The International Linear Collider and its Detectors

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Argonne National Laboratory

International Conference on Particle Physics
In memoriam Engin Arik and collegues
İstanbul, Turkey
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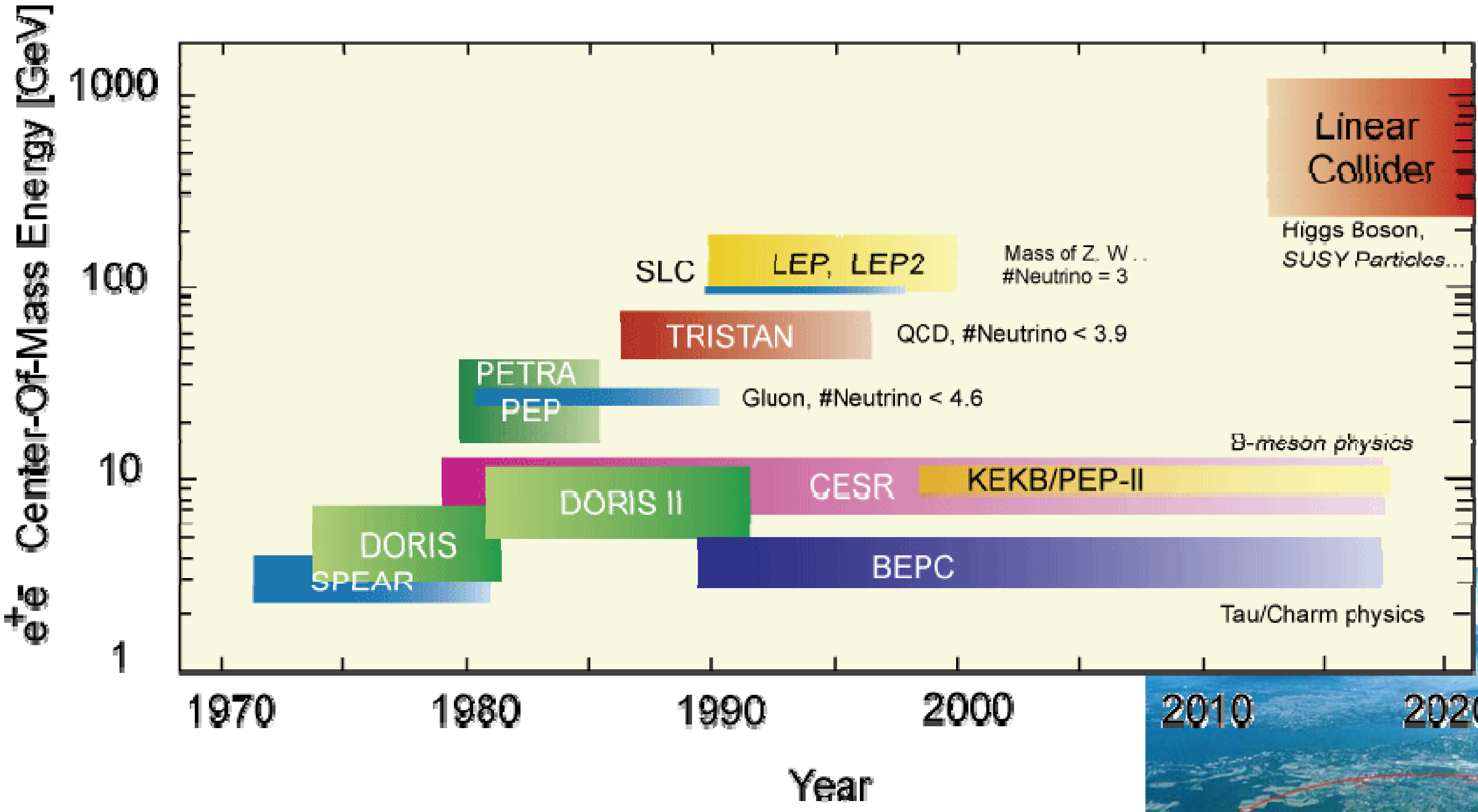
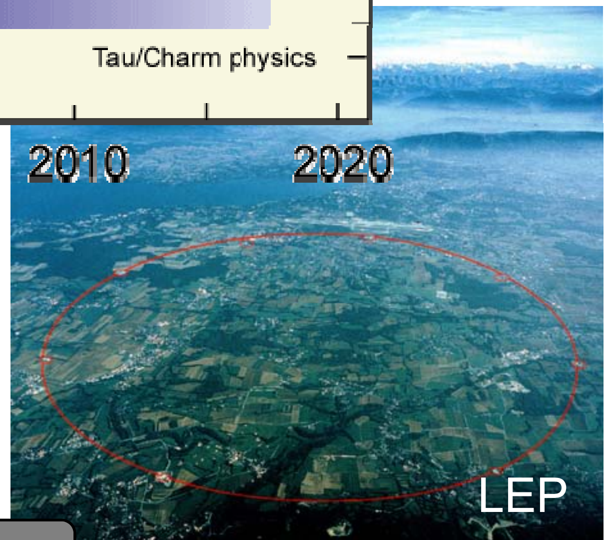
Lepton Colliders of the Past





Circular machines

Synchrotron radiation $\delta E \sim 10^{-4} E^4/\rho$ MeV/turn with E in GeV, ρ in km

Assume $\left\{ \begin{array}{l} E = 500 \text{ GeV} \\ \rho = 2.9 \text{ km (LEP)} \end{array} \right\} \rightarrow$ 1.9 TeV/turn

⇨ **Go linear**

The International Linear Collider

Baseline Machine

E_{CM} of operation 200 – 500 GeV
Luminosity and reliability for 500 fb^{-1} in 4 years
Energy scan capability with <10% downtime
Beam energy precision and stability below 0.1%
Electron polarization of >80%
E_{CM} down to 90 GeV for calibration

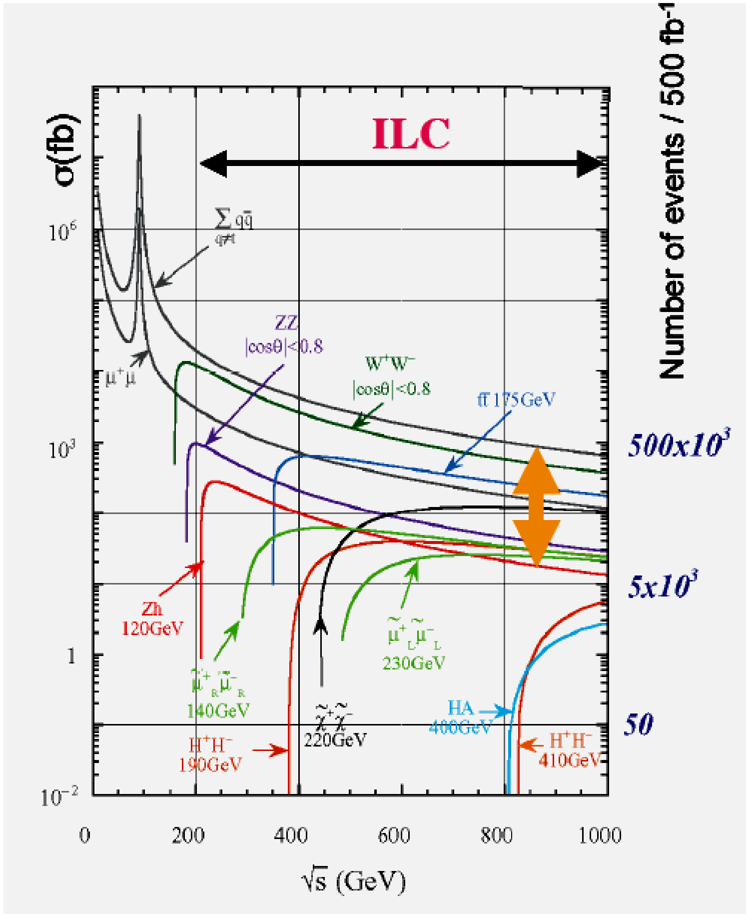
Upgrades

E_{CM} about 1 TeV
Capability of running at any E_{CM} < 1 TeV
$\mathcal{L}$ and reliability for 1 ab^{-1} in 3 – 4 years

As defined in the

International Scope Document

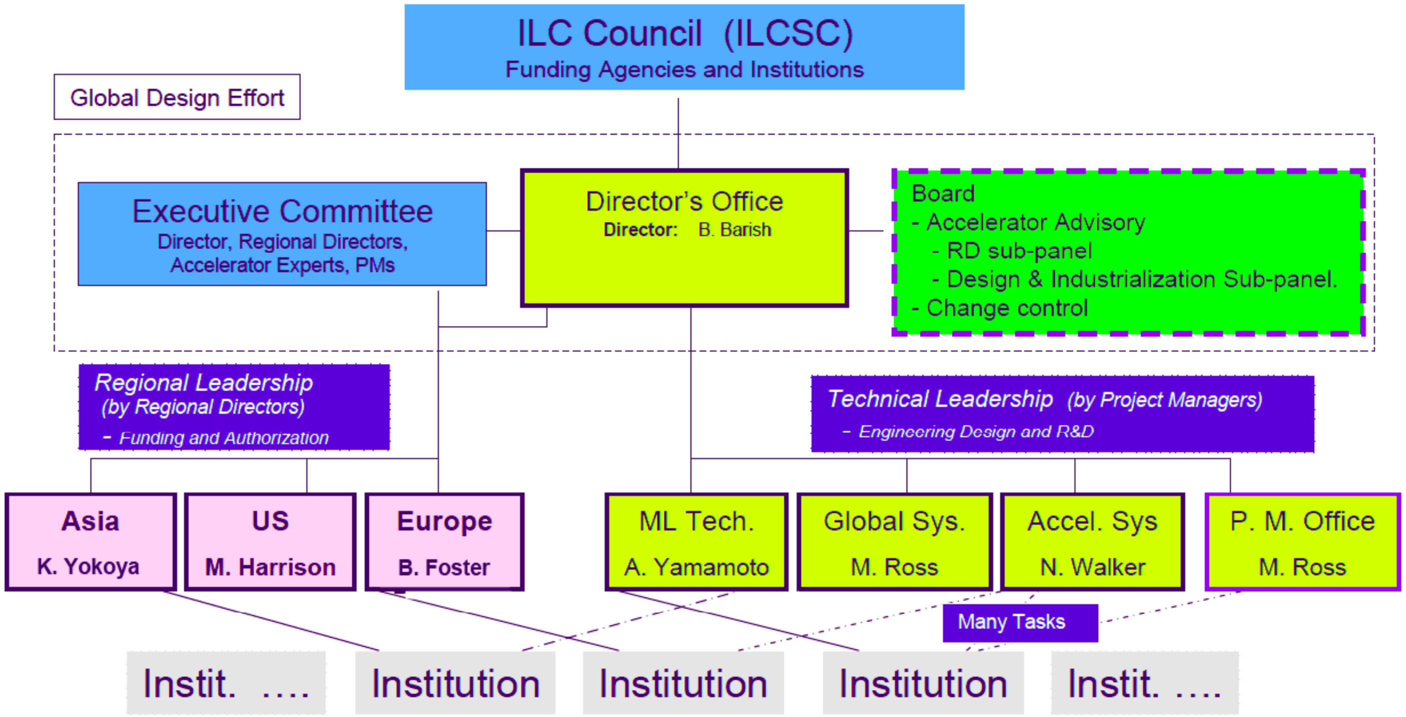
See www.fnal.gov/directorate/icfa/LC_parameters.pdf



Options

Extend to 1 ab^{-1} at 500 GeV in ~2 years
e^-e^-, γγ, $e^-\gamma$ operation
e^+ polarization ~ 50%
Giga-Z with $\mathcal{L}$ = several 10^{33} $cm^{-2}s^{-1}$
WW – threshold scan with $\mathcal{L}$ = 10^{33} $cm^{-2}s^{-1}$

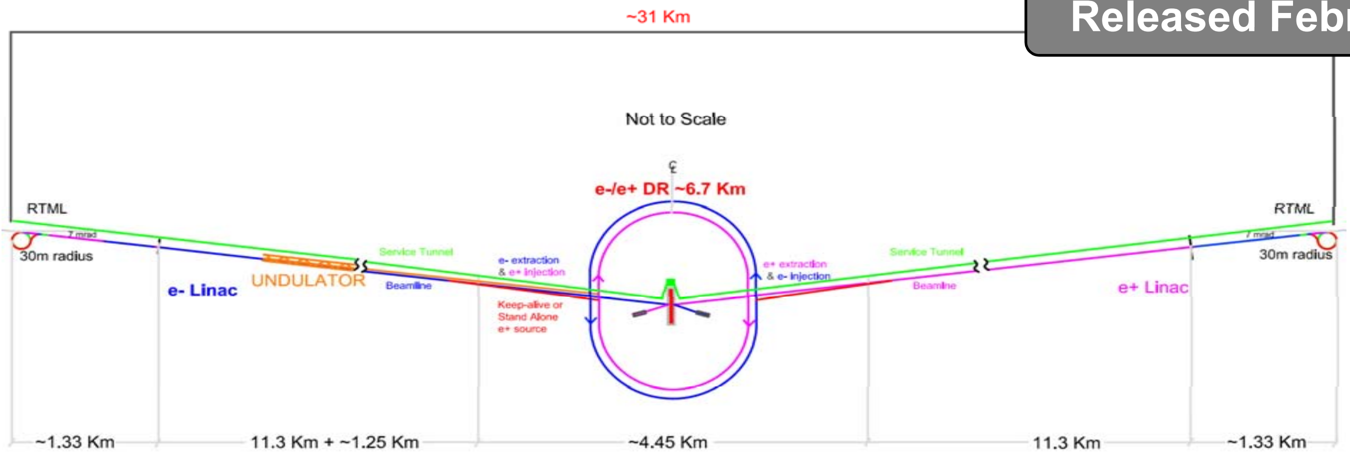
Coordination of Accelerator Design: GDE



Now counting ~500 members

The ILC Reference Design Report

Released February 2007



Schematic Layout of the 500 GeV Machine

Two 11 km **superconducting linacs** operating at 31.5 MV/m for E_{cm} = 500 GeV

Dual tunnels for safety and availability
All tunnels ~ 72.5 km

Centralized **injector**

Circular damping rings for both electrons and positrons
Undulator-based positron source within the e^- linac
Polarized electrons with P ~ 80%

