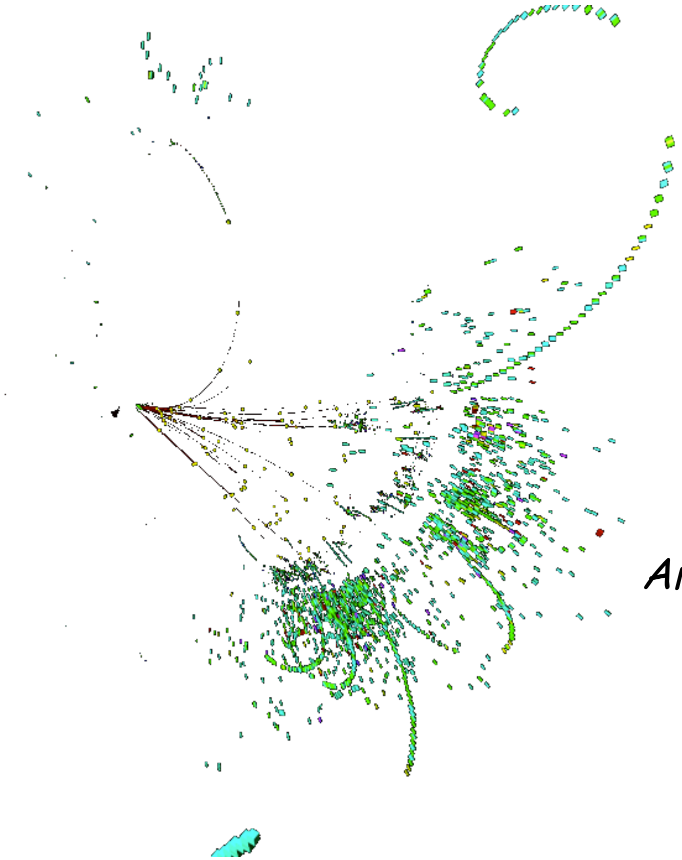
Detector R&D
Status and Overview



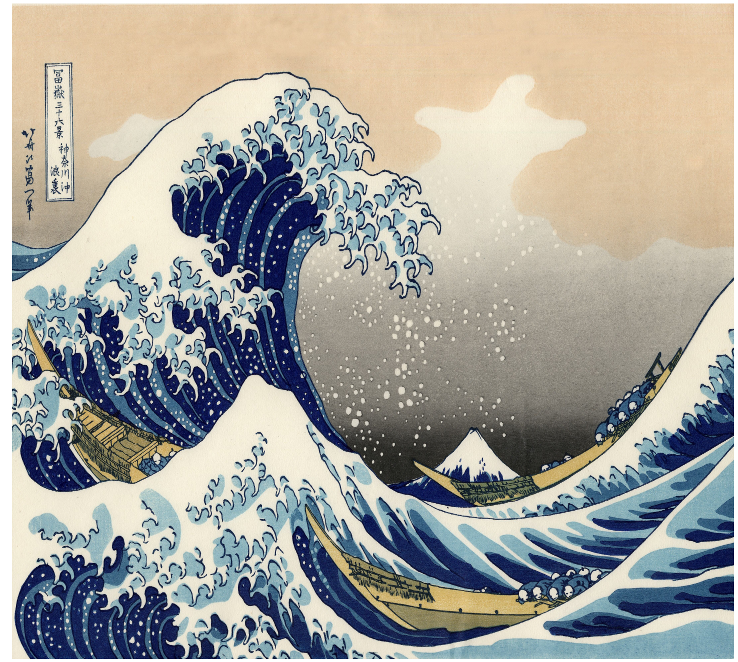
March 19, 2011

Marcel Demarteau
Argonne National Laboratory

ALCPG 2011
Eugene, OR, March 19-23, 2011

Japan

- **Our hearts go out to our Japanese colleagues who suffered three major disasters simultaneously**
  - **Earthquake**
  - **Tsunami**
  - **Nuclear Catastrophe**

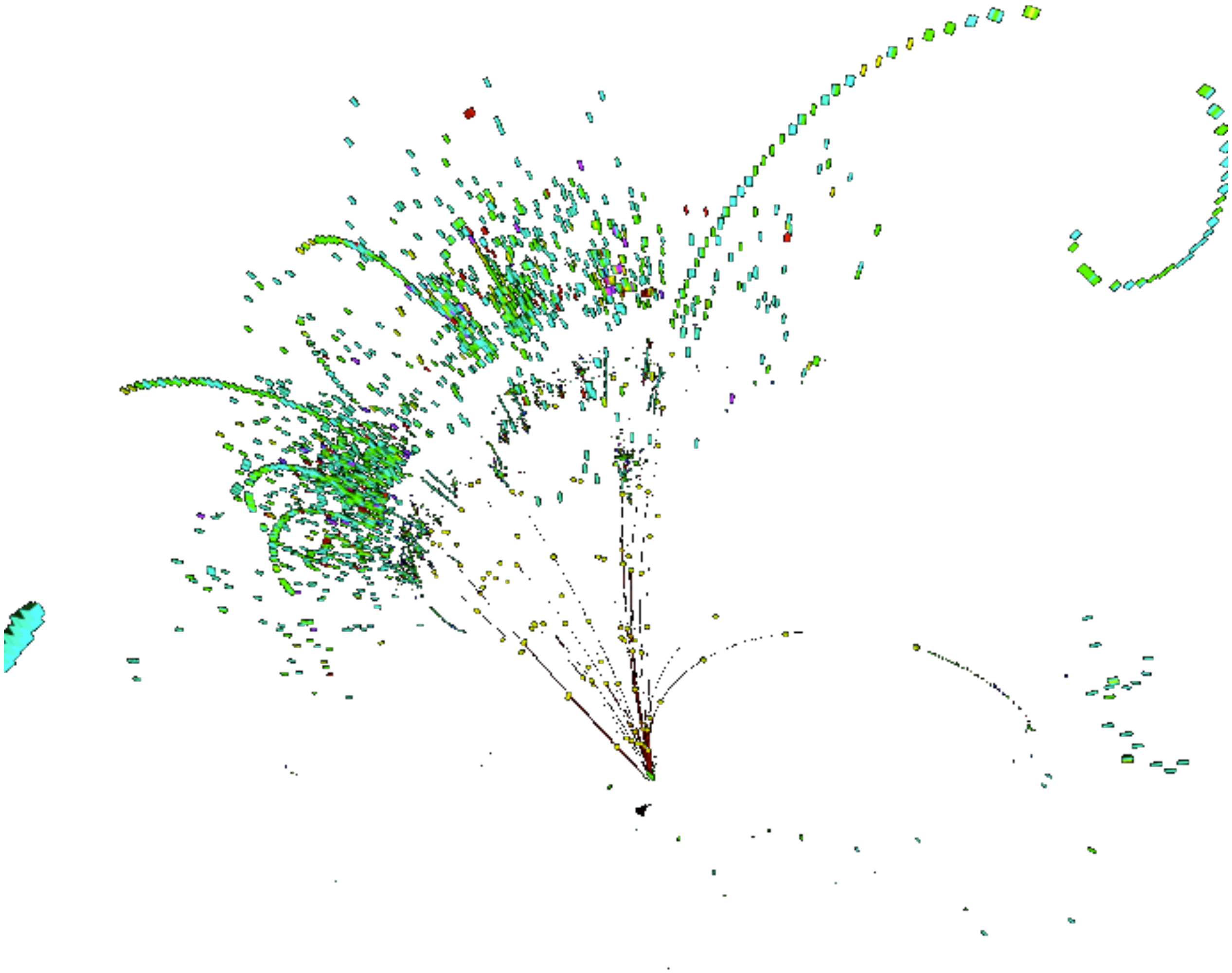


Thus in silence in dreams' projections,
Returning, resuming, I thread my way through the hospitals;
The hurt and wounded I pacify with soothing hand,
I sit by the restless all dark night - some are so young;
Some suffer so much - I recall the experience sad...

Walt Whitman, from *Leaves of Grass*, 1876

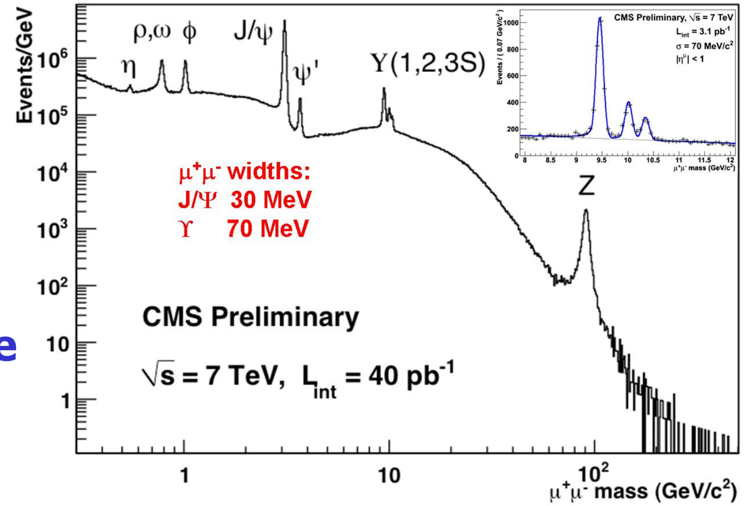
Outline

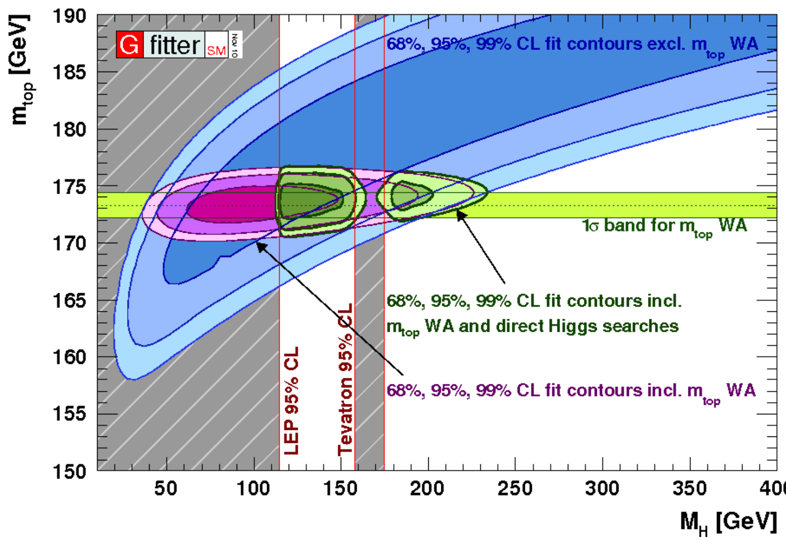
- **The physics drivers**
- **Status of R&D**
- **Reflections**



Physics Goals

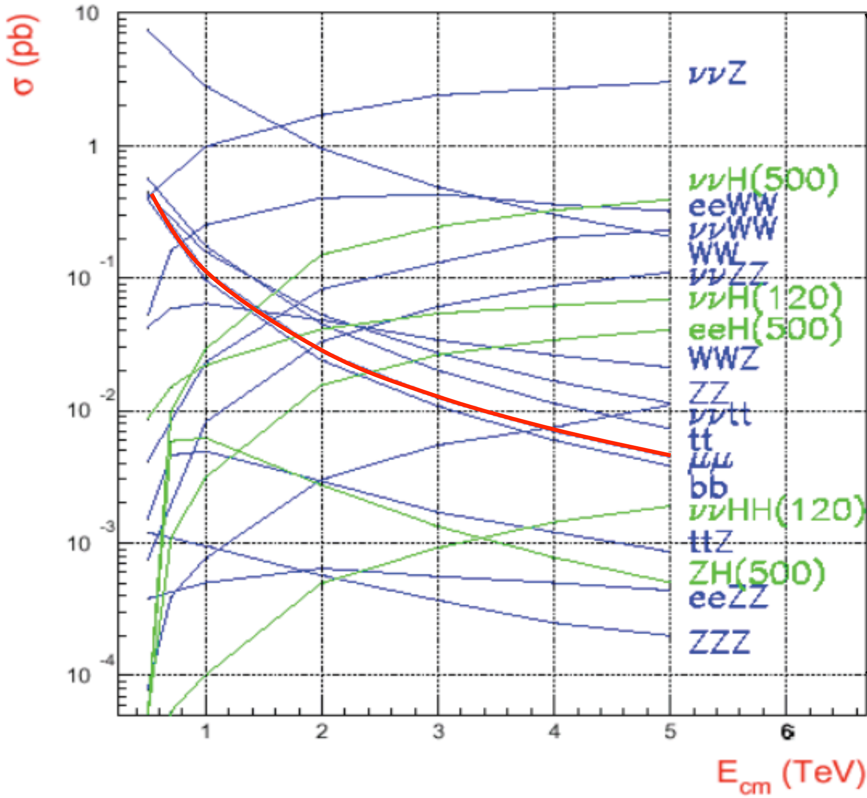
- **The LHC has brought us to the threshold of discovery for new physics, and we expect to cross it, …… momentarily ?**
- **If the new physics is within the ILC center of mass reach, it will let us unravel the structure of that physics**
  - **Electroweak Symmetry Breaking**
  - **Higgs sector(s)**
  - **Extra symmetries, dimensions, …**
- **If no new physics is uncovered at the LHC, precision allows unprecedented probe of SM**
  - **Uncover cracks in SM**
  - **Channels missed at the LHC (trigger or signature)**

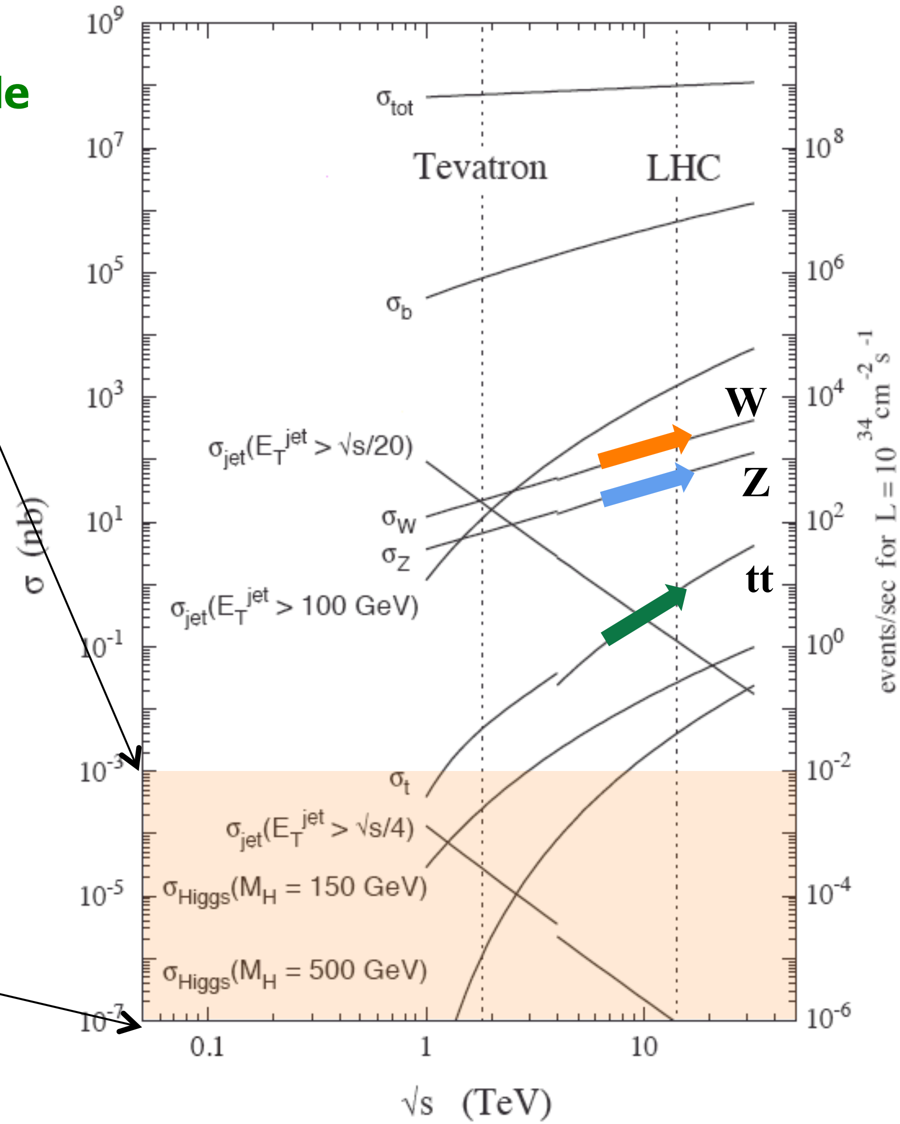




Physics Environments

- **Physics environments of LHC and ILC are radically different**
  - **Small, democratic cross sections**
  - **W / Z separation in hadronic mode**
- **Emphasis on precision, aided by the fact that leptons are elementary particles**





Design Challenges

Physics

- **Unambiguous identification of multi-jet decays of Z's, W's, top, H's, χ's,**

$$ZHH$$

- **Higgs recoil mass and SUSY decay endpoint measurements**

$$ZH \to \ell^+\ell^- X$$

- **Full flavor identification and quark charge determination for heavy quarks**

$$ZH, H \to c\bar{c}, b\bar{b}, \ldots$$

- **Full hermiticity to identify and measure missing energy and eliminate SM backgrounds to SUSY**

$$\tilde{\mu} \text{ decay}$$

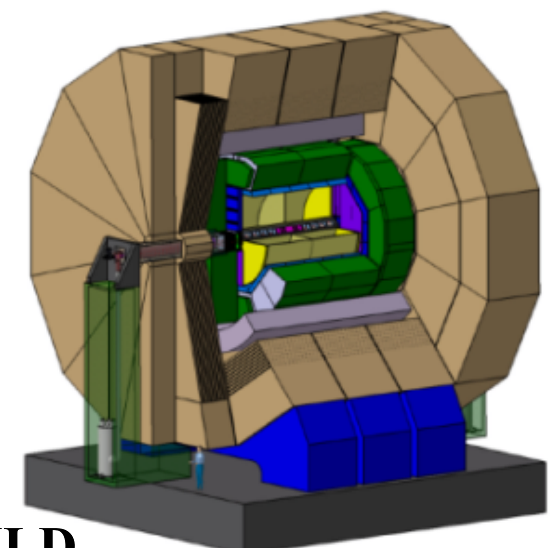
- **The unexpected**

Design Challenges

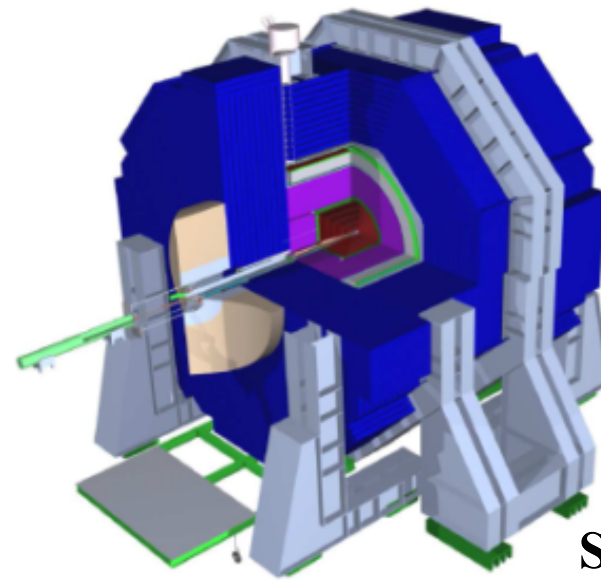
Physics	Detector
• Unambiguous identification of multi-jet decays of Z's, W's, top, H's, χ's, ZHH	• Demands unprecedented jet energy resolution $\sigma_{E_{jet}} / E_{jet} = 3\%$
• Higgs recoil mass and Susy decay endpoint measurements $ZH \to \ell^+ \ell^- X$	• Pushes tracker momentum resolution $\sigma(1/p_T) = 5 \times 10^{-5}\ (GeV^{-1})$
• Full flavor identification and quark charge determination for heavy quarks $ZH, H \to c\bar{c}, b\bar{b}, \ldots$	• Demands superb impact parameter resolution $\sigma_{r\phi} \approx \sigma_{rz} \approx 5 \oplus 10/(p \sin^{3/2}\vartheta)$
• Full hermiticity to identify and measure missing energy and eliminate SM backgrounds to SUSY $\tilde{\mu}$ decay	• Instrumented forward region $\Omega = 4\pi$
• The unexpected	• Smarts

