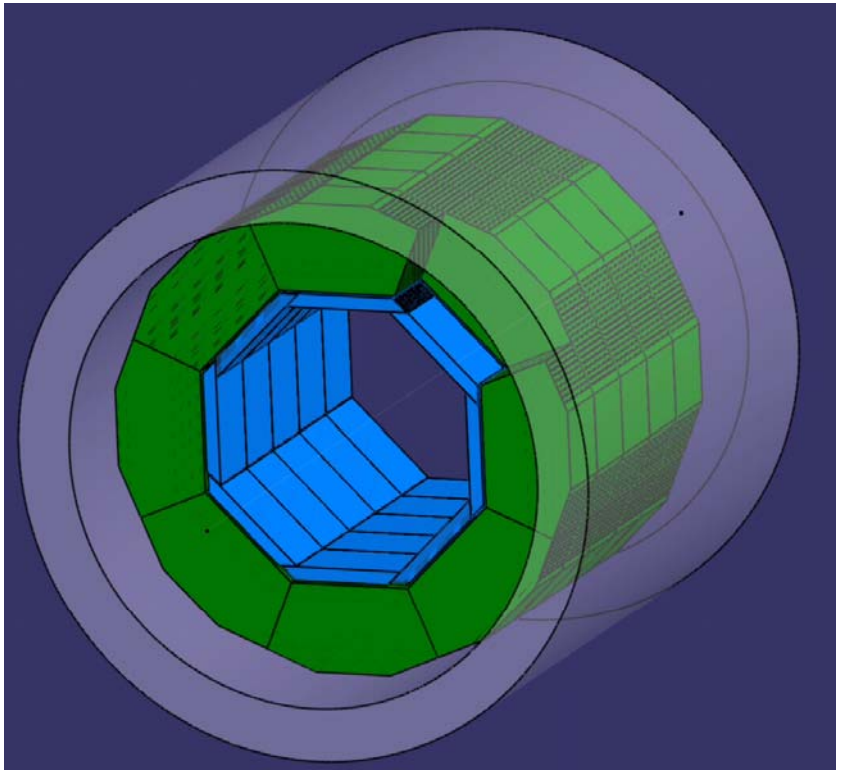
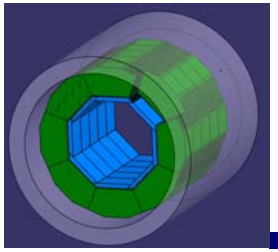


Tile Hadron Calorimeter

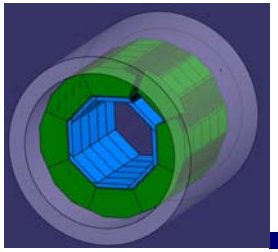
Felix Sefkow

Calorimeter R&D Review
LCWS07, Hamburg, May 31, 2007



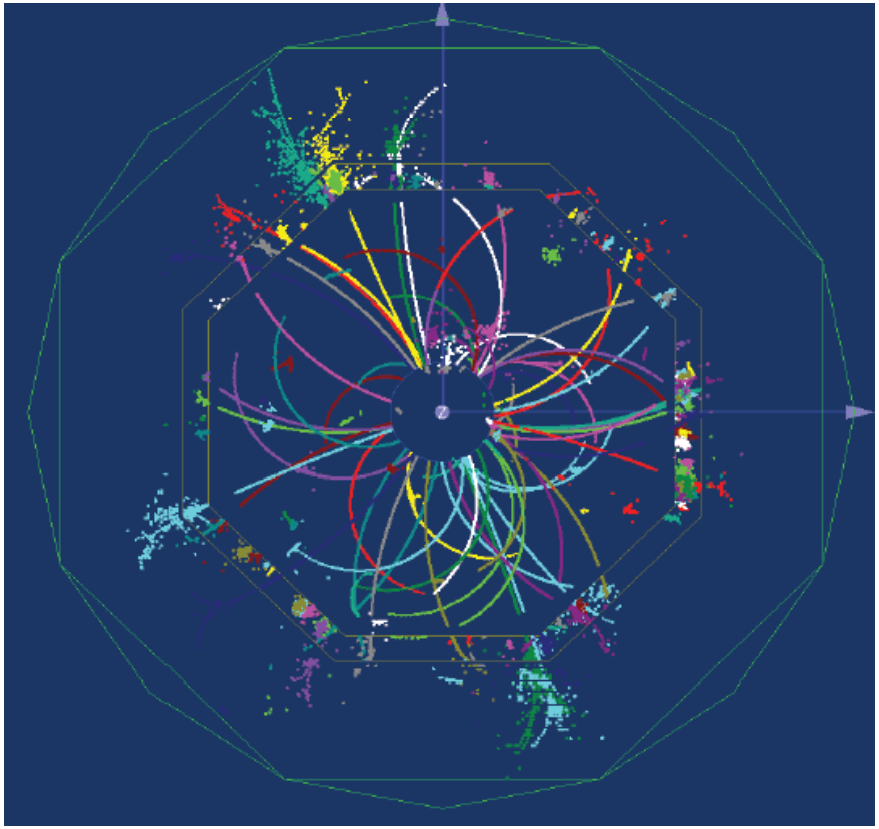
Outline

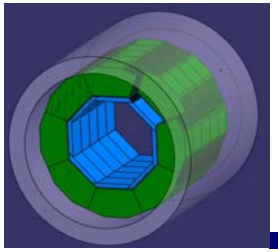
- Conceptual overview
- Test beam prototype
  - HCAL and Tail Catcher
- Future R&D directions



Imaging hadron calorimeter

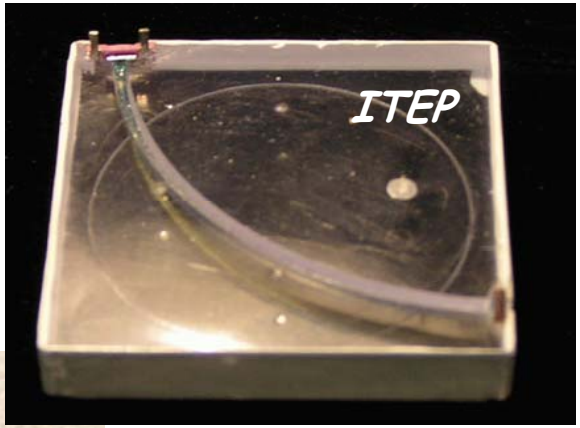
- Particle Flow Approach: Reconstruct each particle individually
- **HCAL:** separate charged from neutral hadrons
  - Measure charged particles in the tracker: remove main part of hadronic energy fluctuations
- Requires high longitudinal and transverse **granularity**
- Still need very good hadron **energy resolution**
  - Software compensation



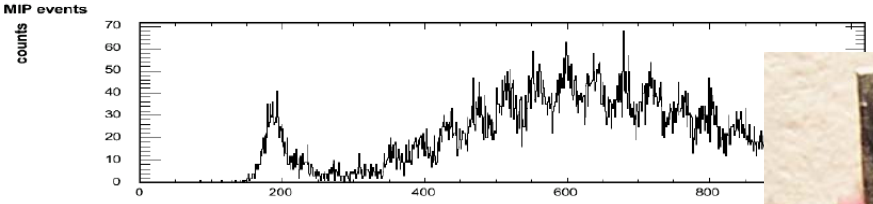


SiPMs for calorimetry

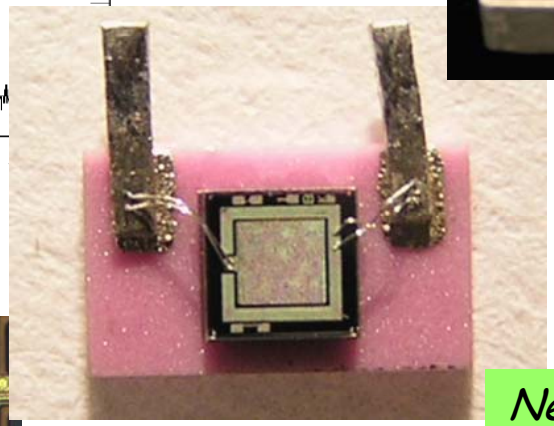
- Multipixel Geiger Mode Photodiodes
  - Developed and produced by MPEPHI/PUSAR
  - Gain 10^6, bias ~ 50 V, size 1 mm^2
  - Insensitive to magnetic fields

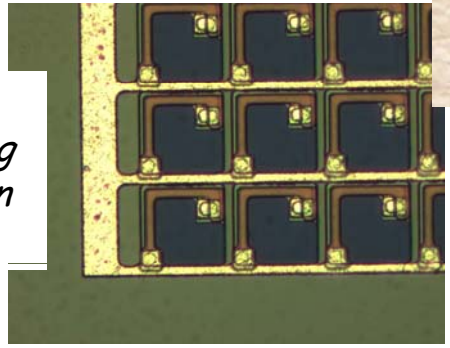


3x3 cm scintillator tile with WLS fibre



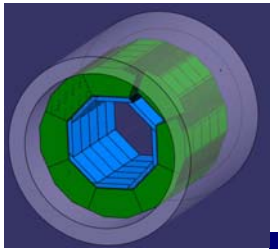
Auto-calibrating but non-linear





1156 pixels with individual quenching resistor on common substrate

New era for scintillator-based detectors: ***High granularity*** *at relatively* ***low cost***



SiPM development

- Long history, see for example

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Status report on silicon photomultiplier development and its applications☆

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[d]*State Unitary Science & Production Enterprise (PULSAR), Okruzhnoy proezd 27, Moscow, Russia*
[e]*University of Hamburg, Germany*

Available online 24 March 2006

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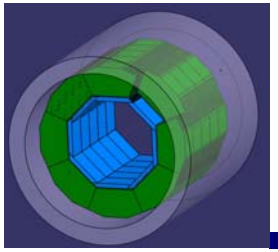
[1] G. Bondarenko, B. Dolgoshein, V. Golovin, A. Ilyin, R. Klanner, E. Popova, Nucl. Phys. B (Proc. Suppl.) 61B (1998) 347 and reference therein;
G. Bondarenko, P. Buzhan, B. Dolgoshein, V. Golovin, E. Guschin, A. Ilyin, V. Kaplin, A. Karakash, R. Klanner, V. Pokachalov, E. Popova, K. Smirnov, Nucl. Instr. and Meth. A 442 (2000) 187 and references therein.

[2] P. Buzhan, B. Dolgoshein, L. Filatov, A. Ilyin, V. Kantzerov, V. Kaplin, A. Karakash, F. Kayumov, S. Klemin, A. Pleshko, E. Popova, S. Smirnov, Yu. Volkov, The advanced study of silicon photomultiplier, in: Proceedings of the Seventh International Conference on Advance Technology & Particle Physics, 2002, pp. 717–728.

[3] P. Buzhan, B. Dolgoshein, L. Filatov, A. Ilyin, V. Kantzerov, V. Kaplin, A. Karakash, F.P. Buzhan, B. Dolgoshein, L. Filatov, A. Ilyin, V. Kantzerov, V. Kaplin, A. Karakash, F. Kayumov, S. Klemin, E. Popova, S. Smirnov, Nucl. Instr. and Meth. A 504 (2003) 48.

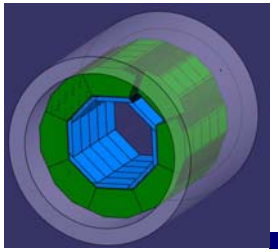
[4] B. Dolgoshein (on behalf of SiPM-Collaboration), Silicon Photomultipliers in particle physics: possibilities and limitations, presented at Workshop "Innovative Detectors for Future Colliders", Erice, Italy, October. 2003.



