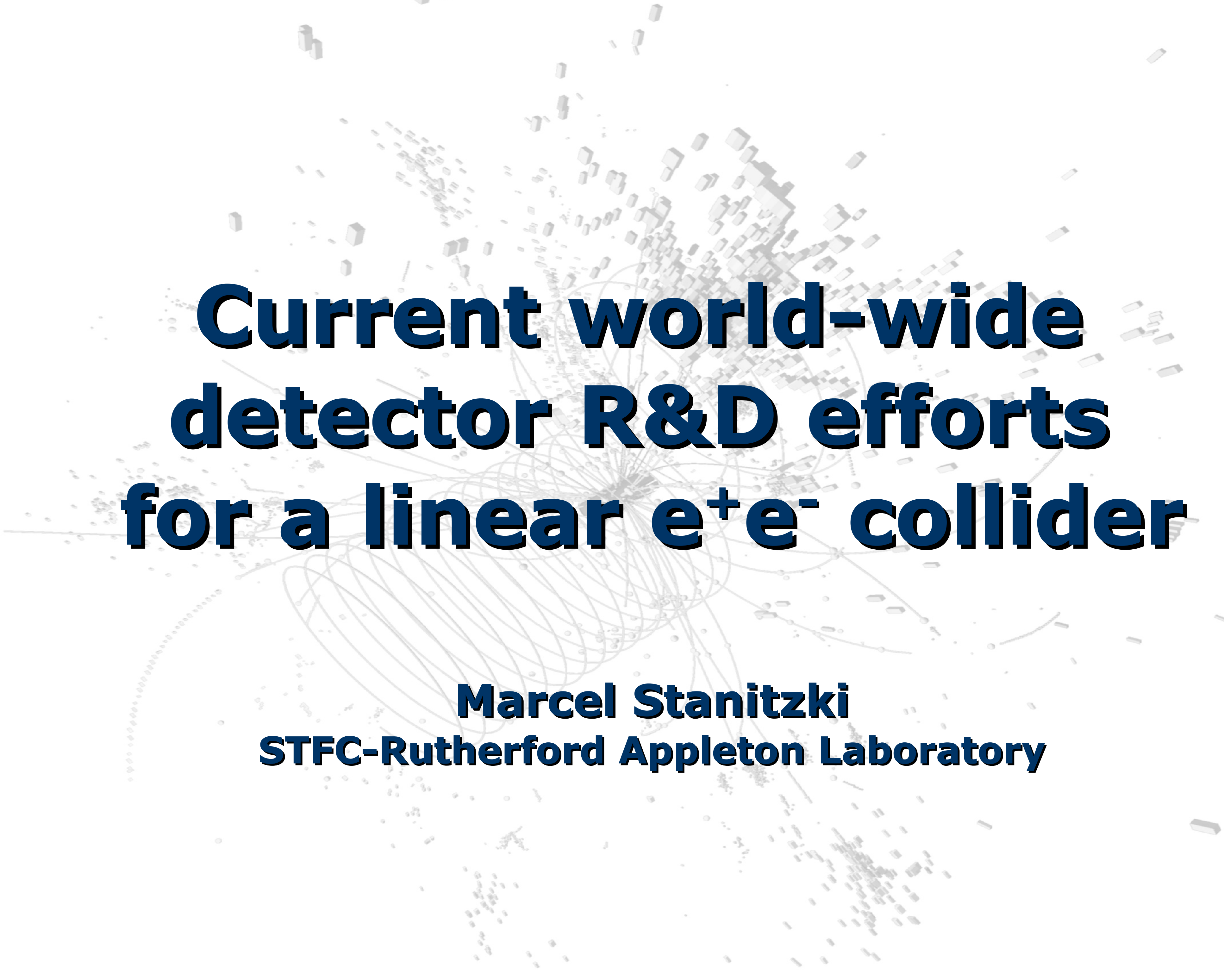


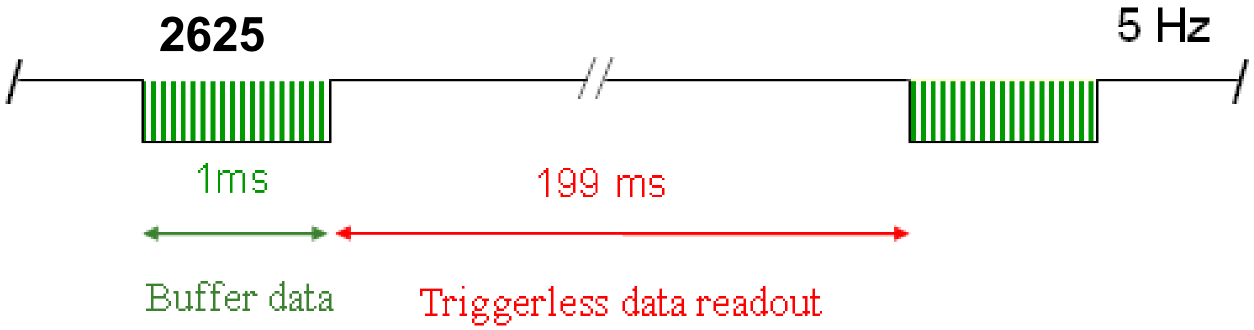
Current world-wide detector R&D efforts for a linear e^+e^- collider

Marcel Stanitzki
STFC-Rutherford Appleton Laboratory

Linear Collider Detector R&D

- Detector R&D has been focused on the ILC detectors
- ILC Detector community has submitted Letters of Intent for ILC Detector concepts to the IDAG in April 2009
- A lot of the R&D is generic and applicable for any Linear Collider Detector, e.g. CLIC Detectors
- In many cases concept-independent R&D groups & collaborations drive the R&D effort
- CLIC Study group has recently joined Linear Collider R&D effort

ILC Environment



- ILC environment is very different compared to LHC
  - Bunch spacing of ~ 300 ns (baseline)
  - 2625 bunches in 1ms
  - 199 ms quiet time
- Occupancy dominated by beam background & noise
  - ~ 1 hadronic Z per train ...
- Readout during quiet time possible
- No Triggers, no pile-up ...

Detector Requirements

- Exceptional precision and time stamping
  - Bunch train is ~3000 bunches over 1 ms (ILC)
- Vertex detector
  - < 4 µm precision w/ ~20 µm pixels
- Tracker
  - $\sigma(1/p) \sim \text{few} \times 10^{-5}$
- Calorimeter
  - $\frac{\sigma_{E_{Jet}}}{E_{Jet}} = ٣ - ٤\%, E_{Jet} > ١٠٠ \quad GeV$

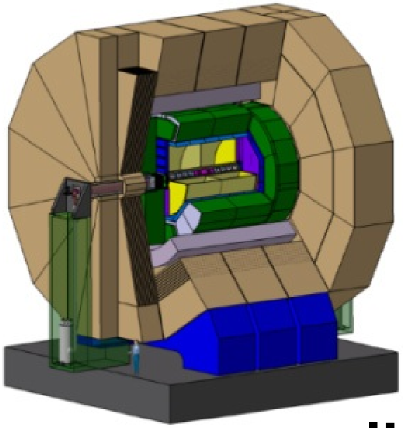
Different challenges than LHC

- Calorimeter granularity
  - Need factor ~200 better than LHC
- Pixel size
  - Need factor ~20 smaller than LHC
- Material budget, central
  - Need factor ~10 less than LHC
- Material budget, forward
  - Need factor ~ >100 less than LHC

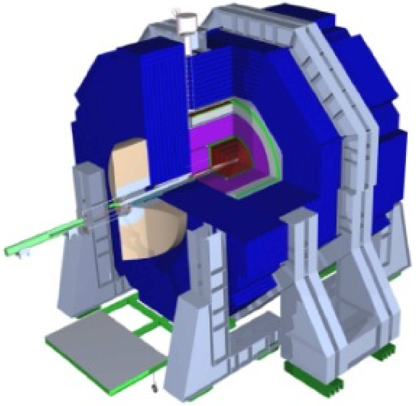
Requirements for Timing, Data rate and Radiation hardness are very modest compared to LHC

Entering the Post-LoI phase …

- The IDAG has now validated two concepts :



ILD



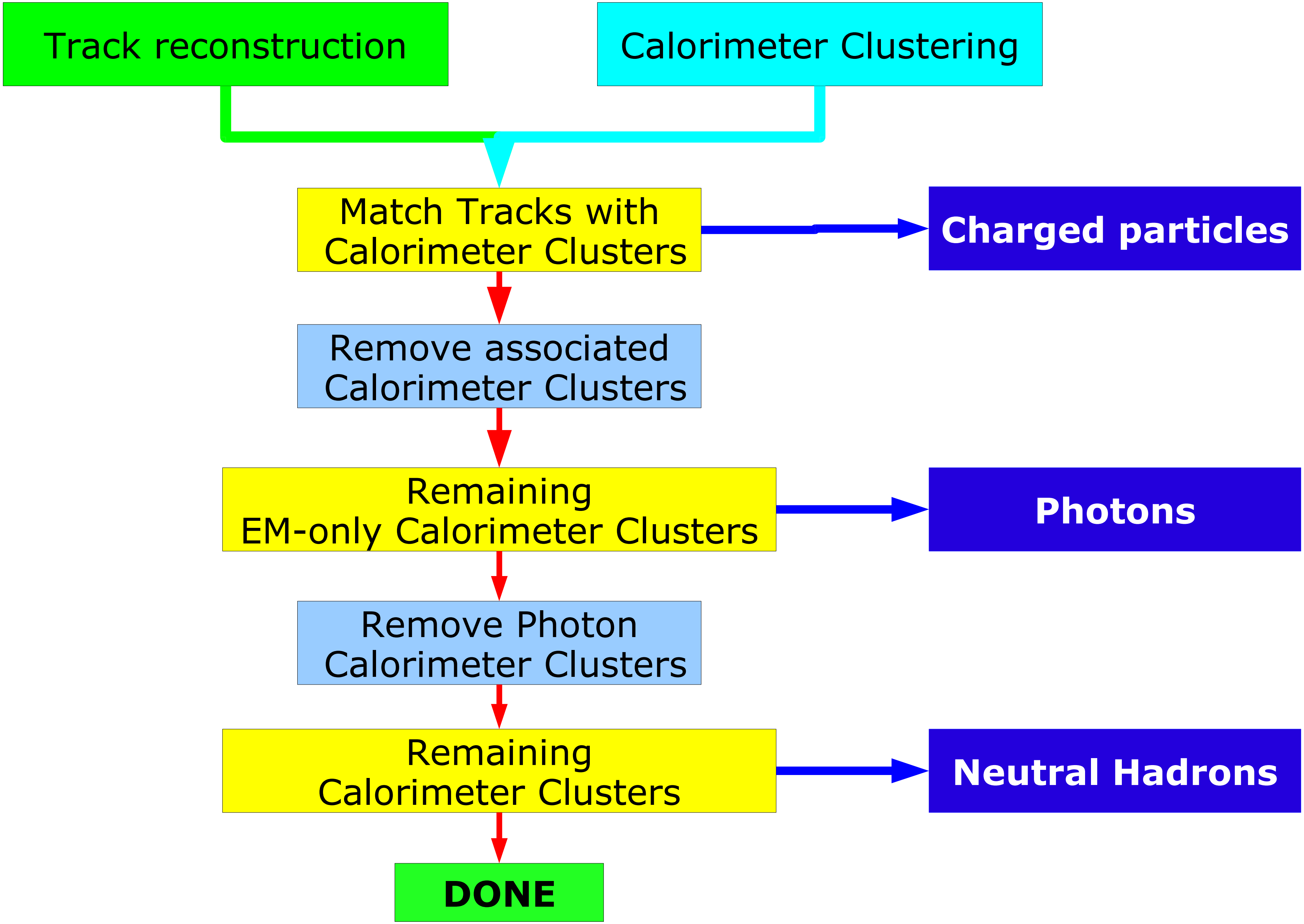
SiD

- Both were invited to prepare a detailed baseline design for 2012
- ILD & SiD build on
  - particle flow paradigm
  - push-pull approach
- ILD & SiD have complementary approaches

Complementary approaches

- Tracking approach
  - ILD: TPC full track following due to large number of hits
  - SiD: Silicon provides robustness due to short time sensitivity and bunch time-stamping
- Radius and Field
  - ILD: Large radius optimizes Particle Flow (PFA) performance
  - SiD: Large field, small radius optimizes vertex detector performance

PFA in a nutshell



Track reconstruction

Calorimeter Clustering

Match Tracks with Calorimeter Clusters

Charged particles

Remove associated Calorimeter Clusters

Remaining EM-only Calorimeter Clusters

Photons

Remove Photon Calorimeter Clusters

Remaining Calorimeter Clusters

Neutral Hadrons

DONE

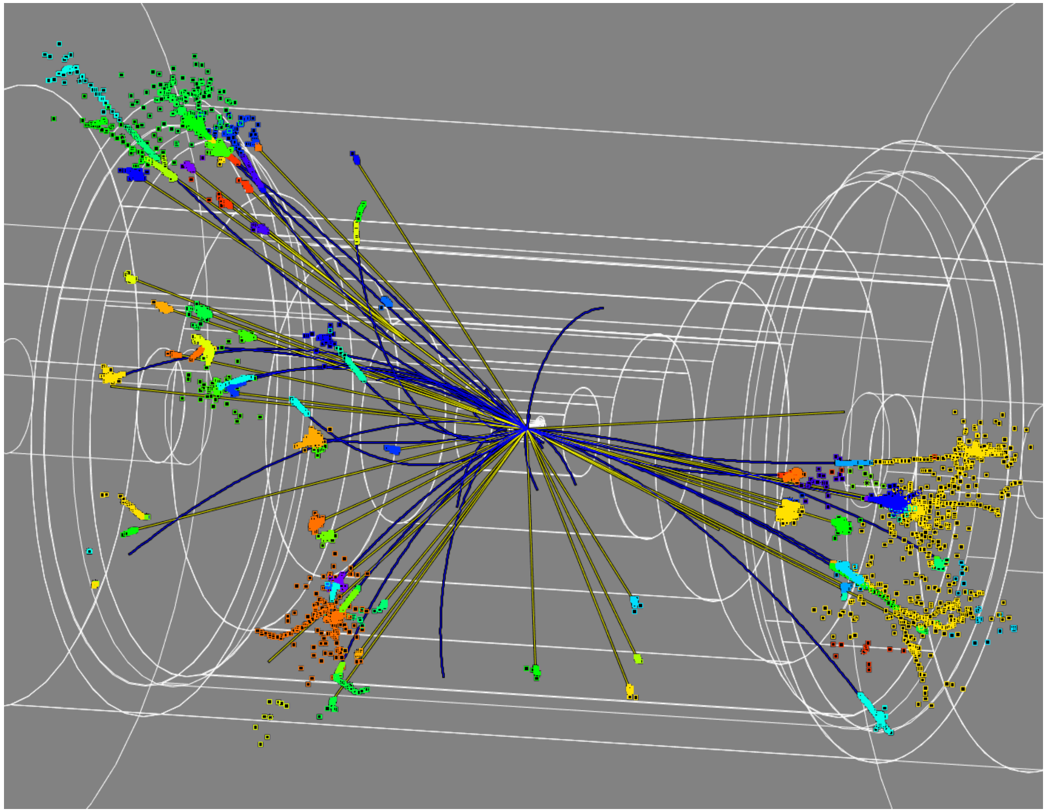
Jet Resolutions

Particle Class	SubDetector	Jet energy fraction	Particle Resolution	Jet Energy Resolution
Charged	**Tracking**	**60%**	$10^{-4}\ \sqrt{E}_{\text{charged}}$	**neg.**
Photons	**ECAL**	**30%**	$11\ \%\ \sqrt{E}_{\text{EM}}$	$6\ \%\ \sqrt{E}_{\text{jet}}$
Neutral Hadro	**HCAL (+ECA**	**10%**	$40\ \%\ \sqrt{E}_{\text{hadronic}}$	$13\ \%\ \sqrt{E}_{\text{jet}}$

- Energy resolution about 14% (driven by HCAL)
- Confusion terms have bigger impact
  - $\sigma_{\text{jet}}^2 = \sigma_{\text{charged}}^2 + \sigma_{\text{EM}}^2 + \sigma_{\text{hadronic}}^2 + \sigma_{\text{confusion}}^2 + \sigma_{\text{threshold}}^2$
- Performance not limited by Calorimetry
  - Need high granularity calorimetry to reduce confusion !
- Current best PFA ~25 % /√E for 100 GeV Jets

Sounds easy

- Associating showers to tracks
  - Showers can overlap
  - Track ambiguities
  - Leakage
- Hadronic showers are most difficult

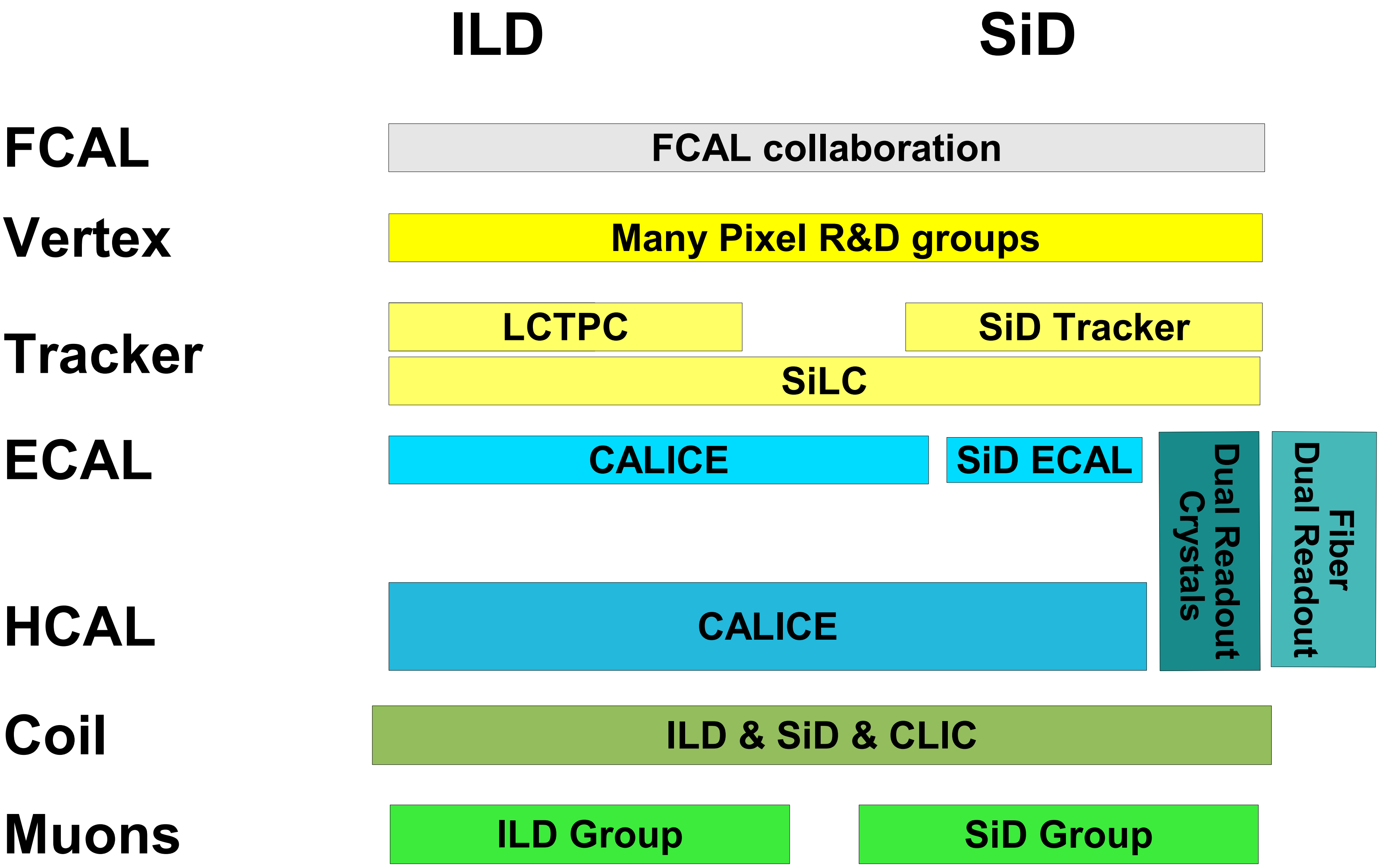


The validated detectors

Detector	ILD	SiD
Design Paradigm	PFA +TPC	PFA + Si-Tracker
FCAL	SiW	SiW
Vertex	5/6-layer silicon pixel	5-layer silicon pixel
Tracking	MPGD-TPC + Silicon strips	Silicon strips
ECAL	SiW	SiW
HCAL	Analog Fe+Scint	Digital Fe+RPC
Solenoid	3.5 T	5 T

These are the baseline choices as defined in the LoIs
Also many options are being pursued

R&D groups



ILD

SiD

FCAL

FCAL collaboration

Vertex

Many Pixel R&D groups

Tracker

LCTPC

SiD Tracker

SiLC

ECAL

CALICE

SiD ECAL

Dual Readout Crystals

Fiber Dual Readout

HCAL

CALICE

Coil

ILD & SiD & CLIC

Muons

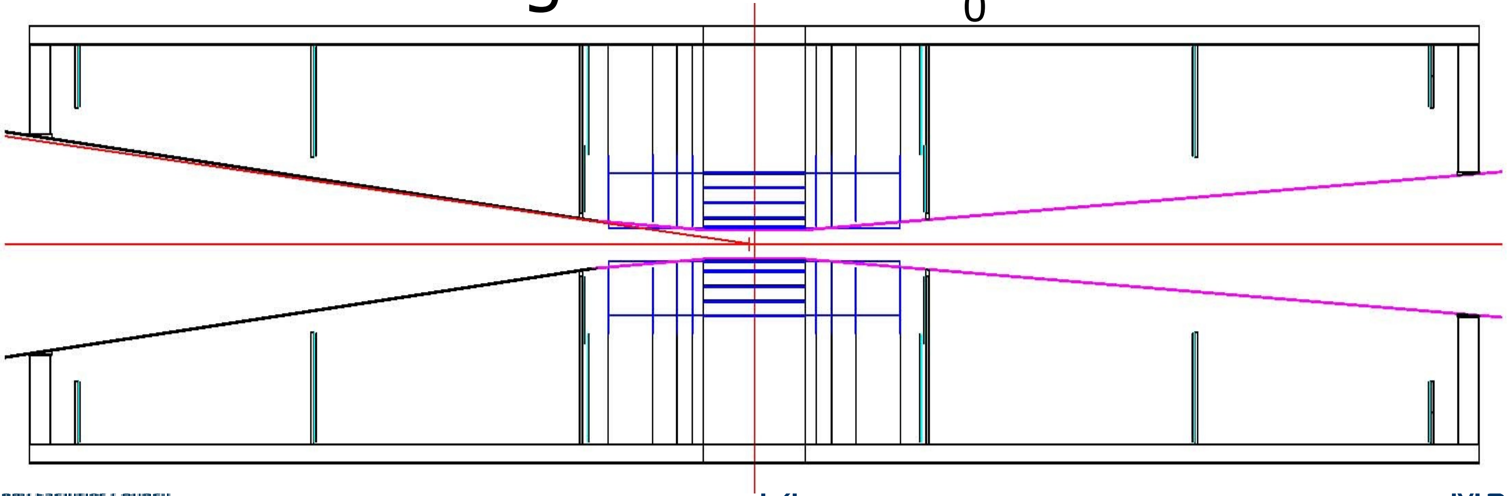
ILD Group

SiD Group

Vertex Detectors ...

