD (GEM, MicroMegas, …)

Dual readout

disentangle hadronic and electromagnetic (E-M) components of every jet

→ per-jet compensation between EM and hadronic response

→ improved energy resolution

ADRIANO concept

A Dual-readout Integrally Active Non-segmented Option

– scintillating fibers: sensitive to both E-M and hadronic components embedded in

– heavy glass: Cerenkov radiation sensitive dominantly to EM comp.

R&D in T1015 collaboration @ FNAL

testing Pb- and Bi-based glasses,

glass machining/moulding techniques,

isolation between Cherenkov and Scintillation

C. Gatto

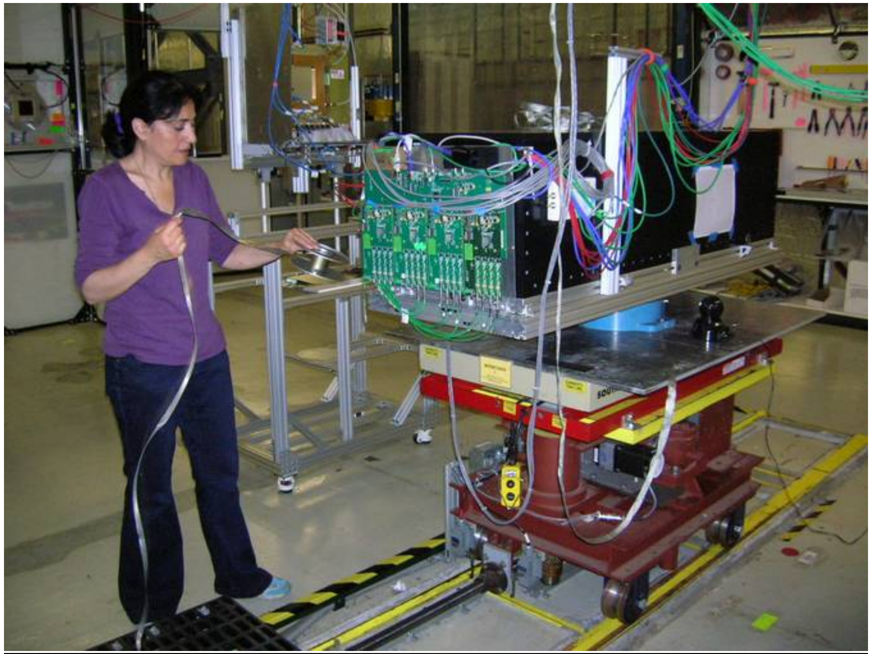
T1015 R&D

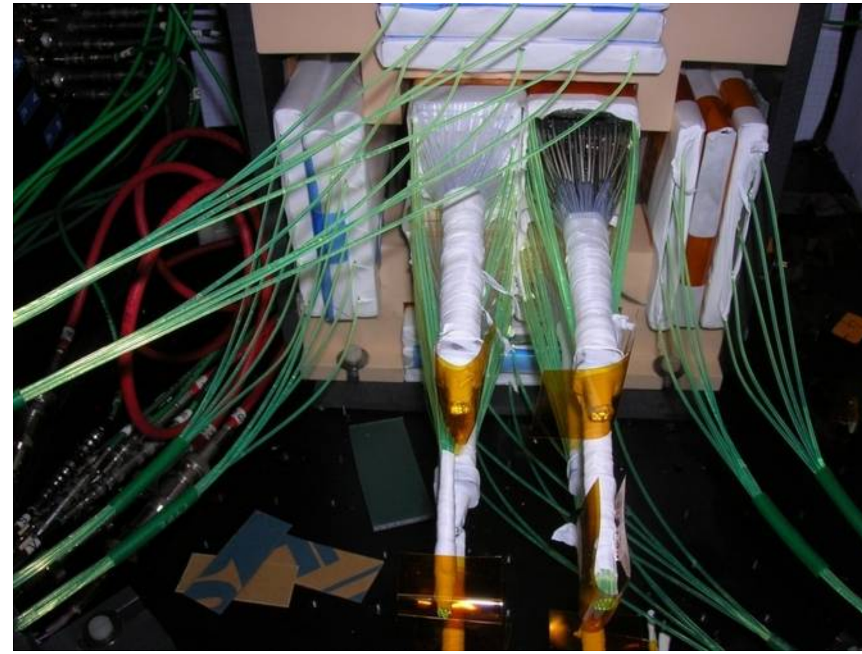
- Exploits dual-readout techniques for
  - High Energy and High Intensity experiments
- Supported by Fermilab and INFN
  - Operating at Fermilab since 2010
- 16 prototypes built and nine test beams completed
- Cerenkov light yield achieved:
  - 4000 pe/GeV for high intensity version
  - >350 pe/GeV for high energy version
- Future R&D will concentrate on cheaper construction techniques
- Energy resolution for high energy version: ~ 30%/√E
- Particle ID also from scintillation vs Cerenkov

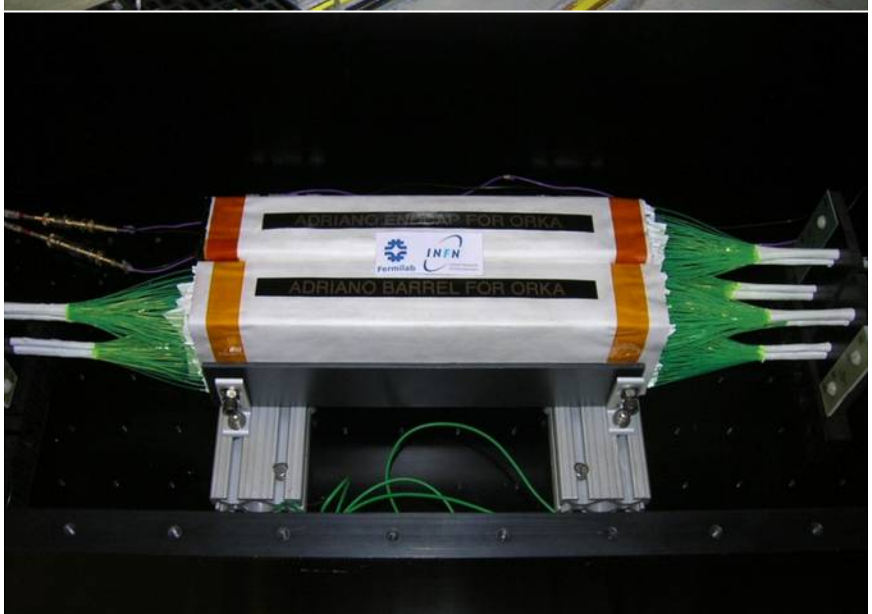
→ Valid alternative to PFA techniques

Pictures from recent test beams

C. Gatto







High granularity – scintillator + SiPM/MPPC both ECAL and HCAL

progress in

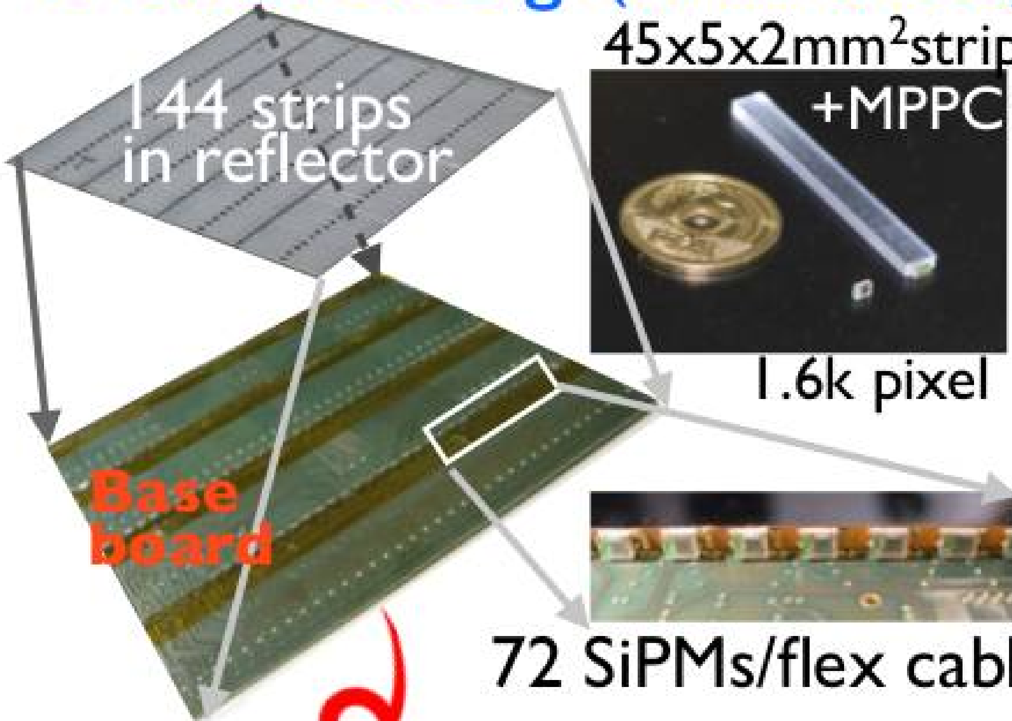
scintillator cell geometries and readout schemes
- square cells or long strips (aspect ratio ~10)
- SiPM positioning ← better for mass production
- improved SiPM devices

