Detectors at Lepton Colliders

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SLAC NATIONAL ACCELERATOR LABORATORY

ILC/C3 vs LHC

- Note that most of the requirements assume a Particle Flow approach - but this could also be re-visited
- Calorimeter granularity
  - Need factor ~200 better than LHC
- Pixel size
  - Need factor ~20 smaller than LHC
- Material budget, central tracking
  - Need factor ~10 less than LHC
- Material budget, forward tracking
  - Need factor ~ >100 less than LHC

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

- Required radiation tolerance from the beam related background affects mostly the innermost layer.
- 1 kGy and 10^{11} n_{eq}/cm^2 per year, assuming neutrons backscattered from beam dump are shielded well enough

ILC vs C3 optimizations

Bunch spacing is different but detector R&D would not be significantly impacted

- ILC~300ns versus C3~3.3 ns

C3 has the potential to go higher in center of mass energy (up to 3 TeV)

- Detector optimization for high energy might lead to different choices
- Beyond 2-3 TeV the beam dynamics at the IP gets challenging

Timeline for ILC detectors

(estimates from Marty)

It will take at least 5 years of fully supported hard work to produce a TDR for a construction start.

- Significant work on a TDR requires rebuilding the collaboration; difficult before the ILC is approved.
- A middle ground might be significant support for the detectors coincident with the pre-lab initiation

Availability of serious R&D support	starting point
Collaboration re-formation	~1 year
TDR	~5 years
Detector Construction	-7 (optimistic) -10 (more realistic) years, primarily dependent of funding levels

SiD had 36 U.S. institutions that signed the LOI (out of 77 total).

The U.S. activity is now only SLAC, FNAL, ANL, PNNL and UTA, UCSC, UCD, and UofO. The national lab activity is almost gone as DOE has almost stopped ILC detector R&D.

Cost scale (2016)

- The SiD construction cost estimate from the DBD is:
  - Base M&S 315 M$
  - Contingency M&S 127 M$
  - Engineering 186 Man-Years
  - Technical 532 Man-Years

- Magnet (162M$) and EMCal (183M) are driving cost of the SiD detector.

WBS	Decription	M&S	M&S Cont	Labor	Labor Cont	Total
1.1.1	Beamline Systems	$ 3,680,000	$ 1,423,000	$ 1,525,864	$ 508,692	$ 7,137,556
1.1.2	VXD	$ 2,797,000	$ 2,035,000	$ 2,200,359	$ 802,325	$ 7,834,684
1.1.3	Tracker	$17,743,797	$ 6,866,105	$ 9,359,577	$ 3,712,232	$37,681,712
1.1.4	EMCal	$99,927,619	$ 39,966,048	$31,946,627	$11,177,819	$ 183,018,113
1.1.5	Hcal	$51,607,707	$ 20,110,325	$ 5,626,083	$ 1,969,129	$79,313,244
1.1.6	Muon Sys	$ 8,299,900	$ 2,904,965	$ 2,502,565	$ 860,550	$14,567,980
1.1.7	Electronics	$ 4,899,887	$ 1,649,911	$ 9,688,085	$ 1,598,125	$17,836,008
1.1.8	Magnet	$ 114,801,030	$ 39,452,437	$ 5,642,201	$ 1,920,276	$ 161,815,944
1.1.9	Installation	$ 4,102,800	$ 1,082,070	$ 4,746,050	$ 1,677,383	$11,608,303
1.1.10	Management	$ 921,000	$ 171,700	$ 9,120,454	$ 2,236,359	$12,449,513
Totals (M$)		$ 308.8	$ 115.7	$ 82.4	$ 26.5	$ 533.3

R&D ideas

Item	Benefits	Duration (years)	R&D Cost (M$)	Cost Benefits (M$) -if R&D successful
Superconducting Cable Improvements	Lower conductor cost, reduce coil by one layer, reduce steel thickness	4	6	50
Eliminate Detector Integrated Dipole (DID)	Lower coil cost, radius, and risk	1	0.1	25
MAP Development	lower cost, lower risk, better performance	4	5	~5
Tungsten Manufacturing Process	lower cost	3	3	~10
Note: There is very substantial R&D that must be done to make the detector possible, and is necessary to make the existing cost estimate plausible!				

