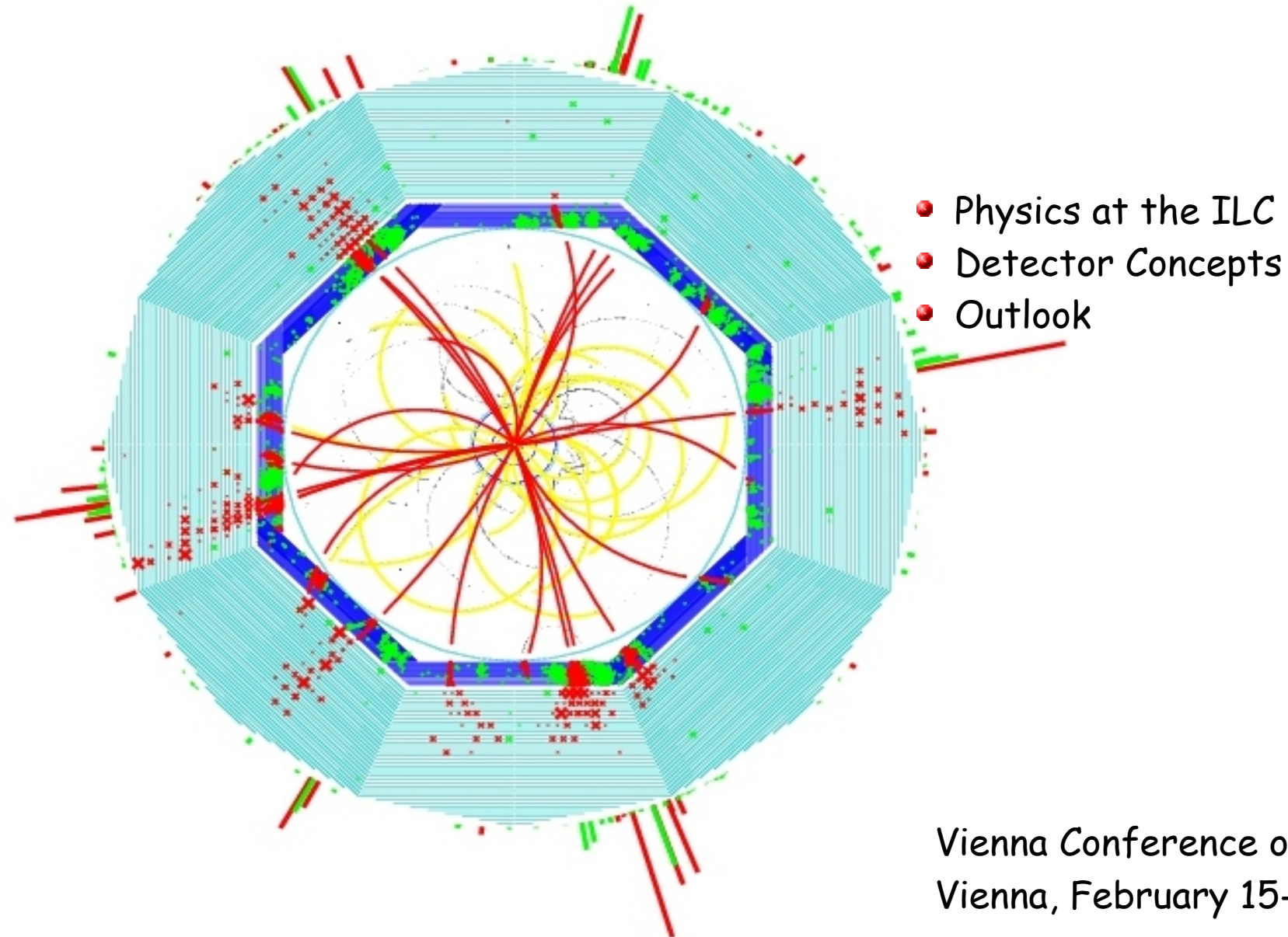
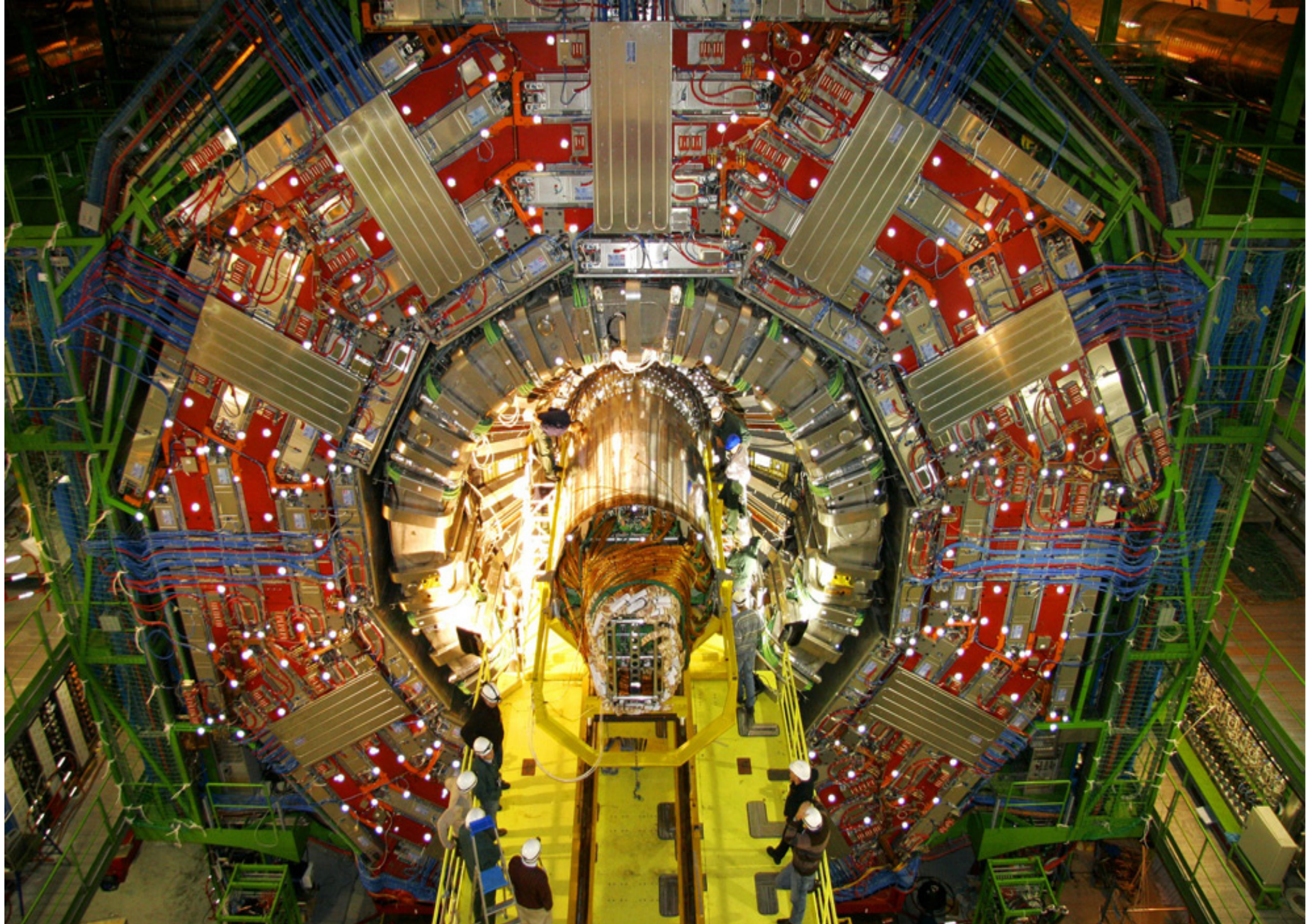


# Detector Concepts at the ILC

Ties Behnke, DESY



Vienna Conference on Instrumentation,  
Vienna, February 15-20



# Collider Types

## Hadron Collider (pp)

Composite particles collide  
 $E(\text{CM}) \ll 2 E(\text{beam})$

Strong interaction in initial state  
Superposition with spectator jets

**LHC:**  $\sqrt{s} = 14 \text{ TeV}$

Fraction of energy available for hard scattering

Small fraction of events analysed  
Multiple triggers  
No polarisation applicable

## Lepton Collider (e+e-)

Pointlike particles collide  
 $E(\text{CM}) \sim 2 E(\text{beam})$

Well defined initial state  
Clear final state

**ILC:**  $\sqrt{s} = 250 \text{ GeV} - 1 \text{ TeV}$

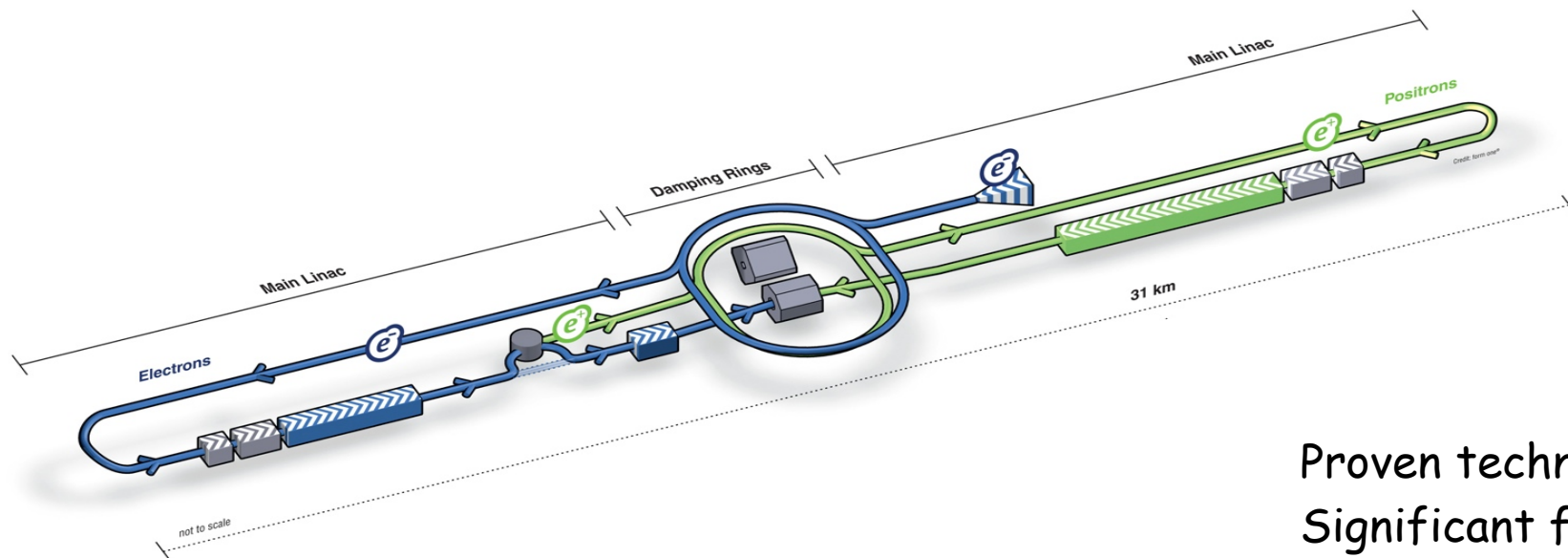
**CLIC:**  $\sqrt{s}$  up to 3 TeV

Nearly full energy of collision will be available for analysis

Most events in detector analysed  
No hardware trigger, very open system  
Polarisation of initial beams possible



# The Linear Collider



Proven technology  
Significant facilities  
exist or are under  
construction (XFEL)

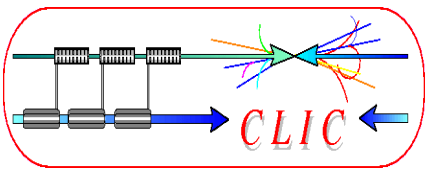
The international Linear Collider:

Superconducting acceleration technology

High Luminosity at  $E=500\text{GeV}$  to  $1\text{ TeV}$  or lower energies

About 31km site length

$E=500\text{ GeV} \rightarrow 1\text{ TeV}$   
 $L=2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$   
 $500 \text{ fb}^{-1}$  in 4 years



# CLIC

## Two Beam Scheme

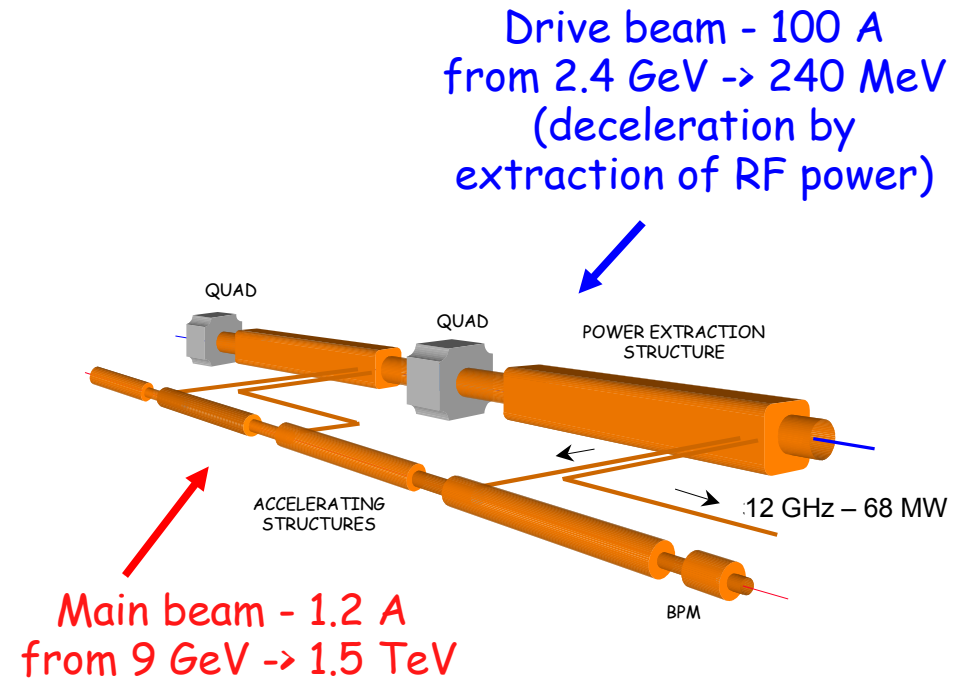
### Drive Beam supplies RF power

- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

### Main beam for physics

- high energy (9 GeV - 1.5 TeV)
- current 1.2 A

Technology is not proven  
Intense R&D effort at CERN



No individual RF power sources

->

CLIC itself is basically  
a ~50 km long klystron...

# The LC Physics Agenda

Explore the physics at the scale of electroweak symmetry breaking

- Higgs Physics
- Standard Model Physics at "Terascale"

Physics beyond the Standard Model

- Search for new physics (Supersymmetry, ...)
- Explore the Terascale

Follow up on any discoveries the LHC might have made

# The LC Physics Agenda

Explore the physics at the scale of electroweak symmetry breaking

- Higgs Physics
- Standard Model Physics at "Terascale"

Physics beyond the Standard Model

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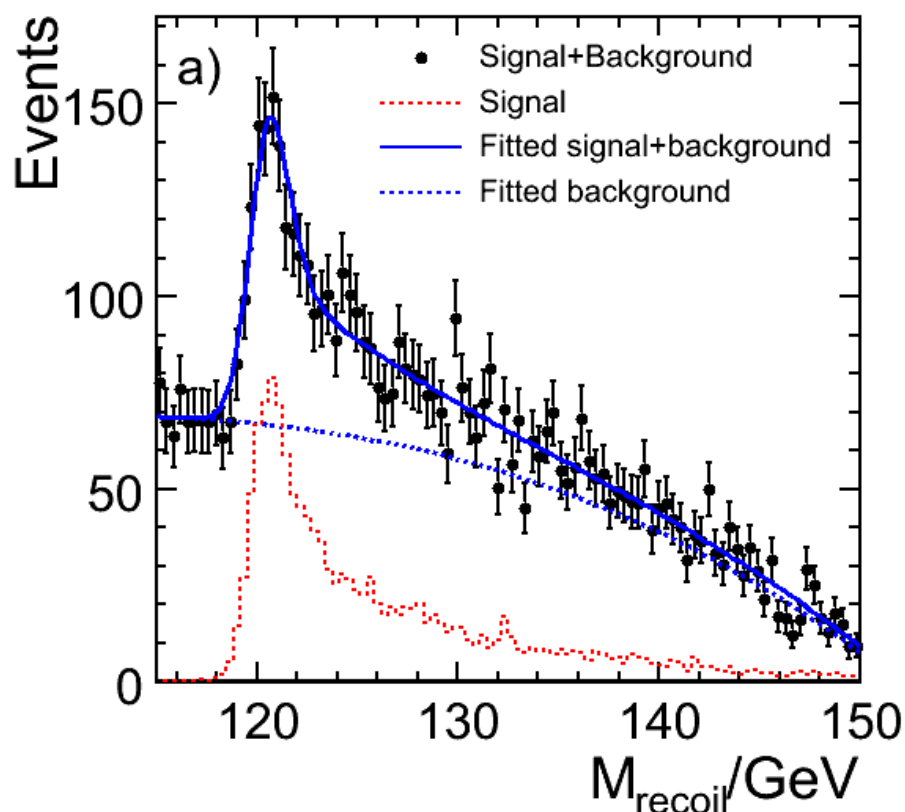
Indirect hints:  
500 GeV option is attractive