Scintillators

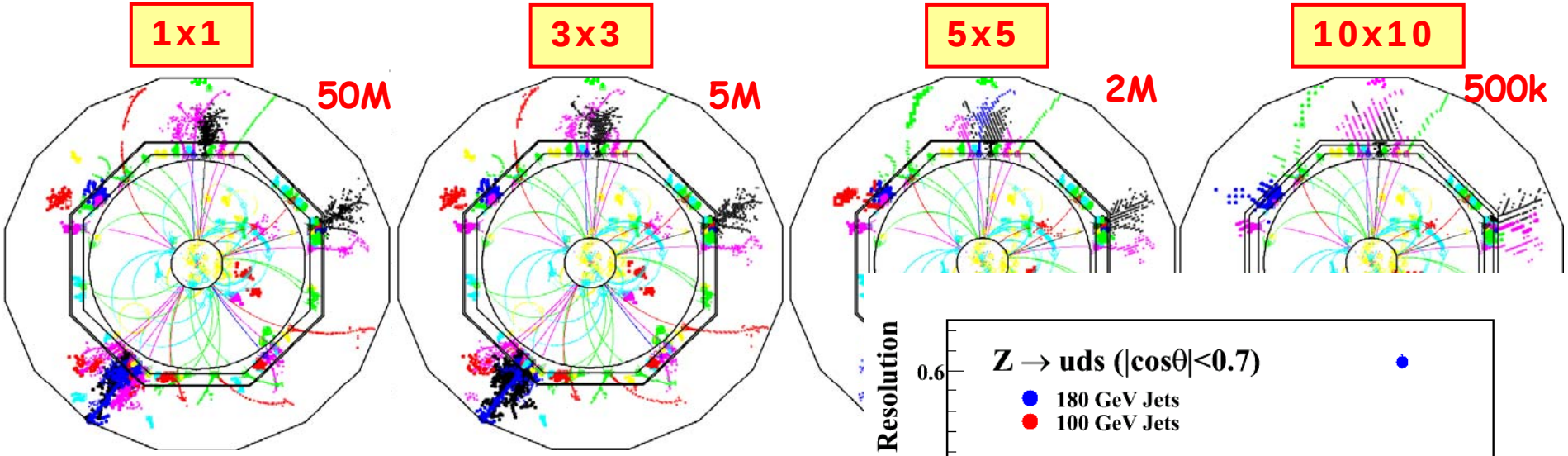
- Originally a baseline/backup solution
- Proven technology
- Robust, high rate capability
- sufficiently rad hard
  - 1 Mrad = 10 kGy or 10^{15} n
- Cheap (not a cost driver)
- Thoroughly optimized
  - Studies at ITEP, DESY, NIU,…

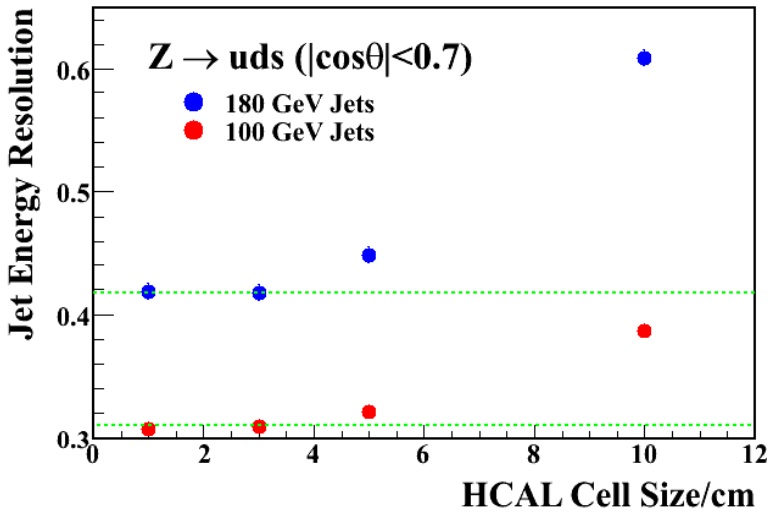
- Trade granularity versus amplitude resolution
- 3 cm size optimized for shower separation
- and semi-digital readout



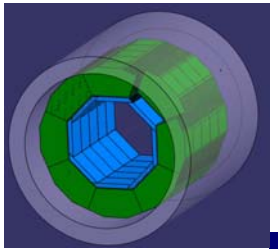
Granularity

- Recent studies with Pandora PFLOW algorithm (M.Thomson)



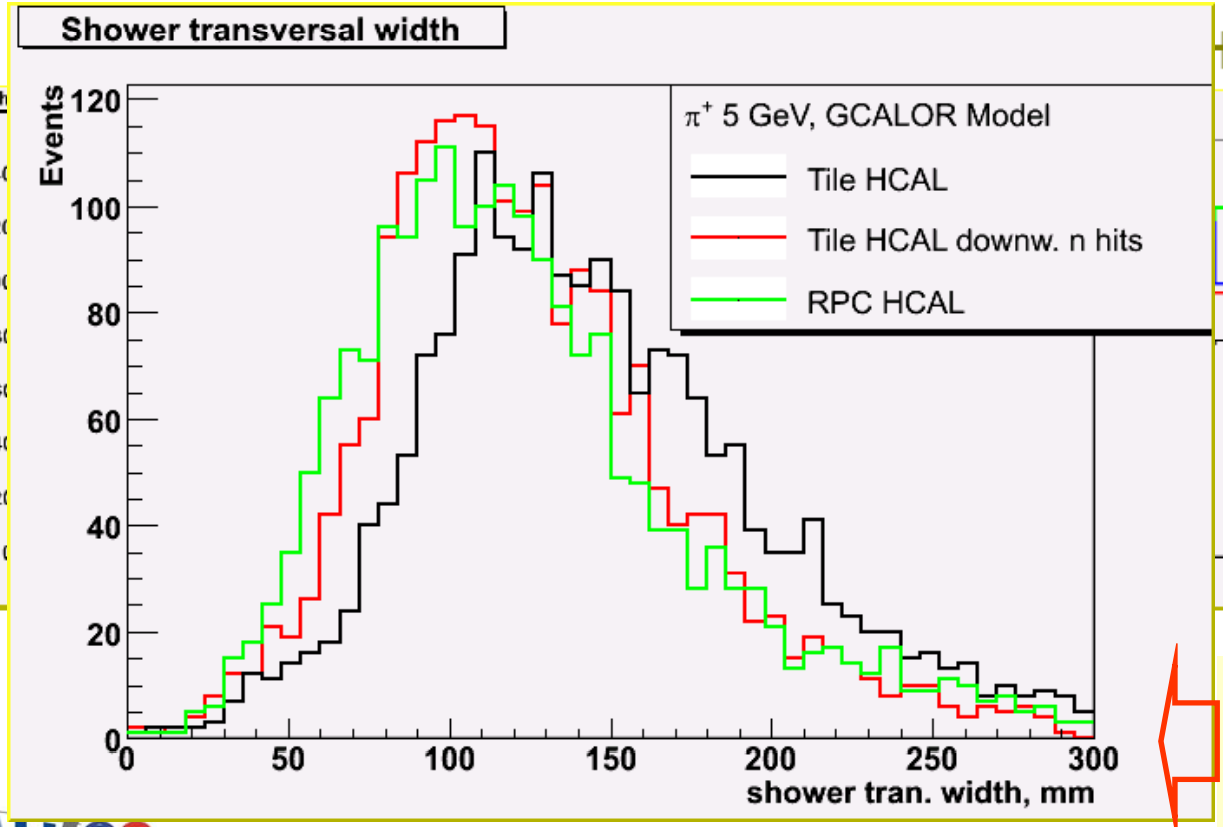


- Confirms earlier studies for test beam prototype
- 3x3 cm^2 nearly optimal
- Granularity vs depth to be done



Imaging quality

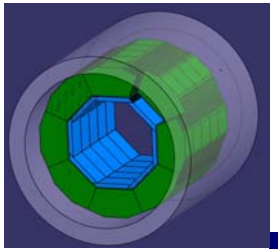
- Shower in scintillator appears* wider than in gas
- Large model dependence of shower width



HCAL

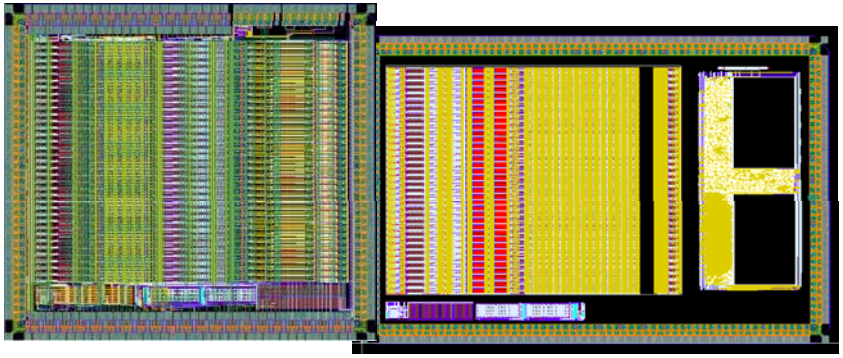
** unweighted*

Use the weights which optimize hadron energy resolution



Readout and calibration

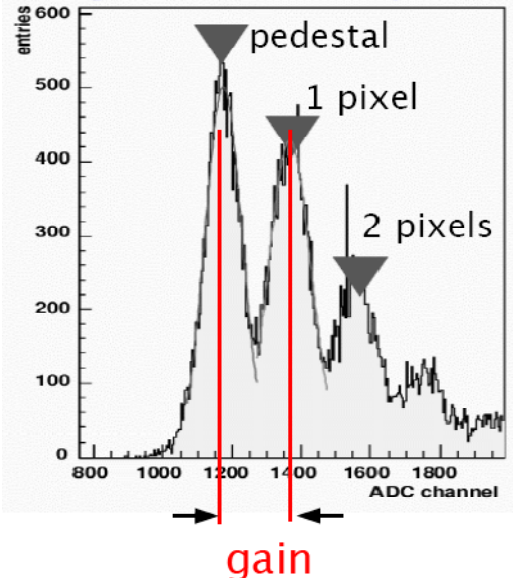
- Readout: follow integrated apporach for ECAL and HCAL
  - Synergies in ASIC development
  - Standardized system downstream

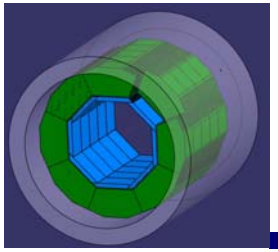


- Calibration: use MIP scale
  - inter-calibration and long-term variations

- Monitoring: auto-calibration
  - SiPM gain variations directly observable (~2%/K)
  - Also needed for non-linearity corrections

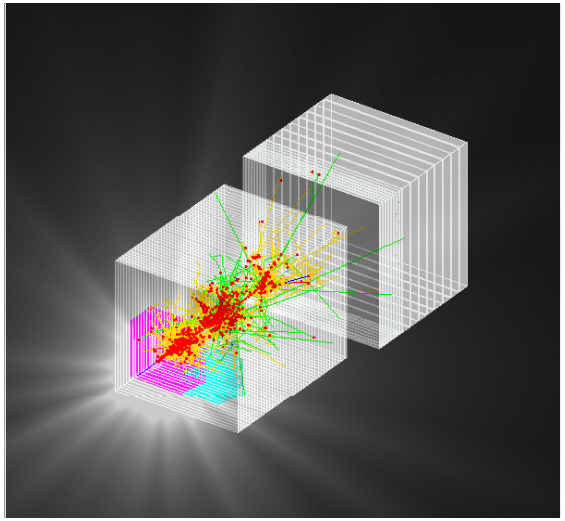
Single Photon Response



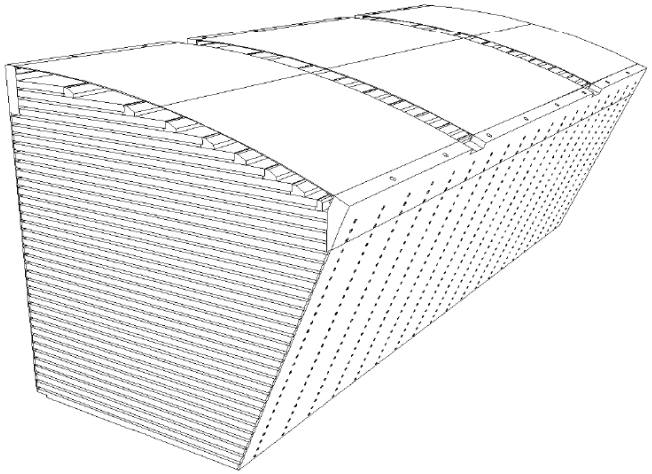


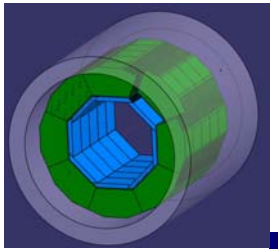
R&D programme

- Test beam programme
  - Fine structure of hadron showers
  - Validate the simulations
  - Large scale test of novel sensor technology
  - Operational experience for system optimization
    - E.g. calibration and correction strategies



