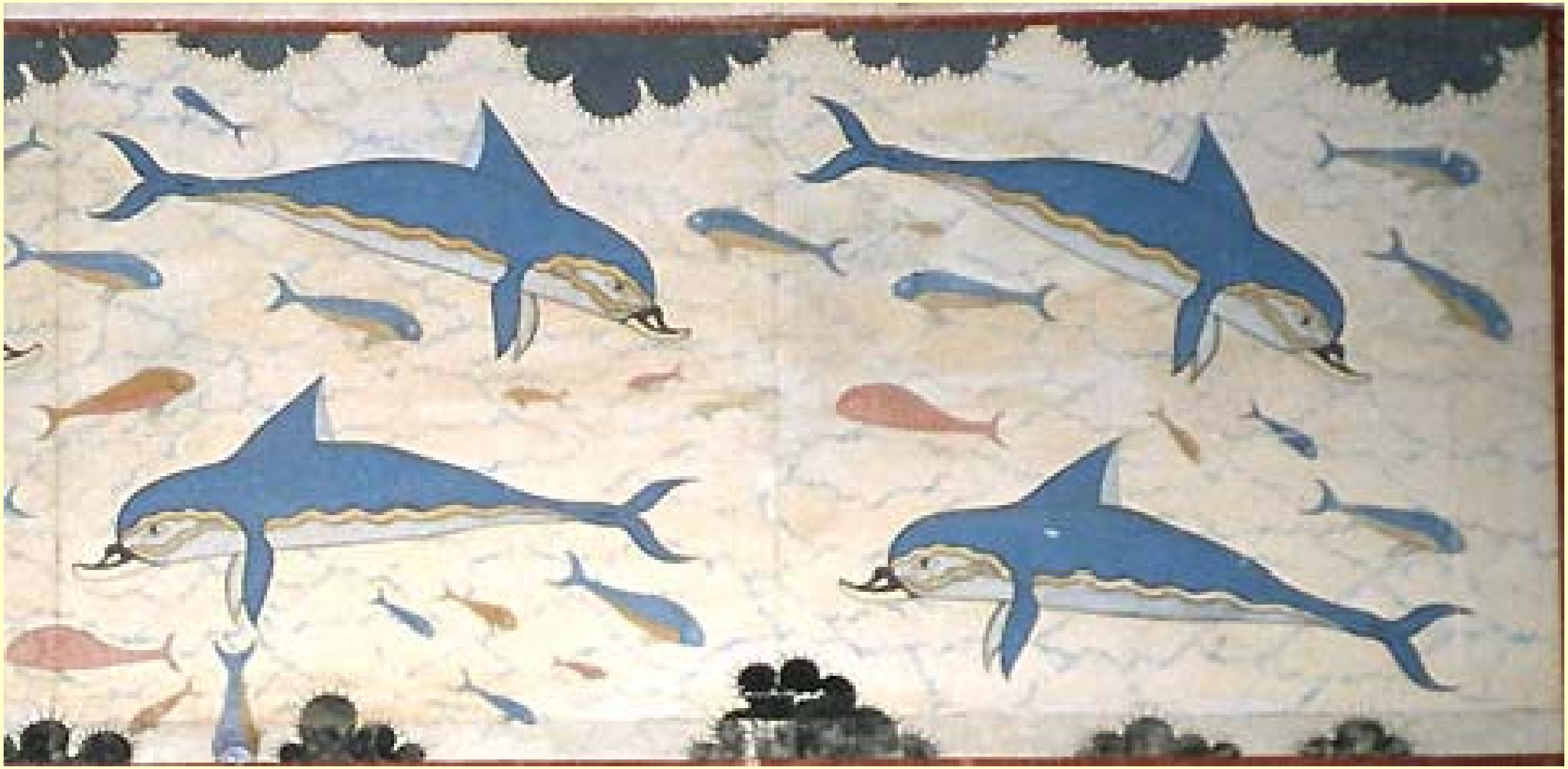
Linear Collider Physics and Detectors



MPGD2009, Κολυμβάρι, Κρήτη

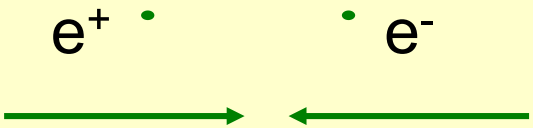
- Physics motivation
- Detector challenges
- Detector concepts
- Component R&D

Klaus Desch
Universität Bonn
12/06/2009

Physics motivation

Physics Motivation

„It is fundamental to complement the results of the LHC with measurements at a linear collider“ CERN council 14/06/2006



e^+ e^-

Why?

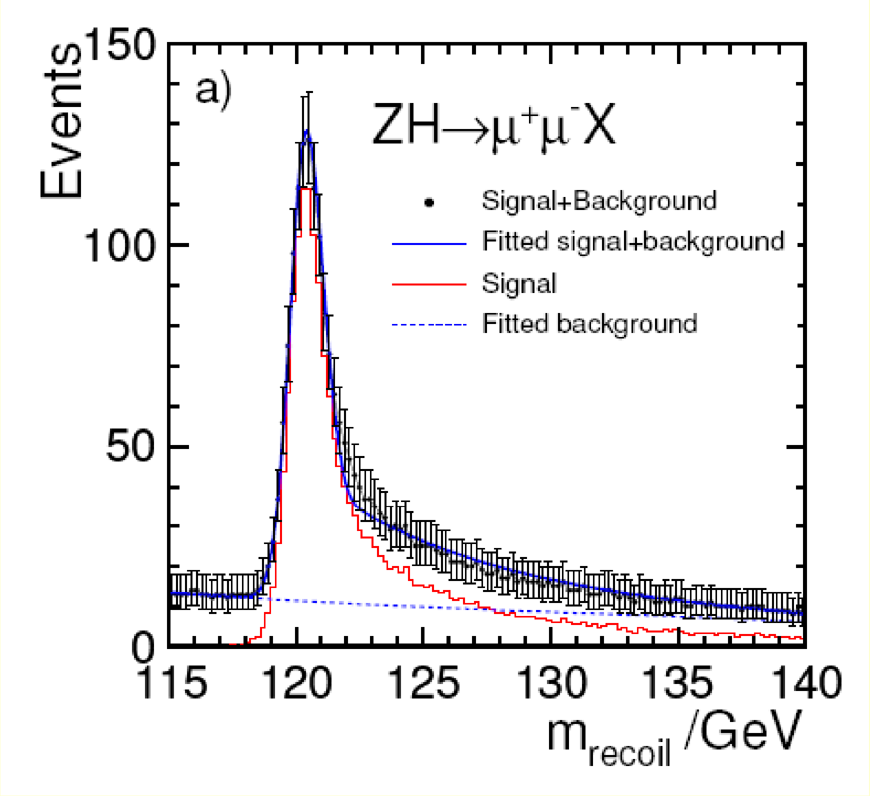
Key features of e^+e^- (“what does not work with hadron collisions”)

- precisely defined and known centre-of-mass energy of hard process
  (machine requirement: low beam energy spread, low beamstrahlung)
- tunable centre-of-mass energy
  (machine requirement: flexibility, high luminosity)
- polarized beams
  (machine requirement: do it! – detectors: measure it!)
- clean, fully reconstructable events (also hadronic f.s.)
  (detector requirement: jet (flavour), lepton reconstruction, full hermeticity)
- moderate backgrounds → no trigger → unbiased physics
  (detector requirement)

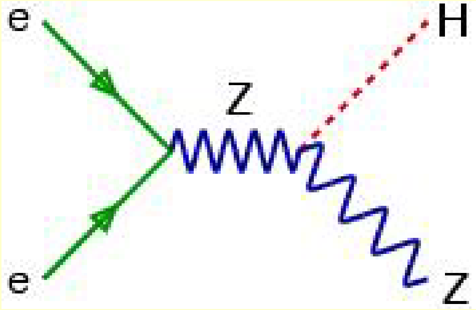
Move significantly beyond LHC capabilities to explore the Terascale

Physics Motivation – Higgs unbiased!

Anchor of LC Higgs physics
(why LC Higgs physics is qualitatively different from LHC)



Full detector simulation & Analysis



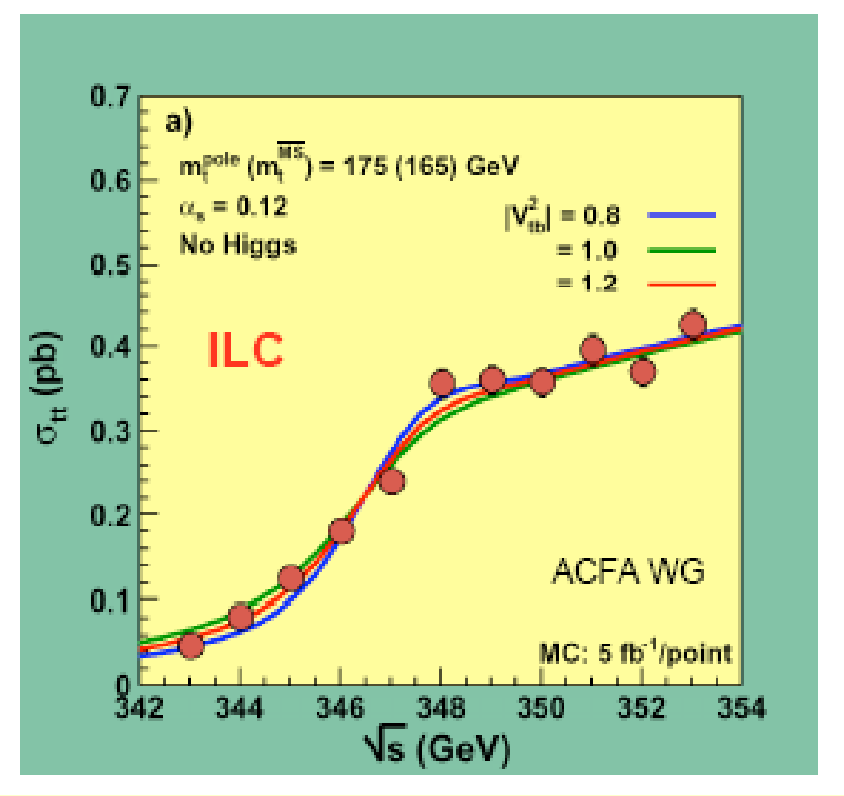
- select di-lepton events consistent with Z→ee/μμ
- calculate recoil mass:

$$m_H^2 = (p_{\ell\ell} - p_{\text{initial}})^2$$

model independent,
decay-mode independent

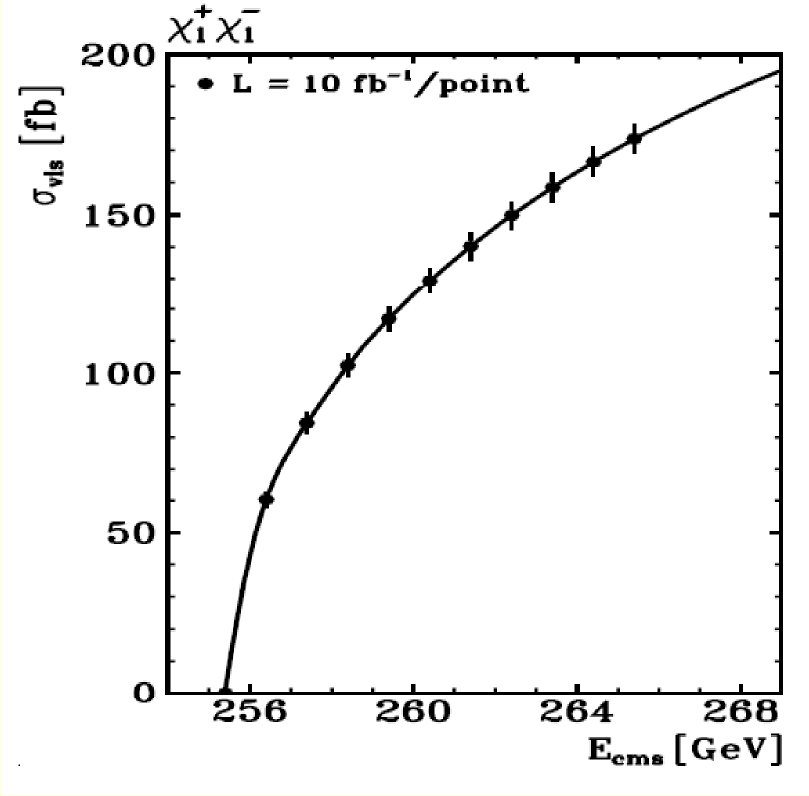
Physics Motivation – Scanning thresholds