Detector Concepts

- **Two validated detector concepts for the ILC**



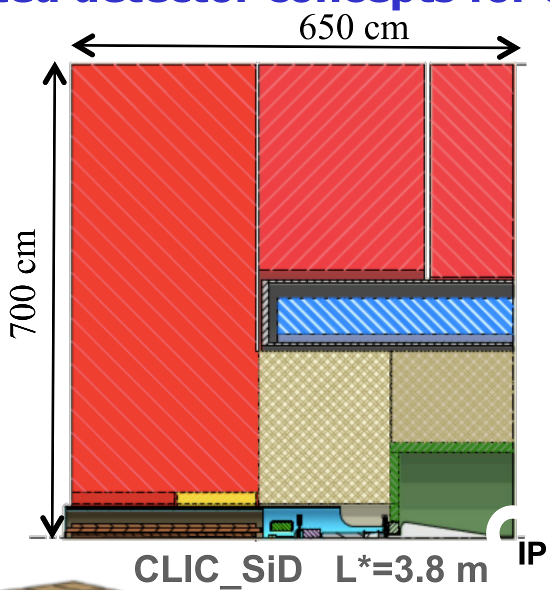
ILD

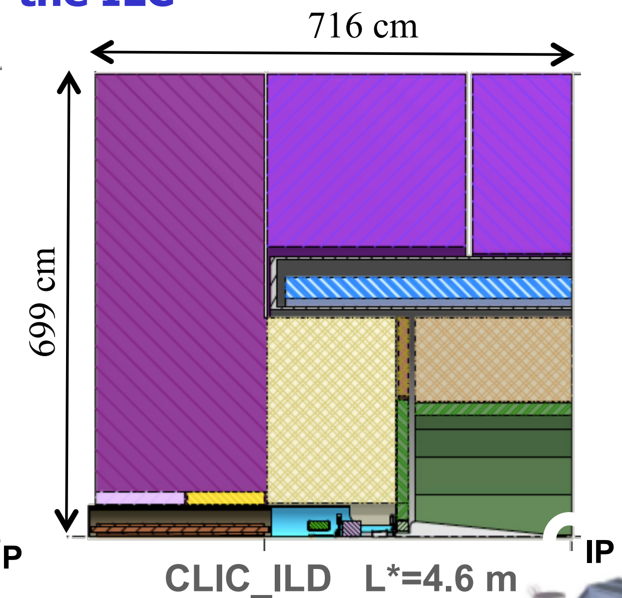


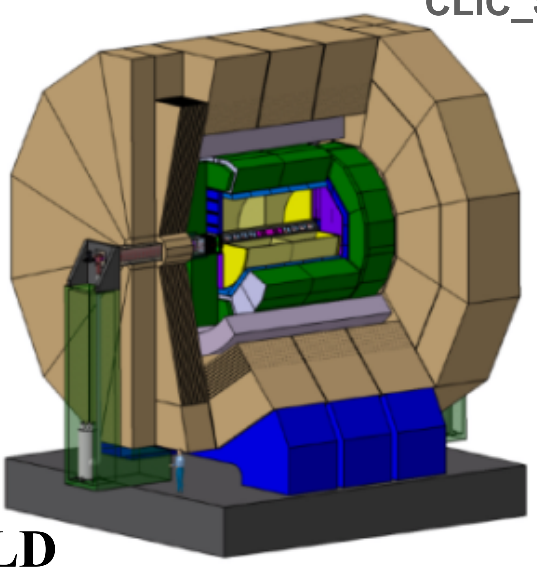
SiD

Detector Concepts plus Siblings

- **Two validated detector concepts for the ILC**

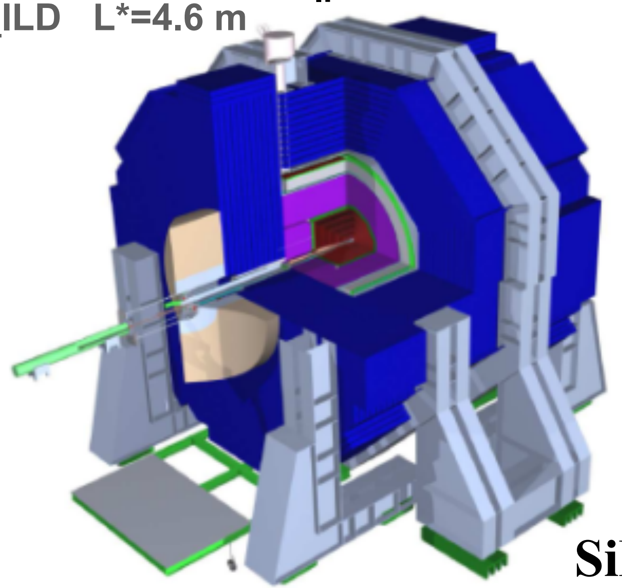






ILD

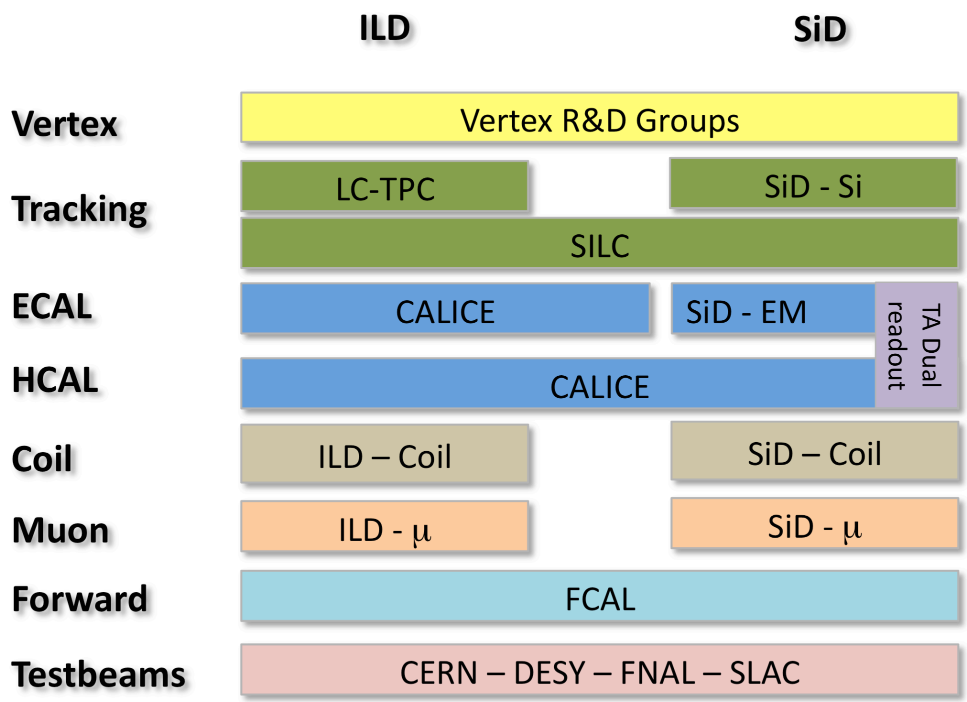
With ILC-CLIC cooperation SiD' and ILD' concepts



SiD

Detector R&D Organization

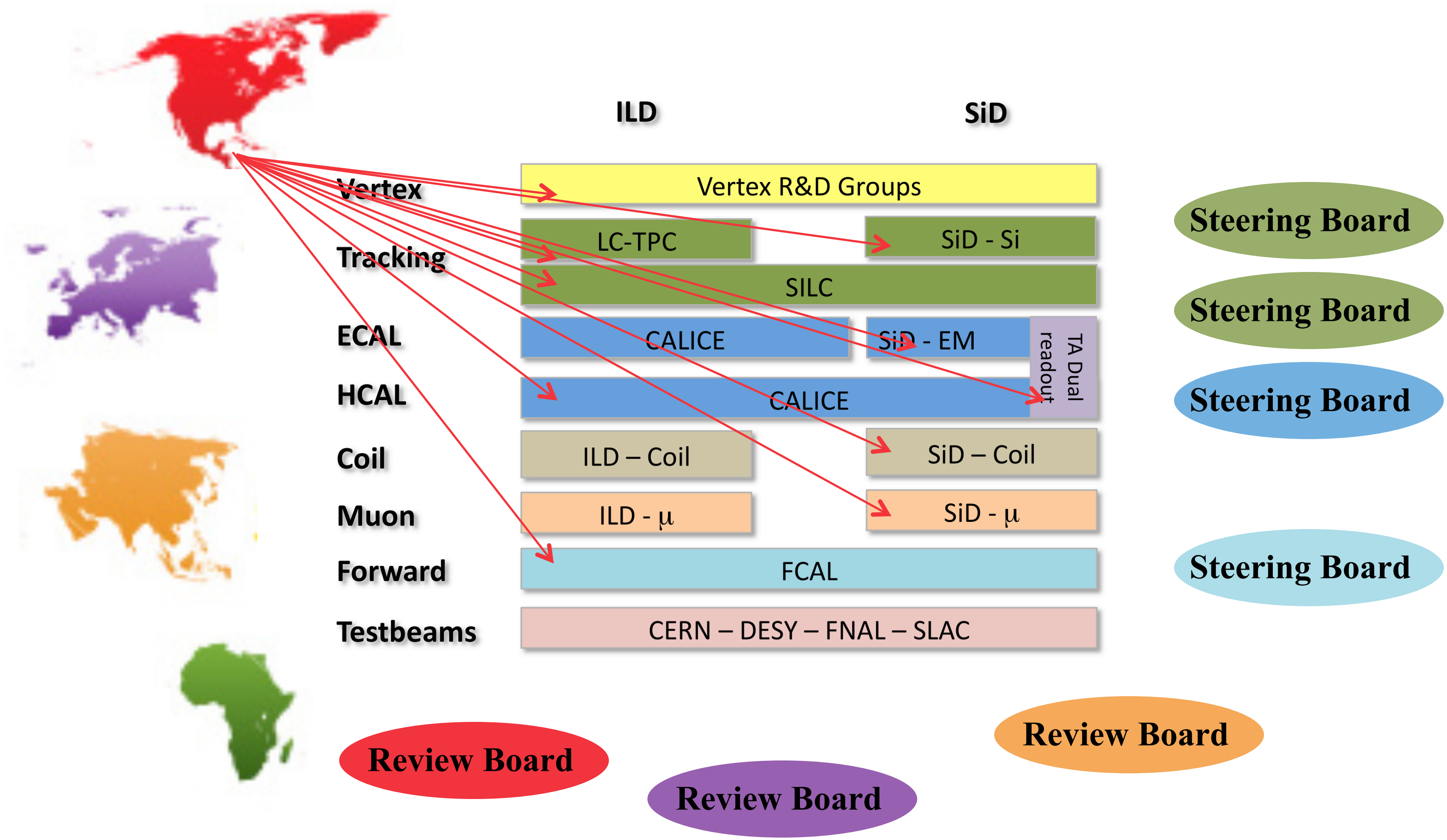
- **The matrix of detector R&D is quite convoluted**
  - **R&D for ILD mainly carried out within horizontal R&D collaborations**
  - **R&D for SiD mainly carried out by the concept**



- **Control held by R&D collaborations, but even that is very limited**

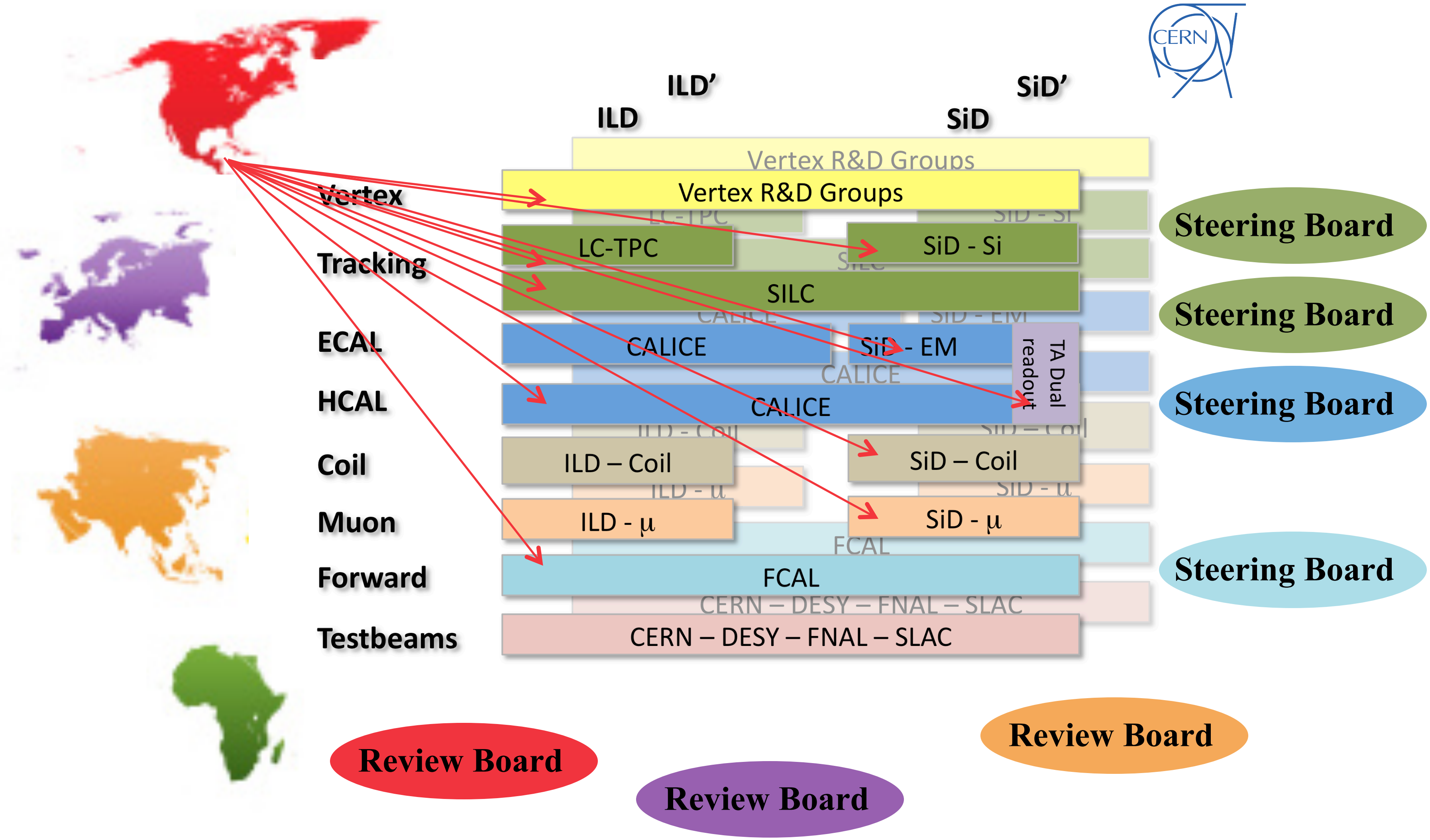
Detector R&D Organization

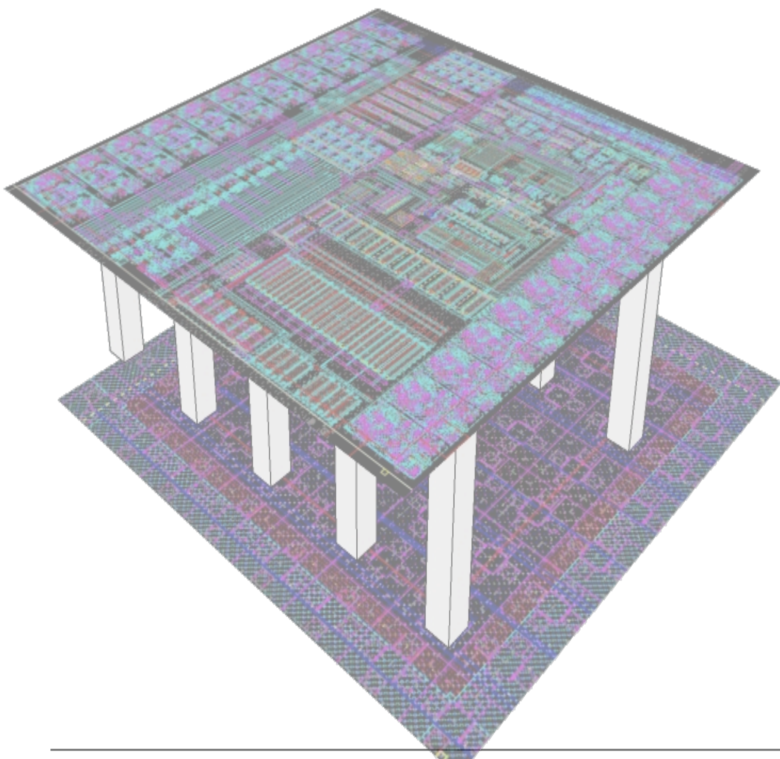
- **R&D based in many regions, many funding sources, many oversight bodies …**



Detector R&D Organization

- **R&D based in many regions, many funding sources, many oversight bodies … … It works !**





Vertex Detectors

Research Thrusts

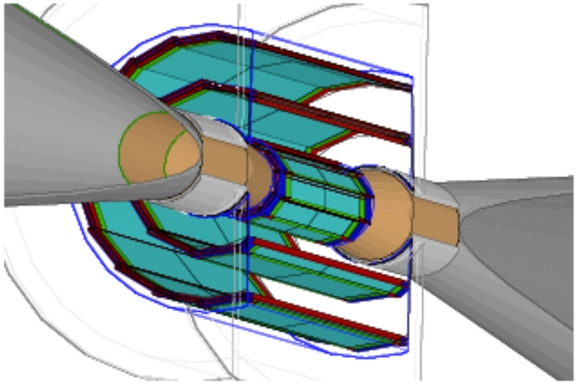
- Precision vertexing/tracking/imaging ideally requires detectors that have
  - zero mass: transparency of ~0.1% X_0
  - zero power: allow for air cooling (< 50 W)
  - zero dead zones
  - zero dead time
  - zero effective occupancy: integration over few bunches
  - zero noise susceptibility: EMI immune
  - 1/zero precision: spacepoint < 5μm,
    impact parameter $5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$)
  - 1/zero pattern recognition capability: many layers close to IP
  - Modest radiation hardness

- These aggressive set of goals and the physics need, has led to a wide range of R&D based on established and emerging technologies

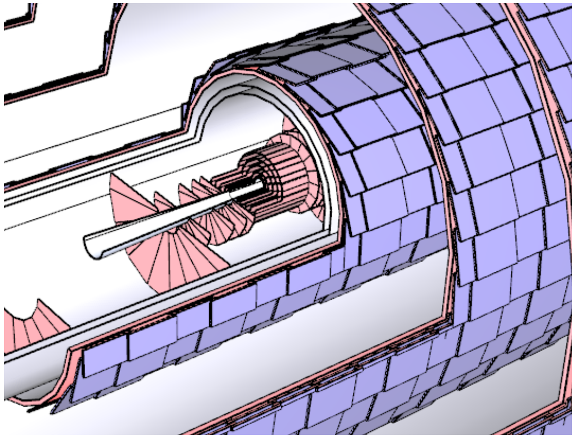
- No technology has established itself yet. It is expected that the experiments will choose the best technology that will meet their needs at the time of the technical design