Single **interaction region** with 14 mrad crossing angle

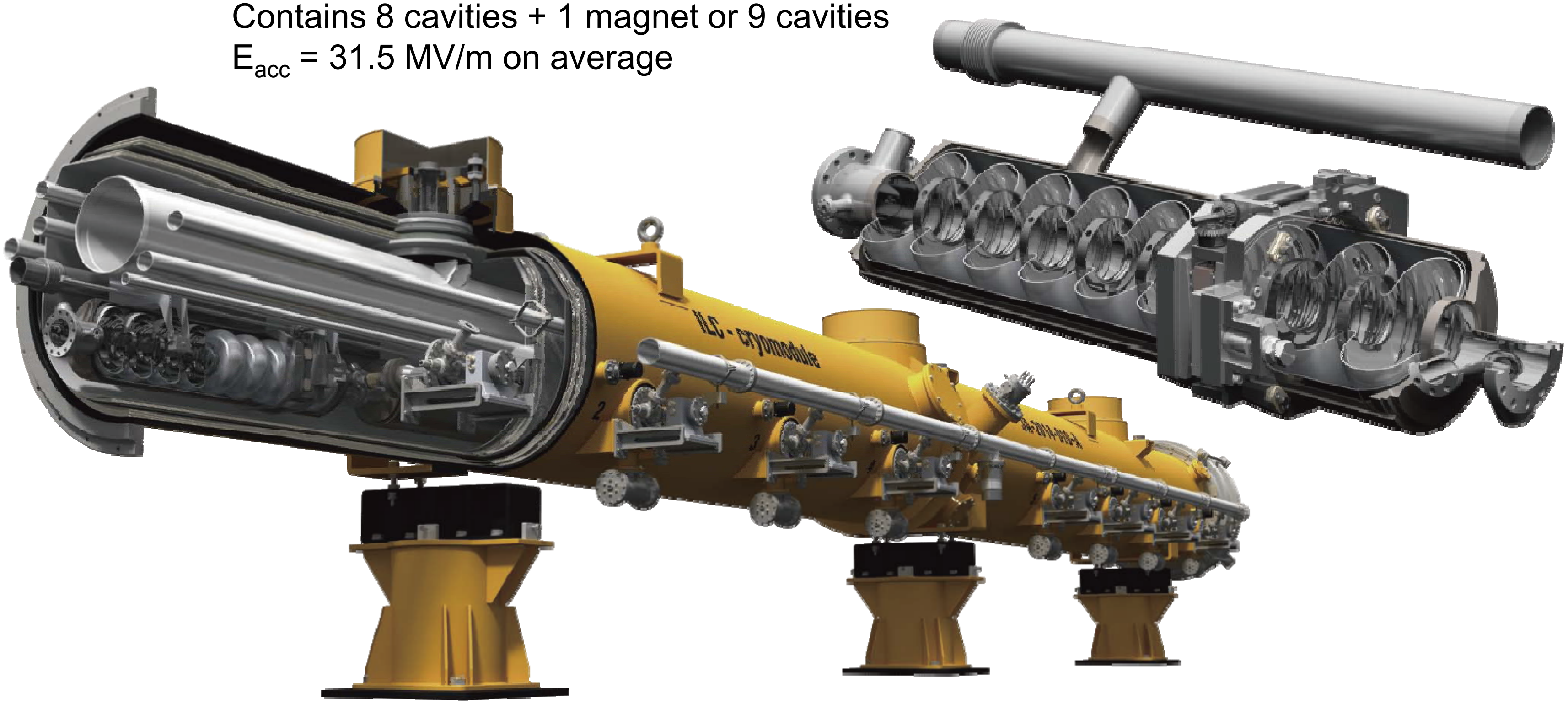
Design Luminosity = $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$
Repetition rate f = 5 Hz

2 detectors in push-pull configuration

ILC Cryomodules for the Main Linacs

Cryomodule

Length ~ 1 meter
Contains 8 cavities + 1 magnet or 9 cavities
E_{acc} = 31.5 MV/m on average



Cryostats

~1700 cryostats serving ~16,000 cavities
3 cryostats to be driven by one 10 MW L-based klystron
In main linacs 560 RF units in total

ILC High-Gradient Cavity R&D

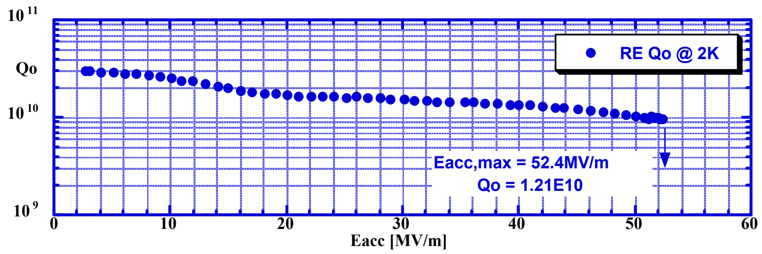
Basic infrastructure for cavity manufacturing
and testing in Asian, European and US laboratories

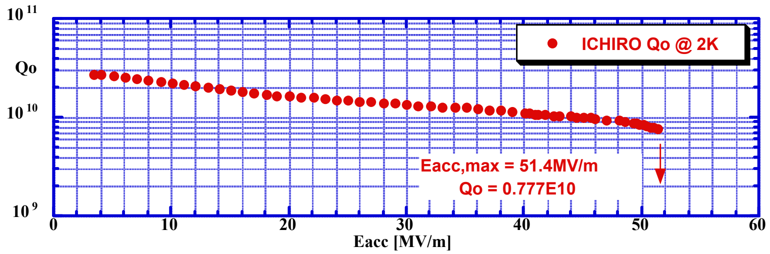
Cryomodule built at FNAL with DESY cooperation

Single cavity tests at KEK

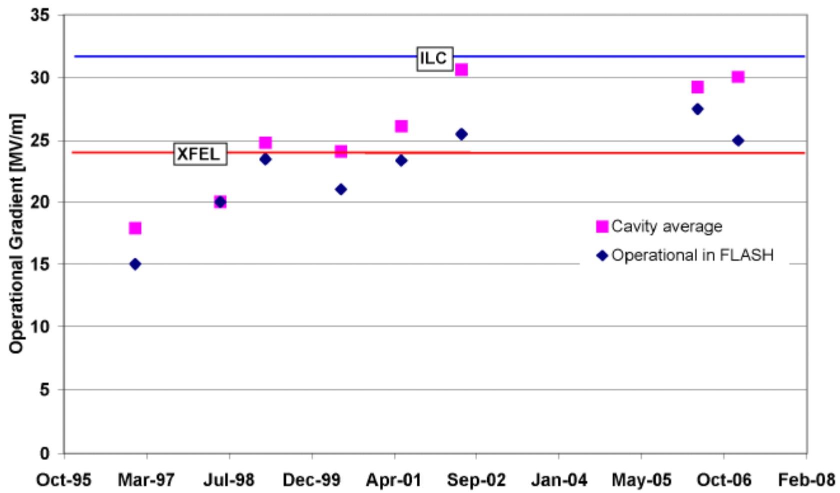
New electro-polishing facility at Argonne

Single cavity tests at KEK



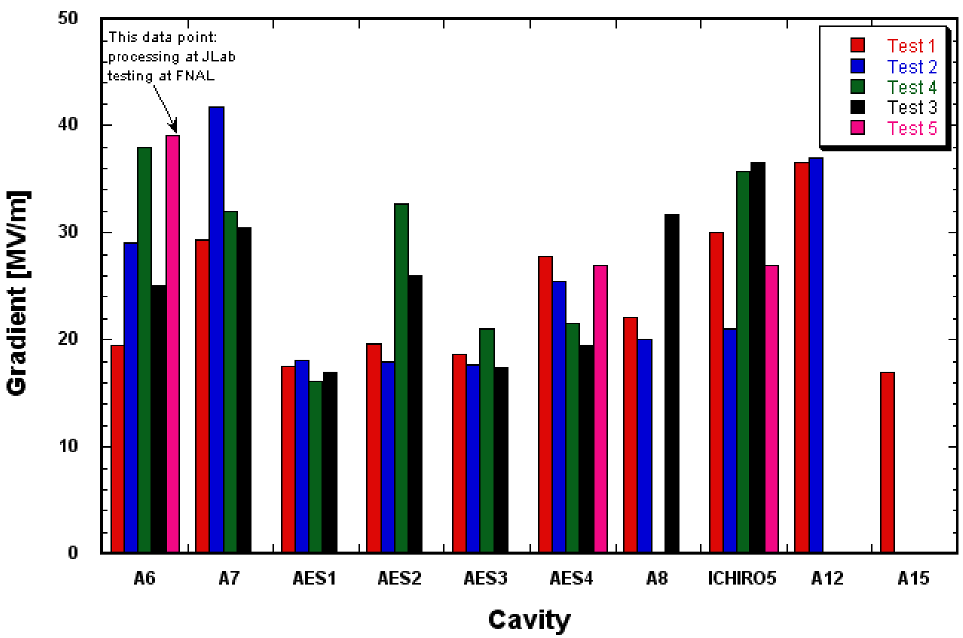


Single cavity gradients of > 50 MeV/m have been achieved



Tests of 9 – cell cavities at DESY

ILC 9-cell cavity processing and test at Jefferson Lab



9 – cell cavities approach or exceed the ILC gradient goal of 31.5 MeV/m

Status and Plans (accelerator)

Two stage technical design phase (TDP)

Phase I

Demonstrate 'Technical Feasibility'
Perform high-priority risk-mitigating R&D

Gradients of 31.5 MeV/m with a 50% yield
Mitigation of electron cloud effects

Value engineering in selected areas

Phase II

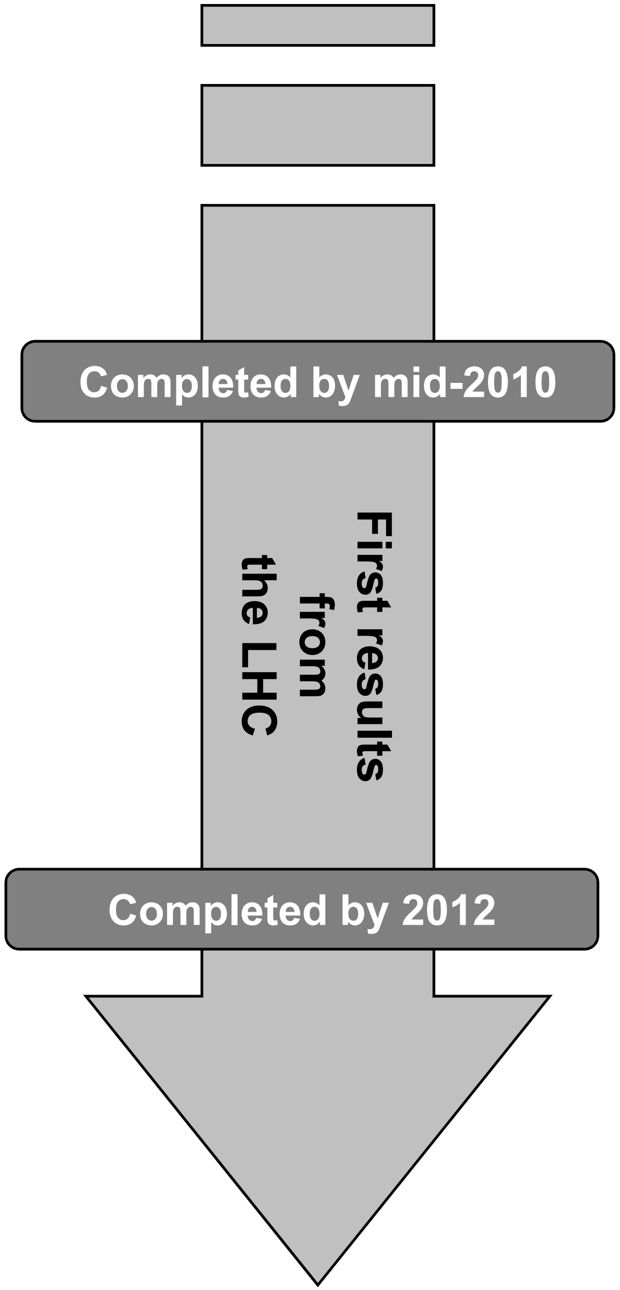
Demonstrate 'Technical Credibility'
Complete remaining critical R&D

→ <u>New baseline design</u>

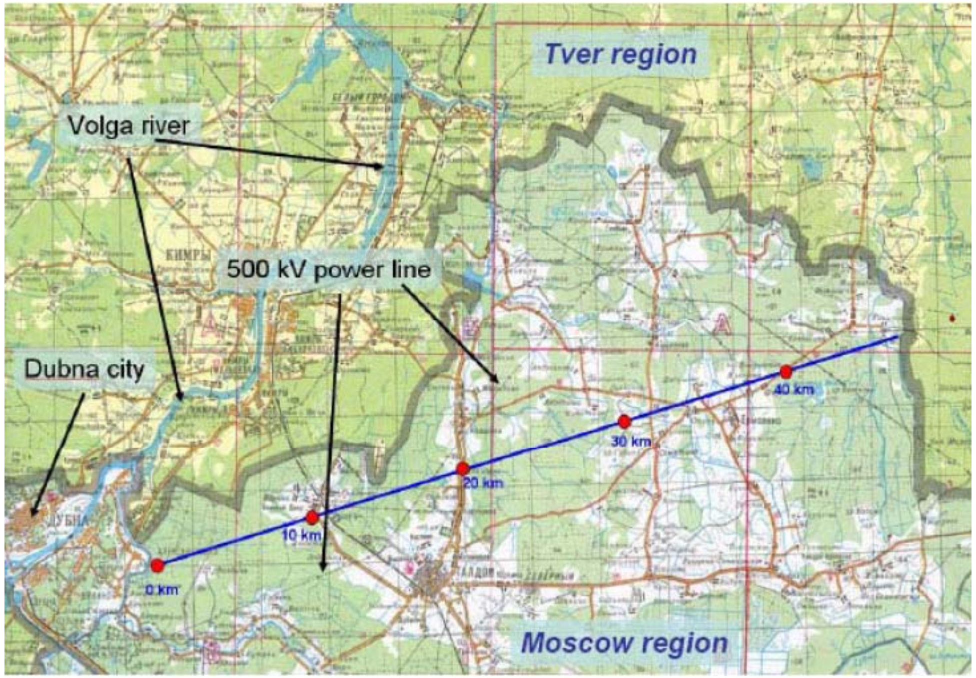
Develop a project implementation plan

Siting
Industrialization
Funding…

Report which can be
handed over to governments



Possible sites

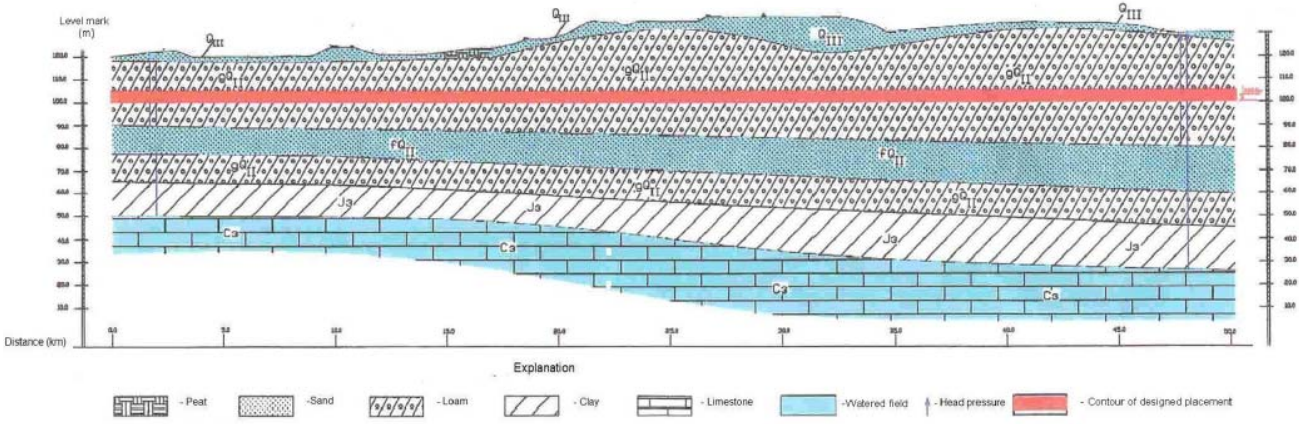


Usual suspects

CERN – Geneva - Switzerland
DESY – Hamburg – Germany
FNAL – Batavia – Illinois
Japan (several sites)