R&D for SiD

- Solenoid : room for improvements over the CMS technology

- Tracker MAPS - (Historically FNAL with some SLAC involvement)
  - On going R&D @SLAC with US-Japan, Japan-US funds
  - Recent new submission at Desy
  - Note that although the vertex detector will be based on a different technology, it will be likely a responsibility of the same institute

- Calorimeter MAPS - historically an area where SLAC had been leading
  - A prototype is under test

- HCAL : Desy lead

SLAC Experience from ATLAS

IBL

- 3D Sensor design and optimization
- DAQ
- electrical services
- Detector QA

ITK

- Pixel vertex detector assembly and testing
- Data transmission
- DAQ

Timing : HGTD (fast timing) ASIC readout chip design

Currently evolving towards 4d Tracking effort

TDAQ

- Luminosity, Beamspot, Trigger algorithms

A natural progression from ATLAS to a lepton collider would be a focus on vertex and tracker detectors

Summary

We will have to evaluate best match between current resources and ILC/C3 detector needs in the next couple of years

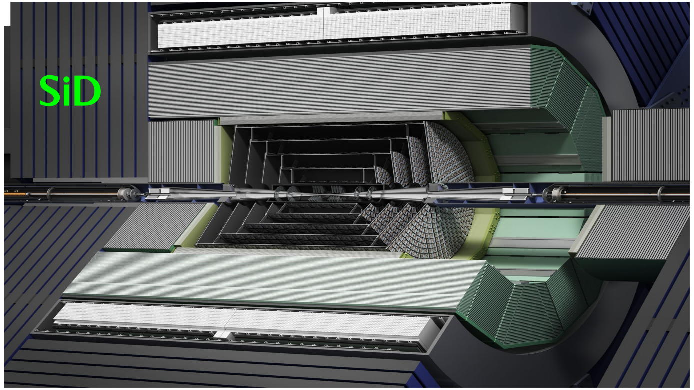
- Important to start now if we want to have a leading role in the future
- Tracker seems to be a natural choice, but other opportunities too
- The way we engage for ILC and C3 might be somewhat different.
    - C3 could be aiming for on site as a host lab and more ambitious coverage would be natural and important.

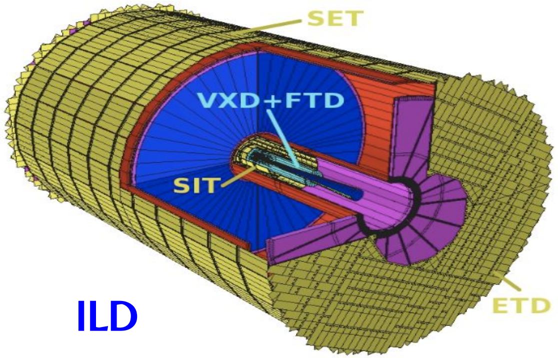
Depending on the $$$ available we could start ramping up with allocated engineering time to follow up on :

- MAPS R&D / Solenoid / VTX detector dedicated technology

Backup

Introduction

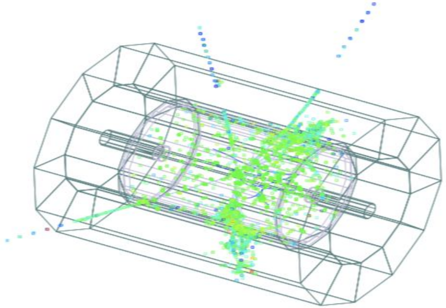




- Future lepton colliders target unprecedented precision on physics ↔ extremely high precision detectors
- Silicon strip and pixel detectors are **key** for precision charged particle tracking, secondary vertexing, and as input to Particle Flow reconstruction - which is assumed as baseline
- Minimizing material budget is vital → Exciting Si pixel & strip technologies in development

