Novelties in Detector R&D

Erika Garutti

- Overview of HEP R&D at DESY and Uni. HH
- R&D for sLHC ➔ Si-tracker
- R&D for ILC ➔ gaseous tracker (Time Projection Chamber)

  (and beyond) ➔ hadron calorimeter

Universität Hamburg

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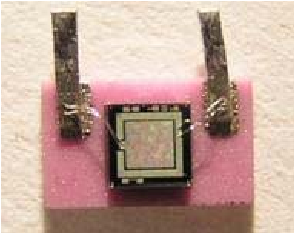
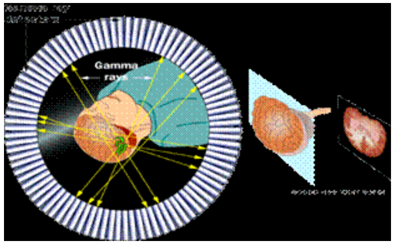
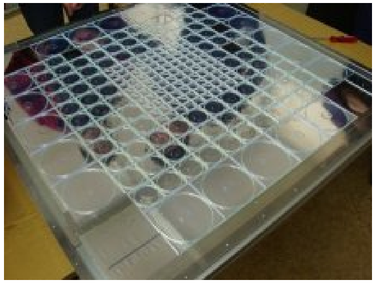
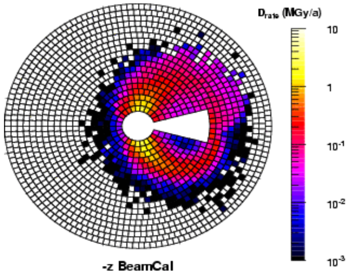
DESY

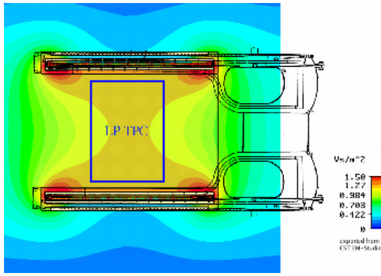
- Detector R&D is a very broad field covering many activities
- Extremely healthy and productive area of research
- Profit from common infrastructures / intensified knowledge exchange / coordinated use of resources
- Attractive for young scientists and for education of master and PhD students











A (incomplete) list of activities

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R&D topic	Key words	Responsible
CMS tracking	Si-detectors	G. Eckerlin, G. Steinbruck
Radiation hardness (Si)	Theory + application	D. Eckstein, R. Klanner
ILC tracking	Time Projection Chamber, gas detectors	T. Behnke
Calorimetry	ILC and beyond, photodetection	E. Garutti, F. Sefkow
ATLAS ALFA	Roman pots	I. Gregor, T. Haas
CASTOR	Very forward calorimeter	K. Borras
Forward calorimetry	ILC, (CMS beam monitoring) diamond, rad. hard	W. Lohmann
Polarimetry	ILC polarimeter, photodetection	J. List
Neutrino physics	OPERA, BOREXINO, COBRA, drift detectors	C. Hagner, R. Zimmermann
ground-based gamma-ray astronomy	Cherenkov Telescope Array, photodetection	D. Horns, C. Spiering

The coming machines

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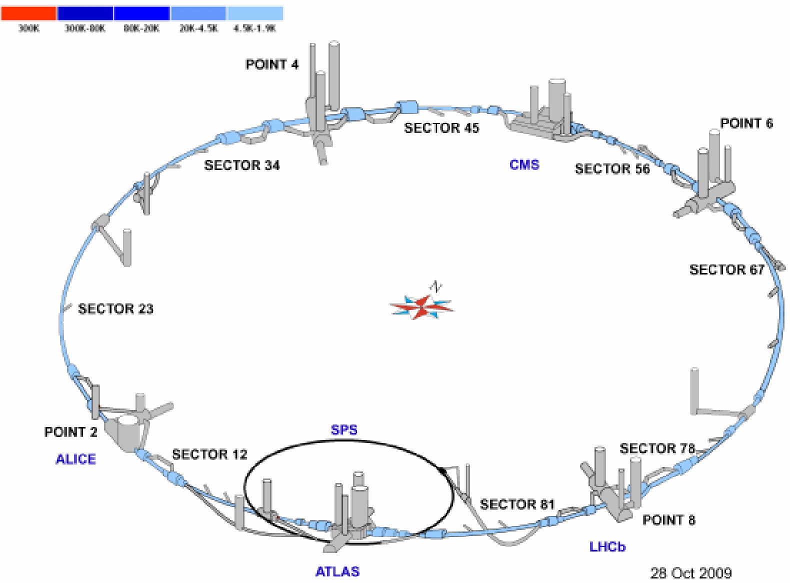
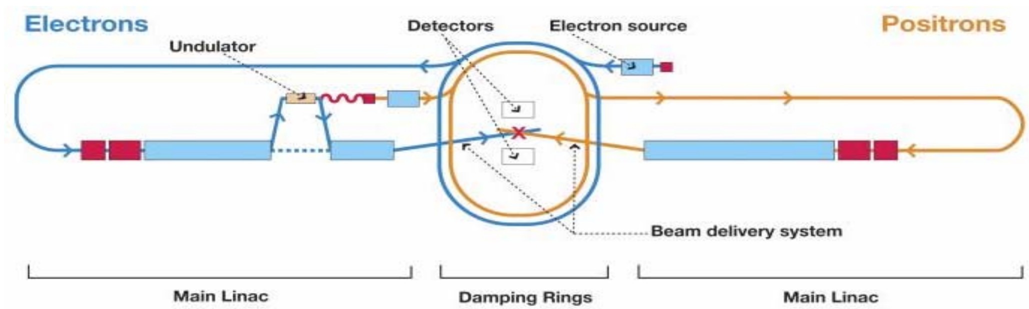
LHC



Planned start of data taking: 2009
➔ Detector R&D for sLHC upgrade started!

ILC



Technical Design Report due in 2012 accompanied by a detector design document
➔Current R&D effort targeted to "technological" prototypes scalable to ILC detector

➔Intensified activity in combined ILC/CLIC technologies

XFEL, PETRA III, not covered in this talk (but possibility for synergy in detector R&D)

LHC upgrade: sLHC

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Expected Equivalent Fluence at sLHC

⇨ **LHC (2009),** $\mathcal{L} = 10^{34}cm^{-2}s^{-1}$

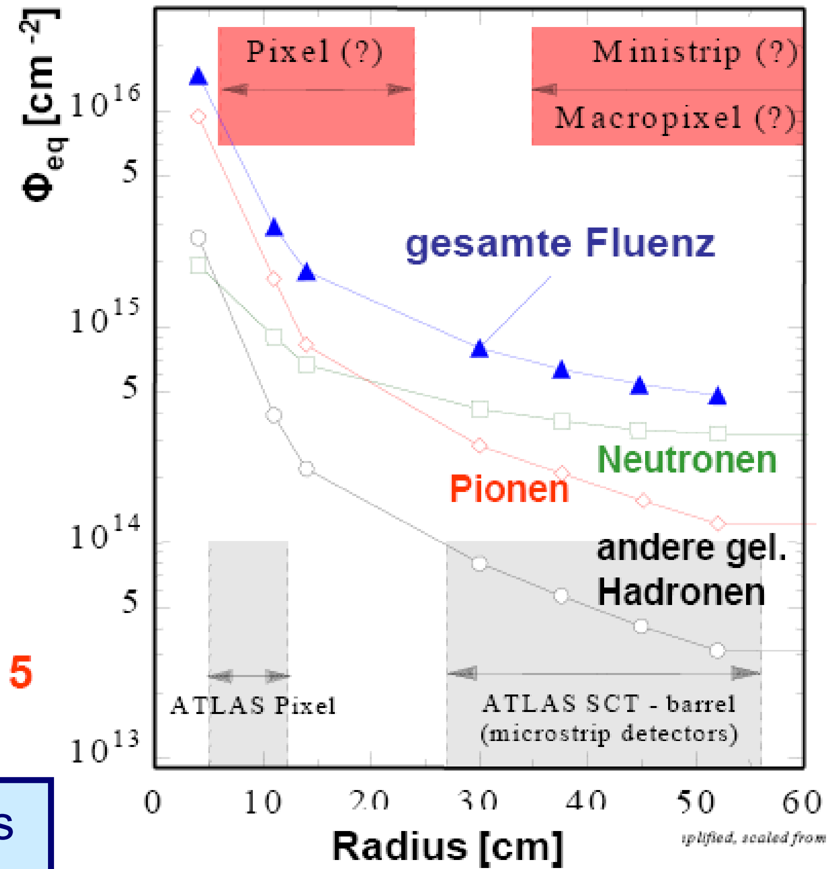
10 years → **500 fb^{-1}** $\Phi(r=4cm) \sim 3 \cdot 10^{15} cm^{-2}$

⇨ **Super-LHC (201?),** $\mathcal{L} = 10^{35}cm^{-2}s^{-1}$

5 years → **2500 fb^{-1}** $\Phi(r=4cm) \sim 1.6 \cdot 10^{16} cm^{-2}$

LHC x 5

ATLAS SLHC 5 Jahre, 2500 fb^{-1}

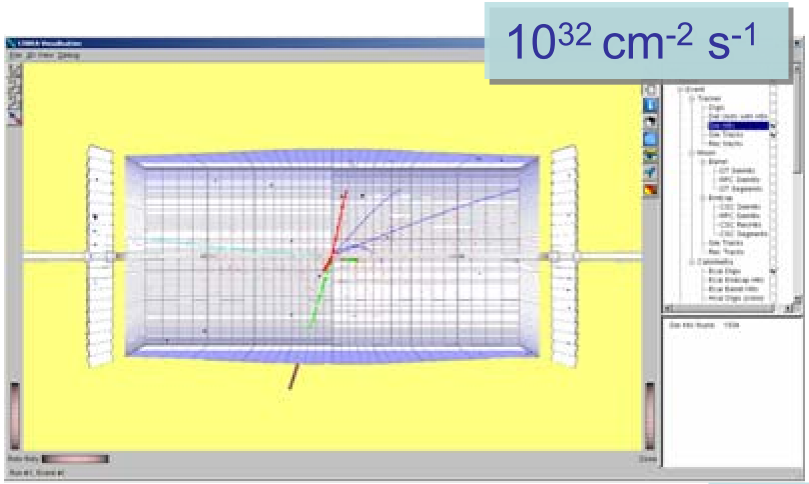


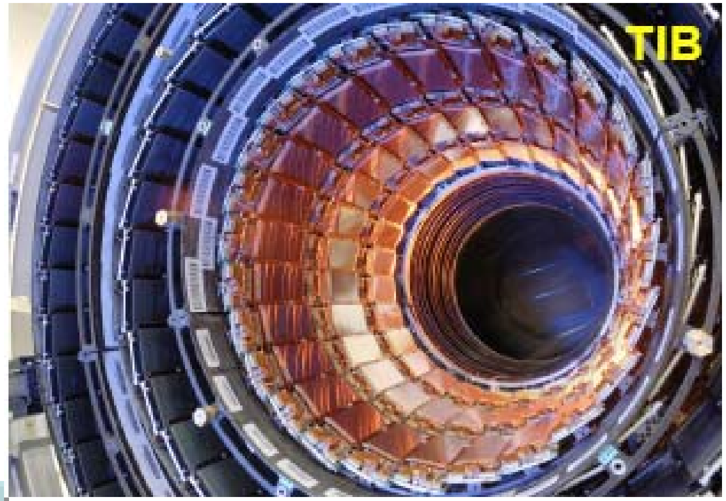
Present detectors do not satisfy requirements
➔ R&D is mandatory !