New on the scene

JINR – Dubna – Russia

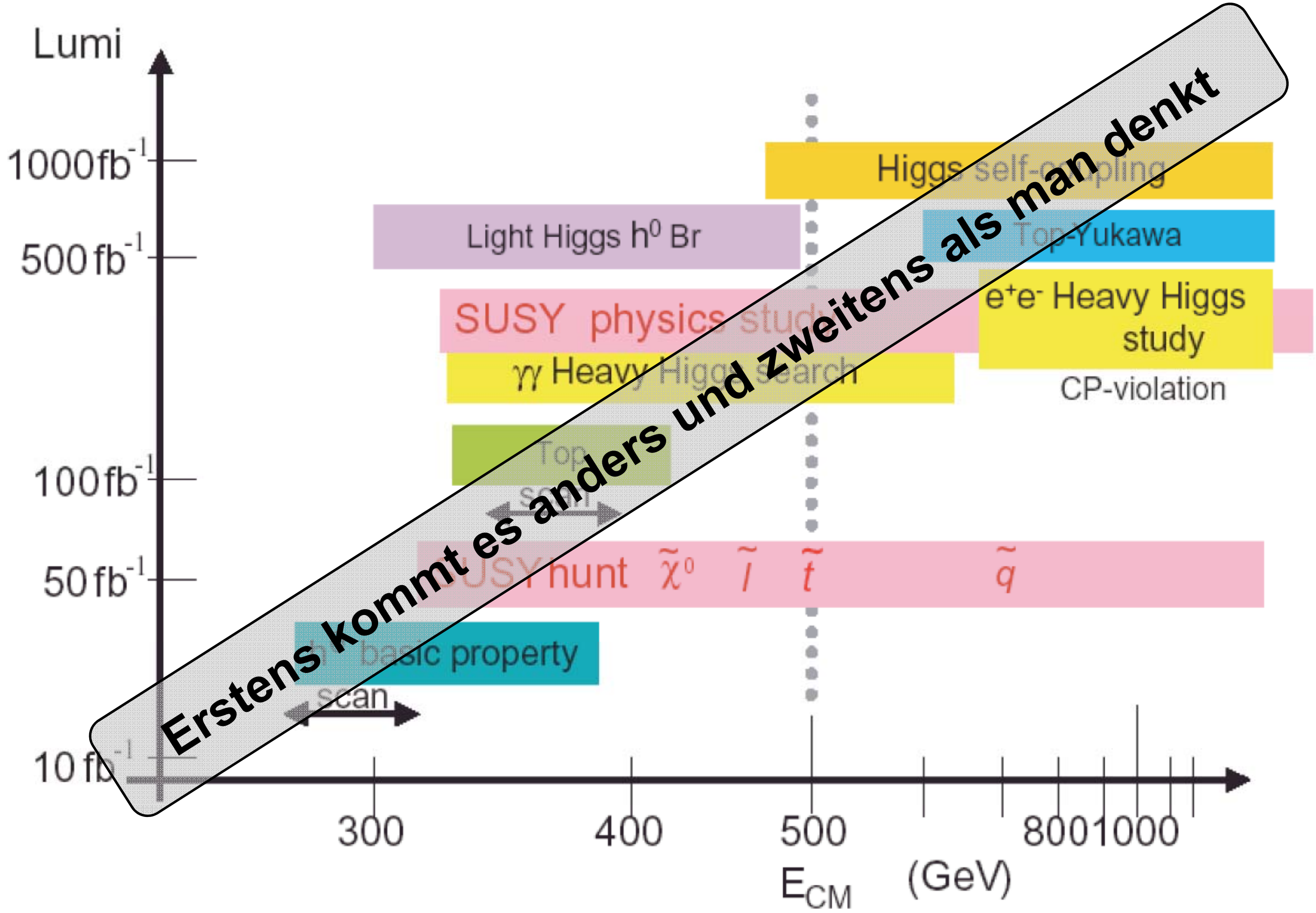


Tunnel at a depth of ~ 20m

Placed in drift clay

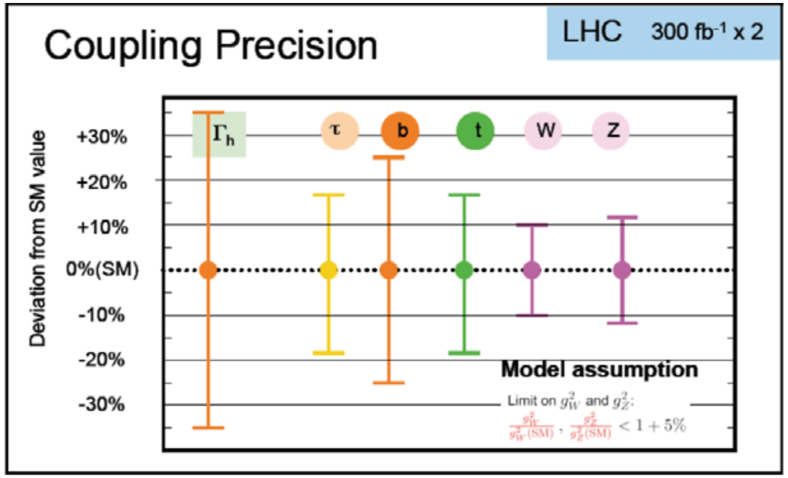
Protected from groundwater by impermeable soil under the tunnel

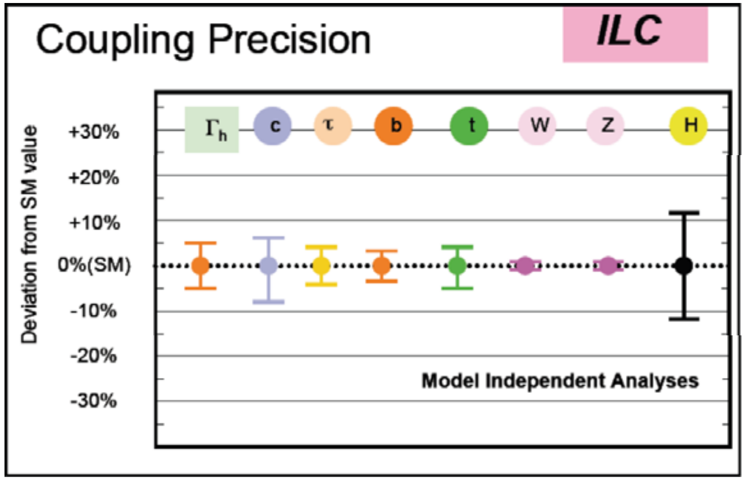
ILC Physics

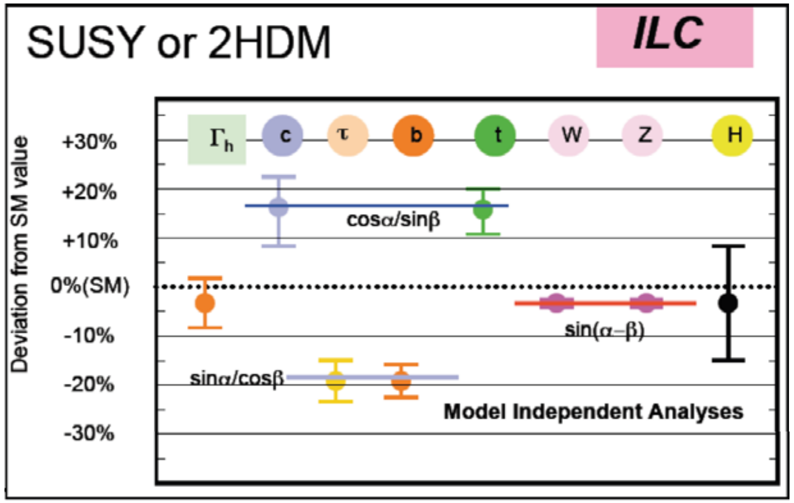


Broad spectrum of physics beyond the current Standard Model
Specifics to be determined with LHC results

ILC as a Precision Machine: Higgs coupling



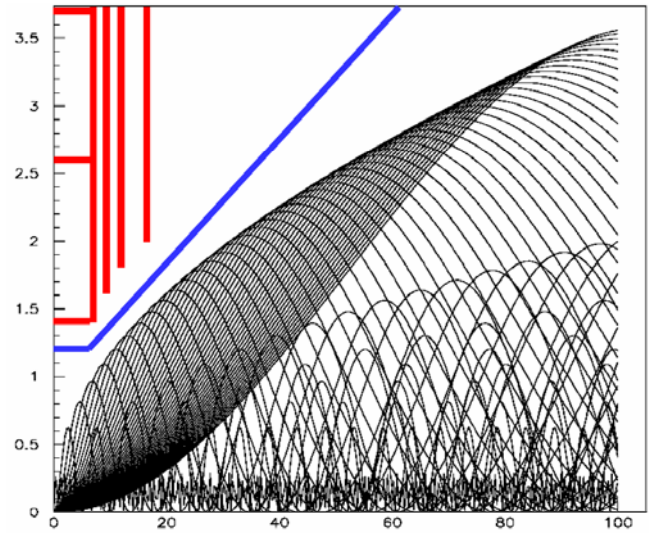




Precision will be needed to identify new particles and disentangle models beyond the Standard Model

Plots by Yamashita

Detector Challenges at the ILC



Envelope of e+e- pair bkgr in 5 tesla field

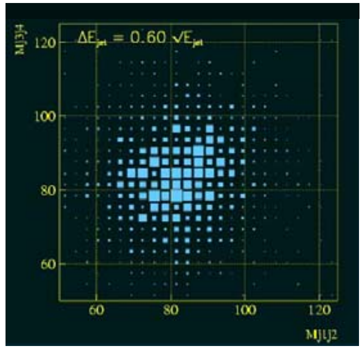
Backgrounds at low angle and small radii

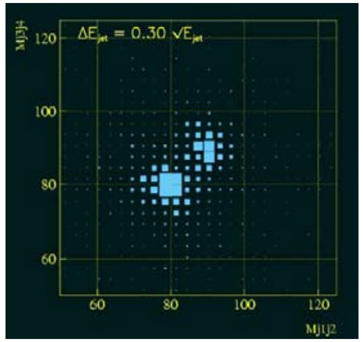
2-photon backgrounds
Beamstrahlung e^+e^- pairs

Jet Energy resolution

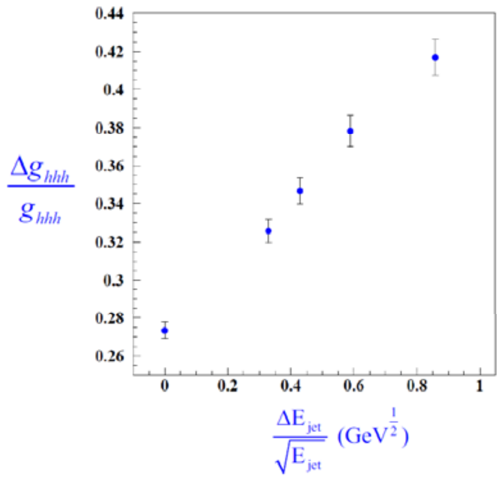
Important for many measurements
$\sigma_{Ejet}/E_{jet} = 60\%/\sqrt{E} \rightarrow 30\%/\sqrt{E}$

Corresponds to 40% increase in luminosity
Allows to identify W's and Z's on an event-by-event basis

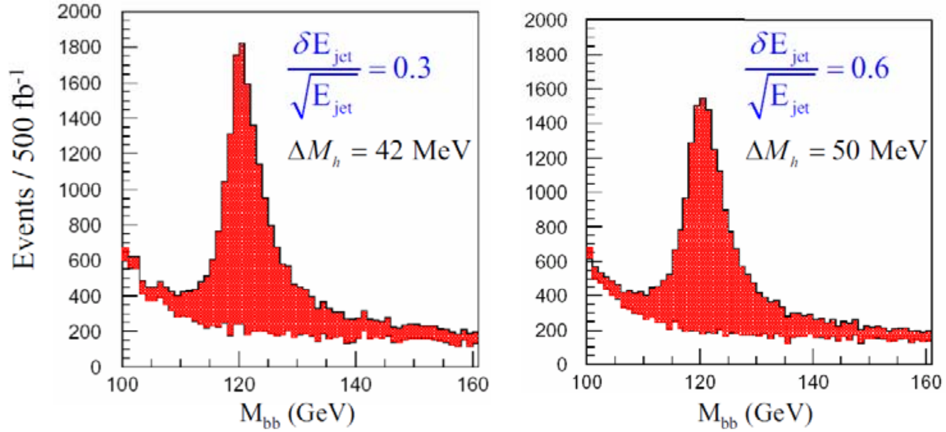




Error in triple Higgs coupling



Reconstructed Higgs Di-jet mass



The ILC Environment

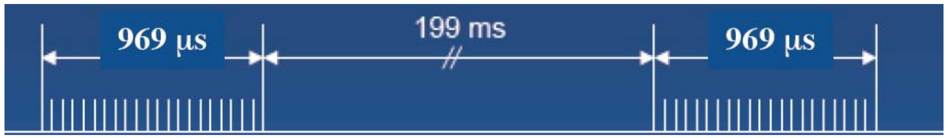
Machine parameter	Value
# trains/sec	5
Train spacing	199 msec
# bunches/train	2625
Bunch spacing	369 nsec
Length of train	969 μsec

High rates at low angles and close to beam pipe

Low rates in barrel

- Order of 1 event/sec

Train structure



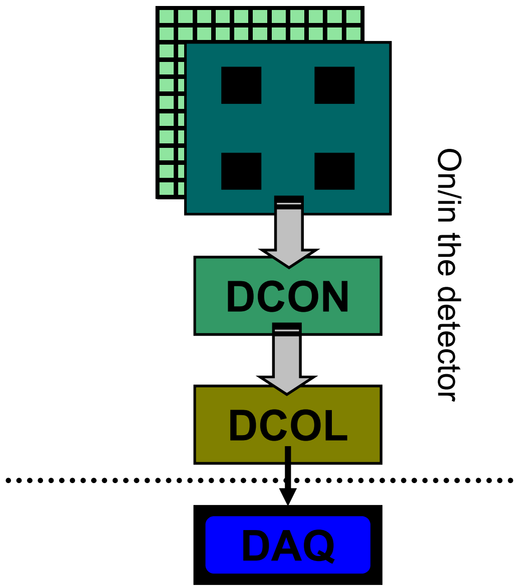
New Trends in Detector Concepts

Embedded (front-end) electronics

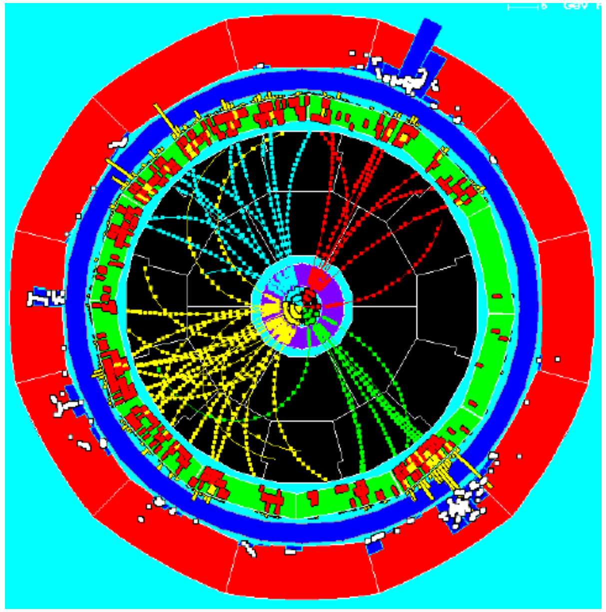
- Front-end of readout electronics part of active detector
- Digitization on the active element
- Only optical link to count house(?)