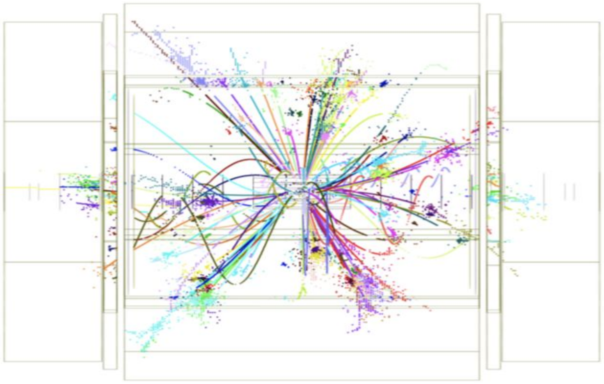
Detectors at ILC

Two detector designs developed with complementary features **that maximize BR²** exploiting the beam-time-structure :



SiD is a compact, cost-constrained detector

- 5 T solenoid magnetic field with with R_{ECAL}=1.27 m
- All-silicon tracking system
- Highly granular calorimeter optimized for particle flow analysis

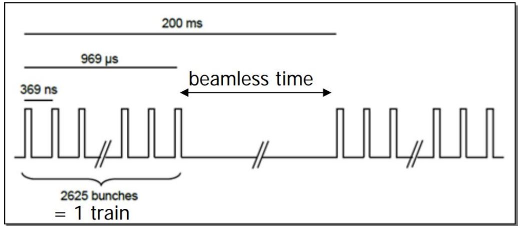


ILD is a large detector

- Time Projection Chamber (TPC) providing continuous tracking for e dE/dx capability, V0 reconstruction
- 3.5 T (4 T) magnet with R_{ECAL}=1.85m (1.46 m) for ILD-L (S)
- Highly granular calorimeter, with minimal material between the int calorimeter.

Physics Drivers → Detector Design Requirements

- Requirements on single point resolution of sensors, location of innermost layer, and overall detector occupancy
  - **Very small pixels** for excellent IP resolution and minimal pattern recognition ambiguity
  - **Minimal material** as close to the interaction point as possible:
    - Goal <0.3% X0 per layer (ideally 0.1% X_0) for vertex detector and <1% X0 per layer for Si-tracker
  - **Low power** to eliminate need for active cooling
- ILC timing structure: Fraction of a percent duty cycle
  - **Power pulsing possible**, significantly reduce heat load
    - Factor of 50-100 power saving for FE analog power
  - Si vertexing & tracking detectors **don't need active cooling**
    - Significant lowers mass budget
  - **Triggerless readout** possible

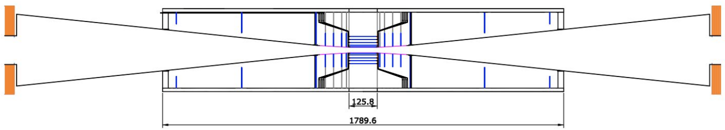


1 ms long bunch trains at 5 Hz

2820 bunches per train

308ns spacing (ILC TDR)

- Compact, cost constrained detector
  - 5 T solenoid B-field with with R_{ECAL}=1.27 m
  - All silicon pixel + strips tracking system
  - Highly granular calorimeter optimized for PFLOW



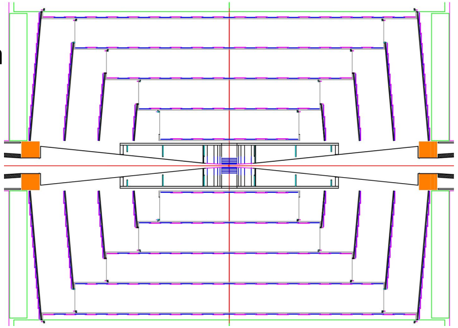
- Pixel Vertex detector
  - 1 kGy and 10^{11} n_{eq}/cm^2 per year
  - **Pixel hit resolution** better then 5 μm in barrel
    - Better if charge sharing is used
  - Less than **0.3% X_0** per pixel layer
    - air cooling → low-mass sensor
  - Single bunch time resolution
    - Low capacitance and high S/N allows for acceptable power dissipation for sin 300-700 ns)