Vertex Detectors for the ILC

- 5 layers of Silicon pixels, either
  - long barrels
  - barrels + endcap disks
- Gas-cooled
- First layer ~ 1.2 cm away from primary vertex
- Occupancy 1 %
- Total Material budget: ~1 % X_0

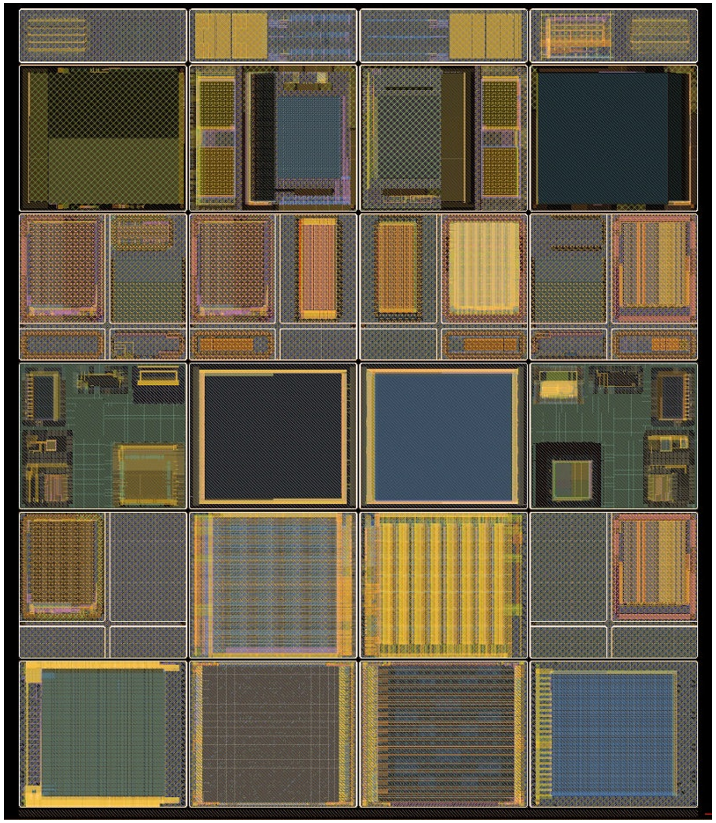


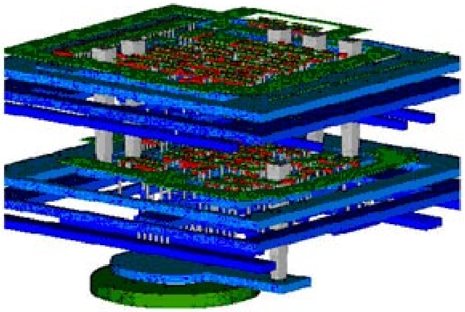
Silicon Pixel R&D

- Continues to be a very active field
- Work on existing concepts
  - MAPS (Mimosa, Chronopixels, LBL, INFN ...), CCD, ISIS, DEPFET, SoI ...
- Some new ideas
  - 4T-MAPS, 3D Integration
- Can only cover a few items ...

3D Silicon Pixel HEP run

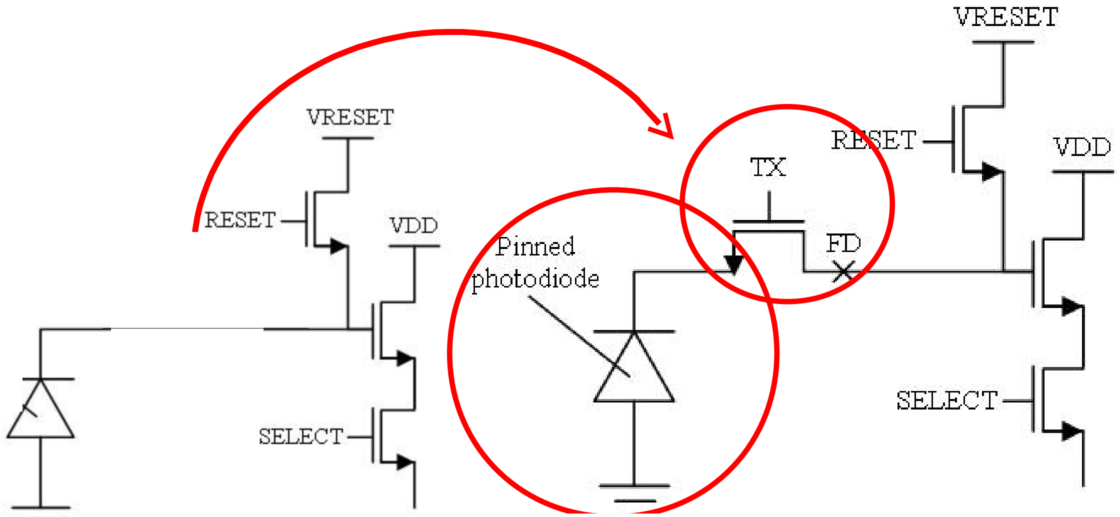
- 130 nm process
  - Chartered Semiconductor
- 3D processing by Tezzaron
  - wafer processing & interconnects
- MPW organized by Fermilab
- 3D Consortium
  - 15 institutes
  - 5 countries
- Silicon Pixels for ILC, SLHC, B factories and more

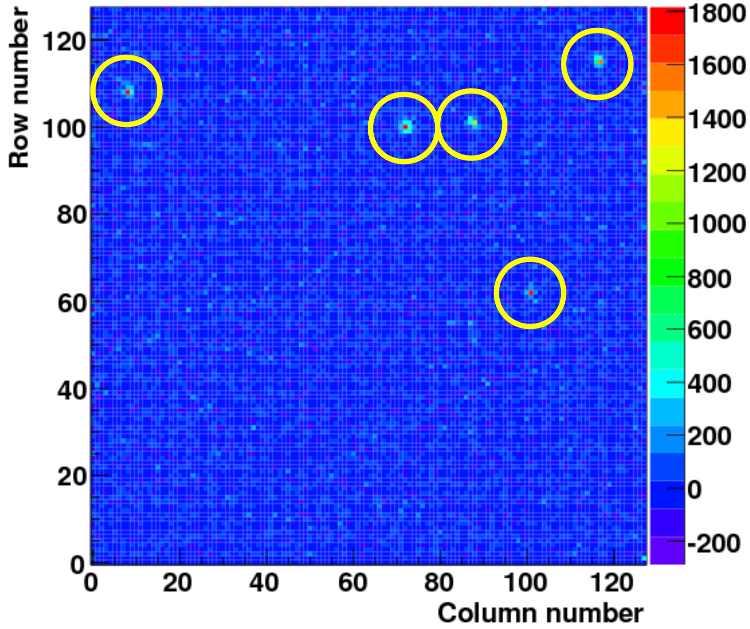




4T Pixels

- **3T MAPS**
  - Simple architecture
  - Readout and charge collection area are the same
- **4T MAPS**
  - Three additional elements
  - Readout and charge collection area are at different points
  - First Chip tested in beam (13 different pixels with 15-45 µm)

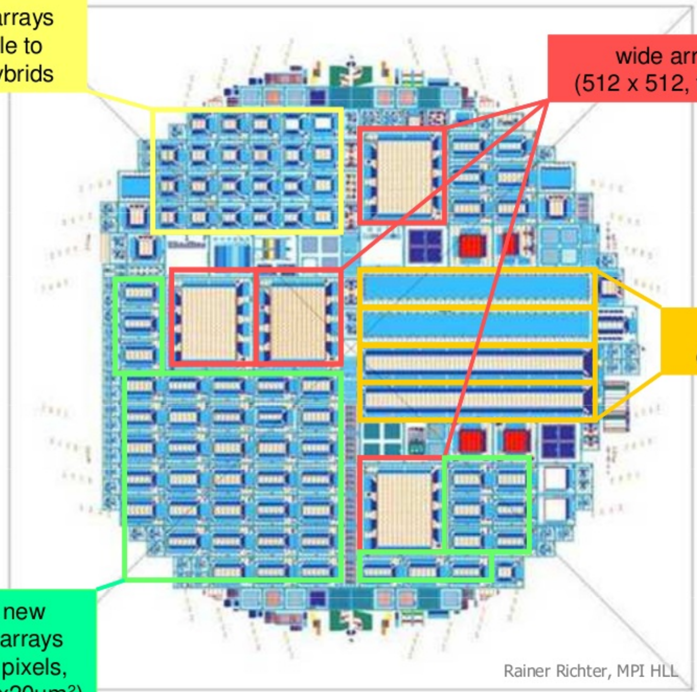




CERN Testbeam August/September 2009

DEPFET

- New generation PXD5
- Longer pixel arrays
  - 256x64 pixels
- New DEPFET variants:
  - Very small pixels (20 µm x 20 µm)
  - Capacitively Coupled Clear Gate (C3G) → New step forward in gain
  - Shorter Gate lengths → Increased internal amplification → Factor 2 better expected)



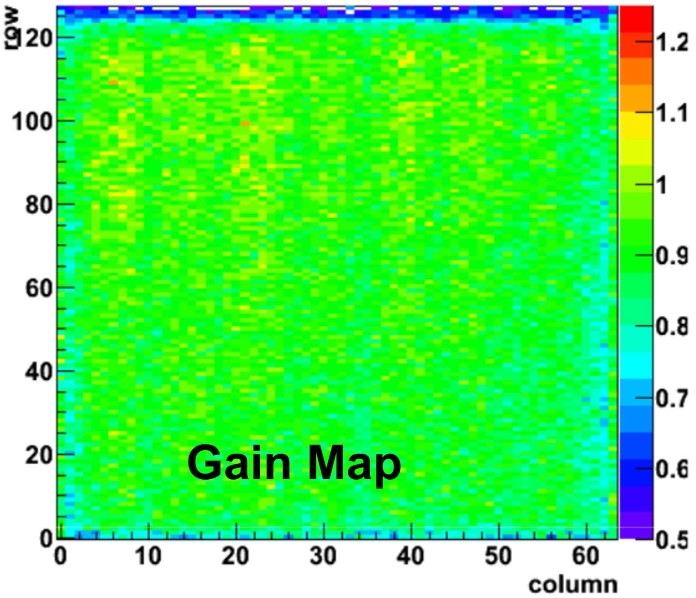
standard arrays compatible to existing hybrids

wide arrays (512 x 512, full ILC)

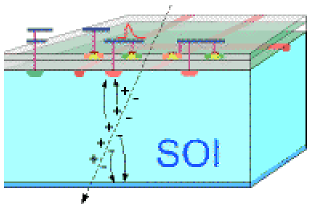
long arrays (256 x 1024, ½ ILC)

various new standard arrays (64 x 256 pixels, down to 20x20µm²)

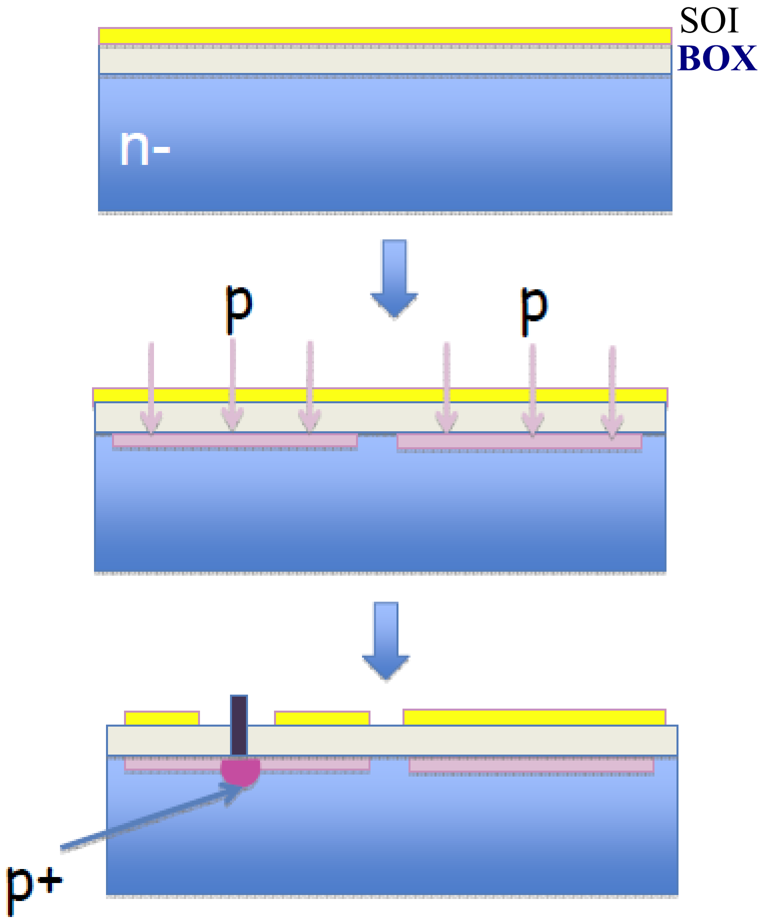
Rainer Richter, MPI HLL



SoI Pixel R&D



- SoI Pixel R&D
  - 200 nm process by OKI
  - KEK sponsored MPW
- Main problem
  - Back-gate effect
- Solution
  - Buried p-Well implant
- Add. Benefits
  - Reduce electric field around p+ sensor
  - improve radiation hardness
- Major step for SoI technology

