LC Detector R&D
Status and Overview

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Outline

- **The physics drivers**

- **Status of R&D**
  - **Vertex detectors**
  - **Tracking**
  - **Calorimetry (electromagnetic)**
  - **Forward calorimetry**

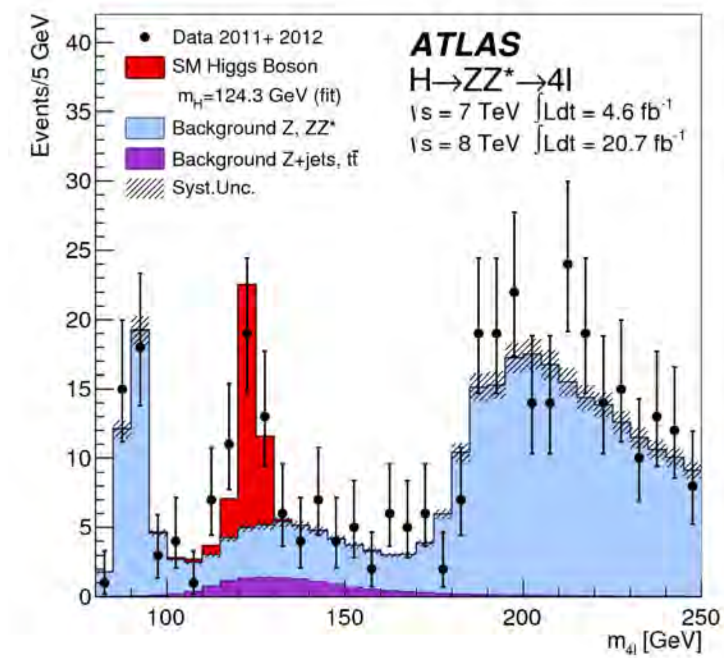
- **Reflections**

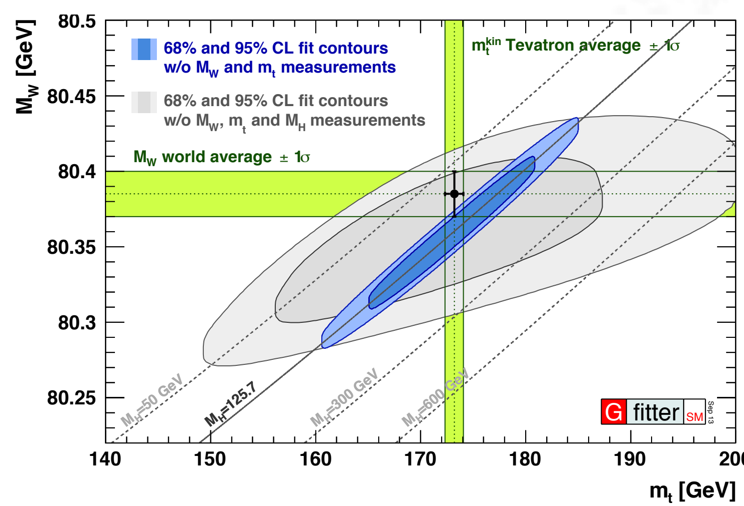
Disclaimer:

- **Impossible to pay justice to the broad spectrum of ongoing detector R&D; had short notice to prepare; apologies for omissions, all errors are mine**

Physics Goals

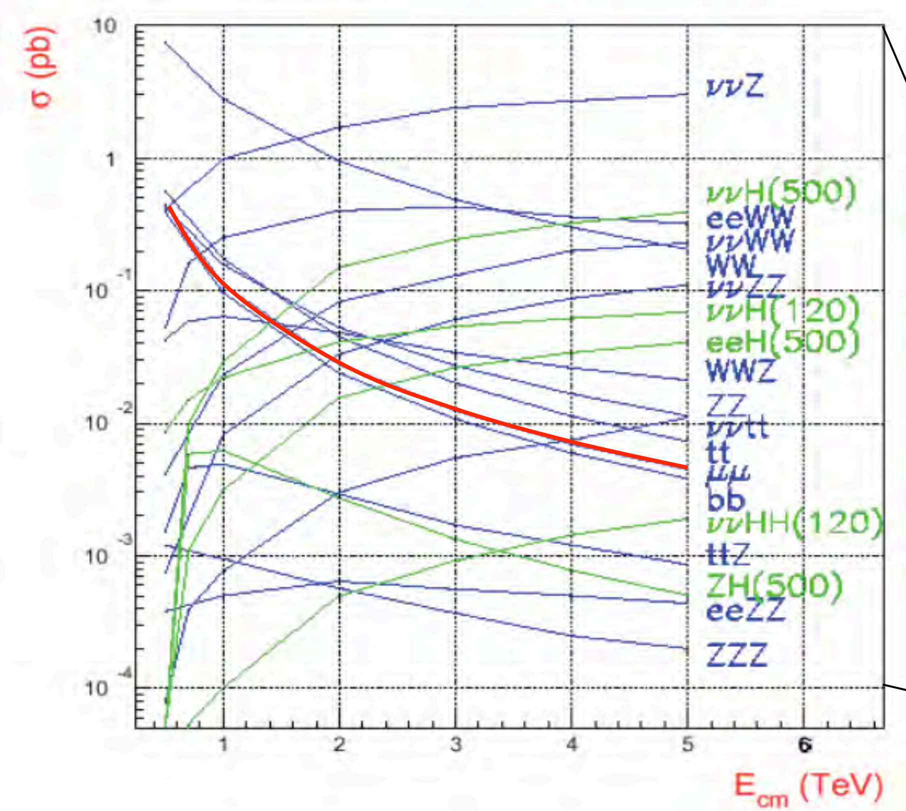
- **The LHC has brought us the Higgs. Now it needs to be explored in its fullest detail**
- **If there is new physics and it is within the ILC center of mass reach, it will let us unravel the structure of that physics**
  - **Electroweak Symmetry Breaking**
  - **Higgs sector(s)**
  - **Extra symmetries, 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)**

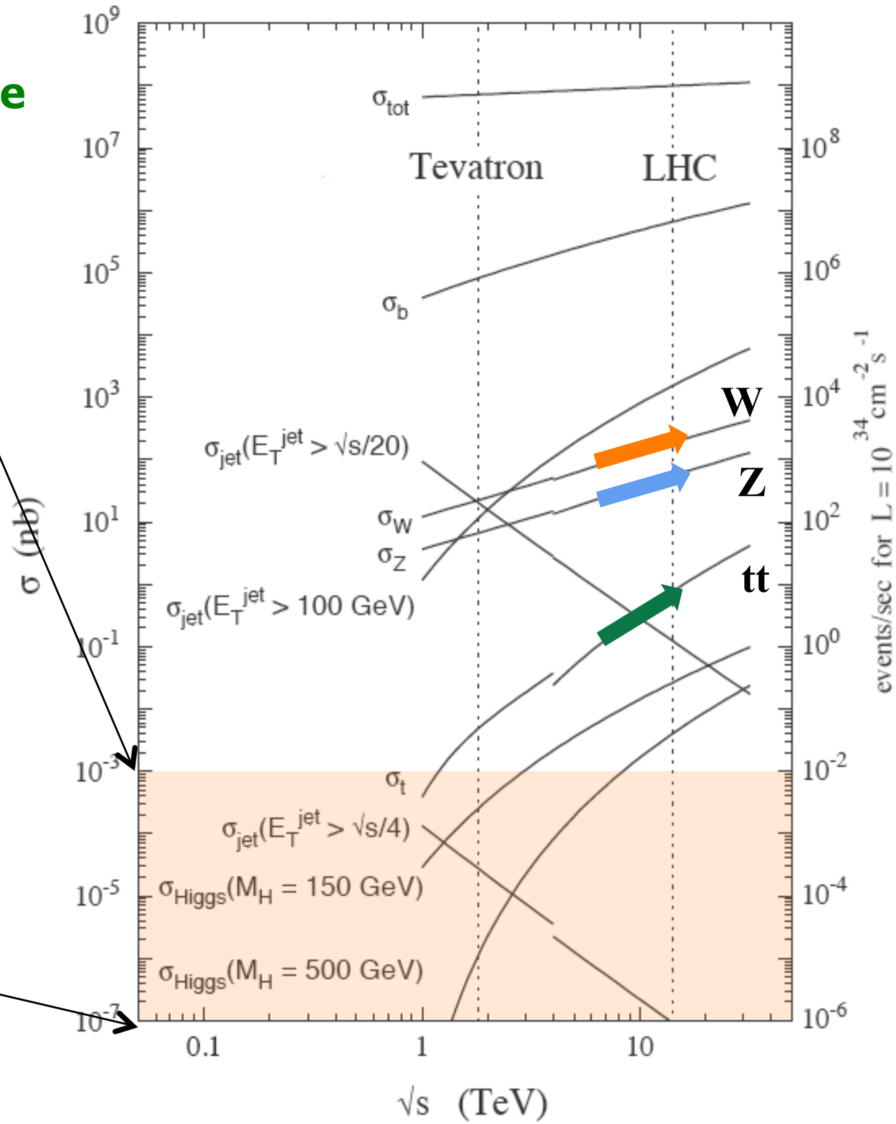




Physics Environments

- **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**

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

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

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

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

  $\tilde{\mu}$ decay

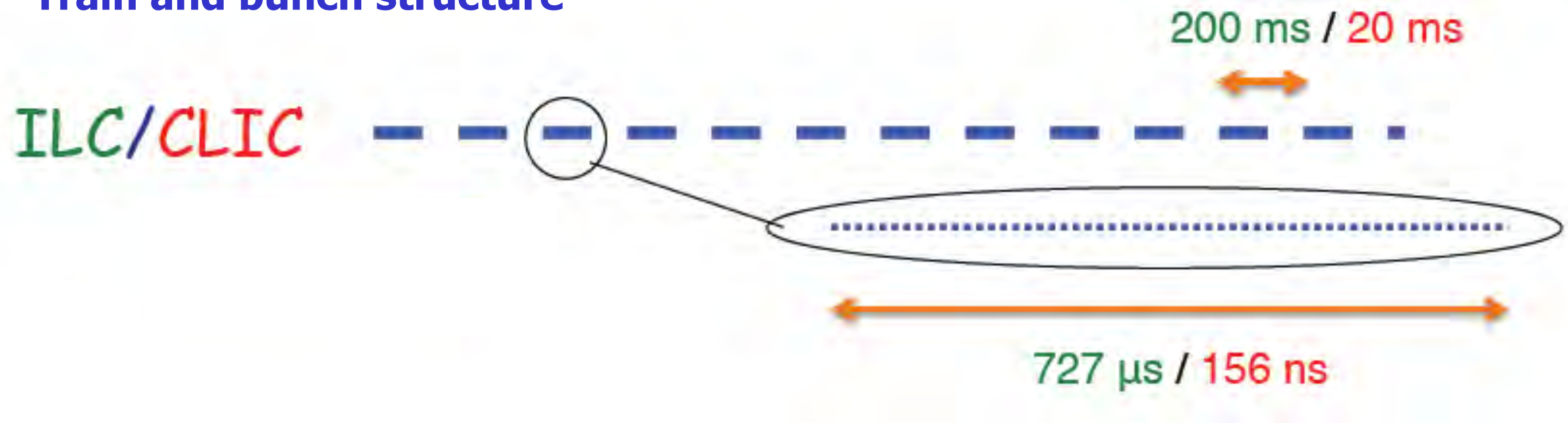
- **The unexpected**

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** $\sigma(1/p_T) = 5\times10^{-5}\ (GeV^{-1})$
• **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**

Machine Challenges

- **Train and bunch structure**

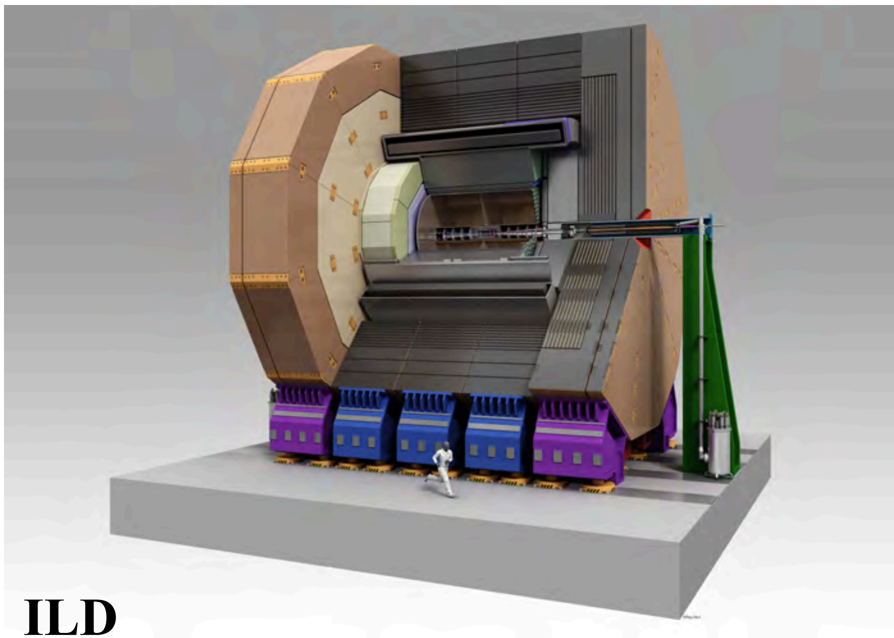


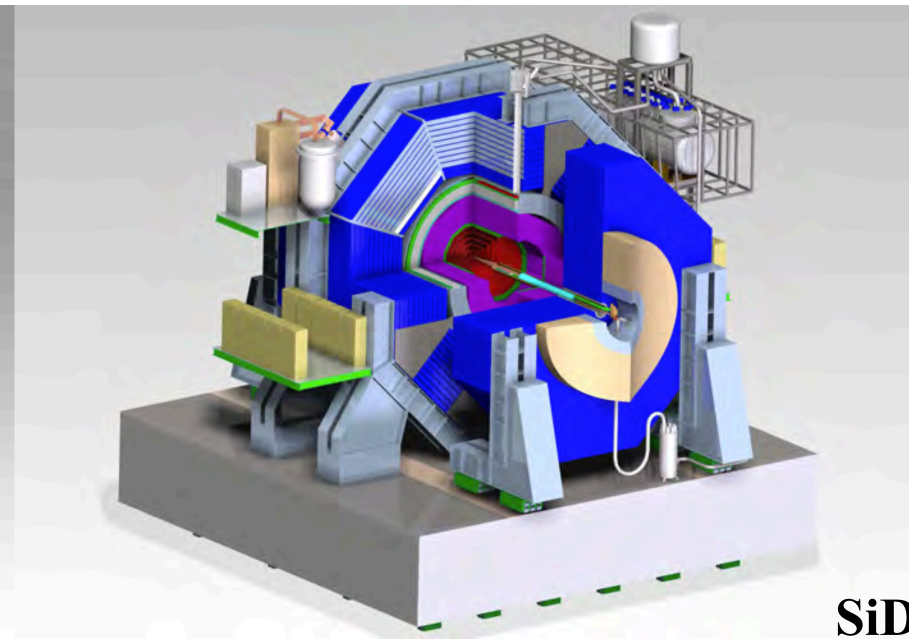
	ILC at 500 GeV	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$2x10^{34}$	6×10^{34}
BX separation	554 ns	0.5 ns
#BX / train	1312	312
Train duration	727 µs	156 ns
Train repetition rate	5 Hz	50 Hz
Duty cycle	0.36%	0.00078%
σ_x / σ_y (nm)	474 / 6	≈ 45 / 1
σ_z (µm)	300	44

