Physics and Detector at the ILC

W. Lohmann, DESY

Why a e^+e^- Collider

Physics essentials

Requirements on the Detector

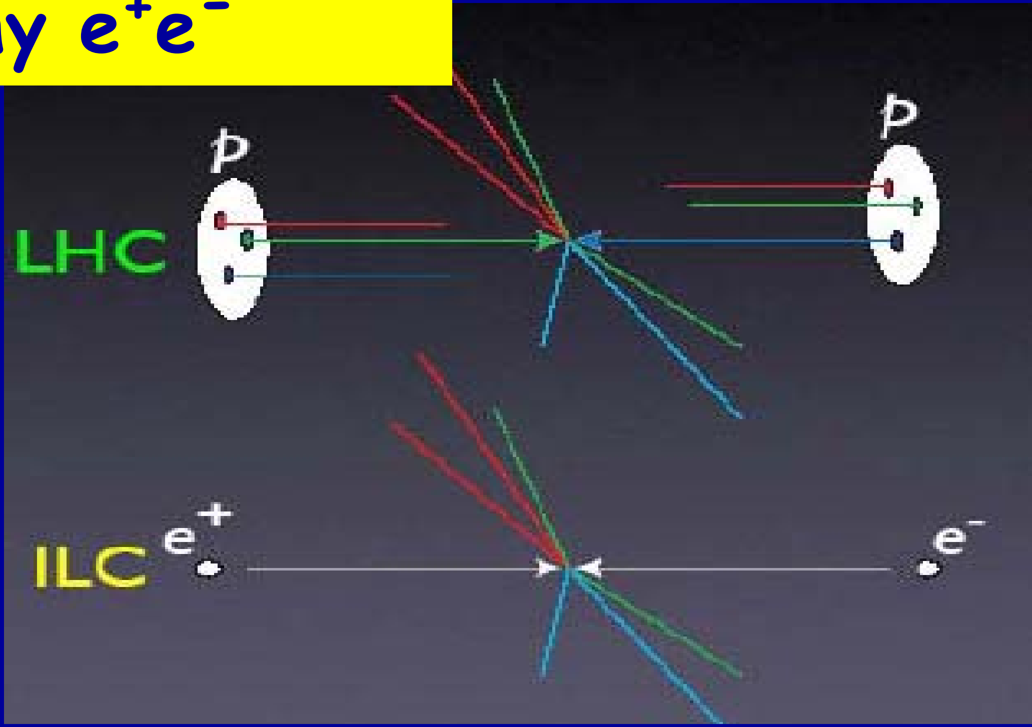
R&D on Subdetectors

Detector Concepts

Technicalities, Organisation ….

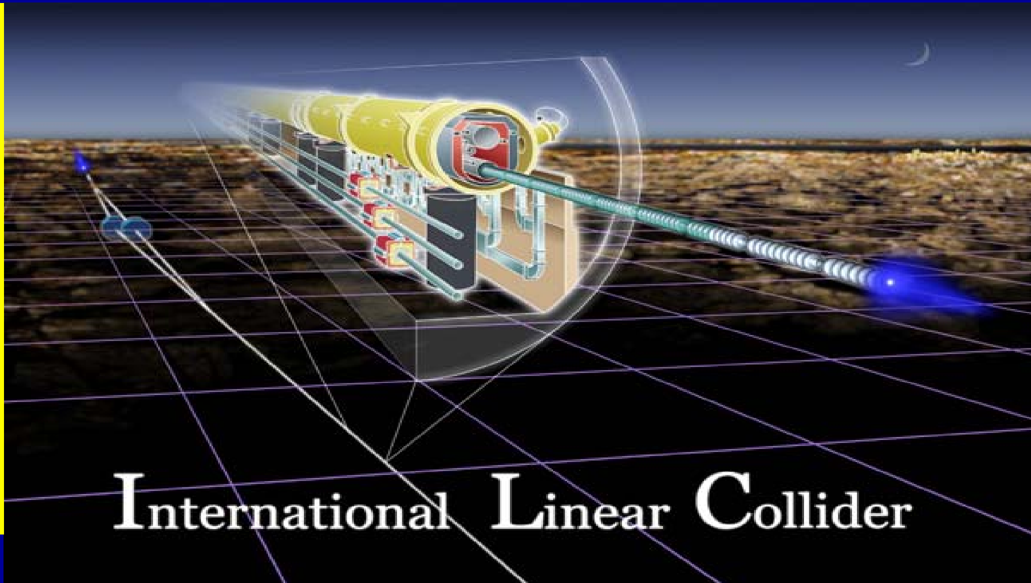
Why e^+e^-

- Electrons are pointlike
- Energy known and tunable
- Polarised beams
- Clear, fully reconstructed events



Cold (SC) Technology
(Developed by the TESLA collaboration, Recommended by the ITRP in 2004)

Frequency: 5 Hz (trains)
About 3000 bunches per train
300 ns between bunches



Accelerator Design

First stage : 90 - 500 GeV

Second stage : up to 1 TeV

Luminosity : 500 fb^{-1} / 4years

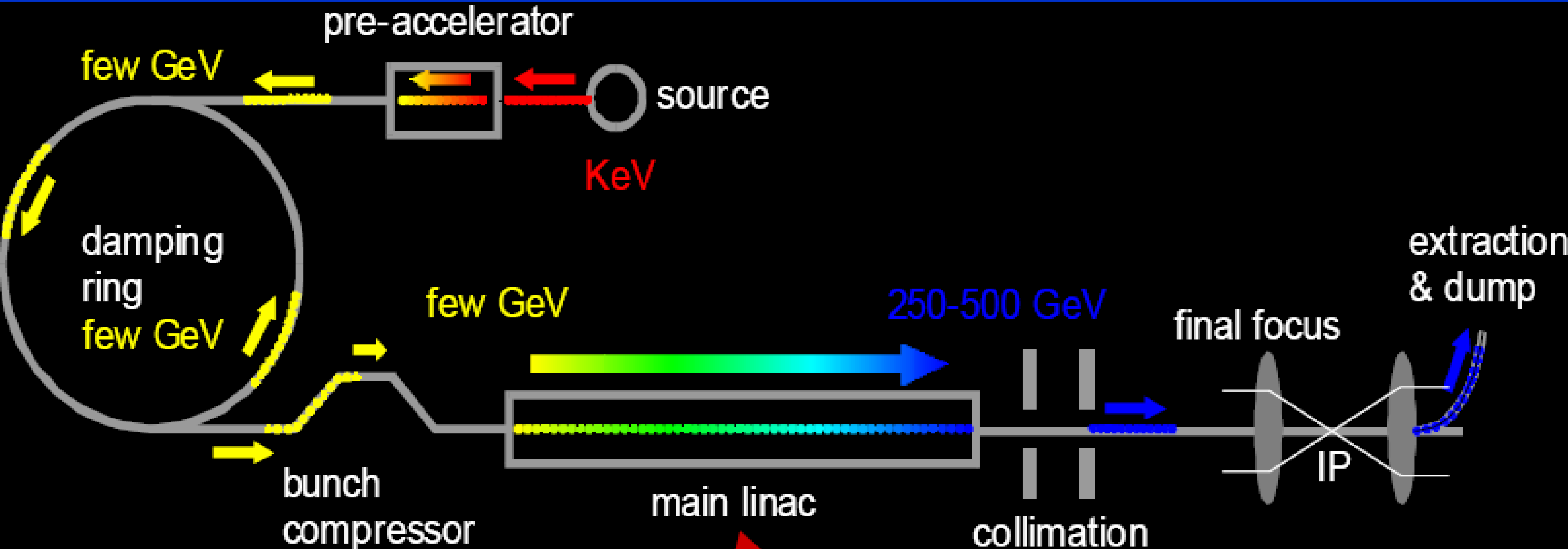
1 ab^{-1} at 1 TeV → $L \sim 2 \times 10^{34}\ cm^{-2}s^{-1}$

Polarisation : 80% e^-

50% e^+ (later phase)

Beam energy uncertainty : $< 10^{-3}$

Options : GigaZ (high lumi running at the Z), e-γ, γ-γ



Physics essentials

Origin of Mass

Space-Time Structure

Dark Matter

New particles or phenomena in the energy range 100 GeV – 1 TeV:
The Terascale – the domain of the ILC!

Origin of Mass

SM of particle physics:

Leptons and Quarks (Fermions, s=1/2) form matter

Gauge Bosons (S=1,Photon,Z,W^+, Gluons) mediate Interactions

Higgs Mechanism

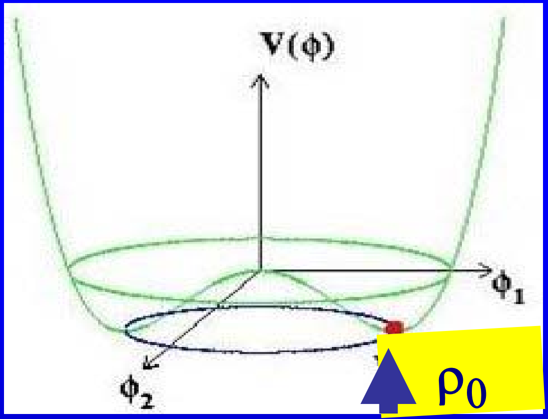
doublets under SU(2)

$$\Phi = \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

$$\mathcal{L}_H = \partial_\nu \Phi^\dagger \partial^\nu \Phi - \mathcal{V}(\Phi)$$

$$\mathcal{V}(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\rho_0 \end{pmatrix}$$



Gauge Boson Masses

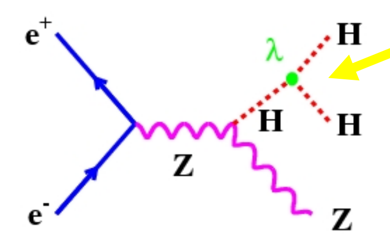
$$m_W^2 = \frac{1}{4} g_1^2 \rho_0^2 = \frac{e^2 \rho_0^2}{4 \sin \theta_W}$$

$$m_Z{}^2 = \frac{1}{4}(g_1^2 + g_2^2)\rho_0^2 = \frac{e^2 \rho_0^2}{4 \sin^2 \theta_W \cos^2 \theta_W}$$

Fermion Masses

$$m_e = \frac{1}{\sqrt{2}} \rho_0 c_e$$

Higgs Field Potential, λ



Higgs Boson

$\rho_0{}^2$=sqrt(2)G_F

Unkonwn:

$$m_H^2 = 2\lambda\rho_0^2$$

$$\lambda \rho_0 h^3$$

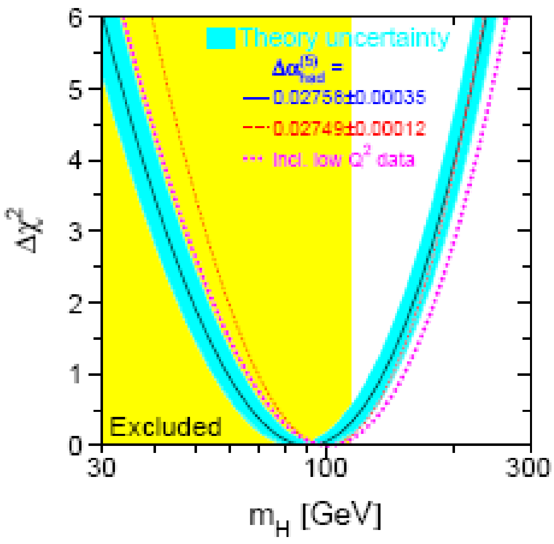
$$\frac{1}{4}\lambda h^4$$

What we know about the Higgs Boson:

From LEP, SLD, Tevatron
(Precision measurements)

$m_H = 91^{+45}_{-32}$ GeV, <186 GeV @ 95% CL

From LEP direct searches: $m_H > 114$ GeV

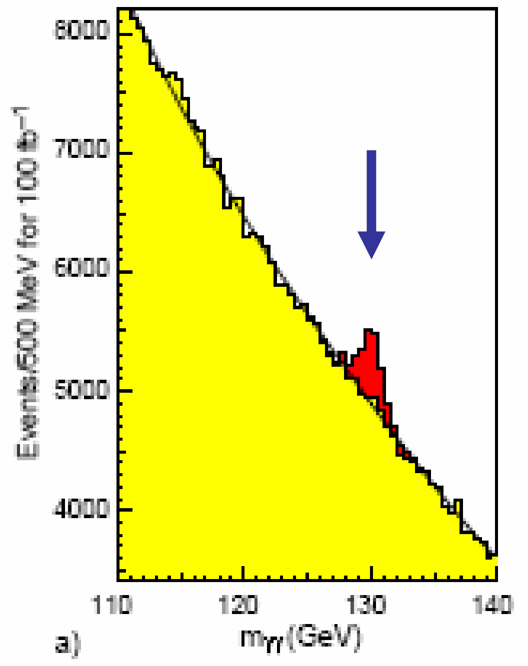


What we may know in (a few) years:

LHC/Tevatron will discover
a ‘light’ SM Higgs Boson

e.g. CMS $H \longrightarrow \gamma\gamma$

$\mathcal{L} = 100\ fb^{-1}$



What we expect from ILC: Understand EWSB!

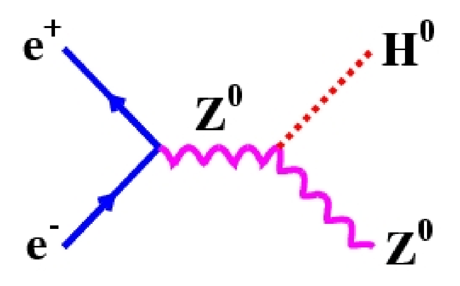
Identification of the Higgs (Mass, Spin, Parity), Couplings

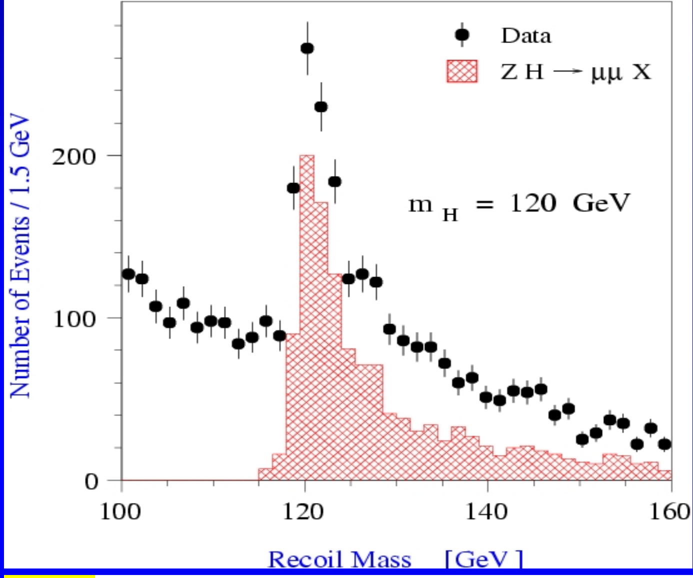
$e^+e^- \longrightarrow Z\,H \longrightarrow l^+\,l^-\,X$

('golden physics channel'), with $\delta(m_{l^+l^-}) \ll \Gamma_Z$

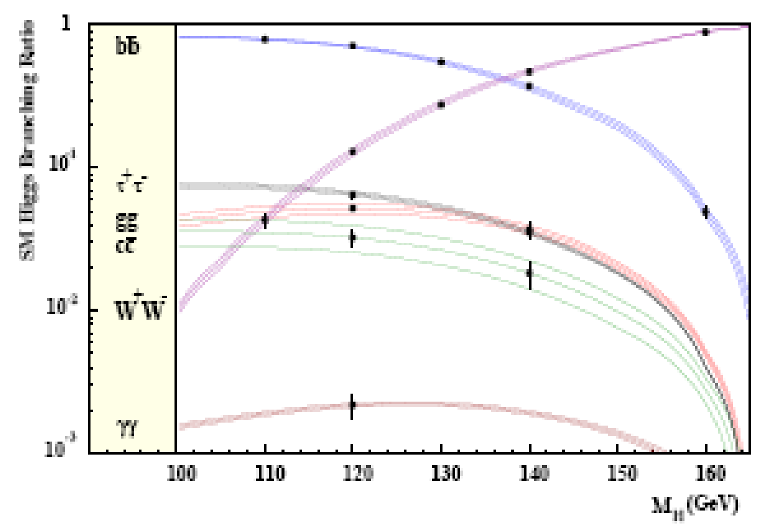
Mass
accuracy ~40 MeV

Momentum and
jet energy resolution



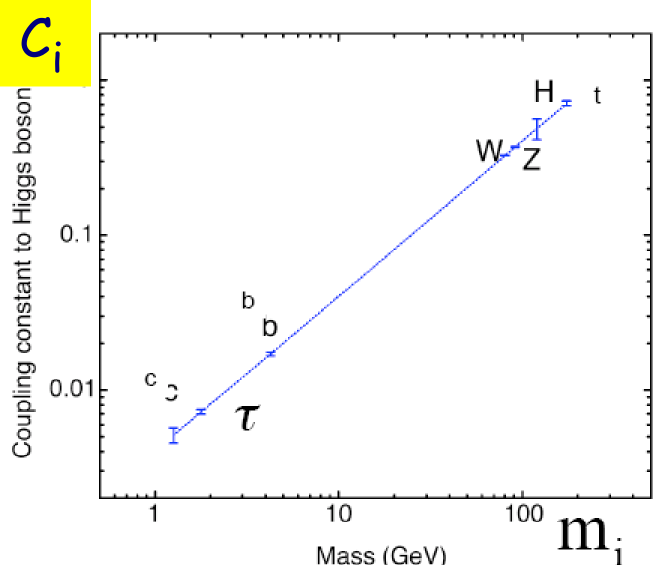


Branching fractions (couplings)



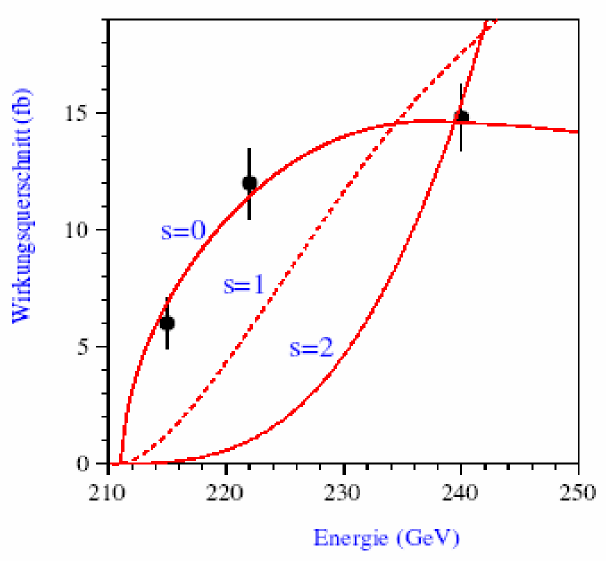
m_H < 140 GeV
Z, W, b, τ, c, t
m_H > 140 GeV
Z, W, t, b
Flavour tagging

C_i



Spin, Parity
CP

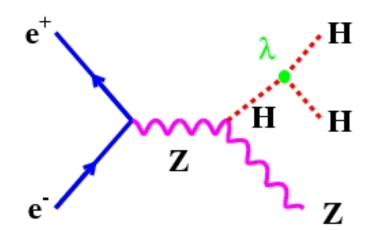
b-tagging,
τ -tagging

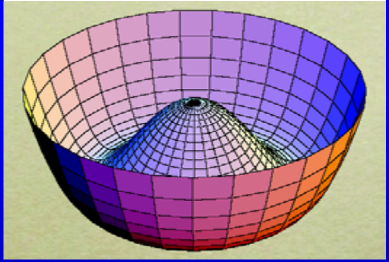


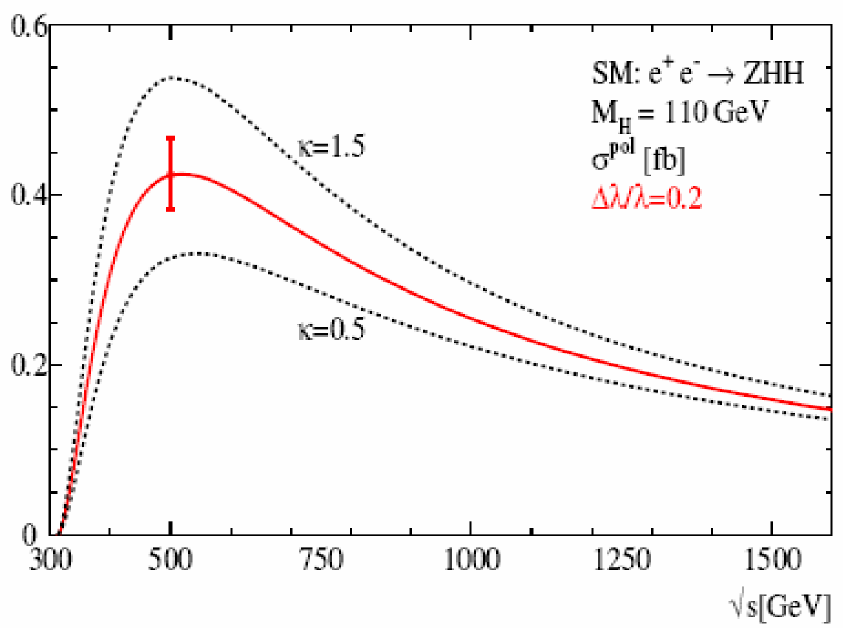
The Higgs boson would be the first elementary particle wit spin 0 !