Results from LHC will  
help to define final  
energy

Follow up on any discoveries the LHC might have made

# Physics Challenges

A very selective  
and incomplete  
view



Explore the complete Higgs Sector,  
including Higgs self coupling

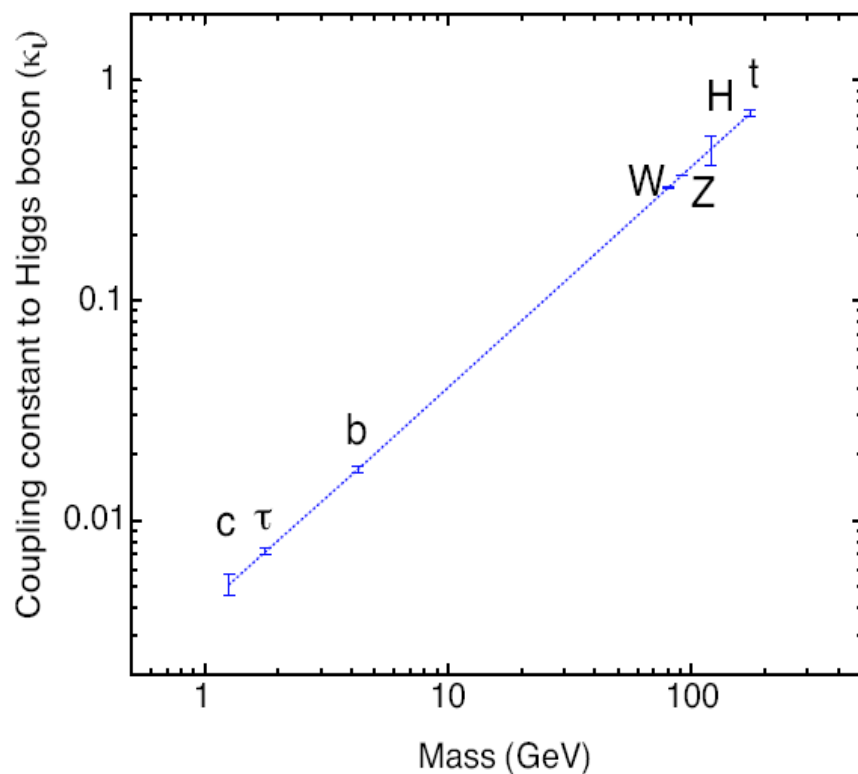
- Multi Jets in the final state
- need excellent jet-energy resolution to get decent measurement

“Fully” explore the physics at the Terascale, establish the models and mechanisms

# Physics Challenges

A very selective  
and incomplete  
view

Coupling-Mass Relation



ACFA LC Study

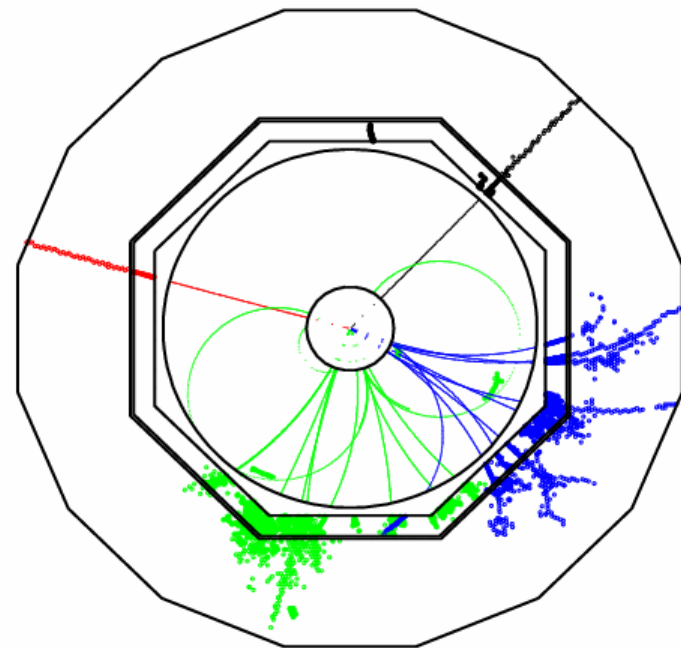
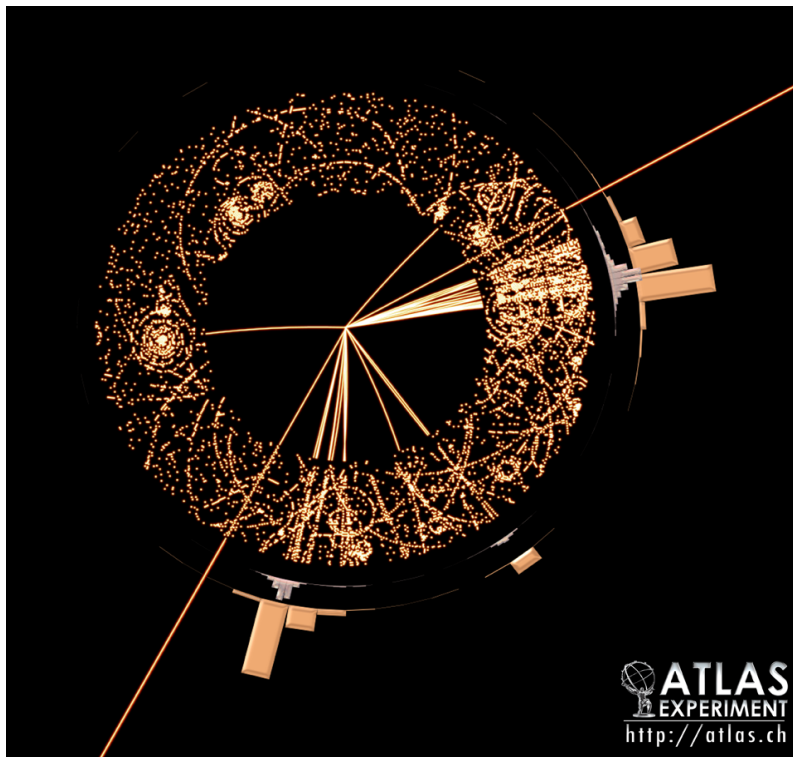
Explore the complete Higgs Sector,  
including Higgs self coupling

- Multi Jets in the final state
- need excellent jet-energy resolution to get decent measurement

**"Fully" explore the physics at the Terascale, establish the models and mechanisms**

# Events at the ILC

- Point like particle collide, few particle per event, clean topologies, ...



™ M. Thomson, Cambridge

Much simpler events than LHC, can focus much more on detailed event properties

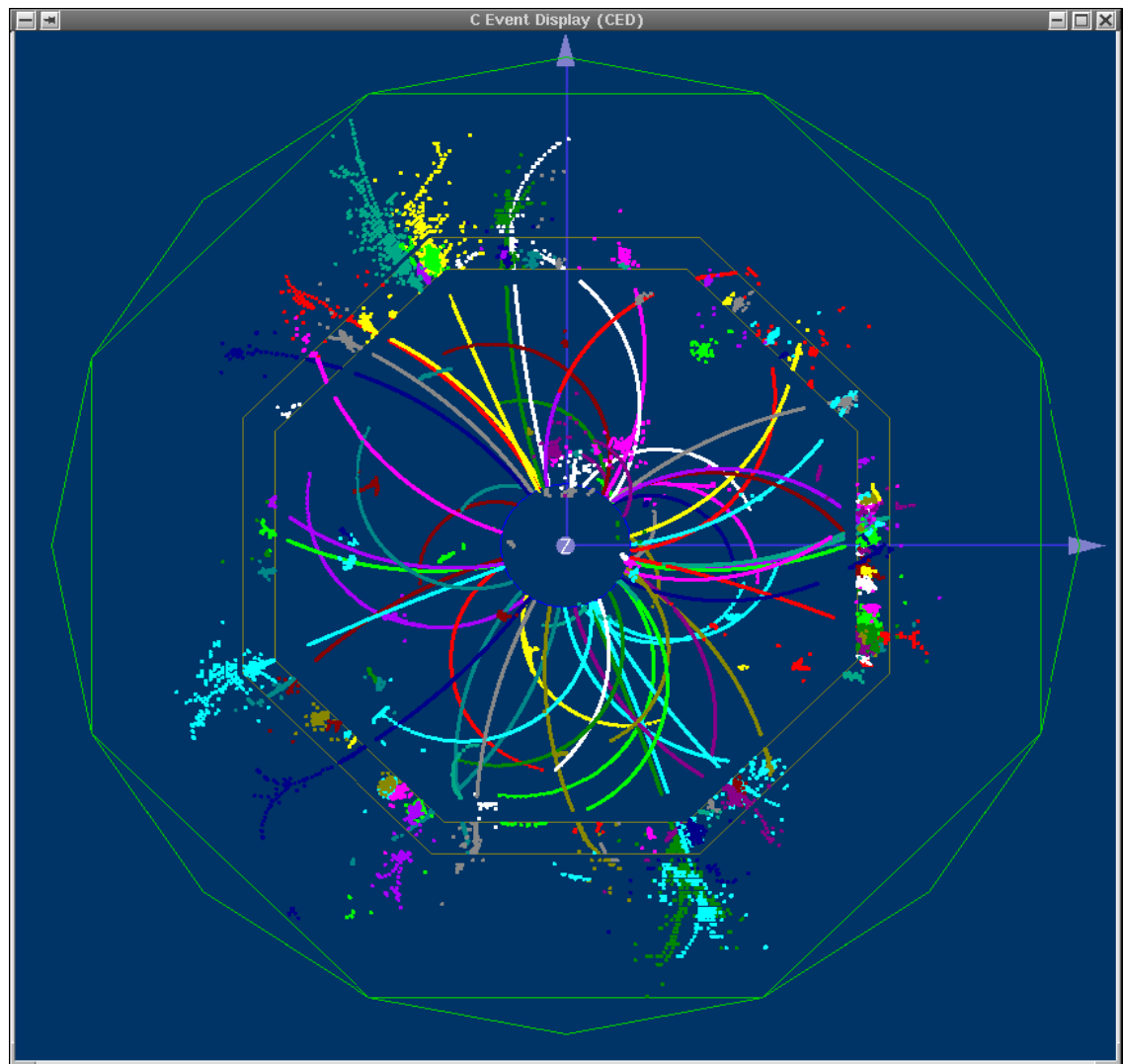
# The States

Events at the ILC:

- multi jet final states
- leptons, often in jets
- forward going physics

Jet energy reconstruction  
plays a central role at the  
ILC

$t\bar{t}$  event at the ILC (ILD model)



# Detector Requirements

Excellent vertexing  
as close as possible to the IP

Robust, three dimensional tracking  
high efficiency, do not forget the low  
energy tracks

Powerful calorimeter  
good photon identification

hermeticity

# Detector Requirements

Excellent vertexing  
as close as possible to the IP

Robust, three dimensional  
high efficiency, do not form  
energy tracks

Jet Reconstruction:  
Energy, Direction  
Particle Flow

Powerful calorimeter  
photon identification

hermeticity

# Event Reconstruction

Excellent jet reconstruction needed

Individual particles  
particle identification  
"calculation" of total jet energy/ mass  
Compensation in software

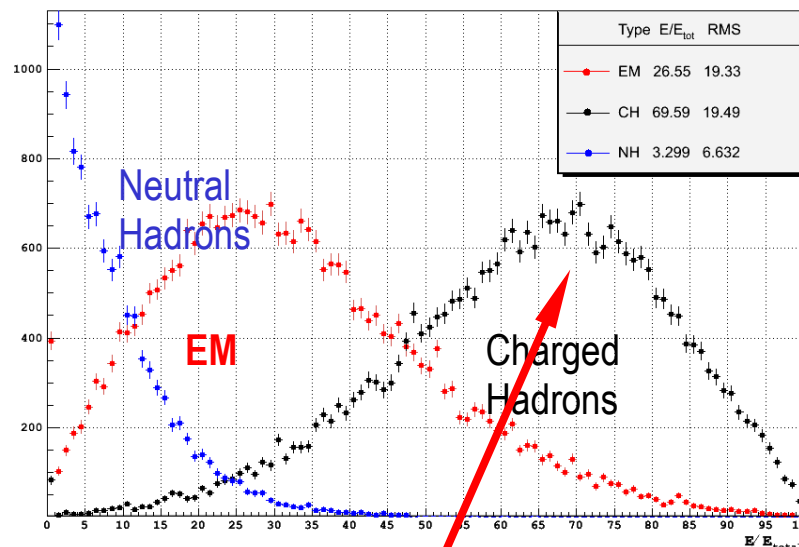
Particle flow

Individual jets  
hardware compensation  
"measurement" of total jet energy

"compensating"  
Calorimetry

# Particle Flow

- Most precise event reconstruction (measured e.g. by jet mass)
- Individual particles are reconstructed: charged and neutrals



Fundamental problem: fluctuations in the calorimeter:

use tracker as much as possible

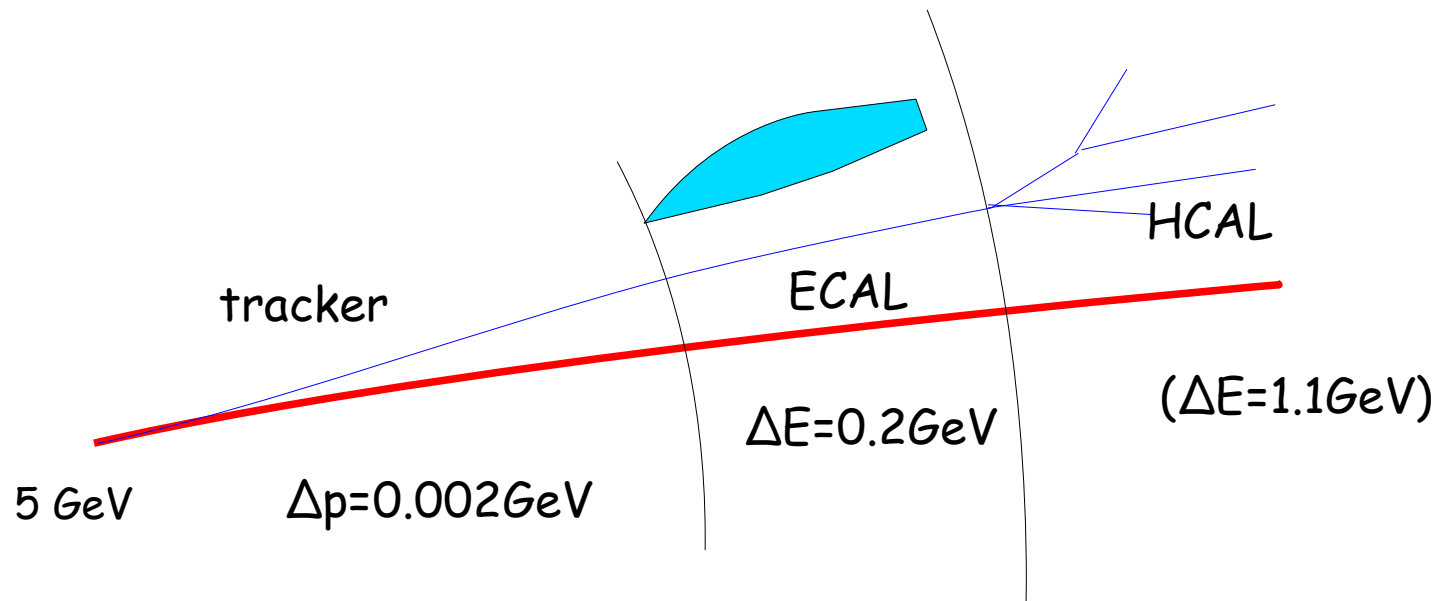
replace information in calorimeter by tracker information

only use calorimeter for neutral particles (photons, neutral hadrons)

Pushes requirements for calorimeter:  
excellent segmentation  
energy resolution is of lesser importance