- **ILC**
  - **Long trains, low rep. rate, long bunch crossing, modest transverse bunch size**
- **CLIC**
  - **Short trains, higher rep. rate, very short bunch crossing, very small transverse bunch size**

Detector Concepts

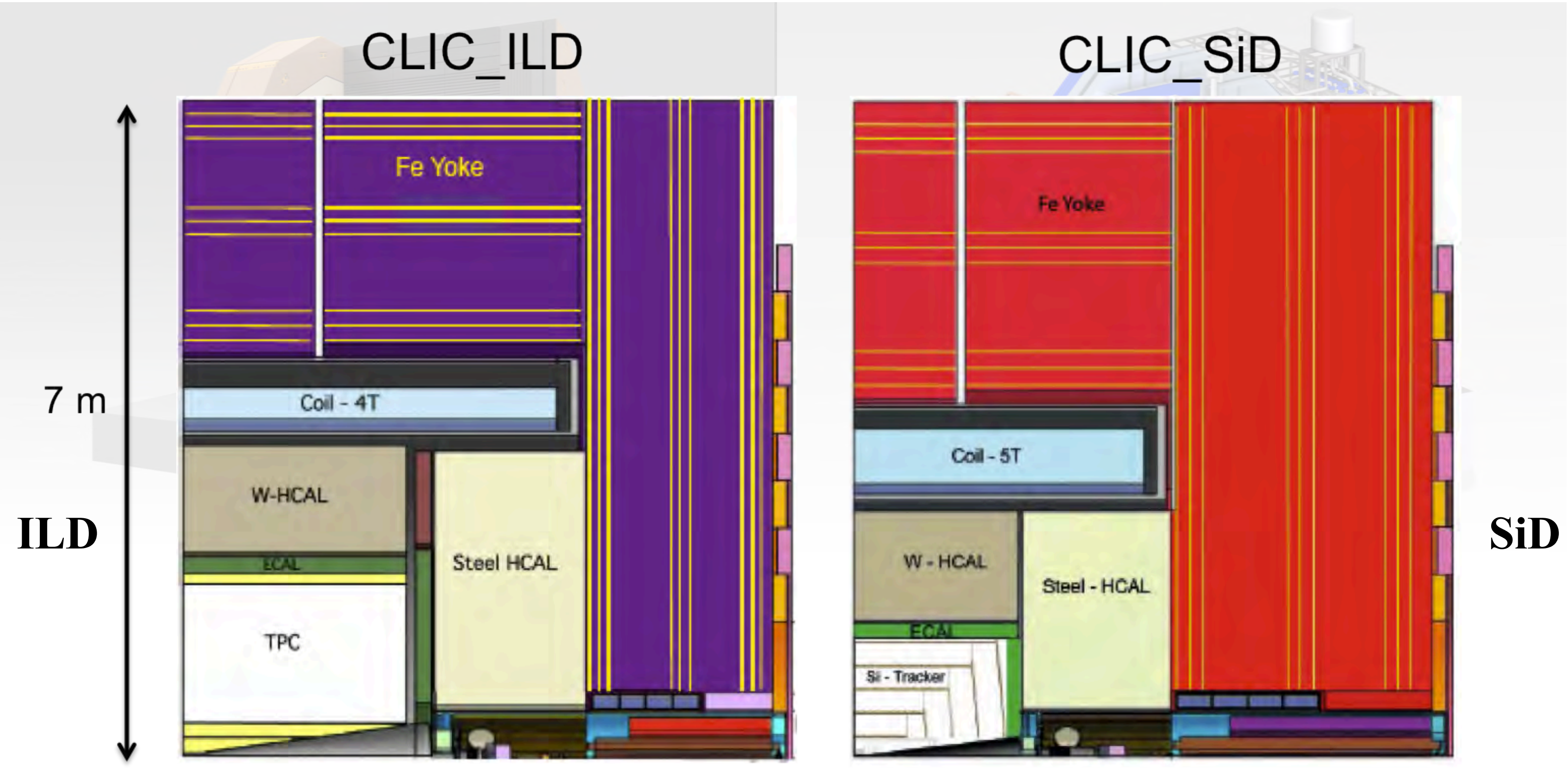
- **Two detectors have completed a Detailed Baseline Design**





Detector Concepts

- **Two detectors have completed a Detailed Baseline Design**
- **With two fraternal twins for CLIC who have completed a Conceptual Design**
- **Most of the R&D is carried out within the context of these concepts**

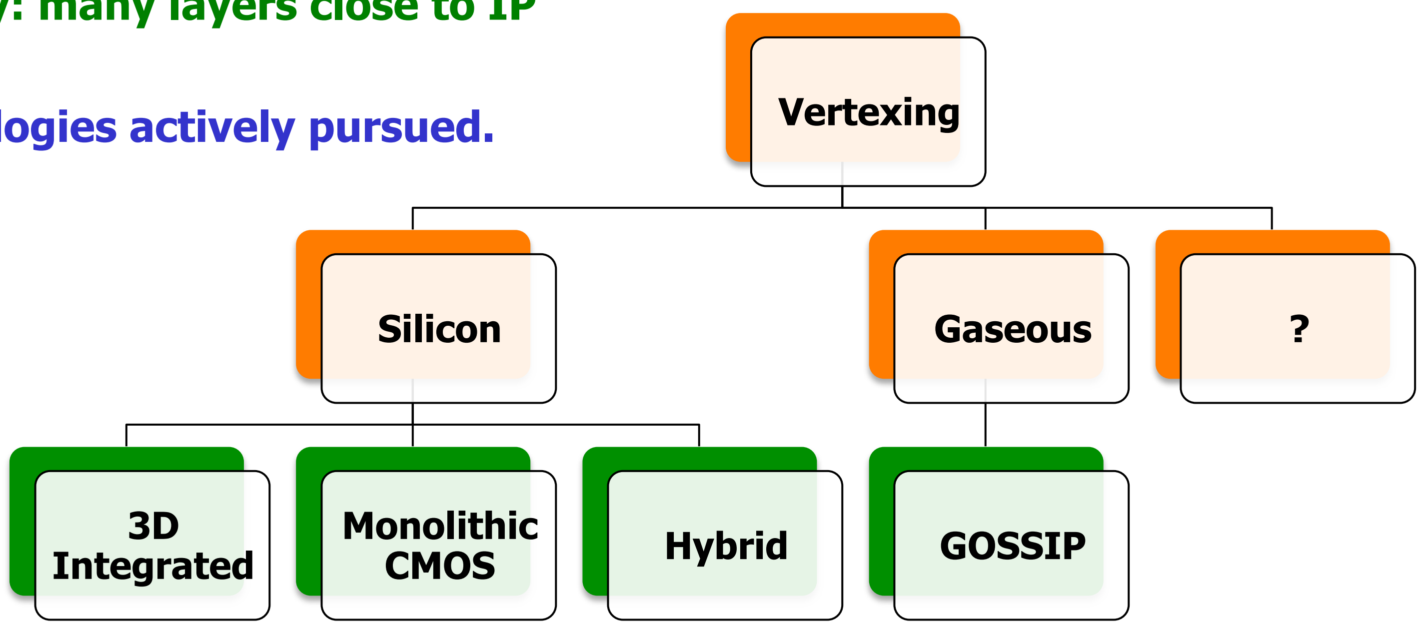


Vertex Detector

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**

- **Many technologies actively pursued.**



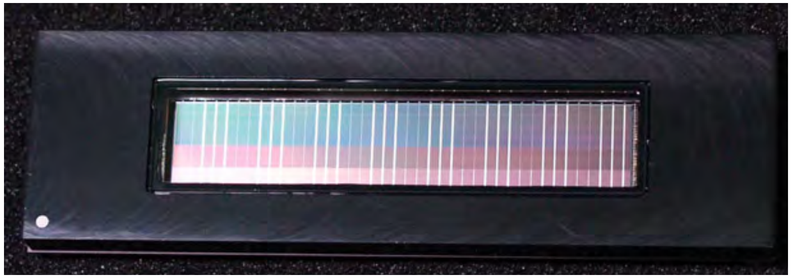
Technologies

	Monolithic CMOS	3D-integrated	Hybrid pixel
Examples	DEPFET, FPCCD, MAPS, HV-CMOS	SOI, MIT-LL, Tezzaron, Ziptronix	Timepix3/CLICpix
Technology	Specialised HEP processes, r/o and sensors integrated	Customized niche industry processes, high density interconnects btw. tiers	Industry standard processes for readout; depleted high-res. planar or 3D sensors
Interconnect	Not needed	SLID, Micro bump bonding, Cu pillars	
granularity	down to 5 μm pixel size		~25 μm pixel size
Material budget	~50 μm total thickness achieveable		~50 μm sensor + ~50 μm r/o
Depletion layer	partial	partial or full	full → large+fast signals
timing	Coarse (integrating sensor)	Coarse or fast, depending on implementation	Fast sparsified readout, ~ns time slicing possible

From D. Dannheim

- **Some technologies already being deployed in various experiments and sciences**
  - **Monolithic: STAR at RHIC, ALICE at LHC, DEPFET at BELLE-II**
  - **Hybrid: CMS and ATLAS at LHC**
  - **3D at NSLS II at BNL**

Fine Pixel CCD Technology



- FP-CCD sensor and readout being developed
- Small Prototype
- Large prototype (real size for inner layer)
  - $62.4 \times 12.3 mm^2$ image area
  - 8ch/chip with several pixel sizes:
    - 4chx6um, 2chx8um, 2chx12um
  - Large area is achieved through stitching
  - Horizontal shift registers for $6 \mu m^2$ do not work properly
  - Plan to test in JPARC beam in 2014

- Current emphasis on cooling:
  - CCD to be operated at -40 ^{o}C
  - Power consumption ~50W
  - Building CO2 cooling system for tests

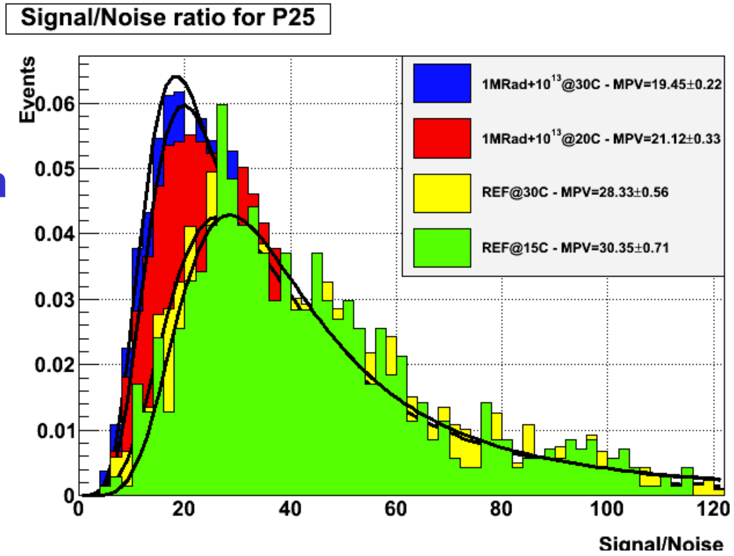
Pixel size (in)	Pixel size (out)	# of ch/chip (in)	# of ch/chip (out)	# of ch (total)	Power consumption
5 um	5 um	28	56	7392	111 W
5 um	10 um	15	15	2280	**34 W**

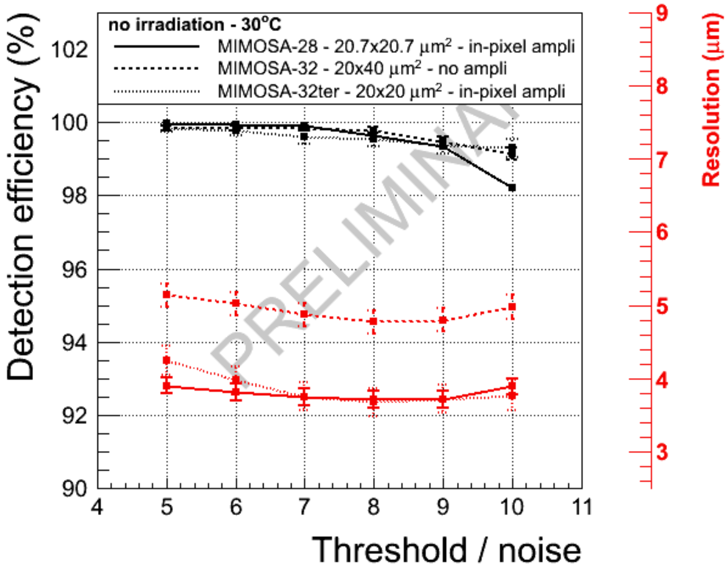
CMOS Pixel Sensor (CPS)

- Monolithic Active Pixel sensors in CMOS process
- Early devices (Mimosa 26/28) in 350nm process
- New devices in 180nm process
  - Allows for faster & smarter pixels
  - Deeper sensitive volume: 18 to 40 µm thick

- Mimosa-32(ter)
  - Pixel pitch 20x20μm^2
  - In pixel amplification & CDS
  - Irradiation: 1 Mrad + 10^{13} n_{eq}/cm^2

