# Detectors for a Linear Collider

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**DESY**

**Vienna, February 22nd, 2007**

# Outline

- The International Linear Collider (ILC)
  - Status of the project
  - Physics motivation
  - Impact on detector design
  - The four detector concepts

- Detector R&D for key components
  - Vertex detectors
  - Tracking
  - Calorimetry
  - Towards lager prototypes

- Conclusions & Outlook

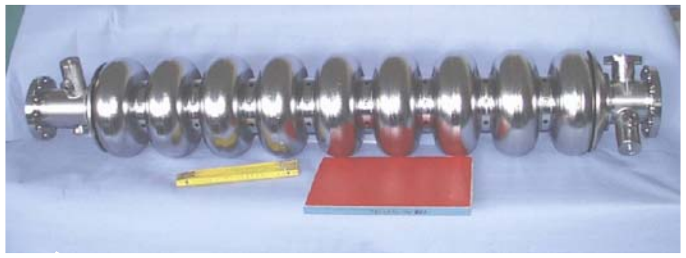
# The International Linear Collider

- **Electron-positron collider**
  - **centre-of-mass energy up to 1 TeV centre-of-mass energy**
  - **luminosities > $10^{34}/cm^2/s$**

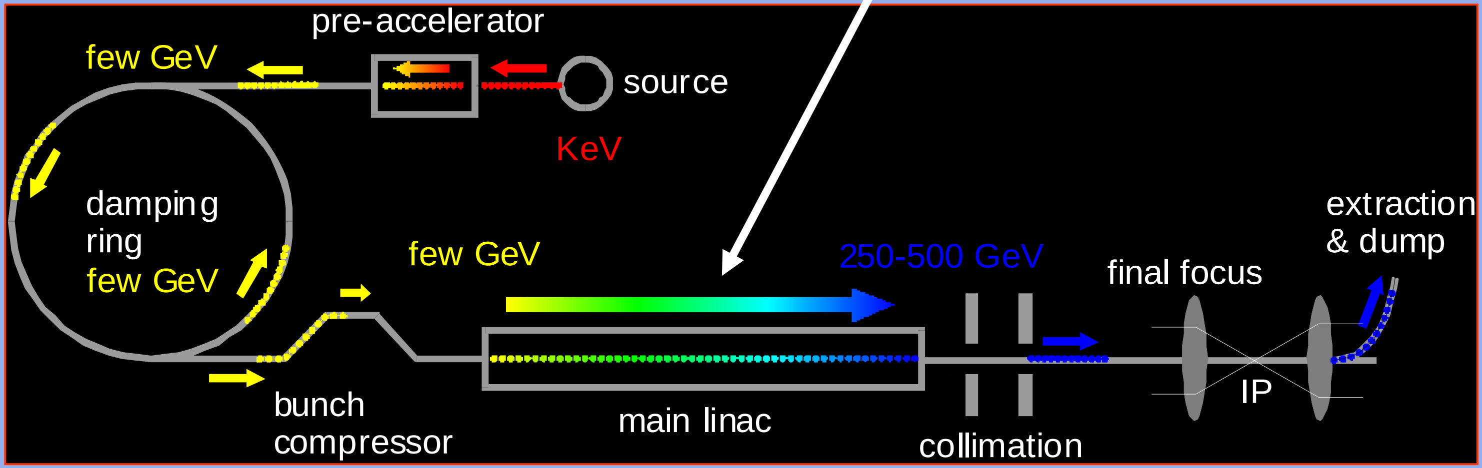
- **The next large High Energy Physics project (after the LHC)**

- **Designed in a global effort**

- **Accelerator technology: supra-conducting RF cavities**



- **Elements of a linear collider:**

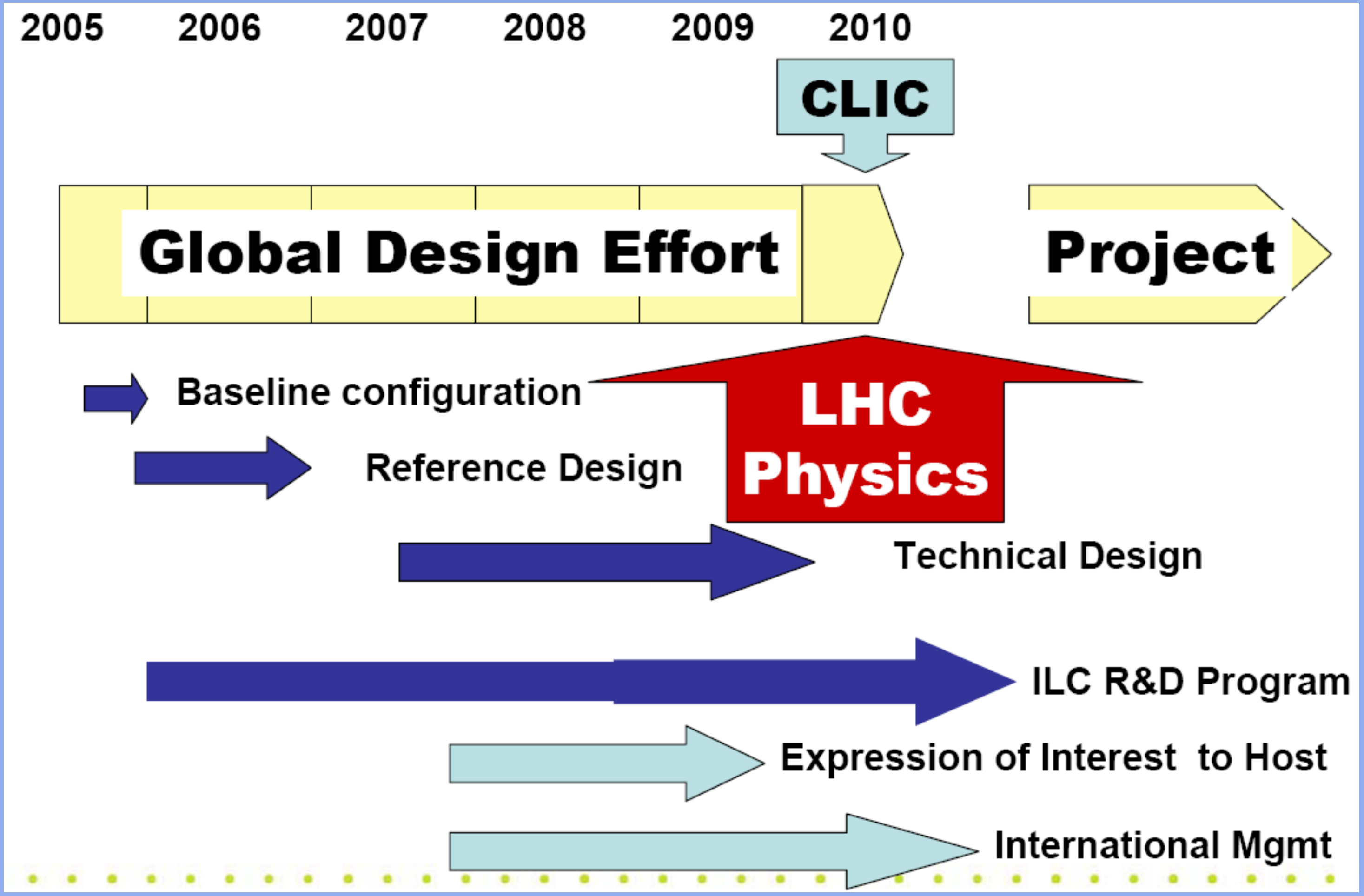


# The International Linear Collider

- International organisation:
  - Global Design Effort (GDE), started in 2005
  - Chair: Barry Barish

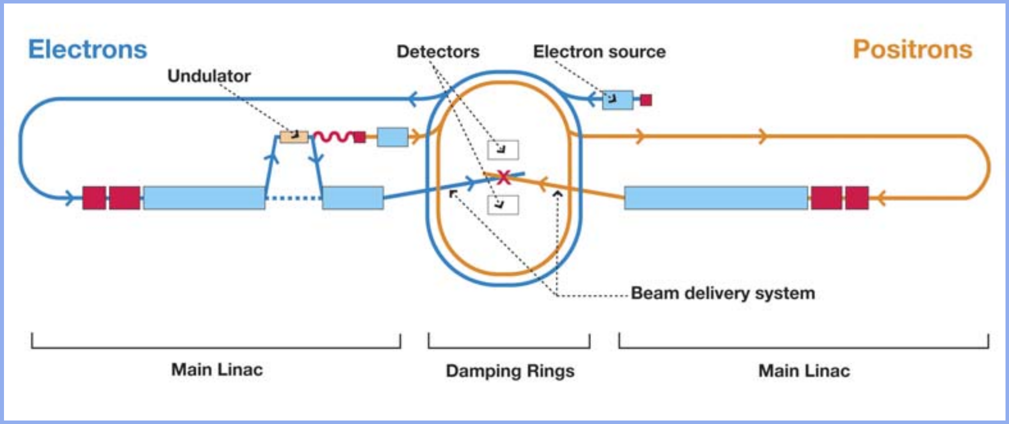
    represenatives from Americas, Asia and Europe

    all major laboratories and many people contributing



# The International Linear Collider

- 2006: Baseline Configuration Document
- February 2007:
  - Reference Design Report presented at Beijing ACFA ILC Meeting
- Layout of the machine:

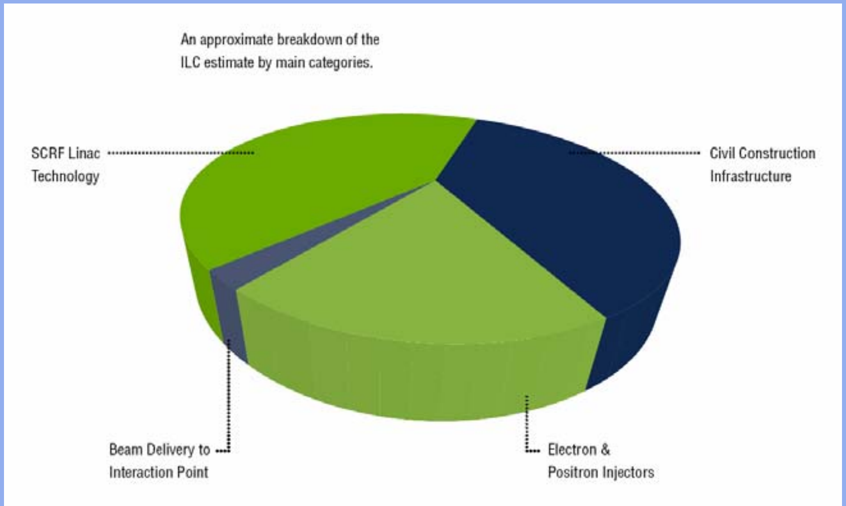



- 2 × 250 GeV
  upgradable to 2 × 500 GeV
- 1 interaction region
- 2 detectors (push-pull)
- 14 mrad crossing angle

- Cost estimate:

  4.87 G$ shared components
  + 1.78 G$ site-dependent
  = 6.65 G$ (= 5.52 G€)

  + 13000 person years

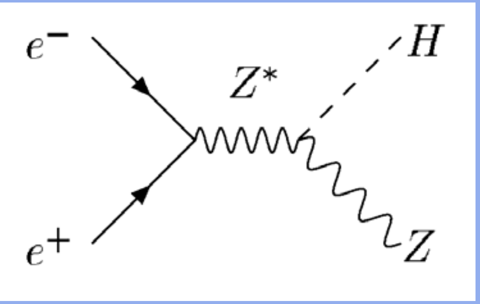


# ILC Physics Motivation

- ILC will complement LHC discoveries by precision measurements
- Here just two examples:

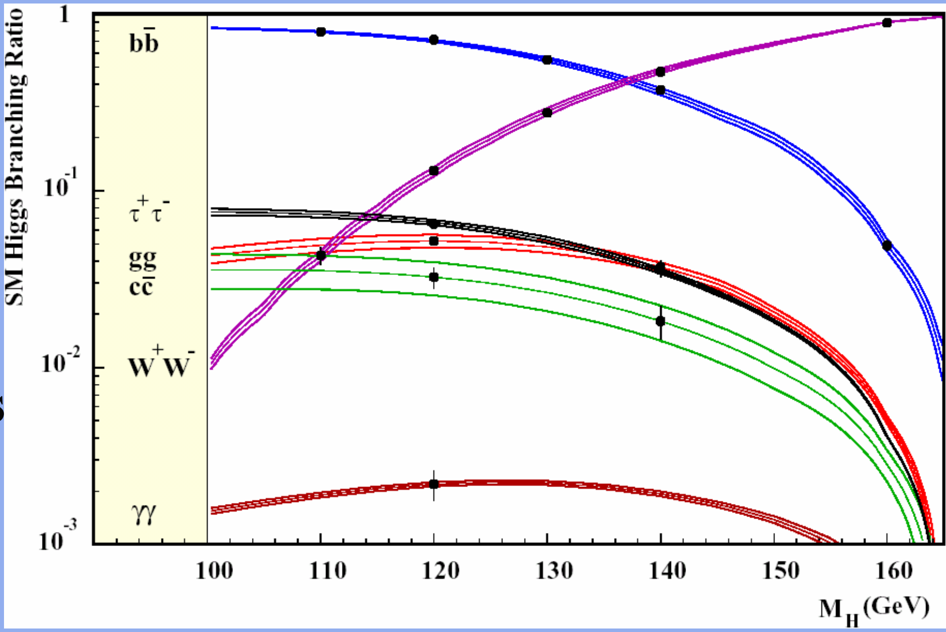
1) There is a Higgs, observed at the LHC

- $e^+e^-$ experiments can detect Higgs bosons without assumption on decay properties Higgs-Strahlungs process (à la LEP)



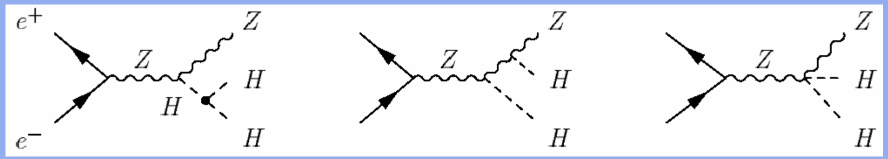

- identify Higgs events in $e^+e^- \rightarrow ZH$ from $Z \rightarrow \mu\mu$ decay

- count Higgs decay products to measure Higgs BRs
- and hence (Yukawa)-couplings

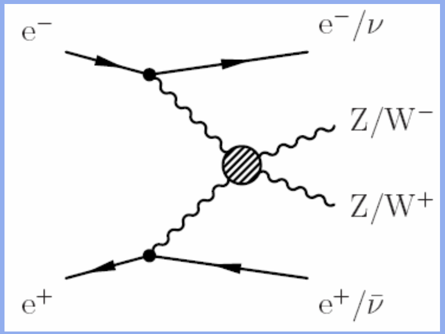


# ILC Physics Motivation

- Measure Higgs self-couplings
  $e^+e^- \rightarrow ZHH$ to establish Higgs potential
  Note: small signal above large QCD background




2) There is NO Higgs (definite answer from LHC!)