Higgs Field Potential, λ

Jet energy resolution,
b-tagging, vertex charge



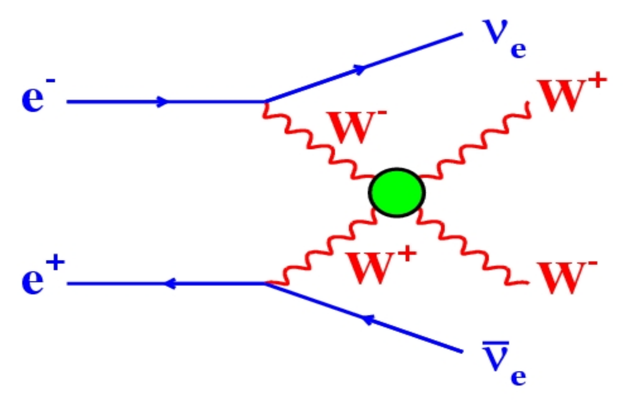




Beyond SM: more complex Higgs sector, e.g. MSSM

Two CP even states: h, H ($m_h < 130$ GeV)
One CP odd state: A
Two charged states: H^{+-}

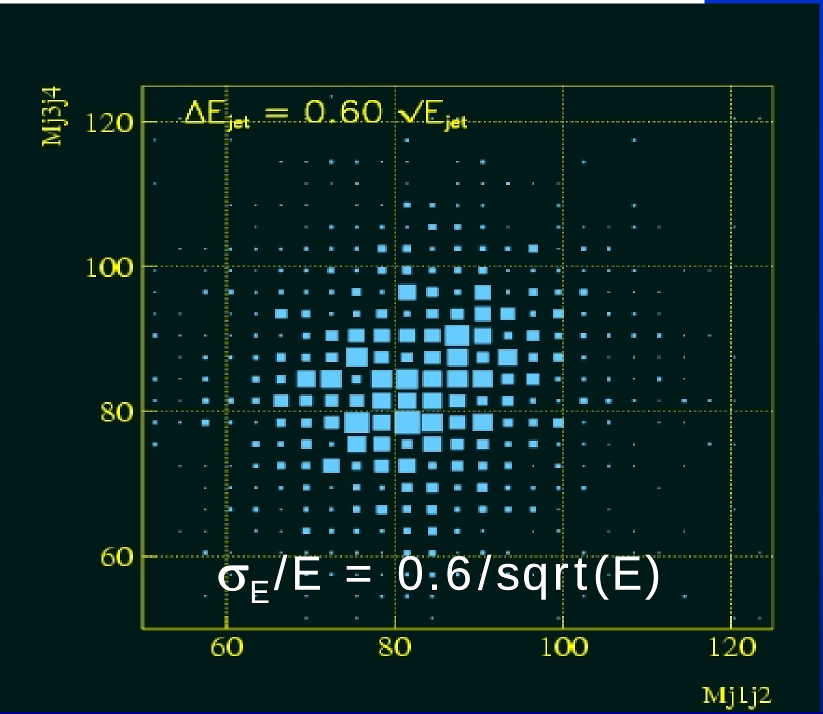
Or, no Higgs Boson:



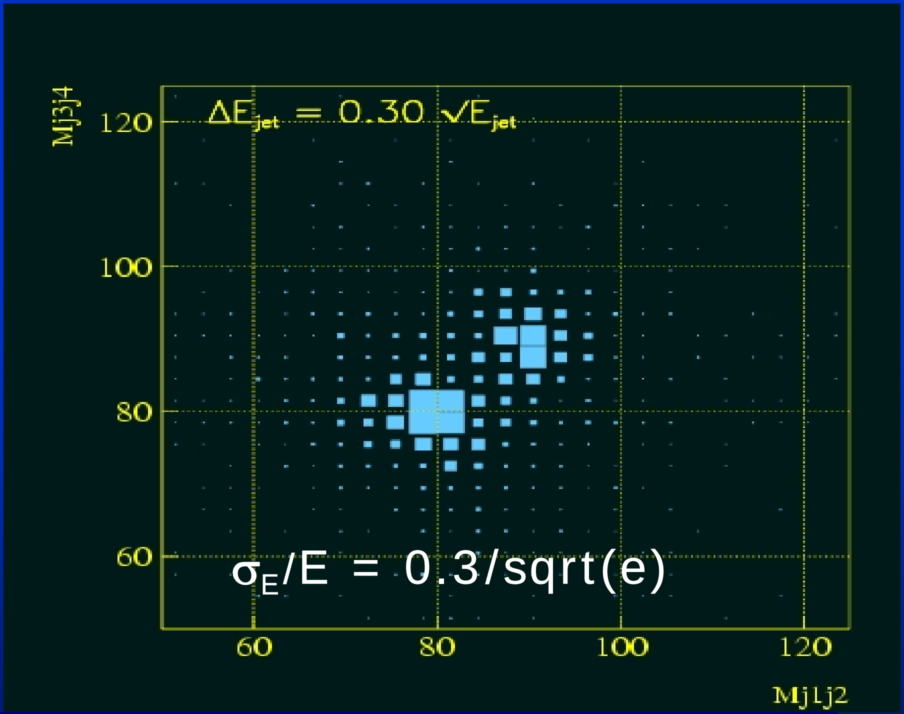
Strong Interactions of Gauge Bosons

-Reconstruction of the W's from the measured Jet energies and directions

Separation of WW and ZZ final states! Jet energy resolution



$\sigma_E/E = 0.6/\mathrm{sqrt}(E)$



$\sigma_E/E = 0.3/\mathrm{sqrt}(e)$

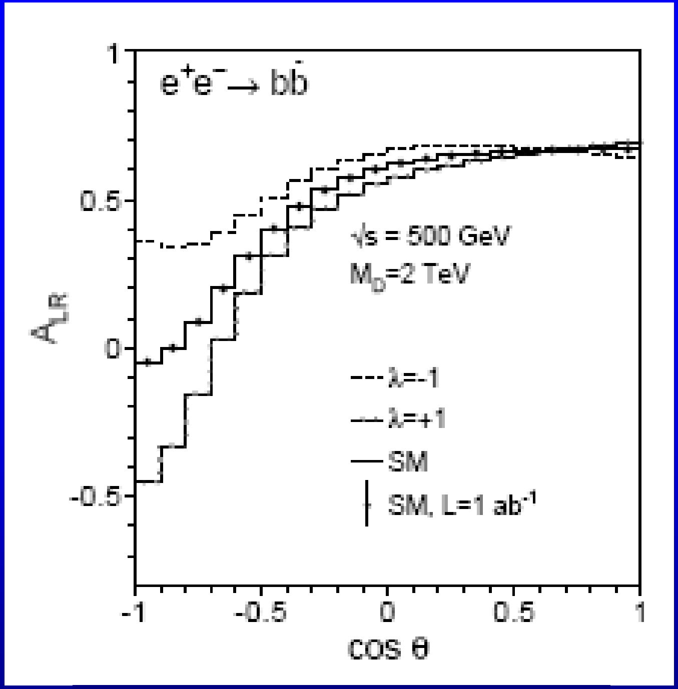
and then search for resonances, new interactions ….

Space-Time Structure

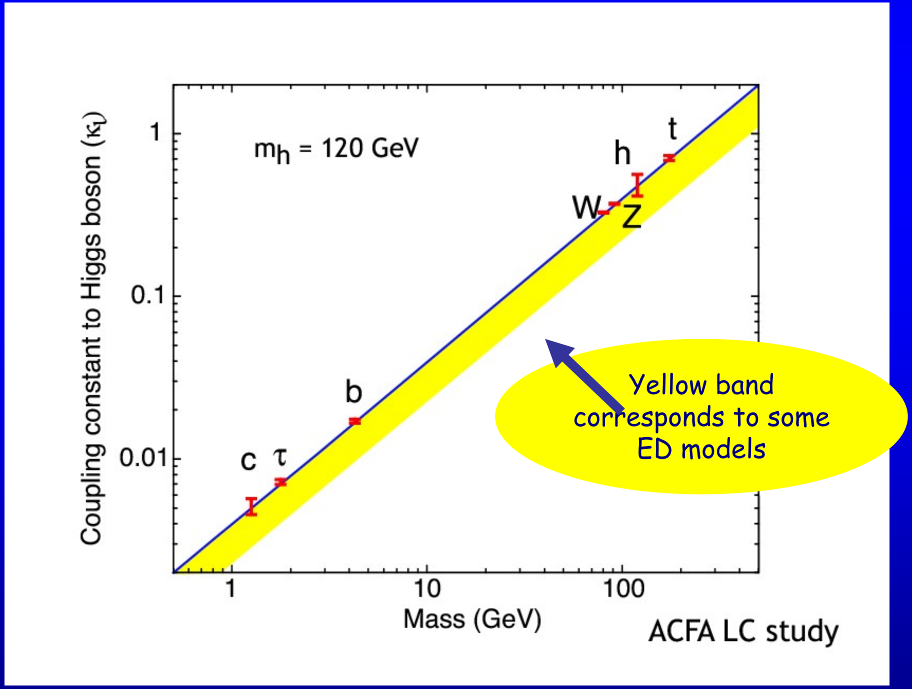
Extra Space Dimensions (Gravity extends to more than three Dimensions, the 'bulk'): K(aluza)K(lein) towers of states

$e^+e^- \longrightarrow f\bar{f}$

Scalar Mode: Radion, mixing with the Higgs Boson



b-tagging, vertex charge

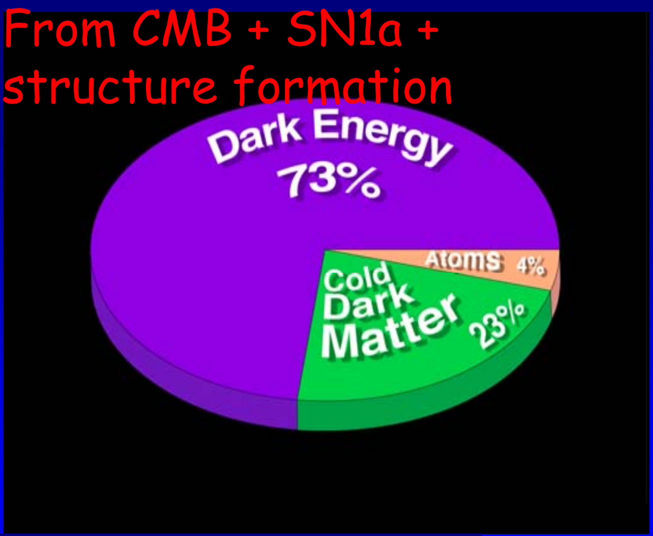


Yellow band corresponds to some ED models

B, c-tagging, τ -tagging

Dark Matter

There is no Cold Dark Matter particle in the SM!



From CMB + SN1a + structure formation

From Observational Cosmology:

Baryon	4 %
Dark Matter	23 %

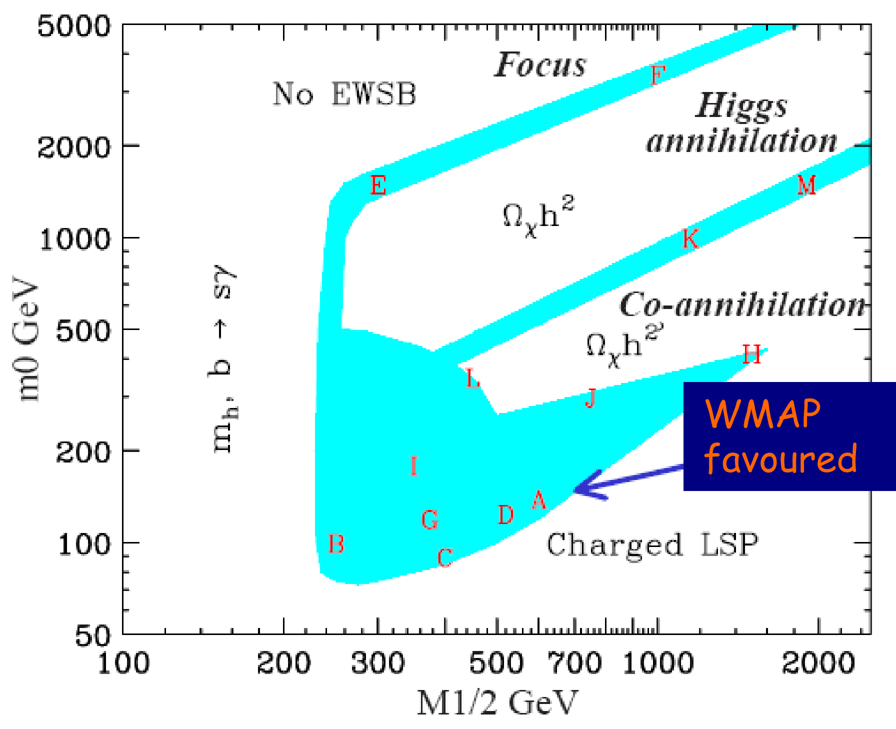
Supersymmetry provides CDM candidates, e.g.:

$e^+e^- \longrightarrow \tilde{\tau}^+\tilde{\tau}^- \longrightarrow \tau^+\tau^-\chi^0\chi^0$,

χ^0 is LSP

Small Δm, difficult to detect
Large background from 4f events

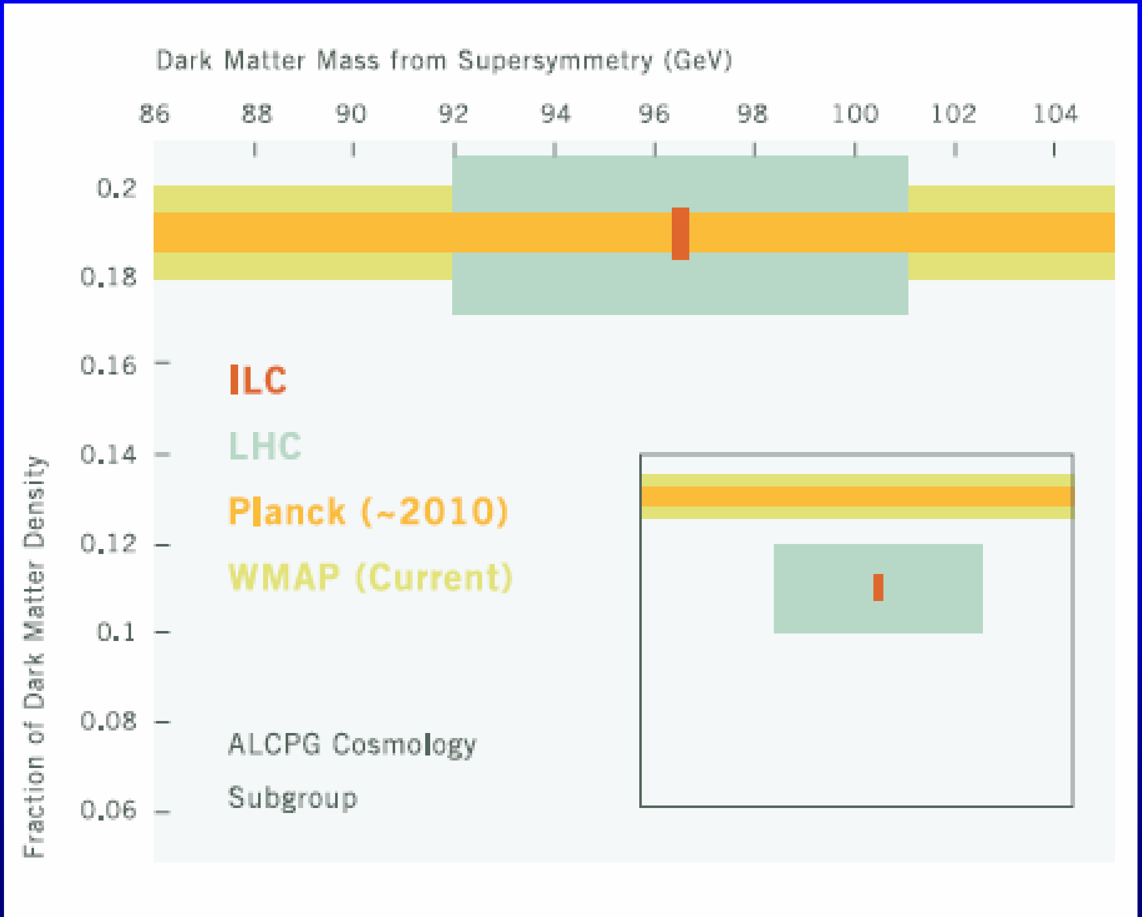
Detector hermeticity



WMAP favoured

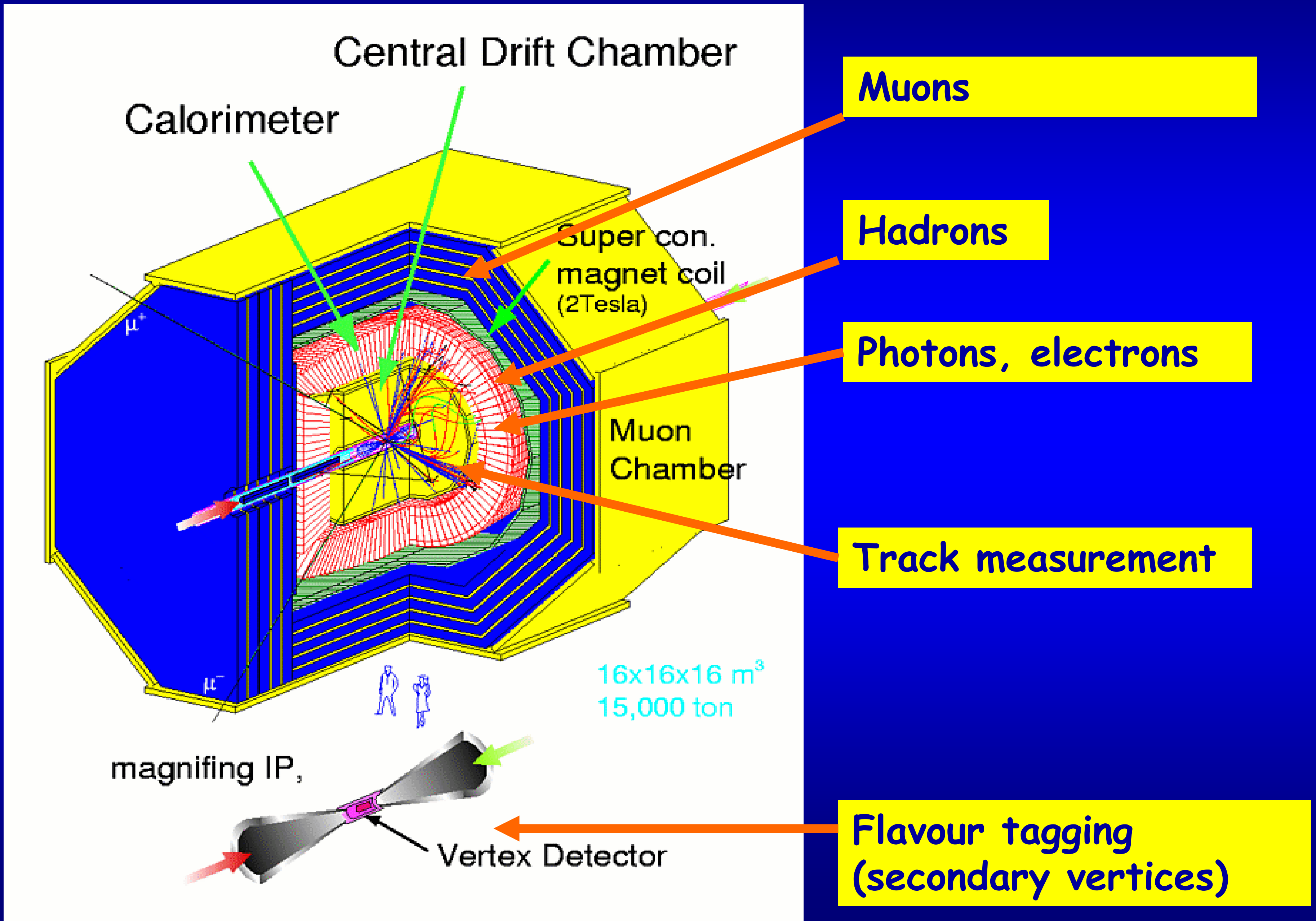
Dark Matter

The target is to discover CDM particles, measure their mass and couplings and compare to observational cosmology



A possible scenario

Detector Example



Muons

Hadrons

Photons, electrons

Track measurement

Flavour tagging (secondary vertices)

Requirements on the Detector

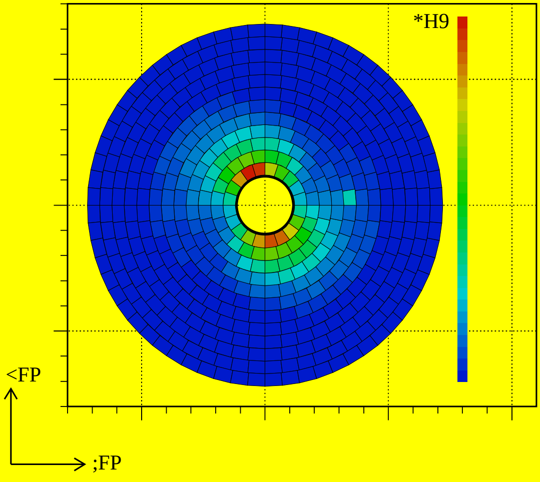
Impact Parameter: (secondary vertices)	1/3 x SLD 1/5-10 x LEP
Momentum resolution	1/10 x LEP
Jet energy resolution	1/3 x LEP, HERA
Hermeticity	> 5 mrad

➡ **A worldwide R&D program is launched**

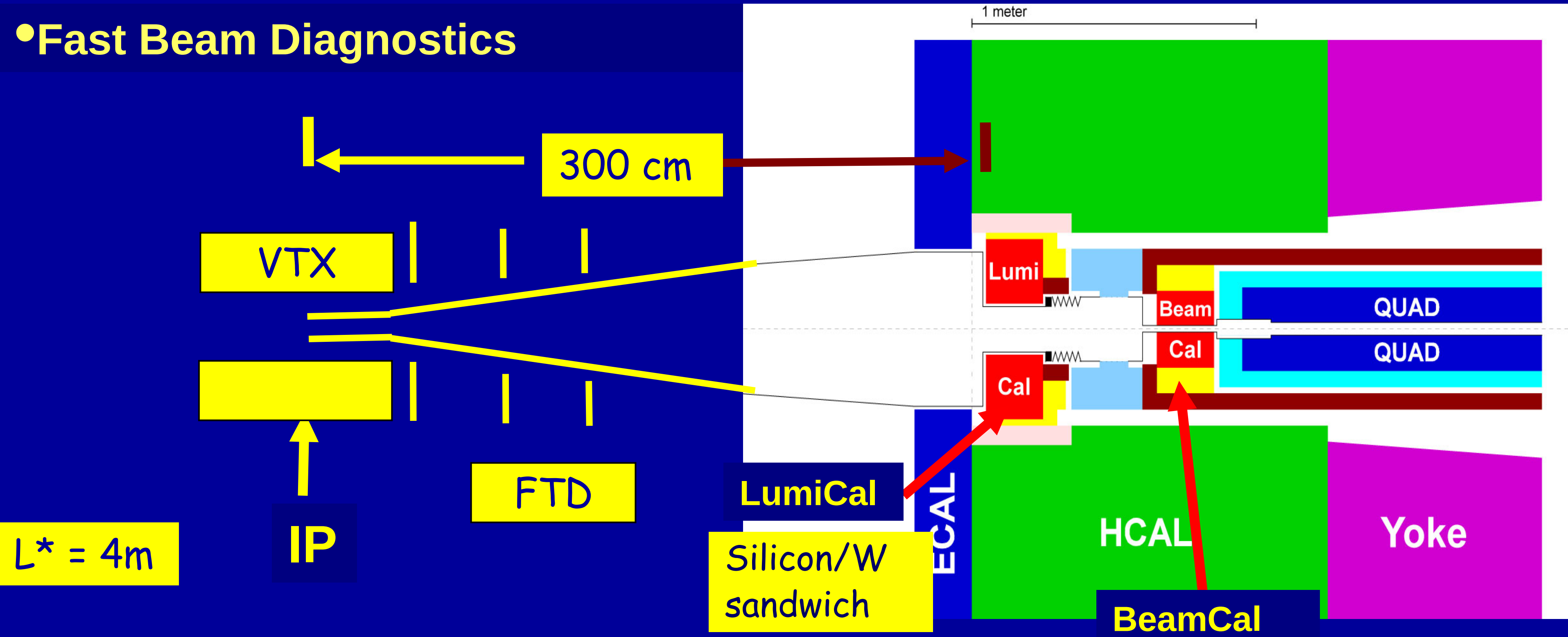
Very Forward Detectors

- Detection of Electrons and Photons at very low angle – extend hermeticity
- Measurement of the Luminosity with precision ($<10^{-3}$) using Bhabha scattering