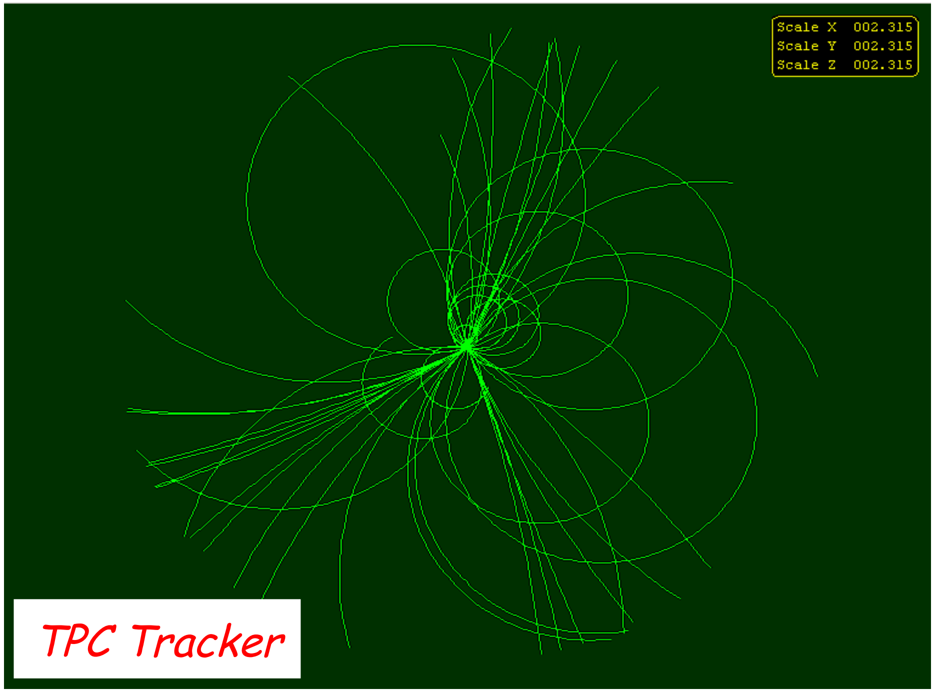


Successfully tested up to 100V bias voltage

For more Details see http://rd.kek.jp/project/soi/

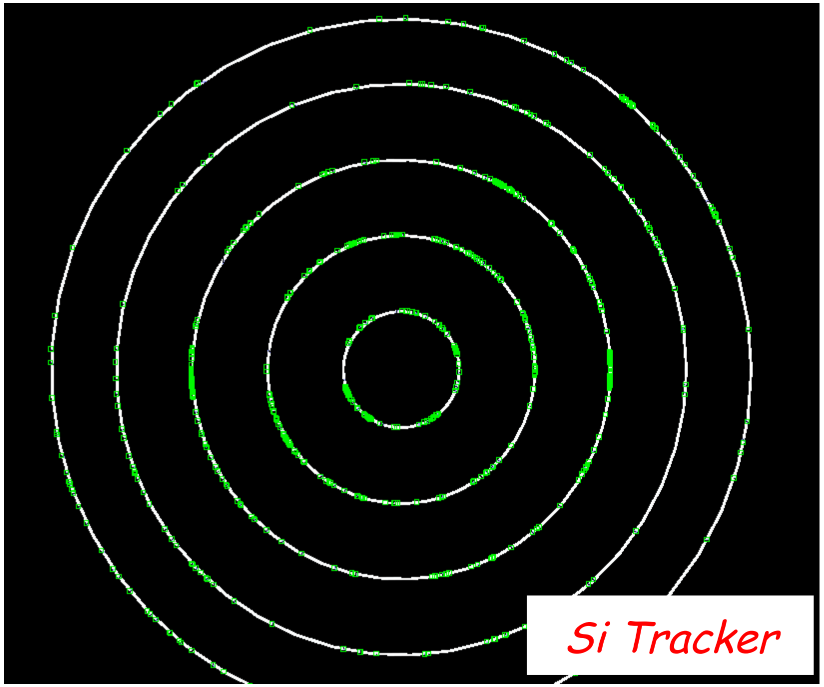
Trackers

ILC Tracking



TPC Tracker

- More points per Track
- Accumulate over 2800 bunches
- Better Particle ID

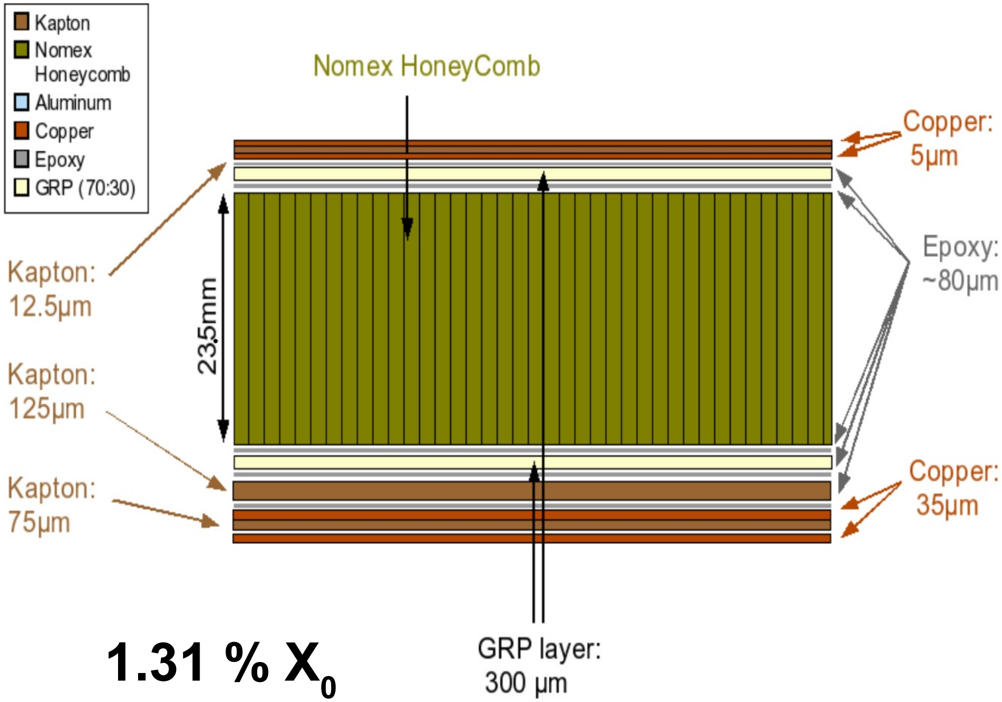


Si Tracker

- Higher precision per Hit
- Single Bunch time-stamping
- Less Material in 4 π

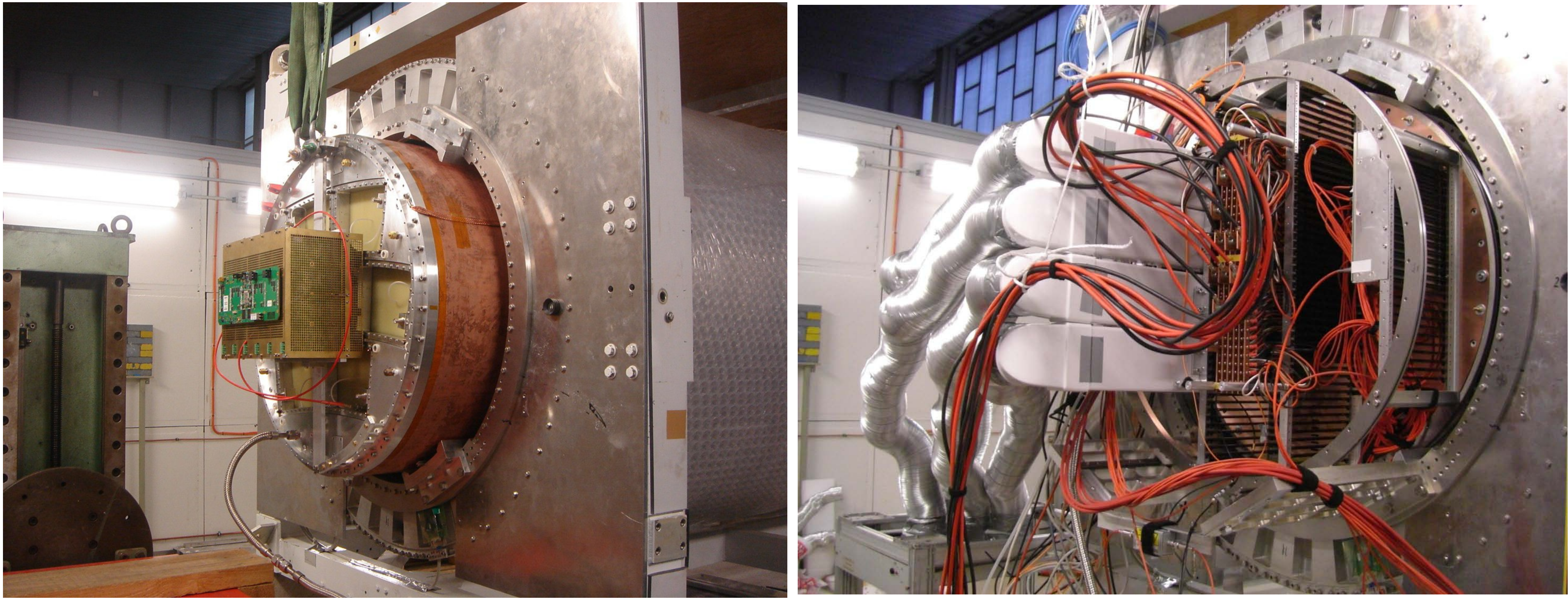
LCTPC

- Large Prototype
- Field Cage
  - Diameter: Inner 720 mm,
  - Outer 770 mm
  - Wall thickness 25 mm
  - Length 610 mm
  - HV up to 20 kV
- Testbeam at DESY
  - Electrons 1-6 GeV
  - using PCMAG (1 T magnet)



1.31 % X_0

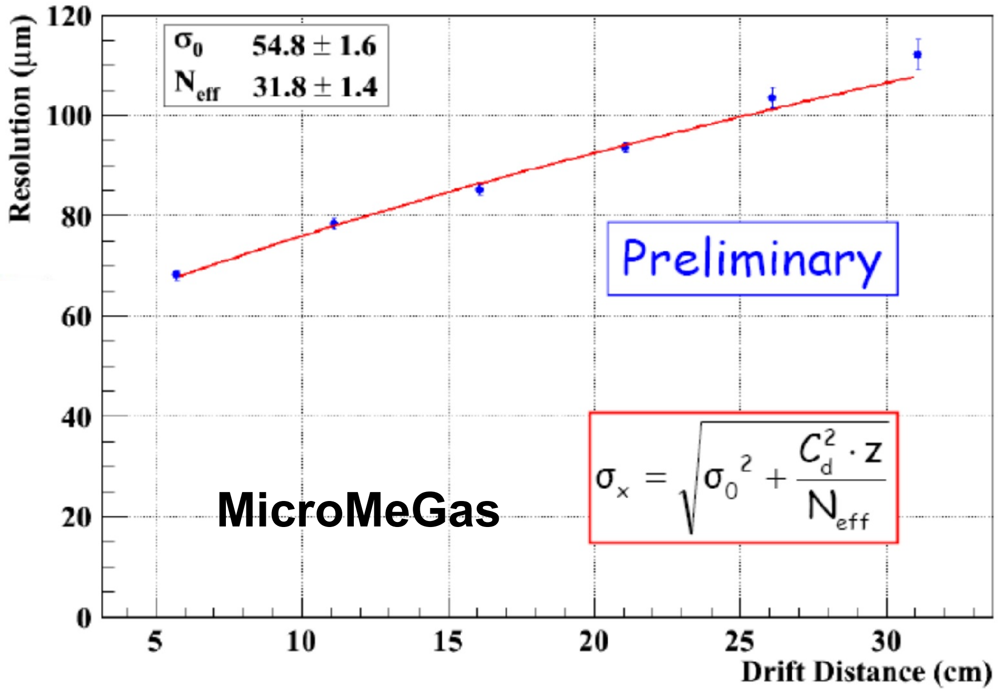
LCTPC at DESY

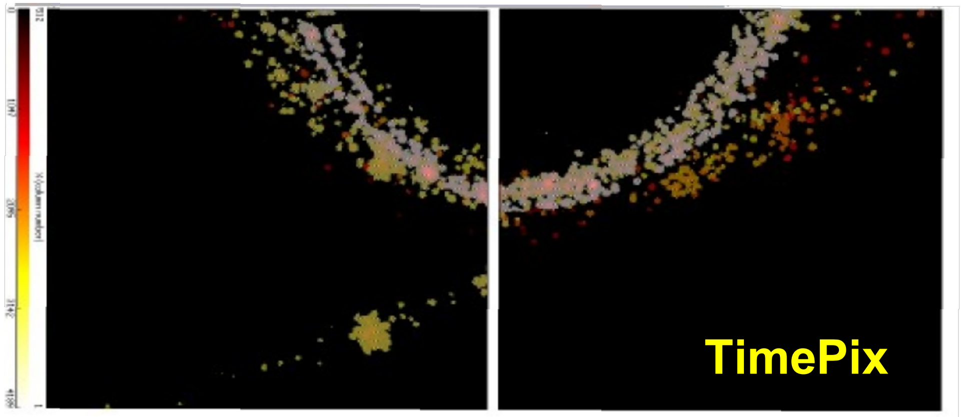


LCTPC inside the PCMAG at DESY

LCTPC readout

- Testing several technologies
- MicroMegas
- Double and Triple GEMS
  - pad readout with ~3000 channels
  - Testing Silicon Pixel readout (TimePix)
- Future Plans
  - Move to a high energy beam in 2011
  - Start designing a TPC for the ILC

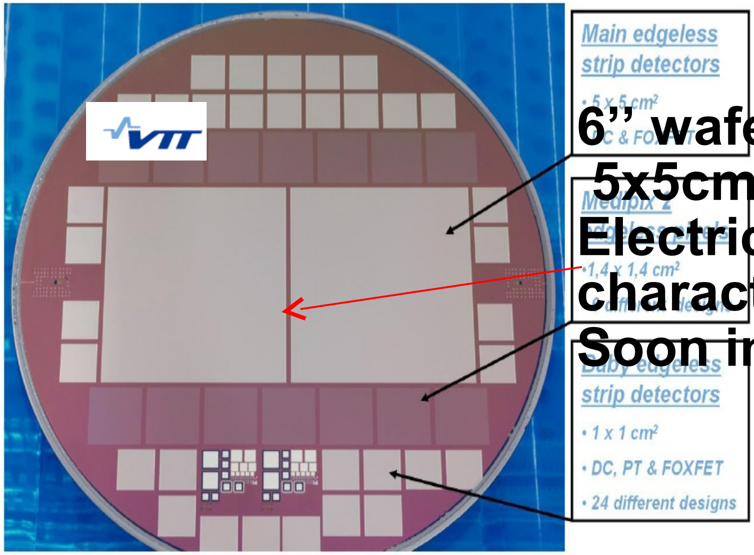




SiLC

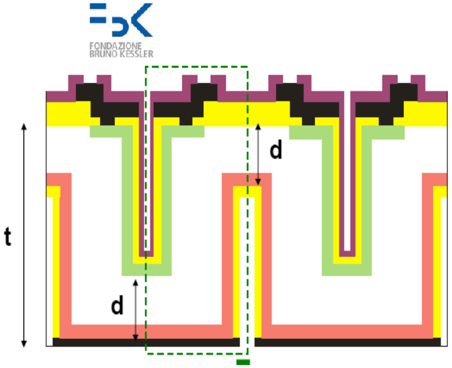
- Baseline
  - 6″ microstrip silicon strips
- Recent developments
  - Active edge SOI strips
  - strips, 8″, 200 µm thick, 50 µm RO pitch, active edge
  - 3D Short strips & pixels
- Readout ASIC work
  - Explore 90nm
  - Direct connection
  - Time over Threshold

Active edge SOI strips

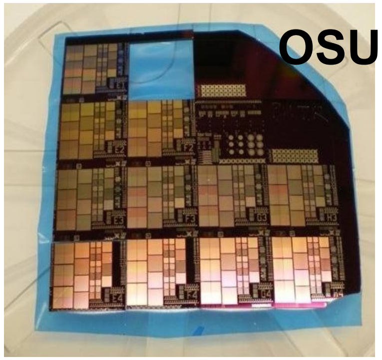


6'' wafer, 5x5cm^2 Electrically characterized Soon in test.

3D Short strips & pixels



3D short strips proto *produced by IRST, test LPNHE (2010)*

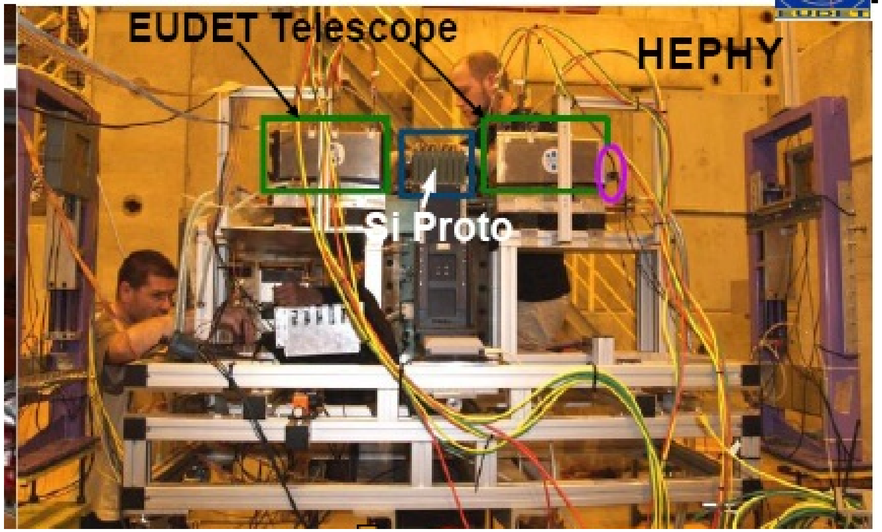


Avalanche Pixel Sensor: high Gain, low % X_0

SILC Testbeams

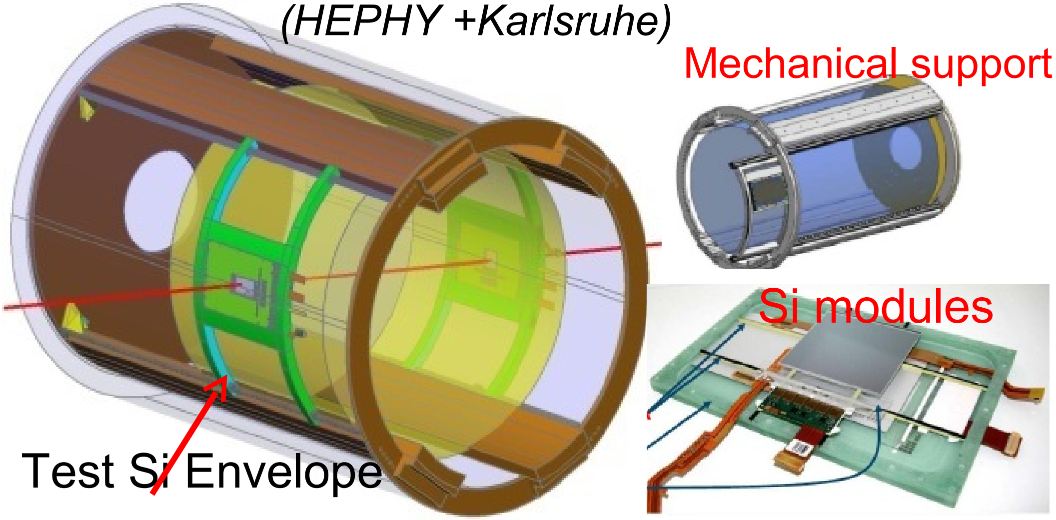
- Beamtest at CERN
  - SPS & PS
- Whole Test beam chain in place
  - DAQ, Mechanics, Software
- Plans
  - In preparation 2010-12: combined test beams with calorimeters
  - Tests on new FEE, new sensors;
  - Larger size prototypes

Combined test with EUDET MAPS telescope (SPS)



Combined test beam with LCTPC (DESY)

(HEPHY +Karlsruhe)

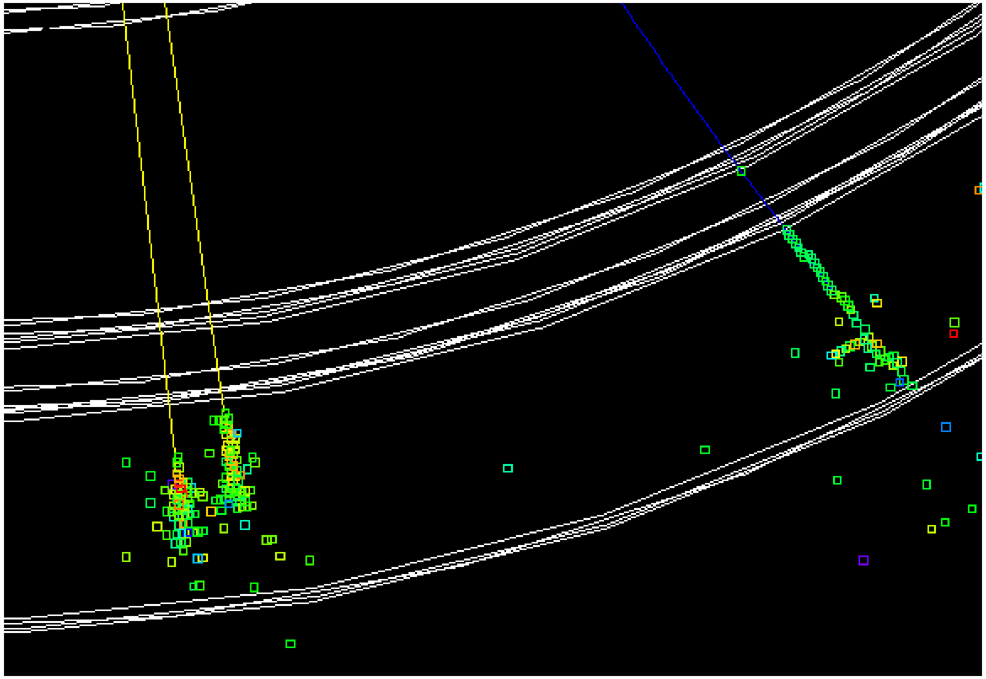


Calorimetry

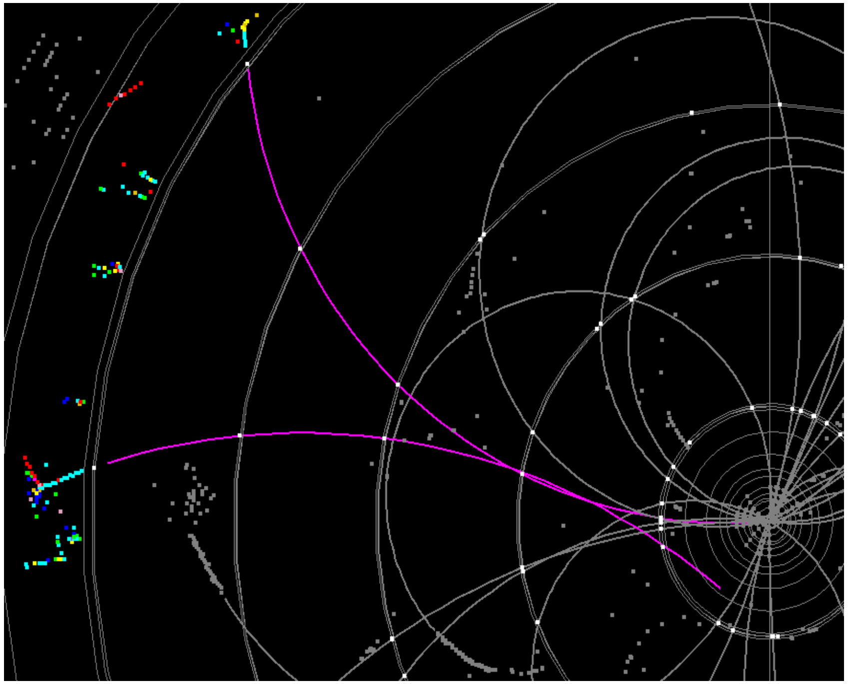
Many choices

- SiD and ILD are both using PFA calorimetry
  - Calorimetry inside the coil ->compactness
- PFA uses highly granular calorimeters
  - Aka Imaging/Tracking Calorimeters
  - Both for ECAL and HCAL
- Sampling Calorimeters 30 X_0 + 5-6 λ_I
- Lateral segmentations
  - ECAL O(5 mm-50 μm^2) /HCAL O(1 cm-3 cm^2)
- Readout either
  - Analog (classical)
  - Digital (Shower particle counter)