20x20 μm pixels in the central region

50x50 μm for the forward tracker disks

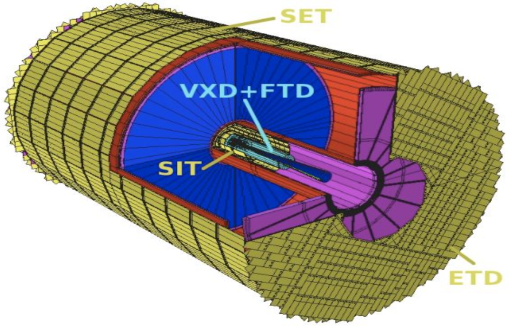
Barrel	R	z_{max}	
Layer 1	14	63	
Layer 2	22	63	
Layer 3	35	63	
Layer 4	48	63	
Layer 5	60	63	
Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	14	71	72
Disk 2	16	71	92
Disk 3	18	71	123
Disk 4	20	71	172
Forward Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	28	166	207
Disk 2	76	166	541
Disk 3	117	166	832

- Strip Tracker:
  - Silicon micro-strips, double metal layers
  - 0.1-0.15% X_0 in the central region

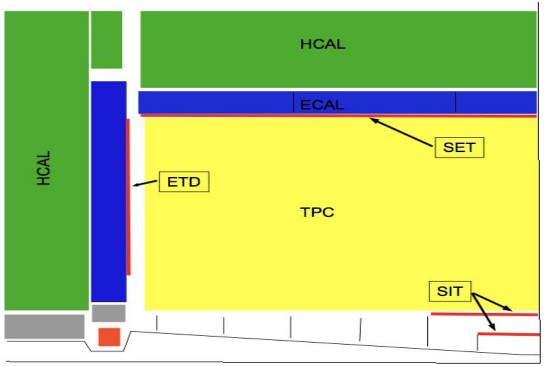


ILD in a nutshell

- Question if all-silicon tracking is too massive **TPC-based** design
  - Large number of hits for a robust pattern recognition
- Tracker = pixel vertex detector + Si-strip detectors + TPC
  - VTX has long barrel approach
    - 17x17μm pixel in 1st layer spatial resolution <3 μm
  - Si-strips: High precision space points outside the TPC system
    - Redundancy in regions b/w main tracker and calorimeters



- Large volume time projection chamber (TPC) w/ 224 points per track.
  - Optimized for 3D point resolution and minimum material in field cage and end-plate (<0.25% X_0)
    - T2K (Ar-CF4(3%)-isobutane(2%)) gas
    - Drift length of 2m in 3.5T field
  - Resolution goal: σ_{point} in rϕ <100 μm (60 μm) full drift (zero drift)
  - Momentum resolution of ~10^{-4} GeV^{-1} with TPC alone
  - **dE/dx based particle identification, 5% resolution**



