Detectors at a Future Linear Collider

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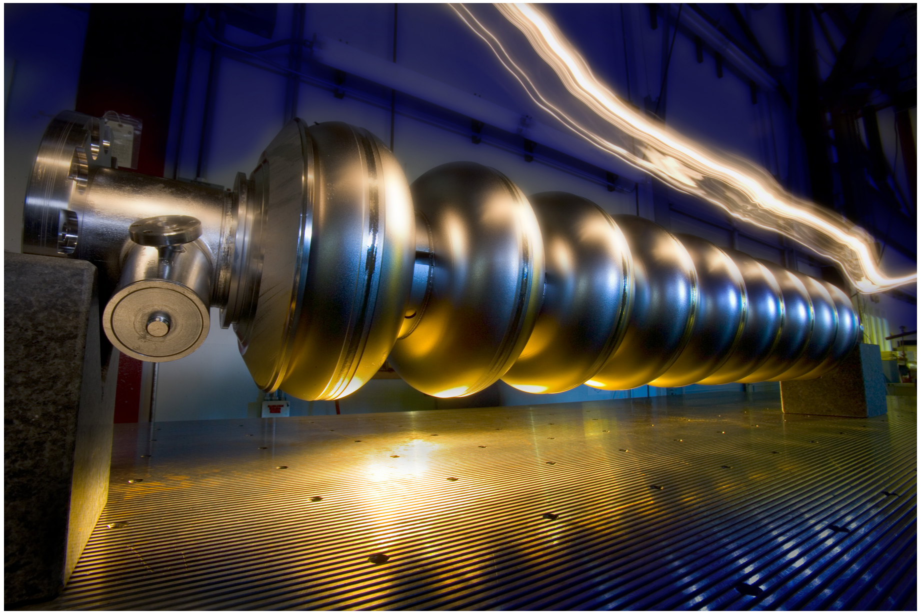


This Talk:

❶ Why a Linear Collider
❷ The ILC
❸ Physics at the ILC
❹ Detectors at the ILC
❺ Calorimetry at the ILC
❻ CLIC
❼ Detector issues for CLIC
❽ Outlook

❶ Why a Linear Collider ?

★The **LHC** and a **LC** provide a complimentary approach to studying the physics of EWSB and beyond

The LHC

- ★ Will *soon* open the door to new physics
- ★ Will push the energy frontier with p-p collisions at ~14 TeV
  - *qq*, *qg* and *gg* collisions in the energy range ~0.5-5 TeV

The ILC (CLIC discussed later)

- ★ A different approach:
  very high precision as opposed to very high energy
- ★ **Electron-positron** collisions in the energy range 0.1-1 TeV
- ★ Very clean final states + high resolution detectors
  - ⇨ very precise measurements (as at LEP)
  - ⇨ detailed understanding of new physics + tight constraints on theory (as at LEP)

★ The case for having both the **LHC** and **ILC** very well studied:

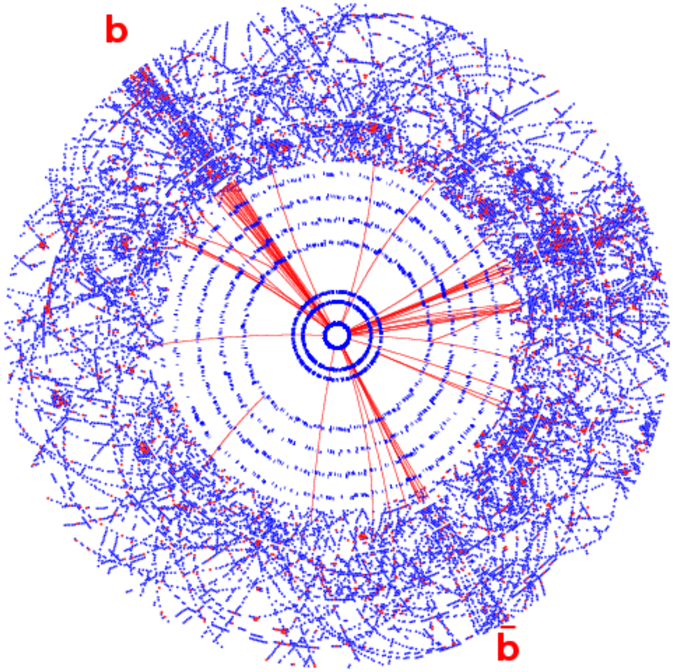
e.g. "Physics Interplay of the LHC and ILC", G. Weiglein et al., Phys. Rept. 426 (2006) 47-358

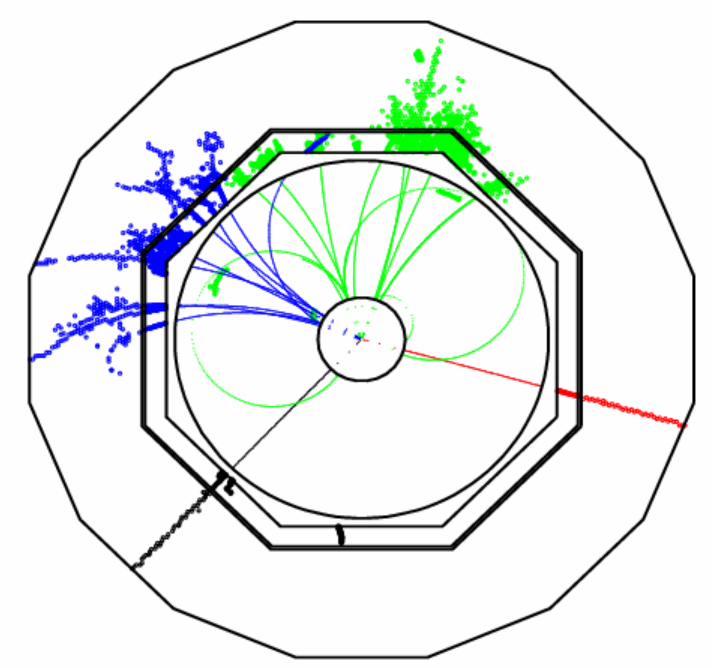
e^+e^- ≡ precision

- ★ **Electron-positron colliders provide clean environment for precision physics**

The LHC $\mathrm{pp} \to \mathrm{H} + X$

The ILC $\mathrm{e^+e^-} \to \mathrm{HZ}$



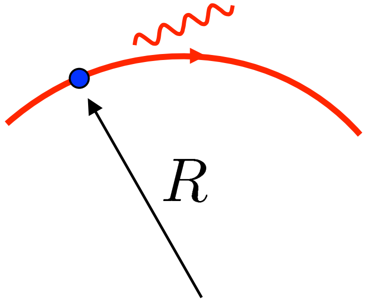


- ★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see** $\mathrm{H} \to b\bar{b}$ **and** $\mathrm{Z} \to \mu^+\mu^-$ **and nothing else…**

Why a linear $e^+ e^-$ collider

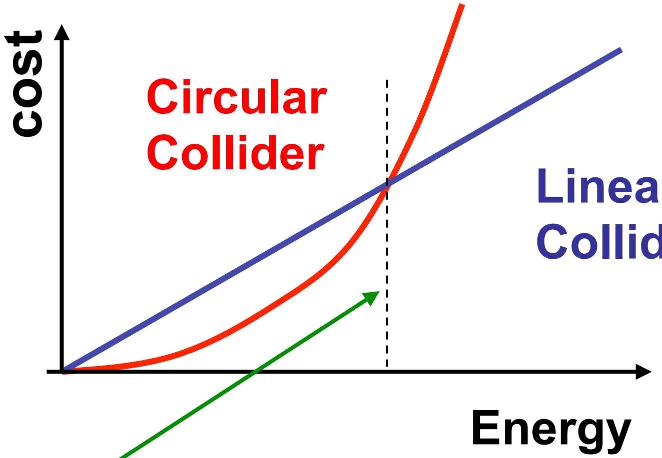
- ★ Circular colliders have a big advantage – circulating beams
- ★ In a linear collider get e^+e^- to full energy in "one shot"
- ★ Hence, most previous e^+e^- colliders were circular machines
- ★ However in a circular collider have to **"fight"** synchrotron radiation
  - accelerating electrons lose energy

$$\boxed{\Delta E \propto \frac{E^4}{m_e^4 R}}$$



Circular machine : $\text{cost} \propto E^2$

Linear machine : $\text{cost} \propto E$



- ★ Breakpoint approximately **$\sqrt{s}$ = 200 GeV** (LEP 2)
- ★ To get above this energy need a linear collider

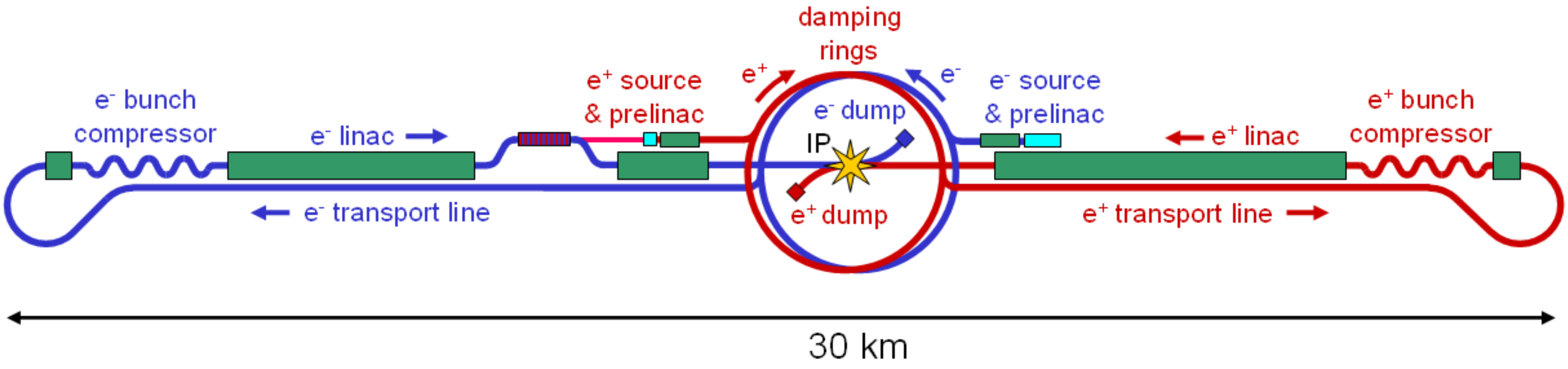
❷ ILC : the machine

Basic Machine Design Parameters

- ★ Centre-of-mass energy adjustable from **200-500 GeV**
  - upgradeable to **1 TeV** (i.e. make it longer)
- ★ Integrated luminosity of **500 fb^{-1}** in first **4 years** operation
  - require high luminosity: **2x10^{34} cm^{-2}s^{-1}**
- ★ Energy stability **<0.1 %** for precision measurements
- ★ Electron polarization of **>80 %** at interaction point (see later)

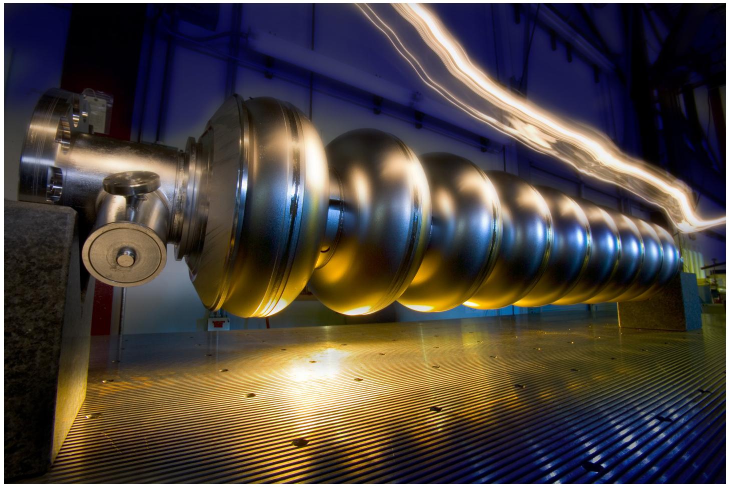
Baseline design for the ILC exists in the form of the "The ILC Reference Design Report (2007)"