Power pulsing

- Reduces power to front-end electronics between trains
- Reduces power by factor ~100
- Reduces need for active cooling (material budget)



Measurement of Jets



Hadronic jets contain both photons and hadrons

Large fluctuations in fraction of photons

Different response to photons and hadrons e/h ≠ 1

e.g. CDF calorimeter e/h ~ 1.4

Significant degradation of jet energy resolution

Improvement through compensation e/h ~ 1

Achieved through careful tuning of scintillator/absorber thicknesses

e.g. ZEUS calorimeter $\sigma_{em} \sim 20\%/\sqrt{E}$ and $\sigma_{jet} \sim 50\%/\sqrt{E}$

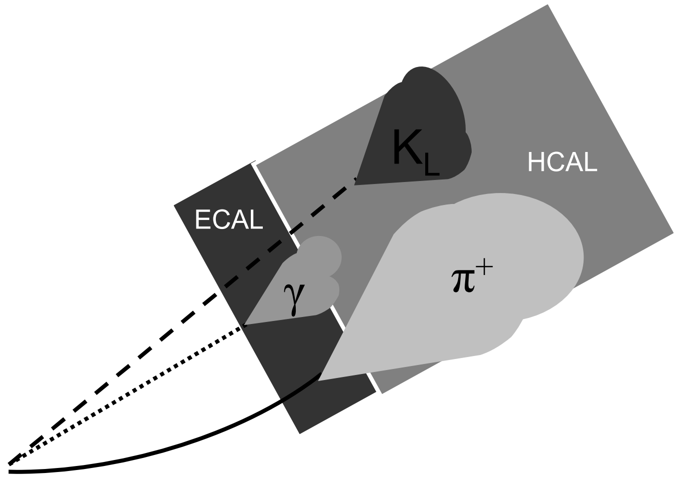
Degradation of electromagnetic resolution

Can we do better?

Two Different Philosophies

Particle Flow Algorithms

Use tracker to measure momentum of **charged particles**
electromagnetic calorimeter to measure **photons**
entire calorimeter to measure **neutral hadrons** (n, K_L^0)
Reconstruct jet energy as some over momenta and energies



Major challenge: identification of calorimeter energy deposits as coming from charged or neutral particles

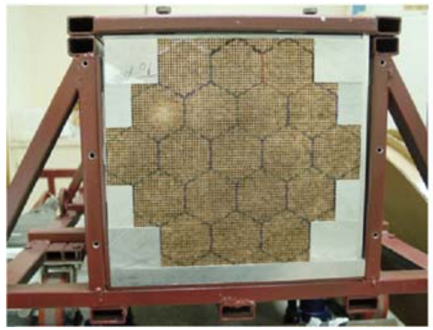
→ Calorimeters with extremely fine segmentation

Dual Readout Calorimetry

Measures both

scintillation light ← all particles
Čerenkov light ← mostly e± (em component)

to determine electromagnetic fraction of the jet and to apply the appropriate calibration



Major challenge: development of technology providing a measurement of both scintillation and Čerenkov light

→ Fibers, (new) crystals

Both camps confident that their approach is superior

The Four ILC Detector Concepts

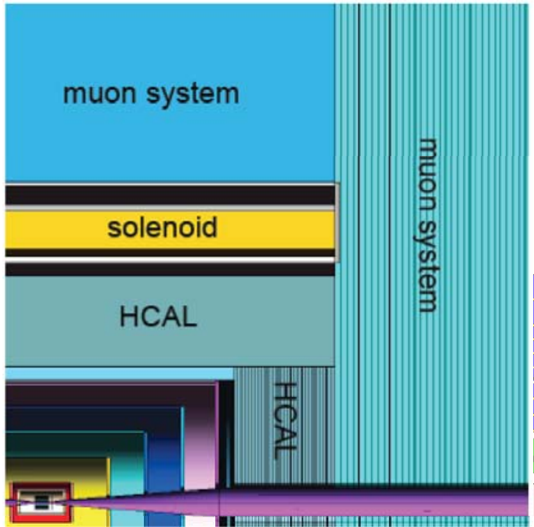
Based on Particle Flow Algorithms

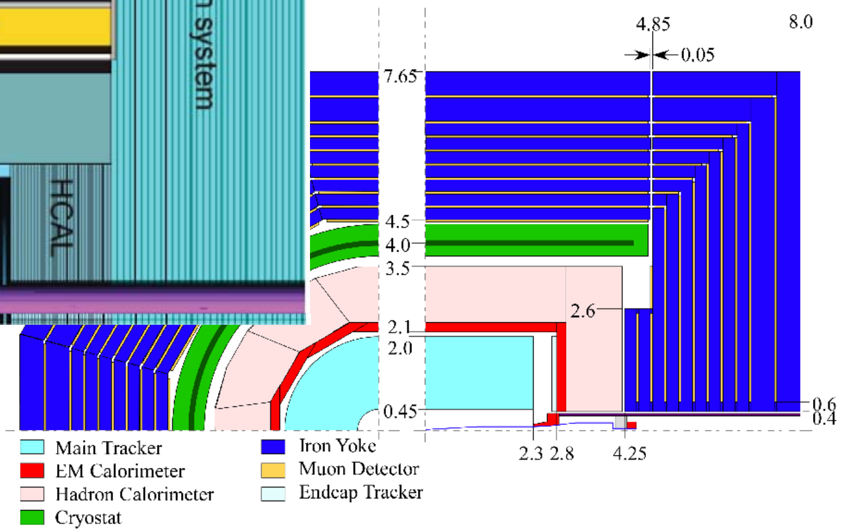
SiD

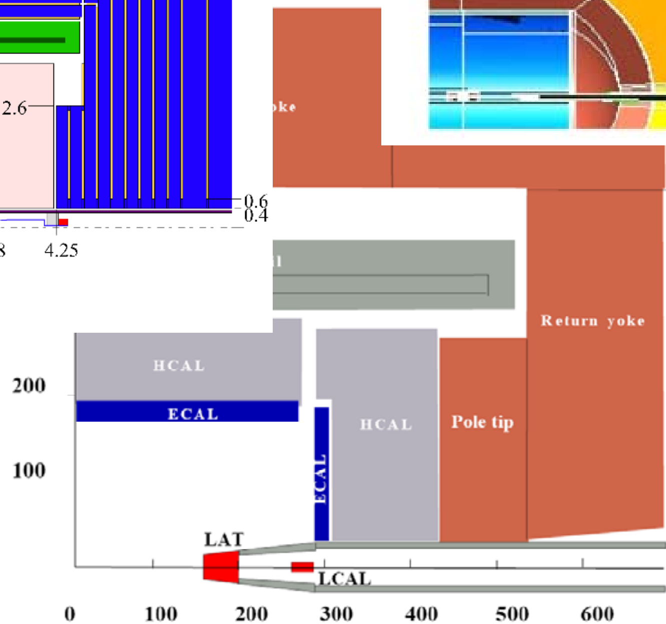
GLD

ILD

Merged → LDC

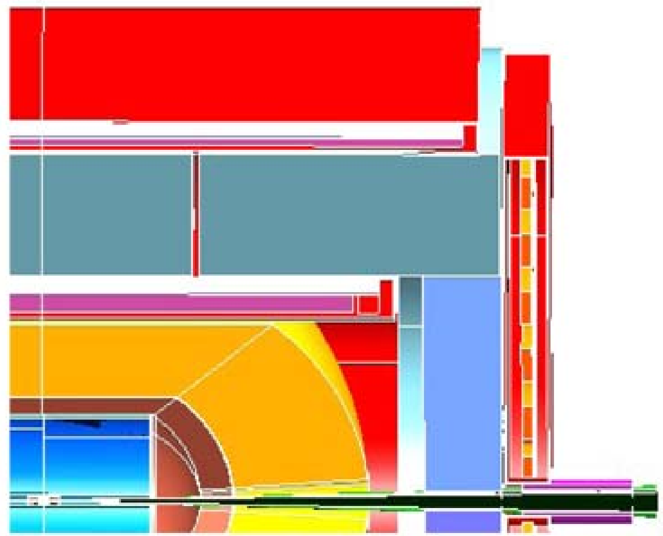






Based on Dual Readout Calorimetry

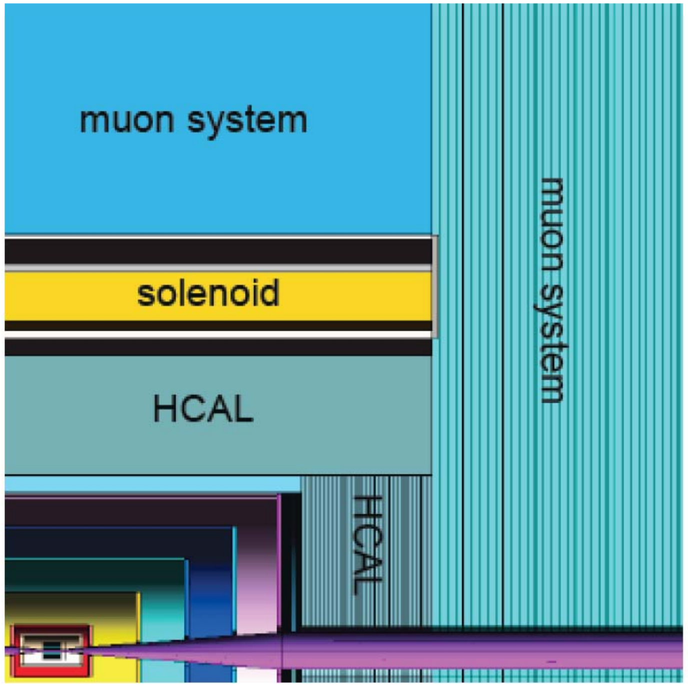
4^{th} Concept

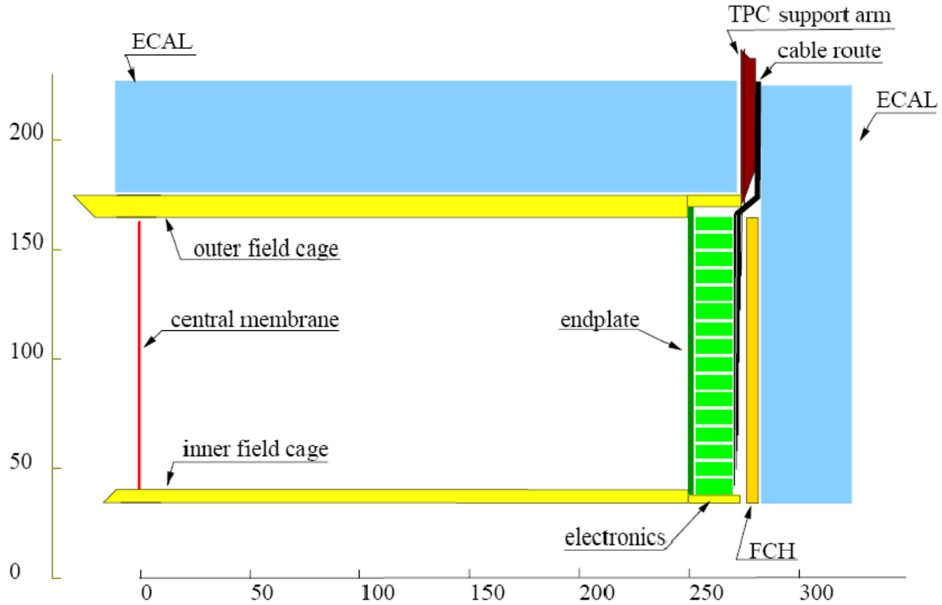


The PFA Detector Concepts

Similarities between SiD and LDC

Pixel vertex detector
Highly granular electromagnetic calorimeter
Highly granular hadron calorimeter
Calorimeters located inside the coil
High magnetic field between 3 – 5 Tesla
Instrumented return yoke for muon identification
(Joint effort on) forward calorimetry





Major difference between SiD and LDC

SiD – Pure Silicon tracker
LDC – Time Projection Chamber + Silicon layers

The 4th Concept

Main features

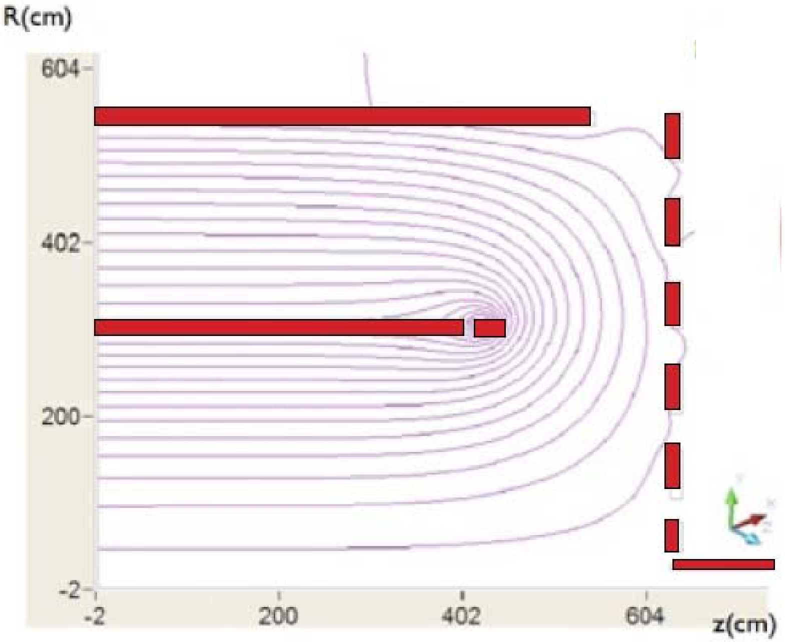
Vertex detector (similar to PFA detectors
Tracking detector

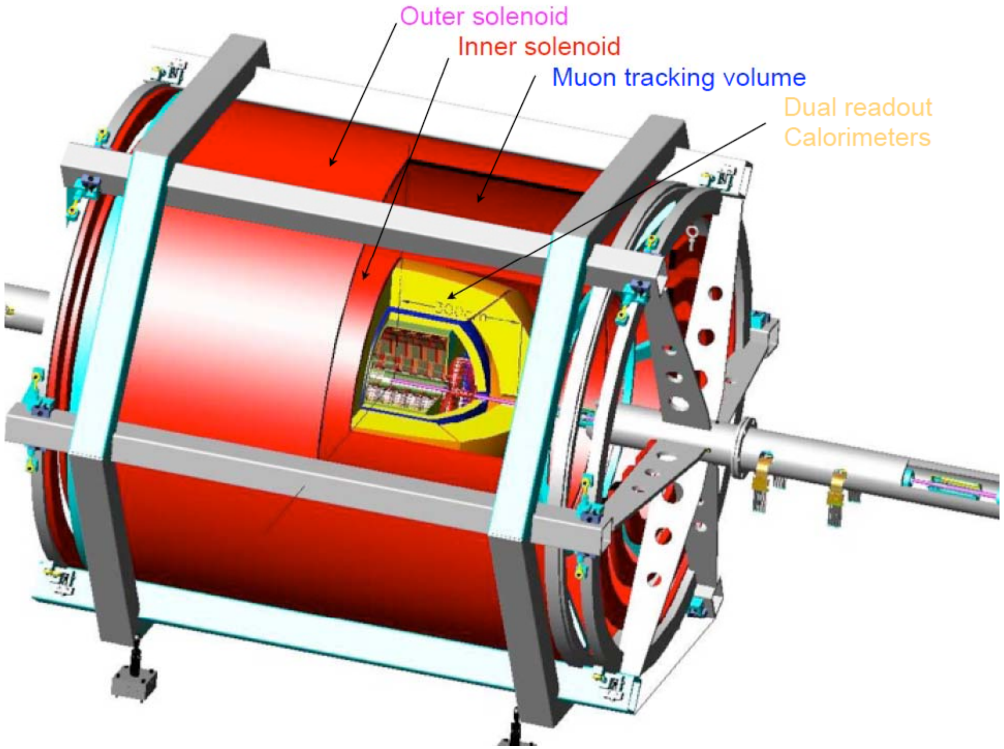
Silicon or TPC or drift chamber ?