Beamstrahlung
Depositions:
20 MGy/year
Rad. hard sensors
e.g. Diamond/W
BeamCal

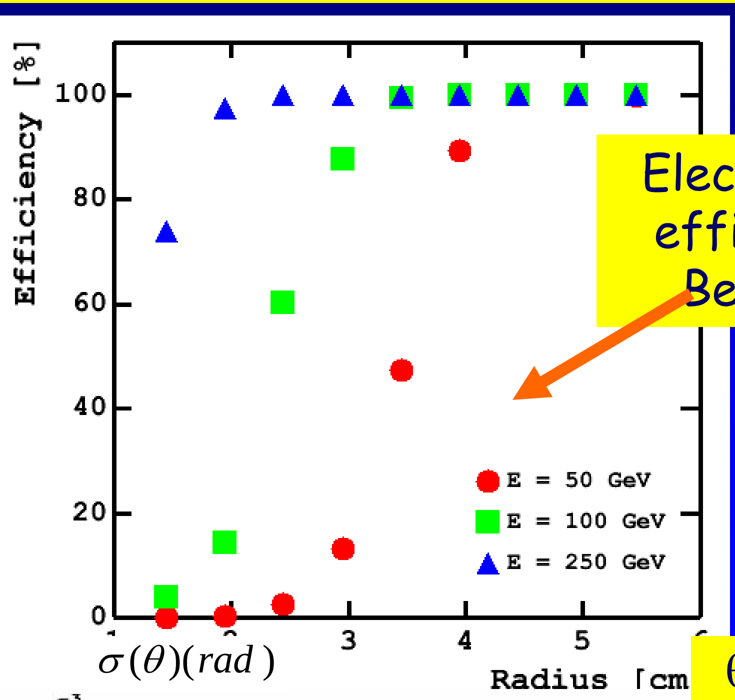


- Fast Beam Diagnostics

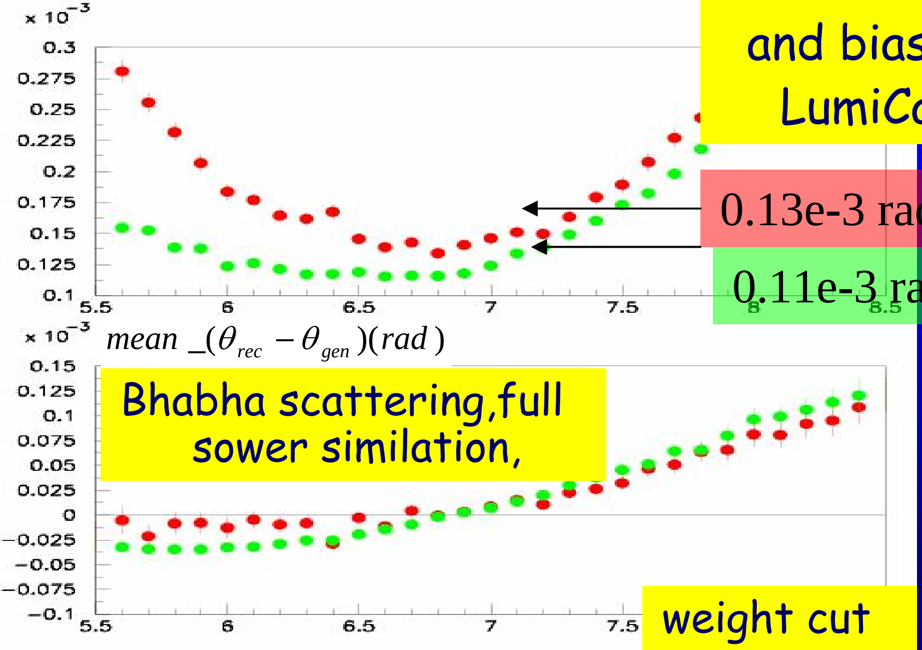


R&D for ILC (DESY PRC R&D 02/01):
Instrumentation of the Very Forward Region of the ILC Detector

Simulation and sensor tests



Electron ID efficiency, BeamCal



θ resolution and bias in LumiCal

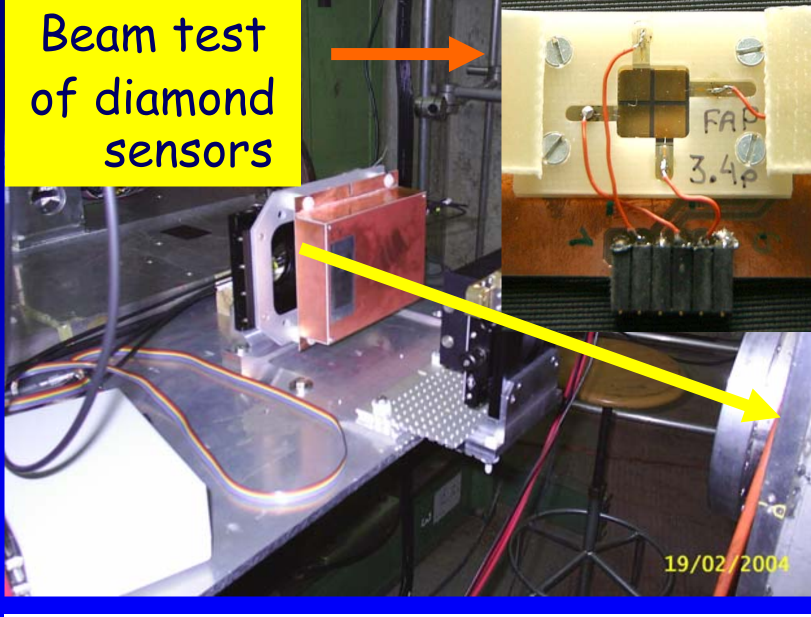
0.13e-3 rad

0.11e-3 rad

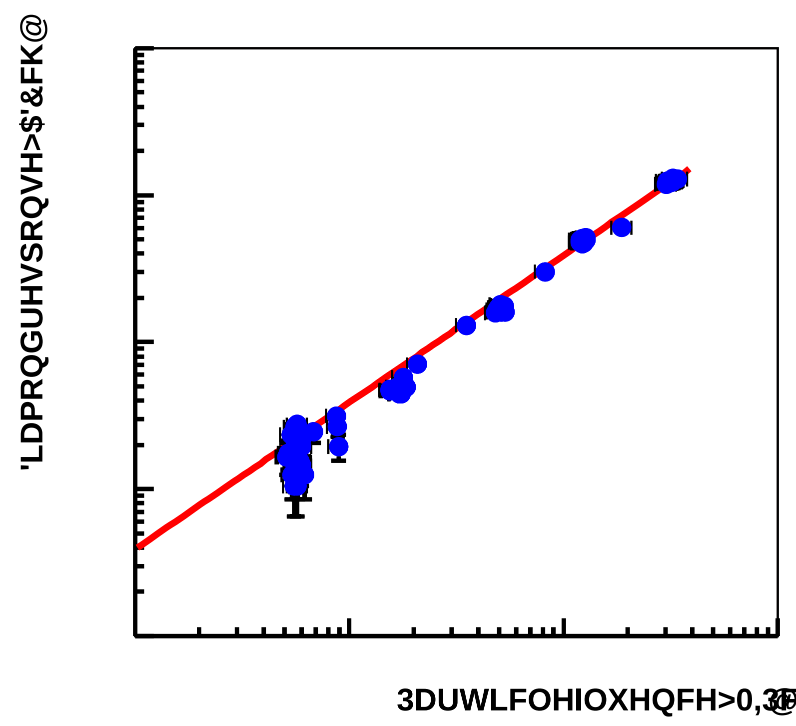
Bhabha scattering,full sower similation,

weight cut

Beam test of diamond sensors

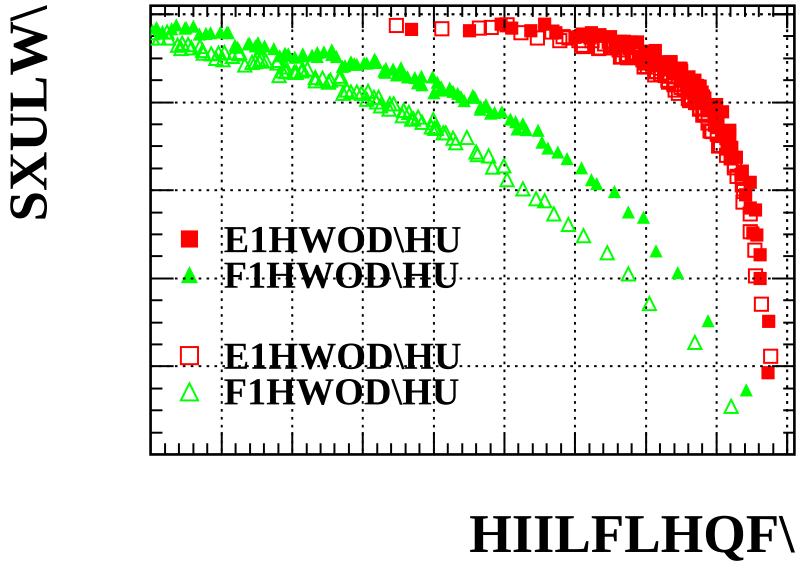


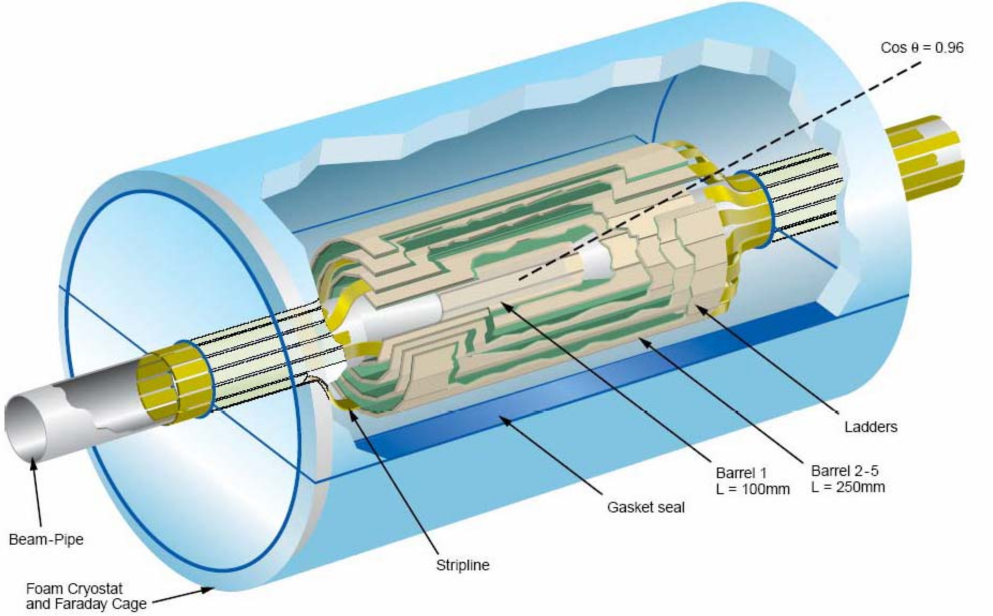
Diamond response



Flux N/cm^2/10ns

Vertex Detector





- Space Point Resolution < 4µm
- Impact Parameter Resolution ($\delta(IP) = 5 \otimes 10/p \sin^{3/2}\theta$) µm
- Vertex Charge Measurement

  Transparent, < 0.1 % X_0 per layer

  Small beam pipe Radius, < 15 mm

  thin walled beam pipe

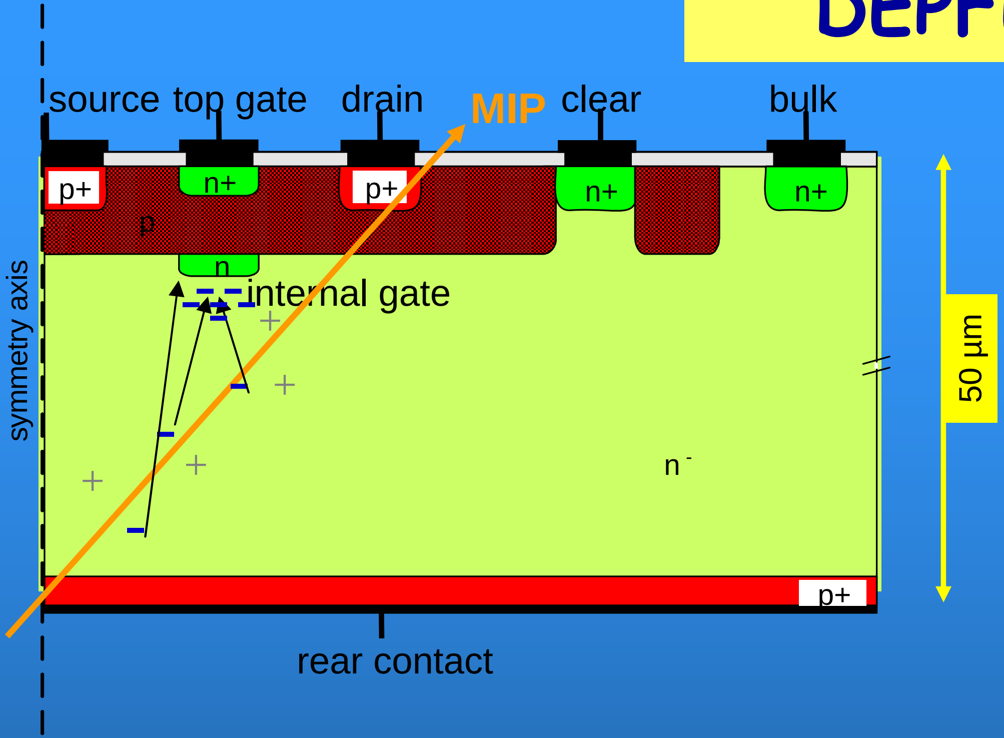
Vertex Detectors

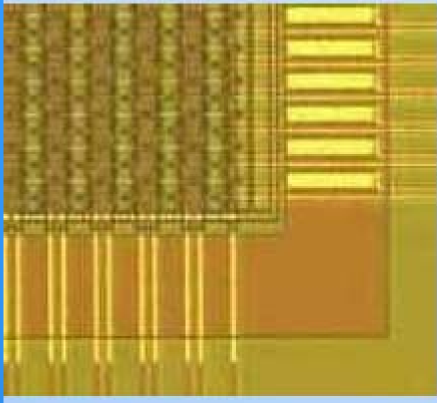
Concepts under Development:

- Charge Coupled Devices, CCD (demonstrated at SLD)
- Fine Pixel CCD, FPCCD
- DEpleted P-channel Field Effect Transistor (DEPFET)
- Monolithic Active Pixel (CMOS), MAPS
- Silicon on Insulator, SoI
- Image Sensor with In-Situ Storage (ISIS)
- Hybrid Pixel Sensors (HAPS)
- …….

11 technologies, 26 Groups around the world

DEPFET





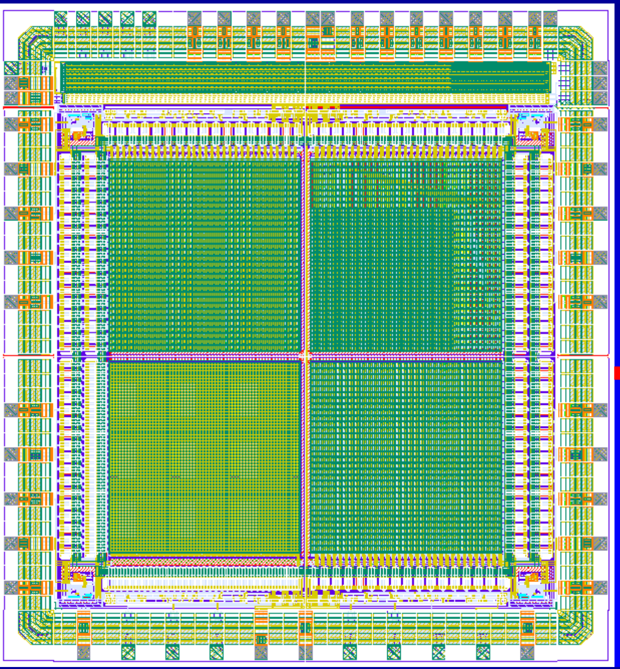
64x128 pixel
double metal matrix
(20x30µm² pixels)

Bonn, Mannheim, Munich

- Full Prototype System built, tested in the Lab and Testbeam
  Pixel size 20 x 30 μm^2, 64 x 128 pixel
- Thinning to 50 µm demonstrated
- Rad. Hardness tested to 1 Mrad (^{60}Co)
- Readout with 100 MHz, Noise tolerable
- Low Power Consumption (5W for a five Layer Detector)

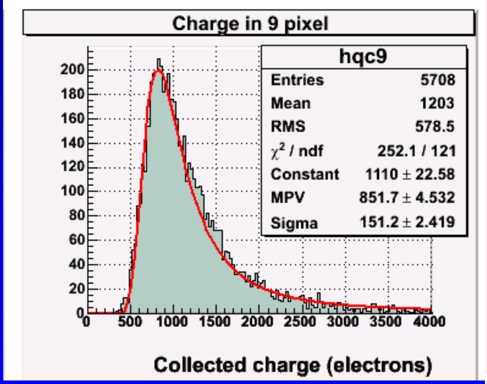
MAPS

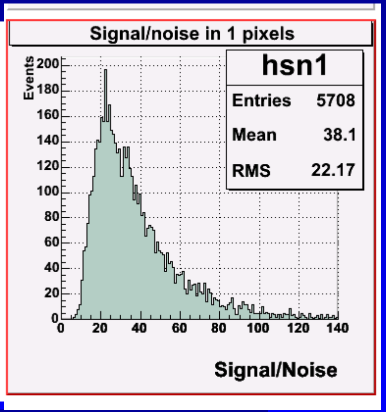
Mimosa-9 (Strasbourg)



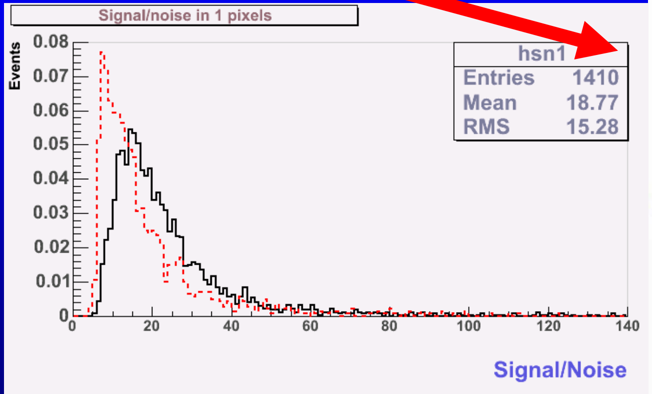
A 1 Mpixel sensor backthinned to 15 μm

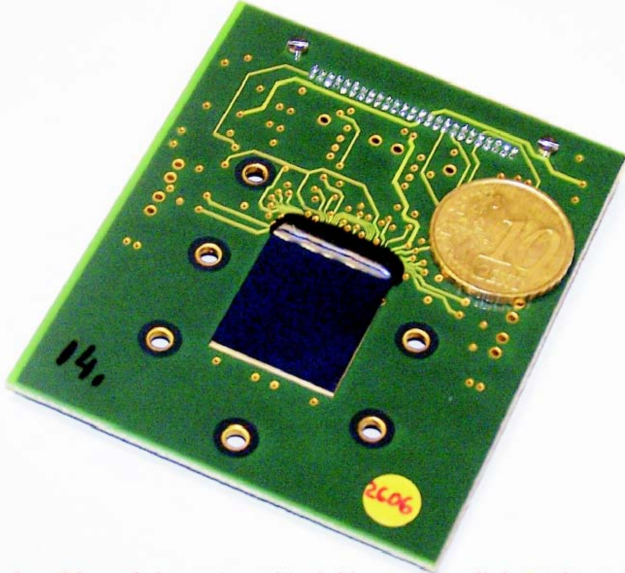
Testbeam results S/N ~ 24





- 20 μm sensitive layer
- 20, 30, 40 μm pitch



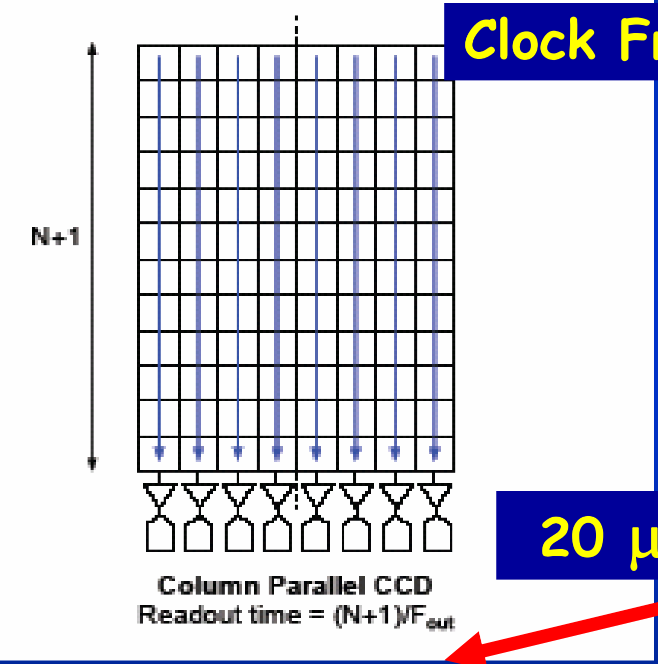


Prototype ladder in 2005 ?