The ILC is much more than the "linear bit"…

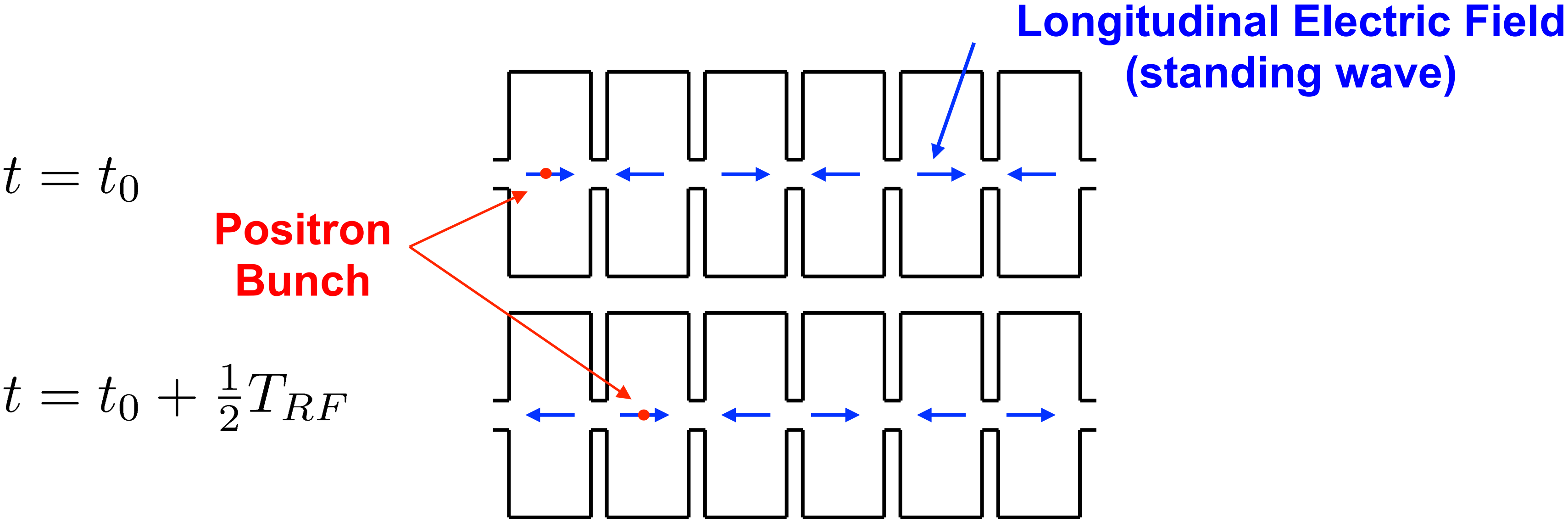


The Linear Accelerator (LINAC)

★ The main accelerating structures are the two **11km** long LINACs



- LINACs built out of 9-cell super-conducting RF cavities operating at 1.3 GHz
- Accelerating gradient of **31.5 MV/m**
- Basic idea - electrons and positrons accelerated in RF standing waves in the cavities



Beam structure and Luminosity

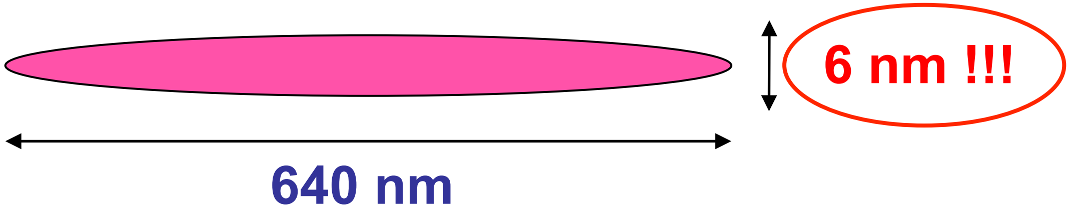
- To achieve high luminosity is challenging:

$$\mathcal{L} \propto \frac{n_b N_e^2 f_{rep}}{2\pi\sigma_x\sigma_y}$$

- To reach the ILC goal of **L = 2x10^{34}cm^{-2}s^{-1}** ⇒ small beam spot at the interaction point !

	L [cm^{-2}s^{-1}]	f_{rep}[Hz]	n_b	N [10^{10}]	σ_x [μm]	σ_y [μm]
ILC	2x10^{34}	5	2760	2	0.6	0.006
SLC	2x10^{30}	120	1	4	1.5	0.5
LEP2	5x10^{31}	10000	8	30	240	4

- Working with such small beam spots has implications…



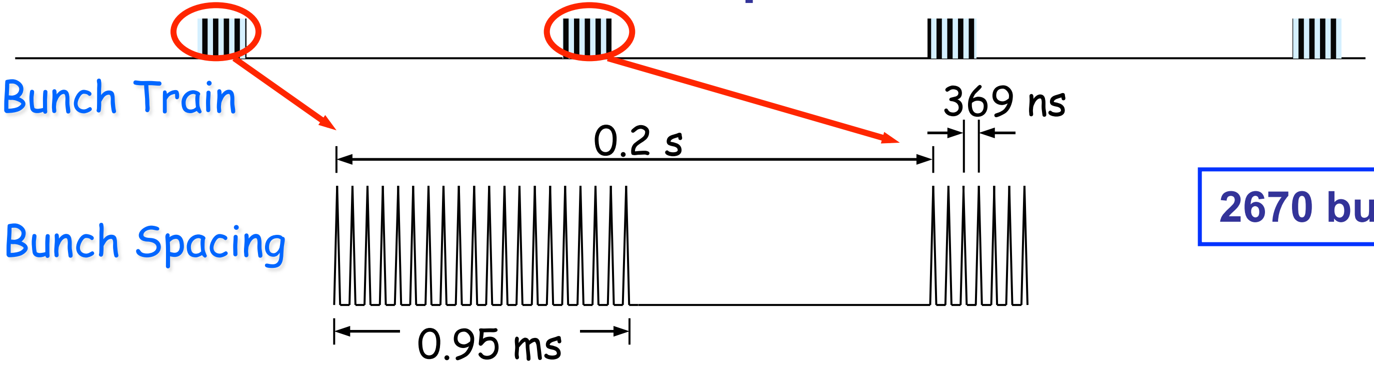
Need highly stable, well-controlled beams

- But a very clean environment for precision physics

❸ Physics at the ILC

★ Main "baseline" features of ILC now fixed (Reference Design Report)

- Luminosity : ~ 10^{34} $cm^{-2}s^{-1}$ (1000xLEP)
- Time Structure : 5 Bunch-trains per second



2670 bunches/train

- Modest physics event rates

  $e^+e^- \rightarrow qq$ ~100/hr $e^+e^- \rightarrow W^+W^-$ ~1000/hr
  $e^+e^- \rightarrow tt$ ~50/hr $e^+e^- \rightarrow HX$ ~10/hr

- "Backgrounds" low

  $e^+e^- \rightarrow qq$ ~0.1 /Bunch Train
  $e^+e^- \rightarrow \gamma\gamma \rightarrow X$ ~200 /Bunch Train

  ~500 hits/BX in Vertex det.
  ~5 tracks/BX in TPC

★ Very clean physics environment: Event rates low, backgrounds modest, "large" time between collisions

ILC PHYSICS PROGRAMME

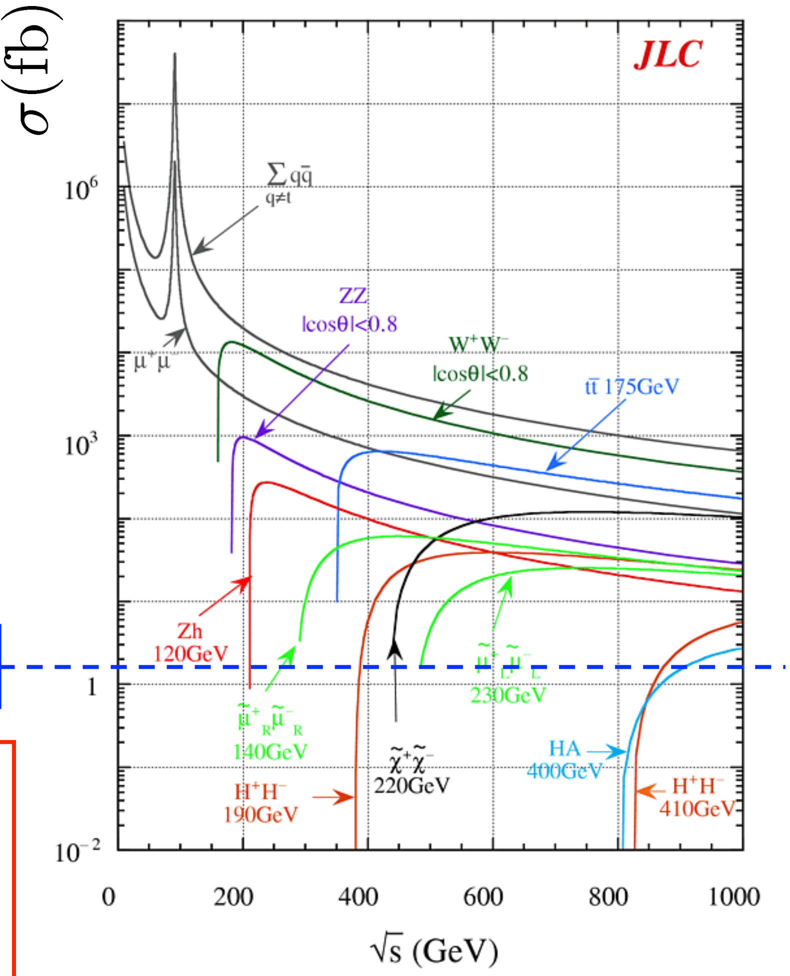
★ e^+e^- collisions at $\sqrt{s}$ = 0.2-1.0 TeV
provide rich environment

★Exact physics programme depends
on what is out there…

★ILC offers Flexibility in running,
e.g. new particle thresholds

★Can accumulate large samples of
cleanly identified/well-measured
events

~1000 events



★ILC Physics = Precision Studies:

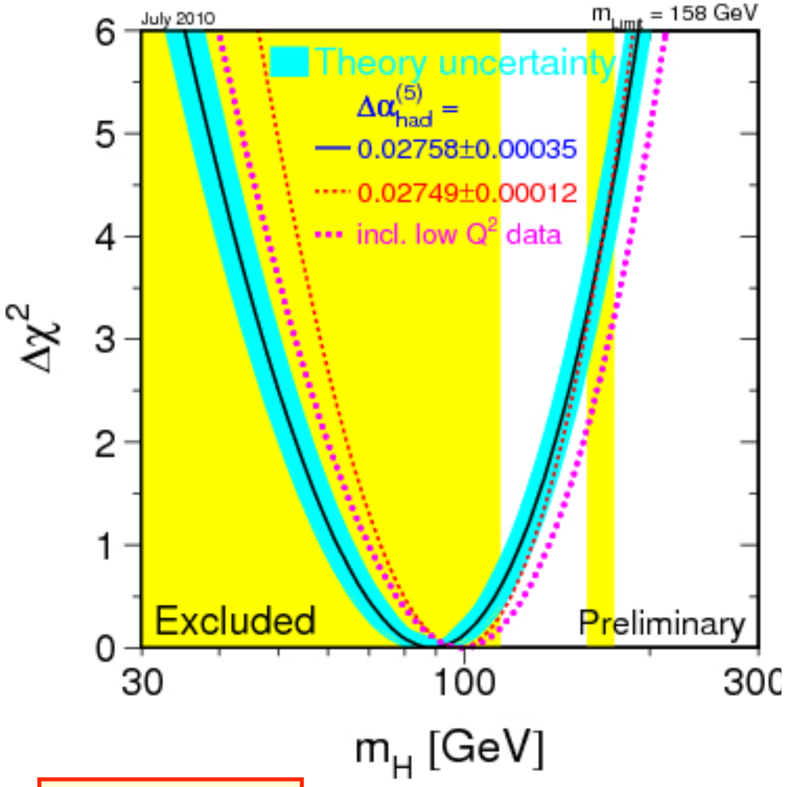
- ♦ Higgs sector (EWSB)
- ♦ SUSY particle spectrum (if exists)
- ♦ SM particles (e.g. W-boson, top)
- ♦ and much more...