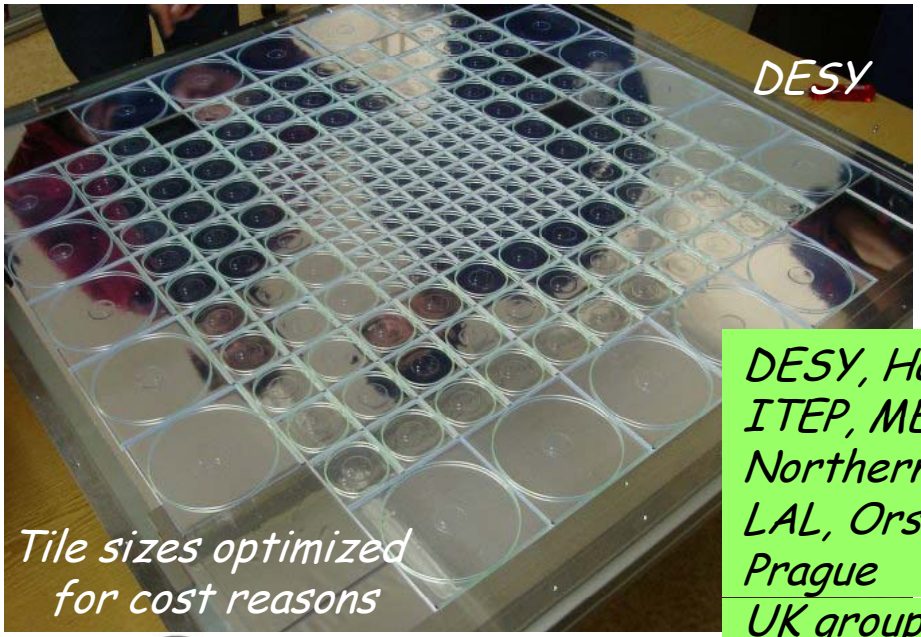
- Technical prototypes
  - Develop solutions for detector integration
    - Embedded electronics
  - Minimize gap width and dead regions
  - Obtain basis for cost estimate

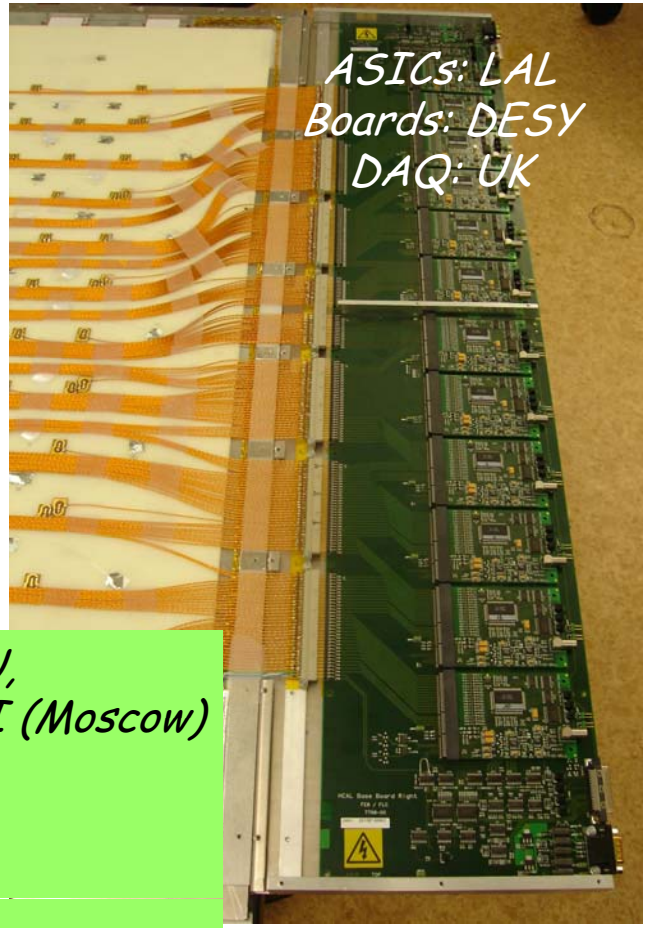




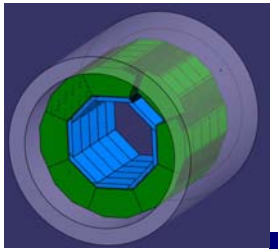
Tile HCAL testbeam prototype

- 1 cubic metre
- 38 layers, 2cm steel plates
- 8000 tiles with SiPMs
- Electronics based on CALICE ECAL design, common back-end and DAQ





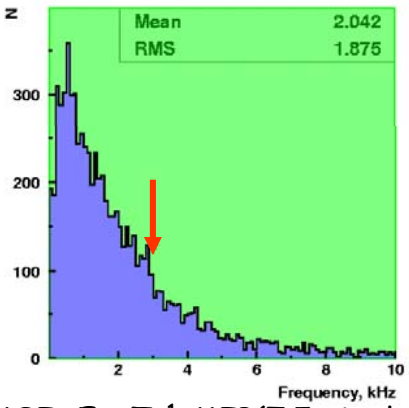
DESY, Hamburg U,
ITEP, MEPHI, LPI (Moscow)
Northern Illinois
LAL, Orsay
Prague
UK groups



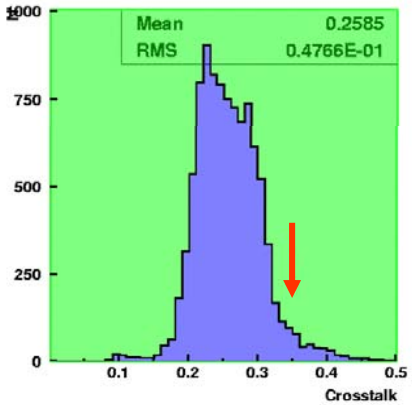
SiPM mass production

~ 10'000 SiPMs

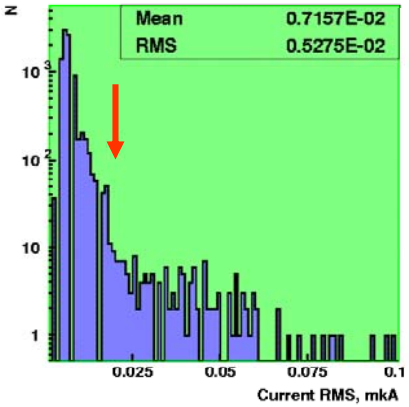
- Production at PULSAR, close collaboration with MEPHI
  - Tests on probe station
- Multi-stage selection procedure at ITEP
  - Stability test at elevated ΔV
  - SiPM test bench with calibrated LED
  - Working point adjusted to 15 pixel/MIP_{nom}
  - Tile WLS SiPM system with Sr source
- Results in data base



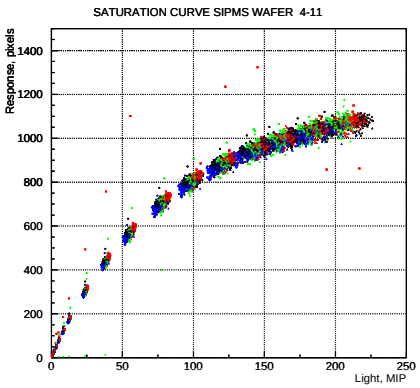
NOISE AT $\frac{1}{2}$ MIP(7.5 pixels)



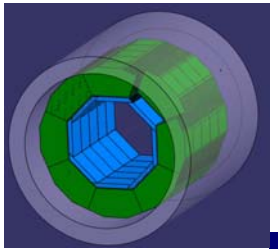
CROSS TALK



CURRENT STABILITY

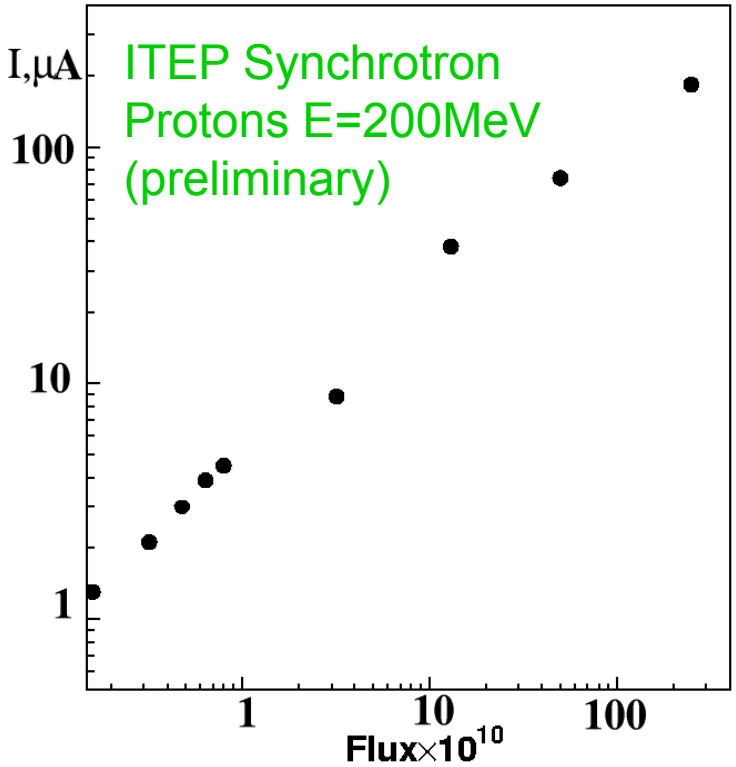


SATURATION CURVE



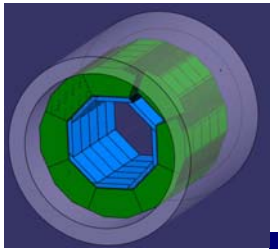
SiPM radiation hardness

- Tested with protons
- Dark current increases with flux
  - As for other Si devices
- Initial noise very small: 0.15 p.e.
  - Suffer sooner
- After 10^{10} / cm^2 single p.e. peaks disappear
  - MIP still seen after > 10^{11} / cm^2
- At ILC $10^{10}/cm^2$ only very close to beam pipe
- **OK for ILC HCAL**
  - Long-term low dose to be studied



Calibration and monitoring

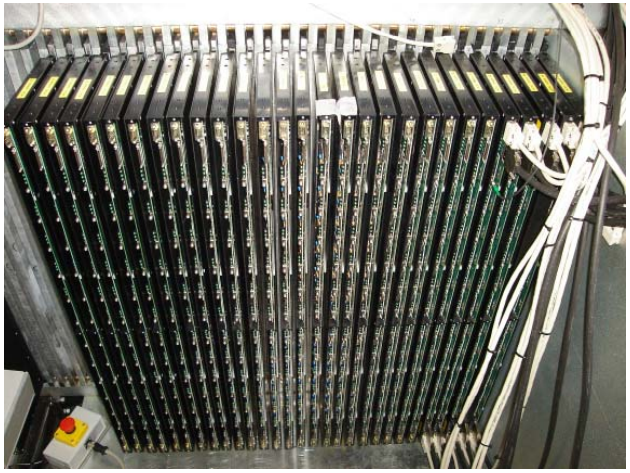
- SiPM response varies by ~ 5% / K (depending on ΔV)
- The test beam prototype has a highly versatile and redundant LED based monitoring system (electronics: Prague)
  - 1 LED illuminates 18 tiles via fibre bundle
  - PIN-diode controled LED reference signals
  - Low light intensity for gain measurements (single p.e. peaks)
  - Large dynamic range for long-term test of saturation
    - Short pulse length (< 10 ns)
  - Temperature sensors
- Ultimately not needed, goal is here to establish procedures



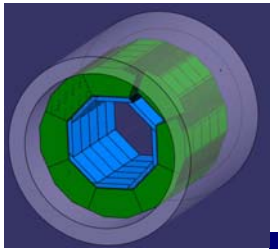
Mechanics

- Versatile stack
  - Modular structure: absorber plates and cassettes
  - FE boards via connectors; can upgrade
  - Adjustable gap width
  - Exchangeable absorber material
  - Exchangeable active modules
  - Adjustable gap width

DESY



- Movable stage
  - Allow for inclined incidence through high granularity core
  - In situ exchange of active layers possible
  - Provisions for needs of gaseous detectors
  - Integration in CERN and FNAL beams prepared

