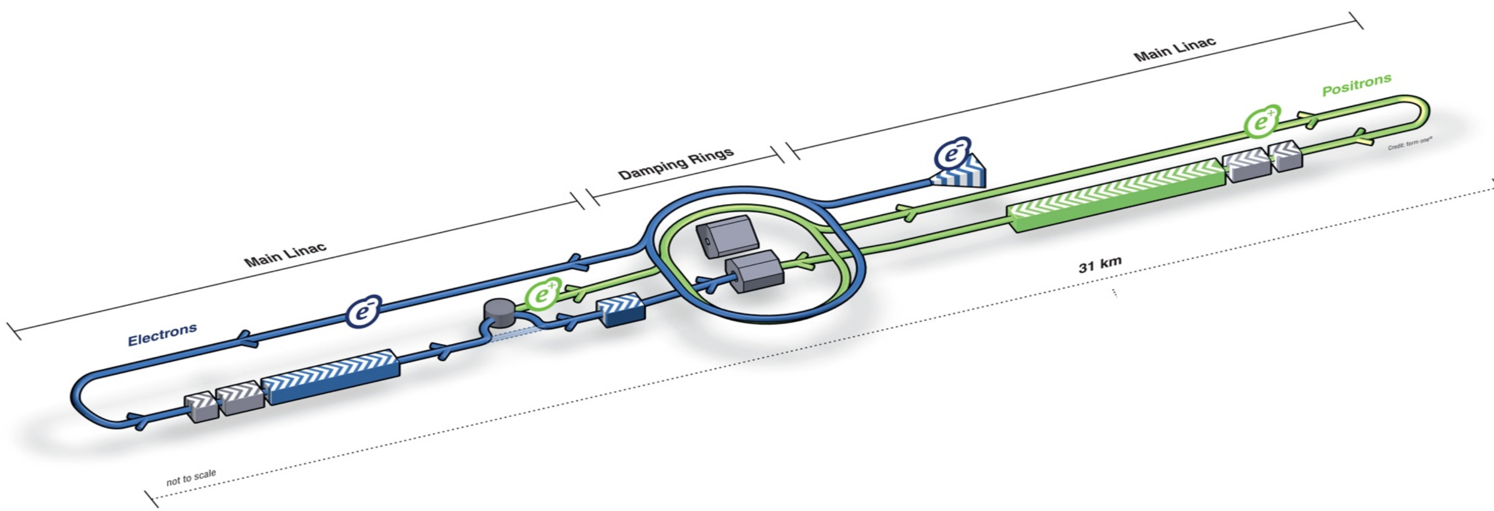
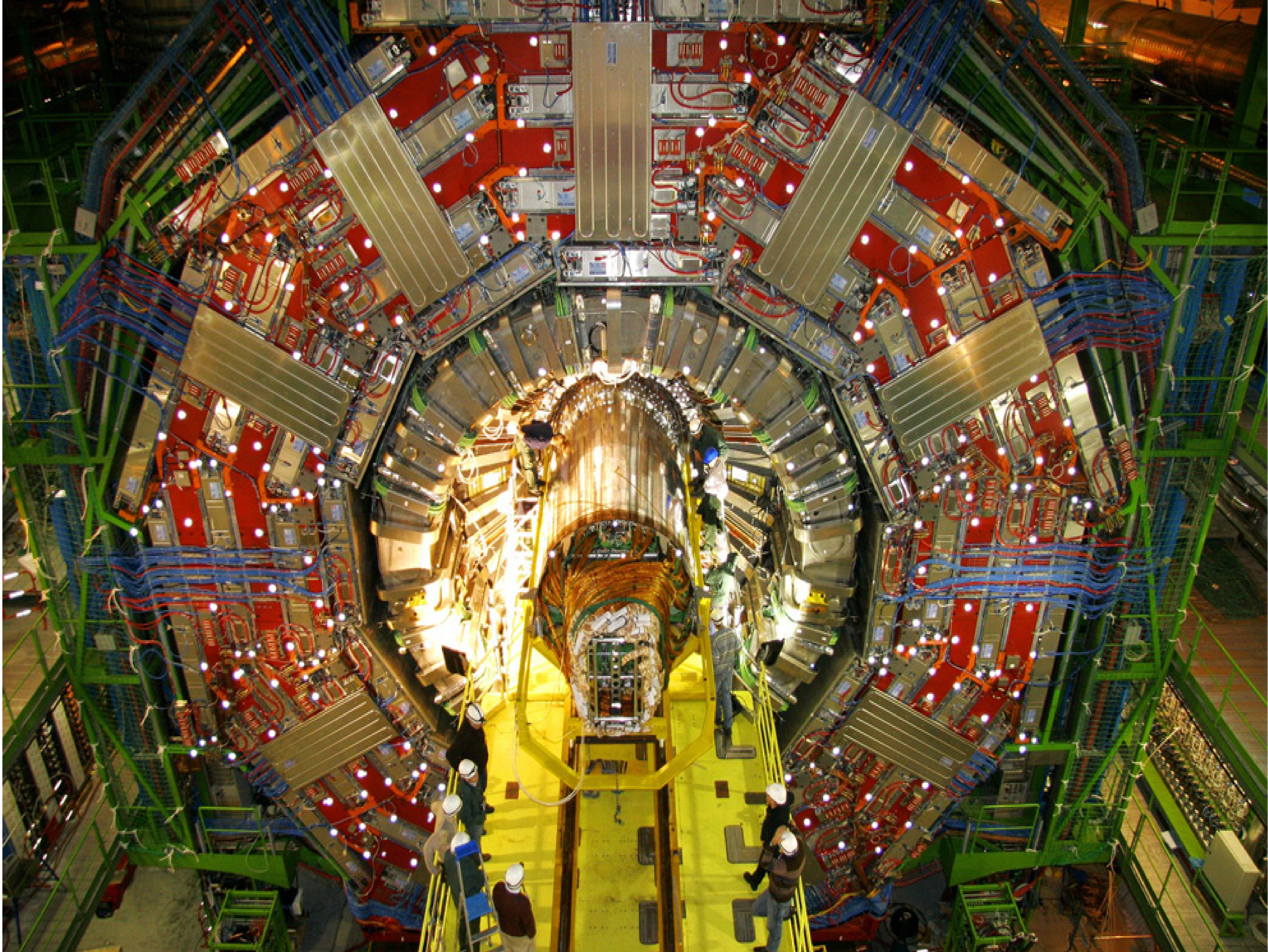
Linear Colliders: ILC

Lecture at CORFU 2010

Ties Behnke, DESY

- Linear Colliders: the physics case, a reminder
- Linear Colliders: accelerator issues for ILC (other technologies (CLIC): see earlier lecture)
- Linear Colliders: Detectors

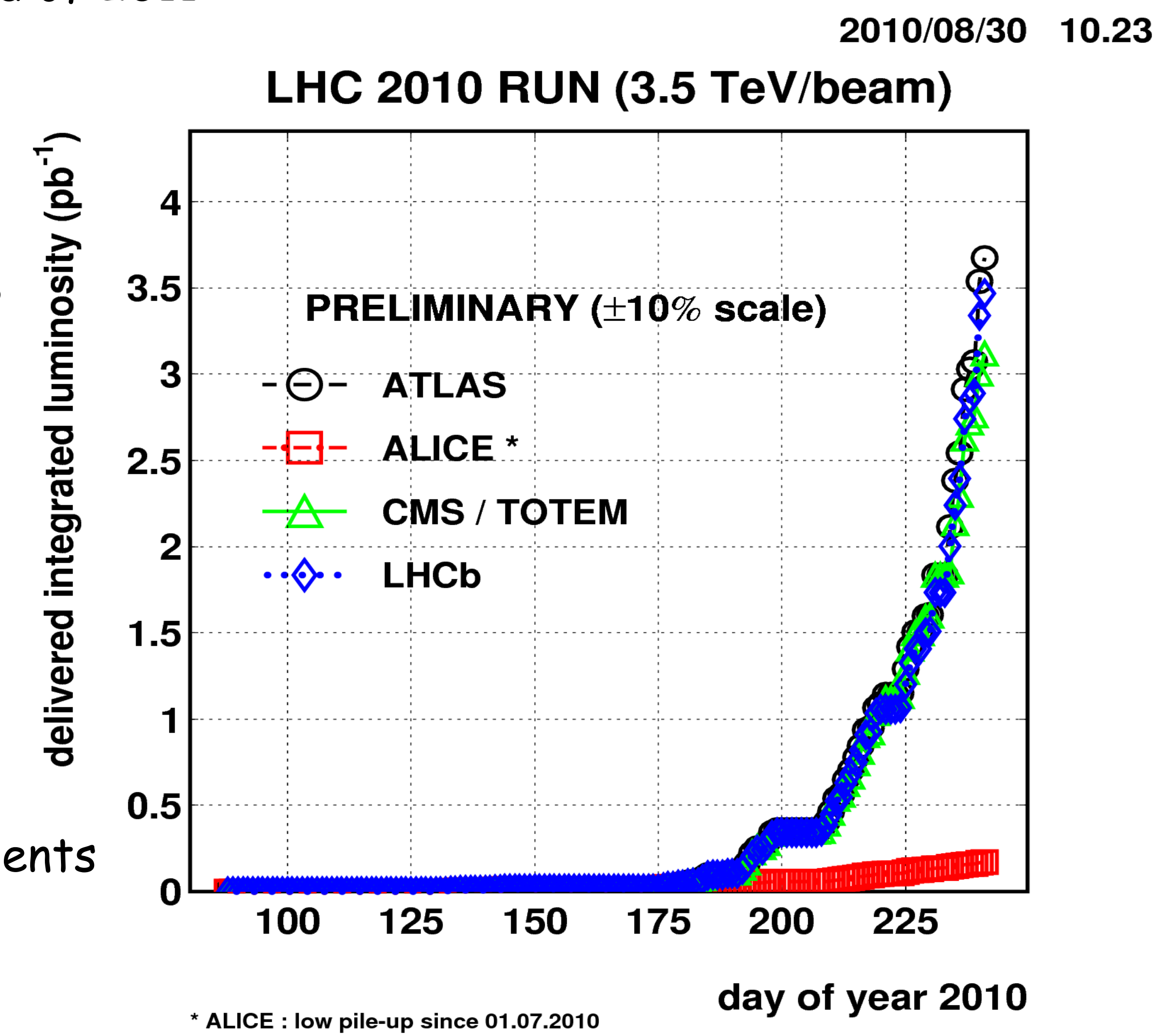




LHC - ILC

LHC has just started to deliver data: expect first significant results at the end of the current run end of 2011

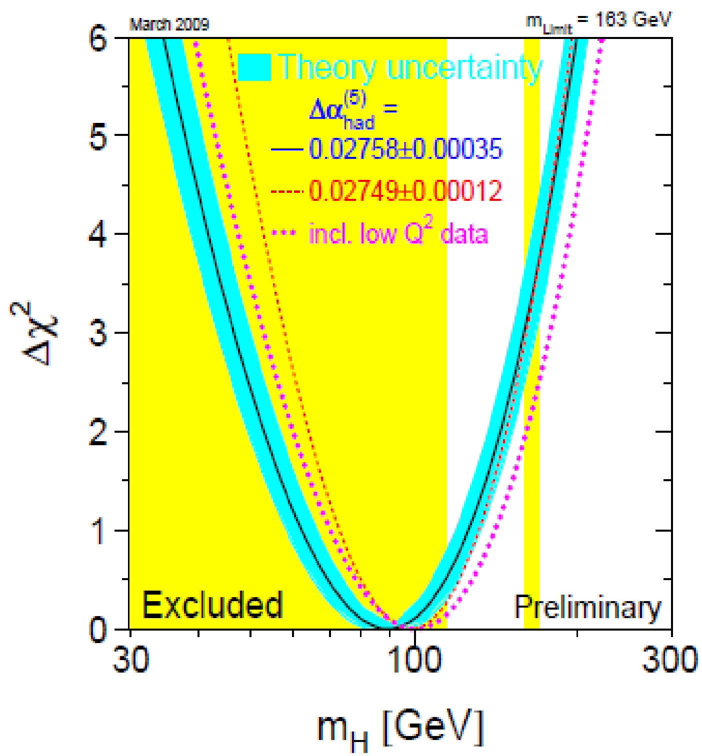
Why talk about a new facility like e+e- collider at this time?

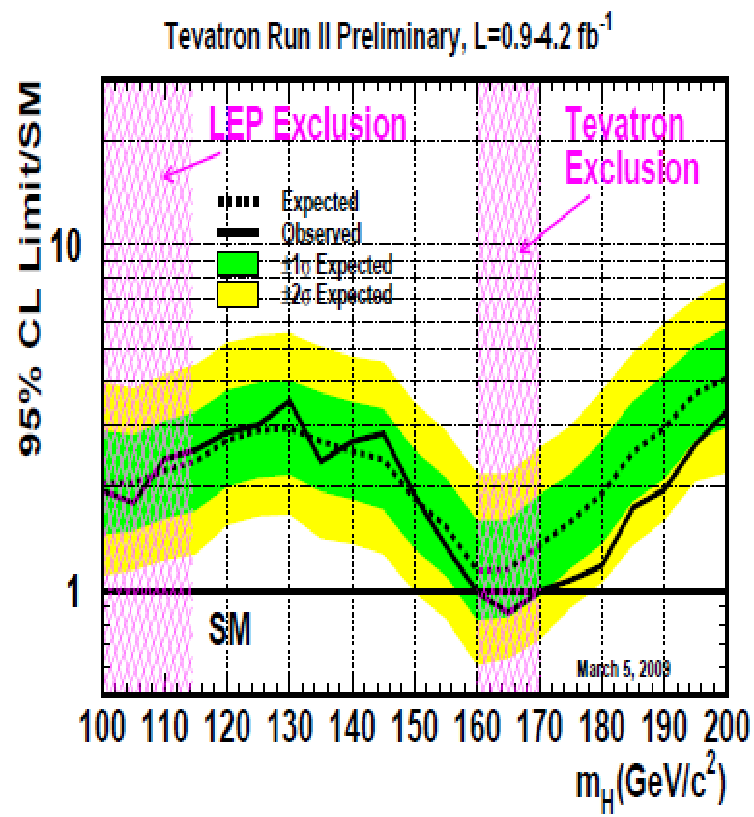


LHC Lumi delivered to experiments

Status of Standard Model

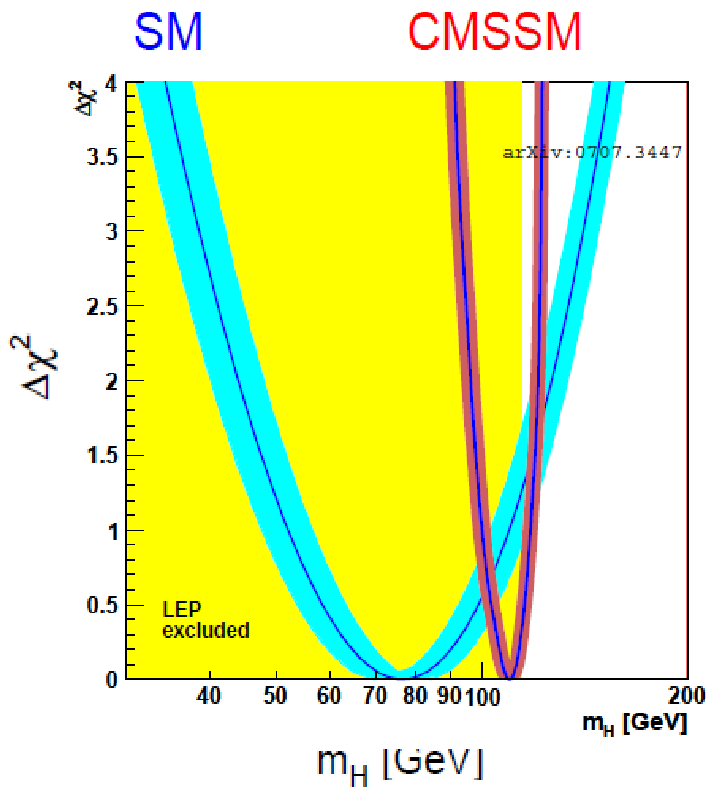
Global electroweak fit: status of the Standard Model, indirect Higgs limit

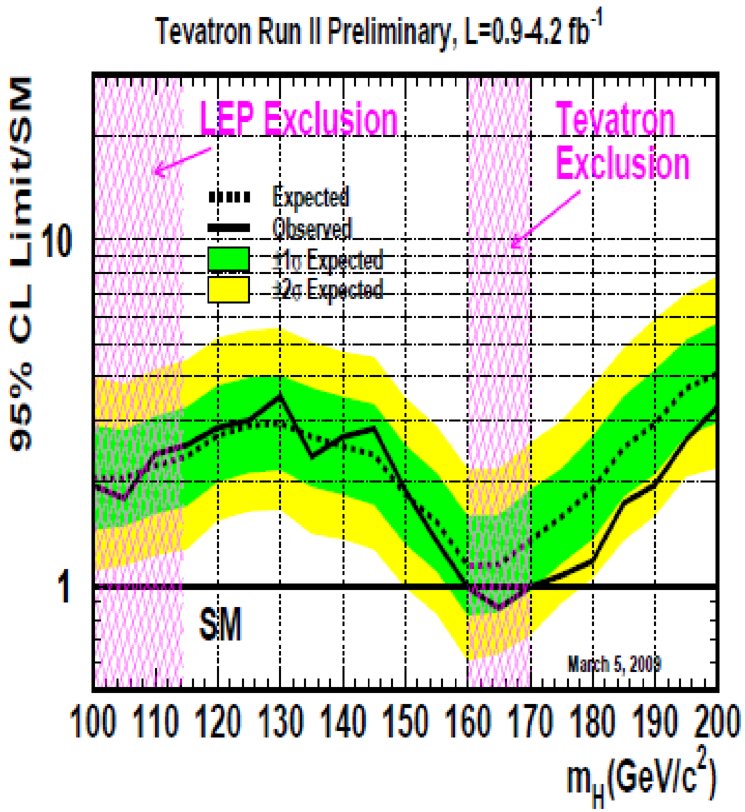




Status of Standard Model

Global electroweak fit: status of the Standard Model, indirect Higgs limit





Low mass Higgs seems favored by data!

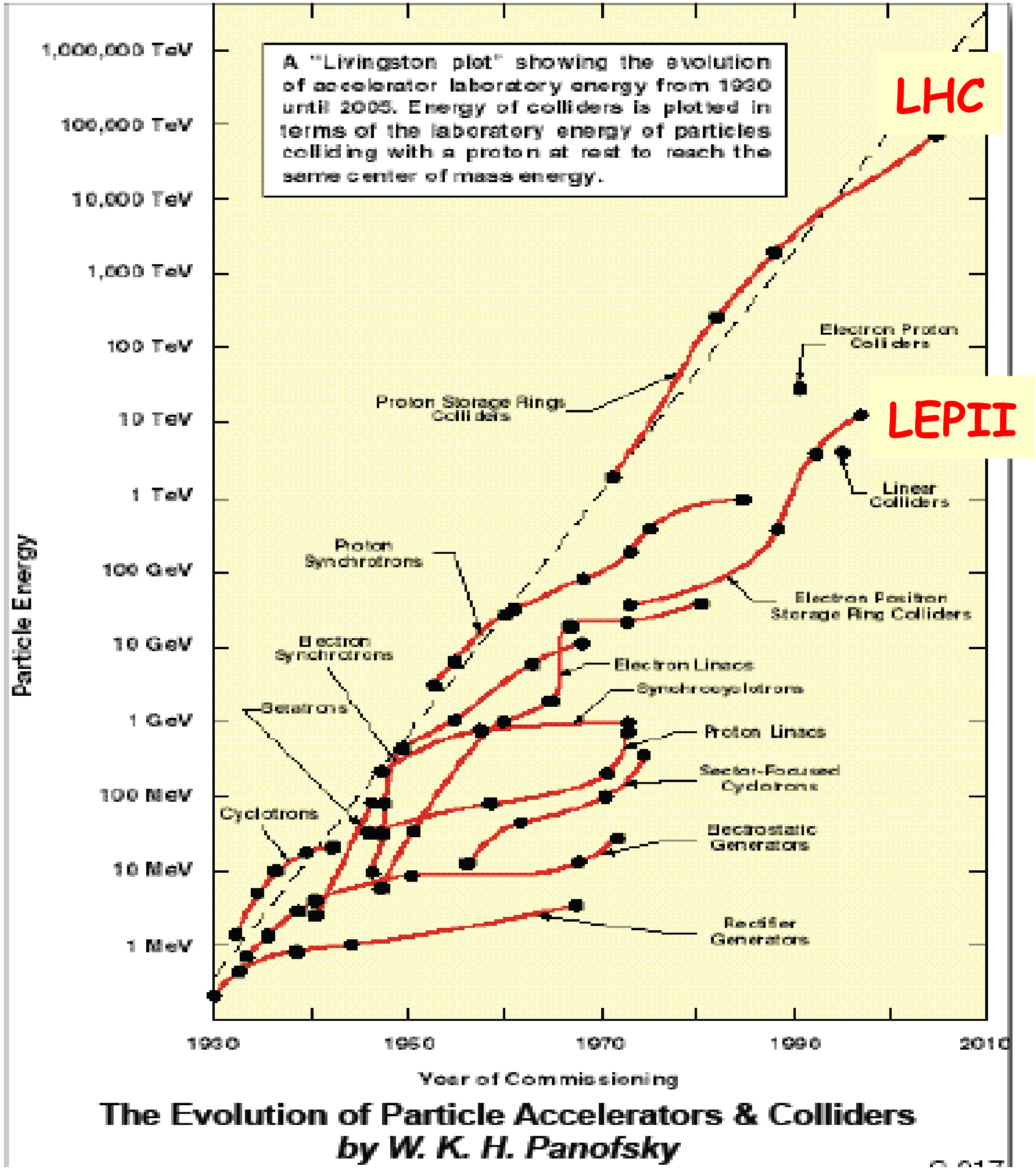
Collider Types

Hadron Collider (pp)	Lepton Collider (e+e-)
Composite particles collide E(CM) << 2 E(beam)	Point-like particles collide E(CM) ~ 2 E(beam)
Strong interaction in initial state Superposition with spectator jets	Well defined initial state Clear final state
LHC: $\sqrt{s}$ = 7-14 TeV Fraction of energy available for hard scattering	**ILC:** $\sqrt{s}$ = 500 GeV – 1 TeV Nearly full energy of collision will be available for analysis
Small fraction of events analysed Multiple triggers No polarisation applicable	Most events in detector analysed No hardware trigger, very open system Polarisation of initial beams possible

Hadron - Lepton

Hadron machines and lepton machines have both made significant contributions to our current knowledge

Best example of recent years: LEP/ Tevatron



Mass reach for New Physics

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	DLHC 28 TeV 100 fb^{-1}	VLHC 40 TeV 100 fb^{-1}	VLHC 200 TeV 100 fb^{-1}	ILC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	5	20	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ	7σ	18σ	6σ	90σ
Z'	5	6	8	11	35	8†	30†
Extra-dim (δ=2)	9	12	15	25	65	5-8.5†	30-55†
q*	6.5	7.5	9.5	13	75	0.8	5
Λcompositeness	30	40	40	50	100	100	400
TGC (λ_γ)	0.0014	0.0006	0.0008		0.0003	0.0004	0.00008

† indirect reach
(from precision measurements)

A.de Roeck: LHC2FC workshop
CERN, 2009

Physics goals at the LC

Discovery of New Physics

- Large potential for direct searches
- Large potential for indirect searches (via precision)
- Complementary to the LHC

Unraveling the structure of New Physics

- Precise determination of the structure and dynamics of NP
- Distinction between models through model independent precise measurements

High precision measurements

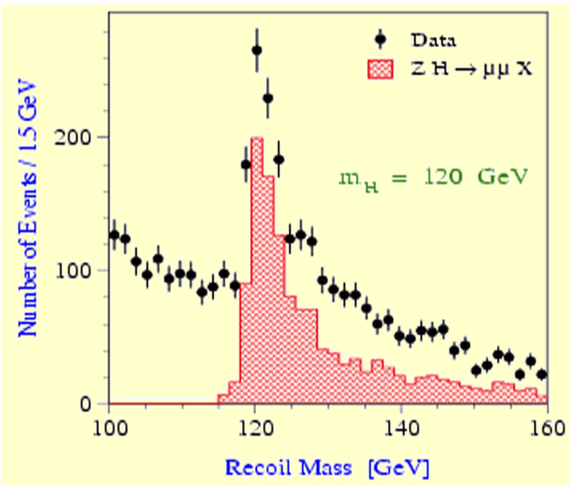
- Test of the SM with unprecedented precision
- Find even small hints of NP through precision measurements