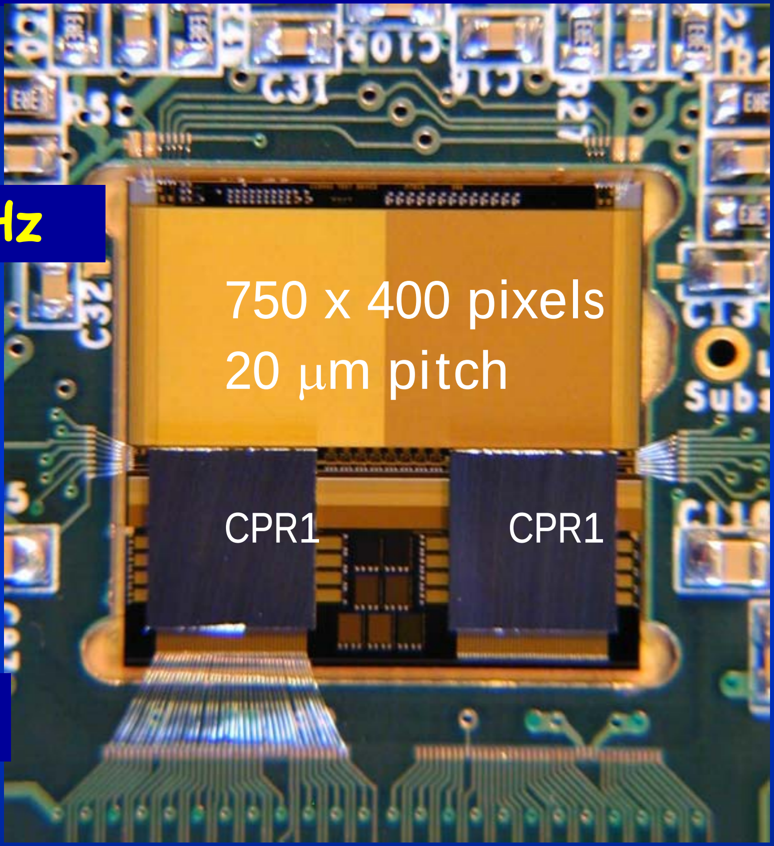
CCD

The first Column parallel sensor and readout chip is operated (LCFI-CCD Collaboration)

- **Separate amplifier and readout for each column**



Clock Frequency ~ 25 MHz



20 μm pitch possible

R&D issues:

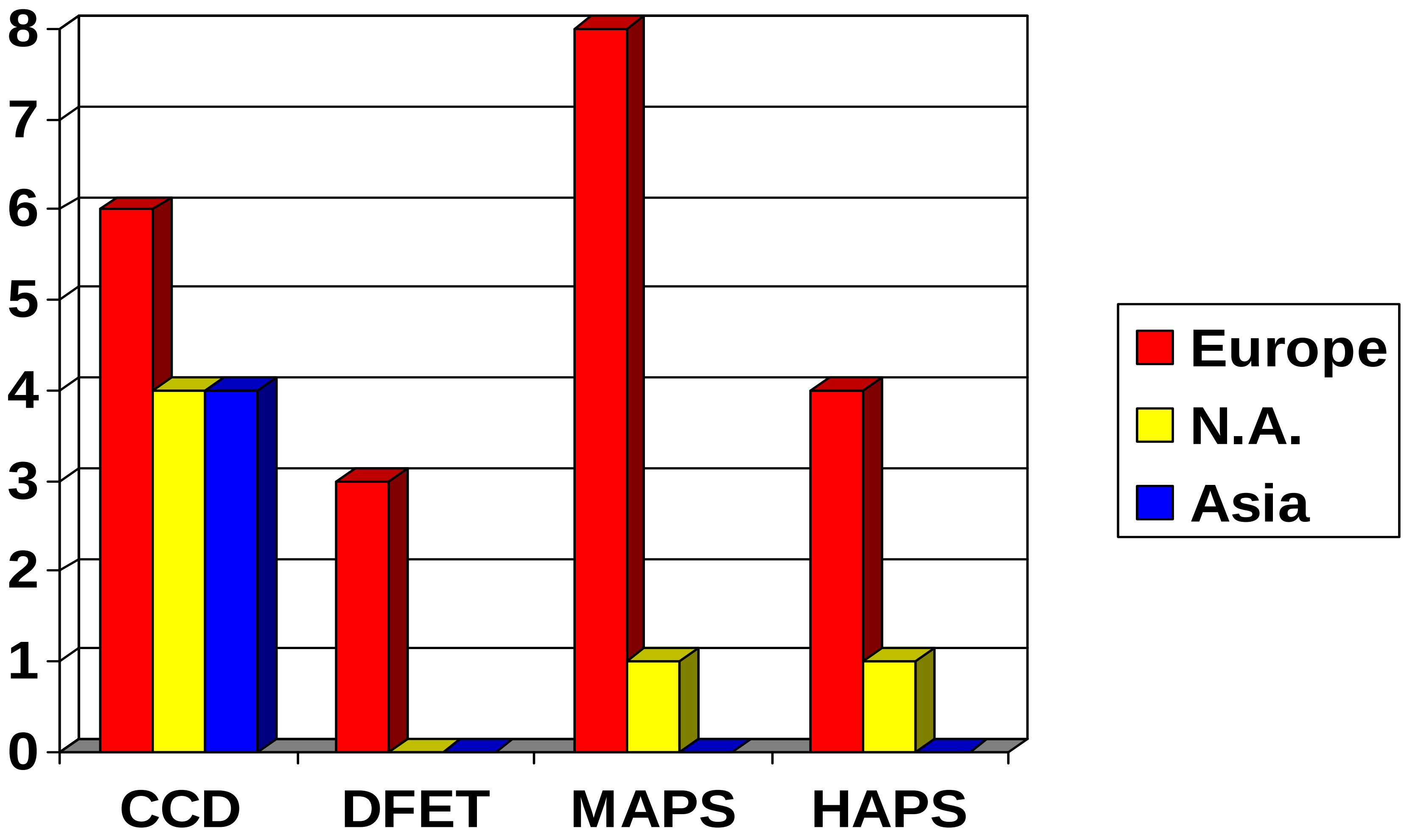
- Readout speed 50 MHz
- Full size ladders (beam test 2010)

New Technologies:

- Fine Pixel CCD (Japan)
- ISIS

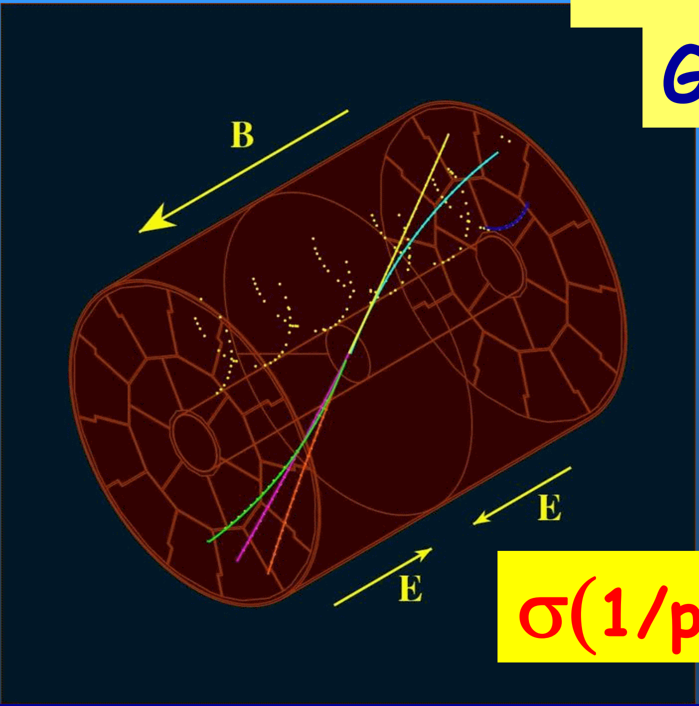
(immune against EMI)

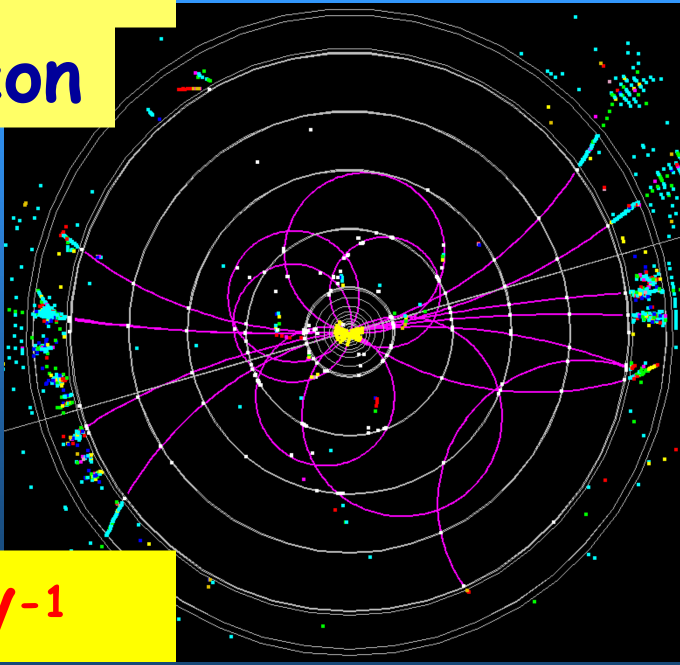
Labs involved from the three Regions



Exchange of informations between the groups
(phone meetings)

Central Tracker
Gaseous or Silicon



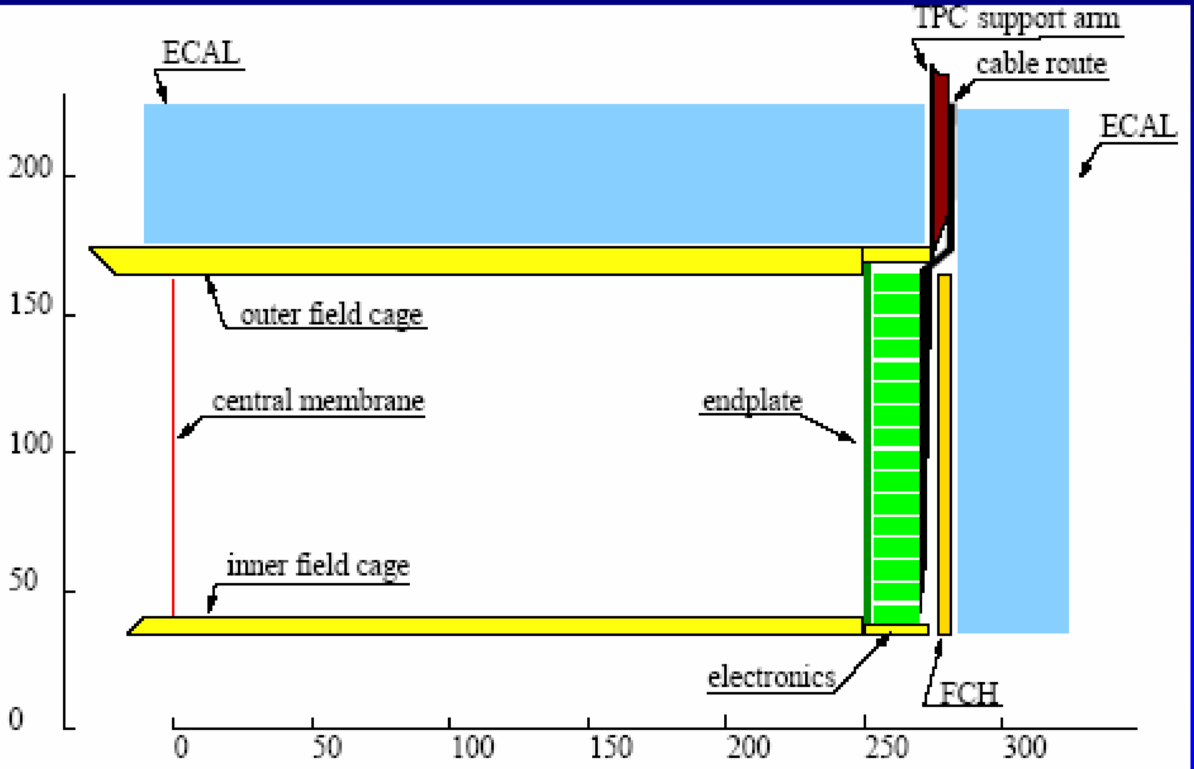


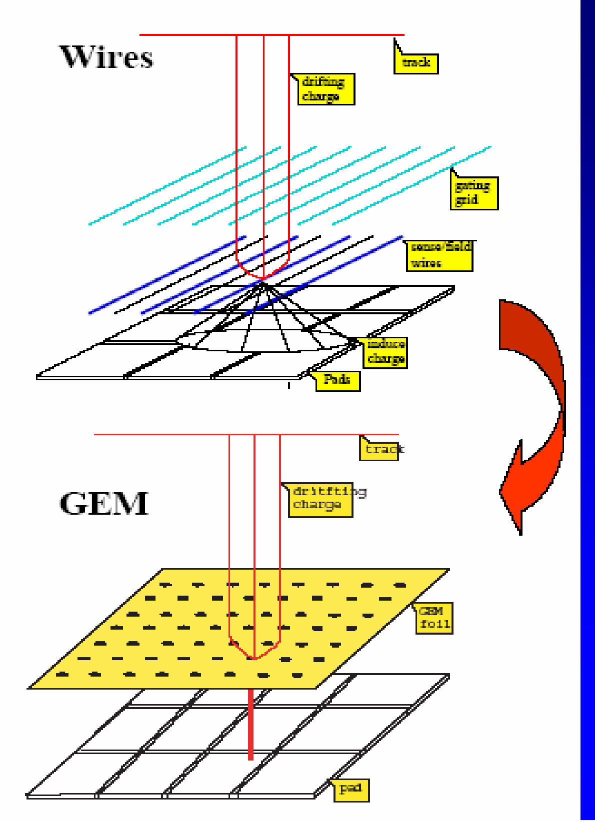
$\sigma(1/p) = 6 \times 10^{-5}\ \mathrm{GeV}^{-1}$

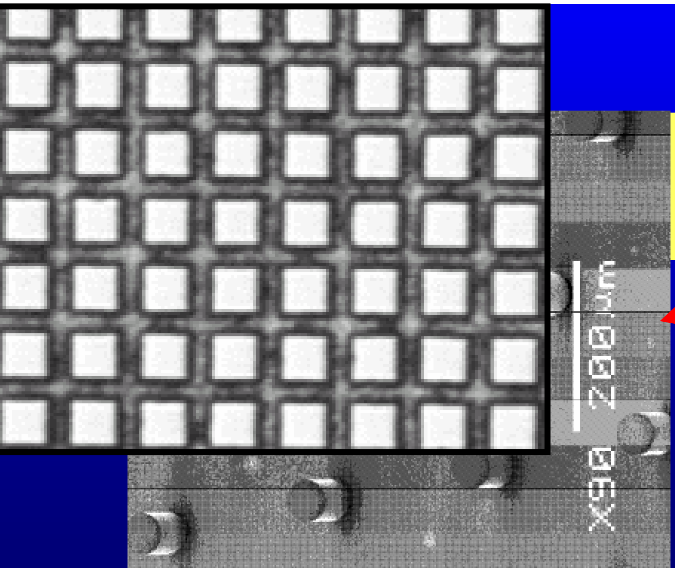
- Field Cage- homogeneous E field
- Mechanical Frame (< 3% X_0)
- Novel Gas Amplification System
- Gas Mixture
- Performance at High B –Field (100μm (Rϕ) Resolution)

- Track reconstruction efficiency
- Long Silicon Strip sensors (Barrel)
- Mechanical Support (<1% X_0 per layer
- FE Electronics (low noise, digitisation)

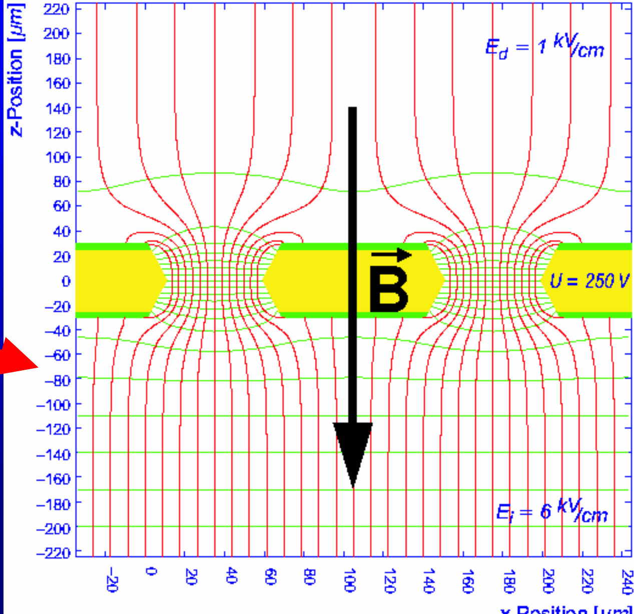
Central Tracker- TPC



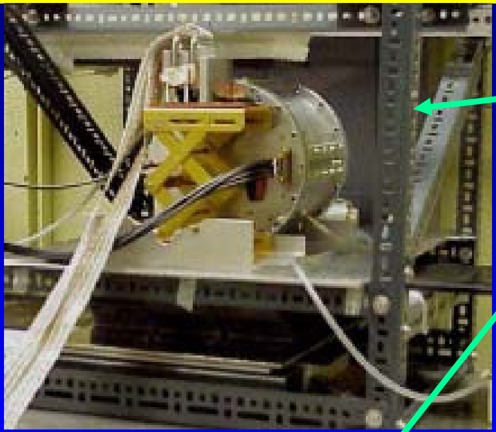




Gas amplification:
Micromegas, GEMs

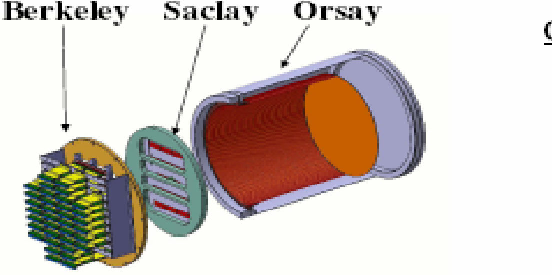


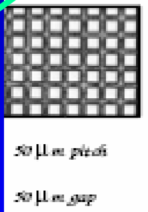
Examples of Prototype TPCs

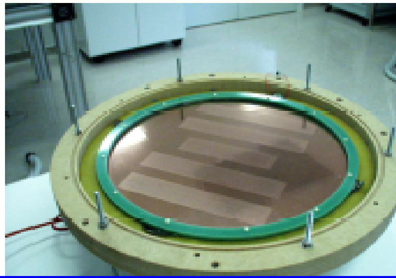


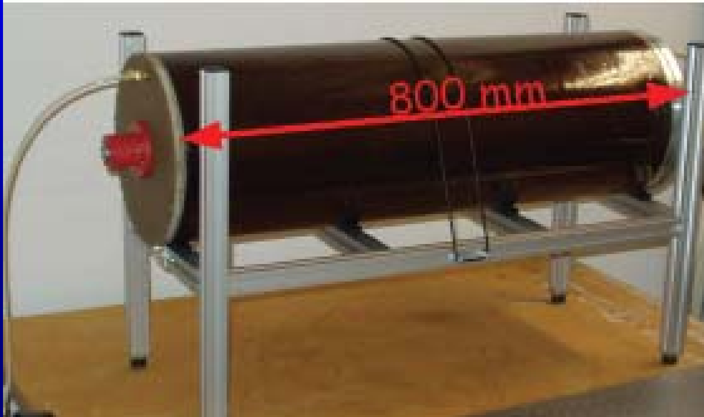
Carleton, Aachen, Desy(not shown) for B=0 studies

Desy, Victoria, Saclay (fit in 2-5T magnets)

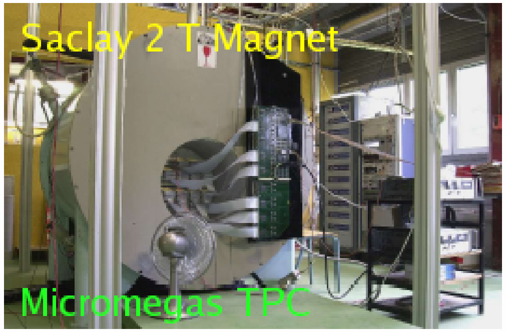




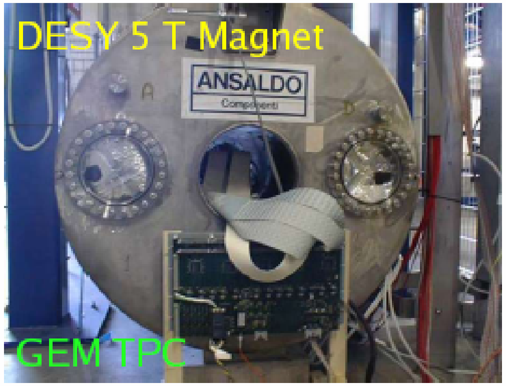




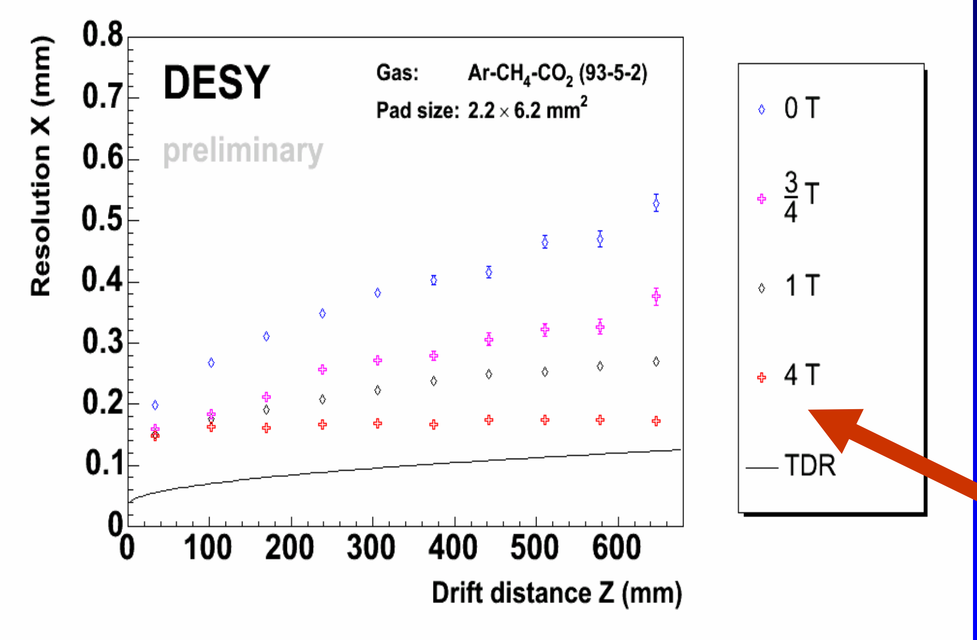
Saclay, Orsay, Berkeley

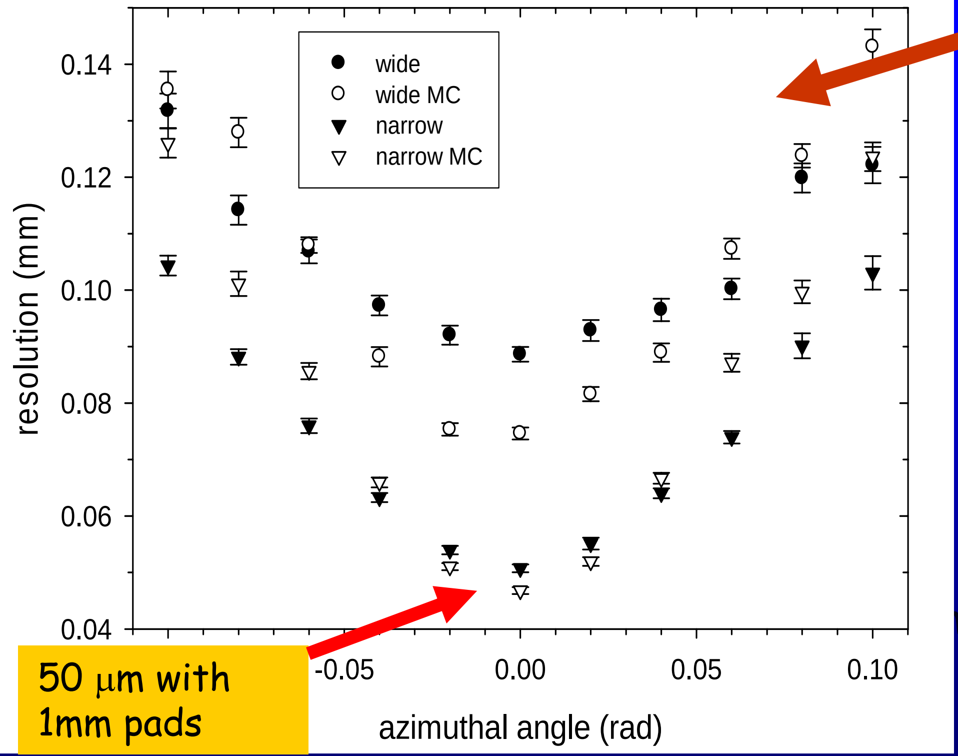


University of Victoria, DESY



Point resolution, GEM



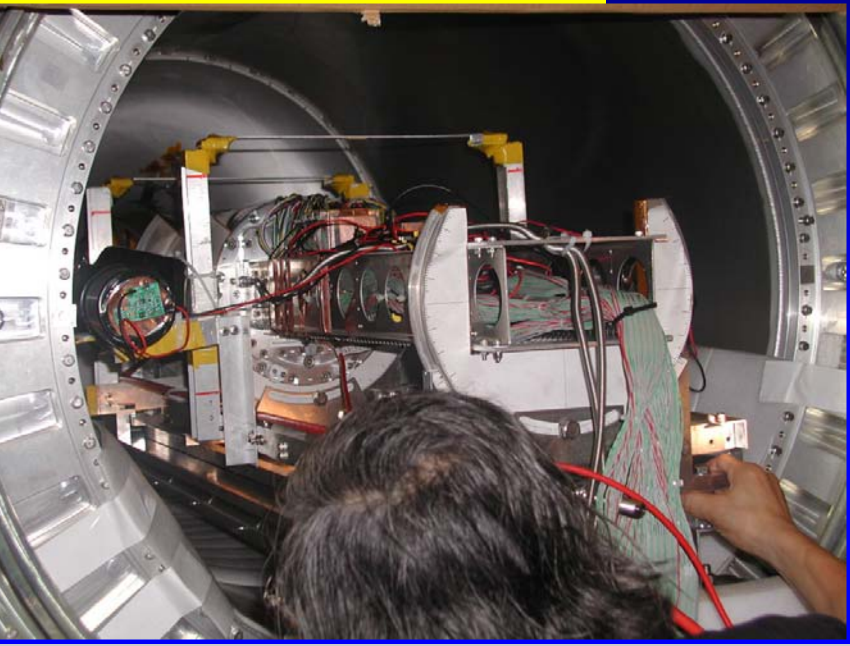


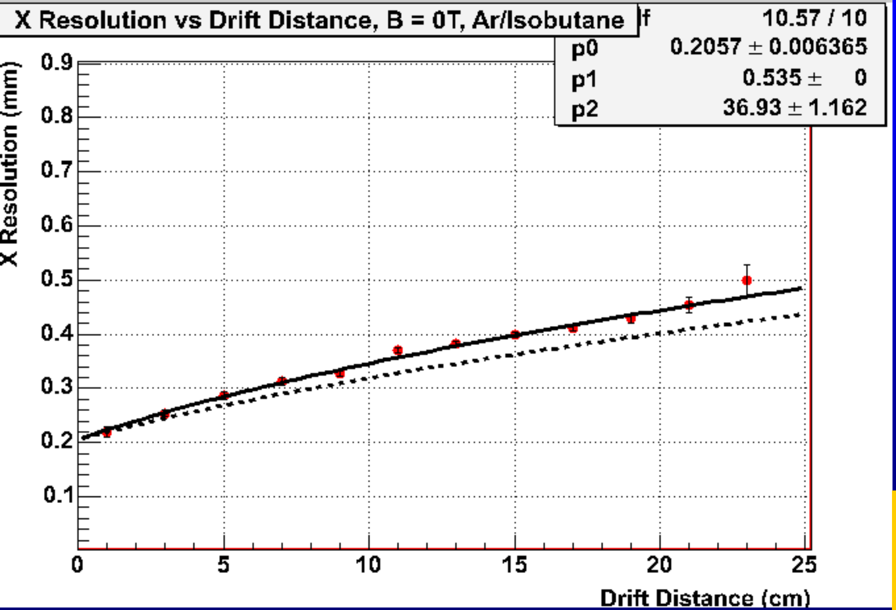
50 μm with 1mm pads

- 2x6mm^2 pads.
- In Desy chamber triple GEM is used
- In Victoria chamber a double GEM
- In general (also for Micromegas) the resolution is not as good as expected from simulations
- Point resolutions of better than 70 μm are reached both for GEMs and Micromegas.(near diffusion limit)