  - Excellent S/N ~ 20
  - Hit resolution ~ 5μm

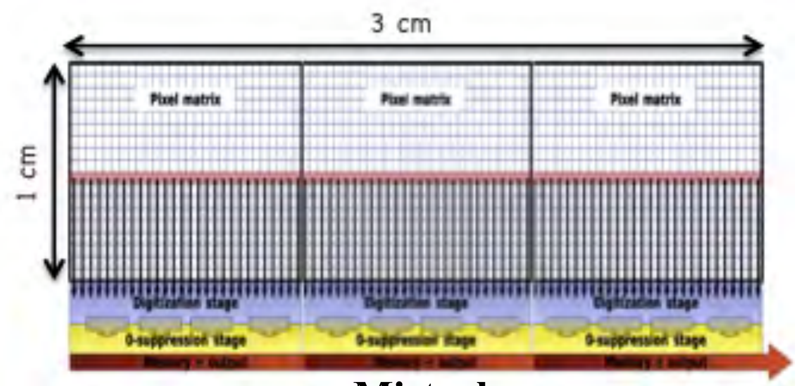




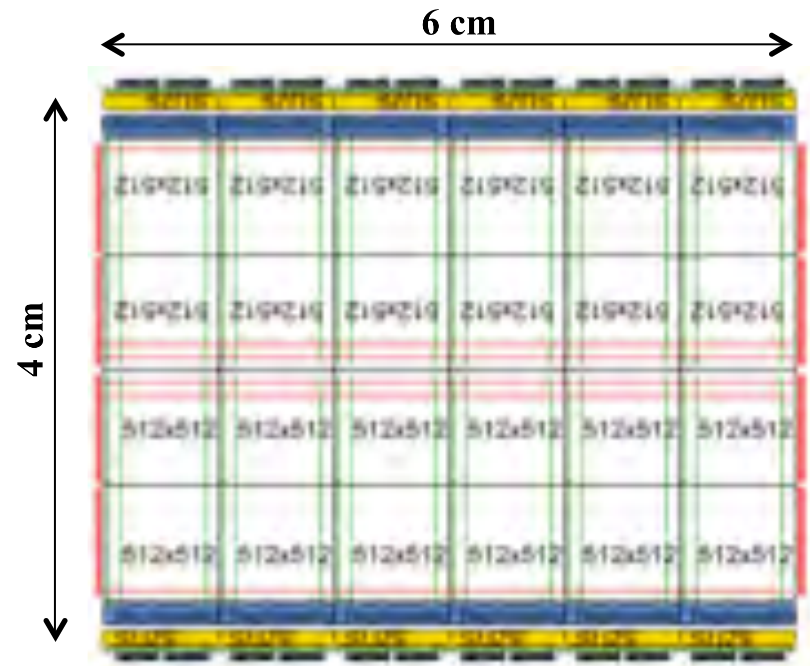
CPS Projection

- **Intermediate steps**
  - **2D zero-suppression logic**
  - **clusters encoded on 4x5 pixel window**
  - **In-pixel amplification + CDS**
  - **In-pixel 3-bits ADC**

- **MISTRAL**
  - **Pixel 22x33 µm2**
  - **Column-level discriminators**
  - **Multi-row read-out → 30 µs**
  - **Power < 350 mW/cm^2**
- **ASTRAL**
  - **Pixel 22x33 µm^2**
  - **Pixel-level discriminator**
  - **Read-out → 15 µs**
  - **Power < 200 mW/cm^2**
- **MIMAIDA**
  - **Sensitive area = 4x6 cm^2**



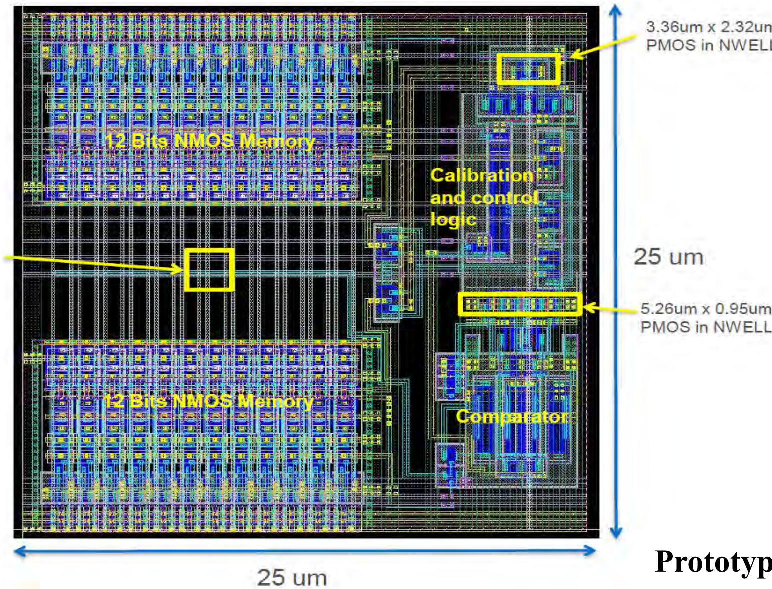
Mistral



Mimaida

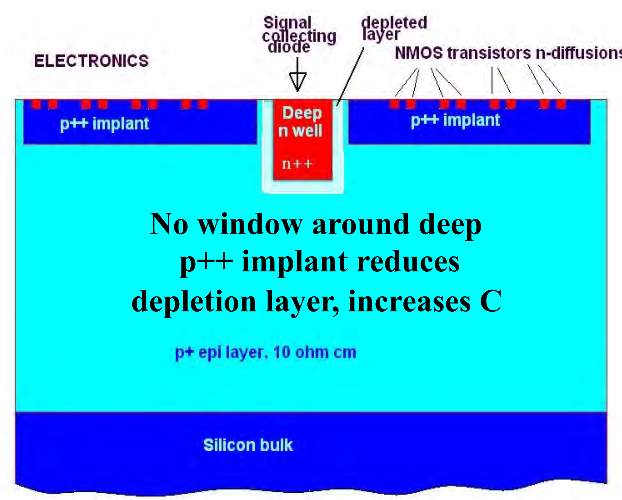
Chronopixel

- **Chronopixel design provides for single bunch-crossing time stamping**
  - **When signal exceeds threshold, time stamp provided by 14 bit bus**
  - **Comparator threshold adjusted for all pixels**
- **Prototype 1**
  - **50x50 μm^2 pixels, 180nm TSMC**
- **Prototype 2**
  - **25x25 μm^2 pixels, 90nm TSMC**



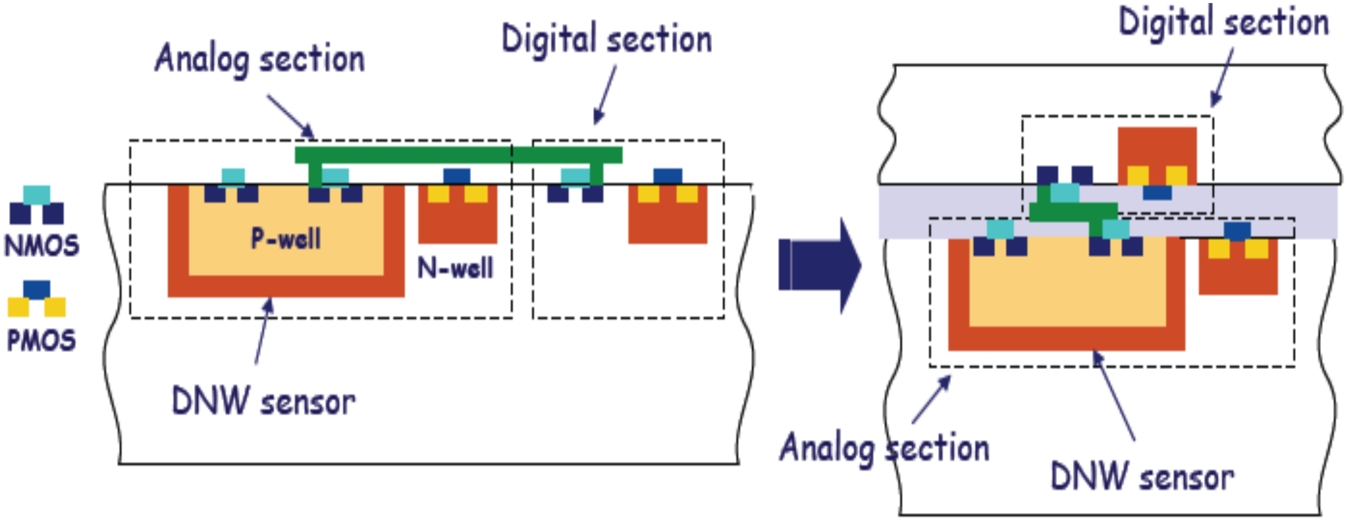
Prototype 2

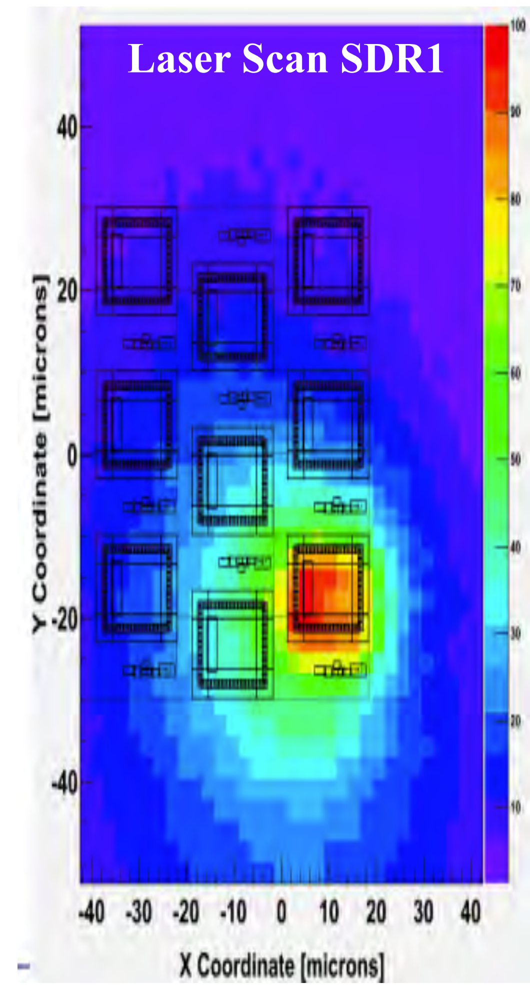
- **Results:**
  - **BX time stamping works (300 ns period)**
  - **Readout between trains demon-strated (sparse readout)**
  - **Pulsed power (2 – 200 ms ON/OFF)**
  - **Comparator offset spread factor 5 worse than prototype 1**
  - **Sensor capacitance larger than expected**



MAPS in 3D

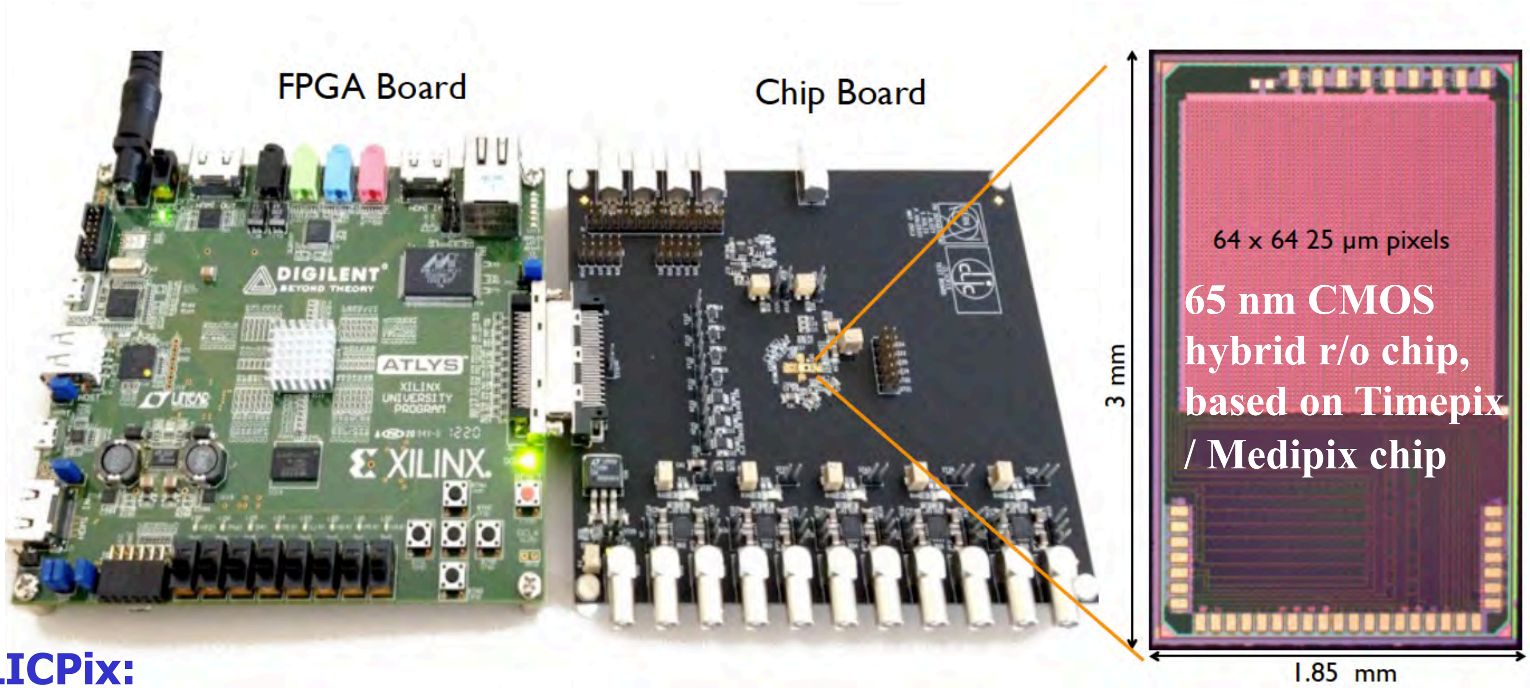
- **Combine MAPS with 3D silicon integration**
  - **retain analogue section within charge sensing pixel, move digital section to separate layer**



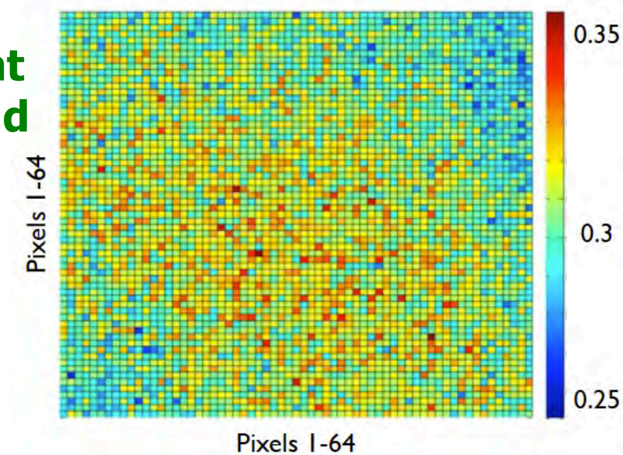


- **Multi-project-wafer run through Tezzaron**
  - **Fully functional 3D chips (SDR1)**
  - **Two tiers, 20x20 μm^2 pixels in 240x256 matrix**
  - **Good S/N and radiation hardness being verfied**
  - **Exploring design with ~200 ns per-pixel time stamp**