Dual readout calorimeter

Crystal electromagnetic calorimeter
Hadronic calorimeter with fibers

Dual solenoid (no return yoke)





Why a dual solenoid?

Eliminates costly iron return yoke

Is a second coil cheaper than a return yoke?

Can be easily instrumented

Measurement of muon momentum

Detector R&D

Many R&D activities for ALL detector subsystems

Personal selection of highlights

Vertex Detector studies

Tracking detectors

PFA development

Highly segmented electromagnetic calorimeters

Highly segmented hadronic calorimeters

Total absorption and dual readout calorimeters

Vertex Detectors

Goal is to

a) minimize mass, power consumption, dead zones, dead time, occupancy, noise susceptibility
b) radiation hardness
c) provide the best possible impact parameter resolution

Accelerator	a (μm)	b ($\mu m \cdot GeV$)
LEP	25	70
SLD	8	33
LHC	12	70
RHIC-II	13	19
ILC	< 5	< 10

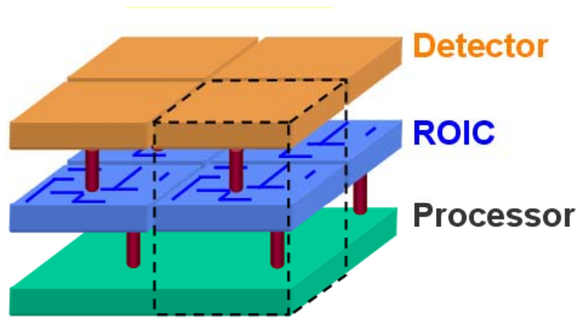
$$\sigma_{IP} = a + b/p \cdot \sin^{3/2}\theta$$

⇒ Pixel sizes ~ 25 x 25 μm^2 needed

Technologies being developed/investigated/perfected

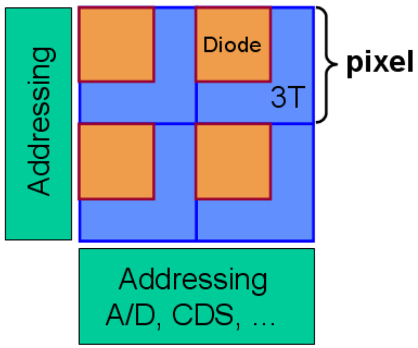
CCDs, DEPFETs, CMOS sensors, 3D – silicon technologies…

e.g. 3D – Vertical Integrated Circuits



'Conventional' MAPS

Sensor and pixel electronics share area → fill factor loss
Control and support electronics on outside

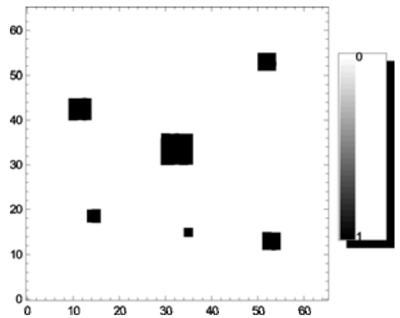


3D – Vertical Integrated Circuits

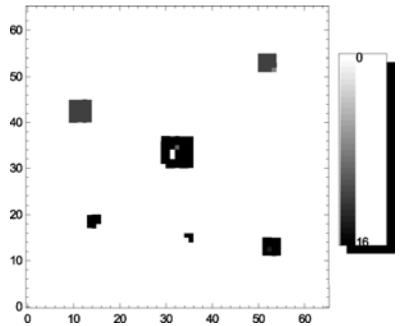
Fully active sensor area
Independent optimization of sensor and readout
Fabrication optimized by layer function
Minimal inactive chip boundaries

Fermilab's VIP-1 Chip

3 metal layers per tier
20 x 20 μm^2 pixels
64 x 64 pixel array
No integrated sensor

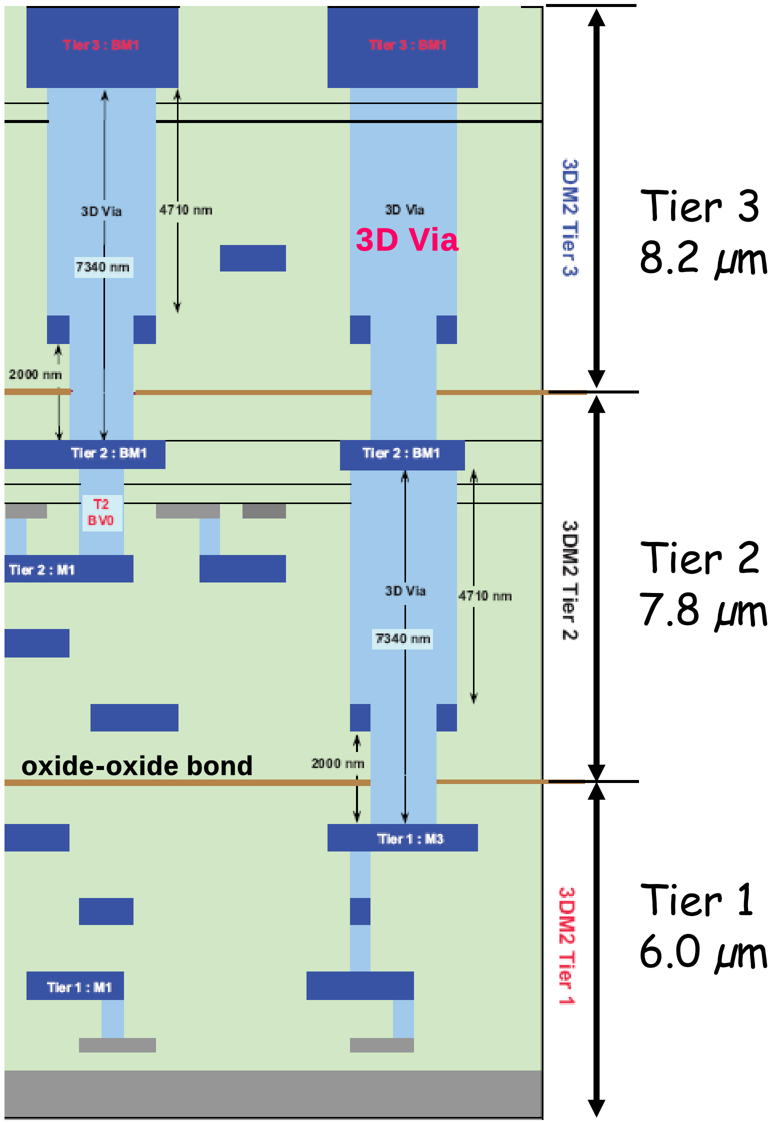


Injection pattern into front-end amplifiers



Read out hit pattern

Proof of principle



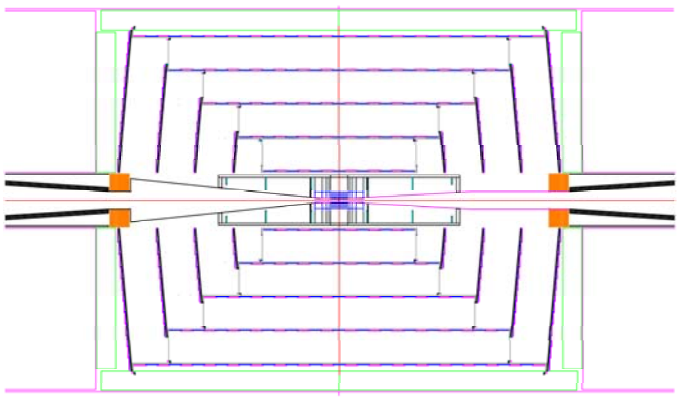
VIP-2 Chip

Submitted on October 16, 2008

Tracking Detectors

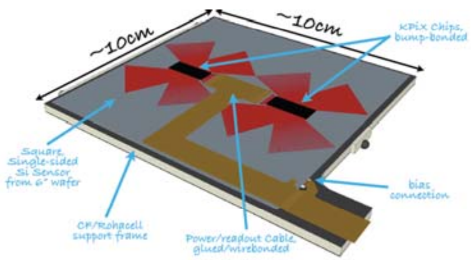
SiD's Silicon Tracker

5 layer barrel with 4 planes in forward direction



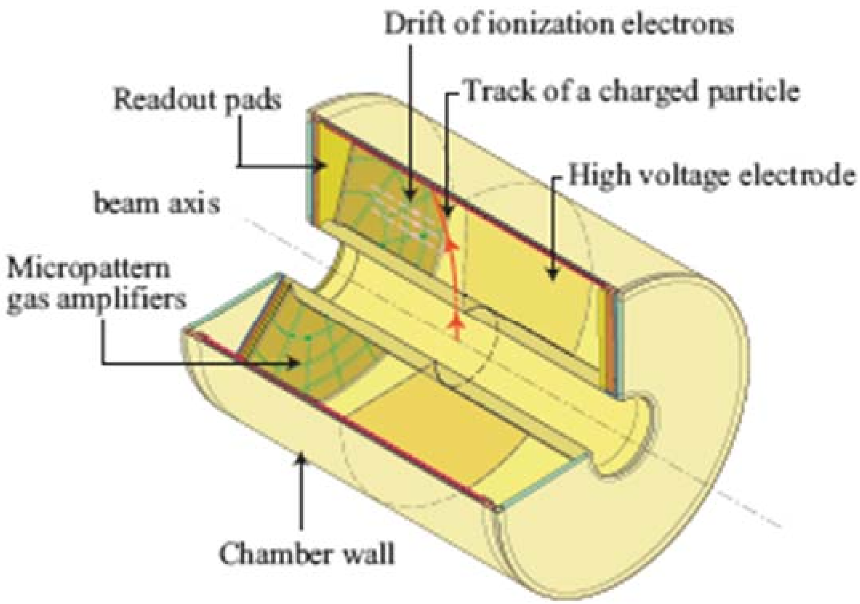
93.5 x 93.5 mm^2 wafers

50 μm pitch
1850 channels



Development of KPiX front-end ASIC

1024 readout channels
14-bit ADC
Integration time 0.5 – 1.0 μs



LDC's Time Projection Chamber

R&D within LC-TPC collaboration

24+ institutes from all 3 regions

Choice of readout technologies

GEMs, Micromegas, Pixel – Silicon detectors
Improved readout segmentation

Traditional multiwire chambers ~ 1 cm
Precision gas detectors ~ 1mm

Development of Particle Flow Algorithms

The idea

Measure charged particles with tracker
Measure neutral particles with calorimeter

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$

Perfect PFA → 18%/√E

Reconstruction of the jet energy

$$\sigma_E/E_{jet} = \sigma_\gamma/\sqrt{E_\gamma} + \sigma_{nh}/\sqrt{E_{nh}} + \text{confusion}$$

Maximum allowed confusion for σ_E/E_{jet} = 3%

E_{jet}(GeV)	Confusion
50	1.59%
100	2.40%
250	2.78%
500	2.89%

Major challenge

PFAs work

Successfully applied at ALEPH, ZEUS, CDF…

At the ILC

PFAs not an after-thought
Detector designs being optimized for their applications

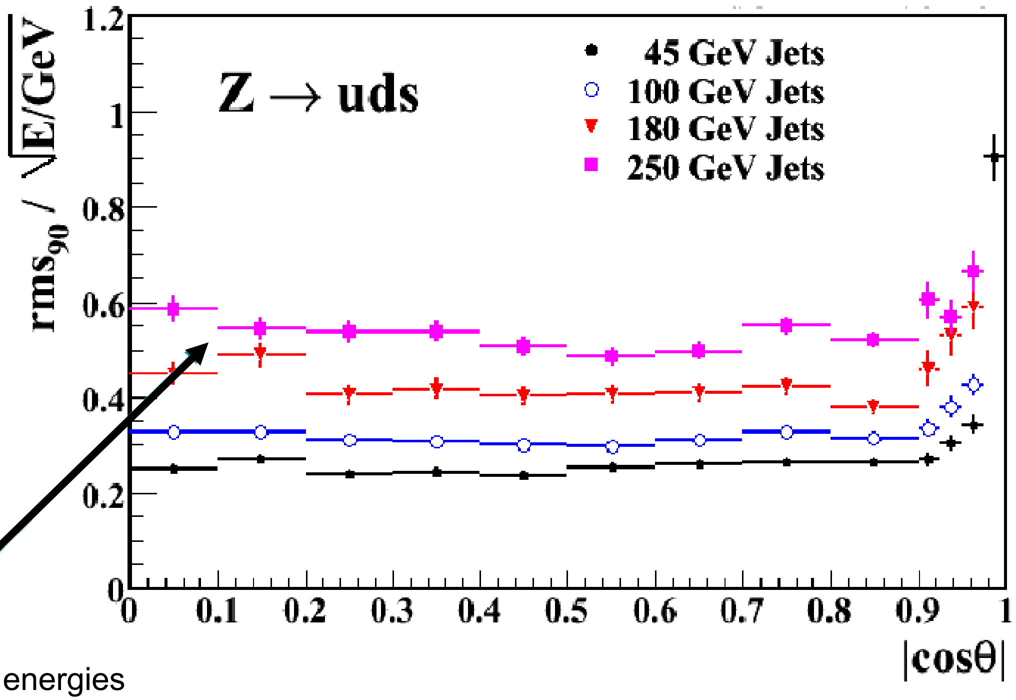
PANDORA PFA

Developed by

Mark Thomson (University of Cambridge)