30%/√E (below 100 GeV)  
is the goal

# What is Particle Flow

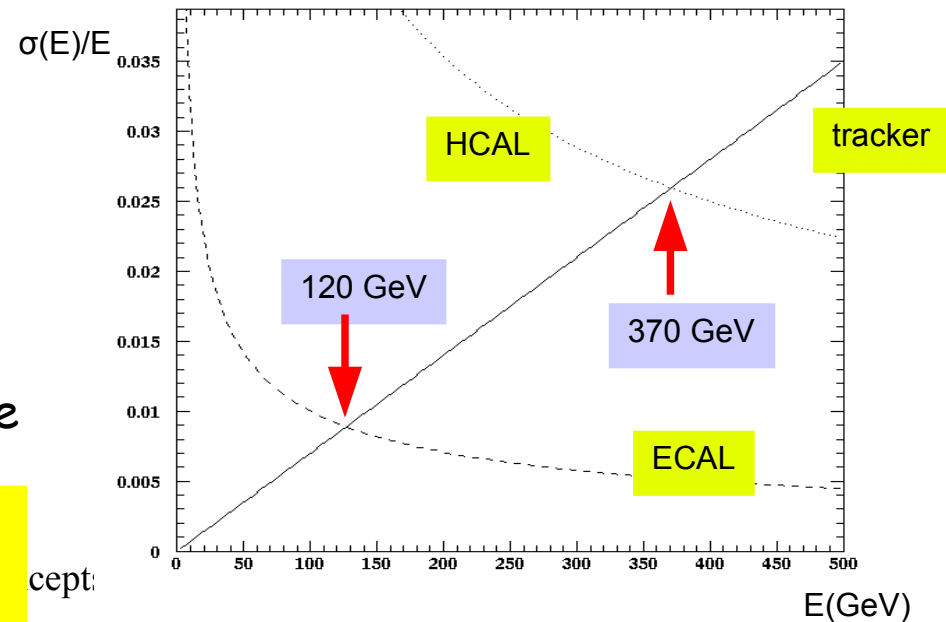


5 GeV electron: 0.002 GeV  
 photon: 0.2 GeV  
 neutron: 1.1 GeV

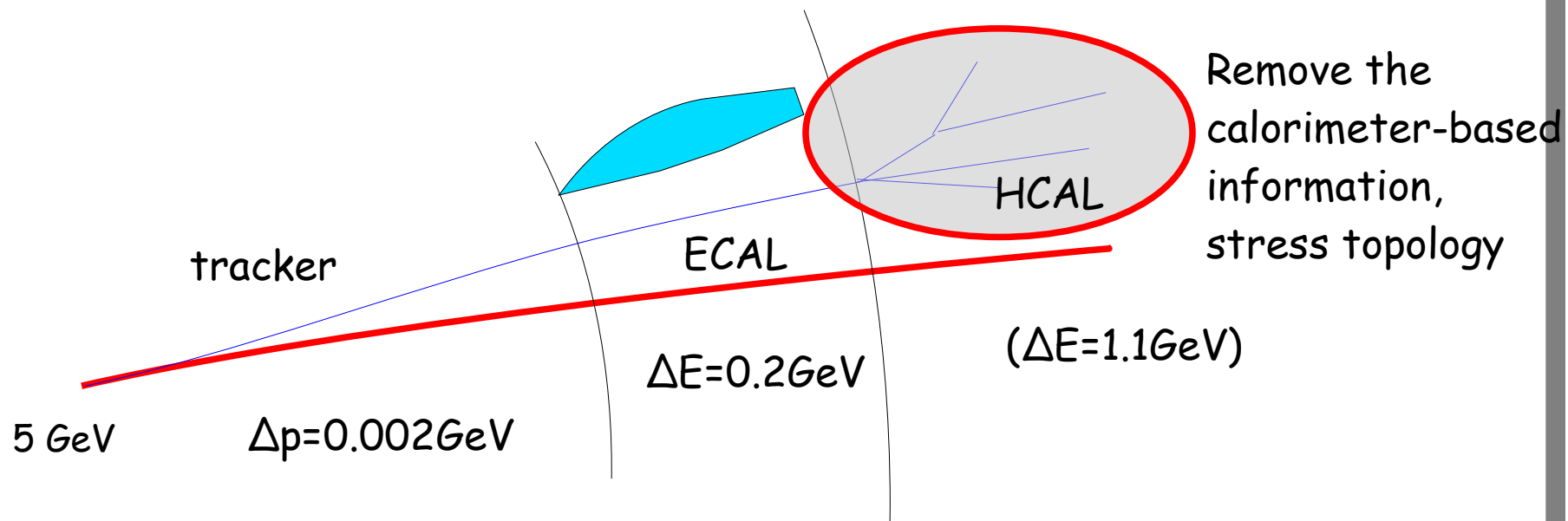
For LC energies: tracker is most precise

Utilize the precise tracker as much as possible

Resolution tracker - Calorimeter



# What is Particle Flow

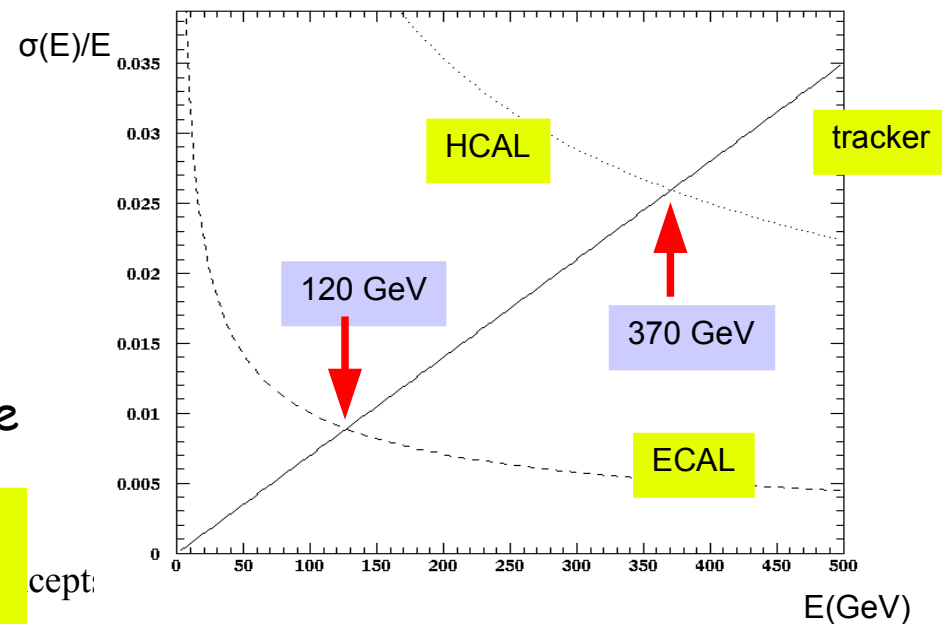


5 GeV electron: 0.002 GeV  
 photon: 0.2 GeV  
 neutron: 1.1 GeV

For LC energies: tracker is most precise

Utilize the precise tracker as much as possible

Resolution tracker - Calorimeter



# Perfect PFA : What theory predicts

- Jet energy resolution  
 $\sigma^2(E_{\text{jet}}) = \sigma^2(\text{ch.}) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(\text{conf.})$

Typically  $w_g = 25\%$  ;  $w_{h^0} = 13\%$

- Excellent tracker :  
 $\sigma^2(\text{ch.}) \ll \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(\text{conf.})$

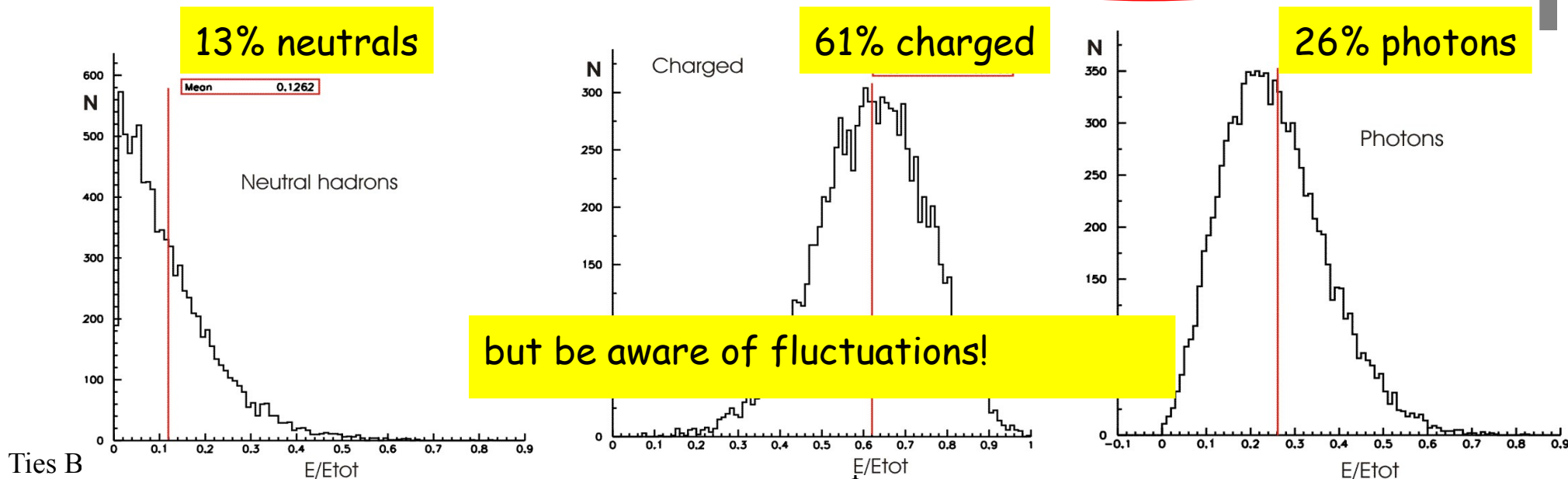
$$A_g = 11\% ; A_{h^0} = 34\%$$

$$\Rightarrow \sigma(E_{\text{jet}})/E_{\text{jet}} = 14\%/\sqrt{E_{\text{jet}}}$$

- Perfect PFA :  $\sigma^2(\text{conf.}) = 0$   
 $\sigma^2(E_{\text{jet}}) = A_g E_{\gamma} + A_{h^0} E_{h^0} = w_g A_g E_{\text{jet}} + w_{h^0} A_{h^0} E_{\text{jet}}$   
 $\sigma(E_{\gamma,h})/E_{\gamma,h} = A_{\gamma,h}/\sqrt{E_{\gamma,h}}$

$$A_g = 11\% ; A_{h^0} = 50\%$$

$$\Rightarrow \sigma(E_{\text{jet}})/E_{\text{jet}} = 17\%/\sqrt{E_{\text{jet}}}$$



# Factors Contributing to Jet mass resolution

$$e^+ e^- \rightarrow Z^0 \rightarrow q \bar{q} \text{ at } 91.2 \text{ GeV}$$

Studies by  
P. Krstonosic

Effect	$\sigma$ [GeV] separate	$\sigma$ [GeV] not joined	$\sigma$ [GeV] total ( %/ $\sqrt{E}$ )	$\sigma$ to total
$E_v > 0$	0.84	0.84	0.84 (8.80%)	12.28
$Cone < 5^\circ$	0.73	1.11	1.11(11.65%)	9.28
$P_t < 0.36$	1.36	1.76	1.76(18.40%)	32.20
$\sigma_{HCAL}$	1.40	1.40	2.25(23.53%)	34.12
$\sigma_{ECAL}$	0.57	1.51	2.32(24.27%)	5.66
$M_{\text{neutral}}$	0.53	1.60	2.38(24.90%)	4.89
$M_{\text{charged}}$	0.30	1.63	2.40(25.10%)	1.57

HCAL becomes very important for ultimate precision

# Design Philosophy

Particle flow as main reconstruction technique

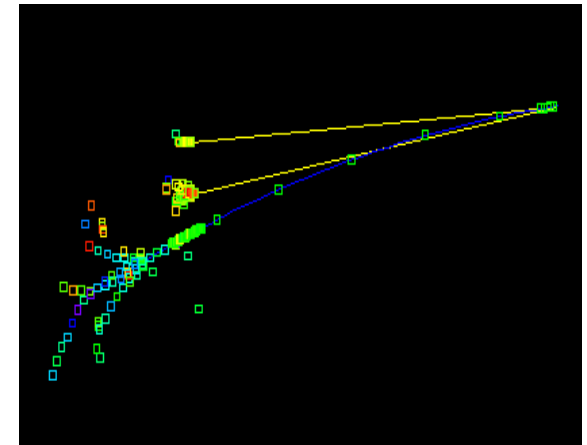
Imaging Calorimeters (CALICE)

Extreme granularity wins over energy resolution,  
in particular in the HCAL

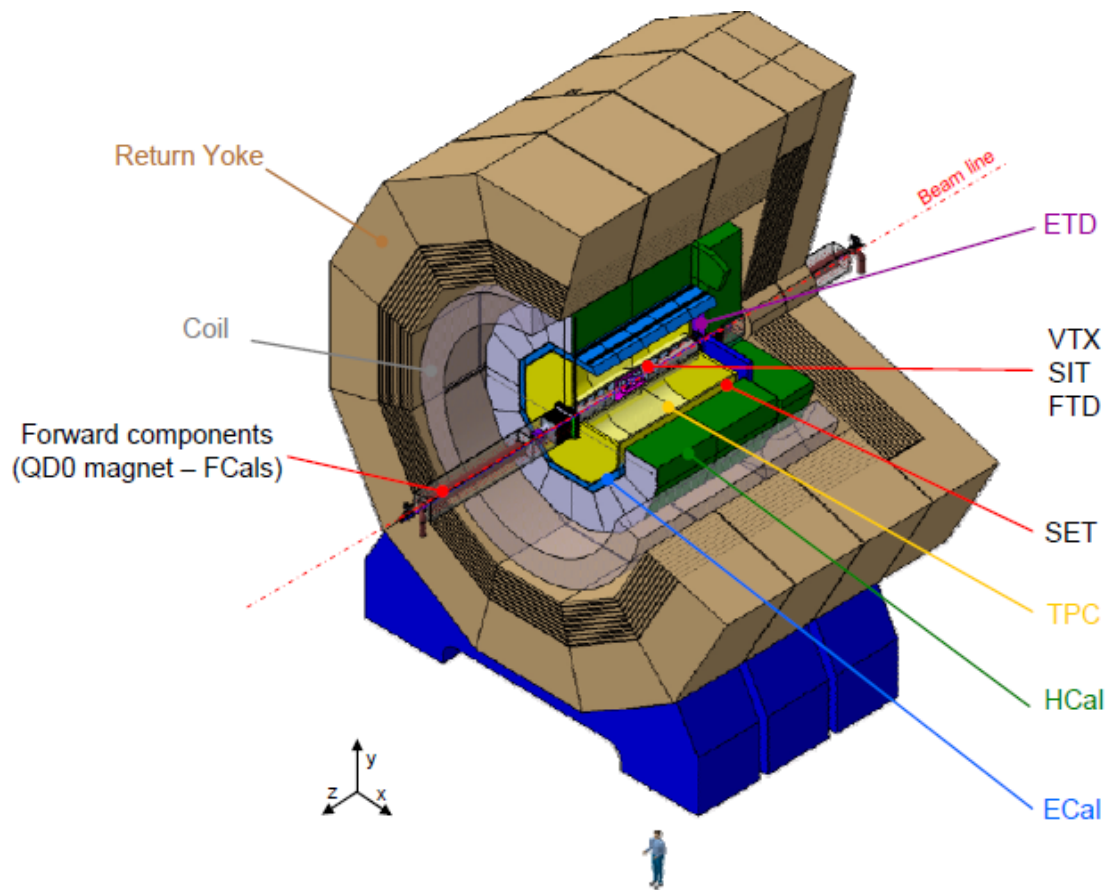
High power tracking

High efficiency, robust tracking in dense environments

High precision vertexing for heavy flavour physics



# Detector Layout



Typical multi-purpose detector

precision tracking  
precision calorimetry  
precision muon system  
hermetic

Two well developed concepts:

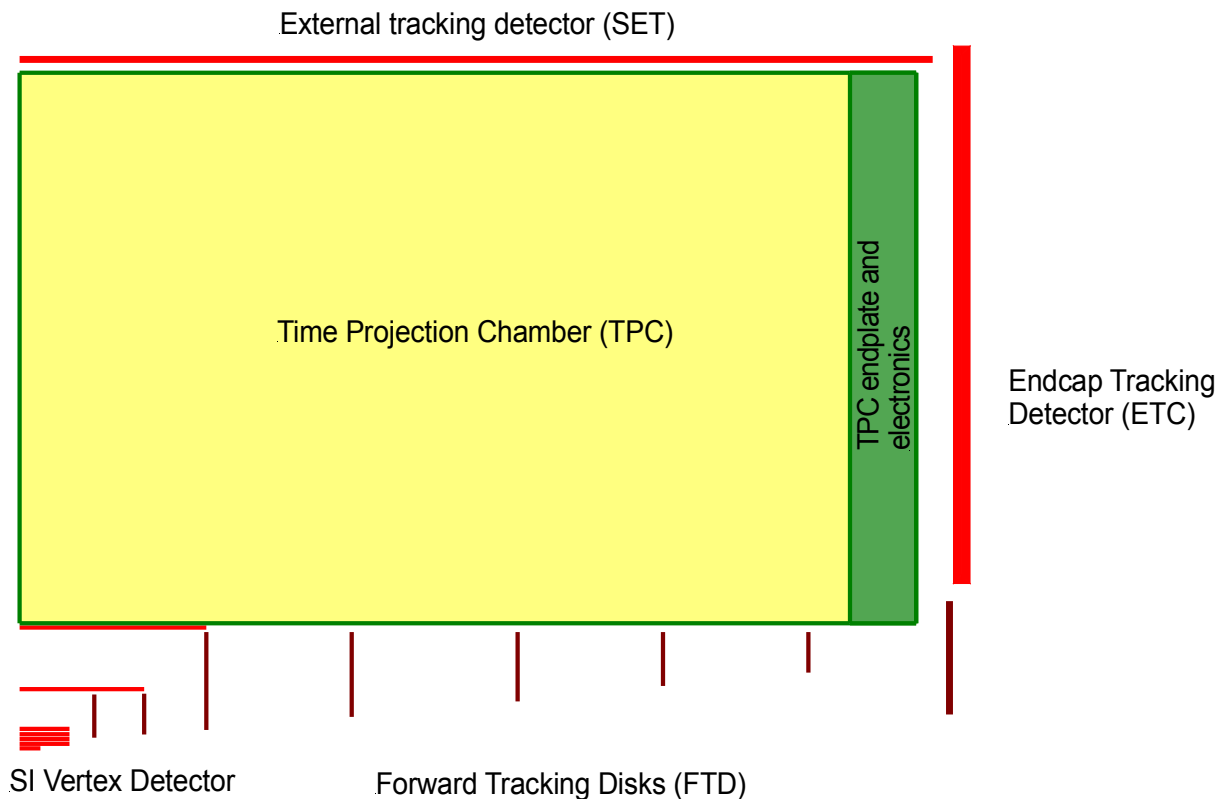
SiD ILD

# Tracking System Layout

Powerful tracking / vertexing system

excellent vertexing capability  
high precision tracking

Proposed layout  
of the ILD  
central tracking  
system



Special Focus on:

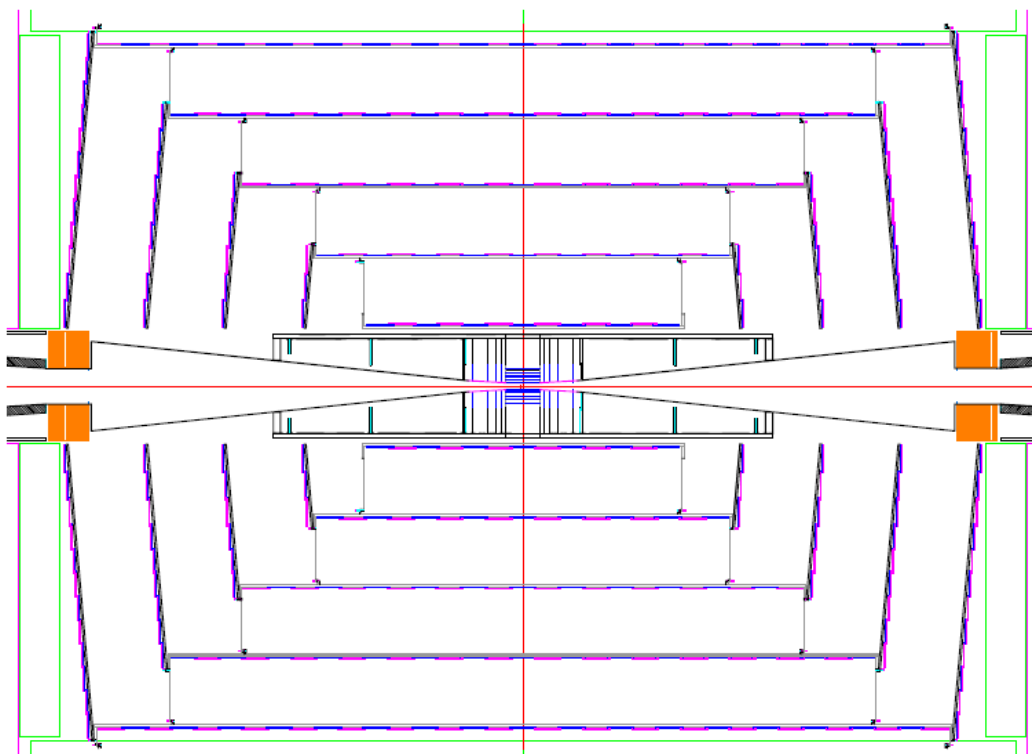
Robustness/  
Redundancy

Excellent precision

# Tracking System Layout

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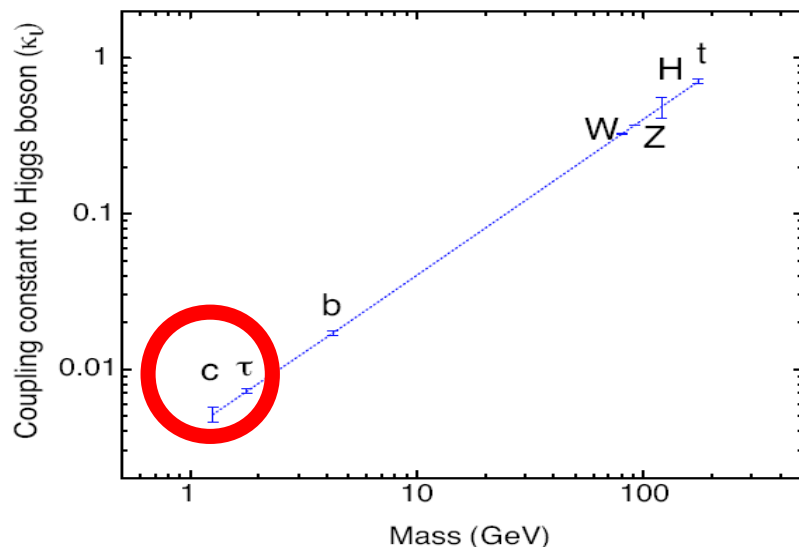
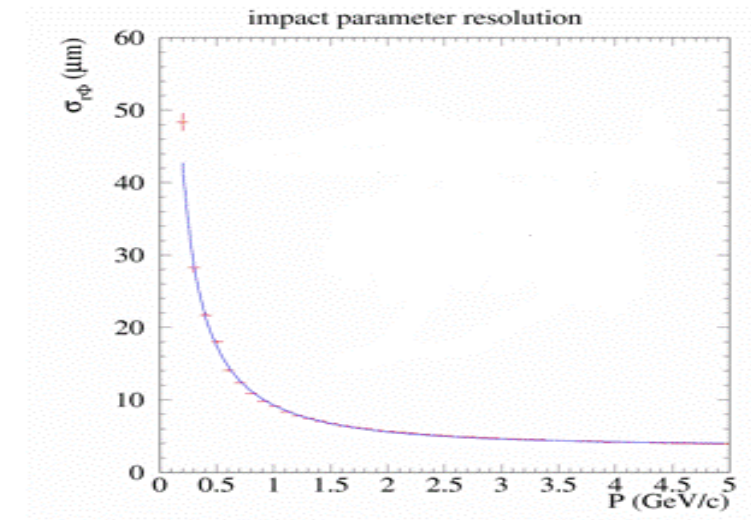
Excellent precision

# Vertexing/ Tracking

Vertexing: excellent vertexing capabilities, thin!

- Key issues:

- measure impact parameter for each track
- space point resolution  $< 3 \mu\text{m}$
- smallest possible inner radius  $r_i \approx 15 \text{ mm}$
- **transparency:  $\approx 0.1\% X_0$  per layer**  
 **$= 100 \mu\text{m}$  of silicon for 5 layers**
- stand alone tracking capability
- full coverage  $|\cos \Theta| < 0.98$
- modest power consumption  $< 100 \text{ W}$



Momentum resolution goal:  $\frac{\delta p}{p} = 5 \times 10^{-5}$

# Vertexing

Pixel detector:

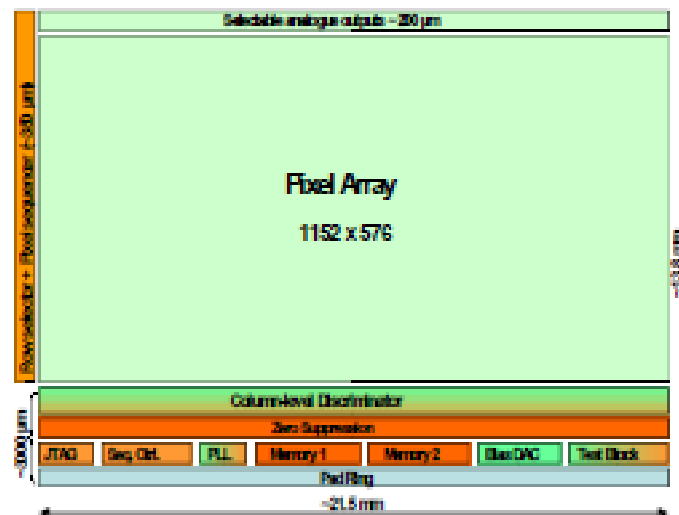
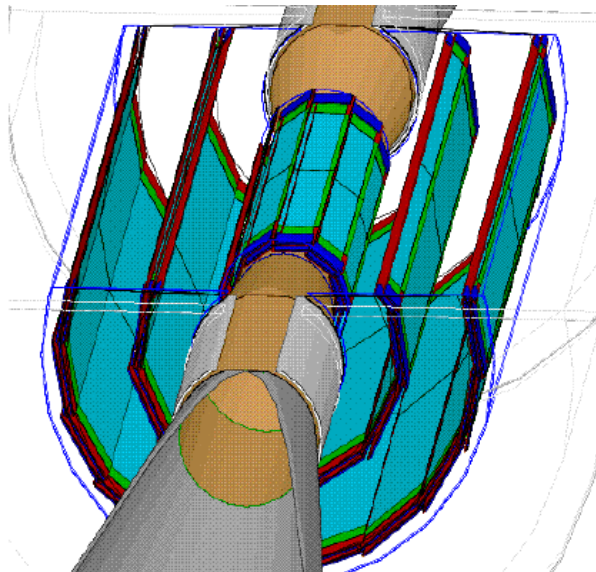
Many different technologies under discussion

Resolution - dead area - material - speed

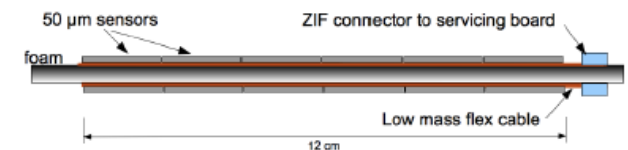
CCD - MAPS - FPCCD - ISIS - others

Low mass structure  
readout speed

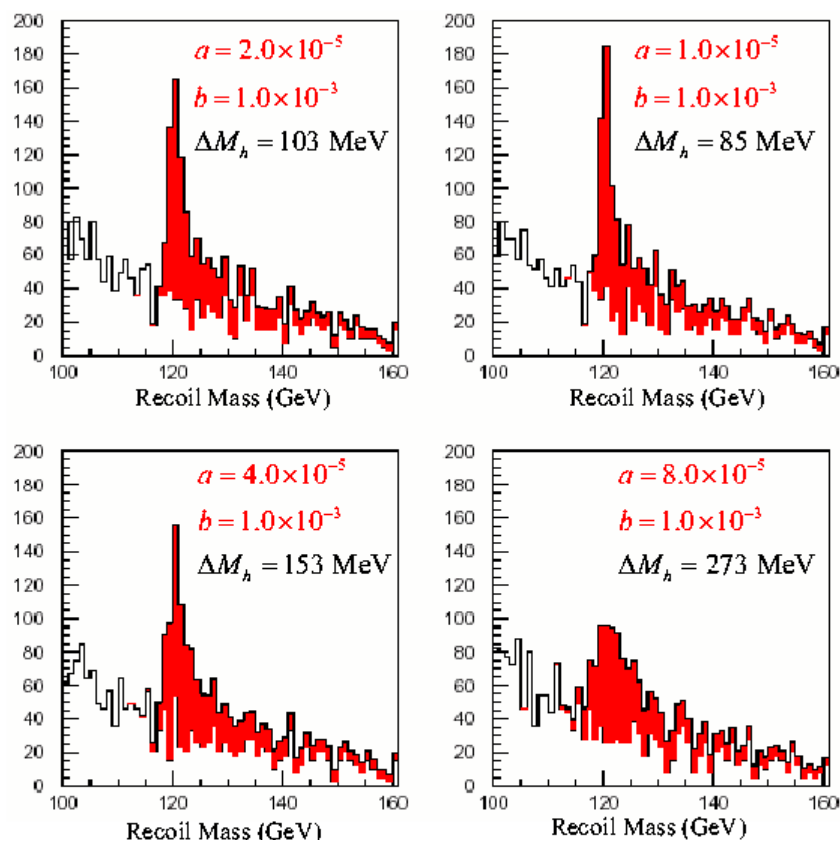
5 pixel layers, as small inner radius as possible, low material



R&D:  
Development of low mass  
ladder prototype ( $\rightarrow$  2012)



# Tracker Benchmarks

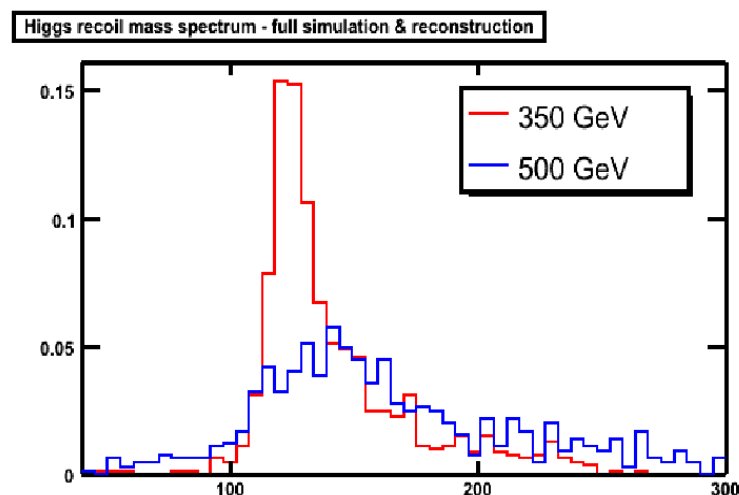


Higgs recoil mass measurement:

clear case for excellent momentum resolution

But be aware:

proper choice of  
CMS Energy may have strong effect



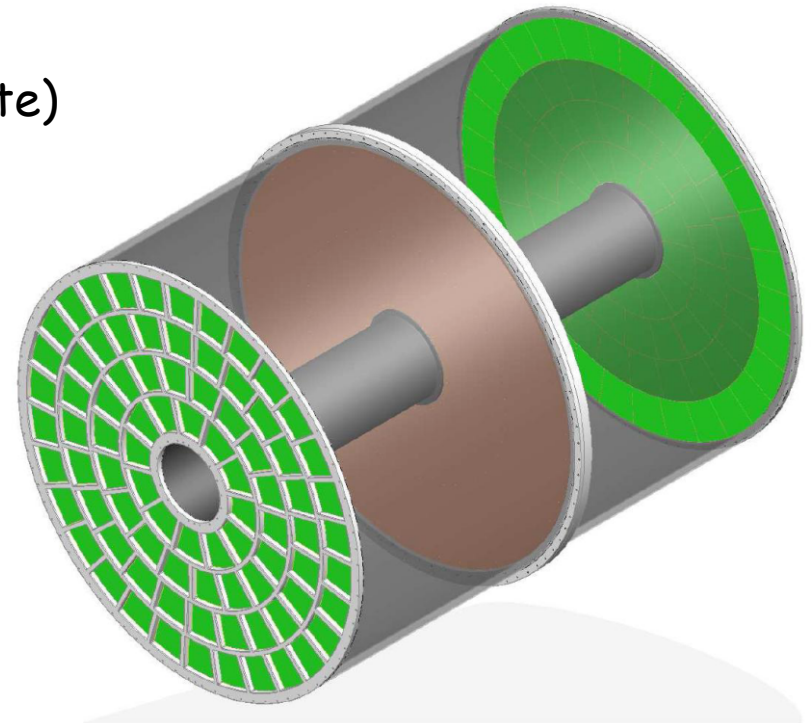
Be aware of single benchmarks -  
have to look at the complete system!