Imaging Calorimeters

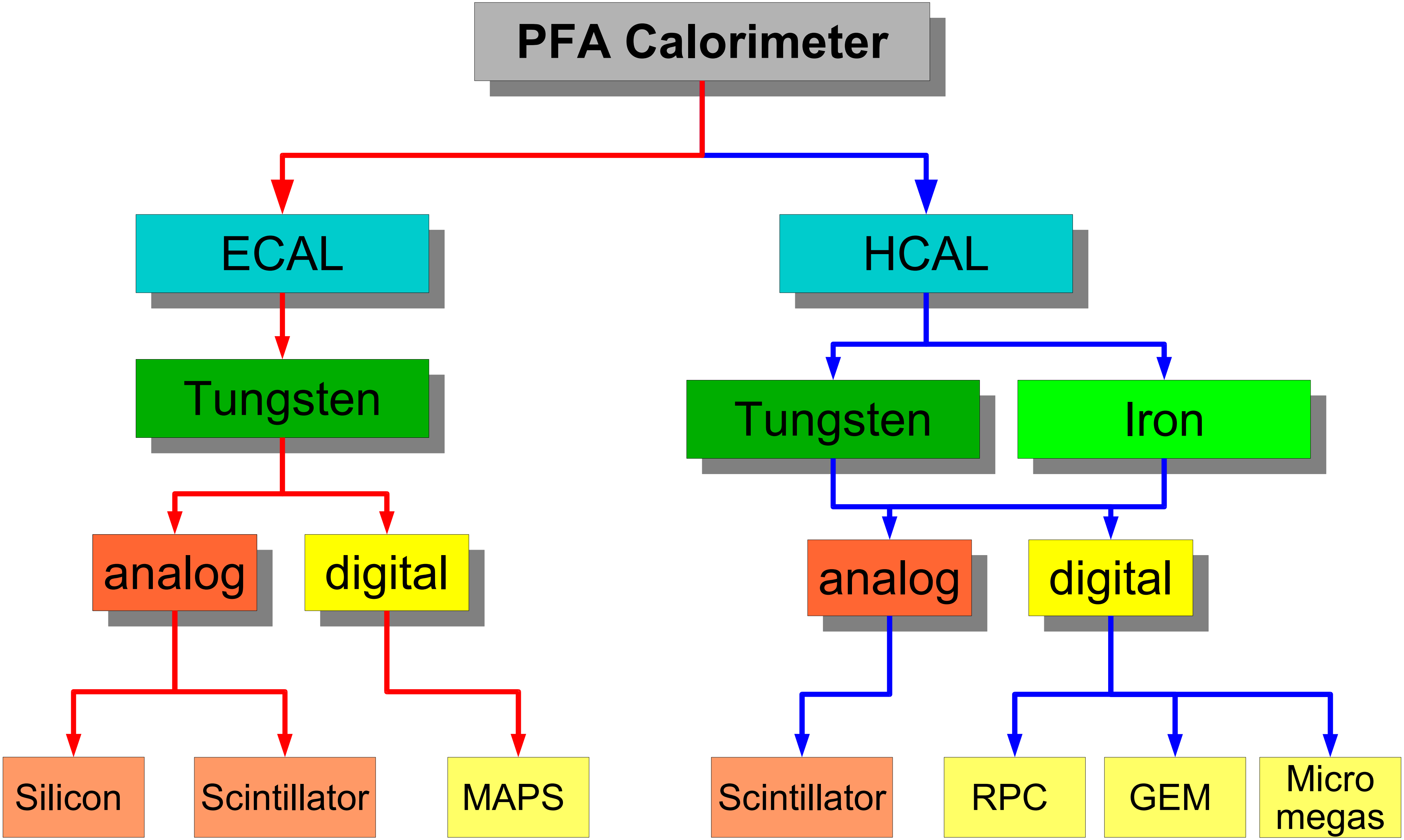


$\tau^+ \rightarrow \rho^+\nu \quad (\pi^+\pi^0\nu)$



Calorimeter Aided Tracking
V^0 finder

Technology Tree



PFA Calorimeter

ECAL

Tungsten

analog

digital

Silicon

Scintillator

MAPS

HCAL

Tungsten

Iron

analog

digital

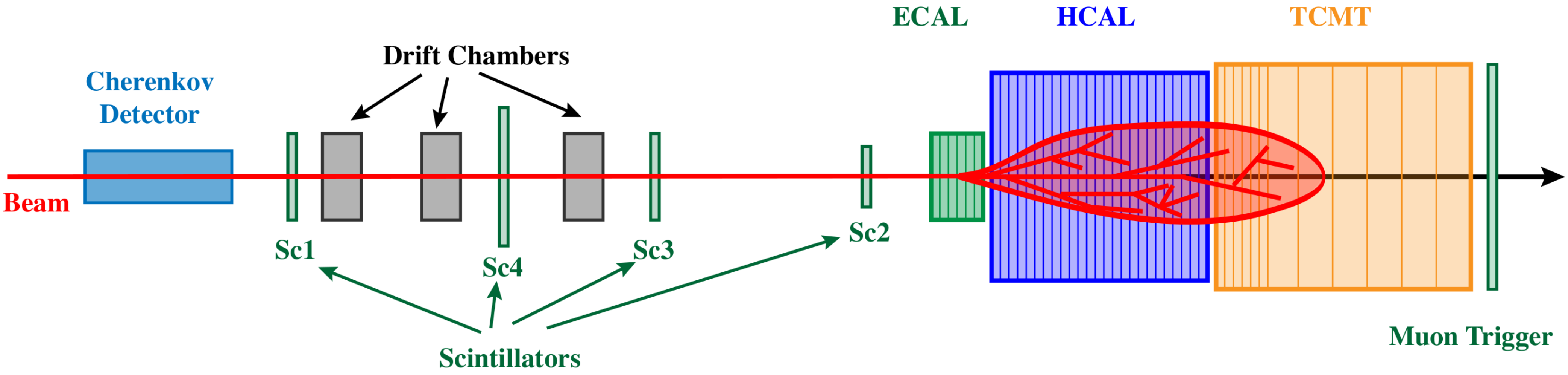
Scintillator

RPC

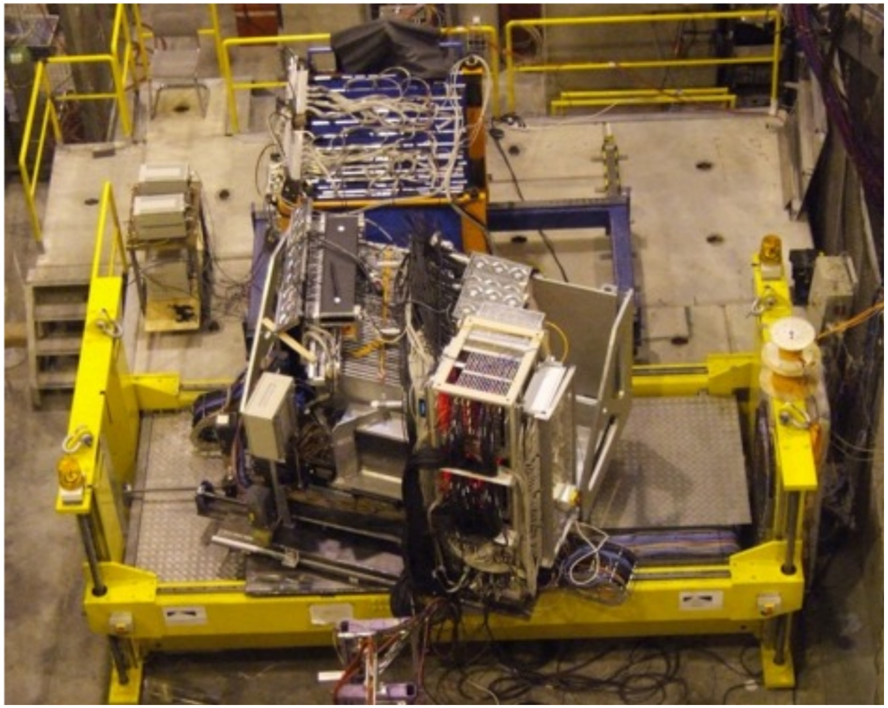
GEM

Micro megas

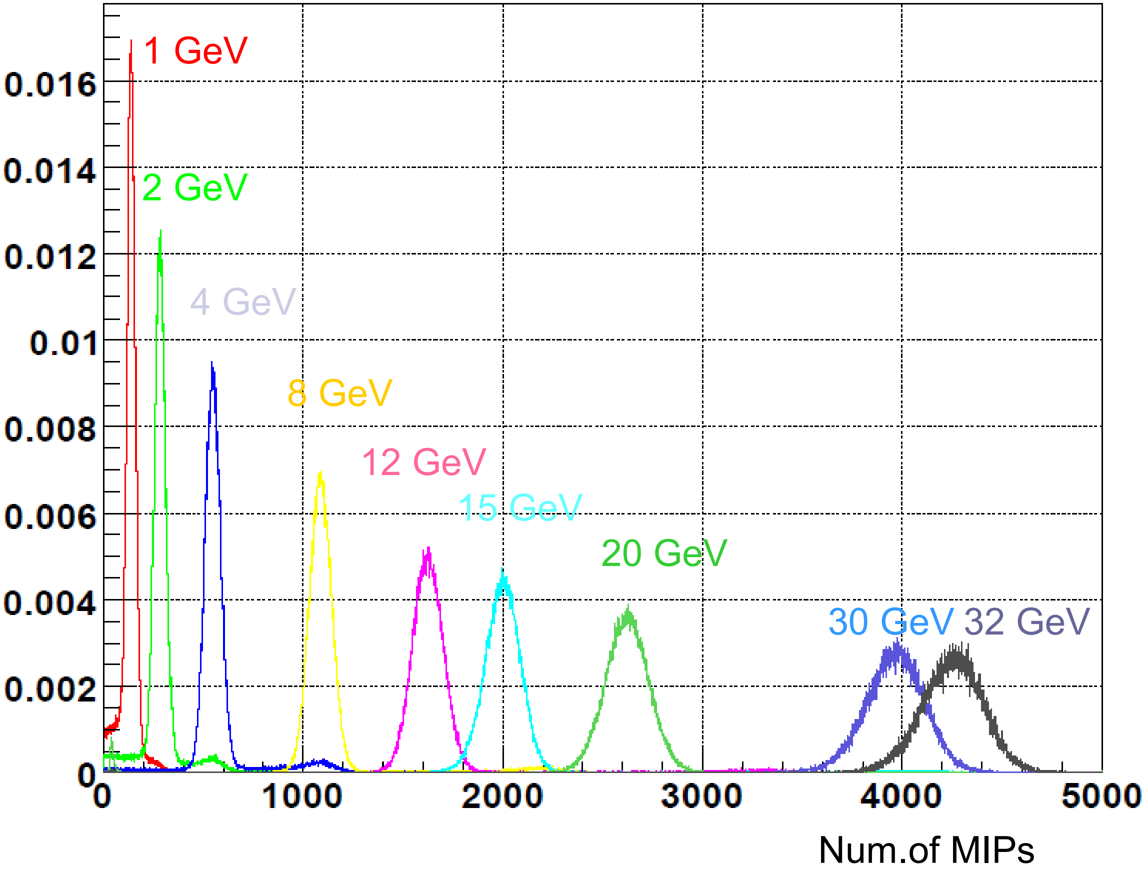
CALICE Beam Test Setup

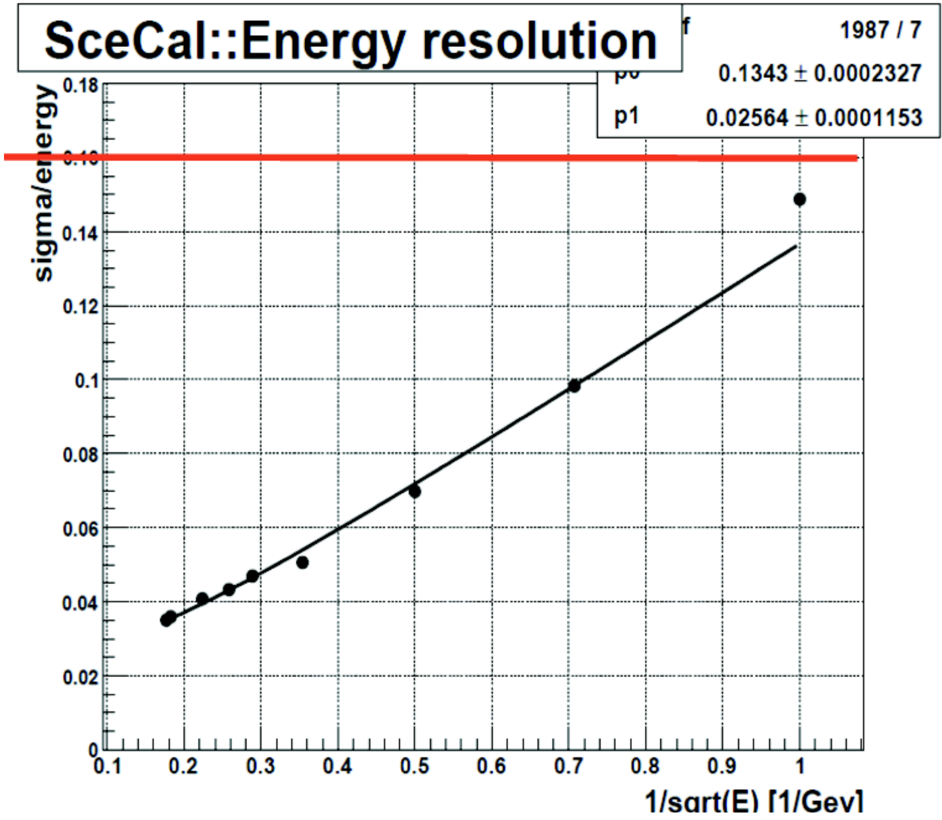


- Extensive test beam campaign
  - DESY: 2006
  - CERN: 2006, 2007
  - FNAL: 2008, ...
- Various beams and energies
  - 2 GeV to 80 GeV
  - μ, $e^{\pm}$, $\pi^{\pm}$, hadrons



CALICE Scint-ECAL

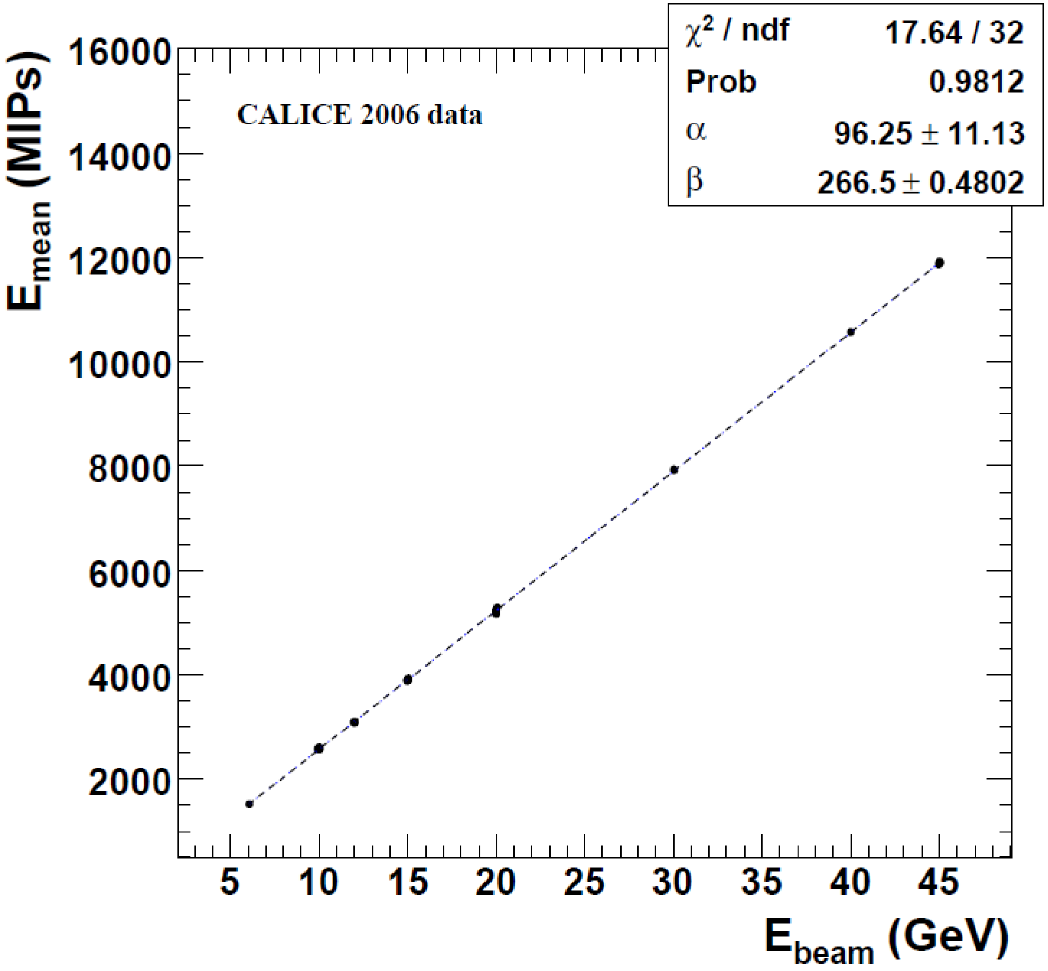


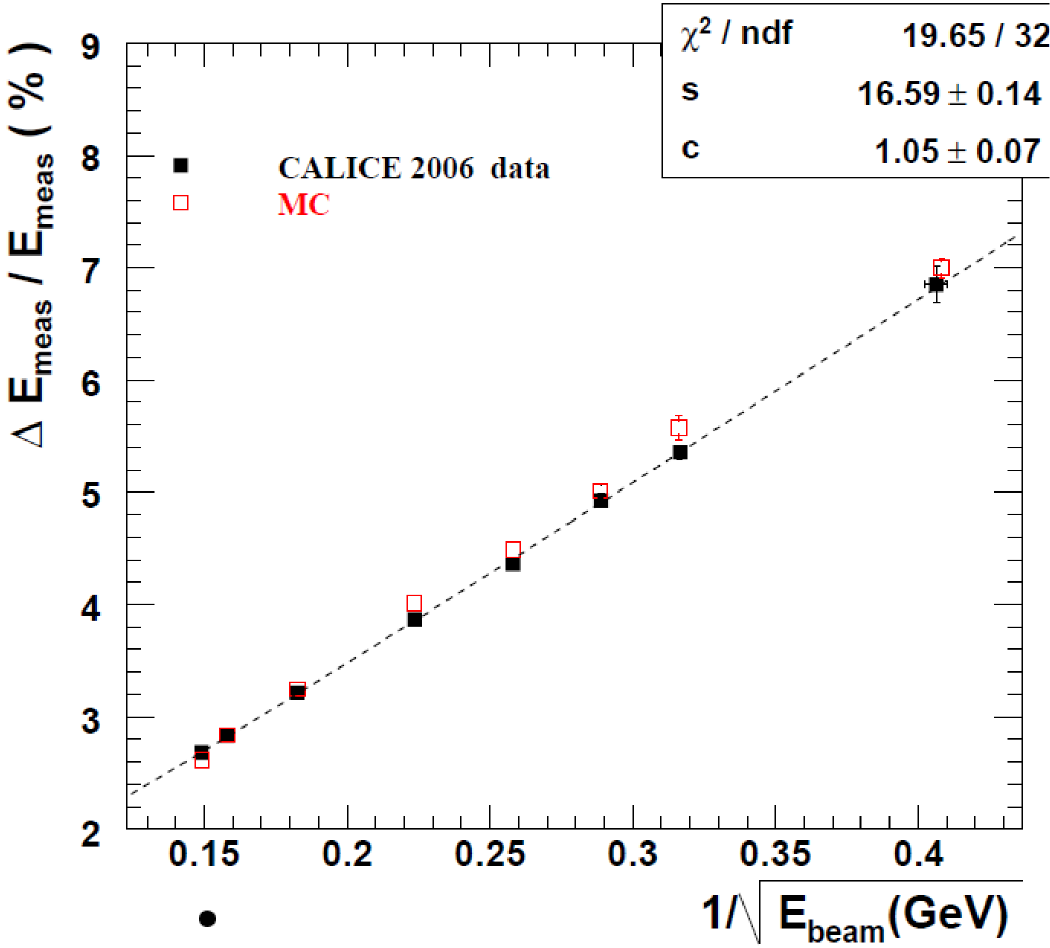


Beam test with W+Scintillator ECAL at Fermilab

$$\frac{\sigma_E}{E} = \frac{13.56\%}{\sqrt{(E)}} \oplus 2.56\%$$

ECAL SiW Results 2006

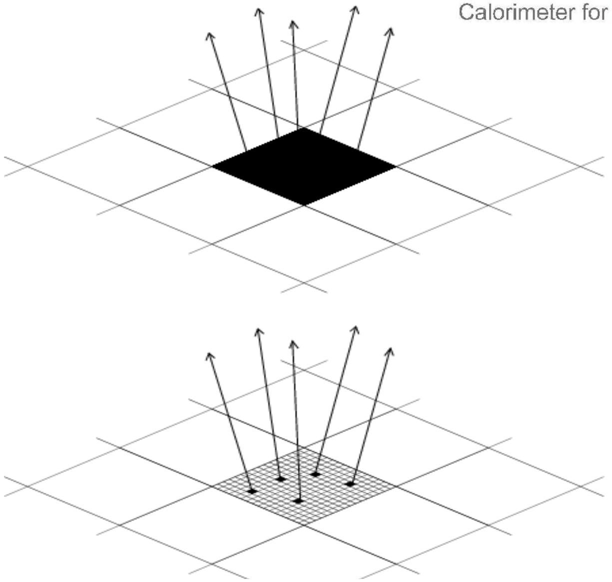


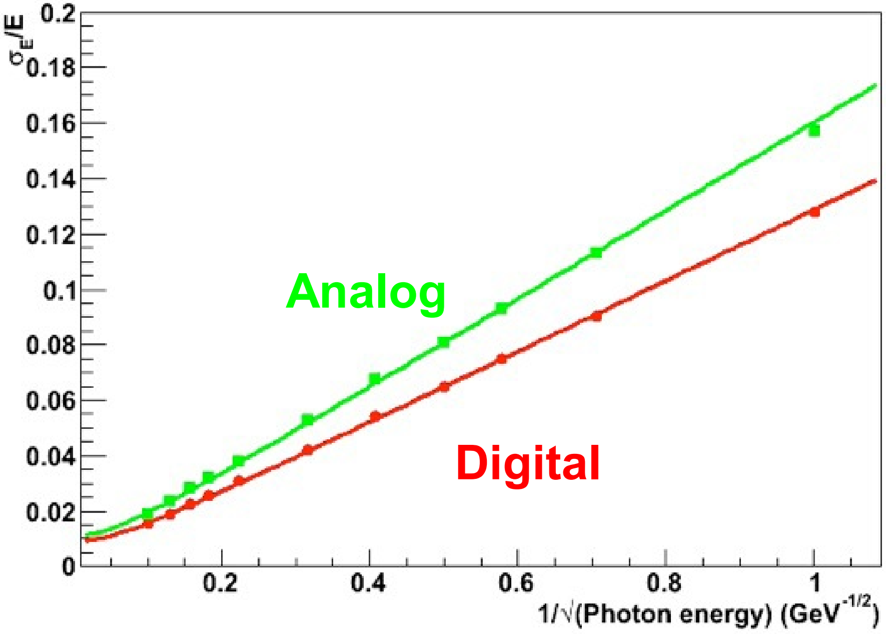


$$\frac{\Delta E_{\mathrm{meas}}}{E_{\mathrm{meas}}} = \left(\frac{16.6 \pm 0.1}{\sqrt{E(\mathrm{GeV})}} \oplus (1.1 \pm 0.1)\right) \%$$