Take Higgs sector as an example of the power of the ILC

The Higgs Boson

Current Knowledge

★ **Precision measurements from LEP + SLD + Tevatron favour**



Precision measurements: (blue band)

$$m_{\mathrm{H}} < 154\,\mathrm{GeV}\;\; 95\,\%\;\mathrm{C.L.}$$

+direct limits (LEP): (yellow exclusion)

$$m_{\mathrm{H}} < 184\,\mathrm{GeV}\;\; 95\,\%\;\mathrm{C.L.}$$

★ **Light Higgs strongly favoured**

The LHC

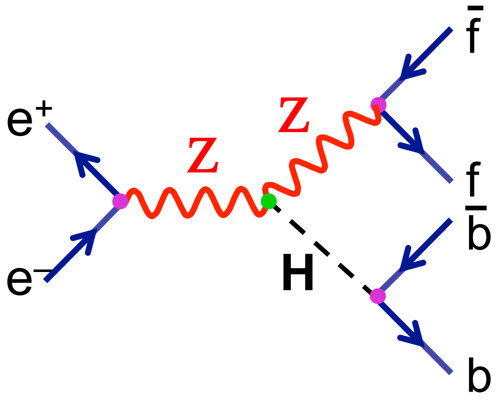
★ **Assuming it exists, the Higgs will be discovered (by 2012?)**

★ **But if light, may be very hard to establish nature of Higgs**

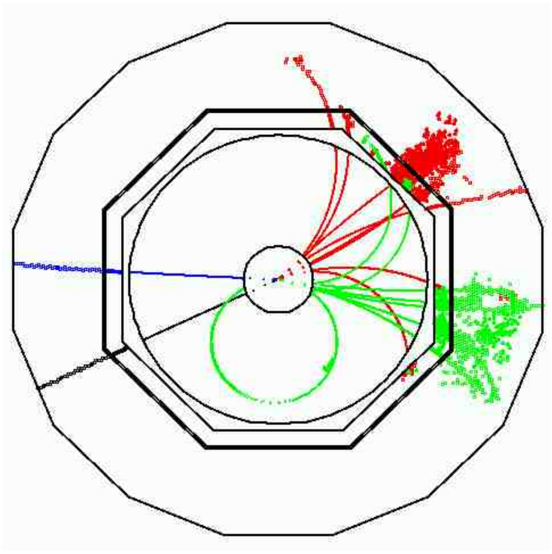
The Higgs at the ILC

★ Large production cross sections

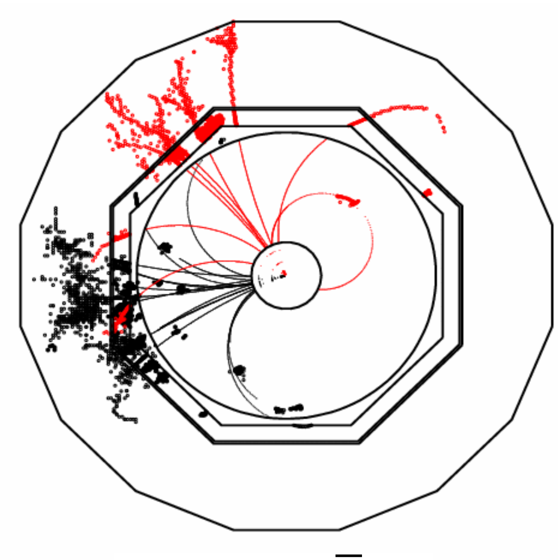
e.g. light Higgs produced by Higgsstrahlung



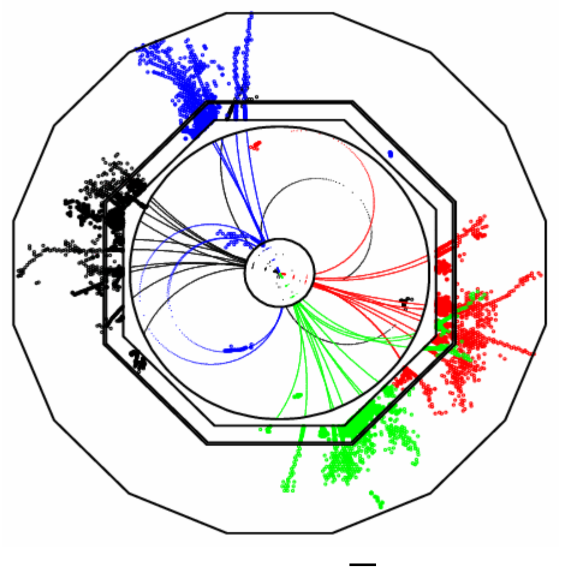
★ Very clean events



$HZ \to b\bar{b}\mu^+\mu^-$



$HZ \to b\bar{b}\nu\bar{\nu}$



$HZ \to b\bar{b}q\bar{q}$

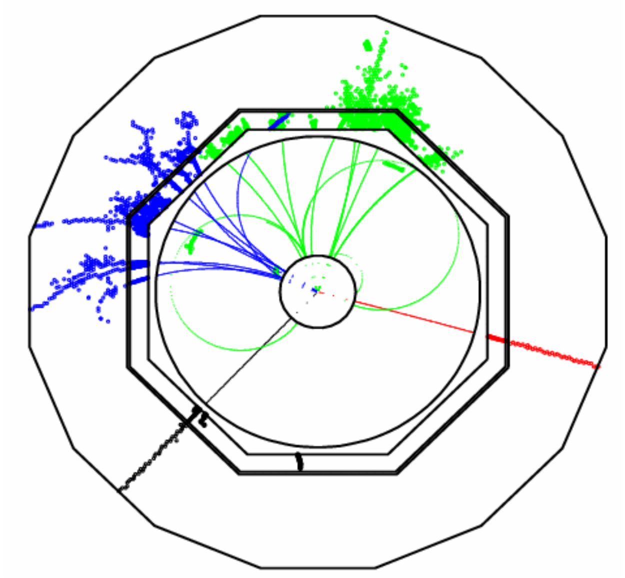
★ Relatively simple to select and identify in all decay topologies

★ Would accumulate **O(10^5)** events (larger than LEP2 WW sample)

The Higgs at the ILC cont.

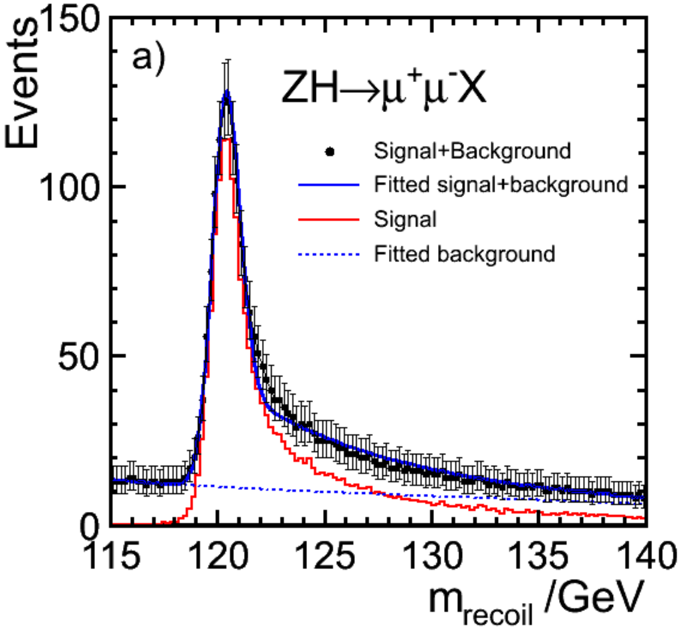
★ **Model-independent studies:**

- mass
- absolute branching ratios
- total width
- spin
- top Yukawa coupling
- self-coupling



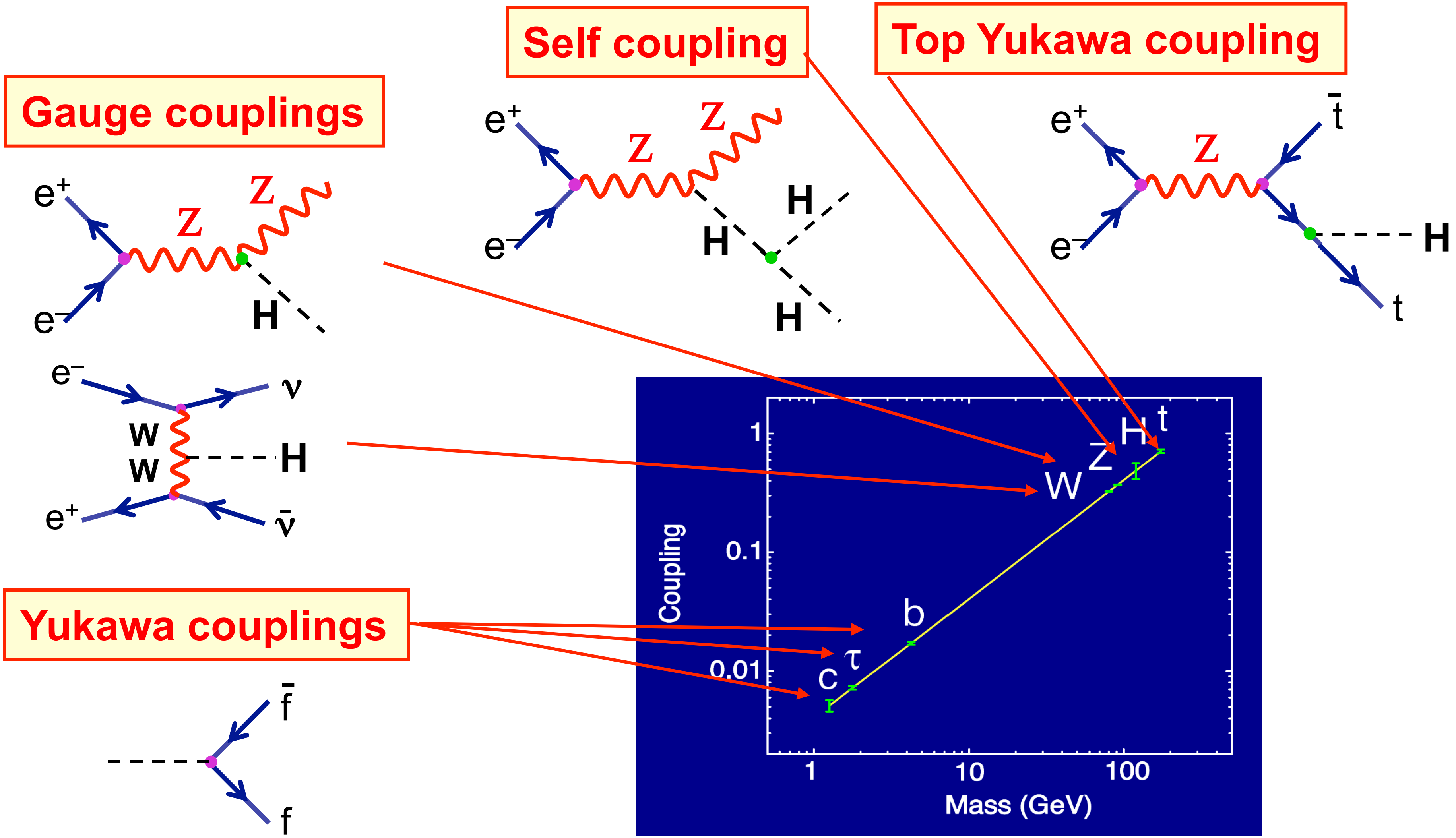
e.g. in $e^+e^- \rightarrow HZ$ have model-independent measurement of Higgs mass by measuring recoil against identified $Z \rightarrow \mu^+\mu^-$ decays