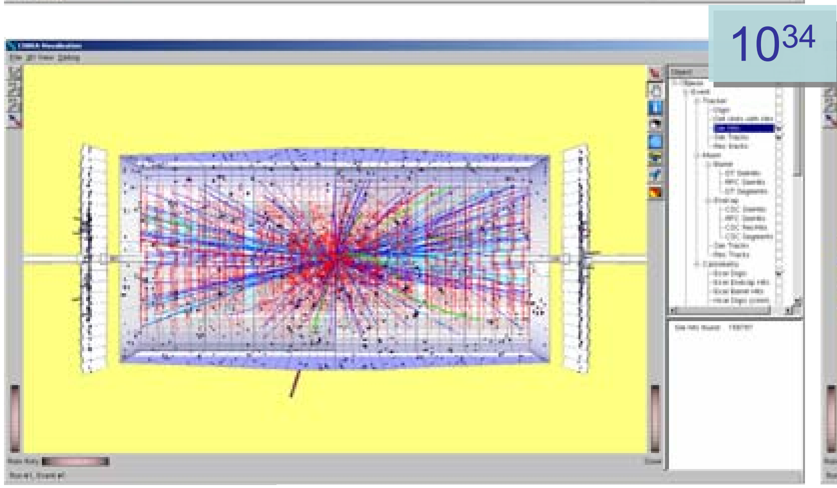
Detector challenge

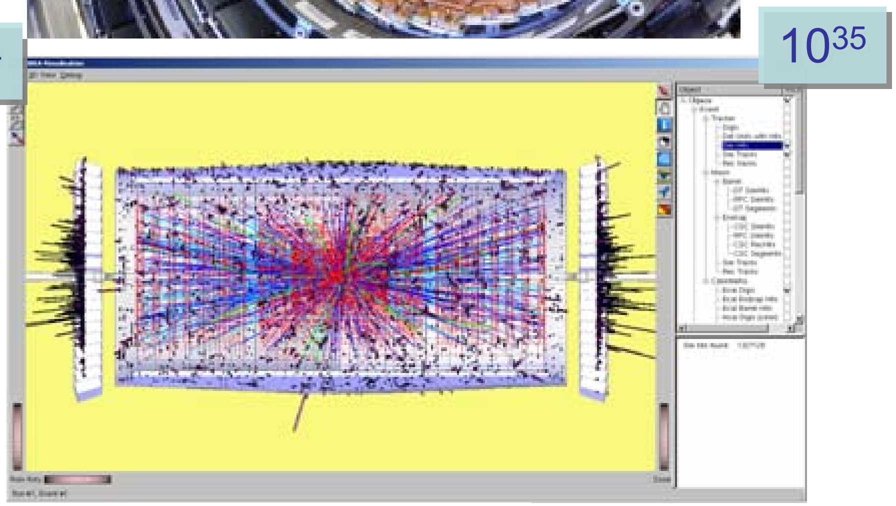
CMS from LHC to sLHC

CMS silicon detector





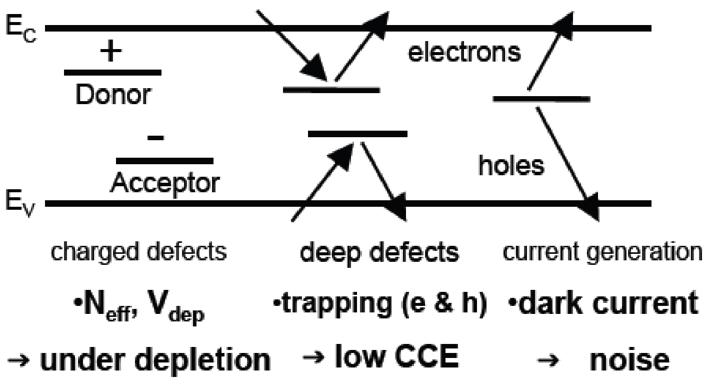




The tracker is the key detector which will require upgrading for sLHC Phase 2

Improving radiation hardness

Radiation damage:



Bulk damage results in changes of the sensor properies such as

- field distribution
  $\Rightarrow$ depletion voltage
- dark current → power, noise
- trapping → signal/noise, charge collection efficiency

Method: "Defect engineering"

- Understand radiation damage
- Correlate defects (microscopic property) with macroscopic parameters
- adjust doping → prevent "damaging" effects
- investigate oxygen-enriched silicon (DOFZ, Cz, MCz, EPI)

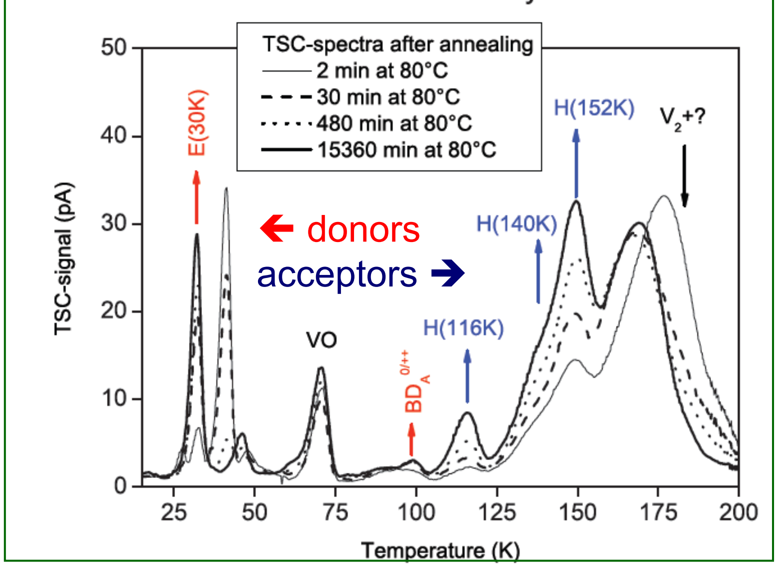
Effective doping

Technique: Thermally Stimulated Current (TSC) - for $\Phi_{eq} > 10^{12}cm^{-2}$
current due to emission from filled traps

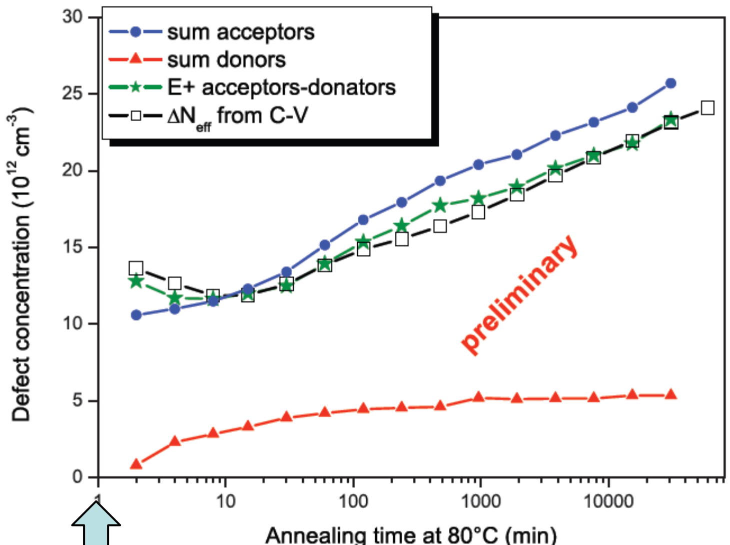
The microscopic measurement

1 MeV neutrons

Defect concentrations by TSC ⇒



Comparison with CV-results



Capacitance-Voltage characteristics ($\Rightarrow N_{eff}$)

- capacitance measured versus reverse bias voltage
- depletion zone w increases until rear side reached (w=d) $\Rightarrow$ depletion voltage V_{dep}
- $V_{dep} = \frac{q_0}{\epsilon\epsilon_0} \cdot |N_{eff}| \cdot d^2$

