Experimental Challenges and Techniques for Future Accelerators

XI ICFA School on Instrumentation in Elementary Particle Physics

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DESY

Outline

> **Lecture 1**
- Future particle physics at the energy frontier: case for a Linear Collider
- Linear Collider Concepts
- Experimental Challenges

> **Lecture 2**
- Detector Concepts
- R&D for detector components
- Vertex detector
- Tracking detectors
- Calorimeters

Detector Concepts

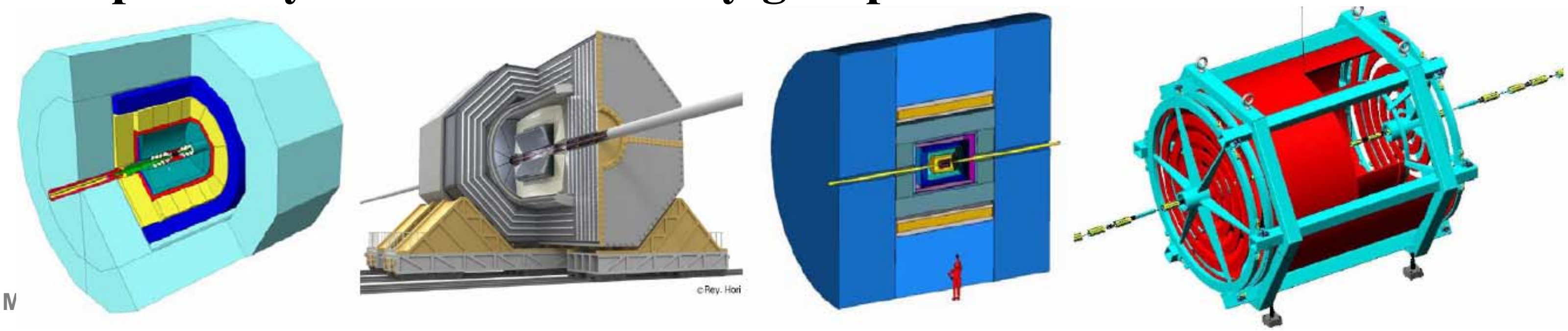
- Four detector concepts (have been) investigated
  - GLD (Global Large Detector)
  - LDC (Large Detector Concept)
  - SiD (Silicon Detector)
  - 4th concept

Merged into one concept: (ILD) International Large Detector

- Summer 2006: Detector Outline Documents (DOD) evolving documents, detailed description

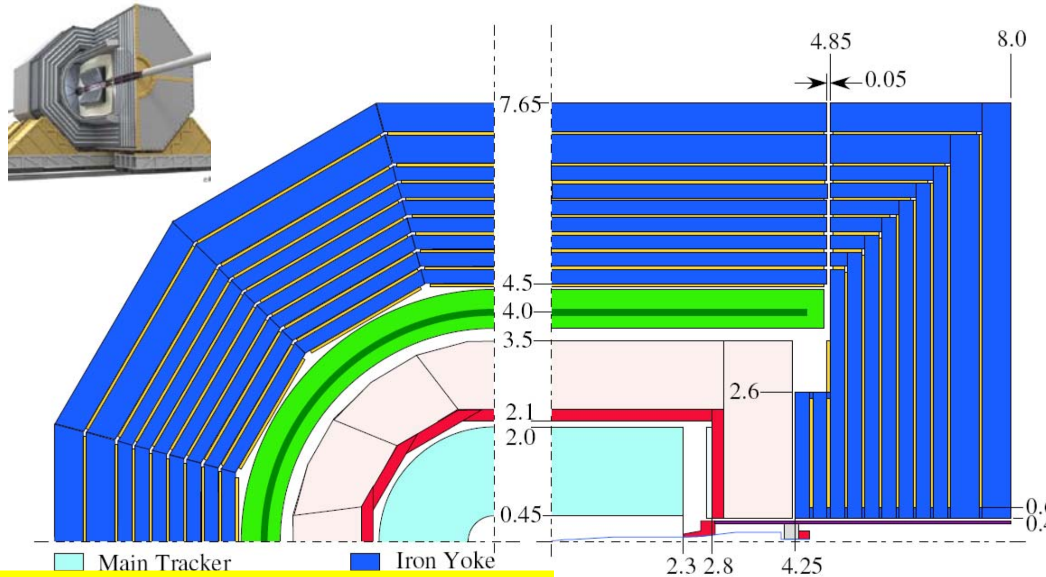
- Summer 2007: Reference Design Reports (RDR) comprehensive detector descriptions, along with machine RDR

- Prepared by international study groups



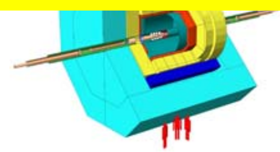
Detector Concepts

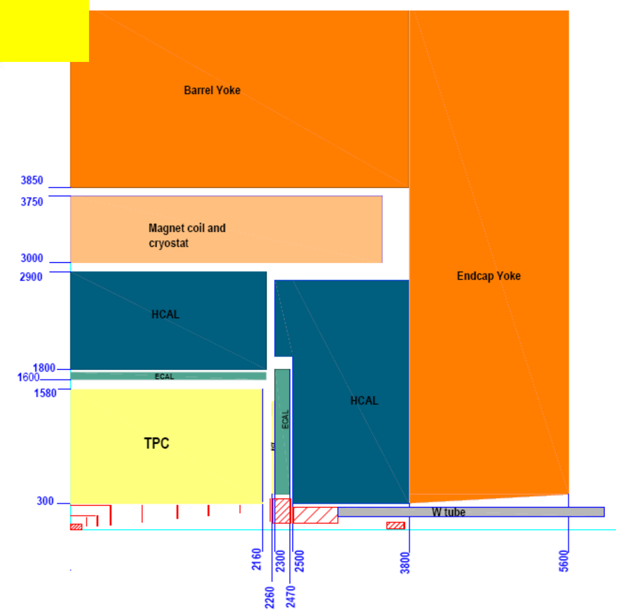
- GLD
  - TPC tracking
    large radius
  - particle flow calorimeter
  - 3 Tesla solenoid
  - scint. fibre µ detector

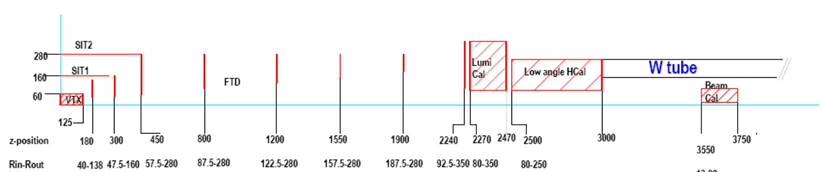


Both concepts are rather similar have merged into one (ILD)

- LDC
  - TPC tracking
    smaller radius
  - particle flow calorimeter
  - 4 Tesla solenoid
  - µ detection: RPC or others

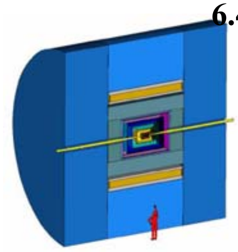


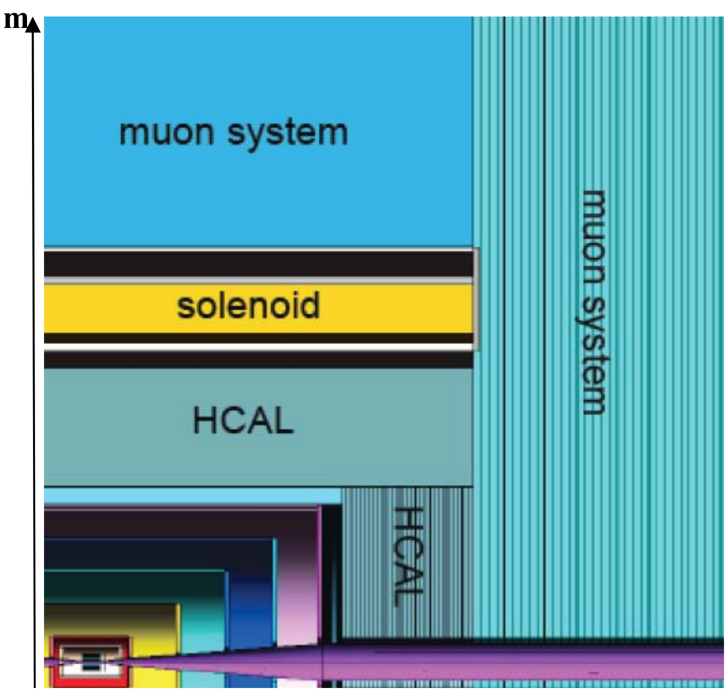




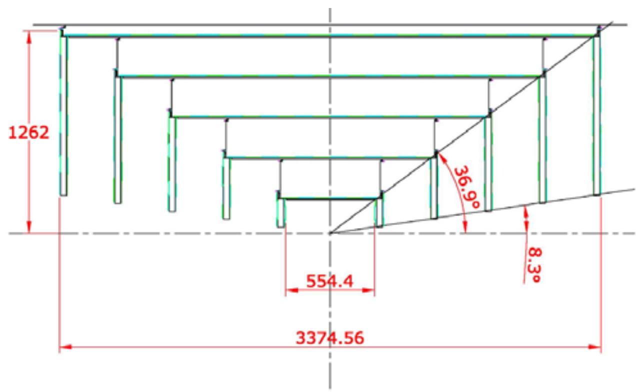
Detector Concepts

- **SiD**
  - silicon tracking
  - smaller radius
  - high field solenoid (5 Tesla)
  - scint. fibre / RPC μ detector

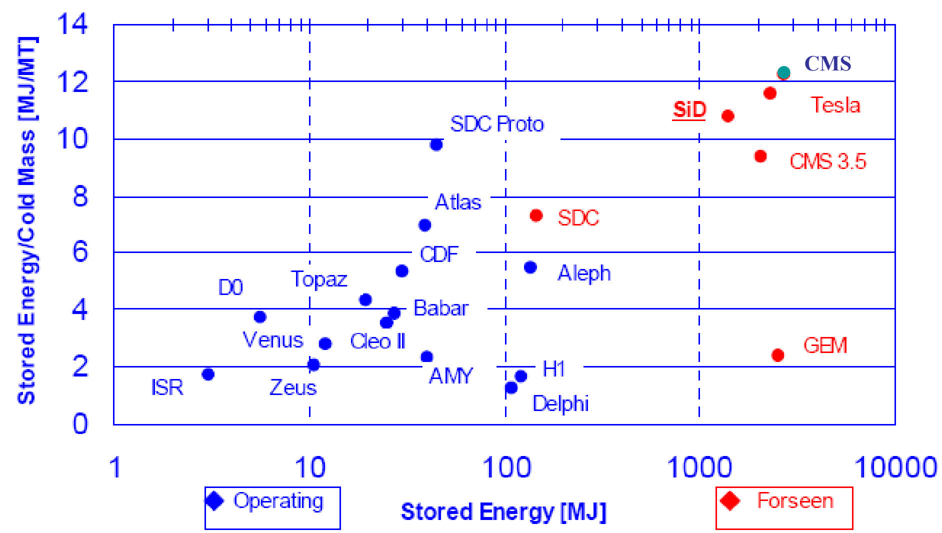




- **Silicon tracker**



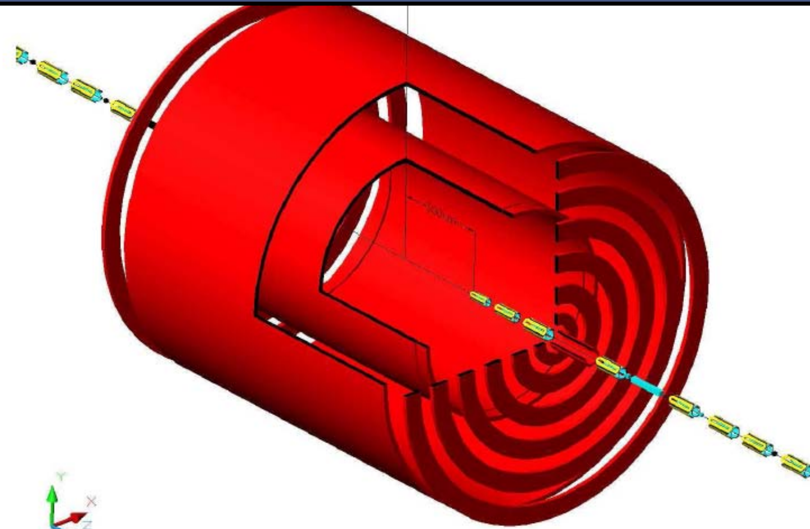
- **Magnet**
  - high field
  - but smaller volume

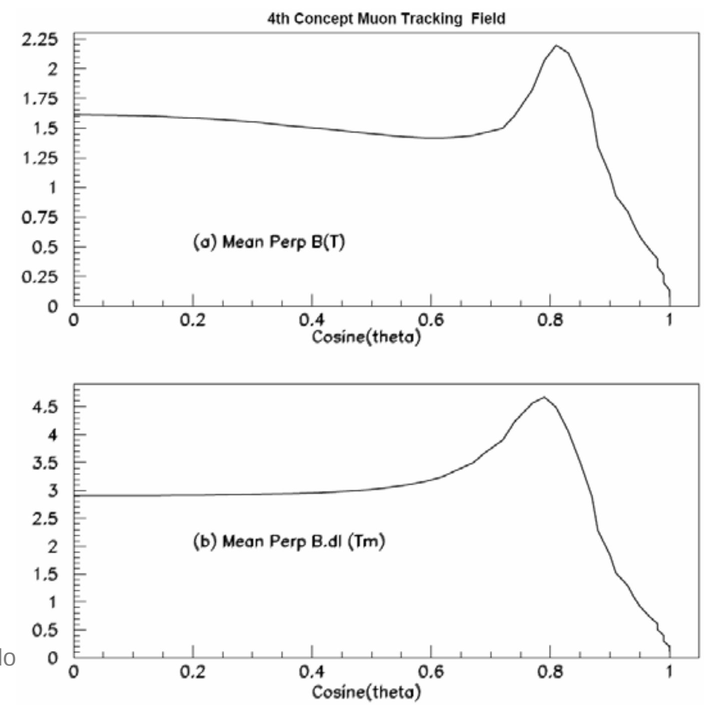


Detector Concepts

- **4th concept**
  - gaseous tracking
  - multiple readout calorimeter
  - iron-free magnet, dual solenoid
  - muon spectrometer (drift tubes)

- **Dual solenoid**
  - iron return yoke replaced by second barrel coil and endcap coils