⇨ $\boxed{\sigma(m_{\rm H}) \sim 30\,{\rm MeV}}$



Higgs couplings

- ★ Can measure all Higgs couplings



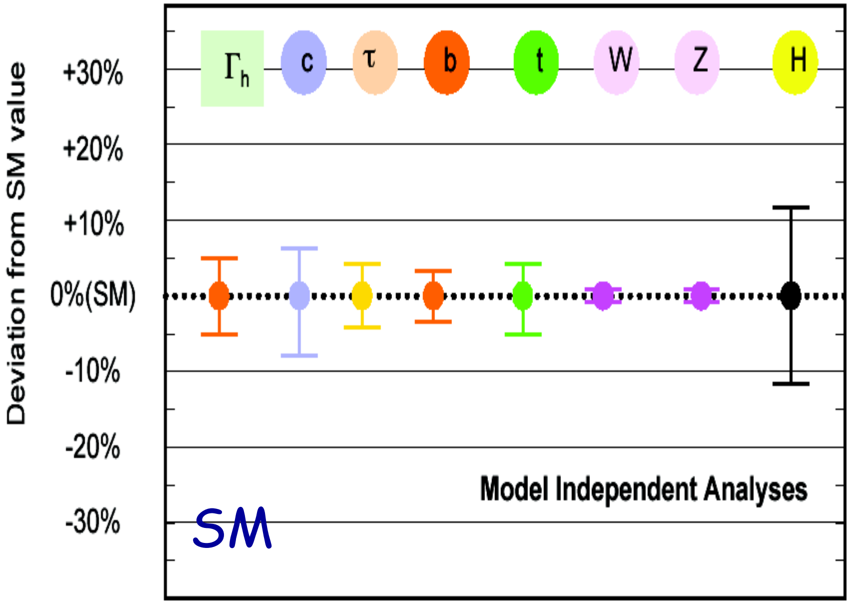
Gauge couplings

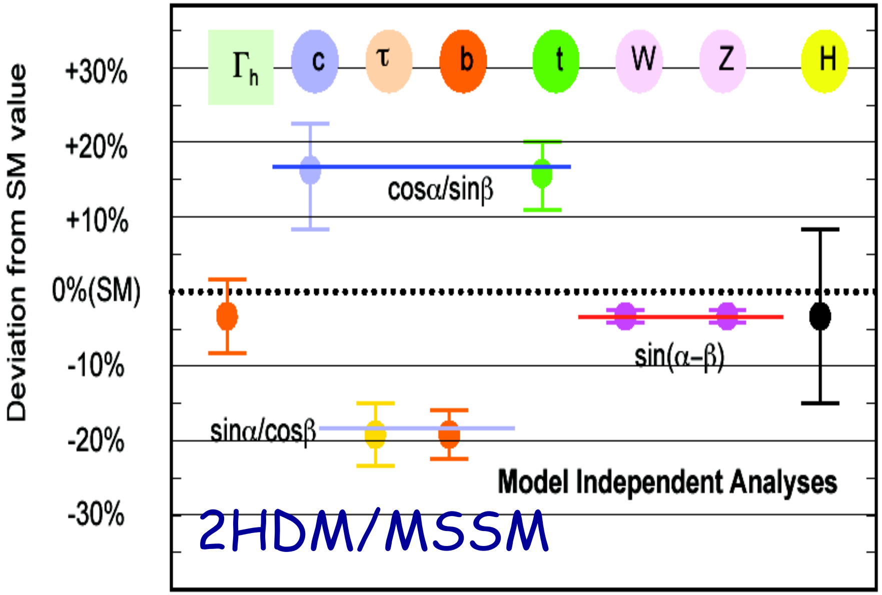
Self coupling

Top Yukawa coupling

Yukawa couplings

- Measurements of Higgs couplings allow underlying physics to be determined
- For expected measurement precision (few %), consider expected deviations from expectation for SM Higgs





- The ILC is a very powerful tool to understand new physics !

have only scratched the surface of ILC physics….

★ The clean ILC environment allows precise physics measurements.

★ These measurements will compliment the high energy/ high luminosity reach of the LHC in pinning down the nature of TeV scale physics

BUT

★ Precision physics at the ILC places stringent requirements on the performance of the ILC detector(s)

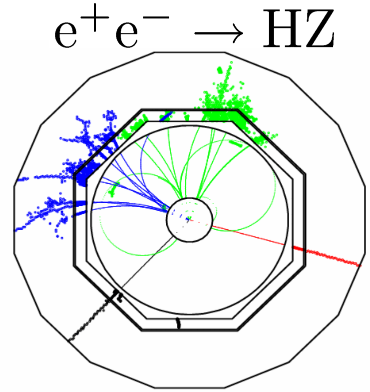
ILC Detector Requirements

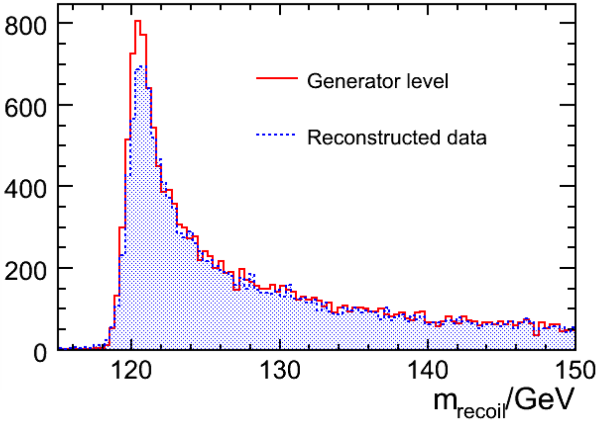
momentum: **(1/10 x LEP)**

e.g. Muon momentum

Higgs recoil mass

$$\boxed{\sigma_{1/p} < 5\times 10^{-5}\,\mathrm{GeV}^{-1}}$$



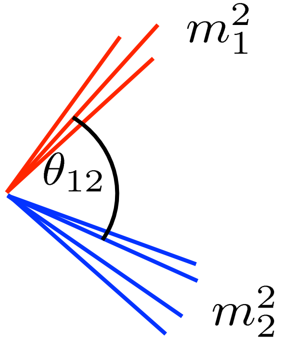


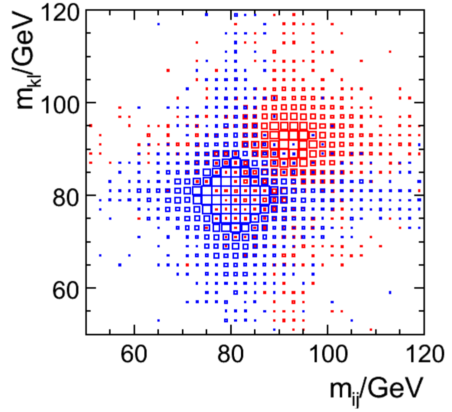
jet energy: **(1/3 x LEP/ZEUS)**

e.g. W/Z di-jet mass separation

EWSB signals

$$\boxed{\frac{\sigma_E}{E} \approx 3-4\,\%}$$



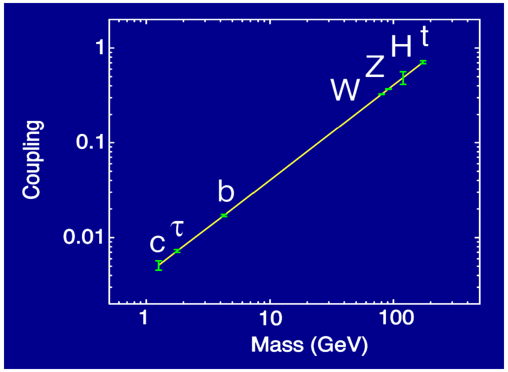


impact parameter: **(1/3 x SLD)**

e.g. c/b-tagging

Higgs BR

$$\boxed{\sigma_{r\phi} = 5 \oplus 10/(p\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}}$$

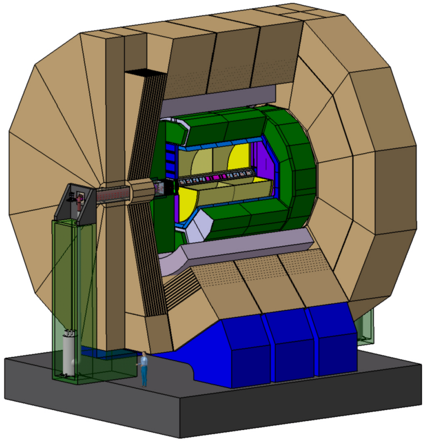


hermetic: **down to θ = 5 mrad**

e.g. missing energy signatures in SUSY

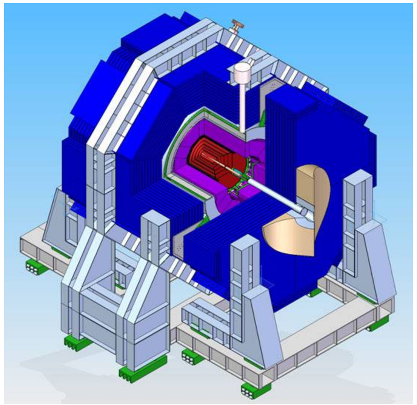
❹ ILC Detector Concepts

ILD: International Large Detector



"Large" : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid

SiD: Silicon Detector



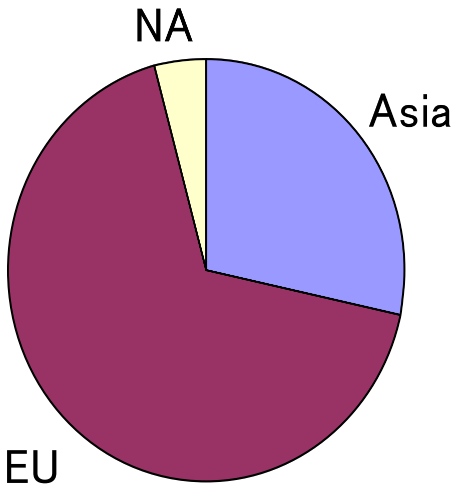
"Small" : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid

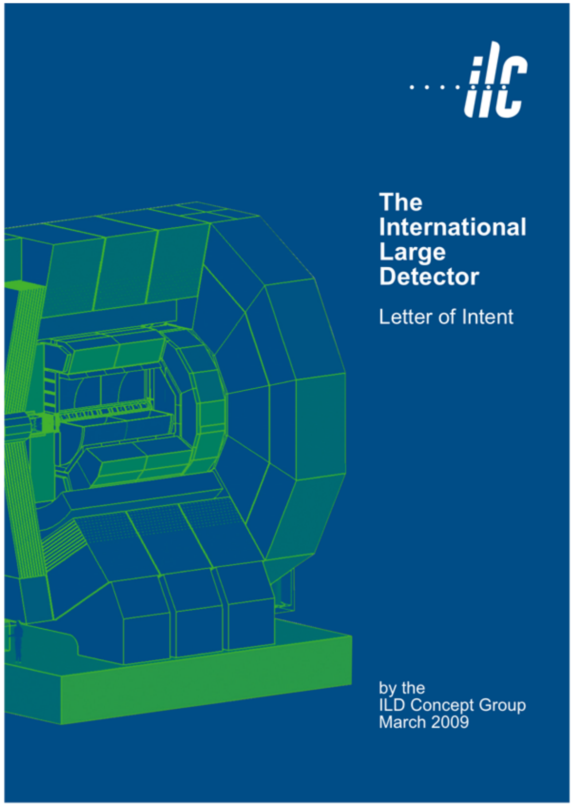
- ★ Both concepts "validated" by IDAG (independent expert review, June 2009)
- ★ Detailed GEANT4 studies show ILD/SiD meet ILC detector goals
- ★ Mostly fairly conventional technology – although many technical challenges

Represent plausible/performant designs for an ILC detector

e.g. The ILD “Letter of Intent”

★ **The ILD LoI**
  - **695 signatories**
  - **32 countries from 148 institutions**
  - **~40 signatories from 13 UK institutes**
  - **Very strong EU and Asian participation**




The International Large Detector

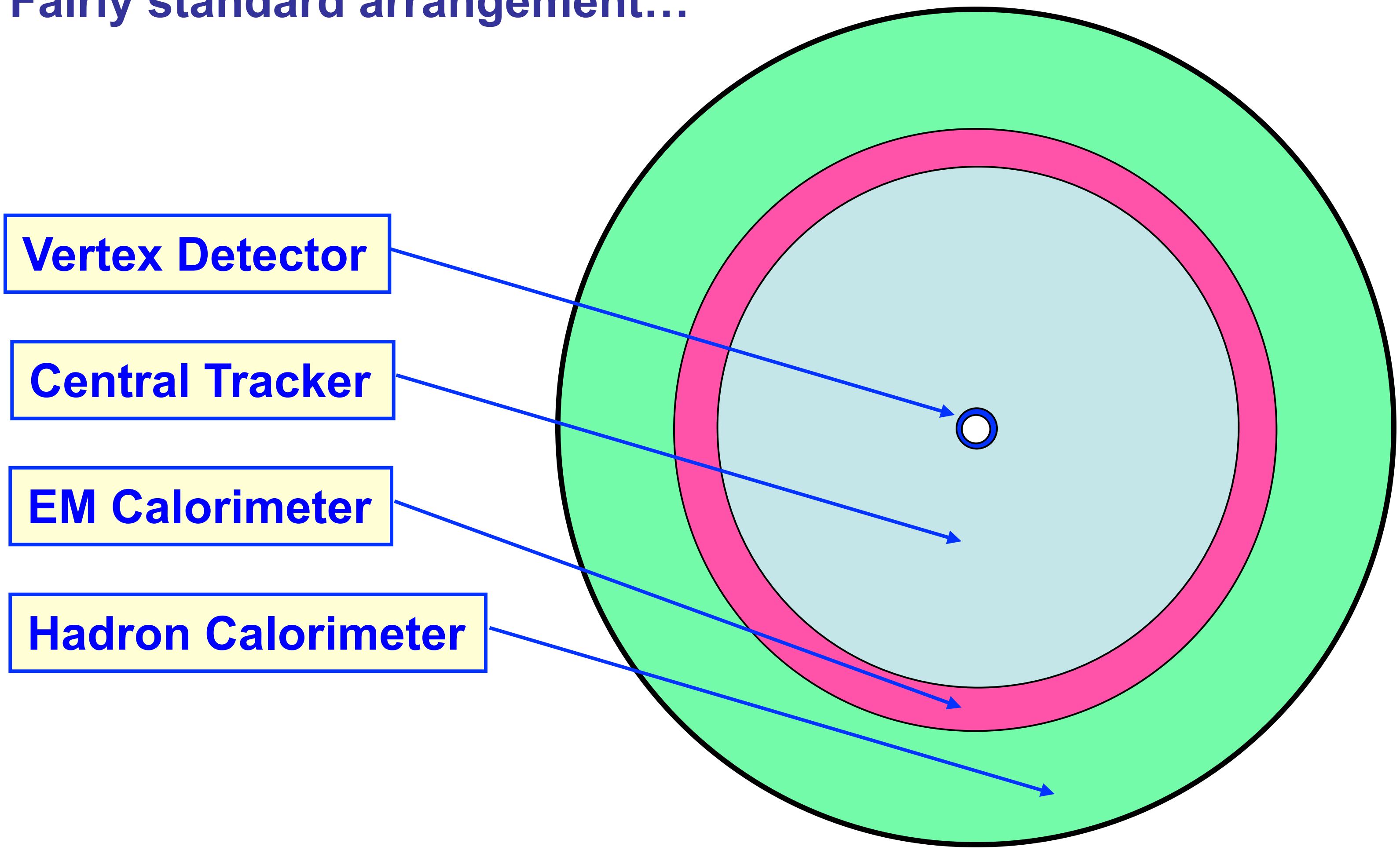
Letter of Intent

by the
ILD Concept Group
March 2009

★ **Concept studies provide framework for detector R&D – ensure it is matched to ILC physics requirements**

Detectors at e^+e^- colliders

- Fairly standard arrangement…



Vertex Detector

Central Tracker

EM Calorimeter

Hadron Calorimeter

- What technologies are needed to give desired performance ?