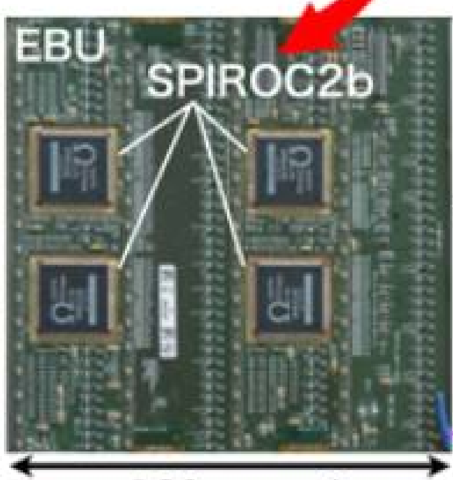
especially in HCAL: imact of Fe *vs* W absorber
- At modest energies, typically use Fe
- W favoured at higher energies (i.e. CLIC)
  - for compactness (solenoid size)

hadronic showers in W showers typically
have larger slow neutron component
→ important to check GEANT4 simulations,
especially of time evolution

ScECAL technological prototype

1. Default design (on trans. EBU)





transverse EBU

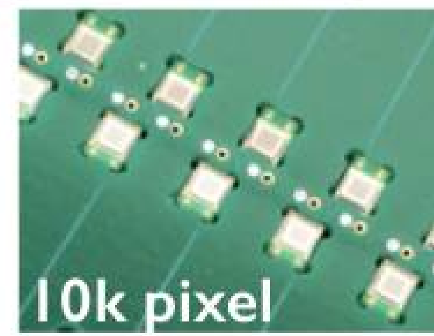
- Individually set bias, amplifier, threshold.
- Auto trigger.
- LEDs for gain monitor