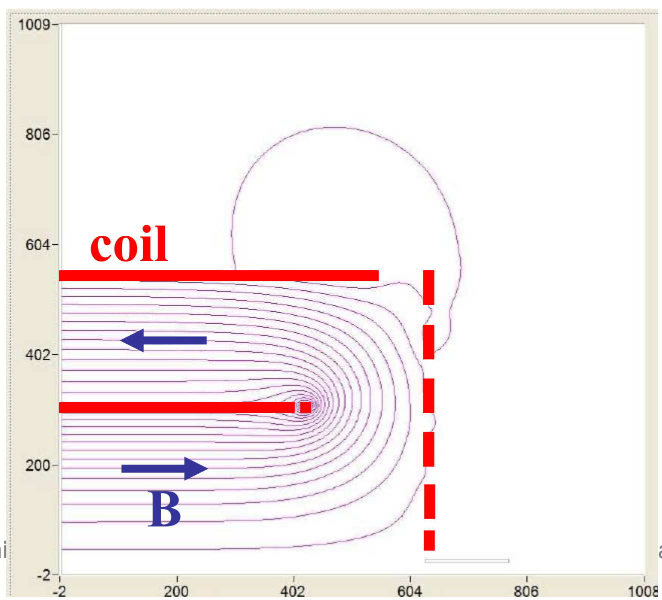




Average field seen by μ:

$\langle B \rangle \approx 1.5$ T

$\langle Bl \rangle \approx 3$ Tm



Detector Concept and R&D efforts

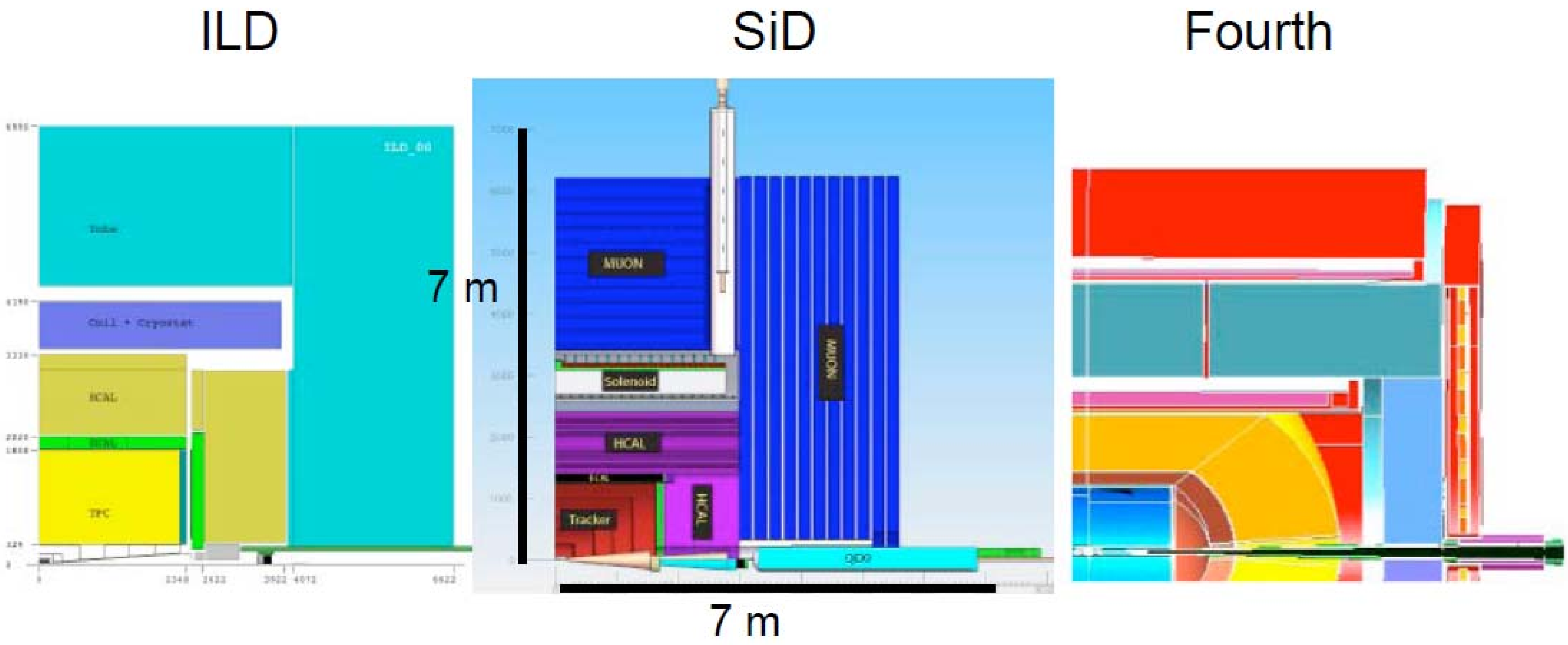
- R&D efforts for key detector elements
- Overlap with detector concepts:

	ILD	SID	4th concept	Detector R&D collaborations
Vertex	X	X	X	LCFI
Tracking				
- TPC	X		X	LCTPC
- Silicon	*	X	*	SILC
Calorimetry:				
- Particle Flow	X	X		CALICE
- Multiple Readout			X	
- Forward region	X	X	X	FCAL

* silicon forward and auxiliary tracking also relevant for other concepts

ILC International Detector Advisory Group

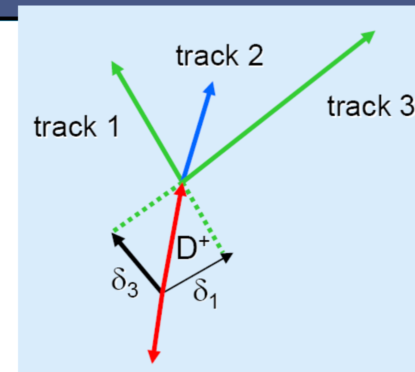
- September 2009: recommendations by „wise men“ on validation of concepts

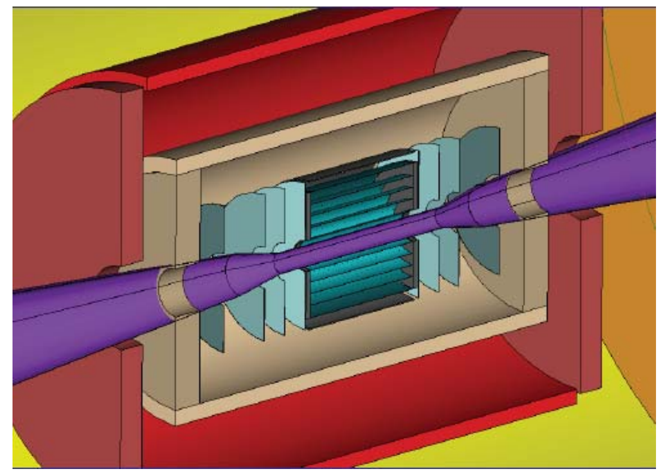


- ILD and SiD concepts should continue to develop
- 4th not validated
  but R&D on dual readout calorimetery should continue (→ CLIC)

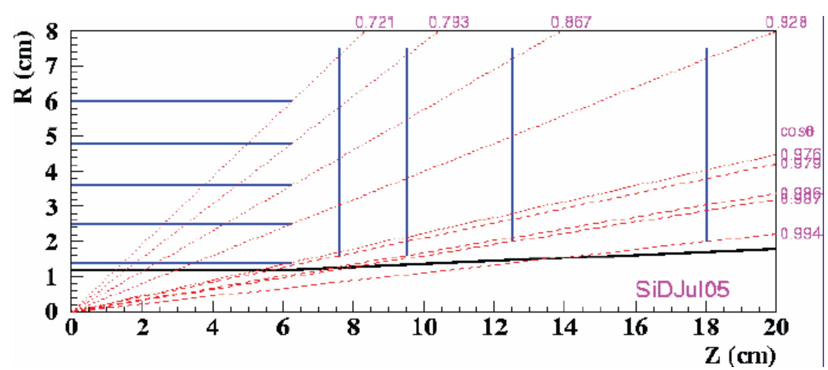
Vertex Detector

- Key issuses:
  - measure impact parameter for each track
  - space point resolution < 5 µm
  - smallest possible inner radius $r_i \approx 15$ mm
  - transparency: ≈ 0.1% X_0 per layer
    = 100 µm of silicon
  - stand alone tracking capability
  - full coverage |cos Θ| < 0.98
  - modest power consumption < 100 W





- Five layers of pixel detectors plus forward disks
  - pixel size O(20×20 µm²)
  - 10^9 channels
- Note: wrt. LHC pixel detectors
  - 1/5 r_i
  - 1/30 pixel size
  - 1/30 thickness



Vertex Detector

- **Critical issue is readout speed:**
- **Inner layer can afford O(1) hit per mm^2 (pattern recognition)**
  - **once per bunch = 300 ns per frame too fast**
  - **once per train ≈ 100 $hits/mm^2$ too slow**
  - **20 times per train ≈ 5 $hits/mm^2$ might work**

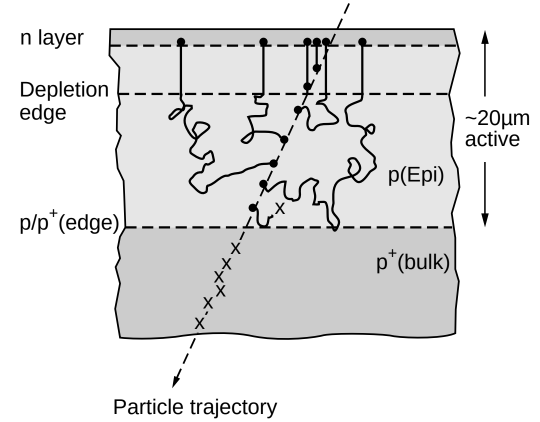
    50 µs per frame of 10^9 pixels!

→ readout during bunch train (20 times)
or store data on chip and readout in between trains
e.g. ISIS: In-situ Storage Image Sensor

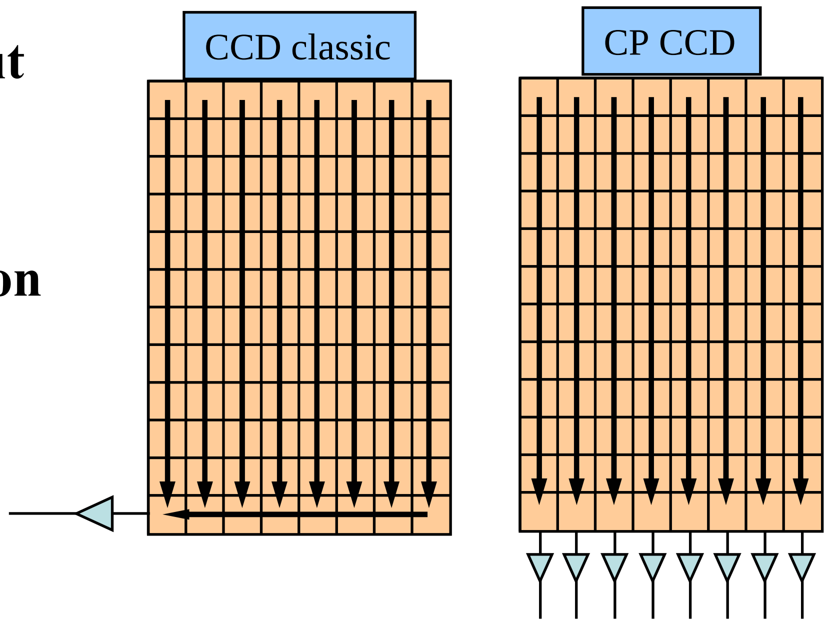
- **Many different (sensor)-technologies under study**
  CPCCD, MAPS, DEPFET, CAPS/FAPS, SOI/3-D,
  SCCD, FPCCD, Chronopixel, ISIS, …
  → Linear Collider Flavour Identification (LCFI) R&D collaboration
- **Below a few examples**
- **Note: many R&D issues independent of Si-technology (mechanics, cooling, …)**

CP CCD

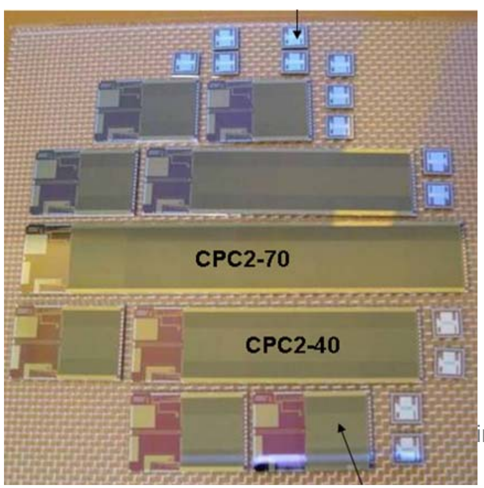
- CCD
  - create signal in 20 µm active layer
  - etching of bulk material to keep total thickness ≤ 60 µm
  - low power consumption
  - but very slow



→ apply column parallel (CP) readout

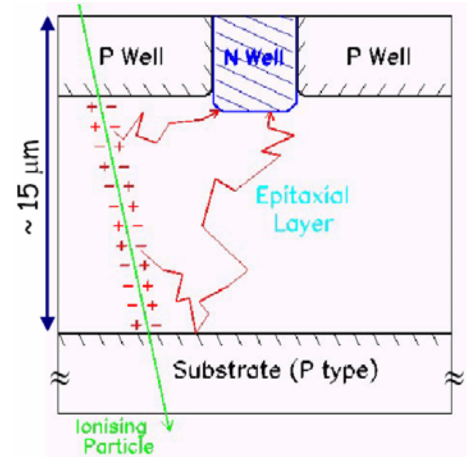


- Second generation CP CCD designed to reach 50 MHz operation

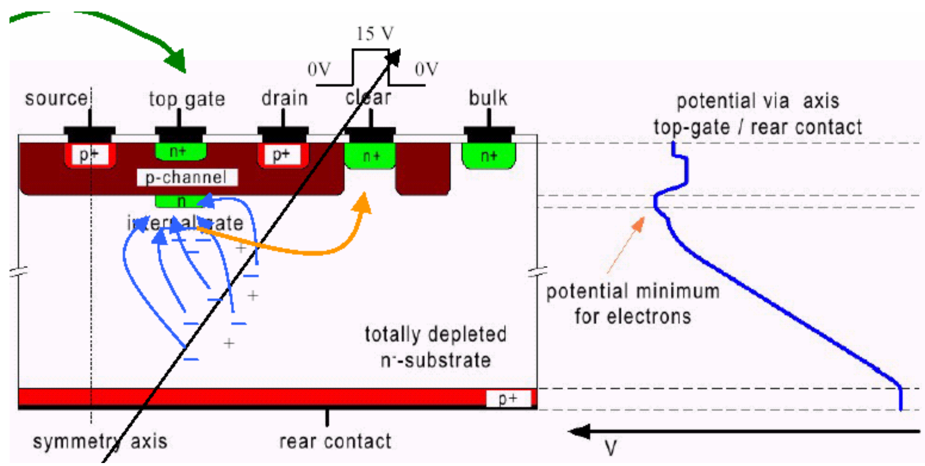


MAPS and DEPFET

- **CMOS Monolithic Active Pixel detectors**
  - **standard CMOS wafer integrating all functions**
  - **no bonding between sensor and electronics**
  - **e.g. Mimosa chip**



- **DEPFET: DEPleted Field Effect Transistor**
  - **fully depleted sensor with integrated pre-amplifier**
  - **low power and low noise**