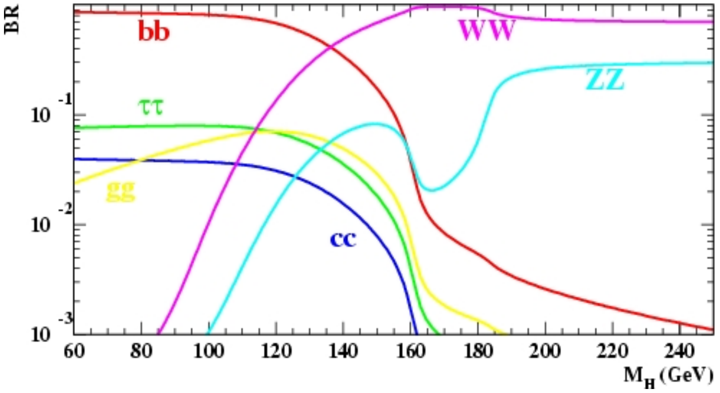
Vertex Detector

★ Important for many physics analyses

e.g. couplings of a low mass Higgs

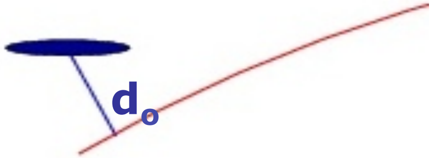
Want to test $g_{Hff} \sim m_f$

O(%) measurements of the branching ratios H→bb,cc,gg



★ Also important for event ID and background rejection

Flavour tagging requires a precise measurement of the impact parameter d_o

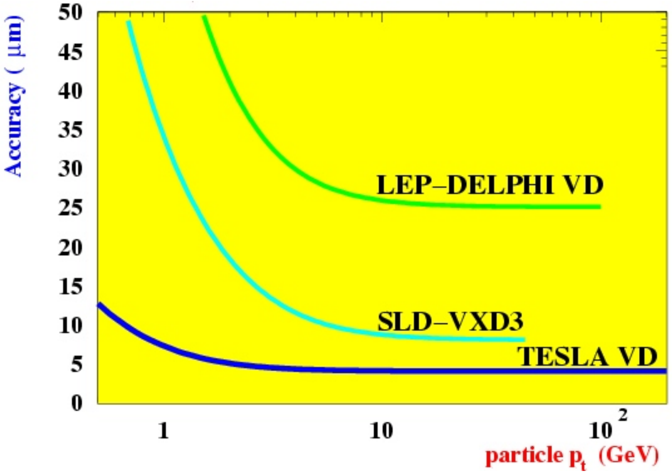


Aim for significant improvement compared to previous detectors

$$\sigma_{d0} \sim a \oplus b/p_T(\mathrm{GeV})$$

Goal: $a < 5\mu m$, $b < 10\mu m$

a: point resolution, b : multiple scattering



Main design considerations:

★Inner radius: as close to beampipe as possible, ~15-25 mm for impact parameter resolution

★Layer Thickness: as thin as possible
suppression of γ conversions, minimize multiple scattering,...

Constraints:

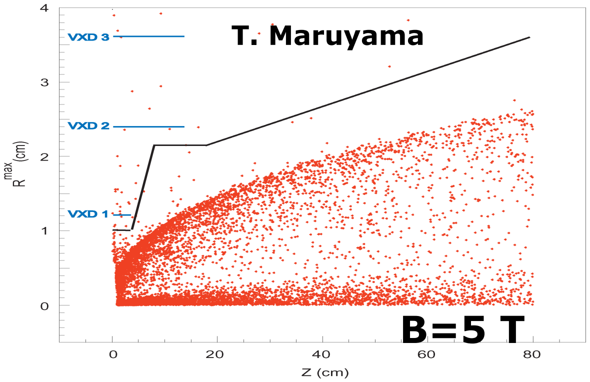
★ Inner radius limited by e^+e^- pair bgd.
depends on the machine + B field

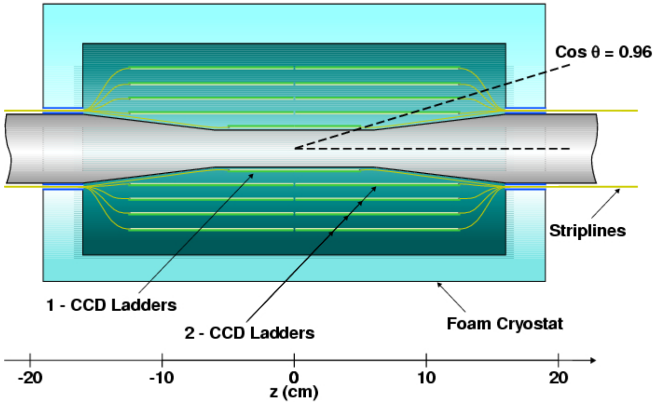
★ Layer thickness depends on Si technology

★ Ultimate design driven by machine + technology !

e.g. ILD option II:

★Pixels : 20x20μm
★Point resolution : 5 μm
★Inner radius : 15 mm
★Polar angle coverage : $|\cos\theta|<0.96$

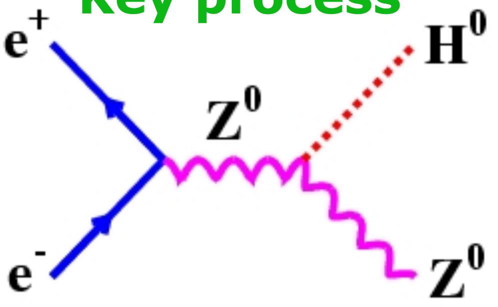




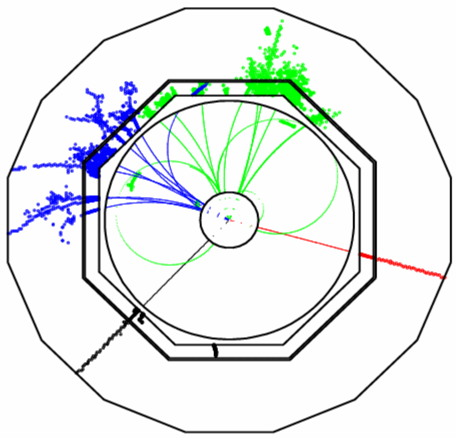
★ Ultimate design depends on worldwide detector R&D

Tracking : Momentum Resolution

Key process



$e^+e^- \to Z^* \to ZH \to \mu^+\mu^- X$



Recoil mass to $\mu^+\mu^-$

⇨ M_H σ_{ZH} , g_{ZHH}

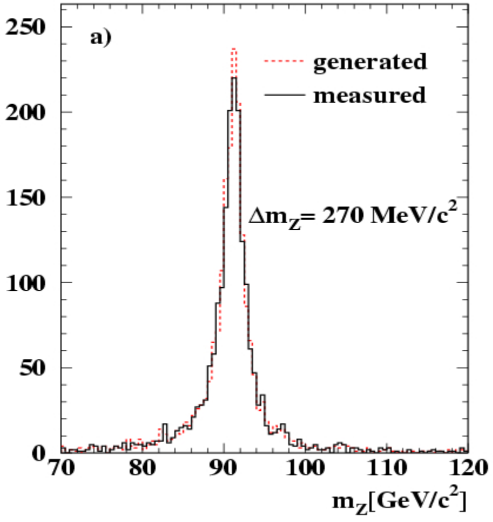
$\mu^+\mu^-$ angular distribution

⇨ Spin, CP,...

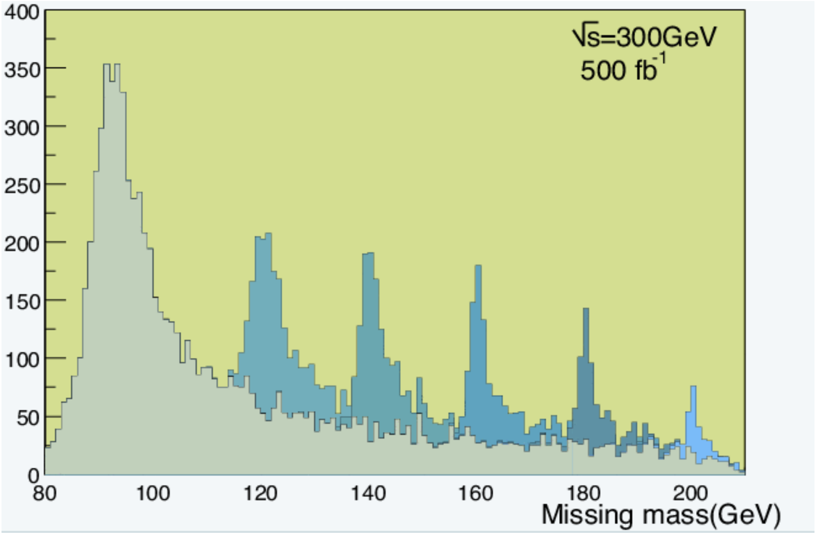
- **Measurements depend on lepton momentum resolution**

goal: $\Delta M_{\mu\mu} < 0.1 \times \Gamma_Z$ ⇨ $\sigma_{1/p} < 5\times10^{-5}\ \mathrm{GeV}^{-1}$