2. Bottom readout

non dead volume from MPPC

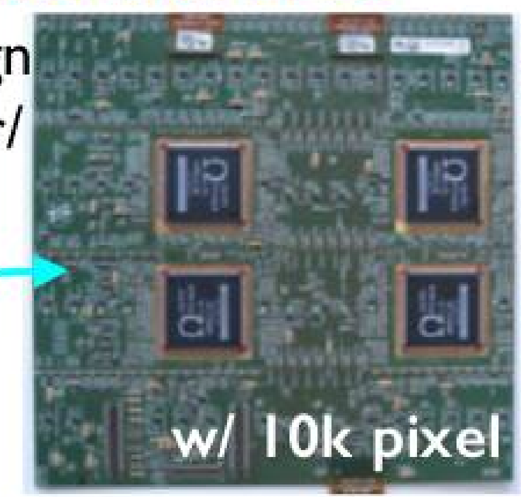
Bottom readout design by Tokyo group

MPPCs embedded into a board



3. longitudinal EBU

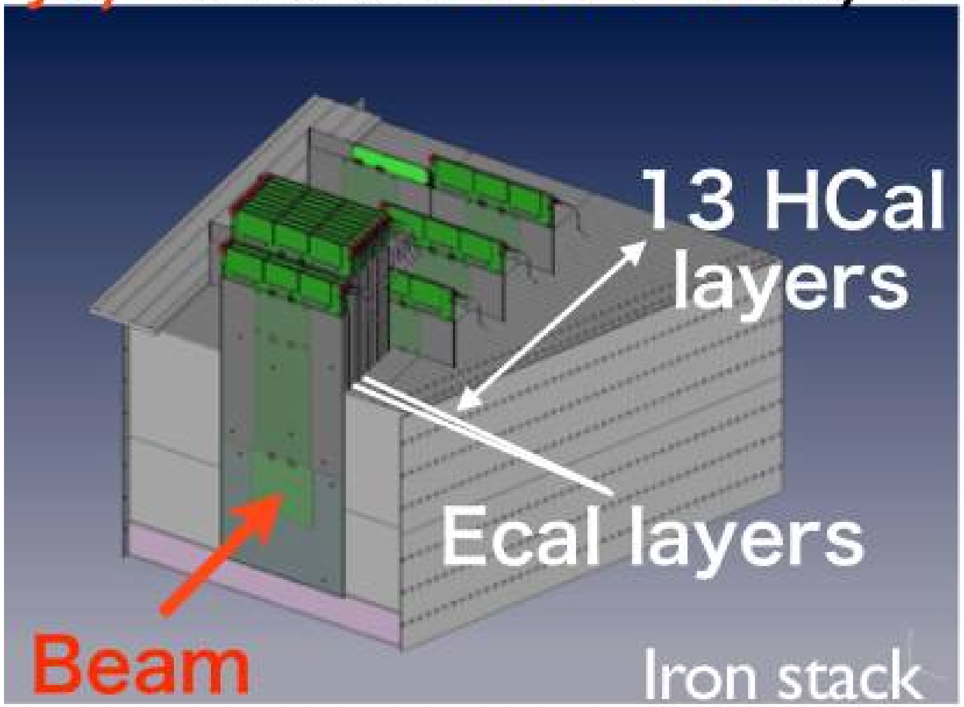
Default design of scintillator/ MPPC



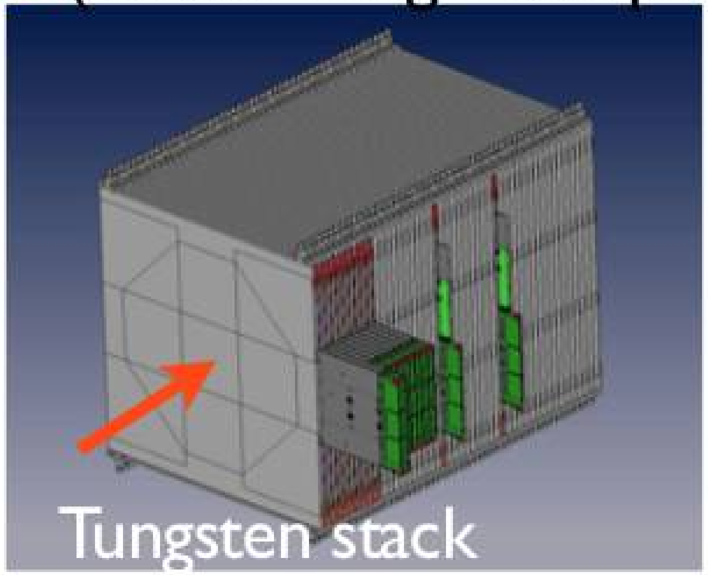
K. Kotera

Test beam experiments 2015 July August

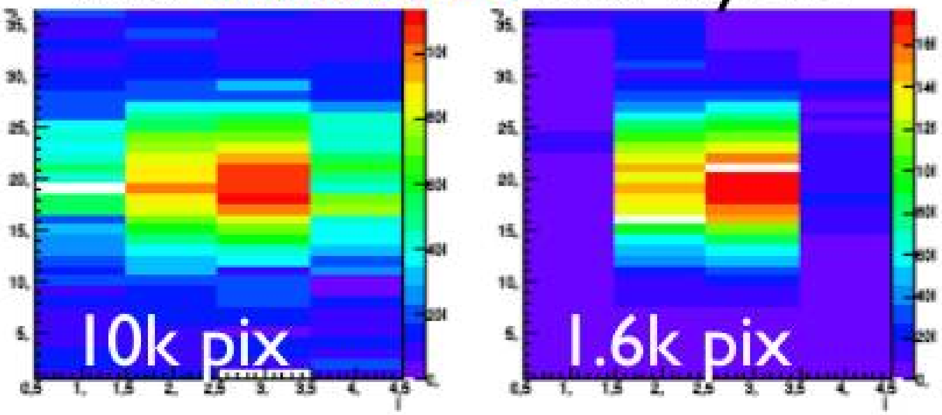
July 2015: two transverse layers

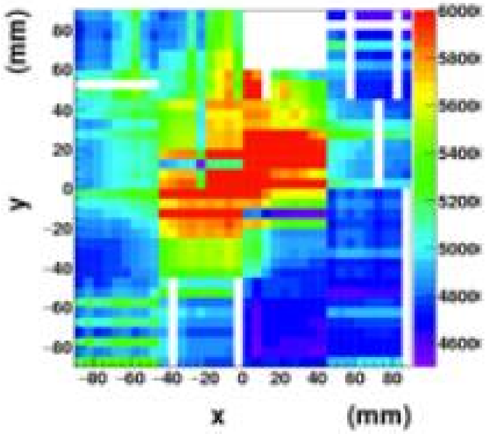


August
transverse(bottom readout 10kpix)
longitudinal(default design 10k pix)
transverse(default design 1.6k pix)



a hit map of 50 GeV pion events
Two transverse Ecal layers





5x5mm^2 segmentation with two layers

K. Kotera

K. Krueger

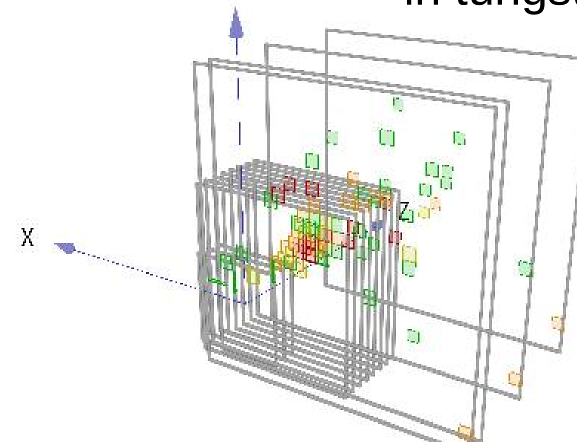
AHCAL Testbeams

first SPS test beam with
    2nd generation electronics and DAQ

2 weeks in EUDAQ steel stack in July 2015
2 weeks in tungsten stack in August 2015
system test:
    scalable DAQ, power distribution and cooling
very stable running of the detector
no instabilities in electronics and DAQ observed

collected data sets
muons for MIP calibration check
energy scan for electrons
energy scans for pions

50 GeV π
in tungsten



next steps
2016: test of a 15 layer e.m. stack with
    high quality photo-sensors at DESY and
    possibly SLAC: test power pulsing!
2017: construction of a big hadronic prototype
2018: test with hadrons at CERN

K. Krueger

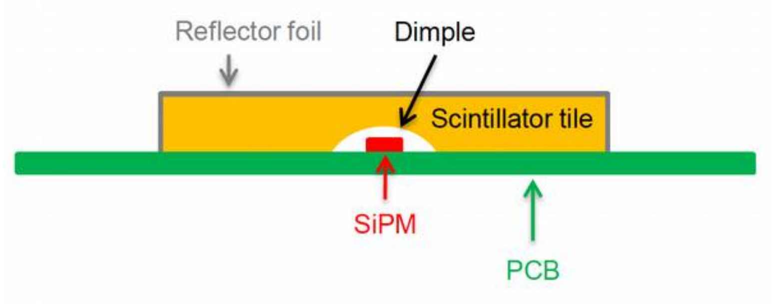
Towards mass production: simplified tile & HBU design

tile design with SiPMs mounted on the side of the tile not suitable for mass assembly

tiles with surface-mount SiPMs fulfil HCAL requirements:
- signal size
- signal uniformity across tile

new HBU design for surface-mount SiPMs:
- SiPMs mounted directly on PCB
- individually wrapped tiles
- mass assembly with pick-and-place machine possible
- further possible improvements identified, to be tested

very positive experience in SPS testbeam



K. Krueger

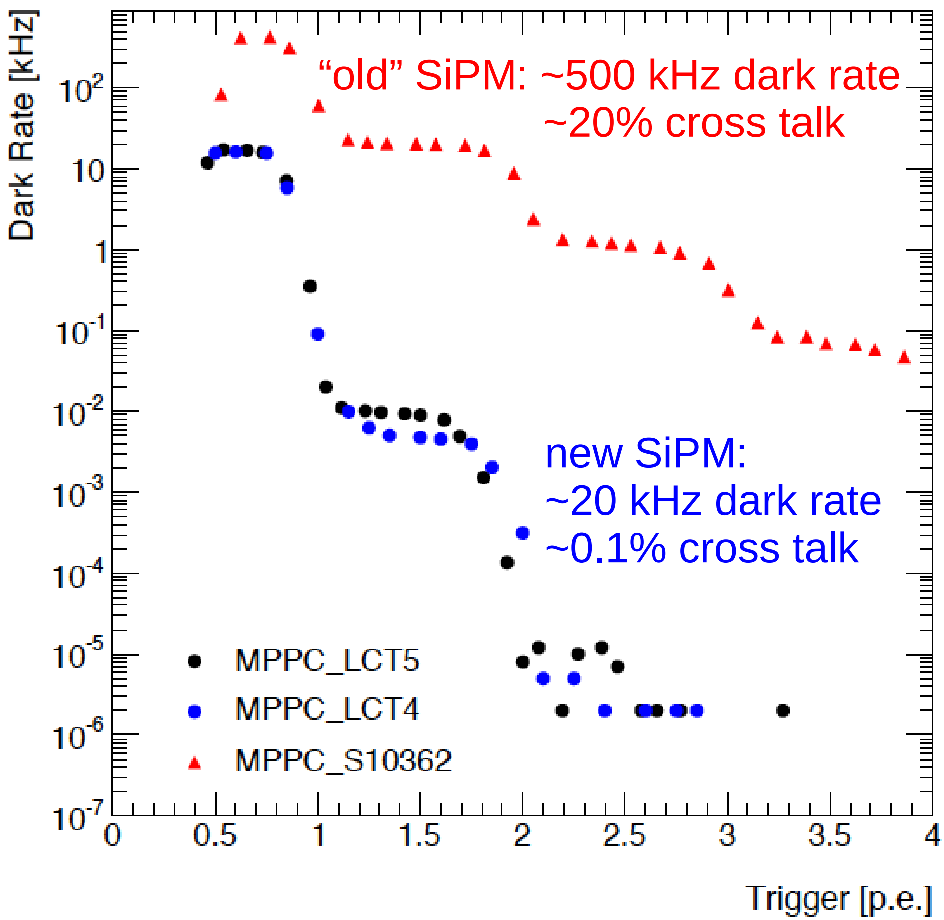
New generation of SiPMs

recent SiPMs show very much improved sample uniformity:
- operating voltage
- gain

very recently, SiPMs with trenches between pixels became available
- → slightly reduced geometrical fill factor
- → dramatically reduced dark rate and pixel-to-pixel cross talk

→ noise-free for typical trigger threshold of AHCAL (~7 p.e)