Discovery of new phenomena via high energy and high precision

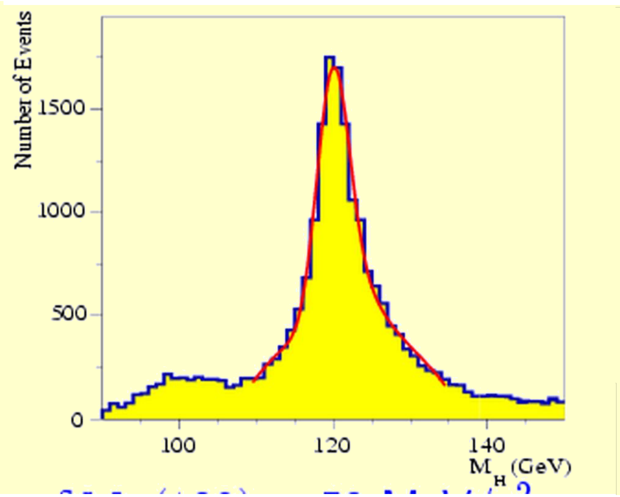
Higgs at the ILC

Determination of mass and width of the Higgs:
most favorable (light Higgs) ee->Z->ZH

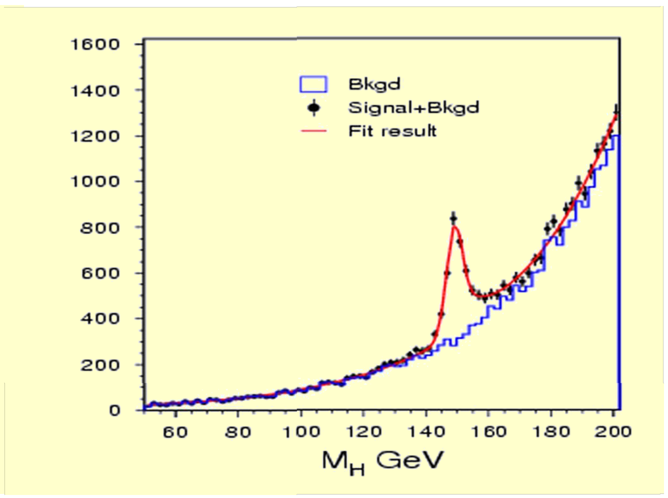
ZH-> μμX



ZH-> qqbb



ZH-> WW qq

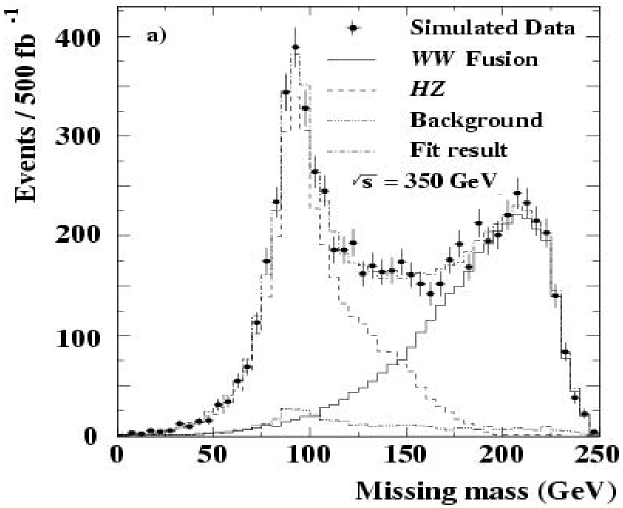


Clear signals in many channels:

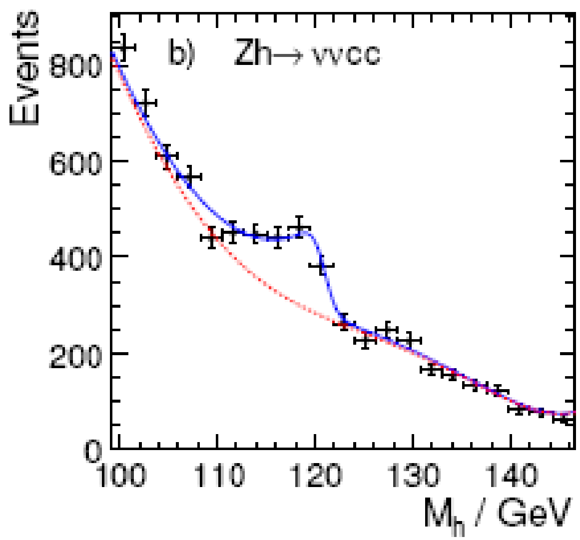
mass		width:
M(Higgs)	ΔM	
120 GeV	40 MeV	to 5-10%
150 GeV	70 MeV	
180 GeV	90 MeV	

Beyond a Discovery

Higgs in WW fusion

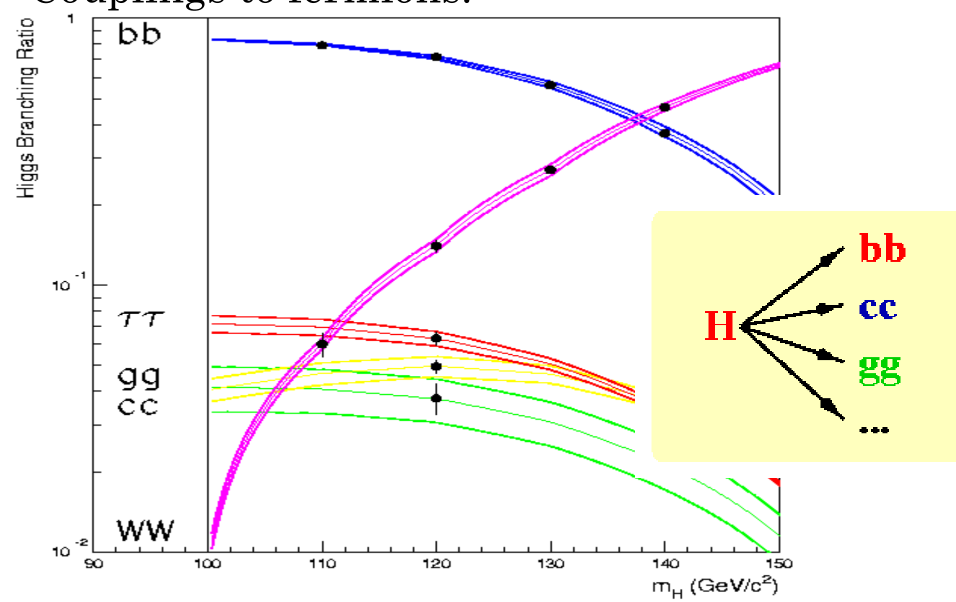


Higgs → cc

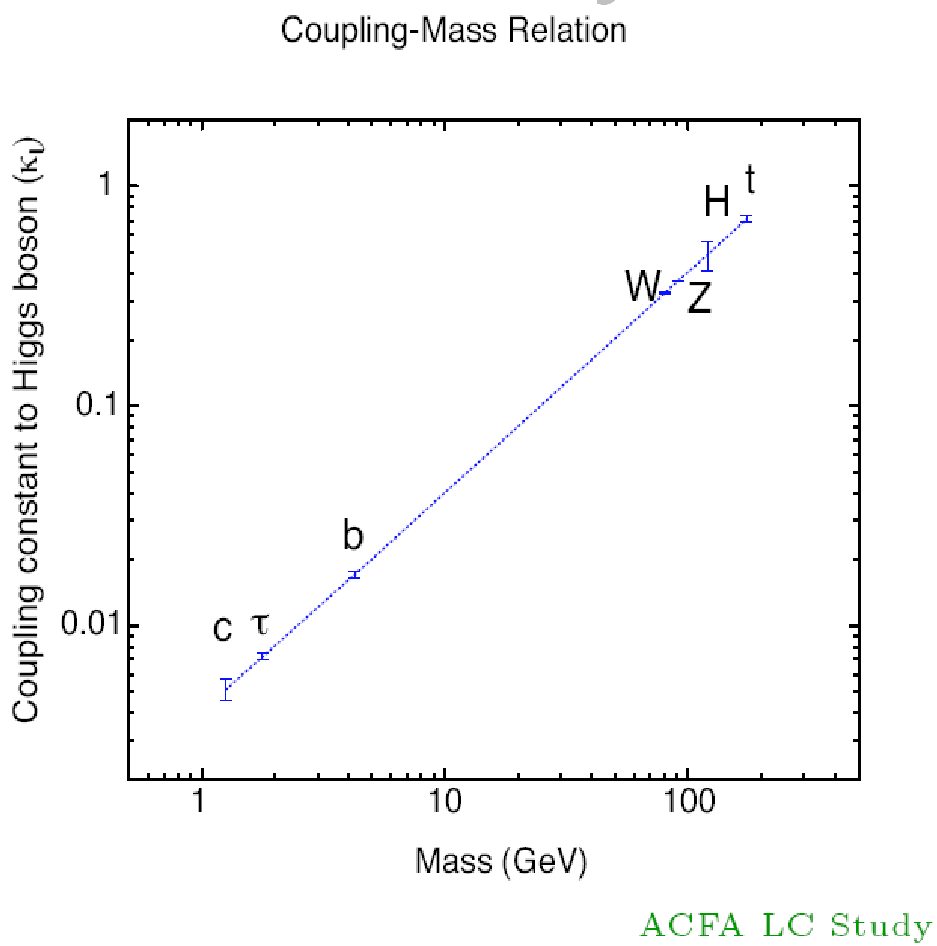


- complete test of our understanding of mass
  - can the Higgs explain the Z/W-mass? is the existence of the Higgs enough?
  - can the Higgs explain the mass of the fermions

Couplings to fermions:



Physics Challenges



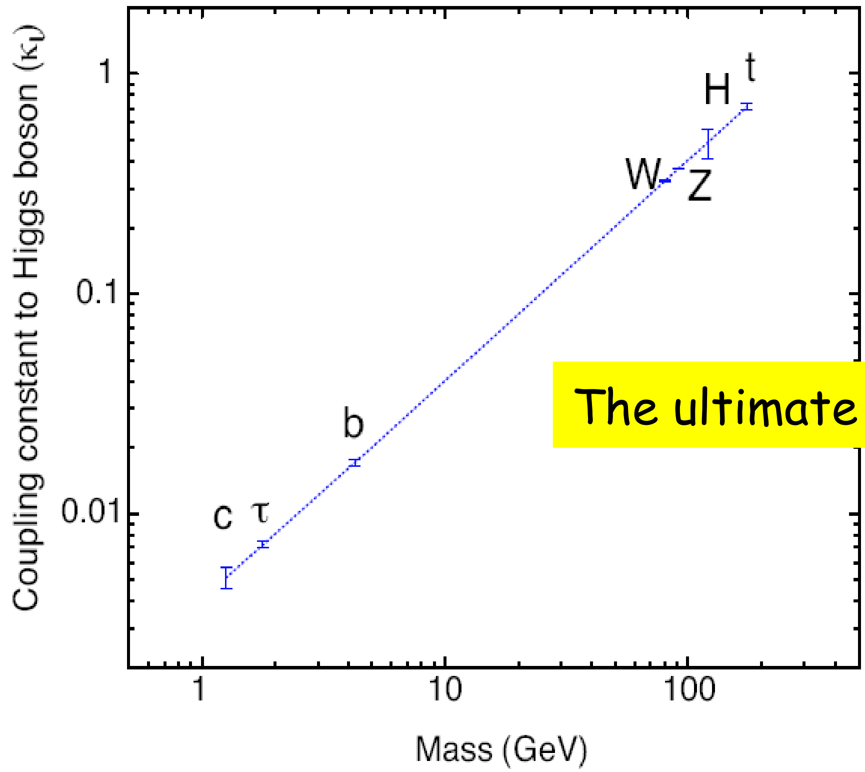
Explore the complete Higgs Sector, including Higgs self coupling

- 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

Coupling-Mass Relation



ACFA LC Study

Explore the complete Higgs Sector, including Higgs self coupling

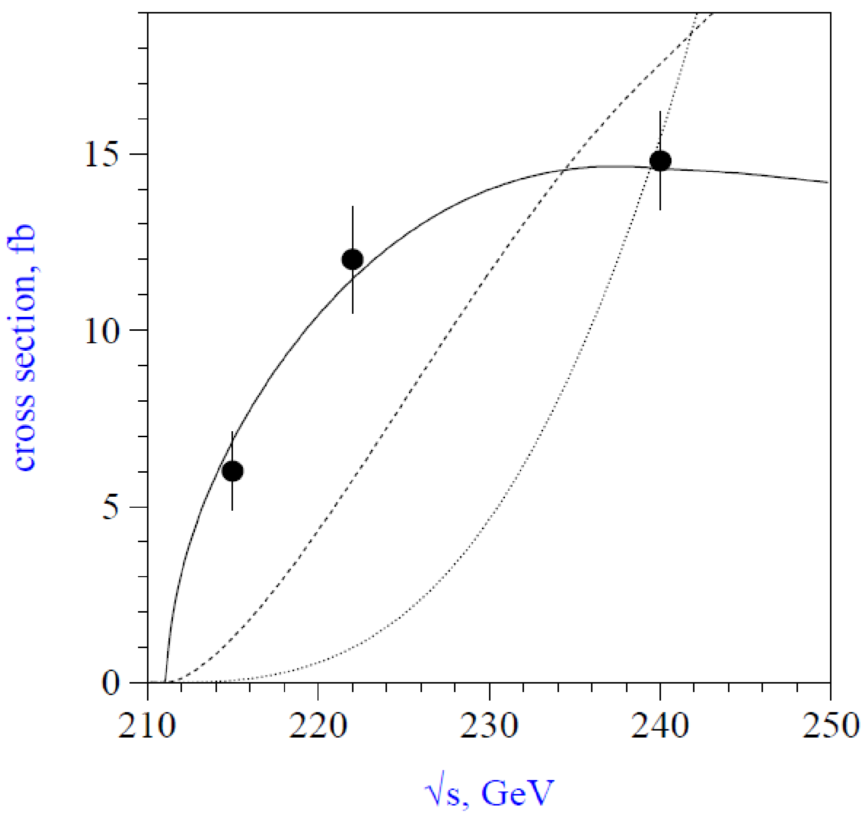
The ultimate Higgs physics plot

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

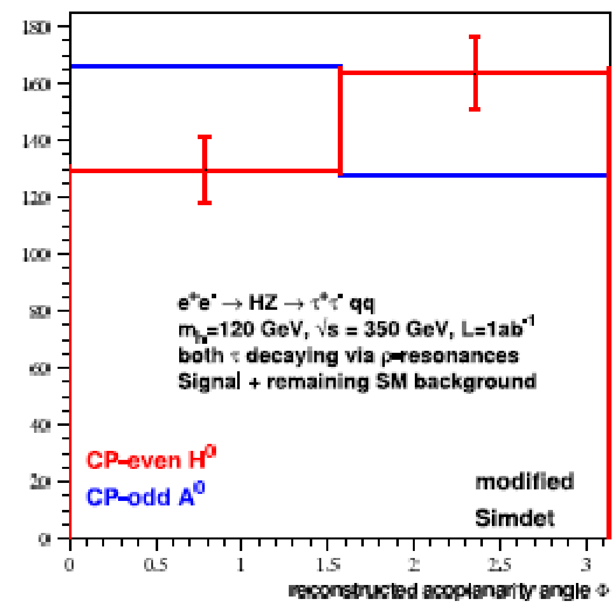
"Fully" explore the physics at the Terascale, establish the models and mechanisms

Higgs Properties

Measurement of Higgs Spin (threshold scan)



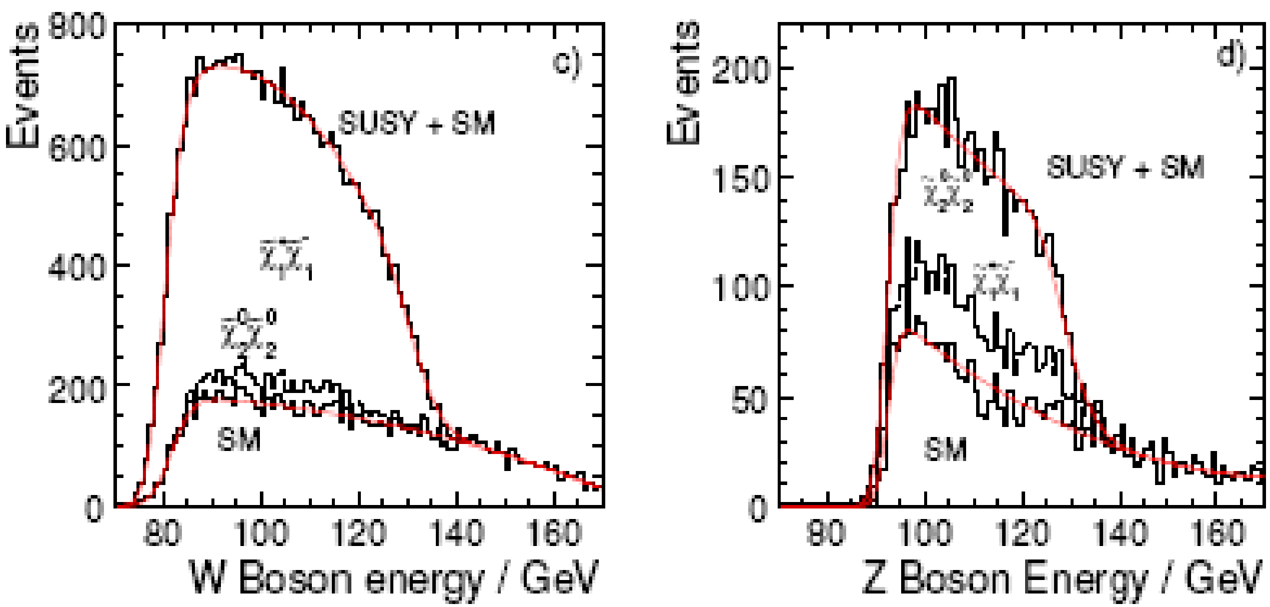
Study of CP properties of a Higgs candidate



Beyond the SM: SUSY Signals

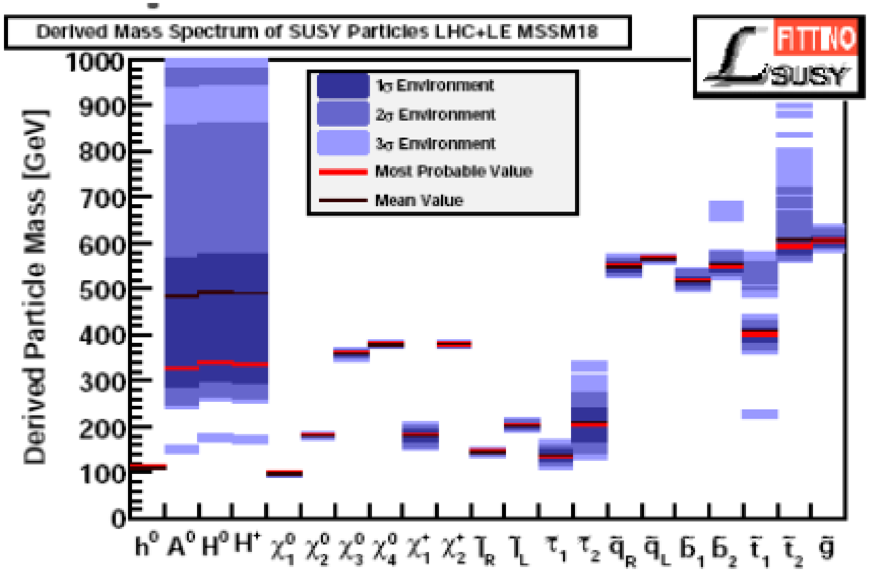
IF SUSY states are within the kinematic reach

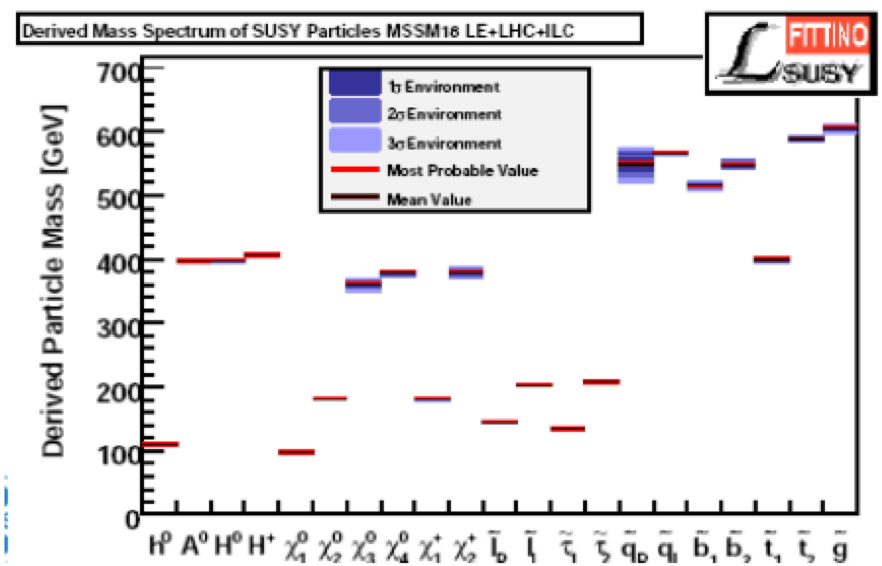
Excellent reconstruction of the states and their properties
(complete reconstruction possible, absolute measurements)



SUSY Masses

P. Bechtle, Fittino code

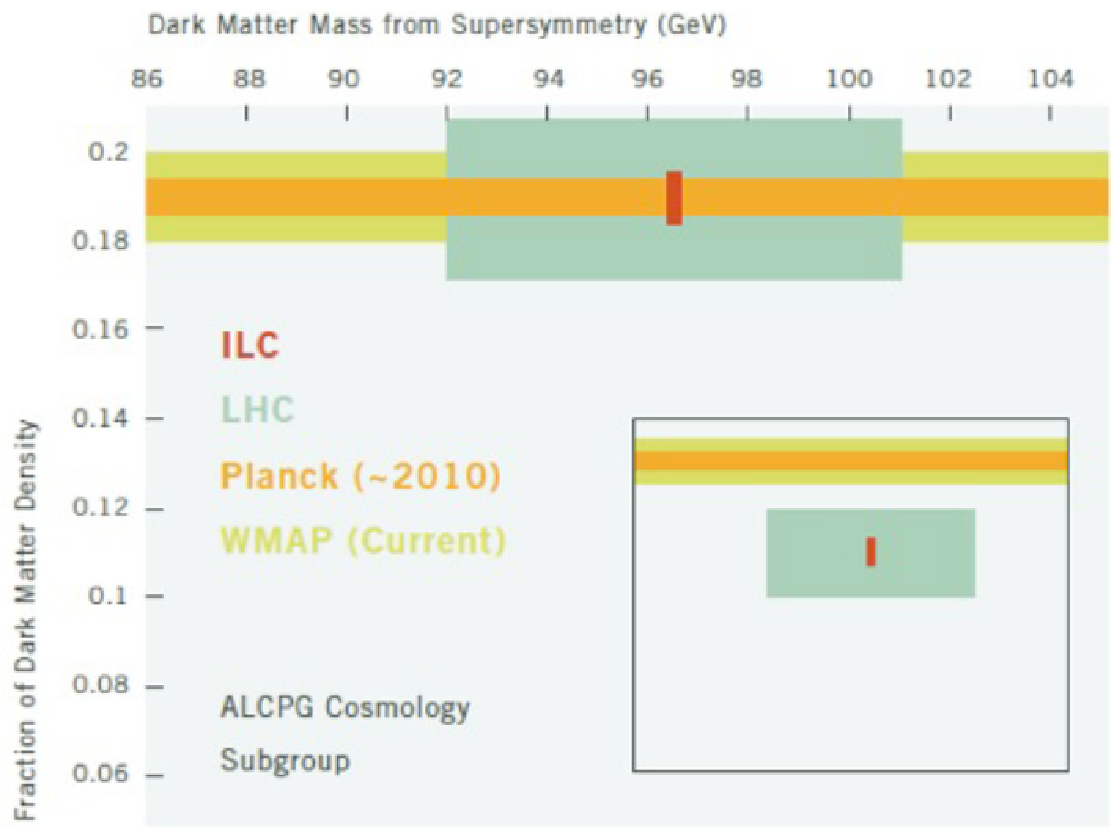


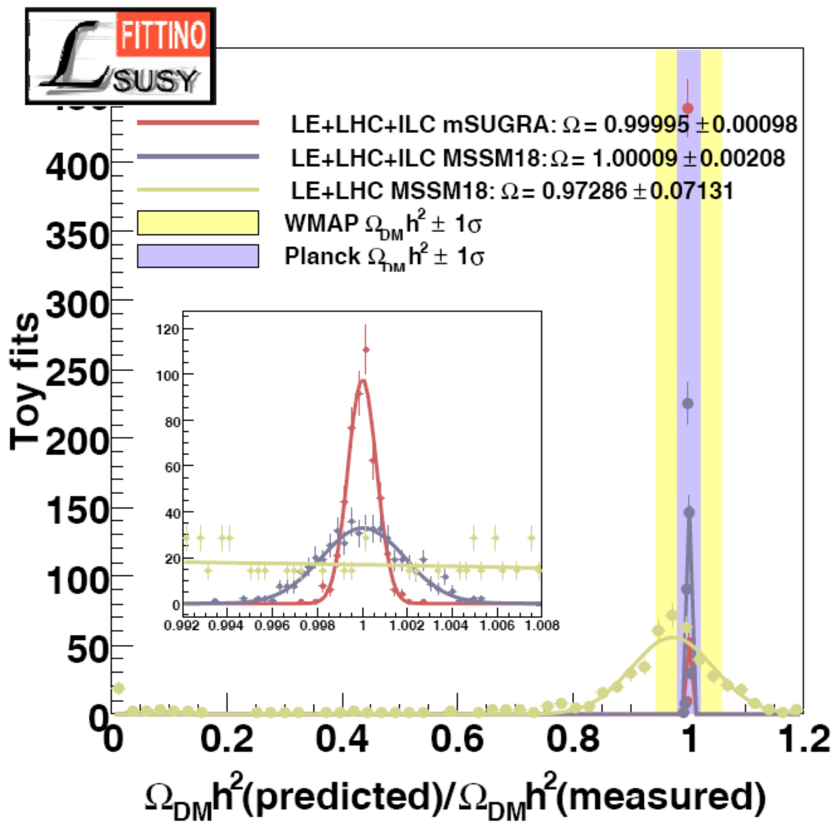


If SUSY masses are within the reach of the ILC:

Strong improvements
Gaussian distributions
Biases nearly disappear

Dark Matter at the ILC



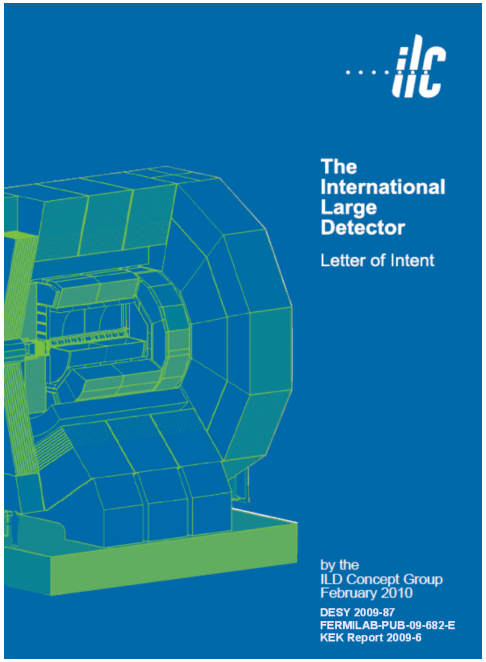


Dark Matter density
Comparison to future
Planck measurements

This was only a very limited selection of topics:

See e.g. the reference design report for the ILC (www.linearcollider.org)

Or the letter of intent of the ILD detector (www.ilcild.org)
for much more detail.