Hybrid Technology

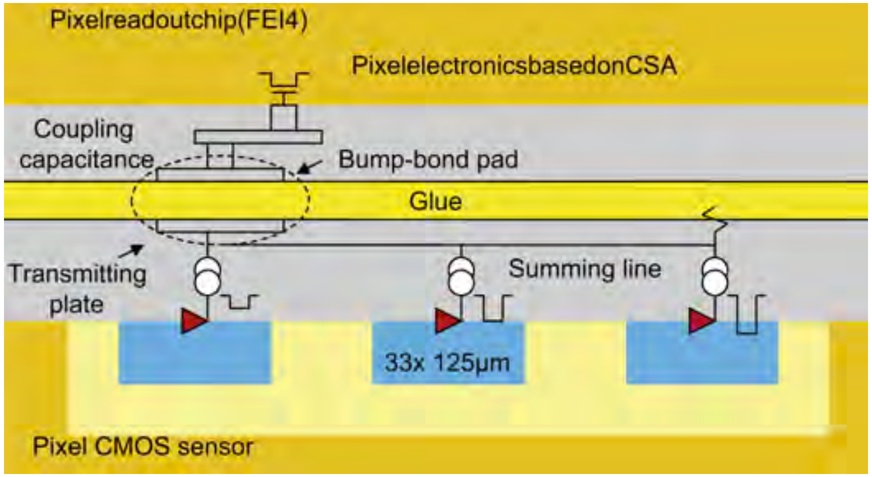


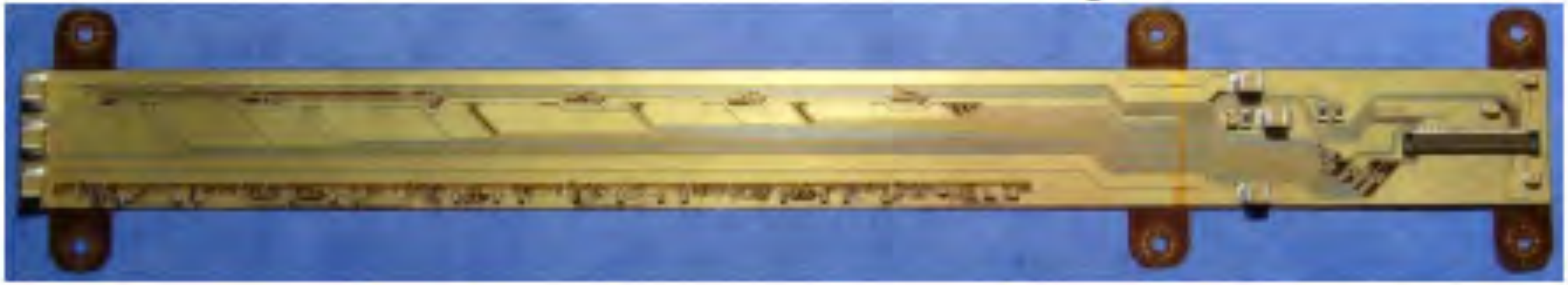
- **CLICPix:**
  - **64 x 64 pixel matrix in 65 nm technology,**
  - **25 µm pixel pitch, simultaneous measurement Time of Arrival (TOA) and Time over Threshold (TOT), power pulsing, data compression**
- **Time Over Threshold gain distribution**
  - **Uniform gain across the whole matrix**
  - **Gain variation is 4.2% r.m.s. (for nominal feedback current**



Other Technologies

- **Capacitive Coupled Pixel Detector**
  - **HV-CMOS chip as sensor that amplifies signal, which is capacitively coupled to readout through, for example, a layer of glue (no bump bonding)**





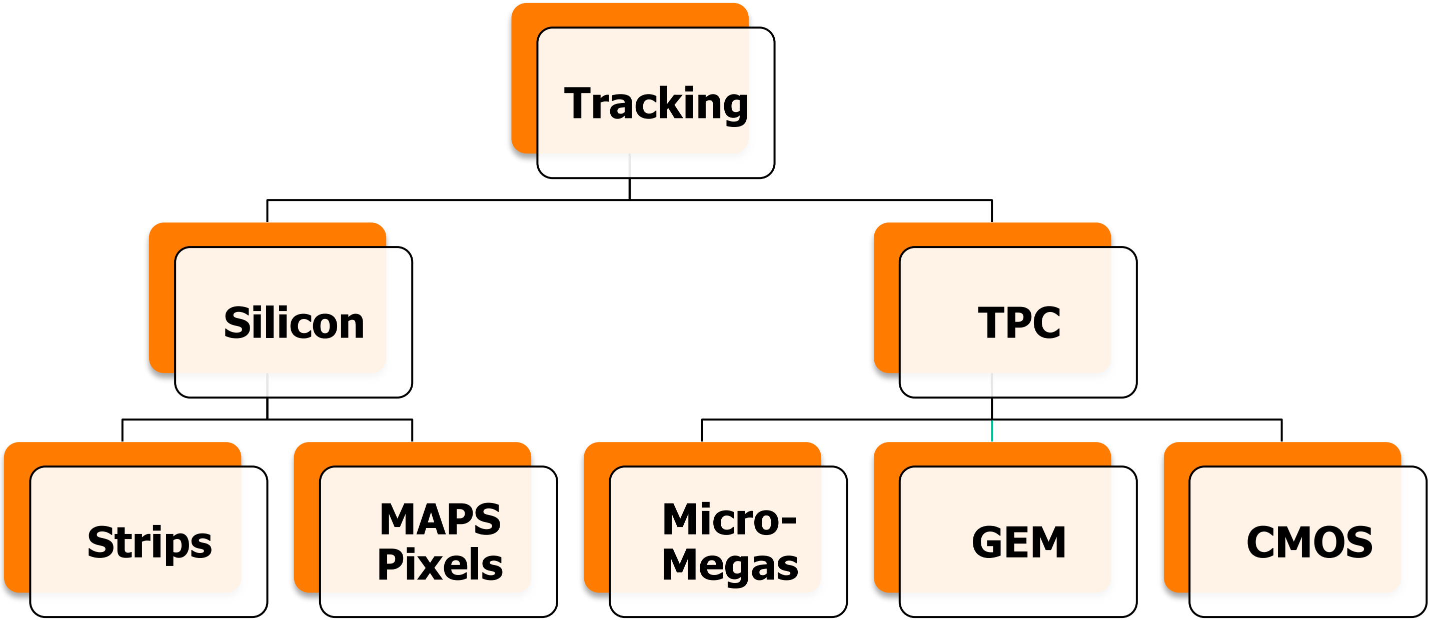
- **Progress in low-mass mechanical design and cooling**
  - **Double-sided Mimosa ladder developed with 0.35% X_0**

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**

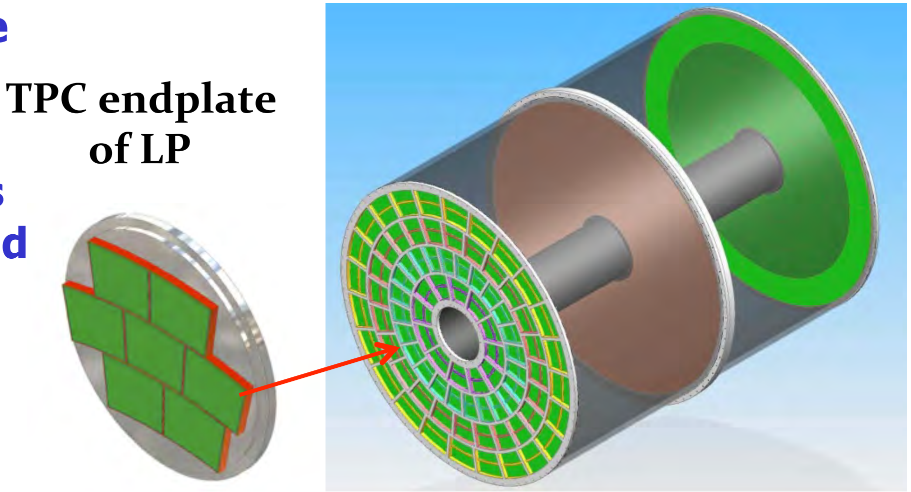
Technology Tree

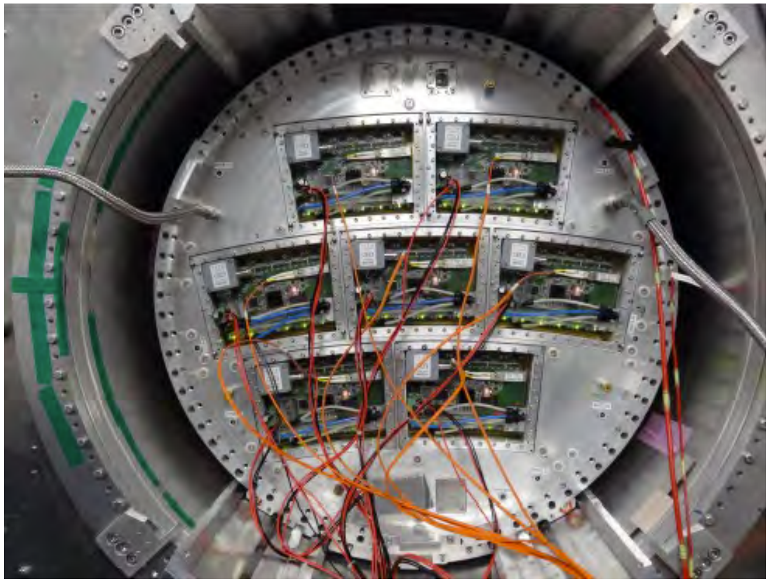


TPC R&D

- **Focus of LC TPC collaboration is on the Large Prototype (LP), inside a 1.2T superconducting solenoid**
- **Endplate was designed that resembles cutout of final endplate, which can hold 7 identical modules**

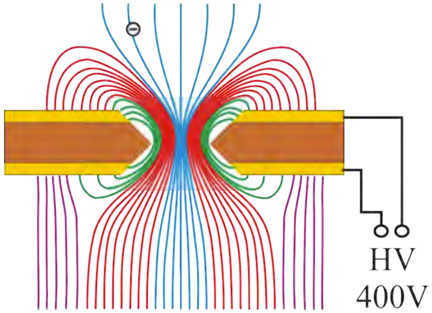
- **Different backframe heights to allow different gas amplification stages**

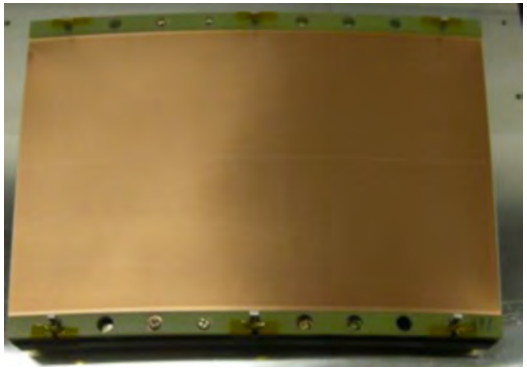




Technologies

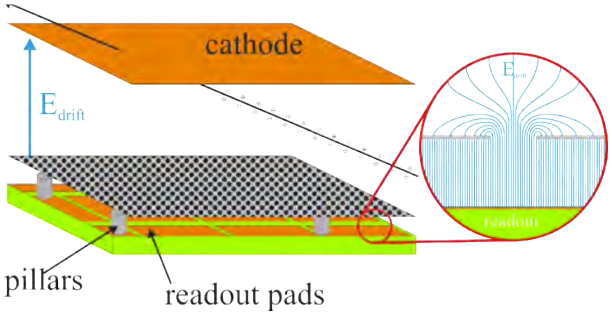
GEM

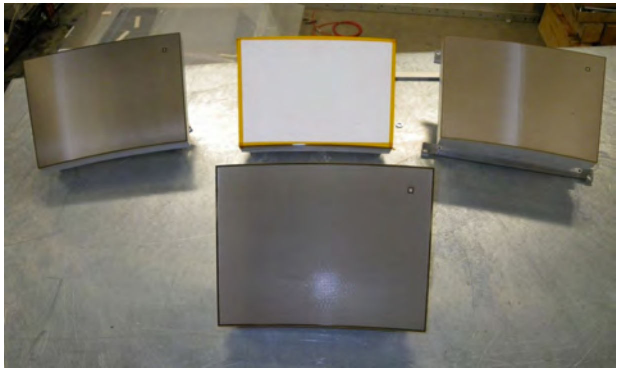




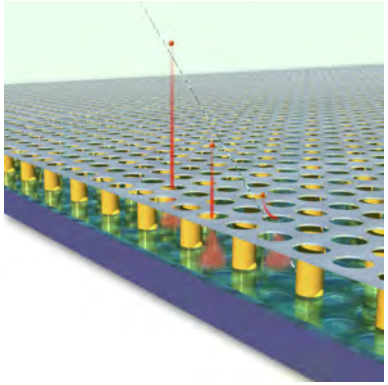
Two variants:
Asian and German

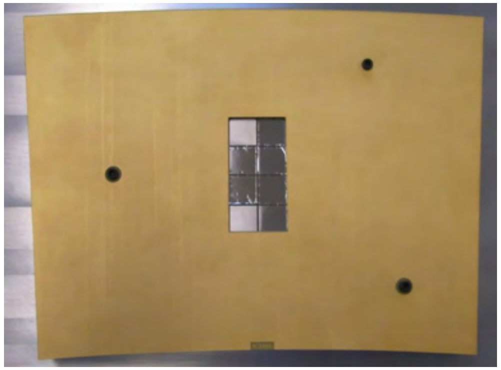
MicroMegas





InGrid

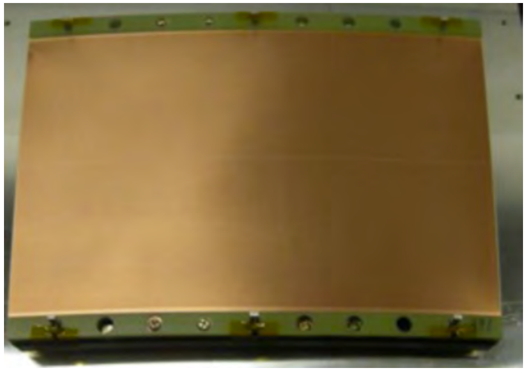




Technologies

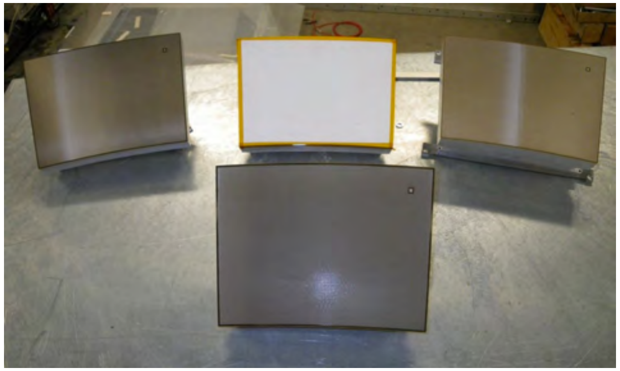
GEM

- **Asian GEM module:**
  - 2 GEMs
  - 1.2x5.4 mm^2 pads
  - 5152 channels/module
- **DESY GEM module:**
  - 3 GEMs
  - 1.26x5.85mm^2 pads
  - 4829 channels/module