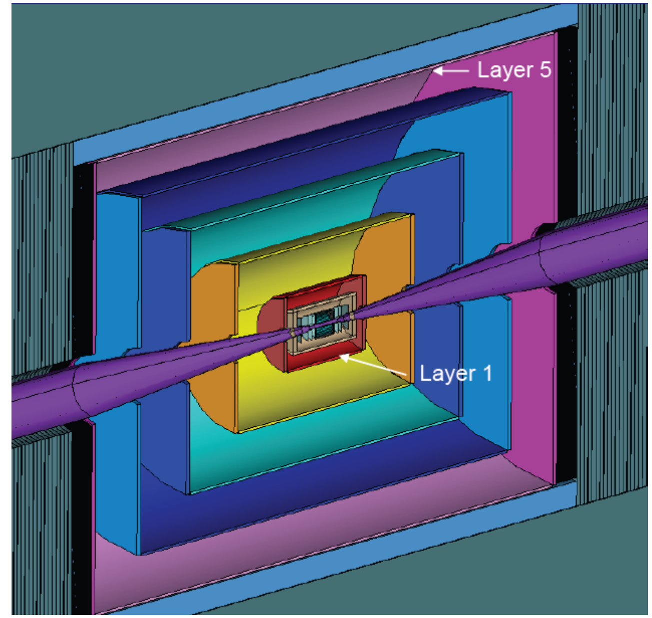


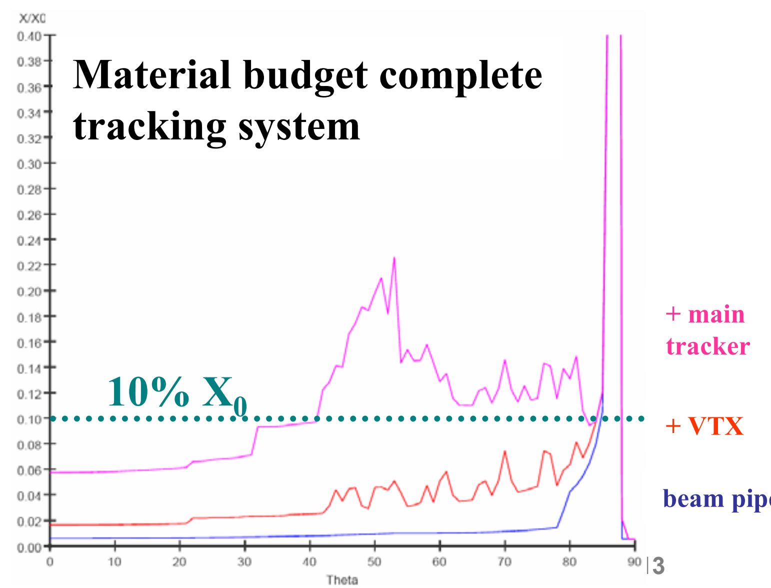
Silicon Tracking

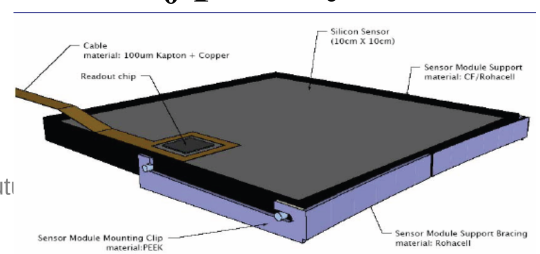
- The SiD tracker:
  - 5 barrel layers
    r_i = 20 cm
    r_o = 125 cm
  - 10 cm segmentation in z
    short sensors
  - measure phi only

- endcap disks
  - 5 double disk per side
  - measure r and phi

- critical issue:
  - material budget
    (support, cooling, readout)
  - goal: 0.8% X_0 per layer



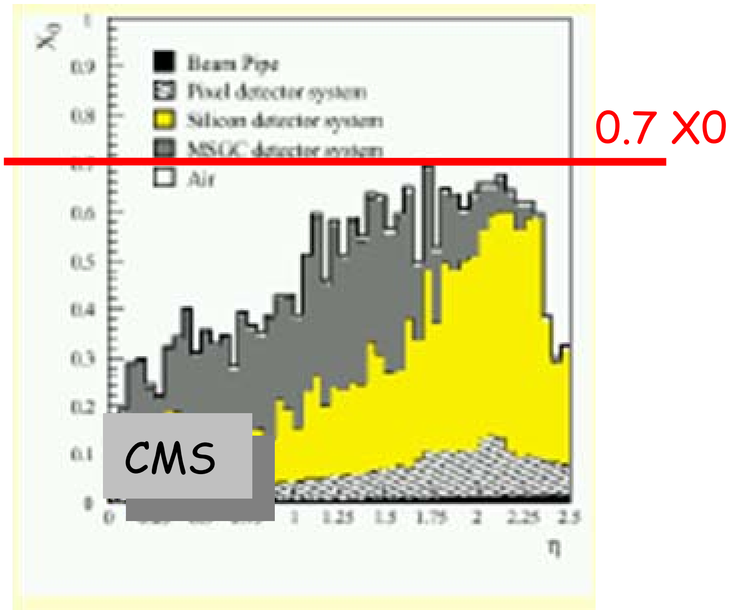




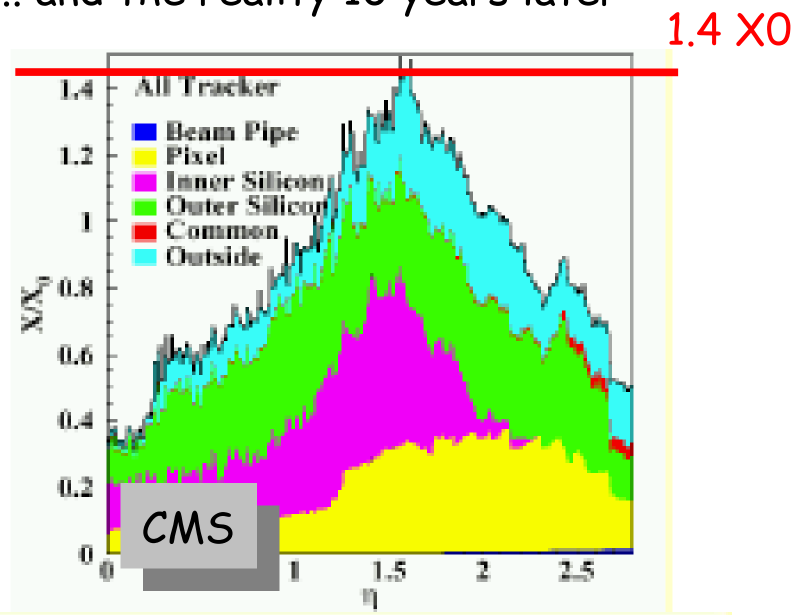
Materials: from Concept to Reality

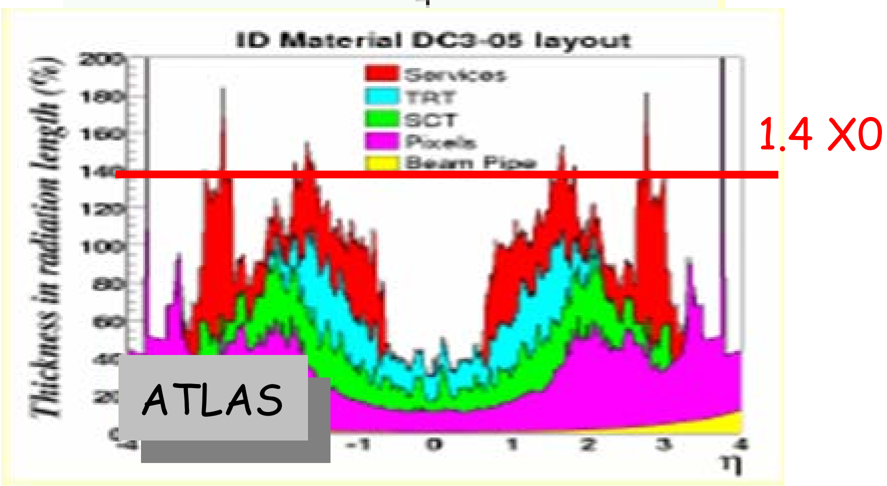
Major difference / advance to LHC detectors is needed:

The detector TDR 1996

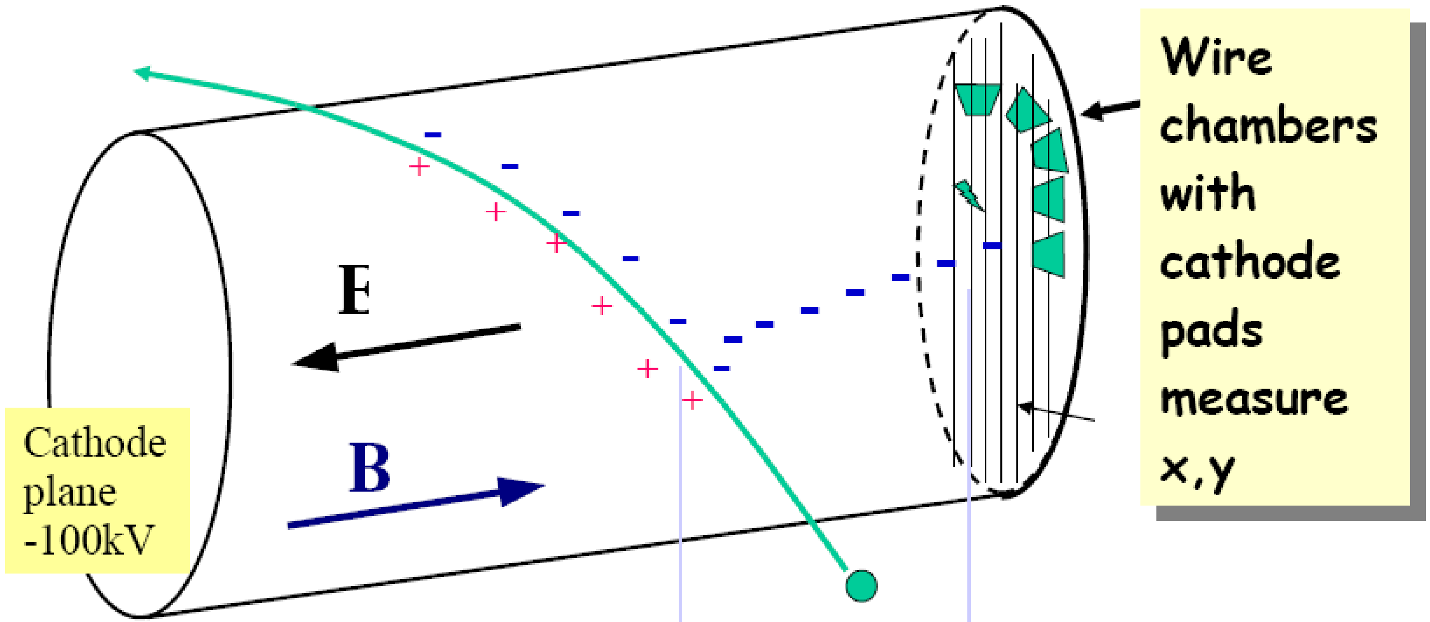


... and the reality 10 years later





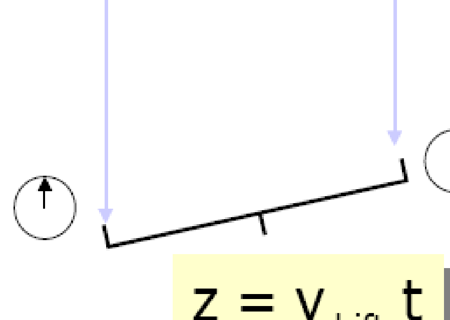
Time Projection Chamber in a solenoid field



Separate two regions:

- Drift along z: 20-30 µs/m.
- Amplify at the end plate

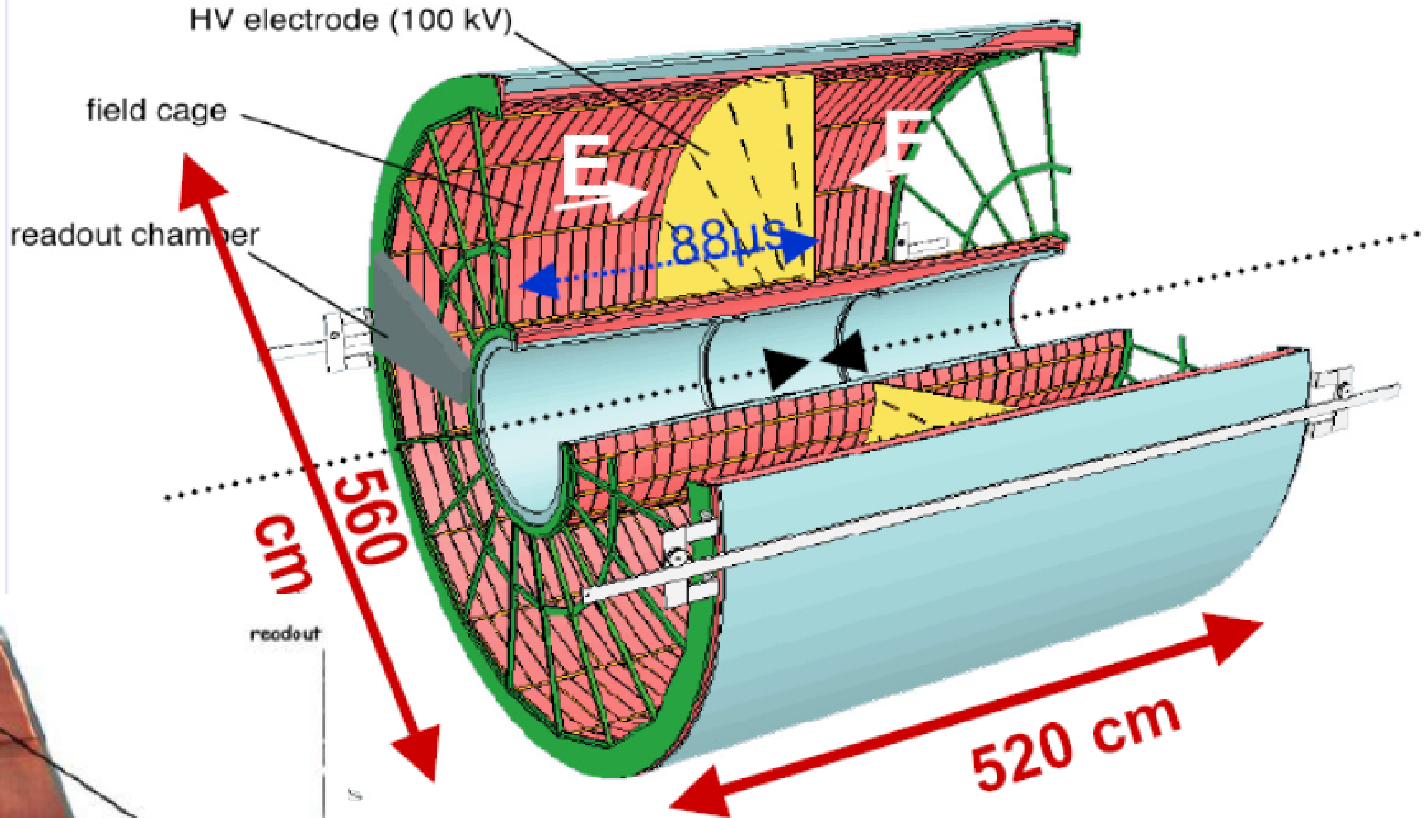
No material inside drift volume!