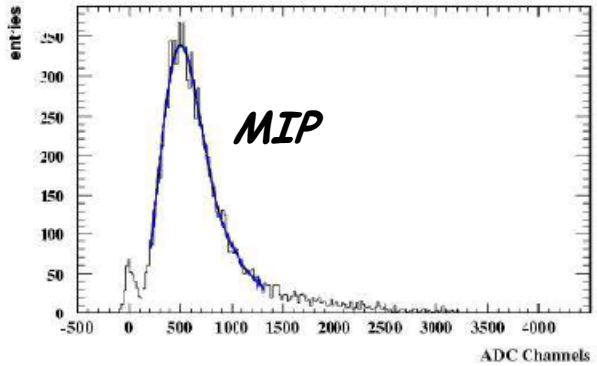


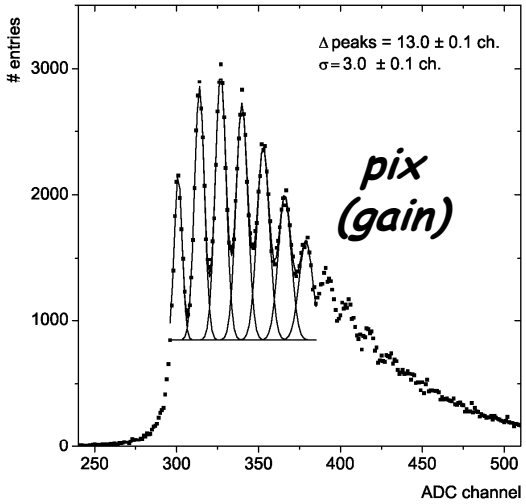
Operational experience

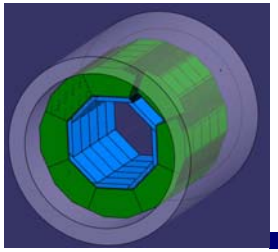
- CERN 2006: 15-13 layers routinely operated
  - Commissioning at DESY invaluable
- Robust and stable: > 90% up-time incl DAQ

- Calibration needs 2 scales: MIP and SiPM pix
  - $E[MIP] = A/A_{MIP} * F(N_{pix})$; $N_{pix}=A/A_{pix}$
  - F is non-linearity correction (test bench)

- Operation:
  - MIP to set noise threshold (1/2 MIP, offline)
  - Pixel to verify working point (15 pix/MIP)



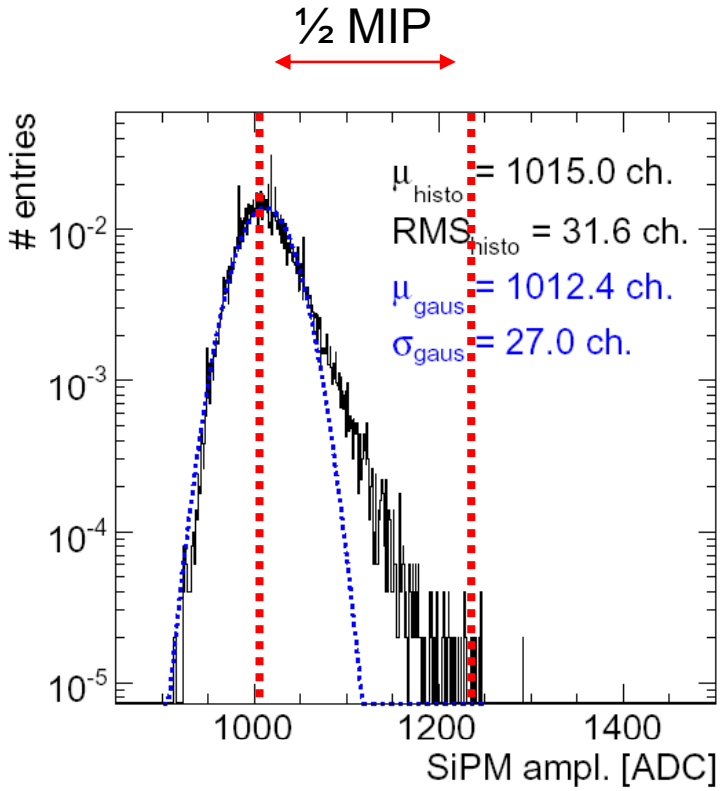




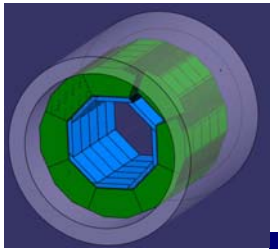
Noise and dead channels

- Electronics noise (SiPM off): Gaussian, width ~1 p.e
- SiPM dark rate: tail
- Above threshold of ½ MIP:
  - 5 hits in 23 layers
  - Occupancy 10^{-3}
  - 3 MIP, 0.1 GeV equivalent
  - Higher in August data

- Channel statistics
  - 98% good
  - 1% bad soldering
  - 1% SiPM long discharge
    - From early selection, improved

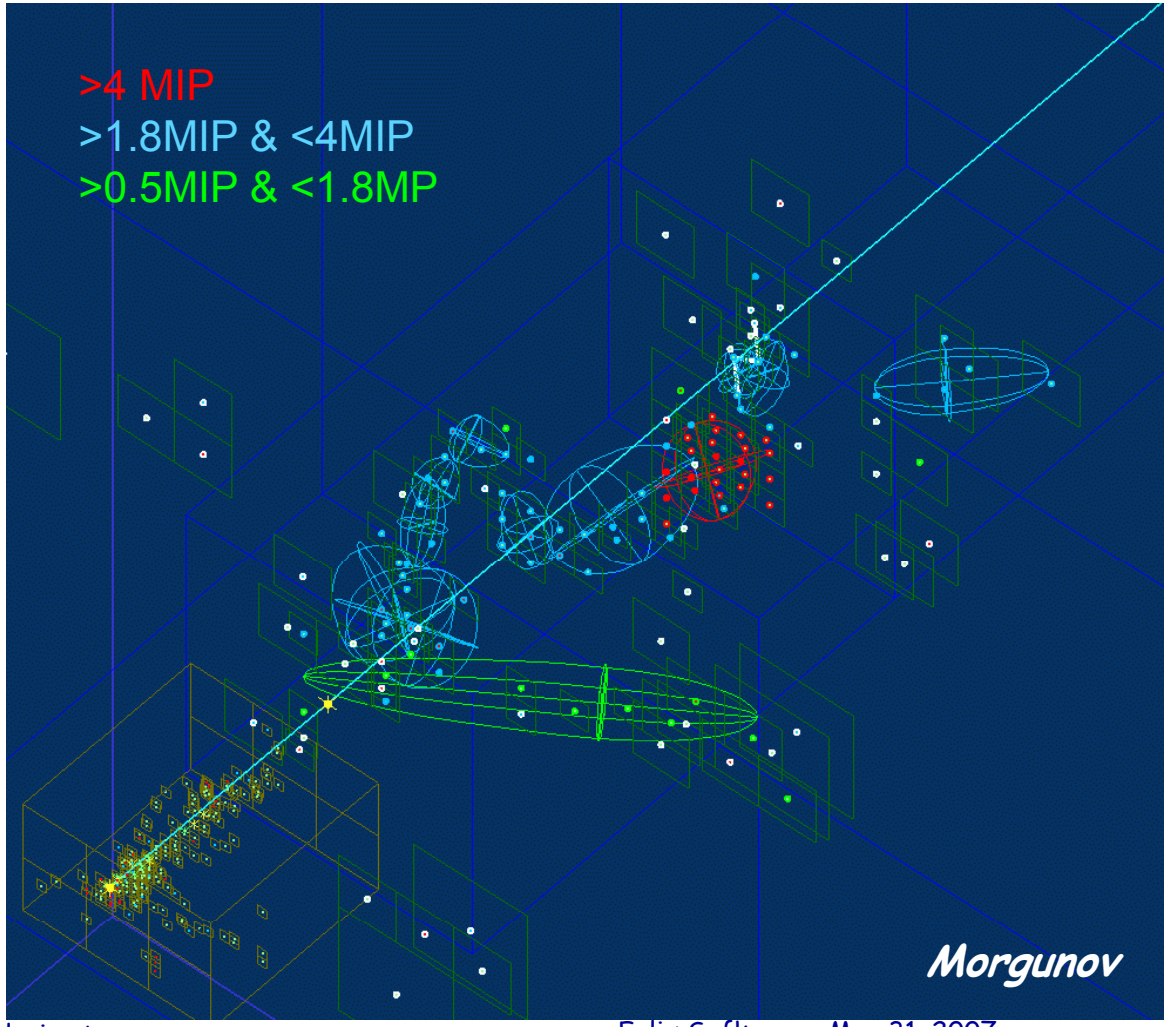


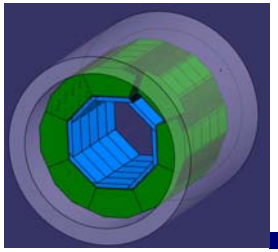
MIP = 450 ch, pixel = 30 ch



Imaging HCAL

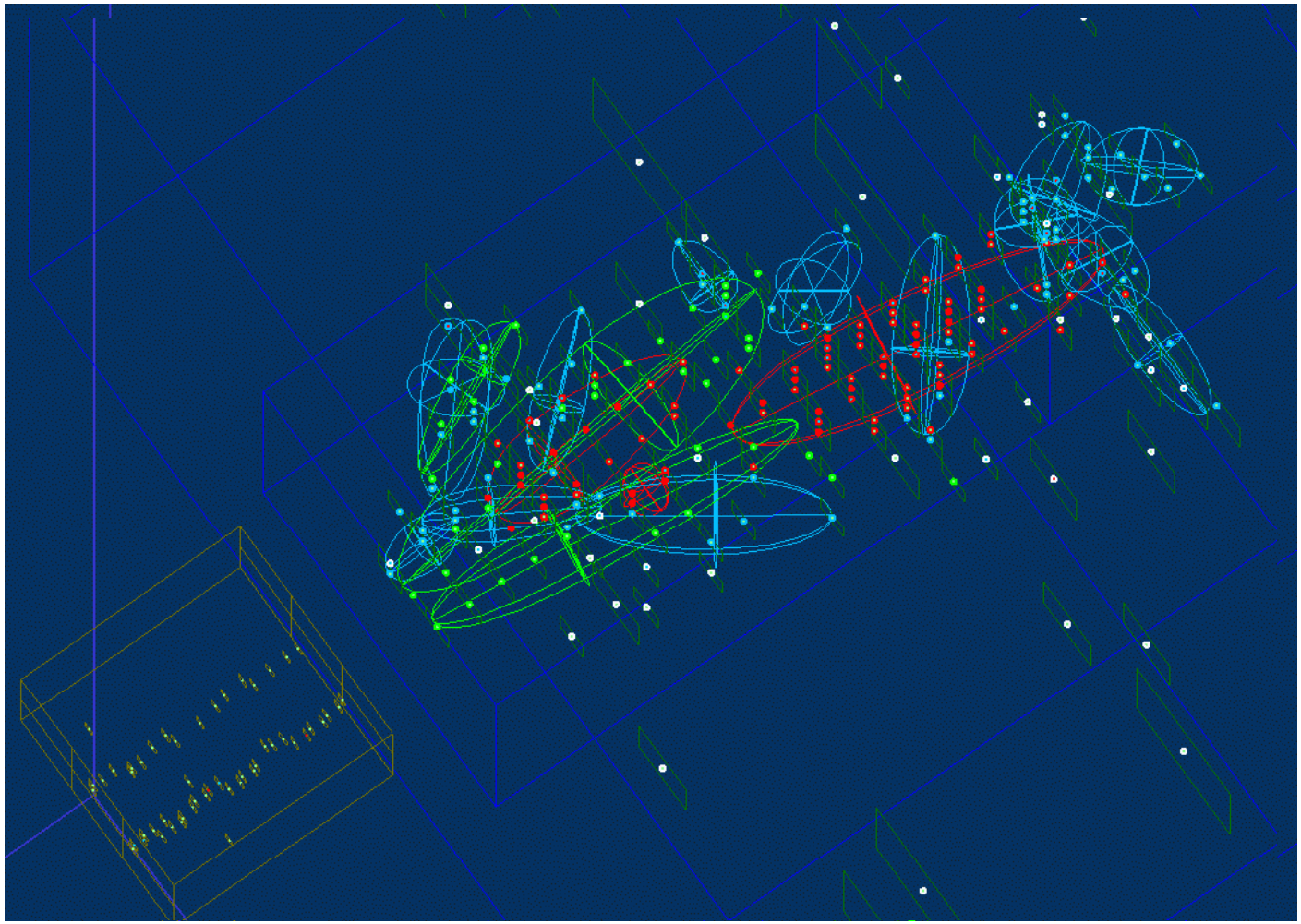
- Substructure visible
- Classification according to amplidude and topology
  - MIP like
  - Hadron like
  - EM like
- Starting point for weighting procedures