Detector Design Options

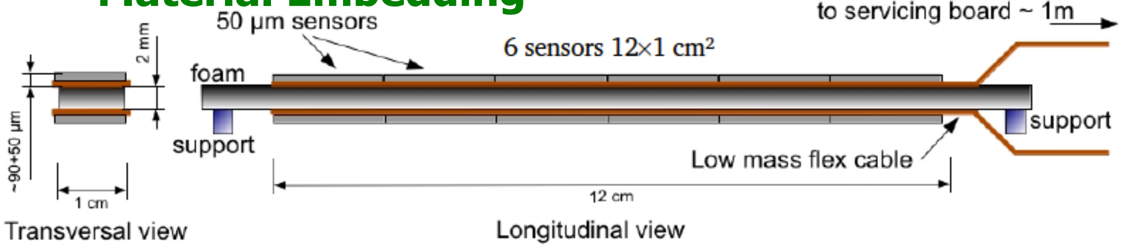
- **Long Barrel Configuration (ILD)**
  - Single geometry for all layers
  - Large charge sharing at small angles and larger occupancies
  - More mass on trajectories at small angle
  - Limited number of space points on particle trajectory at forward angles



- **Barrel and Disk Configuration (SiD)**
  - No precedent for disk geometry for pixel planes and associated services
  - Uniform angular coverage and response

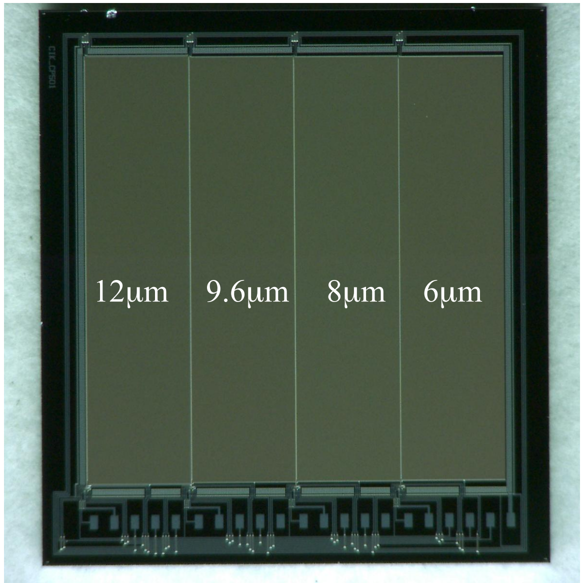


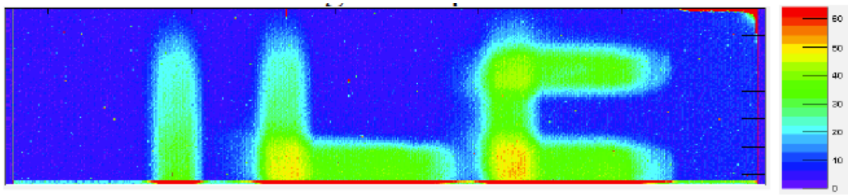
- **Ongoing studies on low-mass support**
  - PLUME: Pixelated Ladder with Ultralow Material Embedding

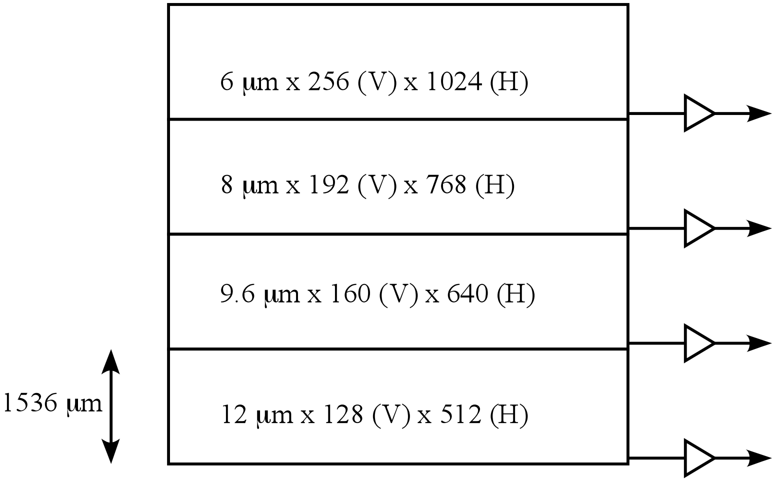


CCD Technology

- **R&D is focused on fine pixel CCD sensors (FPCCD) and readout ASICs**
- **Goal:**
  - **Pixel size : 5μm× 5μm**
  - **Total # modules: 6080**
  - **20,000×128 pixels/module → 10^{10} pixels**
  - **Full depleted, 15 μm thickness**
  - **Readout speed > 10Mpix/s**
  - **Readout noise < 50 e^- , Power < 100 W**
- **Currently produced: FPCCD #3**
  - **Pixel size: 12 – 6 μm**
  - **Sensitive thickness: 15 μm**
- **Tests being carried out:**
  - **Pixel size: 12μm×12μm**
  - **4 frames with 512×128 pix/frame**
- **Status**
  - **Readout speed limited to 1.5Mpix/s**

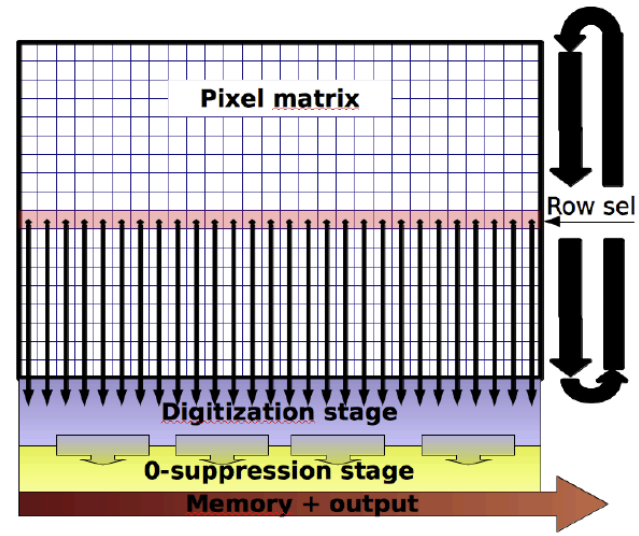


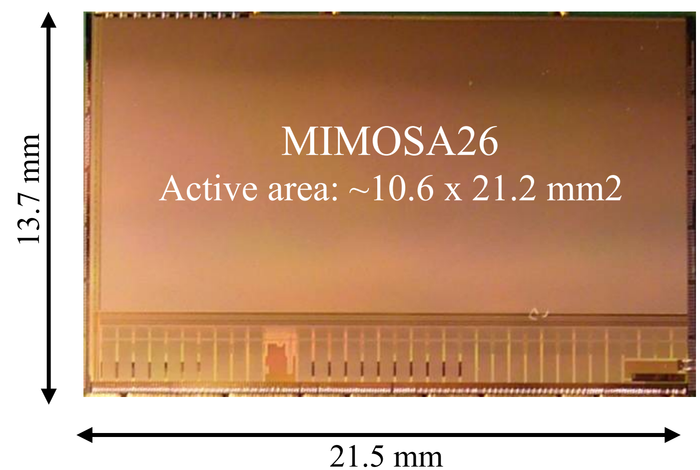




MAPS CMOS

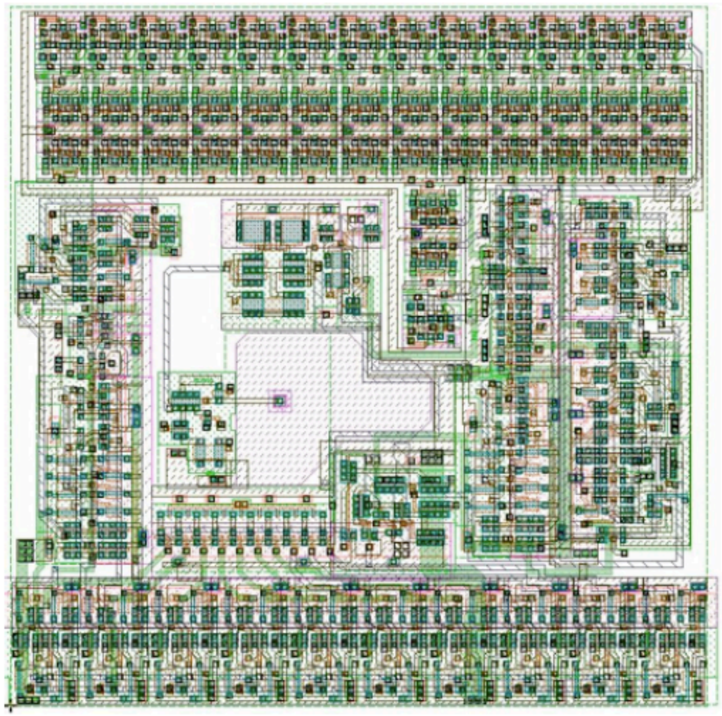
- **Strong Strasbourg group developing CMOS MAPS sensors**
- **Strategy for ILC (ILD)**
  - **Layer 1: spatial resolution**
    - Pixel pitch 16x16 μm^2, binary output
    - $\sigma \leq 3\ \mu m$, integration time $\leq 50\ \mu s$
  - **Layer 2: time resolution**
    - Pixel pitch 16x64-80 μm^2, binary output
    - $\sigma \sim O(5)\ \mu m$, integration time $\leq 10\ \mu s$
  - **Outer Layers: low power**
    - Pixel pitch 35x35 μm^2, 4-bits ADC output
    - 4 cm^2 of sensitive area
    - $\sigma \sim 4\ \mu m$, integration time $\leq 100\ \mu s$
- **Proof of principle: Mimosa 26**
  - **Used in EUDET telescope**
  - **Pixel array: 1152 x 576, 18.4 µm pitch**
  - **10 k images/s**
  - **Also used in STAR VXD upgrade and for CBM MVD**



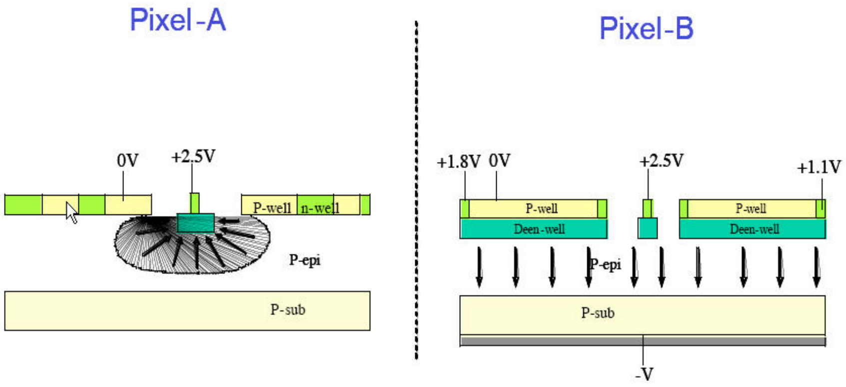


Chronopixel

- **Chronopixel design provides for single bunch-crossing time stamping**
  - **When signal exceeds threshold, time stamp provided by 14 bit bus is recorded into pixel memory, and memory pointer is advanced**
  - **Comparator threshold adjusted for all pixels**



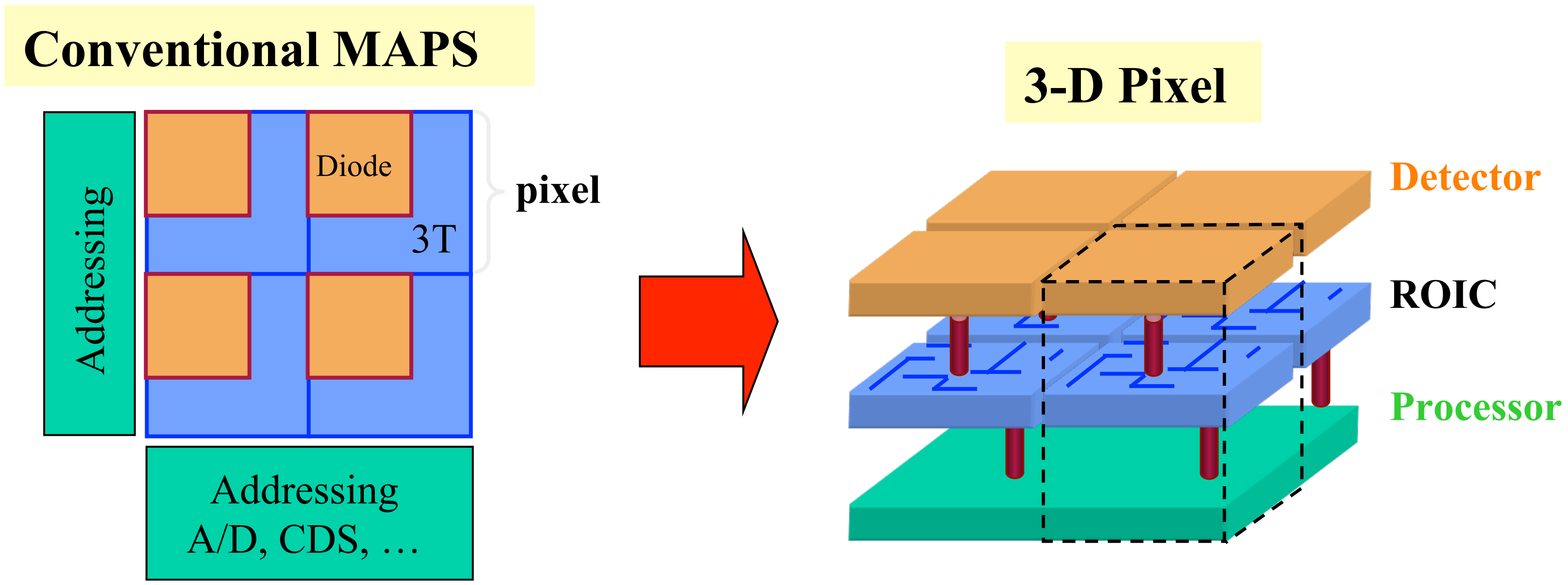
- **Current design**
  - **50x50 μm^2 pixels**
  - **Two pixel architectures**
    - Regular p/n-well design (A)
    - Deep n-well design (B)



- **Tests show that general concept works**
  - **Good sensitivity ($\mu V/e^-$) as designed**
  - **Sensors timestamp max. recording speed (7.27 MHz) is adequate**
  - **Noise figure meets specifications**

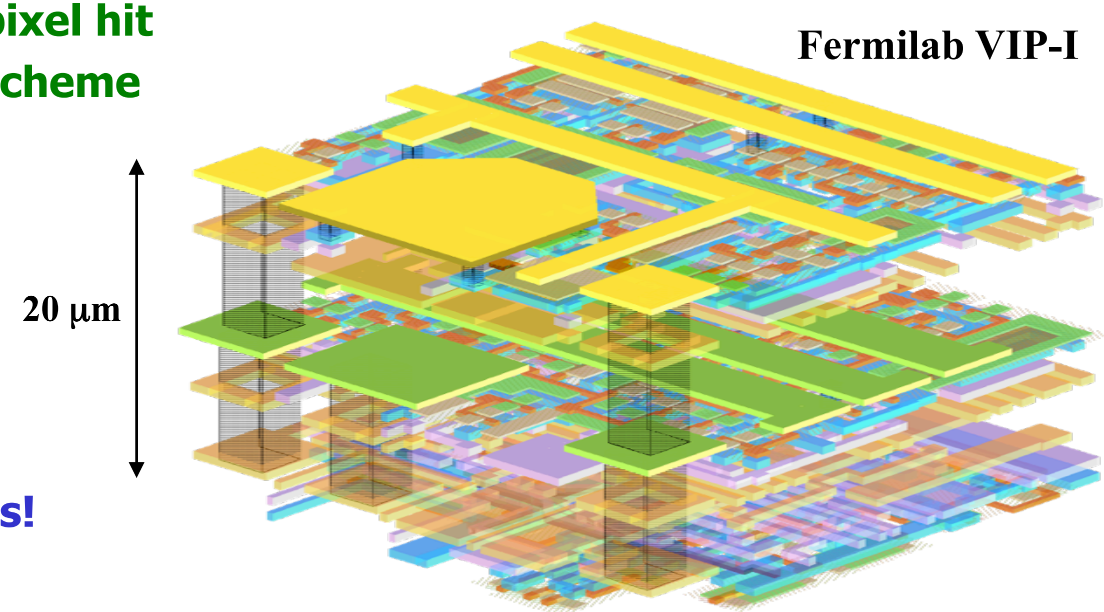
Vertical Integrated Circuits – 3D

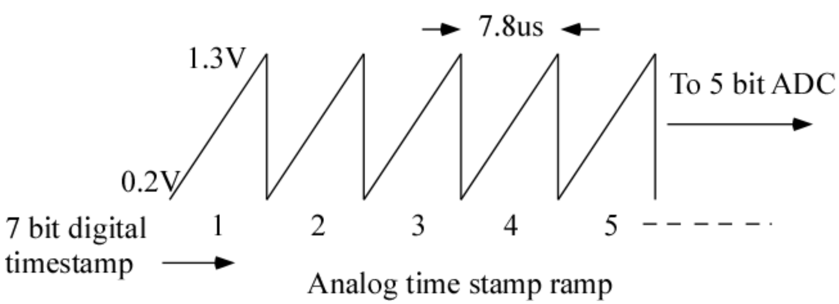
- **Vertical integration of thinned and bonded silicon tiers with vertical interconnects between the IC layers**
- **Technology driven by industry; offers potential for transformational new detectors**



VIP Chip

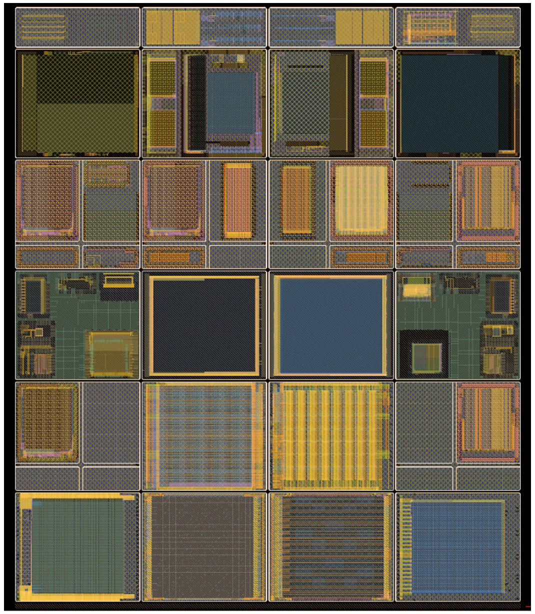
- **Fermilab designed Vertical Integrated Pixel (VIP) chip for ILC pixel detector, through MIT-LL process**
- **First chip was functional and a redesign was submitted VIP-2A, MIT-LL**
  - **Pixel array 48x48, 28x28 μm^2 pixels; design for 1000 x 1000 array**
  - **Provides analog and binary readout information**
  - **7-bit Time stamping of pixel hit**
  - **Token passing readout scheme**
  - **Sparse readout**
- **Chip divided into 3 tiers**
  - **~ 7 μm / tier**
- **New chip, VIP-2A Chip works!**