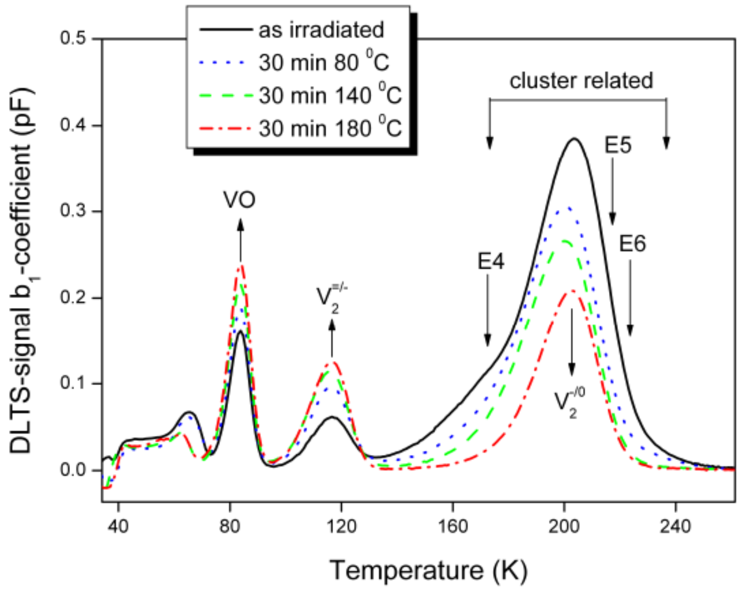
The macroscopic measurement

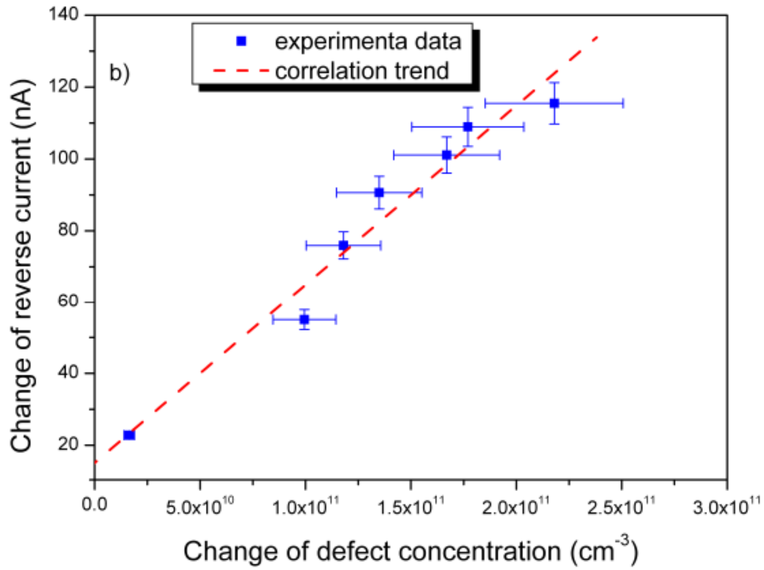
reverse annealing can be explained by deep acceptor traps

Leakage current

Dark current correlates with deep electron clusters

Deep Level Transient Spectroscopy (DLTS) - for $\Phi_{eq} < 10^{12}cm^{-2}$
capacitance transients during the emission from filled traps

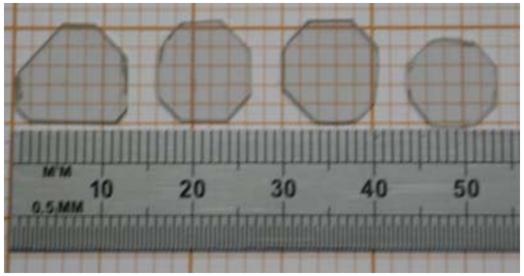




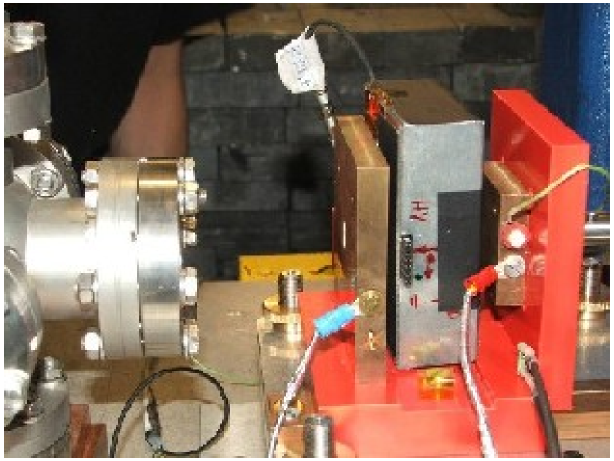
close correlation to cluster related deep electron traps

New sensor materials: Diamond

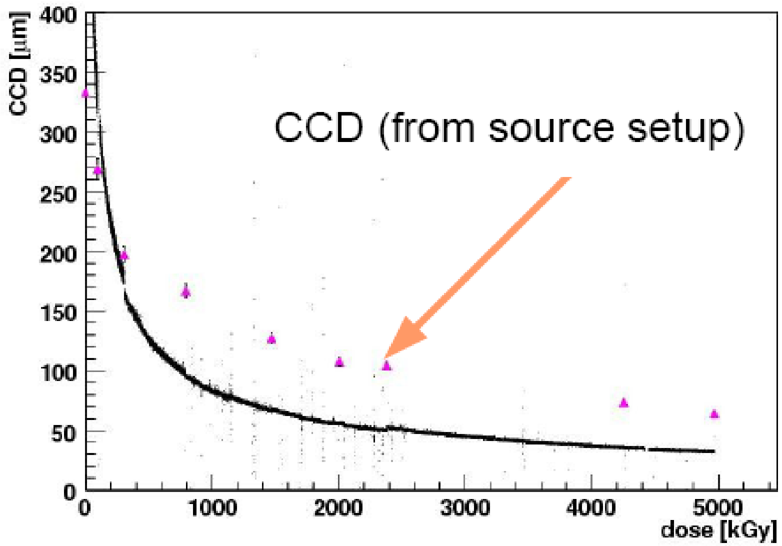
Diamond sensors:
low leakage, radiation hard, low capacitance,
but lower signal and difficult to mass produce



setup for sensor irradiation tests ➔
in an high intensity electron beam



after absorbing 5 MGy CVD diamonds still operational



Development for ILC Forward calorimeter
(FCAL) & CMS beam monitoring

challenges: - radiation hard sensors
- fast readout

New sensor materials: CdZnTe

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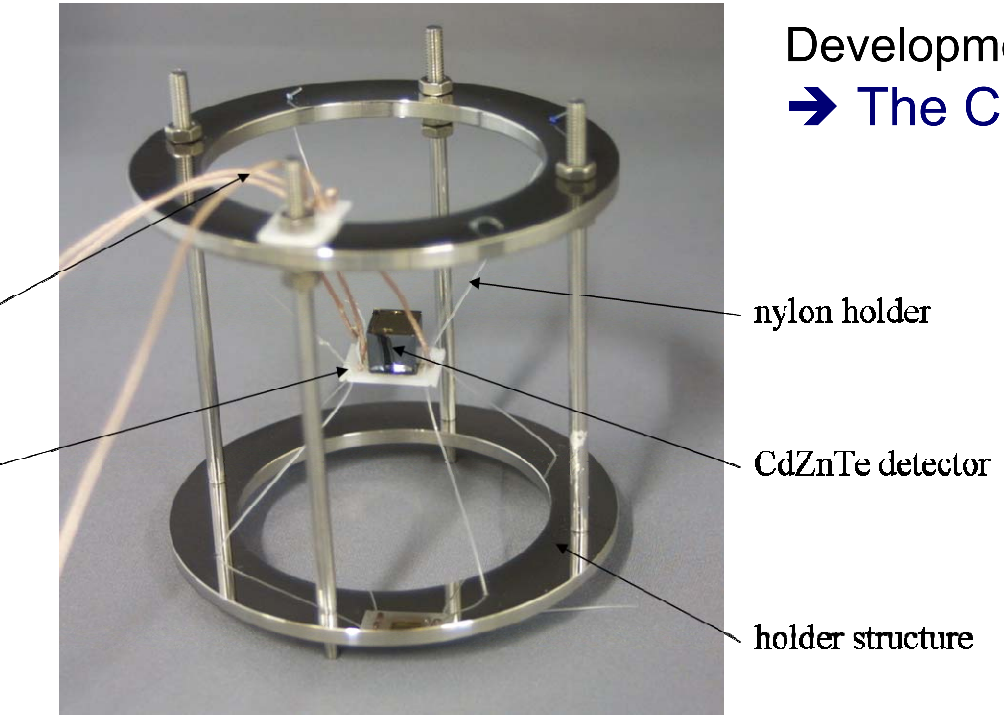


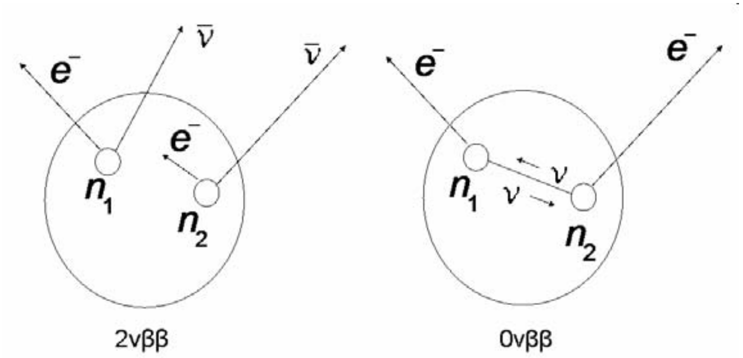
Development for neutrino physics

➔ The COBRA experiment

- detector based on CdZnTe semiconductor
- operated at room temperature
- high density of the crystal provides excellent stopping power
- detector array under design:
  ~6400 crystals
  of 1 cm^3 size (~6.5g)
  for a total of 400 kg

Observation of ββ0ν implies Physics beyond the Standard Model

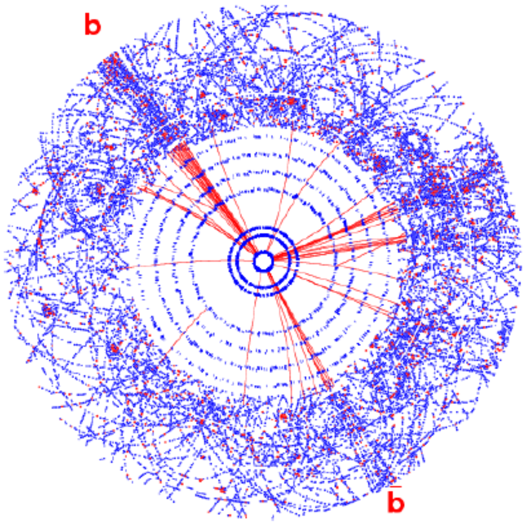
- is the ν its own antiparticle (Majorana)?
- what it the neutrino mass?