How do we realise such a machine?

High Energy Lepton Collider

	LEP-II	Super-LEP	HYPER-LEP
E_{cm}	180 GeV	500 GeV	2 TeV
L	27 km	200 km	3200 km
ΔE	1.5 GeV	12 GeV	240 GeV
€$_{tot}$	2 billion	15 billion	240 billion!

Table by James Jones

High Energy Lepton Collider

	LEP-II	Super-LEP	HYPER-LEP
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$€_{tot}$	2 billion	15 billion	240 billion!

Table by James Jones

- The next e+e- collider will be linear:
- €LC~ E

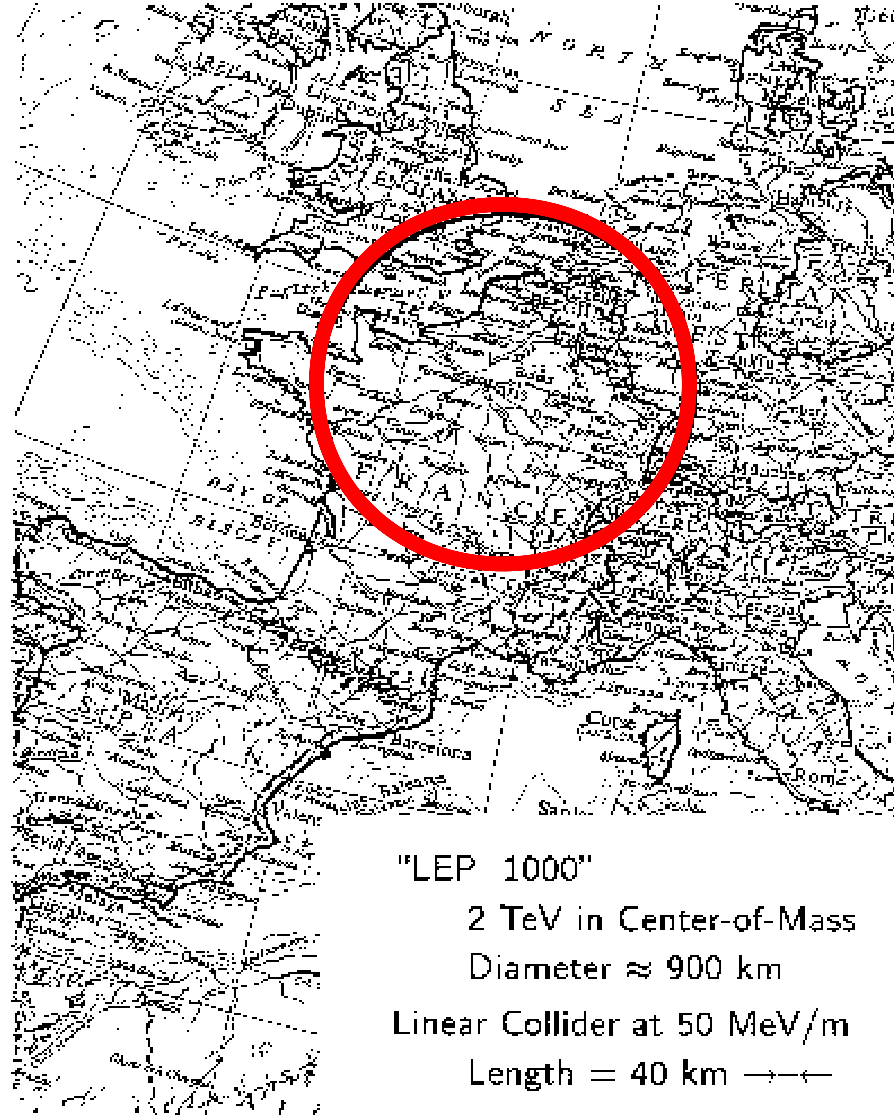
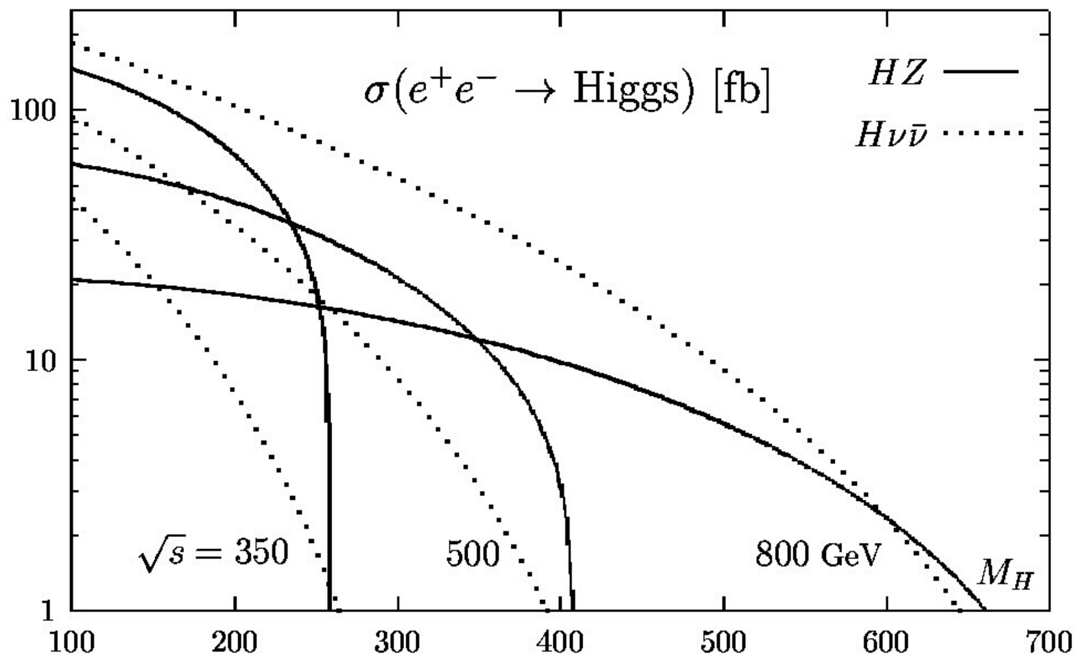


Figure by Gregory Loew

Luminosity Wish

Luminosity - energy

as much as possible of course...



example: SM Higgs production

σ ≈ 20 fb
O(1%) measurement needs
O(10000) events:
need approx. 500 /fb

assume 5 years running,
< 500 days in 5 years

$$L \approx 1 \times 10^{34}\,cm^{-2}s^{-1}$$

The Luminosity Issue

Collider luminosity (cm^{-2} s^{-1}) is approximately given by:

$$L = \frac{n_b N^2 f_{rep}}{A} H_D$$

where:

n_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
A = beam cross-section at IP
H_D = beam-beam enhancement factor

For *Gaussian* beam distribution:

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

Taking power into account:

$$L = \frac{\eta_{RF \rightarrow beam} P_{RF} N^2}{4\pi \sigma_x \sigma_y E_{CM}} H_D$$

Luminosity Issues: storage ring *vs* LC

LEP f_{rep} = 44 kHz

LC f_{rep} = few-100 Hz
(power limited)

factor ~400 in *L* already lost!

$$L = \frac{n_b N^2 f_{rep}}{4\pi\sigma_x\sigma_y} H_D$$

Must push very hard on beam cross-section at collision:

LEP: $\sigma_x\sigma_y \approx 130 \times 6\ \mu m^2$

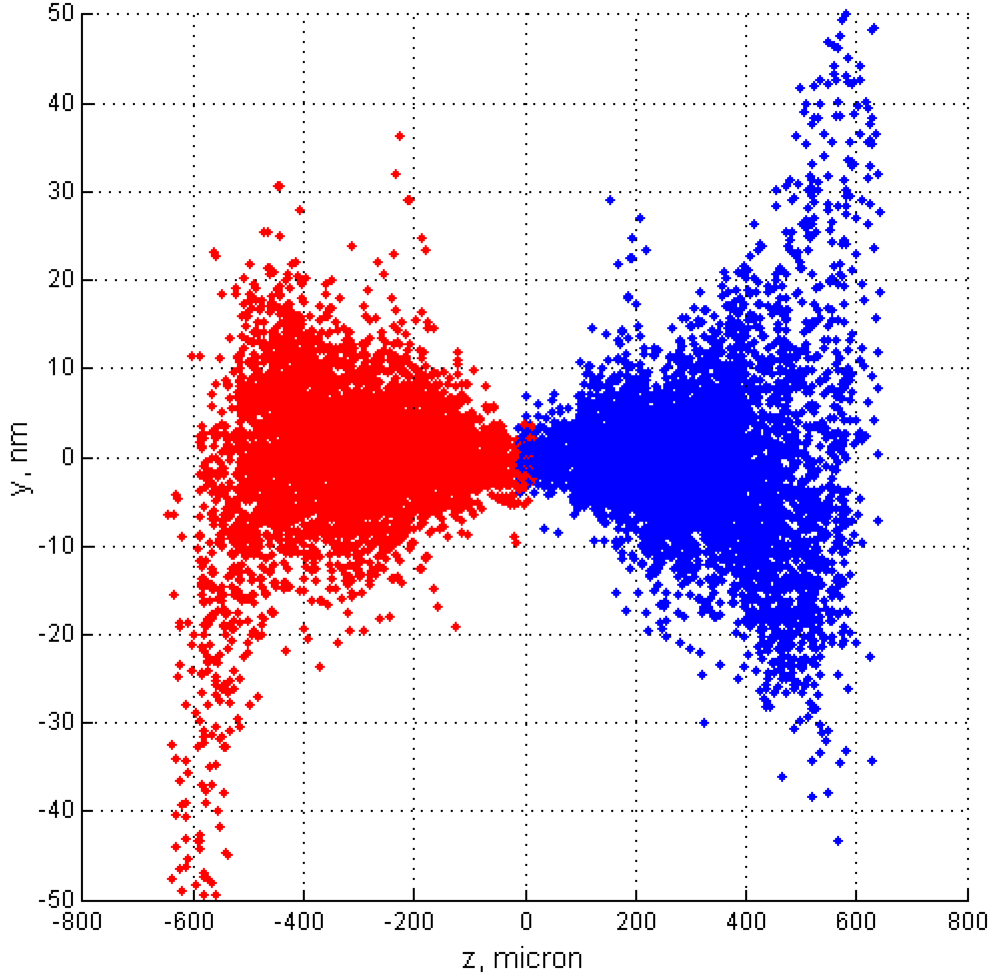
LC: $\sigma_x\sigma_y \approx (200\text{-}500) \times (3\text{-}5)\ nm^2$

factor of 10^6 gain!
Needed to obtain high luminosity of a few $10^{34}\ cm^{-2}s^{-1}$

Single pass machine (LC): can afford to push beam size
problem: beams destroy themselves

Beam Beam Interactions

Simulation of two LC bunches as they meet each other



Andrei Sergey, SLAC

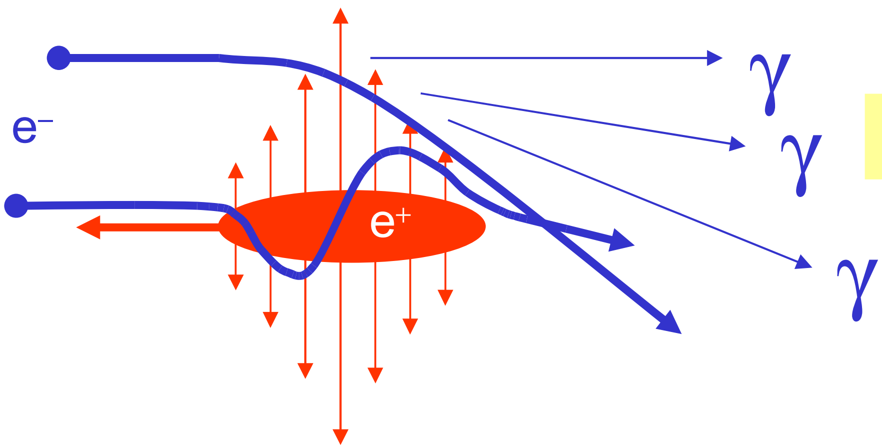
Beamstrahlung

Energy loss from BS: δ_{BS}

typical numbers: 3-10%

$$\delta_{BS} \approx 0.86 \frac{e r_e^3}{\sigma_z} \left(\frac{E_{cm}}{\sigma_z}\right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

(without derivation)

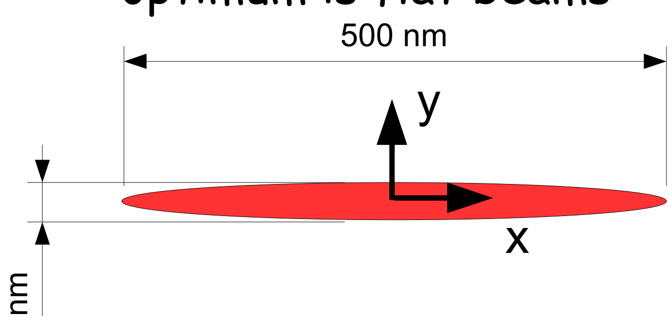


Luminosity:

$$L = \frac{\eta_{RF} P_{RF} N^2}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

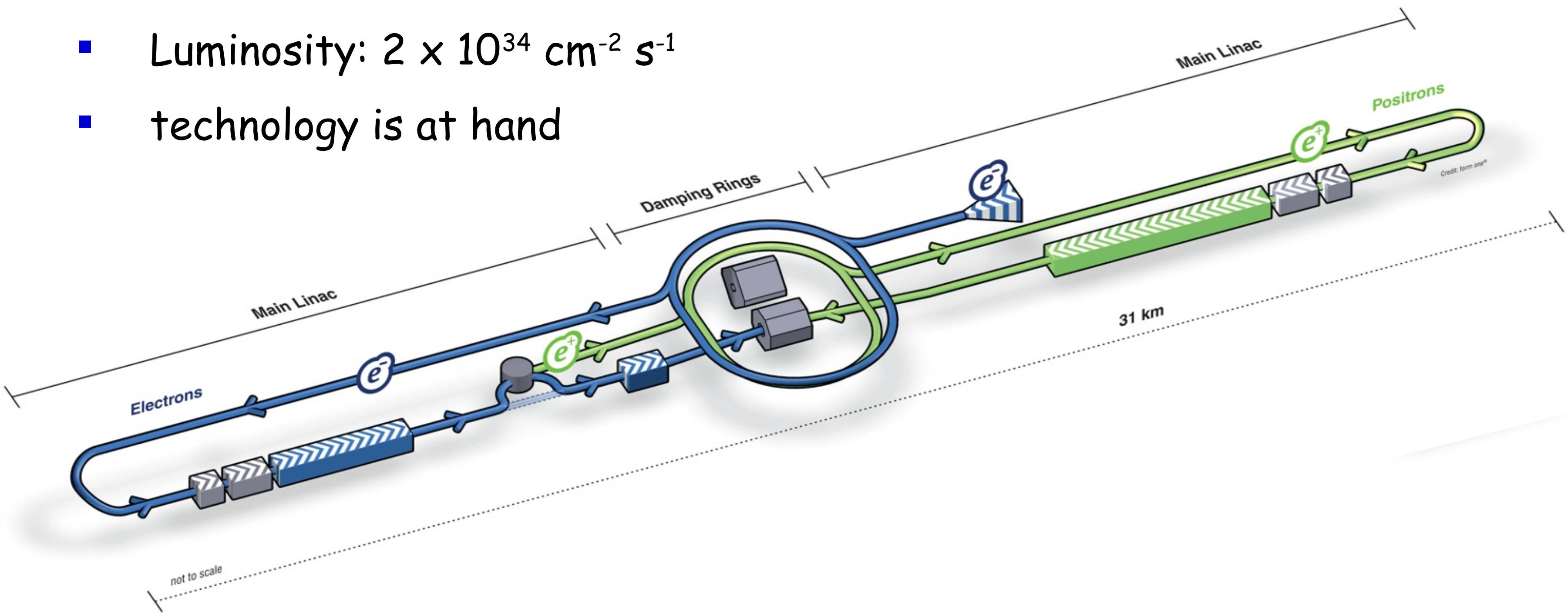
LARGE luminosity: make beams SMALL
SMALL beamstrahlung: make beams LARGE

optimum is flat beams



International Linear Collider

- superconducting acceleration
- 31.5 MeV/m, 1.3 GHz
- mature design (c.f. XFEL)
- 500 GeV (→ 1TeV)
- Luminosity: 2×10^{34} cm^{-2} s^{-1}
- technology is at hand



Global Design Effort

Americas

Labs

ANL
BNL
FNAL
JLAB
LANL
LBNL
LLNL
SLAC
TRIUMF

Universities/Institutes

Colorado Univ.
Cornell
FSU
Iowa Univ.
MSU
Notre Dame Univ.

Europe

labs

Budker
CEA/Saclay
CERN
CIEMAT
CNRS
STFC Daresubry Lab.
DESY
ESRF
GSI
INFN
JINR
LAL-Orsay
PSI

Universities/Institutes

Abertay Univ.
Berlin HU
Birmingham Univ.
Cambridge Univ.
Dundee Univ.
Durham
IFIC
IPJ
IPN-Orsay
IPPP Durham
Krakow
Lancaster Univ.
LAPP-Annecy
Legnaro
Liverpool Univ.
Manchester Univ.
Mannheim
Oxford Univ.
RHUL
Rostock

Asia

labs

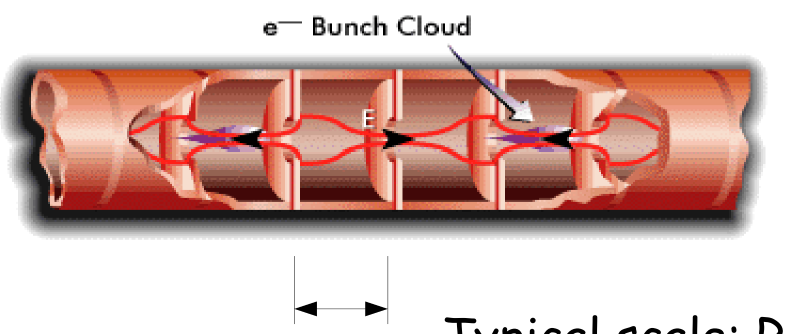
BARC
IHEP
IUAC
KEK
RRCAT
Tsinghua Univ.
VECC

Universities/Institutes

Hiroshima Univ.
KNU
Nagoya Univ.
PAL
TIFR
Tohoku Univ.
Tokyo Univ.
Univ. Delhi

LC technologies

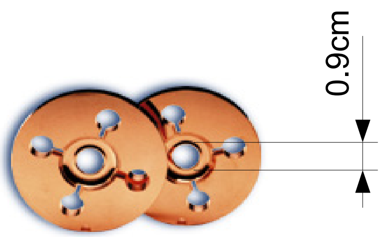
At the core of the matter: cavities, acceleration power



Typical scale: RF wavelength

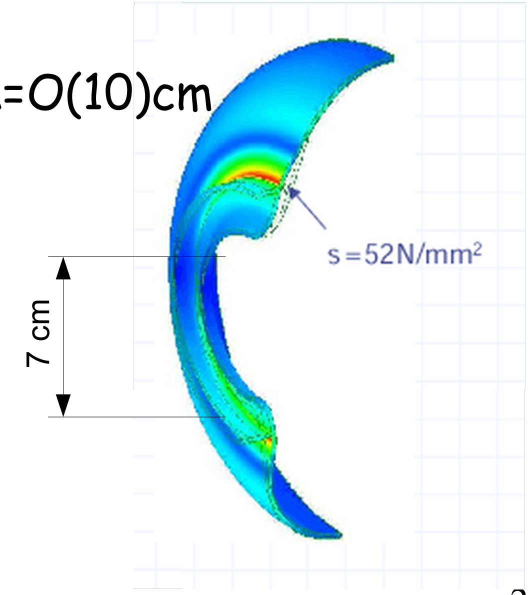
Warm machine (NLC, CLIC)

ν ≈ tens of GHz => λ=O(1)cm



Cold Machine (ILC):

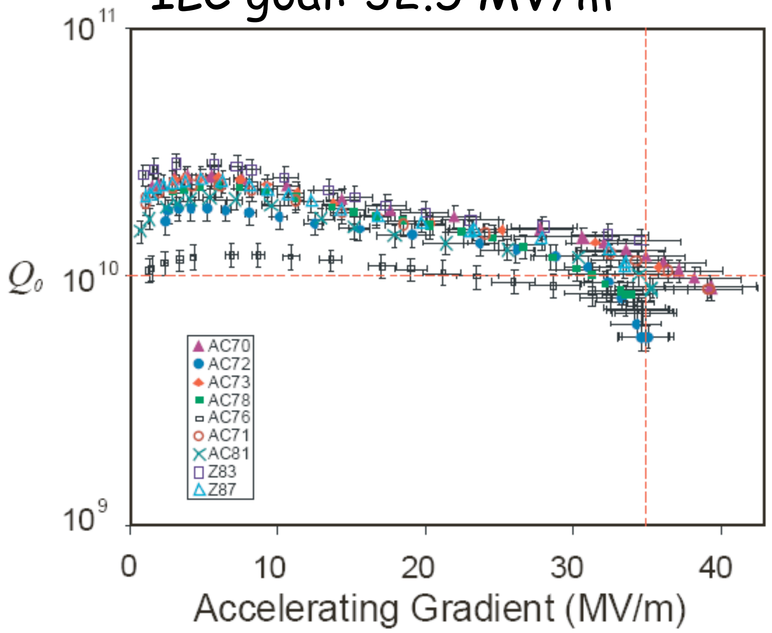
ν ≈ O(1) GHz => λ=O(10)cm

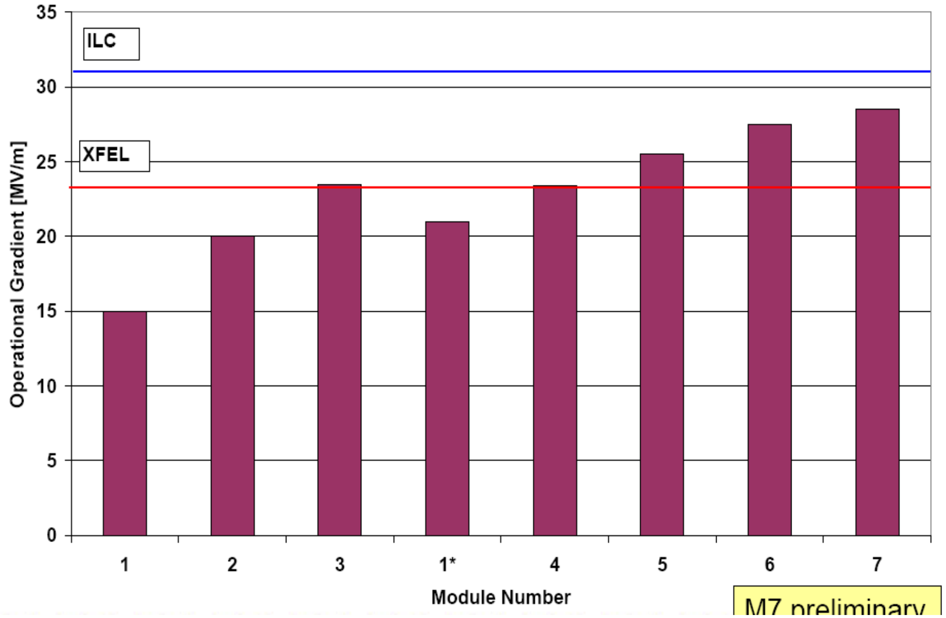


ILC Cavities

Acceleration gradient goal:

- 35 MV/m in 9-cell cavities with production yield >80%
- 50 MV/m have been reached with single cavities
- Mass production reliability is the key problem
- ILC goal: 32.5 MV/m



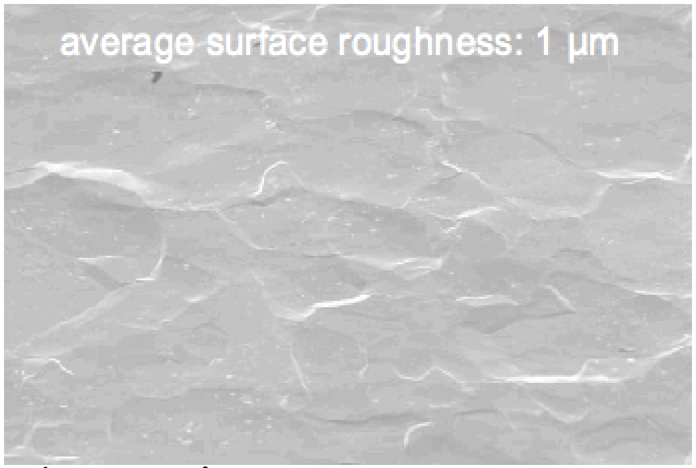


Cavity Quality (Q value)

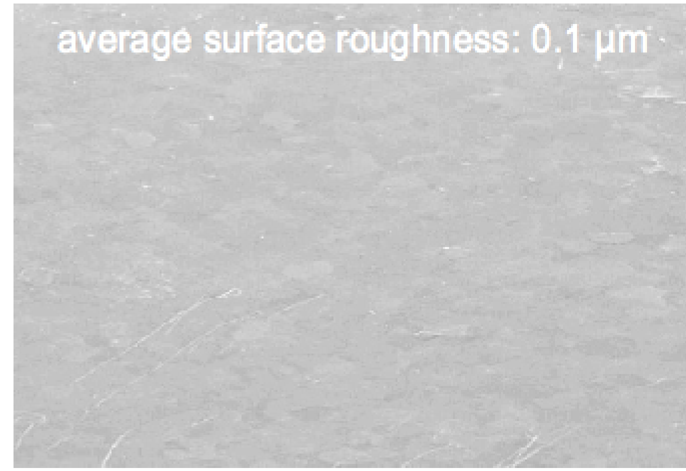
- Superconducting cavity: $Q > 10^{10}$
- A church bell (300 Hz) with $Q = 5 \times 10^{10}$ would ring – once excited – longer than one year!

Cavity treatment

- Electropolishing as major advance in surface preparation

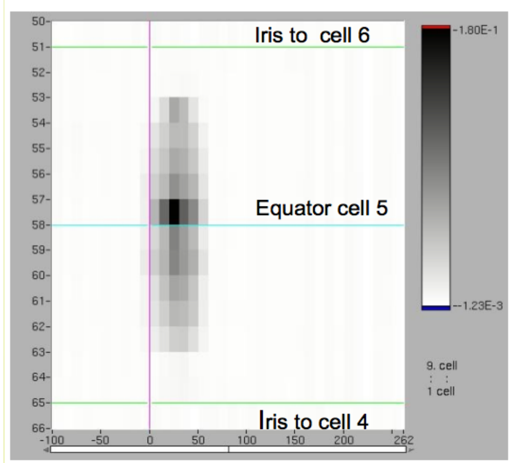


buffered chemical polishing

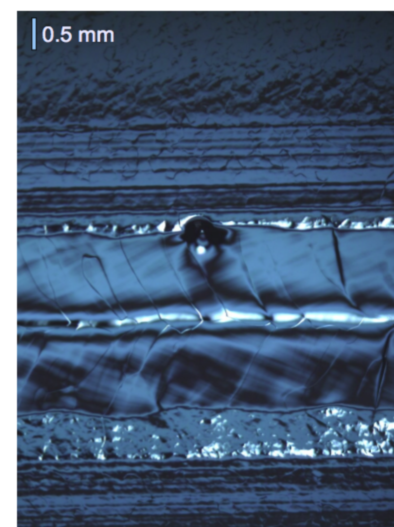


electrolytic polishing

- Industrialisation is the key issue
- Large Synergy with the European XFEL project



Z130: Quench in $3\pi/9$-mode at 22 MV/m



Picture at same location

Accelerator Systems ILC

ILC is a very demanding machine

From source over damping ring to final focus: technical advances are needed

Work is proceeding on all areas within the GDE, coordinated world wide

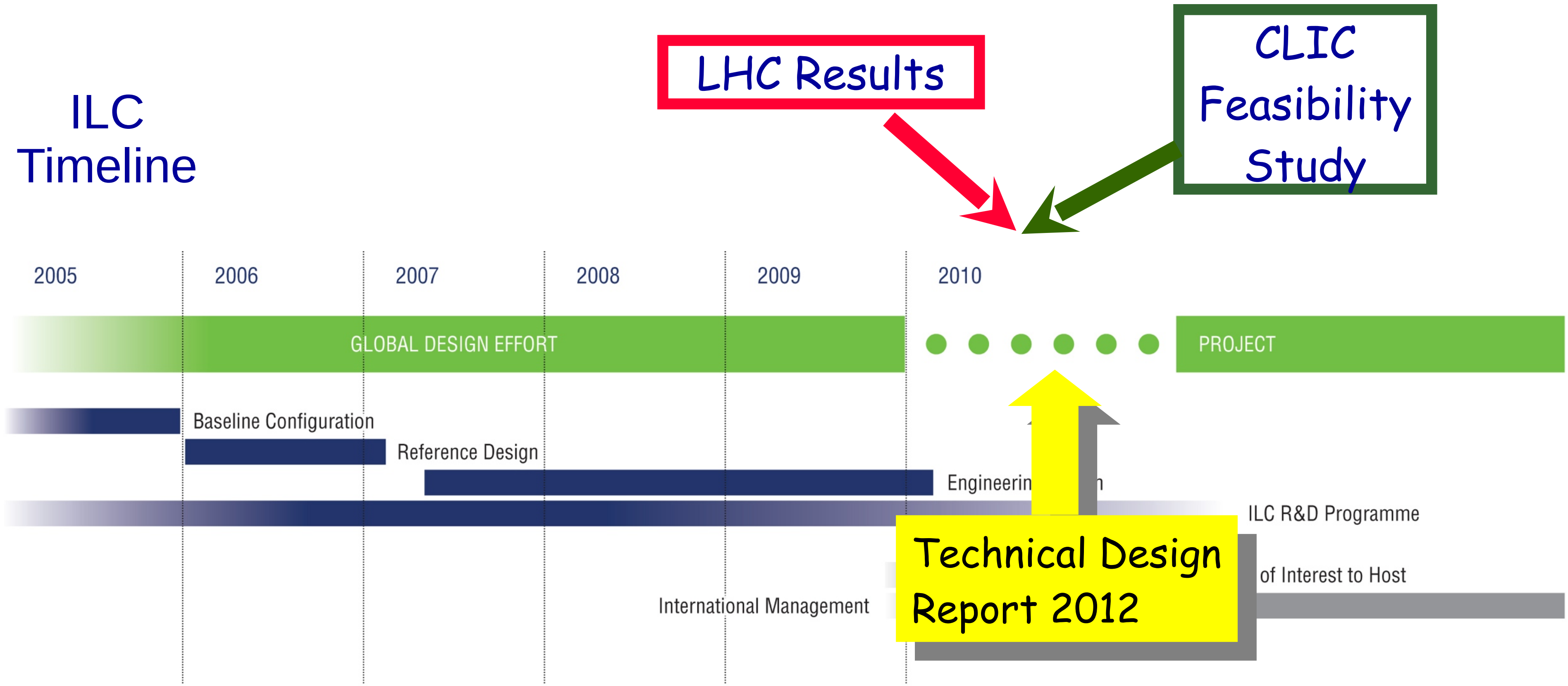
Major large scale test facilities:

- FLASH / TTF at DESY
- ATF2 at KEK
- Cornell damping ring test

Goal: reliable technical design by 2012, backed up by well understood costing

Time Lines

ILC
Timeline



A Detector for the ILC

Several detector concepts are being developed:

Two have reached a certain maturity:

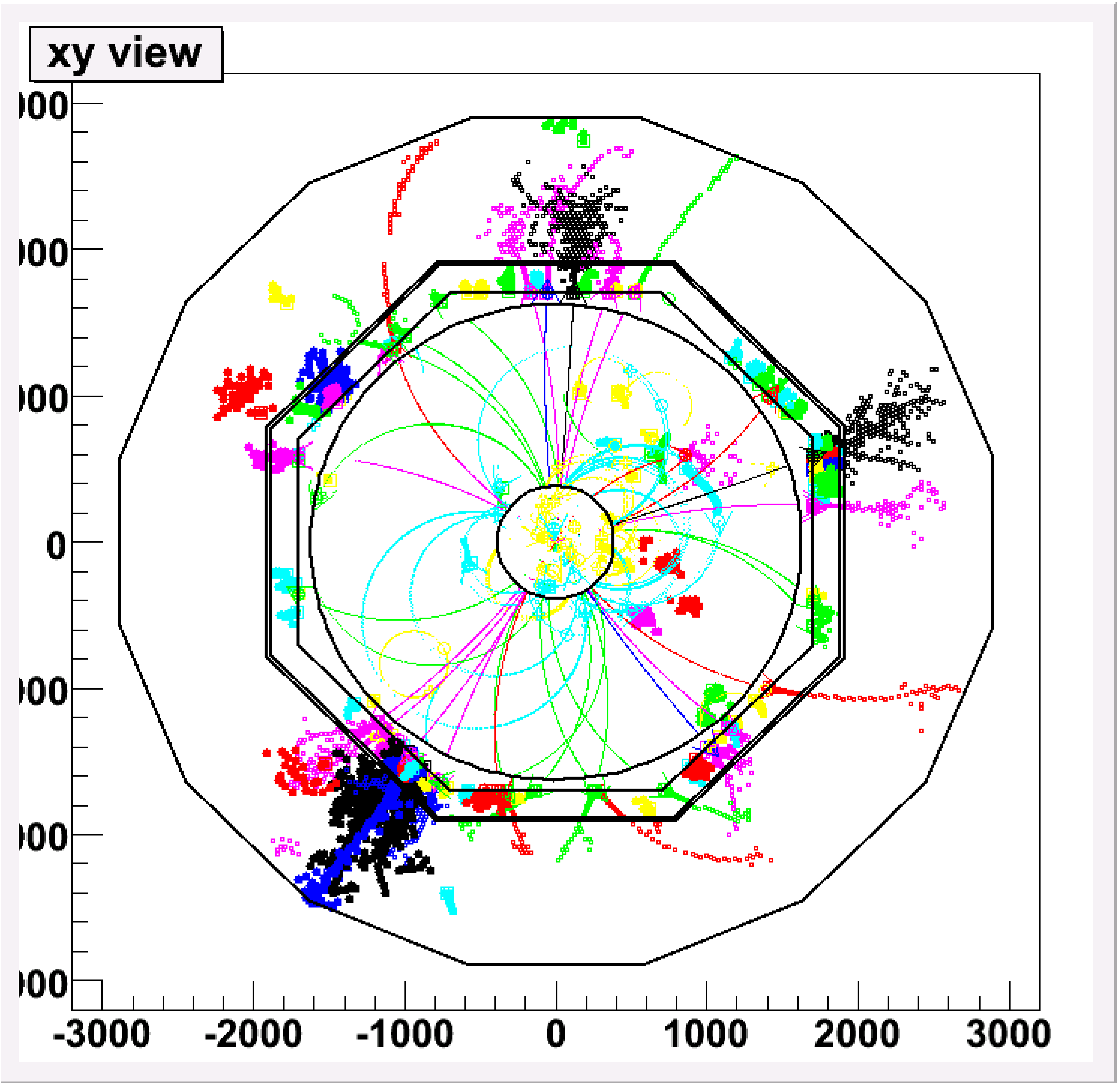
ILD (International Large Detector)

SiD (Silicon Detector)

Both have been evaluated by an international expert group

Other approaches are being discussed

In the following I will mostly discuss ILD
But conceptual differences are small (technological ones are big...)


xy view
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A Detector at the ILC

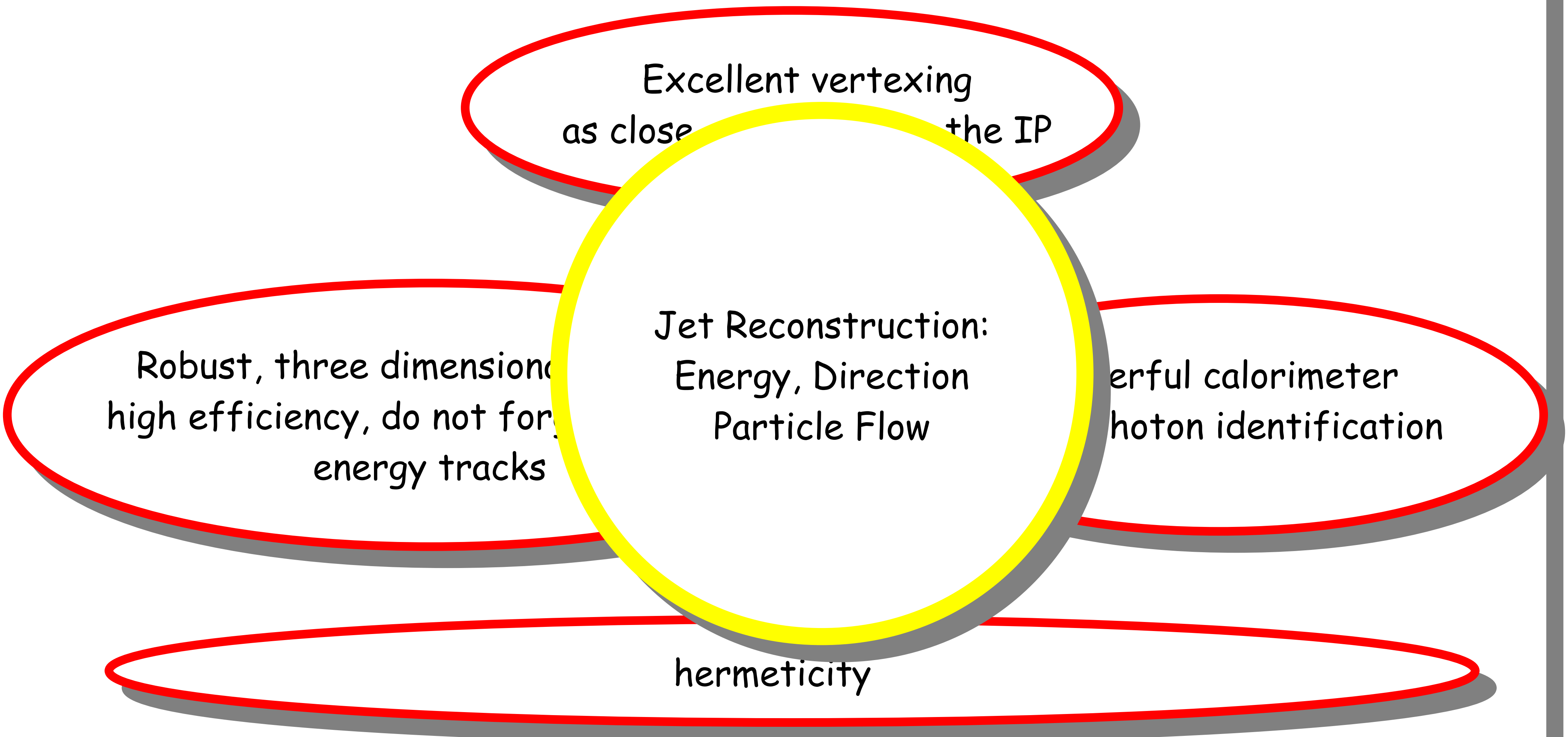
Excellent vertexing
as close as possible to the IP

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

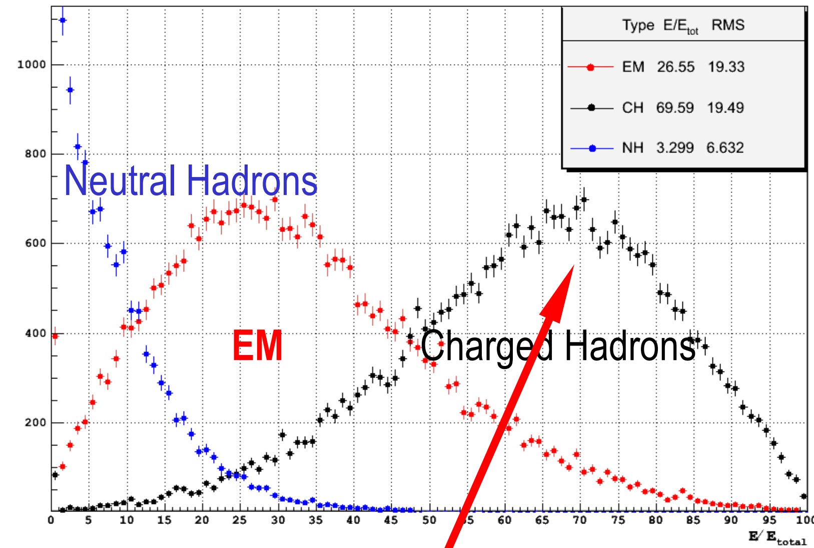
Powerful calorimeter
good photon identification

hermeticity

Detector Requirements



Particle Flow



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

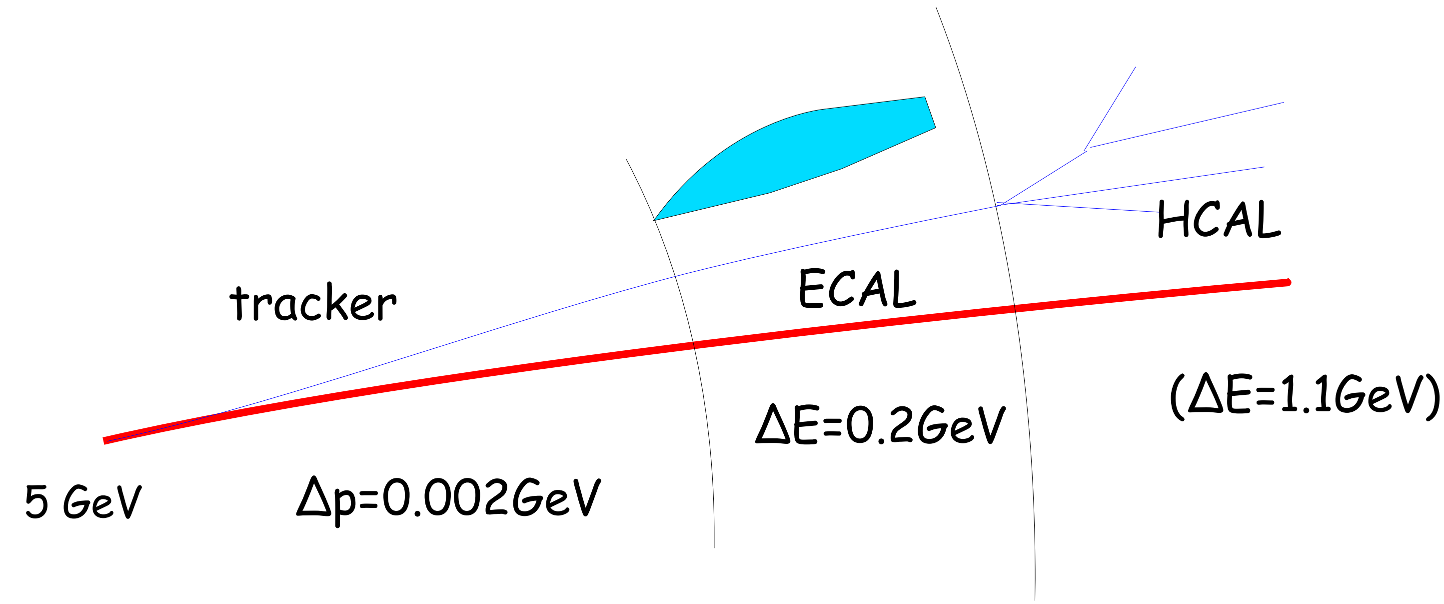
Fundamental problem: fluctuations in the calorimeter: <70%>

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

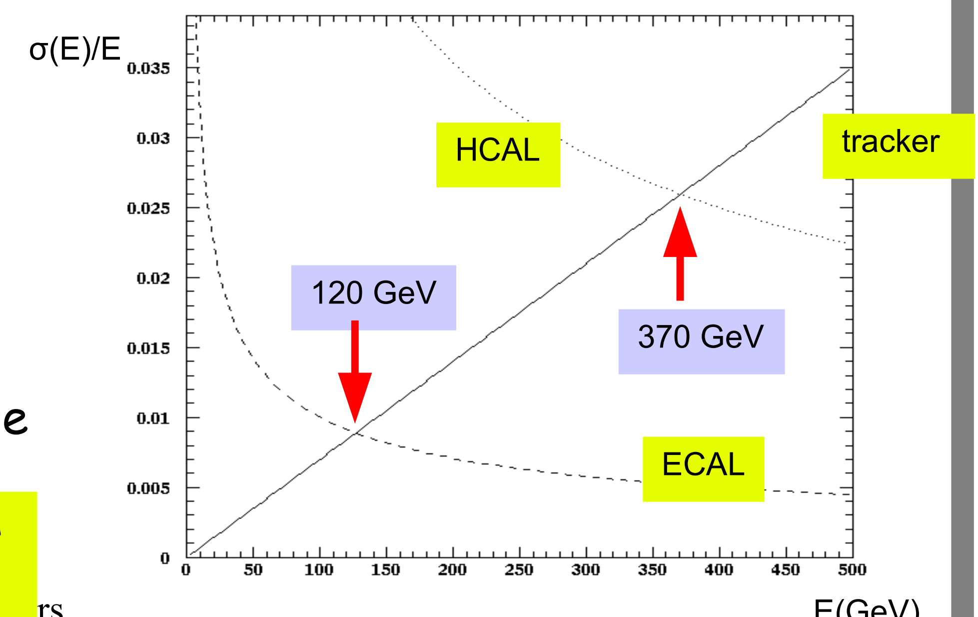
30%/√E (below 100 GeV) is the goal

What is Particle Flow



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

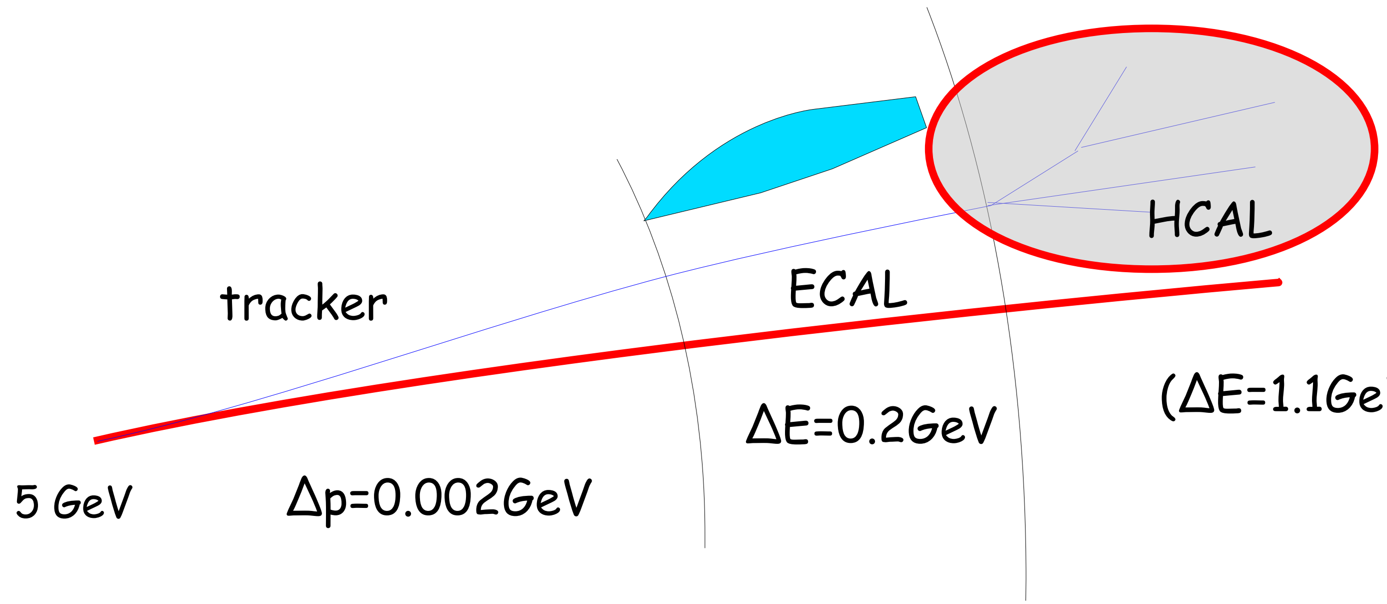
Resolution tracker - Calorimeter



For LC energies: tracker is most precise

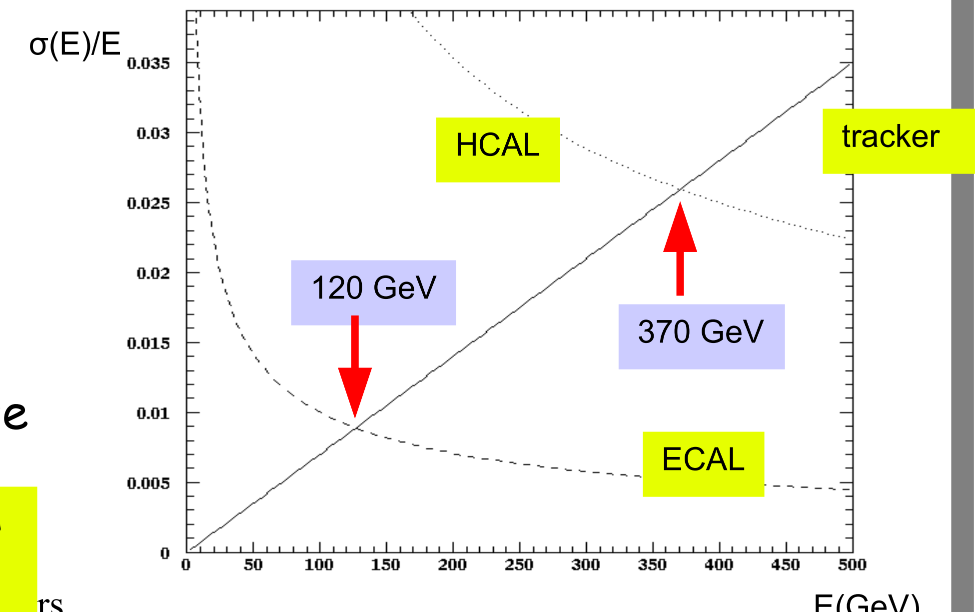
Utilize the precise tracker as much as possible