Time jitter and linearity better than 1%
Control over the full range to 1 ms

Fermilab 3D Multi-Project Run

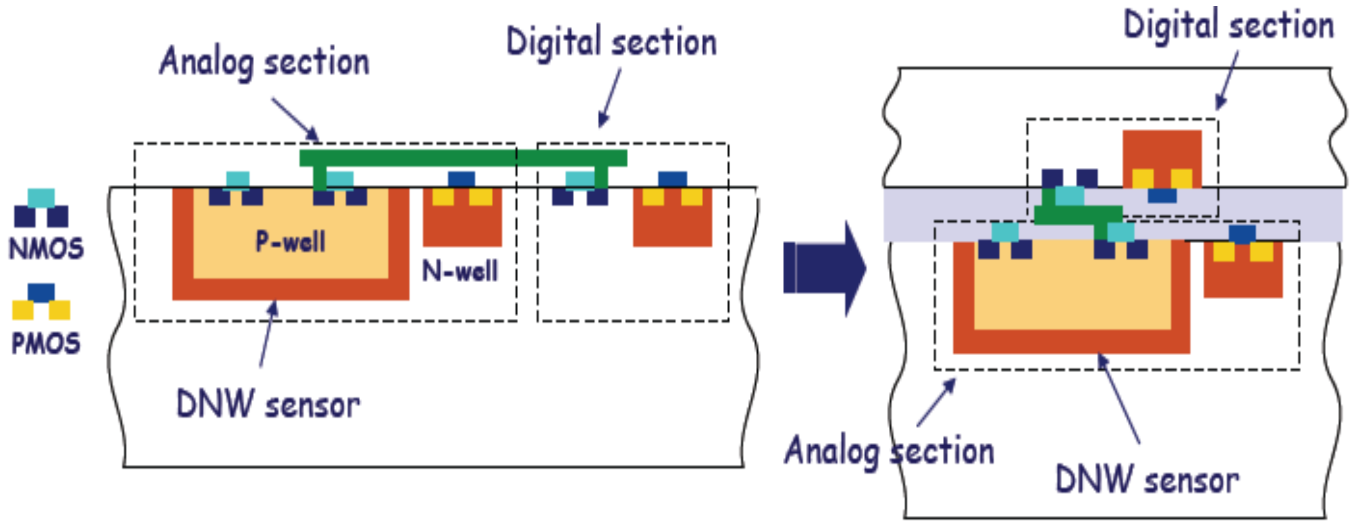


- **Fermilab formed a 3D consortium and hosted a 3D multi project run with Tezzaron**
  - **Two layers of electronics fabricated in the Chartered 130 nm process, useful reticule size is 16x24 mm**
  - **Wafers will be bonded face to face**
  - **Submission closed September 2009**
- **Frame divided into 12 sub-reticules for consortium members**
- **More than 25 two-tier designs (circuits and test devices)**

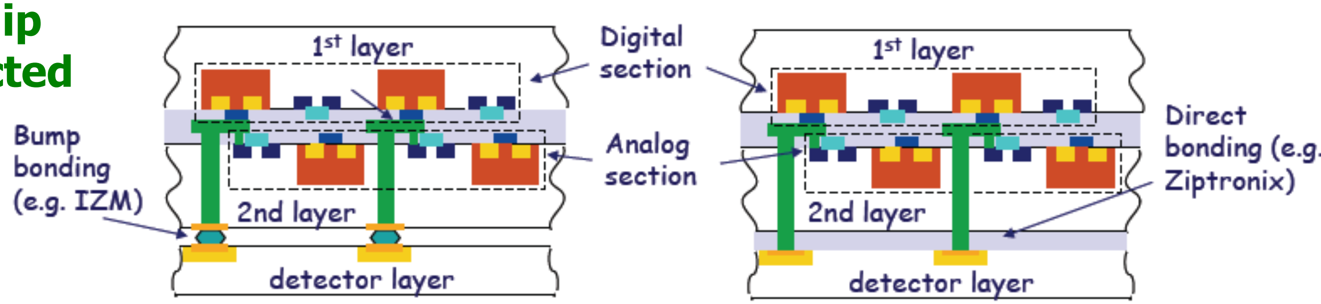
- **Unfortunately there have been a lot of growing pains with this process**
- **But, 2D wafers have been obtained and test well**
- **Full expectation that 3D bonded wafers will be available this year and testing can begin with sensor integration with 3D ICs.**

MAPS in 3D

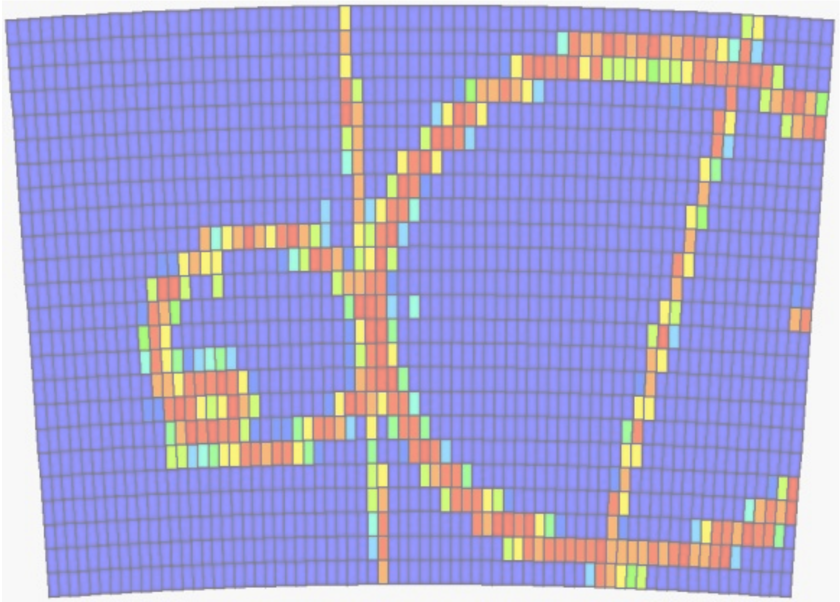
- **INFN has pilot project with Fermilab 3D Tezzaron project for 3D MAPS**



  - **Tier 1: sensor + analog FE + part of the discriminator**
  - **Tier 2: part of the discriminator, digital front-end and peripheral readout electronics**
- **Extend to CMOS FE integrated with high resistivity sensor**
  - **3D front-end chip (2 tiers) connected to HR sensor**



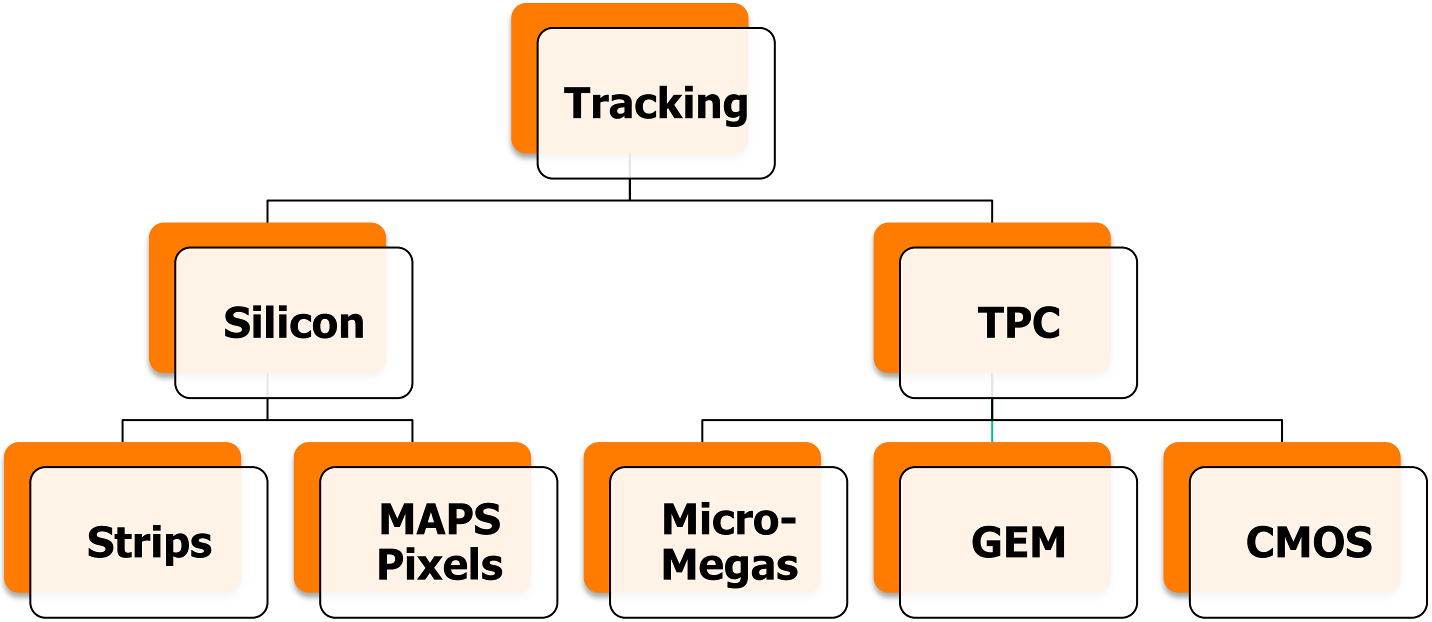
Tracking



Research Thrusts

- **Precision tracking to enable high resolution calorimetric measurements**
  - **Low mass**
  - **Unprecedented momentum resolution:** $\sigma(1/p_T) = 5 \times 10^{-5}\ (GeV^{-1})$
  - **Good double track separation: ~150 μm**
  - **Hermetic, uniform coverage**
  - **Excellent pattern recognition capability**

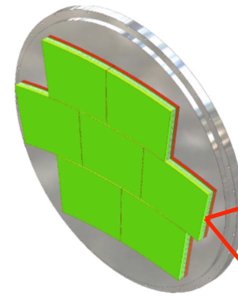
Technology Tree

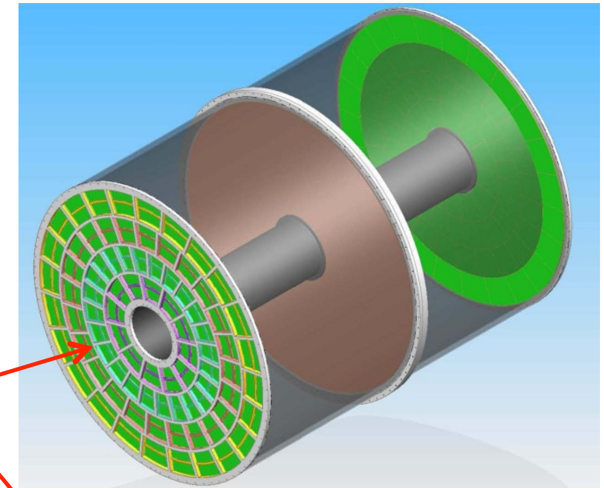


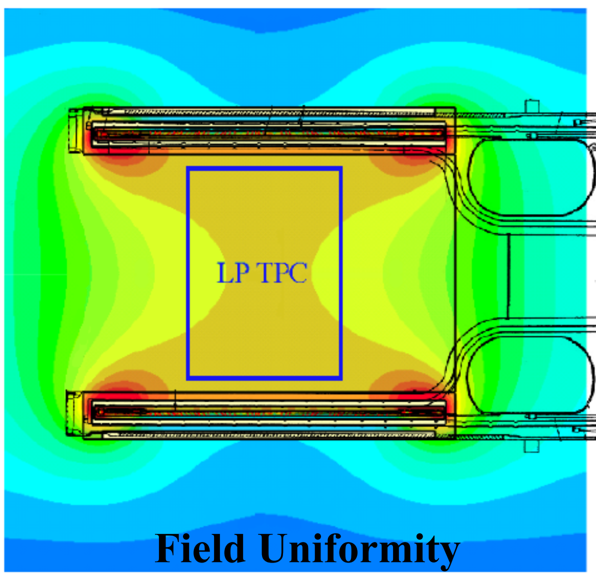
TPC R&D

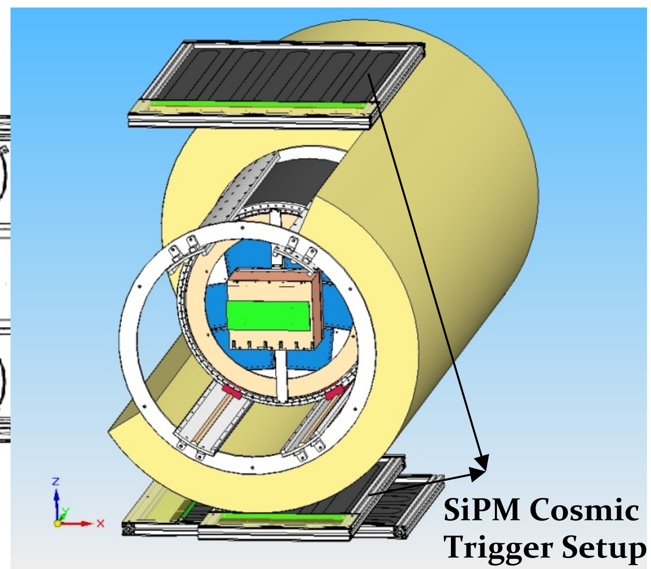
- **Focus of LC TPC collaboration is on the Large Prototype chamber (LP)**
- **Prototype inside PCMAG: superconducting solenoid, 1.2 T**
  - **Extensive series of tests carried out and being planned**

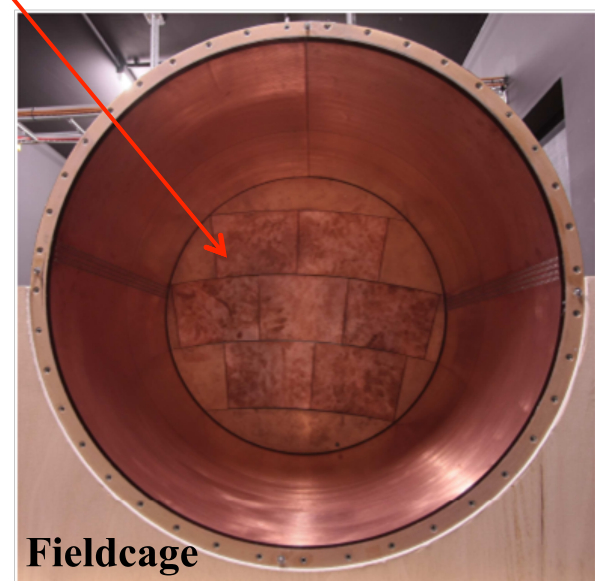
TPC endplate of LP





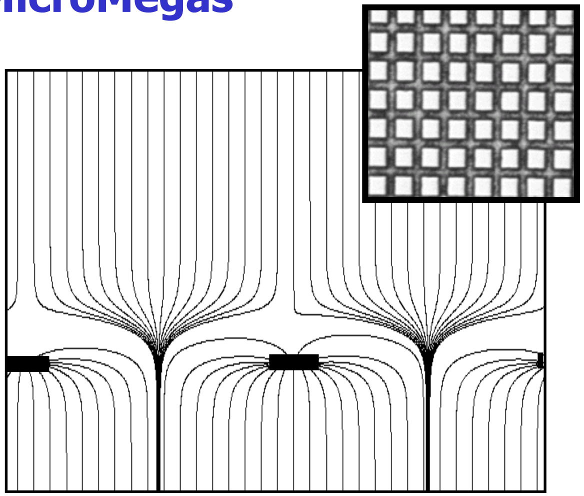




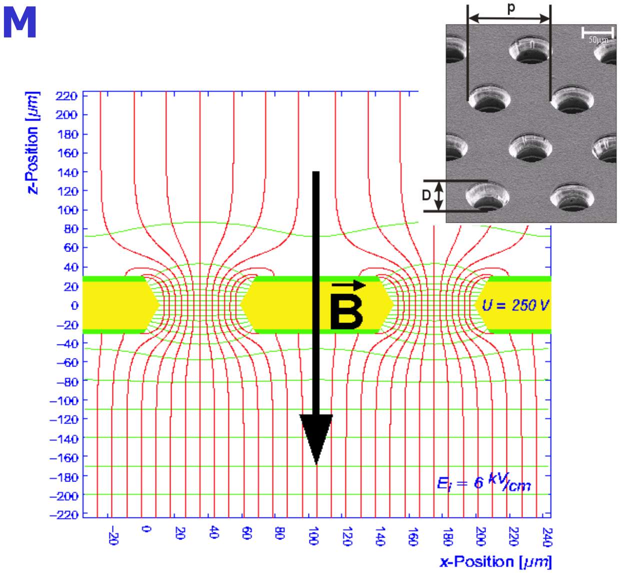


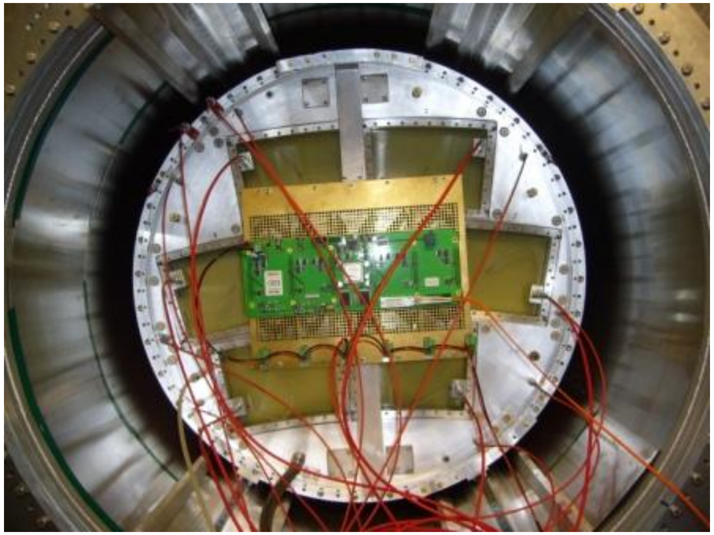
TPC R&D

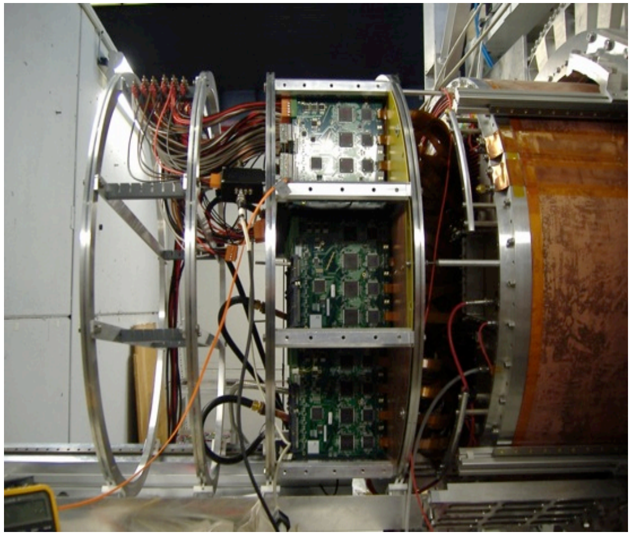
- **MicroMegas**



- **GEM**



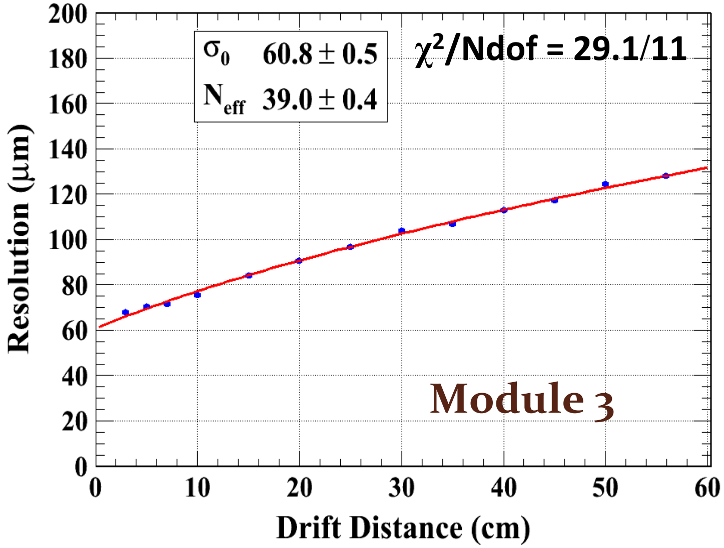




TPC R&D

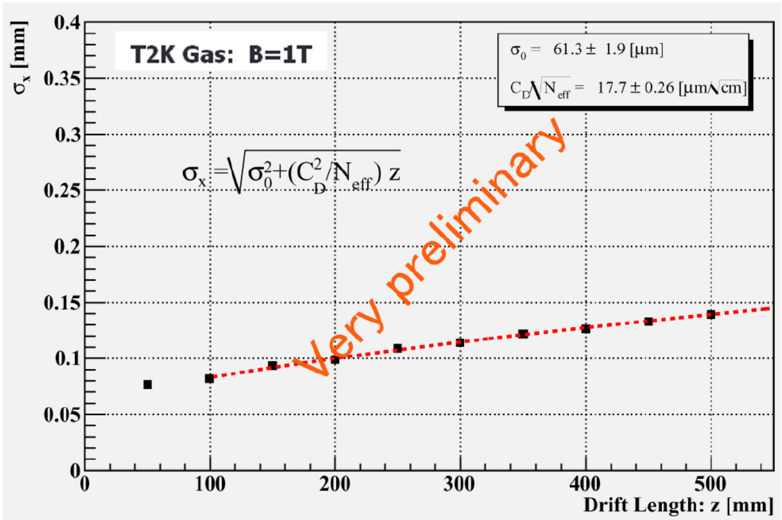
- **MicroMegas**

B=1 T C_d = 94.2 μm/√cm (Magboltz)



- **GEM**

B=1 T σ_o = 61.3 ± 1.9 μm



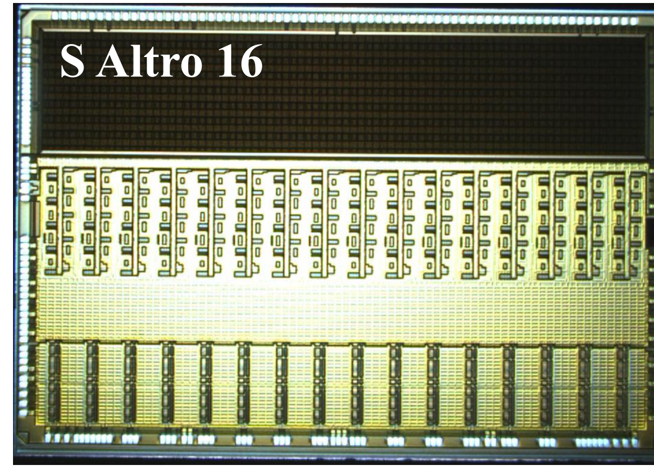
Resolution of 80 μm at 2m drift in B=3.5 T obtained!