- something else must prevent
  e.g. WW scattering from violating
  unitarity at O(1 TeV)
- strong electroweak symmetry breaking?
  $\rightarrow$ study $e^+ e^- \rightarrow WW\nu\nu$, $Wze\nu$ and $ZZee$ events

- need to select and distinguish W and Z bosons
  in their hadronic decays!
  BR ($W/Z \rightarrow$ hadrons) = 68% / 70%

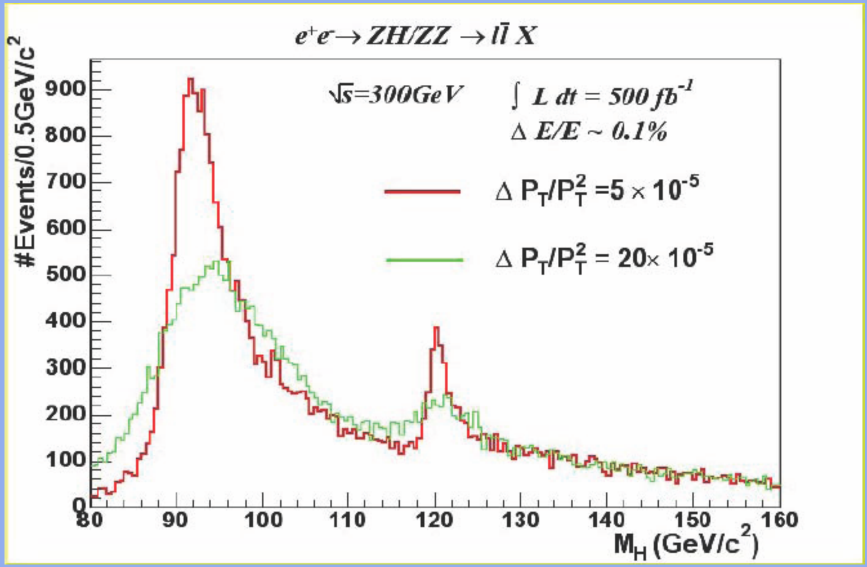
- Many other physics cases: SM, SUSY, new phenomena, …

**Need ultimate detector performance to meet the ILC physics case**

# Impact on Detector Design

- Vertex detector:
  e.g. distinguish c- from b-quarks
  - goal impact parameter resolution
    $\sigma_{r\varphi} \approx \sigma_z \approx 5 \oplus 10/(p \sin\Theta^{3/2})$ µm     3 times better than SLD
  - small, low mass pixel detectors, various technologies under study
    $O(20\times20\ \mu m^2)$
- Tracking:
  - superb momentum resolution
    to select clean Higgs samples
  - ideally limited only by $\Gamma_Z$

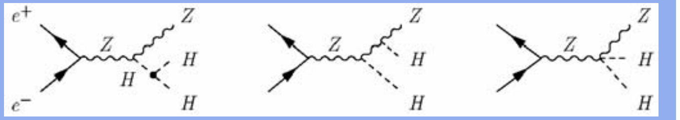
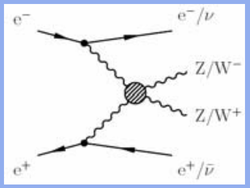
  $\rightarrow \Delta(1/p_T) = 5\cdot10^{-5}$ /GeV
  (whole tracking system)
  3 times better than CMS




Options considered:
- Large silicon trackers (à la ATLAS/CMS)
- Time Projection Chamber with ≈ 100 µm point resolution
  (complemented by Si–strip devices)

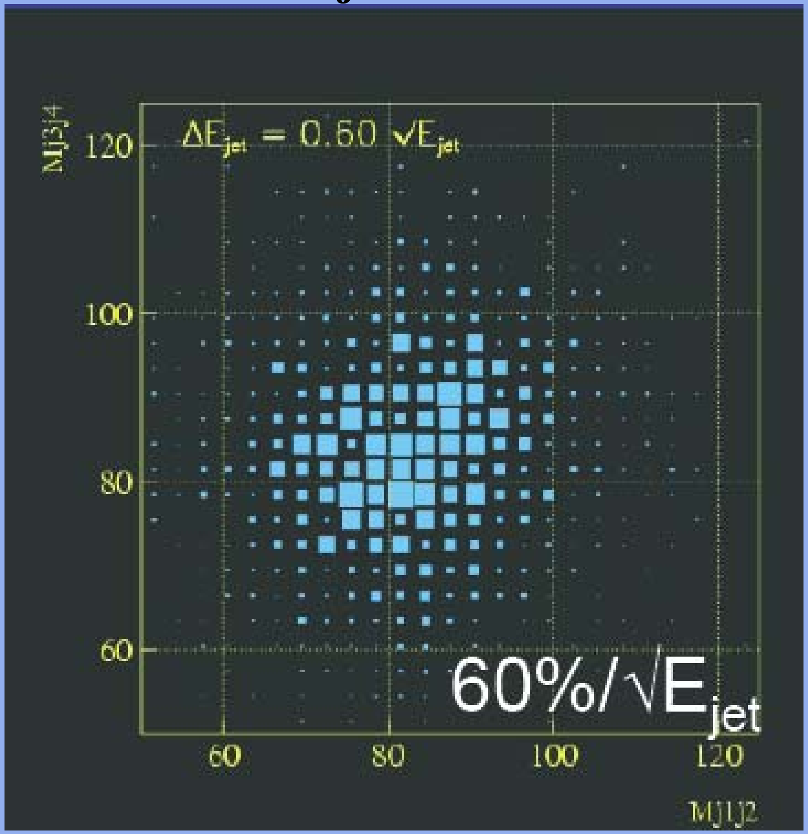
# Impact on Detector Design

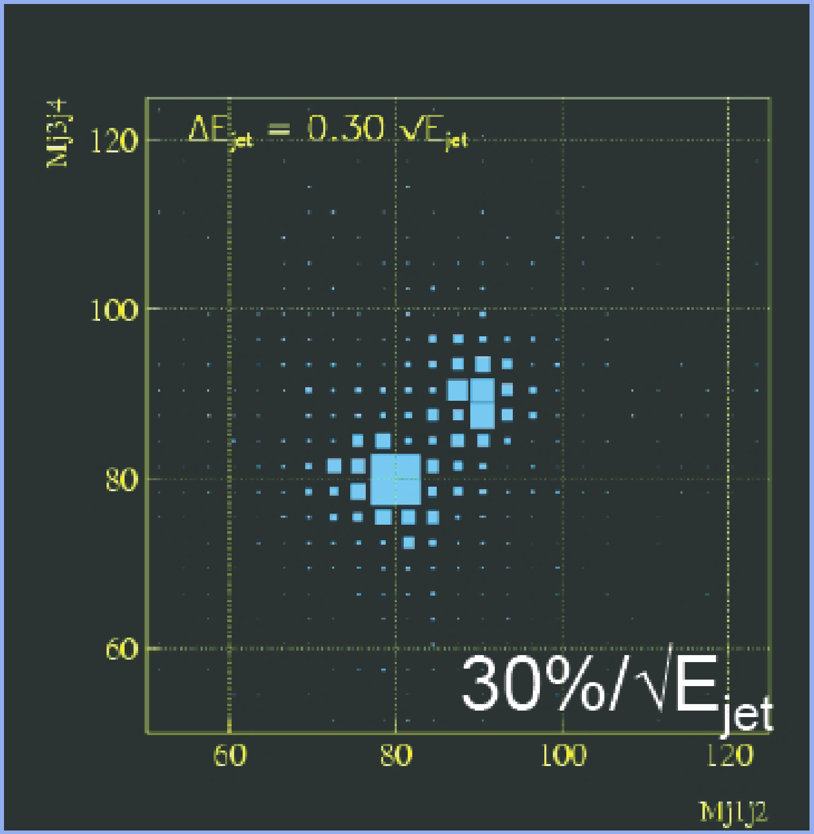
- **Calorimeter:**
  **distinguish W- and Z-bosons in their hadronic decays**
  **→ 30%/√E jet resolution!**

**2 times better than ZEUS**

- **WW/ZZ → 4 jets:**

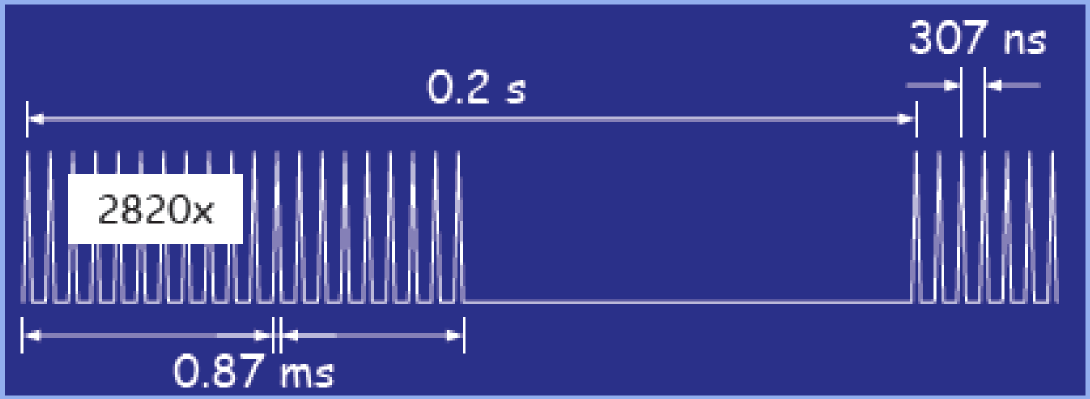


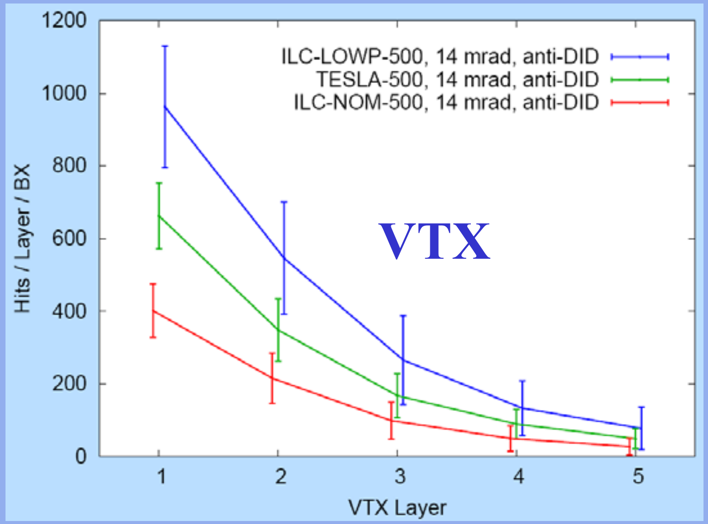

**→ Particle Flow or Dual Readout calorimeter**

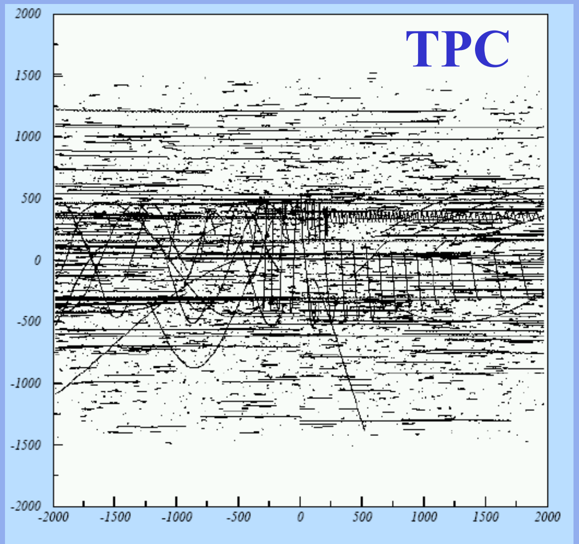
# Detector Challenges at the ILC

- Bunch timing:
  - 5 trains per second
  - 2820 bunches per train separated by 307 ns
    - no trigger
    - power pulsing
    - readout speed
- 14 mrad crossing angle
- Background:
    - small bunches
    - create beamstrahlung → pairs




backgound not as severe as at LHC but much more relevant than at LEP



# Detector Concepts

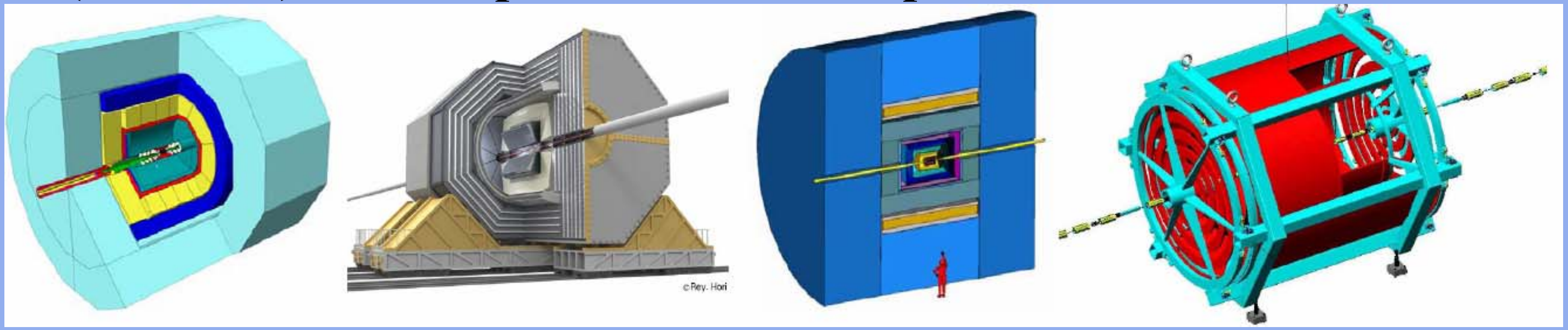


- Four detector concepts are being investigated
  - GLD (Global Large Detector)
  - LDC (Large Detector Concept)
  - SiD (Silicon Detector)
  - 4th concept

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

- Summer 2007: Detector Concept Reports (DCR)
  comprehensive detector descriptions, go along with machine RDR

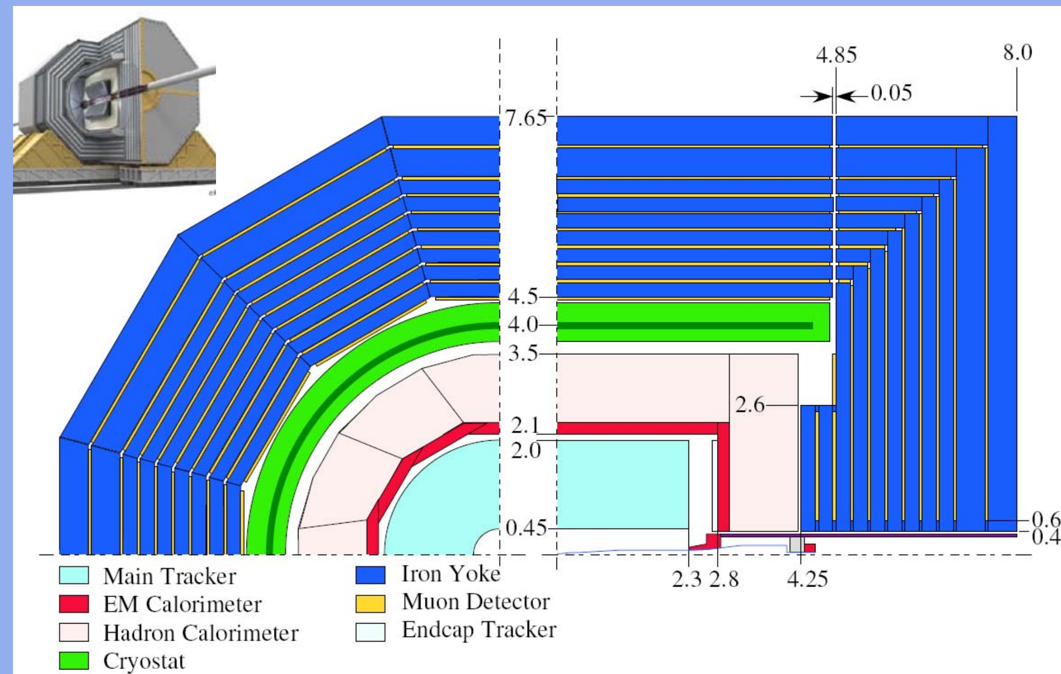
- Prepared by international study groups
  O(100 - 300) authors per detector concept



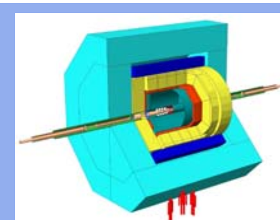
# Detector Concepts

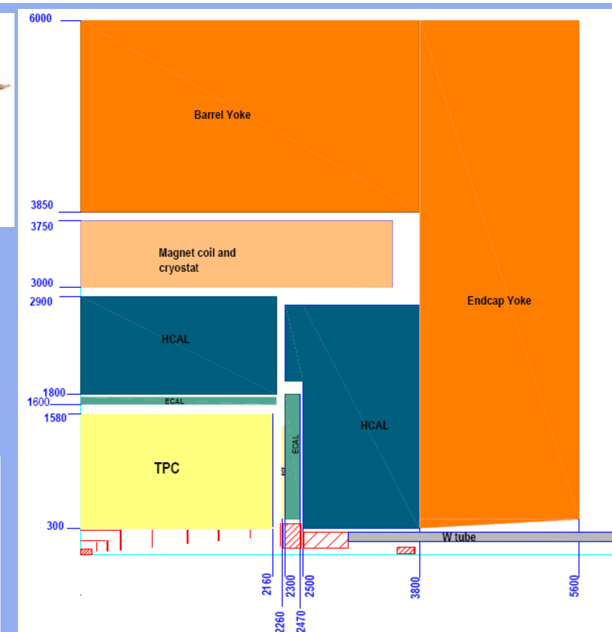


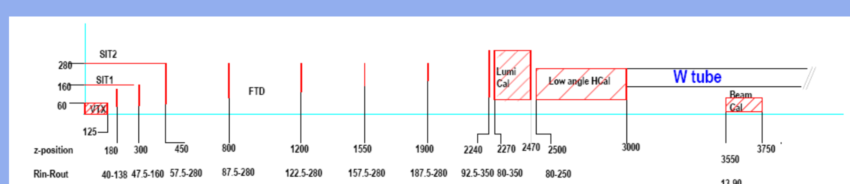
- GLD
  - TPC tracking
    large radius
  - particle flow calorimeter
  - 3 Tesla solenoid
  - scint. fibre μ detector