What is Particle Flow



Remove the calorimeter-based information, stress topology

Resolution tracker - Calorimeter

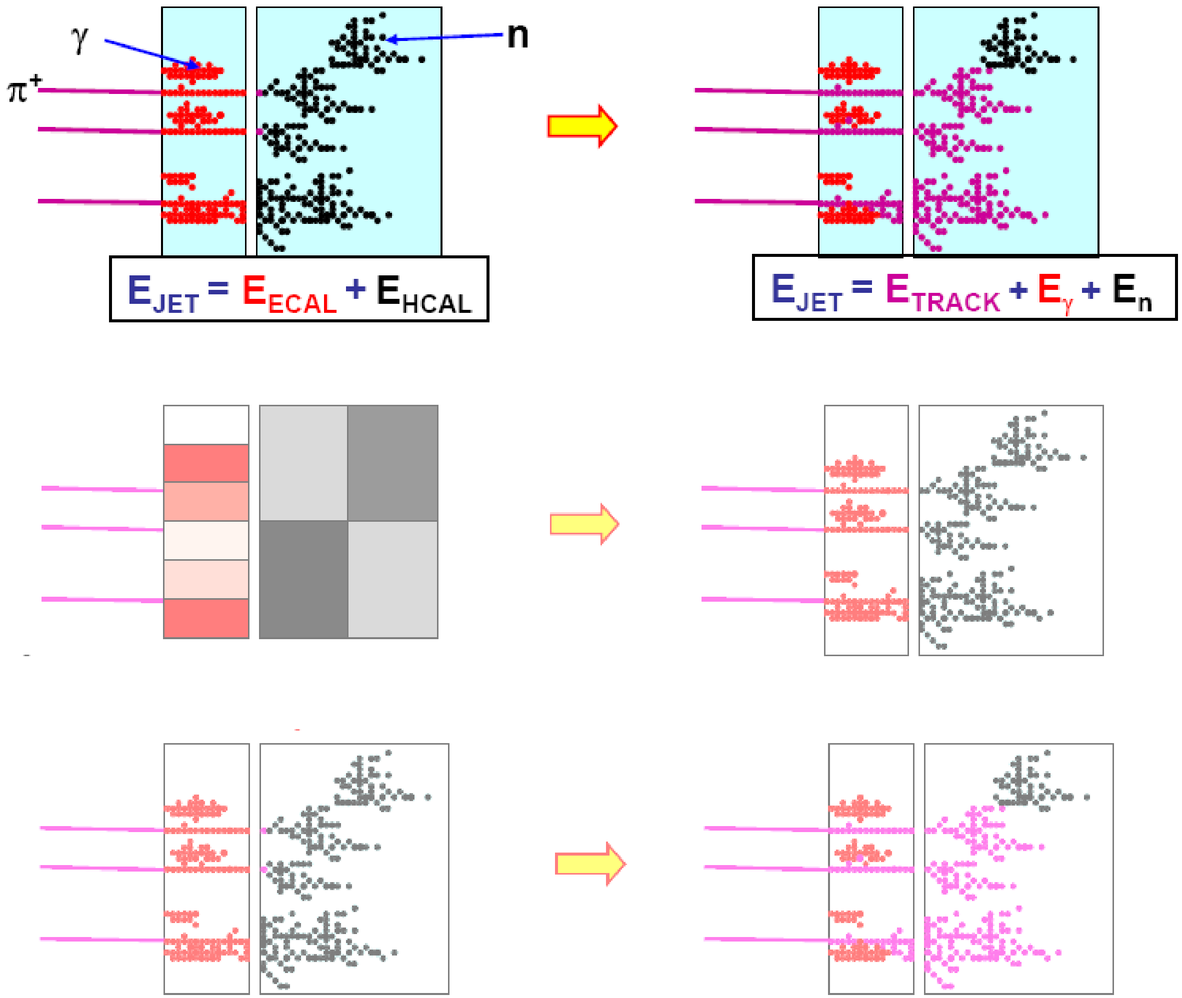


5 GeV electron:		0.002 GeV
	photon:	0.2 GeV
	neutron:	1.1 GeV

For LC energies: tracker is most precise

Utilize the precise tracker as much as possible

Particle Flow



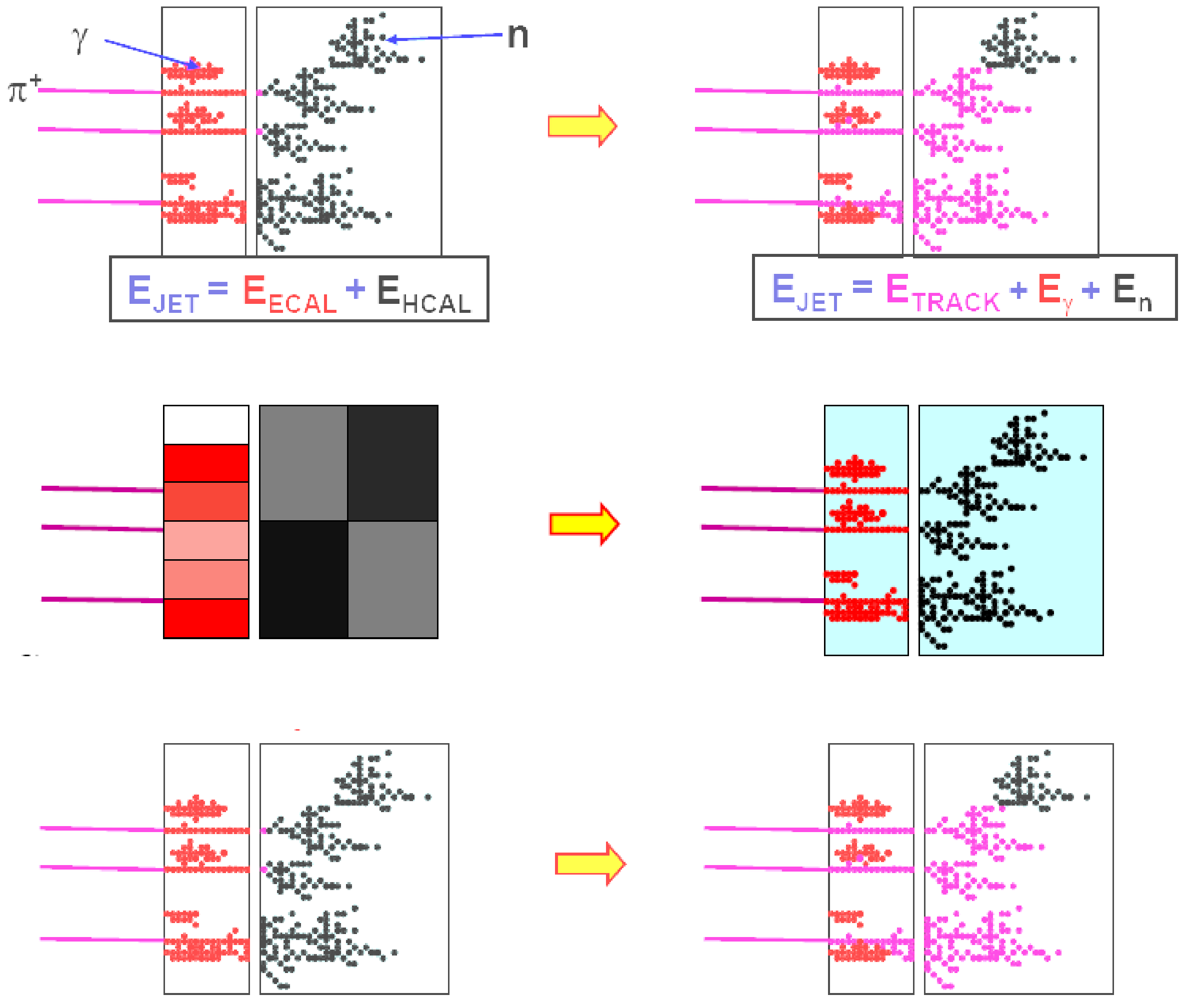
Utilise tracker and calorimeter information

Spatial Resolution in Calo is essential

Software to exploit the granularity is very important

Pictures by M. Thompson, Cambridge

Particle Flow



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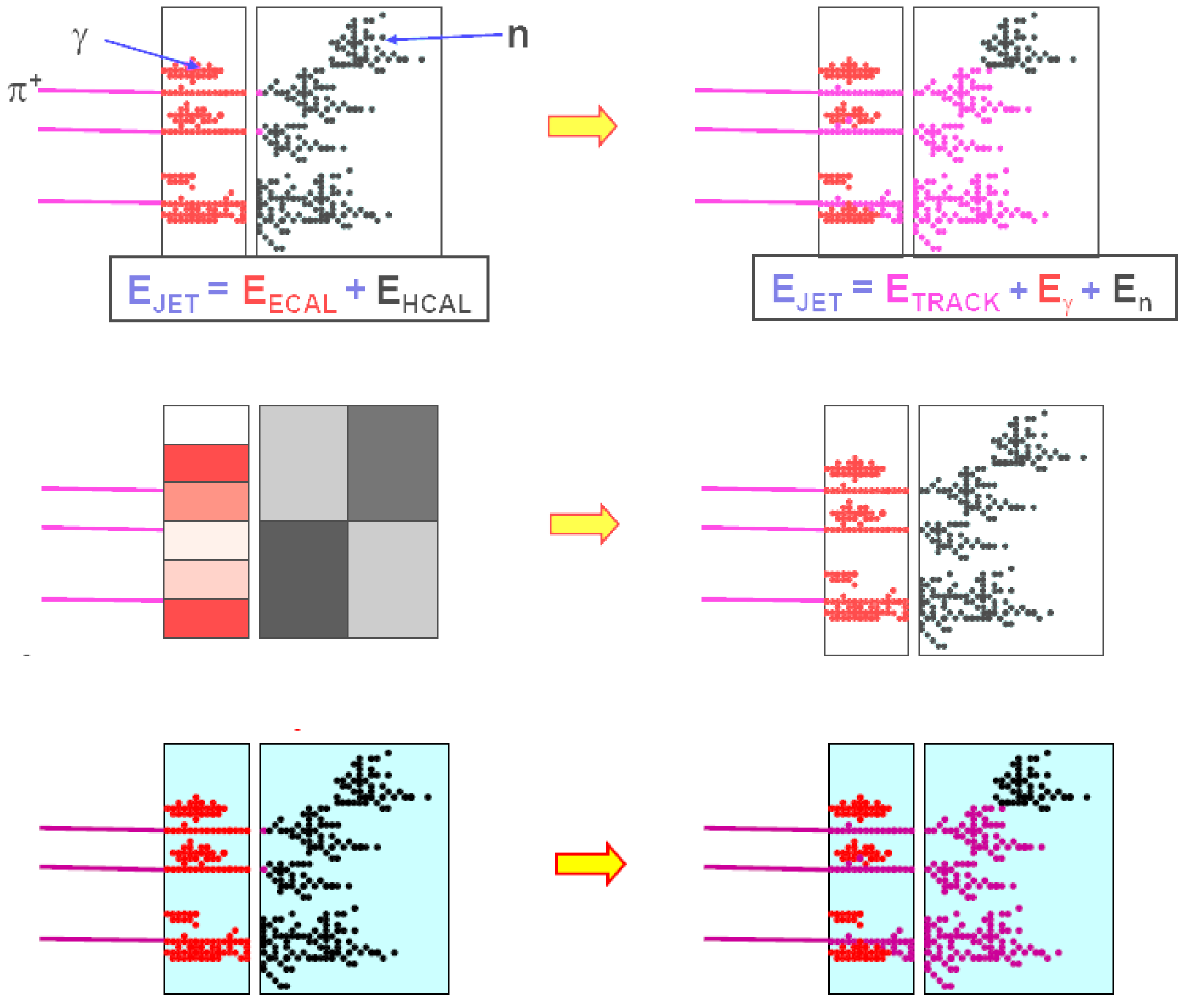
Pictures by M. Thompson, Cambridge

Particle Flow



Utilise tracker and calorimeter information

Spatial Resolution in Calo is essential

Software to exploit the granularity is very important

Pictures by M. Thompson, Cambridge

Factors Contributing to Jet mass resolution

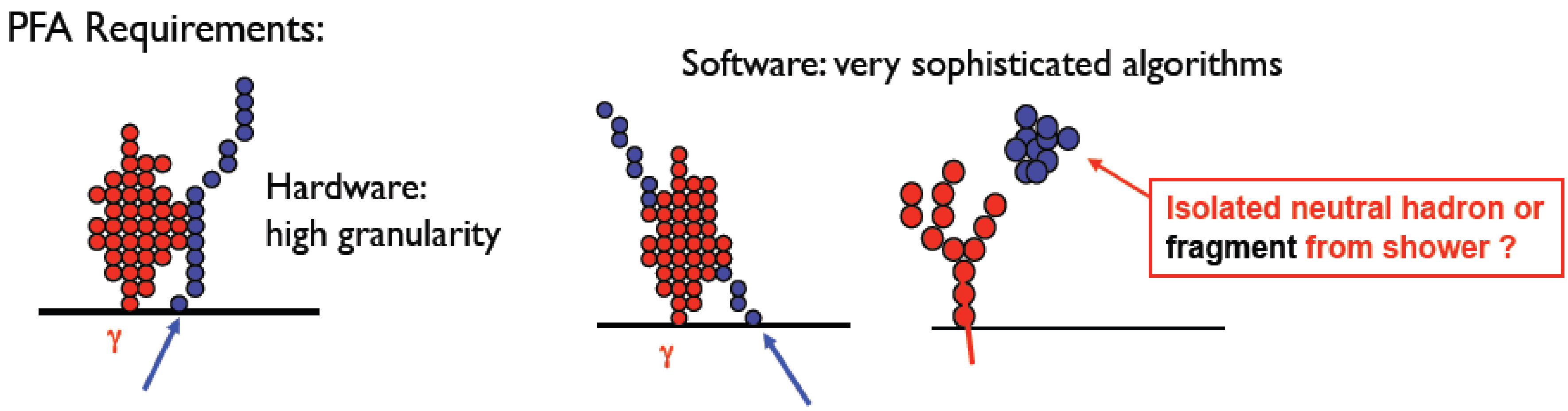
$$e^{+}e^{-}\rightarrow Z^{0}\rightarrow q\bar{q}\ \text{at}\ 91.2\text{GeV}$$

Studies by
P. Krstonosic

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

HCAL becomes very important for ultimate precision

Confusion



Ultimate performance needs excellent software

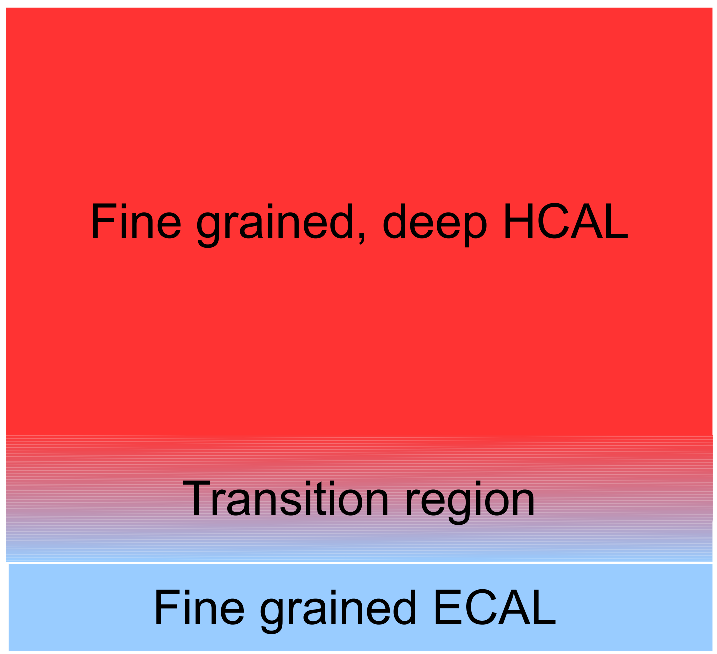
Reduction of the confusion (cluster assignement errors) is most important

The ideal PFLOW detector

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

Traditional energy resolution is important

but not so critically



containment

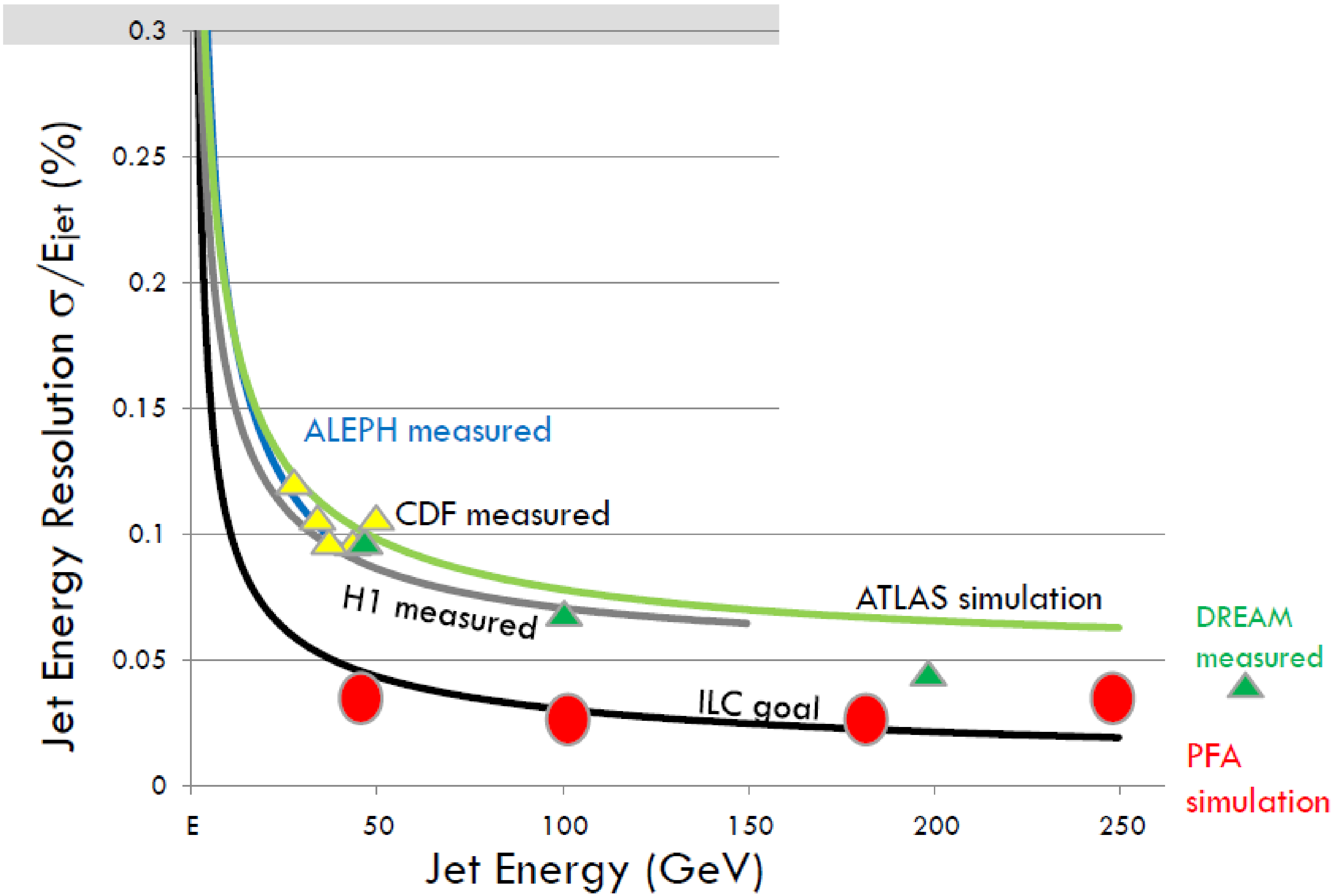
Granularity and longitudinal sampling

As deep as possible

Granularity: “tracking”