New devices with 10µm pixels
- → improved dynamic range, needed for ECAL



for comparison: SiPMs in physics prototype
2 MHz dark rate, 30% cross talk

High granularity – semiconductor

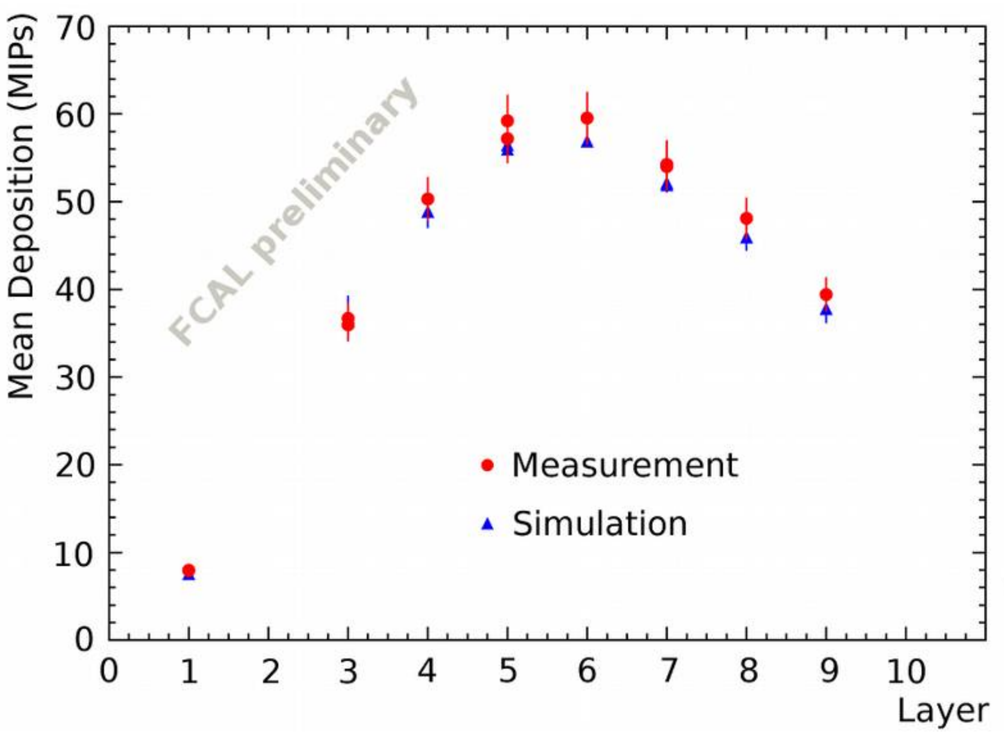
- Silicon
- GaAs
  - for high radiation environment
    - in very forward region

S. Lukic

LumiCal beam test 2014 @ CERN PS, beam T9

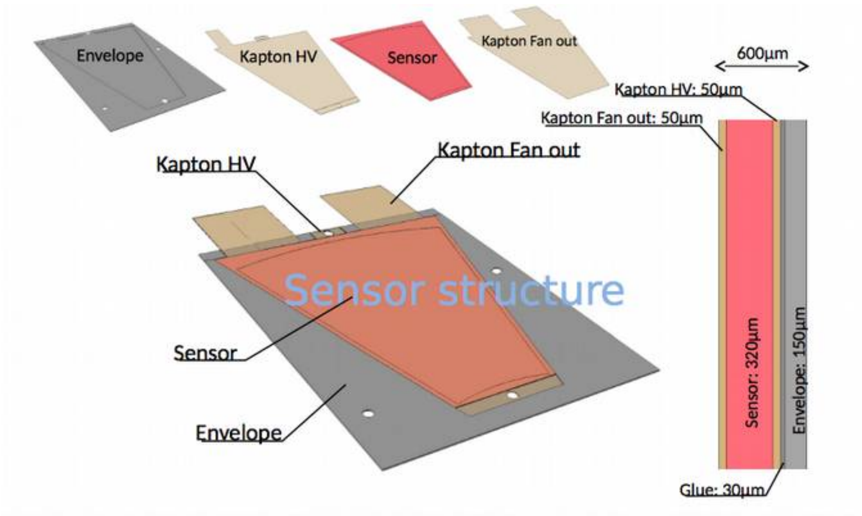
- First time multi-plane operation of a LumiCal prototype
- Excellent signal-to-noise performance of the sensors
- Precise mechanical structure
- Progress in understanding shower development from comparison with Geant4 simulations

LumiCal prototype in the Mechanical structure for beam tests

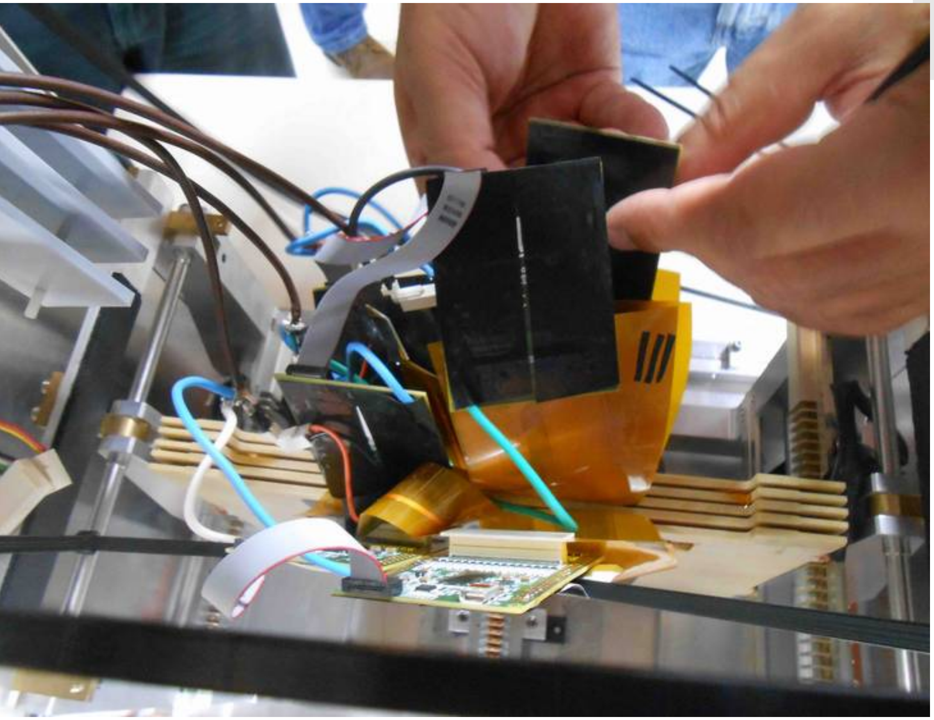


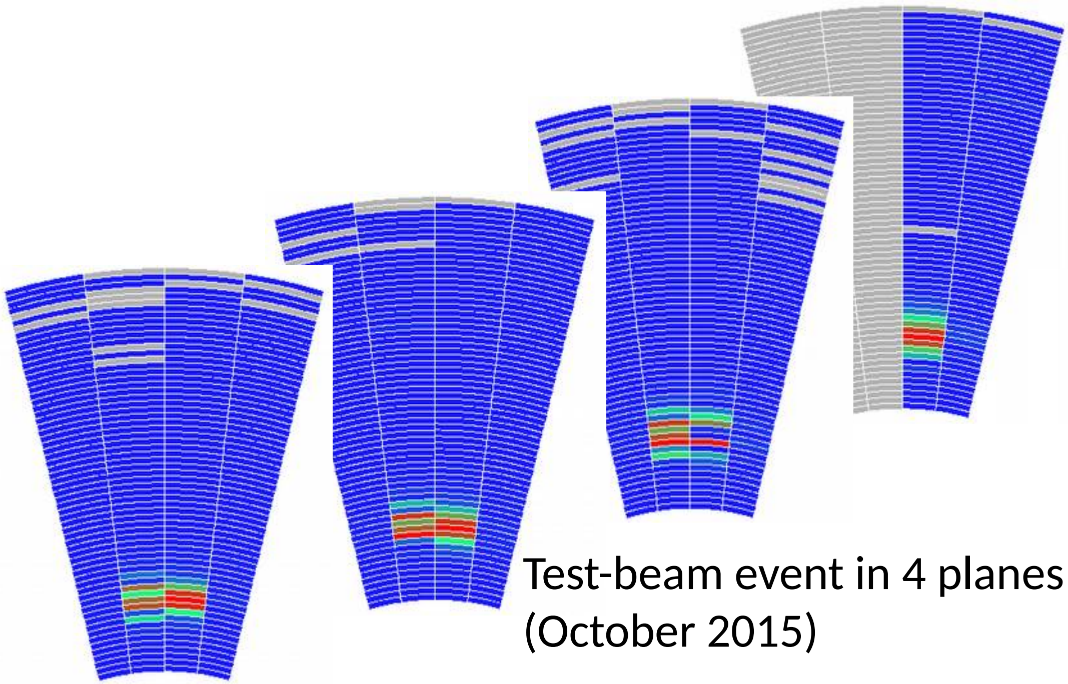
S. Lukic

New sensors for an ultra-compact LumiCal



- Sensor structure thickness below 1 mm required
- 4 new fully-equipped sensors assembled – thickness within 800 µm
- 128-channel APV chips (2 per sensor plane) for readout of all sensor pads.
- Test beam @ DESY Hamburg, October 2015 with a 6-plane DATURA telescope