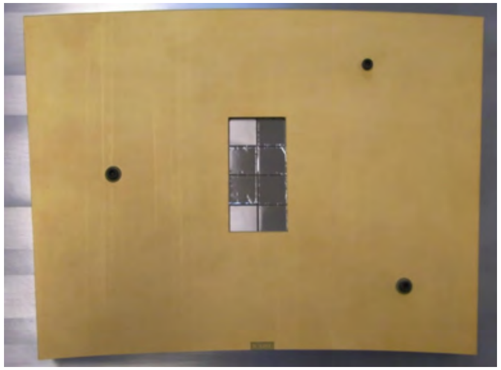
MicroMegas

- **MicroMegas module:**
  - 3x7 mm^2 pads
  - 24 rows with 72 pads
  - 1728 channels/module
  - Testing different resistive foils



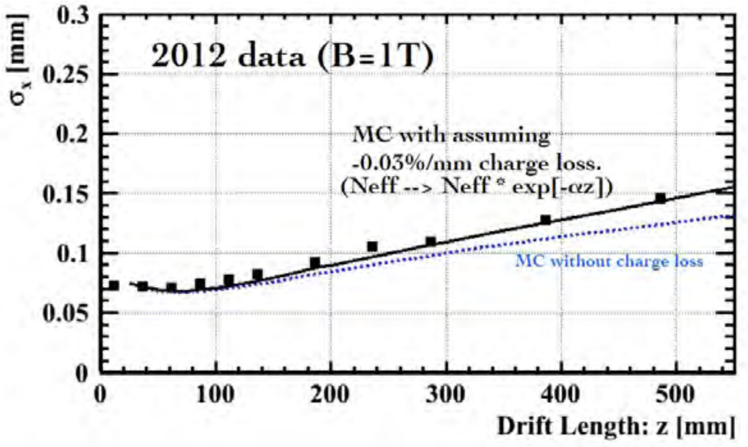
InGrid

- **InGrid module:**
  - 8 integrated MicroMegas grids on TimePix chips
  - 65 000 digital pixels (55x55 μm^2)
  - Time and Time over Threshold (TOT) measurement

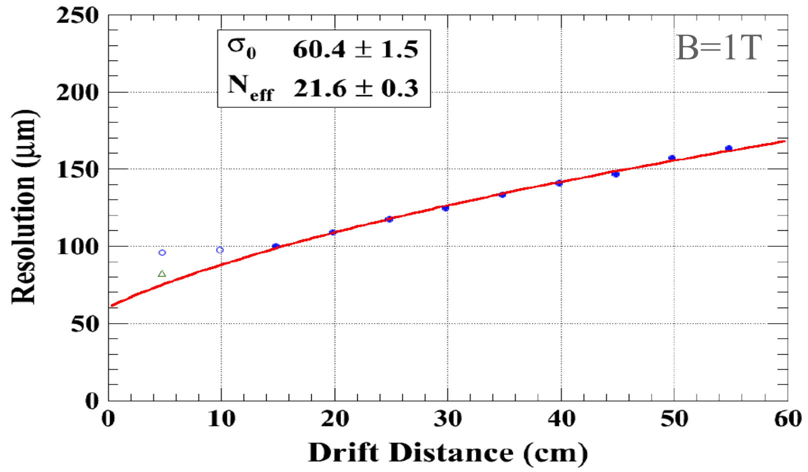


Results

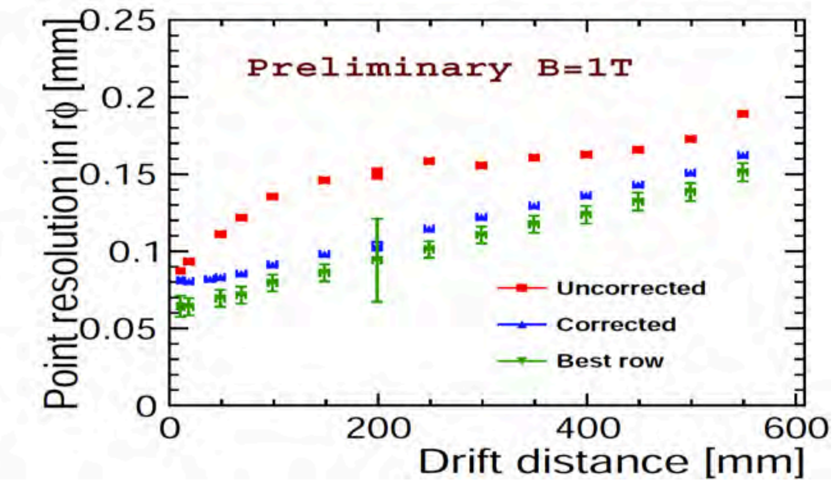
Asian GEM



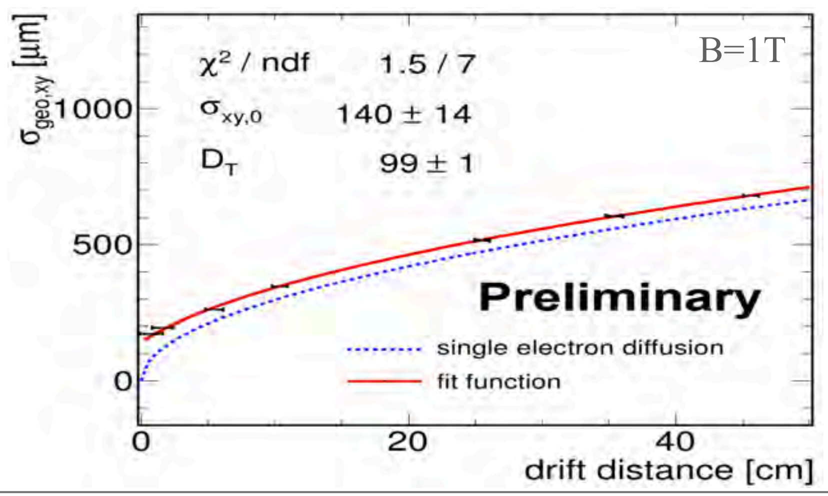
MicroMegas



German GEM



InGrid



TPC Readout

Readout		Pad Size	Electronics	Groups
MPGDs	Micromegas (Resistive anode)	(~ 3 × 7 mm^2 Pad)	AFTER	Saclay-Carleton
	Double GEMs (Laser-etched)	(~ 1 × 6 mm^2 Pad)	ALTRO	Asia
	Triple GEMs (wet-etched)			DESY

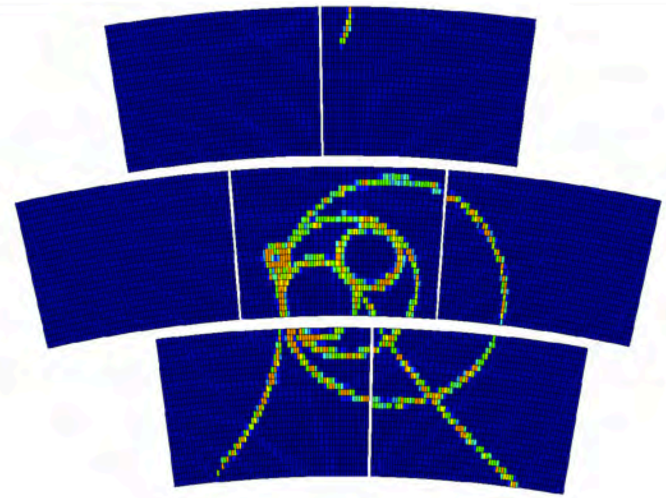
From: Paul Colas

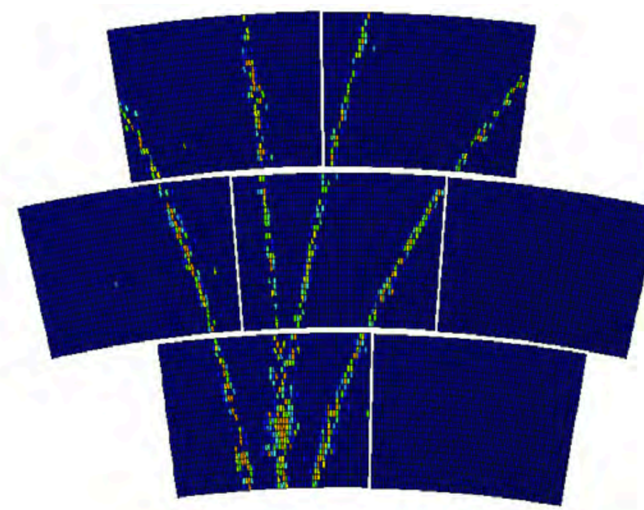
- **Development of the integrated electronics based on the S-Altro chip**
  - **16 channel ASIC with integrated ADC**

- **Possible future development:**
  - **ALICE developing the SAMPA chip for TPC and Muon system readout**
  - **VFAT3 and GdSP chip development for CMS**

Results and Plans

- **All technologies have been operated reliably in the DESY test beam.**
- **A similar transverse spatial resolution was measured for all different pad-based modules (GEM and MicroMegas)**
- **Resolution of 80 μm at 2m drift in B=3.5 T obtained and possibly to be improved upon**
- **Performance of the InGrid modules is very preliminary; Track finding and fitting is challenging and new algorithms have to be developed for dealing with large numbers of track points**
- **Proof of Pixel based readout of large area coverage is pending. Plan to build a completely covered module next year.**
- **All technologies are suffering from field distortions at the module edges.**

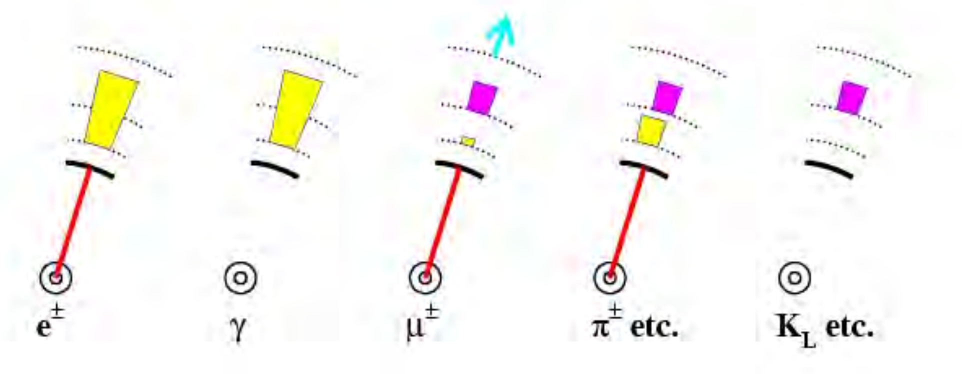




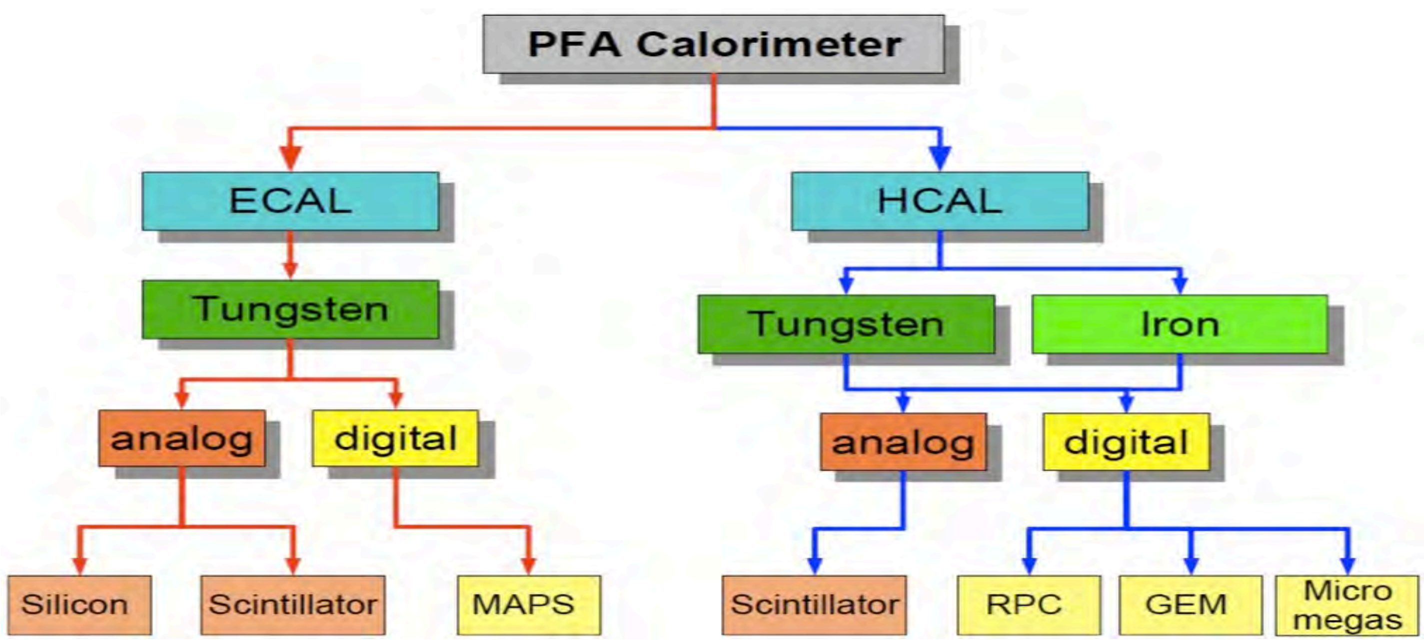
Calorimetry

Research Thrust

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

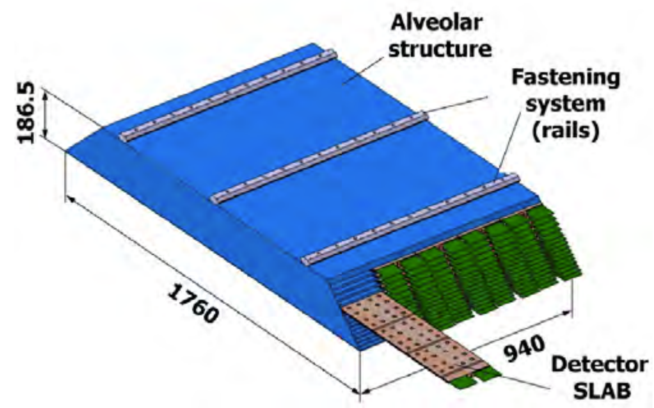


CALICE Technology Tree

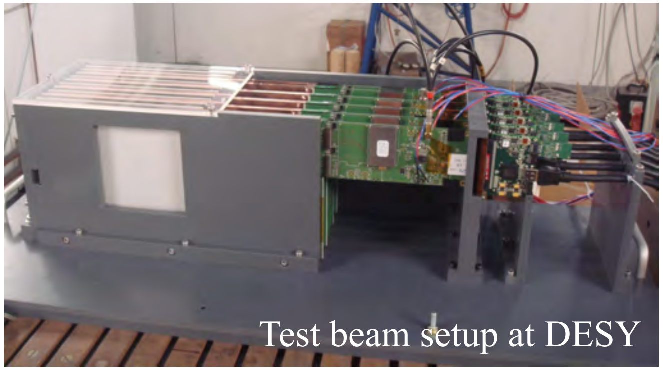


Silicon-W ECAL

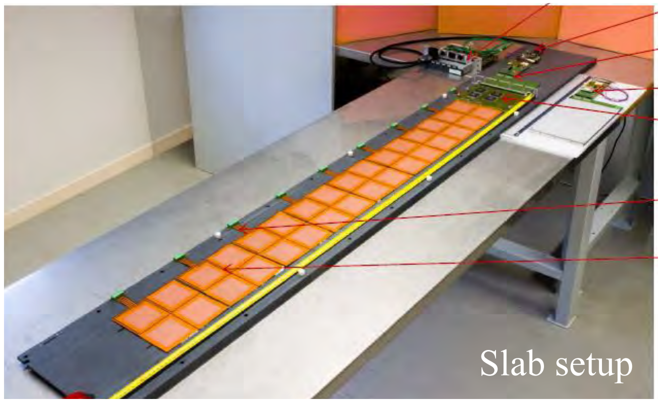
- **Developing a Technological Prototype:**
  - **30 layers of 176 cm long W slabs in 20cm depth, with 8 Active Sensor Units (ASUs) per slab**
    - ASU = ASIC + PCB + Si sensor
  - **Sensor: 9x9cm^2, 16x16 pixels of 5.5x5.5mm^2**
  - **ECAL ~100 M channels**