- **Read out based on T2K AFTER electronics (Saclay)**
  - **April/May: new AFTER electronics**
  - **Late 2011 (B=0): 7 Micromegas modules with new AFTER electronics**

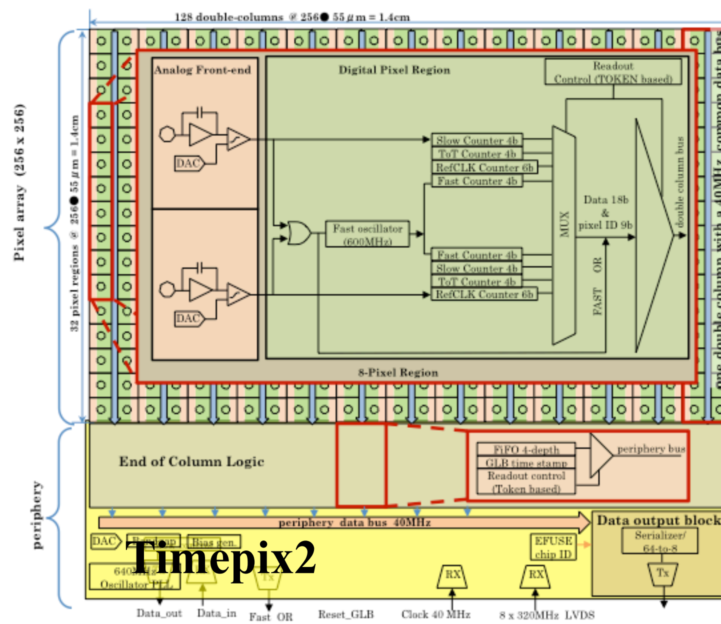
- **Read out based on ALTRO electronics (EUDET, Lund, CERN)**
  - **New ALTRO electronics developed**

TPC Readout

- S-Altro 16 chip: a 16 channel front-end chip; each channel comprises :
  - Low-noise progrmble pre-amp, shaper, ADC,
  - Digital Signal Processor
  - Max sampling frequency: 40MHz
  - Max readout frequency: 80MHz
  - IBM 130nm CMOS
- ASIC currently being tested

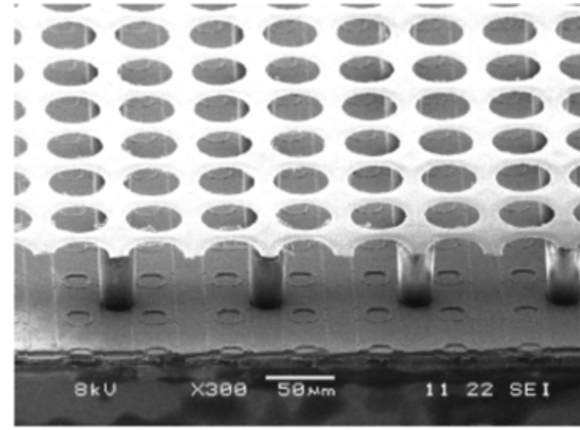


- TimePix2 for pixelized TPC readout; matrix layout: 256x256 pixels (Pixel size 55x55 µm)
  - Low minimum detectable charge:
    - < 500 e- minimum threshold
  - Time stamp and TOT simultaneously
    - Fast time-stamp ~1.5ns
    - Slow time-stamp ~ 25ns
  - TOT 8-10 bit
  - Sparse Readout

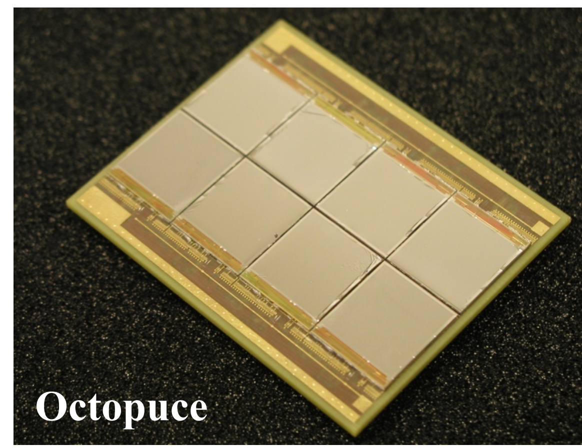


GridPix

- **Octopuce : 8 InGrids (integrated MicroMegas grids on TimePix chips) bonded on a LP panel**
  - **65 000 digital pixels (55 μm x 55 μm)**
  - **Time and Time over Threshold (TOT) measurement**
  - **Tests started inside 1T magnet**



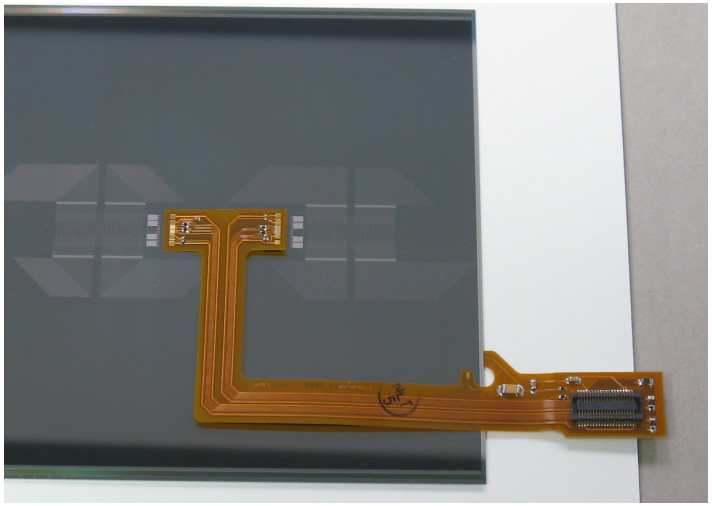
- **Activities:**
  - **Octopuce, maybe second Octopuce plane**
  - **DESY 3-GEM module beam test on LP**
  - **Asian 2-GEM module beam test**
  - **S-Altro16, new AFTER, TimePix2 chips**
  - **Continued engineering studies for new endplate (Cornell)**
  - **Preparation cooling and power pulsing tests**
  - **PCMAG upgrade in Aug'11-Jan'12**



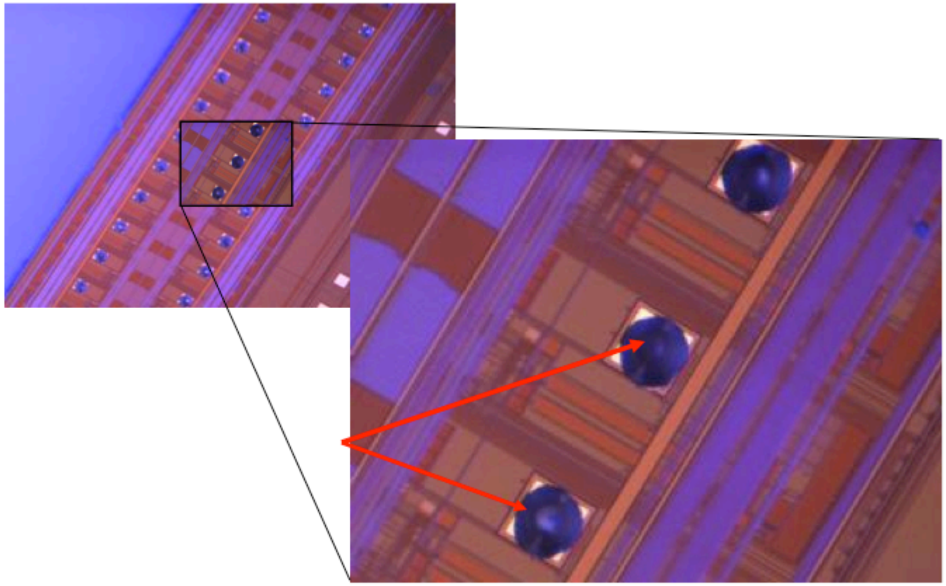
- **Vibrant R&D program**

Silicon Tracking

- **Silicon Strip modules with hybrid-less design**
  - **Two ASICs directly mounted on a sensor with 2k strips**
  - **Double-metal trace routing**
  - **Power and clock routed over sensor**



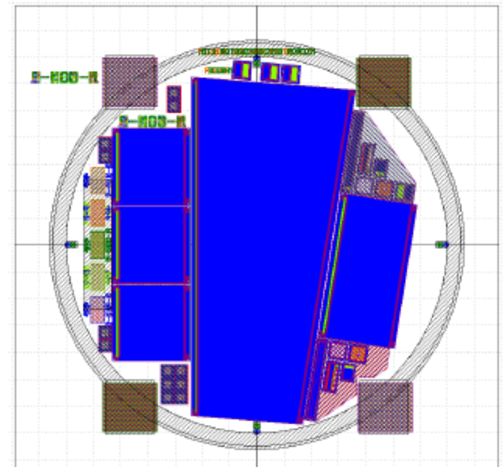
- **Component test of:**
  - **kPix: 1k-channel ASIC**
  - **Low-mass cable**
  - **Low-mass ASIC bonding**
    - Gold stud attachment using thermo-compression 300-350 C
    - 160 g/bump ok
  - **Low-mass module design**
  - **Induced readout noise**
  - **Power pulsing and induced Lorentz force in B-field**

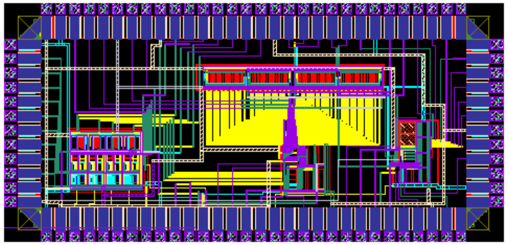


Silicon Tracking

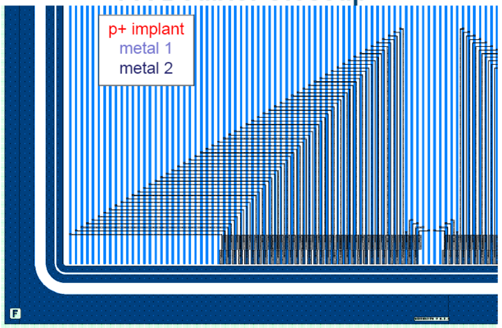
- **A very broad R&D program carried out within the SILC collaboration**
  - **Investigating double-sided silicon detectors for the forward regions**
  - **Development of a 128-channel silicon tracker readout chip: SiTRK**
  - **Silicon strip sensors with integrated pitch adapters**
  - **Edgeless sensors**
  - **…**

Trapezoidal sensor with test structures

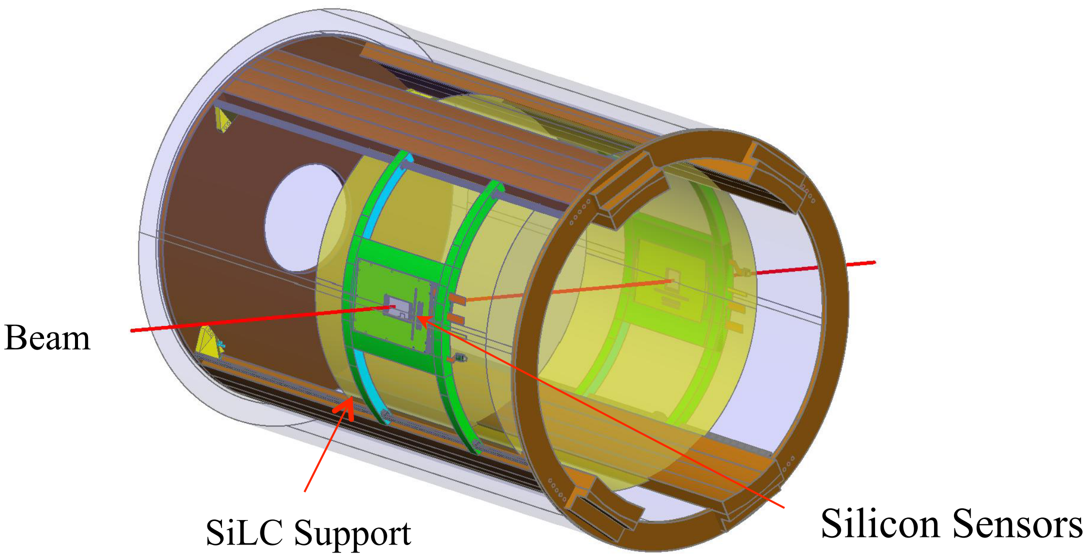


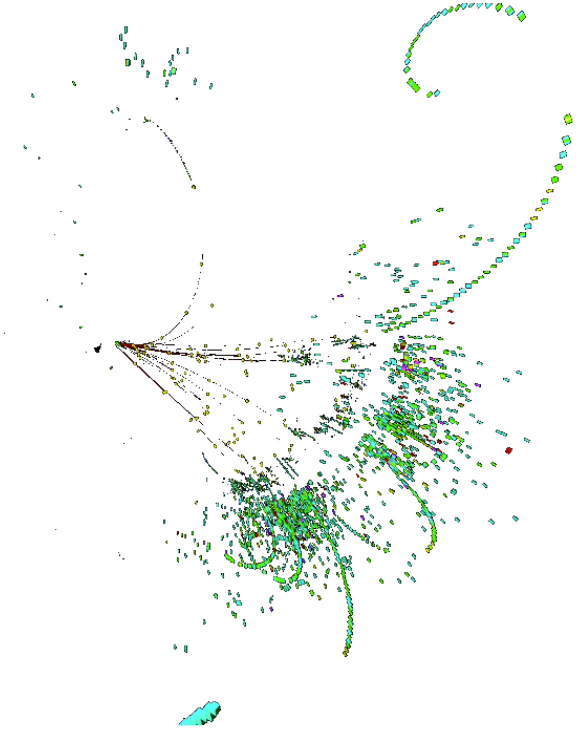


PA Double: Closeup



- **Joint test beam efforts with LC TPC collaboration**

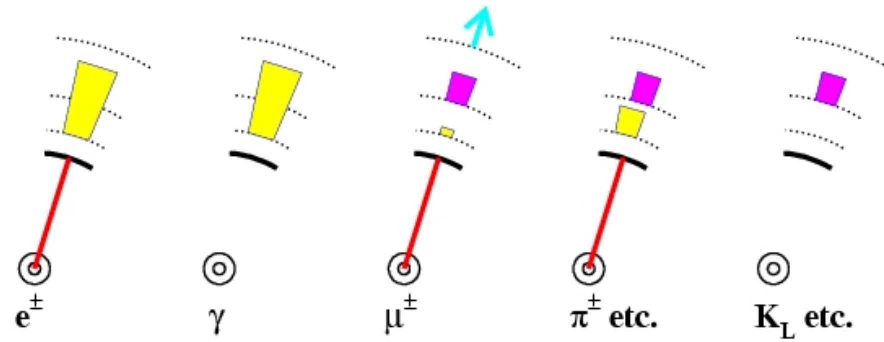




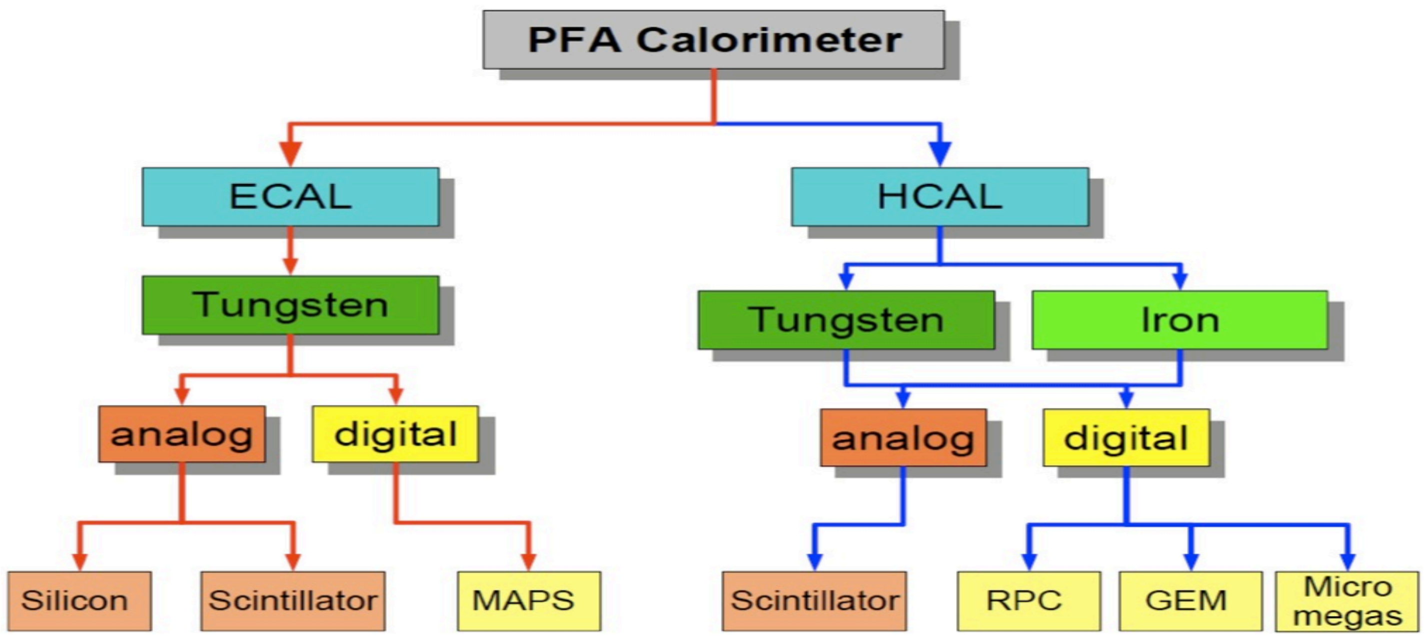
Calorimetry

Research Thrust

- **Calorimetry based on Particle Flow**
  - **Reduce the function of the calorimeter to measuring the energy of neutrals only**
  - **Key word is granularity !**