DECAL

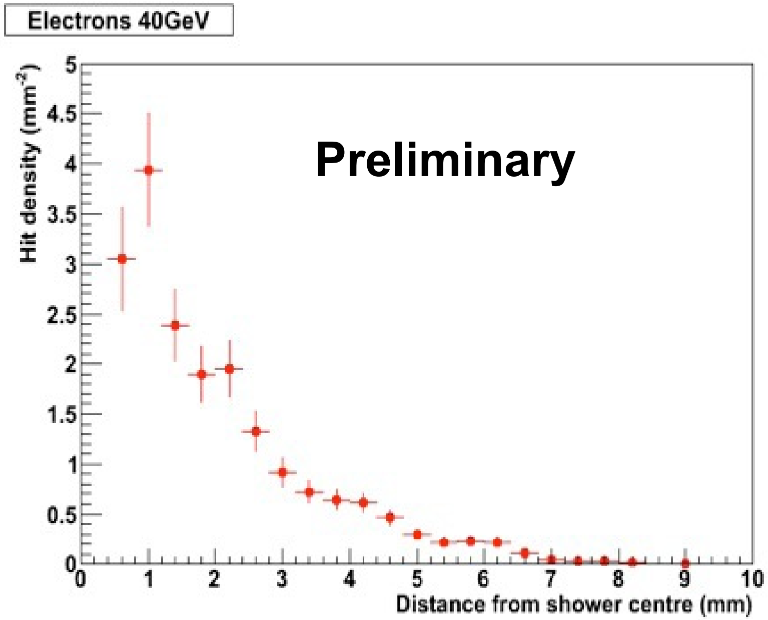
- A digital ECAL counts the number of particles in a shower
  - Shower densities of 100 particles/mm^2
  - Requires 50 x50 µm Pixels
  - Less fluctuations-> better resolutions
- Can be realized using CMOS Monolithic Active Pixels Sensors



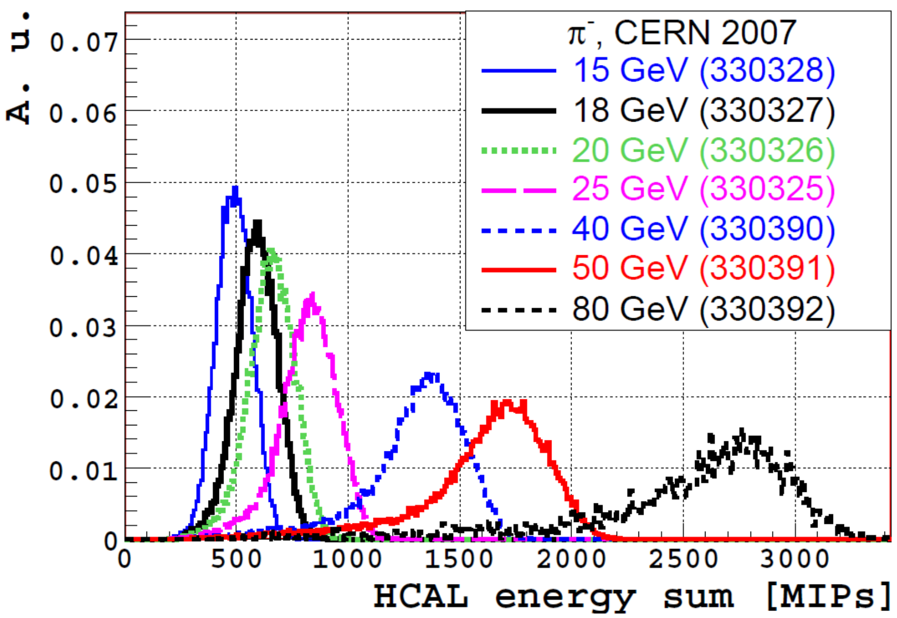


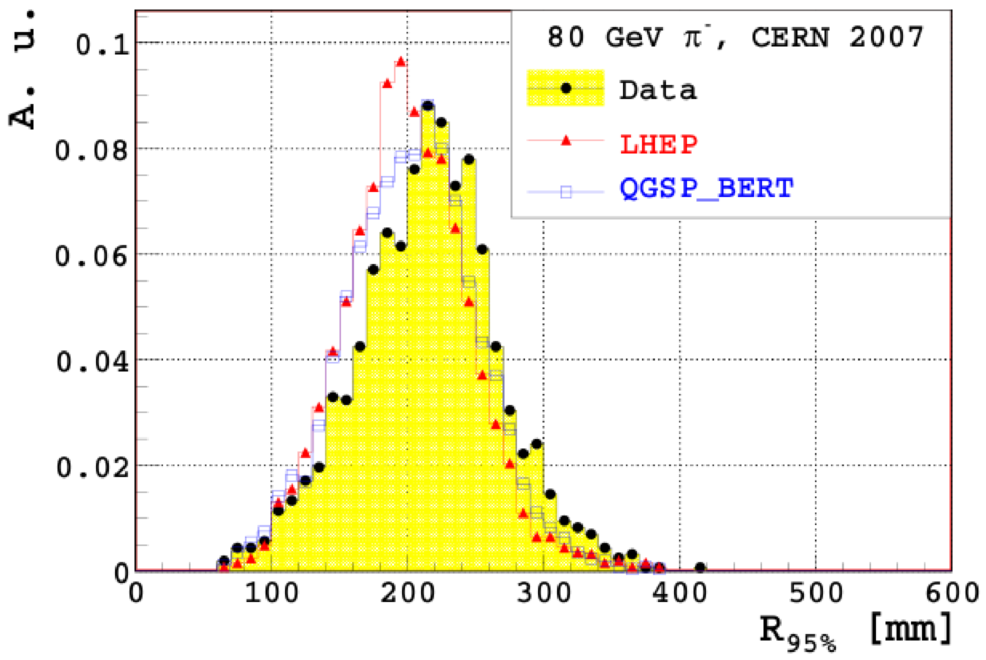
DECAL Technology

- TPAC MAPS sensor for DECAL using CMOS
- Potentially significant price advantage over high resistivity Si diodes
- Tests of sensor prototypes at CERN in 2009: 8.4 x 8.4 mm^2 sensitive area
- Further Test beam planned at DESY



CALICE AHCAL



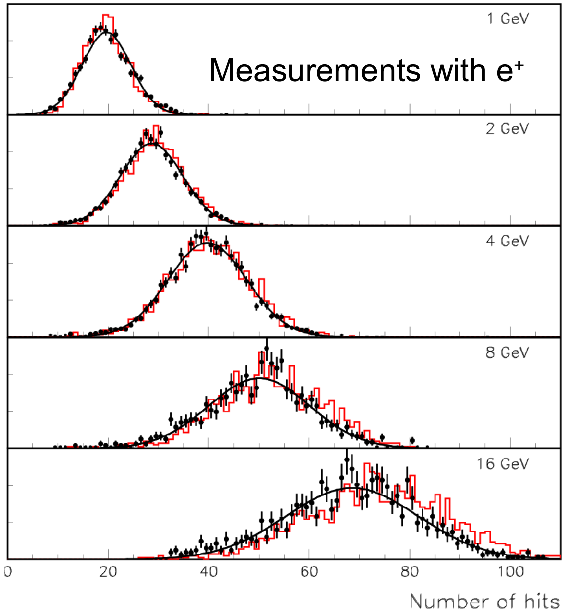


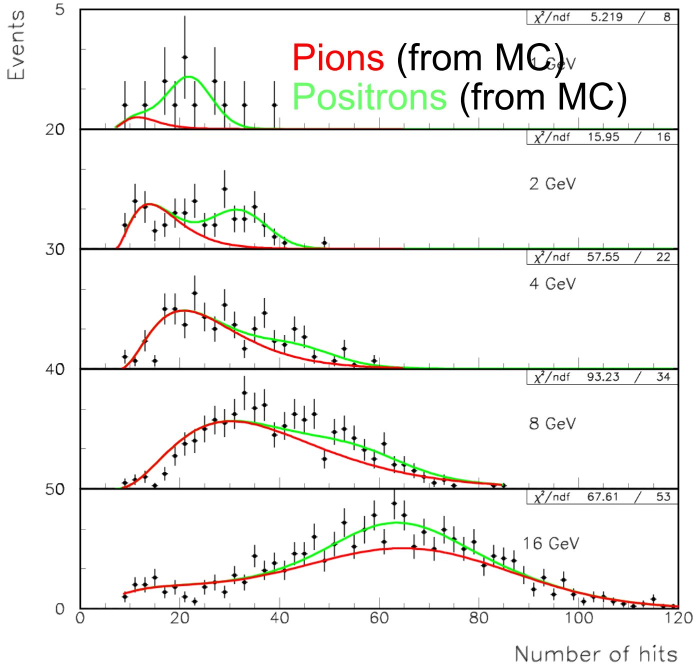
$R_{95\%}$ - shower radius, at which approx. 95% of the total AHCAL energy is transversally deposited

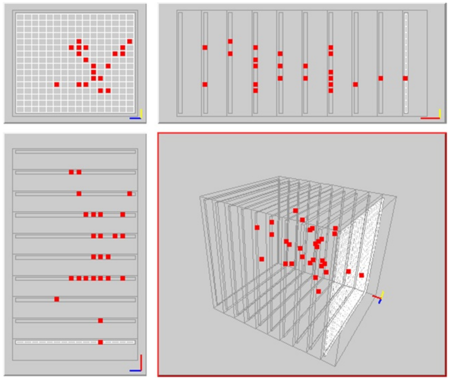
- Data Analysis of 2007 makes good progress
- Tests of hadronic shower models
  - Now have the sensitivity to do this

CALICE DHCAL

- Preliminary investigations completed
- Development and study of thin (glass) RPCs
- Development of a digital (1-bit) readout system for large number of channels
- Tests of a small prototype with cosmic rays and in the FNAL testbeam
- Reasonable agreement between measurements and Monte Carlo simulations of the set-up

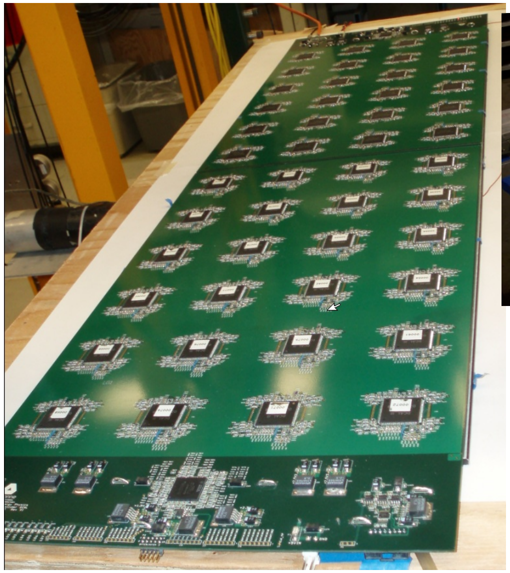


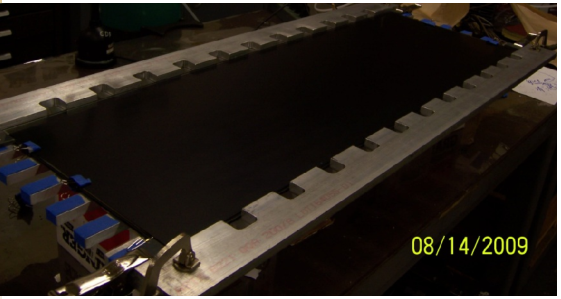


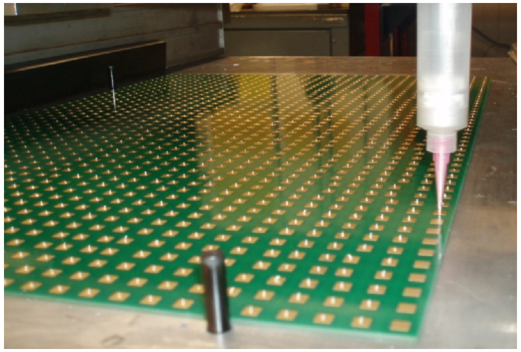


DHCAL 1 m^3 Stack

- 7/114 chambers (32 x 96 cm2) assembled and tested
- Front-end chip (DCAL III) produced (~ 10,600) and fully tested → no design flaws detected
- Readout boards prototyped and tested with cosmic rays
- Almost all fixtures for mass production in hand
- Construction to be completed by **April 2010**
- Tests in FNAL test beam in 2010/2011



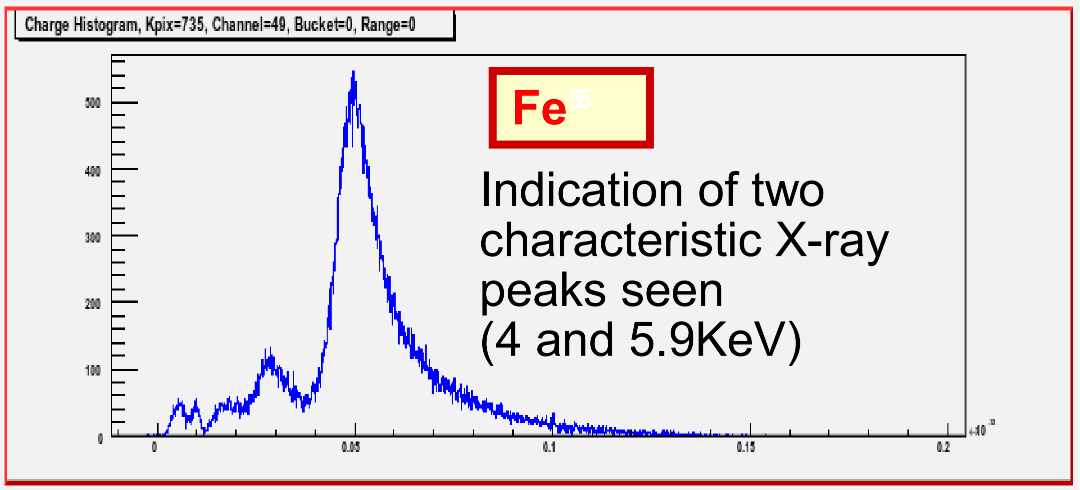




Collaborative effort of
Argonne, Boston, FNAL, Iowa and UTA

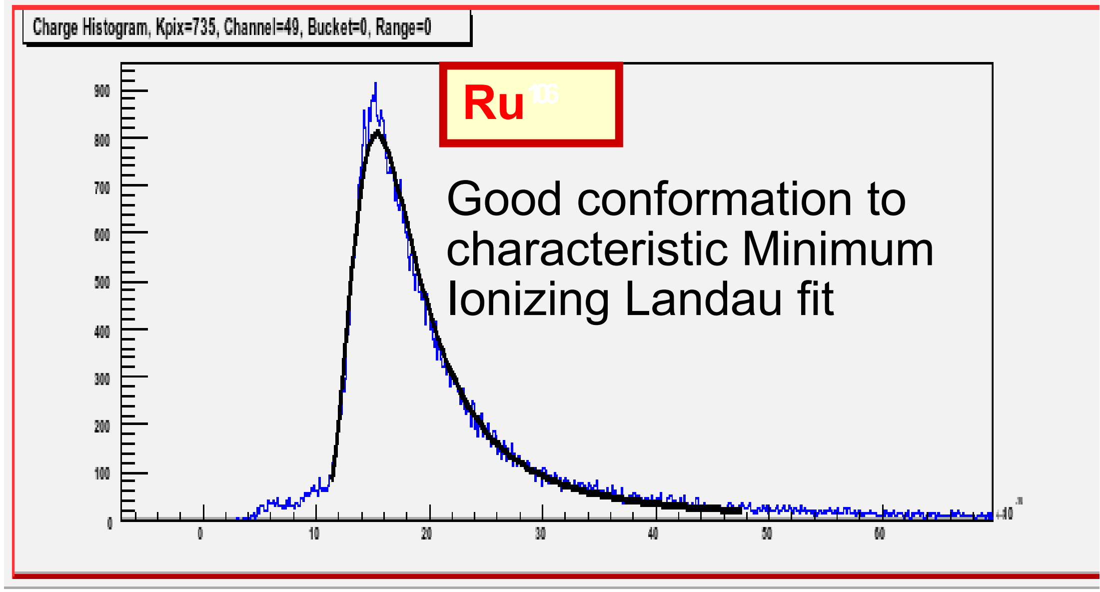
DHCAL GEM

- Double-layer GEM
  - Readout using KPiX
- Development of GEM foils
  - Collaboration with CERN
- Plans for Beam test
  - 30x30 cm array (2010)
  - 30 x100 cm array (late 2010)
  - 100x100 cm planes to use in CALICE HCAL (2011)



Fe^{55}

Indication of two characteristic X-ray peaks seen (4 and 5.9KeV)



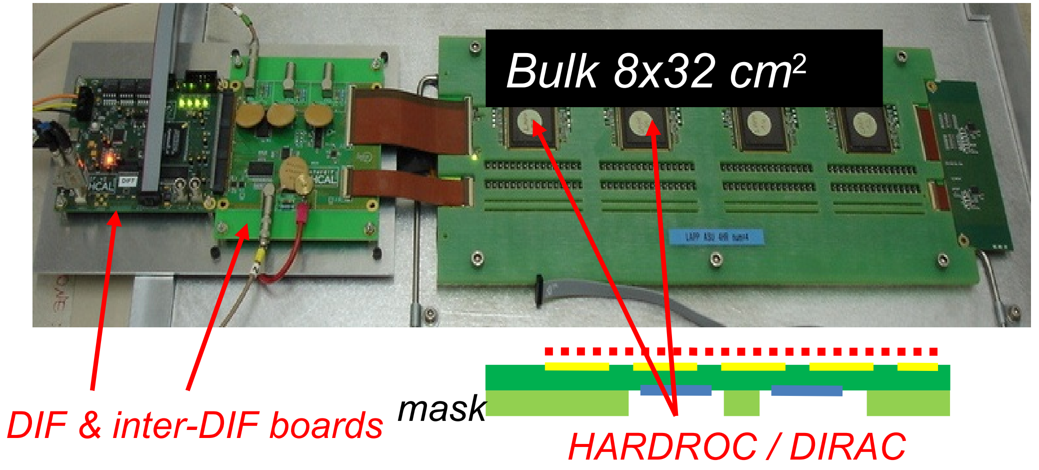
Ru^{106}

Good conformation to characteristic Minimum Ionizing Landau fit

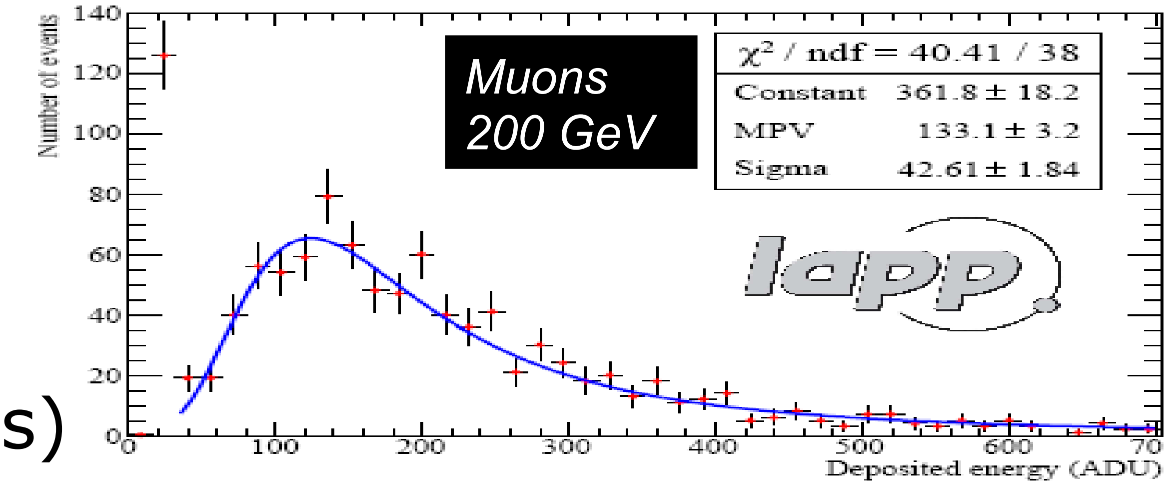
DHCAL MicroMegas

- Prototypes:
  - 1 cm^2 readout pads
  - 3 mm of Ar/iC$_4$H10 95/5
- Analog readout prototypes for characterization (GASSIPLEX chip)
  - 6x16, 12x32 cm^2
- Digital readout prototypes with embedded electronics (HARDROC/DIRAC chips)
  - 8x8, 8x32, 32x48 cm^2