Ultraprecise mass determinations from threshold scans



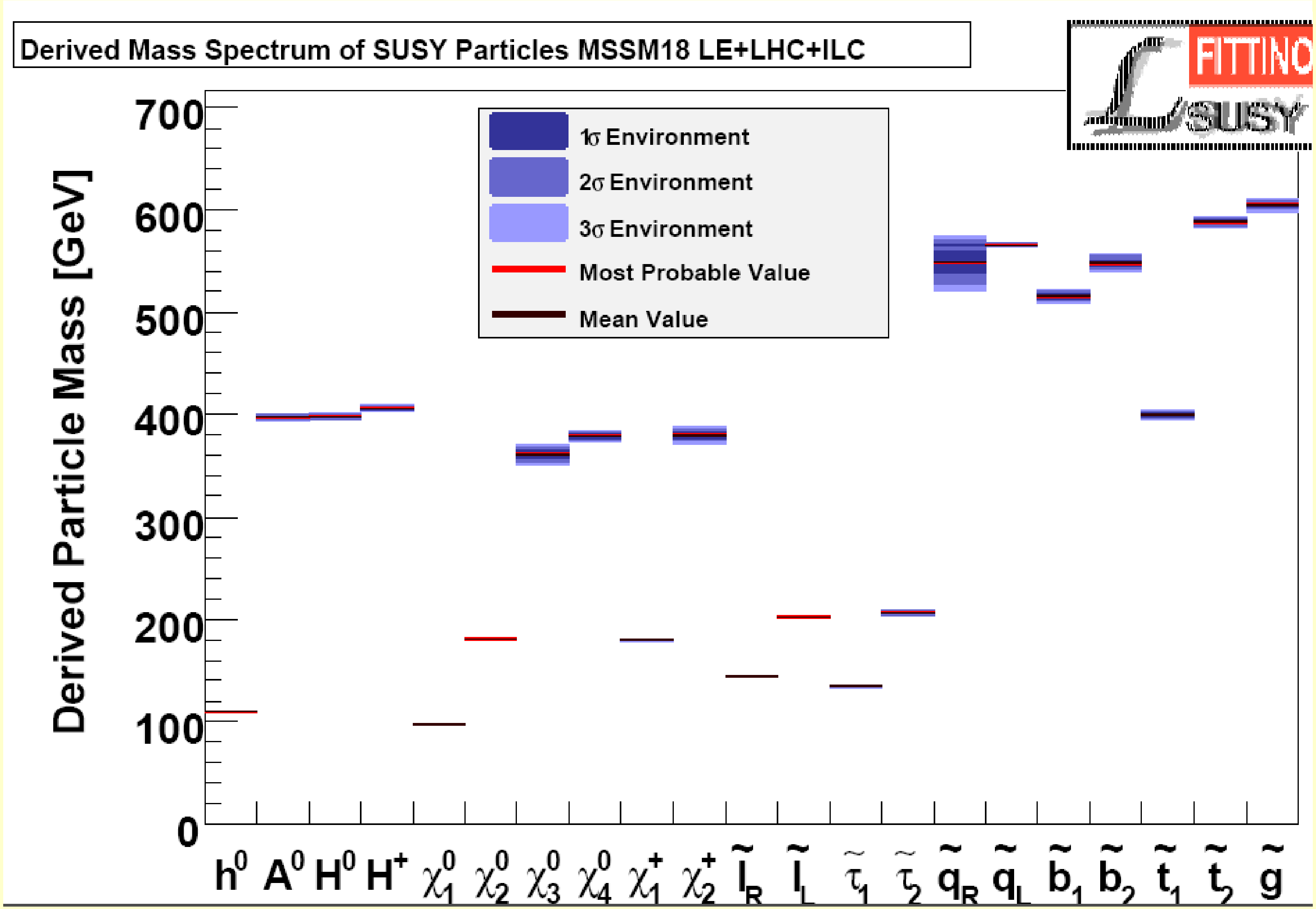
Top quark mass with ~100 MeV precision

mainly a challenge for machine + theory



Chargino production at threshold
[Martyn]

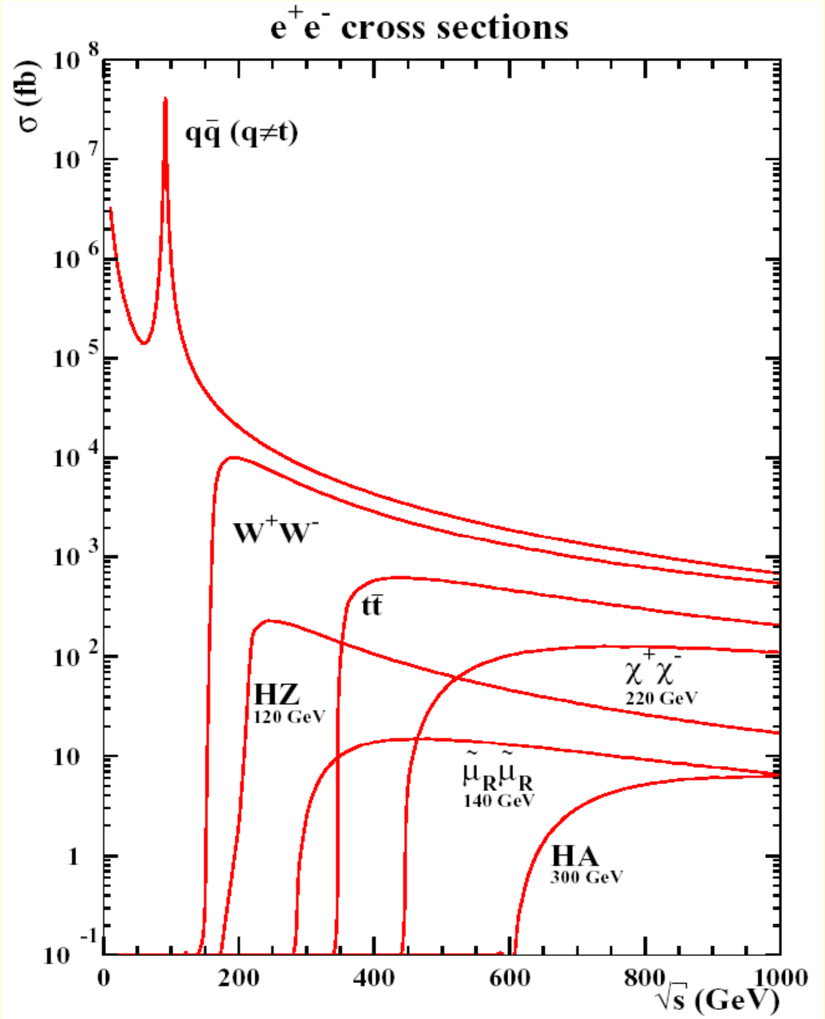
Physics Motivation – New physics



Detector challenges

Detector challenges

$$\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-) = (\hbar c)^2 \frac{4\pi\alpha^2}{3s} = \frac{87\ \text{nb}}{s\ (\text{GeV}^2)} = 87\ \text{fb at 1 TeV}$$



<u>Remark:</u>

e^+e^- cross section at √s > 500 GeV are small o (10-100 fb), multi-fermion processes smaller

500 fb^{-1} at 500 GeV are „only“

- 40000 HZ events
- 2500 HZ, Z→ll events
- 5000 smoun (m=140) pairs
- 200 HHZ events

By far most measurements at LC will be statistics-limited

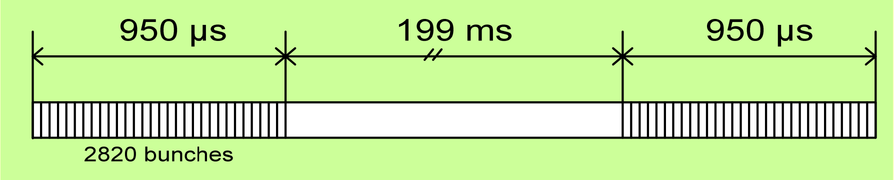
Consequences:

Luminosity requirement of $2\text{x}10^{34}$ is a lower limit!

Must (and can) reconstruct all (including) hadronic final states → detector

Detector challenges: ILC environment

Beam time structure



Bunch spacing ~ 300 ns

One readout frame has to integrate many bunch crossings for VTX,TPC

Background rates (beamstrahlung)

0.04 hits/mm^2/BX in the VTX inner layer (1.5 cm)
(or 400 hits/BX in the inner layer)

Occupancy of ~10% per bunchtrain

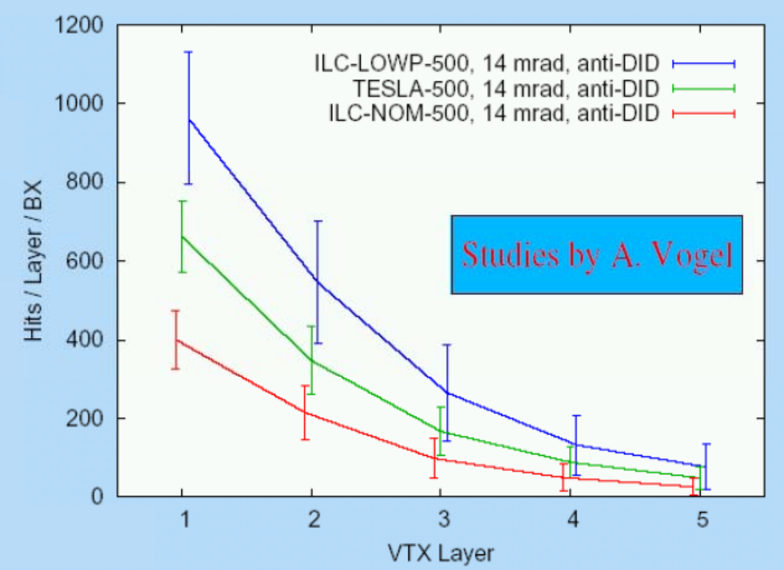
- read 20 frames per bunchtrain (1 ms)

or:

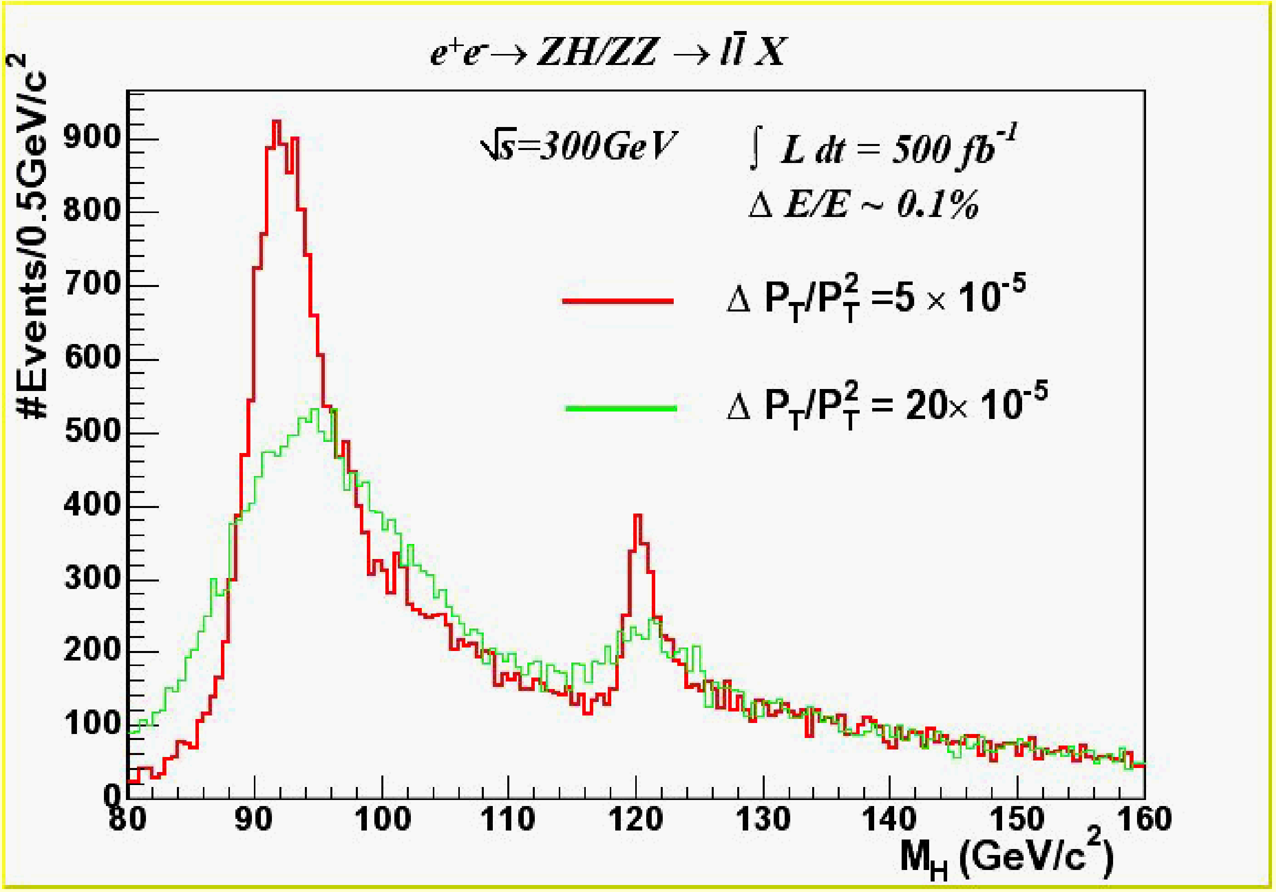
- internal storage of ~ 20 frames

Radiation Hard up to 360 kRad

and 10^{12} n/cm^2 (10 years)



Detector challenges: Tracking



Goals:

$\Delta p_T/p_T^2$ <

5×10^{-5} /GeV

ε > 99.5%
down to 7^0

momentum resolution counts!