Current performance

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	24.9 %	3.7 %
100 GeV	30.7 %	3.1 %
180 GeV	43.0 %	3.2 %
250 GeV	52.2 %	3.3 %



Leakage at high jet energies

ILC performance goal achieved

Open question

Are hadronic showers simulated properly? (see later)

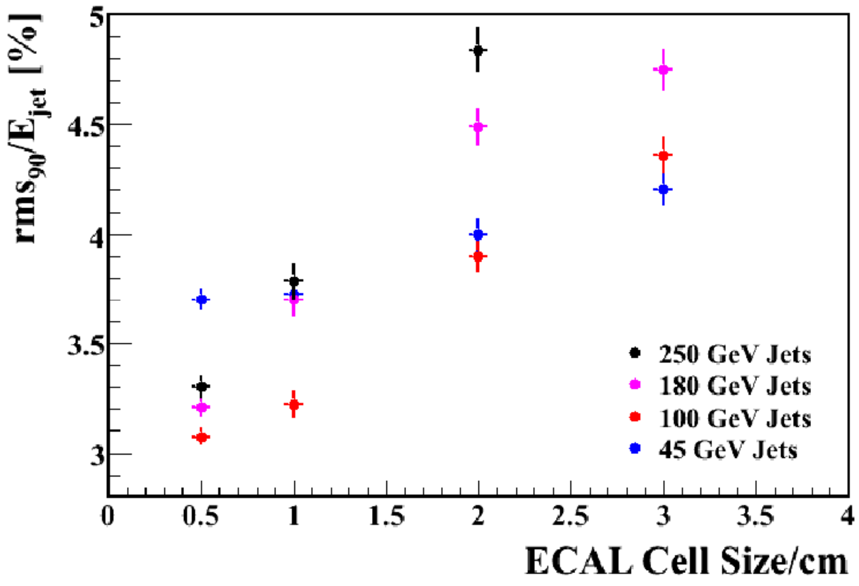
Is there room for improvement?

At low energies, resolution dominated by calorimeter resolution
At high energies, confusion more important

Contribution	σ_E/E			
	45 GeV	100 GeV	180 GeV	250 GeV
Calo. Resolution	3.1 %	2.1 %	1.5 %	1.3 %
Leakage	0.1 %	0.5 %	0.8 %	1.0 %
FullLDCTracking	0.7 %	0.7 %	1.0 %	0.7 %
Photons "missed"	0.4 %	1.2 %	1.4 %	1.8 %
Neutrals "missed"	1.0 %	1.6 %	1.7 %	1.8 %
Charged Frags.	1.2 %	0.7 %	0.4 %	0.0 %
"Other"	0.8 %	0.8 %	1.2 %	1.2 %

Studies of detector design parameters

Performance as function of B-field strength
Dependence on ECAL inner radius
Dependence on HCAL cell size
Dependence on ECAL cell size
….



CALICE Collaboration

Goals

Development and study of finely segmented calorimeters for PFA applications

Strategy

Study of physics, proof of technological approach → **physics prototypes**
Development of scalable prototypes → **technical prototypes**

Projects

Calorimeter	Technology	Detector R&D	Physics Prototype	Technical Prototype
ECALs	Silicon - Tungsten	Well advanced	Exposed to beam	Design started
	MAPS - Tungsten	Started		
	Scintillator - Lead	Well advanced	Exposed to beam	
HCALs	Scintillator - Steel	Well advanced	Exposed to beam	Design started
	RPCs - Steel	Well advanced	Being constructed	(Design started)
	GEMs- Steel	Ongoing		
	MicroMegas - Steel	Started		
TCMTs	Scintillator - Steel	Well advanced	Exposed to beam	

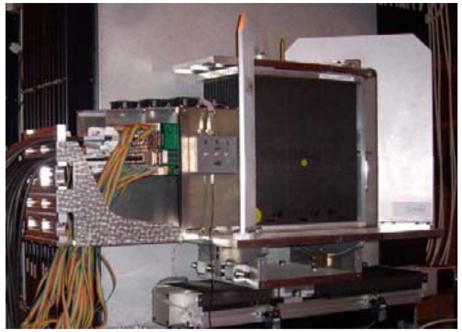
4 regions

14 countries

51 institutes

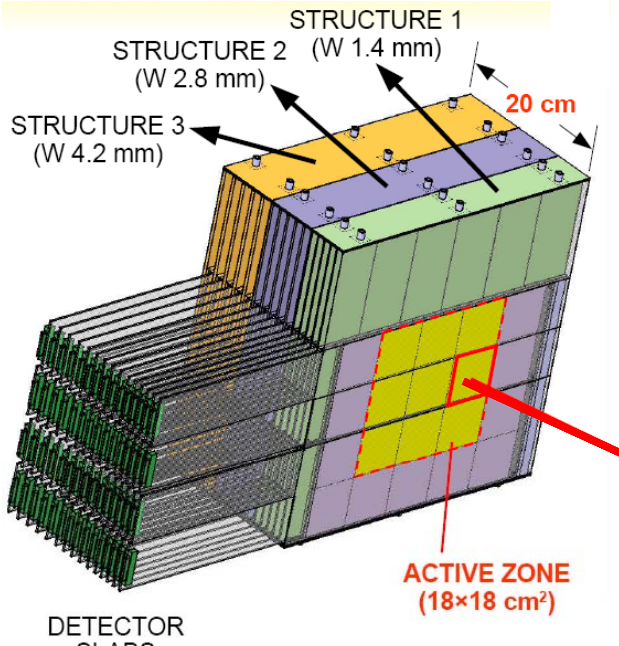
293 physicists

Silicon – Tungsten ECAL



Physics prototype

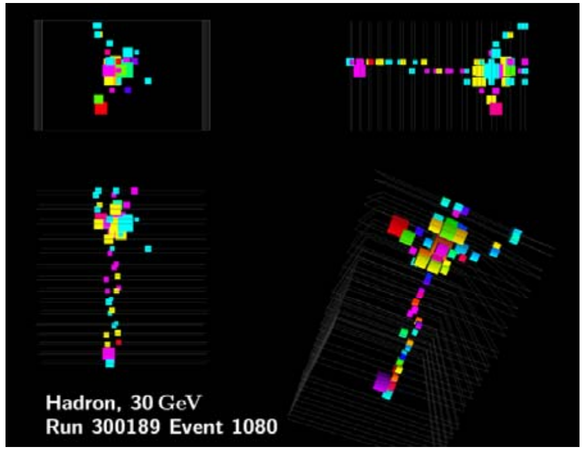
3 structures with different W thicknesses
30 layers; 1 x 1 cm^2 pads
18 x 18 cm^2 instrumented
→ 9720 readout channels



X_0^W = 3.5 mm

Tests at DESY/CERN/FNAL

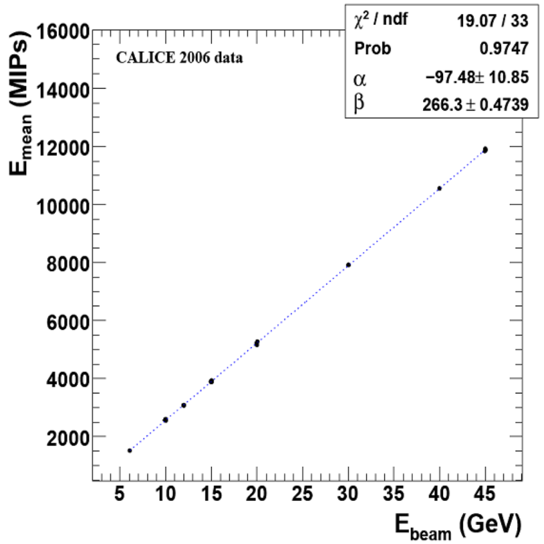
Electrons 1 – 45 GeV
Pions 1 – 180 GeV

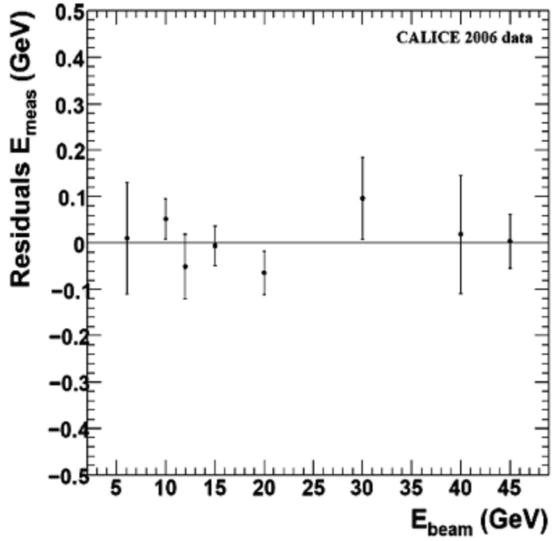


Electronic Readout

Front-end boards located outside of module
Digitization with VME – based system (off detector)

Results from Test Beam





Response to electrons

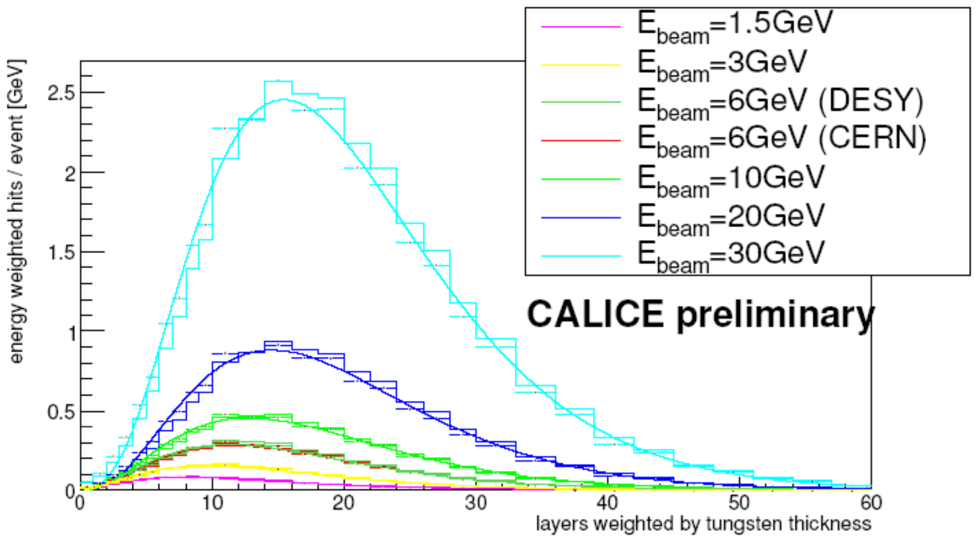
Linearity better than ± 1%

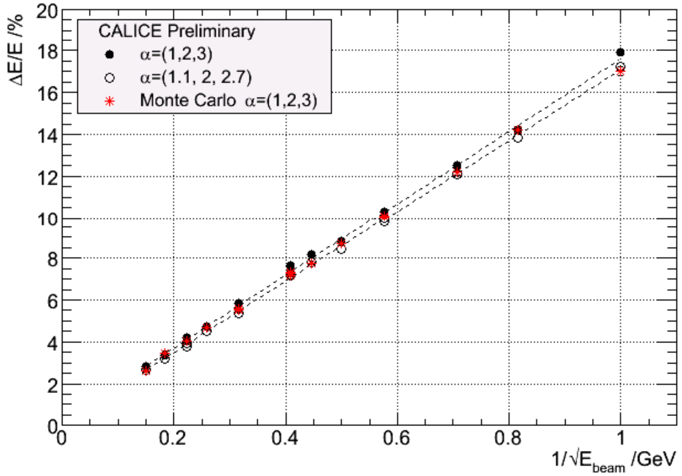
Resolution

$\Delta E/E = (17.13/\sqrt{E/GeV} + 0.54)\%$

agrees well with MC simulation

Longitudinal shower shape
agrees well with MC simulation

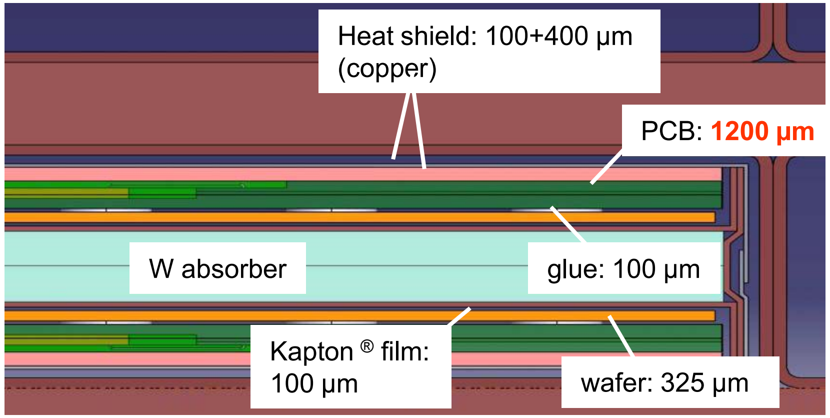


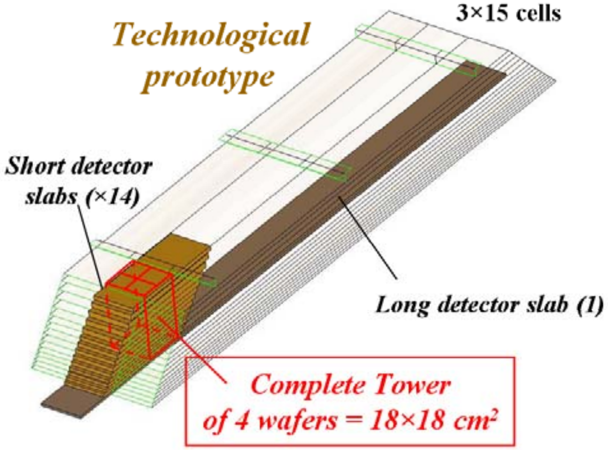


Towards a Technical Prototype

Study and validation of technological solutions

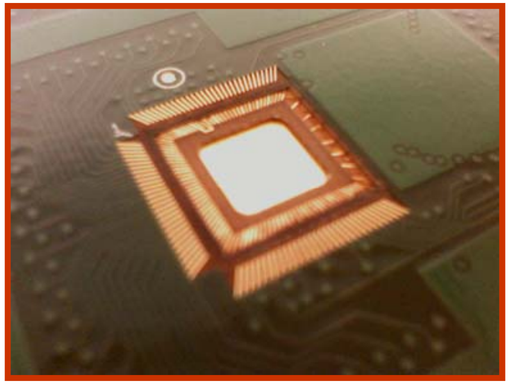
Sizes of structures
Molding process
Cooling system
New electronic readout scheme
Industrialization
Cost