4 ASICs = 256 channels



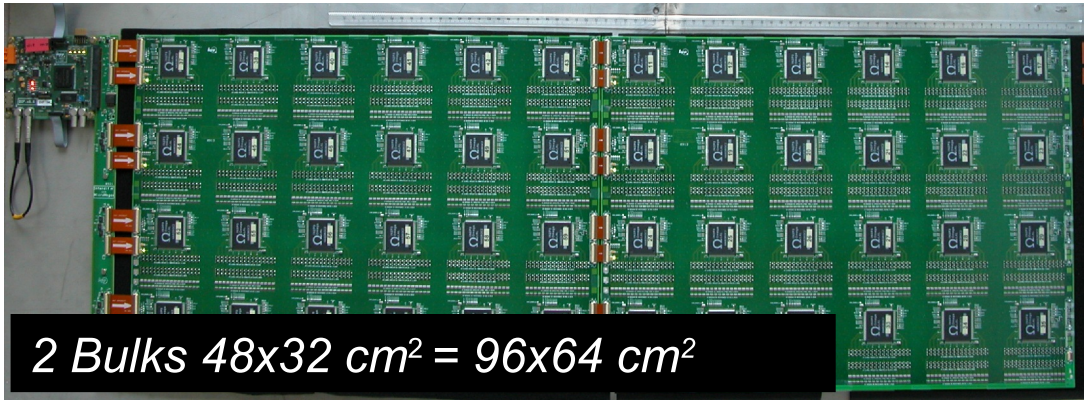
Energy deposited in a single pad

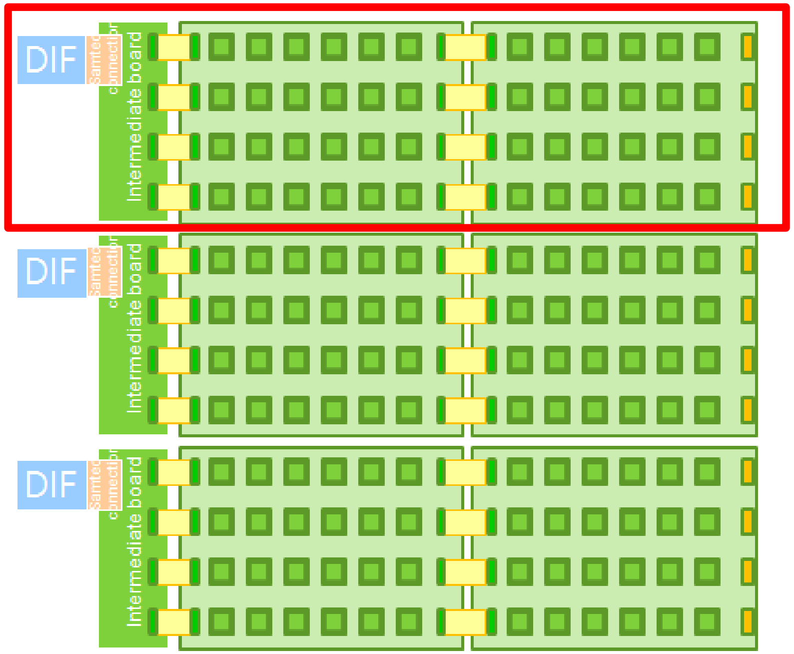


MPV Dispersion ~11% over all the pads

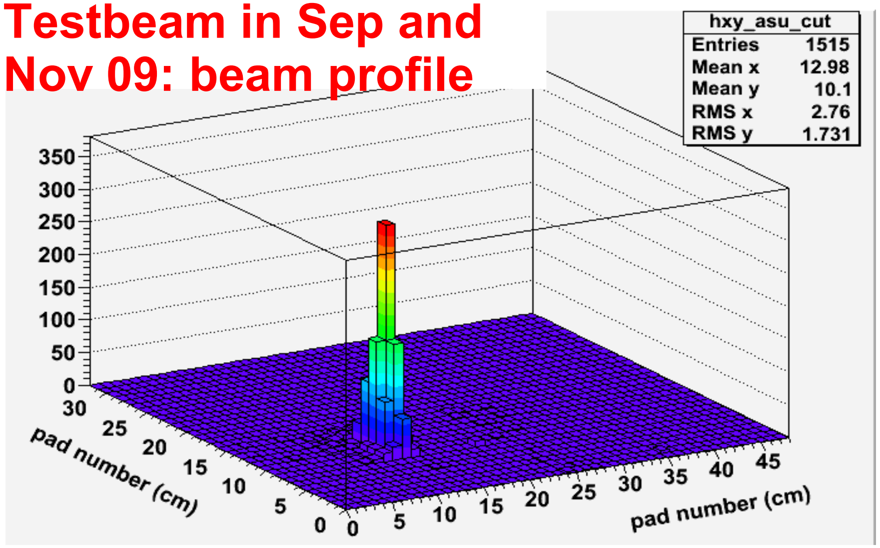
DHCAL 1 m² prototype

- New chambers (48x32 cm²) with 24 HARDROC
- Plans
  - 2010: Assembly of 4 ASU with 24 HARDROC2 each inside 1 m²
  - 2011: Testbeam using sDHCAL 1 m³ steel structure


2 Bulks 48x32 cm² = 96x64 cm²

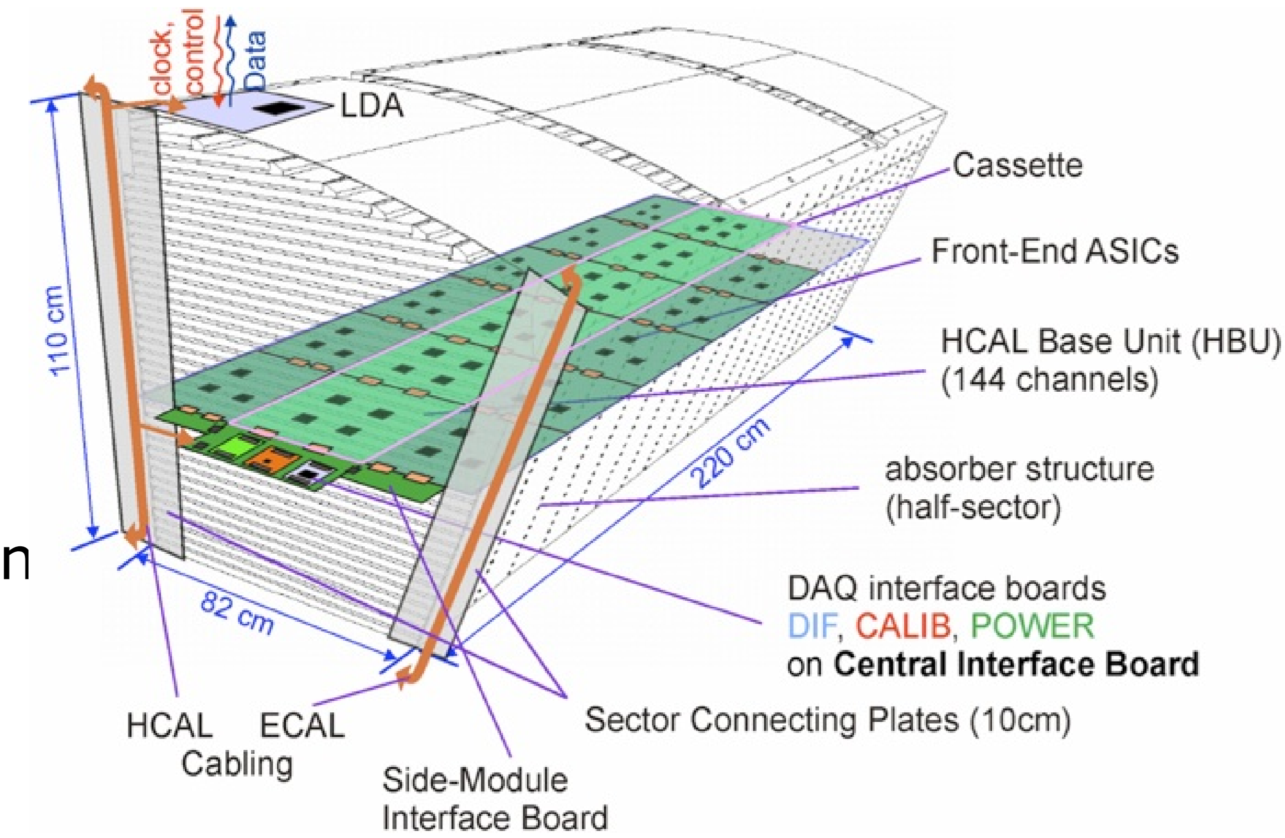


Testbeam in Sep and Nov 09: beam profile



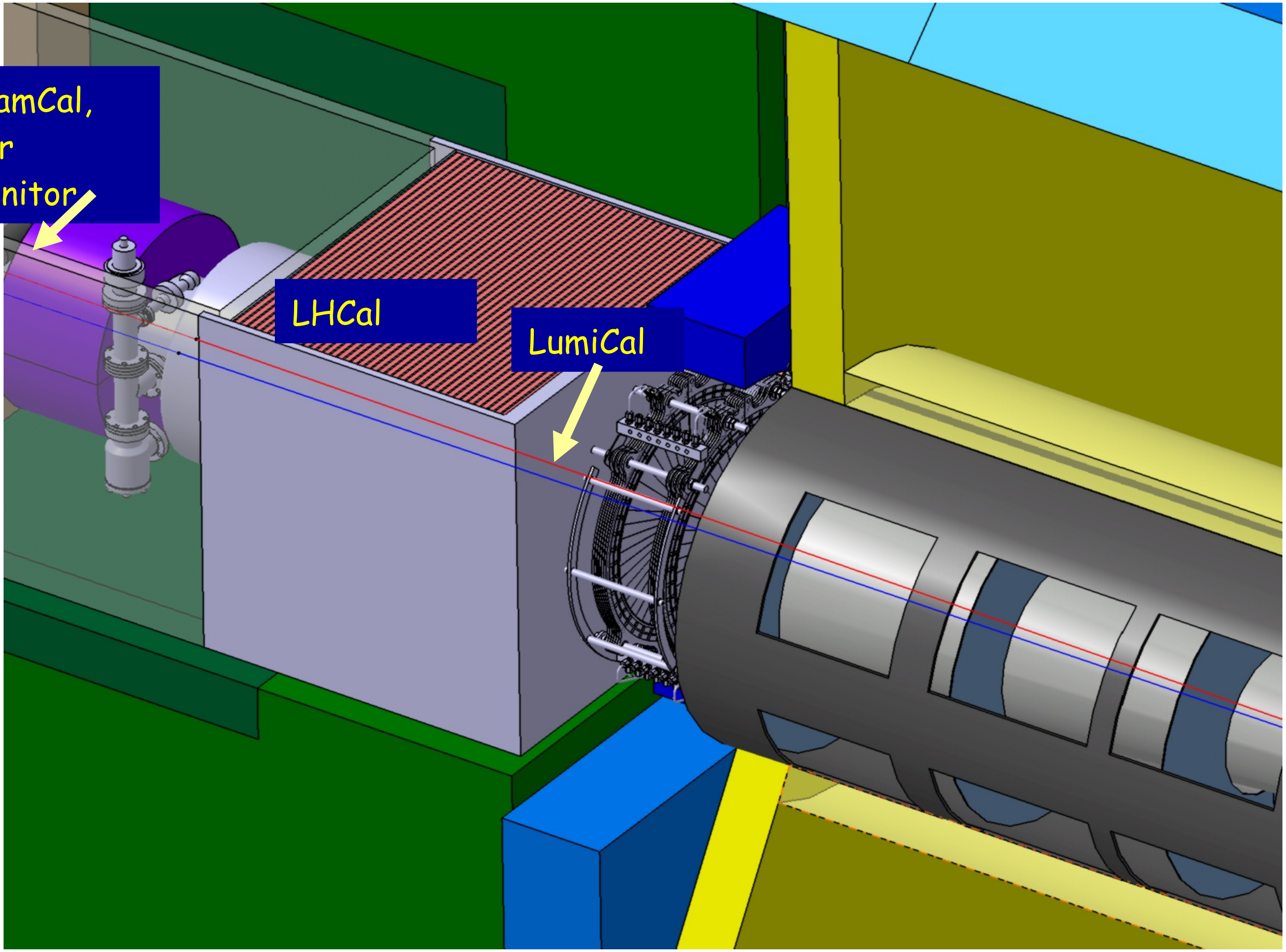
Future Plans

- Future Plans focused around technical prototypes
  - Minimize dead areas
  - System integration
  - Power pulsing
- Important input for the detailed baseline designs

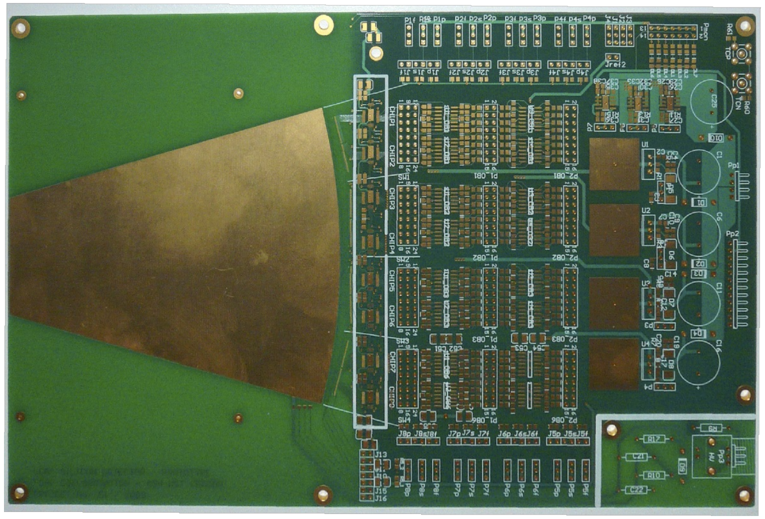


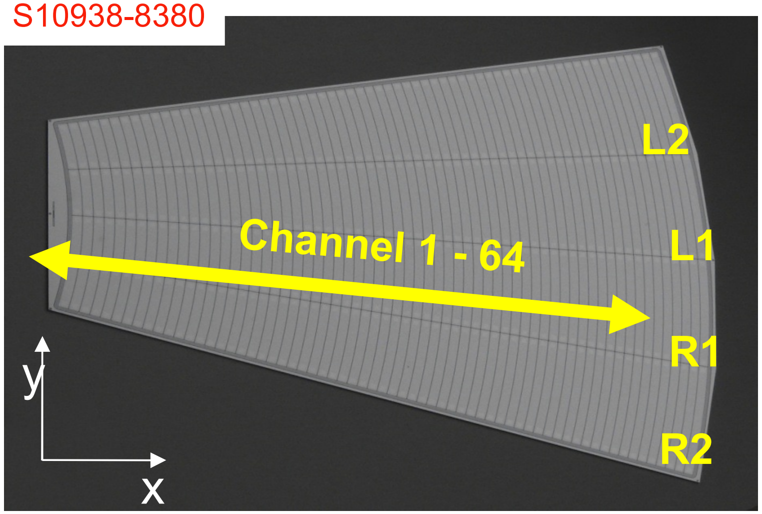
Forward Region

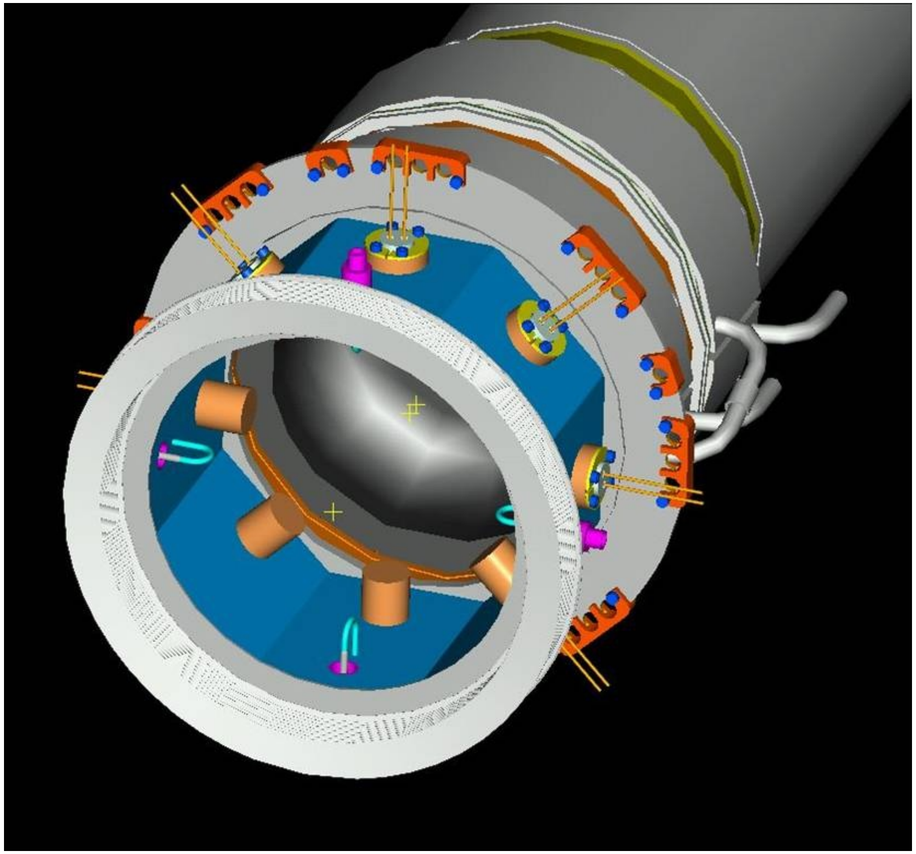
FCAL



FCAL







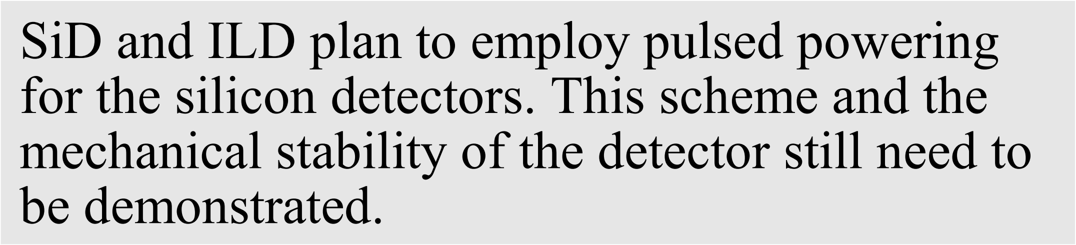
FCAL designed, constructed and installed a Beam-Condition Monitor at FLASH
(4 diamond and 4 sapphire sensors)

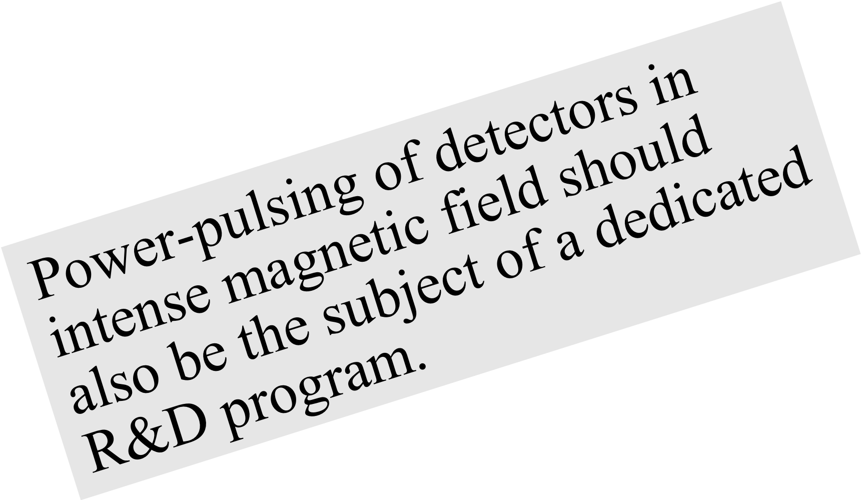
The other side

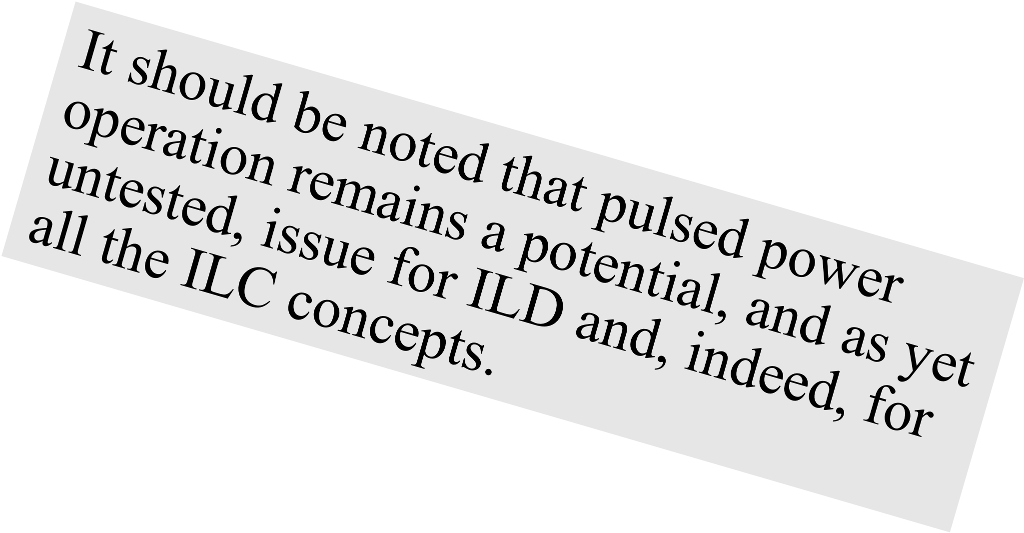
- ILD & SiD have also identified these areas as critical:
  - Alignment
  - Advanced Powering Schemes (DC-DC, Serial powering)
  - Power pulsing
  - Mechanical structures
  - Superconductors