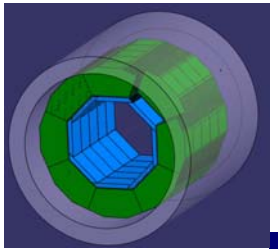




Two hadrons

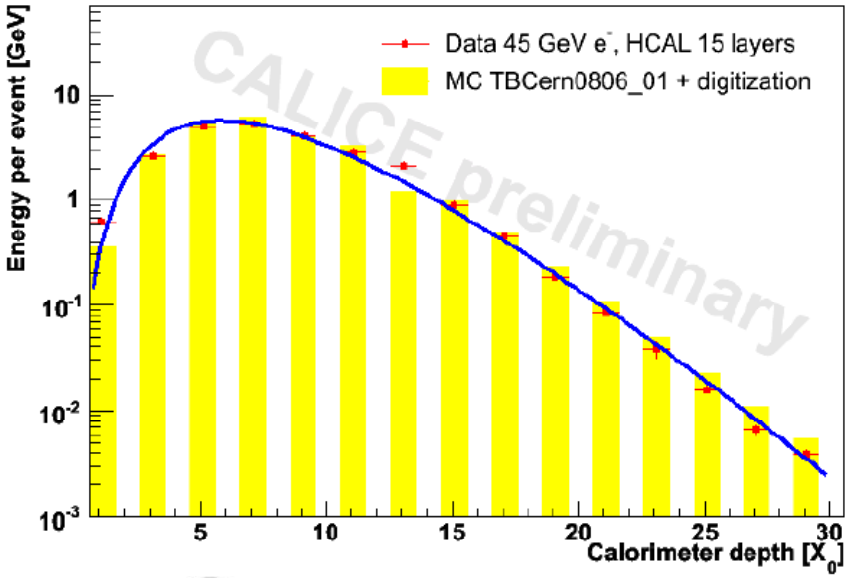
- Starting point for particle flow studies
  - Event overlays
  - Frag-ments
  - …

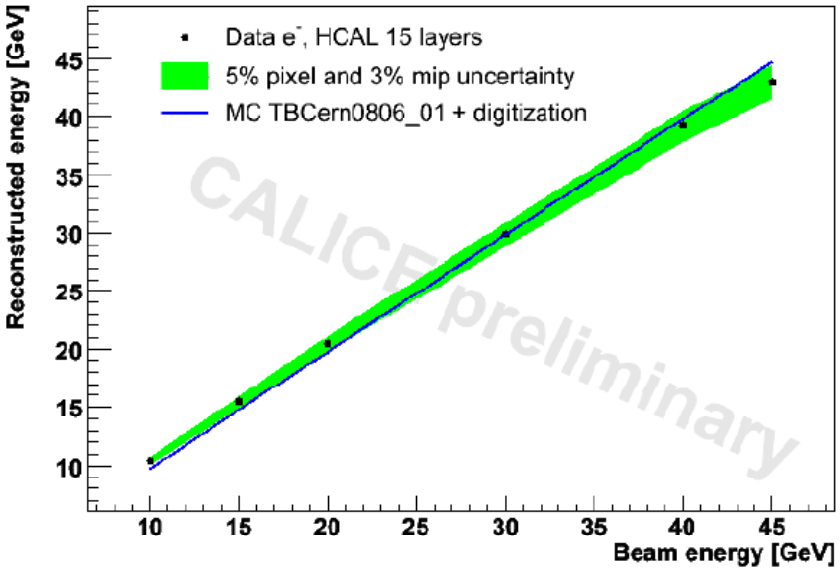


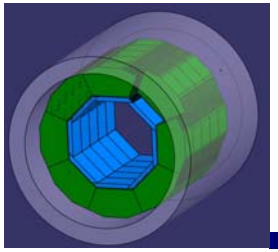


Electron data

- Check detector understanding (MC) and calibration
- Profile: data shower earlier, as already seen in ECAL
- Linearity: not perfect yet, but sufficient for hadron analysis

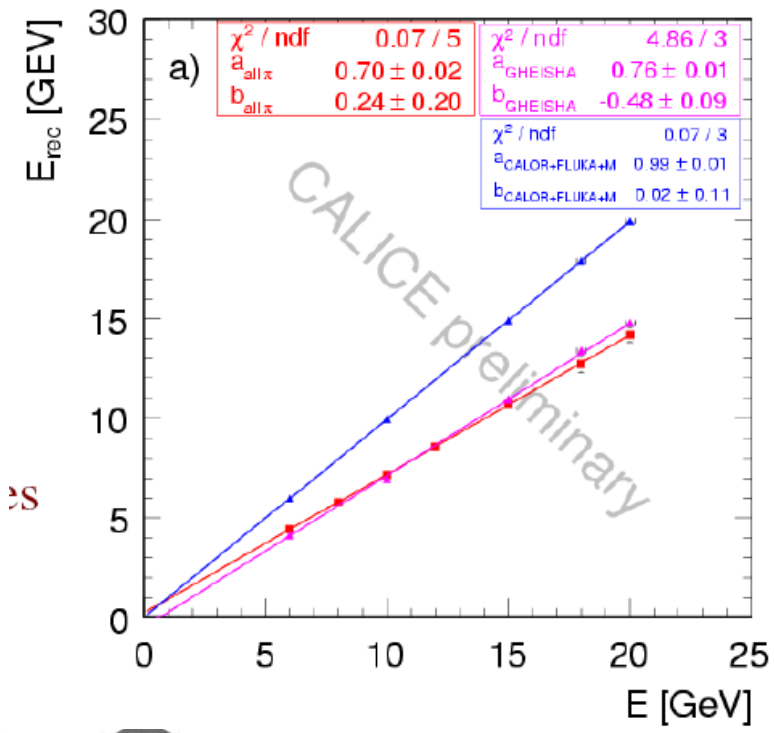


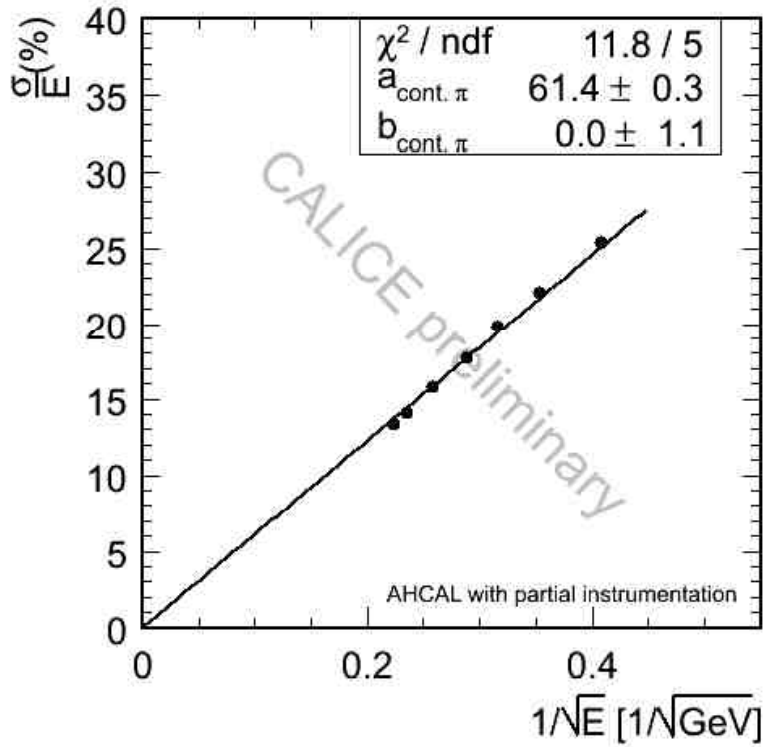


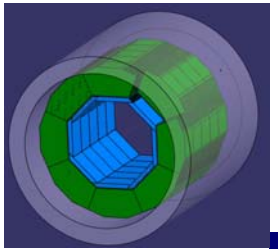


Hadron data

- Hadron data: linearity and resolution "within expectations"
  - Whatever this means: HCAL not complete yet, MC not digitized yet
  - Small constant term for contained showers ☺

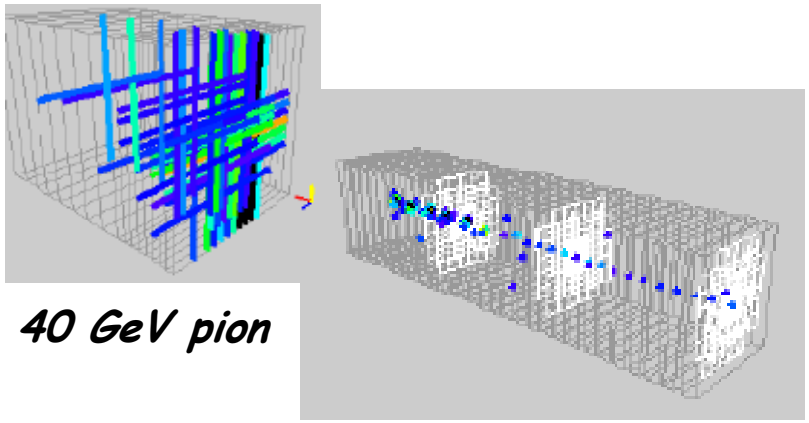




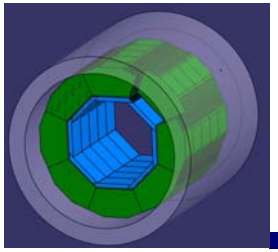


Tail Catcher Muon Tracker

- Scintillator x and y strips (100x5x0.5cm^3) WLS SIPM
- HCAL readout electronics (320 channels)
- NIU with DESY and FNAL



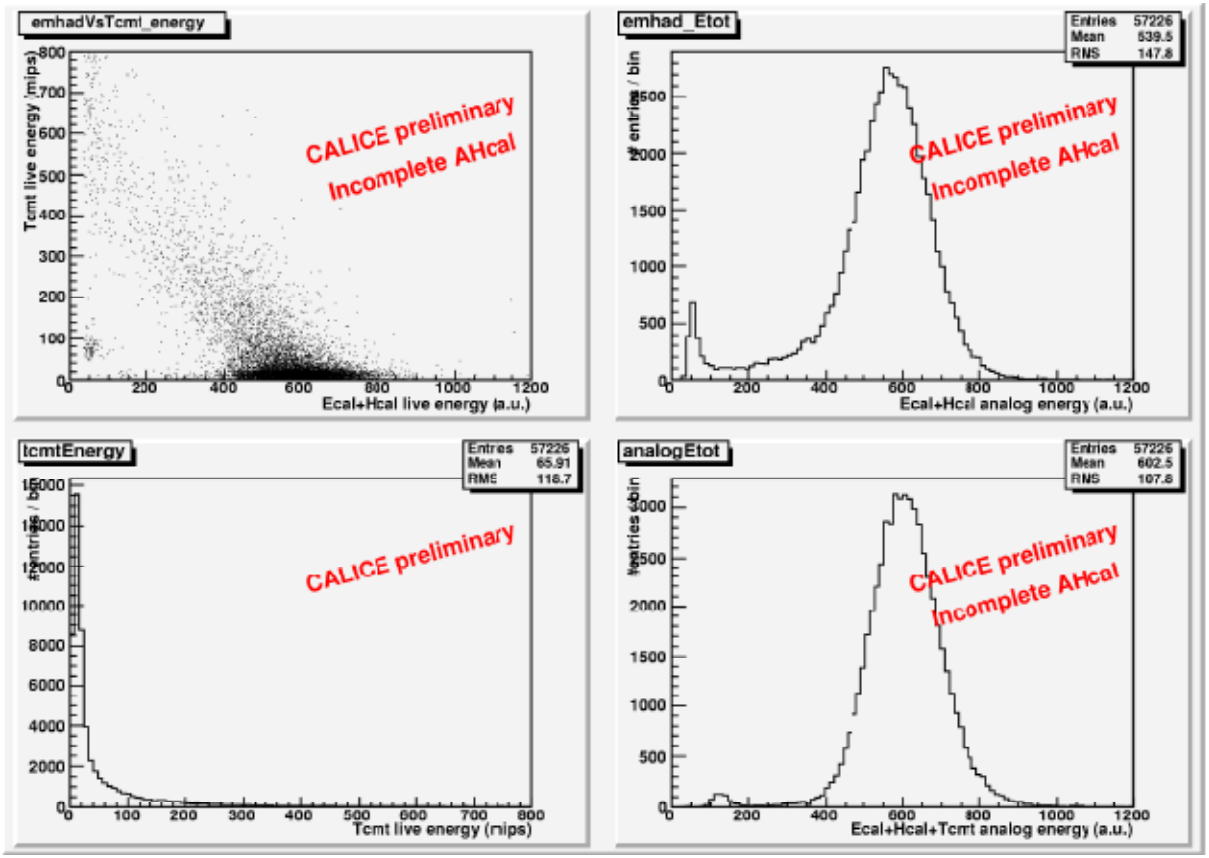
40 GeV pion



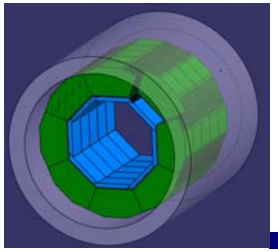
Combined data

20 GeV pions

Drastic improvement

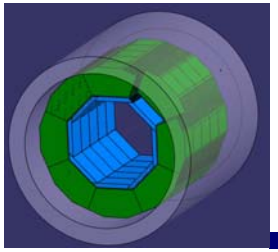


- Similar analysis also done in semi-digital approach (2 bit, 3 thresholds)