Sensor

9 x 9 cm^2 wafers
0.5 x 0.5 cm^2 pads



Readout

Skiroc ASIC
64 channels/chip
12 – bit ADC on chip
Chip embedded into PCB board

Structure

Absorber = 20 x 2.1mm + 9 x 4.2 mm (23 X_0)
Thickness of slab = 6.8 mm
Thickness of active gap = 2.6 mm
Number of channels = 37890

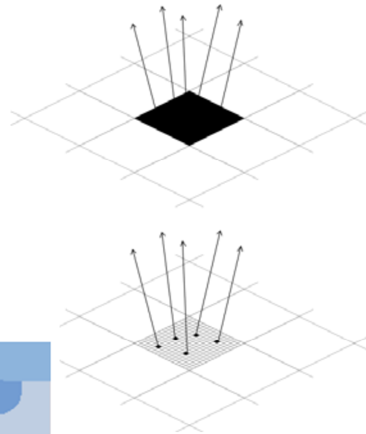
Time scale

Mechanical tests (cooling) during remainder of 2008
Chips available summer 2009
Tests in later part of 2009

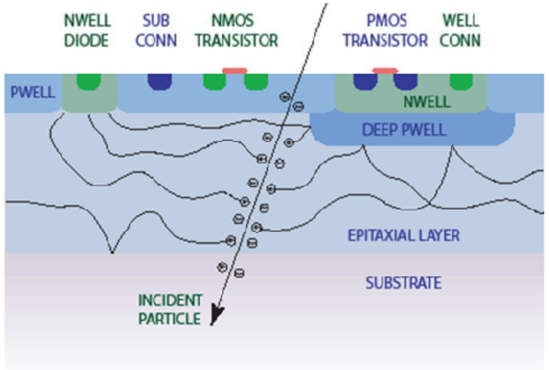
Monolithic Active Pixel Detectors – MAPS

Ultimately segmented calorimeter

Make small pixels, such that probability of more than one hit is small



→ 50 x 50 μm^2 pixels
→ 10^{12} channels for ILC detector ECAL
→ Only hit/no hit information (digital readout)



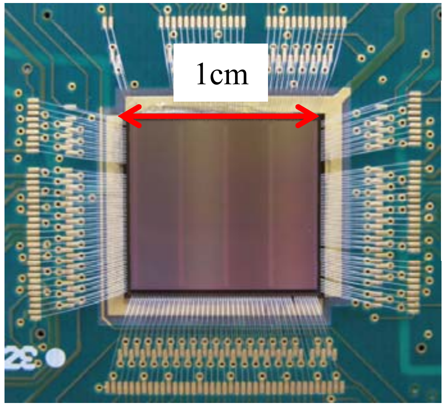
CMOS MAPS detectors

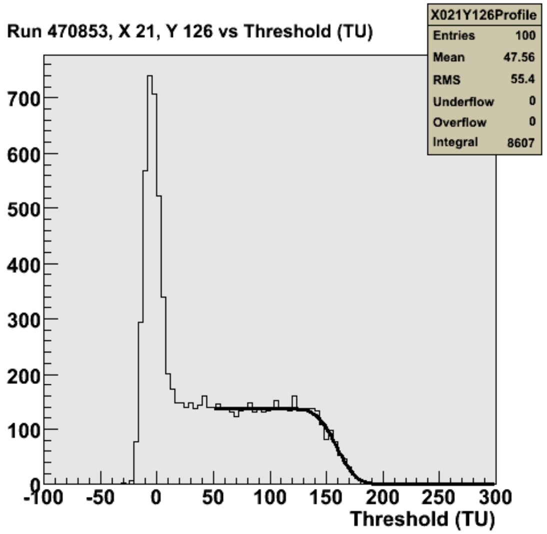
Integrates readout into pixel

First prototype TPAC 1.0 sensor

Total area 1 x 1 cm^2
168 x 168 pixels each with an area of 50 x 50 μm^2
0.180 μm CMOS process
Hits stored with 13 – bit time stamp
First tests encouraging

e.g. Threshold scan with laser





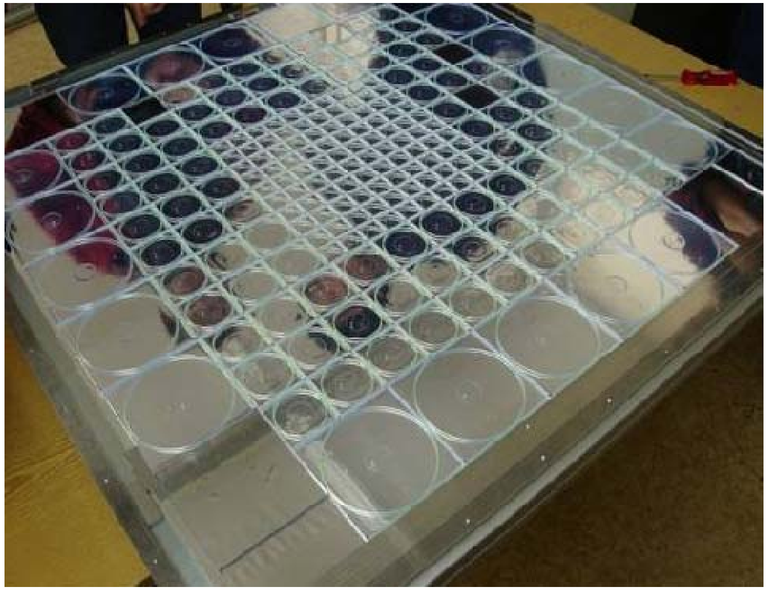
First look at showers in 2009

Scintillator – Steel Hadron Calorimeter

First calorimeter to use SiPMs

Physics prototype

38 steel plates with a thickness of 1.2 X_0 each
Scintillator pads of 3 x 3 → 12 x 12 cm^2
→ ~8,000 readout channels
Scintillator 5 mm thick

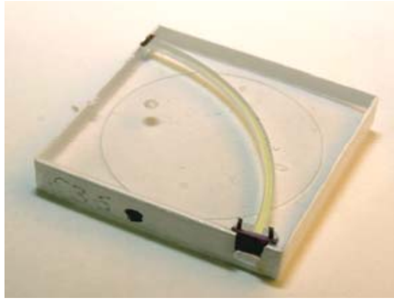


Electronic readout

Silicon Photomultipliers (SiPMs) ← work in B-fields
Digitization with VME-based system (off detector)

Tests at DESY/CERN/FNAL

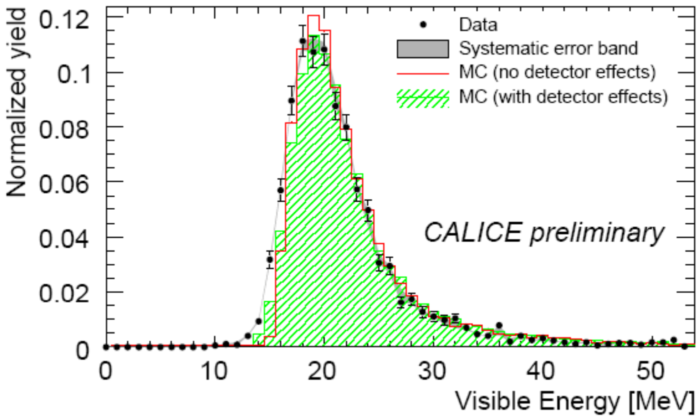
Muons (for calibration)
Electrons 1 – 45 GeV
Pions 1 – 180 GeV/c



Results from Test Beam

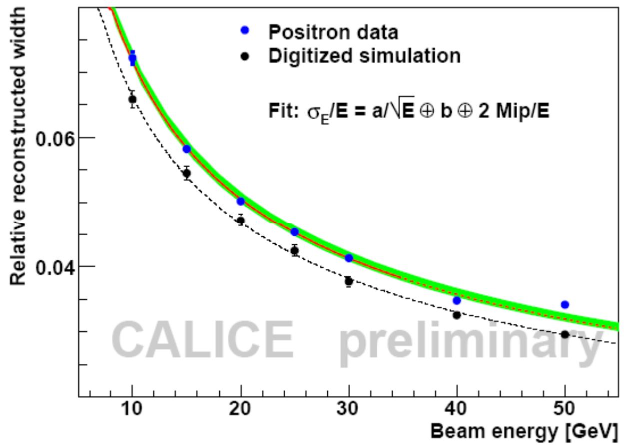
Calibration with Muons

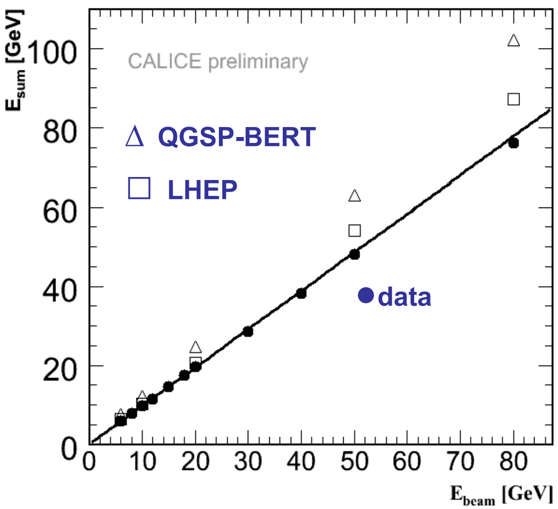
Reasonable agreement with simulation
Effects such as SiPM saturation included in simulation

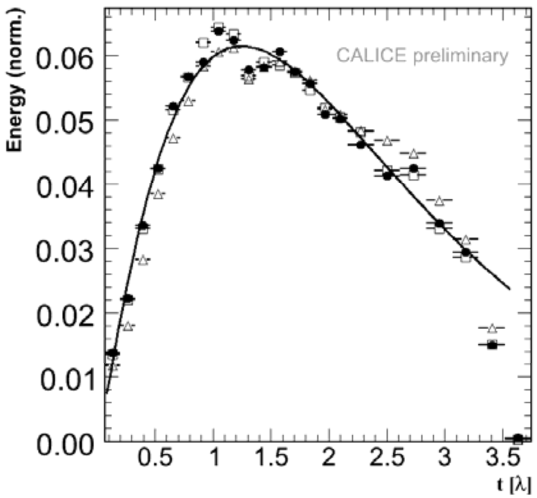


Response to electrons

Trend adequately simulated
Prediction somewhat better than data







Tests with pions

Response quite linear
Precise measurement of longitudinal shower profiles

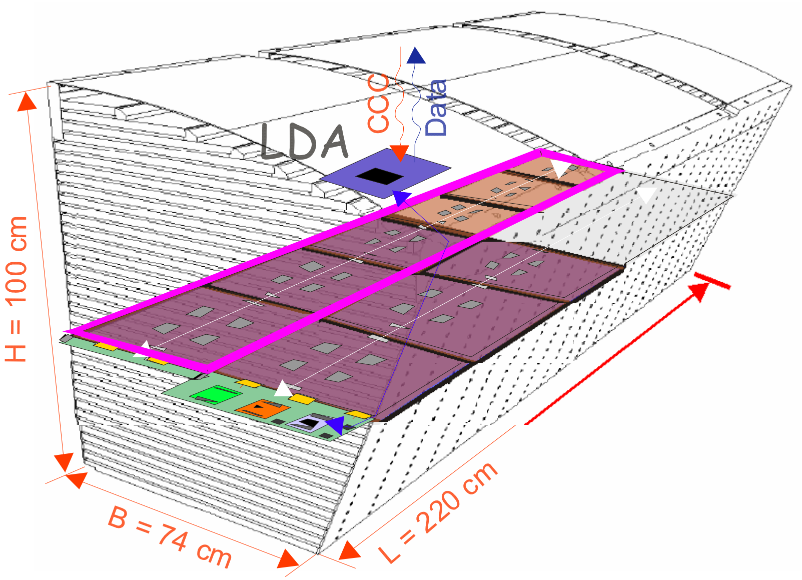
Comparison with 2 different hadron shower

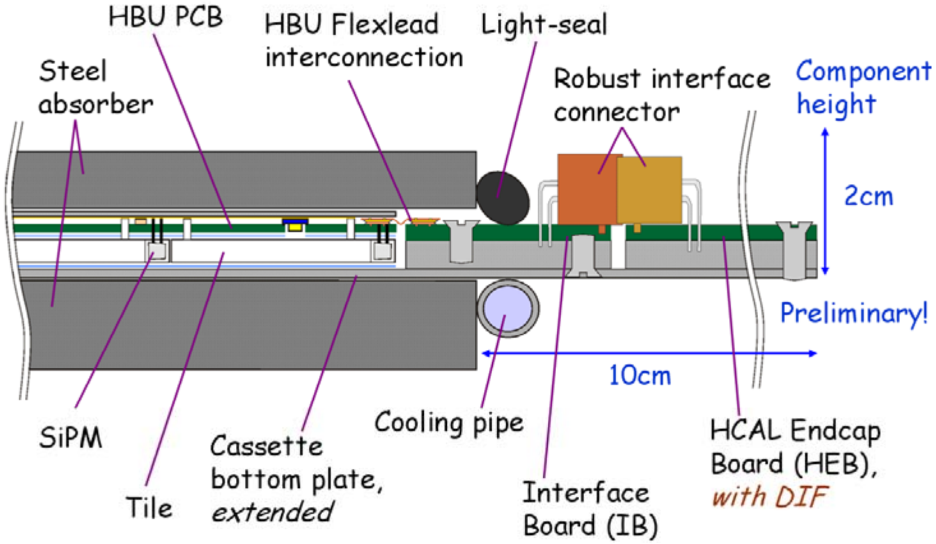
→ Some disagreement
→ Too early to draw firm conclusions

Towards a Technical Prototype

Next steps involve

Integration of electronic readout with active element
Consistent design of scalable module
Implementation of all peripherals: cooling, LV power etc.