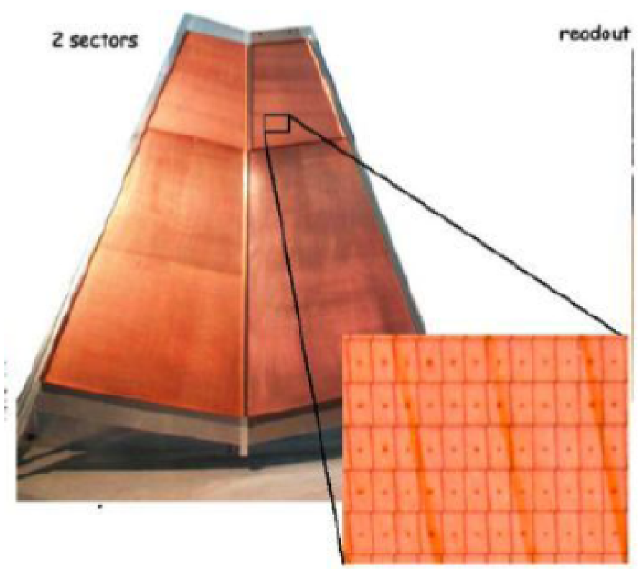
E||B: drifting electrons curl around B field lines: limited spread.

TPC Tracking

ALICE TPC



readout:

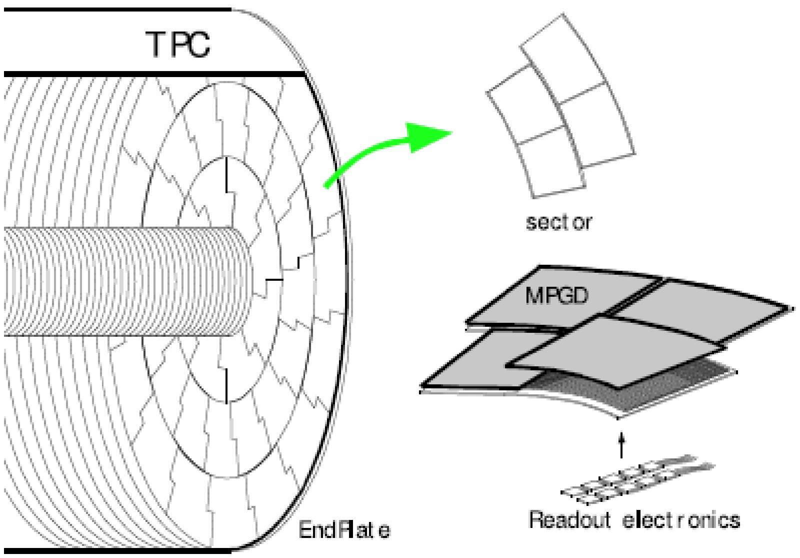


max. drift time 88 µs.
LHC operates with low luminosity at ALICE (pp and PbPb).

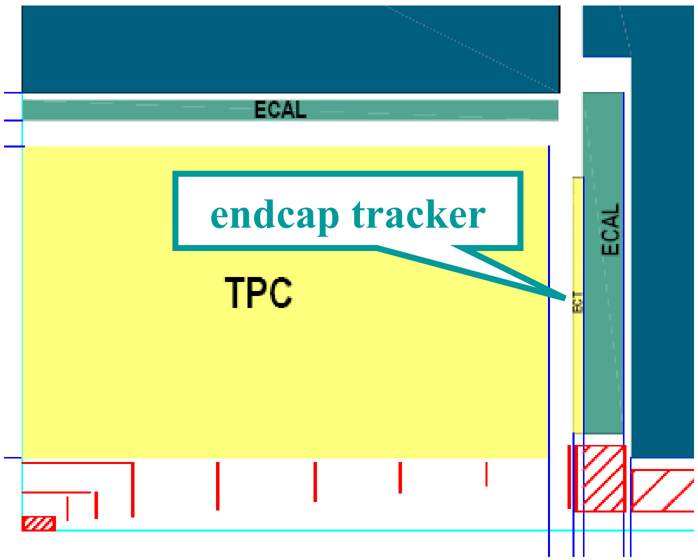
Time Projection Chamber

- GLD, LDC and 4th:
  high resolution TPC as main tracker
  - 3 – 4 m diameter
  - ≈ 4.5 m length
  - low mass field cage
    - 3%X_0 barrel
    - < 30% X_0 endcap
  - ≈ 200 points/track
  - ≈ 100 µm single point res.

  → $\Delta(1/p_T) = 10^{-4}$ /GeV
  (10 times better than LEP!)



- Complemented by Forward Tracking
  - endcap between TPC and ECAL
  - Si strip, straw tube, GEM-based, … are considered



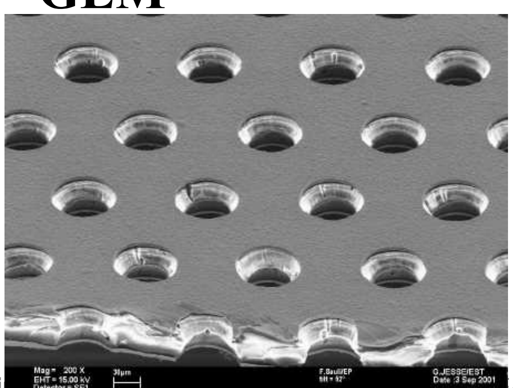
- TPC development performed in LCTPC collaboration

Time Projection Chamber

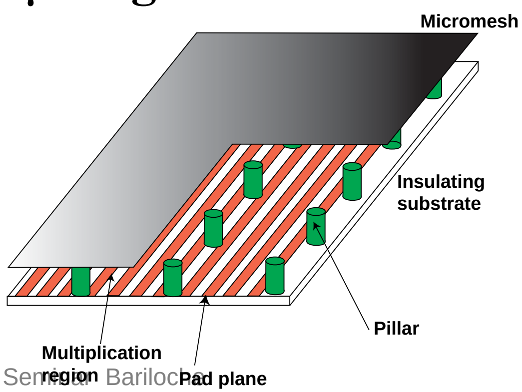
- New concept for gas amplication at end flanges:
  Replace proportional wires by Micro Pattern Gas Detectors (MPGD)

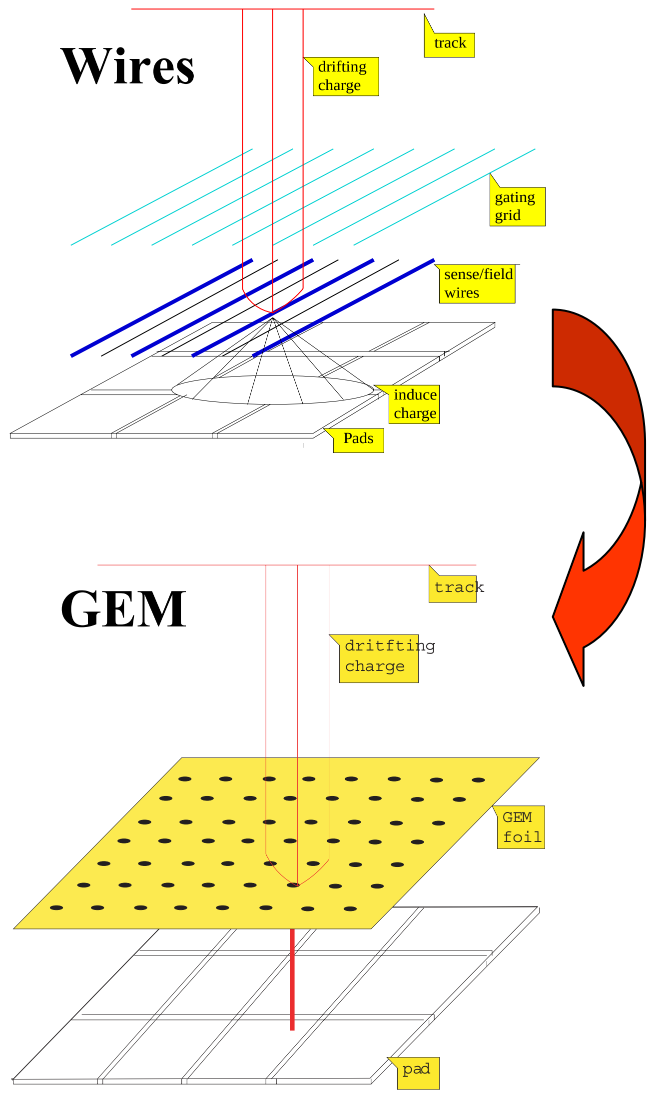
- GEM or MicroMegas
  - finer dimensions
  - two-dimensional symmetry
    → no E×B effects
  - only fast electron signal
  - intrinsic suppression of ion backdrift

GEM



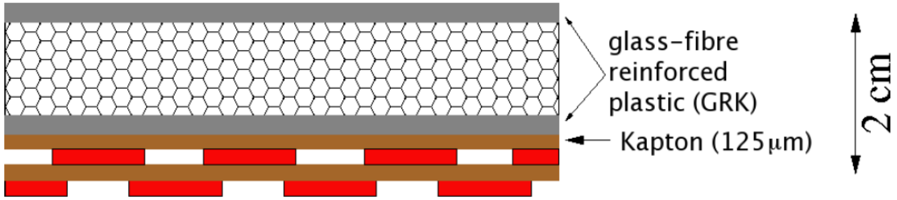
µMegas





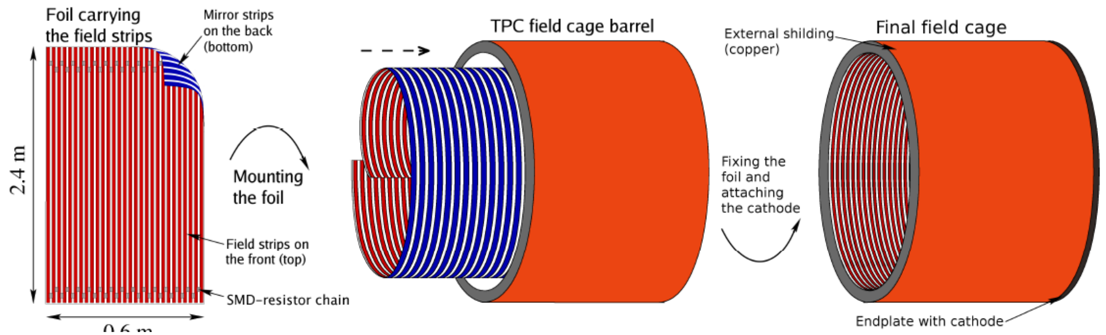
Time Projection Chamber

- Low mass fieldcage
  - large prototype under construction
  - using composite material



Large Prototype wall

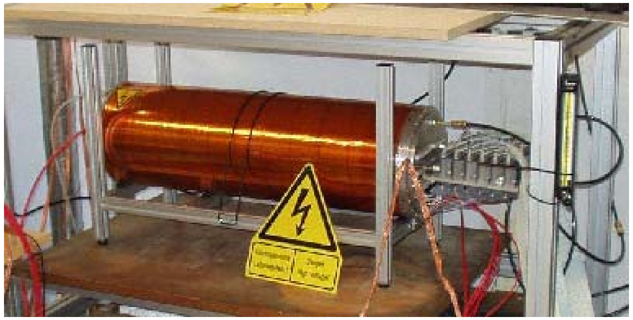
≈ 1% X_0



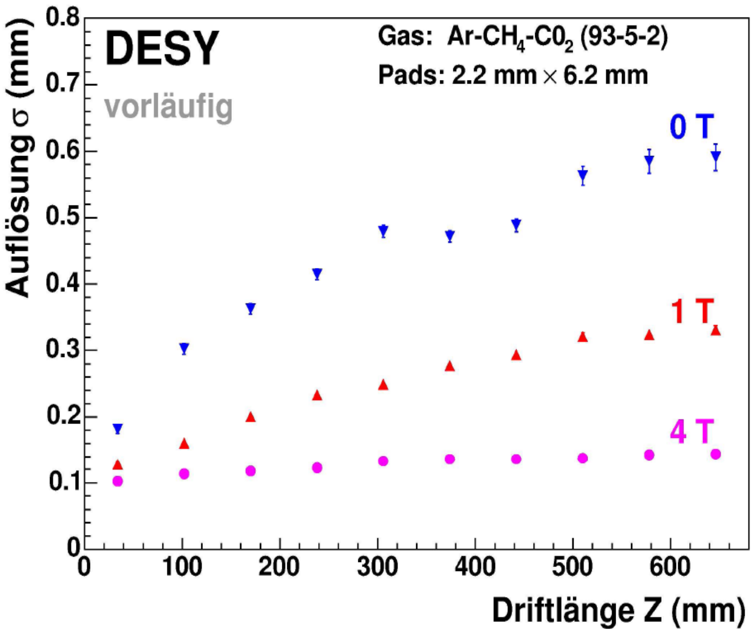
- Electronics
  - few 10^6 channels on endplate (ILD)
  - low power to avoid cooling
  - two development paths:
    - FADC based on ALICE ALTRO chip
    - and TDC chips

Time Projection Chamber

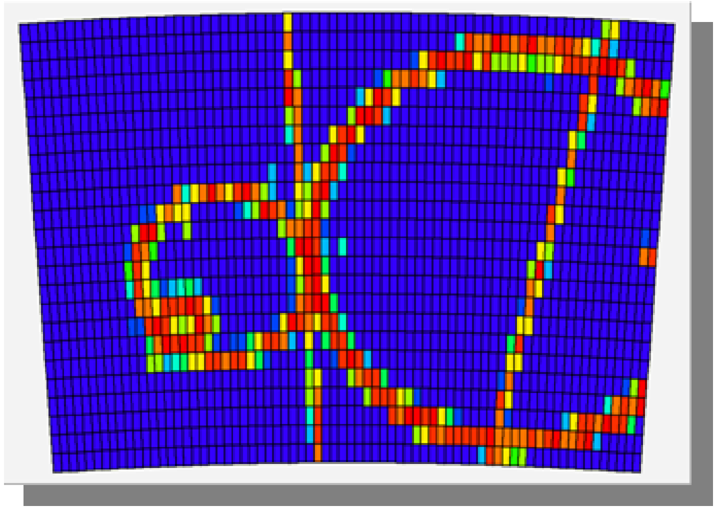
- **Principle of MPGD based TPC established**