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

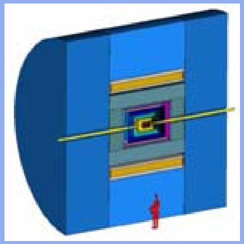


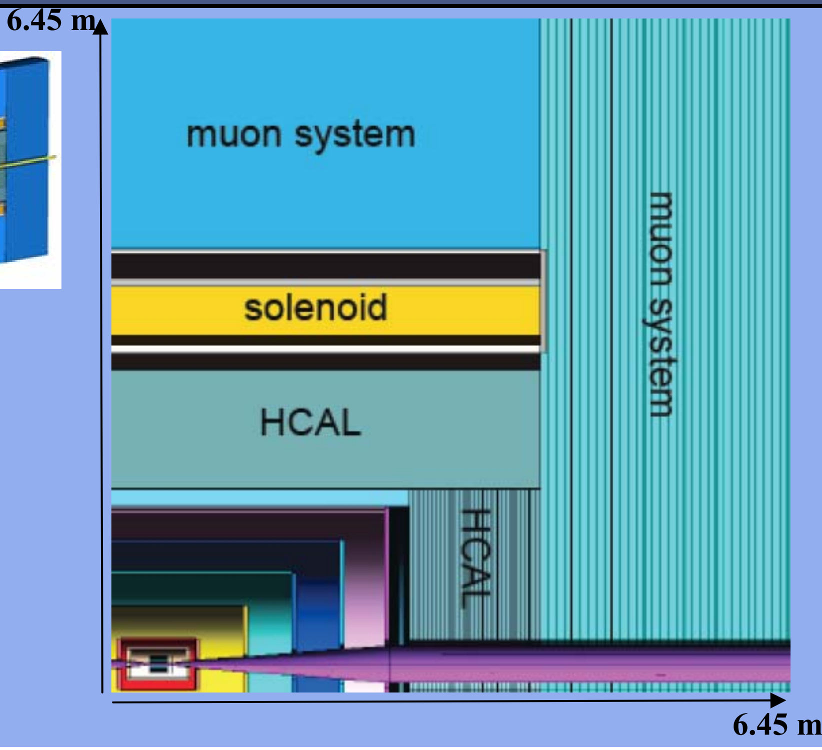


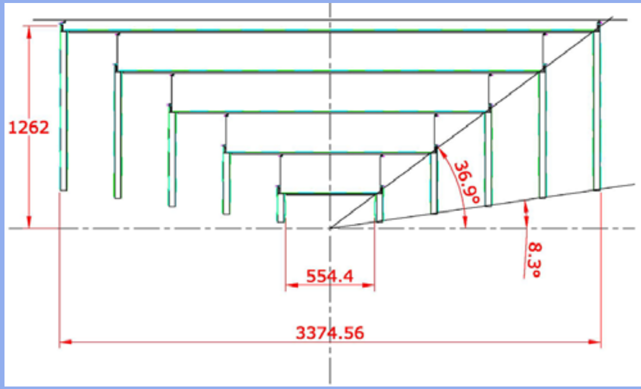
# Detector Concepts

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

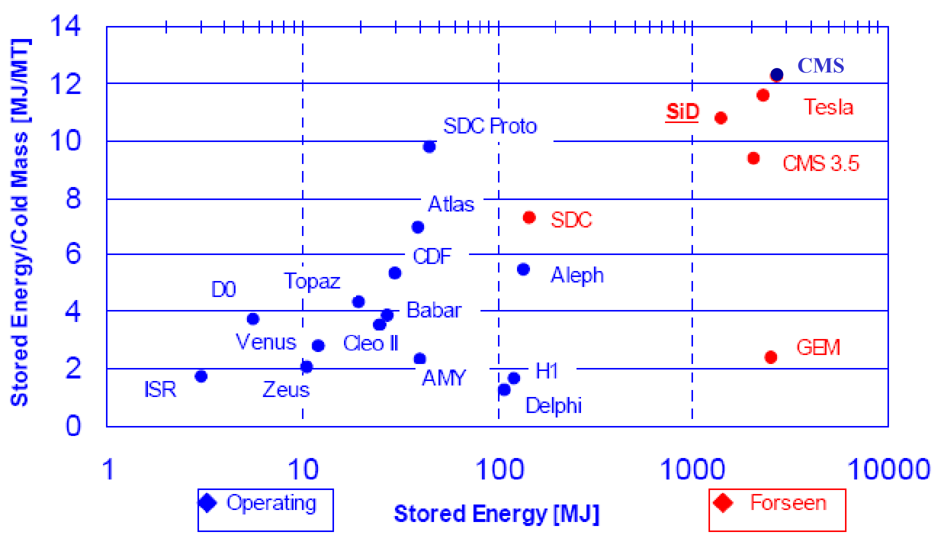





- **Silicon tracker**



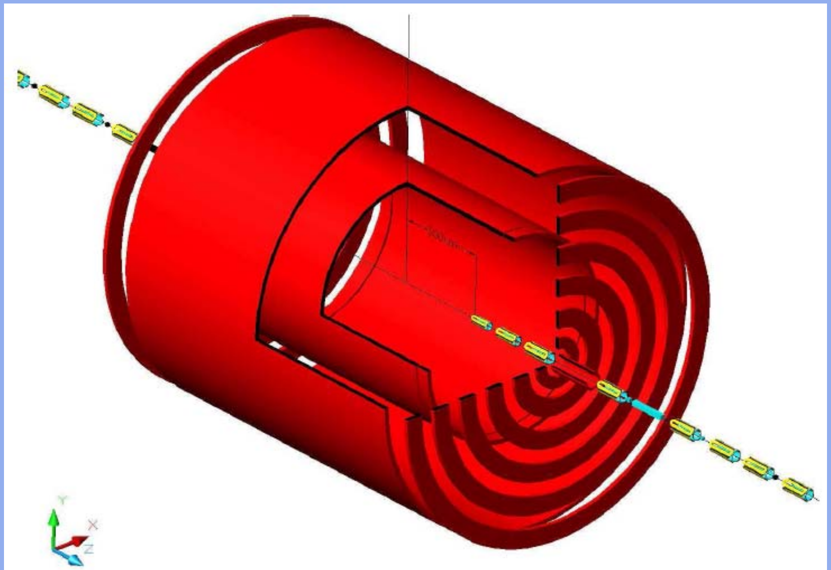

- **Magnet**
  - **high field**
  - **but smaller volume**

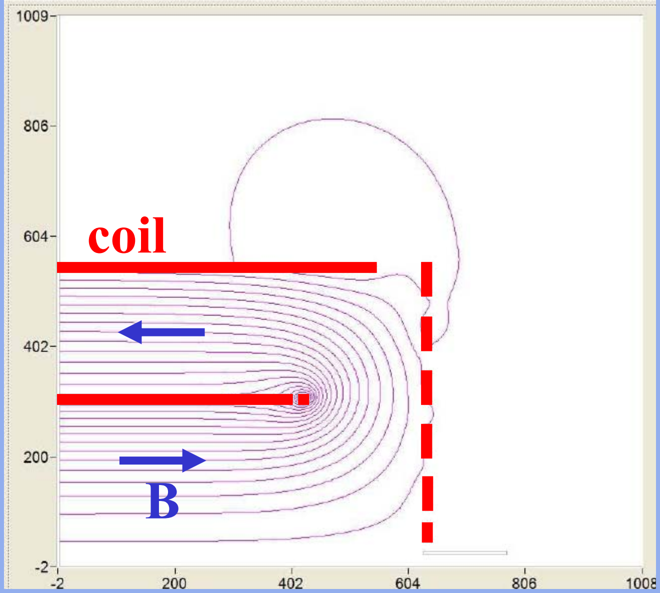


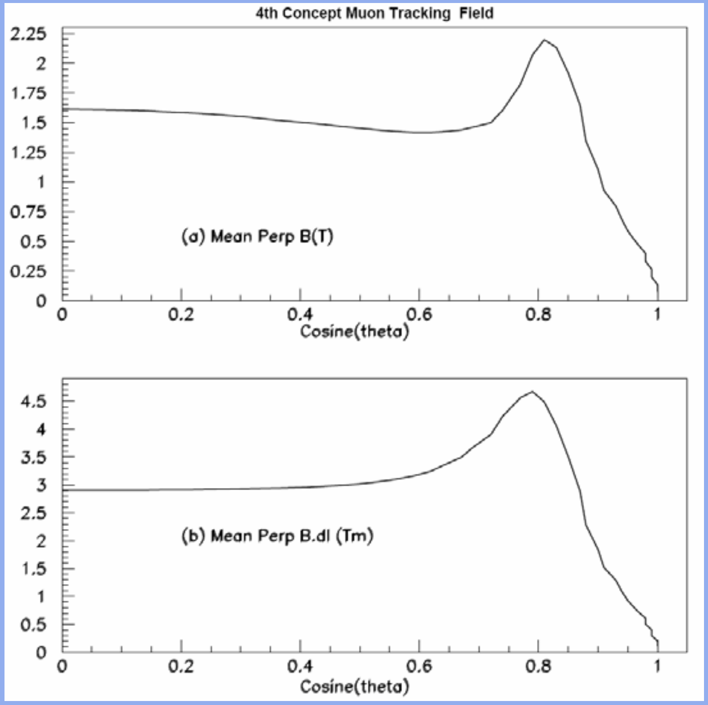
# Detector Concepts

- **4th concept**
  - TPC
  - multiple Readout Calorimeter
  - iron-free magnet, dual solenoid
  - muon spectrometer (drift tubes)

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






Average field seen by μ:

<B> ≈ 1.5 T

<Bl> ≈ 3 Tm

# Detector Concept and R&D efforts



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

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

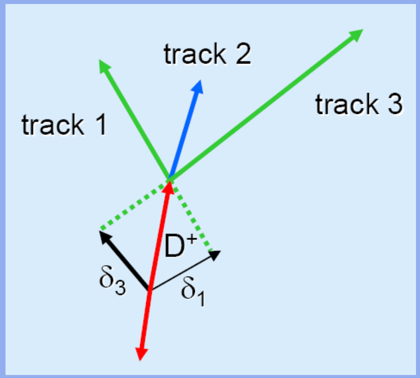
* silicon forward and auxiliary tracking also relevant for other concepts

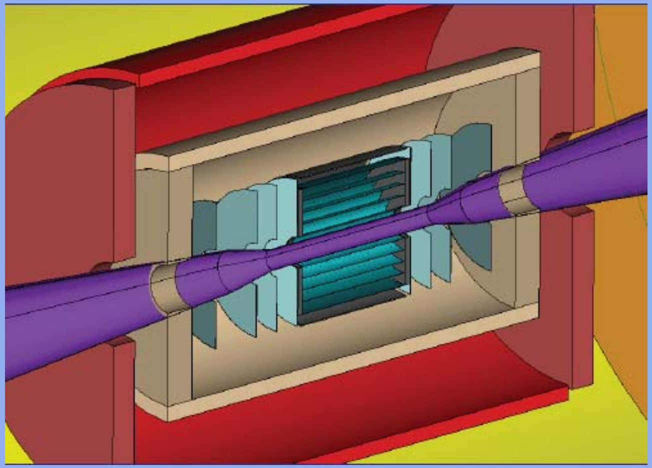
# Vertex Detector

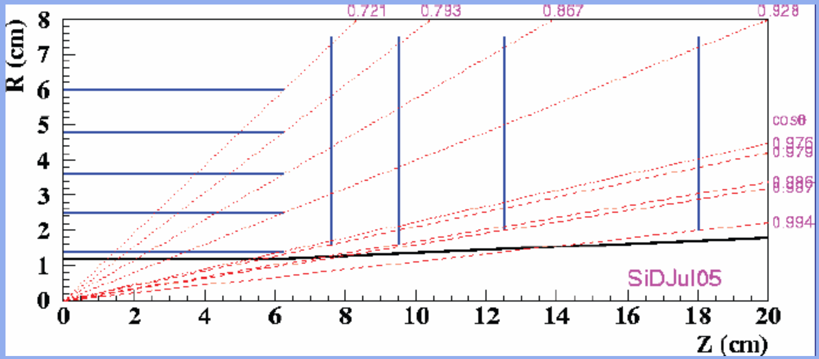
- Key issuses:
  - measure impact parameter for each track
  - space point resolution < 5 µm
  - smallest possible inner radius $r_i \approx 15$ mm
  - transparency: ≈ 0.1% $X_0$ per layer
    = 100 µm of silicon
  - stand alone tracking capability
  - full coverage |cos Θ| < 0.98
  - modest power consumption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

- Five layers of pixel detectors plus forward disks
  - pixel size O(20×20 µm²)
  - $10^9$ channels

- Note: wrt. the 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**

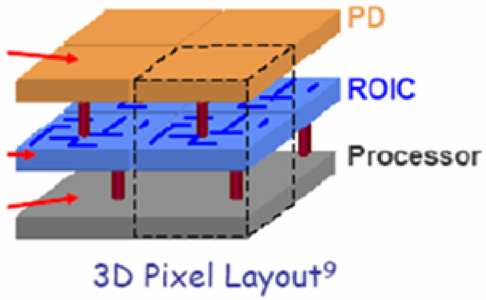
- **Many different (sensor)-technologies under study**
  **CPCCD, MAPS, DEPFET, CAPS/FAPS, SOI/3-D,**
  **SCCD, FPCCD, Chronopixel, ISIS, …**
  **→ Linear Collider Flavour Identification (LCFI) R&D collaboration**
- **Below a few examples**

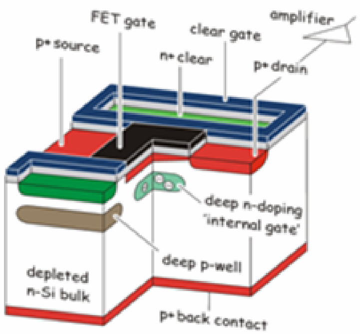
- **Note: many R&D issues independent of Si-technology (mechanics, cooling, …)**

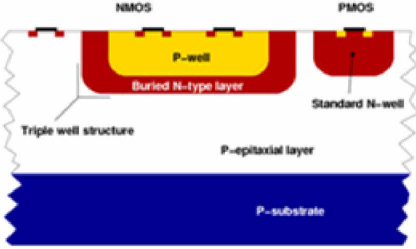
# Technologies

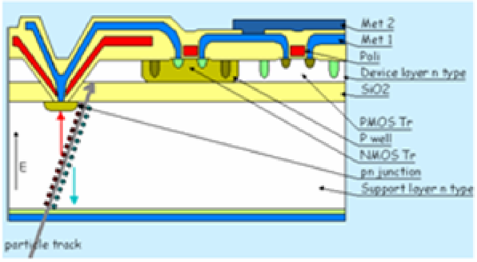
Many different technologies

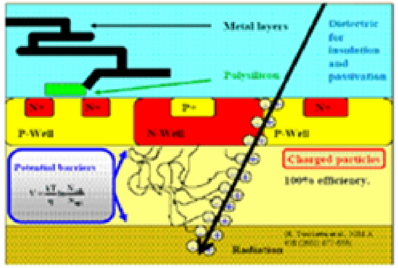
CP-CCD
DEPFET
FAPS
FP-CCD
MAPS
MAPS (tripple well)
SOI
3D



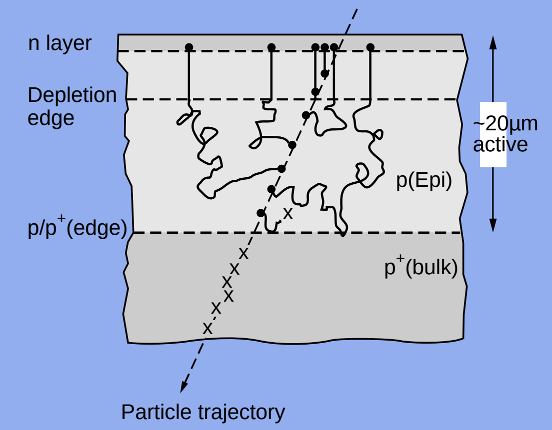



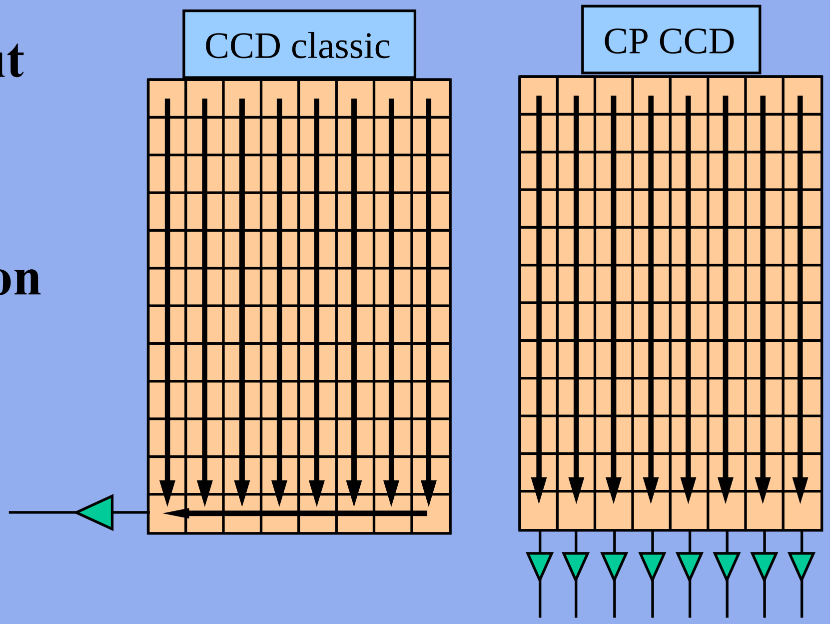

Excellent reviews by Konstantin Stefanov, Joel Goldstein, Rainer Richter, Hans Krueger, Marc Winter, Devis Contarato, Valerio Re, Tadashi Nagamine, Ray Yarema, Wojciech Kucewicz