Beam Test @ KEK

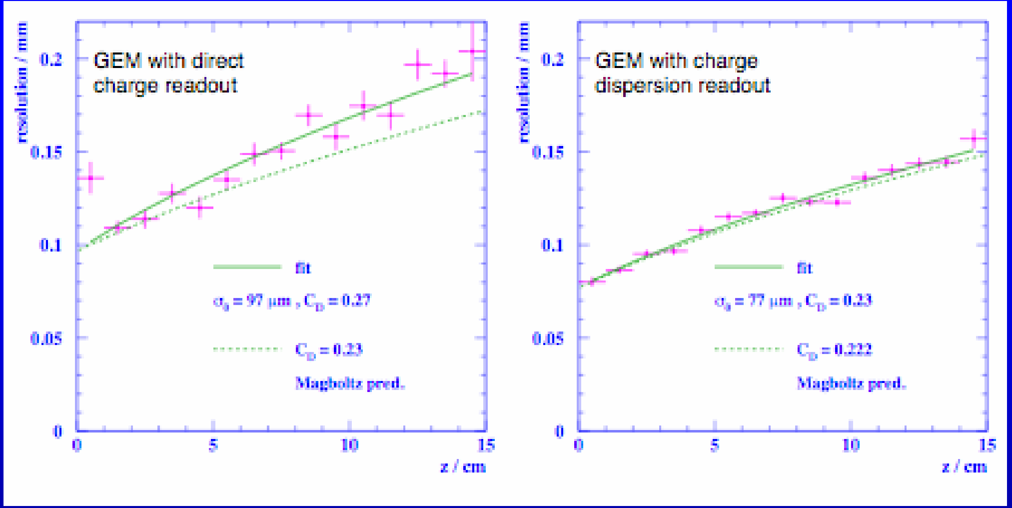
π 2 beam line





Comparison of the different gas amplification techniques with the same field cage (munich TPC)

Effect of charge spread using resistive foil (important at large B)



V_{drift} (Ar+5%iso) = 4.181 +- 0.034 cm/μs
Magboltz simul. : 4.173 +- 0.016

TPC, status and next steps:

- A large international Community is engaged in TPC R&D
- Both GEMs and MICROMEGAS seem to work
- Construction of a 'Large Prototype'
- Full System Test with the 'Large Prototype' in a beam

A Collection of ongoing R&D topics:

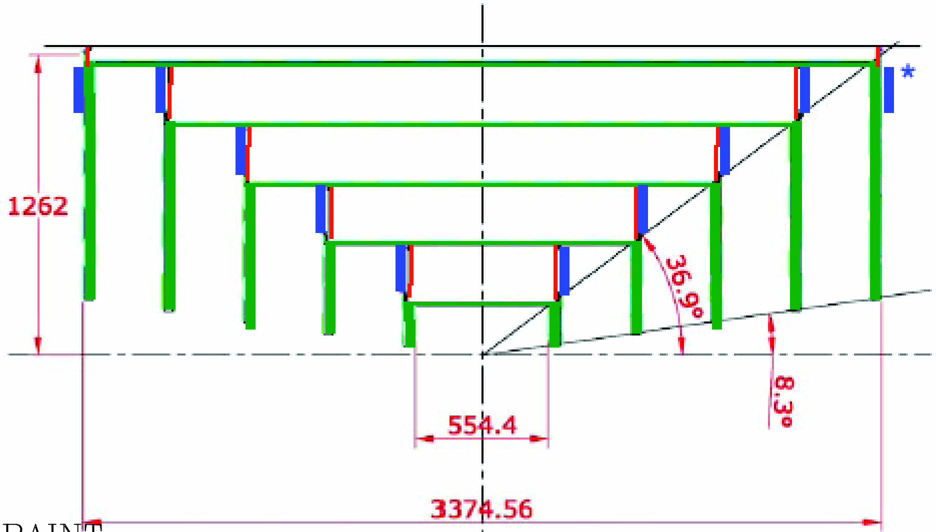
- Choice of gas mixture (Diffusion, D-velocity)
- Ion feedback

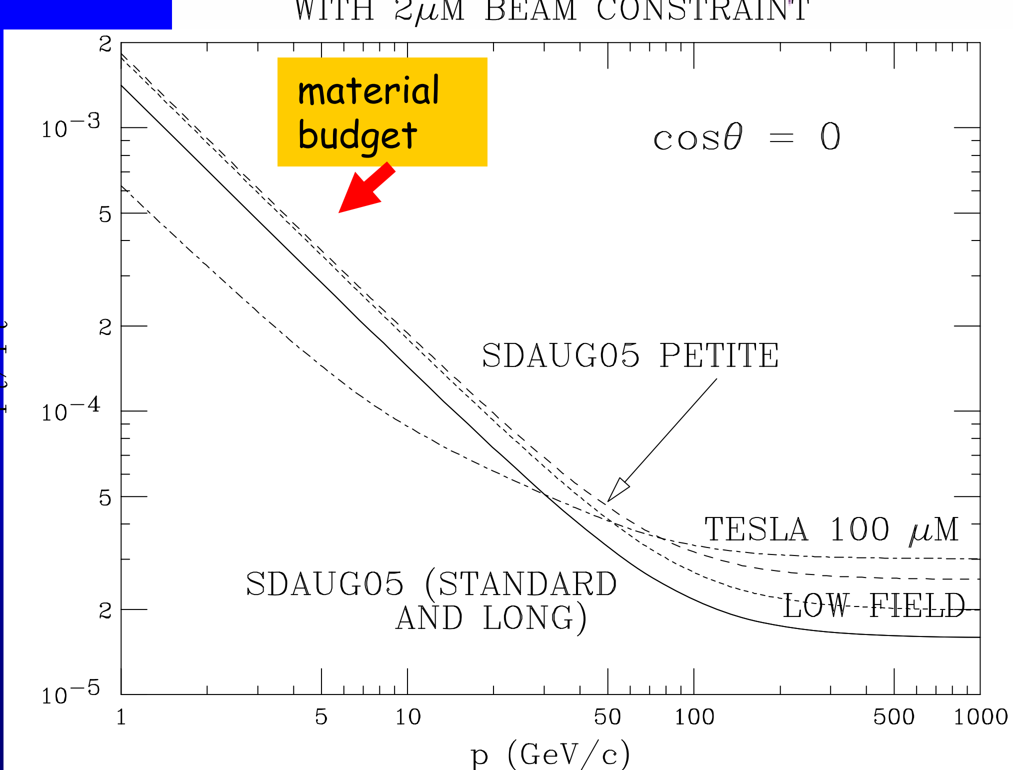
- Readout electronics (pad density)
- Magnetic field homogeneity

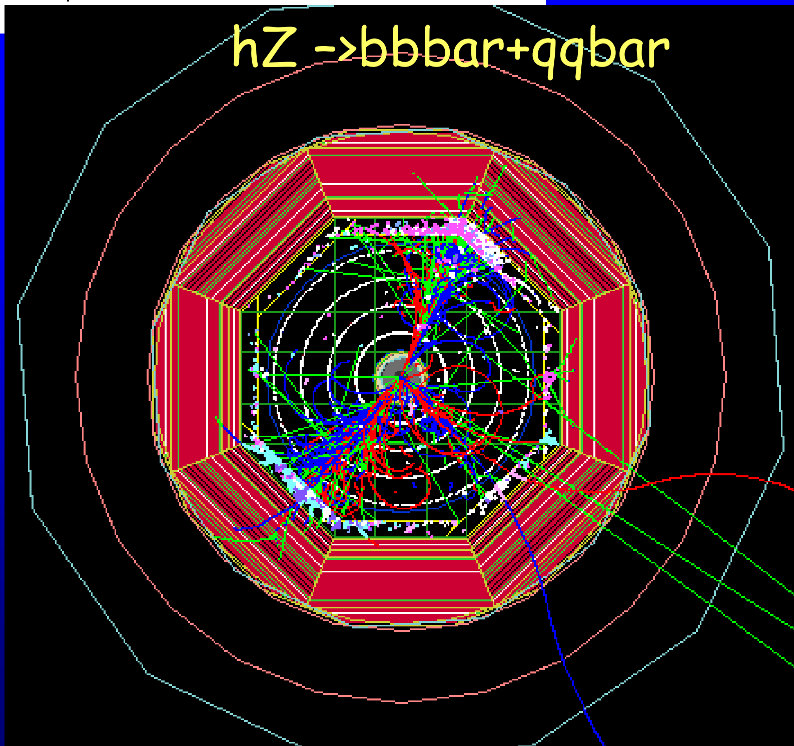
Copyright 1998 Frantisek Staud

Central Tracker - SID/SiLC

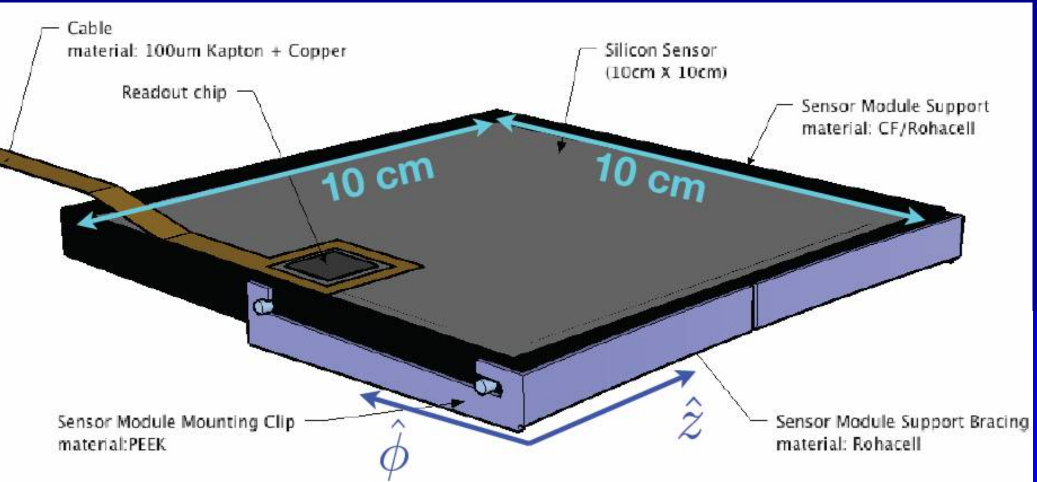
- Closed CF/Rohacell composite cylinders
- Nested support via annular CF rings
- Power/readout distribution mounted on support rings*



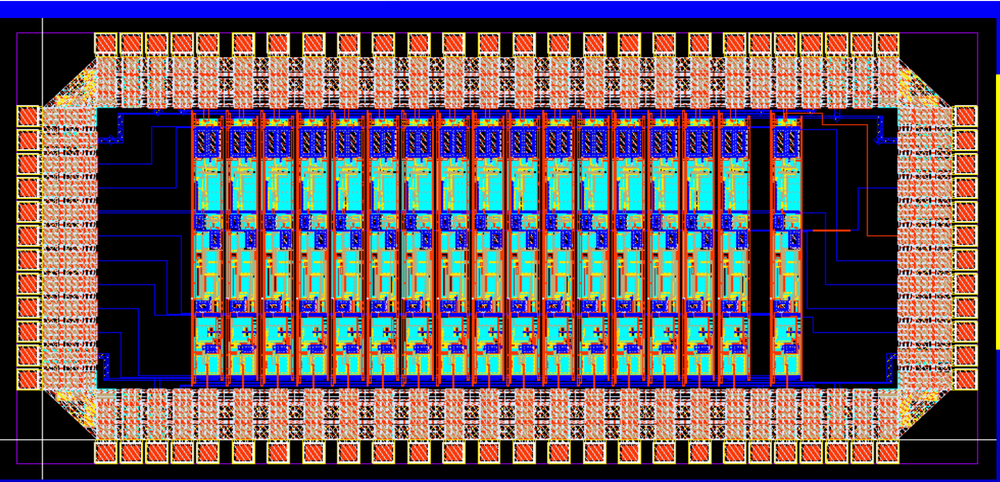

material budget


hZ ->bbbar+qqbar

SID/SiLC



A tile containing Si-strip sensors forming the cylindrical detector layers
Readout by one ASIC (under development



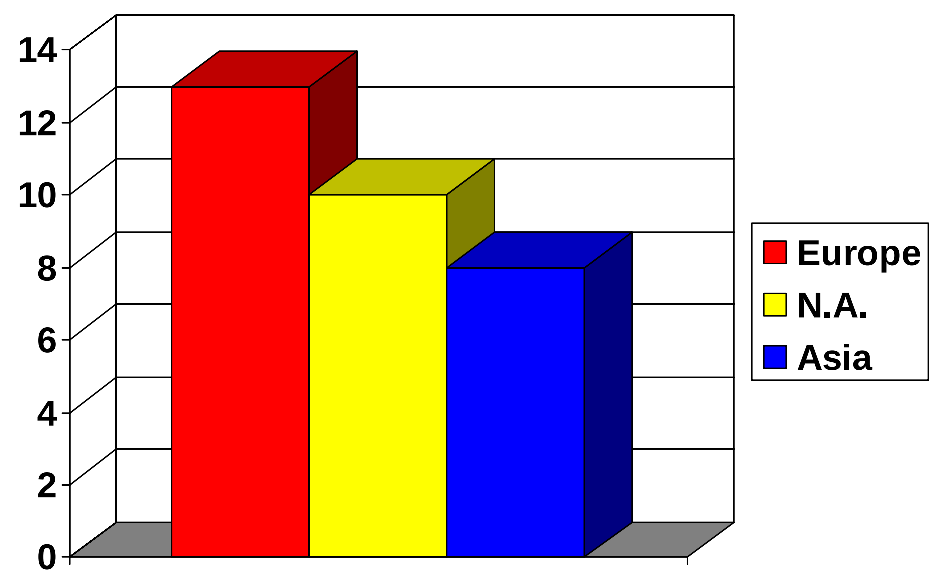
FE readout chip prototype for Long ‘ladders’ (.18μm UMC)
16 channel pream, shaper. ADC)
Lab. Tests are promising

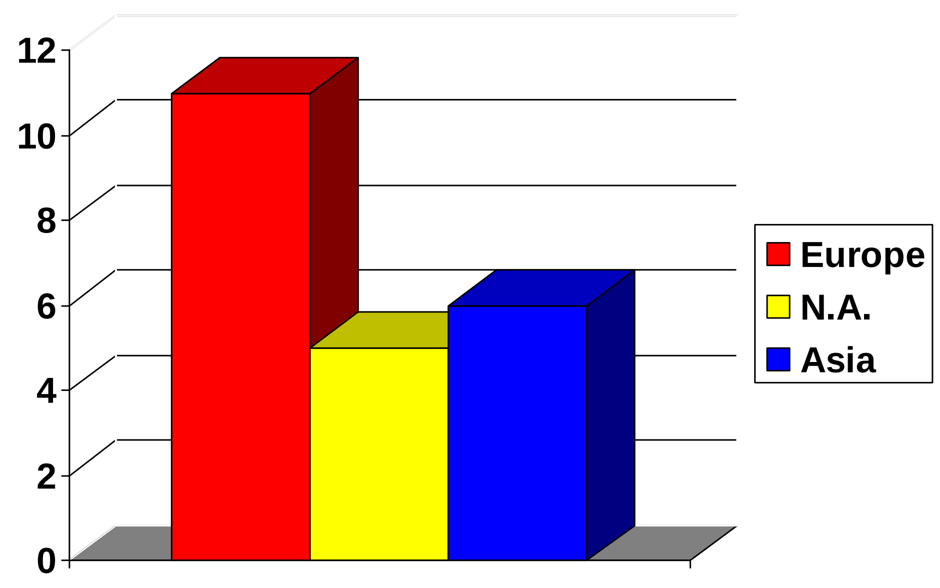
SiLC plans testbeam measurements with a prototype ladder in the fall of 2006

Labs involved from the three Regions

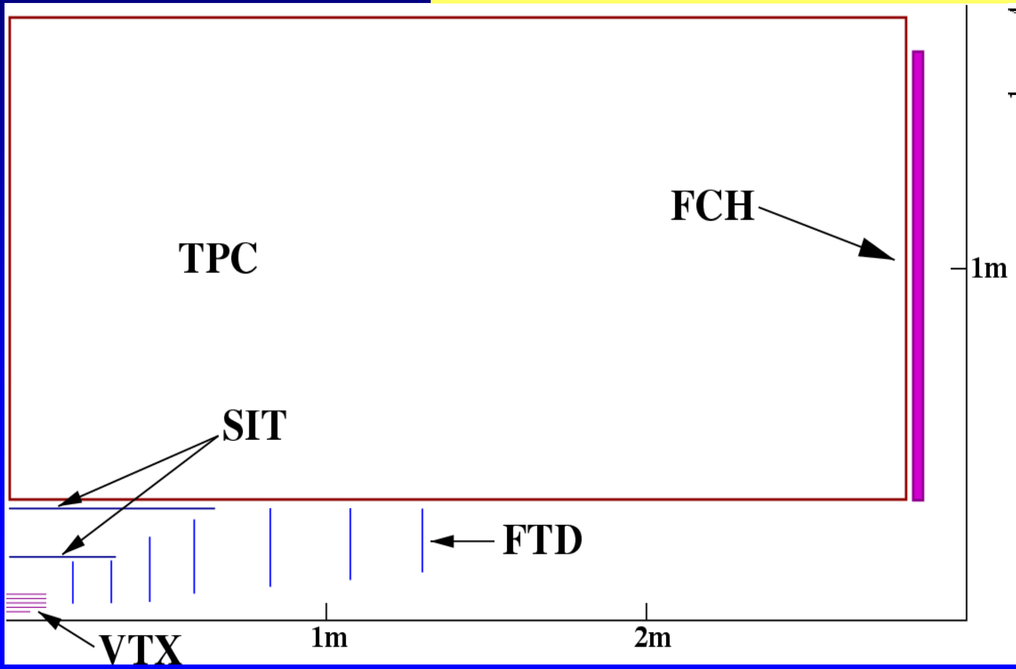
TPC

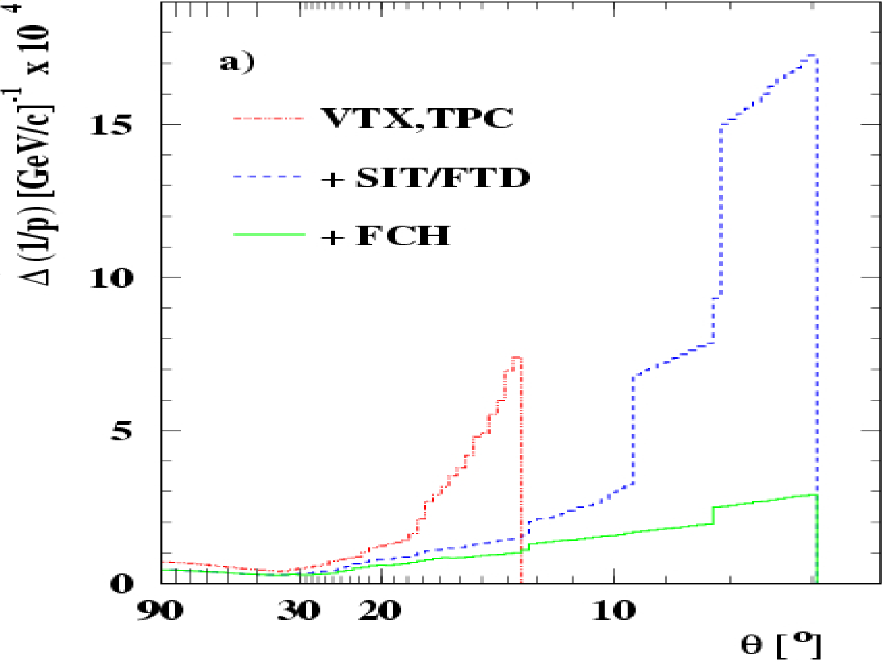
SID/SiLC





FORWARD TRACKING

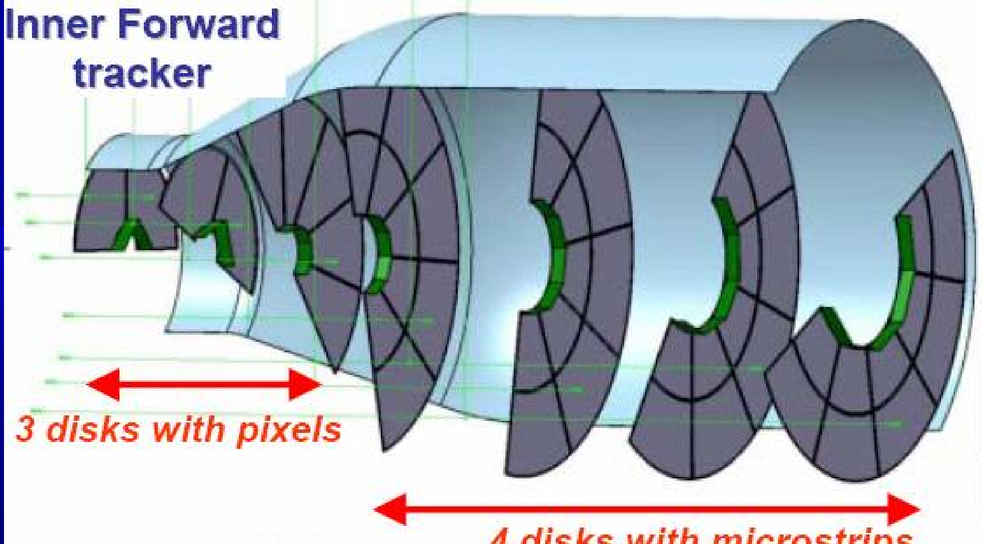




- SIT: Silicon strips
- FTD: Silicon disks
- FTC: Straw tubes, GEMs

Design studies in DESY/JINR

SiLC proposal for FTD



Calorimetry

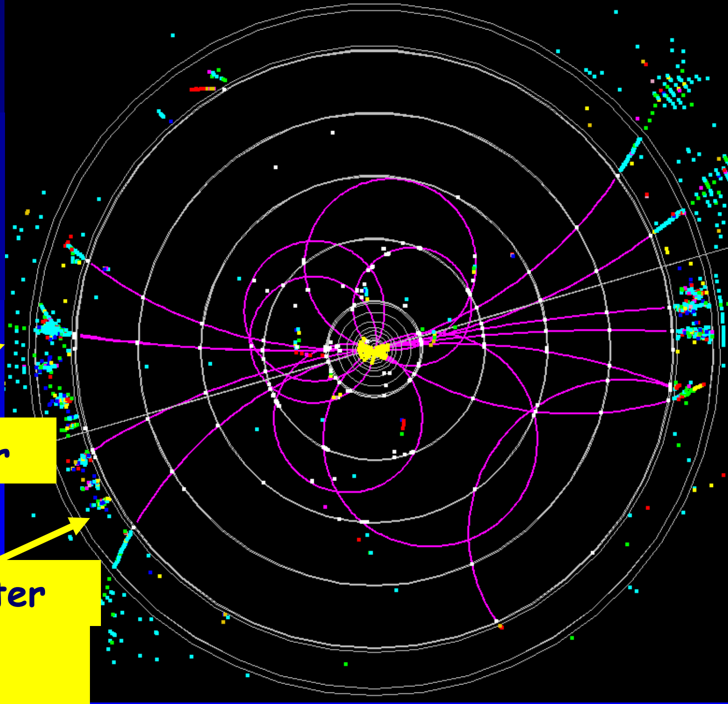
'Particle' flow concept requires to identify showers of individual particles in a jet