→ optimize tracker radius, B-field, single point resolution, material

Pixel Vertex Detector

Goals:

Impact parameter resolution

$$\sigma(IP)_{r\text{-}\phi} = 5\mu m \oplus \frac{10\mu m}{p(GeV/c)\,\sin^{3/2}\theta}$$

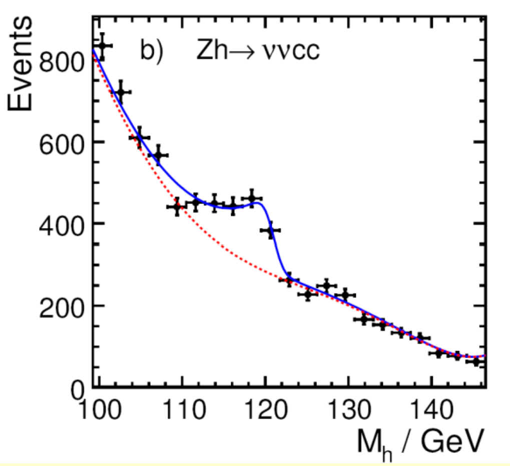
- Excellent point resolution < 4
  Pixel size 20-30 µm
- Low material budget
  0.1% X_0 per layer
- close to IP (15 mm)
- stand-alone tracking

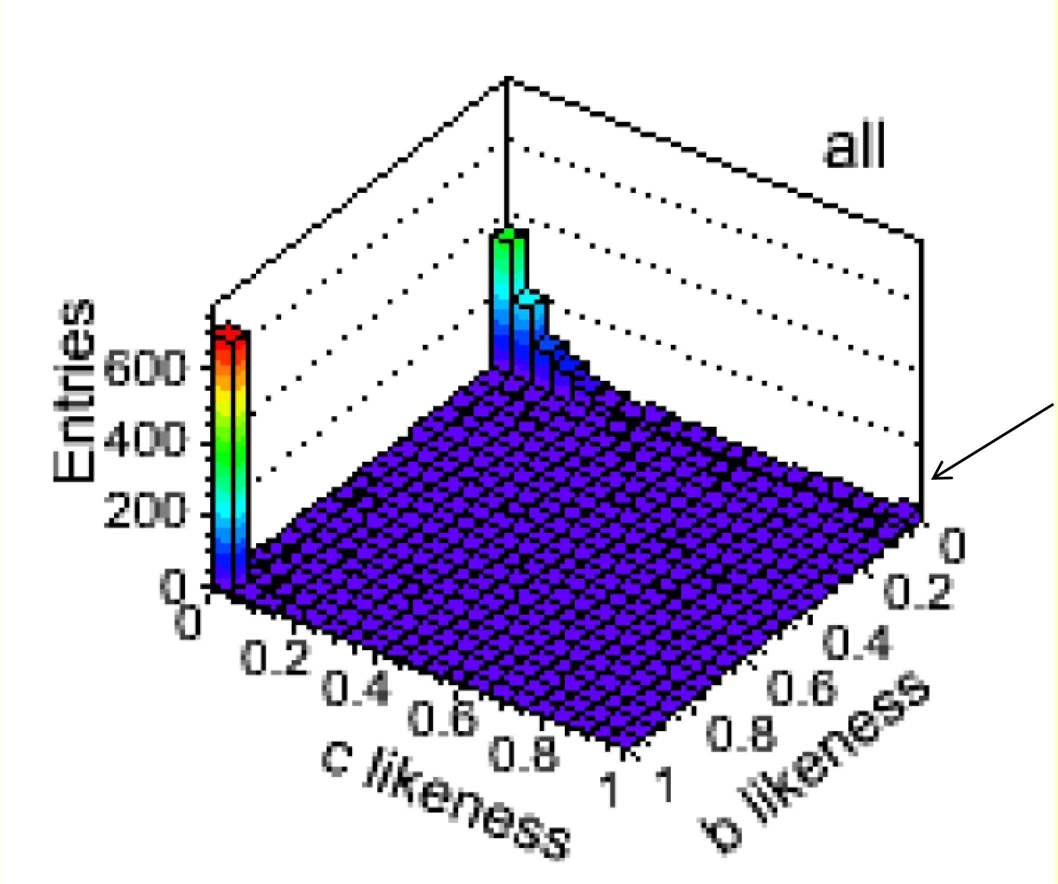
Detector challenges: Vertex reconstruction

(ambitious) goal: reconstruct sub-dominant (few%) H→cc decay

probably only direct measurement of H-up-type quark coupling!

goal:





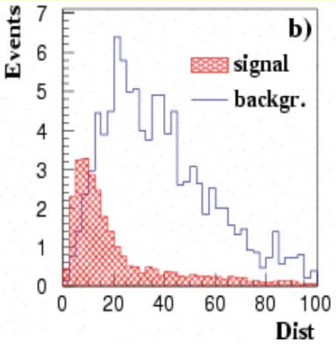
this is H→cc

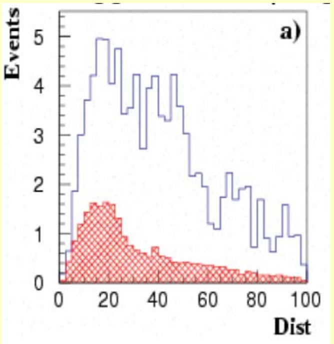
Detector challenges: Jet reconstruction

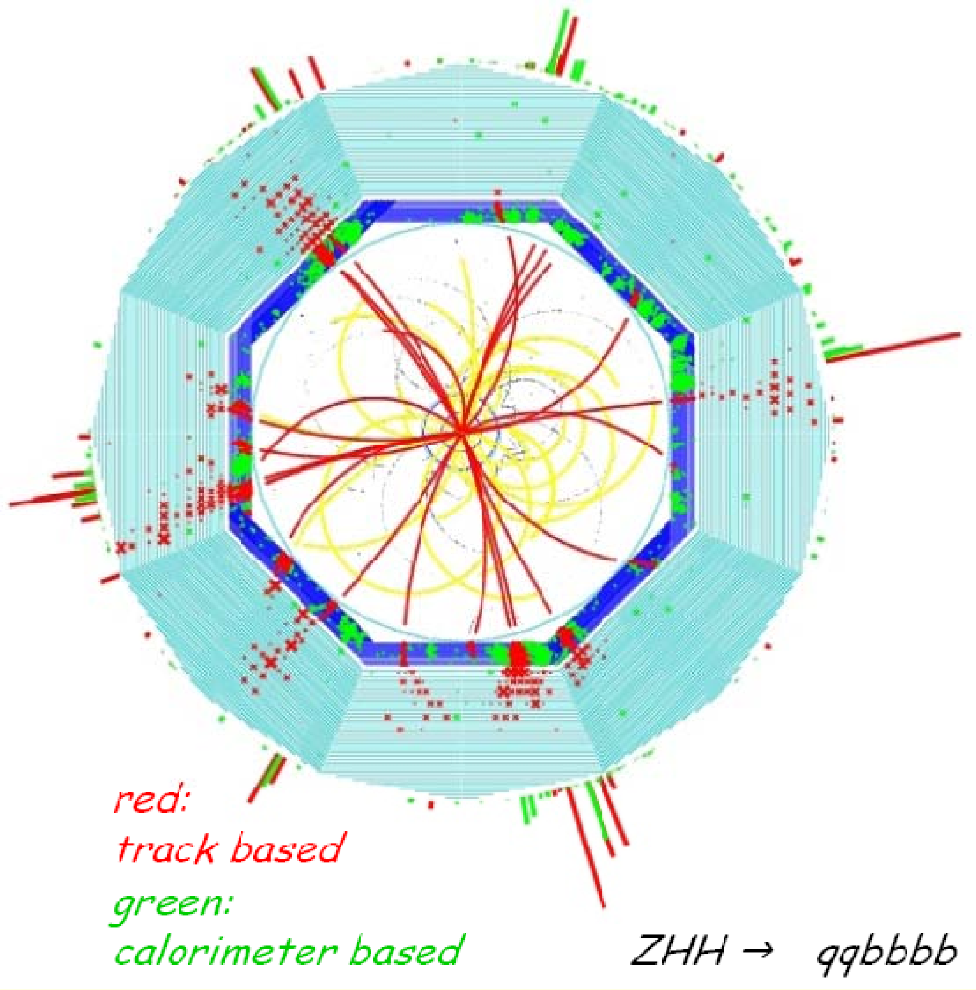
Need to measure sub-fb
cross sections
in multi-jet final states!

e.g. ZHH→ qqbbbb

not a question of better or worse but a question of
do or don´t







red:
track based

green:
calorimeter based

ZHH → qqbbbb

Two approaches:

1. Particle Flow
2. Compensating Caolrimetry

Detector challenges: Exclusive reconstruction

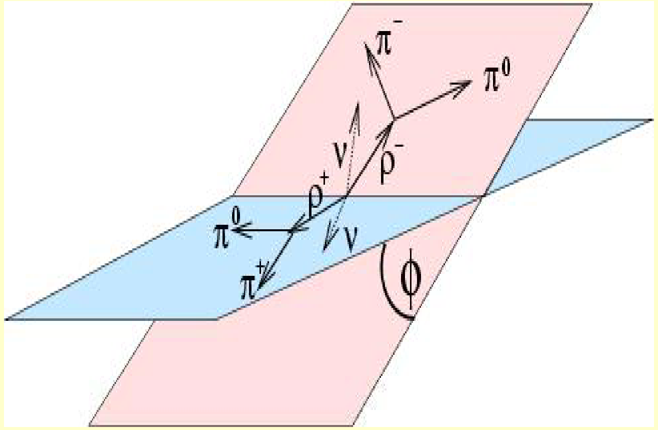
Jet energy resolution is not all

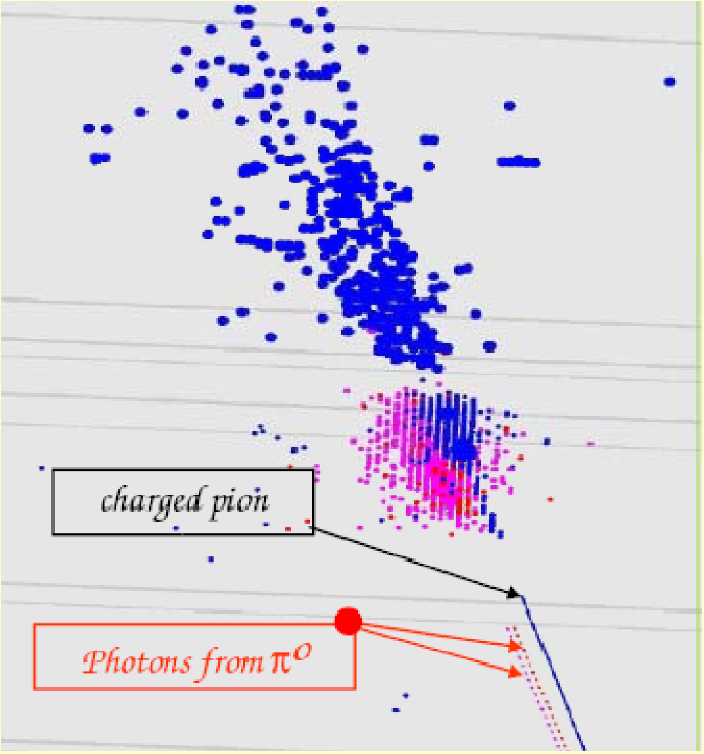
Sub-structure of jets important

e.g. for tau lepton reconstruction:

Sometimes it's not enough to know that it was a tau

Need to reconstruct its decay mode to measure its polarisation





Tau-Leptons challenge the whole detector!