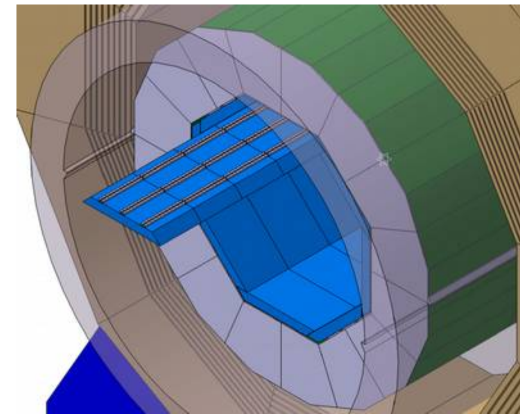
Test-beam event in 4 planes (October 2015)

V. Balagura

Silicon-tungsten ECAL for ILD

p-n junction without amplification, key features:
- easily segmentable (5x5 mm^2 pixels) ⇒ high granularity
- stable response (7000 e-holes / MIP / 100 um thickness), intrinsically linear, no saturation, no dependence on environmental changes, stable in time (several years of beam tests) ⇒ lowest systematics

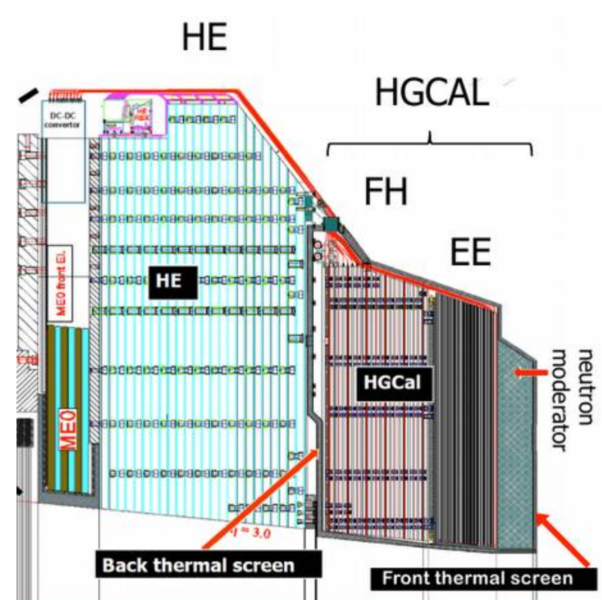
Small Moliere radius = 9 mm
Large interaction / radiation length ratio = 28



but: high cost (less expensive than tracker Si:
~ 2.5 EUR / cm2 for mass production)

Energy resolution: $16.6\% / \sqrt{E} \oplus 1.1\%$, NIM A608 (2009) 372

CMS High Granularity CALorimeter: phase-2 upgrade of ECAL+HCAL endcaps for High Luminosity LHC
(≥140 pile up evs, up to 10^{16} n/cm^2)



Approved this spring, similar Si active detectors, inspired by ILC SiECAL, good synergy between two projects.

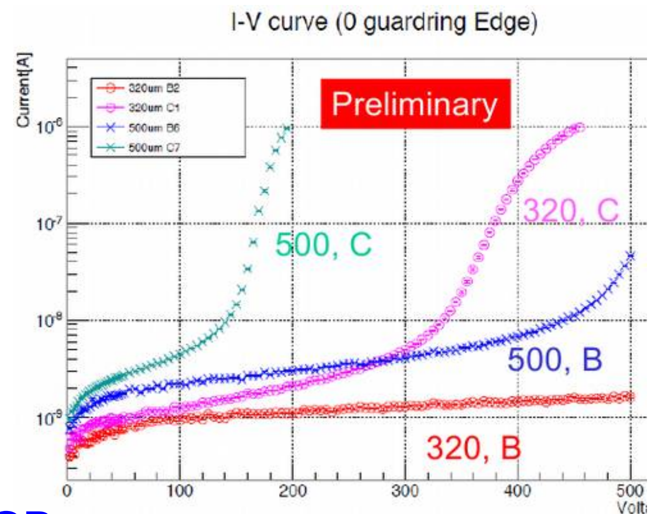
EE: 28 layers of W/Cu+Si,
FH: 12 layers of brass+Si

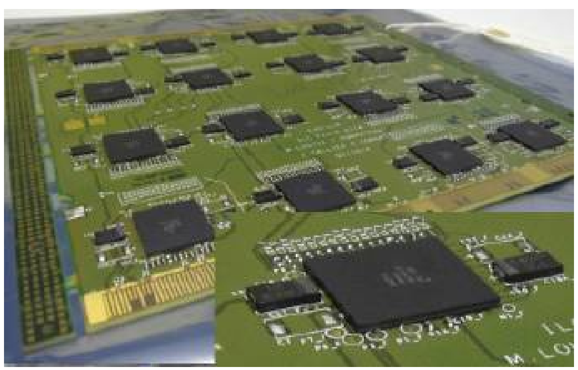
Common CERN beam tests planned (spring 2016), common front-end chips production (end 2015)
(SKIROC for HGCAL: much faster, no power pulsing).

Sep 2015: expression of interest for ATLAS:
High Granularity Timing Detector, Si timing preshower between LAr barrel and end-cap cryostats in $2.5<\eta<4$ (4 layers in $\Delta z=6$ cm, $\delta t\sim50$ psec), also inspired by CALICE SiW ECAL.

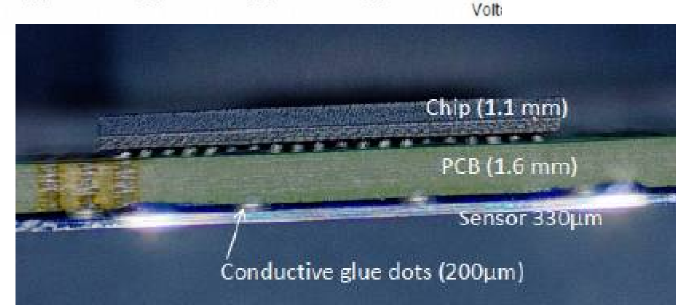
Recent ILD R&D

Si sensor studies: 320 – 500 – 700 um thickness, various guard ring designs, including “no GR” from Hamamatsu.

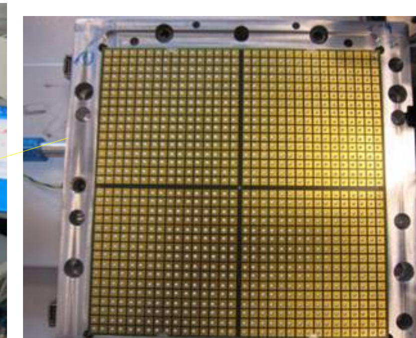




A few detectors with new PCB (ILD channel density, $\sim$5x5 mm^2) carrying 4 sensors, 1024 channels have been recently assembled, tests at CERN SPS on 4-16 Nov.