# CP CCD

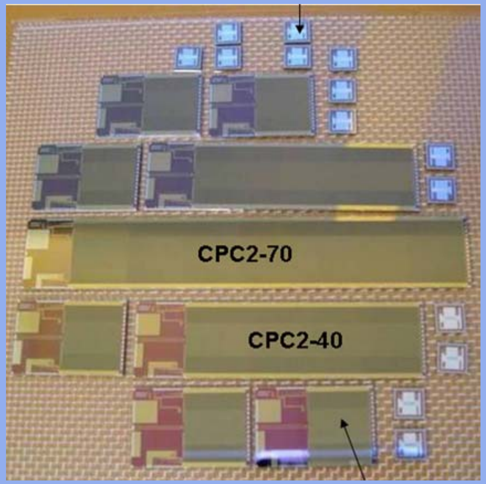
- **CCD**
  - **create signal in 20 µm active layer**
  - **etching of bulk material to keep total thickness ≤ 60 µm**
  - **low power consumption**
  - **but very slow**




**→ apply column parallel (CP) readout**

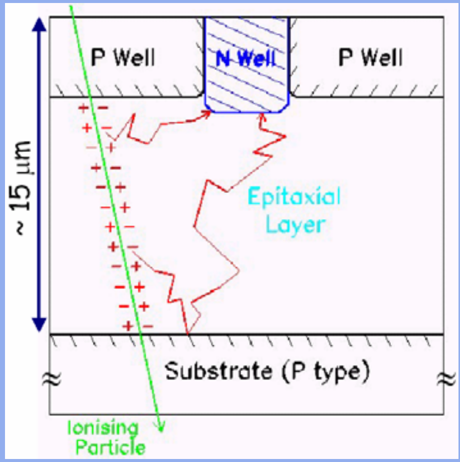



- **Second generation CP CCD designed to reach 50 MHz operation**

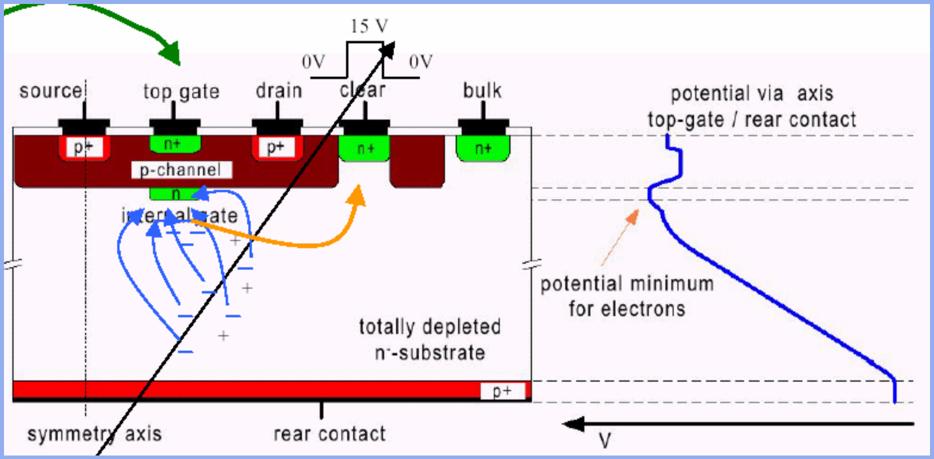


# MAPS and DEPFET

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



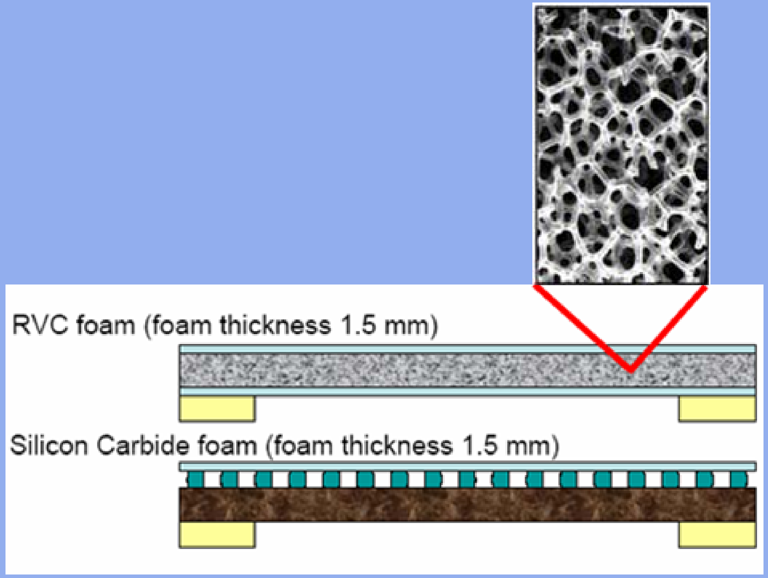

- DEPFET: Depleted Field Effect Transistor
  - fully depleted sensor with integrated pre-amplifier
  - low power and low noise



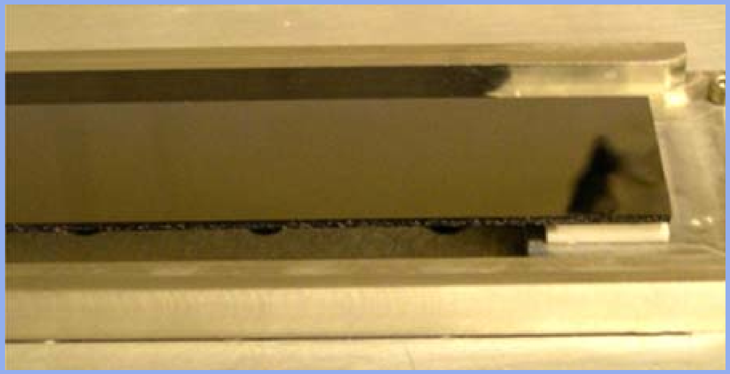
# Vertex Detector Support

- Mechanical support structure goal 0.1% $X_0$ per layer

- Example:
  - Reticulated Vitreous Carbon (RVC)
  - or Silicon Carbid SiC foams
  both good thermal match to Si




1.5 mm RVC foam + 2×25 μm silicon
= 0.09% $X_0$
1.5 mm SiC foam + 25 μm silicon
= 0.16% $X_0$ (reducible, less dense foam)
achieved



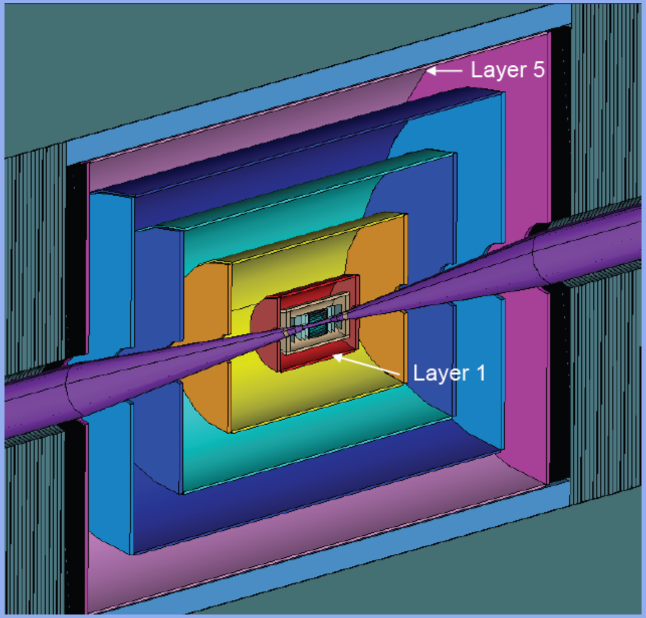
- can be adopted to all detector technologies

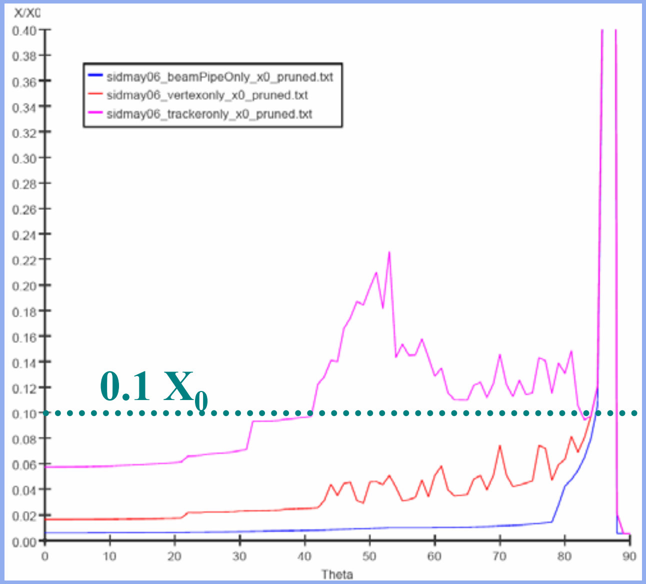
# Silicon Tracking

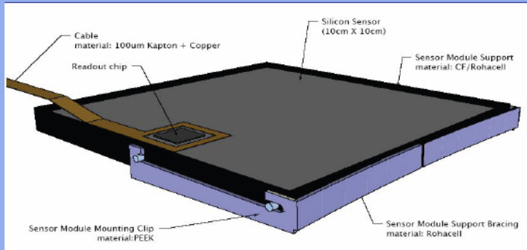
- The SiD tracker:
  - 5 barrel layers
    $r_i = 20$ cm
    $r_o = 125$ cm
  - 10 cm segmentation in z
    short sensors
  - measure phi only

- 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



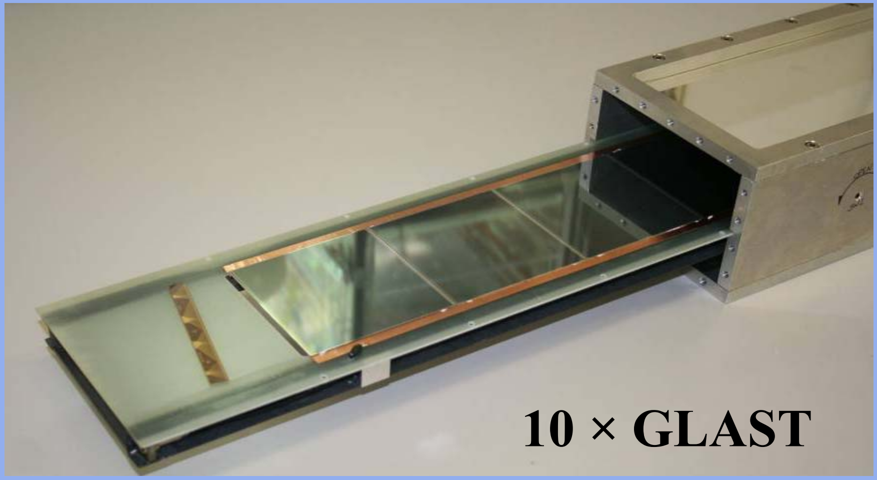



# Silicon Tracking

- Alternative design: long ladder
  - Silicon tracking for the Linear Collider (SiLC) collaboration
  - for all-silicon tracker
    or silicon enveloppe (→TPC)

- Development of low noise electronics
  - amplification & pulse shaping
  - passive cooling
  - exploit low duty cycle

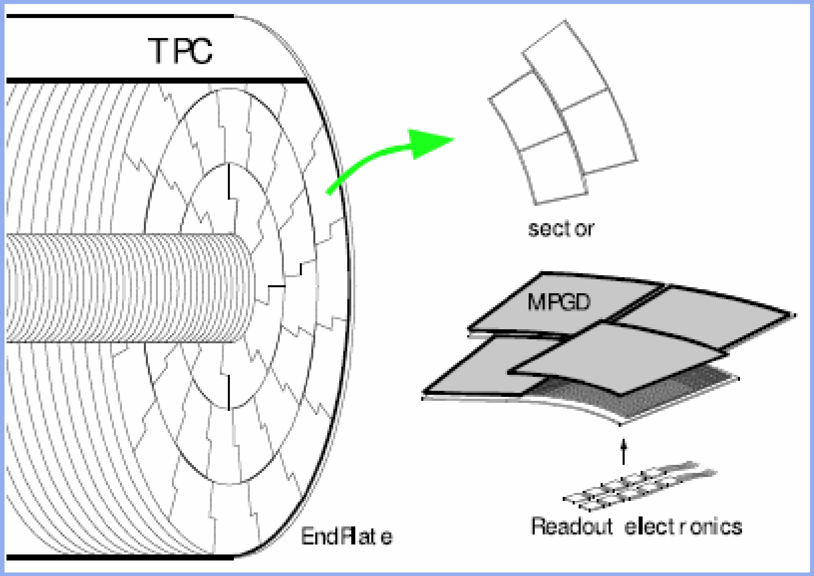
Prototype modules:

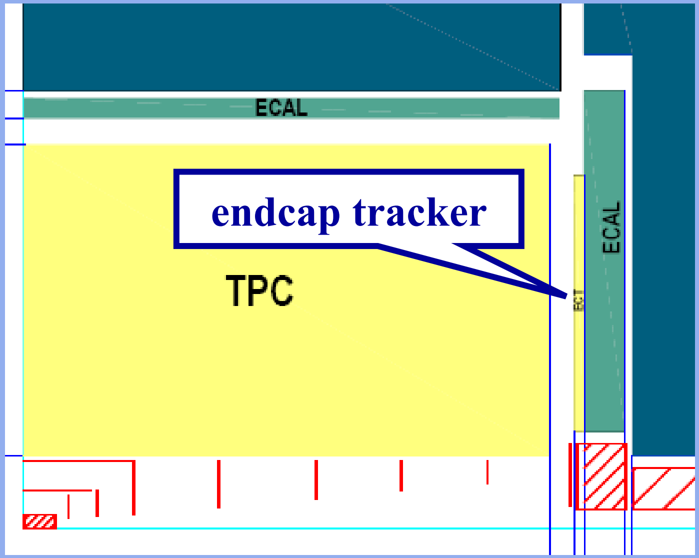
# Time Projection Chamber

- 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.