- **Test beam of partial modules at DESY**
  - **Power pulsing successfully tested**
  - **ILC extrapolation = 2.5 kW for full ECAL**

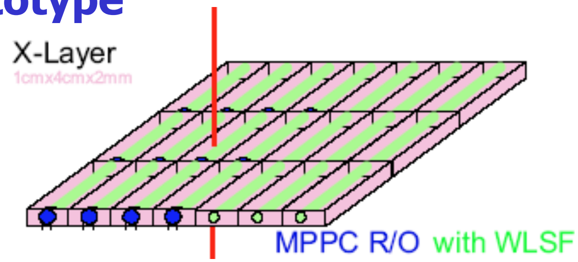

Test beam setup at DESY

- **Full slab being assembled on the bench**
  - **Thermal tolerances are demanding**
  - **Mechanical tolerances are demanding**
- **Schedule**
  - **New sensors ordered, without guard rings**
  - **Bench tests continuing with possible beam test**

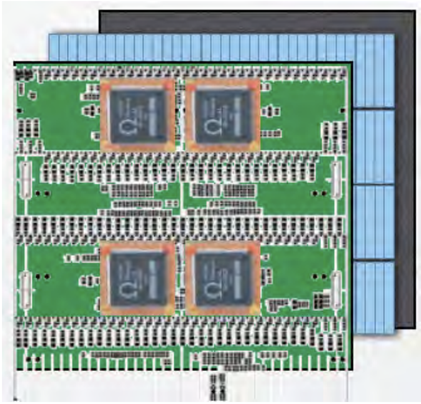

Slab setup

Scintillator ECAL

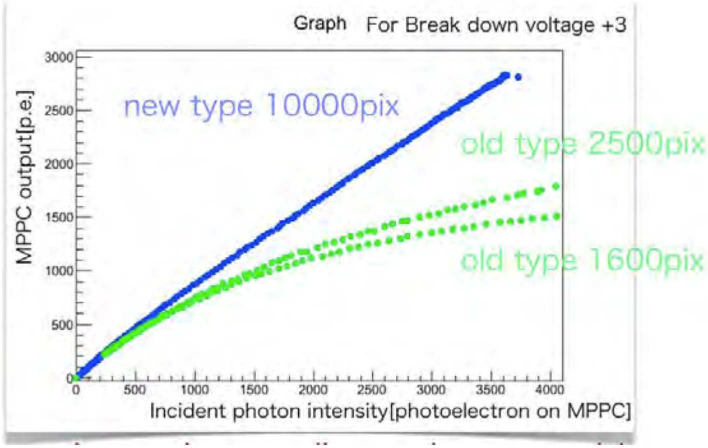
- **Scintillator ECAL also developing Technological Prototype**
  - **Scintillator strips : 5mm x 45mm x 2mm**
  - **Readout MPPC directly**
  - **Embedded read out ASIC layer (SPIROC2b)**



- **Taken test beam data**
  - **Good MIP signal but not completely separated from noise**



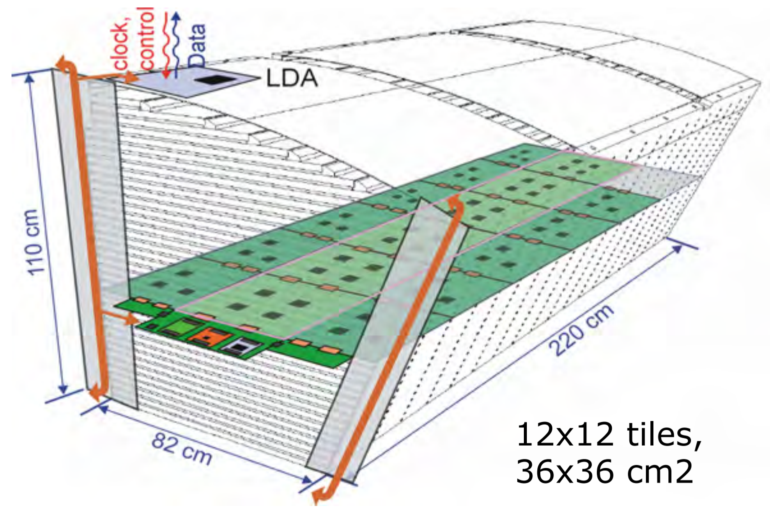
- **Moving towards new Hamamatsu MPPCs**
  - **10,000 pixels/1x1 mm^2**
    10 μm pitch
  - **Improve dynamic range and linearity**



- **Work also beginning on development of a "hybrid" ECAL: scintillator + silicon**
  - **ECAL is the most expensive sub-detector**

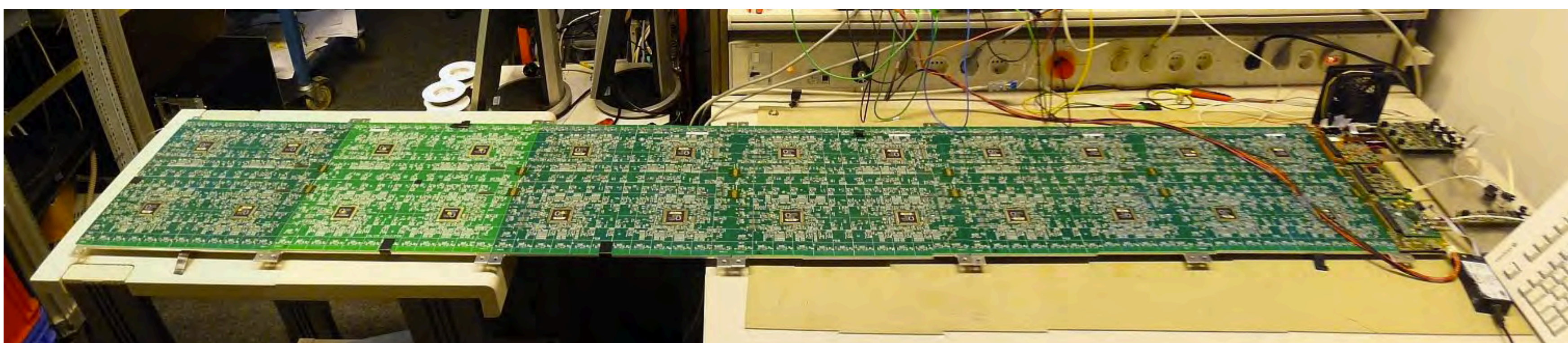
Analogue HCAL

- **Building 2nd generation prototype with fully integrated readout**
  - **48 layers, 220 cm long, 135 cm deep**
  - **3x3 cm^2 scintillator tiles with SiPMs**
  - **Integrated electronics (SPIROC chip)**
  - **LED SiPM calibration**
  - **Power-pulsing**
  - **Active layer thickness of 5.4 mm**



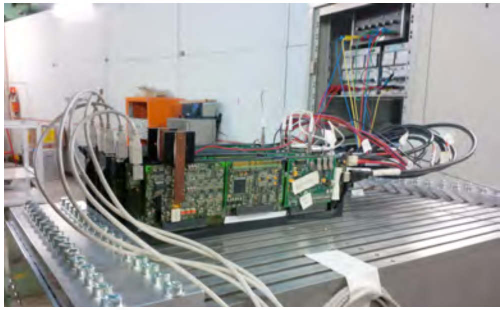
12x12 tiles,
36x36 cm2

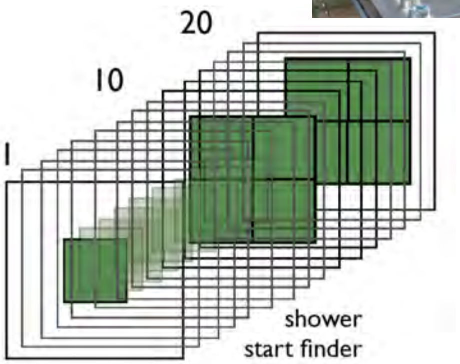
- **Successful operation of a slab of full ILC module length (6 readout boards, 2.2 m long)**
  - **Very good signal quality**

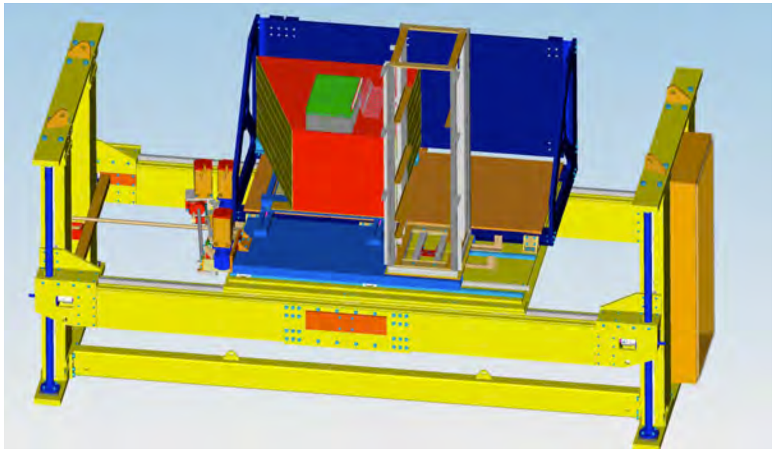


AHCAL Test Beam Plans

- **2013-14:**
  - **EM stack, 10-15 layers**
  - **~200 channels**
- **2015-16:**
  - **Hadron stack with shower start finder, 20-30 HBUs, ~ 4000 ch.**
- **2017-18:**
  - **Hadron prototype**
  - **20-40 layers, 10-20,000 ch.**
- **Gradual SiPM and tile technology down-select**
- **Exercise mass production and QC procedures**

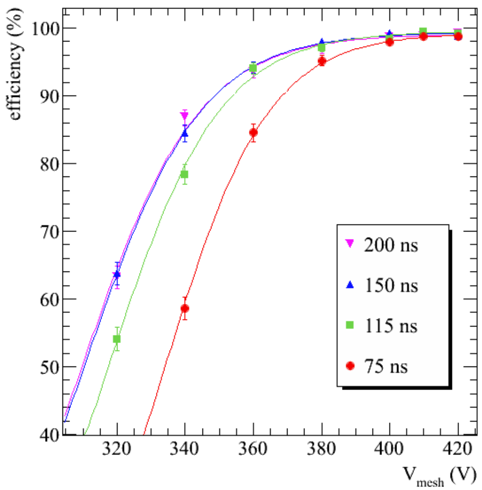


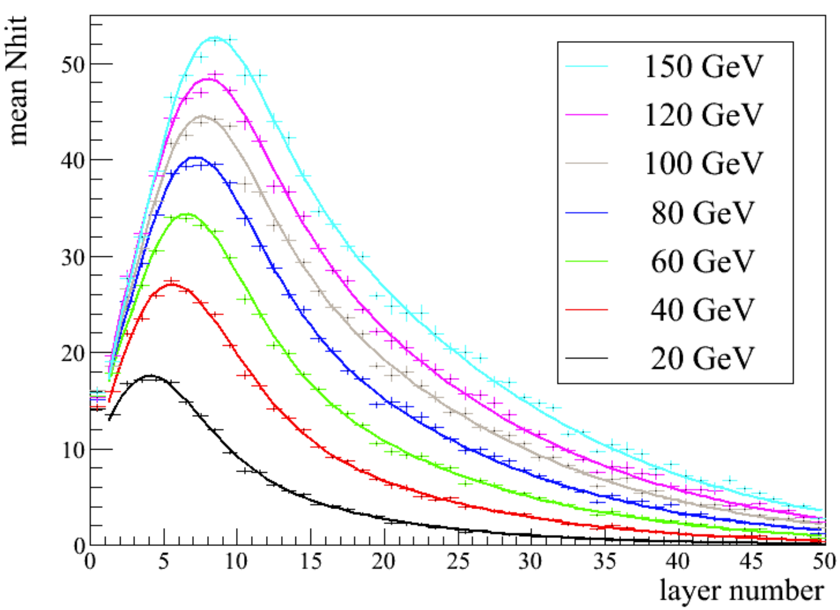




Semi-Digital HCAL: MicroMegas

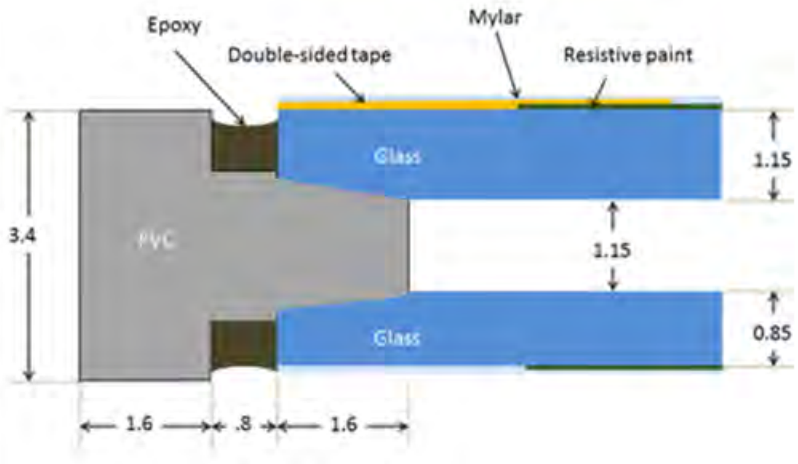
- **Four 1m² MicroMegas chambers built and tested with SD-HCAL readout electronics with three thresholds**
- **Tested Stand-alone**
  - **Muon beam, efficiency tests**
- **Integrated into a 50-layer calorimeter at CERN**
  - **Measured longitudinal profiles**
  - **Response and linearity**