From Marcel Demarteau @TILC09:
Many detectors, and a large part of the physics program, depends on novel powering schemes such as power pulsing, serial powering or DC-DC conversion
Yet there is very little R&D ongoing in the community addressing these issues

IDAG also picked up on this

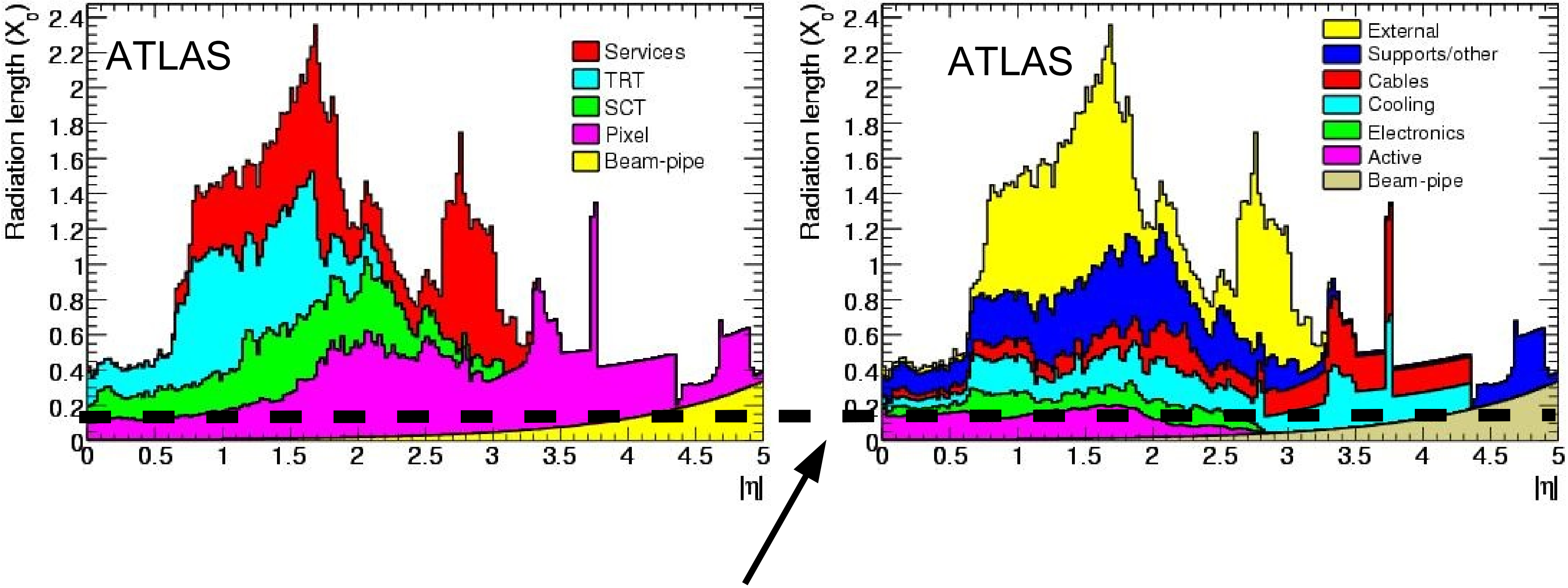

SiD and ILD plan to employ pulsed powering for the silicon detectors. This scheme and the mechanical stability of the detector still need to be demonstrated.


Power-pulsing of detectors in intense magnetic field should also be the subject of a dedicated R&D program.


It should be noted that pulsed power operation remains a potential, and as yet untested, issue for ILD and, indeed, for all the ILC concepts.

Taken from *IDAG Report on the Validation of Letters of Intent for ILC detectors*

Experiences with LHC Trackers

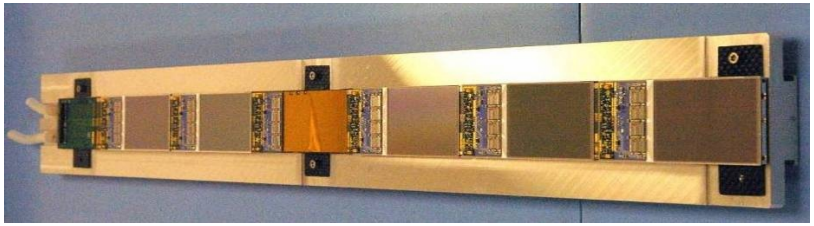


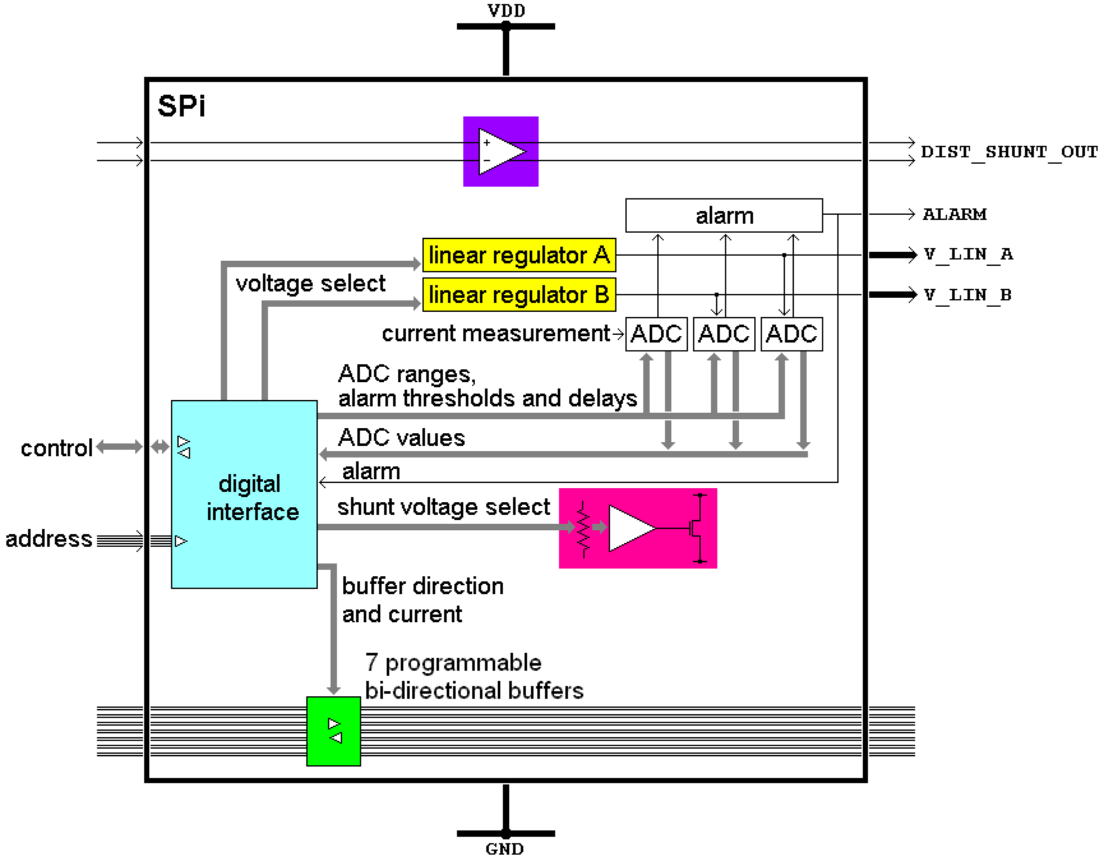
ILC Goal for the entire Tracking System

Lessons learned:
Don't underestimate cabling and services

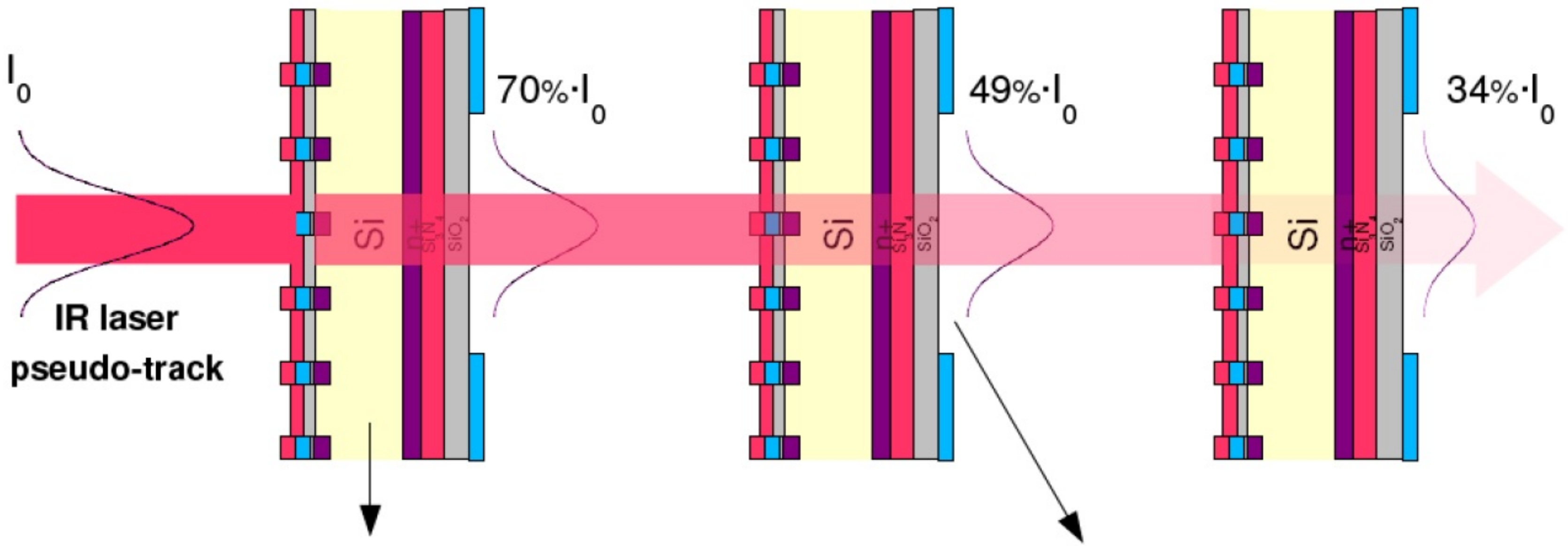
Serial Powering & SPi

- Driven by ATLAS upgrade
  - Serial Powered Staves
- SPi Chip
  - Generic Serial Powering ASIC
  - 0.25 µm CMOS
  - Made by Fermilab, RAL, UPenn
- Open question
  - How well does this work with pulsed power ?
- DC-DC also very active field





IR Silicon Alignment



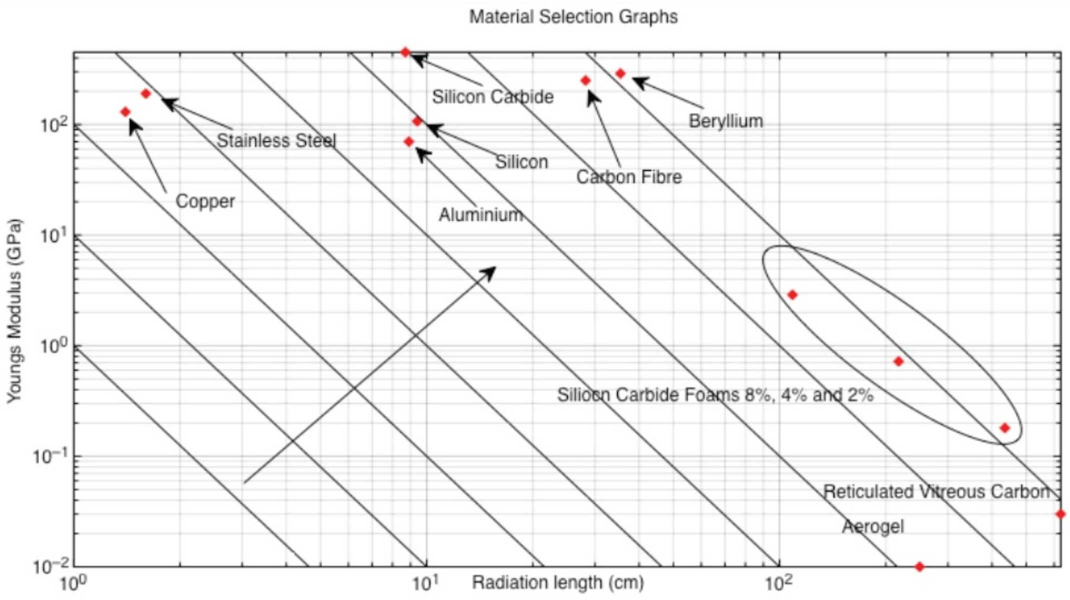
IR light is partially absorbed by Si

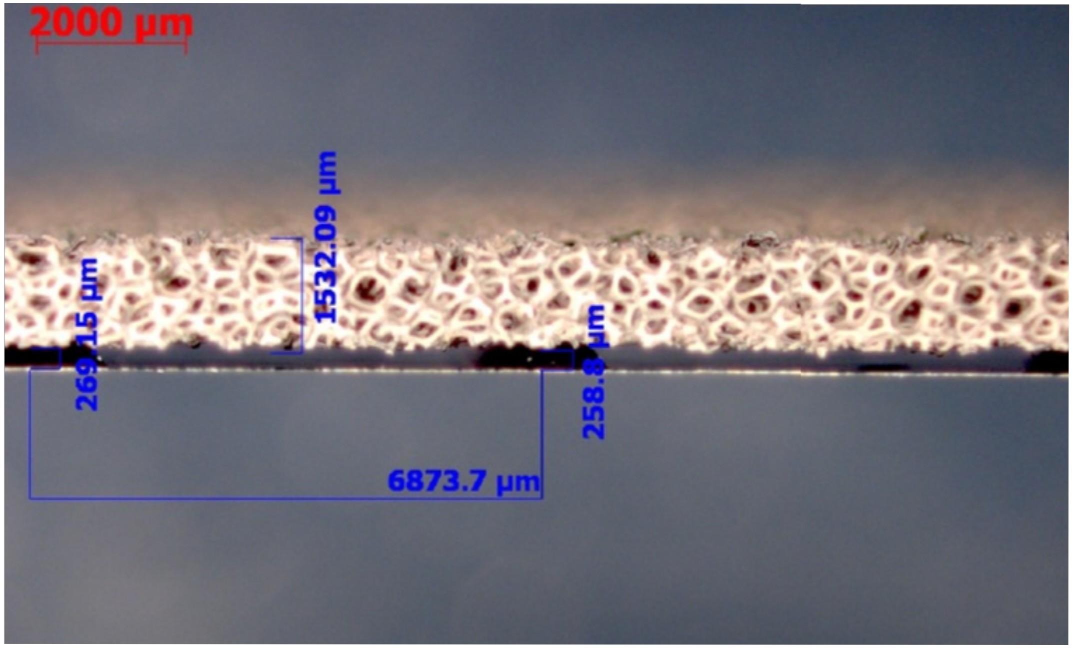
Φ~1 mm opening in Al allows beam-through

- Si is almost transparent to IR light.
- IR beam plays role of straight tracks
- Measure position across several sensors
- Minimum impact on system integration & material budget
- Straightforward DAQ integration

Low Mass Structures

- Low Mass Collaboration
  - *Investigate use of low mass support structures for detectors using silicon sensors.*
- Focus on Silicon Carbide foams
  - Construct ladders
  - Integrate cooling
  - Mechanical properties
  - Machining

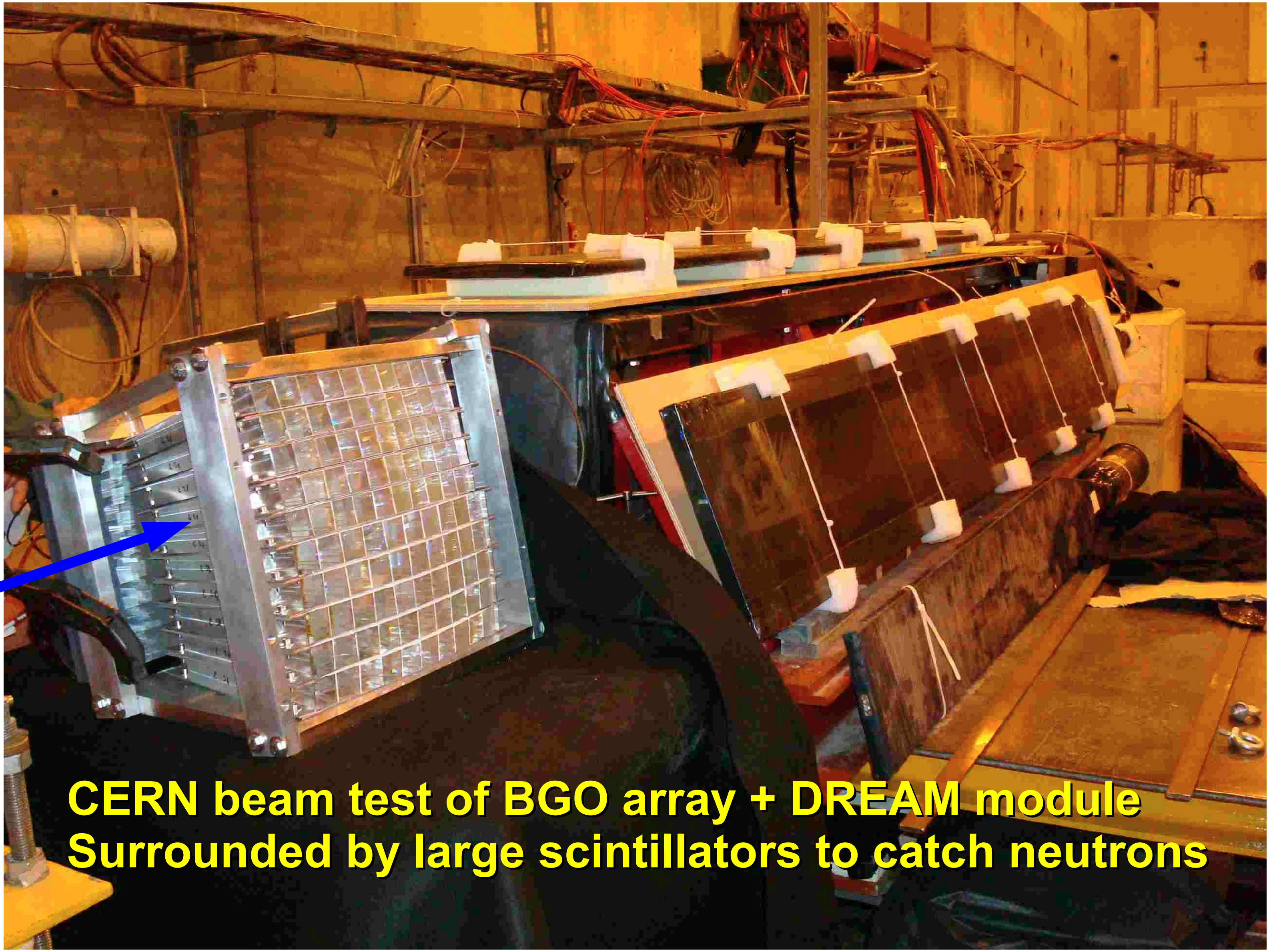




What about higher energies

- LHC may tell us
  - Need to run at 1 TeV or beyond
- ILC detectors not optimized for >1 TeV running
  - Explore PFA at higher energies
  - Or go for dual-readout calorimetry?
- If CLIC-type machine
  - Very different beam structure
  - Specific R&D needed