Separation of 'neutral' and 'charged' depositions

Charged particles in a jet are most precisely measured in the tracker

Summing up the the energy:

measurement from tracking (charged), ECAL and HCAL (neutrals) :

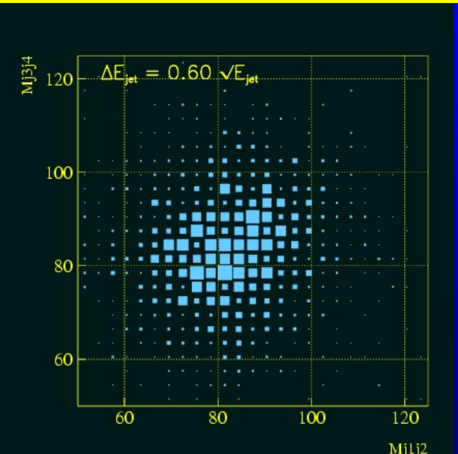


Charged cluster

Neutral cluster

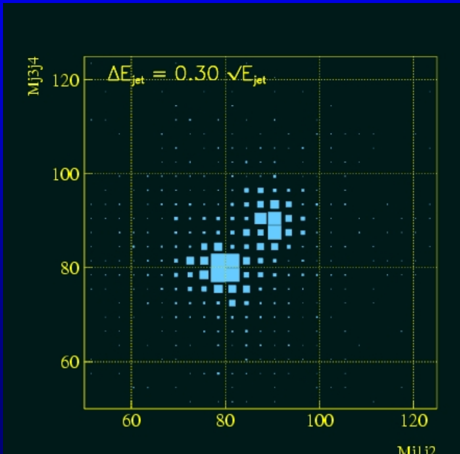
Granularity (longitudinal and transversal)
(1x1 cm^2)
Compactness (small X_0, R_M)
Mip detection (charged particle tracking)
Photon direction measurement ('imaging')

Δ E /E = 30%/ sqrt(E) for jets!



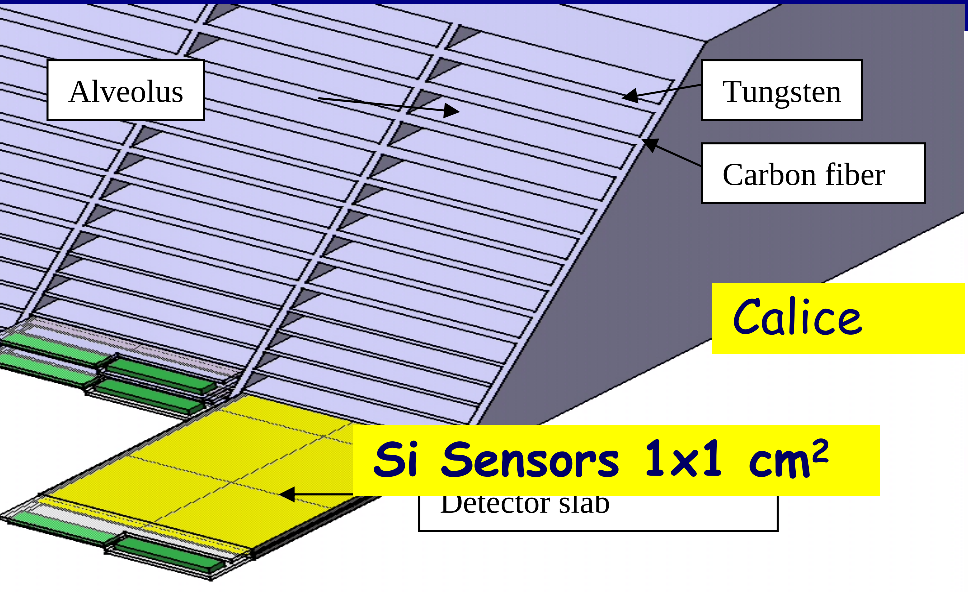
60%/√E

30%/√E



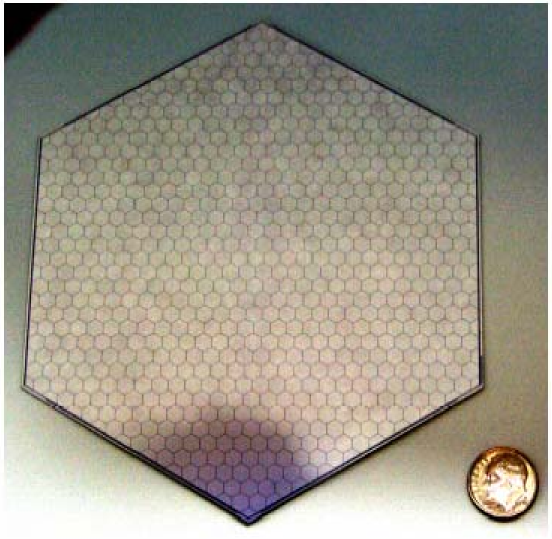
Crucial for separation of WW and ZZ final states

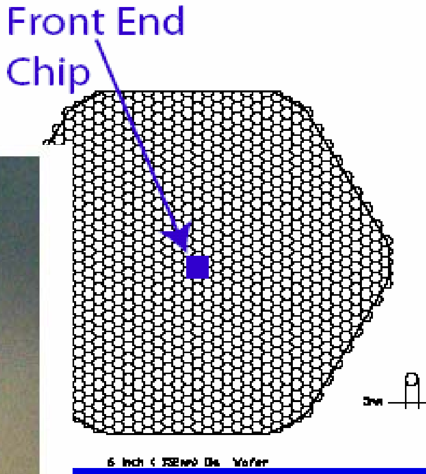
ECAL Si/W Technology



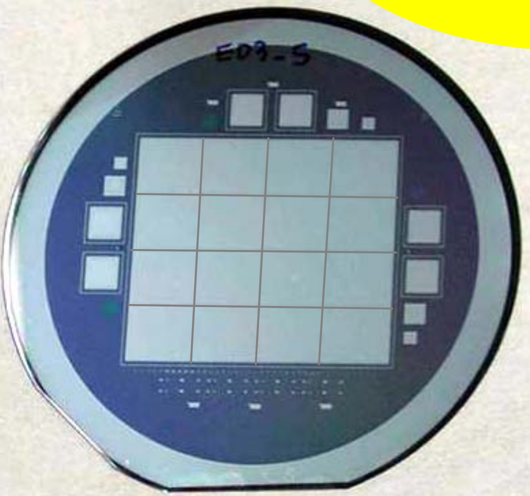
Calice

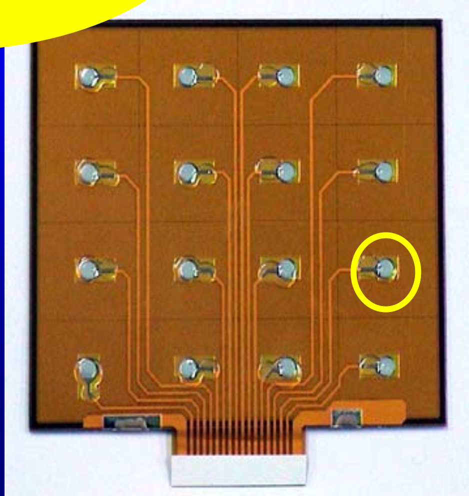
Si Sensors 1x1 cm^2





5 inch waver manufactred in Korea



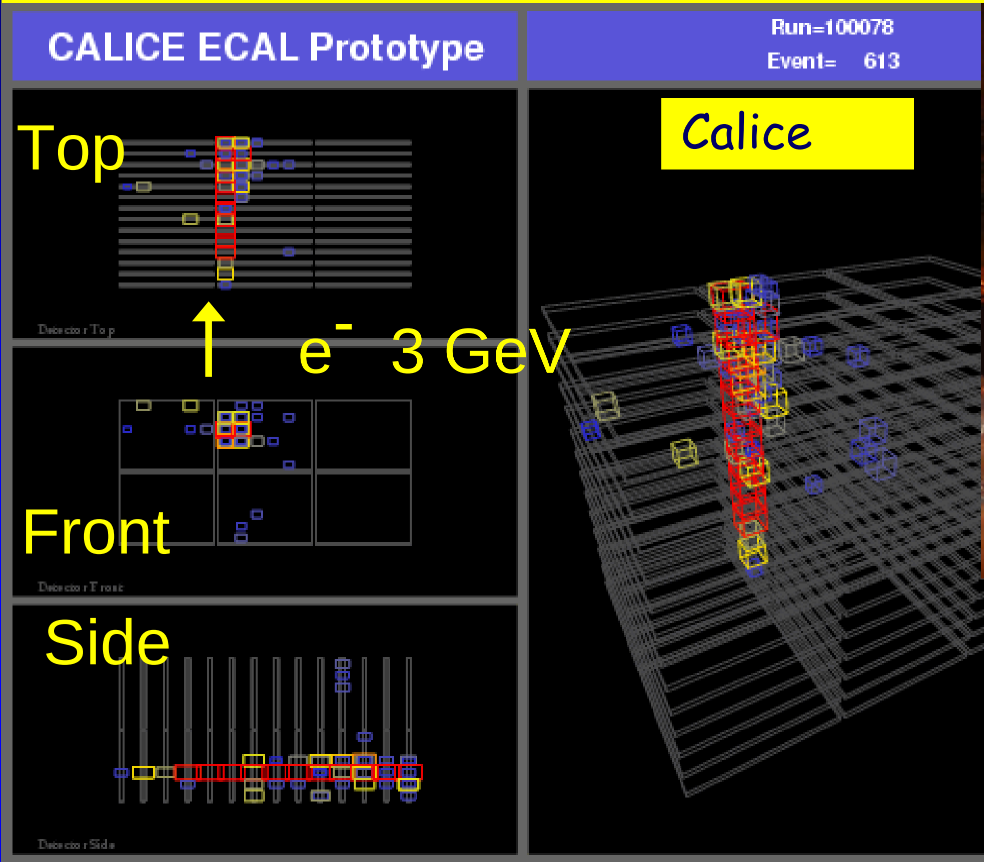


6 inch waver manufactred in US

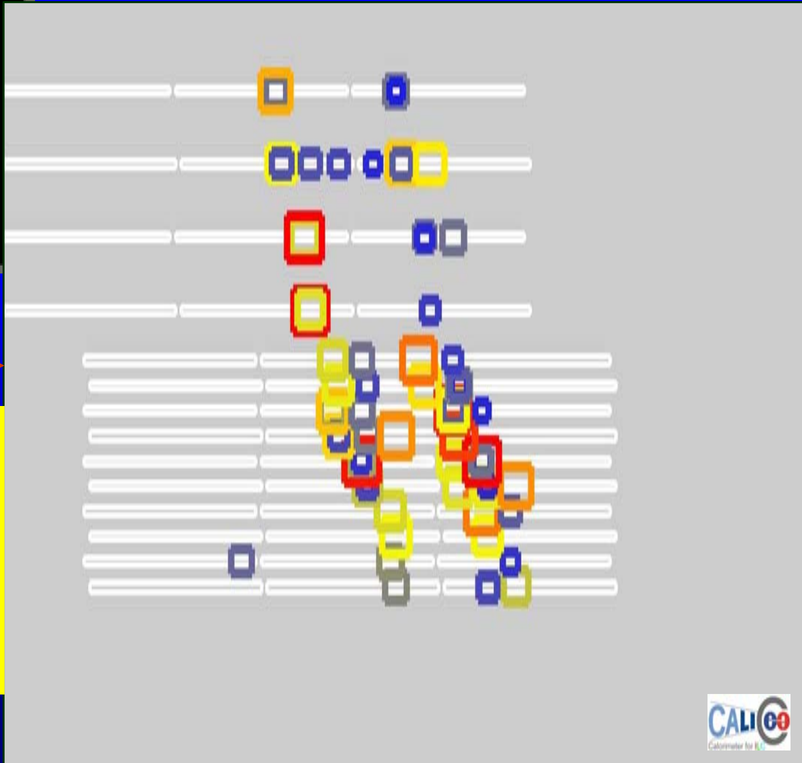
BNL/SLAC/Oregon

- 5 mm pads (1/2 R_M)
- Each 6 inch waver is readout by one chip
- Electronics under way
- Test beam in 2005

Testbeam measurements: DESY, CERN



Univs. From Korea

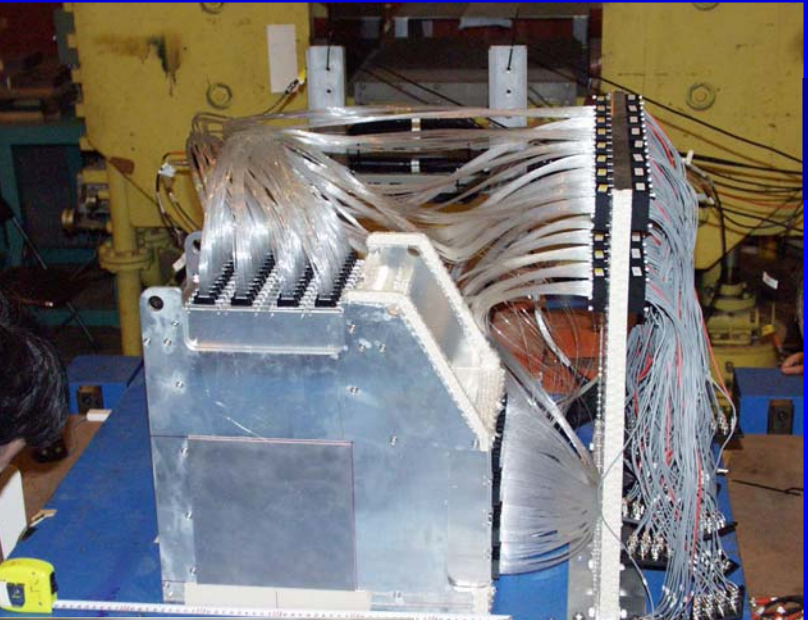


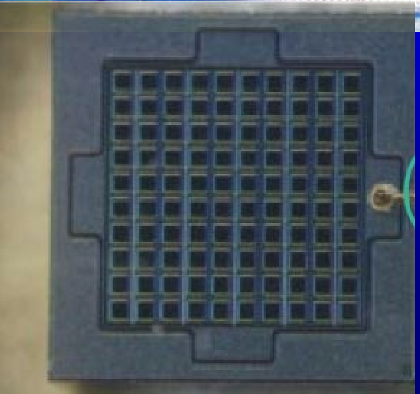
First real test versus the Particle Flow Algorithm, two electrons close together

ECAL Other Technologies

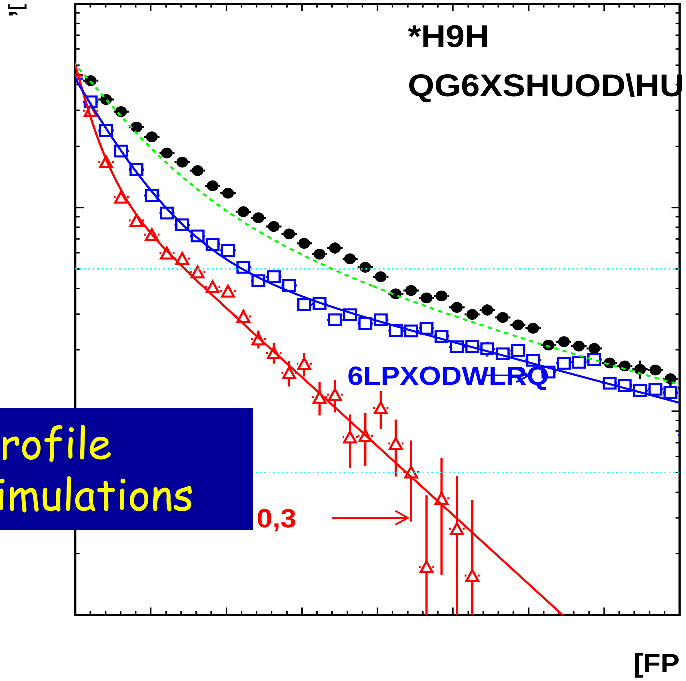
Hi granularity Scintillator (1x1 cm^2)

Scintillator Strip/WLS Testbeam

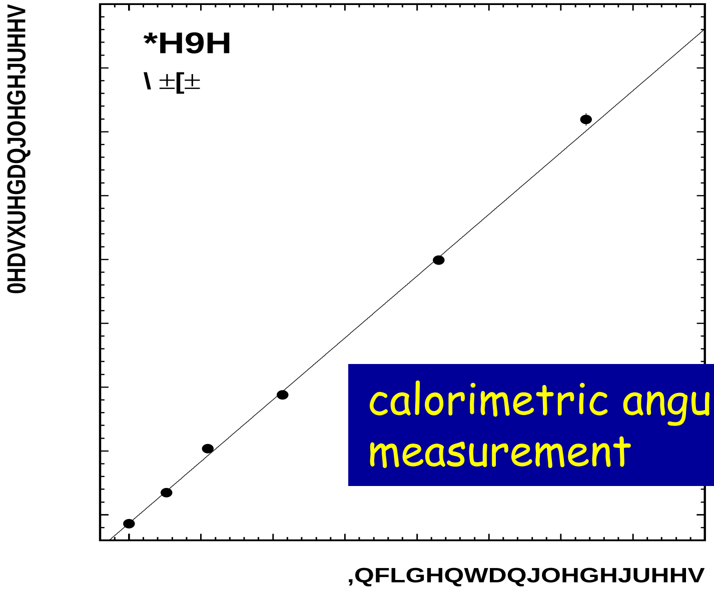




SiPM from Hammatsu, to be used for the readout of Scintillator blocks



Lateral shower profile measurements/simulations

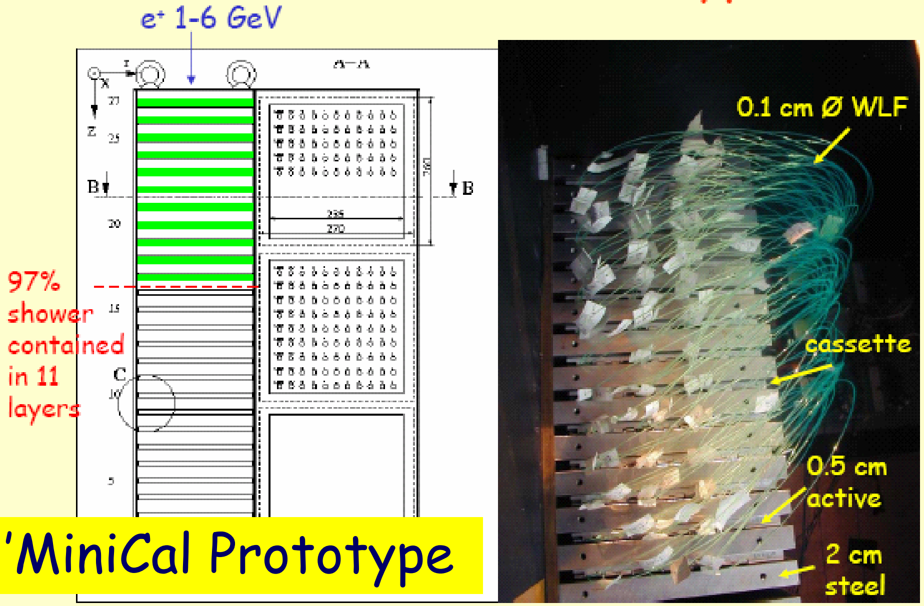


calorimetric angular measurement

HCAL – Analog or Digital

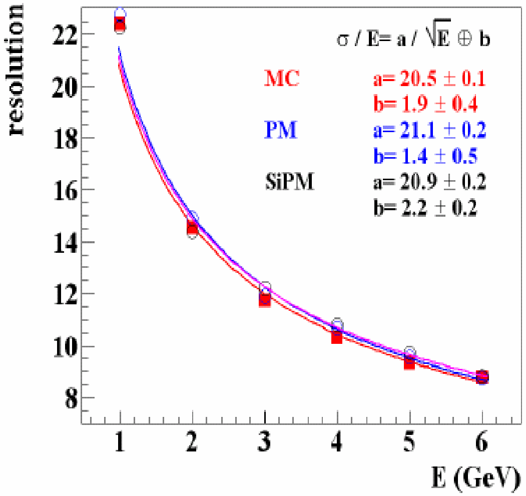
Analog: Steel-Scintillator Sandwich
with SiPM readout

Sensors:
Large area tile layers equipped with WLS fibres and SiPMs



'MiniCal Prototype

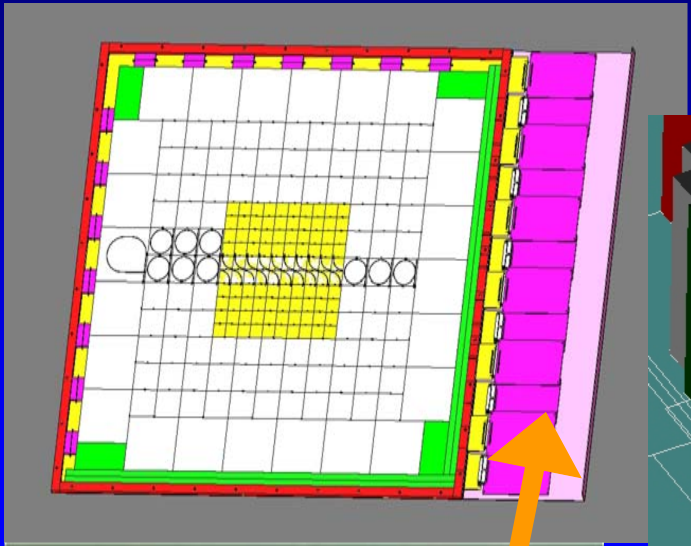
PM and SiPM Resolution



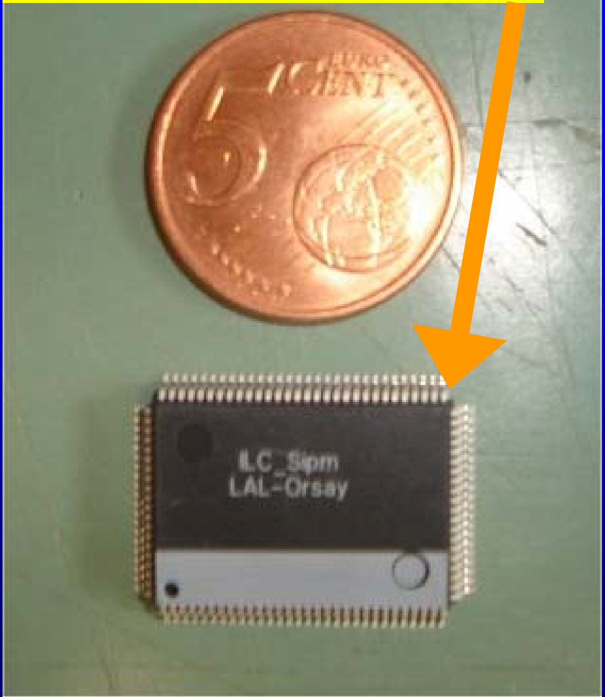
Analysis of SiPM and PM already presented.