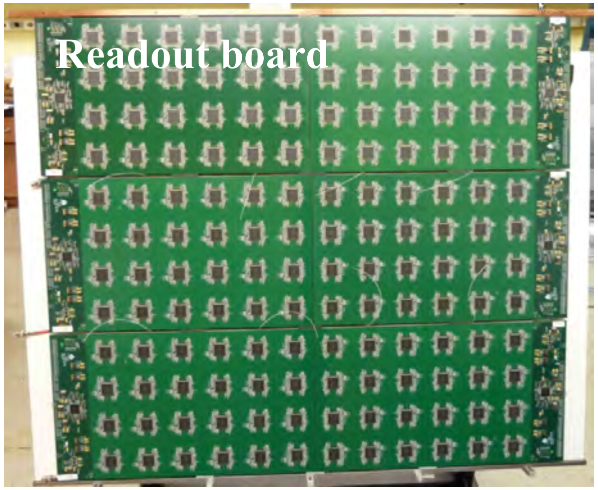




Digital HCAL: RPC

- **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
- **Successfully tested at Fermilab and CERN**
  - **Fermilab tests with ECAL**
  - **CERN tests with W absorber**



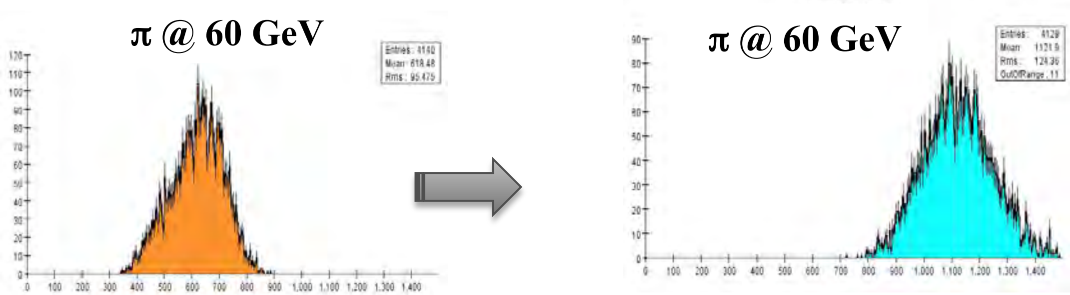


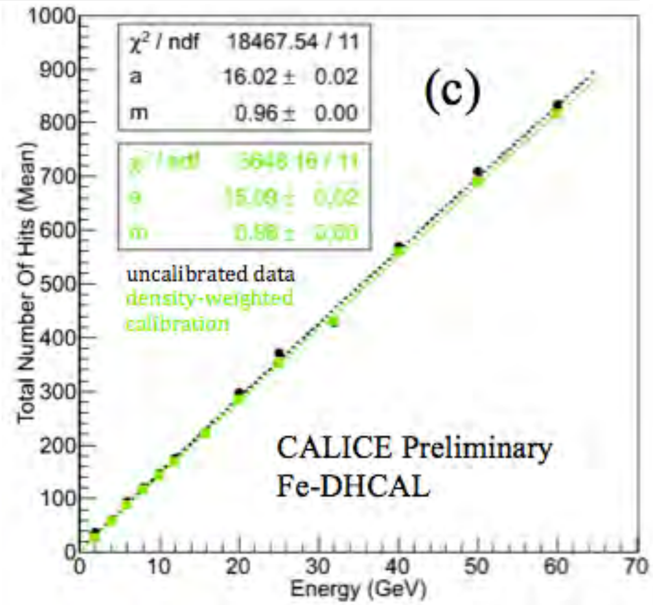
Digital HCAL: RPC

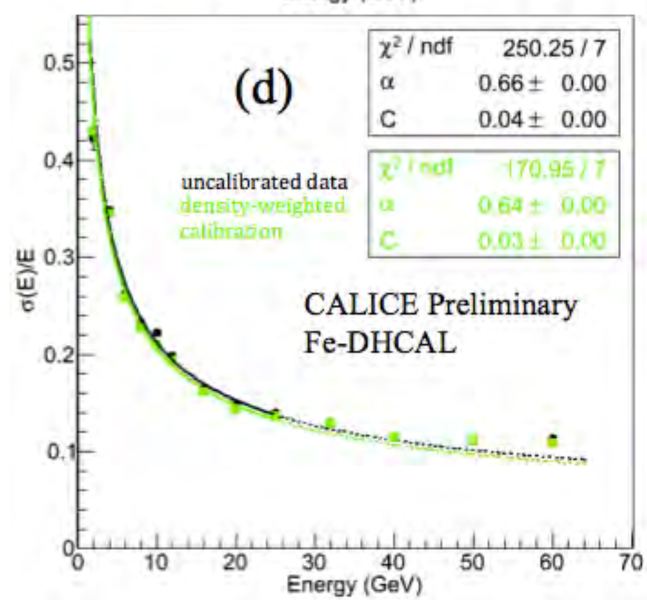
- **Linearity of pion response: fit to aE^m**
  - **Density- weighted calibration; calibration highly non-trivial**
    - a=15.09, m=0.98
  - **1 – 2% saturation (in agreement with expectation)**
  - **Proof of digital calorimetry**

- **Energy resolution fit (Fe)**
  - **C=0.33, S=0.64/√GeV**
  - **Monte Carlo prediction of 58%/√E with negligible constant term**

- **Resolution Gaussian after calibration**

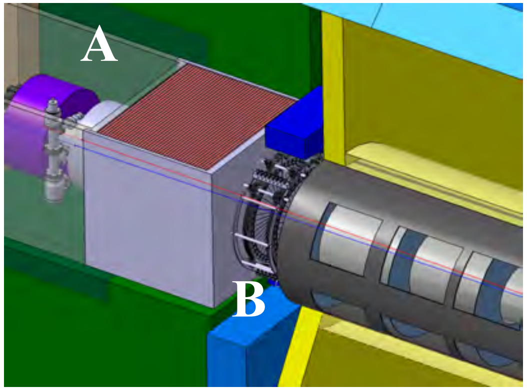


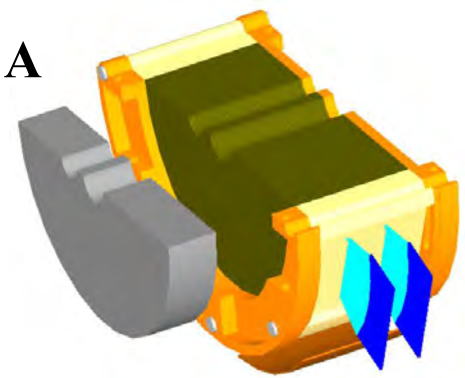


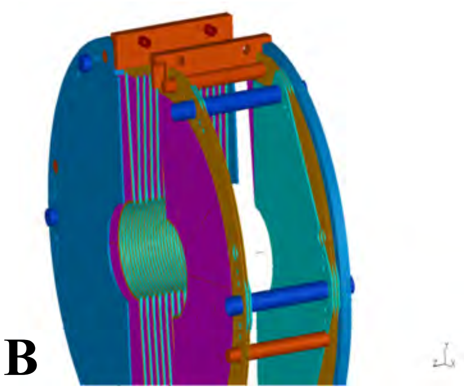


Forward Calorimetry

Forward Instrumentation







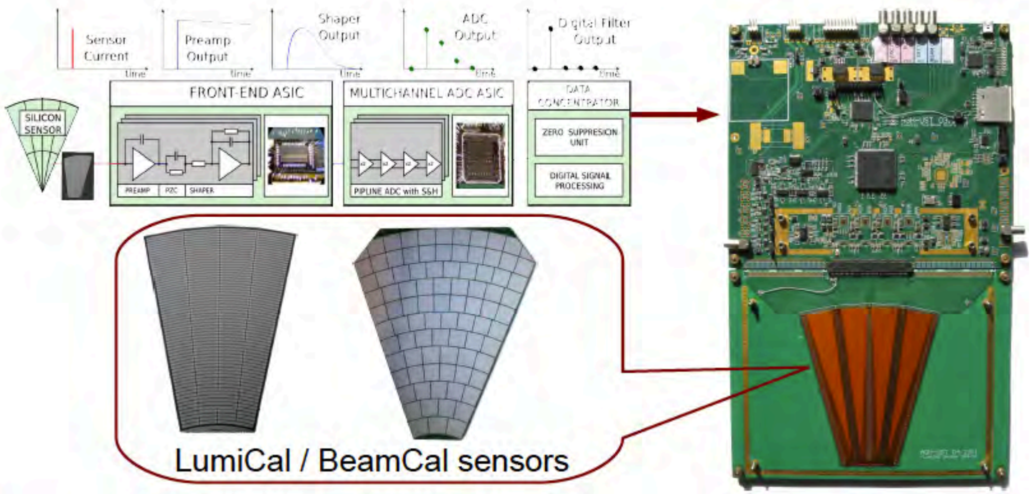
- Precision physics relies heavily on forward instrumentation

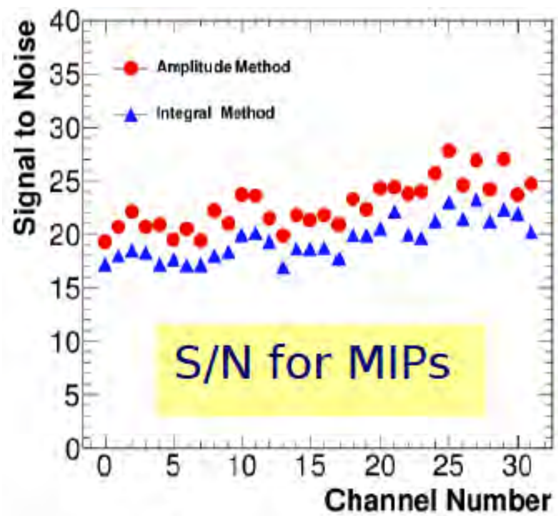
- Beamcal (+ pair monitor): Fast luminosity estimate (bunch-by-bunch)
  - Beam parameter estimation
  - Fast feedback to the machine
  - Hermeticity & Low angle electron tagging

- Luminosity monitor: Precise measurement of luminosity
  - 10^{-3} at ILC
  - Hermeticity
  - Low angle physics

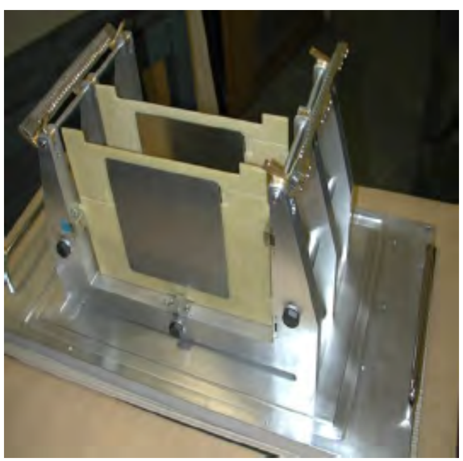
FCAL Beam Tests

- **Completed test beam**





- **Planned test beam**



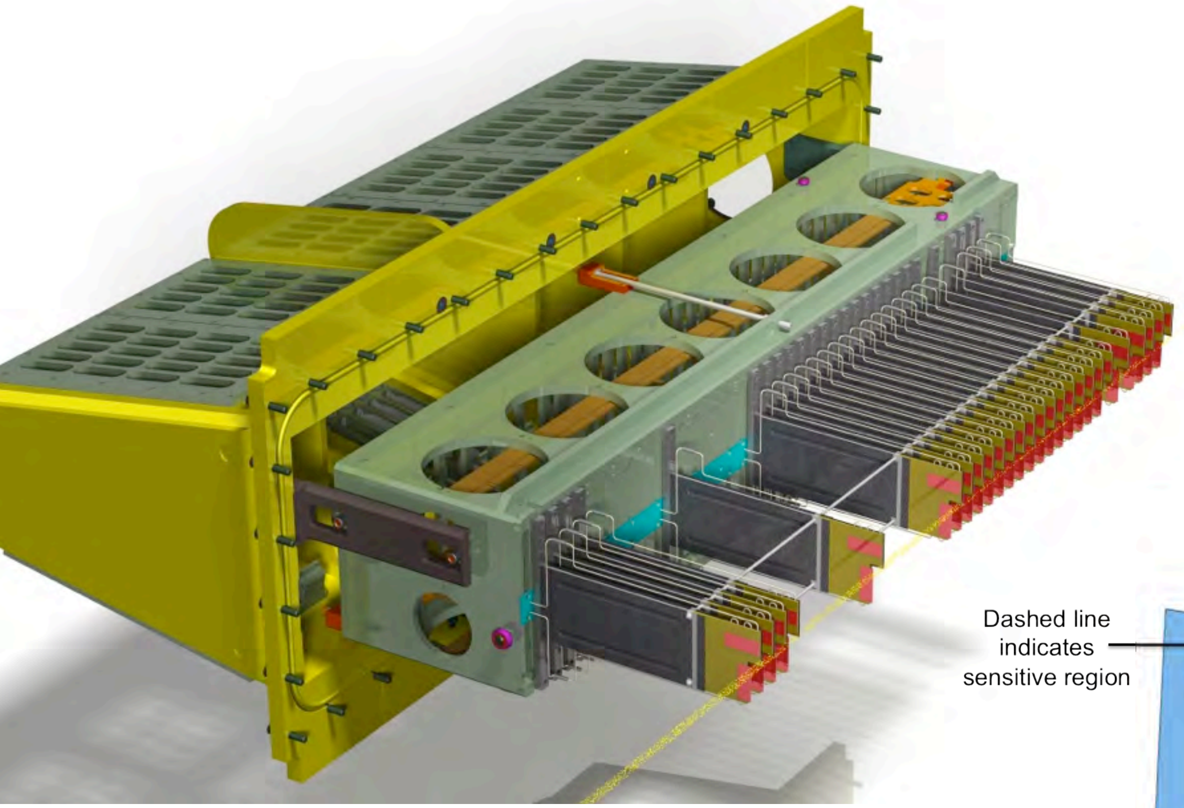
Production of sensors for 30 BeamCal layers