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




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



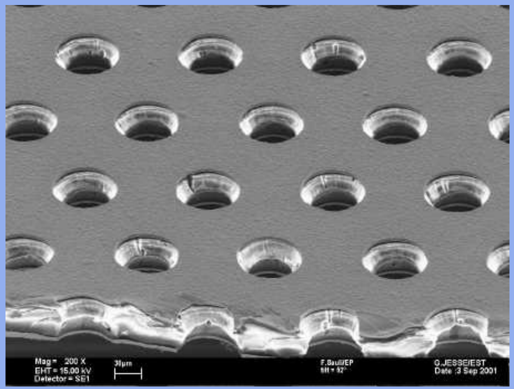

- TPC development performed in LCTPC collaboration

# Time Projection Chamber

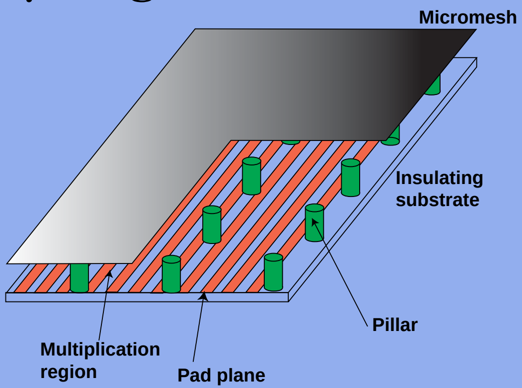
- New concept for gas amplication at end flanges: Replace proportional wires by Micro Pattern Gas Detectors (MPGD)

- GEM or MicroMegas
  - finer dimensions
  - two-dimensional symmetry $\rightarrow$ no $E\times B$ effects
  - only fast electron signal
  - intrinsic suppression of ion backdrift

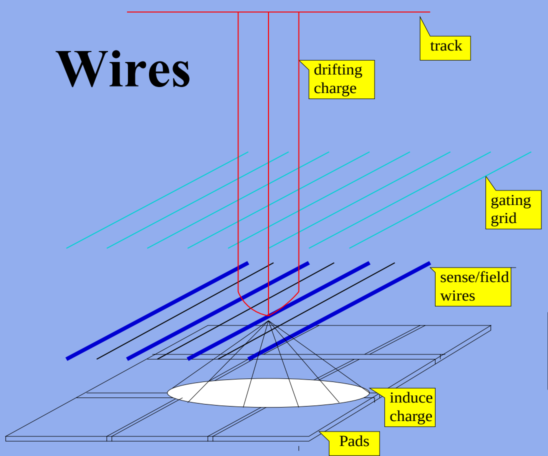
**GEM**



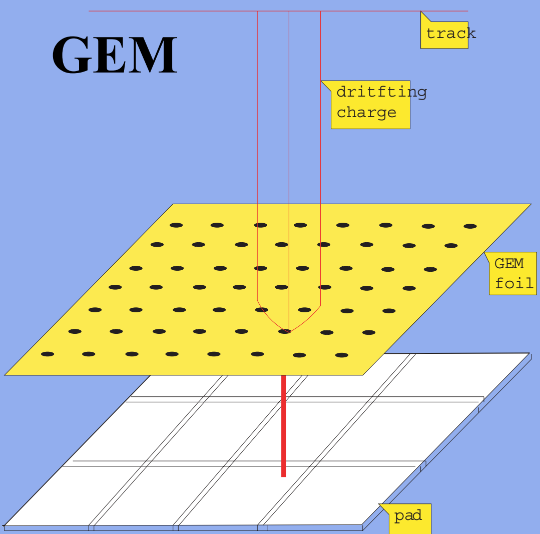
**µMegas**




**Wires**



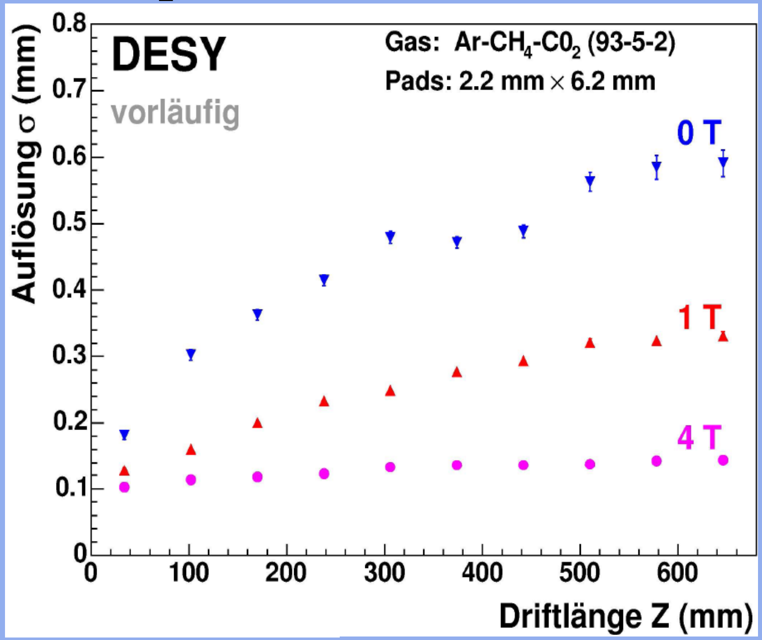

**GEM**



# Time Projection Chamber

- **Principle of MPGD based TPC established**
  **many small scale prototype experiments over the last ≈ 5 years**

**Example:**

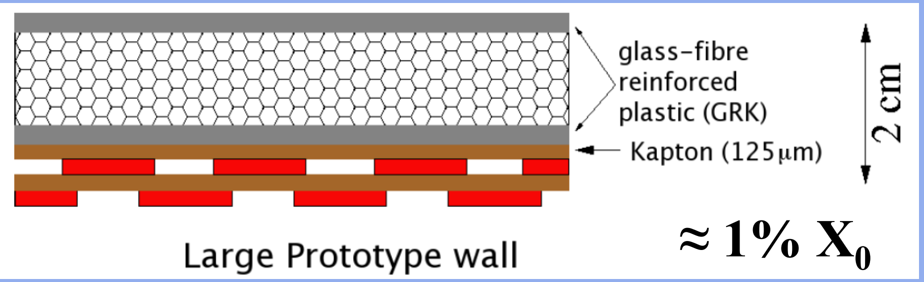


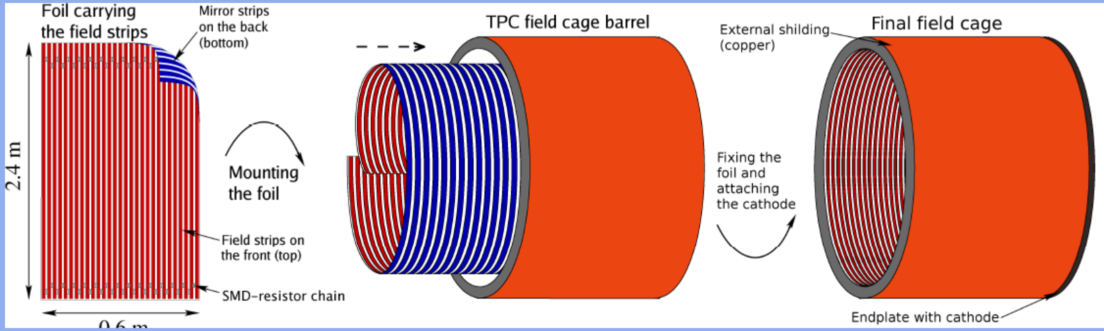

- **cosmics, testbeam**
- **magnetic field**

- **under construction for experiments (MICE, T2K)**

**Single point resolution O(100 μm) established in**
**- small scale prototypes**
**- high magnetic fields**

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

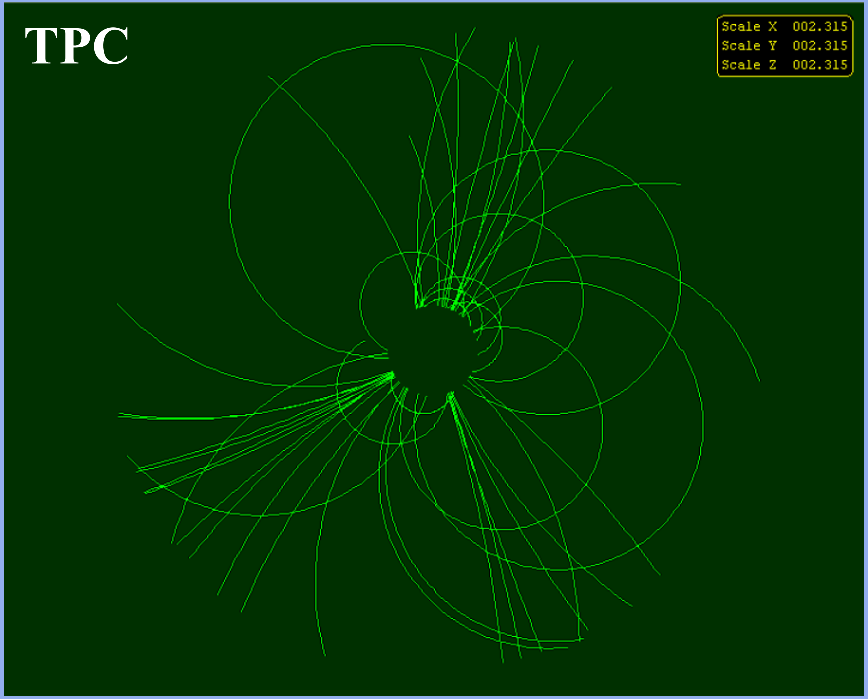


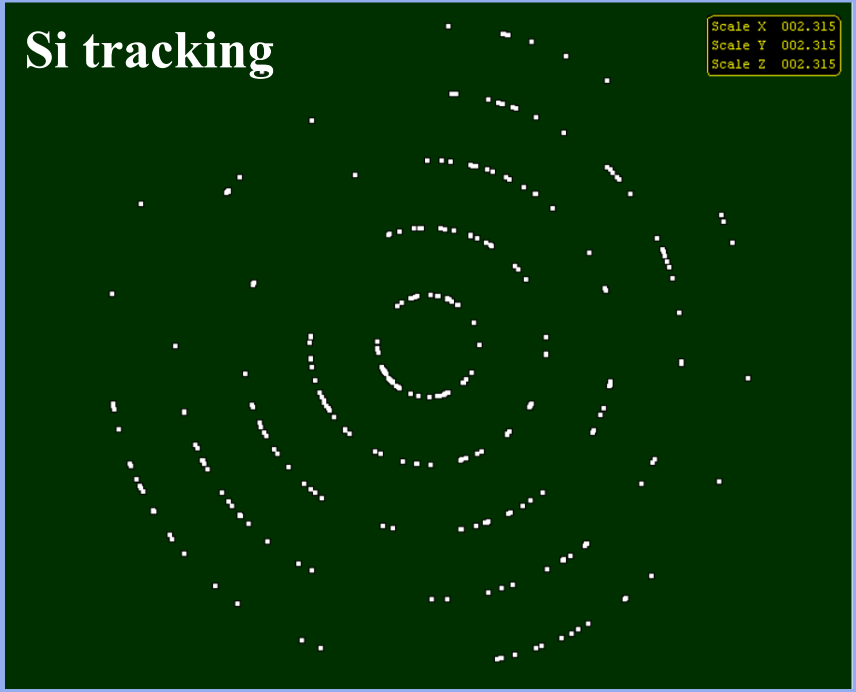




- Electronics
  - few $10^6$ channels on endplate
  - low power to avoid cooling
  - two development paths:
    - FADC based on ALICE ALTRO chip
    - and TDC chips

# 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)

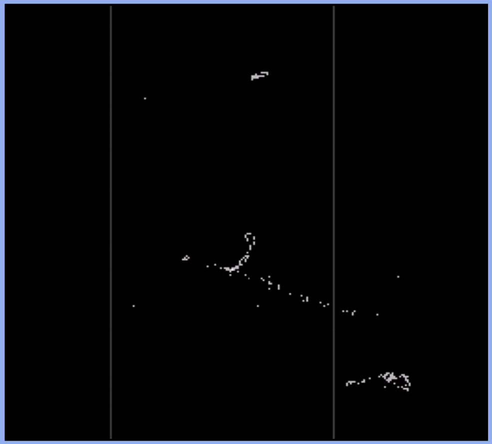


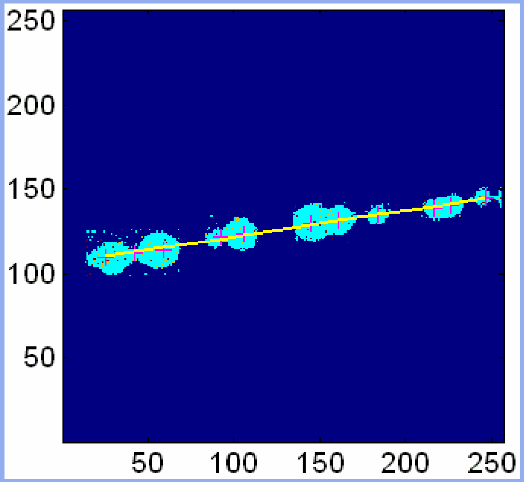
# Silicon TPC Readout



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



(Micromegas)

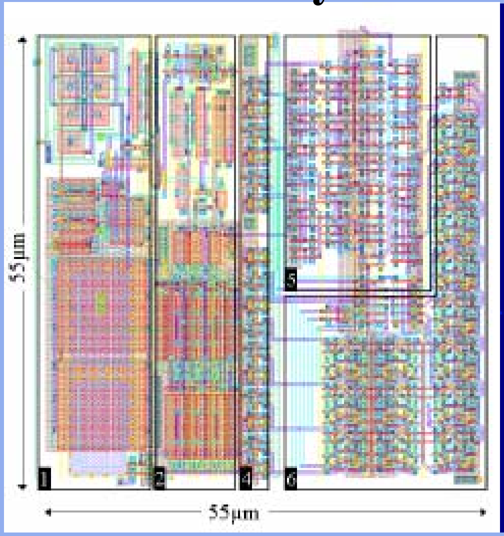



(GEM)

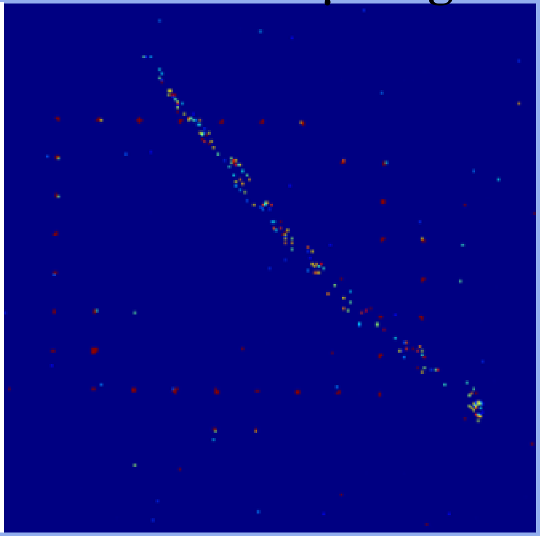
- **Medipix (2-d) → TimePix (3- d)**
- **50 - 150 MHz clock to all pixel**
- **1st version under test**

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

**TimePix layout**




**TimePix + μMegas**



# Calorimetry

- The 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

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

| 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 resolution
  $\sigma = \sigma_{charged} \oplus \sigma_{photons} \oplus \sigma_{neutral} \oplus \sigma_{confusion}$

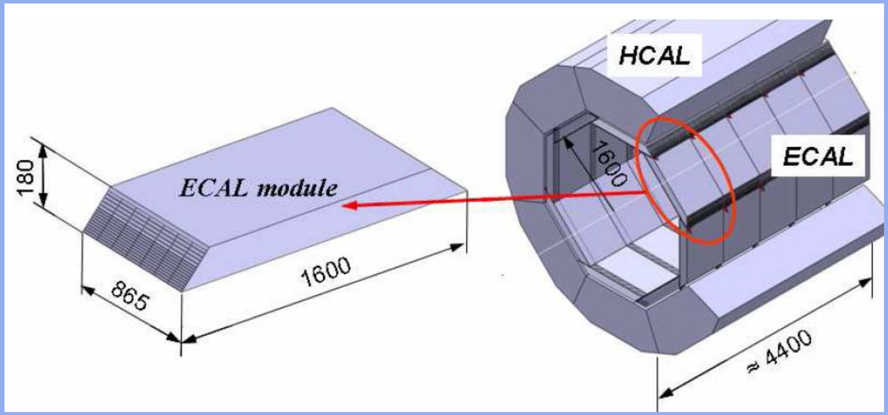
- confusion term arises from misassignment, double counting, overlapping clusters, …

- minimizing confusion term requires highly granular calorimeter both ECAL and HCAL

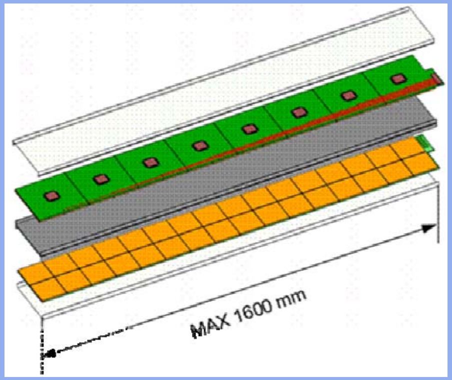
# Calorimetry

- 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

- GLD, LDC, 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



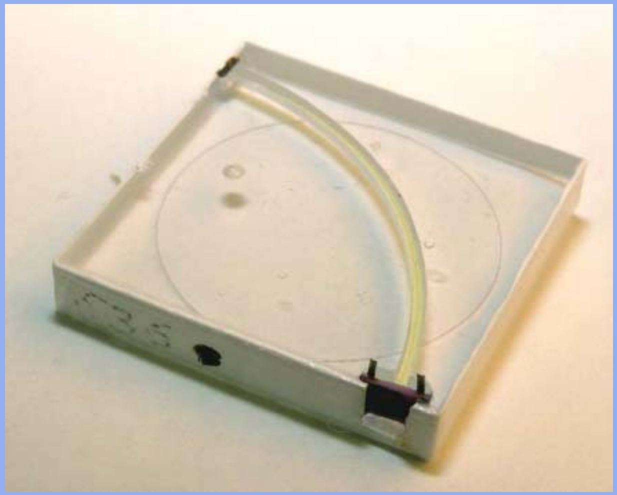

ECAL slab
- FE ASIC
- PCB board
- Si pads

- Alternative:
  W + Scintillating strips (GLD)

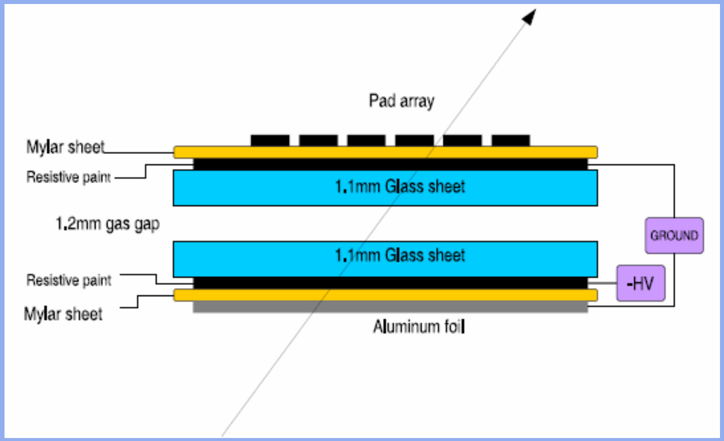
# Calorimetry

- **HCAL:**
  **2 options under consideration**

- **Analogue Scintillator Tile calorimeter**
  - **moderately segmented 3×3 $cm^2$**
  - **use SiPM for photo detection**