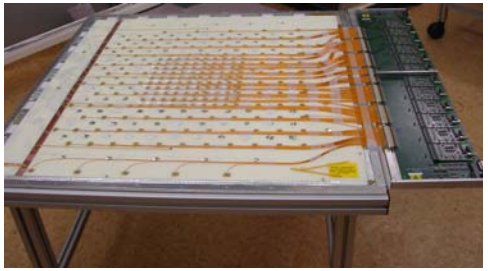
Testbeam 2007 and beyond

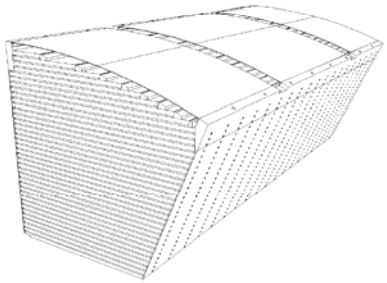
- CERN 2007: 2 periods of 3 weeks each in July and August
  - Use same beam line (H6) as in 2006
  - Complete detector, angular incidence for HCAL and combined data
- Move to FNAL end of this year
- Goals at FNAL 2008:
  - Low energy hadrons (1 GeV), particle ID
  - CERN FNAL connection of data samples
  - Gas scintillator comparison reference points
  - Common "all scintillator" run with Scint W ECAL (el'x being prepared)
- And beyond:
  - Lead as HCAL absorber
  - Time-sensitive (2nd generation) electronics
    - Test neutron hit tagging for PFLOW and hadronic energy resolution
  - Maybe test strip option, *if* encouraged by simulation and PFLOW reconstruction studies

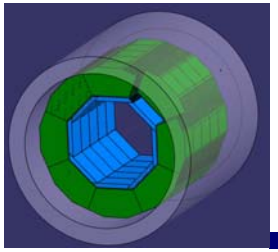


HCAL technological prototype

- Limitations of test beam prototype: not scalable
  - Front end electronics components can be integrated
  - Scintillator and active layer thickness can be minimized
  - Electronics can be optimized to SiPM signal
  - Calibration system can be simplified
  - Assembly can be less labour-consuming
- An example for a scintillator calorimeter with integrated photo-sensors does not exist
- Integration issues:
  - Tile SiPM coupling, tile positioning, SiPM connection
  - ASIC integration, power pulsing, power supply, cooling
  - PCB sub-division, interconnections
  - DAQ interface
  - Calibration system

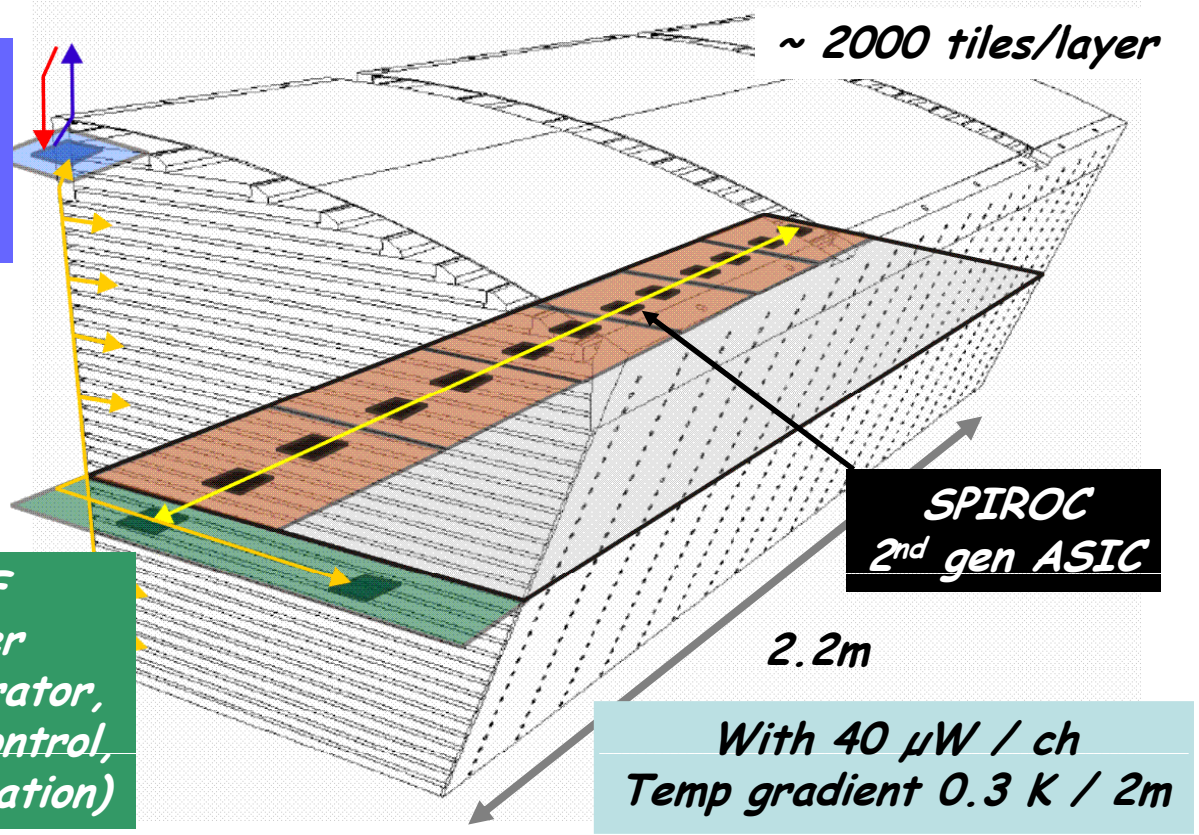




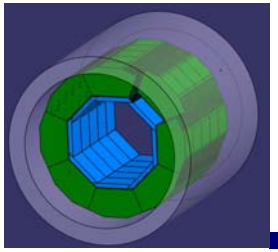


Technical prototype architecture

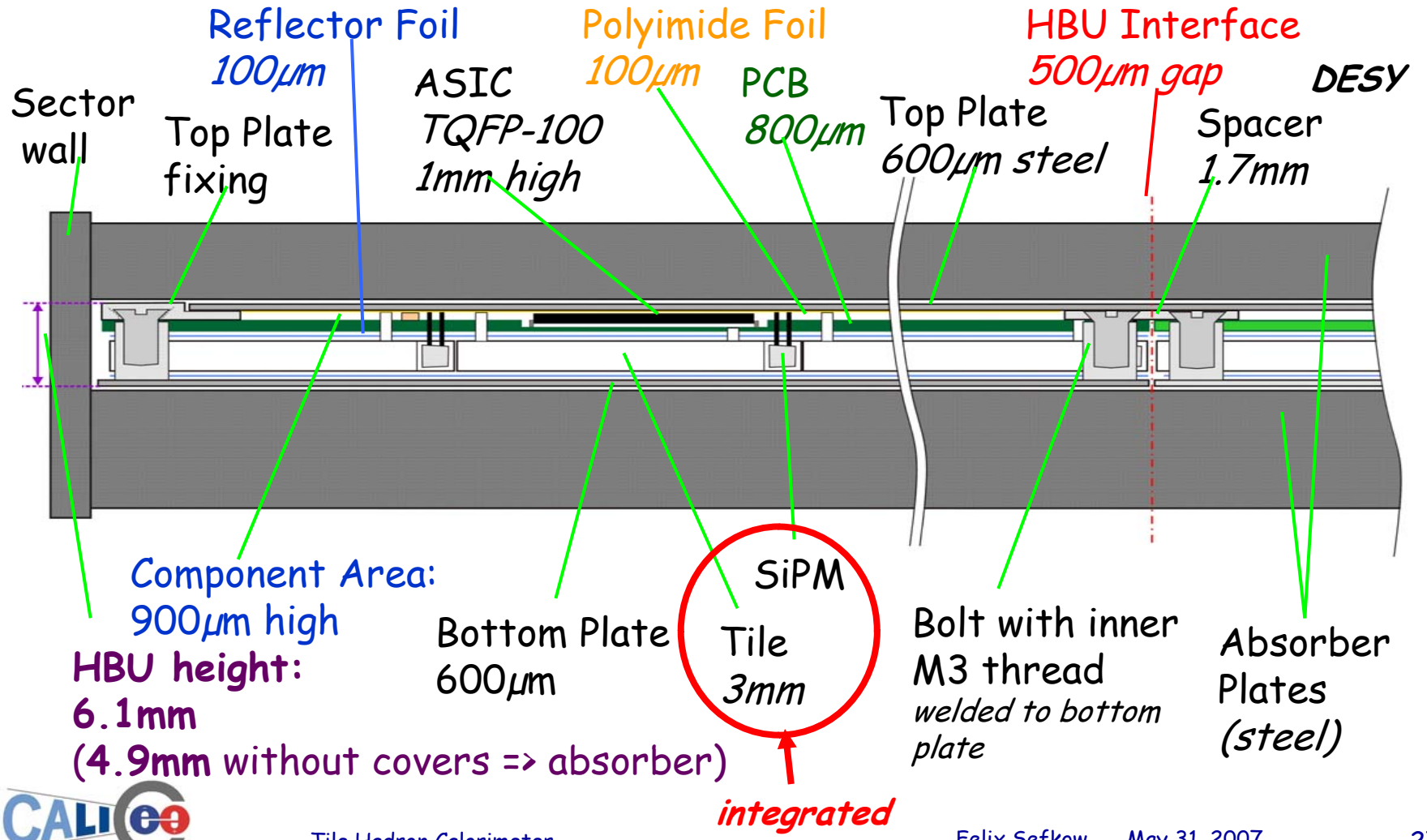
- Very similar to SiW ECAL
- Following CALICE / EUDET DAQ concept

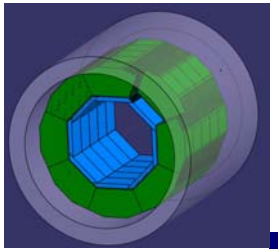


Layer units (assembly) subdivided into smaller PCBs
HBUs: Typically 12*12 tiles, 4 ASICs



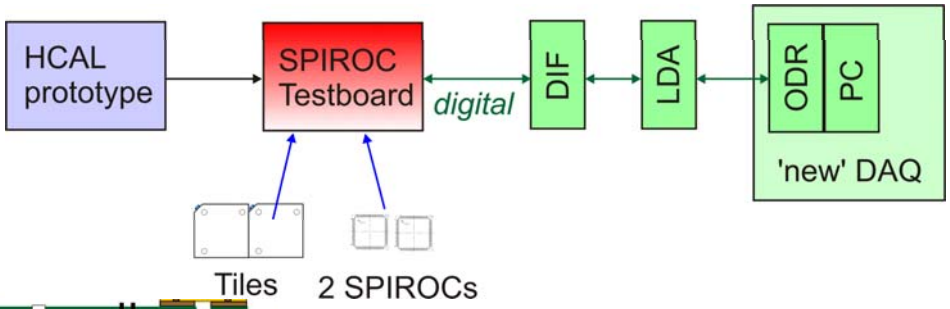
Integrated layer design

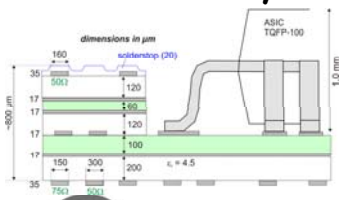


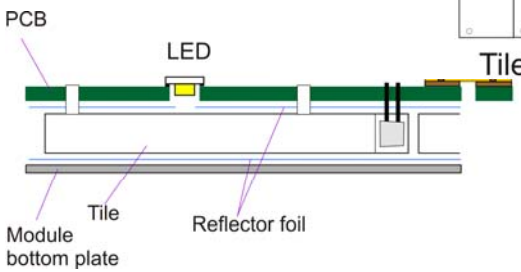


Schedule

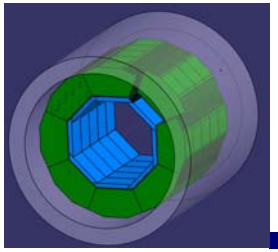
- EUDET programme implies coherent schedule for technical prototypes
- Some milestones:
  - ASICs: 1st proto in 2007, 2nd in 2008
  - DAQ: proto in 2008, system in 2009
  - Module: design in 2008, built in 2009
- Started series of smaller test boards to validate design approach (DESY)
  - LED integration
  - ASIC integration
  - Power system