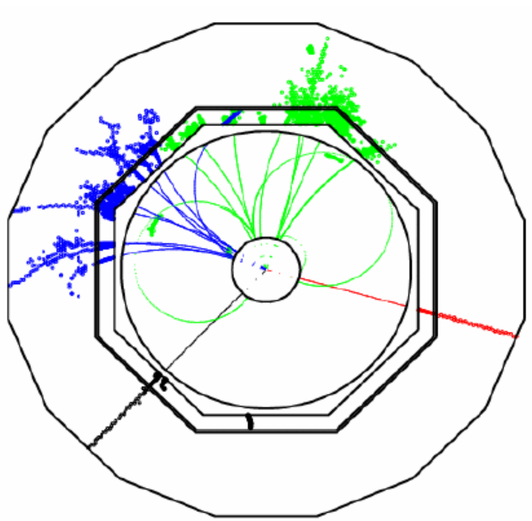
From LHC to ILC

★ **Electron-positron colliders provide clean environment for precision physics**

The LHC $\mathrm{pp} \to \mathrm{H} + X$



The ILC $\mathrm{e}^+\mathrm{e}^- \to \mathrm{HZ}$



★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see $\mathrm{H} \to b\bar{b}$ and $\mathrm{Z} \to \mu^+\mu^-$ and nothing else…**

High precision ILC physics demands a high precision detector:

➔ high precision vertex (flavor tagging) and tracking (Higgs from di-lepton recoil mass)

➔ precision calorimetry (heavy bosons reconstruction from di-jet decay)

Particle Flow paradigm

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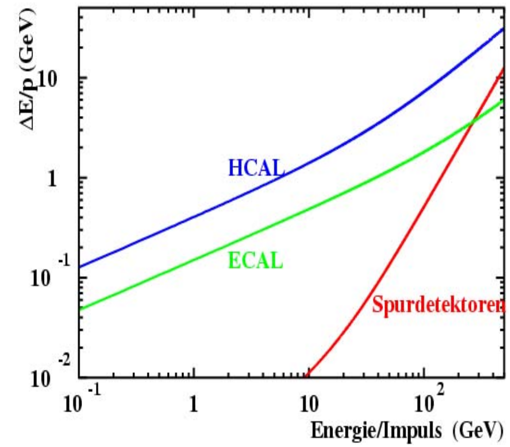
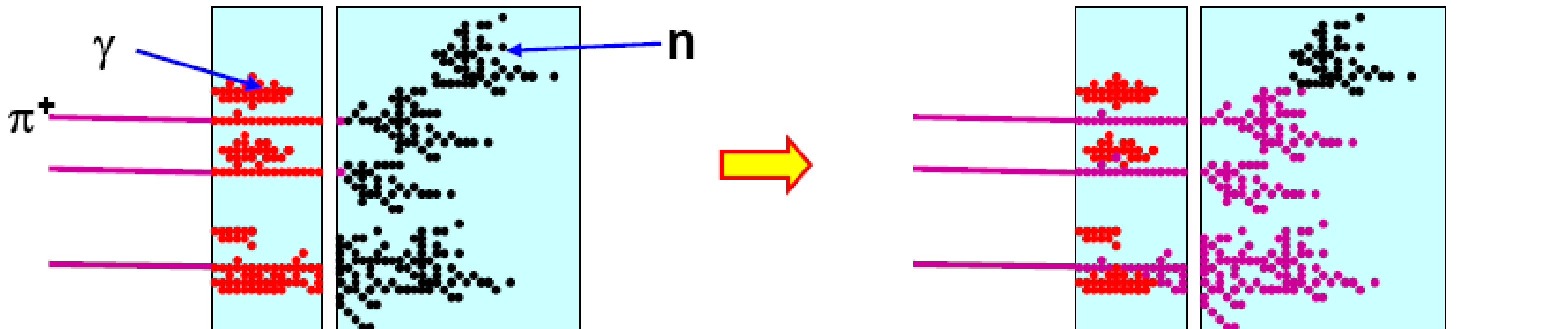
➔ reconstruct every particle in the event

- up to ~100 GeV Tracker is superior to calorimeter ➔
- use tracker to reconstruct $e^{\pm}, \mu^{\pm}, h^{\pm}$ (<65%> of E_{jet})
- use ECAL for γ reconstruction (<25%>)
- (ECAL+) HCAL for h^0 reconstruction (<10%>)

➔ HCAL E resolution still dominates E_{jet} resolution

➔ But much improved resolution (only 10% of E_{jet} in HCAL)





$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

PFLOW calorimetry = Highly granular detectors (CALICE)
+ Sophisticated reconstruction software

ILC vertex: Pixel detector

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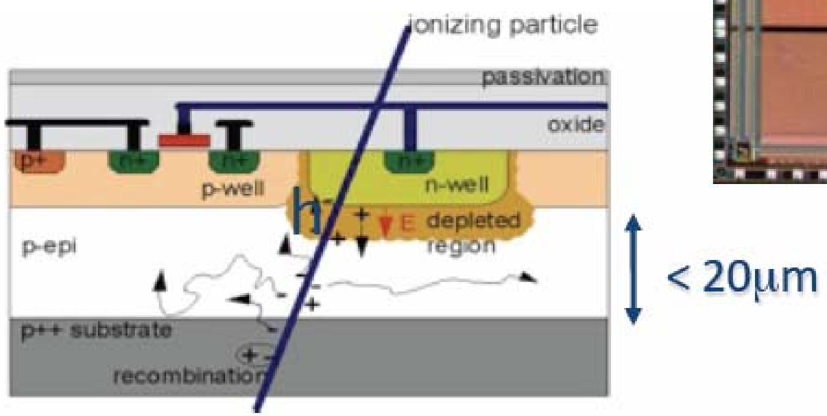
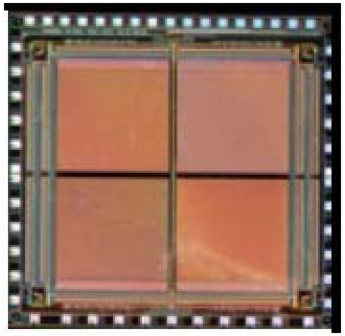
MAPS technology:



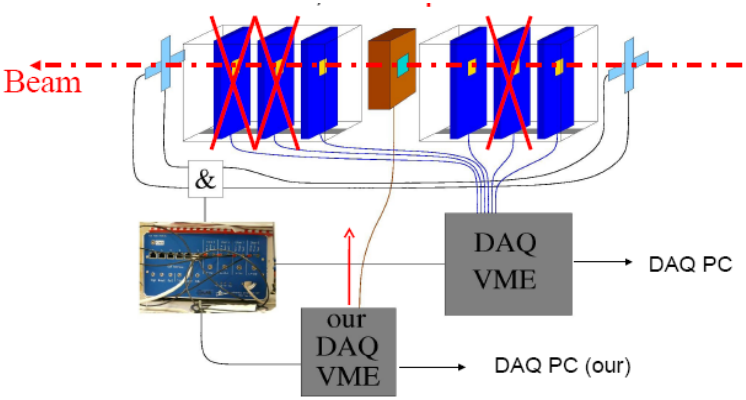


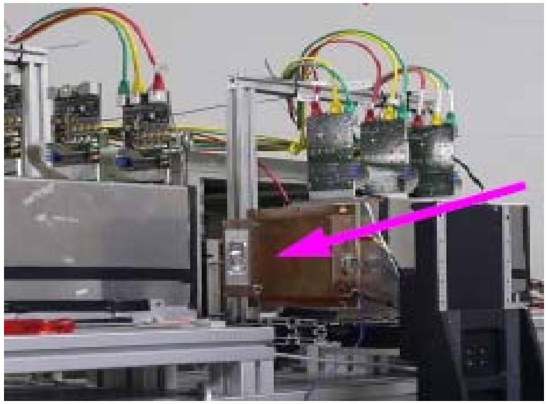
Features of the MIMOSA – detectors:

- Single point resolution 1 µm – 3 µm
- Pixel – pitch 10-40 µm
- Thinning achieved 50 - 120µm
- S/N for MIPs 20 – 40
- Detection efficiency > 99%
- Radiation hardness: 1MRad ; 2×10^{13} n_{eq}/cm^2
- Produced in various commercial CMOS-processes

EUDET telescope:
high resolution (σ<3µm) pixel beam telescope consisting of up to six planes of Monolithic Active Pixel Sensors

Testbeam equipment for diamond sensor performance studies using the EUDET telescope





ILC tracking: TPC

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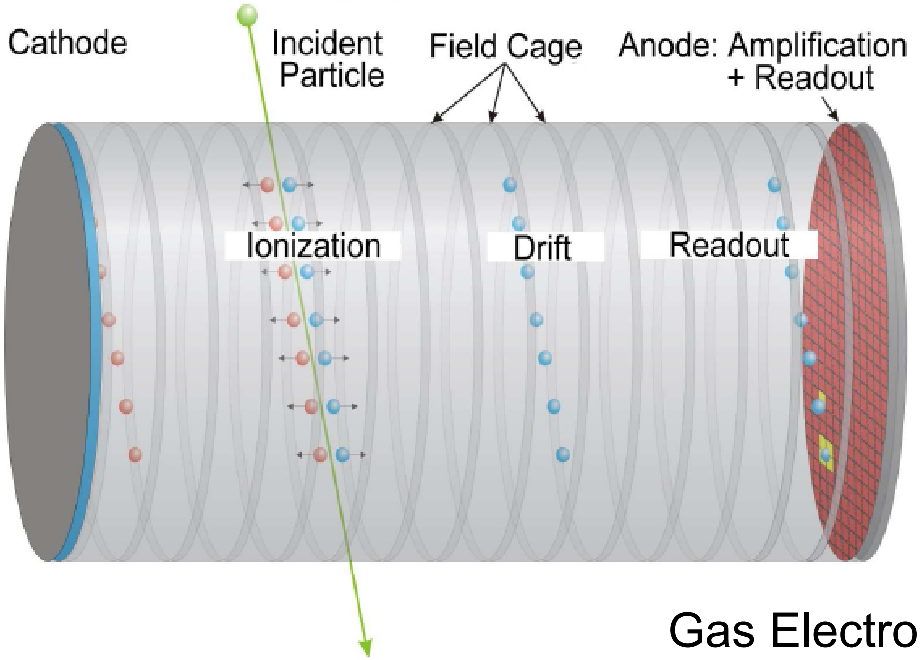
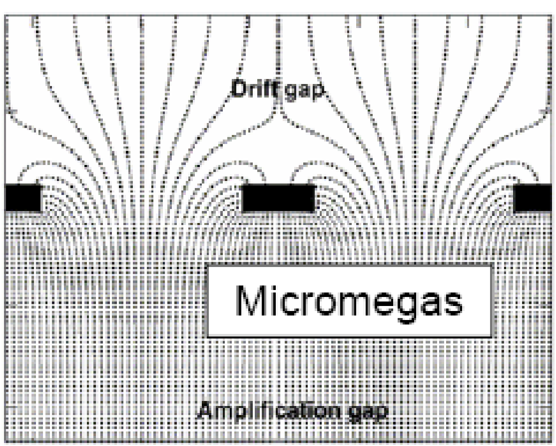
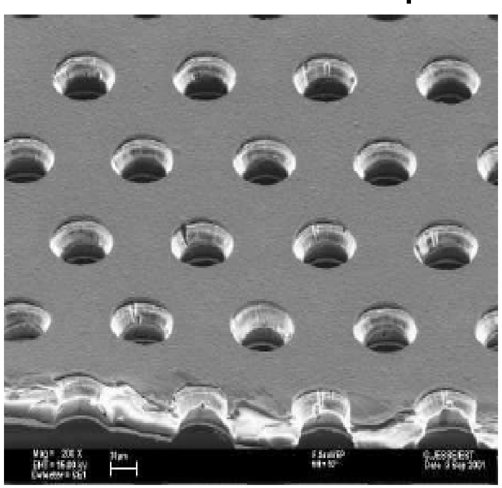