Precision, high efficiency tracking

Anticipated Performance



F. Simon, MPI Munich

A Detector at the ILC

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

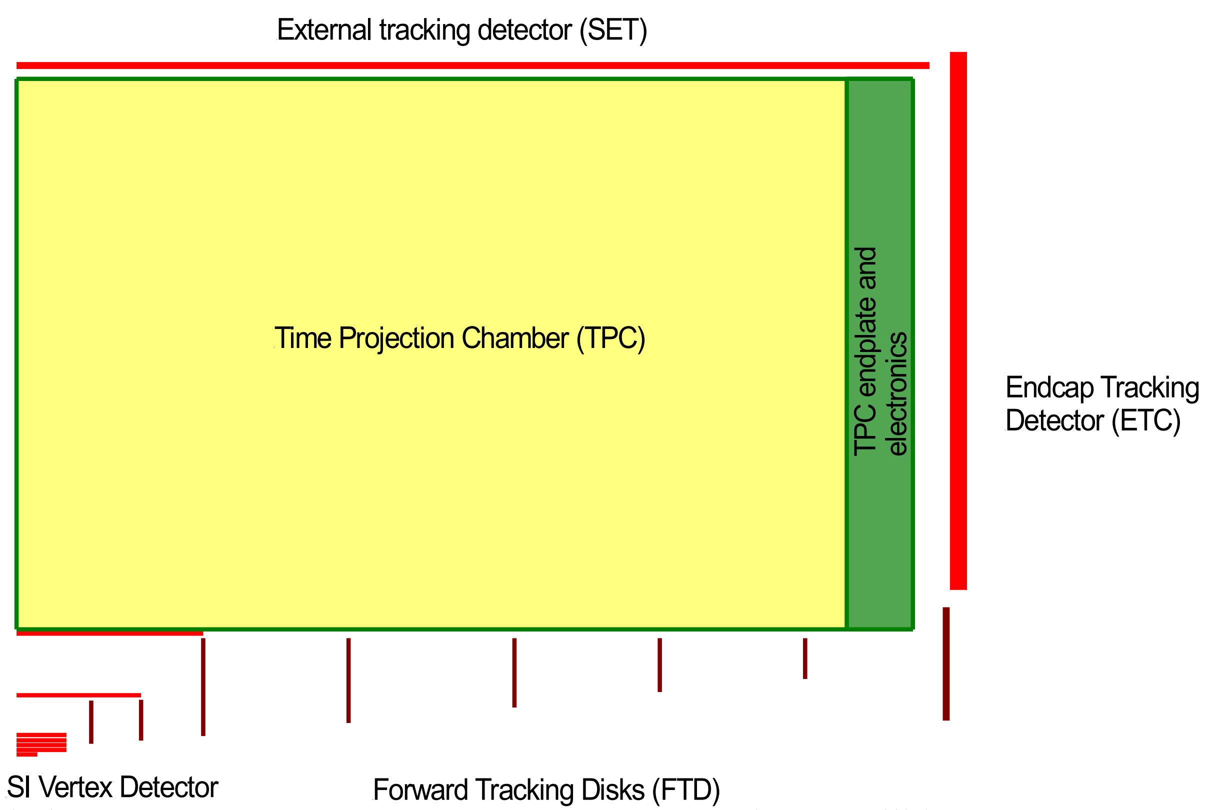
hermeticity

Tracking 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 Layout

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excellent vertexing capability
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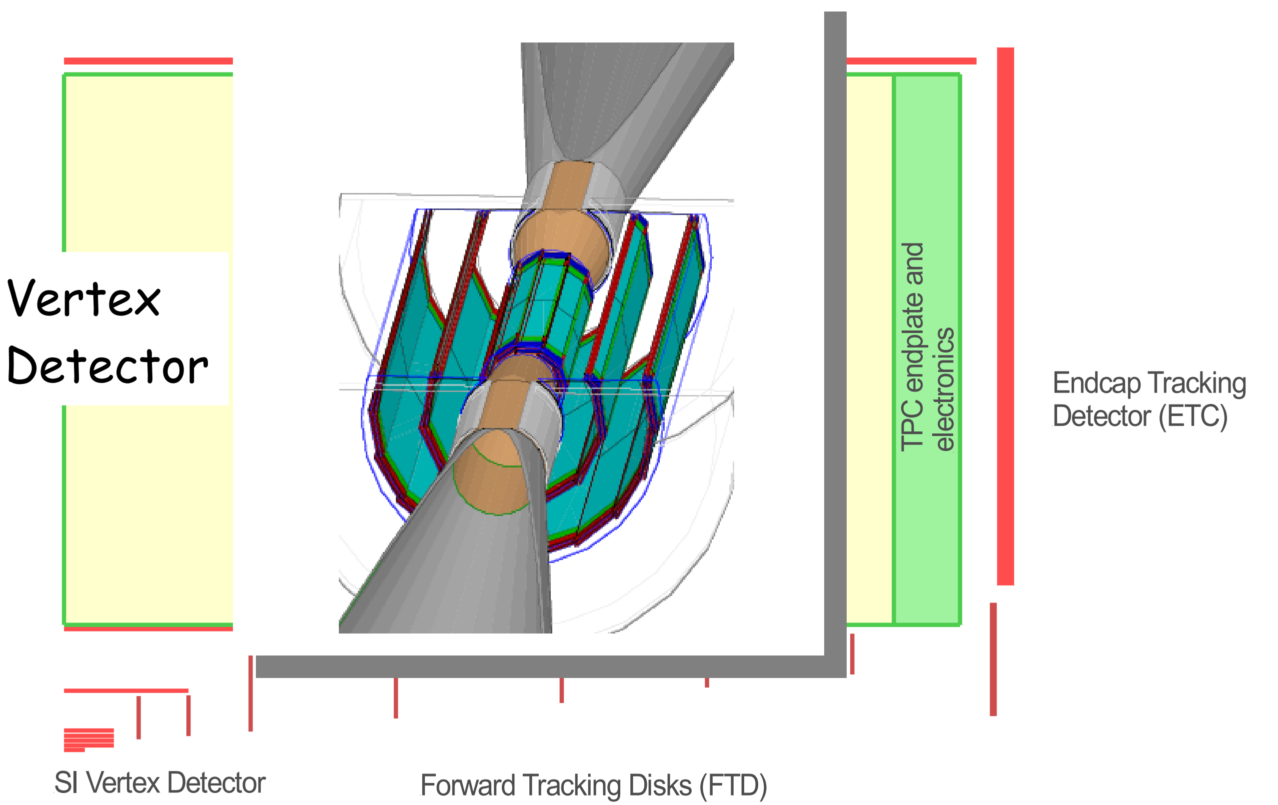


Special Focus on:

Robustness/ Redundancy

Excellent precision

Tracking Layout

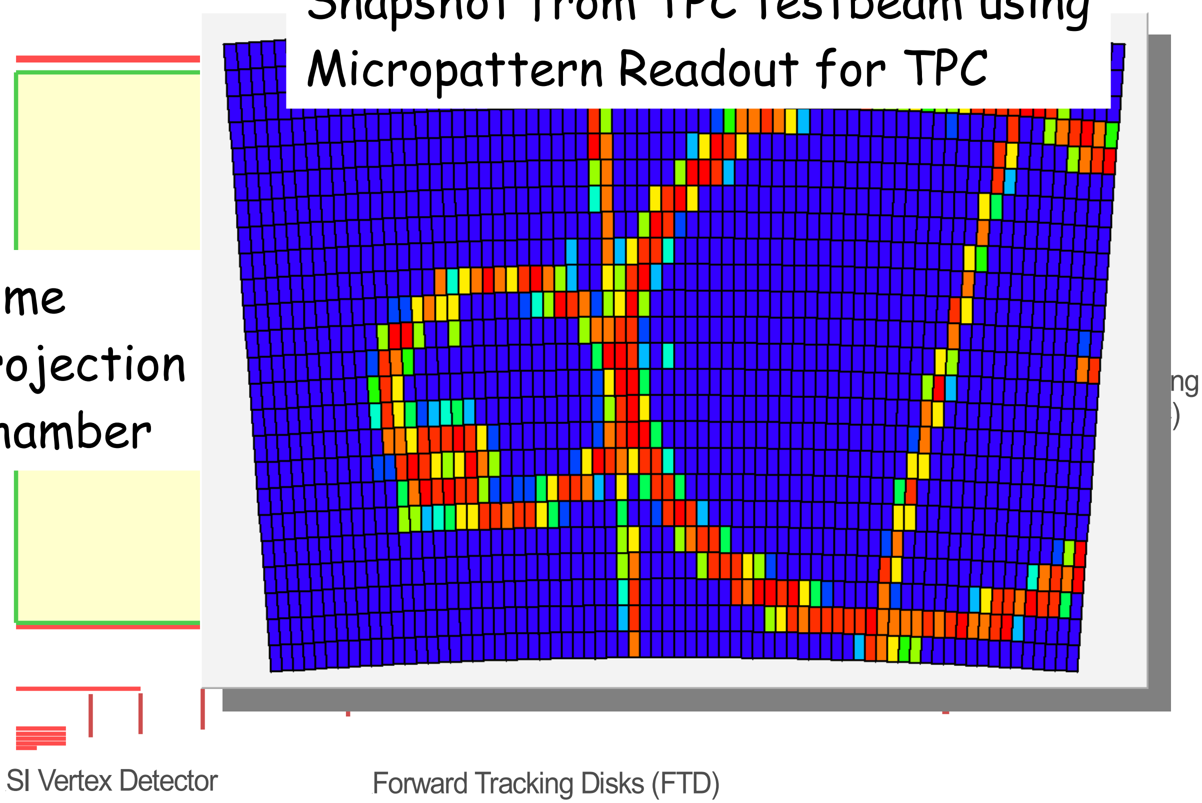
Powerful tracking / vertexing system

- excellent vertexing capability
- high precision tracking

Proposed layout of the ILD central tracking system

Snapshot from TPC testbeam using Micropattern Readout for TPC

Time Projection Chamber



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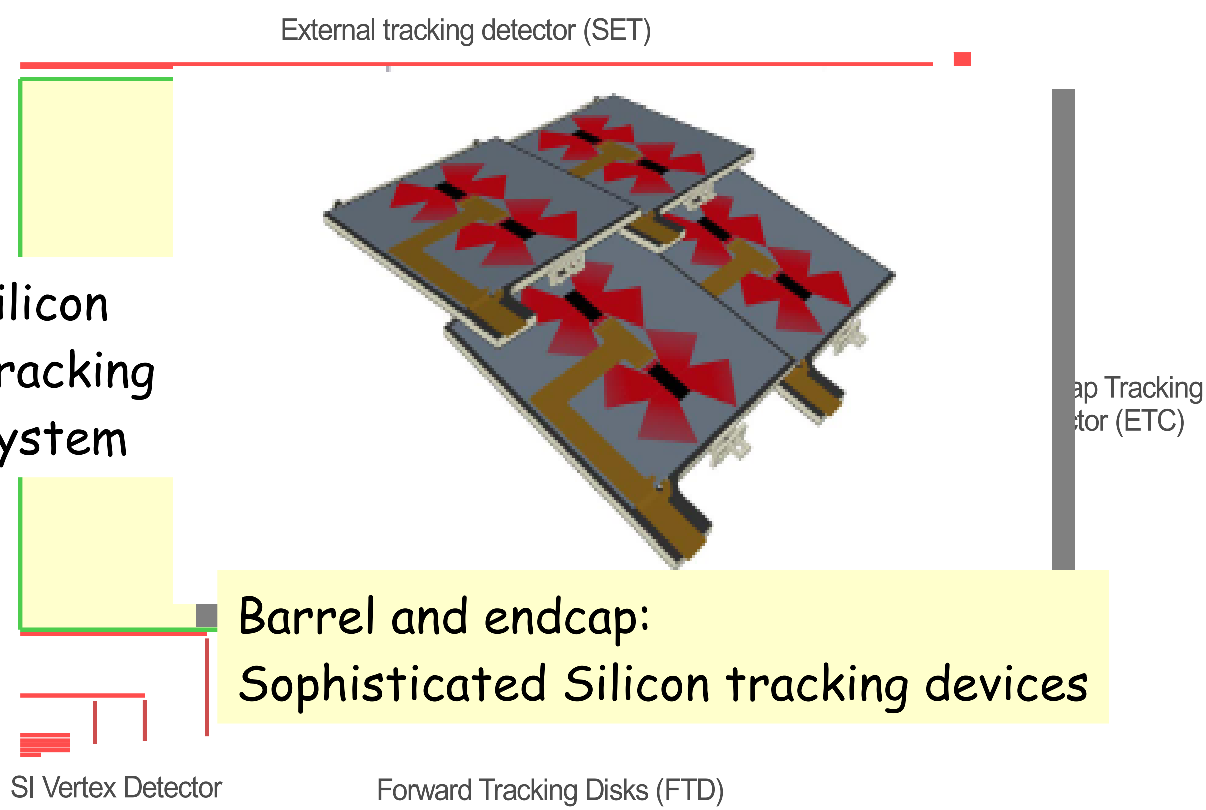


Silicon Tracking System

Barrel and endcap:
Sophisticated Silicon tracking devices

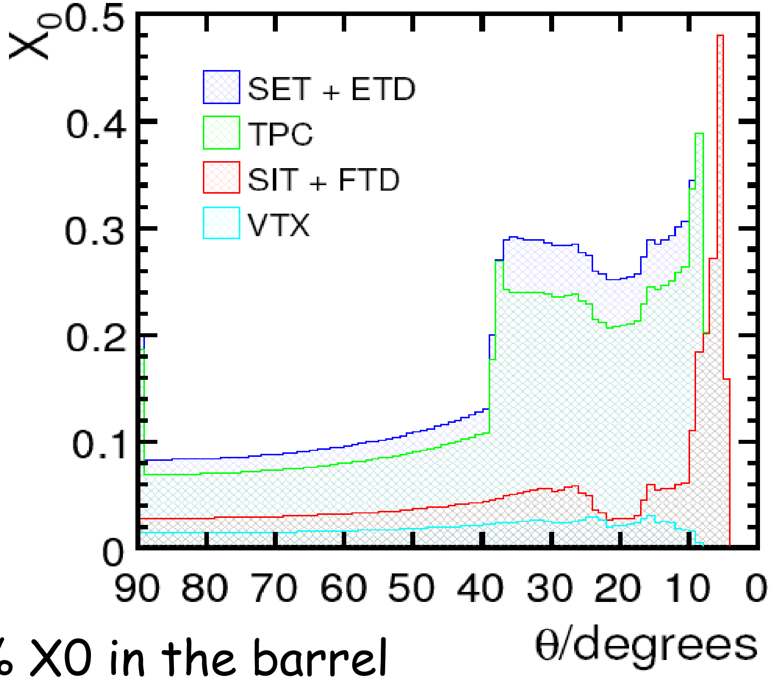
Special Focus on:

Robustness/ Redundancy

Excellent precision

Radiation hardness is not an issue!

Material in the Tracker



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

Goal: very light tracking system:

total material before calorimeter < 10% X0 in the barrel
<30% (or less) in the endcap

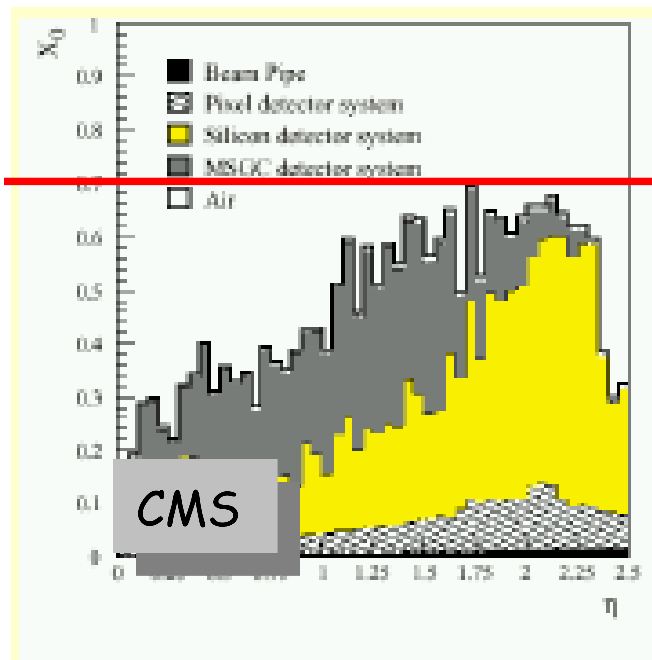
including all services, all support structures, cables, etc.

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

Materials: from Concept to Reality

Major difference / advance to LHC detectors is needed:

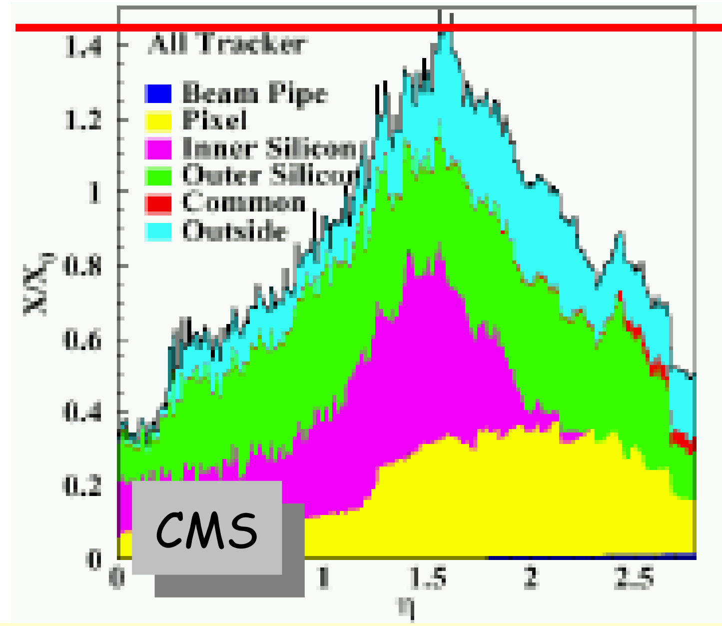
The detector TDR 1996



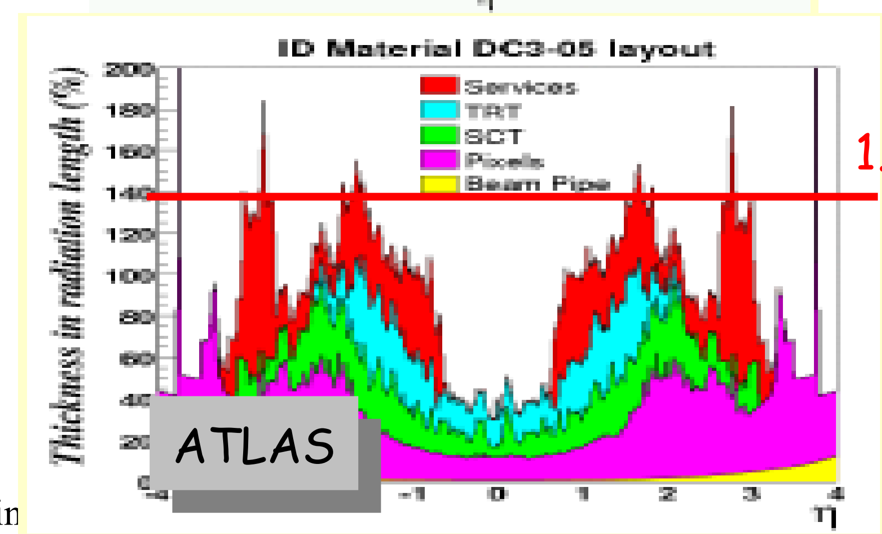
0.7 X0

... and the reality 10 years later

1.4 X0



1.4 X0

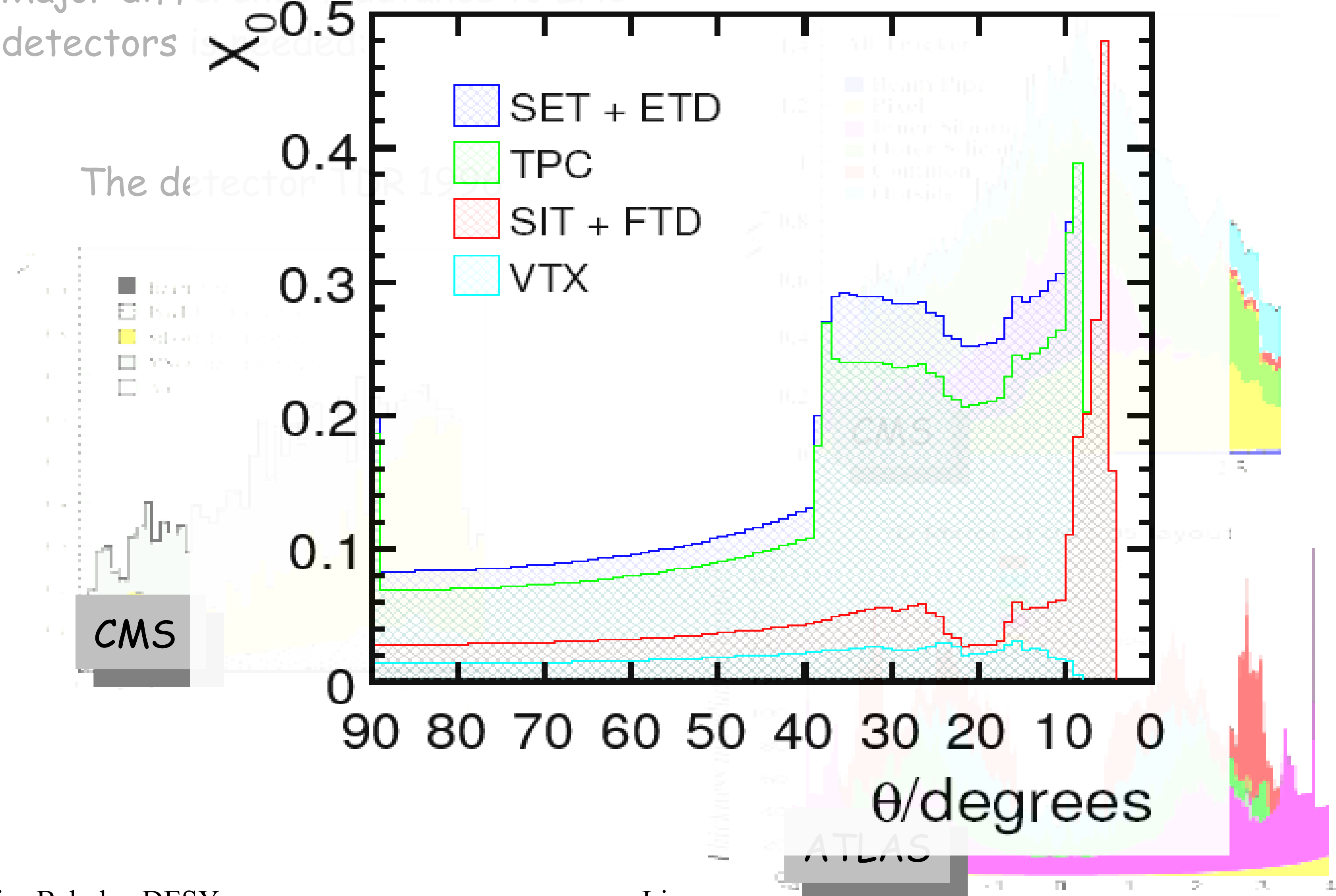


The ILC Goal

Major difference / advance to LHC detectors is needed:

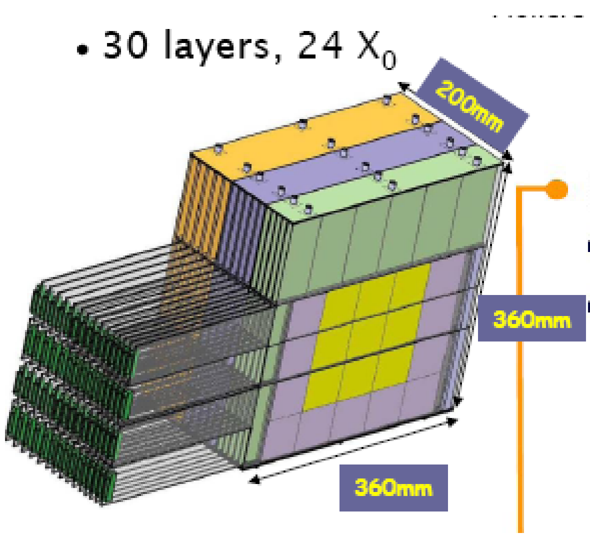
... and the reality 10 years later

The detector TDR 19

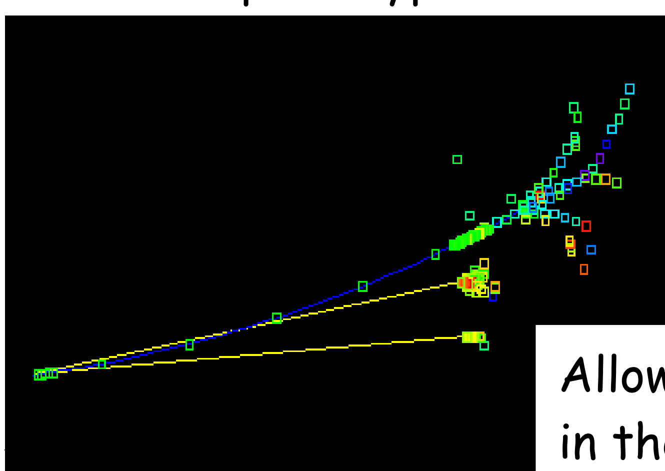


PFLOW ECAL

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

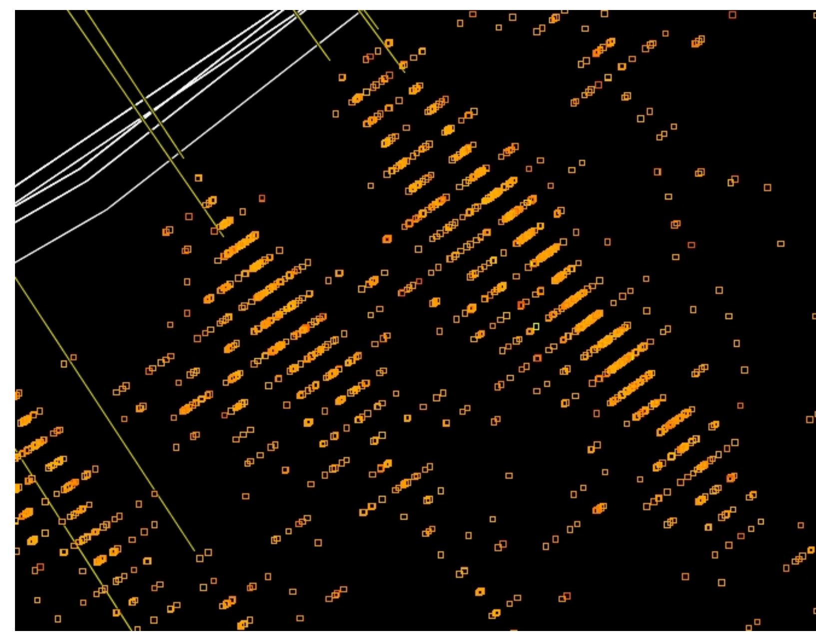


CALICE prototype



Allows “tracking”
in the calorimeter

Extreme direction:
MAPS sensors in the ECAL



Very detailed shower images

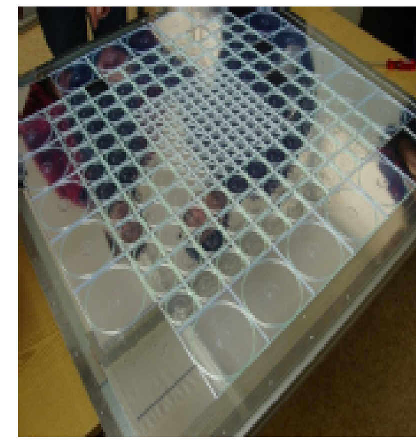
PFLOW HCAL

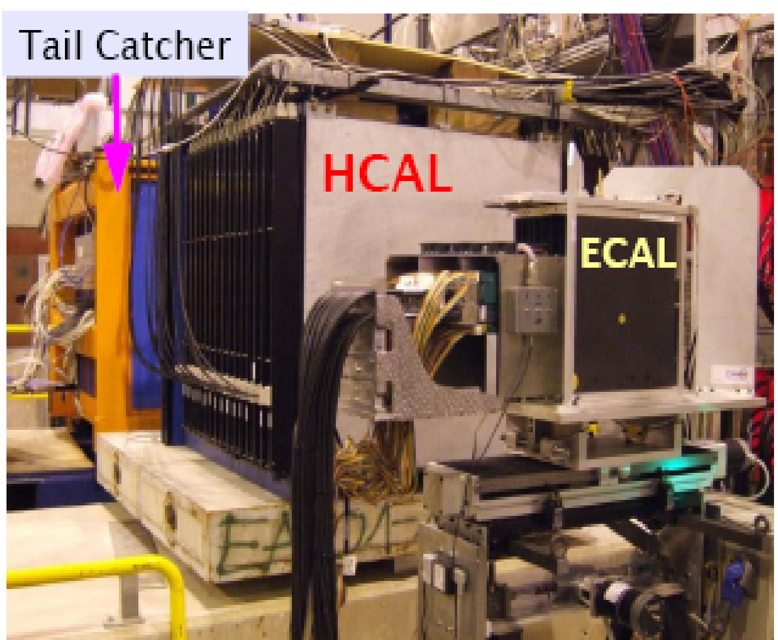
HCAL plays crucial role in a particle flow calorimeter