Detector challenges: Summary

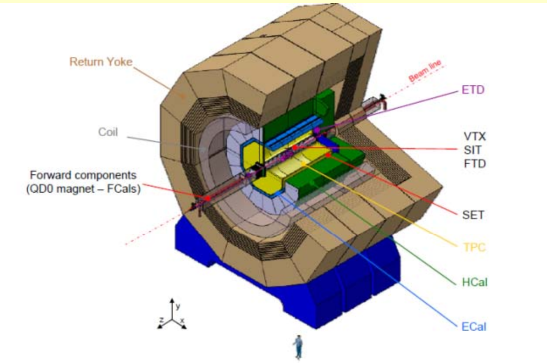
- ILC environment allows for a huge step in precision
- Radiation, Occupancy much relaxed w.r.t. LHC
- Physics demands to fully reconstruct both leptonic + hadronic events

Major guidelines for a ILC detector concept:

1. Jet reconstruction
2. Robust + precise charged particle tracking
3. Very precise vertex detector

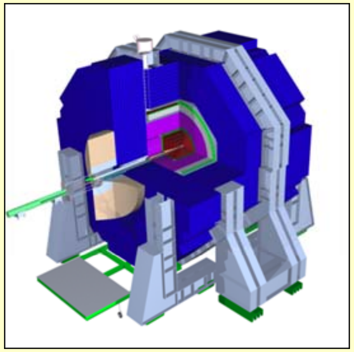
Detector concepts

Detector concepts - Overview



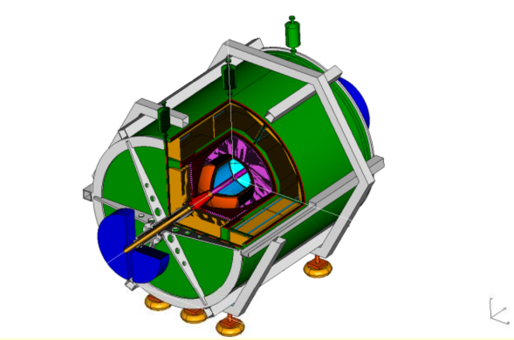
ILD – merger of LDC (ex-TESLA) and GLD

Particle flow + large TPC



SiD

Particle flow + all silicon tracker

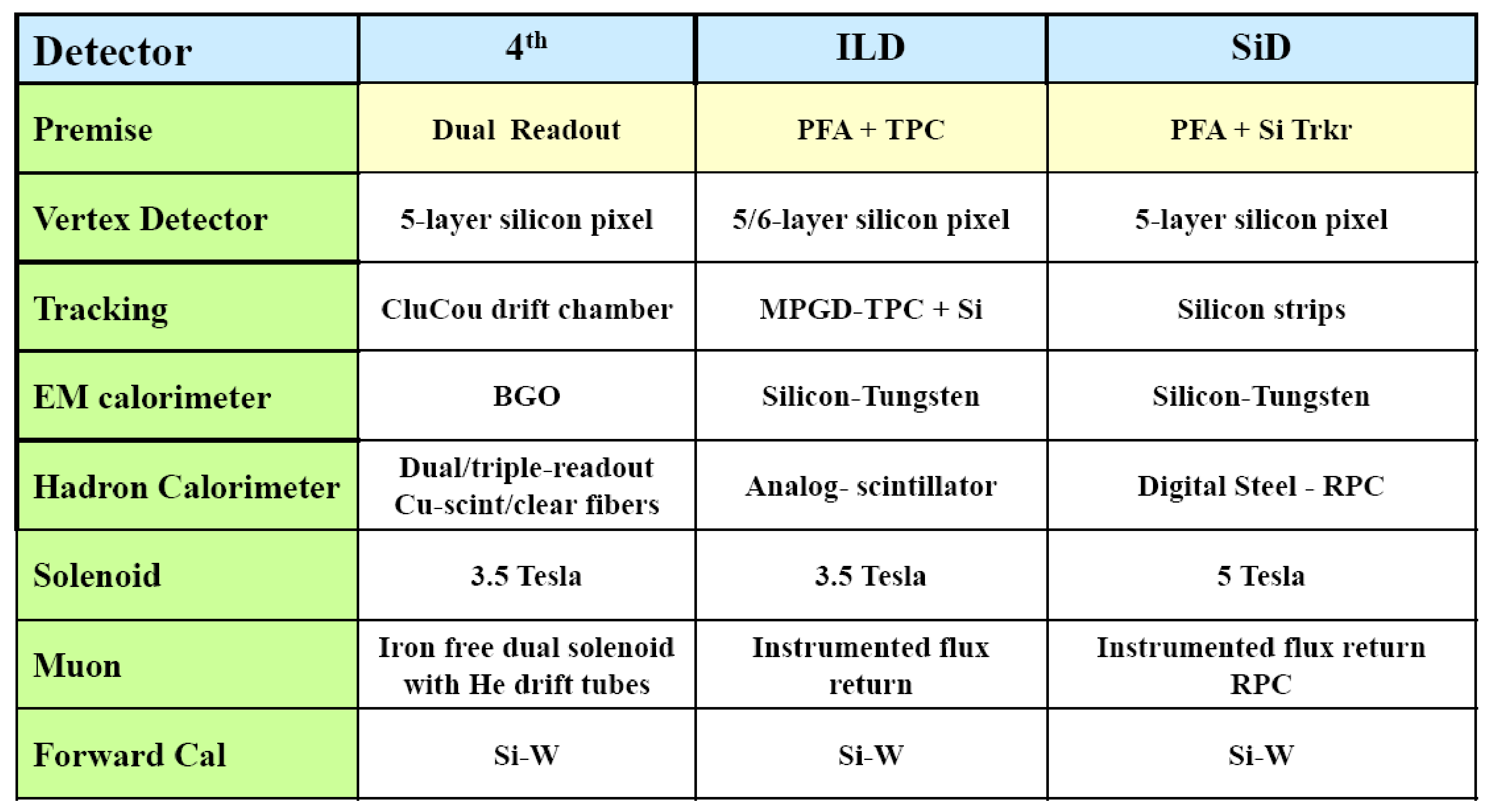


4th

„Doing it all differently…"

no Particle flow – DREAM compensating calo.
Large Drift chamber
dual solenoid

Detector concepts - Overview



Detector	4th	ILD	SiD
Premise	Dual Readout	PFA + TPC	PFA + Si Trkr
Vertex Detector	5-layer silicon pixel	5/6-layer silicon pixel	5-layer silicon pixel
Tracking	CluCou drift chamber	MPGD-TPC + Si	Silicon strips
EM calorimeter	BGO	Silicon-Tungsten	Silicon-Tungsten
Hadron Calorimeter	Dual/triple-readout Cu-scint/clear fibers	Analog- scintillator	Digital Steel - RPC
Solenoid	3.5 Tesla	3.5 Tesla	5 Tesla
Muon	Iron free dual solenoid with He drift tubes	Instrumented flux return	Instrumented flux return RPC
Forward Cal	Si-W	Si-W	Si-W

Note: those are „baseline“ choices [M.Demarteau]

technologies not finally selected!

Particle Flow

What is the best way to measure the energy of a jet?

Classical: purely calorimetric
typically 30% e.m. and 70% had. energy

for ΔE/E(em) = 10%/√E and ΔE/E(had) = 50%/√E
→ ΔE/E(jet) ~ 45%/√E

→ could do better
than that with
compensation
4th concept

PFlow: combine tracking and calorimetry optimally

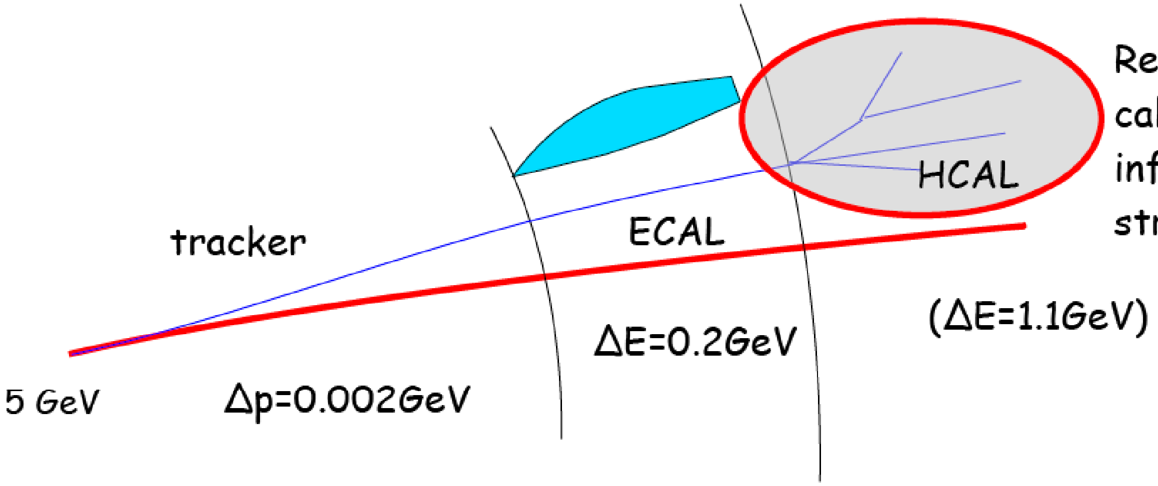
typically 60% charged, 30% em(neut), 10% had(neut)

need to separate charged from neutral in calorimeter!
momentum resolution negligible at ILC energies

→ ΔE/E(jet) ~ 20%/√E in principle (for ideal separation)
→ ΔE/E(jet) ~ 30%/√E as a realistic goal

PFlow has further advantages: tau reconstruction
leptons in jets
multi-jet separation (jet algorithms…)

Particle Flow – How does it work?



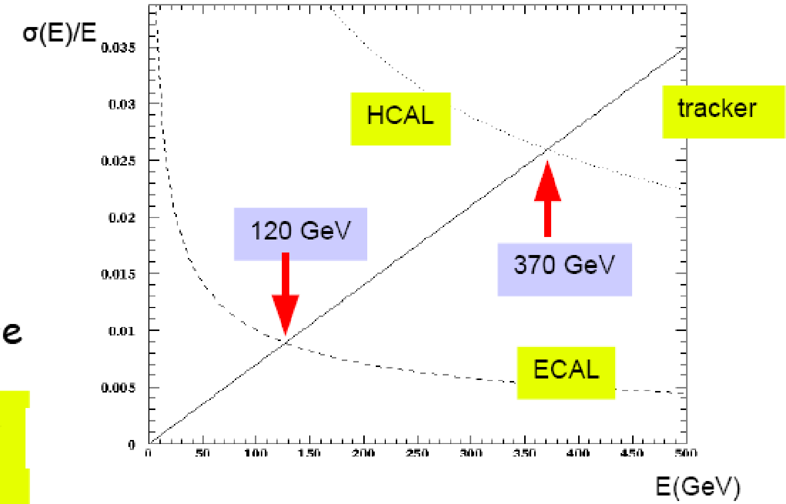
Remove the calorimeter-based information, stress topology

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

For LC energies: tracker is most precise

Utilize the precise tracker as much as possible

Resolution tracker - Calorimeter

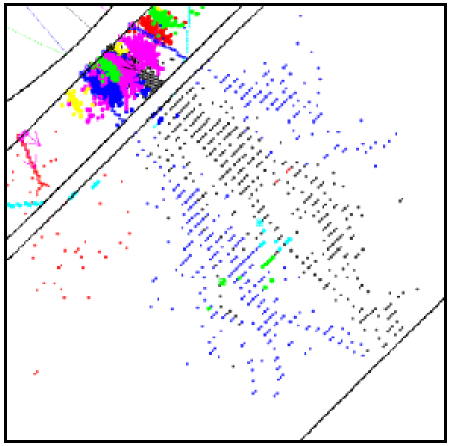


[Behnke]

Particle Flow – Performance in ILD

★ **Benchmarked using:**

- $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ decays at rest
- $|\cos\theta| < 0.7$



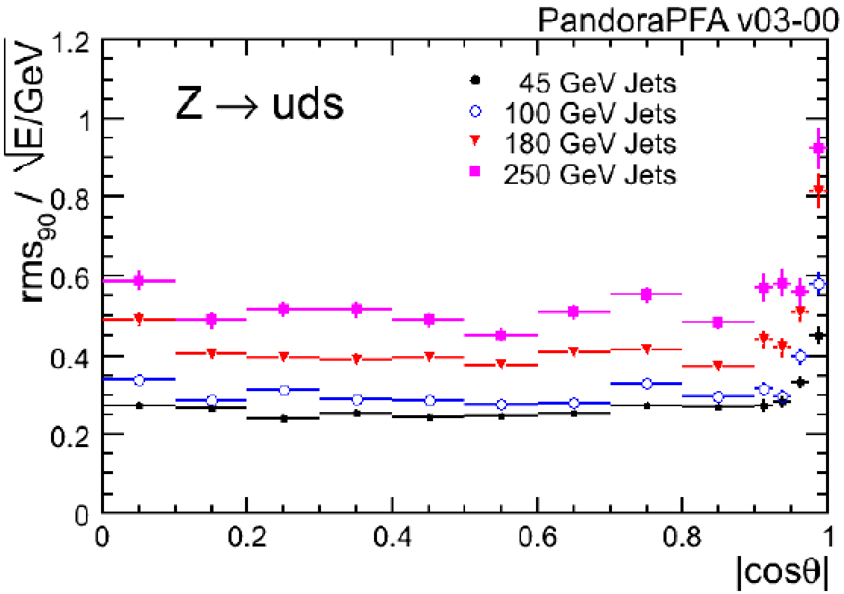
E_j	$\sigma(E_{jj})$	$\sigma(E_{jj})/\sqrt{E_{jj}}$	$\sigma(E_j)/E_j$
45 GeV	2.4 GeV	25 %	3.7 %
100 GeV	4.1 GeV	29 %	2.9 %
180 GeV	7.5 GeV	40 %	3.0 %
250 GeV	11.1 GeV	50 %	3.2 %

di-jet

jet

NOTE:

- $\sigma_E = \mathrm{rms}_{90}$
- In terms of statistical power $\mathrm{rms}_{90} \times 1.1 \approx$ Gaussian equiv.
- No strong angular dependence down to cosθ~0.975

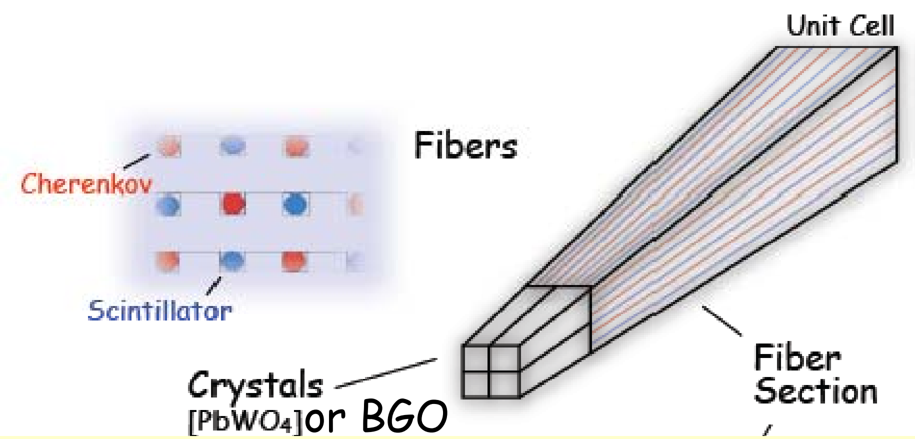


[Thomson]

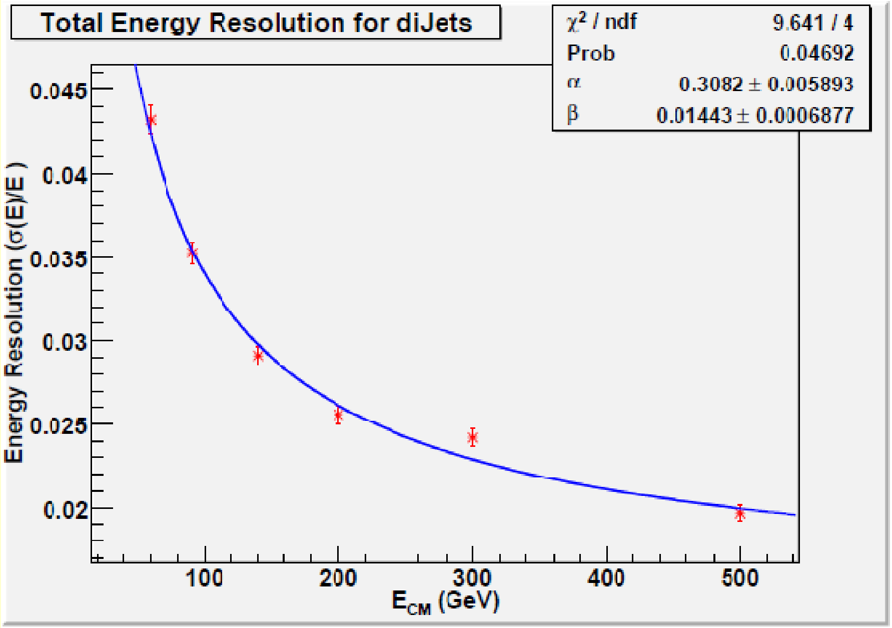
Alternative: Dual Readout Calorimetry (DREAM)

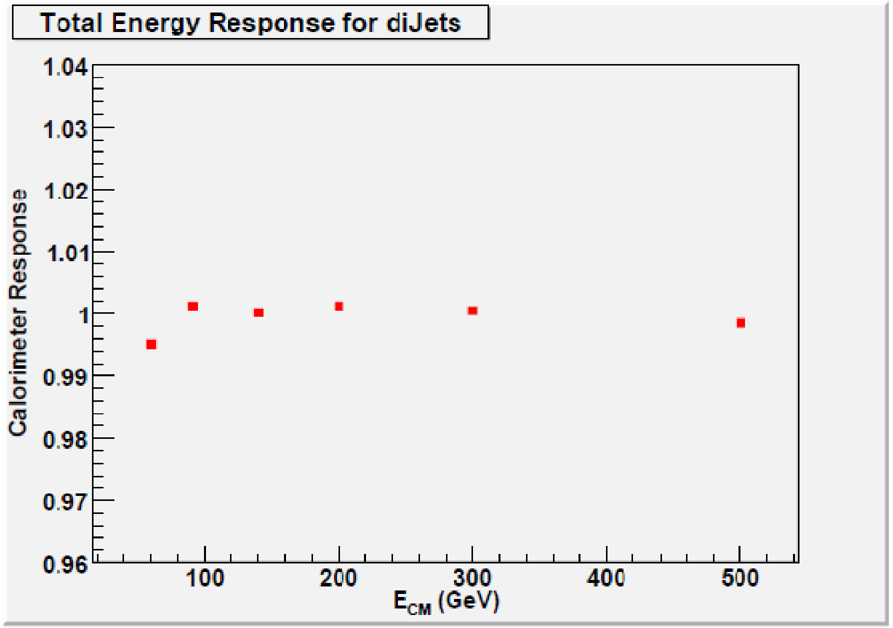
Concept: achieve seperated (or separable) measurements of EM and Had component of a hadronic shower

- crystals for EM section
- fibre („Spaghetti“) sampling HCAL with 2 different fibres:
  - Cerenkov (clear) fibres sensitive mainly to EM component
  - Scintillating fibres sensitive to total ionising (EM+HAD) component
  - Neutron component from time history measurement



Alternative: Dual Readout Calorimetry (DREAM)



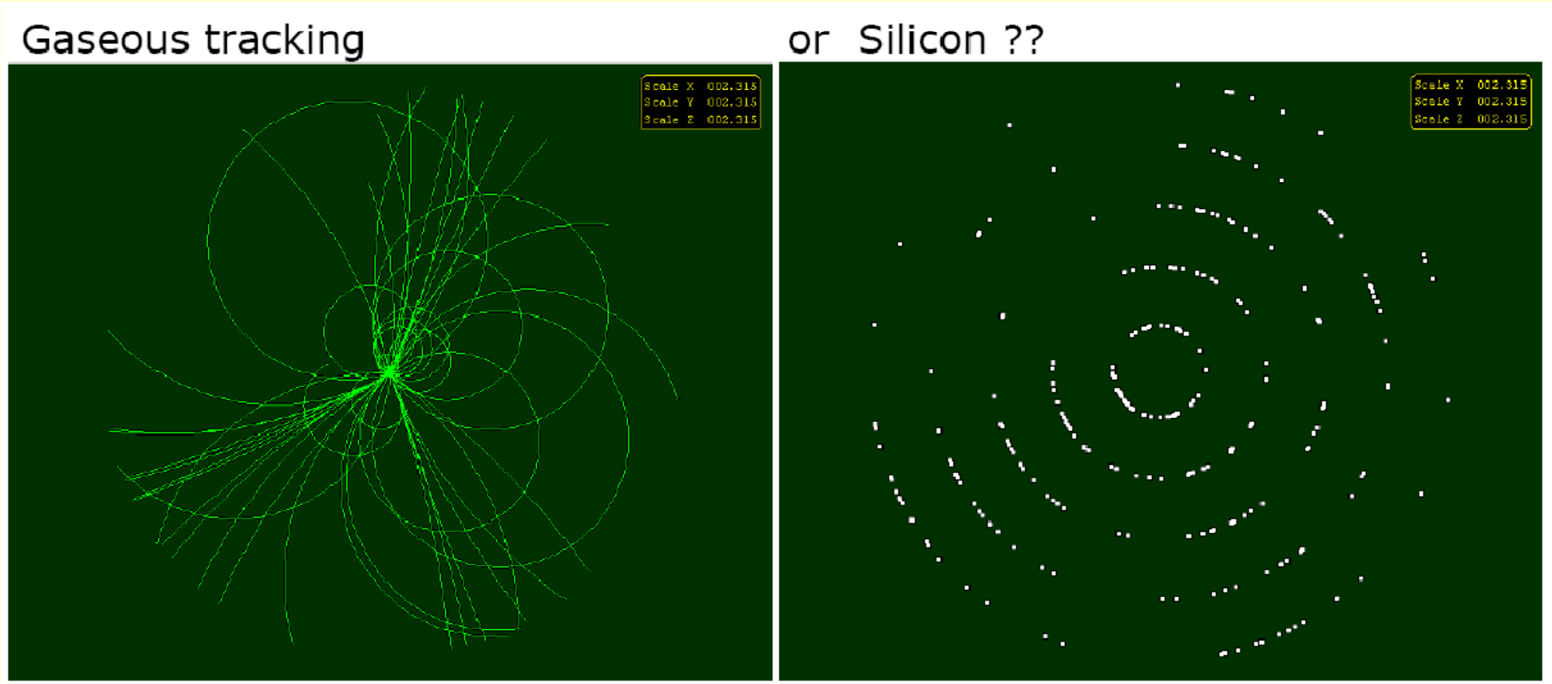


Particle species	Gaussian resolution stochastic term	σ_E/E constant term
electrons	$1.7\%/E^{0.48}$	$\oplus\ 0.1\%$
pions	$19.1\%/E^{0.43}$	$\oplus\ 0.3\%$
jets	$30.8\%/\sqrt{E}$	$\oplus\ 1.4\%$

Good jet energy resolution possible
No or poor segmentation, in particular in depth

Tracking: Si vs. Gas

$$\sigma(\frac{1}{p_T}) \propto \frac{\sigma_{spatial}}{\sqrt{N_{sample}}} \cdot \frac{1}{B \cdot L^2}$$



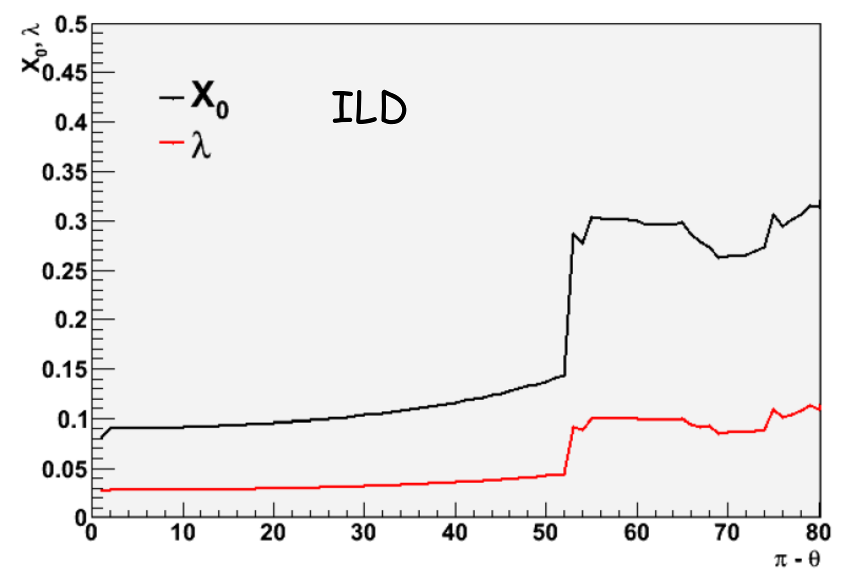
Time Projection Chamber (TPC)