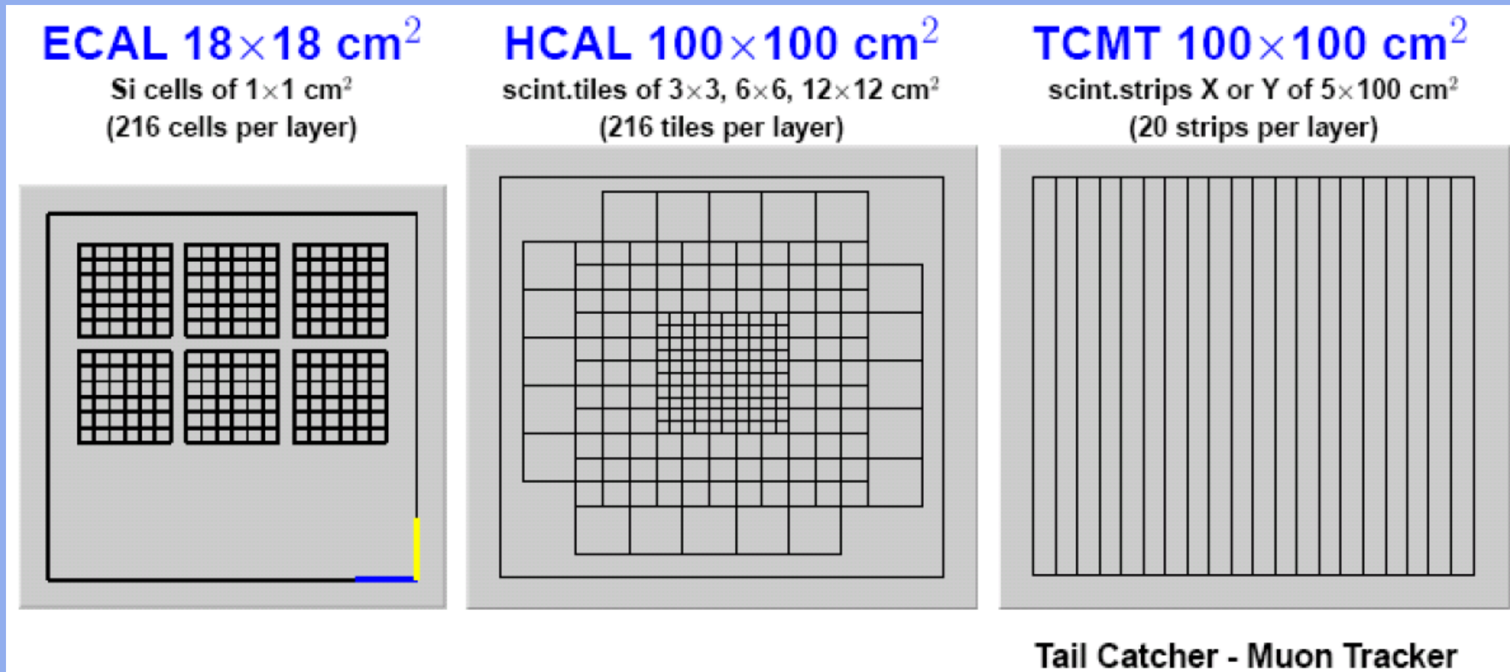


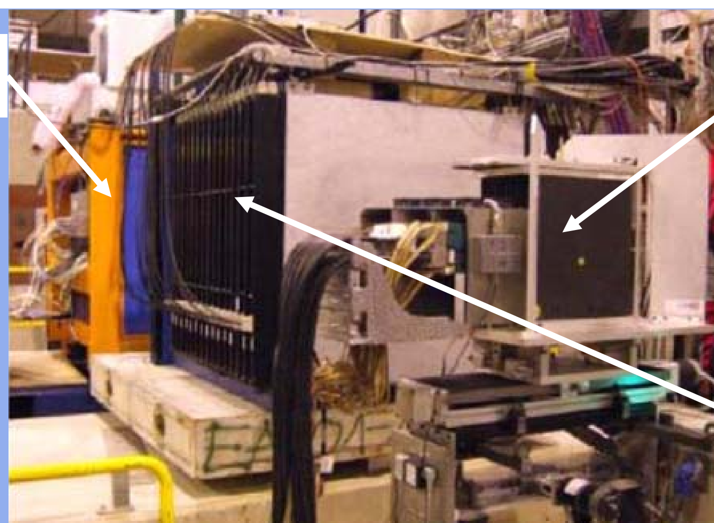
- **Gaseous Digital HCAL**
  - **finer segmentation 1×1 $cm^2$**
  - **binary cell readout**
  - **based on RPC, GEM or µMegas detectors**



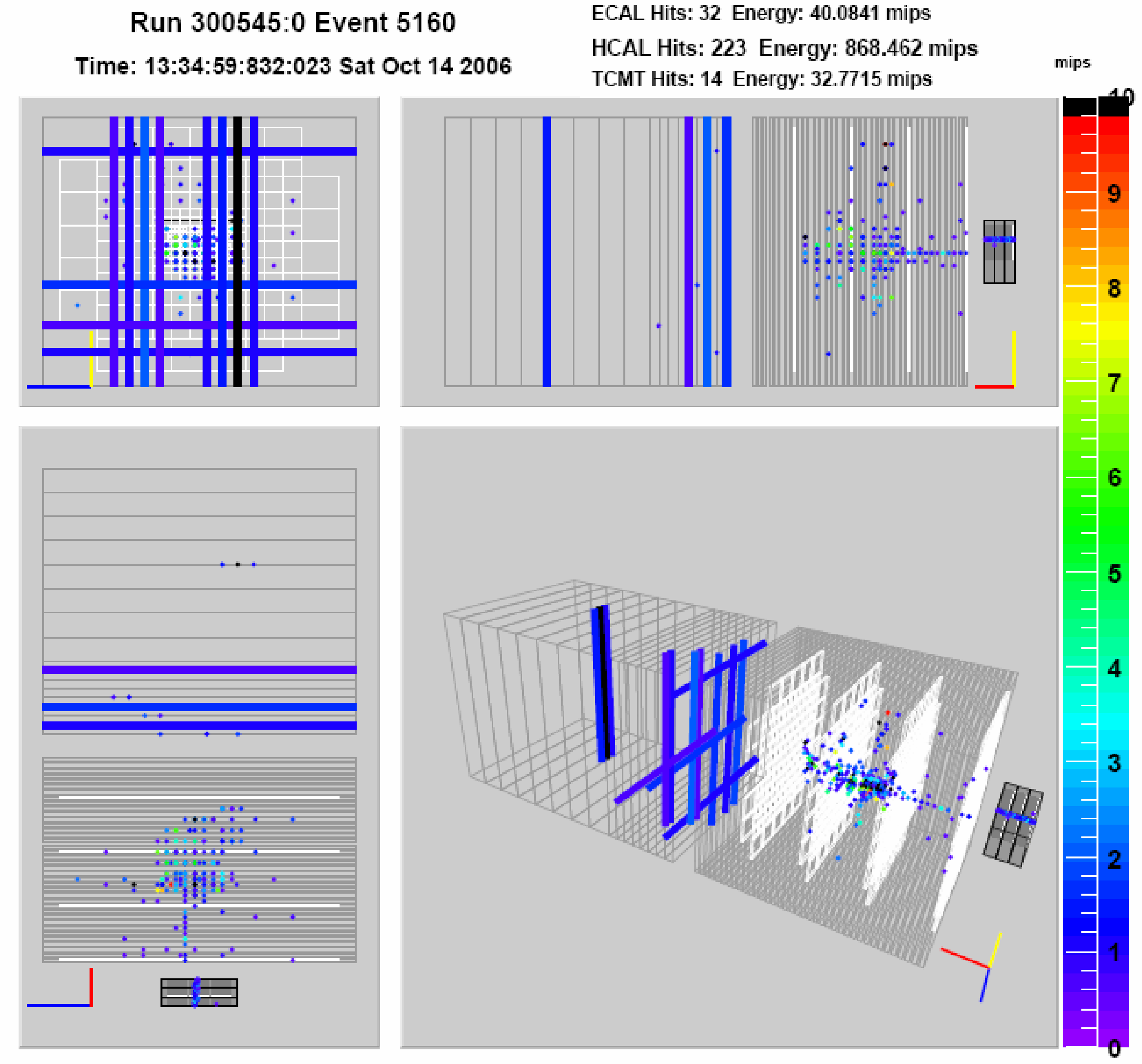
# Calorimeter

- **CALICE Testbeam at CERN (2006)**



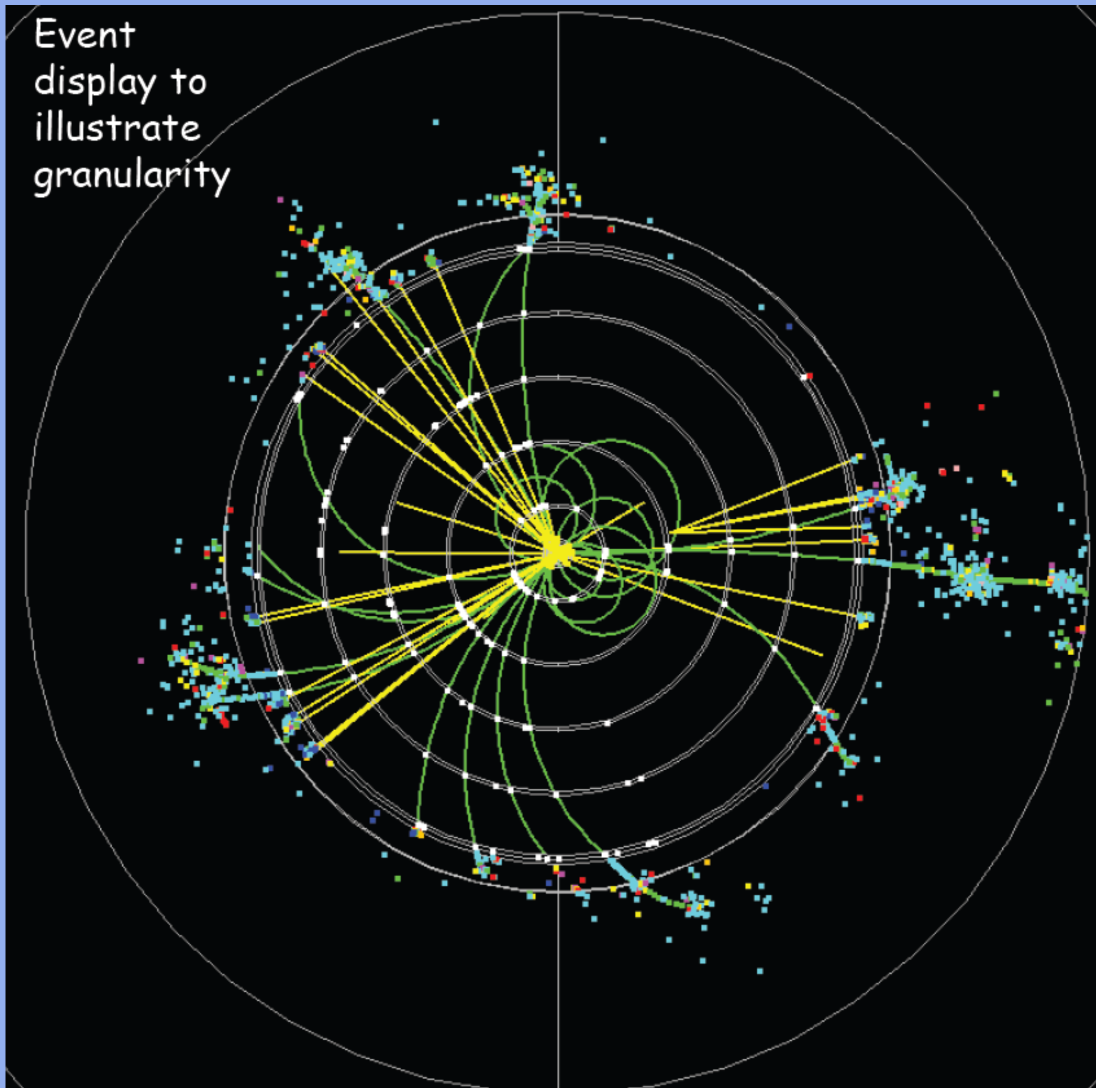
- **CALICE Testbeam at CERN (2006)**

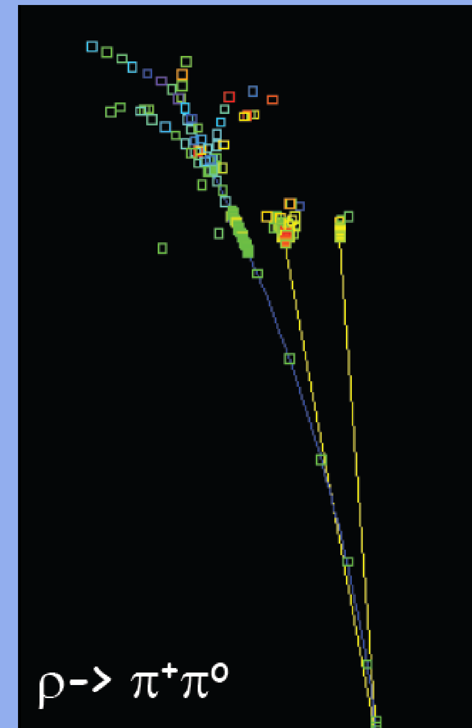



$\pi^-$ **30 GeV**

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

- **Simulation of an ILC event**



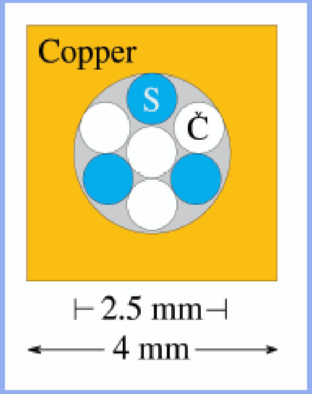
# Dual Readout Calorimeter



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

- **Fluctuations of local energy deposits concept**
- **Fine spatial sampling with SciFi every 2mm**
- **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**

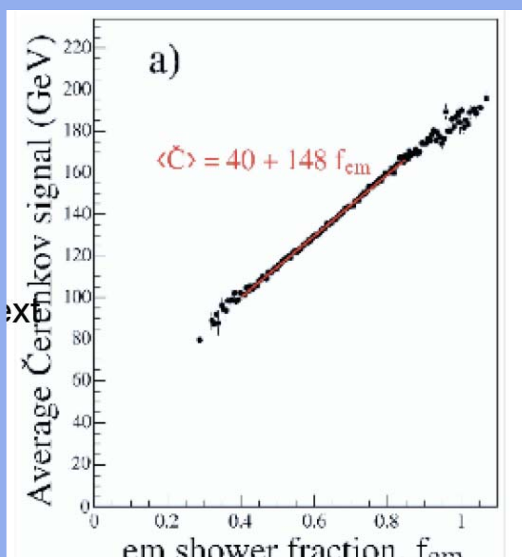
# Dual Readout Calorimeter

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

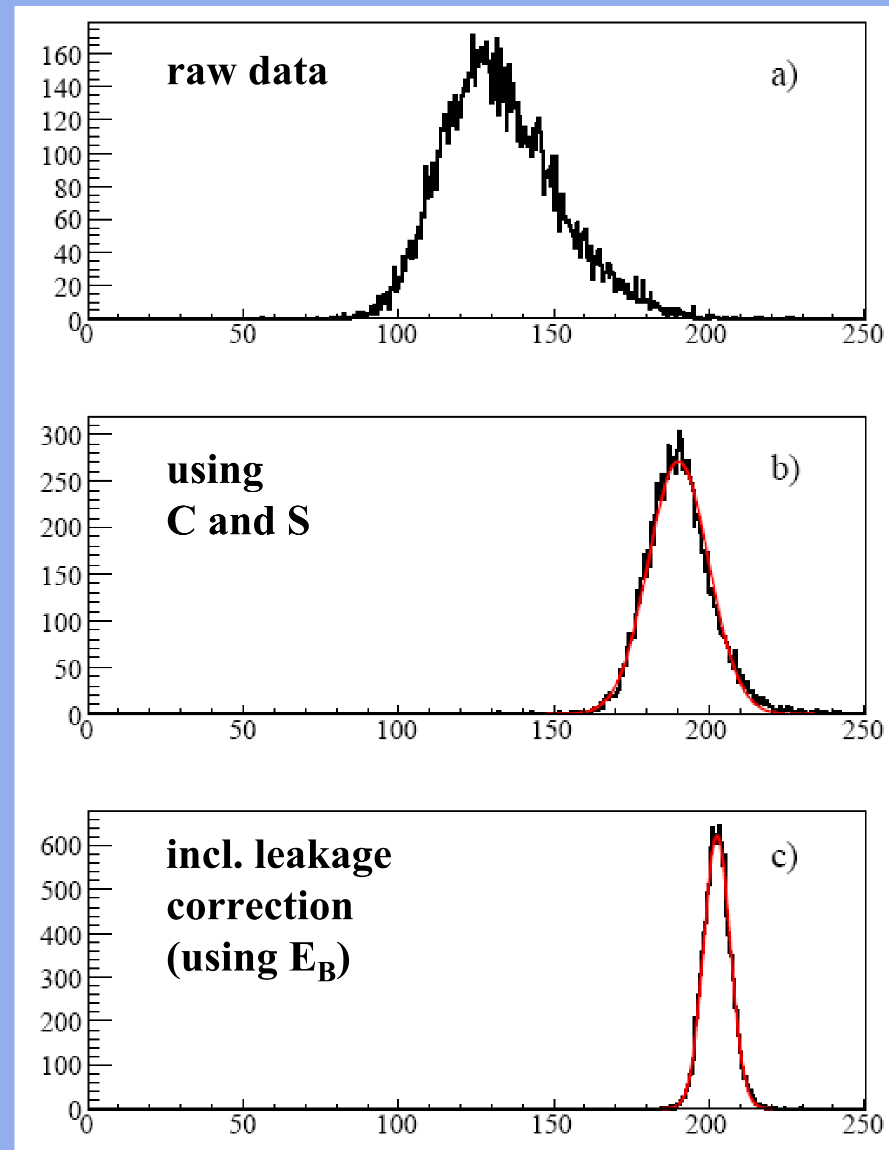
$$(e/h)_C = \eta_C \approx 5$$
$$(e/h)_S = \eta_S \approx 1.4$$