- **Use $\mu\mu$ mass to select Z**



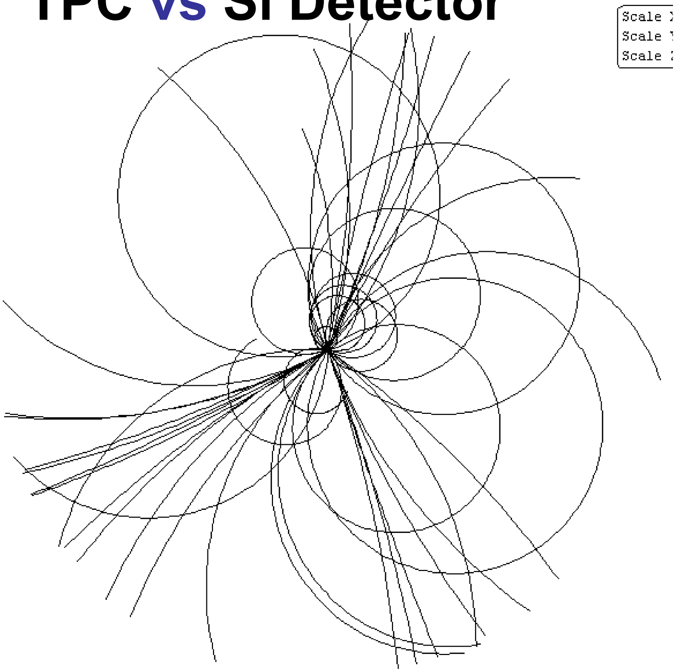
- **Recoil mass gives m_H**

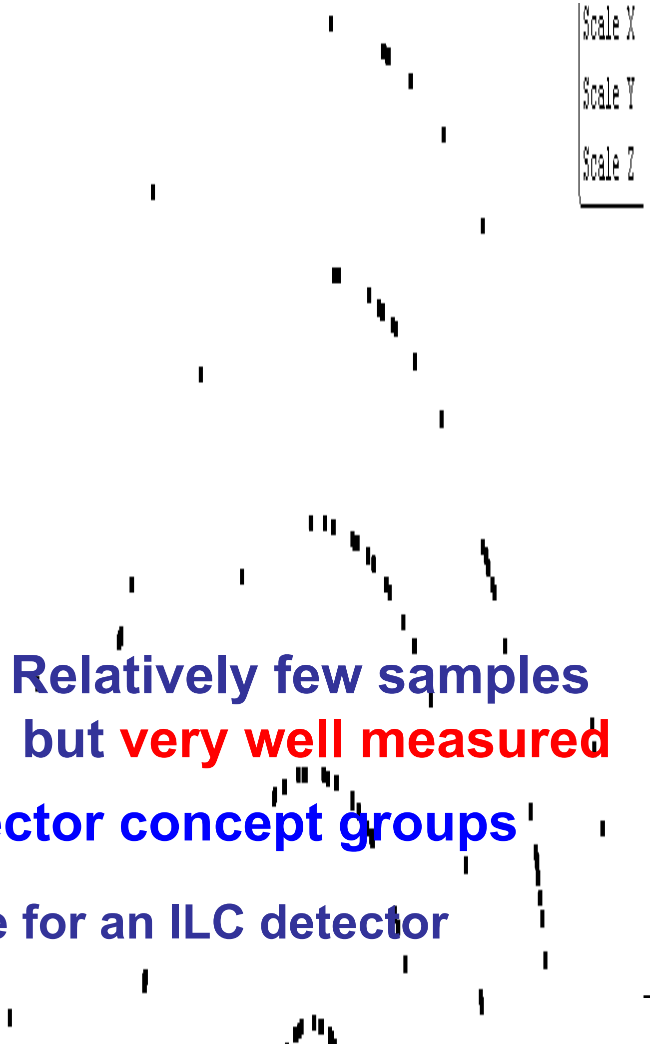


Two main tracker options

i) Gaseous Time Projection Chamber (e.g. ALEPH)
ii) Si Tracker (e.g. ATLAS but with much less material)

★ **TPC** vs **Si Detector**





★ Large number of samples

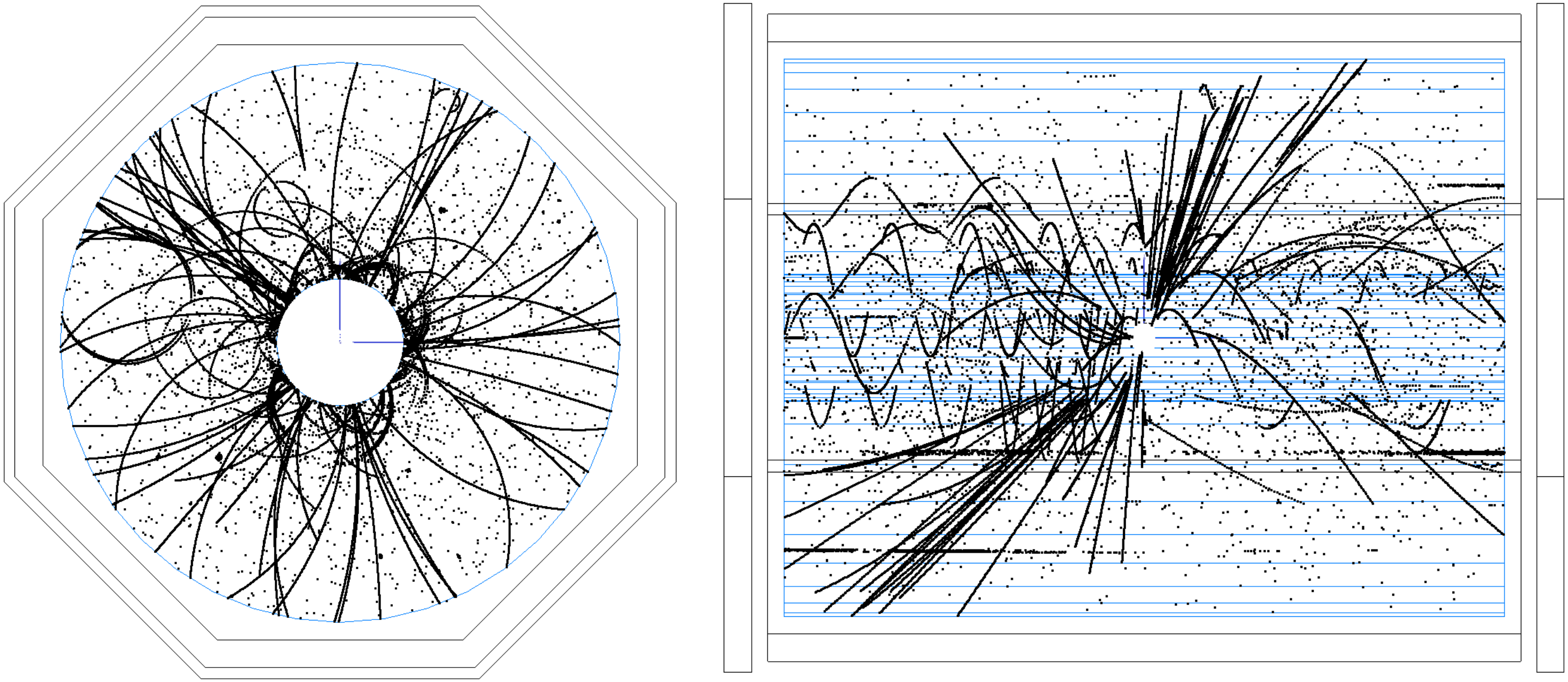
★ Relatively few samples
but very well measured

★Both options being studied in detector concept groups
- TPC : ILD
- Si : SiD

} Both look suitable for an ILC detector

ILC Tracking Environment

- ★ e.g. TPC with **150 BXs** of background shifted in **z**
- ★ Superimpose on fully-hadronic top-pair events at 500 GeV

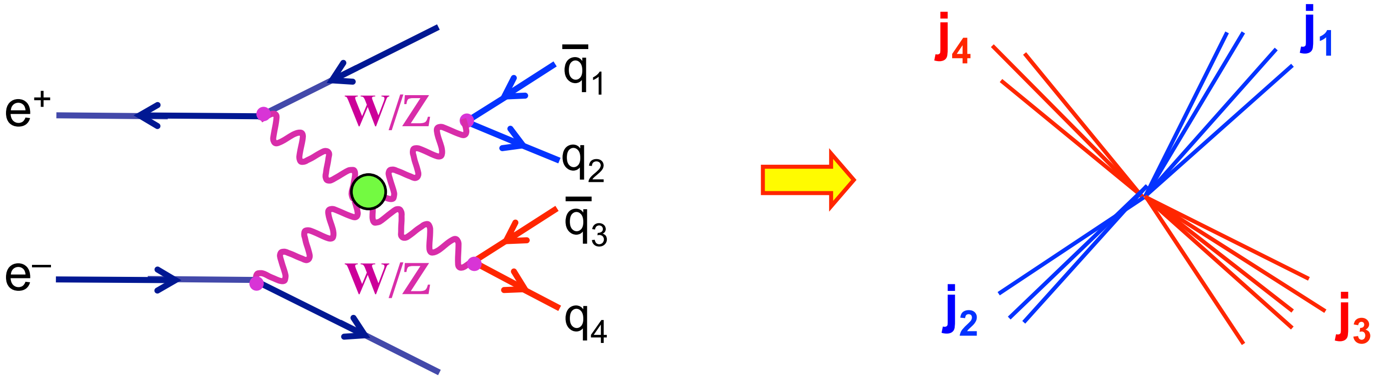


- ★ TPC occupancies are very low (negligible c.f. ALICE)
- ★ ILC tracking environment very clean

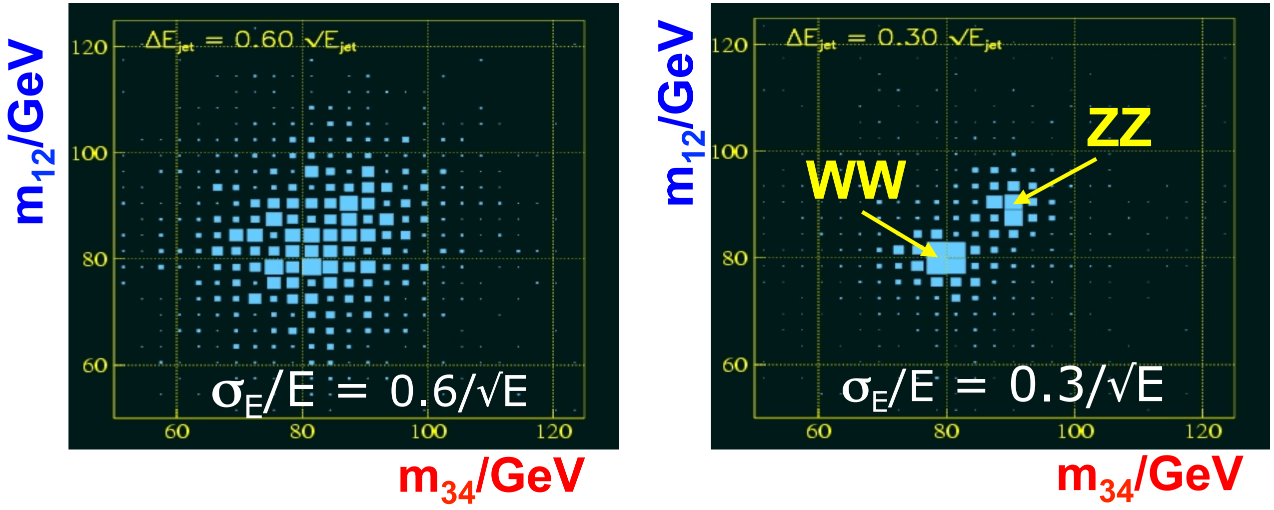
❺ Calorimetry at the ILC

★ **Any future collider experiment geared towards precise measurements requires very good jet energy resolution to maximise physics reach:**

Often-quoted example at ILC: $e^+e^- \rightarrow \nu\overline{\nu}W^+W^-$ **vs.** $e^+e^- \rightarrow \nu\overline{\nu}ZZ$



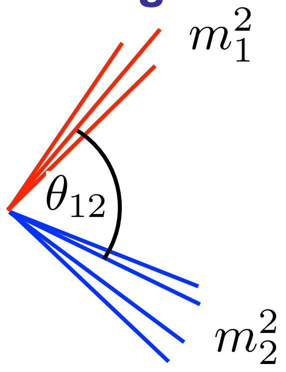
Reconstruction of two di-jet masses discriminates between WW and ZZ final states



Calorimetric Requirements

★ **Aim for invariant mass resolution comparable to Gauge boson width (i.e. once width dominates have reached the point of diminishing return)**

★ **For a pair of jets have:**



$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$

★ **For di-jet mass resolution of order**

$$\frac{\sigma_m}{m} \approx \frac{\Gamma_Z}{m_Z} \approx \frac{\Gamma_W}{m_W} \approx 0.027$$

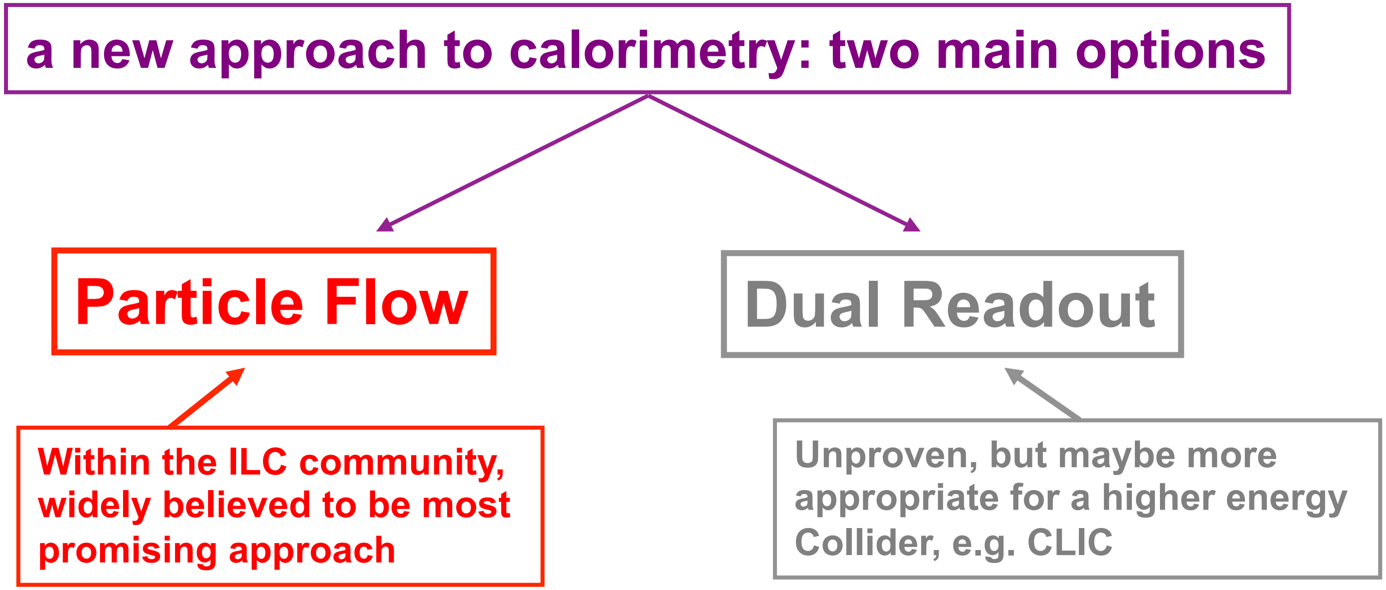
⇒ $\boxed{\sigma_{E_j}/E_j < 3.8\%}$

e.g. for a TeV lepton collider $\boxed{\sigma_E/E < 0.30/\sqrt{E(\mathrm{GeV})}}$