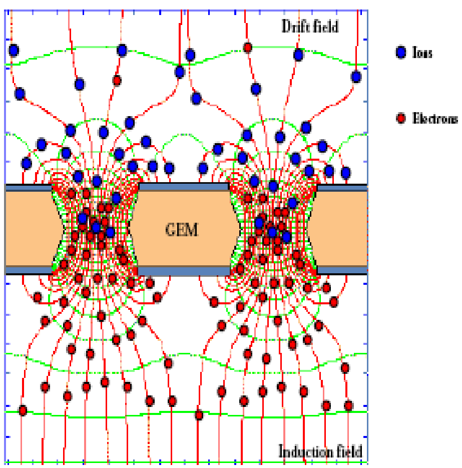
Measure particle tracks using
a gas filled sensitive volume
parallel plate capacitor
➔ true 3-D space point measurements
Large volume: many space points (~200)
with minimum of material (<4% X_0)
➔ Energy loss measurement (~5% res.)

Technological break-through:
Micro Pattern Gas Detector
not limited by ExB effects



Gas Electron Multiplier GEM

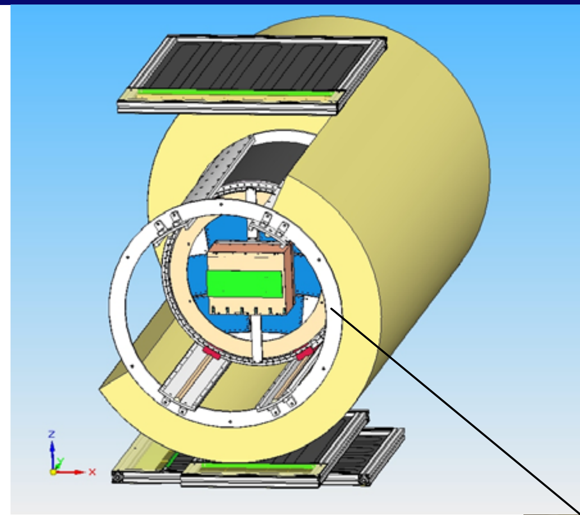




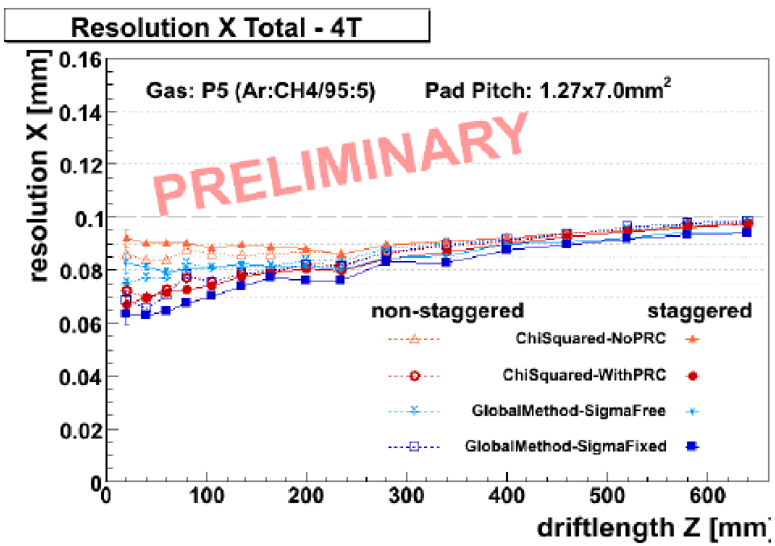
TPC setup at the DESY test beam

Example of infrastructure for multiple-users (EUDET, HGF–Alliance)

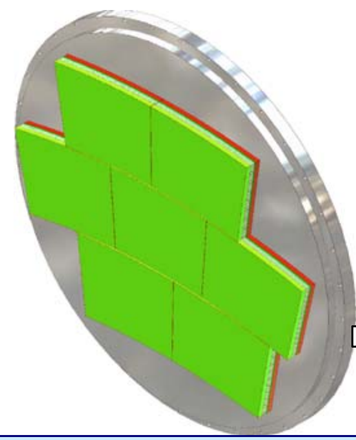
PCMAG:
superconducting magnet,
up to 1.25 T
e^- test beam @ DESY

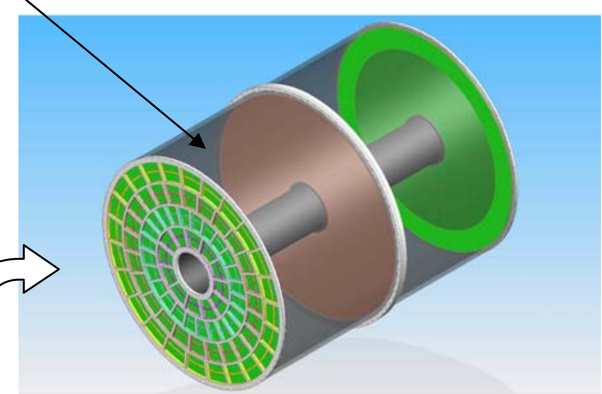


Prove of technology with medium TPC:



Large Prototype = ½ TPC





end-plate hosting
various readout technologies

The Field Cage

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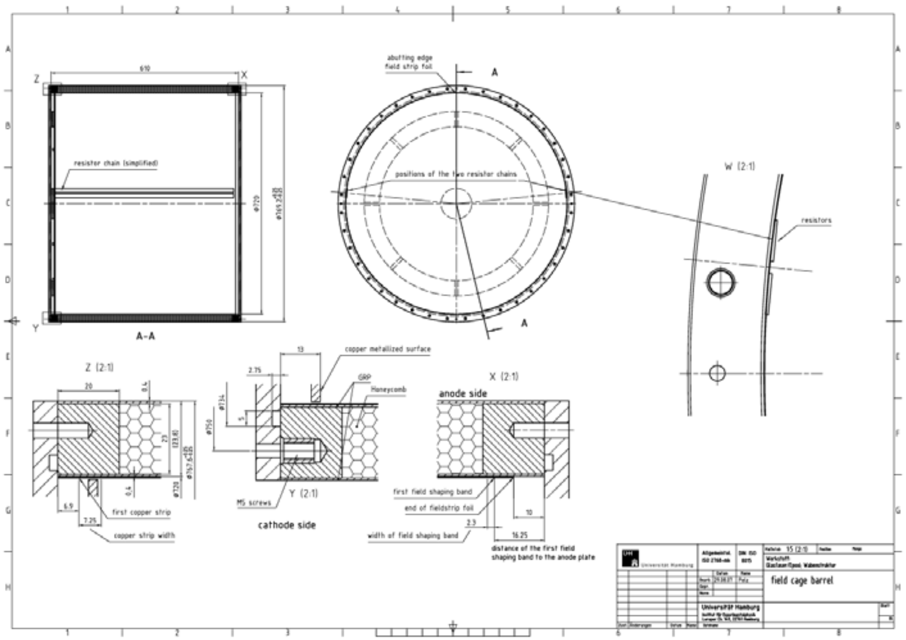
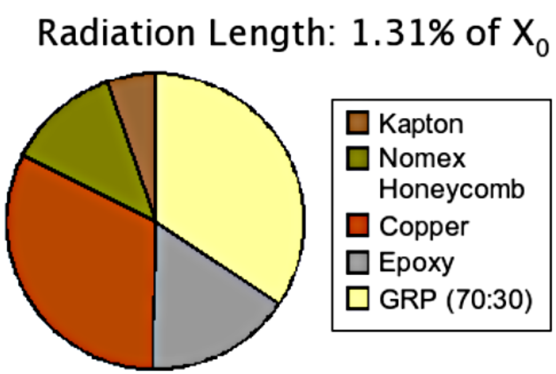
Design: DESY and University of Hamburg



Diameter:	Inner 720 mm, Outer 770 mm
Wall thickness:	25 mm
Length:	610 mm
HV to be applied:	up to 20 kV

Material budget below ILC specs. (barrel <4% X_0)



Test of various readout technologies

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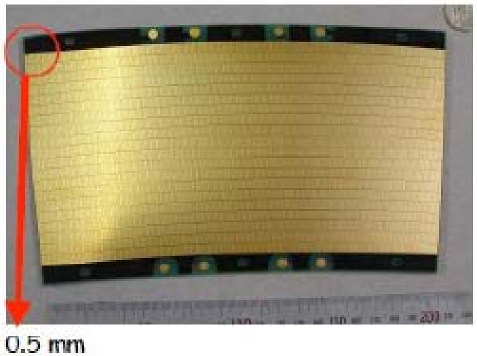
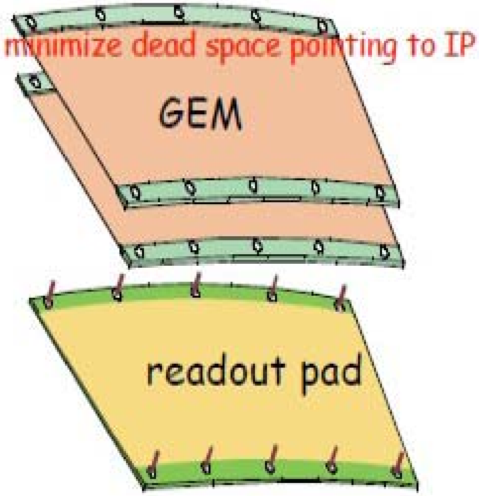
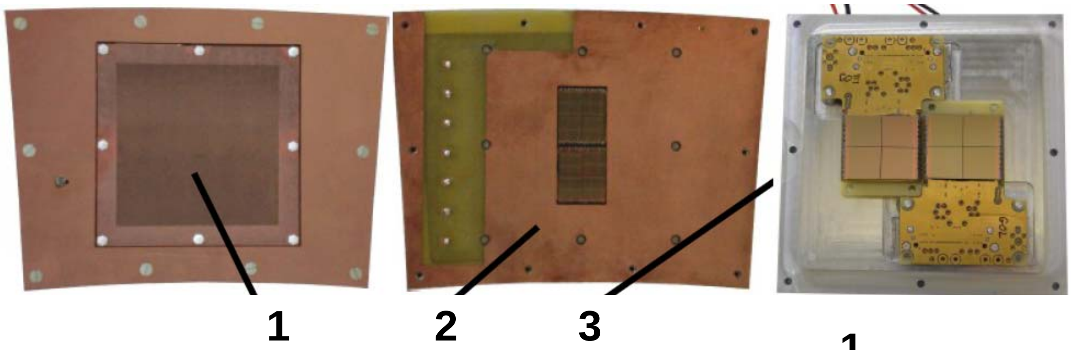
Double GEM structure