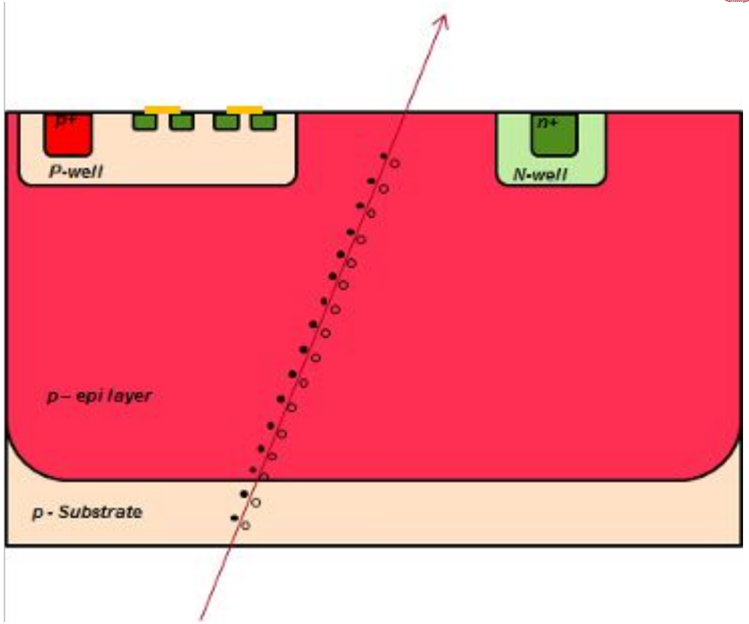
Sensor technology overview

- Sensor's contribution to the total material budget of vertex detector is 15-30%
- To meet the physics performance sensors will have to be less than 75 µm thick with ~ 5 µm hit resolution (17-25µm pitch) and low power consumption:
  - continuous r/o during the train with power cycling
  - delayed after the train → either ~5µm pitch for occupancy or in-pixel time-stamping
- Several possible choices for the VTX detector:
  - Monolithic Active Pixels (MAPS)
    - CMOS Pixel Sensors (CPS)
    - Fully Depleted on High Resistivity Substrate (DNwel sensing)
    - Fully Depleted SOI technologies
  - Depleted Field Effect Transistors (DEPFET)
  - Fine pixel Charged Coupled Devices (CCD)
  - 3D integration

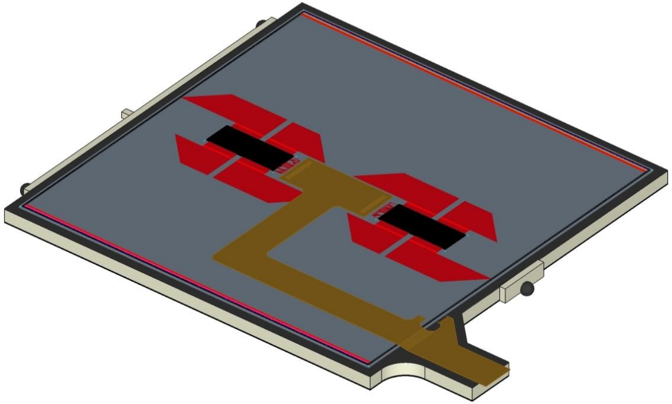
The general landscape is also changing rapidly with advances in microelectronics

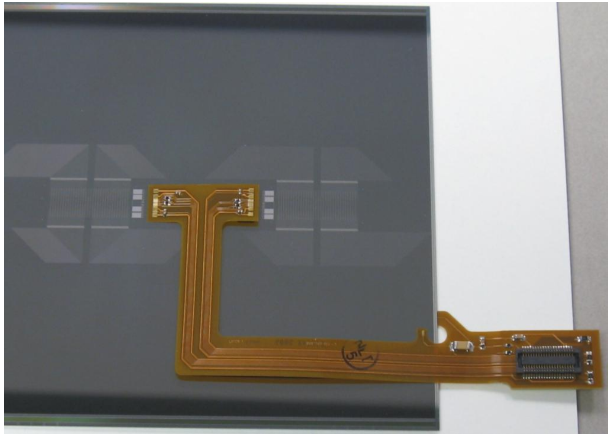
MAPS for SiD tracker detector

- Monolithic technologies have the potential for providing higher granularity, thinner, intelligent detectors at lower overall cost.
  - Significantly lower material budget: sensor and readout electronics are integrated on the same chip
    - Eliminate the need for bump bonding and can be thinned to less than 100µm
  - Smaller pixel size, not limited by bump bonding
  - Lower costs - can be implemented in standard commercial CMOS technologies
- Over the past decade, SiD has developed a first generation of sensors, readout with KPiX – which is the baseline approach.



kPixM





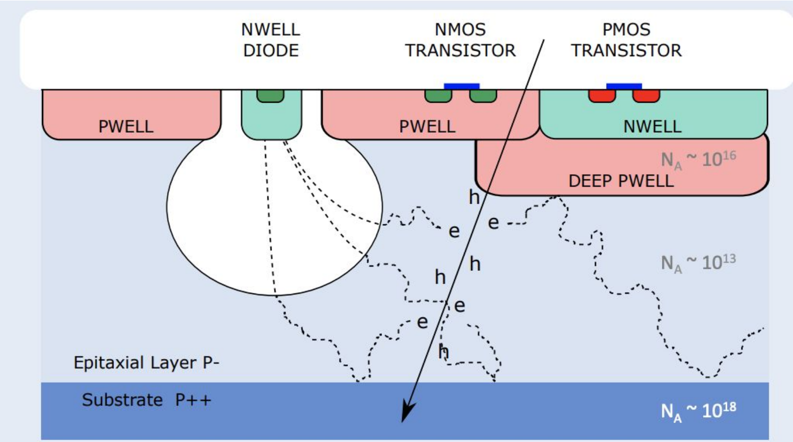
- SLAC has developed a Monolithic version of kPix (kPixM) class of devices both for the tracker and the E-calorimeter:
  - kPixM-Trk has pixels of 50µmx500µm size arranged in a 2400x200 matrix.
    - A position resolution of <14 µm is expected
  - To be useful for a collider detector, the area of MAP sensors will be O(100)m^2