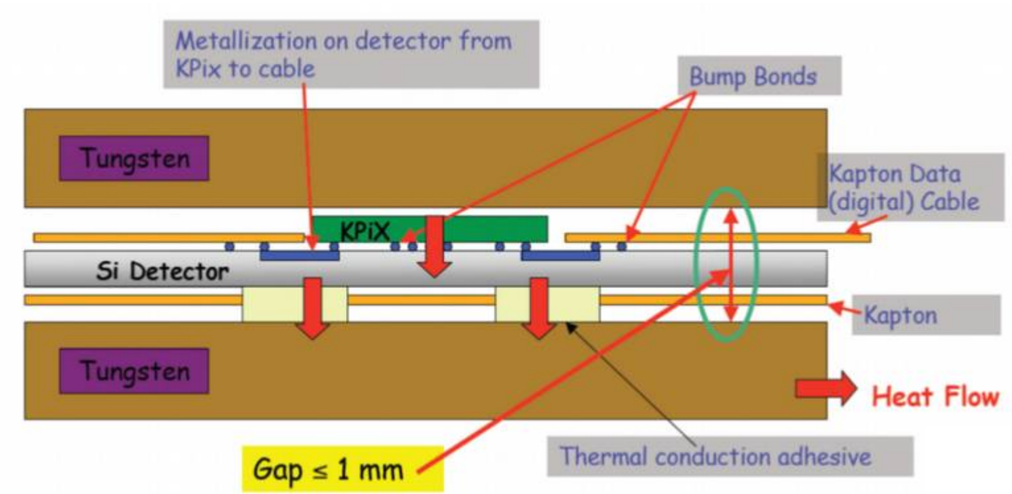


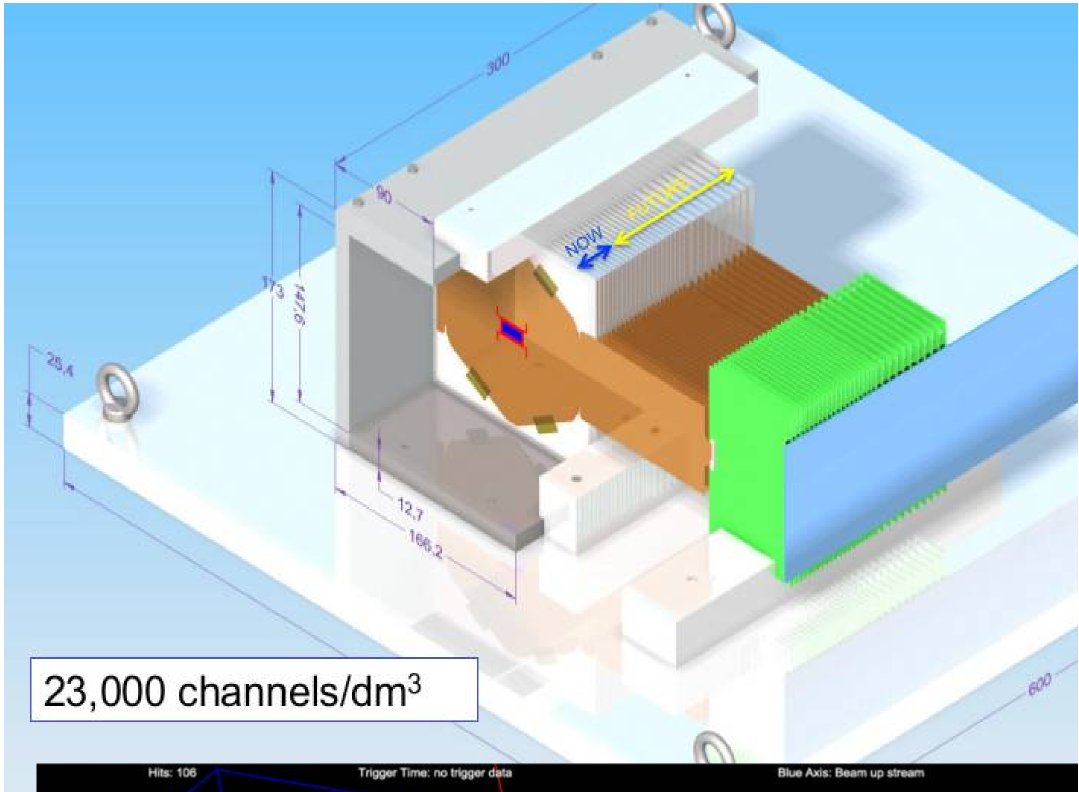
4 sensors are glued to PCB with $\sim$20 um precision by robot

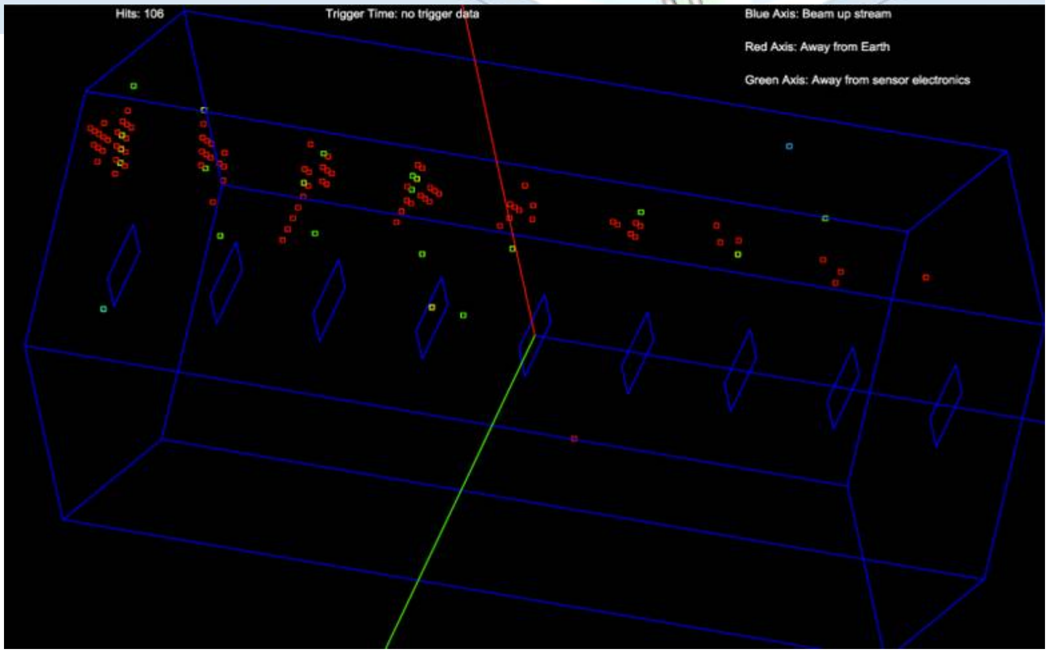


V. Balagura

SiD silicon-W ECAL







Ultra-compact design

multi-layer prototype detector constructed and being tested

technical lessons:

- bonding of ASIC to sensor
- parasitic coupling along signal traces
- mitigating strategies developed

Recent studies on monolithic active pixel detectors: kPixM-CAL

High granularity – gas

Micro-pattern gas detectors

Resistive Plate Chambers

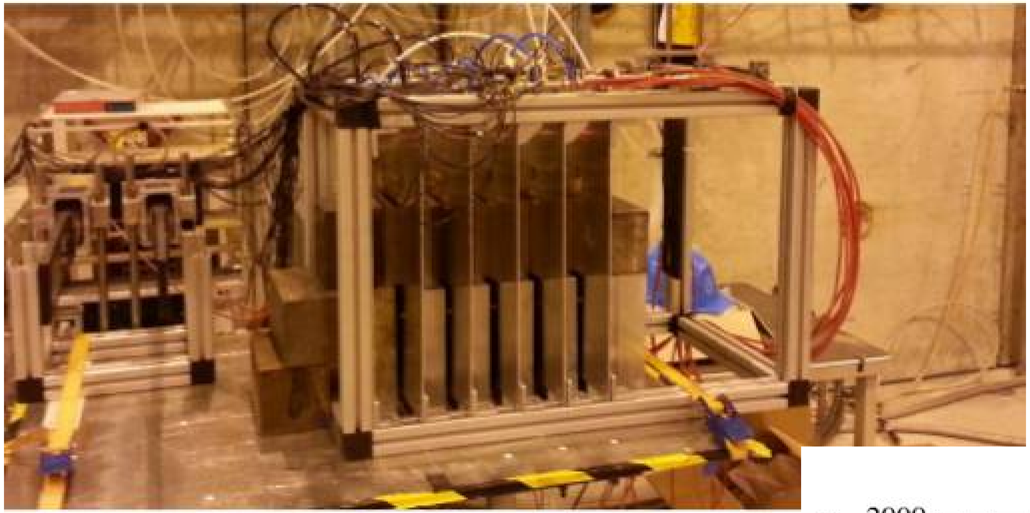
typically read out in (semi-)digital way
→ count number of hits