Single point resolution O(100 µm) achieved in small scale prototypes



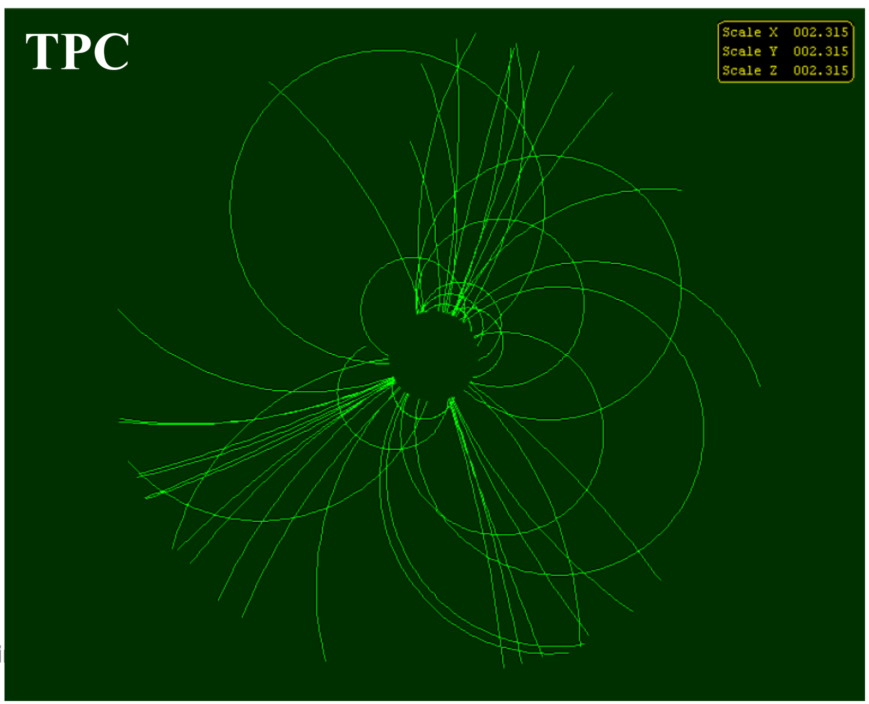
- **Large ILC TPC prototype**

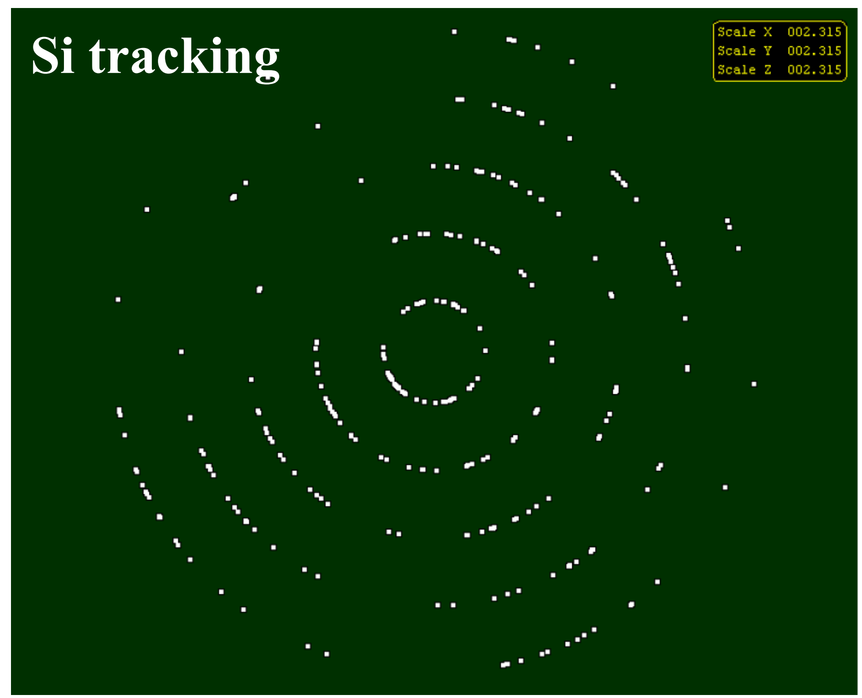


TPC versus Silicon Tracking

- TPC
  - 200 space points (3-dim) → continuous tracking, pattern recognition
  - low mass easy to achieve (barrel)

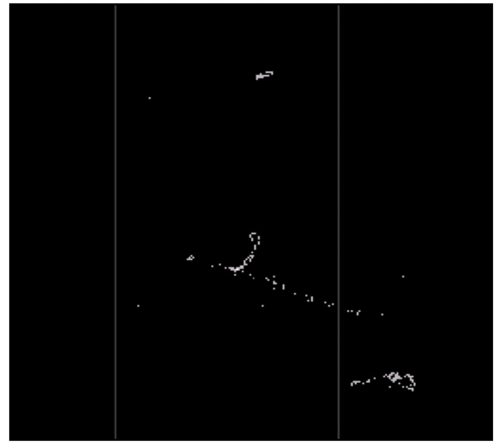
- Silicon tracking
  - better single point resolution
  - fast detector (bunch identification)



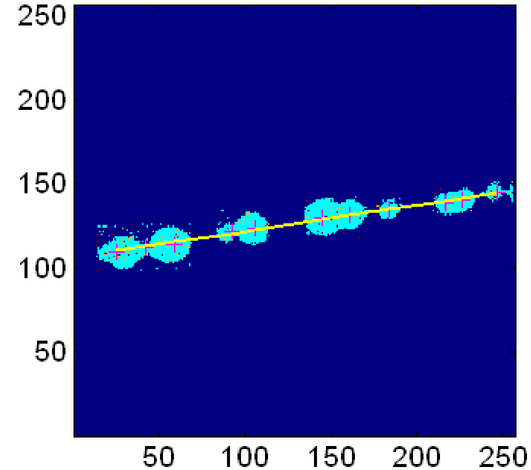


Silicon TPC Readout

- **Combine MPGD with pixel readout chips**
- **2-d readout with**
  - **Medipix2 0.25 µm CMOS**
  - **256×256 pixel**
  - **55 ×55 µm²**



(Micromegas)

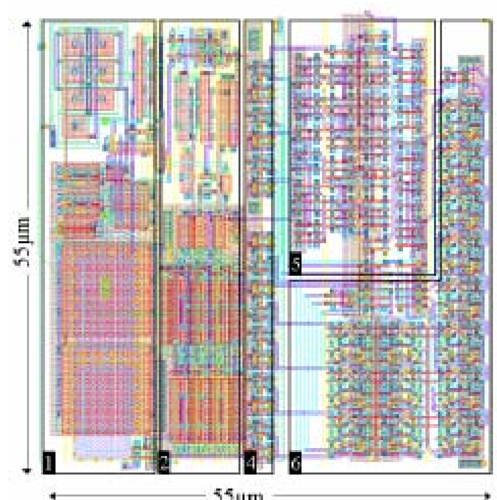


(GEM)

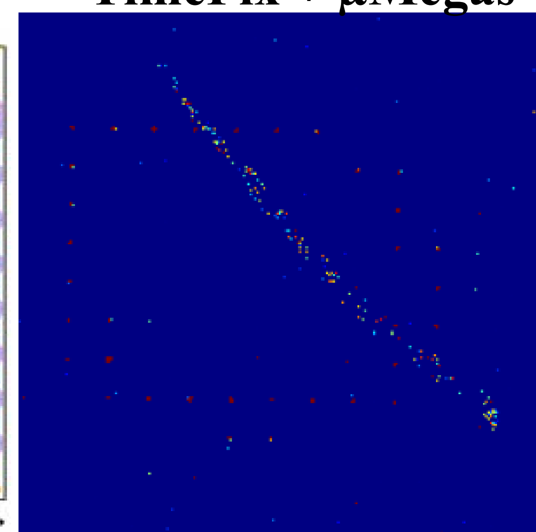
- **Medipix (2-d) → TimePix (3- d)**
- **50 - 150 MHz clock to all pixel**
- **1st version under test**

- **Will eventually lead to**
  - **TPC diagnostic module**
  - **cluster counting to improve dE/dx**

TimePix layout

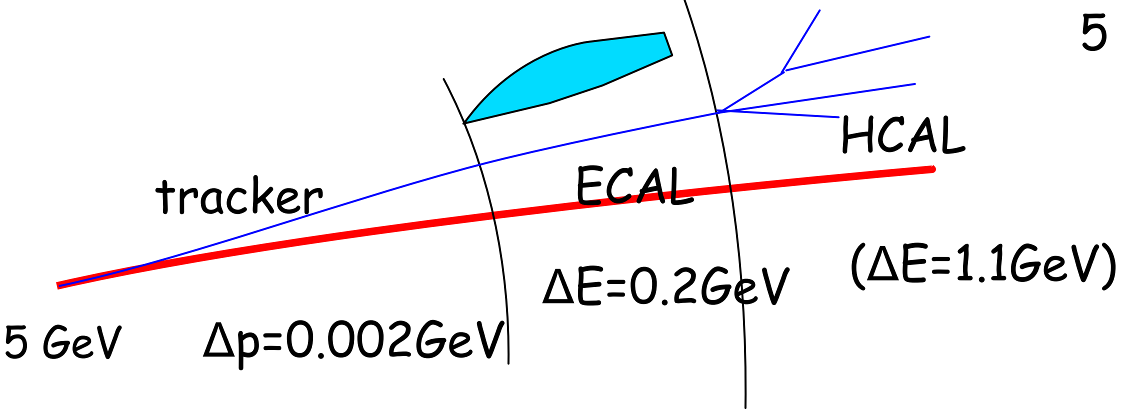


TimePix + µMegas



Calorimetry

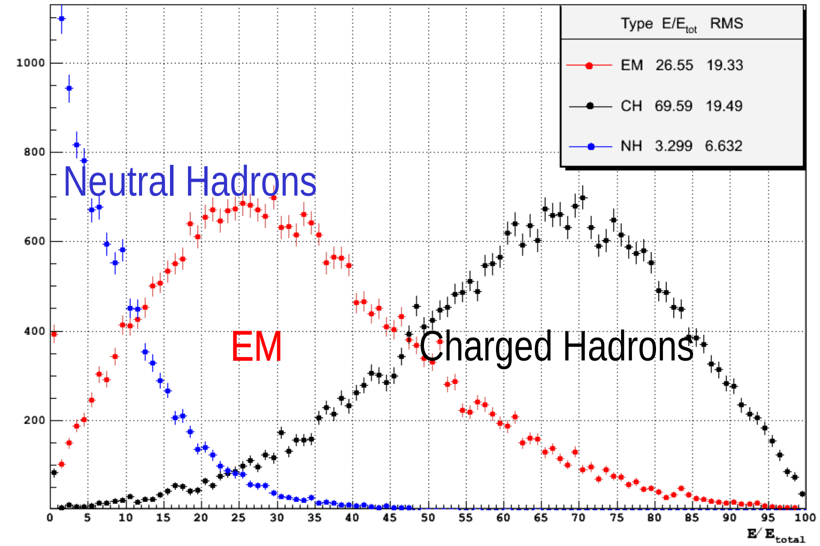
- **The Particle Flow Algortihm (PFA)**
  consider 5 GeV particles in a jet



	error
5 GeV electron:	0.002 GeV
photon:	0.2 GeV
neutron:	1.1 GeV

- **Average visible energy in a jet**
  ≈ 60% charged particles
  ≈ 30% photons
  ≈ 10% neutral hadrons

- **but be aware of large jet-by-jet fluctuations of the composition**



Calorimetry

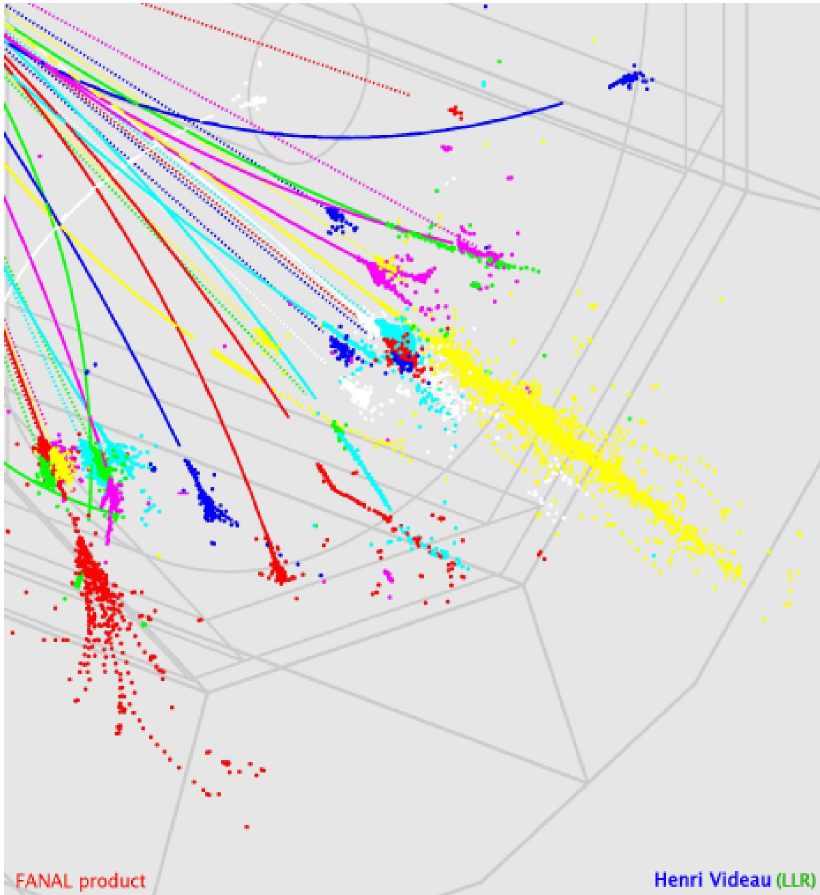
- The paradigm of Particle Flow Algortihm (PFA) for optimum jet energy resolution:
  - try to reconstruct every particle
  - measure charged particles in tracker
  - measure photons in ECAL
  - measure neutral hadrons in ECAL+HCAL
  - use tracker + calorimeters to tell charged from neutral

particles in jet	fraction of energy in jet	detector	single particle resolution	jet energy resolution
charged particles	60 %	tracker	$\frac{\sigma_{p_t}}{p_t} \sim 0.01\% \cdot p_t$	negligible
photons	30 %	ECAL	$\frac{\sigma_E}{E} \sim 15\%/\sqrt{E}$	$\sim 5\%/\sqrt{E_{jet}}$
neutral hadrons	10 %	HCAL+ECAL	$\frac{\sigma_E}{E} \sim 45\%/\sqrt{E}$	$\sim 15\%/\sqrt{E_{jet}}$

  - Jet energy resolution
    $\sigma = \sigma_{charged} \oplus \sigma_{photons} \oplus \sigma_{neutral} \oplus \sigma_{confusion}$
  - confusion term arises from misassignment, double counting, overlapping clusters, …
  - minimizing confusion term requires highly granular calorimeter both ECAL and HCAL