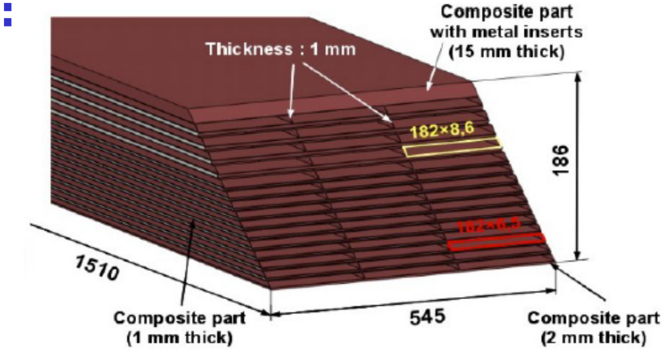


CALICE Technology Tree

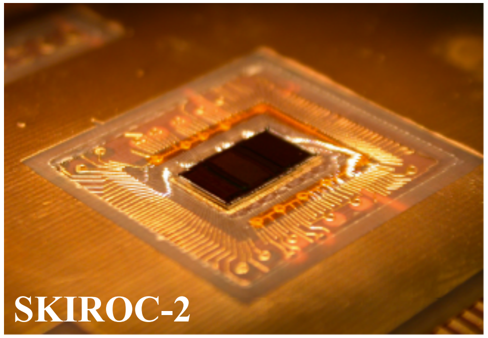


Silicon-W ECAL

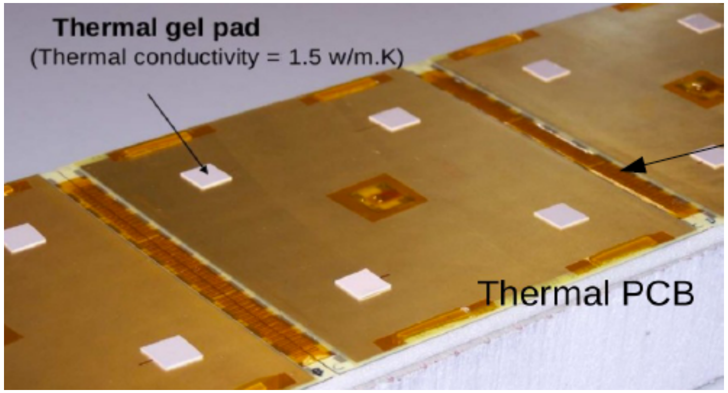
- **Studies with the Si-W physics prototype nearly completed**
- **Development of Technological Prototype started:**
  - **Final detector-like mechanical structure**
    - ~2/3 scale
  - **Final detector-like powering and services**



- **Assembly:**
  - **Final mechanical assembly underway**
    - ~40 silicon sensors purchased, ~10 ordered
  - **Readout with SKIROC-2 ASIC; critical step to move forward**
  - **PCB interconnections possibly with anisotropic conductive film (3M)**

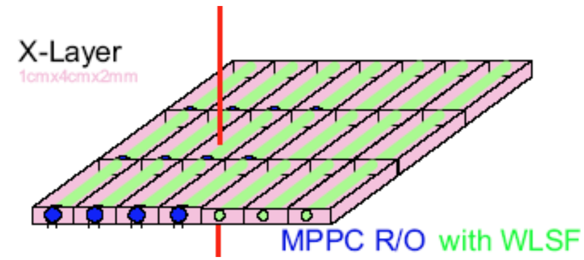


- **Schedule**
  - **Tests of first layer this year at DESY**
  - **Test with SKIROC2 chip, 2012**
  - **Multi-layer tests end 2012, 2013**

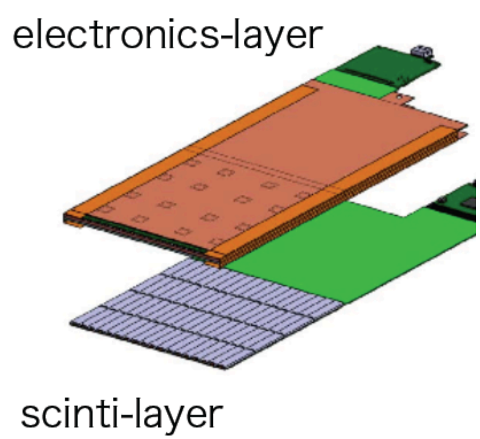


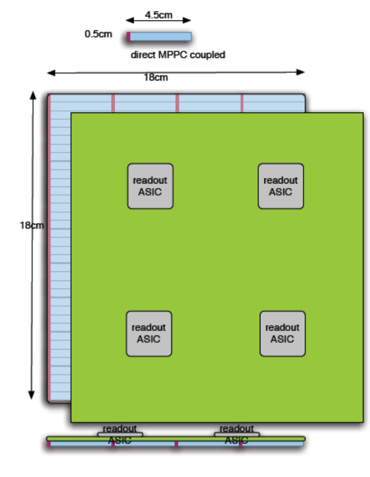
Scintillator ECAL

- **Design uses 5mm scintillator strips (x,y), 5mm wide with MPPC readout**

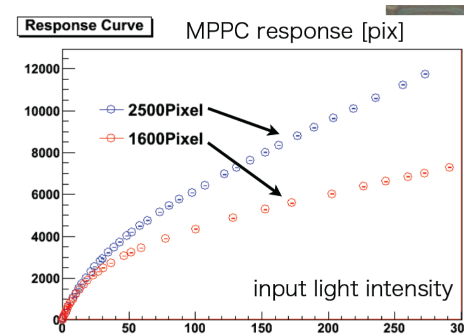


- **Current focus is on Layer Integration**
  Wonderful demonstration of CALICE leverage
  - **Uses EUDET absorber structure (French)**
  - **Uses AHCAL readout electronics (DESY)**





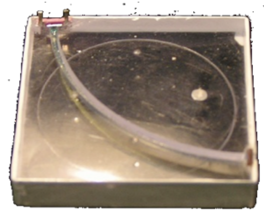
- **New Hamamatsu MPPC employed**
  - **1600 pixels/1x1 mm² → 2500 pixels/1x1mm²**
  - **Improve dynamic range and linearity**



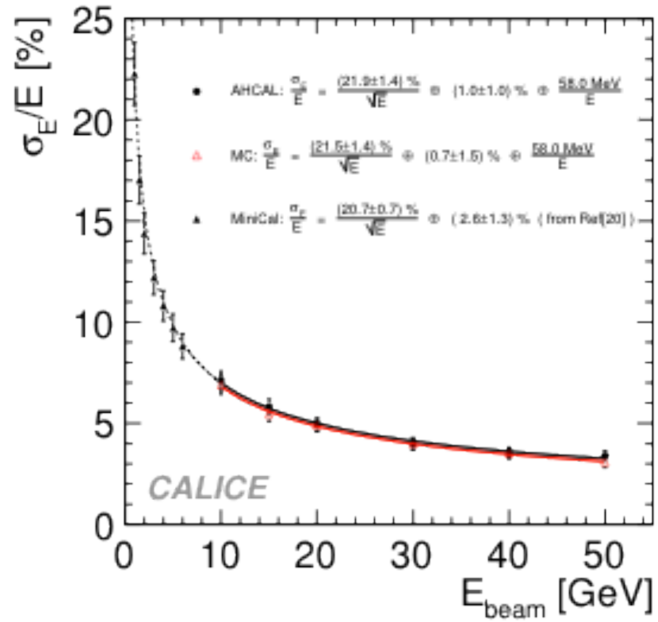
- **Schedule:**
  - **Complete construction in 2011**
  - **Test beam in 2012**

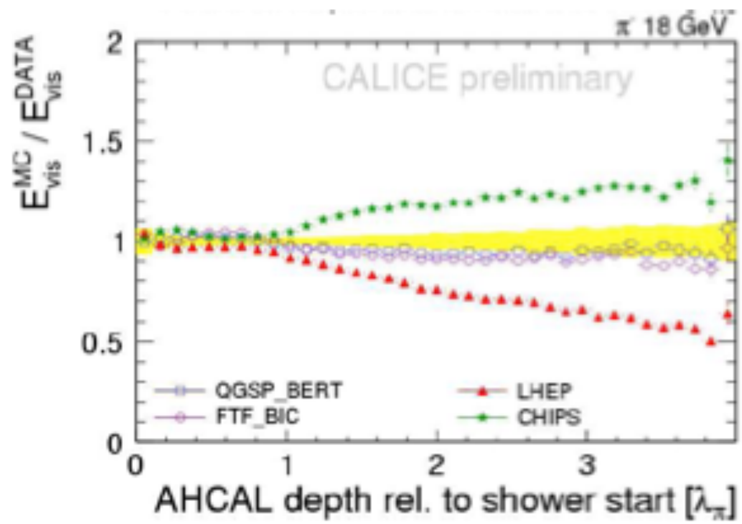
Analogue HCAL Analysis

- **Analogue HCAL is based in scintillator tiles, with MPPC readout**



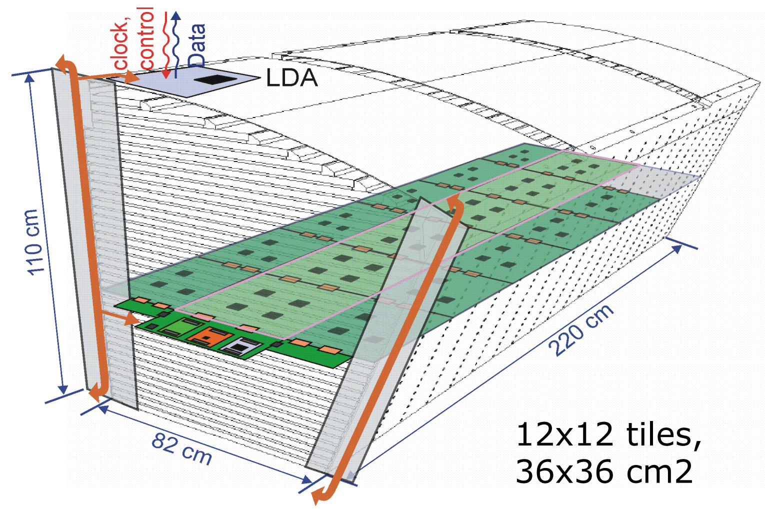
- **Physics prototype data from both CERN and Fermilab**
  - **Publications coming up**
  - **New results appearing**
- **Electromagnetic response measured; established detector modeling for hadronic analyses**
  - **Detailed test of Geant 4 hadron shower models, exploit fine granularity, capability to tag shower start point**
- **Scintillator planes now serving in W stack in CERN testbeam**



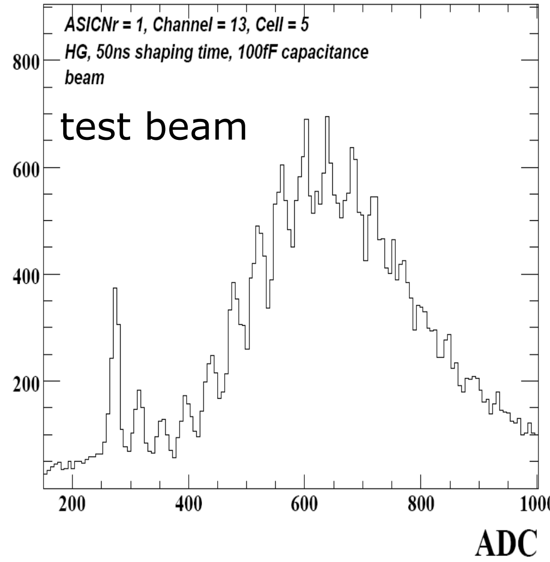


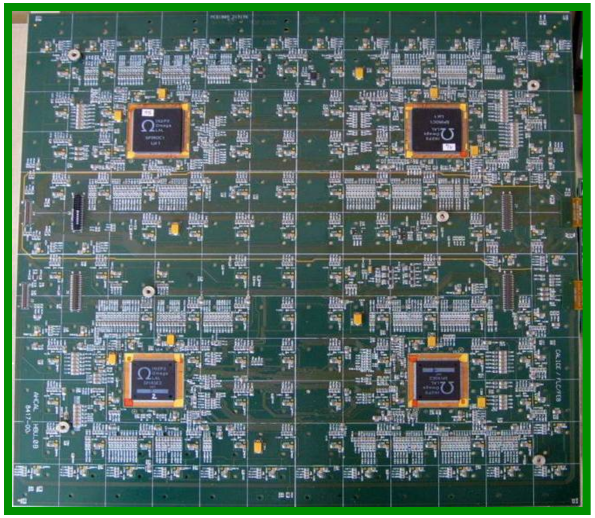
Analogue HCAL: Next Prototype

- **2nd generation prototype has integrated readout ASICs and LED system - and time measurement**
- **Prototype roadmap:**
  - **2010: 1st HBU**
  - **2011: full layer (2000 ch)**
  - **2012: several options**
    - instrument part of ILD wedge
    - tungsten HCAL



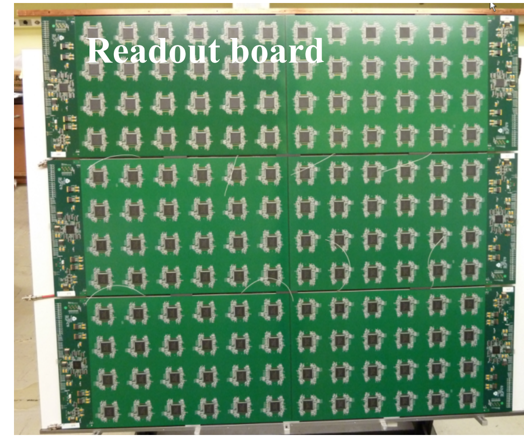
New full readout board

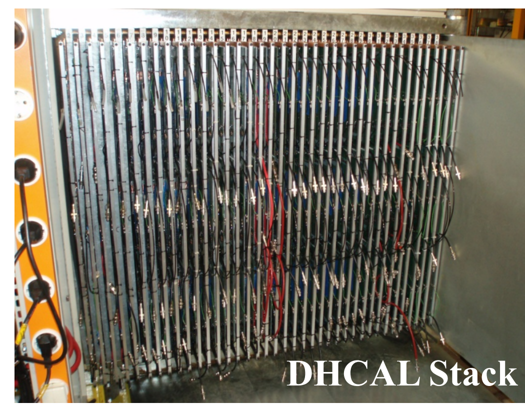




Digital HCAL: RPC

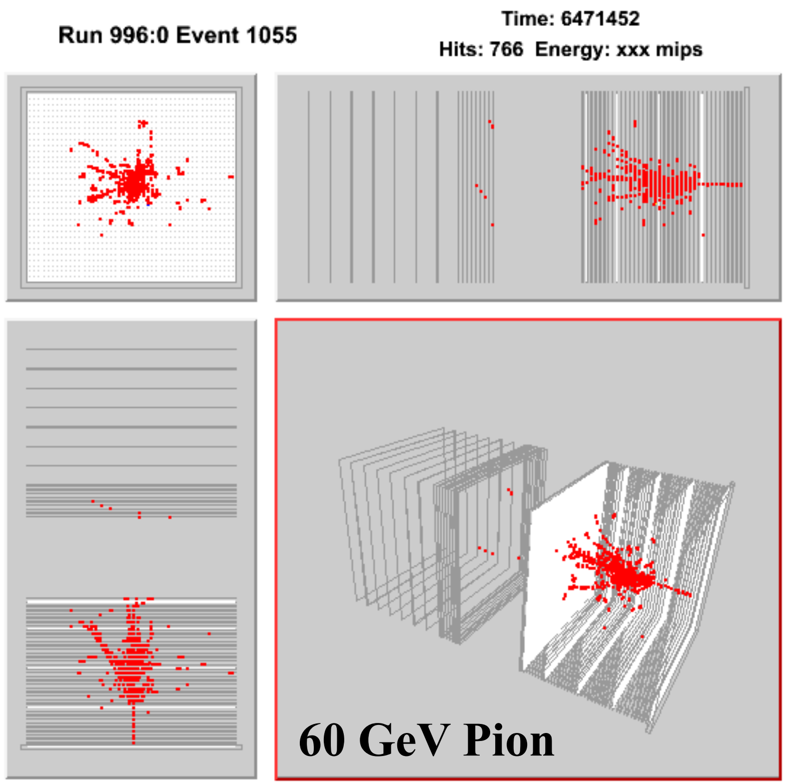
- **Digital hadron calorimetry based on glass RPCs with 1x1 cm^2 readout pads**
- **Large scale prototype built**
  - **350,000 channels DHCAL + 120,000 channels for Tail Catcher**
    - 10,000 DCAL III ASICs
    - 205 RPCs, 337 Readout boards
    - Low Voltage (384 channels)
    - High Voltage (64 channels)

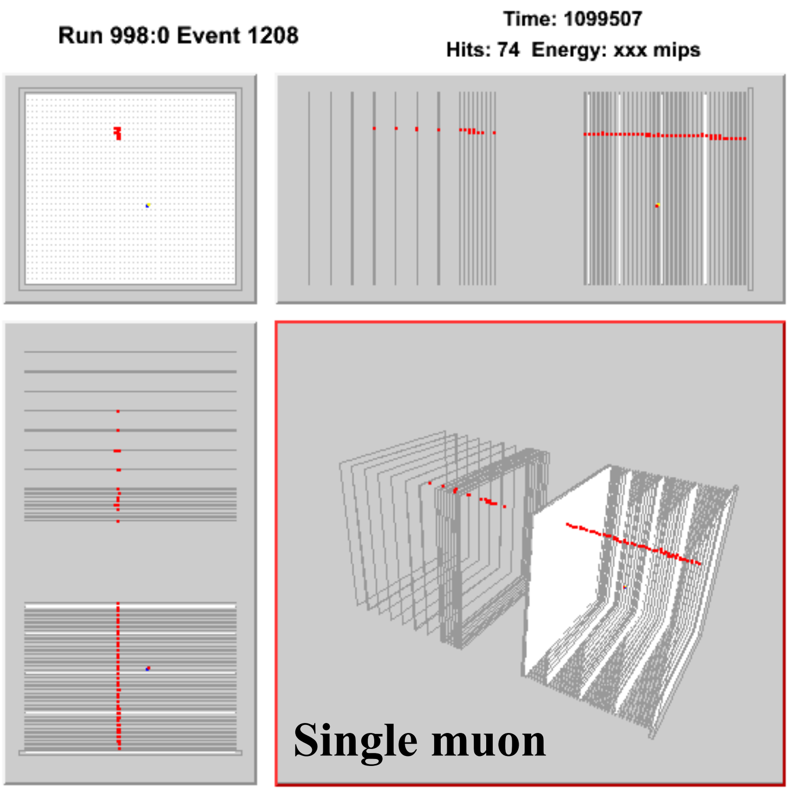




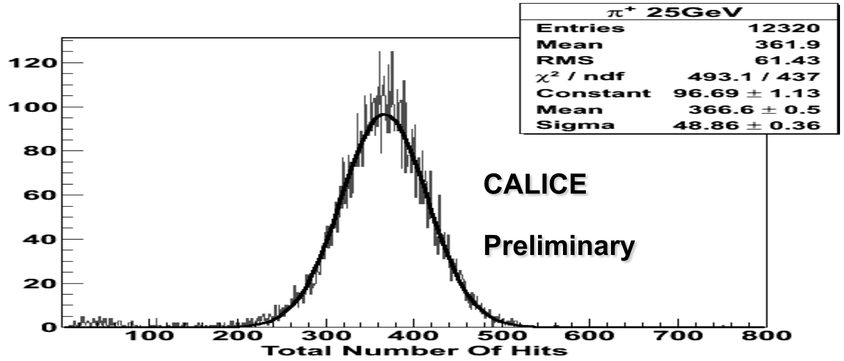
- **Currently still taking data at Fermilab**
- **Schedule**
  - **April 2011: Combined with the CALICE Silicon-W ECAL**
  - **Fall: DHCAL with W plates (?)**