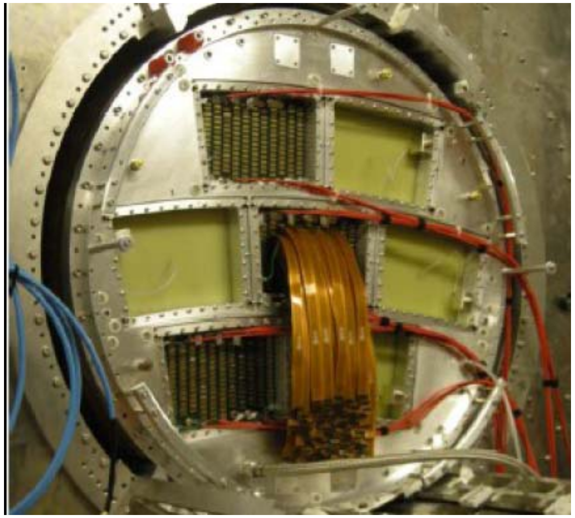




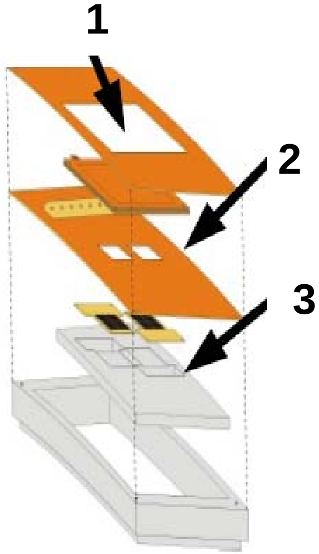
A. Sugiyama, Saga Univ.

3-GEM structure & TimePix chip





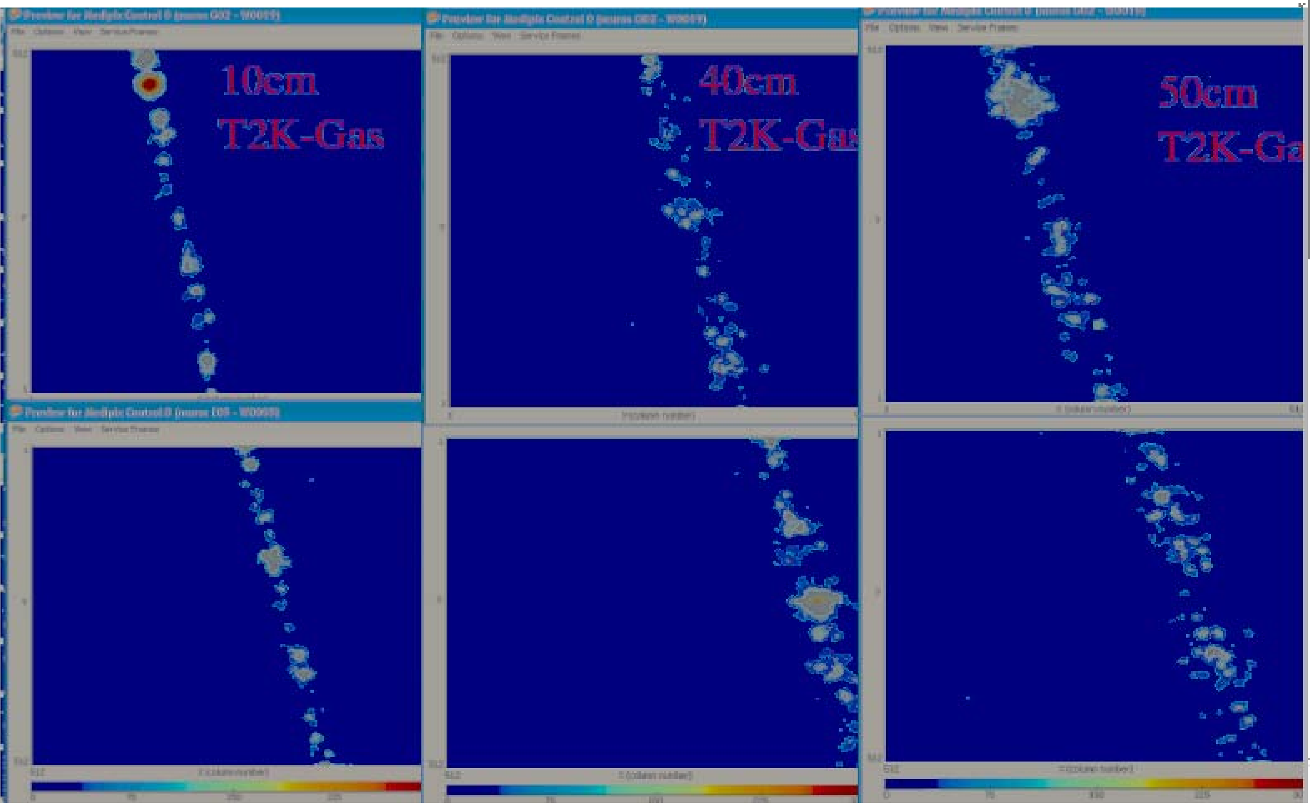
user interface

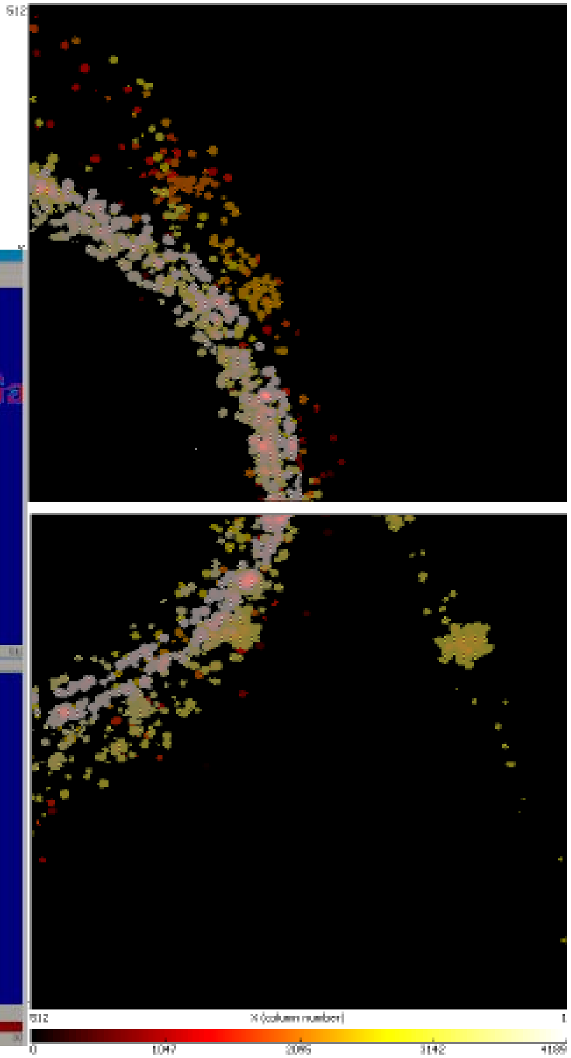


J. Kaminski, Univ. of Bonn

3-GEM Structure & TimePix

Largest amount of readout channels on one anode for a TPC so far: # ch ~ 500 k





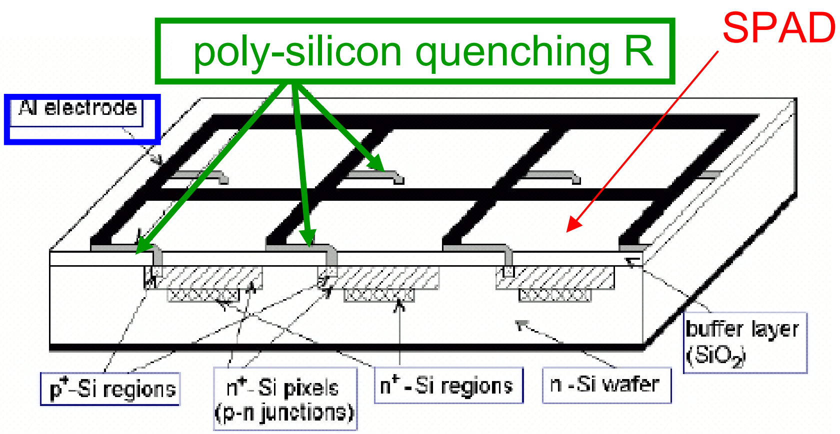
J. Kaminiski, Univ. of Bonn

The Silicon-PhotoMultiplier

A SiPM is a pixellated Avalange PhotoDiode operated in Geiger mode, i.e. above breakdown voltage.
Single pixels are connect in parallel via an individual limiting (quenching) resistor.