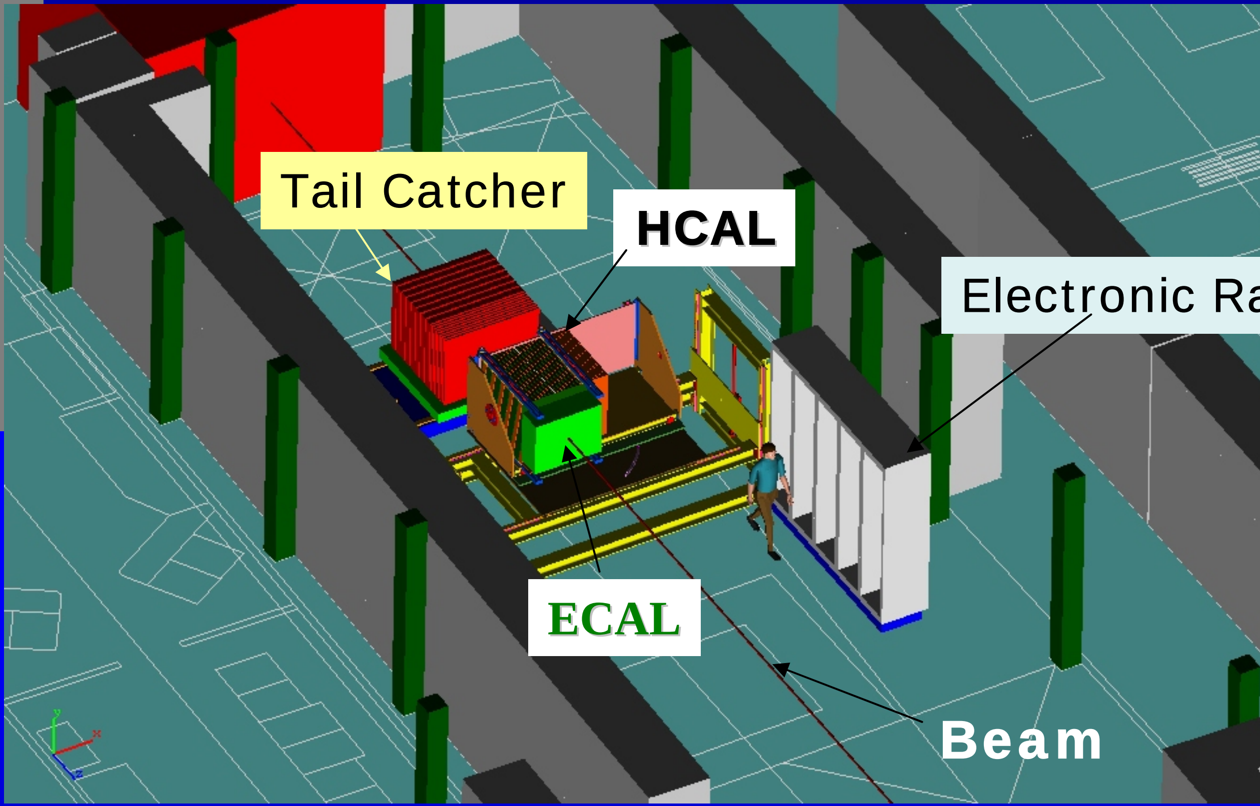
MC fits data within 5% level

1 m^3 Tile HCAL prototype



Readout Elecronics



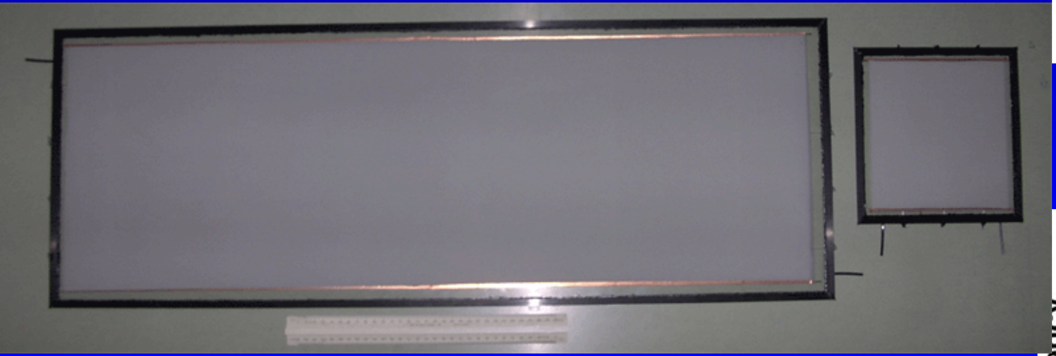


Commissioning at DESY in 2005,
Hadron test beam 2006/7 (CERN, FNAL)

HCAL – Analog or Digital

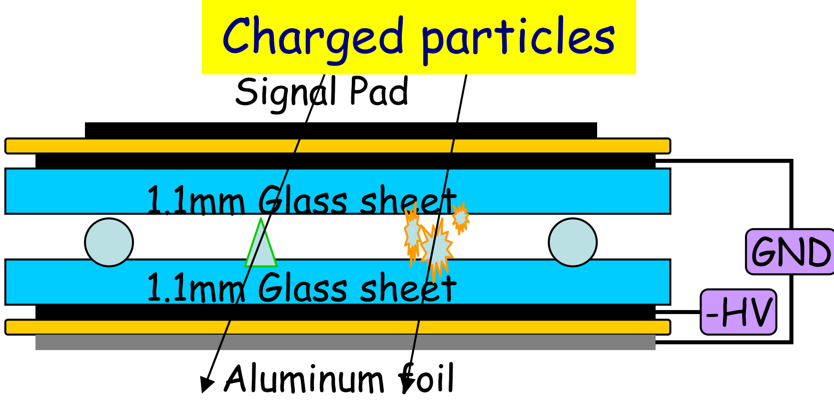
Digital Cal, RPC as sensor, pad readout

Example: ANL

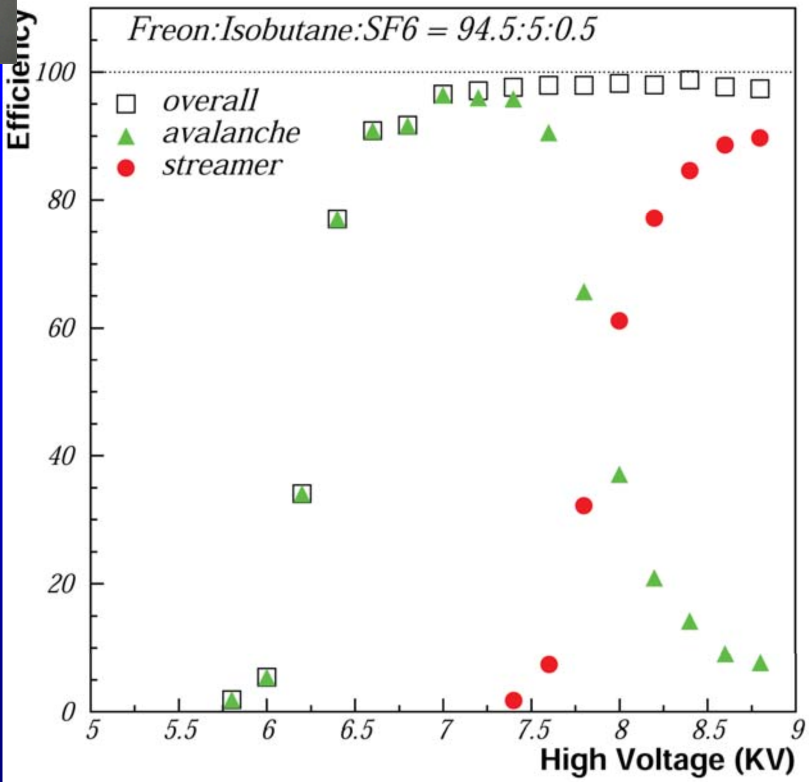


- About 10 RPC prototypes of different design built
- Multichannel digital readout system
- Large Size RPCs with exellent performance
- Ready to built RPCs for a 1 m^3 prototype cal (2007)

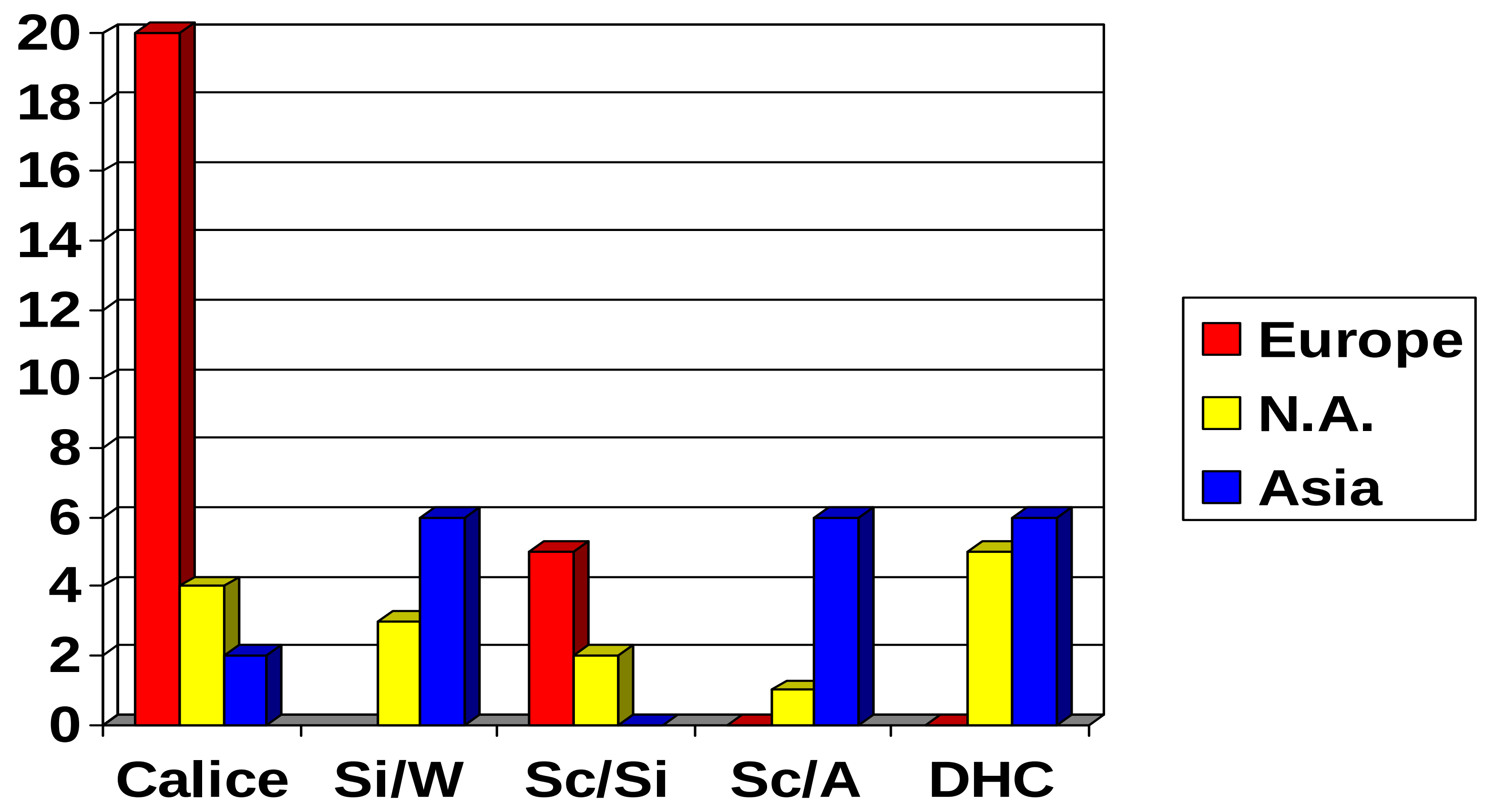
Alternative technology: GEM as sensor, pad readout



Size: 30x100 cm^2



Labs involved from the three Regions



- CALICE includes institutes from all regions
- N.A. groups and CALICE plan a joint testbeam program at FNAL

Status in R&D

The nice things:

- Lots of activities in all subdetectors
- Simulations to optimise the design of all components are ongoing
- Mechanics design studies under way
- Readout concepts are designed and under test
- Testbeam studies are done for many sensors, but not yet all
- A few prototype detectors started studies with testbeams

Status in R&D

The challenges left:

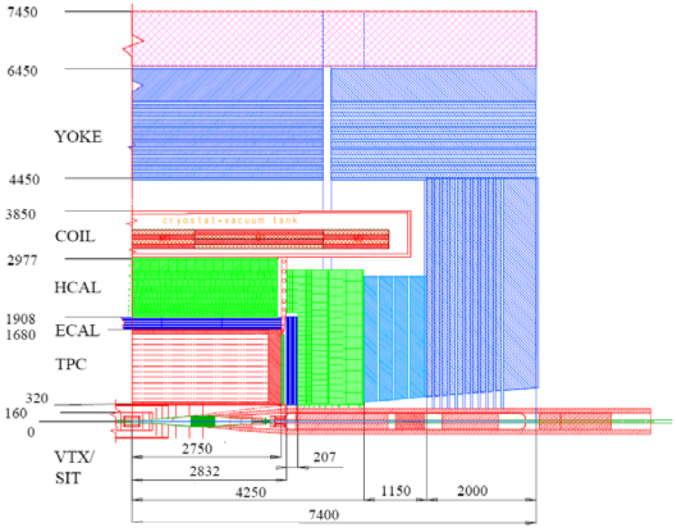
- There are essential parameters to be better understood
- Testbeam studies must be extended to all sensor types
- Testbeam studies for prototypes of all subdetectors are the Major Topic for the next years-
  the only way of proof of the performance goals
- Testbeam results are input for refined simulations-
  improved designs or redesigns
- Prototypes and testbeams need a new level of funding
- I am sure I forgot something

Detector Concepts

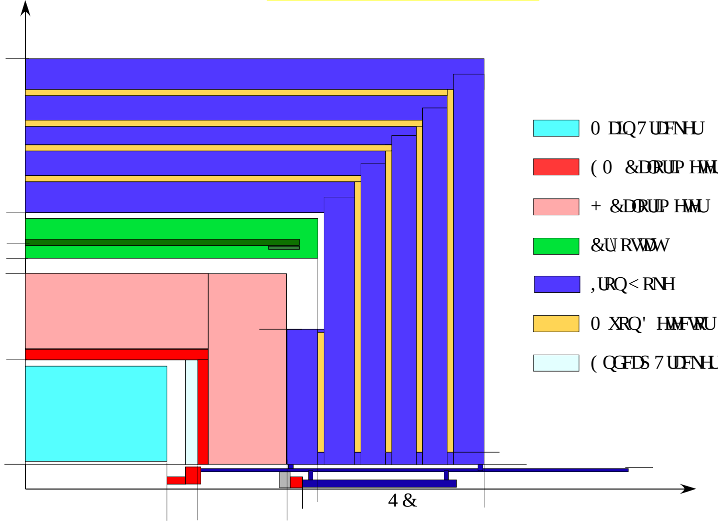
LDC

B = 4 T

L_{tr} = 1.6 m



GLD



B = 3 T

L_{tr} = 2 m

SiD

B = 5 T

L_{tr} = 1.2 m

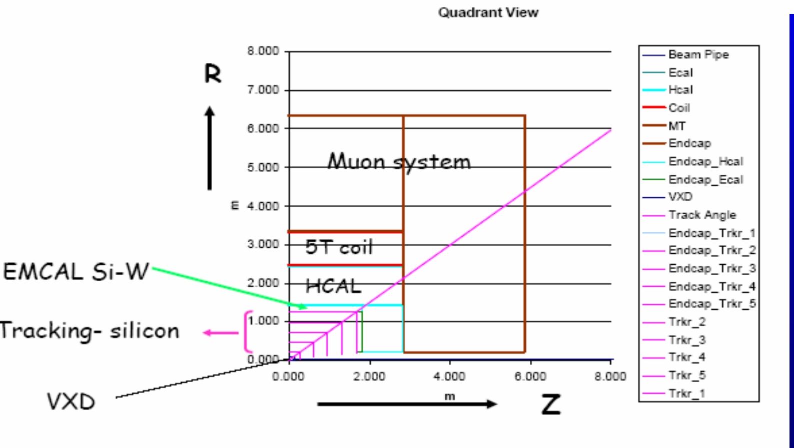


Figure of merit:

$$\frac{BL_{tr}^{2}}{\sqrt{\sigma^{2}+R_{M}^{2}}}$$

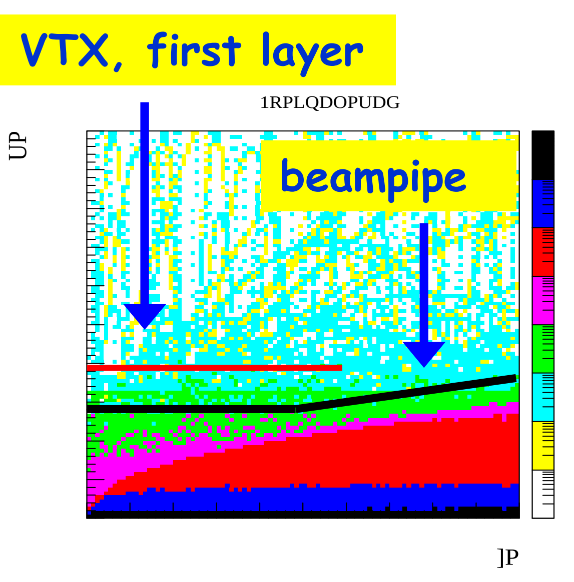
R_M: Moliere Radius
e.g. Si/W: 1 cm
Scint./W: 1.8 cm
Scint./Pb: 2.5 cm

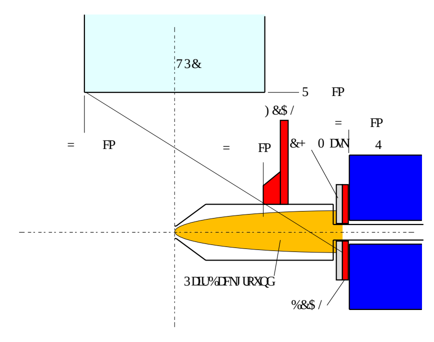
σ: cell size in the calorimeter (usually cm^2)

However: Large L_{tr} - large Calorimeter radius R_{cal}
- costs ~ R_{cal}^2

SiD concept: small L_{tr}, compensate by boost of B

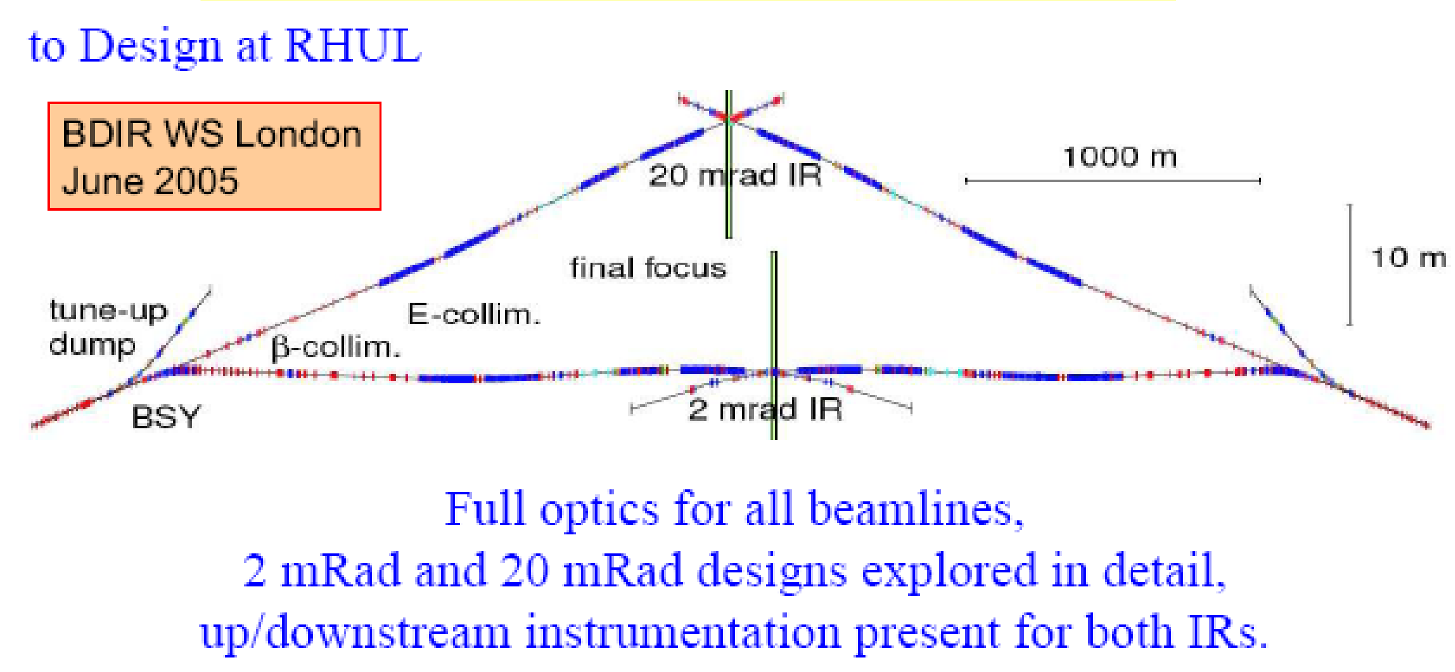
Beam-beam interaction may favour large B:





Beamstrahlung remnants are squeezed to smaller radius
→ smaller beampipe

Interaction Region



to Design at RHUL

BDIR WS London
June 2005

Full optics for all beamlines,
2 mRad and 20 mRad designs explored in detail,
up/downstream instrumentation present for both IRs.