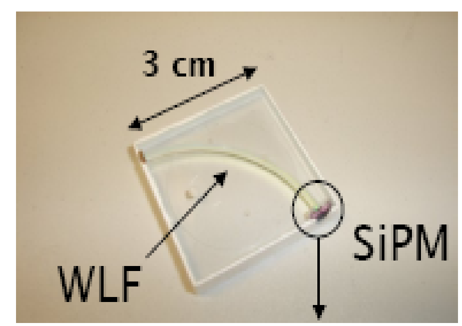
Simulation of hadronic shower is problematic

Typical cell sizes 3x3 cm² with analogue readout

Digital option investigated (smaller cells, 1bit readout)







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

PFLOW HCAL

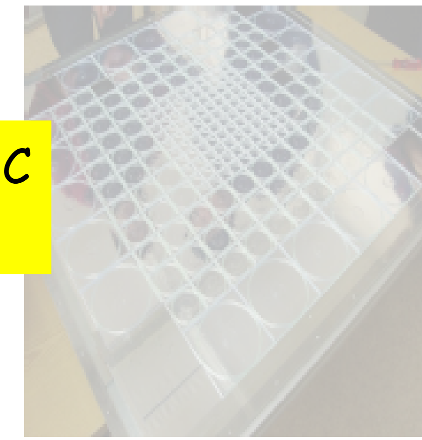
HCAL plays crucial role in a particle flow calorimeter

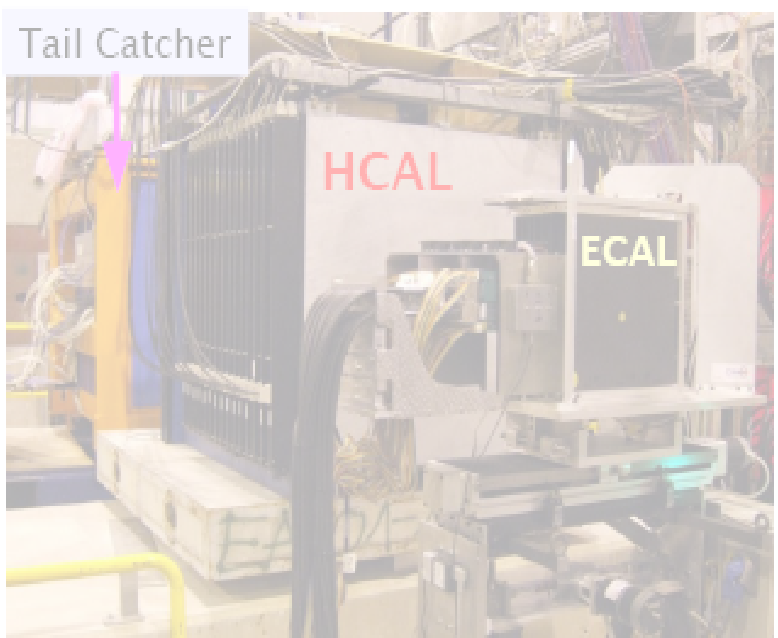
Simulation of hadronic shower is problematic

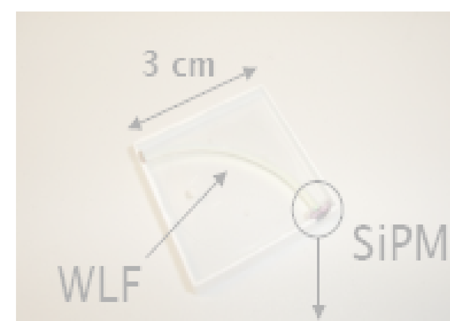
Ty

Overall: about 1000 times the channel count from LHC
– Totally new type of calorimeters --

Digital option investigated (smaller cells, 1bit readout)



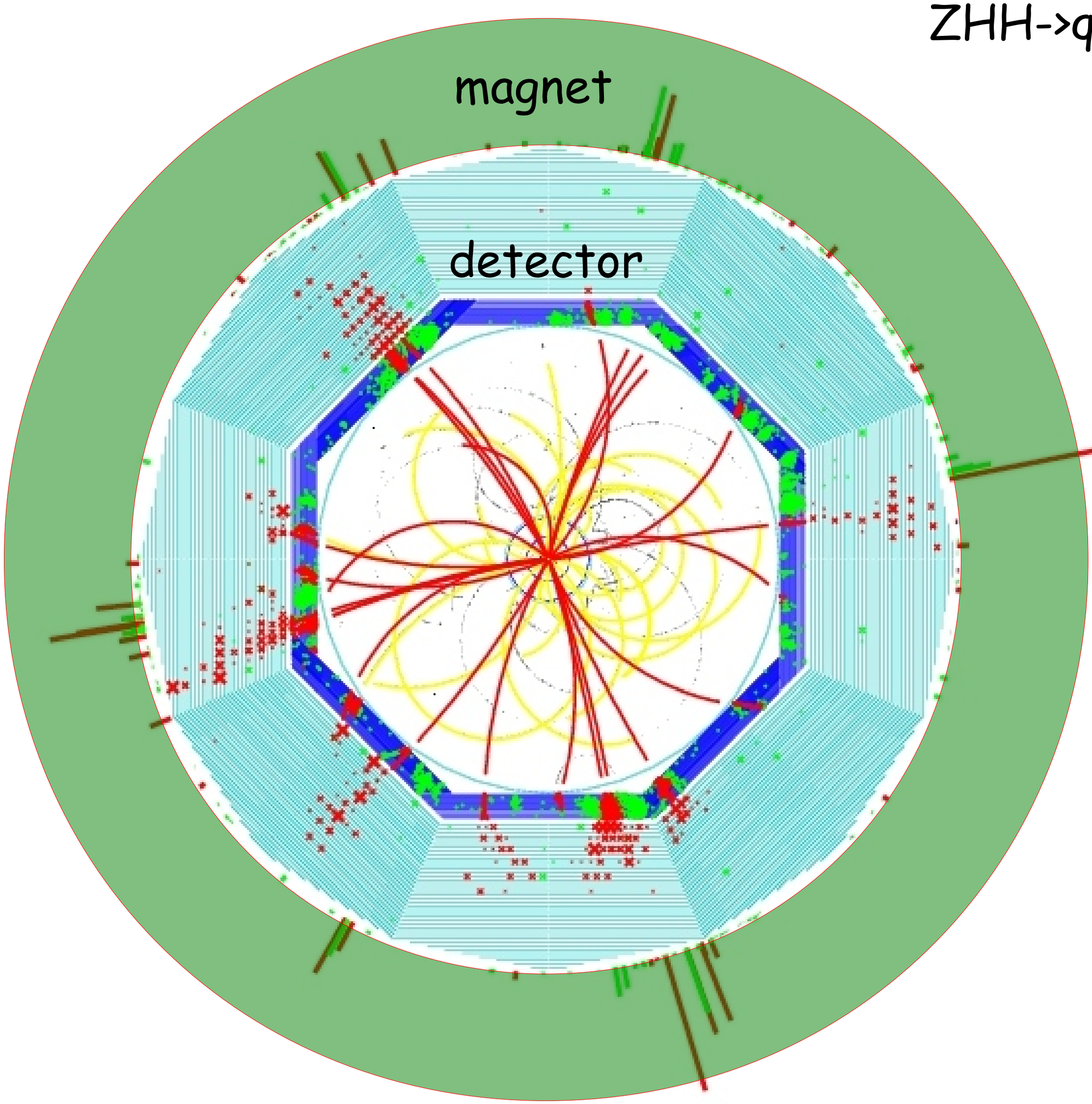




Major effort (CALICE) to protoype such a calorimeter for the ILC

Putting it together

ZHH->qqbbbb event at 500 GeV



Powerful vertex/ tracking/ calorimeter

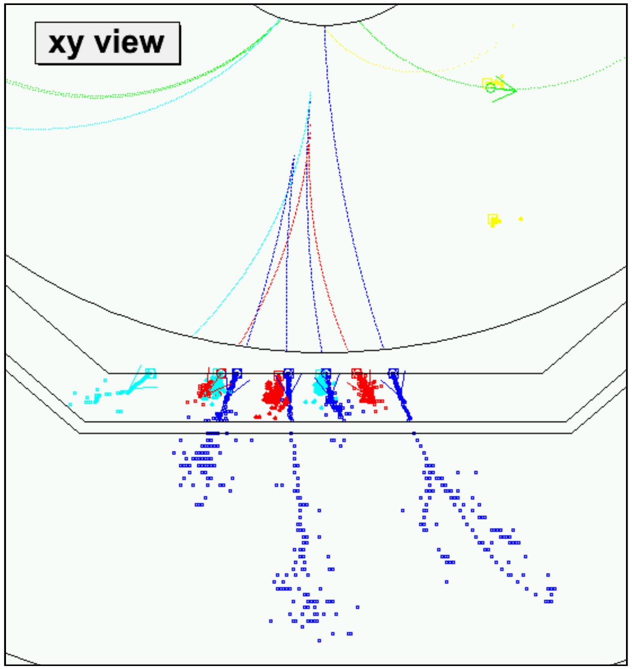
put all this into a strong B field

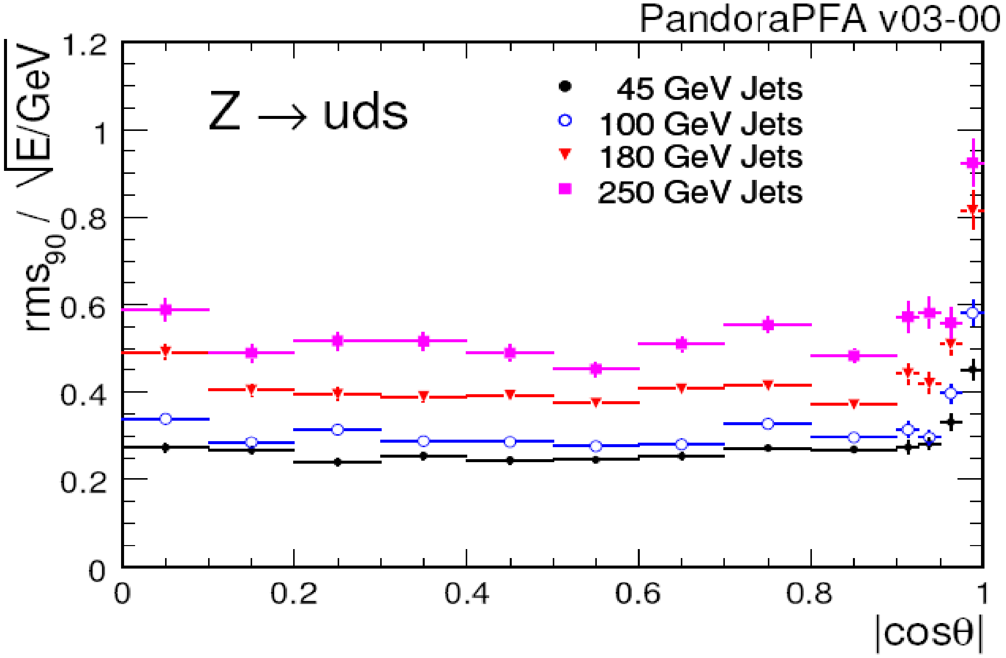
have some muon ID on the outside

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

'HH → qqbbbb

How well does it work?





M. Thomson

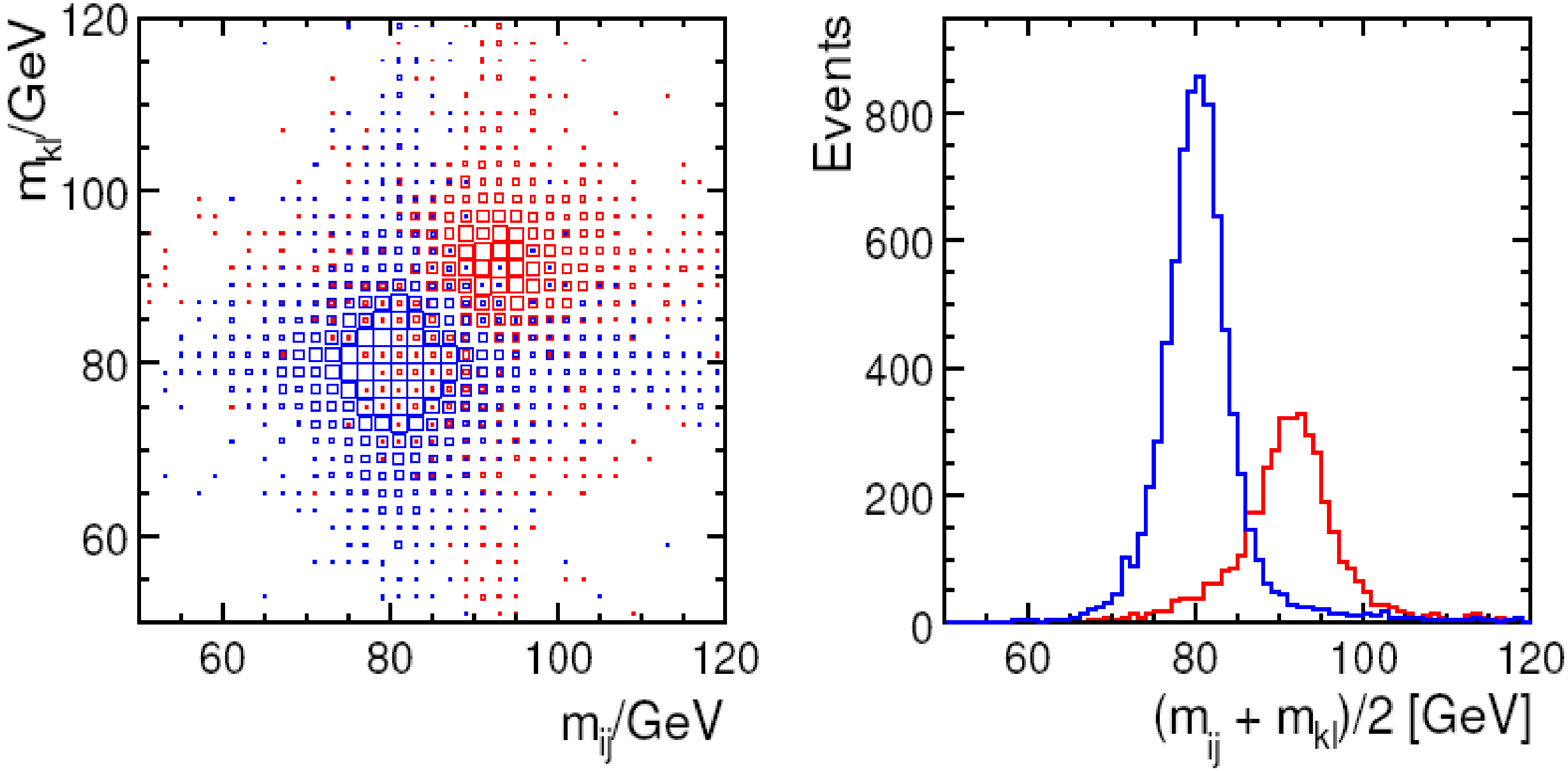
Simulation of an event

Resolution about 30%/√E for jets below 100 GeV

Particle flow gives ~2x better performance than traditional approach (<100 GeV jets)

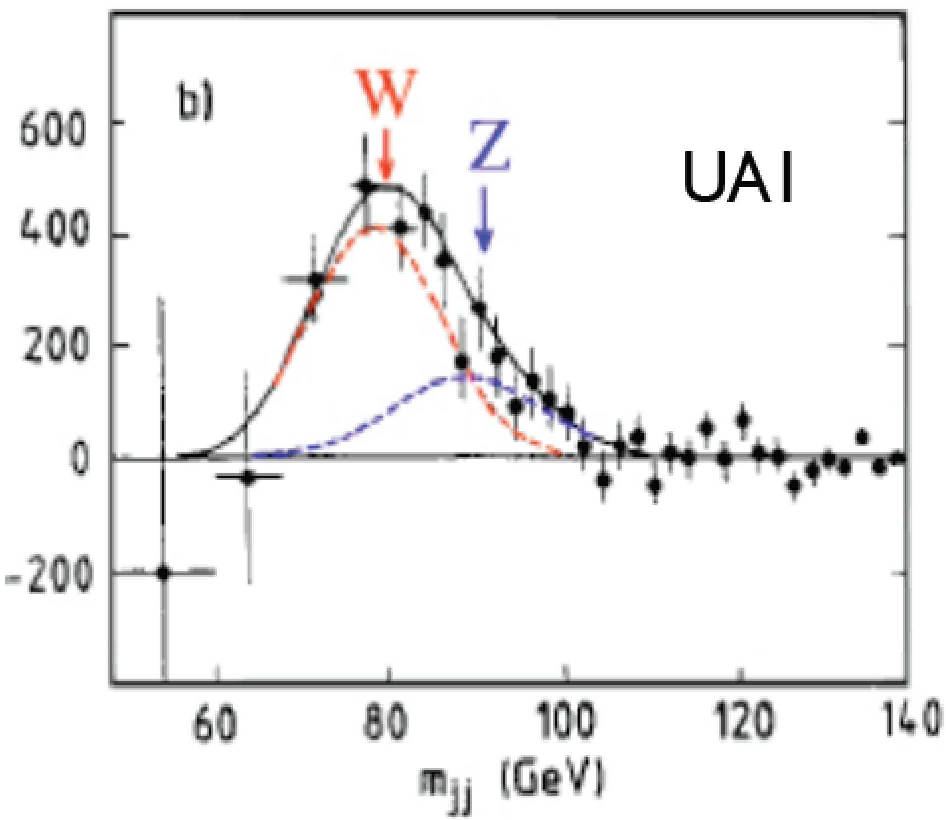
Significant achievement over the last few years

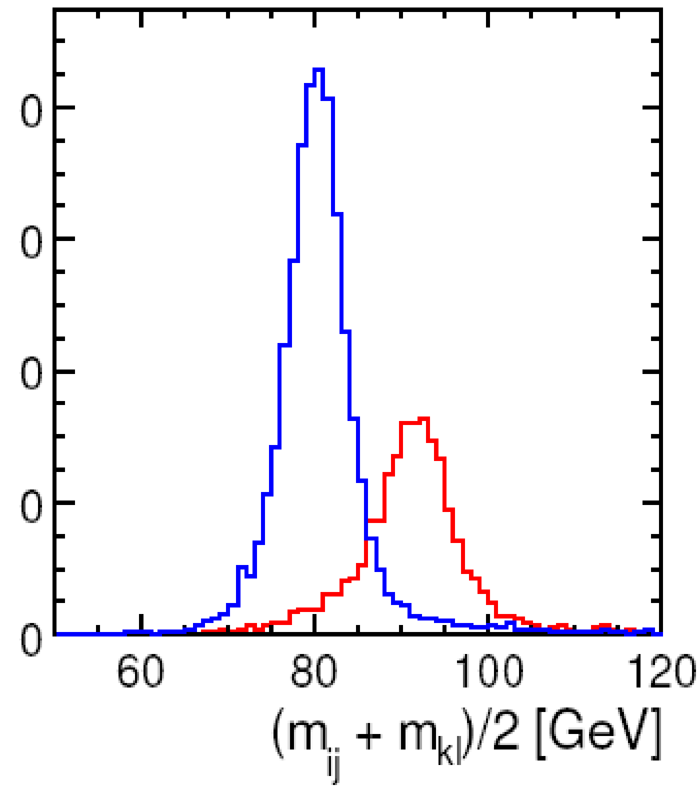
W-Z separation



Crucial for many channels (SUSY, others)
Crucial to understand and separate SM from NP

W-Z separation: Comparison

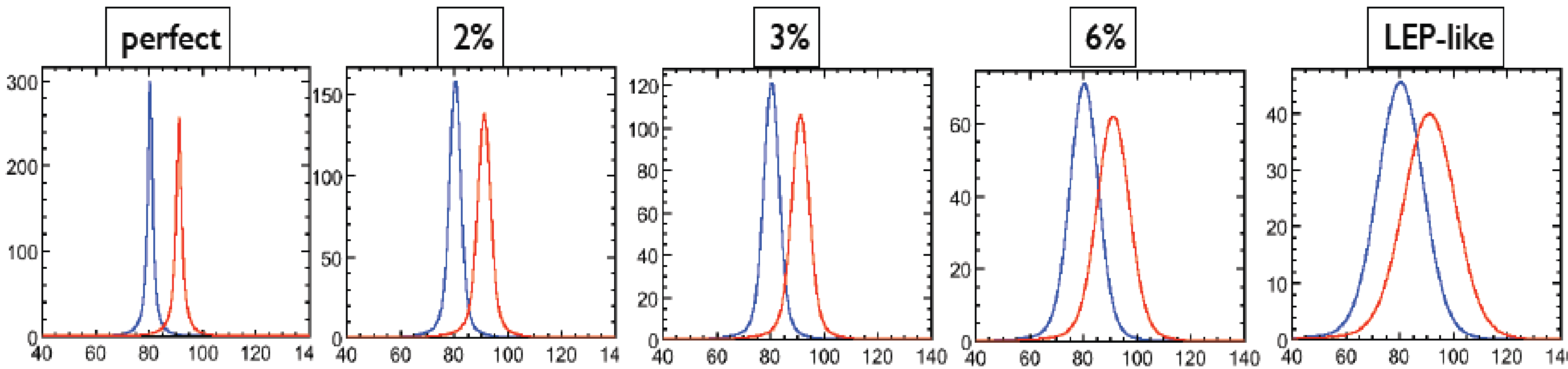




Crucial for many channels (SUSY, others)
Crucial to understand and separate SM from NP

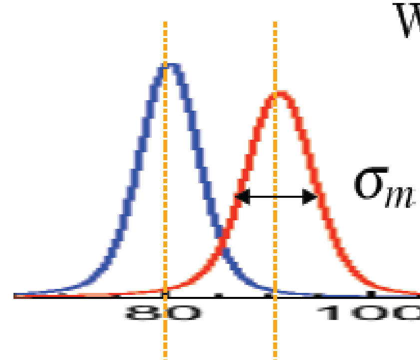
W-Z Separation

Simulating W-Z separation for different resolutions:



Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

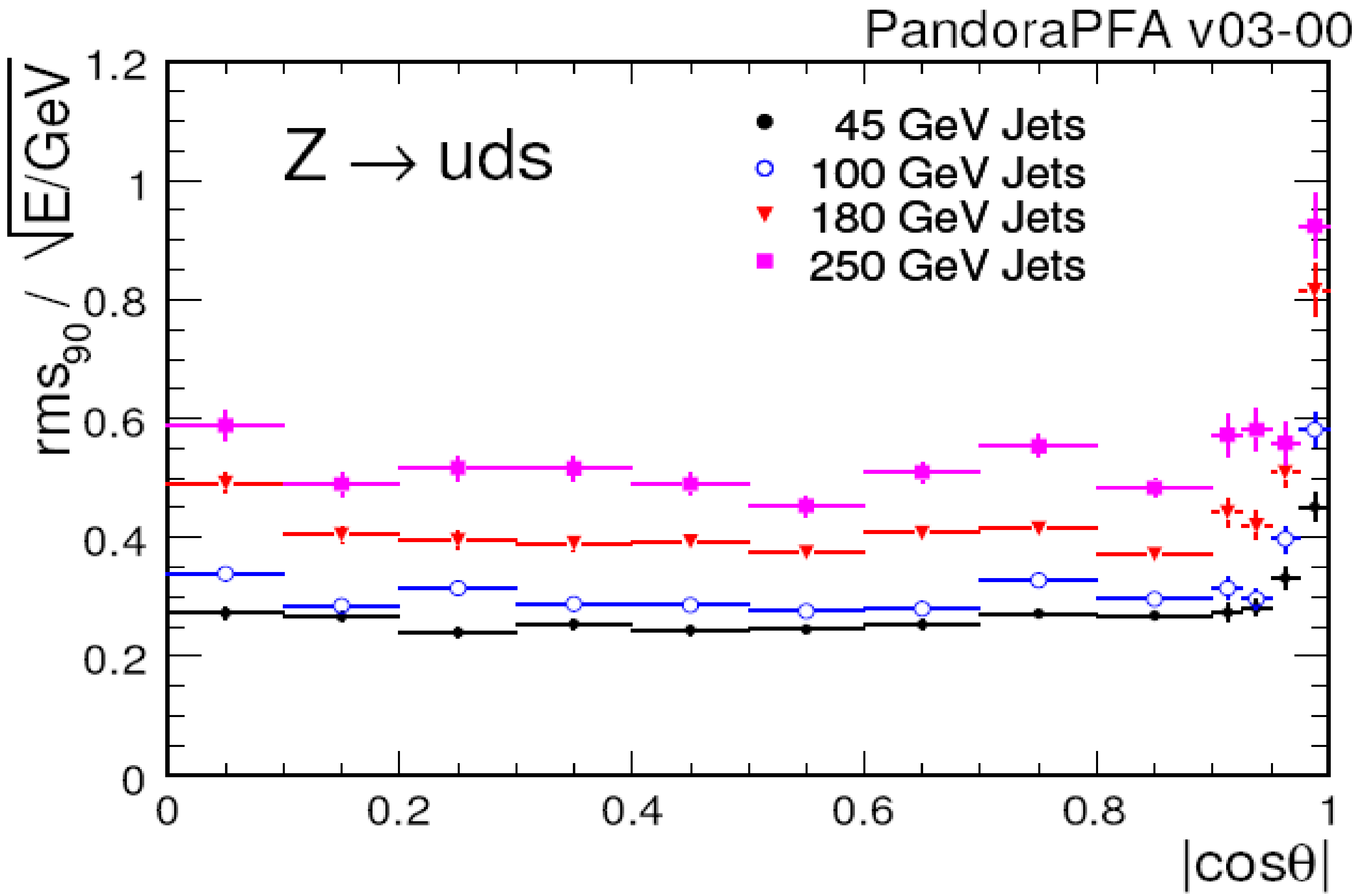
$$\text{W/Z separation} = (m_Z - m_W)/\sigma_m$$



effective gaussian equivalent mass resolution

3.5% is about optimum: due to intrinsic width, better does not really buy a lot

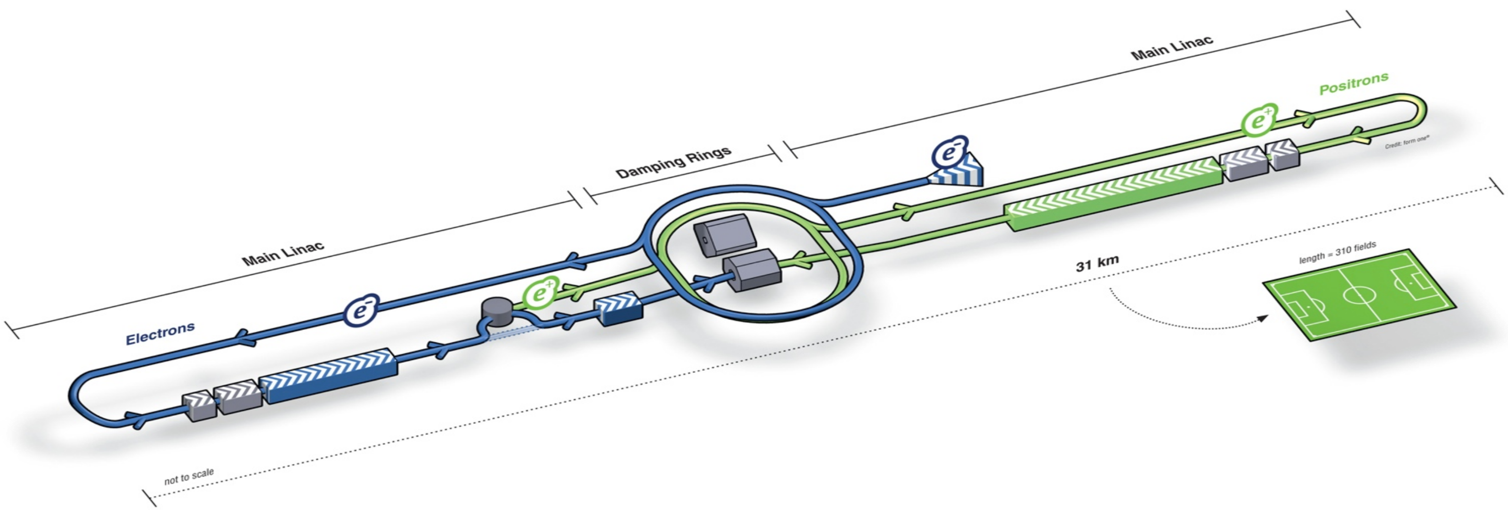
Performance



Two Detectors

Additional complication:

One interaction region,
but two detectors:



Two Detectors

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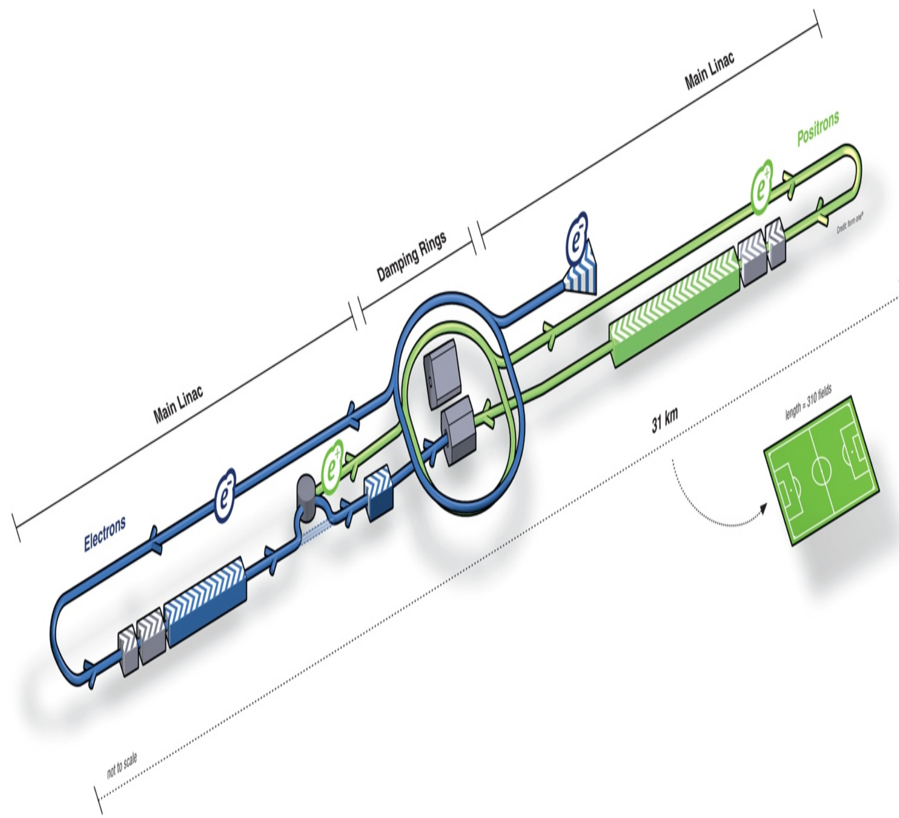
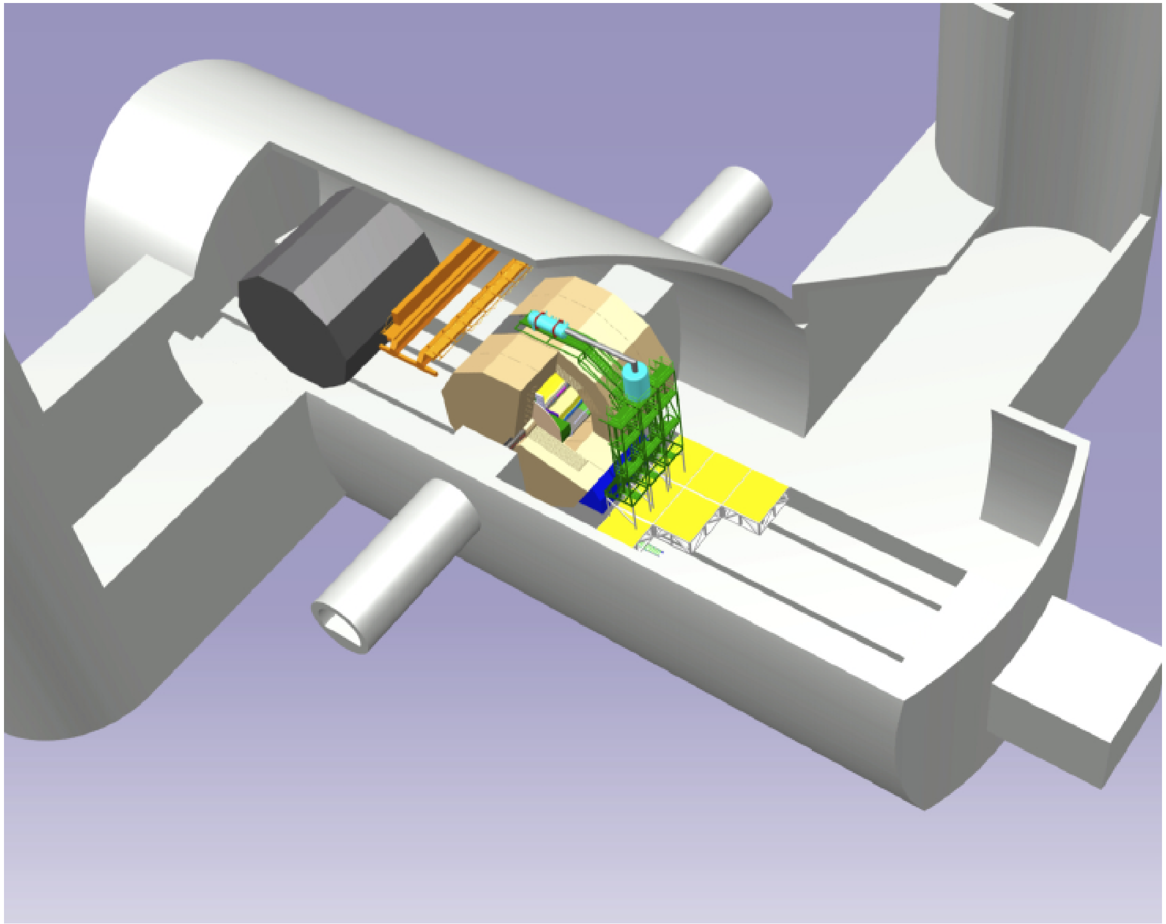


Two Detectors: Push Pull

Additional complication:

One interaction region,
but two detectors:

push pull operation anticipated



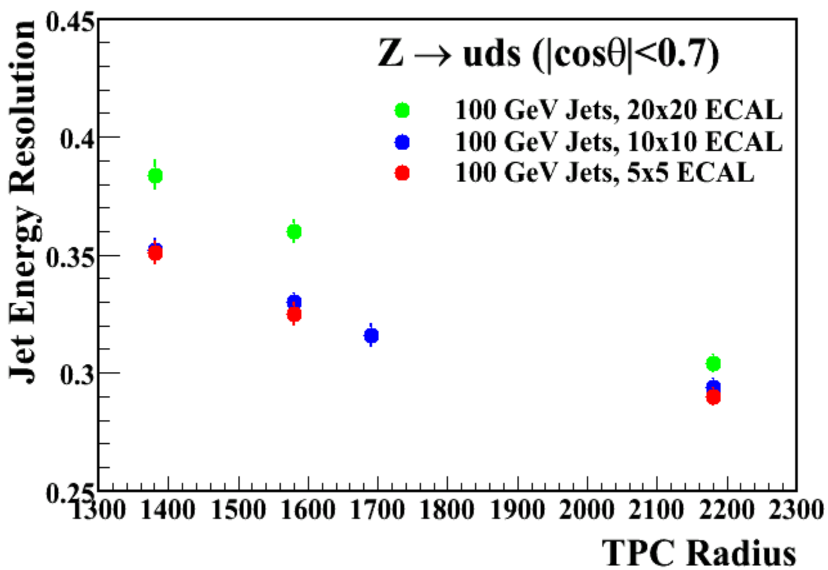
Conclusions

- Linear Collider offer complementary strength to LHC
- Wide range of physics topics can be studied at the LC
- LC is indispensable for precision studies and to determine and distinguish models
- Detectors at LC are a significant challenge
- A mature design (ILC) exists, is pushed to project level in international collaboration

Of course a lot will depend on the LHC and its findings,
But in a few years we should know which LC we need to build

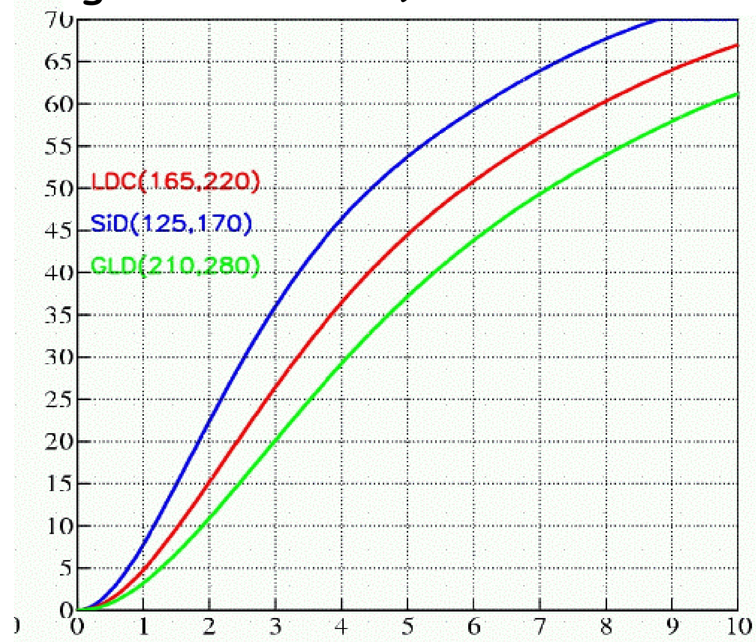
Detector Optimization: ECAL

Brient 2004
Thomson 2007



First full reconstruction results

Photon separation
(fraction of second photon within
given distance)



Cell size in cm

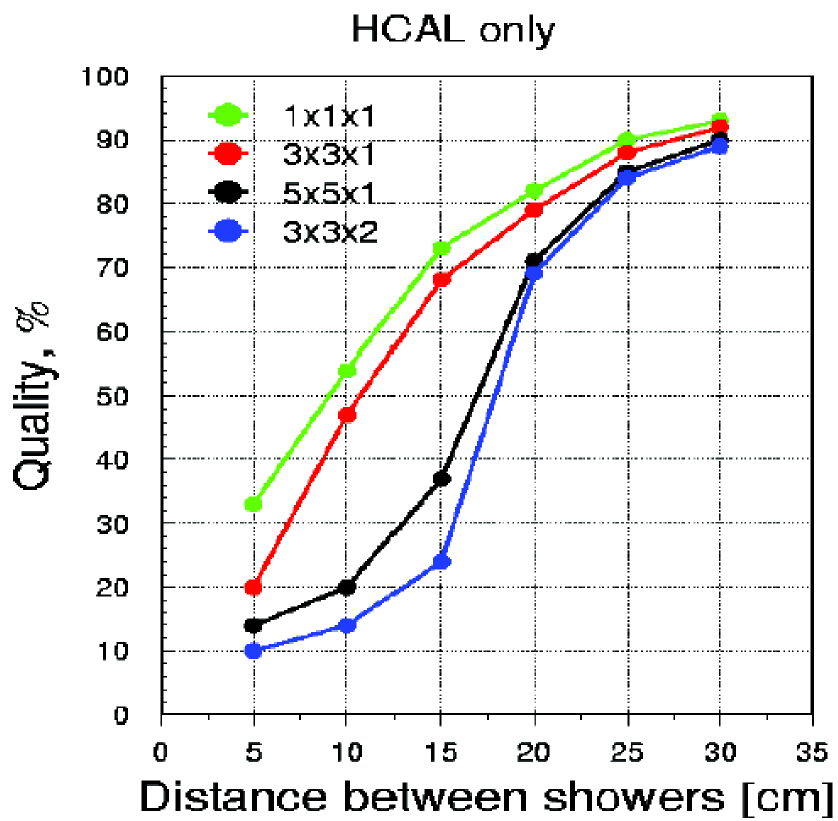
1x1 cm^2 cell sizes seem reasonable

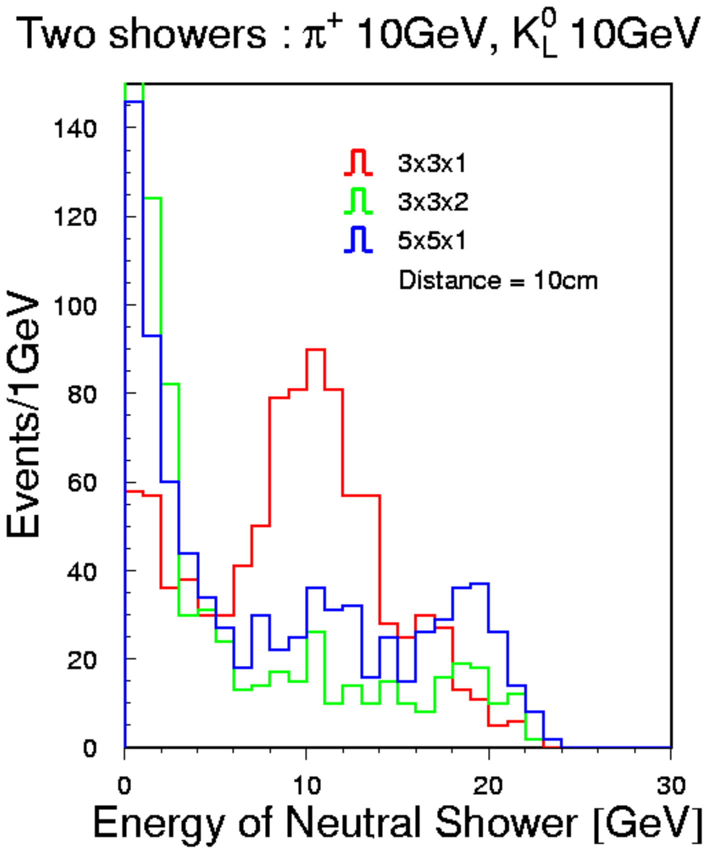
not a huge gain by smaller cells seen at the moment

Detector Optimization: HCAL

A. Raspereza,
V. Morgunov,
Snowmass 2005

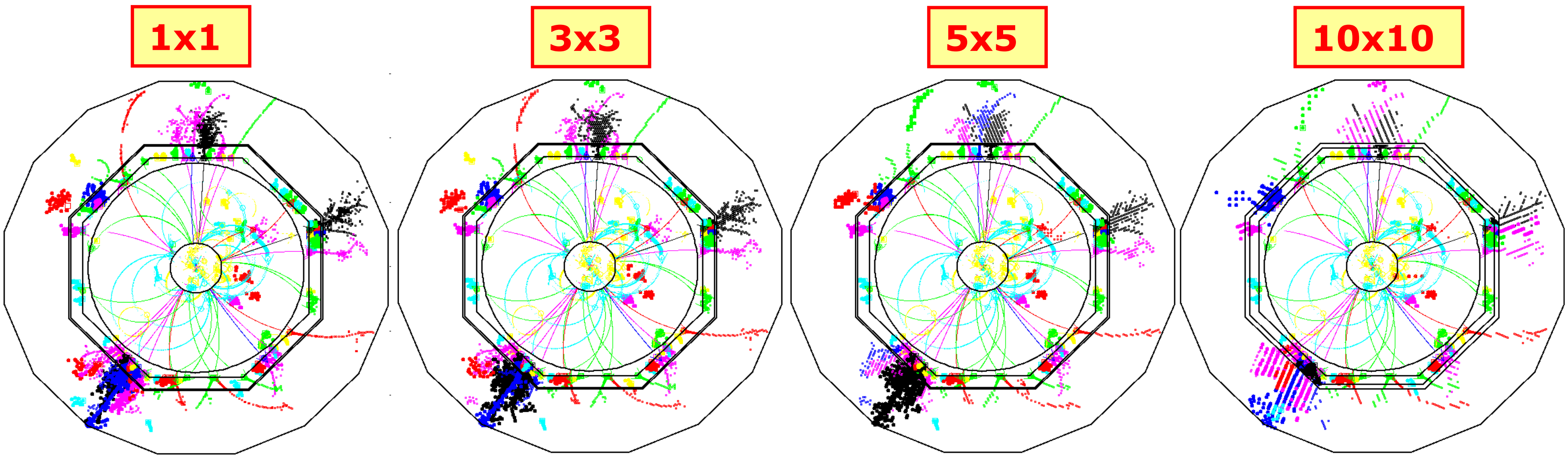
HCAL optimization:
reconstruction of overlapping hadronic showers

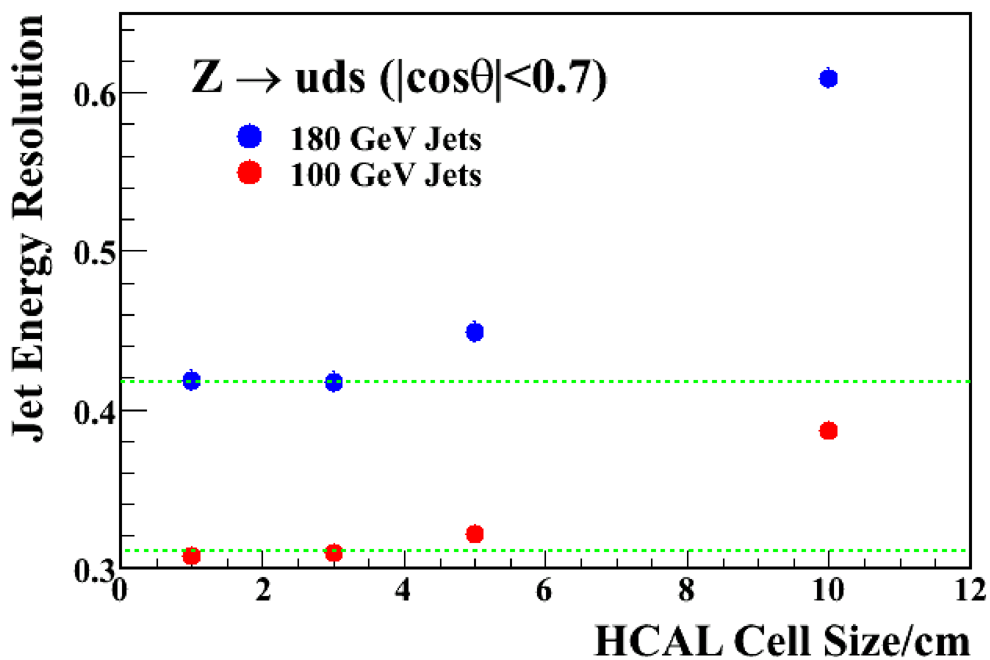




Detector Optimization: HCAL

M. Thomson, Paris 2007





"Preliminary Conclusions"

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