Digital HCAL: RPC



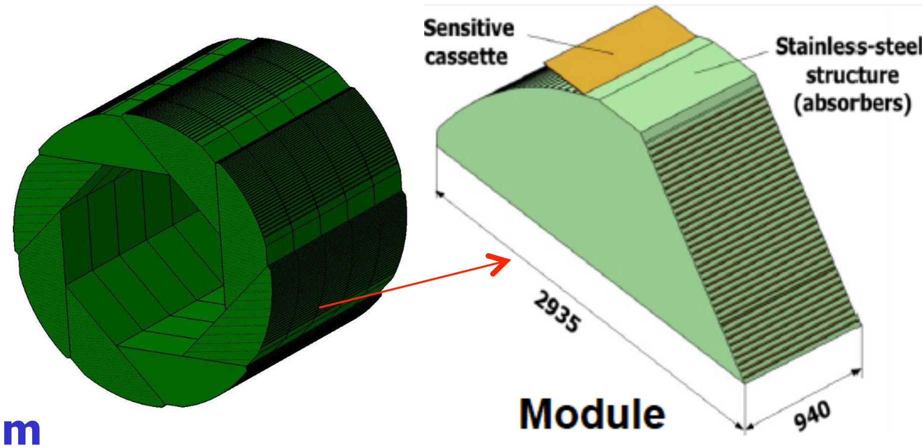


- **The concept of a DHCAL with RPCs is close to being validated**

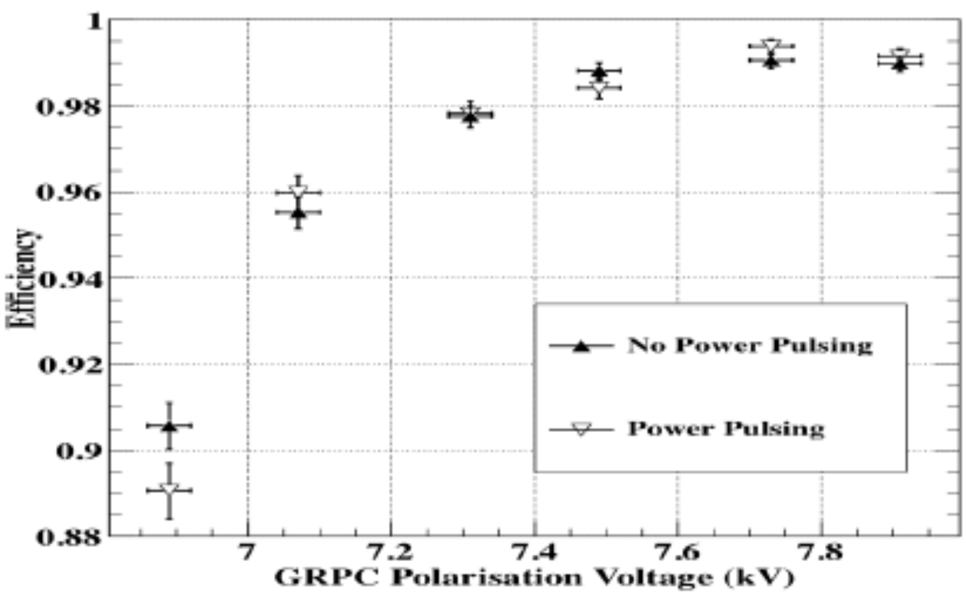


Semi-Digital HCAL: RPC

- **A technological prototype is being built for the SDHCAL**
  - **48 layers, 2 cm absorber and 0.6 cm thick glass RPC**
  - **Depth 6λ**
  - **1x1 cm² pads, 442,368 channels**



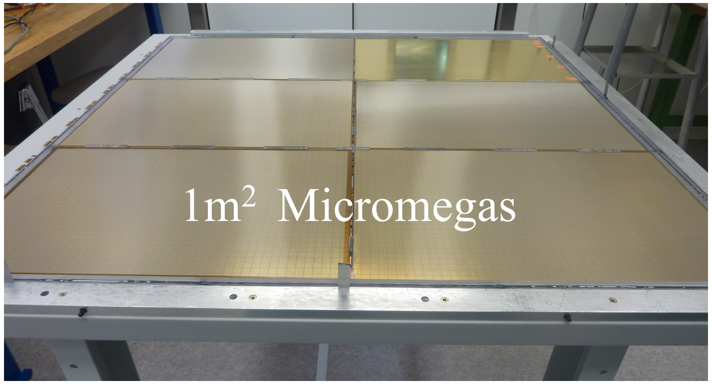
- **Two cassettes tested in CERN testbeam with and without power pulsing**

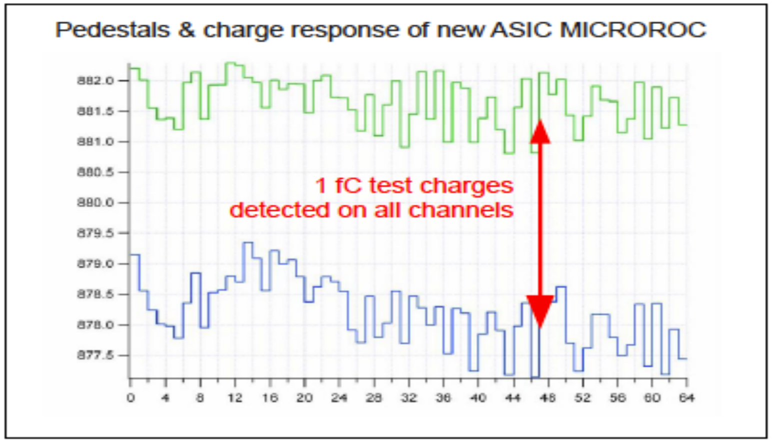


Digital HCAL

MicroMegas

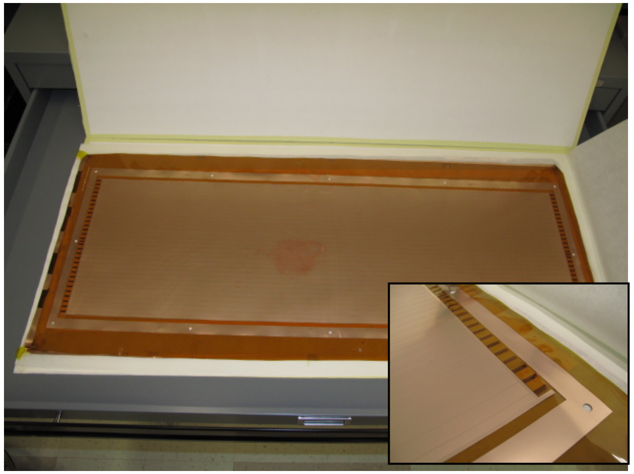
- **Design of 48x32cm² PCB equipped with ASIC, pads and mesh**
- **1 m² chamber with dead zone < 2%**
- **Deploy new ASIC: MICROROC**

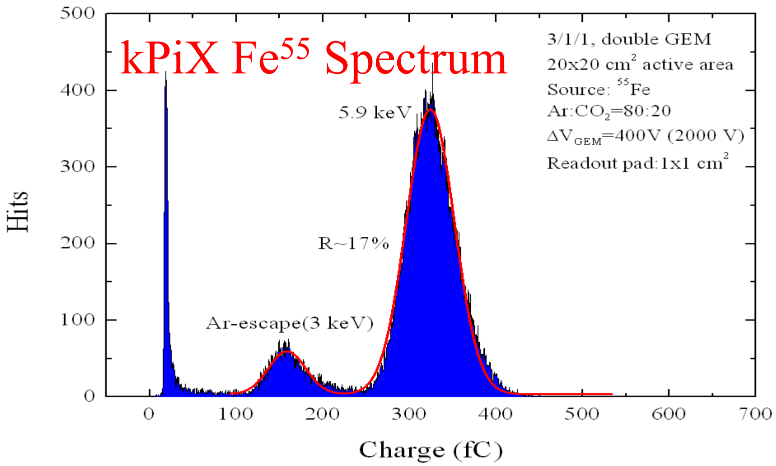


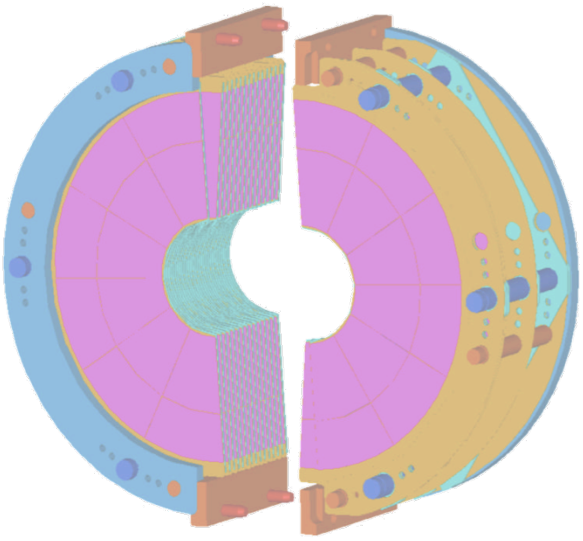


GEM

- **Design of 1m² GEM foils**
- **Readout with kPiX and DCAL ASIC**

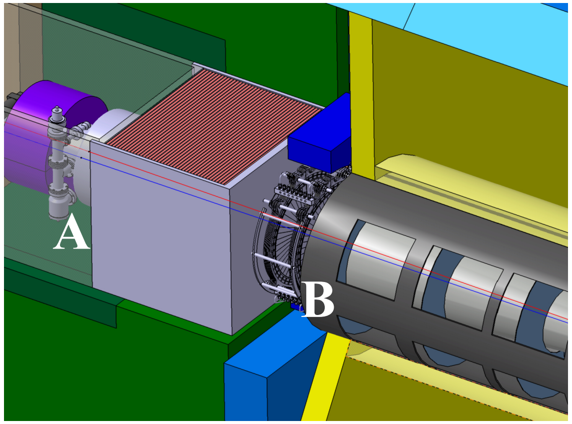




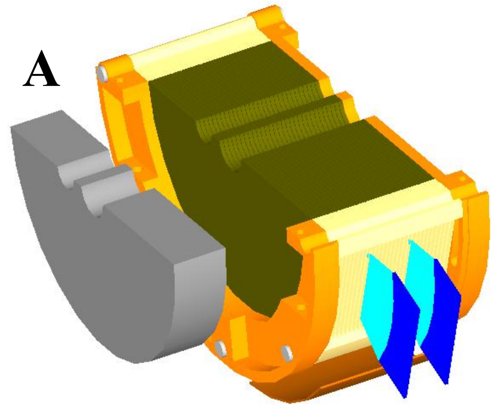


Forward Calorimetry

Forward Instrumentation

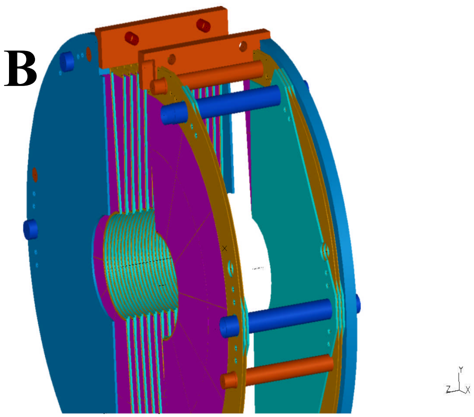


A



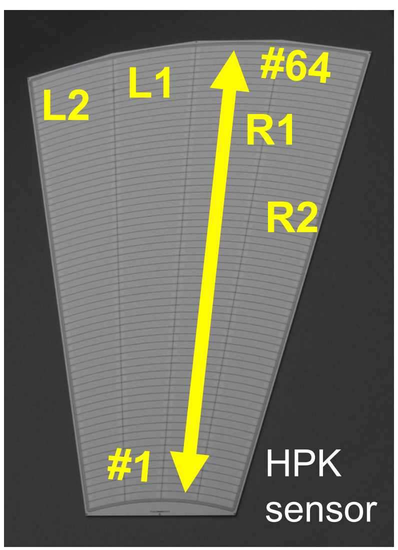
Beamcal + pair monitor

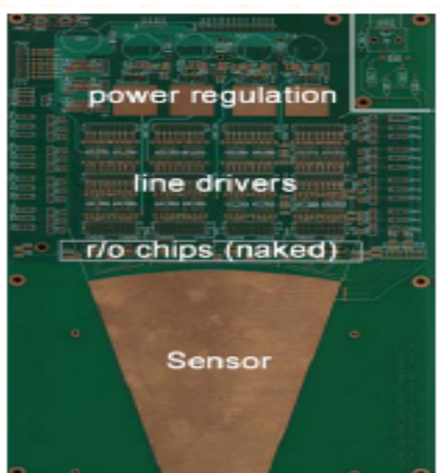
B

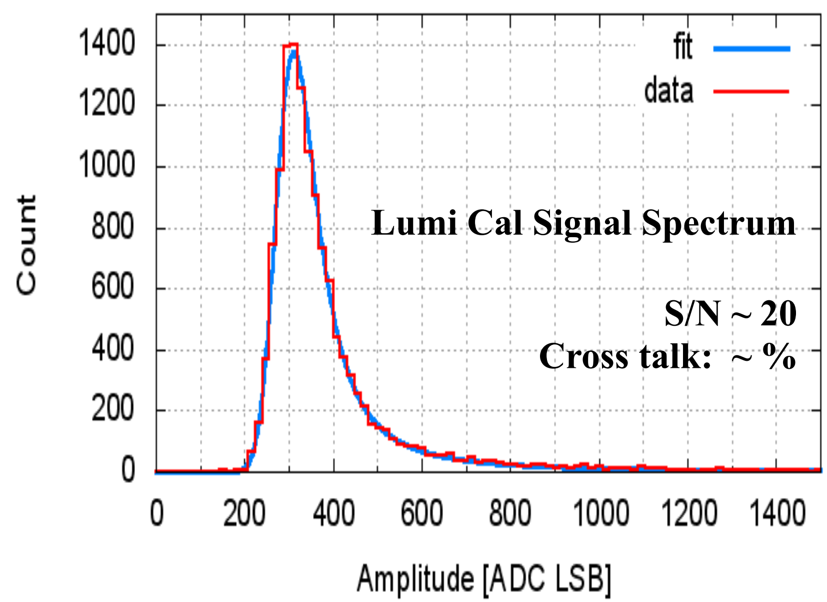


Luminosity monitor

- **Beam test with 4 GeV electrons at DESY**

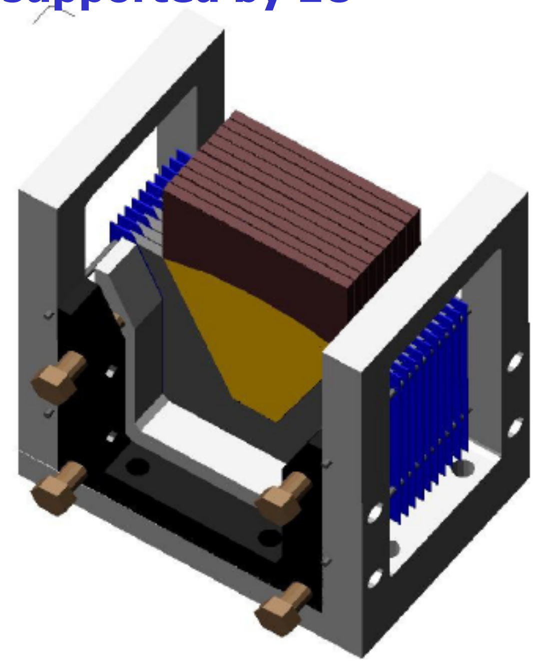




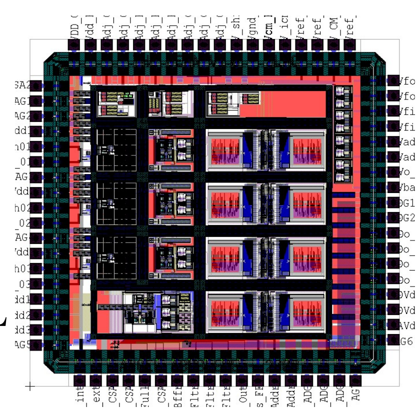


FCAL Prototype

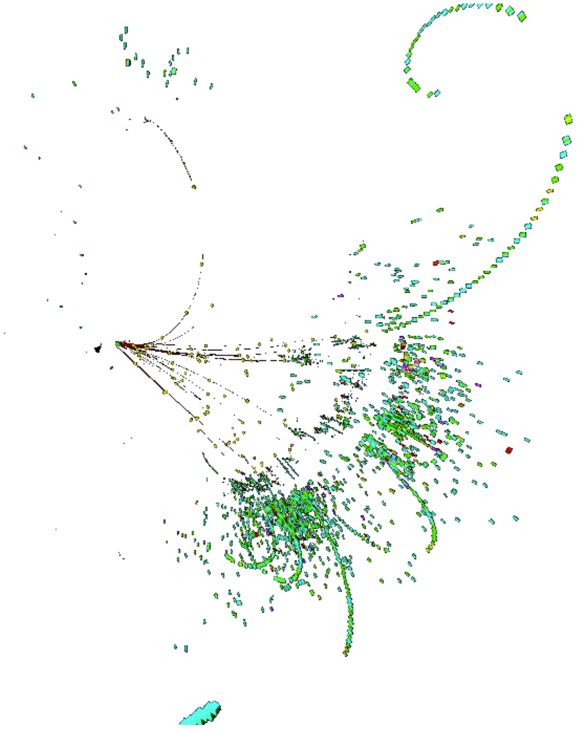
- **Collaboration preparing for a prototype calorimeter, supported by EU through AIDA program**
  - **Flexible, high precision tungsten structure**
  - **Fast FE Readout**
  - **Innovative connectivity scheme**
  - **Position control devices**



- **Read out employs kPix ASIC**
  - **Adapted to FCAL with fast feedback system**
  - **72 channels**
- **Exploits common European infrastructure**
  - **Power pulsing**
  - **Data acquisition**
  - **Tracking in front of the calorimeter**