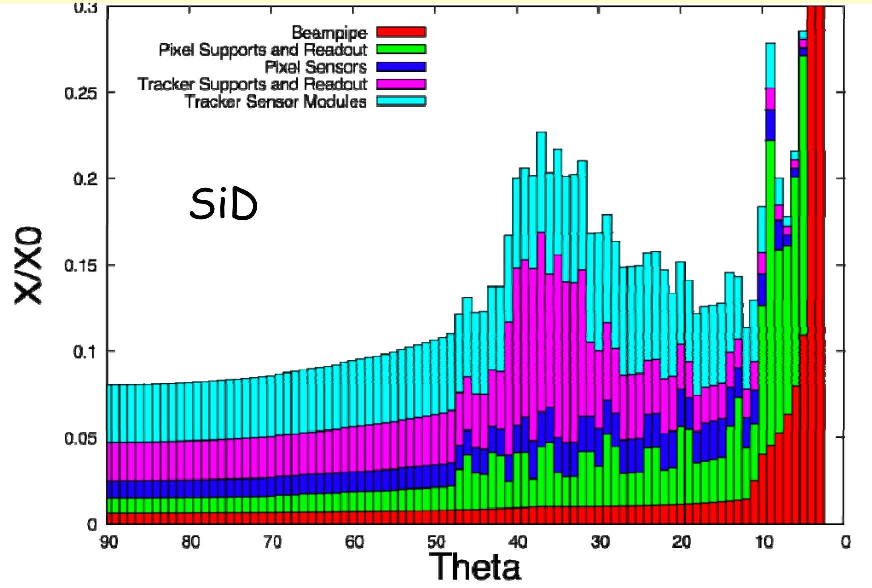
- 200 space points (3D) → continuous tracking, pattern recognition
- low mass easier to achieve, especially in the barrel region

Silicon tracking

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

Tracking: Material

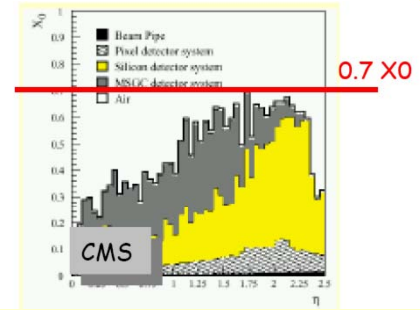




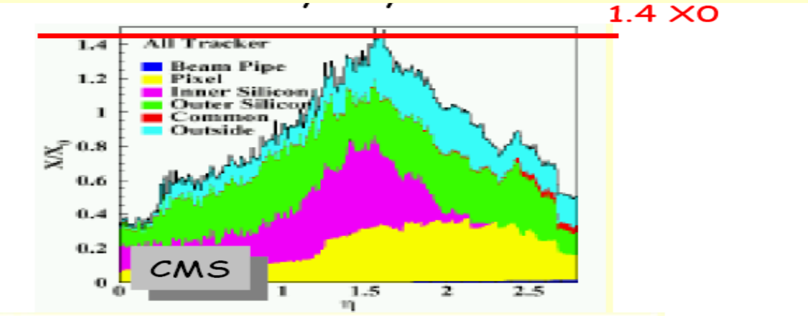
looks similar „on paper"

- TPC in central region safe / endplate is the challenge
- remember X_0 history of LHC detectors

1996

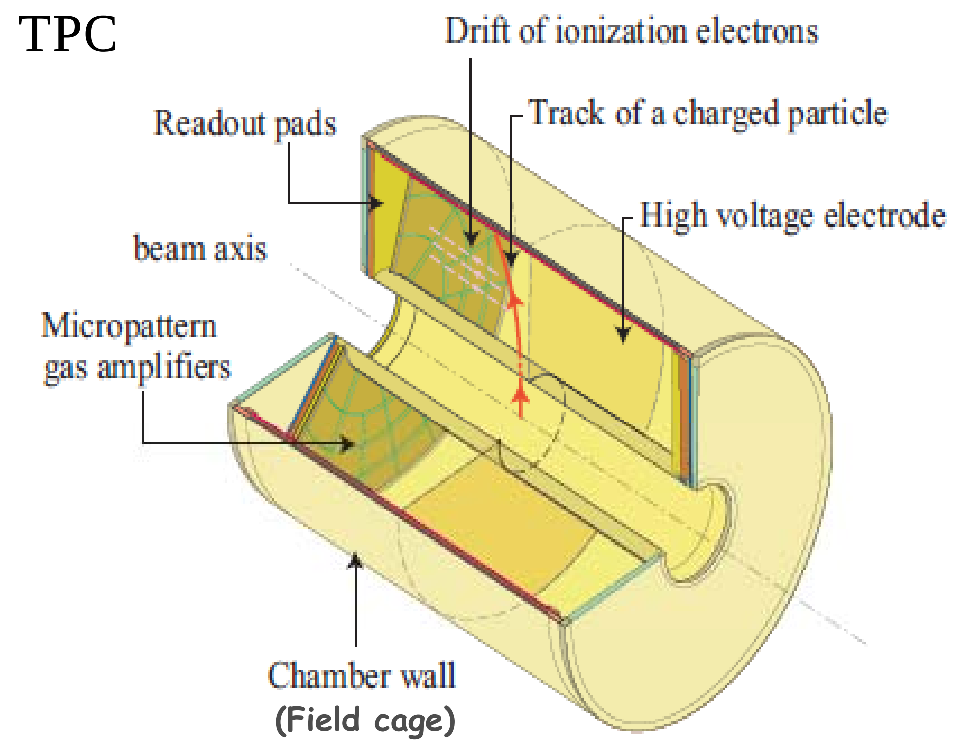


→ 2006



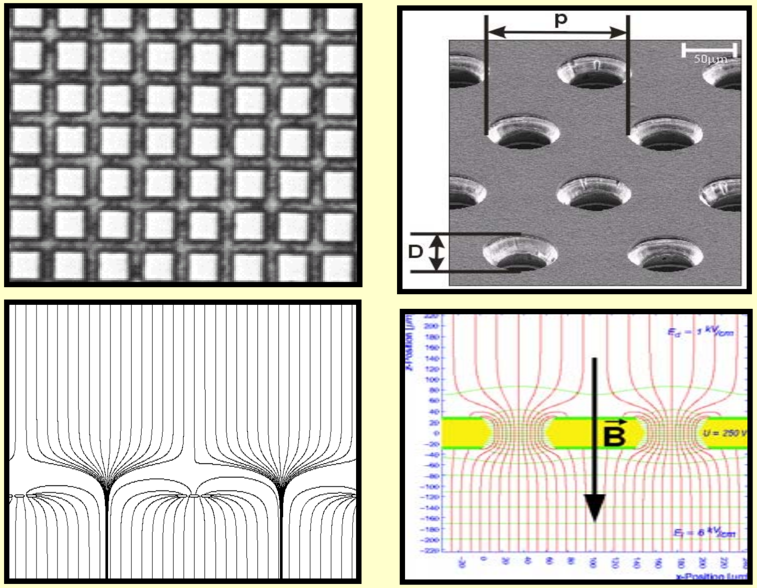
ILD: Gaseous Tracking(TPC) + Si envelope

Traditional TPC with MWPC: limited space resolution,
No true 2D symmetry, ExB effects
⇒ use Micro-Pattern Gas Detectors (MPGD) ("micro" = 50-150 μm)



LC TPC: R=2m L=4-5 m

Gas amplification


MicroMEGAS

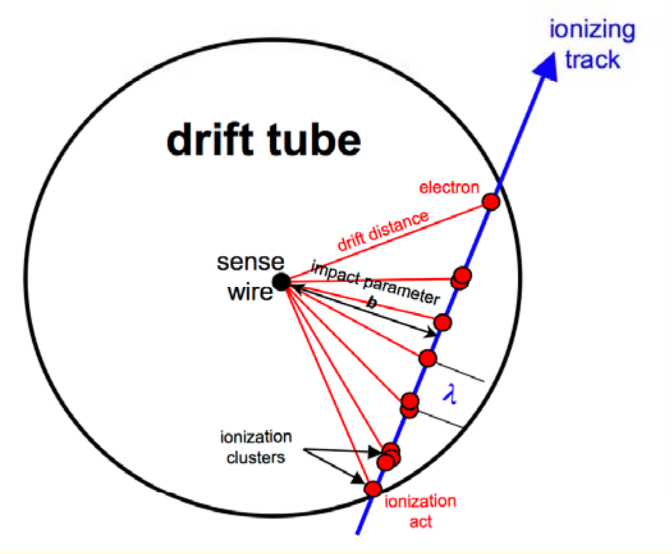
GEM

Readout schemes:
small pads (~1x4mm^2)
pixels (~100x100μm^2)

Gaseous Tracking: Drift Chamber (4th)

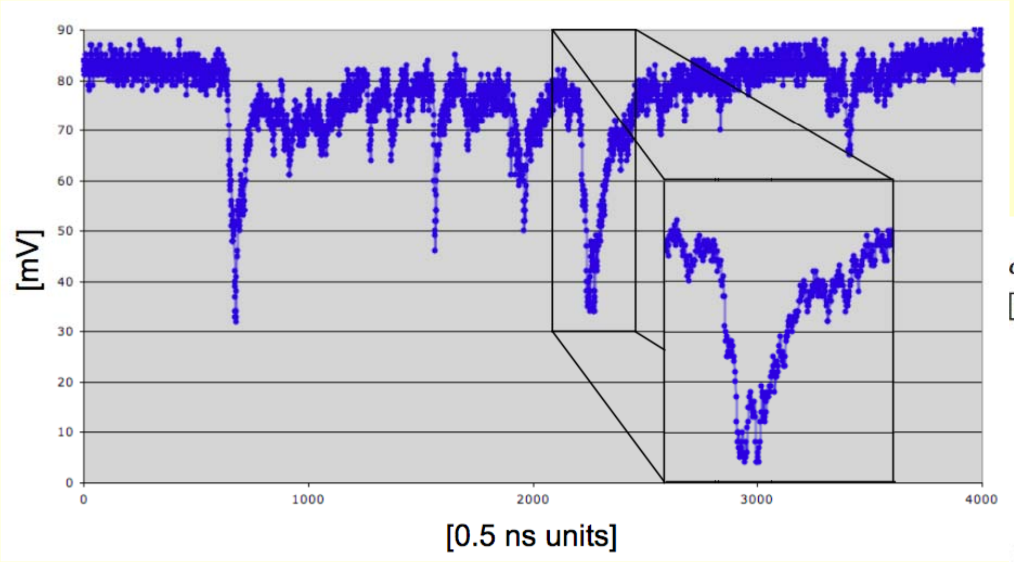
Alternative approach for charged particle tracking in 4th concept

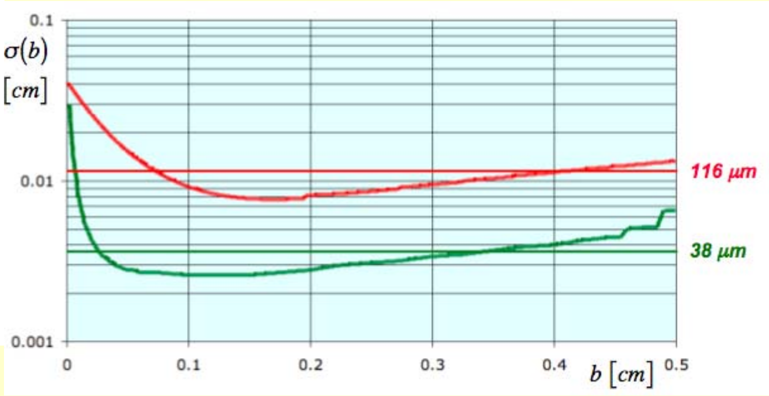
Large drift chamber with dE/dx capability via cluster counting



Cluster timing:

record the drift times of all individual ionization electrons collected on a sense wire → multi-GHz FADC needed