# TPC

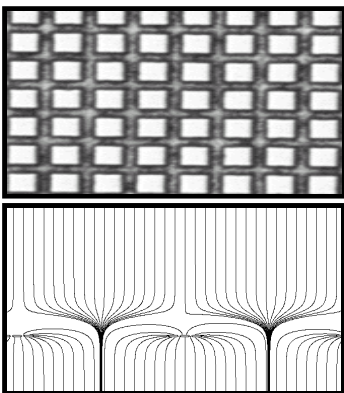


## Design (goal) of ILD TPC

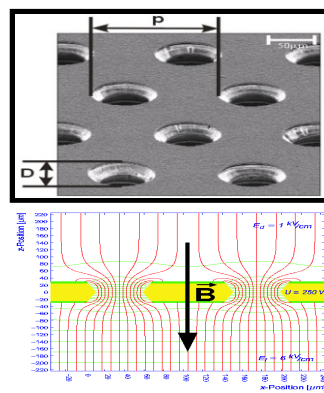
- Micro pattern gas detector (MPGD) as the TPC endcap detector
- $0.4\text{m} < R < 1.8\text{m}$ ,  $|Z| = 2.15\text{m}$
- $\sigma_{\text{point}}(r\Phi) < 100\mu\text{m}$
- $\sigma_{\text{point}}(z) \sim 0.5\text{mm}$
- Two-hit resolution  $\sim 2\text{mm}(r\Phi)$ ,  $6\text{mm}(z)$
- Material budget  $\sim 4\%X_0$  (r),  $15\%X_0$  (endplate)
- Momentum resolution:
  - $\delta(1/p_{\text{T}}) \sim 9\text{E-}5/\text{GeV}/c$  (TPC only)
  - $\delta(1/p_{\text{T}}) \sim 2\text{E-}5/\text{GeV}/c$  (all trackers)



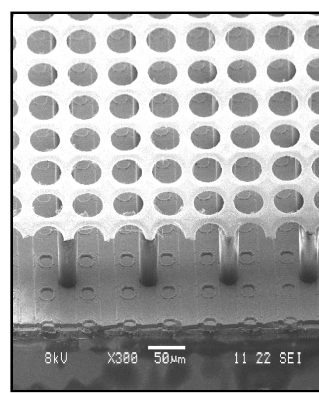
MicroMEGAS



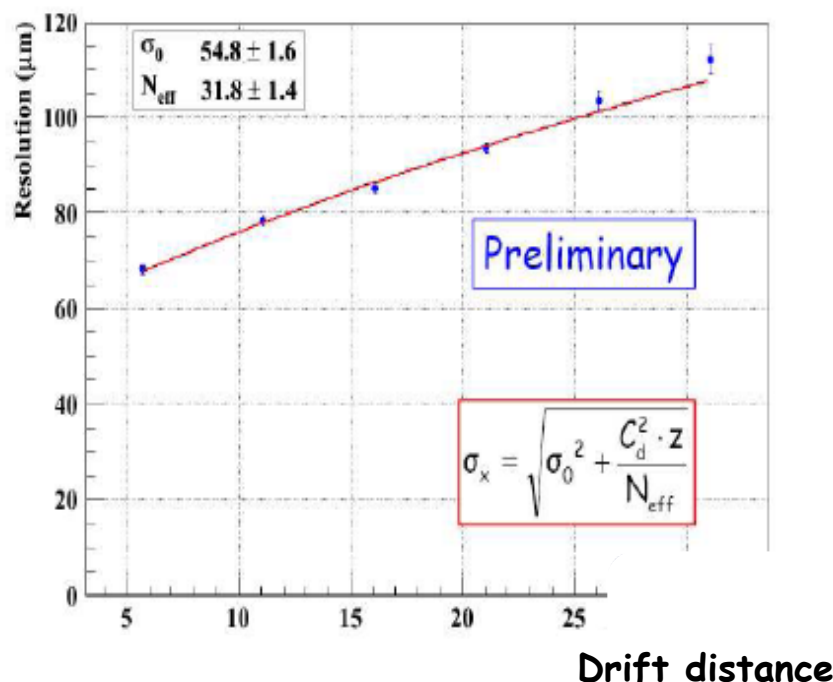
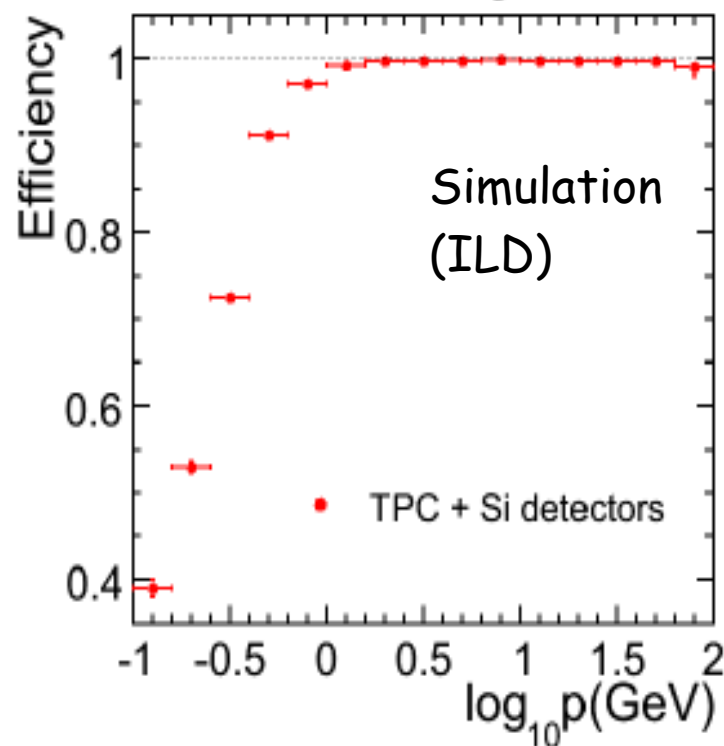
GEM



Ingrid TimePix



# Tracker Performance

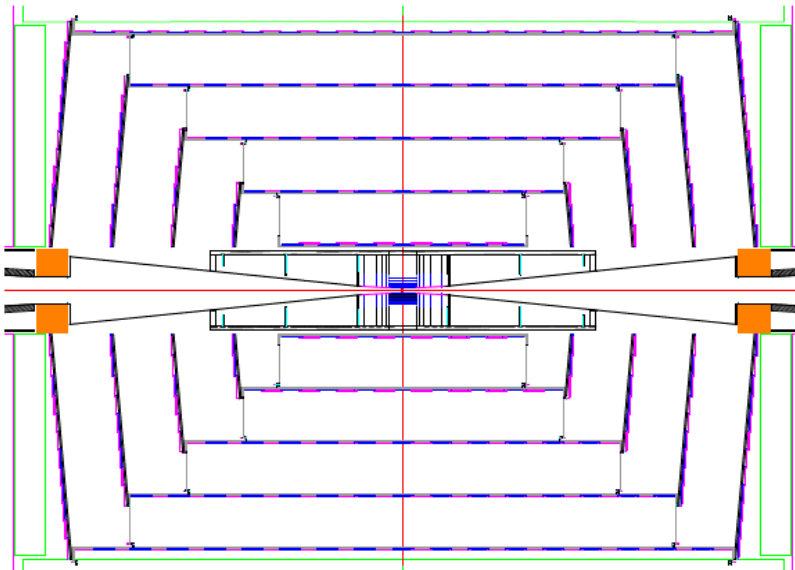


Prototype  
results  
(LCTPC)

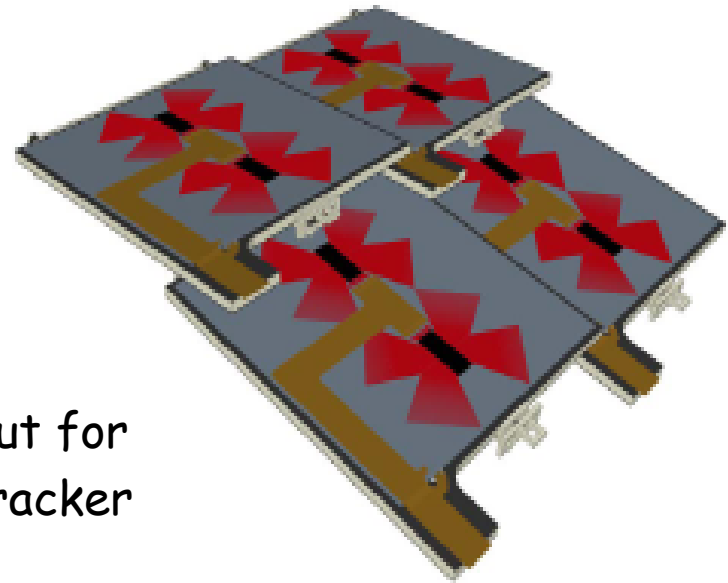
Simulated performance of the tracker

- excellent pattern recognition
- stable performance even in the presence of backgrounds

# All Silicon Tracker



Ladder layout for  
all Silicon tracker



5 layer Pixel Vertex detector  
5 layer Silicon strip detectors

Light weight, robust tracking system

Power pulsing reduces cooling requirement significantly:  
Look at air cooling option

# Material in the Tracker

TPC based  
tracker

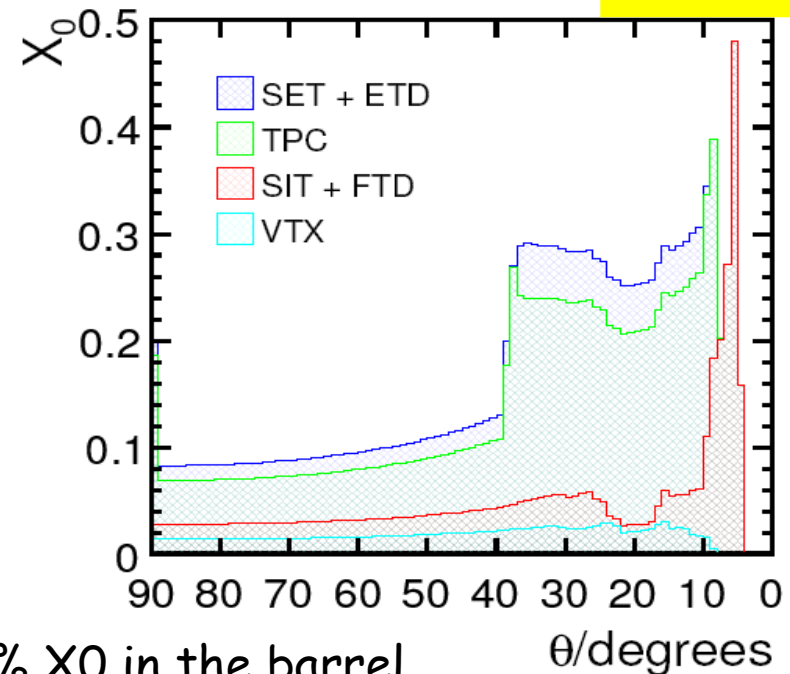
Low material tracker is key goal  
of R&D in the next few years

Goal: very light tracking system:

total material before calorimeter < 10%  $X_0$  in the barrel  
<30% (or less) in the endcap

including all services, all support structures, cables, etc.

Realistic (but optimistic) estimates make this believable...



# Material in the Tracker

Full Silicon  
Based tracker

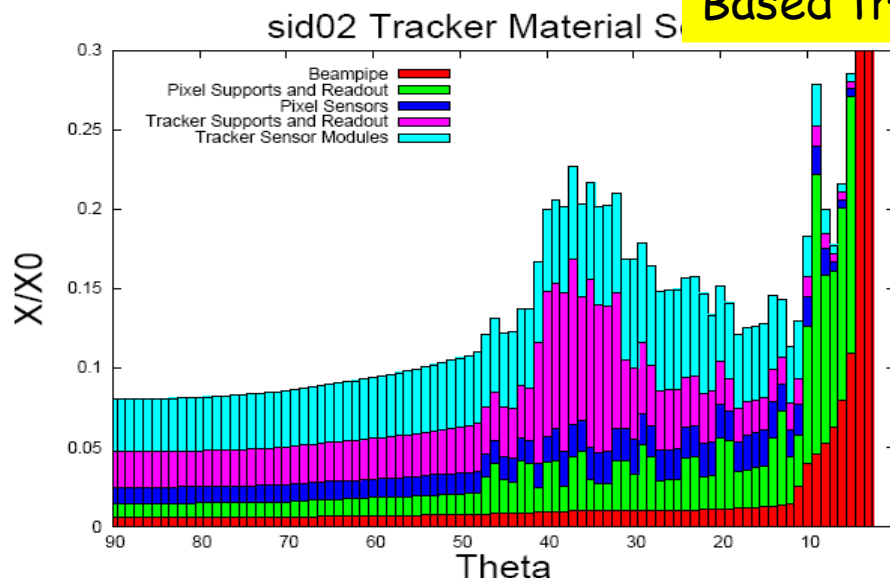
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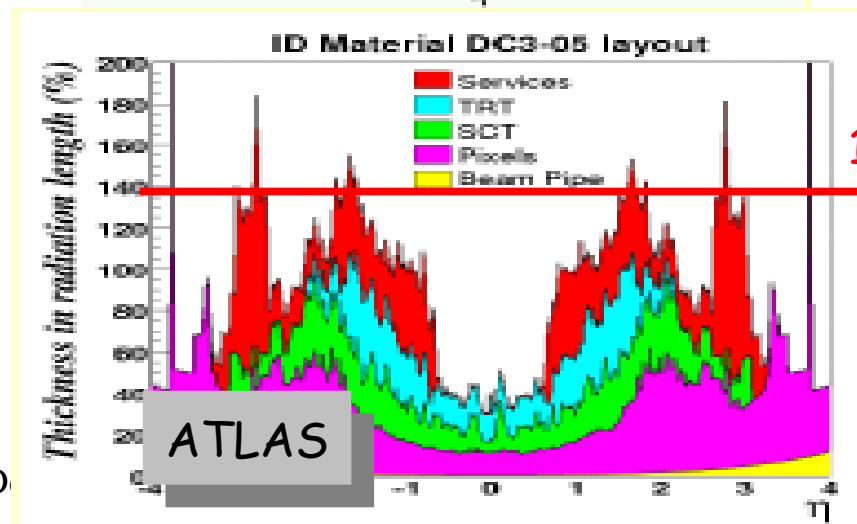
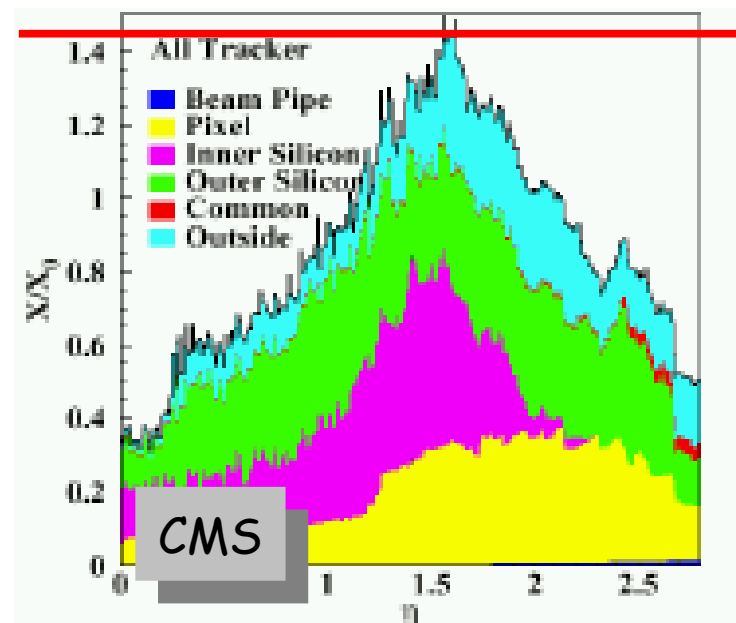
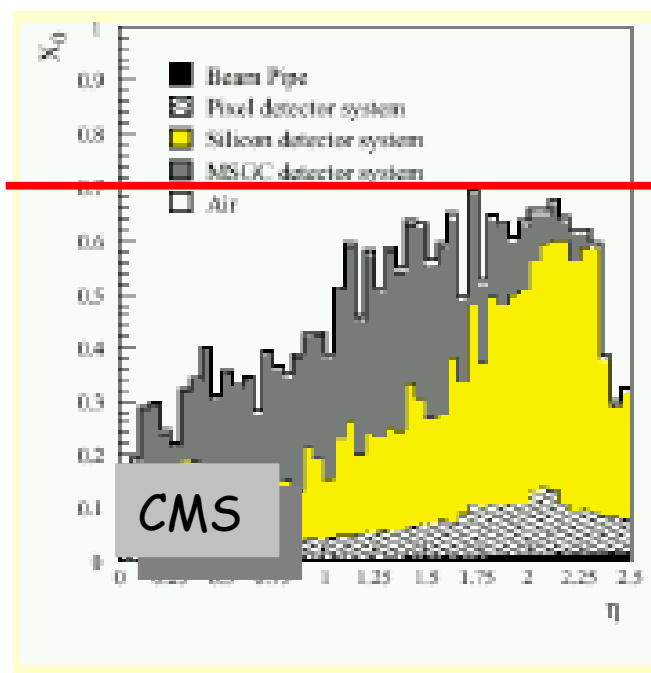


# Materials: from Concept to Reality

Major difference / advance to LHC detectors is needed:

... and the reality 10 years later

The detector TDR 1996

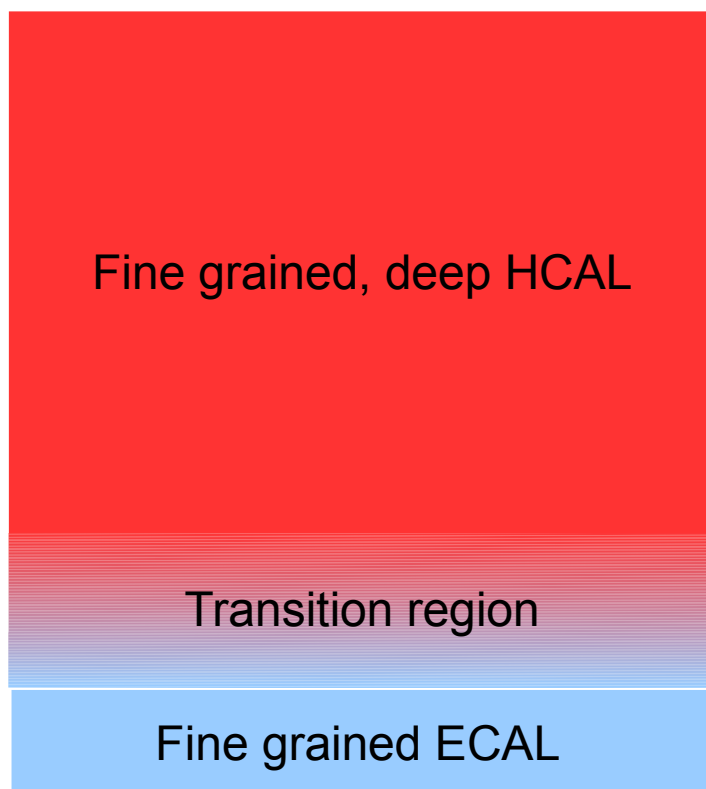


# The ideal PFLOW calorimeter

- Extremely dense (small Moliere Radius)
- Extremely granular (particle separation)