KPiX Track module:

- 25/50 µm strip pitch
- Two KPiX chips per sensor
- low mass readout cable services two chips and is also bump bonded to the face of the sensors

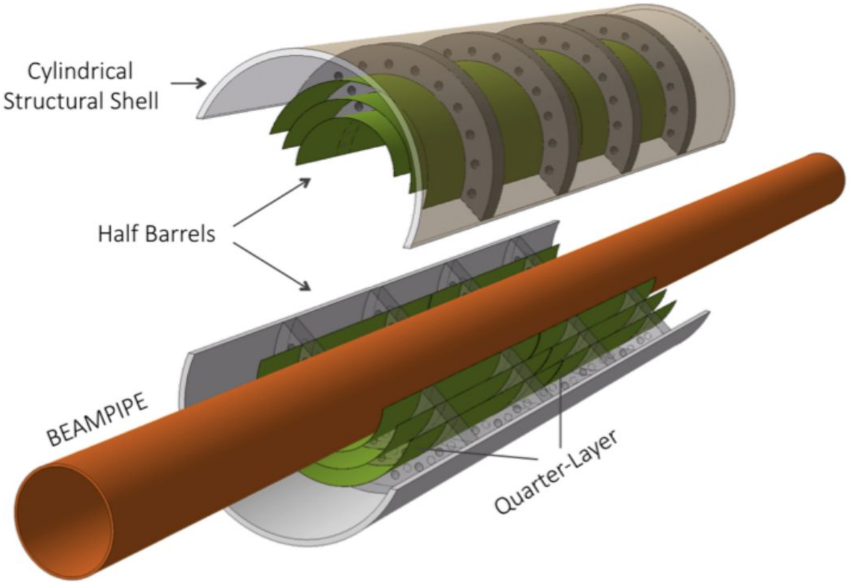
CMOS in HEP

- CMOS-MAPS originally conceived by the HEP mainly in the ILC framework (since 2000)
  - **STAR** HEAVY Flavour Tracker @ RHIC(2014):
  - With the current tracker upgrade **ALICE** redefined the new state-of-the art in CMOS MAPS technology and its applications in HEP
- ALice PIxel DEtector (ALPIDE) employes CMOS Pixel sensor used in imaging process
  - Full CMOS circuitry within active area
  - Sensor thickness = 20-40 µm (0.02-0.04% X_0)



- The used technology offers further opportunities: smaller feature size, **bending** that directly impact the key measurements that highly rely on precise vertexing and low material budget

ALICE: Bent MAPS for Run 4



Bending Si wafers + circuits is possible

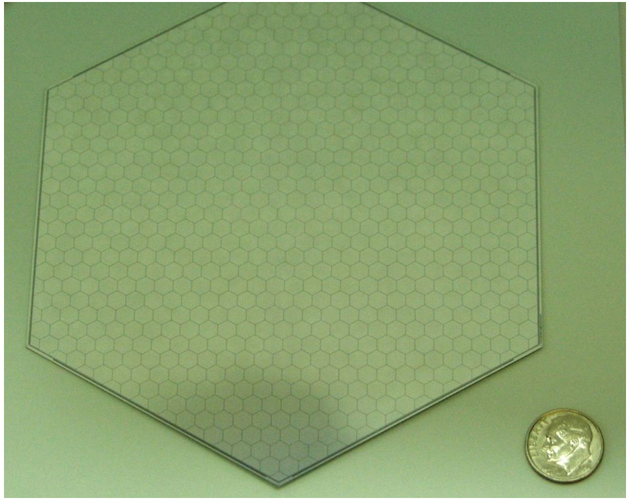
Recent ultra-thin wafer-scale silicon technologies allow:

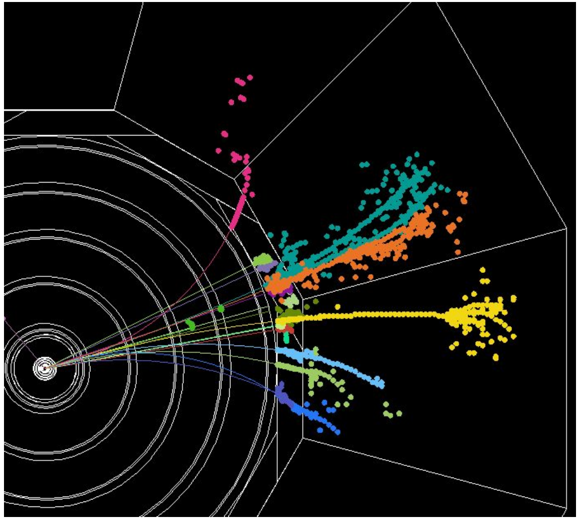
Sensor thickness = 20-40 µm - 0.02-0.04% X0

Sensors arranged with a perfectly cylindrical shape a sensors thinned to ~30µm can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)

Calorimetry- Optimized for Particle Flow – Baseline sensors

- SiD ECAL
  - "Imaging" calorimeter utilizing 30 layers of Si with 5 mm pixels.

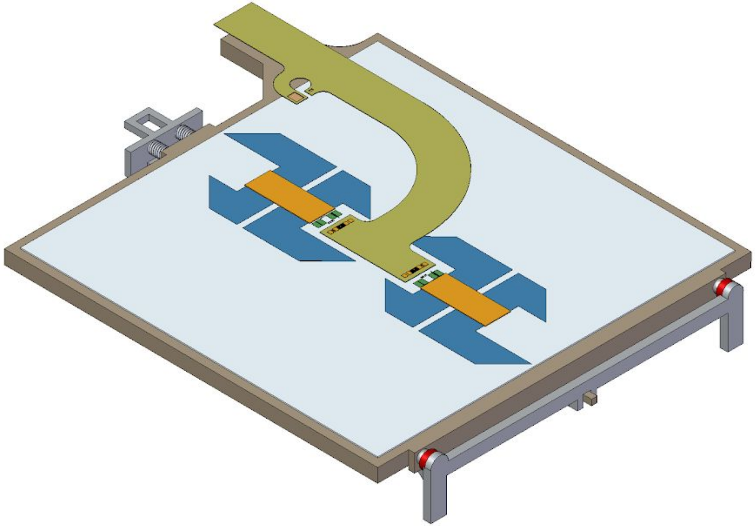


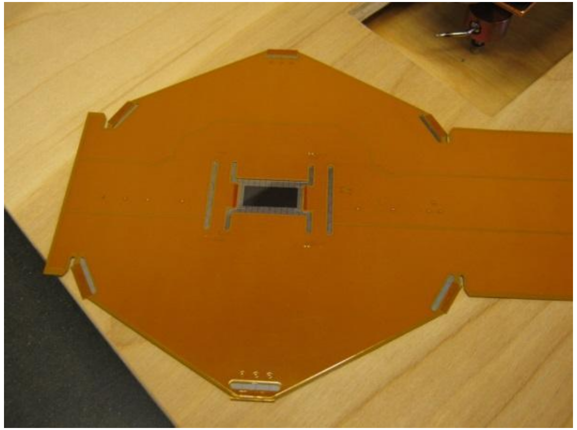


Particle flow significantly improves jets resolution by reducing contribution of hadron calorimeter resolution.

Pandora simulation: ΔE/E ~3-4%

Baseline Sensor Module





- Hamamatsu high resistivity sensors with bump bonded SOC KPiX.
  - Sensors are expensive, lots of handling
  - KPiX tailored to ILC
- Perfect solution 25 years ago.
- It’s time to develop Collider Detector MAP’s

CDMAP's

- Environment is benign. ~0 hit rate, 100 kRads lifetime dose.
- Tracker: 67 m^2 sensor area
- EMCal: 1200 m^2 sensor area
- C3 (Cool Copper Collider) 120 Hz Train rate, 75 bunches spaced by 3.3 ns.
- ILC 5 Hx Train rate, 1312 bunches spaced by 554 ns.