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

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




**200 GeV $\pi^-$ beam at CERN**



- **From DREAM to an ILC calorimeter:**

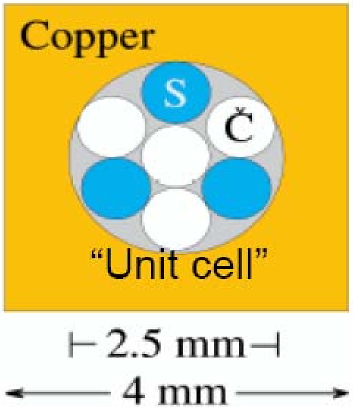
DREAM module

3 scintillating fibers
4 Cerenkov fibers

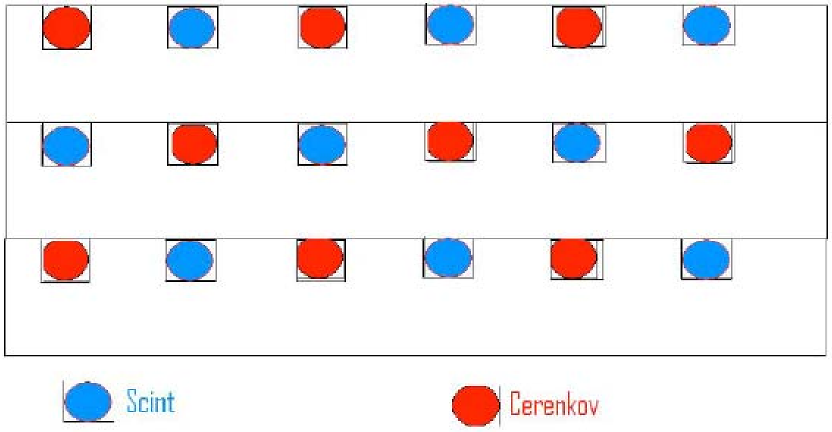
ILC-type module

2mm W, Pb, or brass plates;
fibers every ~2 mm

(Removes correlated fiber hits)



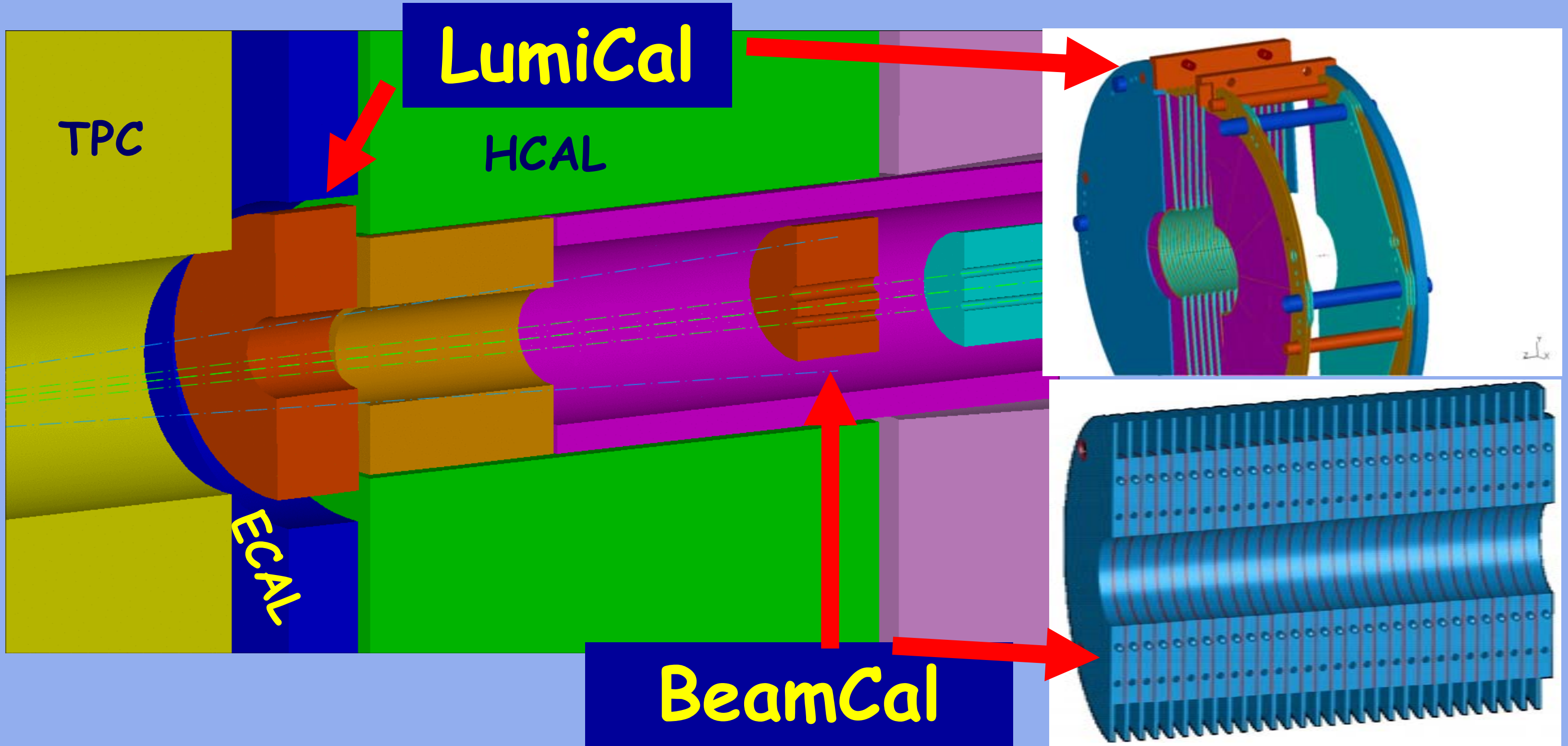

→



# Forward Calorimetry

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

- Detector technology: tungsten/sensor sandwich
- Example: LDC design for zero cross angle
  to be adapted for 14 mrad ILC design



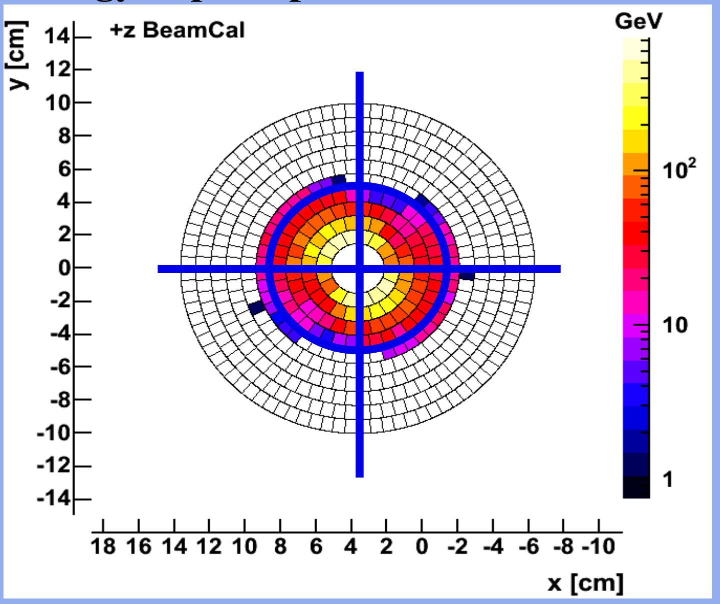
# BeamCal

- Challenges:
  - ≈ 15000 $e^+e^-$ pairs per BX in MeV range, extends to GeV
  - total deposit O(10 TeV)/BX
  - ≈ 10 MGy yearly rad. dose

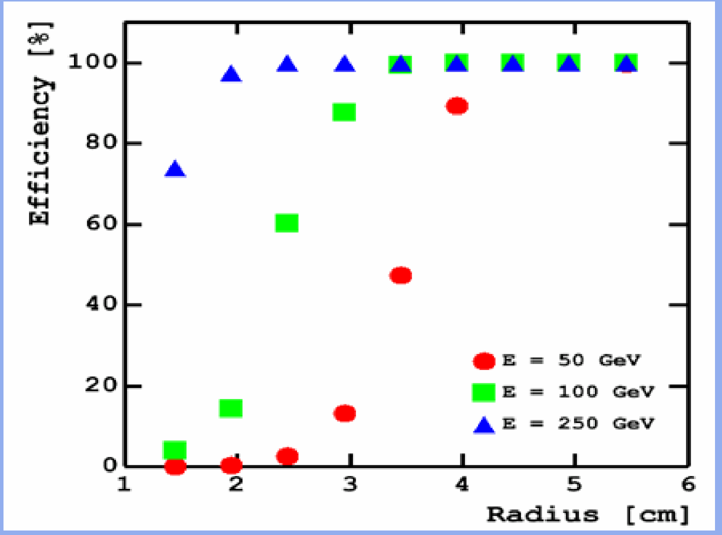
  - identification of single high energy electrons to veto two-photon bkgd.

- Requires:
  - rad. hard sensors (diamond)
  - high linearity & dynamic range
  - fast readout (307 ns BX interval)
  - compactness and granularity

**Energy deposit per BX:**



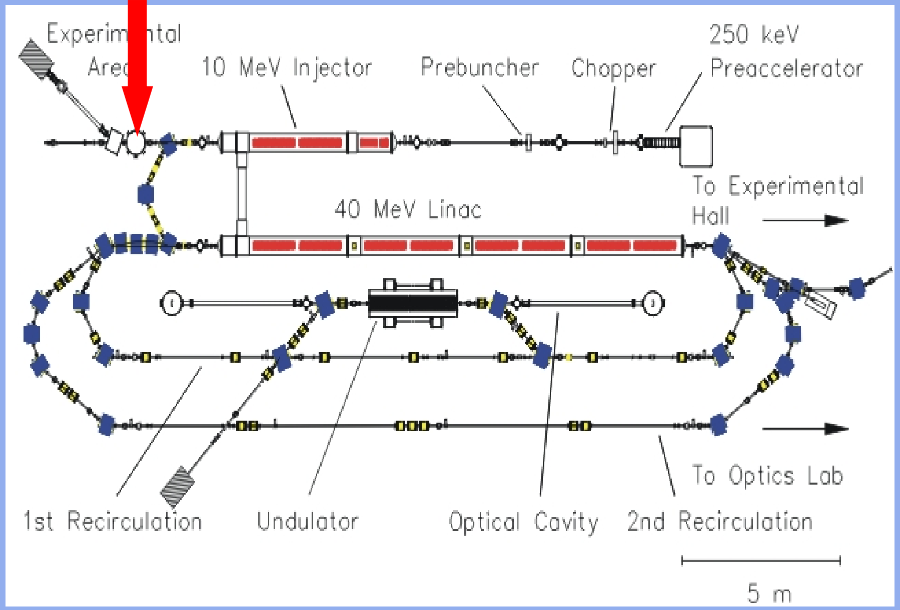

**Electron ID efficiency:**



# Forward Calorimetry

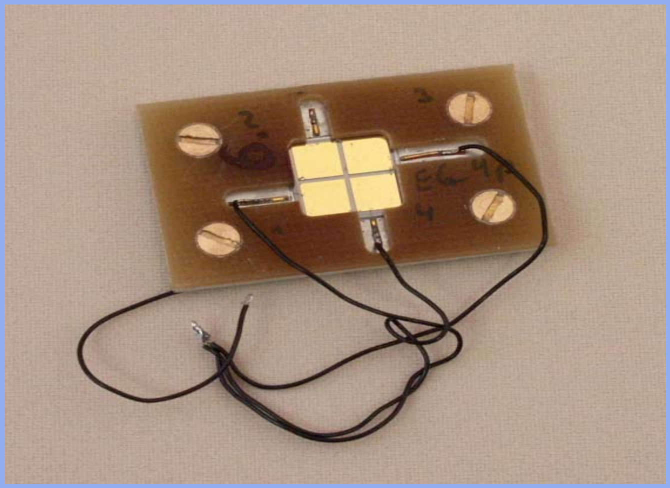
- Sensors tests at DALINAC (Darmstadt)
  current 1 – 100 nA (10 nA ≈ kGy/h)

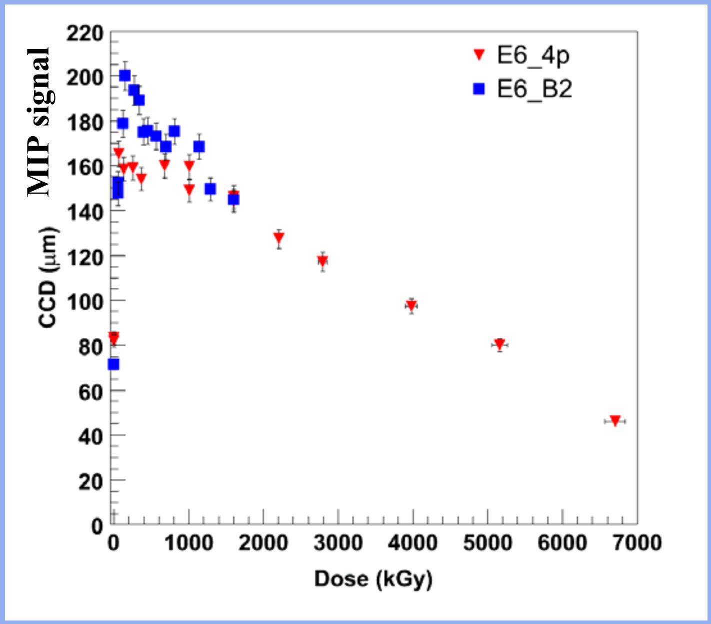
10 MeV




- Alternative sensor materials
  - GaAs
  - SiC
  - radiation hard silicon

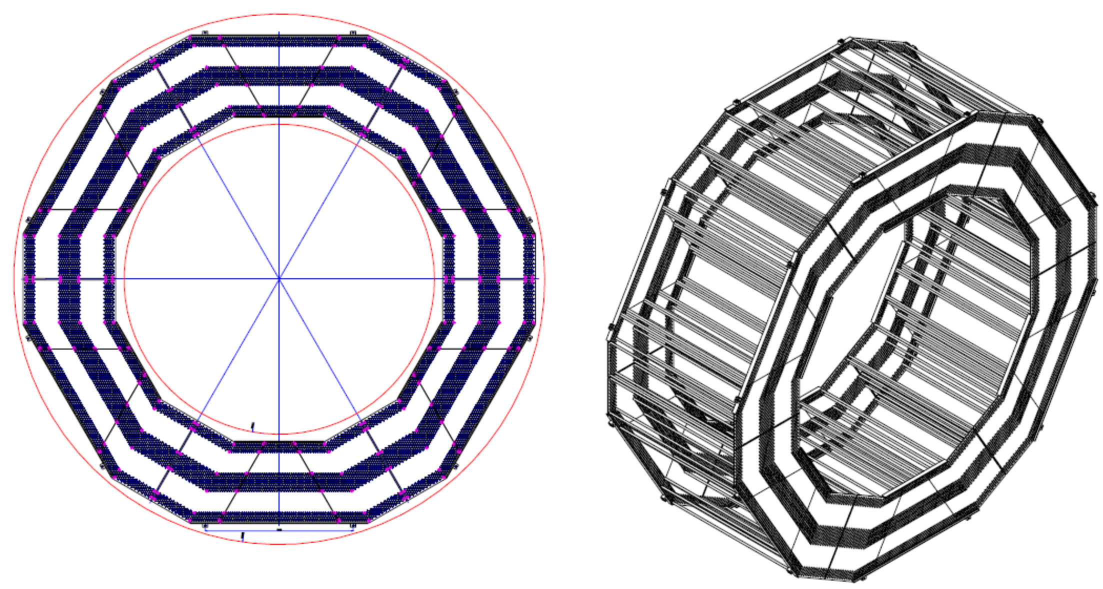
Diamond sensor after ≈ 7 MGy

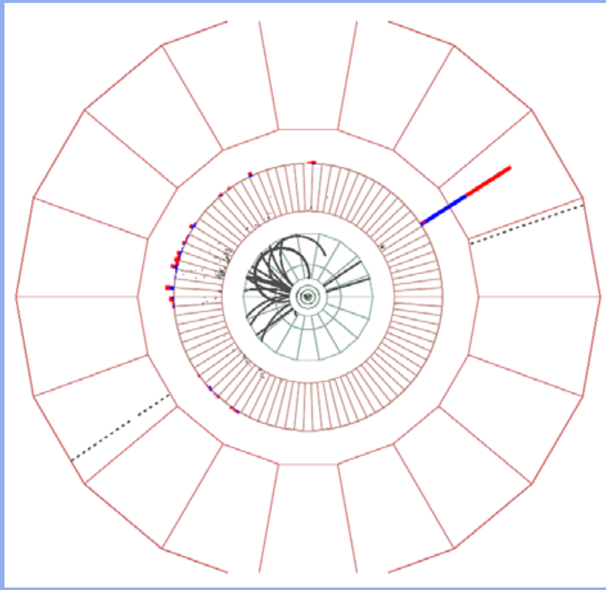




# Muon Detectors

- GLD, LDC & SiD have muon detection only: RPC, scint. fibre detector momentum in central tracker
- 4th concept:
  - muon spectrometer between coils
  - high precision drift tubes