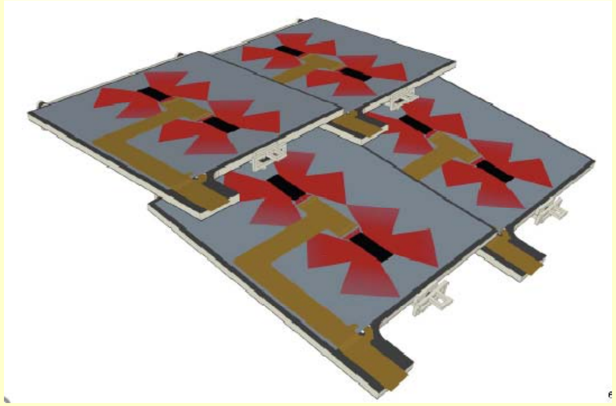


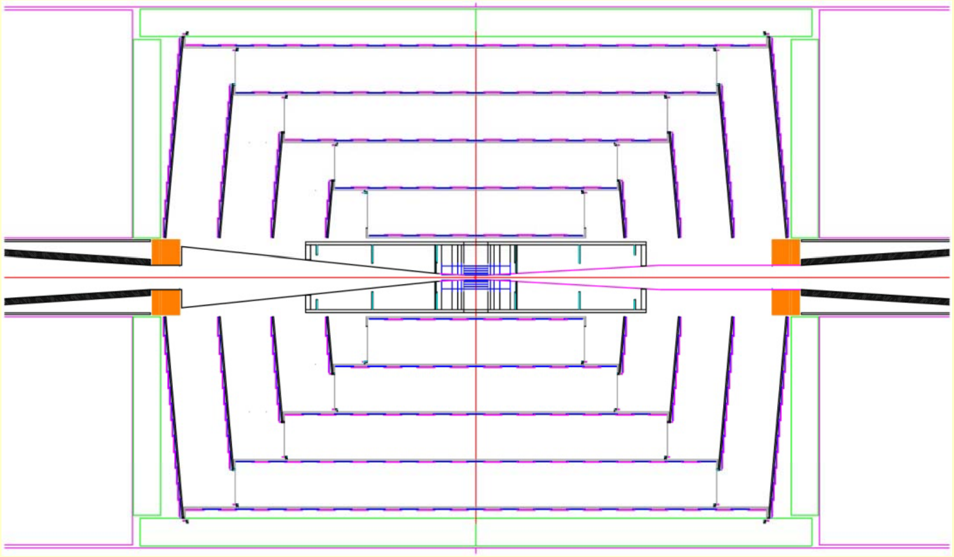


Silicon Tracking

~100 m^2 Si Strips: Barrel single sided (r-φ); endcaps double sided

Modular low mass sensors tile CF cylinders





~10 x 10 cm; 320 μm thick; 25 μm sense pitch; 50 μm readout S/N > 20;

< 5 μm hit resolution (prototype fabricated);

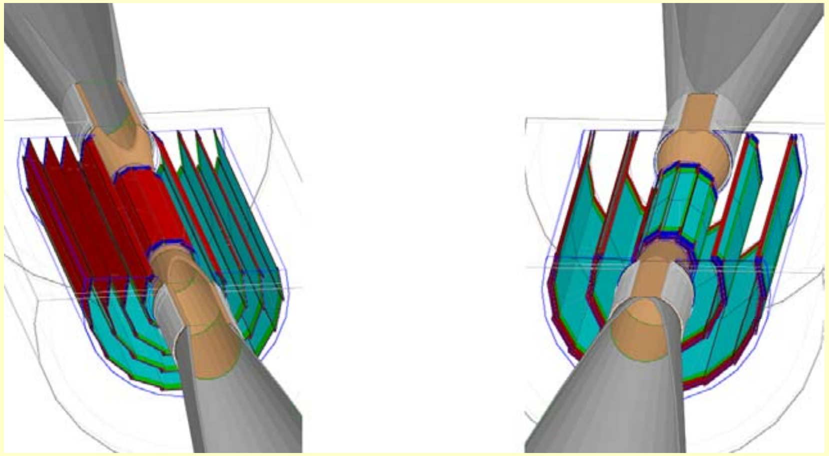
Bump bonded readout with 2 KPiX chip; no hybrid

KPiX measures amplitude and bunch # in ILC train

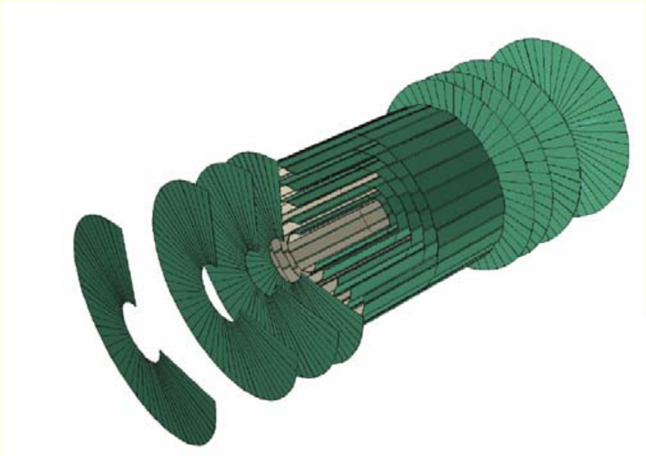
Pulsed Power: 20 μW/channel avg; ~600 W for 30 M channels; gas cooling

Vertex Detectors

ILD: 5 layers or 3 double layers



SiD: short barrel + disks



Hybrid pixels a la LHC are not an option (material, cooling)

→monolithic technologies, various options studied
(MAPS, CCD, DEPFET – maybe Gossip (not yet proposed…)

Target performance:

Single point resolution: < 3 μm

Material budget: ~ 0.1%X_0 / layer

Inner radius: ~ 15 mm

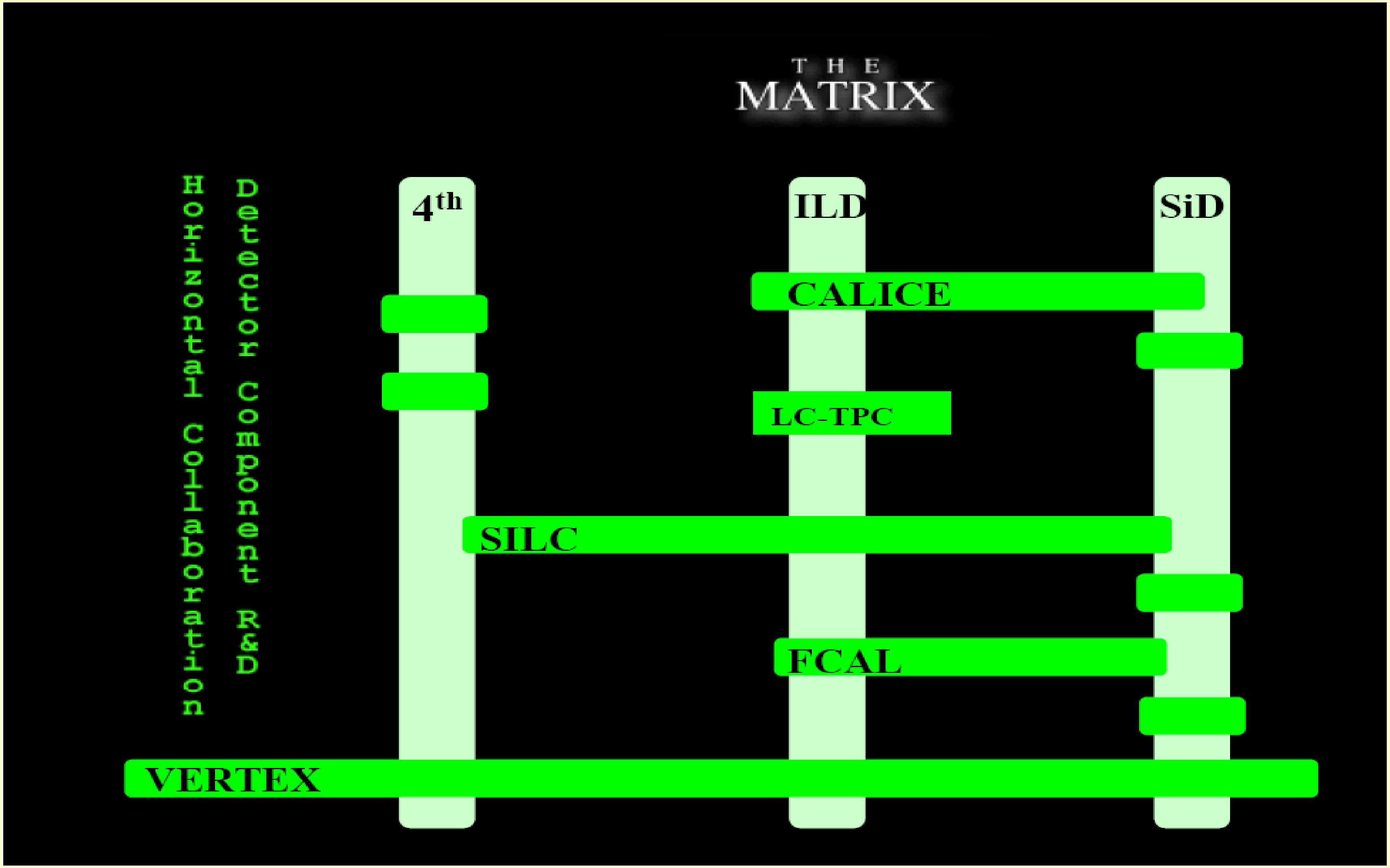
Component R&D

„Horizontal“ R&D

Collaborations

(I won´t be complete here)

Detector concepts vs. Component R&D



→ try to do as much R&D as possible <u>across different detector concepts</u>

MPGDs in ILC Detectors

LC-TPC: MPGD readout

- GEMs → T. Matsuda Sat, 11:35h
- Micromegas → D. Attie Sat, 11:10h
- Micromegas + resistive foil → M. Dixit Sun 11:05h

-+ resisitve foil

- GEMs + Pixels → J. Kaminski Sat, 12:00h
- Ingrids

Digital HCAL

- with GEM r/o → A. White Fri, 16:40h
- with Micromegas r/o → M. Chefdeville Fri 17:05h

Vertex Detector (using Gossip) (not yet proposed…)

will not cover those in detail…

Component R&D – PFlow Calorimter

CALICE collaboration: Calorimetry for Linear Collider Experiments

Goal: prepare realistic proposal for fine-grained PFlow calorimeters (ECAL + HCAL) by 2012

2 stages:

„Physics“ prototypes:
  proof of principle
  validate simulation (Geant4 showers)
  validate reconstruction (PFlow algorithms)

„Engineering“ prototpyes:
  address technical design issues
  compact mechanics
  integrated electronics

Stage 1 – various testbeam campaigns at DESY, CERN, Fermilab 2006-2009

now going into Stage 2

CALICE – 1st generation test beams

Prototypes:

SiW ECAL, ScintFe HCAL (SiPM r/o) – complete

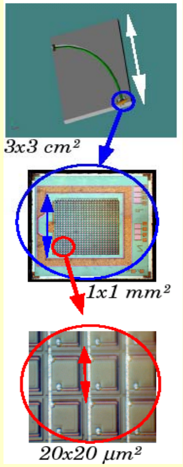
ScintW ECAL, ScintFe HCAL – ~complete

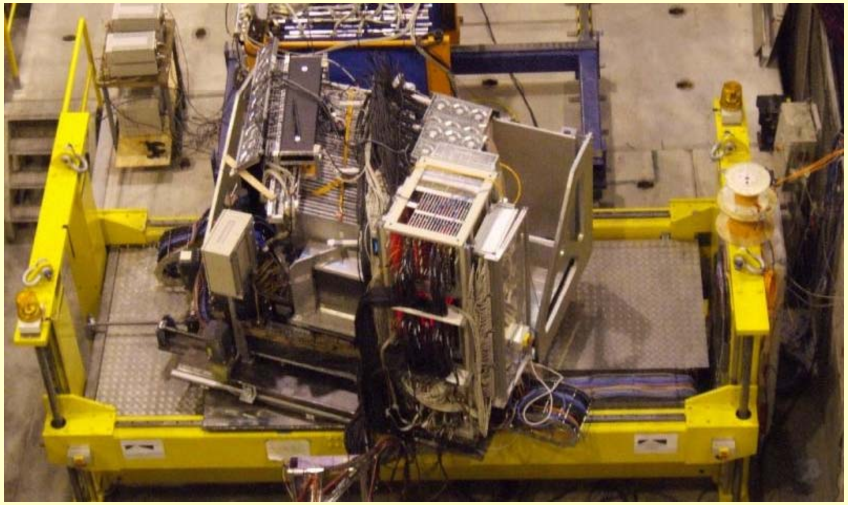
SiW ECAL, RPC/GEMFe HCAL – under construction