Traditional energy  
resolution is important

but not so critically



containment

Granularity and  
longitudinal sampling

As deep as possible

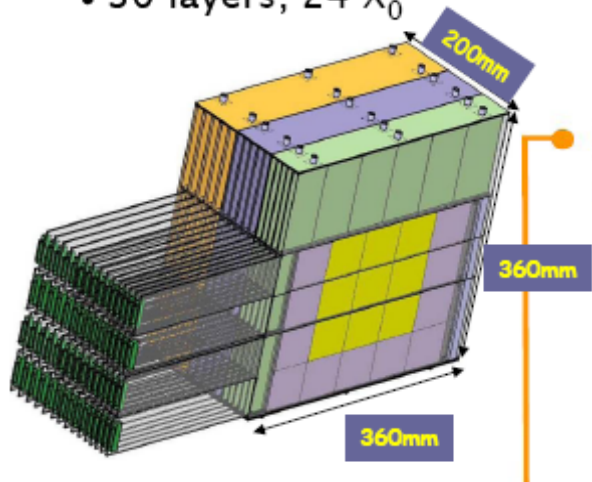
Granularity: "tracking"

# PFLOW ECAL



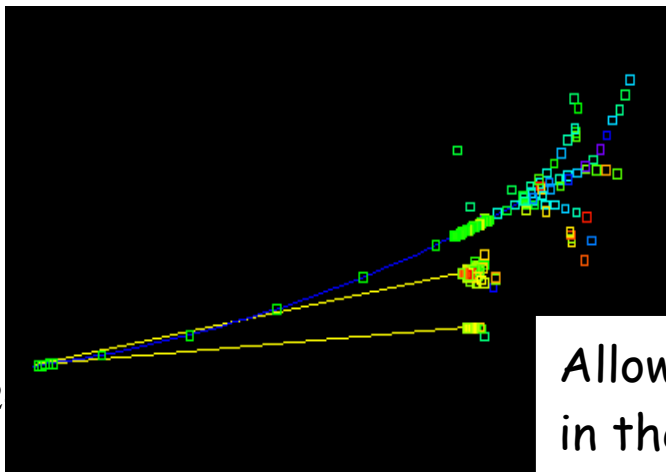
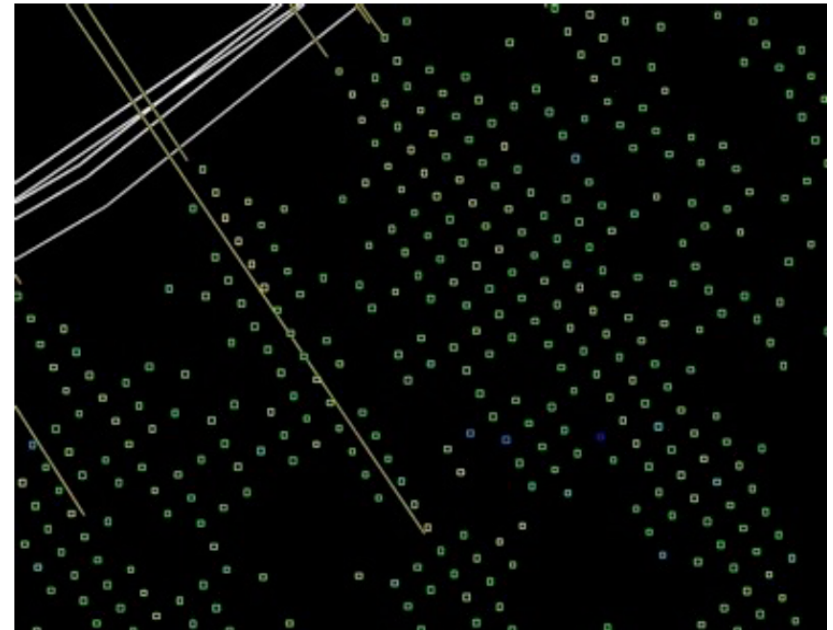
Typical granularity for ECAL:  $0.5\text{cm} \times 0.5\text{cm}$  to  $1\text{cm} \times 1\text{cm}$ ,  
SI detectors, Tungsten absorbers

- 30 layers,  $24 X_0$



CALICE prototype

Normal analogue ECAL  
segmentation:



Allows "tracking"  
in the calorimeter

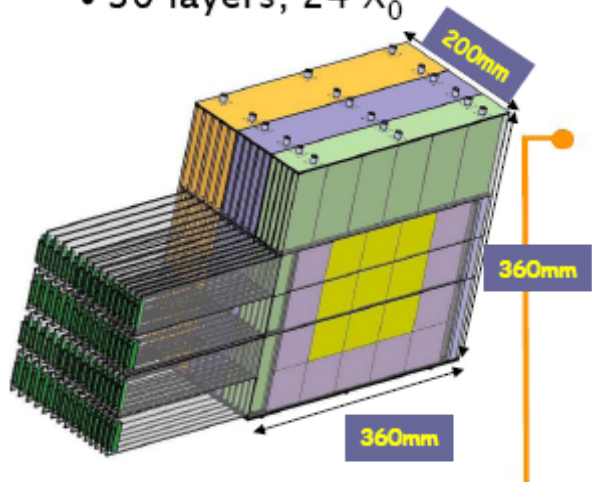
Very detailed shower images

# PFLOW ECAL



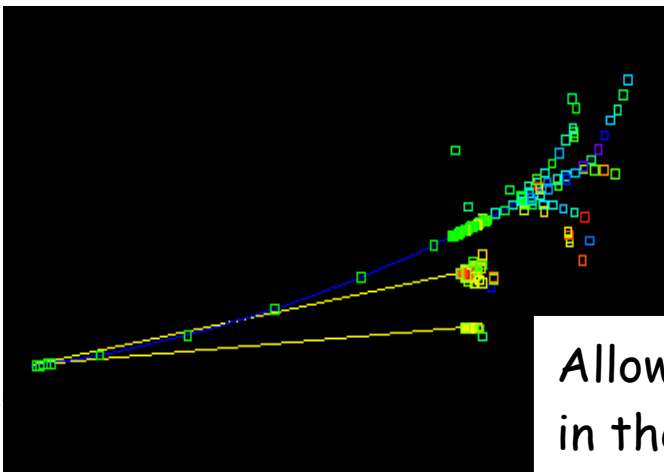
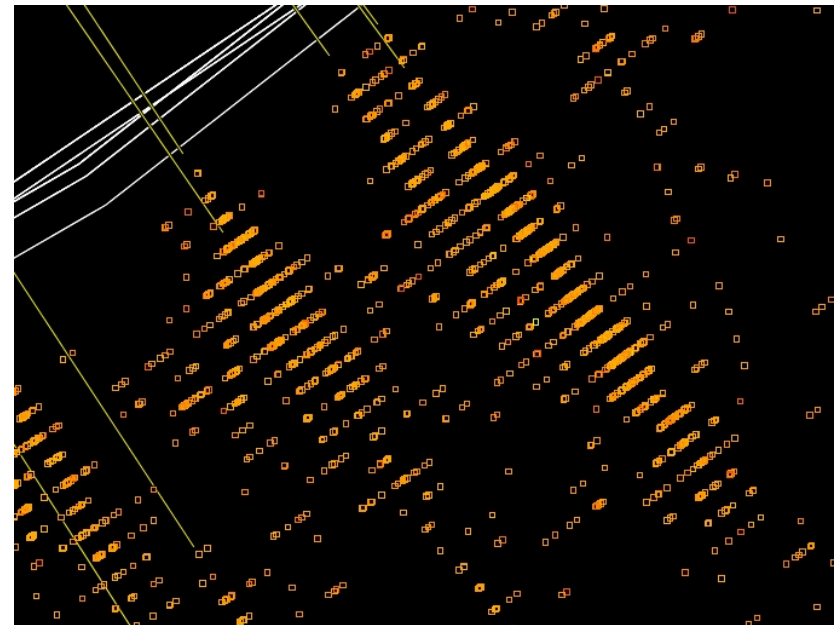
Typical granularity for ECAL: 0.5cmx0.5cm to 1cmx1cm,  
SI detectors, Tungsten absorbers

- 30 layers,  $24 X_0$



CALICE prototype

Extreme segmentation:  
MAPS sensors in the ECAL



Allows "tracking"  
in the calorimeter

Very detailed shower images

# PFLOW HCAL

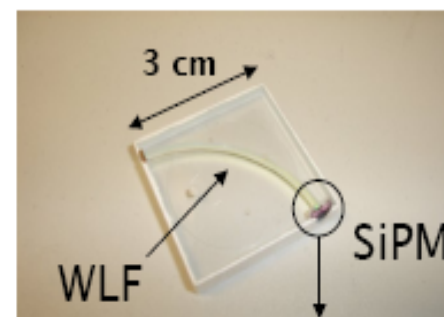
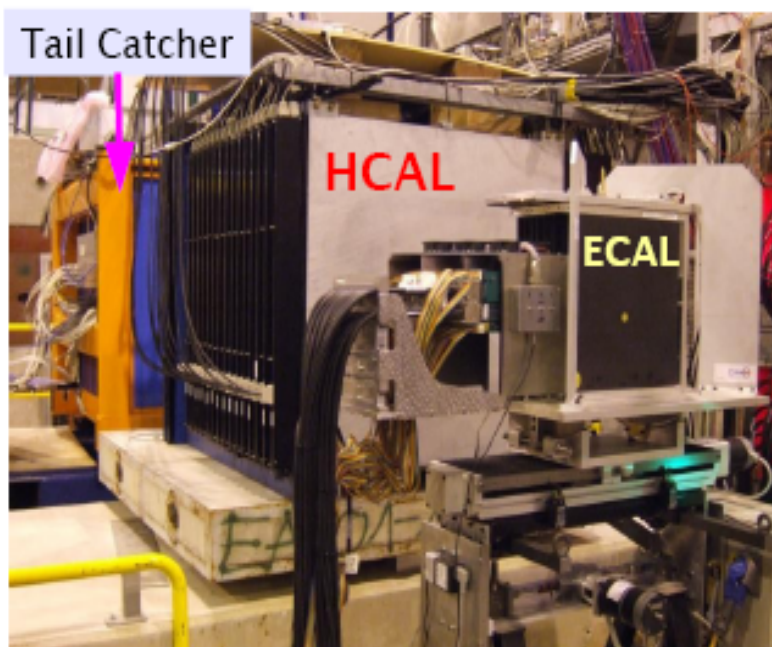
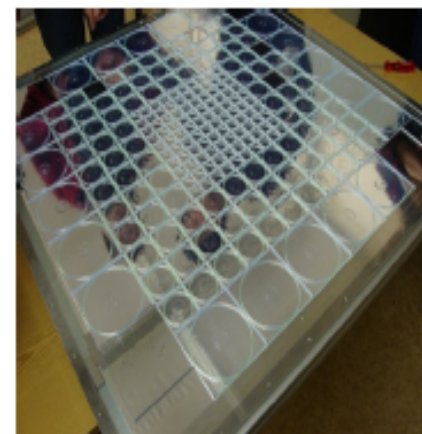


HCAL plays crucial role in a particle flow calorimeter

Simulation of hadronic shower is problematic

Typical cell sizes  $3 \times 3 \text{ cm}^2$  with analogue readout

Digital option investigated (smaller cells, 1bit readout)



Major effort (CALICE) to prototype such a calorimeter for the ILC

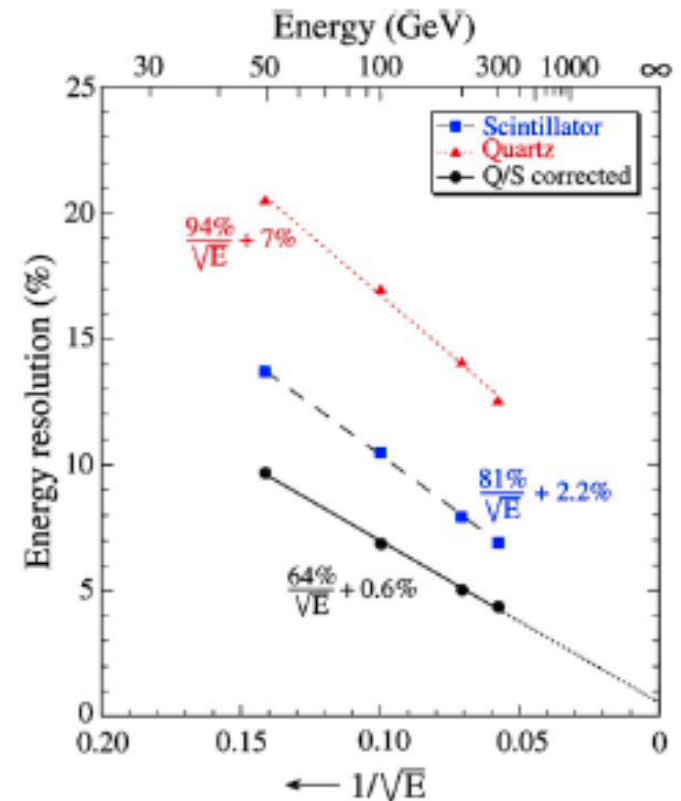
# Non-PFLOW: DREAM

Dual readout calorimeter (DREAM):

- Scintillator and Cerenkov fibers
- Sensitivities to EM and had part are different

Measure individually the EM and the EM+HAD component of a shower

Good energy resolution possible  
compensation by software "easy"  
segmentation is difficult, in particular in depth



Is this an alternative to the "particle flow" calorimeters?

# Forward Instrumentation



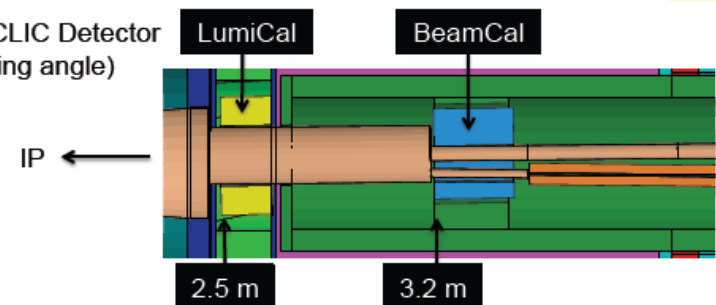
Forward region is very challenging:

- high backgrounds due to beam beam background
- instrumentation down to very small angles to maximise physics reach
- difficult mechanical environment due to crossing angle

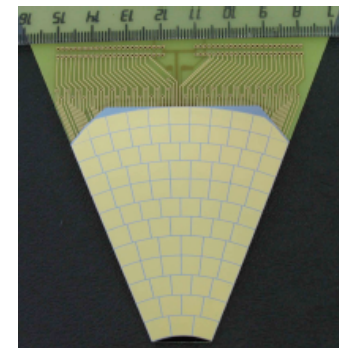
Fine grained high precision calorimeters  
Radiation hard, fast

Spinoffs to CMS and other fields

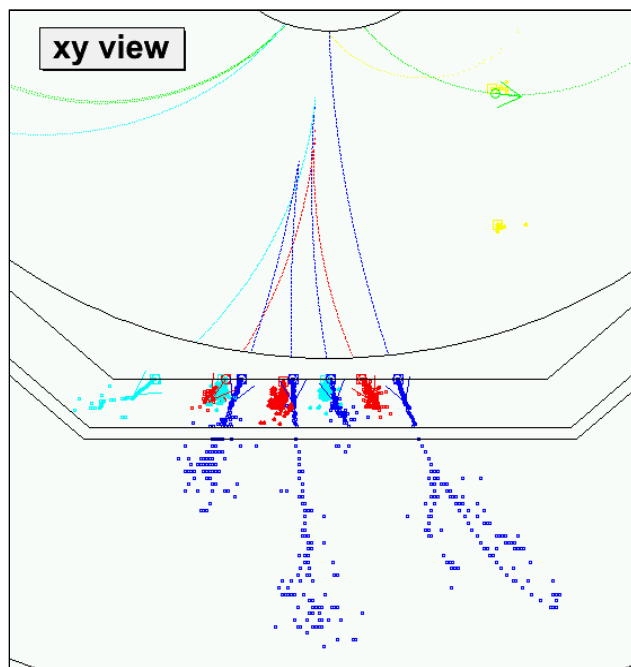
Example of CLIC Detector  
(larger crossing angle)