$H^0Z^0 \rightarrow W^+W^-\mu^+\mu^- \rightarrow jje^-\bar{\nu}_e\mu^+\mu^-$

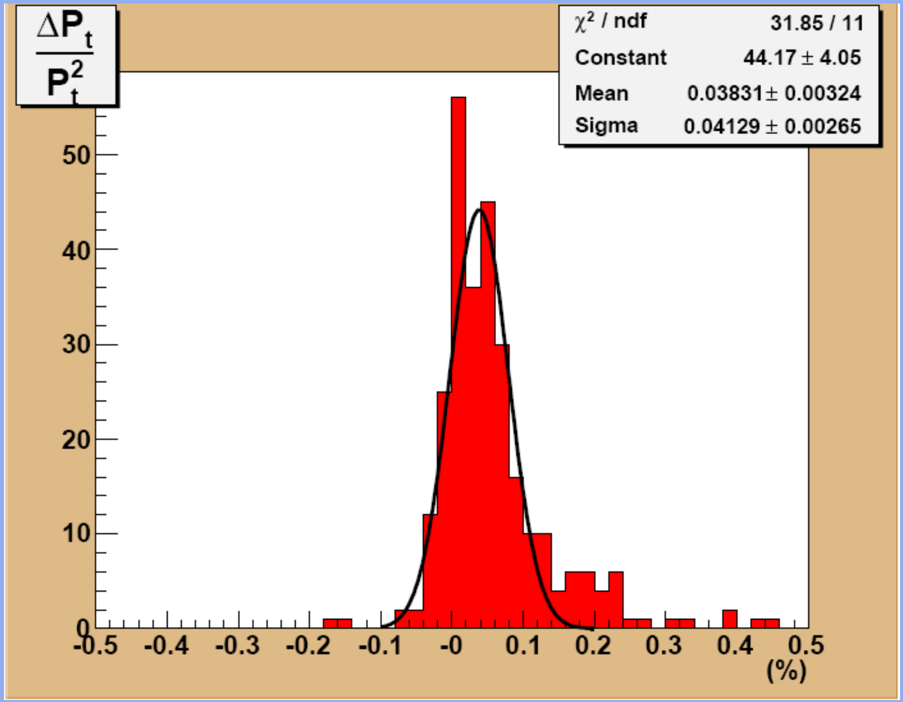
- low $p_T$-threshold for muons
- excellent $\pi/\mu$ separation

also exploiting multiple readout calorimeter

- **Disclaimer:**
  - **all in early design phase**
  - **comparison difficult**
  - **assume that R&D is succesful and large scale detectors will keep performance**

- **A few DOD plots on performance from simulation studies**

- **4th concept:**
  **- muon spectrometer**
  **$\sigma(1/p_T) \approx 4 \cdot 10^{-4}$ /GeV**

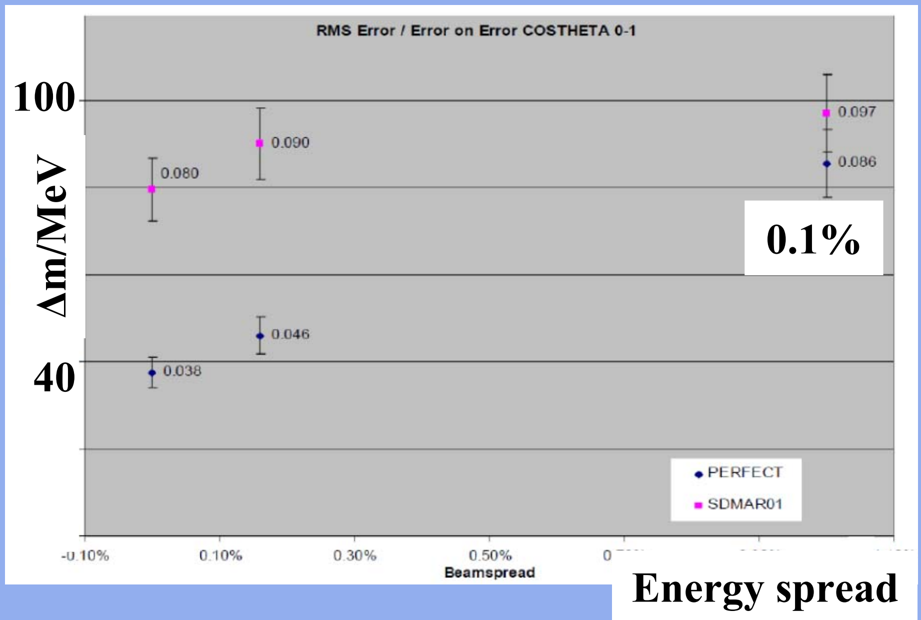


# Detector Performance



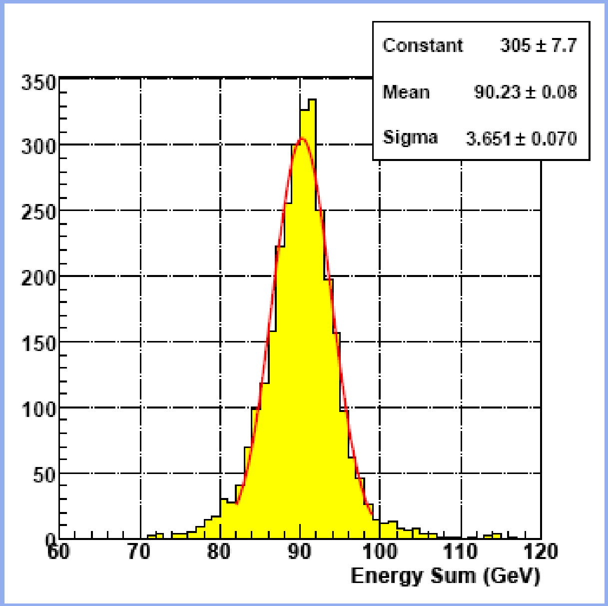
- **SiD Tracking:**

  143 GeV selectron at 1 TeV
  mass measurement from end point
  - 0.1% beam energy spread
  - 100 MeV error
    not limited by tracker




- **GLD calorimetry:**
  test of PFA with Z-pole events
  $Z \rightarrow$ hadrons

  38% mass resolution
  improvements are still possible



# Detector R&D in Europe

- **Next step:**
  **from small scale proof-of-principle experiments to larger scale prototypes**

- **Example:**
  **the EUDET programme in Europe**
  - **improvements of infrastructures for larger scale detector prototypes (not only ILC)**
  - **devised in close cooperation with the international R&D collaborations**

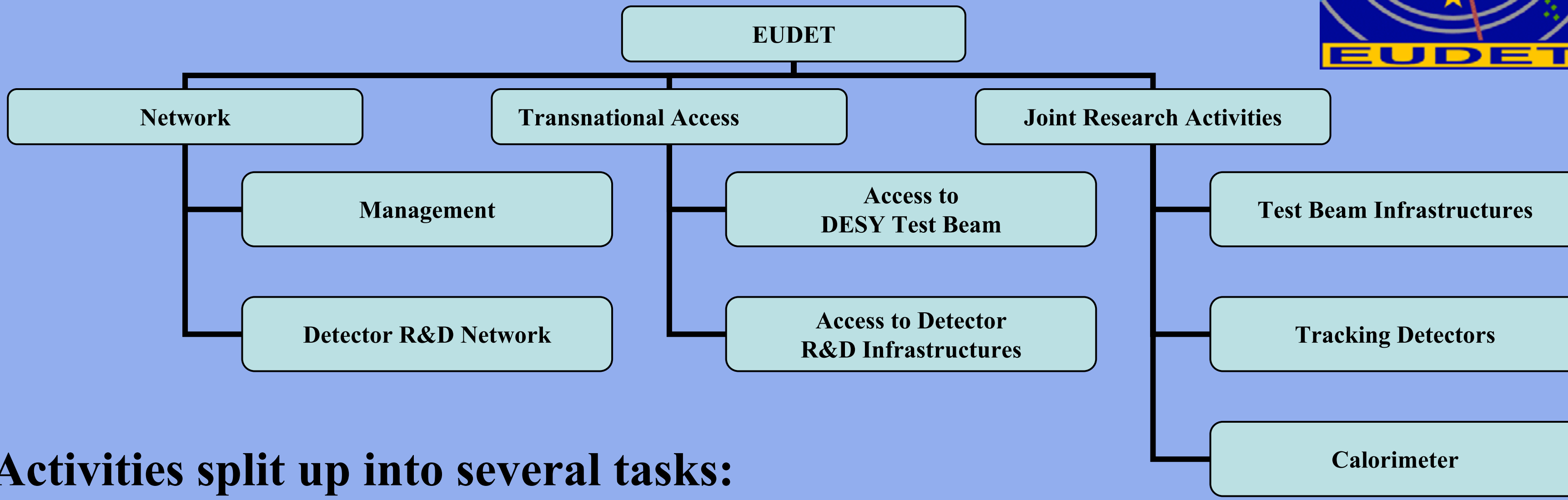
- **Transnational Access:**
  - **support for (European) groups**
    - **DESY testbeam**
    - **usage of EUDET infrastructures**

- **More information at [www.eudet.org](http://www.eudet.org)**

# Detector R&D in Europe



## European infrastrucutre projects are based on three pilars:




## Activities split up into several tasks:

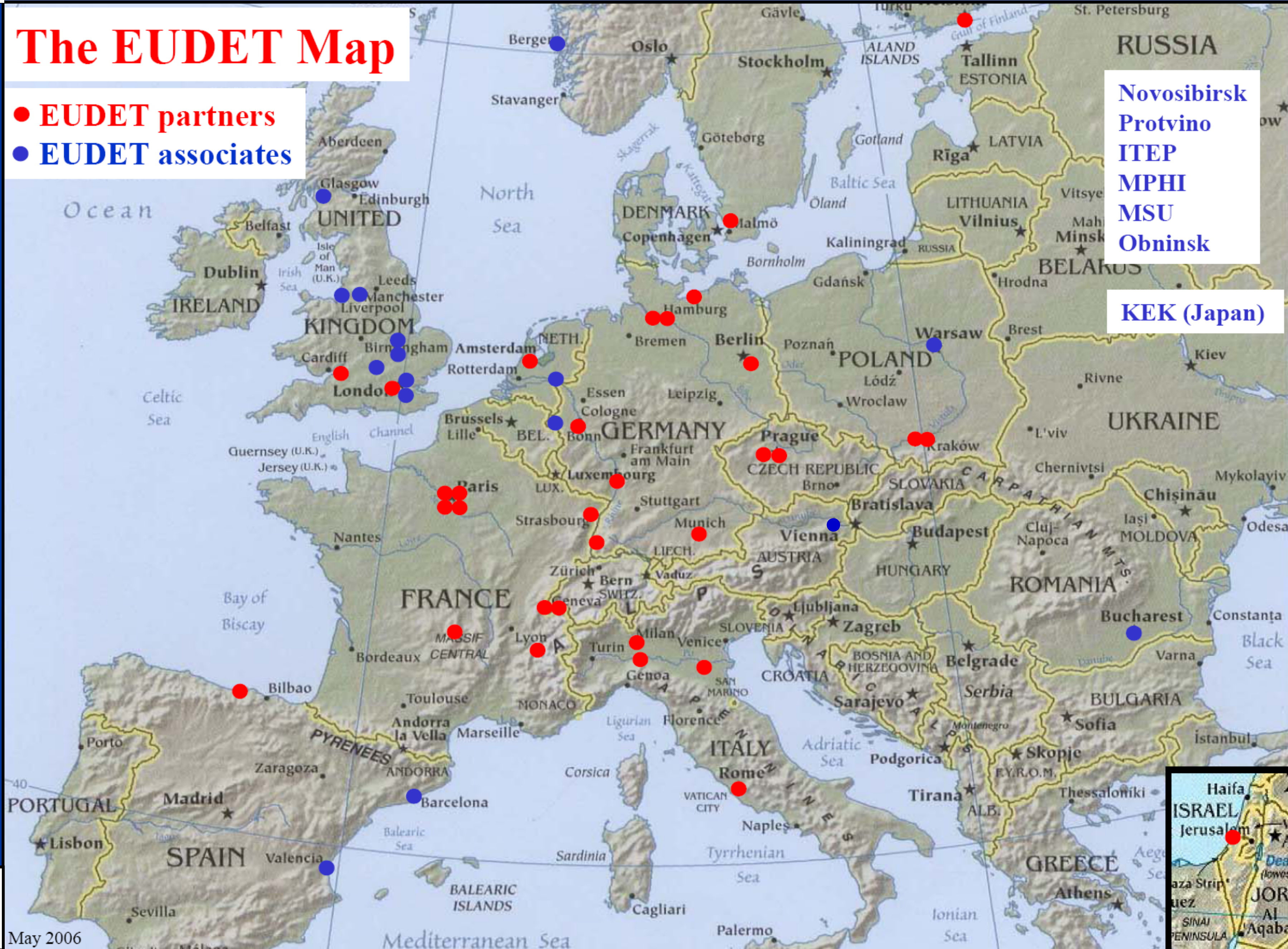
**Detector R&D Network:**
- Information exchange and intensified collaboration
- Common simulation and analysis framework
- Validation of simulation
- Deep submicron radiation-tolerant electronics

**Test Beam Infrastructure:**
- Large bore magnet
- Pixel beam telescope

**Tracking Detectors:**
- Large TPC prototype
- Silicon TPC readout
- Silicon tracking

**Calorimeter:**
- ECAL
- HCAL
- Very Forward Calorimeter
- FE Electronics and Data Acquistion System

# EUDET



The EUDET Map
● EUDET partners
● EUDET associates
Novosibirsk
Protvino
ITEP
MPHI
MSU
Obninsk
KEK (Japan)
May 2006

# Conclusion & Outlook

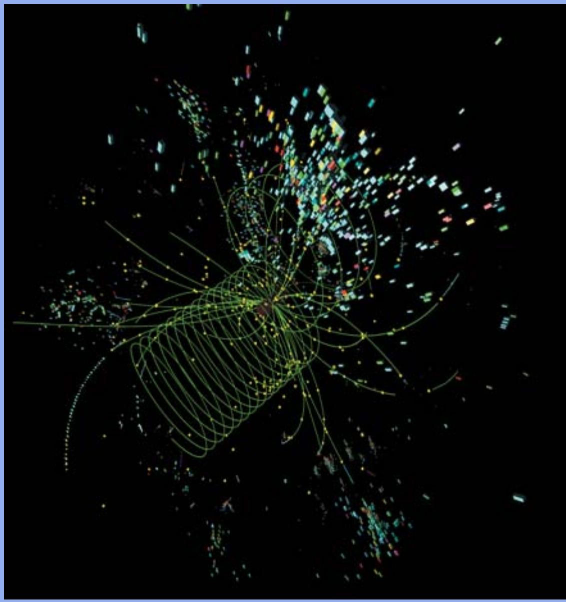
- ILC: 500 → 1000 GeV Linear Collider
  next large collider project

- Requires detectors with unprecedented performances
  - challenges different than at the LHC

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

- Next steps:
  - engineering designs for machine and detectors
  - detector R&D move to larger scale prototypes
  - requires intensified international collaboration

- Need to increase efforts to have ILC and two detectors ready next decade



Simulated ee → ZZ