Digital ECAL (MAPS) – proof-of-principle in preparation

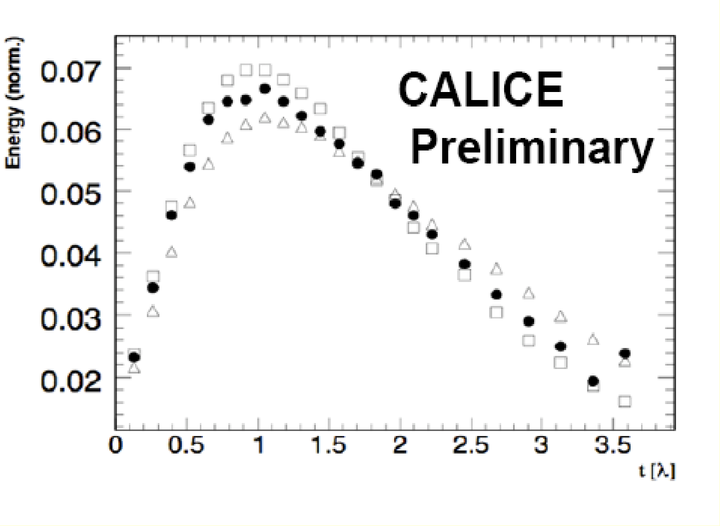
Data analysis under way

SiPM



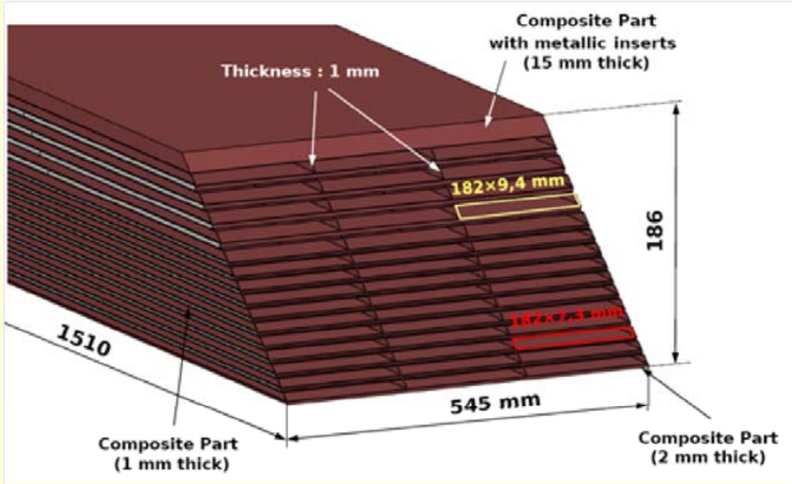


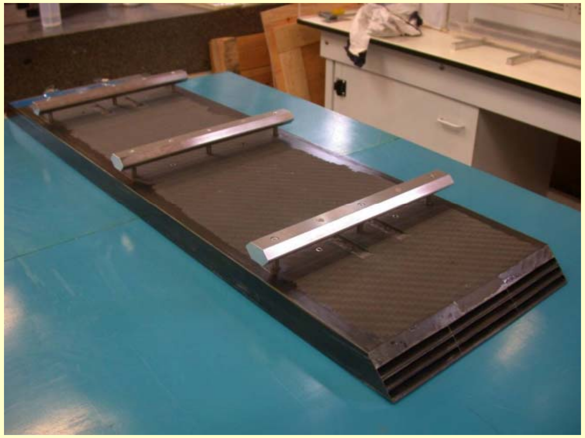
Setup at CERN



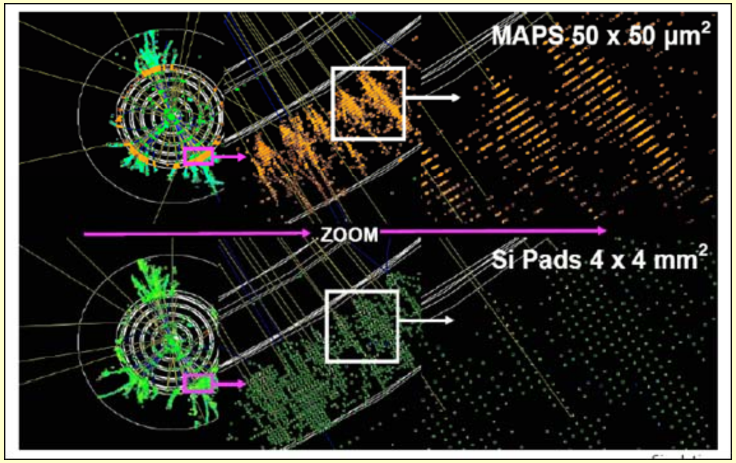
First shower profiles

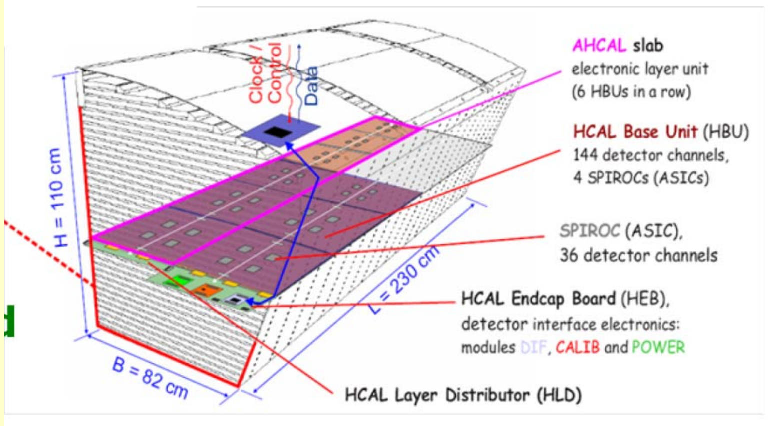
CALICE – 2nd generation prototypes





Address integration issues - Realistic dead space - Cost





LC-TPC

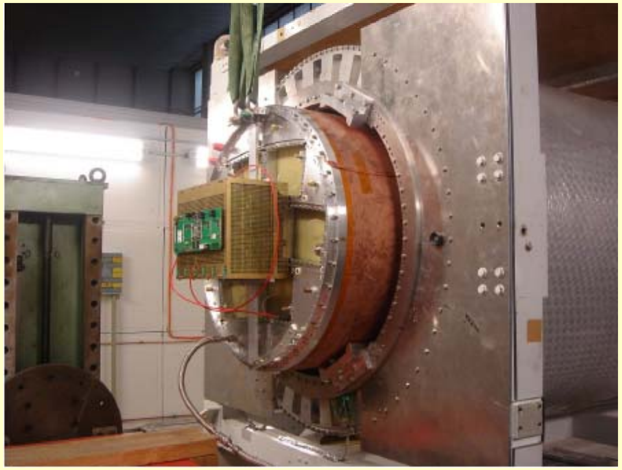
Goal: prepare a realistic proposal for high-resolution TPC with MPGD readout by 2012

3 phases:

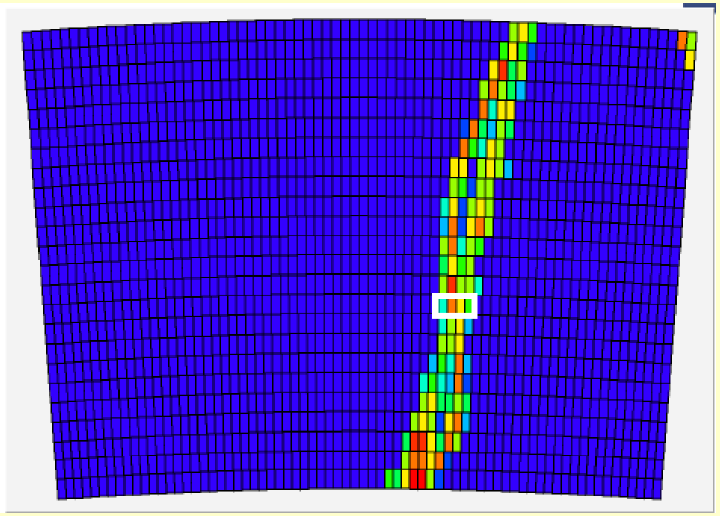
Demonstration phase – small prototypes
- ~done for pad readout – ongoing for Pixel-R/O (Timepix)

Consolidation phase – „Large Prototype“ at EUDET facility at DESY
- ongoing

Design phase – engineering design (endplate material, electronics integration, cooling)



Large TPC Prototype in 1T PCMAG



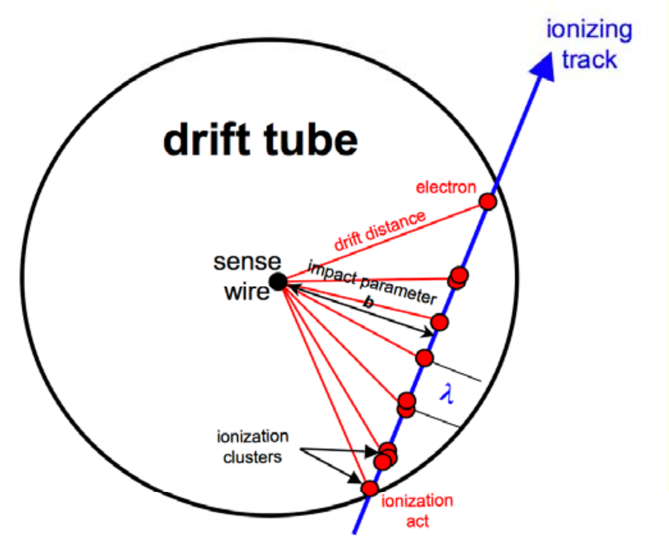
Component R&D – CLUCOU Drift Chamber

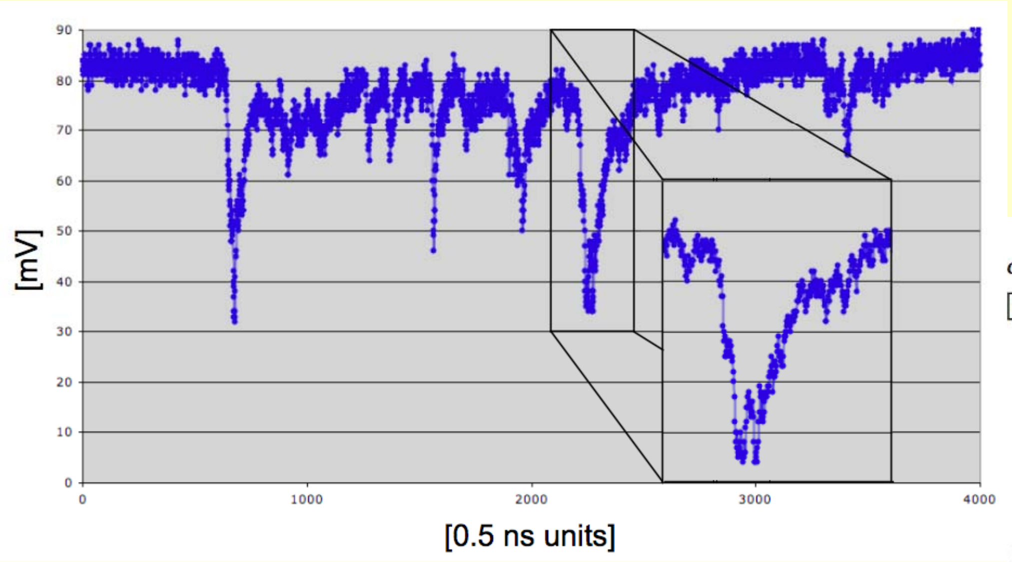
Alternative approach for charged particle tracking in 4th concept

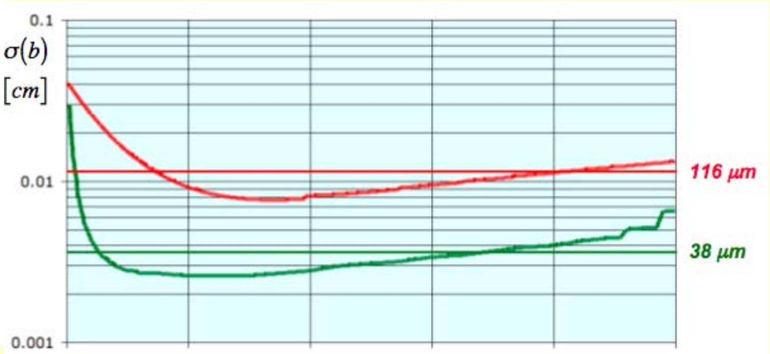
Large drift chamber with dE/dx capability via cluster counting

Cluster timing:

record the drift times of all individual ionization electrons collected on a sense wire → multi-GHz FADC needed







Cluster Timing

Component R&D – Resources & Manpower

- rather large world-wide effort for LC detector
- recently also CERN set up a group for a CLIC detector concept (based on ILC detector concepts and technologies)
- manpower critical, especially in US
- some important aspects not yet addressed, e.g. powering schemes
- not all possible synergies are exploited
  - → common testbeam infrastructure for a „vertical“ test
  - → trans-concept software platform
  - → synergies with other experiments/projects, e.g. sLHC (example Gossip / Pixel-TPC …)
- funding(!)   in EU: improve infrastructure with next FP7 call

Timescales and Plans

2007

Call for Letters of Intent

2009

Submission of LoI´s (done)

Iteration with IDAG Evaluation in fall

Move on towards Engineering design

Continue with critical R&D

2012

Prepare (light) engineering design report

in step with machine

Be technically ready

Demonstrate that we can start if we may

ILC research director
(S. Yamada)

Conclusions

- ILC (+CLIC) detector pose a challenge to detector development
- Detector LoIs exist and are being reviewed
- Now entering phase of (light) engineering design (on top of fundamental R&D
- MPGDs play an important role in many ILC subedectors

A typical LC event

precise reconstruction

is important!

this example:

- lack of statistics
  (only one Diskos found,
  but very low background)

- no good theory yet
  (noone understands what is
  written there)

fascinating…