Test with new readout and development of alignment system

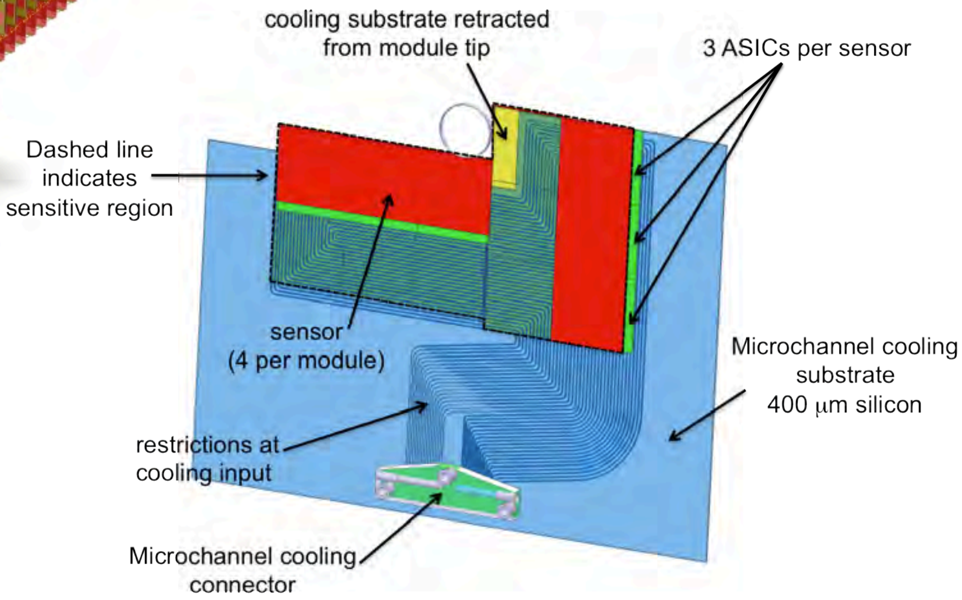
Observations

Elsewhere

- **There is a lot of cutting-edge development going on by other experiments**

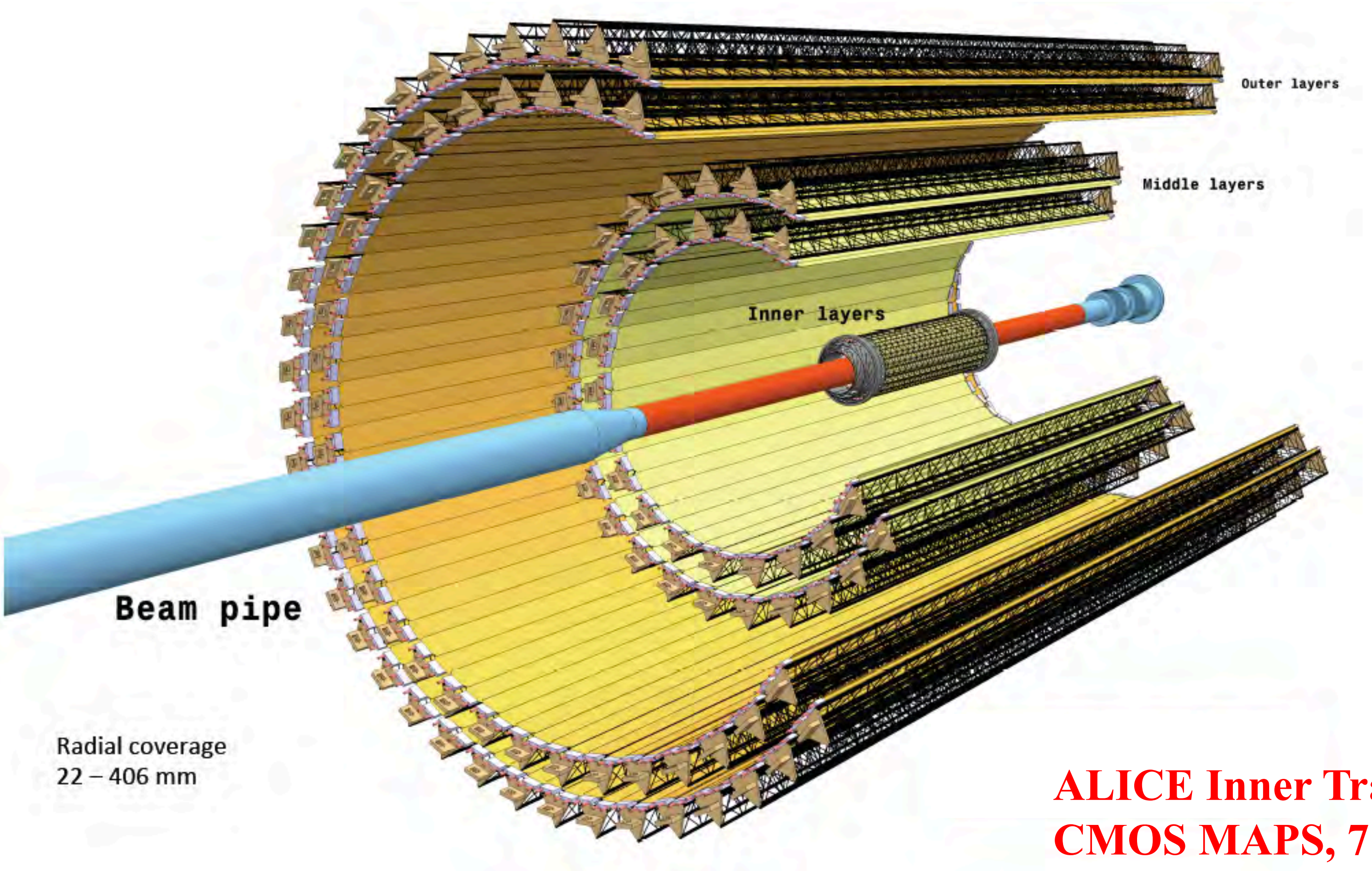


LHCb VELO detector with integrated micro-channel CO_2 cooling at a pressure exceeding 50 bar



Taking data: 2018

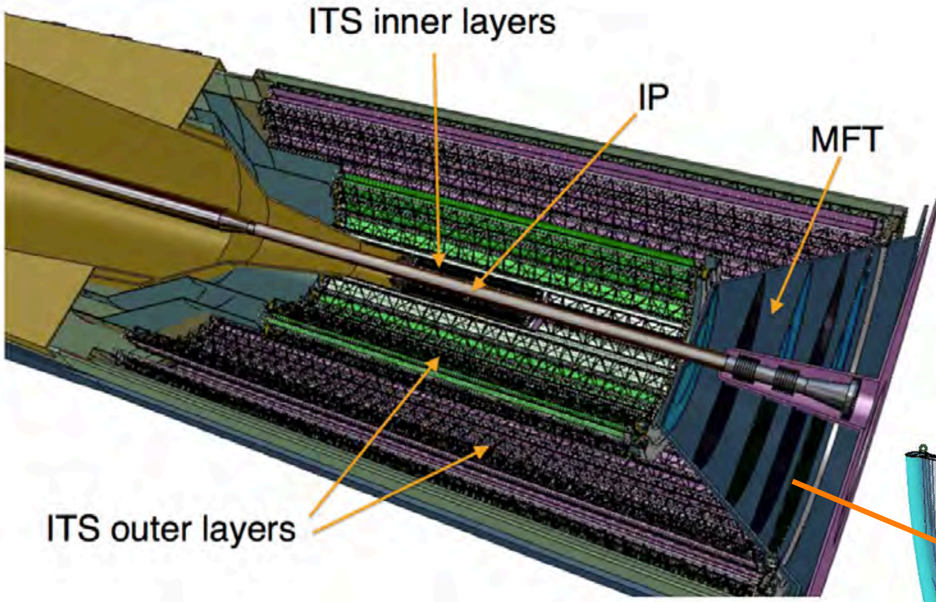
Elsewhere



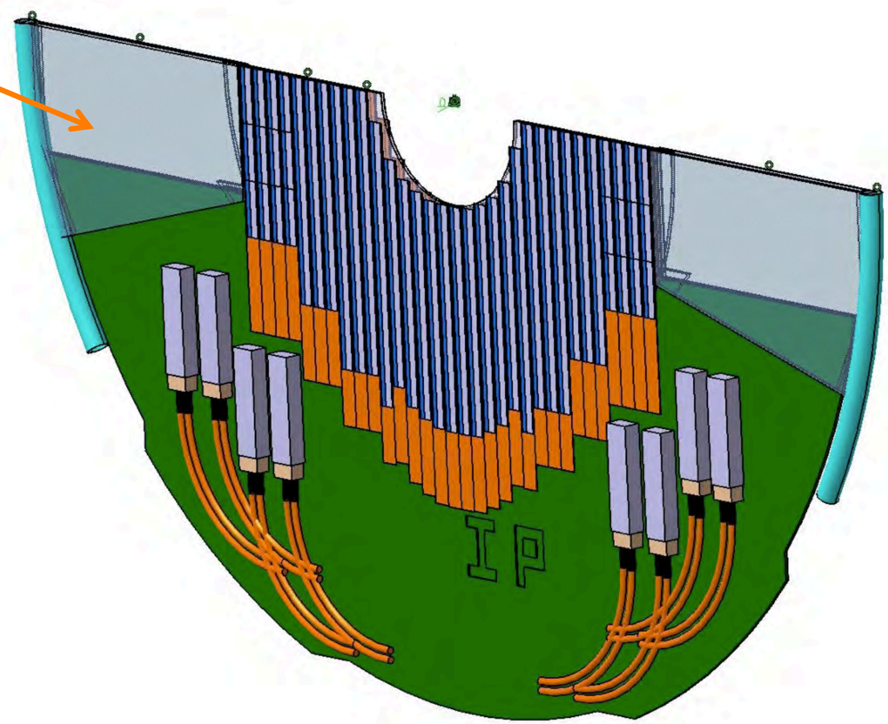
ALICE Inner Tracker System,
CMOS MAPS, 7 Layers
25 Giga pixels!

Taking data: 2018

Elsewhere

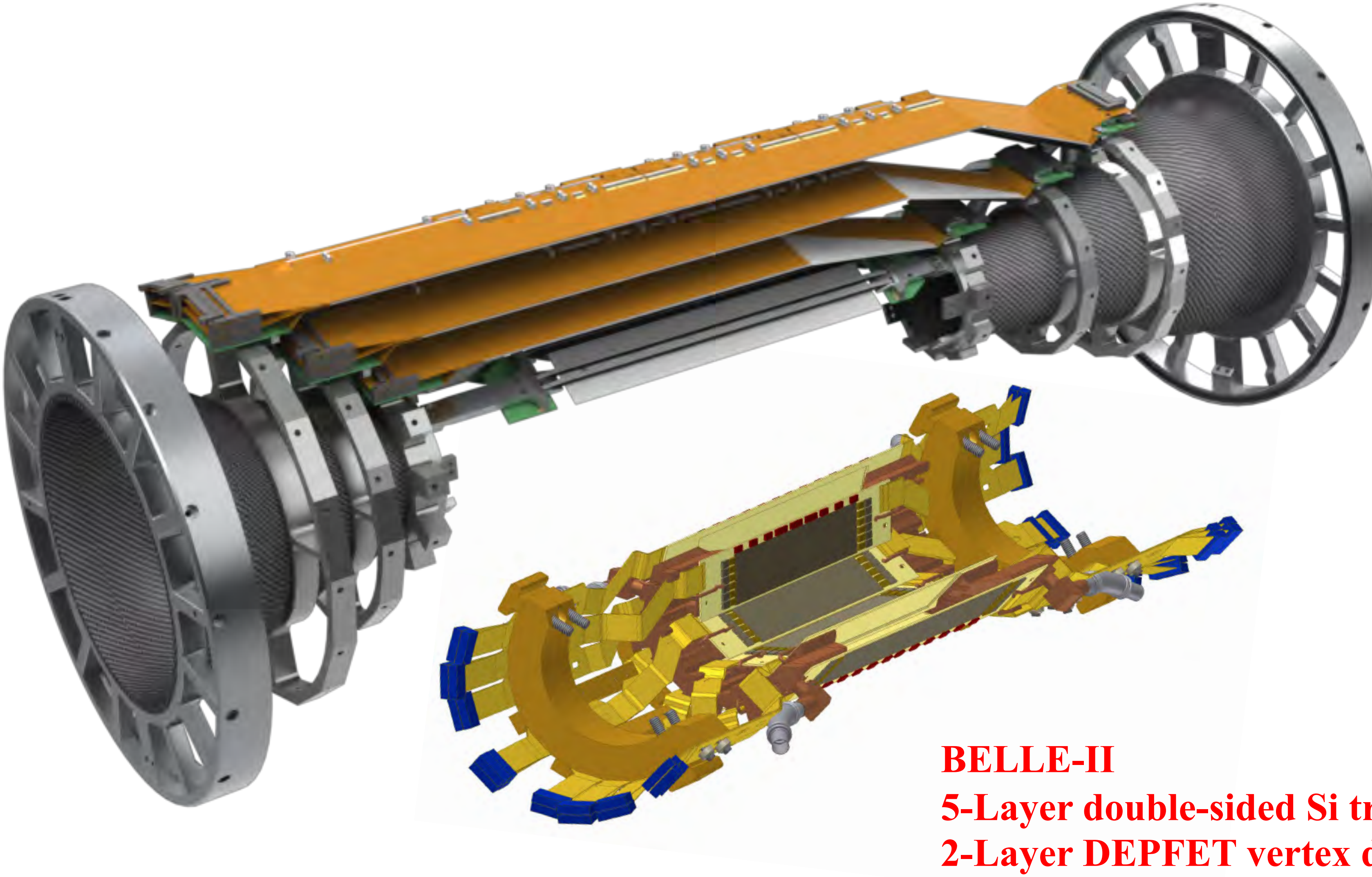


ALICE Muon Forward Tracker
Five disks of CMOS MAPS pixels
25x25 μm^2



Taking data: 2018

Elsewhere



BELLE-II
5-Layer double-sided Si tracker
2-Layer DEPFET vertex detector

Taking data: 2015

Closing

- The LC Detector Community has mounted a very impressive detector research program with very impressive results over a short period with relatively few resources.
- The community is post-DBD, but not yet in the project era.

- There are many ambitious projects outside the LC community with more imminent physics results; there has been good synergy.
- At the same time, there is going to be big pressure on the detector community in the near future, both in terms of human and material resources
  - LHC upgrades
  - Long Baseline Neutrino Program

- A careful bridging of the detector development to the project phase will be of significant importance.