Particle flow simulation

idea: reconstruct each particle separately: tracks, γ, n, K^0_L, μ



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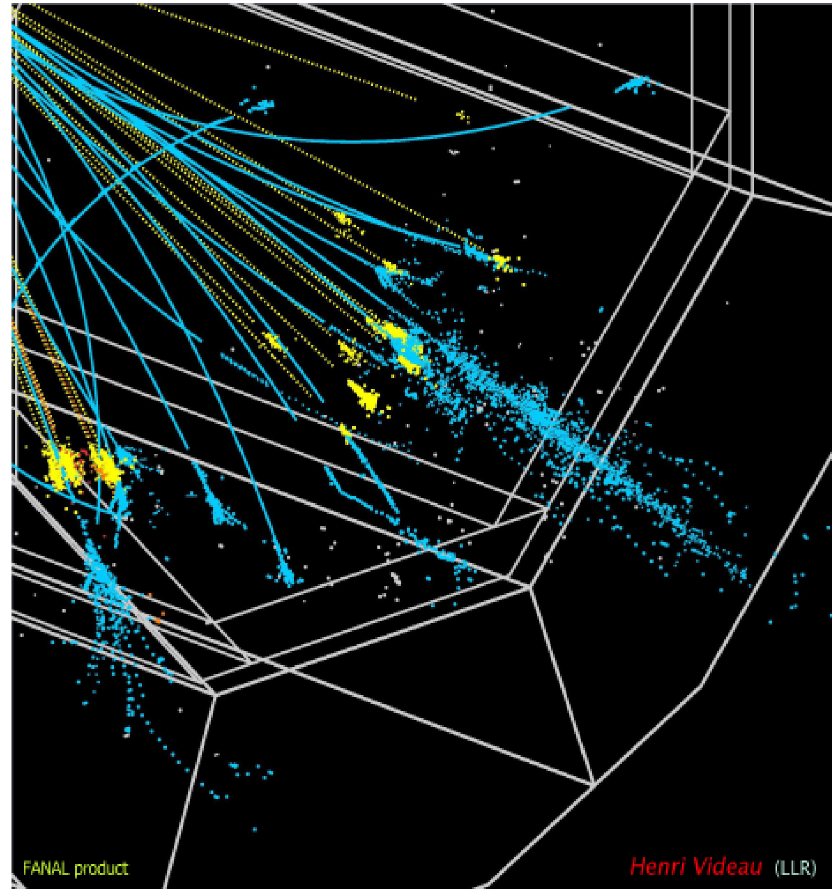


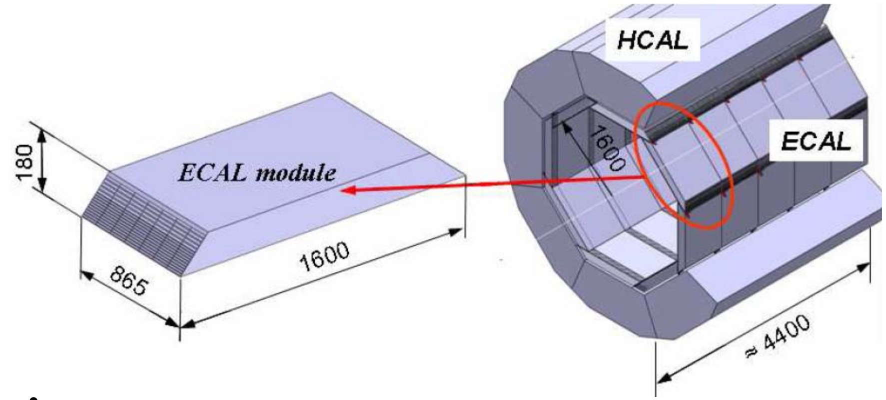
reconstructed

Calorimetry

- CALICE collaboration (Calorimeter for the Linear Collider Experiment)
  > 30 institutes from > 10 countries

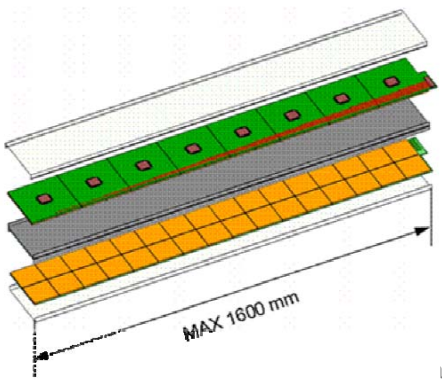
  - performs R&D effort to validate the concept and design calorimeters for ILC experiments

- ILD, SID concepts
  based on PFA calorimeters



- ECAL:
  - SiW calorimeter
  - 23 X_0 depth
  - 0.6 X_0 – 1.2 X_0 long. segmentation
  - 5×5 mm^2 cells
  - electronics integrated in detector

- Alternative:
  W + Scintillating strips

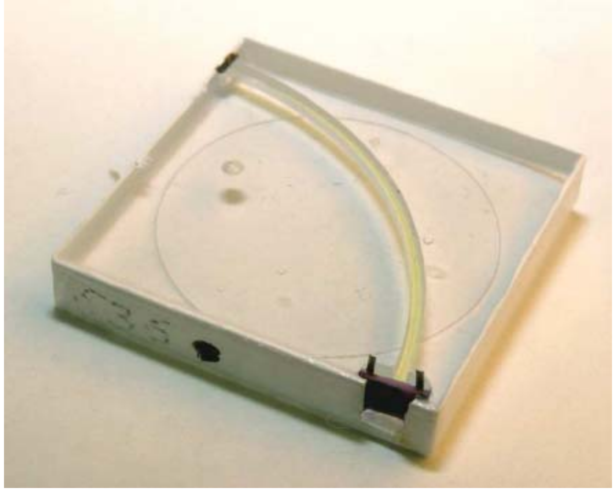


ECAL slab
- FE ASIC
- PCB board
- Si pads

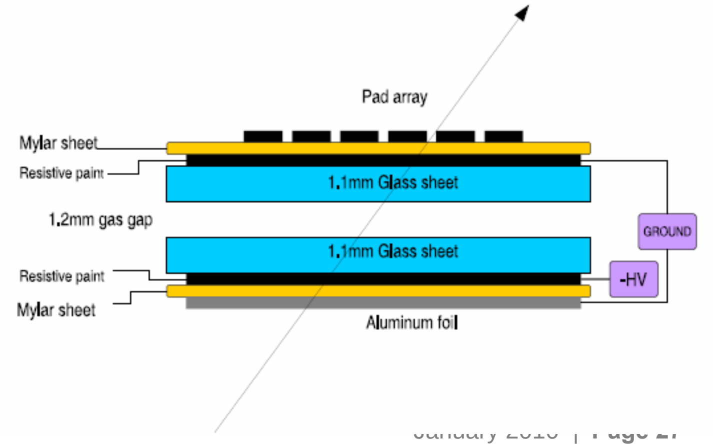
Calorimetry

- **HCAL:**
  2 options under consideration

- **Analogue Scintillator Tile calorimeter**
  - **moderately segmented 3×3 cm²**
  - **use SiPM for photo detection**



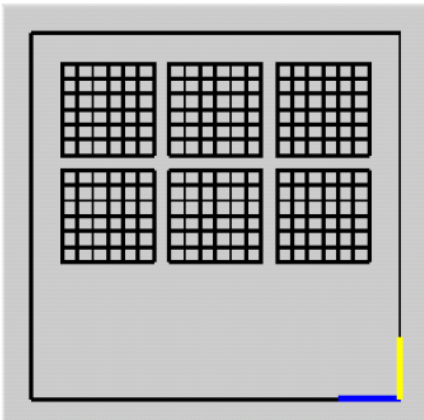
- **Gaseous Digital HCAL**
  - **finer segmentation 1×1 cm²**
  - **binary cell readout**
  - **based on RPC, GEM or µMegas detectors**



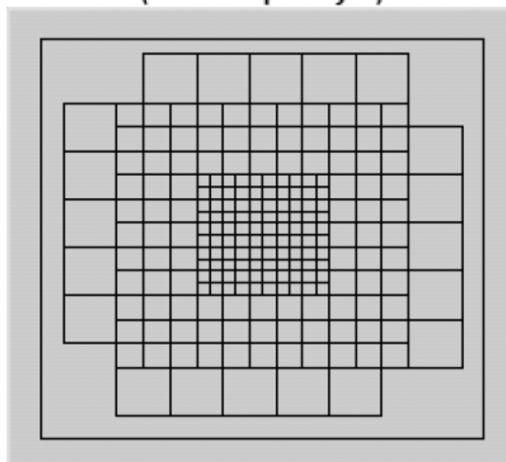
Calorimeter

- **CALICE Testbeam at CERN**

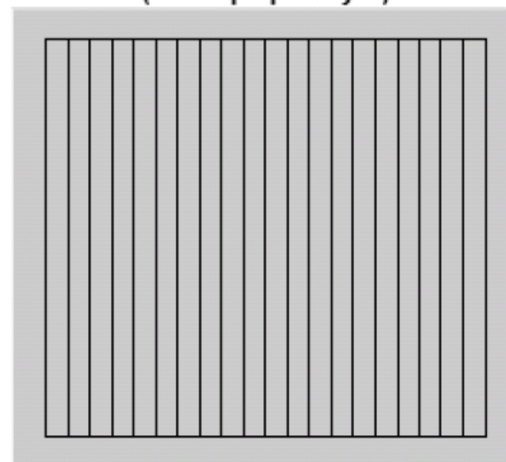
ECAL 18×18 cm²
Si cells of 1×1 cm²
(216 cells per layer)



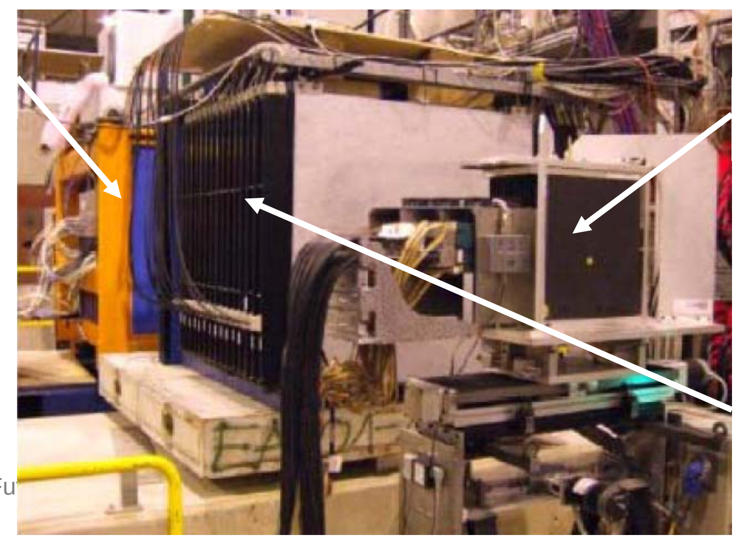
HCAL 100×100 cm²
scint.tiles of 3×3, 6×6, 12×12 cm²
(216 tiles per layer)



TCMT 100×100 cm²
scint.strips X or Y of 5×100 cm²
(20 strips per layer)