★ **Very hard (may not be possible) to achieve this with a traditional approach to calorimetry; limited by typical HCAL resolution of > 55%/√E(GeV)**

e.g. best at LEP: $\sigma_\mathrm{E}/\mathrm{E} \approx 60\,\%(1 + \cos\theta_\mathrm{JET})/\sqrt{(\mathrm{E}(\mathrm{GeV}))}$

⇒ **a new approach to calorimetry**



a new approach to calorimetry: two main options

Particle Flow

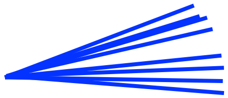
Within the ILC community, widely believed to be most promising approach

Dual Readout

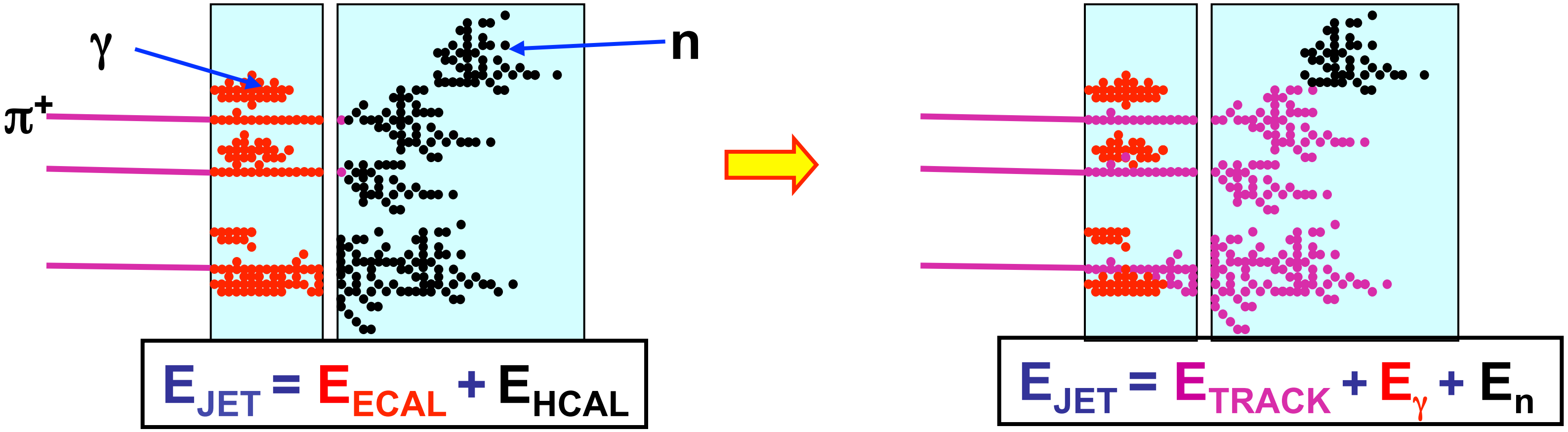
Unproven, but maybe more appropriate for a higher energy Collider, e.g. CLIC

Introduction to Particle Flow Calorimetry

- **In a typical jet :**
  - **60 %** of jet energy in charged hadrons
  - **30 %** in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - **10 %** in neutral hadrons (mainly n and K_L)



- **Traditional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL !
  - **~70 %** of energy measured in HCAL: $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically "poor" HCAL resolution limits jet energy resolution



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

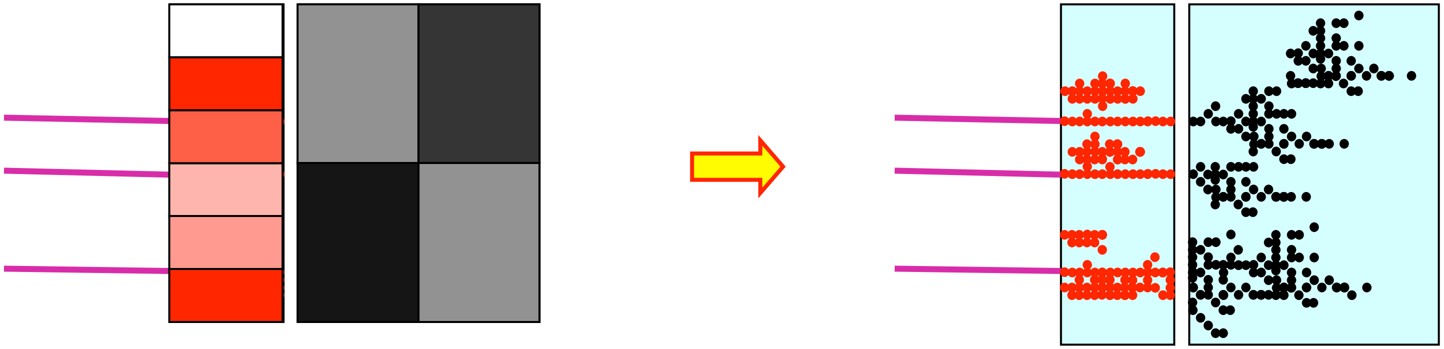
- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⟹ much improved resolution

Particle Flow Calorimetry

Hardware:

★ Need to be able to resolve energy deposits from different particles

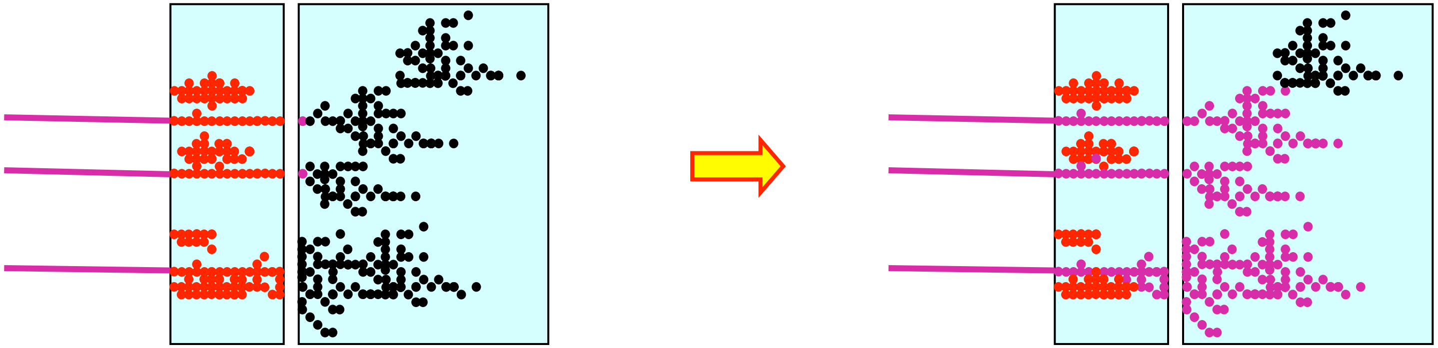
→ Highly granular detectors (as studied in CALICE)



Software:

★ Need to be able to identify energy deposits from each individual particle !

→ Sophisticated reconstruction software



★ **Particle Flow Calorimetry = HARDWARE + SOFTWARE**

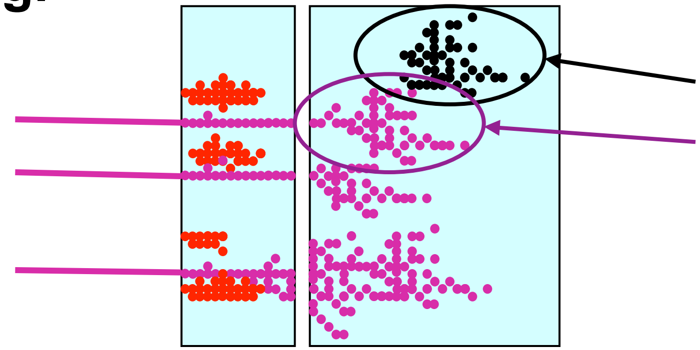
Particle Flow Reconstruction (PFA)

Reconstruction of a Particle Flow Calorimeter:

★ **Avoid double counting of energy from same particle**

★ **Separate energy deposits from different particles**

e.g.

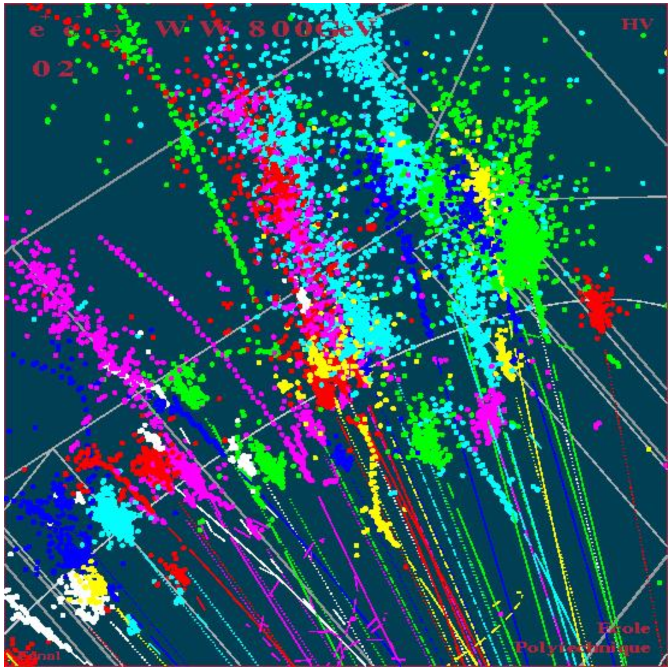


If these hits are clustered toghether with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution not the intrinsic calorimetric performance of ECAL/HCAL

sounds easy….

… it isn’t !