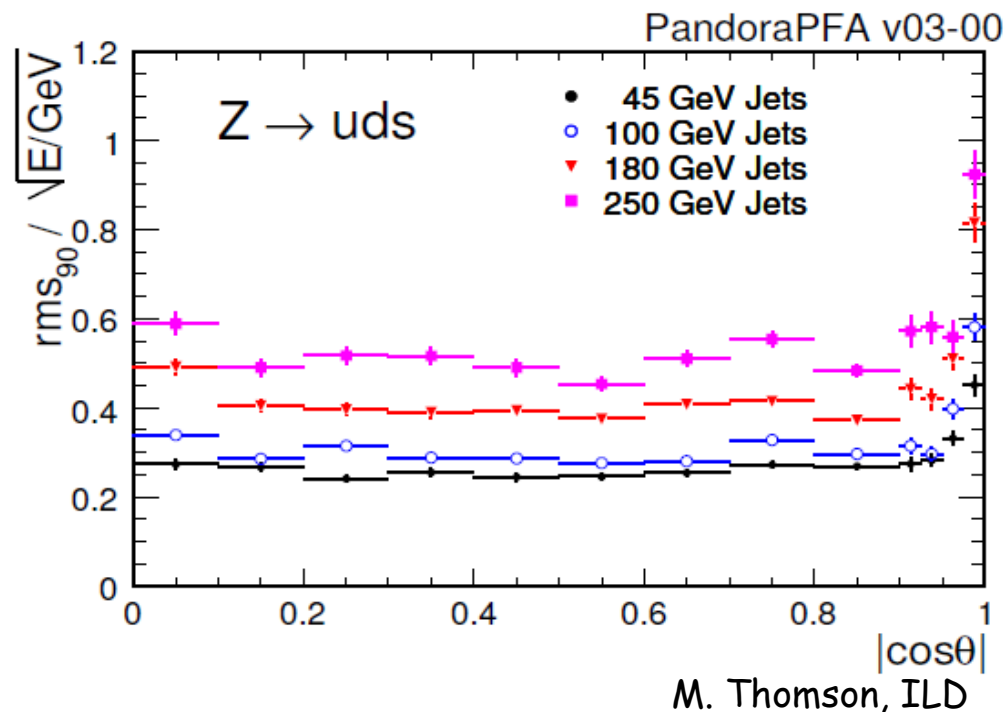
GaAs sensor  
for BeamCal



# Particle Flow in Simulation



Simulation of an event



Resolution close to  $30\%/\sqrt{E}$  for jets below 100 GeV

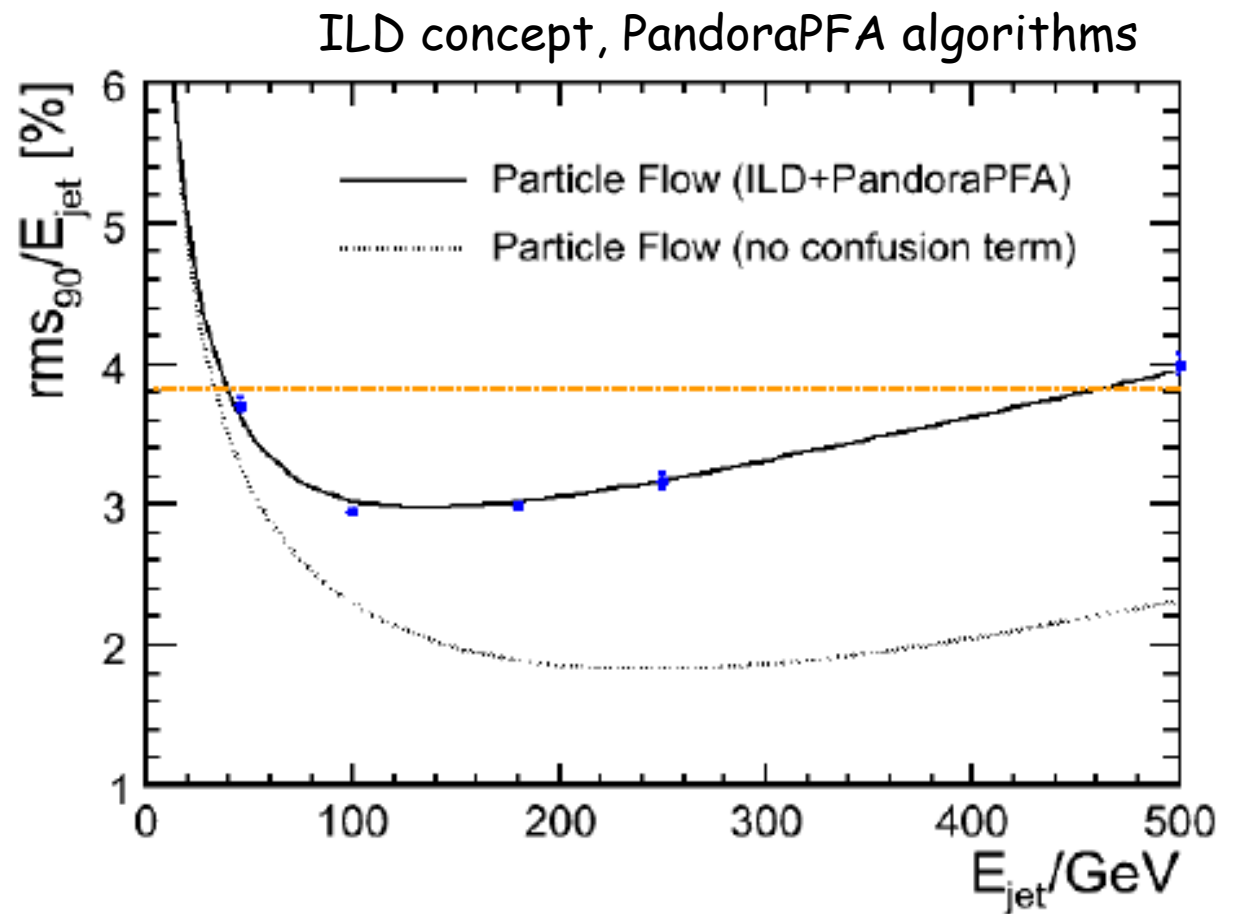
Particle flow gives  $\sim 2\times$  better performance than traditional approach ( $<100$  GeV jets)

Software is an important part of the detector optimization and development

# Particle Flow

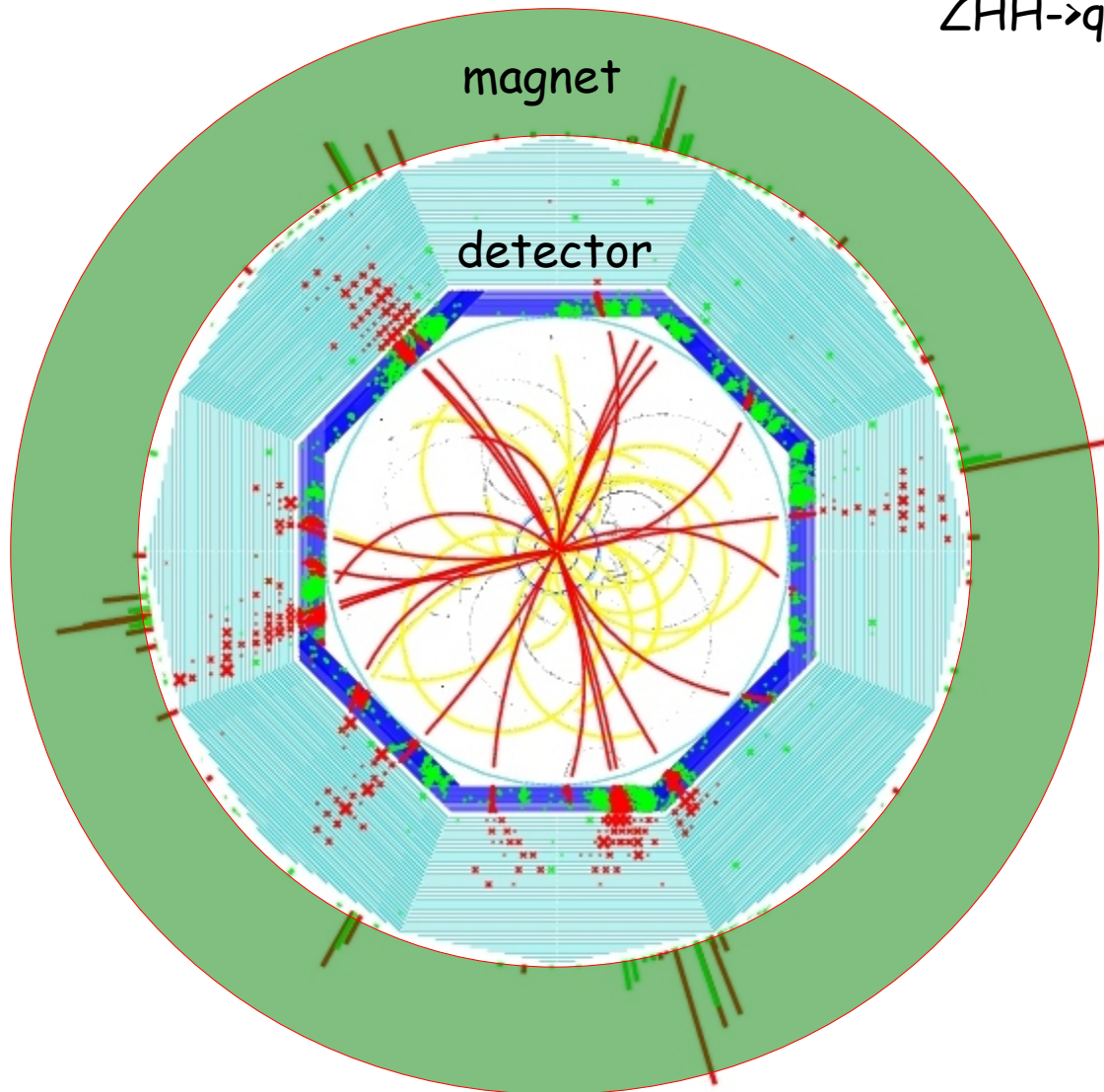
Particle Flow performance at higher energies:

Algorithms are mature  
enough  
and reach anticipated  
performance  
Up to 500 GeV jets



# Putting it together

$ZHH \rightarrow qqbbbb$  event at 500 GeV



Powerful vertex/ tracking/  
calorimeter

put all this into a strong  
B field

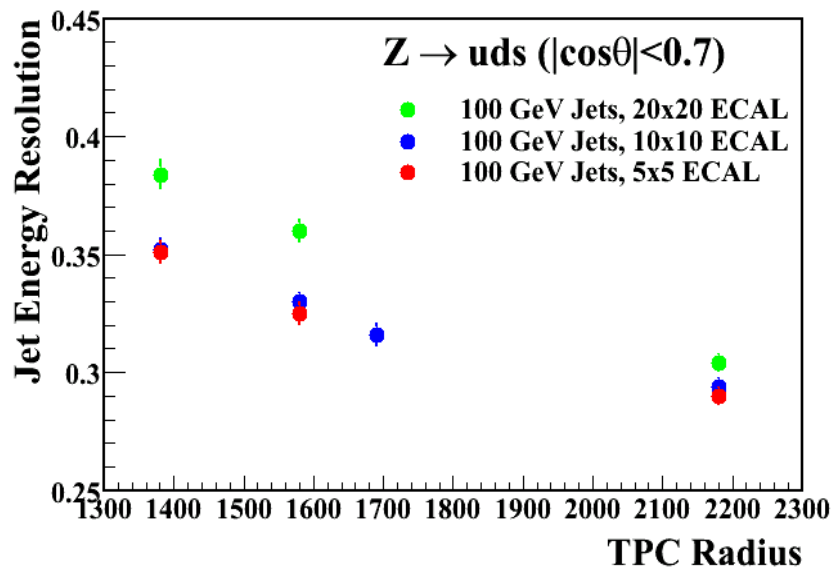
incidentally have some muon  
ID on the outside

I have not talked about the forward  
region etc.. sorry

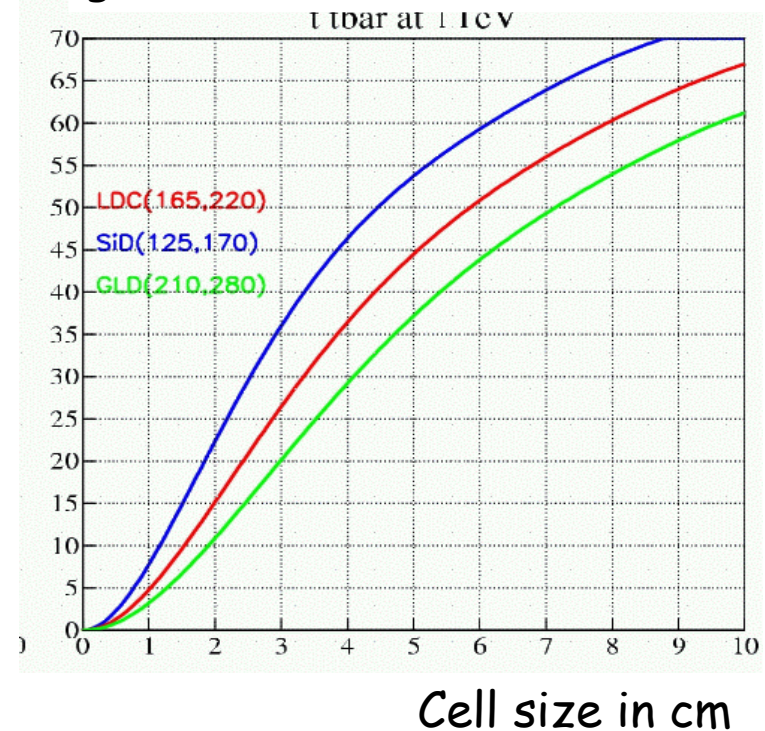
$\cancel{H} \rightarrow qqbbbb$

# Detector Optimization: ECAL Brient 2004 Thomson 2007

Photon separation  
(fraction of second photon within  
given distance)



Full reconstruction results



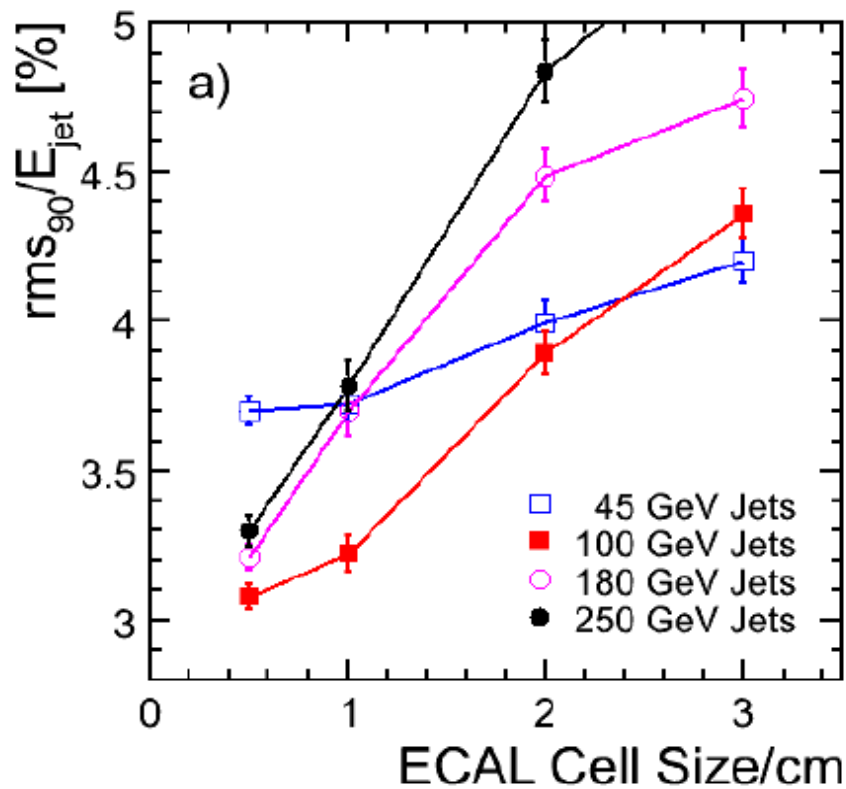
1x1 cm<sup>2</sup> cell sizes seem reasonable