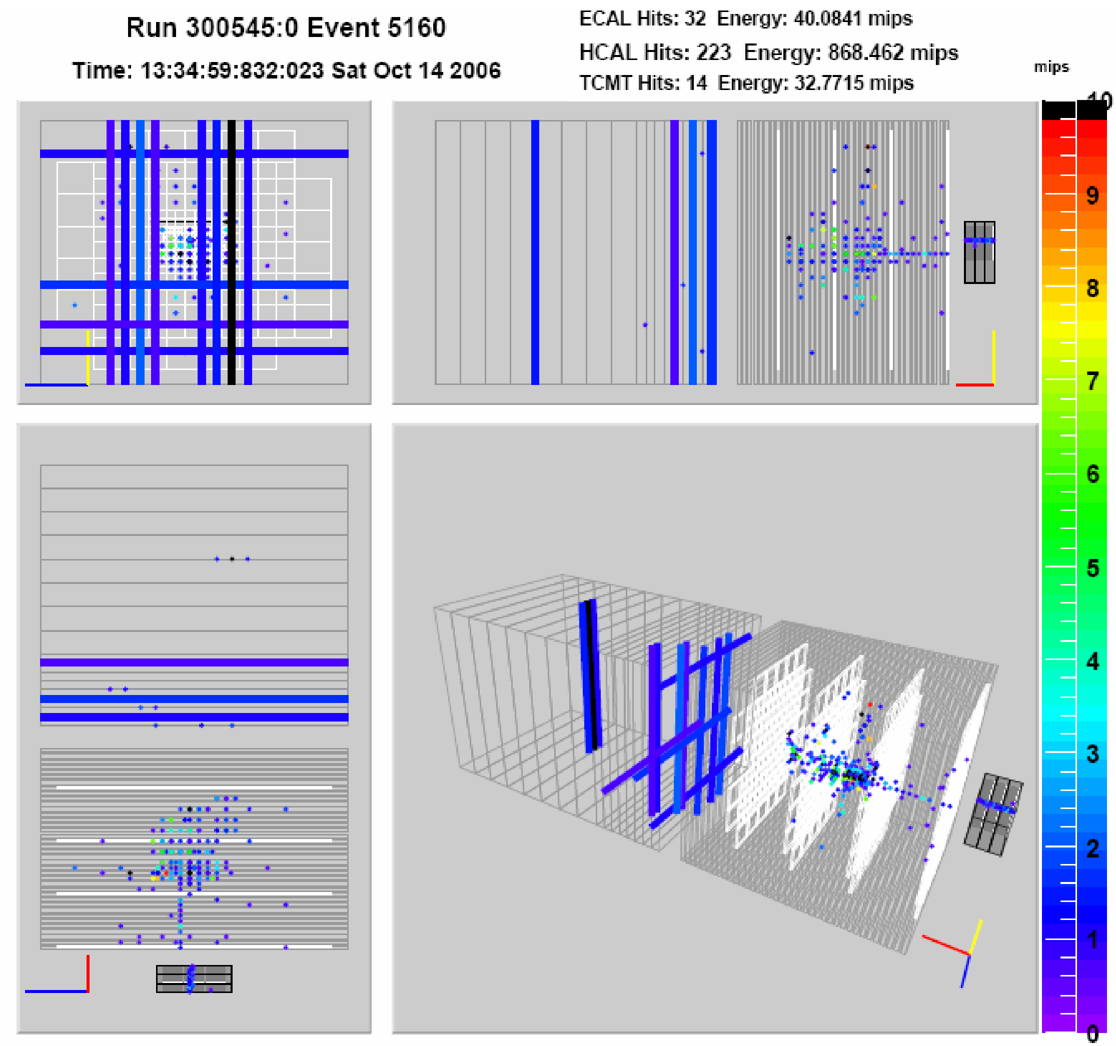


Tail Catcher - Muon Tracker



Calorimeter

- **CALICE Testbeam at CERN**



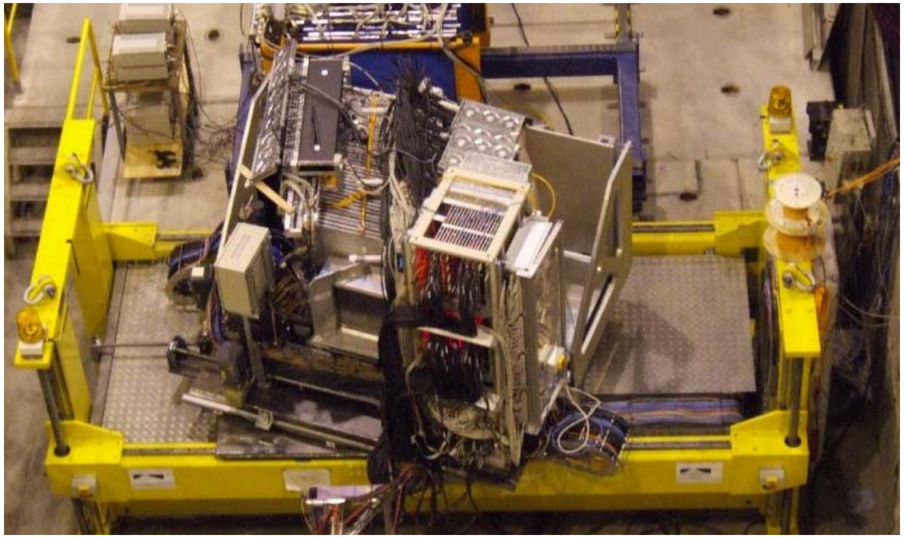
π^- **30 GeV**

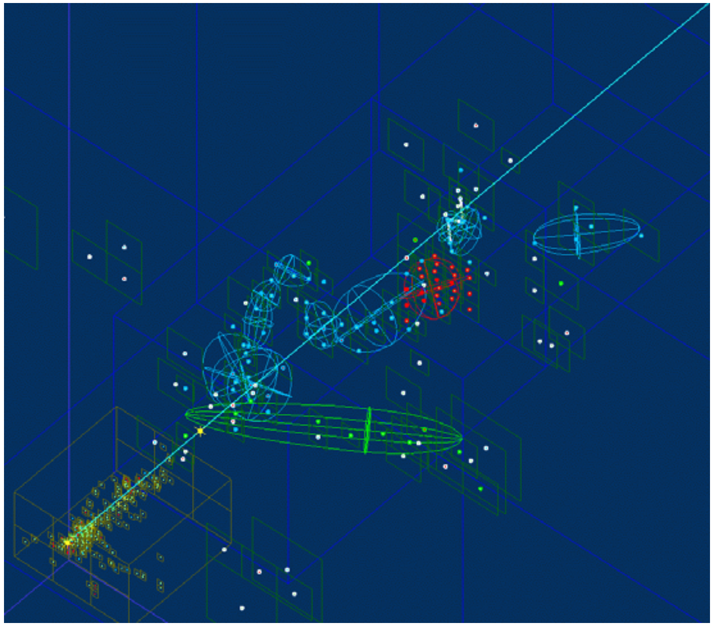
ECAL threshold = 0.5 mip
HCAL threshold = 0.5 mip
TCMT threshold = 0.7 mip

- **CALICE prototype now at FNAL**

Use of calorimeter test

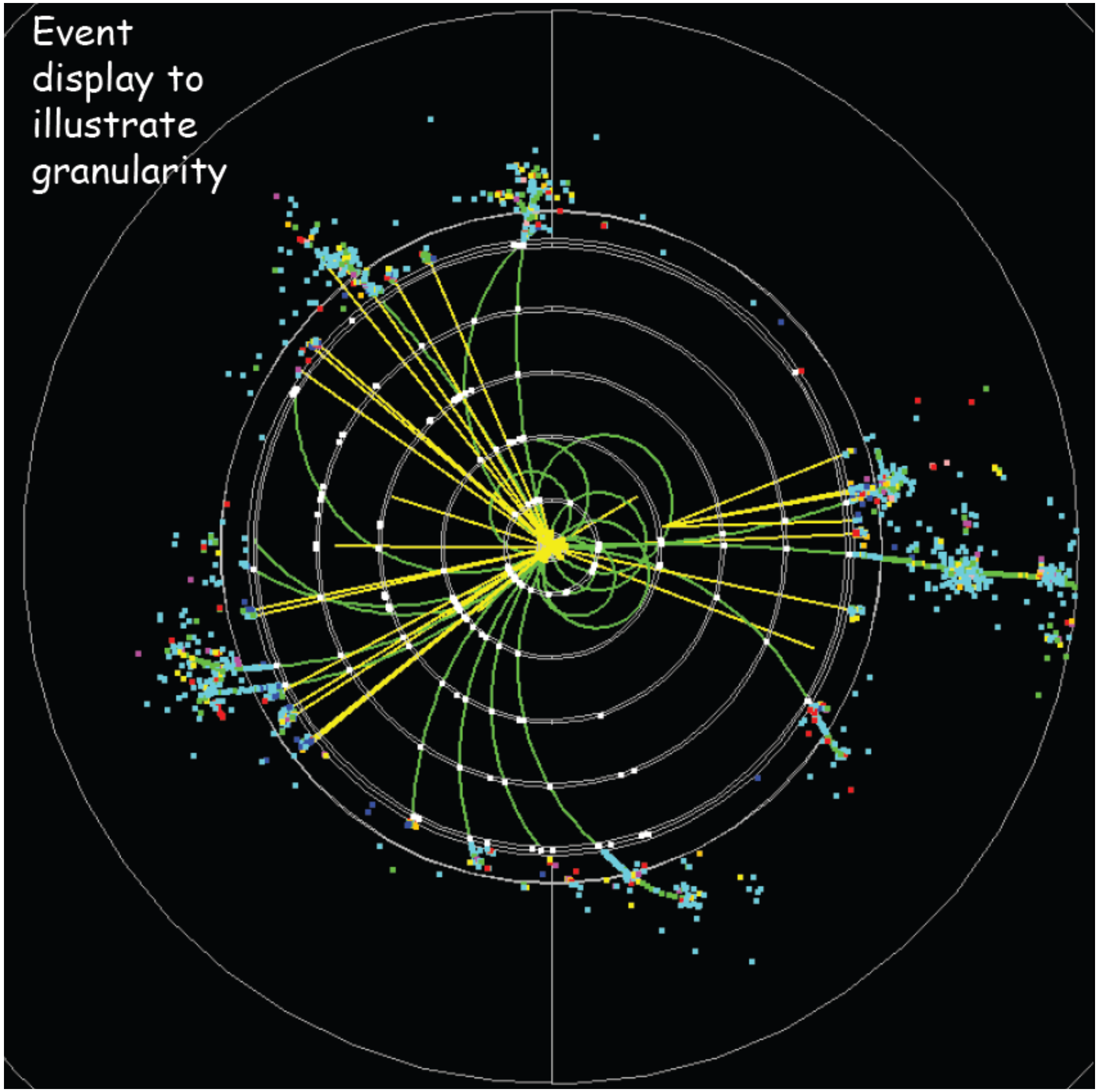
- Prove technologies
- Validate Monte Carlo
- Develop reconstruction algorithms

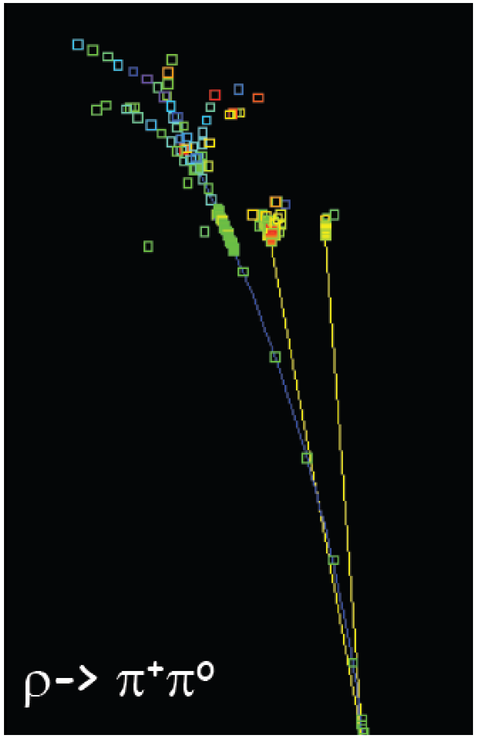




Calorimeter

- **Simulation of an ILC event**



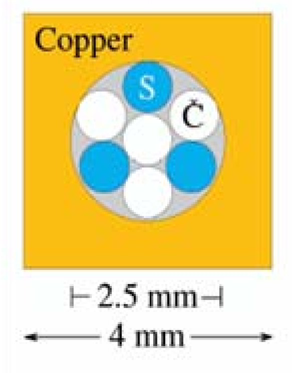


Dual Readout Calorimeter

- 4th concept
  - calorimetry based on dual/triple readout approach
  - complementary measurements of showers to reduce fluctuations

- Fluctuations of local energy deposits
- Fine spatial sampling with SciFi every 2 mm
- like SPACAL (H1)

- Fluctuations in electromagnetic fraction of shower energy
- clear fibres measure only EM component by Cerenkov light of electrons (E_{th} = 0.25 MeV)
- like HF (CMS)



Dual Readout Module (DREAM) in testbeam at CERN

- Binding energy losses from nuclear break-up
- try to measure MeV neutron component of shower (history or Li/B loaded fibres)
- triple readout

A different approach: Dual Readout Calorimeter

Concept:

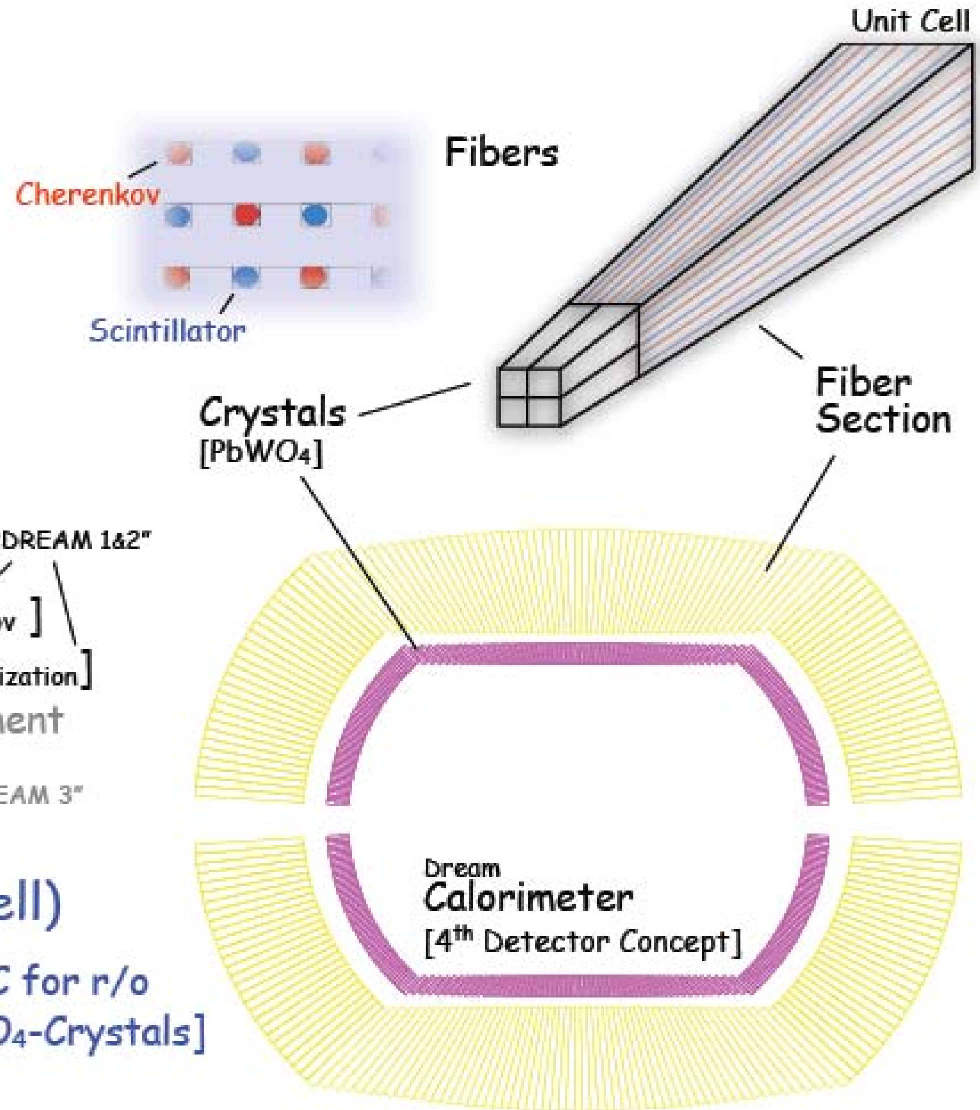
Cherenkov-assisted
Hadron Calorimetry

$$\frac{E_{\mathrm{em}}}{E_{\mathrm{tot}}} \sim \frac{E_{\mathrm{Cherenkov}}}{E_{\mathrm{Ionization}}}$$

"DREAM 1&2"

EM: clear fibers, Č-light [$E_{\mathrm{Cherenkov}}$]
Charged: scintillation fibers [$E_{\mathrm{Ionization}}$]
Neutrons: time history measurement

"DREAM 3"

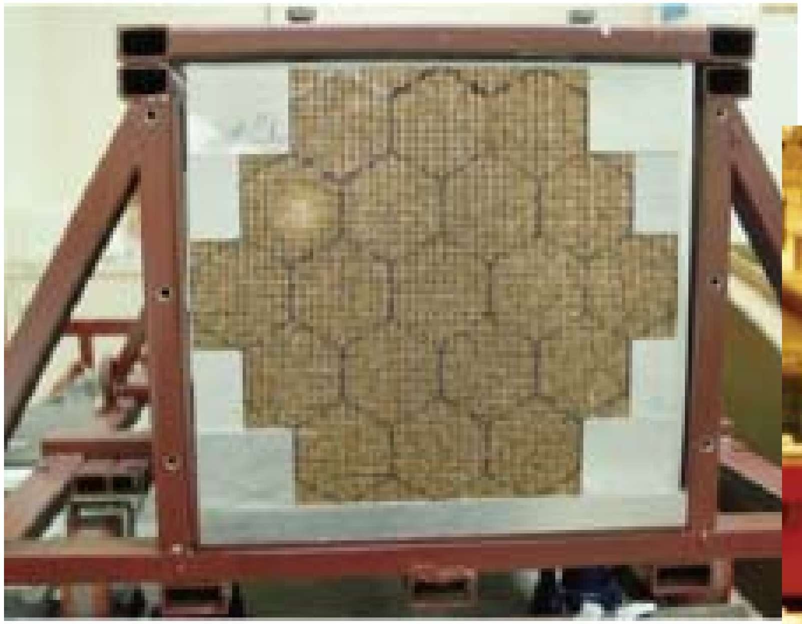


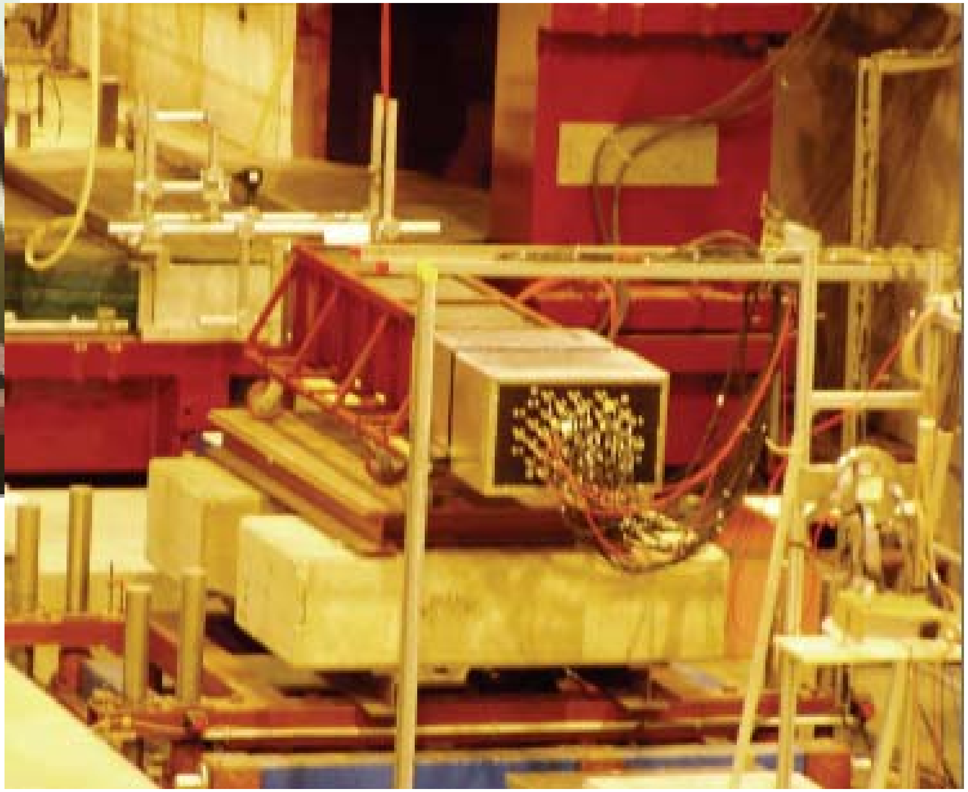
Plans:

Scaleable module (unit cell)

Fiber Section: W absorber, MPPC for r/o
EM Section: Dual-readout [$PbWO_4$-Crystals]

DREAM Test module





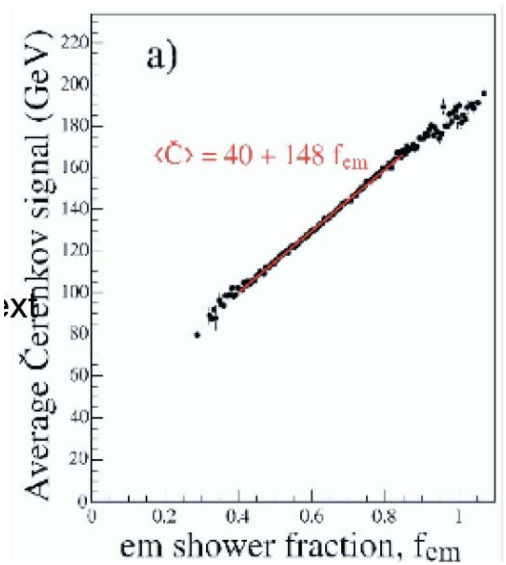
Dual Readout Calorimeter

- **DREAM testbeam:**
  - measure each shower twice

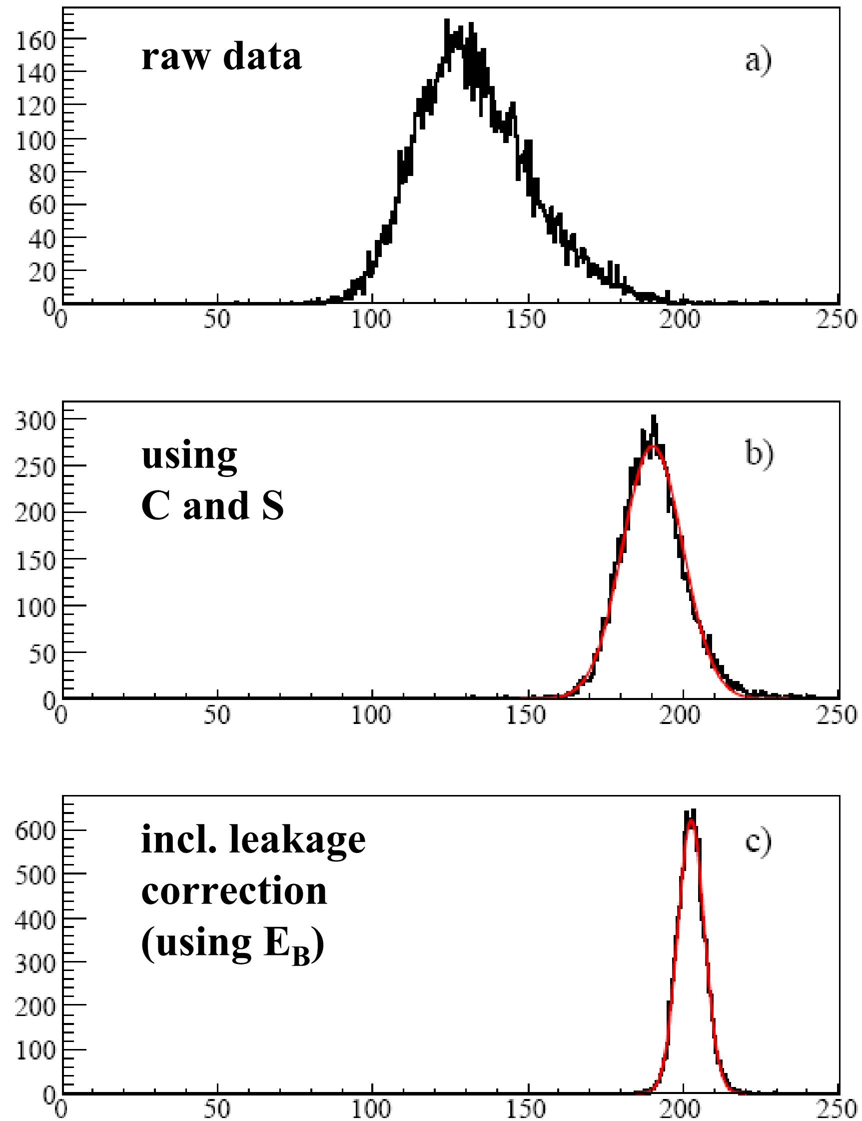
$$(e/h)_C = \eta_C \approx 5$$
$$(e/h)_S = \eta_S \approx 1.4$$

$$C = [f_{em} + (1 - f_{em})/\eta_C]E$$
$$S = [f_{em} + (1 - f_{em})/\eta_S]E$$

$$\rightarrow C/E = 1/\eta_C + f_{em}(1 - 1/\eta_C)$$

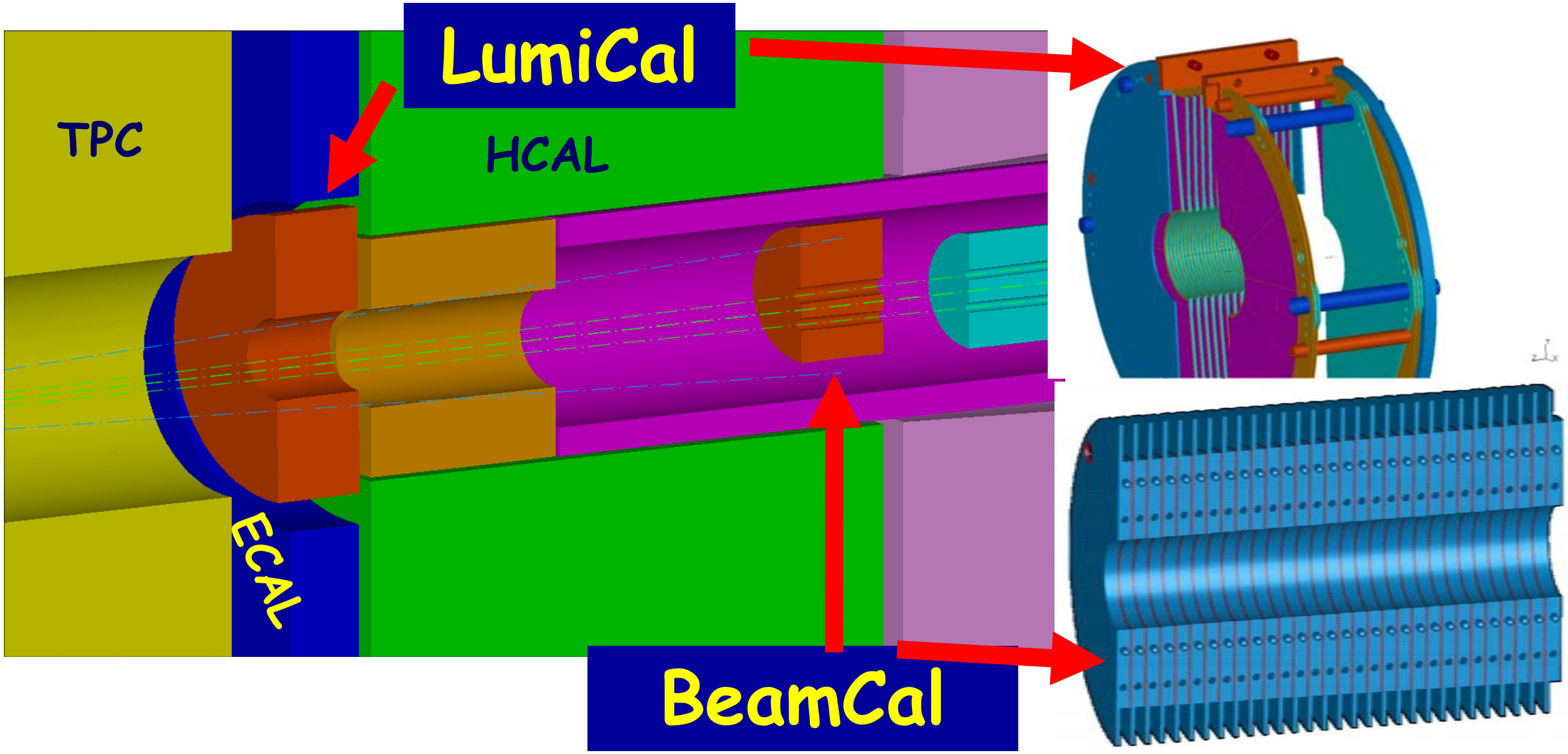


200 GeV π^- beam at CERN



Forward Calorimetry

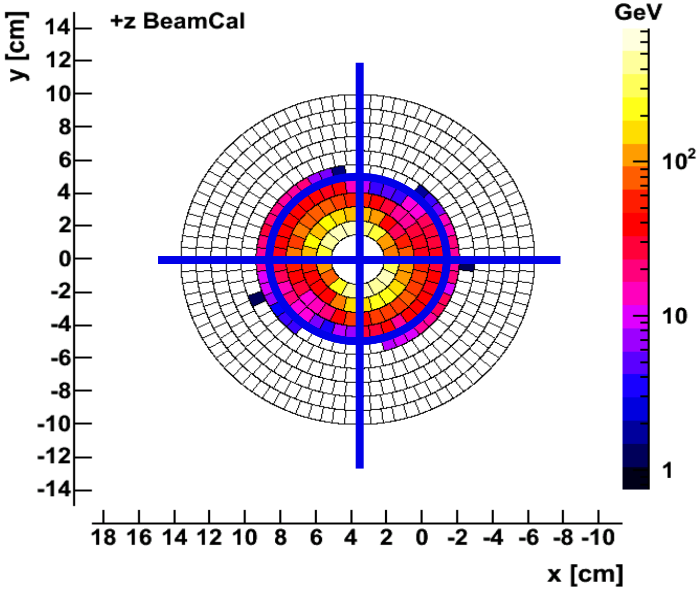
- **Forward calorimeters needed**
  - **LumCal: precise luminosity measurement**
    precision < 10^{-3}, i.e. comparable to LEP or better
  - **BeamCal: beam diagnostics & luminosity optimisation**



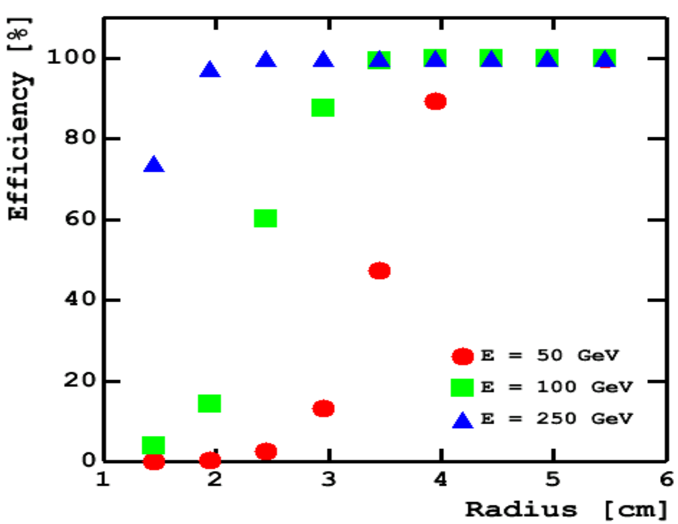
BeamCal

- Challenges:
  - ≈ 15000 e^+e^- pairs per BX in MeV range, extending to GeV
  - total deposit O(10 TeV)/BX
  - ≈ 10 MGy yearly rad. dose
  - identification of single high energy electrons to veto two-photon bkgd.
- Requires:
  - rad. hard sensors (diamond)
  - high linearity & dynamic range
  - fast readout (300 ns BX interval)
  - compactness and granularity

Energy deposit per BX:



Electron ID efficiency:



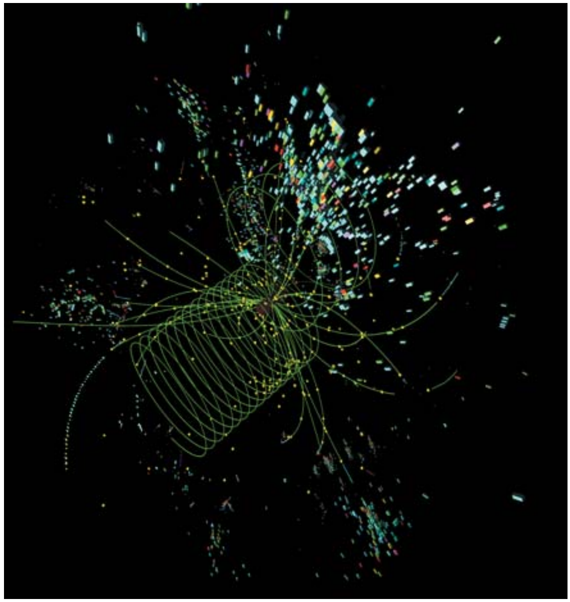
Conclusion & Outlook

- Linear Collider is the next big project in particle physics
  - ILC: 500 → 1000 GeV supraconducting technology
  - CLIC: → 3000 GeV two-beam acceleration

- Ideally complements LHC discoveries by precision measurements

- Requires detectors with unprecedented performances
  - challenges different than at the LHC
  - precision is the main issue

- 2 detector concepts under development
- R&D on detector technologies
  - candidate technologies
  - identified & verified in small scale experiments
- Many questions still to be answered



Simulated ee → ZZ