Two Detectors, because:

- Confirmation and redundancy
- Complementary Collider options
- Competition
- Efficiency, reliability
- Historical lessons

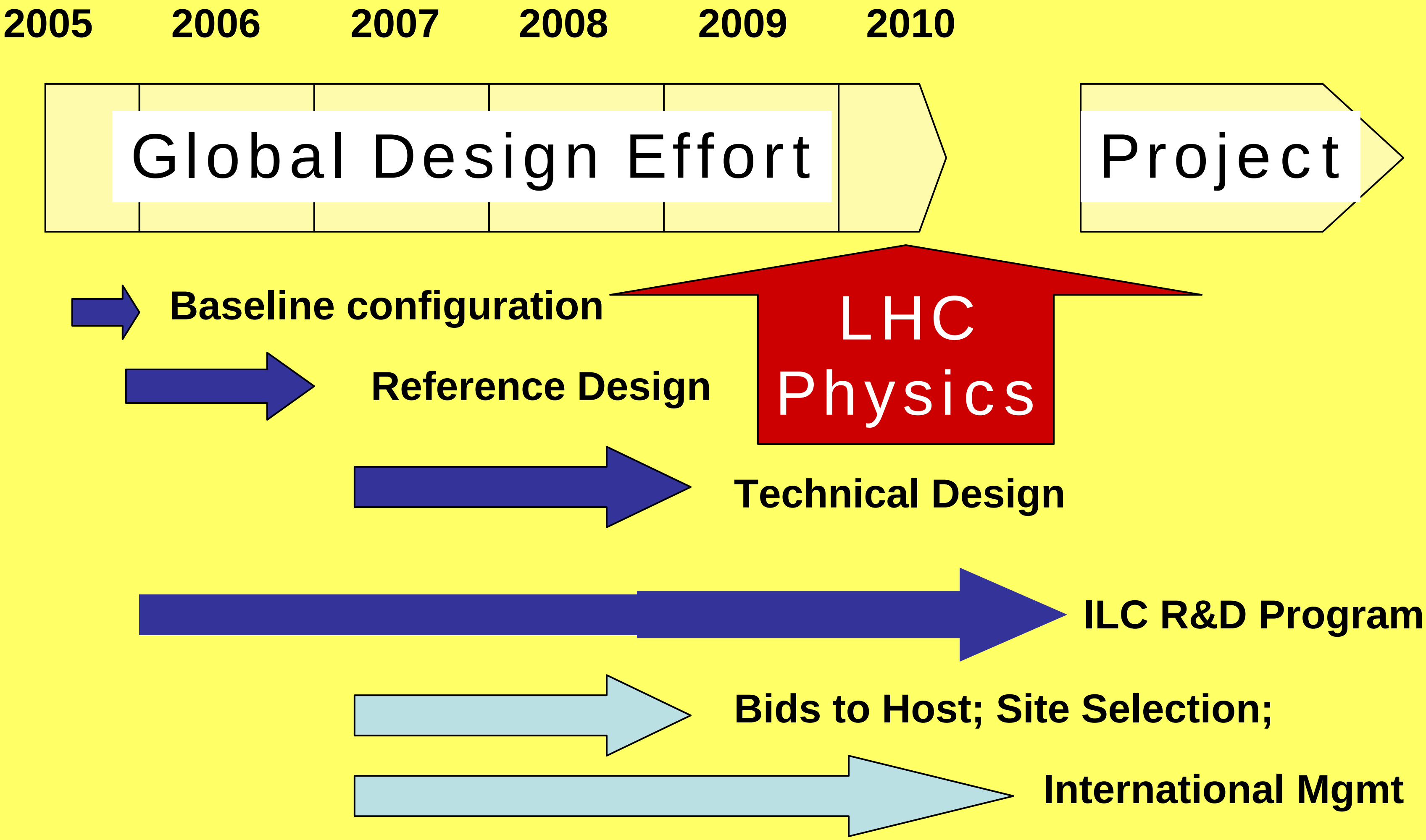
The Snowmass adventure

More than 750 physicists from around the world came to work together

A 'virtual' Lab, GDE is formed to manage the world-wide effort (Accelerator, Detector, Physics ..)
Several working groups are formed,
People from all parts of the world overtook clear responsibilities

The Lab (GDE) has a director, Berry Barish (and regional directors for Europe, NA and Asia)

The GDE Plan and Schedule



2005 2006 2007 2008 2009 2010

Global Design Effort

Project

LHC Physics

Baseline configuration

Reference Design

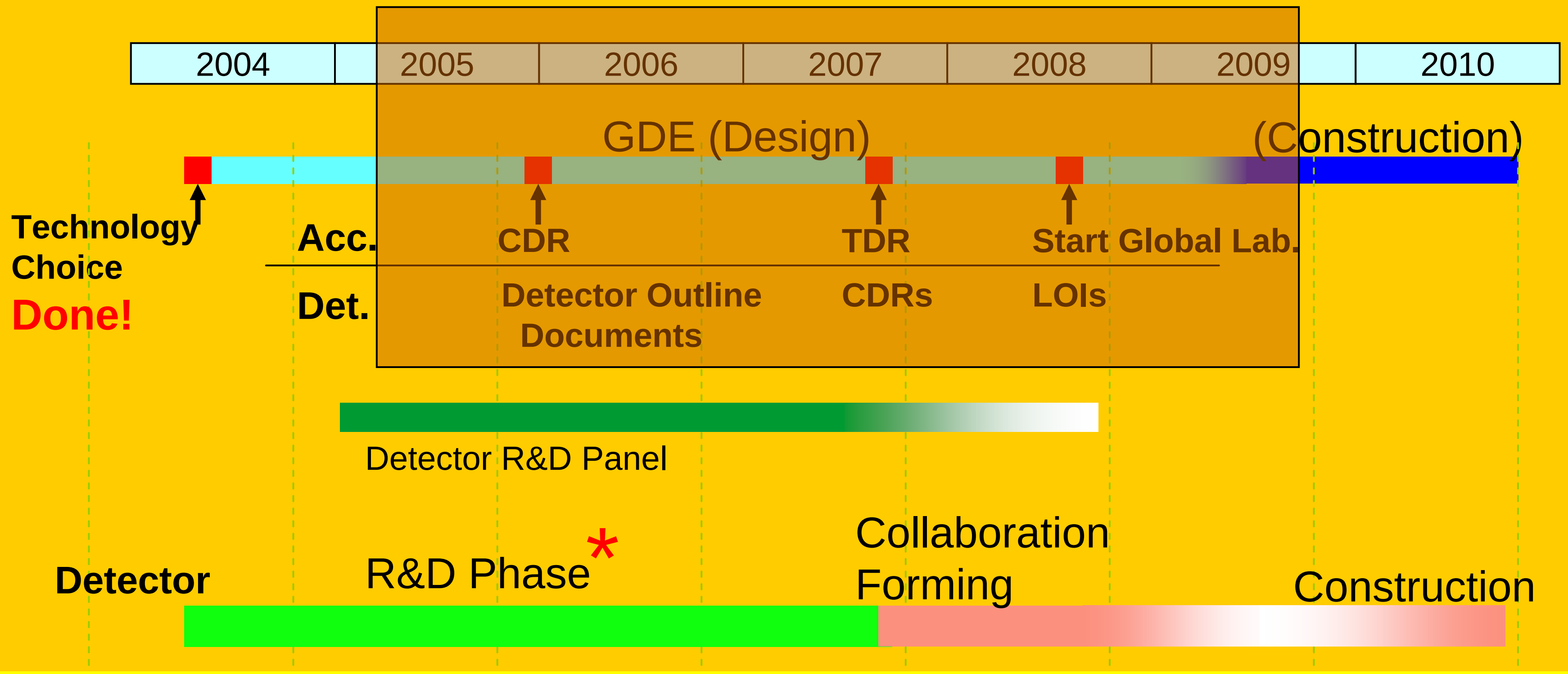
Technical Design

ILC R&D Program

Bids to Host; Site Selection;

International Mgmt

Detector R&D



2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010

GDE (Design)

(Construction)

Technology Choice

Done!

Acc.

CDR

TDR

Start Global Lab.

Det.

Detector Outline Documents

CDRs

LOIs

Detector R&D Panel

Detector

R&D Phase*

Collaboration Forming

Construction

Next Steps: Accelerator BCD (Baseline Configuration Document) end 2005

Detector R&D Panel Report end 2005

3 (or 4?) DODs March 2006

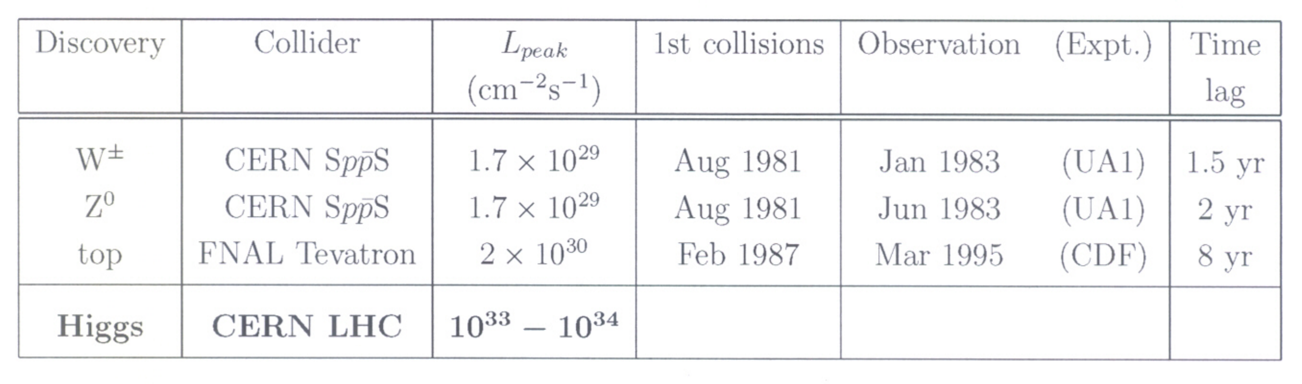
DCR (Detector Concept Report) end 2006

[*] In practice, detector R&D will extend much later, being continued within the approved collaboration(s)

ILC-LHC

- The Success of LHC will be a big boost for our field
- We are going ahead aggressively ahead to elaborate the case for the ILC, following our schedule
- Once we have collisions at the ILC an exciting Synergy with LHC will realized

Historic lesson:



Discovery	Collider	L_{peak} ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	1st collisions	Observation	(Expt.)	Time lag
$W^{\pm}$	CERN Sp$\bar{p}$S	1.7×10^{29}	Aug 1981	Jan 1983	(UA1)	1.5 yr
Z^0	CERN Sp$\bar{p}$S	1.7×10^{29}	Aug 1981	Jun 1983	(UA1)	2 yr
top	FNAL Tevatron	2×10^{30}	Feb 1987	Mar 1995	(CDF)	8 yr
Higgs	**CERN LHC**	$\mathbf{10^{33} - 10^{34}}$				

ILC has a compelling physics case

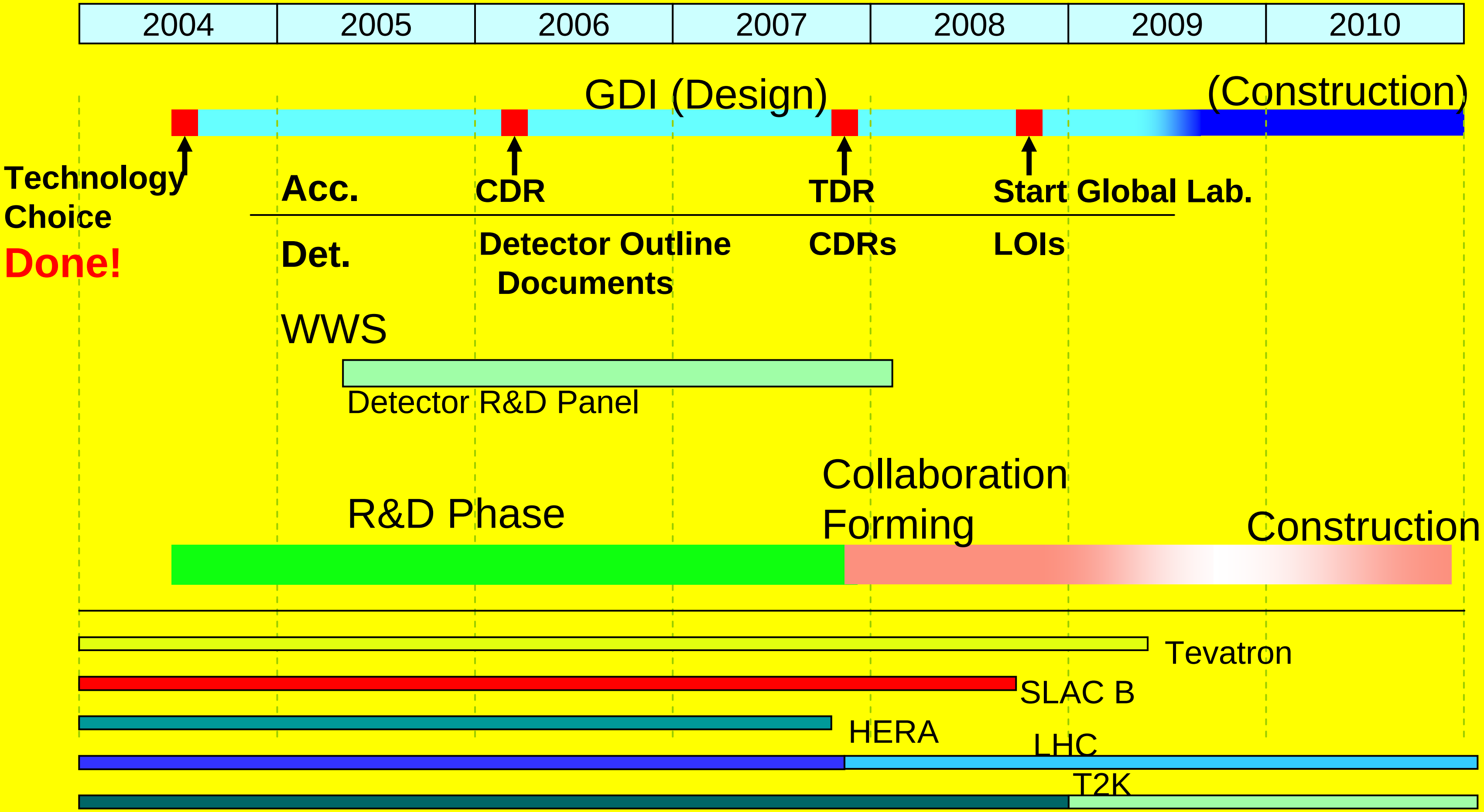
The accelerator will be SC (great success for the TESLA collaboration)

The Community made an important step to an 'International Organisation'

The R&D program for the ILC detector is exciting (Don't miss it)

Backup slides

Time Schedule



2004 2005 2006 2007 2008 2009 2010

GDI (Design)

(Construction)

Technology Choice

Done!

Acc.

CDR

TDR

Start Global Lab.

Det.

Detector Outline Documents

CDRs

LOIs

WWS

Detector R&D Panel

R&D Phase

Collaboration Forming

Construction

Tevatron

SLAC B

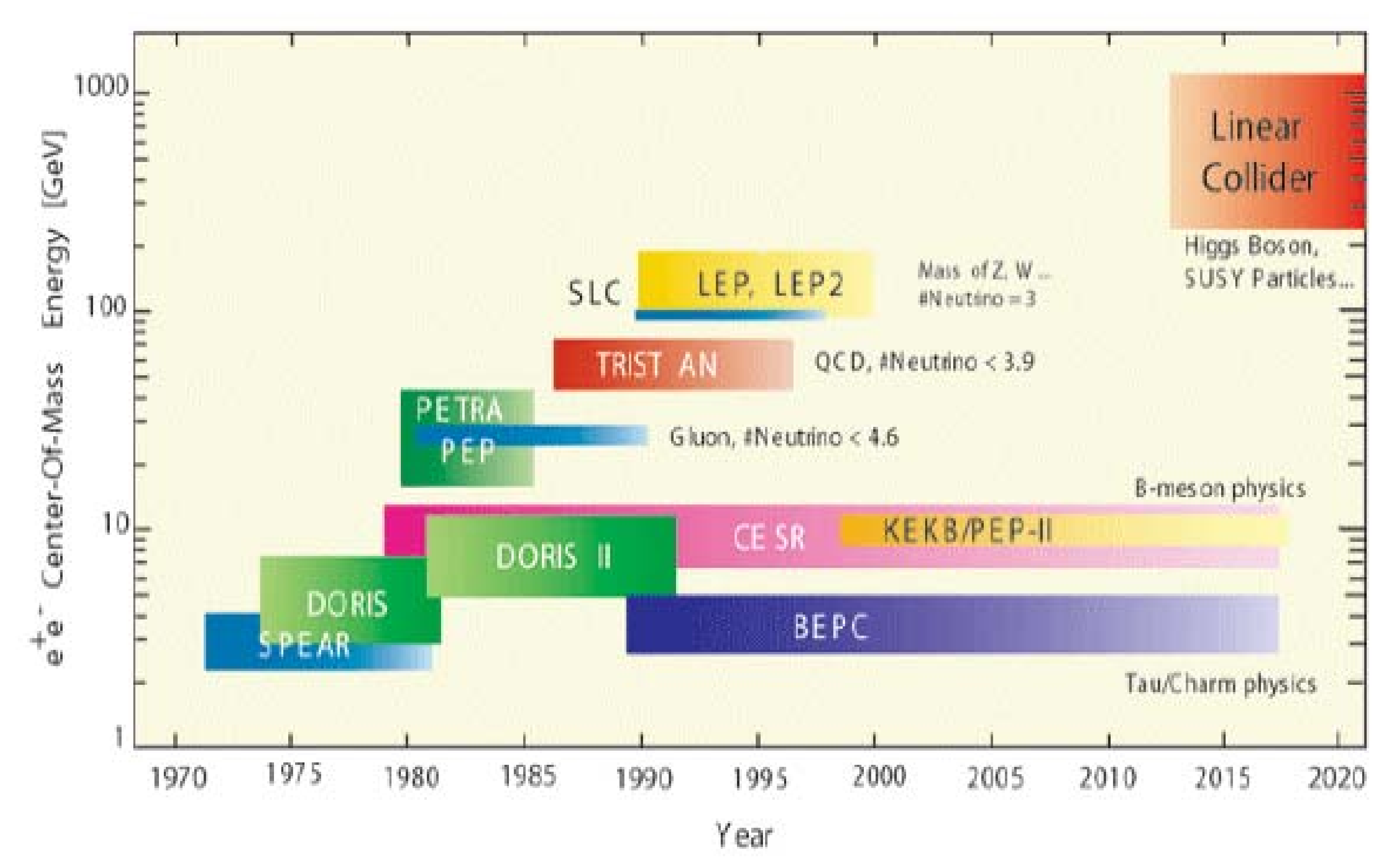
HERA

LHC

T2K

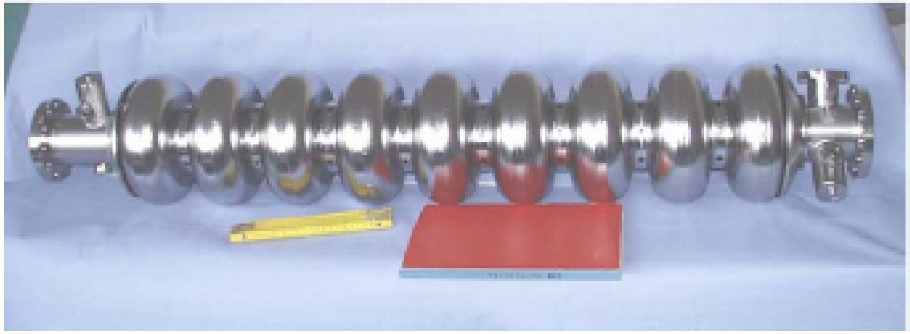
Taken from Y. Sugimoto

Energy Frontiere



The Recommendation

- **We recommend that the linear collider be based on superconducting rf technology**

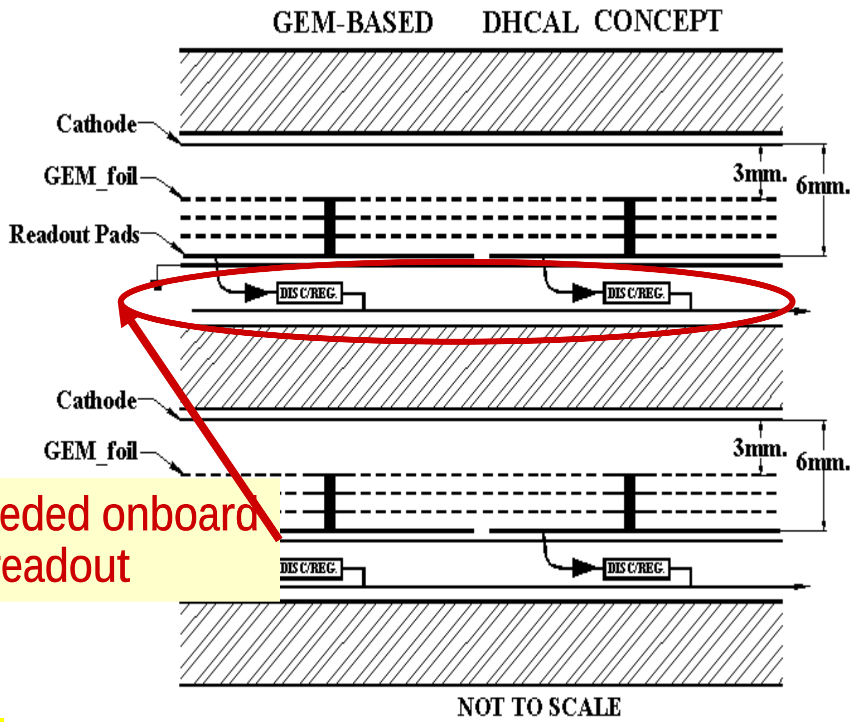


  - This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both (from the Executive Summary).
  - The superconducting technology has several very nice features for application to a linear collider. They follow in part from the low rf frequency.

HCAL – Analog or Digital

Digital Cal, GEM as sensor, pad readout

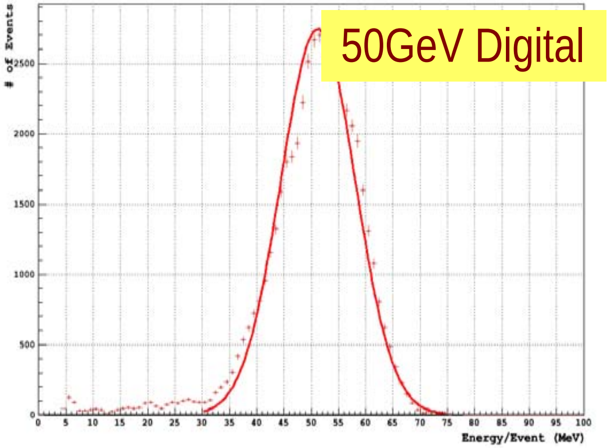
3mm side walls and spacers installed



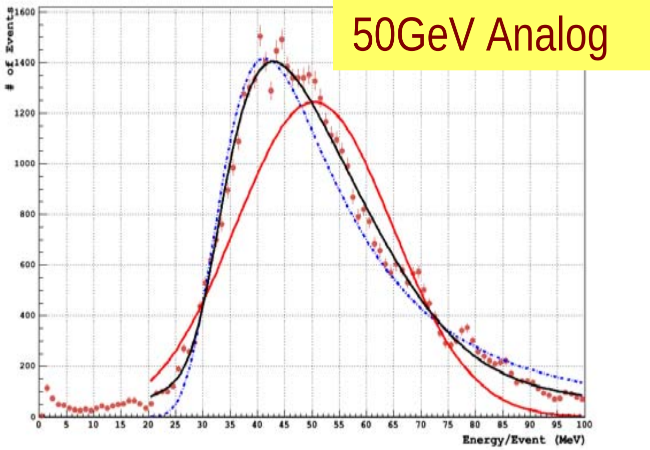
Embeded onboard readout

Development of large area GEM foils (Arlington)

Promising results from Simulations



50GeV Digital



50GeV Analog