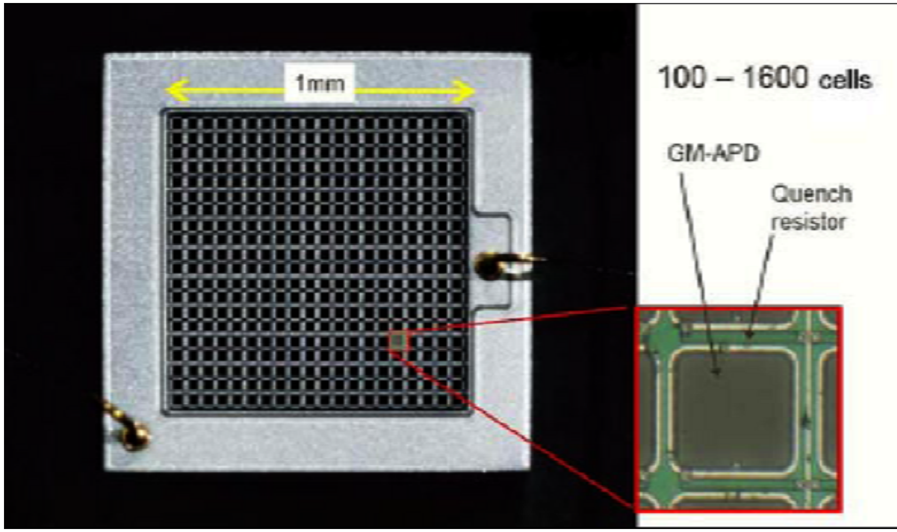
$$\Delta Q = \Sigma\, \Delta Q_i = N \cdot (C_{pixel} \cdot \Delta V)$$

➔ typically i ~ 100-1000 pixels / mm²



Some typical pixel parameter:
- -pixel size ~20-30μm
- -pixel capacitance C_{pixel} ~ 50fmF
- -quenching resistor R_{pixel} ~ 1-10 MΩ

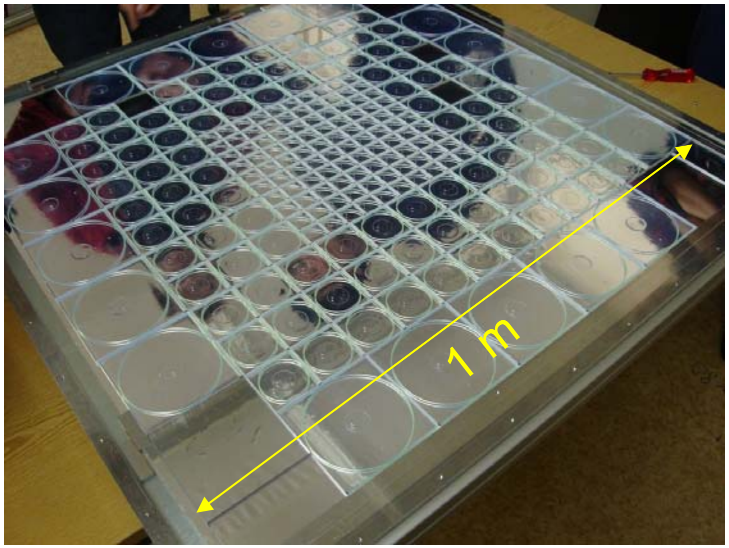
- -small depletion region ~ 2μm
- -strong electric field (2-3)x10^5 V/cm
- -very short Geiger discharge develop< 500ps



DESY/Uni.HH contributed from the early phase to of SiPM development

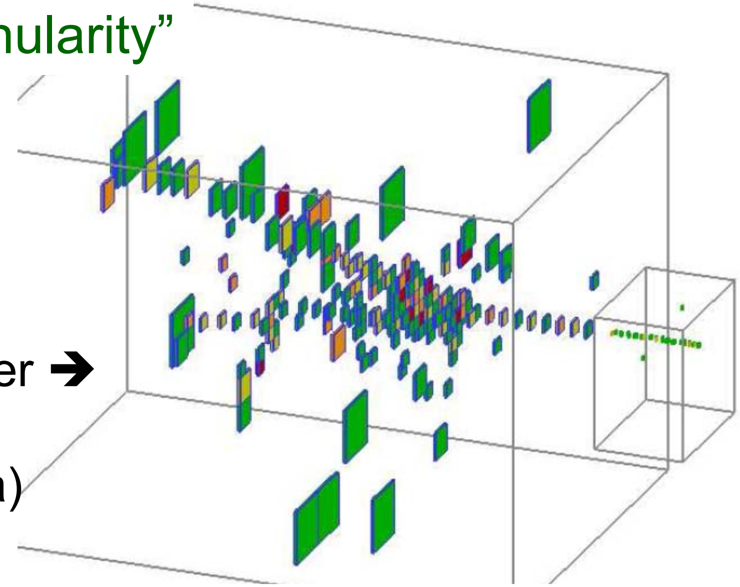
Imaging calorimeter

HCAL prototype for ILC: key word "high granularity"

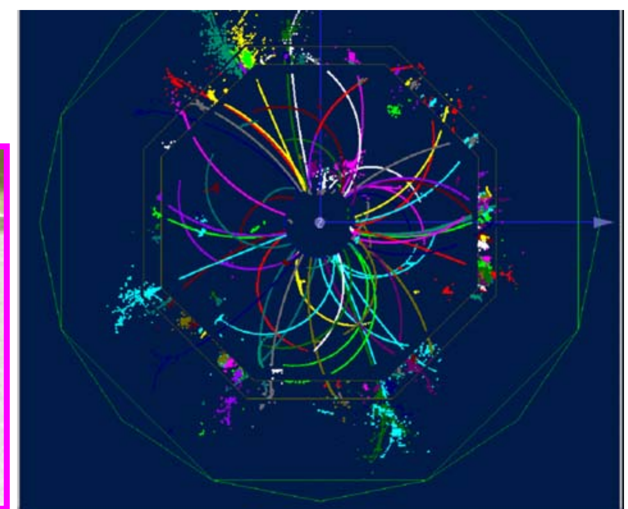


← calorimeter layer

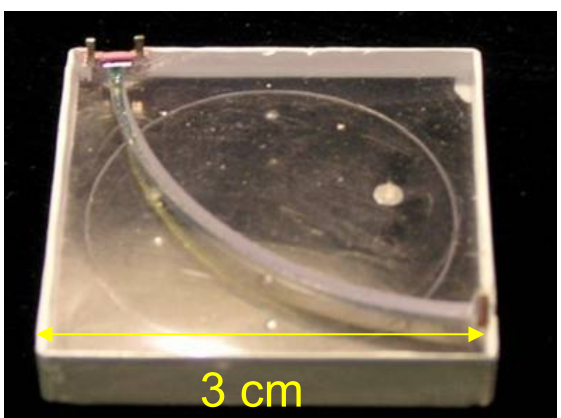
hadronic shower as seen by the HCAL (TB data) →

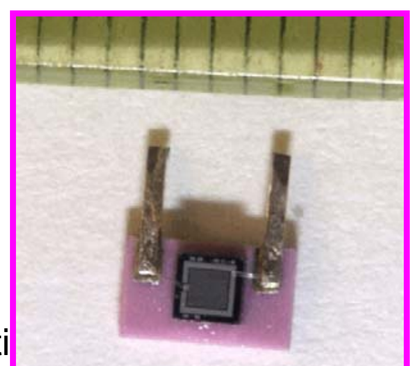


PFLOW at work: an ILC event



The HCAL building block: scintillator tile with Silicon-Photomultiplier readout

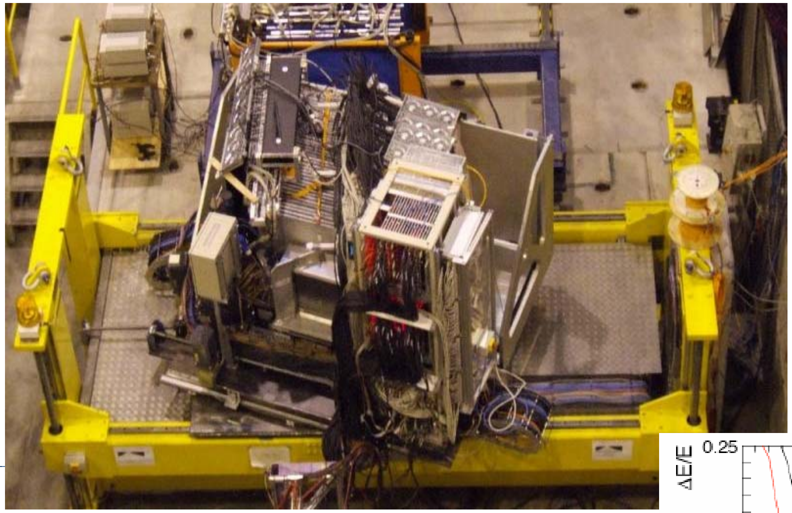




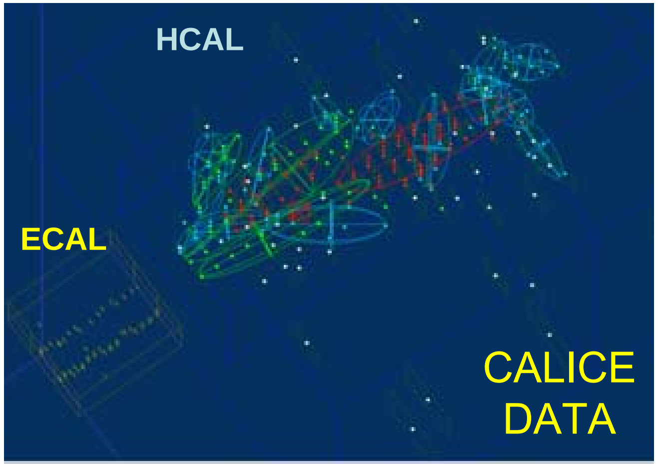
Validating PFLOW

CALICE collaboration: test beam campaigns at CERN & FNAL with highly granular calorimeters

~30TByte data collected (>300 M ev)

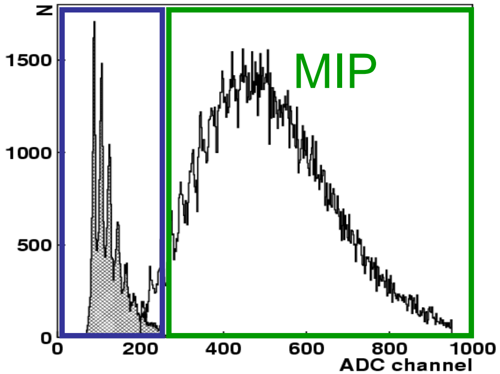


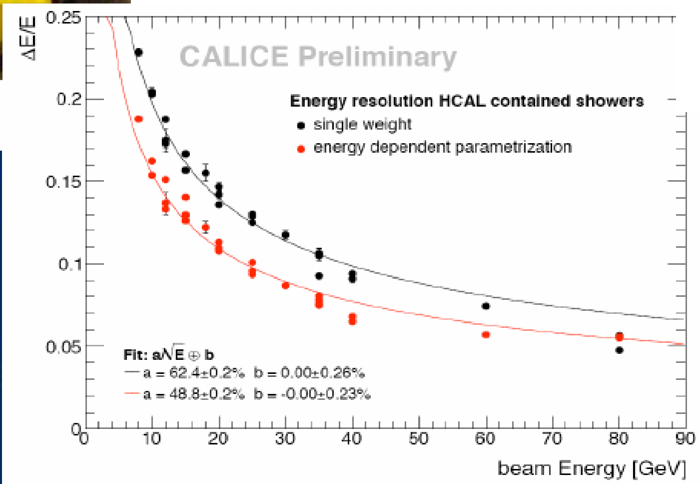
CALICE installation at CERN SPS



Single photoelectron → spectrum from SiPM offers possibility of self calibrating each cell