not a huge gain by smaller cells seen at the moment

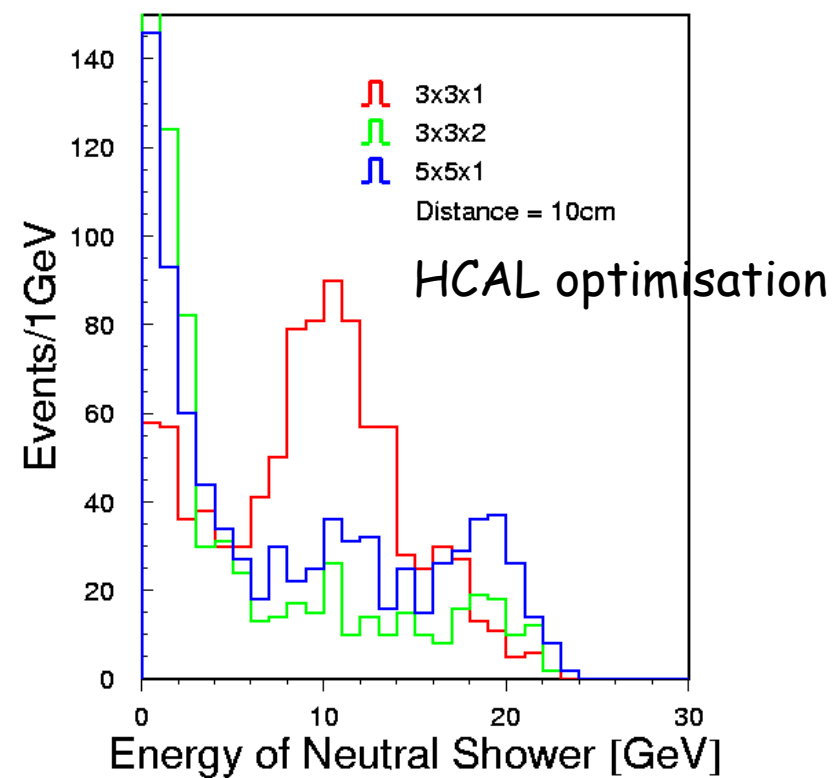
# Detector Optimization: HCAL

A. Raspereza,  
V. Morgunov,  
Snowmass 2005

HCAL optimization:  
reconstruction of overlapping hadronic showers

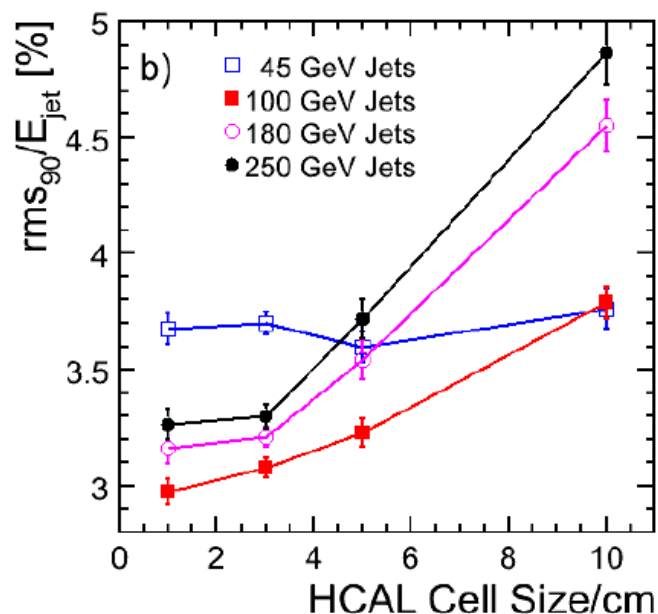
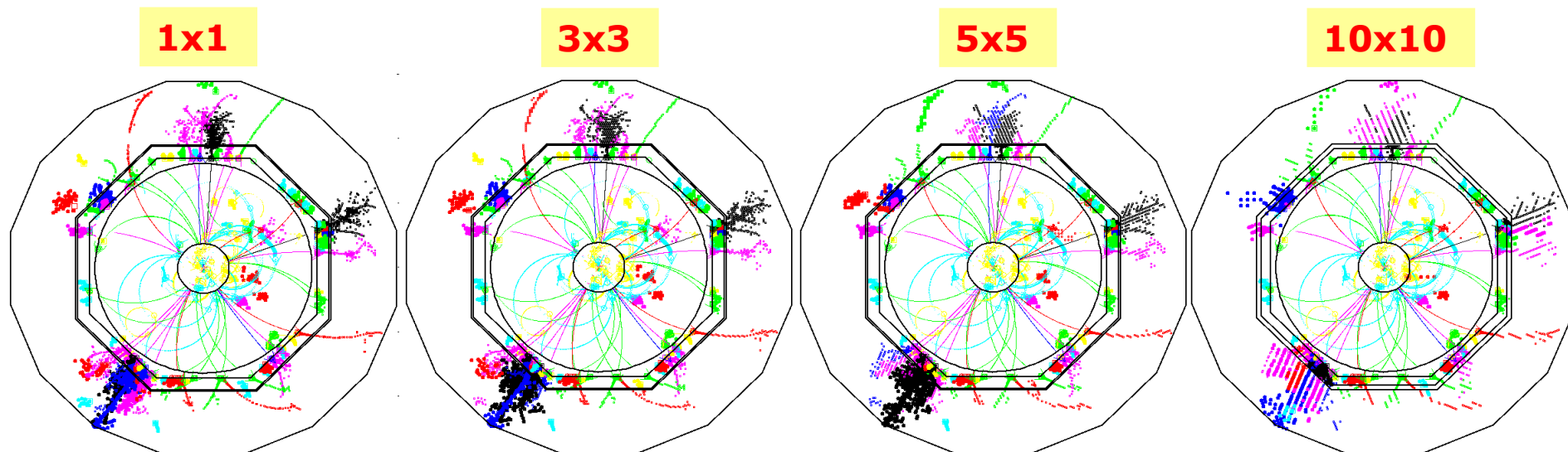


Two showers :  $\pi^+$  10GeV,  $K_L^0$  10GeV



# Detector Optimization: HCAL

M. Thomson,  
Tsukuba 2009



## “Preliminary Conclusions”

- ♦ 3x3 cm<sup>2</sup> cell size ok
- ♦ No advantage -> 1x1 cm<sup>2</sup>
  - physics ?
  - algorithm artefact ?
- 5x5 cm<sup>2</sup> degrades PFA

# Challenges

Apart from technological challenges (plenty for each sub-detector)

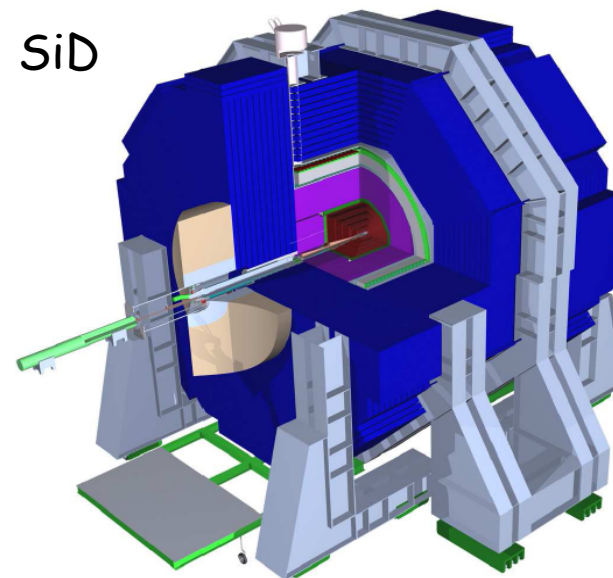
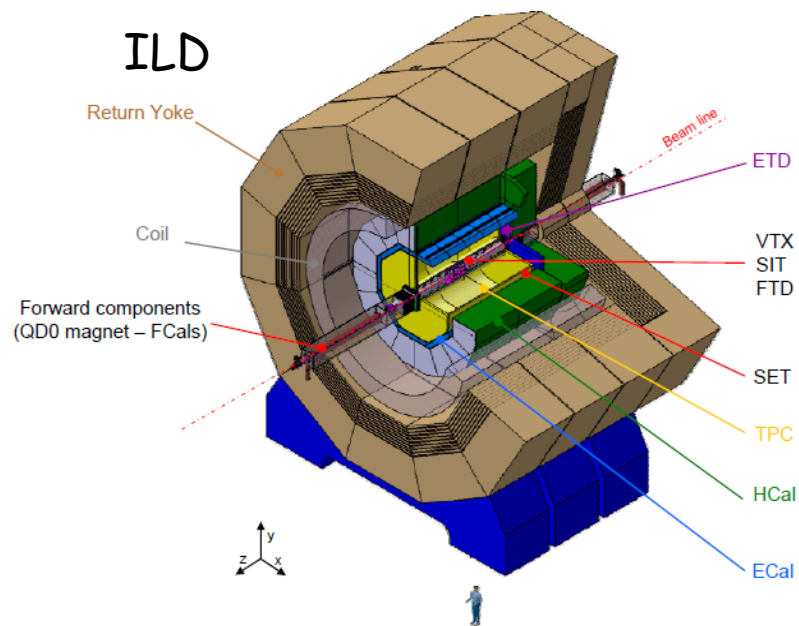
General issues:

- Material budget in the tracker
- Power pulsing: needed for low mass detectors, technically not proven
- Alignment precision: need excellent alignment, concepts are not proven
- Push-Pull operation: impact on alignment, time lost due to re-alignment
- How do the concepts work at higher energies? The Road to CLIC...

# Detector Concepts at the ILC

Develop an integrated design of a possible detector at the ILC;

- Research into technologies: R&D collaborations
- Combine things into one detector: Concept Groups



# A Comparison

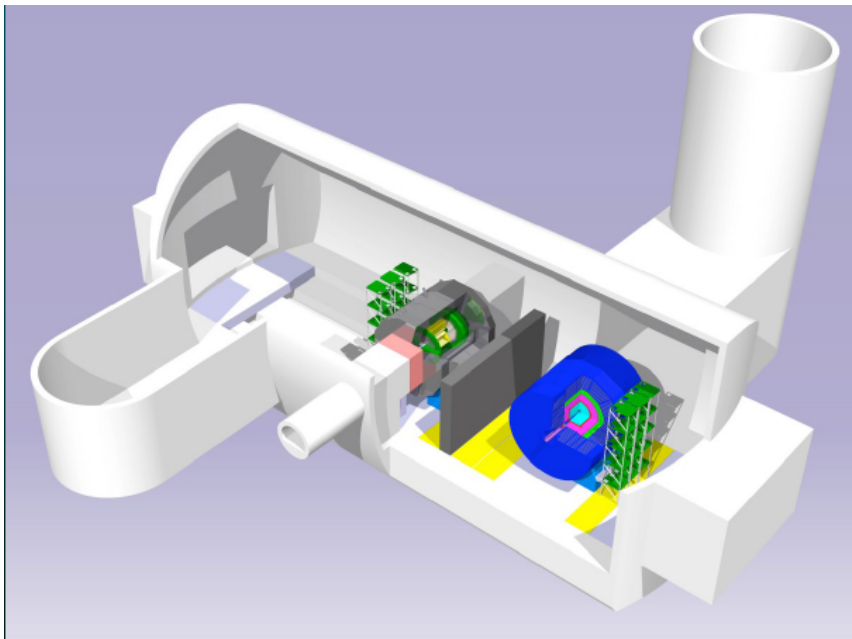
	SiD	ILD
Vertex	Si-pixel	Si-pixel
Tracker	Silicon strip	TPC
ECAL	Si-W	Si-W
HCAL	RPC digital	Fe-Scint
Field	5T	3.5-4T
Event Reco	PFLOW	PFLOW
main base	US	Europe/ Asia

# Experiments at the ILC

One collider, one beam, two experiments:

- ➡ Two beam lines, switching beam from experiment to experiment
- ➡ One beam line, switching experiments from in-beam to standby

Push-Pull configuration favored because of cost considerations

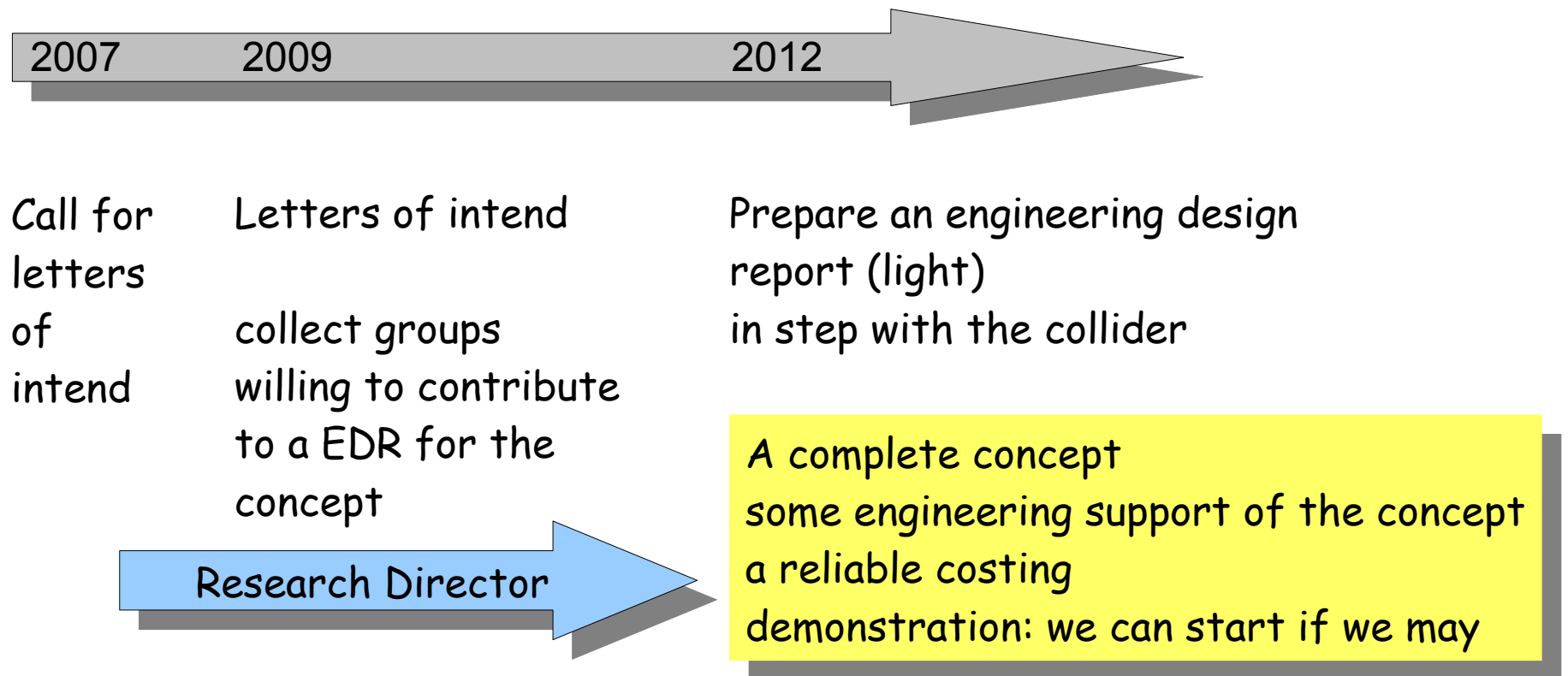


Can this be done?  
How quickly?  
Loss of efficiency?  
Alignment?

Highly non trivial

# Detector Roadmap

The roadmap for detectors at the ILC;



# R&D at the ILC - NOW

Organized in two complementary ways:

Technology R&D collaborations

Look primarily at technologies  
concentrate on sub-detectors

horizontal

LCFI, MAPS, SILC...  
CALICE, LC-TPC,  
FCAL, ...

Detector Concept groups

vertical

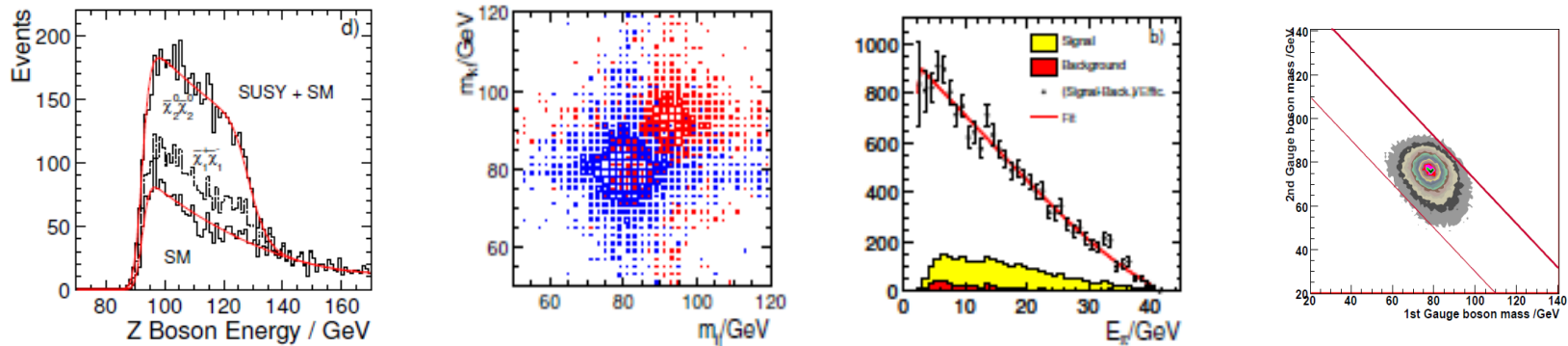
Look at the overall concept  
optimize the interfaces between sub-detectors  
Look at integration issues

SiD, ILD

# Letter of Intent

Concept groups submitted letter of intent in 2009:

- Significant progress on understanding the concepts
- Many results based on detailed and full simulation and reconstruction



Concepts have been reviewed by international review body  
Chairperson Michel Davier

# The Next Years

Lots of detector R&D remains to be done:

Many great opportunities for interesting work and novel technological developments:

e.g. SiPM, SI readout for TPC, Timepix, new pixel detectors,  
low mass mechanics, advanced Silicon tracking, etc etc etc

Have to face the challenge of preparing a coherent design without cutting technological developments off at the wrong moment

Make sure we are following realistic but challenging developments

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# Conclusion and Outlook

The ILC physics program remains as interesting as ever

The ILC faces many interesting technological challenges:

great progress has been made over the last few years to meet them.  
much progress still needs to be done before we can build these detectors.

Concept groups ("Proto"-Collaborations) have formed to design and push specific detector concepts in a friendly but competitive environment

The ILC remains an exciting project

Experimentation at the ILC is as challenging as experimentation at the LHC!