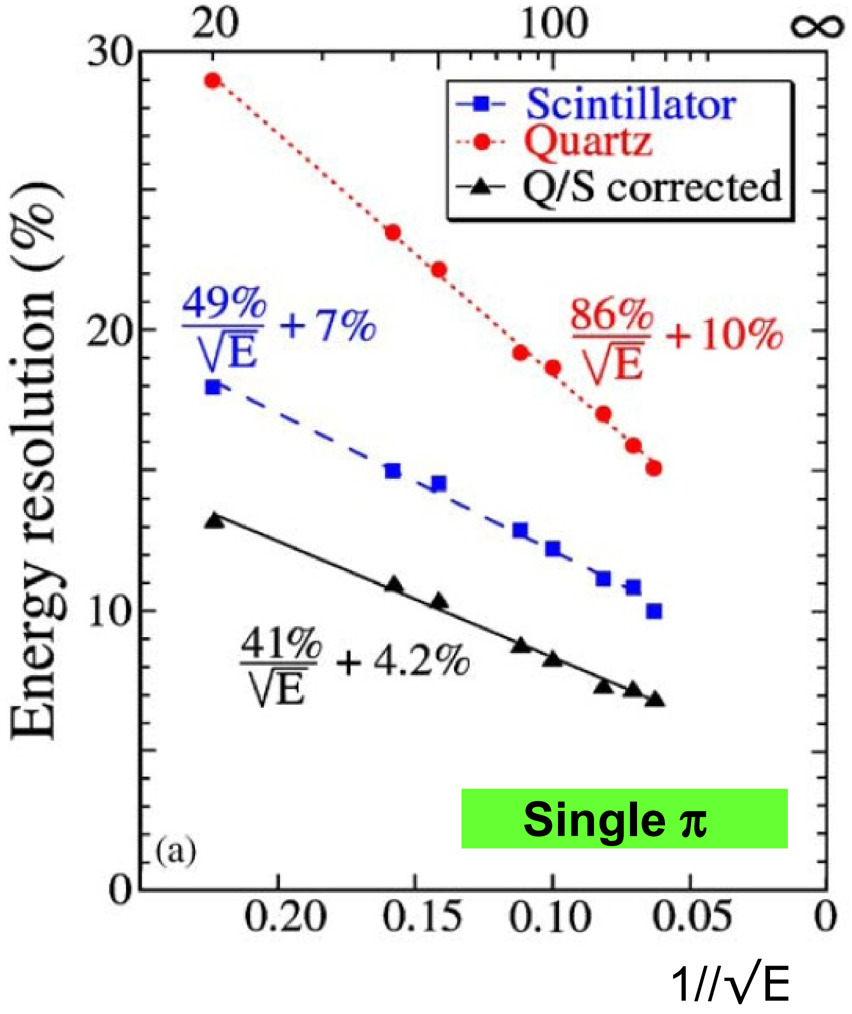
Dual Readout Progress



SPS Beam

CERN beam test of BGO array + DREAM module
Surrounded by large scintillators to catch neutrons

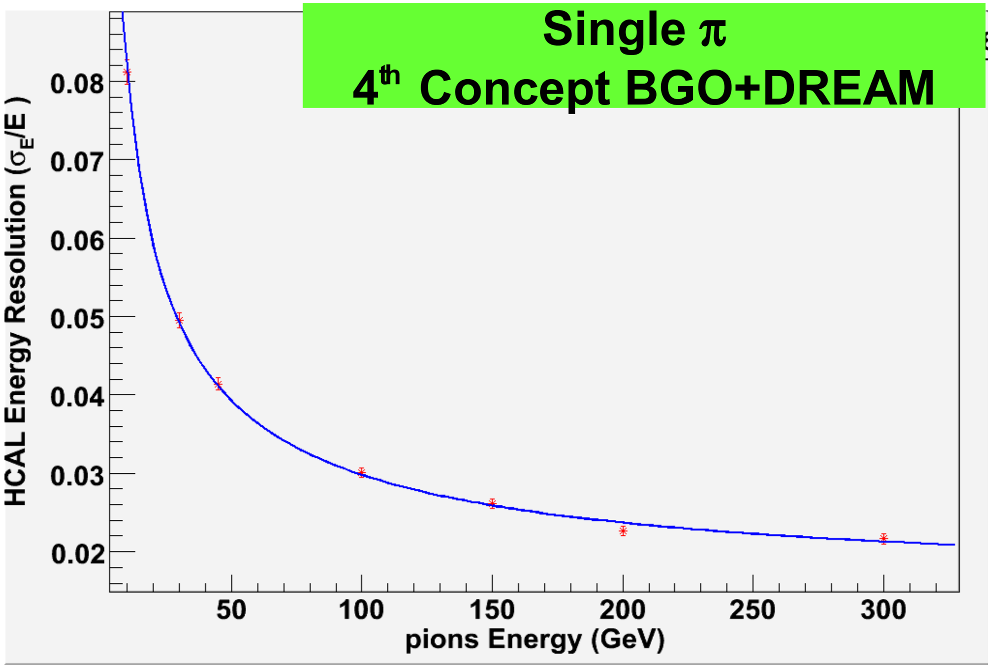
Energy Resolutions



Single π

DREAM module results

- Not using particle energy
- see NIM A 537 (2005) 537–561



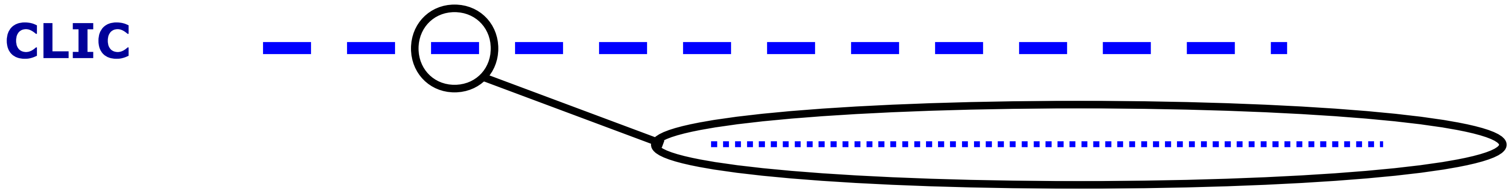
Single π
4th Concept BGO+DREAM

$$\frac{\sigma_E}{E} = \frac{29\%}{\sqrt{(E)}} \oplus 1.2\%$$

From Simulation

CLIC Bunch structure

Train repetition rate 50 Hz



CLIC:	1 train = 312 bunches	0.5 ns apart	50 Hz
ILC:	1 train = 2680 bunches	337 ns apart	5 Hz

Consequences for a CLIC detector:

This is quite different to the ILC …
specific R &D is needed

CLIC R&D

R&D needed beyond present ILC developments:

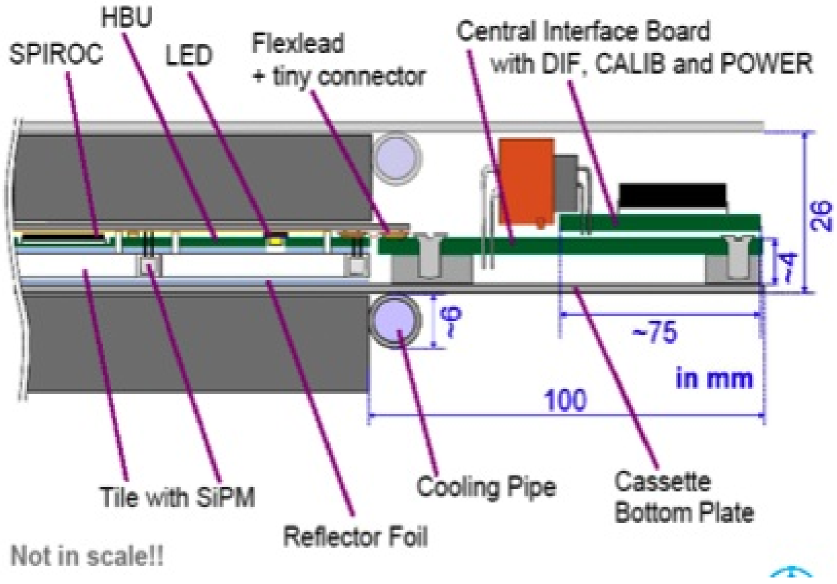
- Time stamping
  - Most challenging in inner tracker/vertex region; trade-off between pixel size, amount of material and timing resolution (~10ns)
  - Needed for most other sub-detectors (e.g. calorimetry at ~20 ns level)
- Power pulsing and DAQ developments (Timing)
- Hadron calorimetry
  - Dense HCAL absorbers to limit radial size (PFA calorimetry based on W)

Coil R&D

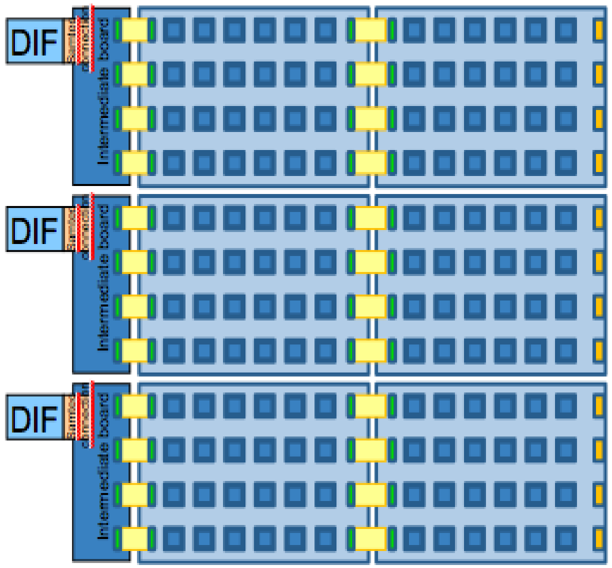
- Solenoid coil
  - Large high-field solenoid concept
  - Reinforced conductor (new Al alloys, nano-structured aluminium, cable-in-conduit)
  - Overall solenoid design and ways to reduce yoke mass
- Overall engineering design and integration studies
  - For heavier calorimeter, larger overall CLIC detector size etc.
  - In view of sub-nm precision required for Final Focus quads

W-HCAL R&D

- Motivation:
  - To limit longitudinal leakage CLIC HCAL needs ~7λ_i
  - A deeper HCAL pushes the coil/yoke to larger radius (significant cost and risk increase
  - A tungsten HCAL is more compact than Fe-based HCAL, while resolutions are similar (increased cost of tungsten barrel HCAL compensates gain in coil cost)
- Plans
  - Use CALICE HCAL mechanics
  - Replace Fe with W
  - Scintillator planes & MicroMegas
  - Beam test in 2011



Not in scale!!



Summary

- LC Detector R&D continues to be an exciting field
  - Impossible to do justice in 40 minutes
- R&D results needed to make choices for the detailed baseline designs
  - These results will require additional funding
- Cost of Detectors components is becoming a concern
  - **Especially for Silicon**
- S(LHC) and Linear Colliders share common problems
  - Common R&D tasks ?
- Acknowledgments
  - J. Blaha, J. Brau, M. Breidenbach, M. Demarteau, J. Goldstein, J. Hauptman, R. Ichimiya, R. Lipton, L. Linssen, W. Lohmann, A. Para, R. Poeschl, J. Repond, A. Ruiz, A. Savoy-Navarro, F.Sefkow, R.Settles, F. Simon, J. Timmermans, M. Trimpl, M. Vos, D. Ward, M. Weber, A.White, J. Yu

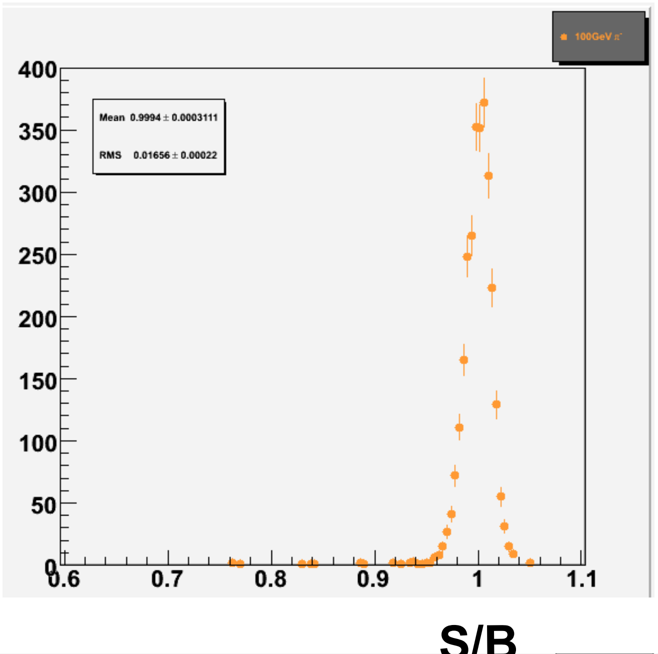
Backup ...

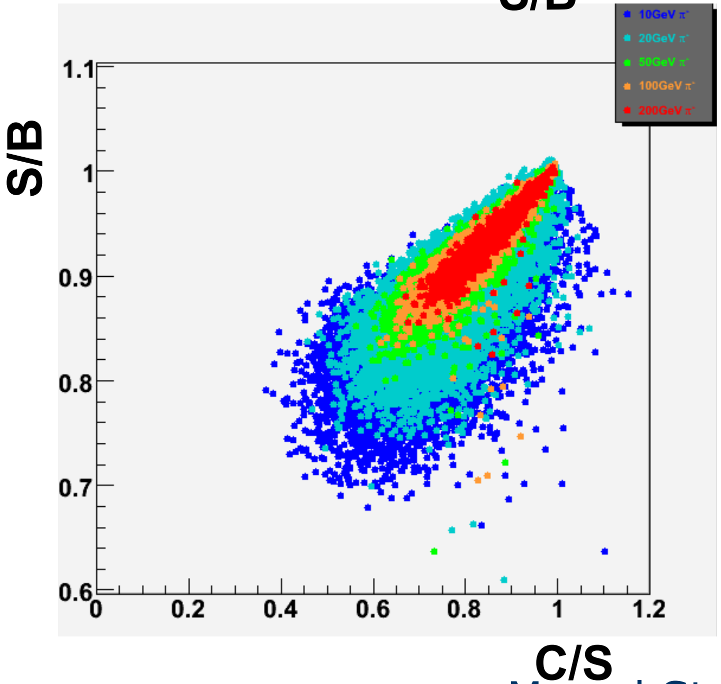
Coil R&D

- CLIC/ILC put high demands on solenoid (beyond CMS experience)
- Possible R&D subjects
  - Reinforced conductor (new Al alloys, nano-structured aluminium, cable-in-conduit)
  - Overall solenoid design and ways to reduce yoke mass
  - Optical-fiber based temperature/strain measurements in winding pack
- Several institutes have show interest (CEA-Saclay, CERN, Genova-INFN, FNAL, KEK, Protvino, SLAC)
- Two upcoming meetings are foreseen:
  - At CERN on October 15th (in the margin of CLIC’09)
  - Hefei China, in the margin of MT21 (October 18-23)

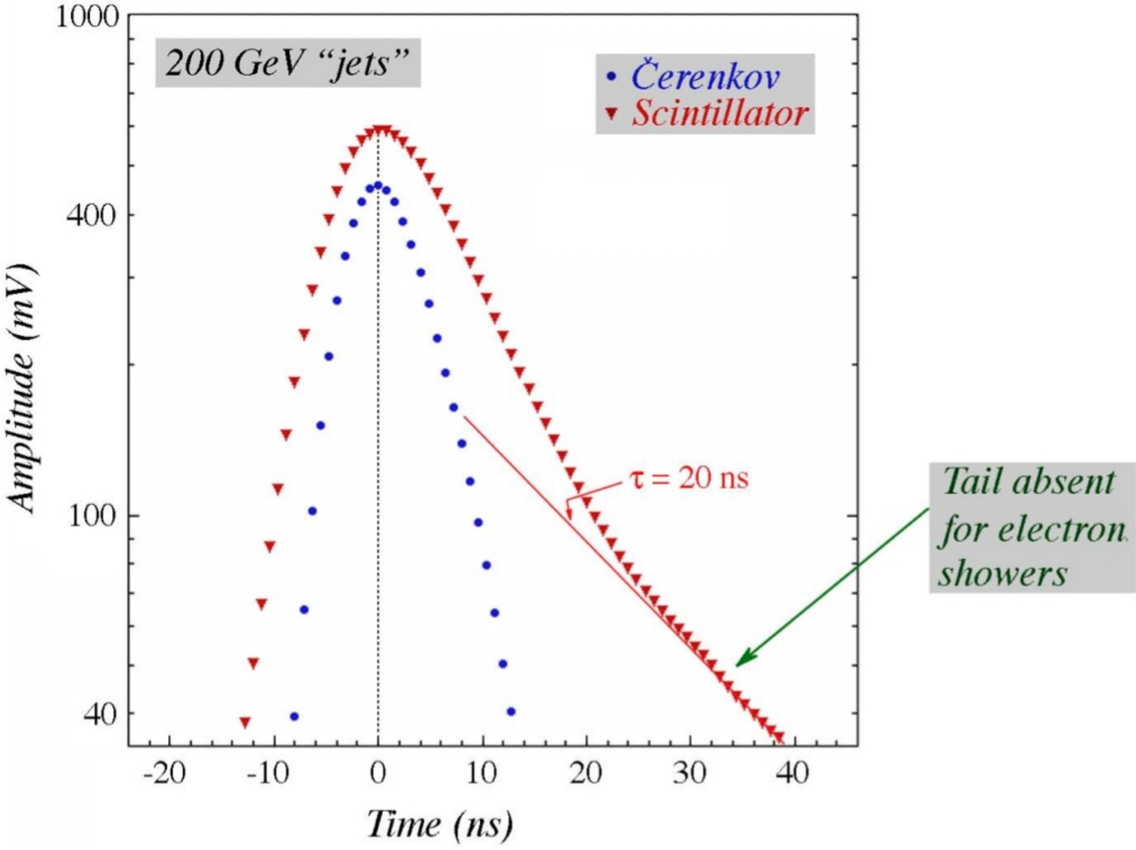
DualReadout using Crystals

- Alternative approach
  - Total Absorption HCAL
- Readout
  - Čerenkov +Scintillation
- Extensive GEANT4 studies
  - 15 %/√E achieved
- Investigating suitable crystals
- Come up with a system design
  - Can it be build ?

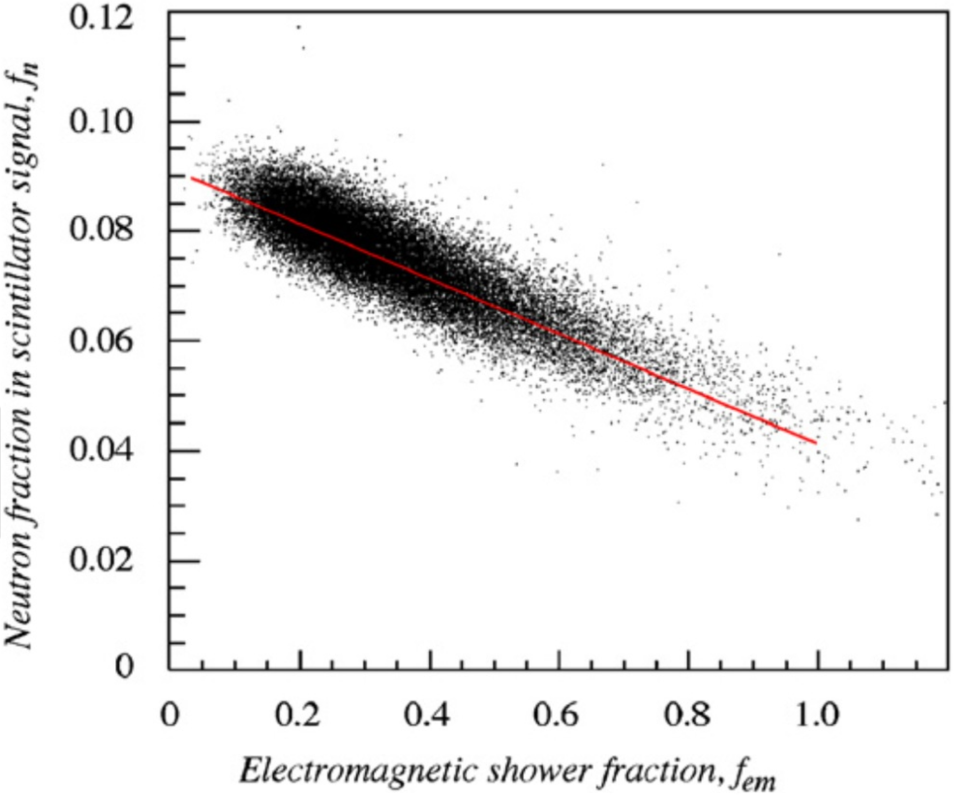




MeV Neutron Particle ID



Tail absent for electron showers



Neutron fraction, f_n

- improve energy resolution
- form "hadronic" ID

`"Neutron signals for dual-readout calorimetry," NIM A598 (2009) 422.`

Critical Areas of R&D defined

Area	ILD	SiD
Vertex Pixel R&D	x	x
Silicon Strips	x	x
TPC	x	
ECAL	x	x
HCAL	x	x
Dual Readout Crystals		x
Muon	x	x
FCAL	x	x

A lot of common interest !