Single photoelectron



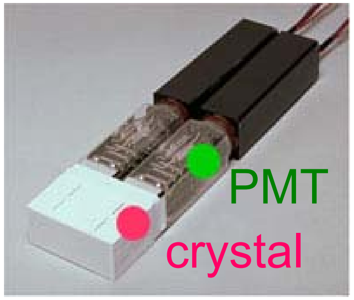


62.4% stochastic term improves to 48.8% using parameterized weighting techniques

ongoing analysis to study shower separation in the HCAL data → first prove of principle of Particle Flow

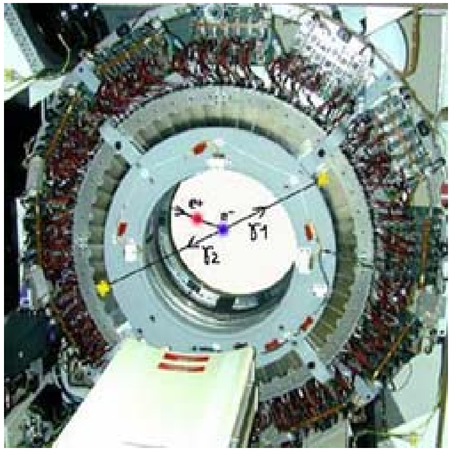
Positron Emission Tomography

- How can a calorimeter save your life? ➔ PET



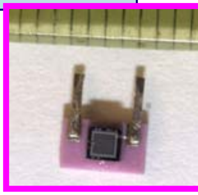
a commercial PET system
for hospital treatment

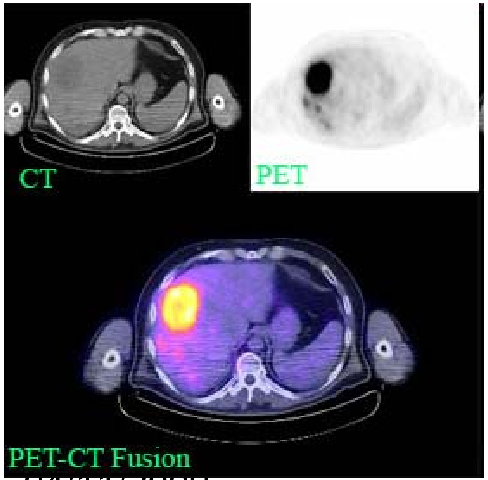
the same system without cover
doesn't it look like something familiar?

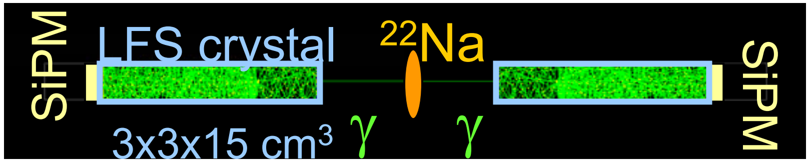


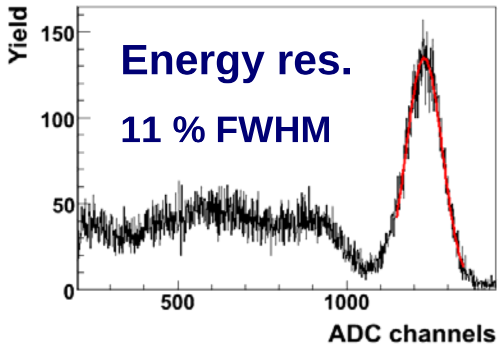
basic unit of a PET:
crystal (LSO, BGO) + PMT

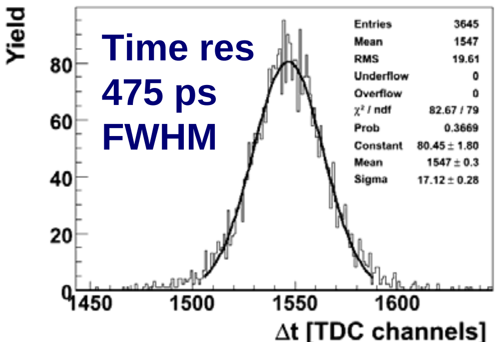
SiPM offers: higher granularity,
good time resolution
compact system, low HV & cost





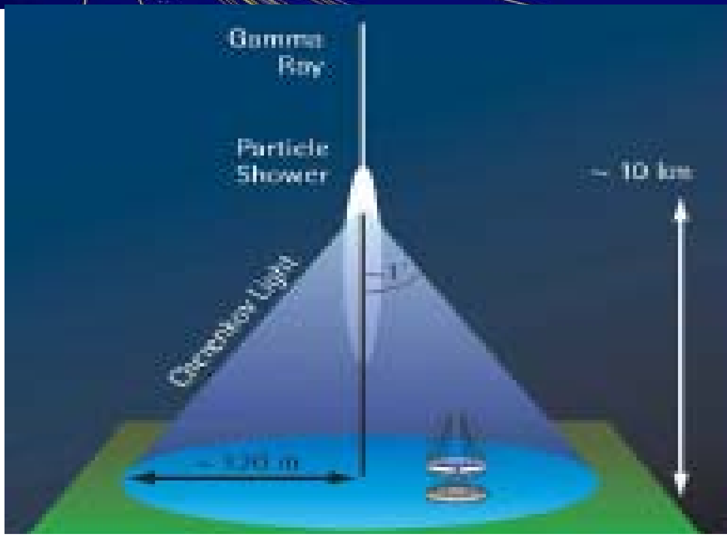






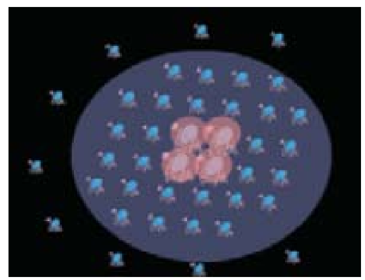
Ground based Gamma Ray Astronomy

Landesexzellenzinitiative Hamburg

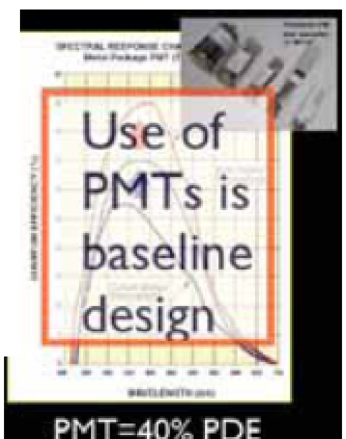


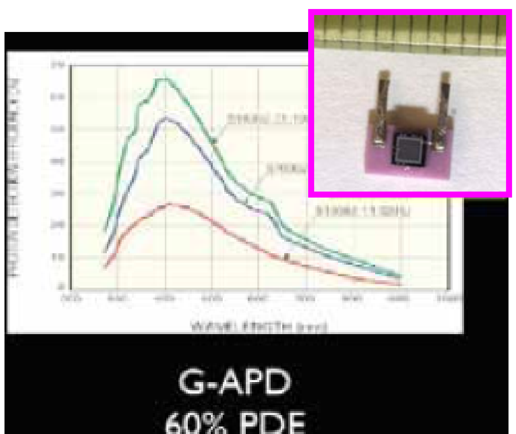
Gamma Ray induces electromagnetic cascade
➔ Relativistic particle shower in atmosphere
➔ Cherenkov light
fast light flash (~ns)
100 γ / m^2 (1 TeV Gamma Ray)

Next generation: Cherenkov Array Telescope (CTA)



All-sky coverage from two sites (N,S) each with L, M, S size telescopes



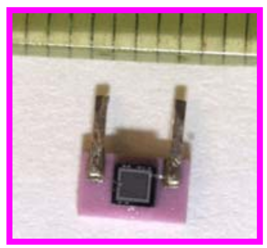


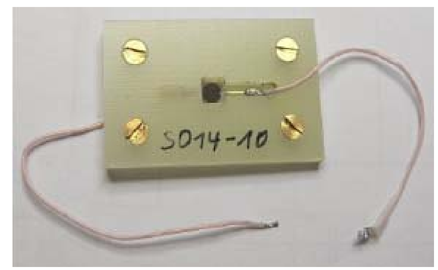
CAMERA

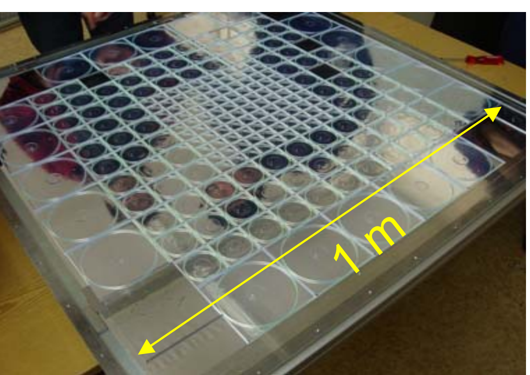
- Expensive
- Camera composed of 1000 – 2000 pixels
- Fast timing response (~1ns) to cope with EAS Cherenkov flashes
- Electronics inside the camera
- Keep low weight

R&D activities at DESY & Uni. HH

LEXI LANDESEXZELLENZINITIATIVE HAMBURG → Profit from common infrastructures / intensified knowledge exchange / coordinated use of resources ← PHYSICS AT THE TERA SCALE Helmholtz Alliance (virtual detector laboratory)







Detector laboratory

Conclusions

- many exciting activities in detector R&D field
- increasing opportunities to intensify cooperation with the upcoming projects
  ➔ will impact on quality and visibility of our work
- important spin-off to other fields (medical application, photon science)

LEXI
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