Time scale

Calibration and Detector-Interface boards by end of 2008
Full detector slab by sommer/fall 2009
Beam tests in 2010

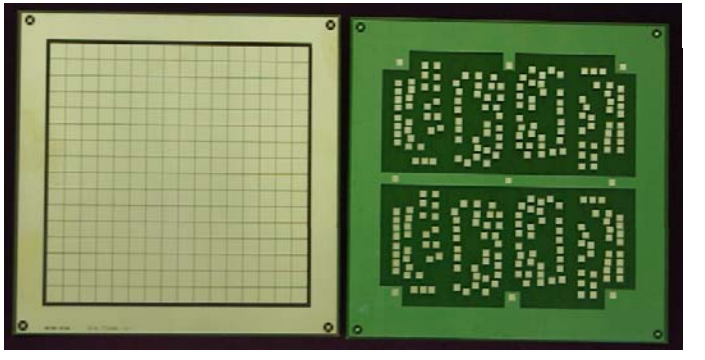
RPC – Steel Hadron Calorimeter

Novel idea: Digital Hadron Calorimeter (DHCAL)

Replace high-resolution readout of a small number of towers with the single-bit (digital) readout of a large number of channels (~10^7)

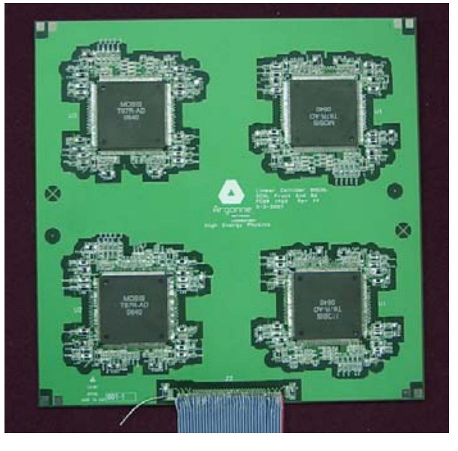
Use Resistive Plate Chambers (RPCs) as active element

- Simple in design
- Easy to assemble
- High efficiency
- Low noise rates
- Reliable
- Cheap
- Slow



Readout of 1 x 1 cm^2 pads

Energy reconstructed as function of N_{hit}



Development of electronic readout system

Centered around the DCAL chip

- Developed specifically for the DHCAL readout
- Reads out 64 channels
- Variable, common threshold between 5 ÷ 700 fC
- Output is hit pattern + time stamp (100 ns)

Remainder of readout system includes

- Pad boards, Front-end boards, Data concentrators, Data collectors and a Tming and Trigger module

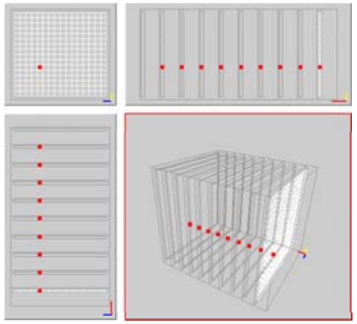
Results from Test Beam

Assembled small prototype calorimeter

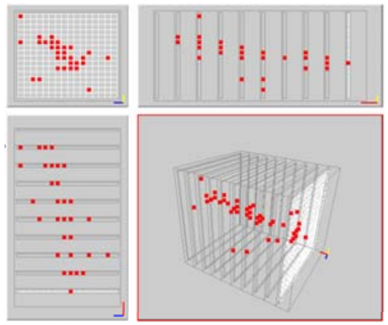
Up to 10 RPCs, each with an instrumented area of 16 x 16 cm^2
Steel absorber plates of ~1.2 X_0

Measurements with cosmics rays and μ's in test beam

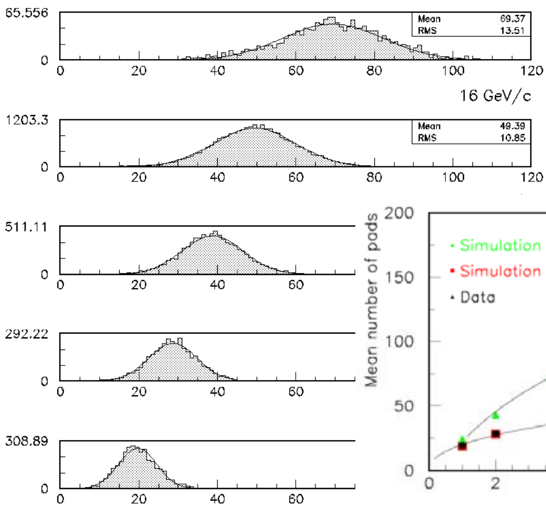
Measurement of noise rate
Measurement of efficiency and pad multiplicity

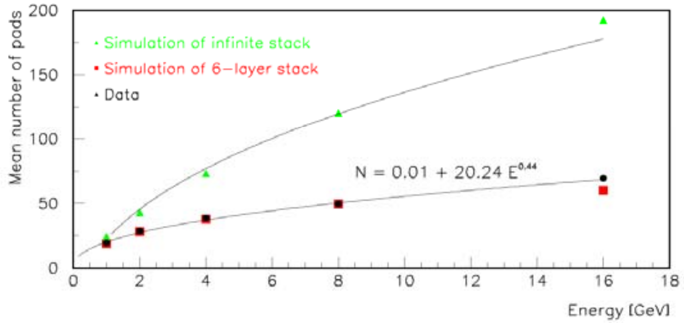


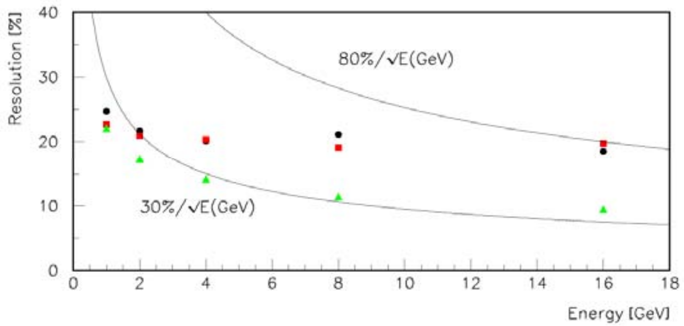
A single μ



A π^+ shower







Measurements with positrons

Only 6 layers in stack
Response to 1,2,4,8, and 16 GeV e^+
Simulation in good agreement

First validation of DHCAL concept

Construction of a DHCAL Physics Prototype

Description

40 layers each 1 x 1 m^2
~400,000 readout channels
Inserted into CALICE HCAL test structure

Planned tests

In Fermilab test beam
Tests with μ, $\pi^\pm$, $e^\pm$
Comparison with various MC models of hadronic showers
Comparison with scintillator – analog HCAL (CALICE)

Important for PFA development

Status

RPC R&D completed
DCAL ASIC ordered (need 6,000 chips)
Pad – ,Front-end and Data concentrator board design completed
Remainder of system identical to small scale test

Time scale

First layer by end of CY 2008
Ten layers early in 2009
Remainder later in 2009
Data analysis in 2009/2010

Test beam run plan to be determined

Total Absorption and Dual Readout Calorimeters

Different apprach from PFAs to improve the jet energy resolution

The problem

Hadron showers (jets) contain both an

electromagnetic component (π^0)
non-electromagnetic component ($\pi^{\pm}$, p…)

Calorimeter response to these typically not the same (e/h ≠ 1)
<**f_{em}**> is energy dependent → non-linear response to hadrons
Large fluctuations in **f_{em}** → poor resolution
(In addition there are fluctuations in the nuclear break up energy loss)

Underlying idea

Measure scintillation light ← contributions from all ionizing particles in shower (e, π, p…)
Measure Čerenkov light ← contributions mostly from $e^{\pm}$

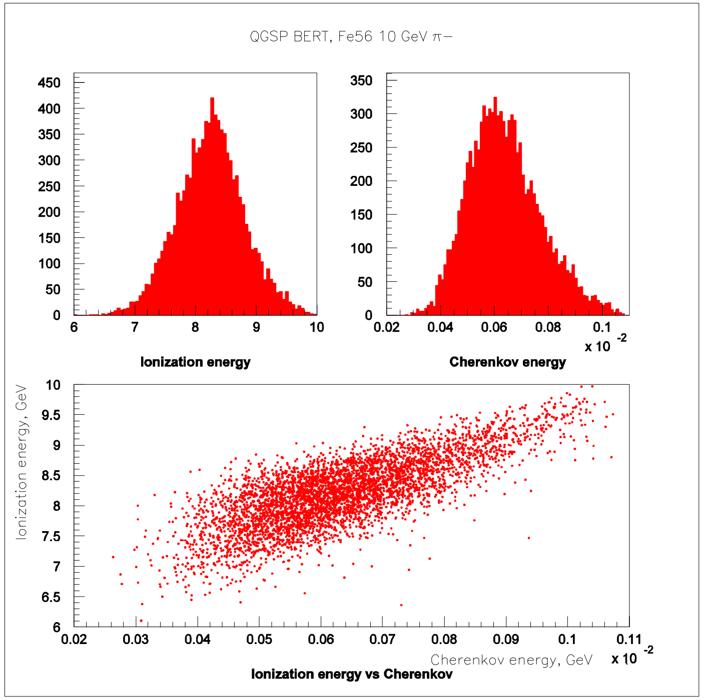
→ allows to determine the electormagnetic fraction **f_{em}** of a shower (jet)
→ apply the appropriate corrections

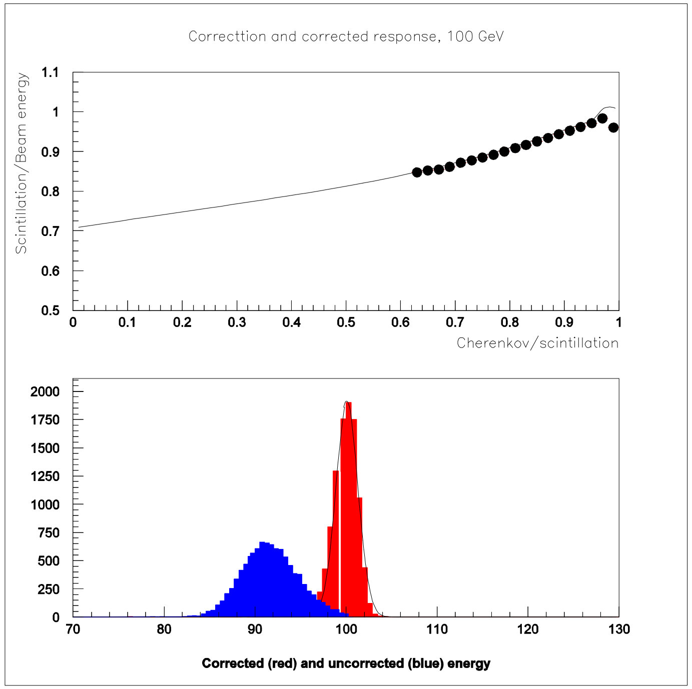
Conceptual design of a dual readout calorimeter

6 layers of 5 x 5 x 5 cm^3 crystals
3 embedded Si pixel detectors for e/γ position/direction
9 layers of 10 x 10 x 10 cm^3 crystals
4 (or 8) photodetectors/crystal: half of them with filters for Čerenkov light

Monte Carlo simulation

Assumed crystals build of various materials with a density of 8 g/cm^3
Optical properties defined by refractive index n
Summed up scintillation (= ionization) and Čerenkov lights (light collection assumed to be 100%)



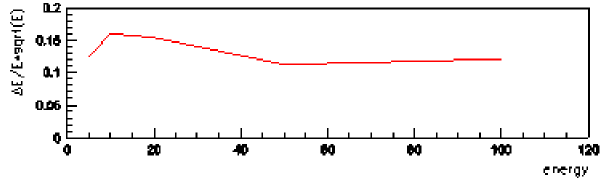


Results for single particles

Good linearity of the corrected response
Excellent resolution for single particles

$\sigma_E/E \sim 12\%/\sqrt{E}$ for pions (in simulation)

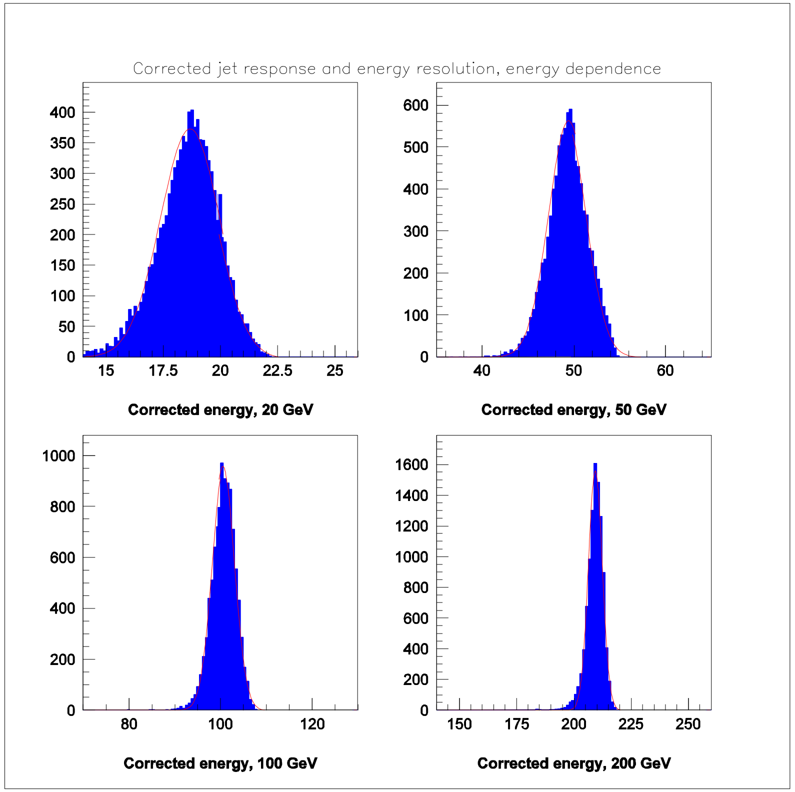
No evidence of a constant term up to 100 GeV



Results for hadronic jets

Excellent resolution

$\sigma_{Ejet}/E_{jet} \sim 22\%/\sqrt{E}$ (in simulation)



Open questions

Suitable crystal

- High density
- Affordable
- Good light propagation

Light propagation

- To be implemented in simulation

Not yet a proven concept…

Concluding Remarks

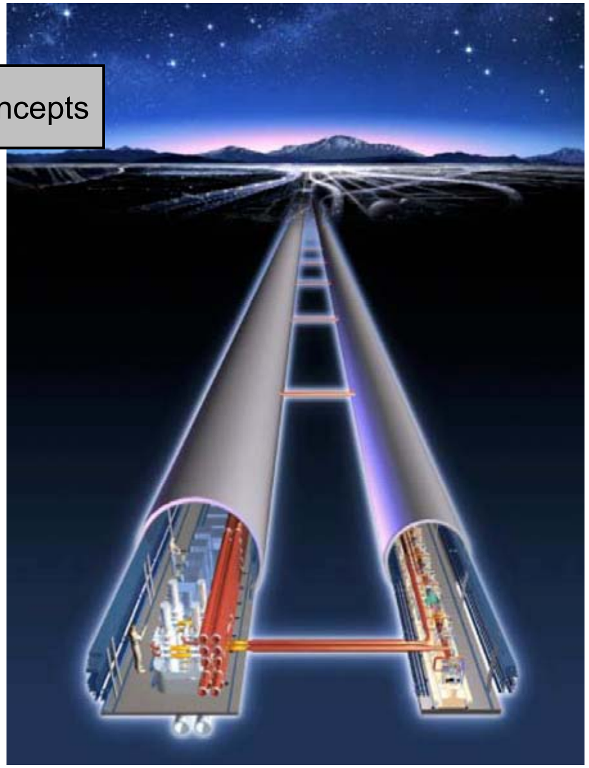
- ♦ Despite recent set-back in funding (UK and US), the physics priority of the ILC remains as strong as ever
- ♦ The ILC is the highest priority project for the future of particle physics
- ♦ Large and worldwide effort in both

  Accelerator R&D
  Detector R&D

  ← Exploring/Implementing/perfecting many novel concepts

- ♦ Future of project depends critically on LHC results
- ♦ Assuming first results from the LHC available by 2012

Machine and detector designs will be mature enough to initiate construction within a short time span



Acknowledgments

Everyone, whose slides/material I have used. In particular

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Marcel Demarteau, Julien Fleury, Adam Para, Mark Thomson,
Nabu Toge, David Ward, Richard Wigmans…