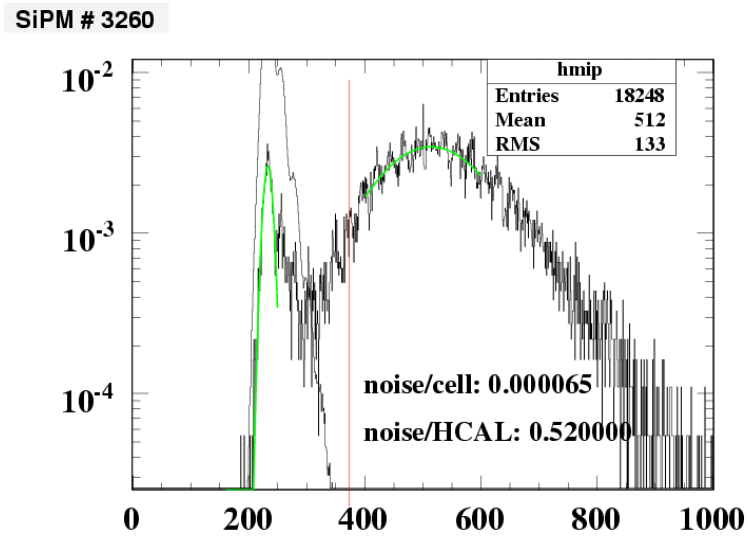


Alternative approach at NIU, Integrate sensor in PCB



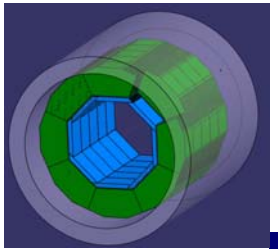
SiPM limitations

- Critical parameter for SiPM performance (in HCAL) is noise above $\frac{1}{2}$MIP threshold
  - Occupancy < 10^{-4} ➔ rate < 300Hz
  - Depends on dark rate, inter-pixel crosstalk, light yield; Rule of thumb
    $N(T) = N_{dark} * (Xtalk)^{T=LY/2}$
  - E.g. 2 MHz * $(0.3)^7$ = 400 Hz



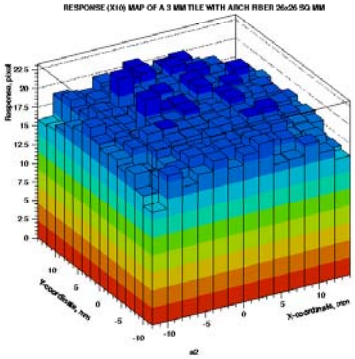
- Need to gain leeway for simplification of design and operation
  - More light? higher thresold, but less dynamic range
  - More area? Higher threshold, but also more dark rate

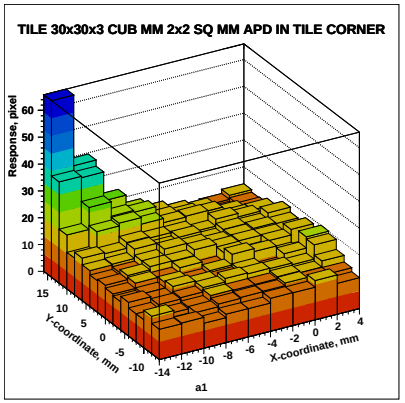
- Developpers progress on dark rate, Xtalk, spectral efficiency
  - Close interaction with ECAL and HCAL groups

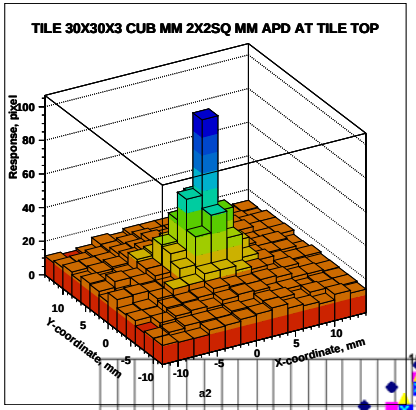


Direct coupling

- SiPM directly on tile, no WLS fibre: simplify production
- Tested with SiPMs, MPPCs, MRS-APDs at ITEP and DESY
  - E.g.: with blue-sensitive MPPC-1600 see 7-9 pixels / MIP for 5mm tile
    - sufficient thanks to low noise
    - but no room for thinning the scintillaltor



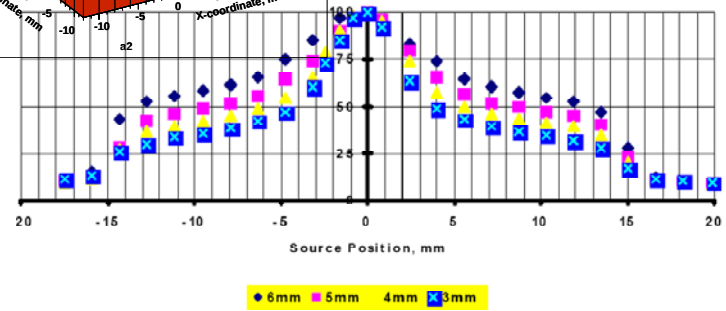


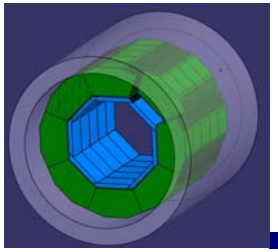


ITEP

Non-uniformity much worse than with WLS fibre
Increases for thinner tilees

NIU





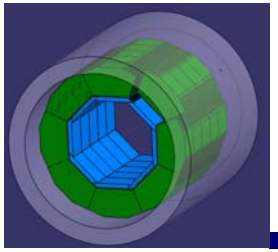
Summary

- The novel multi-pixel Geiger mode photo-diodes (SiPMs) open revolutionary detector design options with highly segmented scintillators – which meet the ILC performance goals.

- A prototype with 8000 channels has been built and successfully operated in the CERN test beam. The results will be used to test the simulations and guide the further optimization of the detector concept.

- In the next years, more R&D will be done to further consolidate and optimize the technology, and to proceed towards a realistic detector design in time for the EDR.

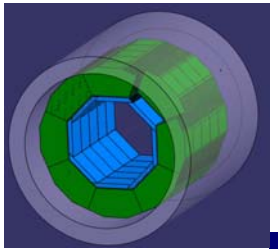
- A TCMT system has been built using the same technology; it is attractive to continue this approach for the next generation.



Conclusion

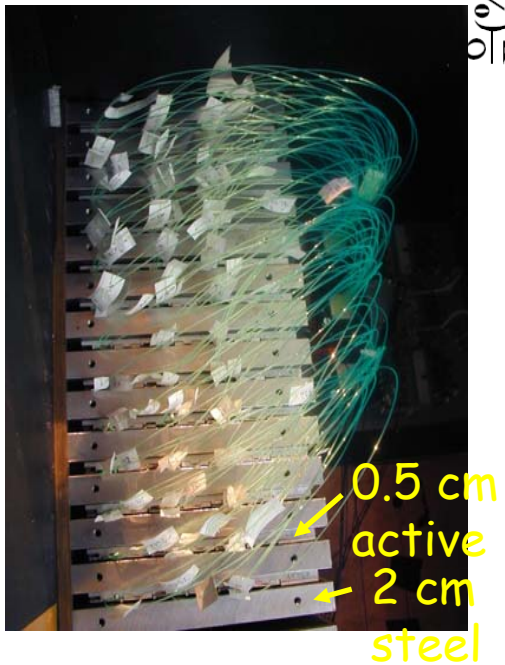
- We could start to design and build a detector TODAY, if given the go-ahead.
- We work towards proposing an even BETTER detector for the EDR.

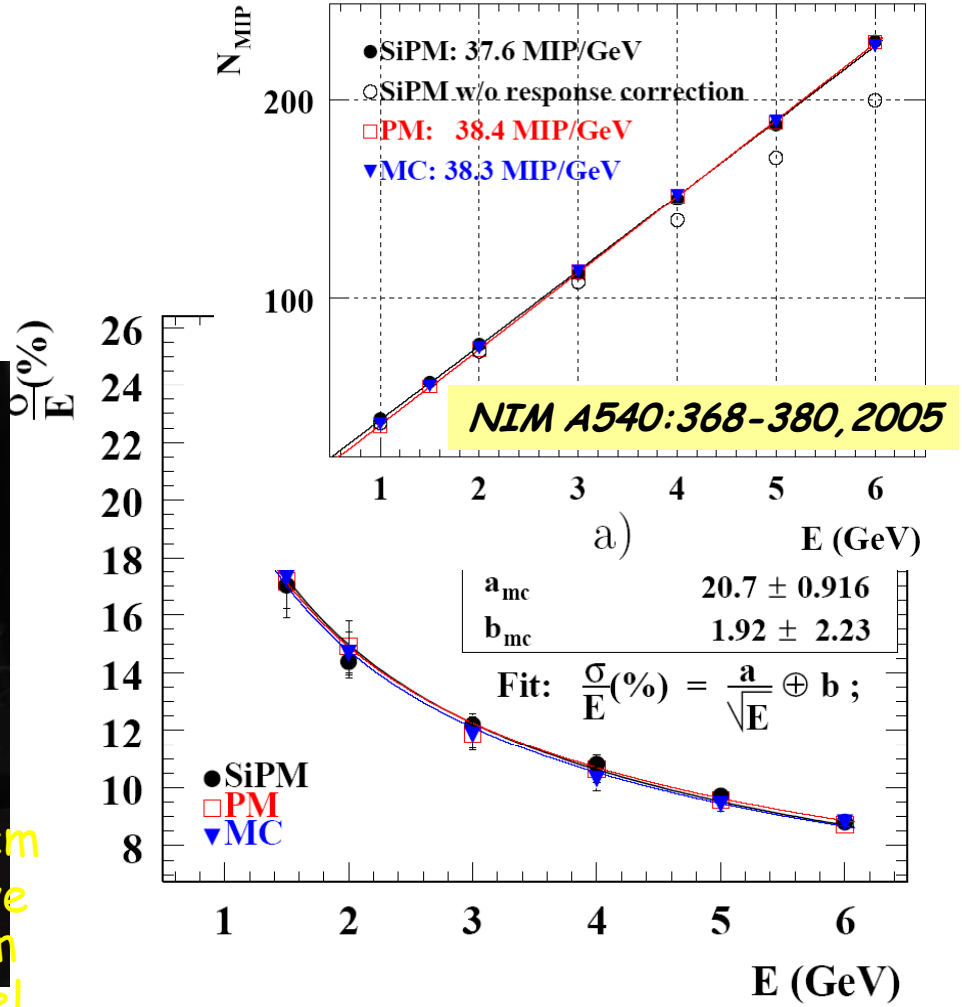
Back-up slides



Minical testbeam results

- 100 SiPM channel "minical"
- Non-linearity can be corrected (at tile level)
  - Does not deteriorate resolution





Selection of SiPMs

1. Long term stability test: ~48 hours at elevated HV (~+3V->5 μA)

Selection criteria: SiPM current < 5 μA

2. Tune of operation HV and saturation curve measurement with LED

Tune HV till number of pixels per MIP 14.25 < ***Npix*** < 15.75

Selection criteria:

SiPM gain $G > 4*10^5$

Noise frequency at zero level $F_0 < 3$ MHz

Noise frequency at ½ MIP level $F_{1/2} < 3000$ Hz

Crosstalk < 0.35

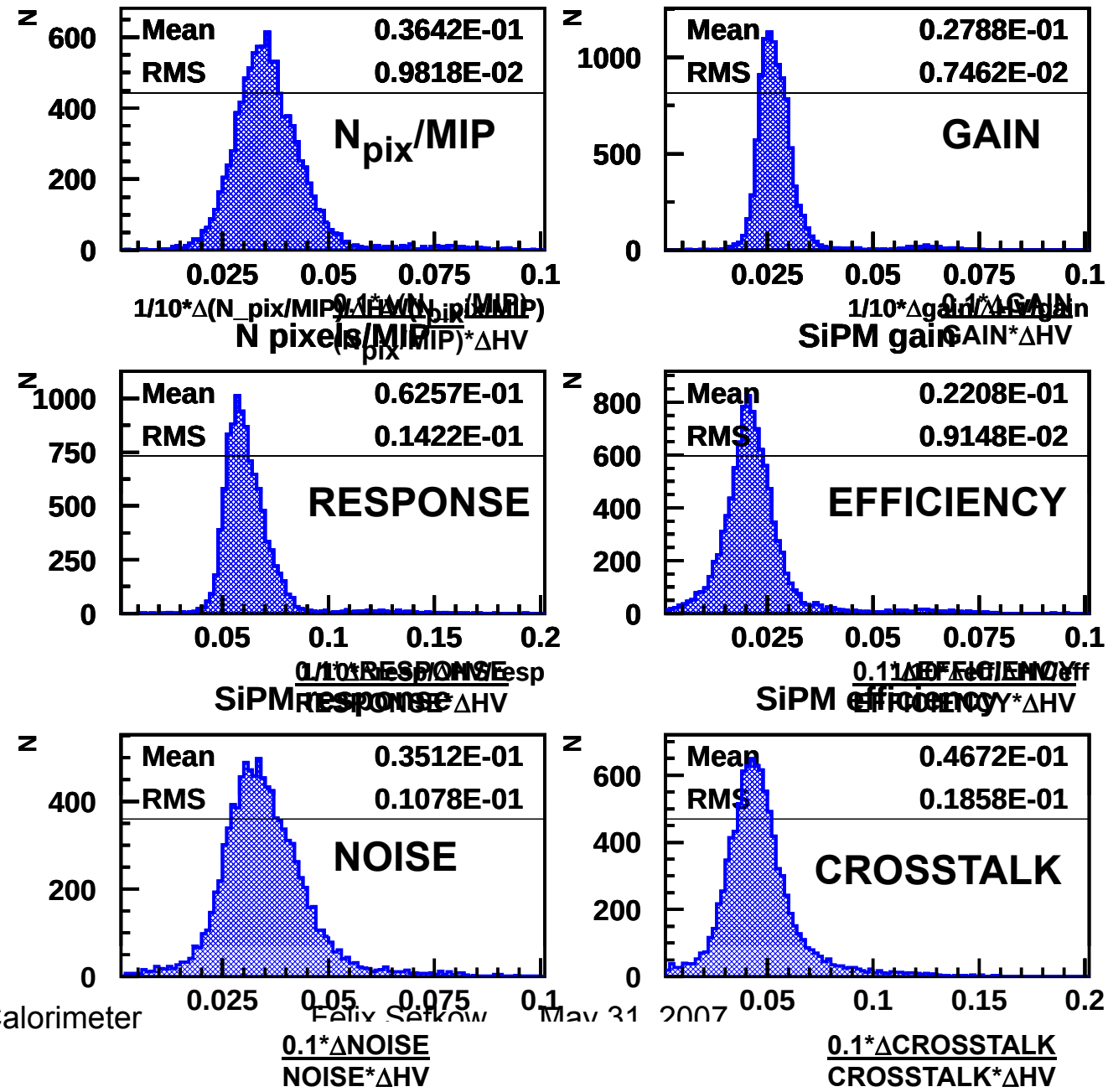
SiPM current $I < 2$ μA

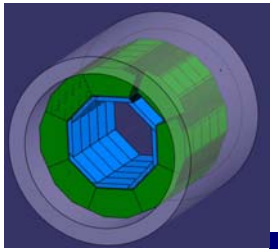
RMS of multiple SiPM current measurements $RMS_I < 20$ nA

Number of pixels at maximal light (~200MIP) during measurement of saturation curve $N_{pix\ max} > 900$

3. Check Tile-WLS Fiber-SiPM system with Sr source

SIPM PARAMETER VARIATION AT 0.1 V HV VARIATION

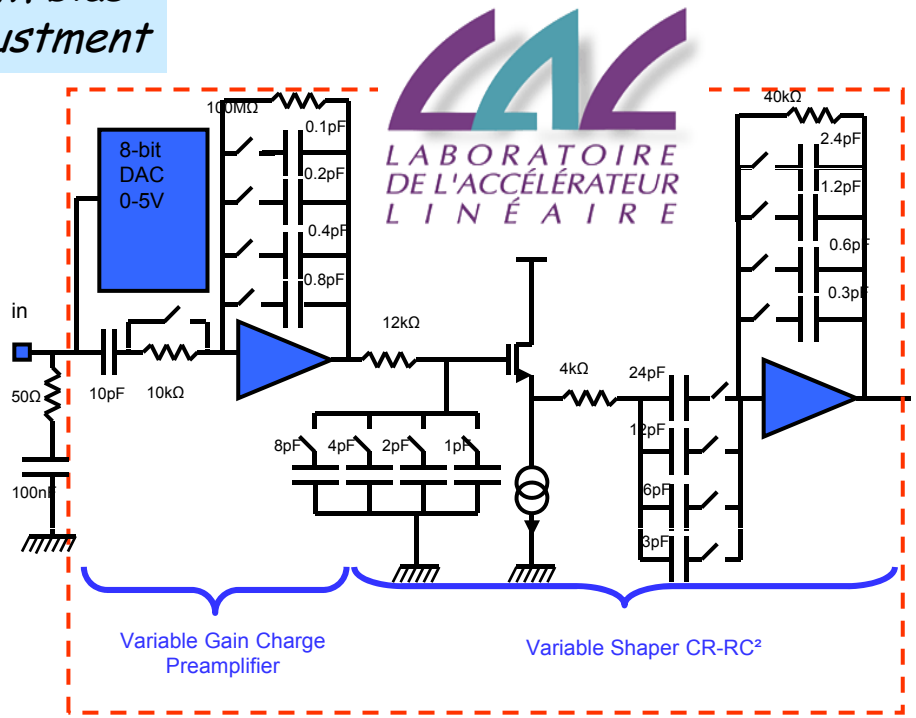


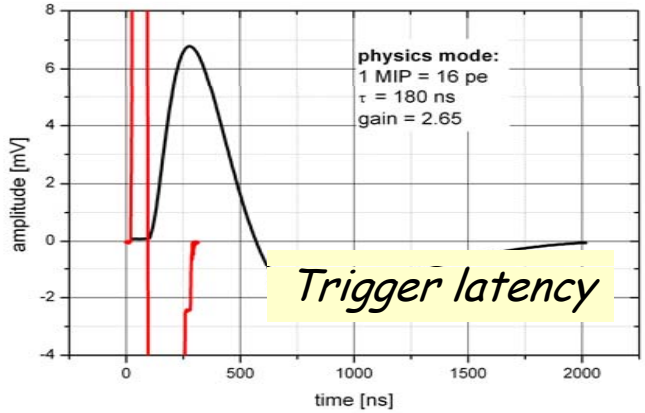


SiPM Front-end electronics

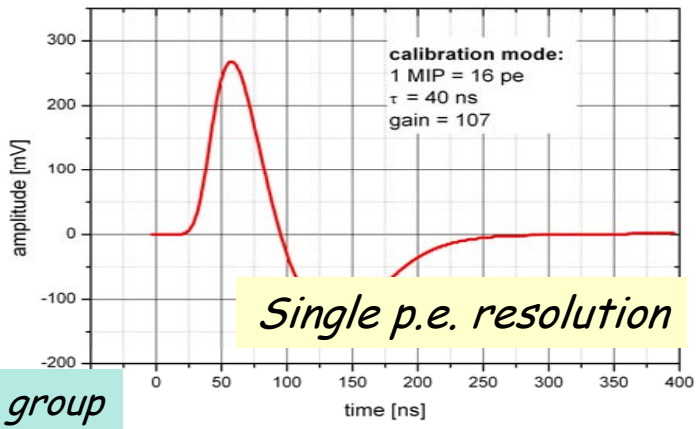
- ILC-SiPM chip: 18ch Pre-amplifier, shaper, track and hold, mux
  - based on CALICE SiW ECAL chip

SiPM bias adjustment



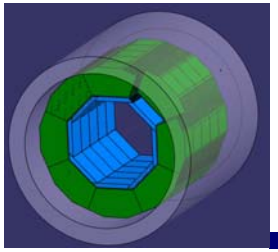


Trigger latency

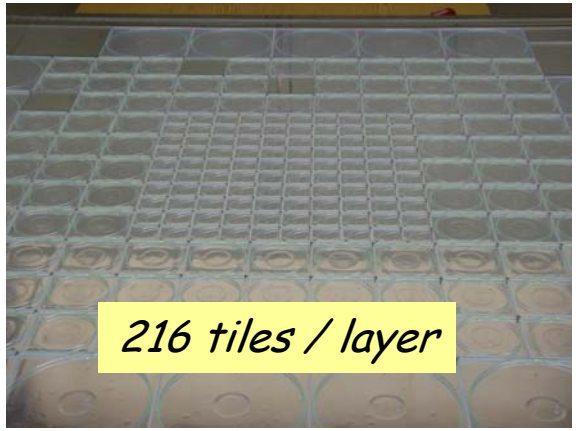


Single p.e. resolution

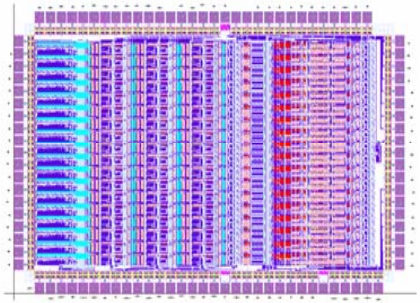
Alternative concept (fast digitization) being studied by JINR group



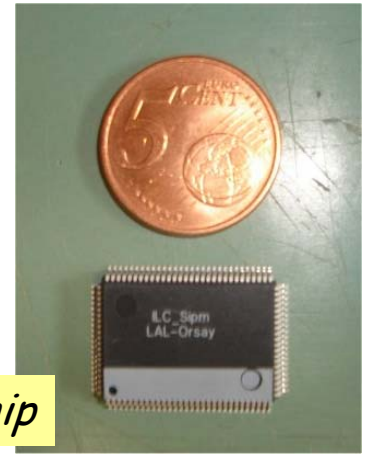
HCAL readout architecture



216 tiles / layer

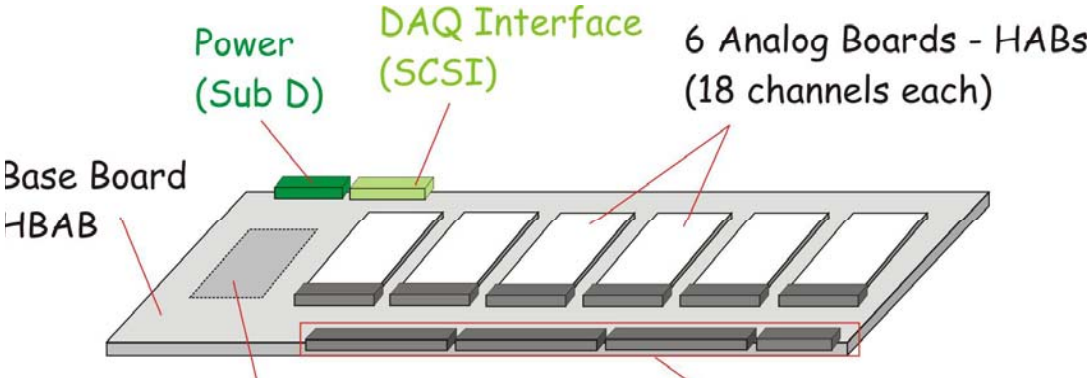


18 analog channels / chip



ILC_SiPM chip

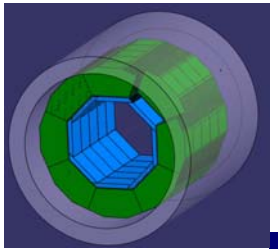
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE



2 base boards (12 piggy backs) / layer

CRC
CALICE Readout Card

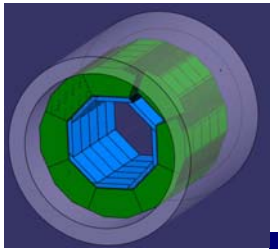
8 layers / DAQ board



Scint – SiPM – PCB integration

- Two possibilities:
  1. Photo-sensor scintillator unit + PCB with VFE
  2. Scintillator + PCB with photo-sensor and VFE

- We follow option 1, based on the good experience with TB prototype
  - Stable optical connection
  - Early and easy single channel quality control
  - independent of final electronics (schedule)
- Option 2 is followed by NIU and FNAL
  - Advantage: automated SMD technology for photo-sensor mounting



Tile PCB positioning

- The first "LEGO tile" with positioning pins has been produced at ITEP
  - Individual tie positioning to match PCB precision for SiPM connection
- Discussions with scintillator producer have started
  - Mass production with injection molding seems feasible
- Mega-tiles / mega-strips can use same or different positioning method
  - PCB design largely unaffected