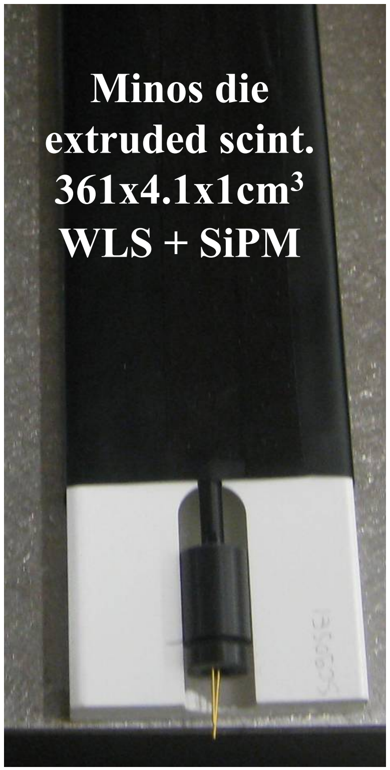
FCAL kPix



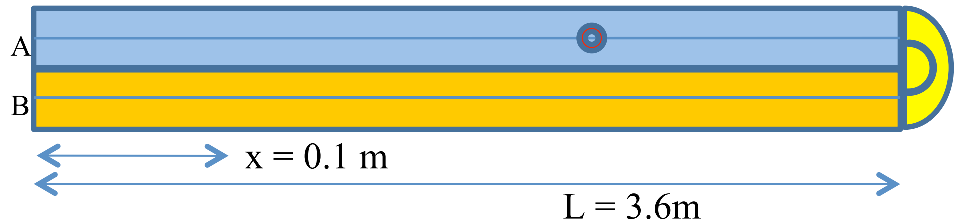
Muons

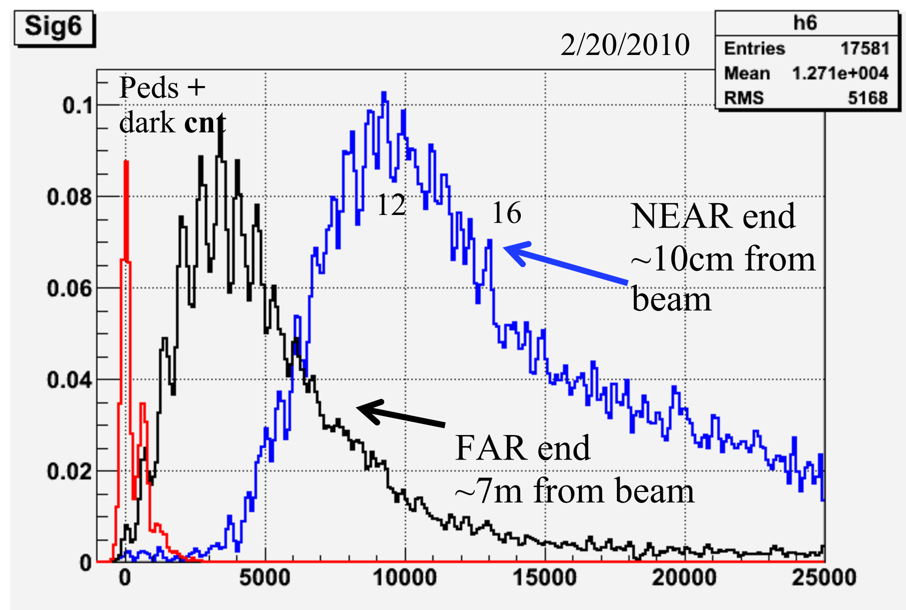
Muon Detectors

- **Double scintillator strip, read out with SiPM with integrated wave form digitizer (212 MHz) studied as muon detector in Fermilab test beam**



  - **Next steps: 16, 32, then 64 strips in four stations to test:**



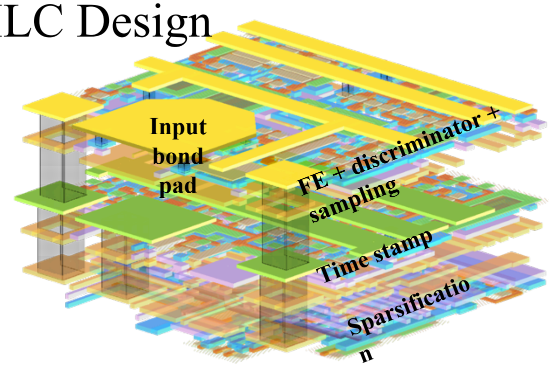


Show me !

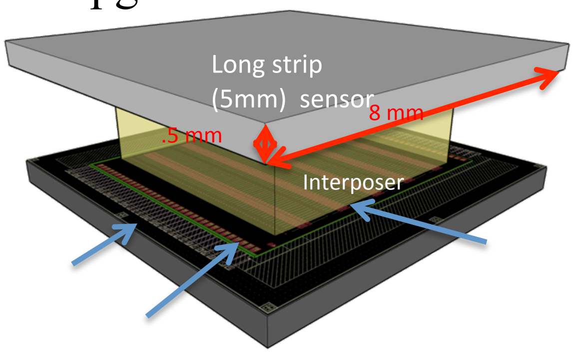
Benefits of ILC Detector Program

- **The development of new technologies and the implementation in prototype detectors has been very beneficial to the community at large**
  - **3D Silicon**

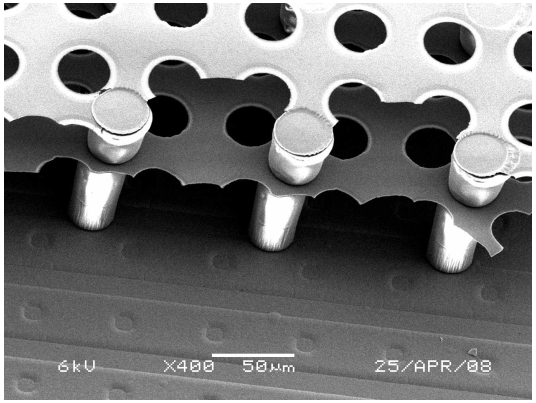
ILC Design

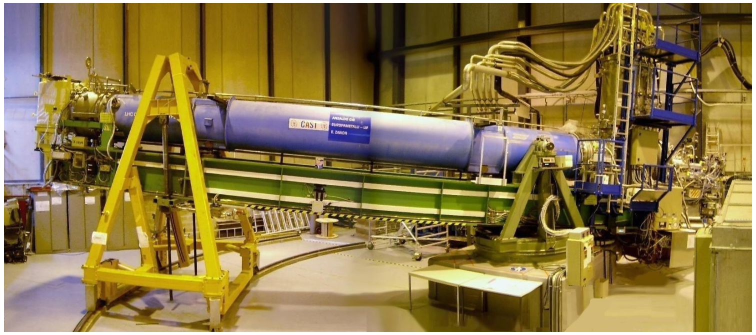


LHC Upgrade



  - **INGRID technology**

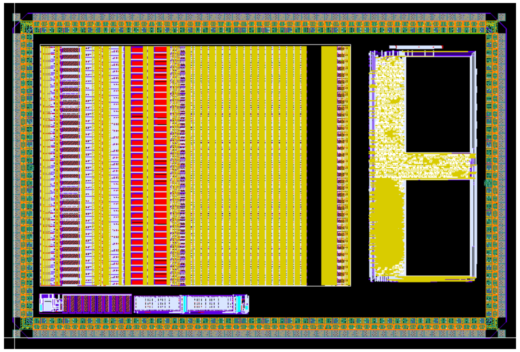




CAST

Benefits of ILC Detector Program

– **Readout Chip for SiPM Analog Hadron Calorimeter: SPIROC**

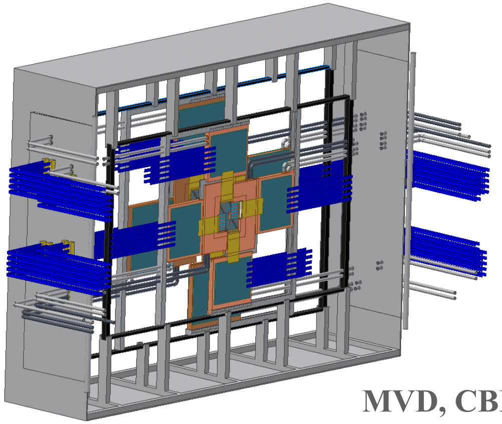


SPIROC

3000 chips deployed in
PEBS balloon experiment

– **Mimosa Pixel Array**

Pixel matrix: 1152 x 576
18.4 μm pitch, 10 k images/s

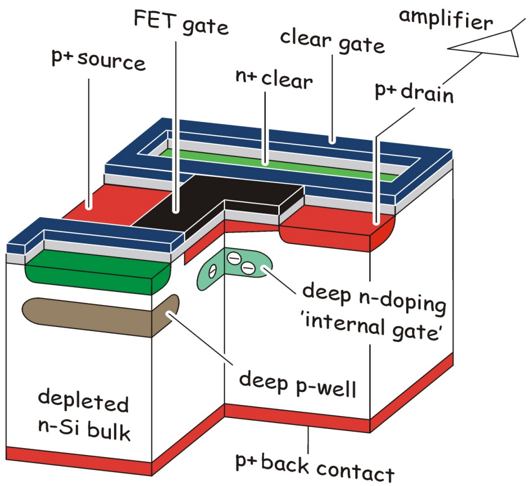


MVD, CBM

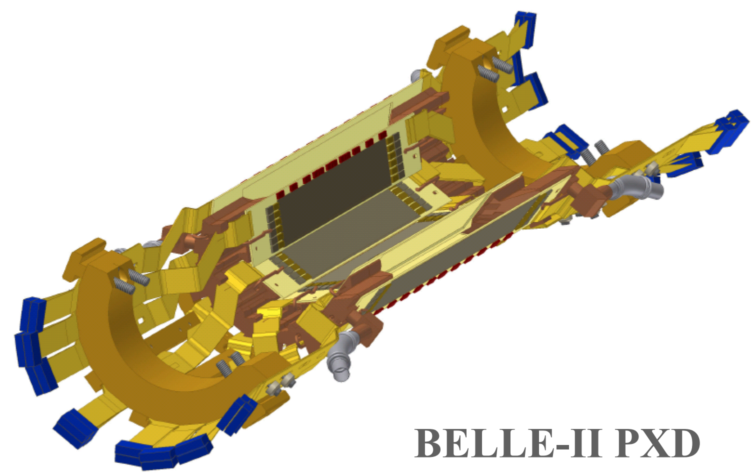
… and EUDET beam telescope
and vertex detector for STAR

Benefits of ILC Detector Program

- **Development of the DEPFET technology brought to full detector level stage within the ILC framework**

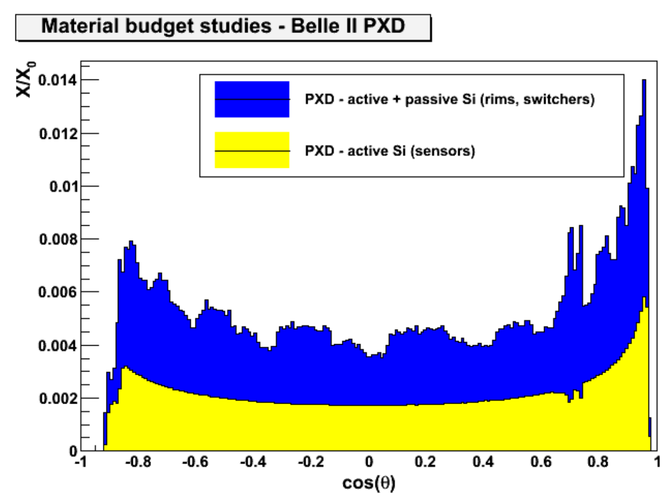


DEPFET



BELLE-II PXD

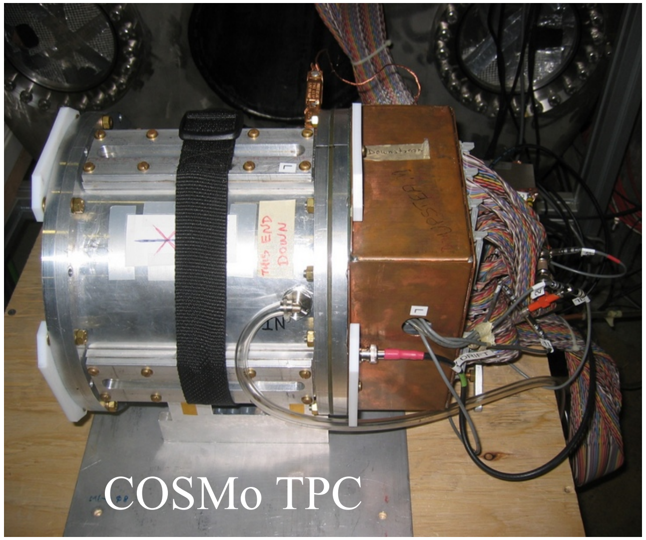
- **ILC material budget goal achieved by DEPFET**



- **If it had not been for the ILC detector R&D program, BELLE-II would not have had a viable vertex detector technology**

Benefits of ILC Detector Program

- **Micromegas TPC work carried out within the LCTPC collaboration**



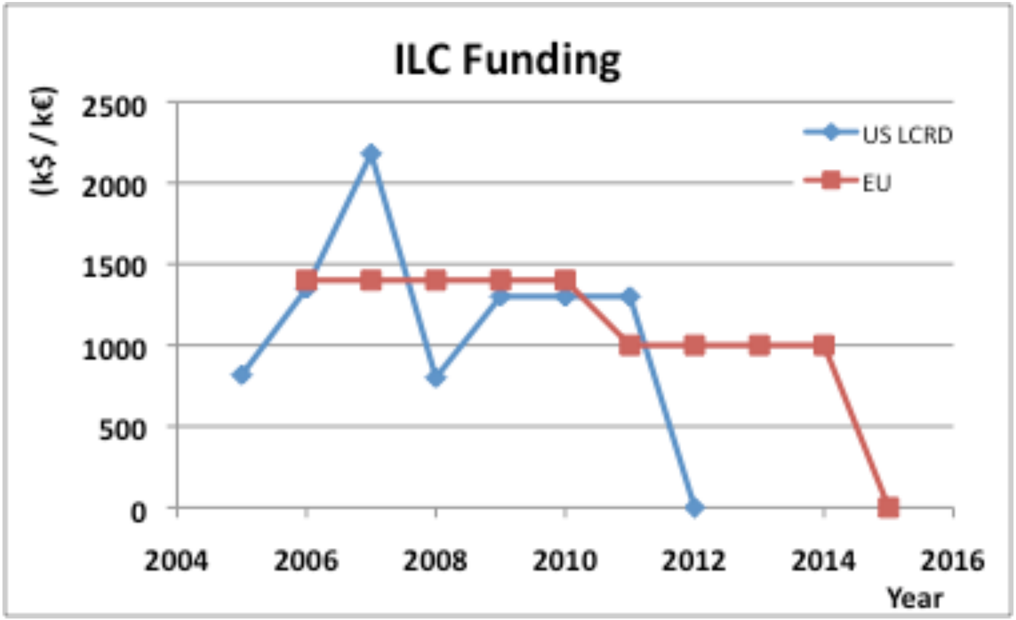
T2K TPC

- **Quote: "I can confirm that the ILC TPC R&D was essential for T2K near detector TPCs. In fact, without the ILC TPC R&D program, there would have been no T2K TPCs"**

Dean Karlen, February 2011

Support

- **Even though the fruits of the ILC detector development are clearly visible inside and outside of HEP, support is still diminishing**

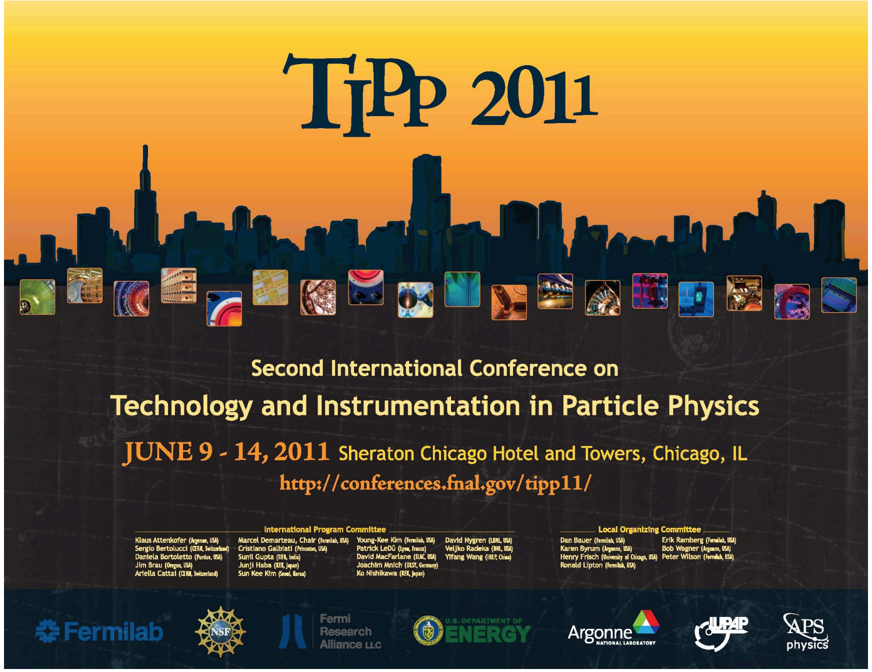


- **US ILC support**
  - Universities (LCRD)
  - Terminates in FY12
- **EU support**
  - EUDET, 2006-09 €21.5 M
  - AIDA, 2011-15 €27 M,
  - Funding geared towards infra-structure

- **Some other observations:**
  - **US initiated new detector R&D program for collider detectors with overall funding of $3M (shared with LHC)**
  - **Japanese funding as it exists will terminate this year**
  - **Individual country contributions to R&D collaborations can widely fluctuate from year to year (+/- 30%)**
  - **UK funding has been eliminated**

Own Advocates

- **We have to be our own advocates: to garner support, the burden is on us to inform and educate the agencies and community about the excellent work being carried out and its benefits!**



- **We hope to see many in June in Chicago !**
  - **http://conferences.fnal.gov/tipp11/**

- **Also workshop on power delivery and power pulsing, May 9-10, Orsay**
  - **http://ilcagenda.linearcollider.org/conferenceDisplay.py?confId=5010**

In Search of the Radical Solution

- **In the January 2011 issue of the magazine Scientific American there is an interview with a famous Indian scientist :**

  "In Search of the Radical Solution"

- **The sentiment in that interview applies, I believe, equally well to detector development in our field**

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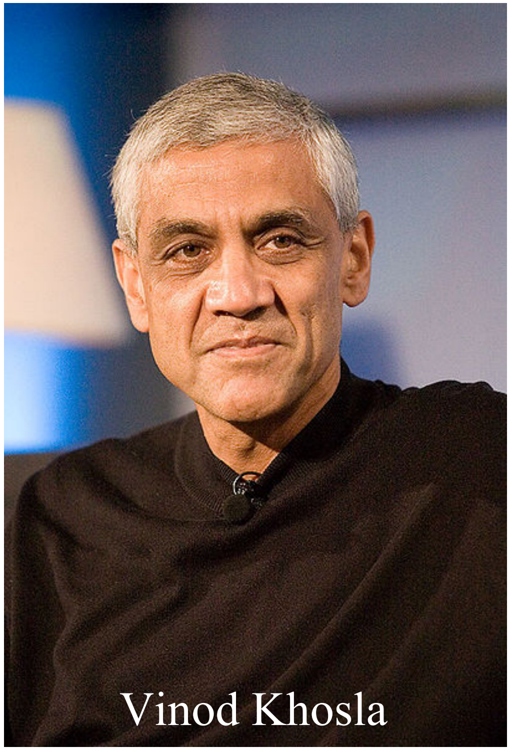

- **Reinvestment in other than incremental, non-scalable innovations technologies is needed**

- **"The greatest payoffs will come from fundamentally reinventing mainstream technologies"**

-- Vinod Khosla
co-founder SUN microsystems
venture capitalist

http://www.scientificamerican.com/article.cfm?id=in-search-of-the-radical-solution
http://ScientificAmerican.com/jan2011/khosla

Summary

- **Excellent R&D being carried out in the framework of the ILC all over the world; apologies to all excellent efforts not mentioned !**
- **AIDA program in Europe provides badly needed continuity**
- **The spin-off of ILC originated detector development is significant**
- **The community, however, seems unable to leverage that significant accomplishment**
- **Open-ended R&D is, in the long-term, not sustainable. The biggest disadvantage for a continued viable detector R&D program is the fact that there is no construction timeline for the ILC**