Micro Pattern Gas Detectors

Recent development of resistive Micromegas detectors

built-in suppression of sparks

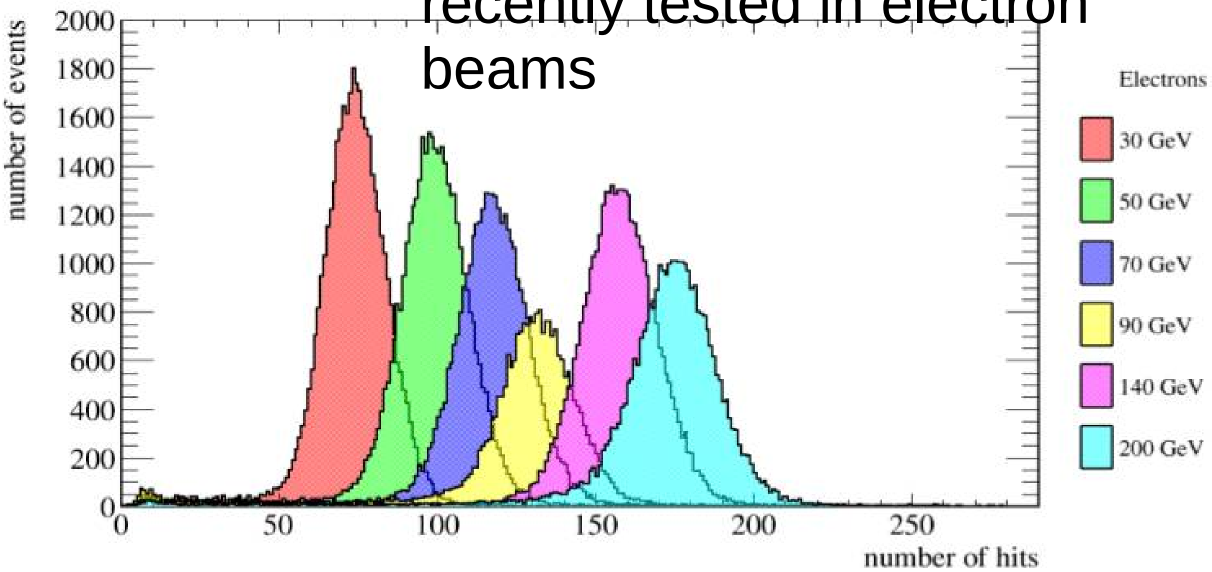
tuning of resistivity allows variation of high rate capability



Small calorimeter prototype

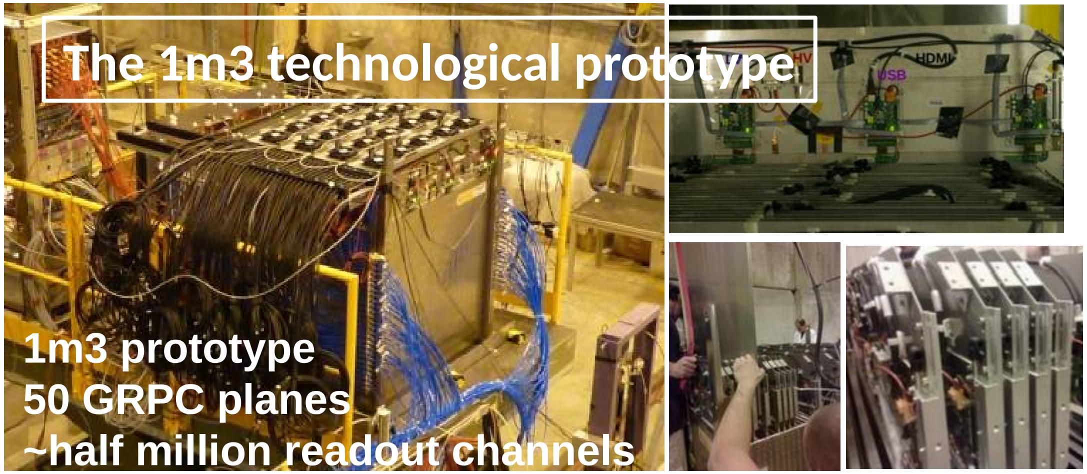
6-layers of resitivity Micromegas in 20 X_0 of steel absorber

recently tested in electron beams



Semi-digital Hadronic Calorimeter (SDHCAL)

M-C Fouz



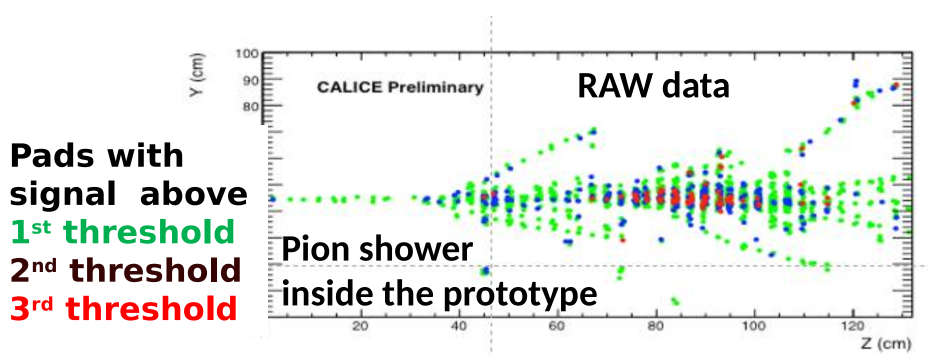
Detector :
Glass Resistive Plate Chambers (**GRPC**)**~1x1 m2**
Readout by **$1x1cm^2$ pads,**
semi-digital readout with
3 thresholds (0.114pC, 5pC, 15pC).
count number of pads over thresholds
→ **3 vs. 1 thresholds improves the energy resolution for particles >40 GeV**

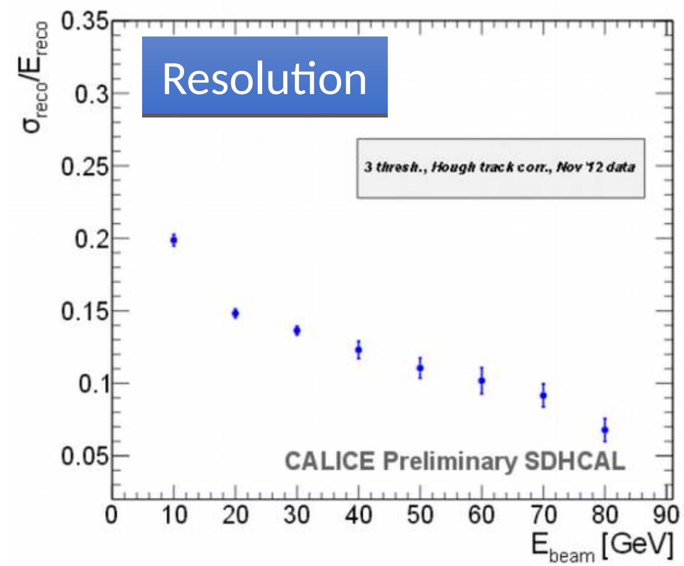
Electronics : HARDROC ASIC chip, **embedded in detector**. **Power pulsed** electronics

GRPC + electronics located in a **cassette** (**stainless steel, part of the absorber, 2x2.5mm thickness)**

Self-supporting **mechanical structure**: **51 Stainless steel absorber plates (each 15 mm thickness)**

Extensively tested on test beam
Good performance
GRPC **efficiency ~95% Multiplicity ~1.8 pads**
Reasonable energy resolution and excellent tracking capabilities



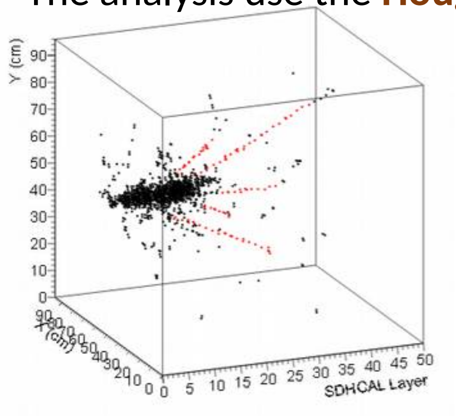


Semi-digital Hadronic Calorimeter (SDHCAL)

M-C Fouz

Single Track Reconstruction

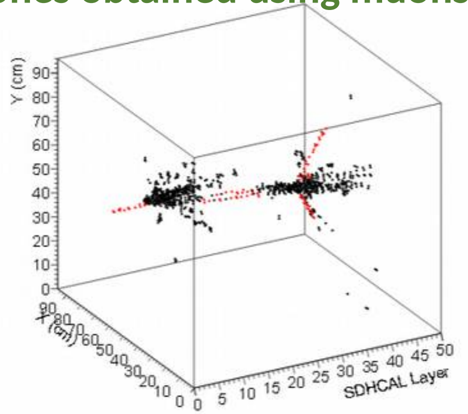
The excellent tracking capabilities allow to **distinguish single tracks** inside the shower
The analysis use the **Hough Transform Technique** (CaliceAnalysisNote CAN-047)



The tracks extracted from showers can be used for calibration, using them (requiring good tracks with good χ^2) to check the **efficiency** and **multiplicity** of the individual GRPCs

The values obtained are compatibles with the ones obtained using muons

This can be **very helpful in the PFA studies** as well to **disentangle the close-by hadronic showers** by **connecting clusters produced by hadronic interaction of secondary charged particles to the main one**



Development of new prototypes

G O A L S

- Build a **few large GRPC** with the final dimensions foreseen for ILD
- Equip the GRPCs with a **new version of the electronics being developed**
- Design and build, with the same procedures as the final one, an **absorber mechanical structure** capable to host up to 5 large GRPC (290x91m^2)

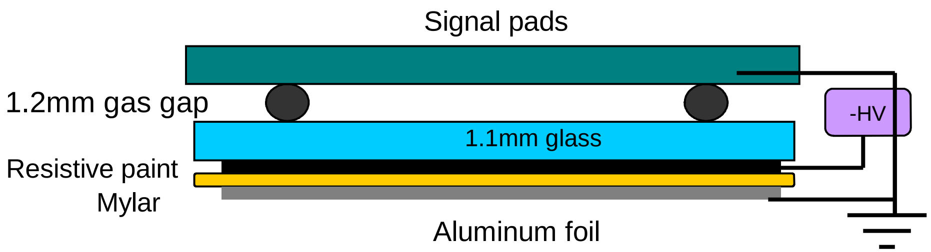
Ongoing

See more details at ***ILD Status plans*** **(later today) &** ***Technological SDHCAL for future lepton colliders*** **(Calorimetry Session)**

CALICE RPC-based DHCAL,
with purely digital readout

Large 1m3 prototype cocstructed, extensively tested using
different beams and absorber materials
many data collected, analyses continuing

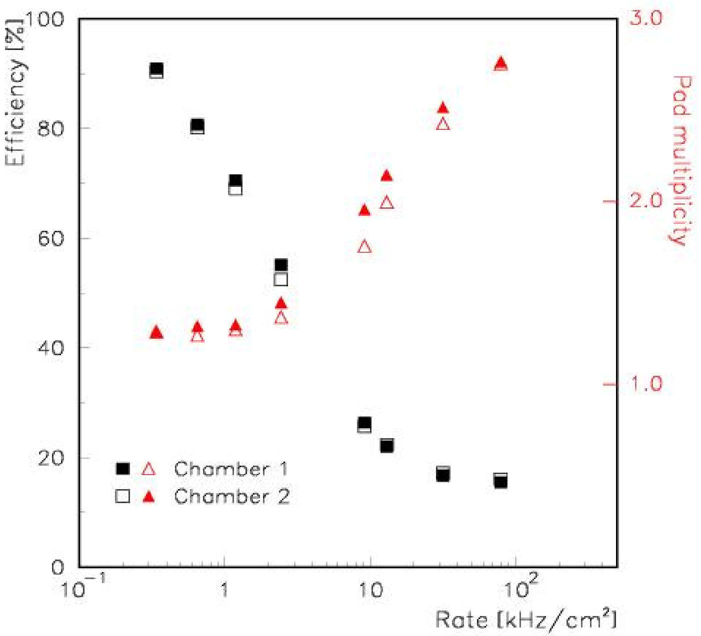
recent stdies on different RPC types, e.g. 1-glass RPC



Measurements with Test Beam

Rate capability better than 2-glass

Pad multiplicity close to 1



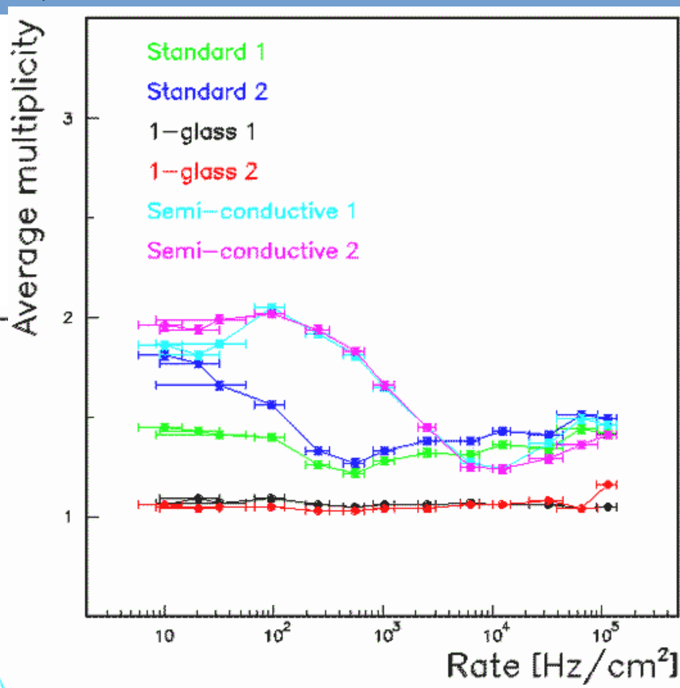
JINST 10 (2015) P05003

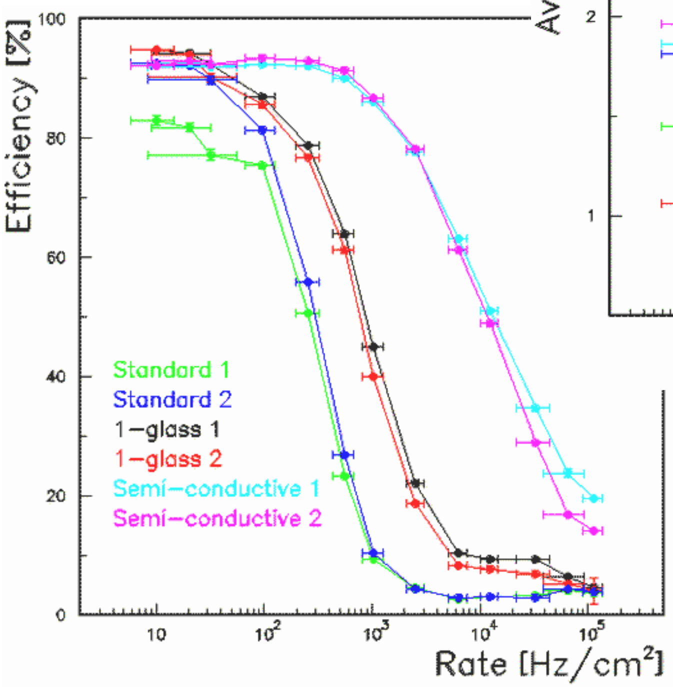
J. Repond

Testing different RPC designs

J. Repond

RPC design	Number of glass plates	Area A [cm²]	Bulk resistivity ρ [Ωcm]	Total thickness t of the glass [cm]	Conductance per area of the glass $G = (\rho \cdot t)^{-1}$ $[\Omega^{-1}cm^{-2}]$
Standard 2-glass	2	400	4.7×10^{12}	0.22	1.0×10^{-12}
1-glass design	1	1536	3.7×10^{12}	0.11	2.4×10^{-12}
2-glass, semi-conductive glass (Schott Glass Techn. Inc)	2	400	6.3×10^{10}	0.28	5.6×10^{-11}





As expected, decrease in efficiency with increasing rate

1-glass design better than standard RPC

Semi-conductive chamber better than 1-glass design

Pad multiplicity close to unity for 1-glass design

Pad multiplicity high for semi-conductive chamber (thicker glass)

Summary

LCC calorimeters will be rather
different to existing calorimeters

Various technologies being considered
to realise these devices

Tests progressing
both on physics performance
and on designs applicable to large-scale systems

For more details,
join the calorimetry/muon sessions

Material from V. Balagura, C. Gatto, K. Kotera, M-C Fouz, S. Lukic,
K. Krueger, R. Frey, J Repond