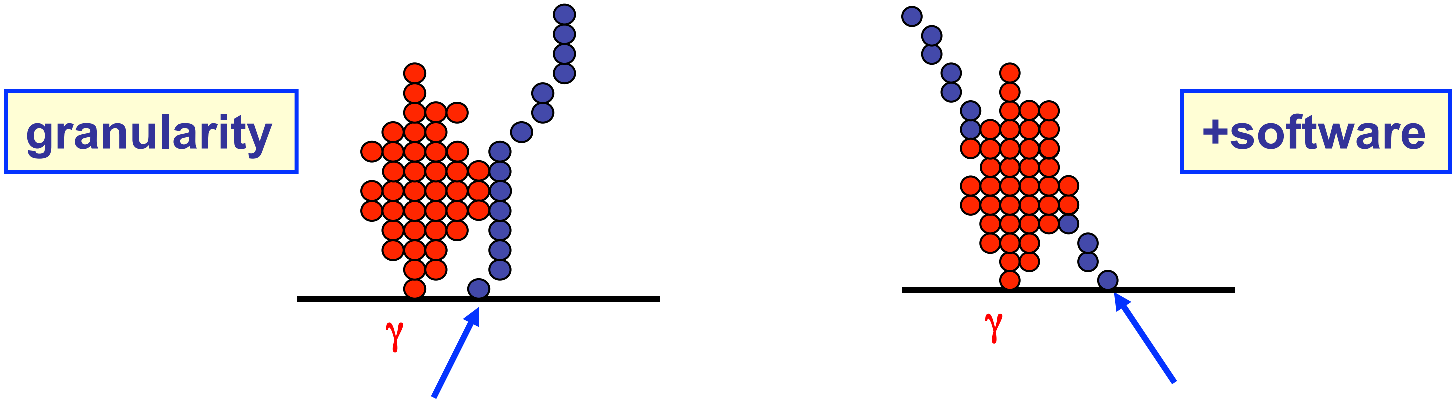
- ★ Separation of energy deposits in dense jet environment is very hard
- ★ Completely **new problem**: requires development of new techniques
  : even the basic approach is unclear
- ★ Performance = **HARDWARE + SOFTWARE** to evaluate potential of particle flow calorimetry need “realistic” particle flow reconstruction

Practical PFA Calorimetry

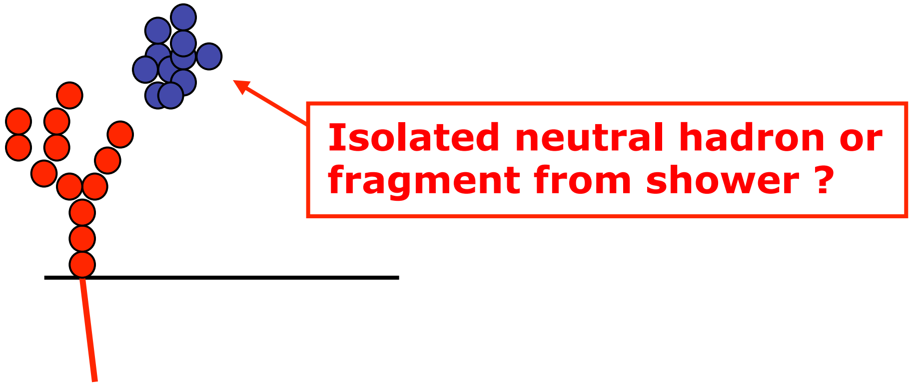
★ **How to separate energy deposits + avoid double counting**

e.g.

★ **Need to separate “tracks” (charged hadrons) from photons**



★ **Need to separate neutral hadrons from charged hadrons**



Isolated neutral hadron or fragment from shower ?

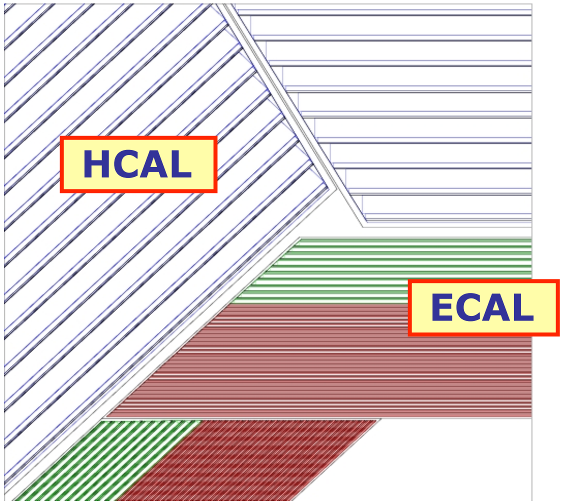
⇨ **granularity more important than energy resolution**

Calorimetry at the ILC

★ ILD and SiD concepts designed for particle flow calorimetry, e.g. ILD*

ECAL:

- SiW sampling calorimeter
- Tungsten: $X_0/\lambda_{had} = 1/25$, $R_{Mol.} \sim 9\text{mm}$
  - → Narrow EM showers
  - → longitudinal sep. of EM/had. showers
- longitudinal segmentation: 30 layers
- transverse segmentation: 5x5 mm^2 pixels



HCAL:

- Steel-Scintillator sampling calorimeter
- longitudinal segmentation: 48 layers (6 interaction lengths)
- transverse segmentation: 3x3 cm^2 scintillator tiles

Comments:

★ Technologically feasible (although not cheap)

★ Ongoing test beam studies (CALICE collaboration)

*Other ILD calorimetry options being actively studied, e.g. RPC DHCAL, Scintillator strip ECAL

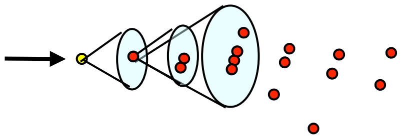
Particle Flow Calorimetry : reconstruction

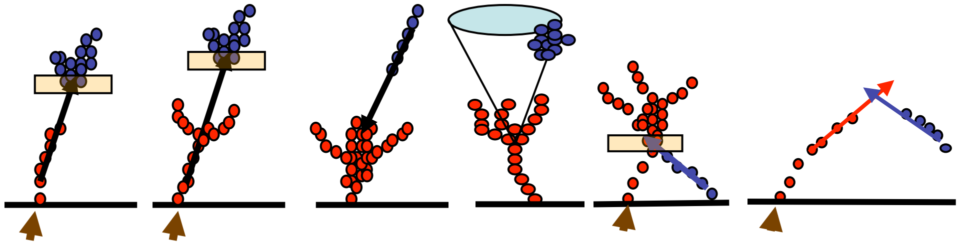
PandoraPFA:

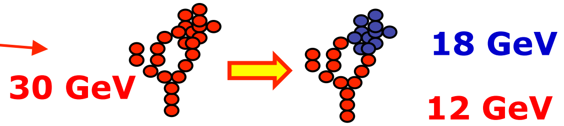
- ★ Developed in context of cluster reconstruction for CALICE
- ★ Aim was to prove Particle Flow Calorimetry can work
- ★ Optimised for CALICE-like electro-magnetic and hadronic calorimeters
- ★ A sophisticated algorithm with many new ideas
- ★ Particle Flow is much more than calorimeter reconstruction
  - ▪ e.g. treatment of tracks in calorimeter reconstruction is crucial !

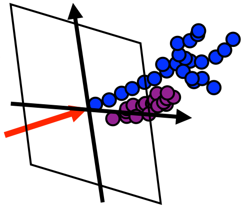
Eight Main Stages:

- i. Tracking
- ii. Loose clustering in ECAL and HCAL
- iii. Topological linking of clearly associated clusters
- iv. Courser grouping of clusters
- v. Iterative reclustering (using tracks)
- vi. Photon Recovery
- vii. Fragment Removal
- viii. Form Reco Particle Objects



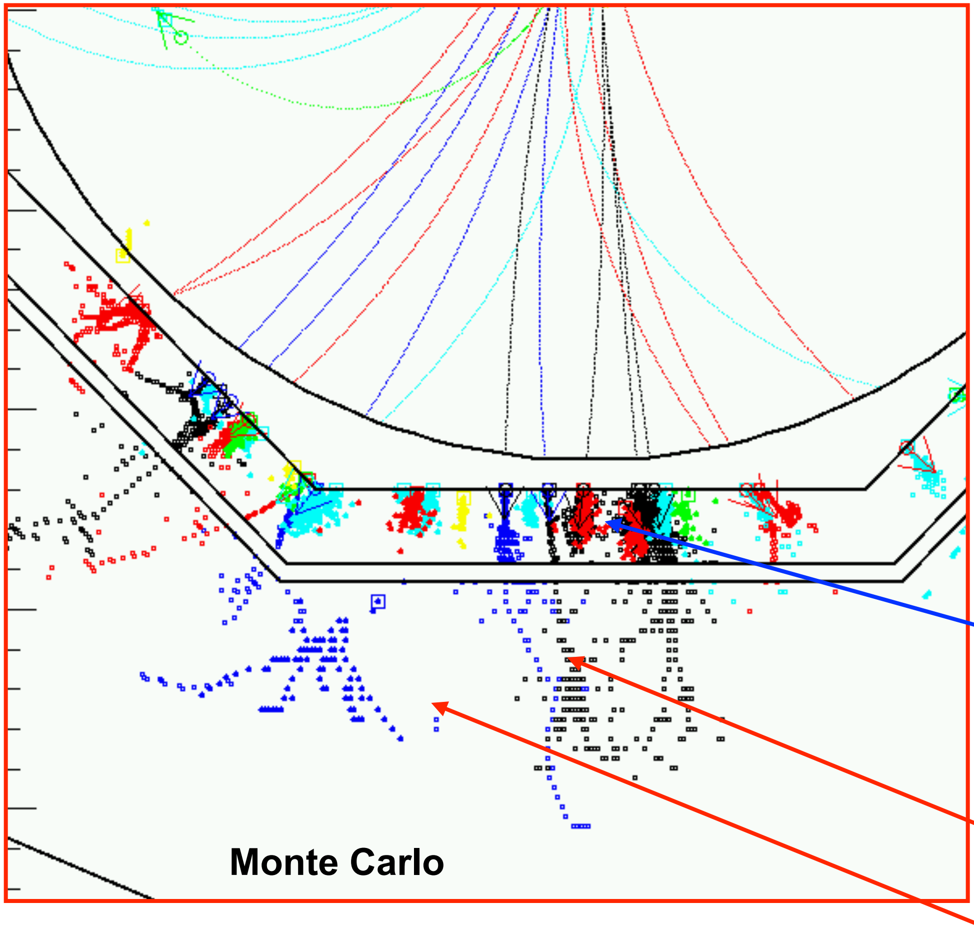






Putting this together…

100 GeV Jet



photon

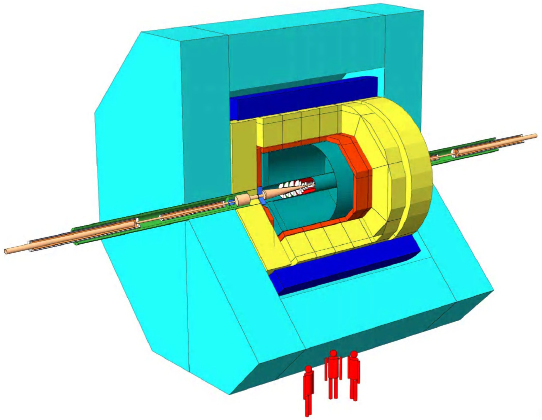
charged hadron

neutral hadron

★ Reconstruct jet properties from **tracks + photons + neutral hadrons**

Particle Flow: Proof of Principle

- ★ Using GEANT4 simulations of **ILD** detector concept for the **ILC**



E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$
45 GeV	23 %
100 GeV	29 %
180 GeV	39 %
250 GeV	47 %

Typical ILC jet energies

UNPRECEDENTED jet energy performance !!!

- ★ For 45 GeV jets, performance now equivalent to 23 % / √E
- ★ Factor 2 – 3 better than a traditional calorimetric approach !!!
- ★ Potentially a big impact on physics sensitivity
- ★ Clear demonstration that Particle Flow Calorimetry works (in principle)
- ★ However, for higher energy jets, performance still dominated by "confusion", i.e. imperfect reconstruction (not a physical limit)

For more details, see:
"Particle Flow Calorimetry and the PandoraPFA algorithm", MT, NIMA 611(2009)

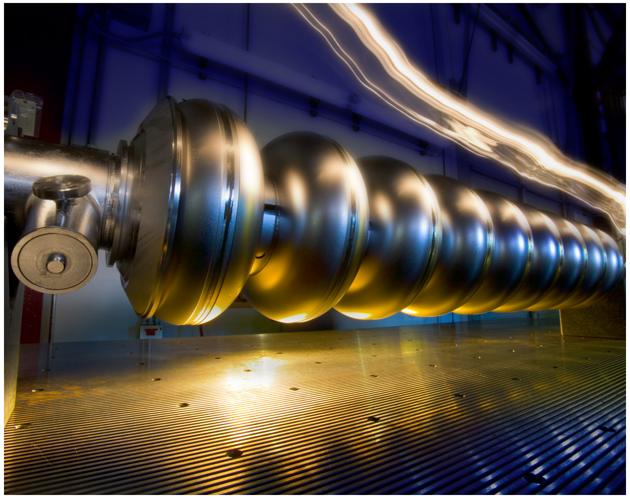
Confident that we can build a PFA based detector which meets all ILC performance goals

- ★ **What about CLIC ?**

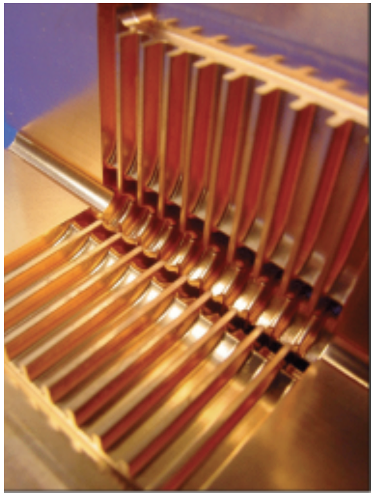
❻ CLIC

★ Renewed impetus on CERN **C**ompact **L**inear **C**ollider:
  - significantly increased CERN funding for accelerator R&D
  - CLIC CDR due late Summer 2011: Accelerator + Detector/Physics

ILC



CLIC

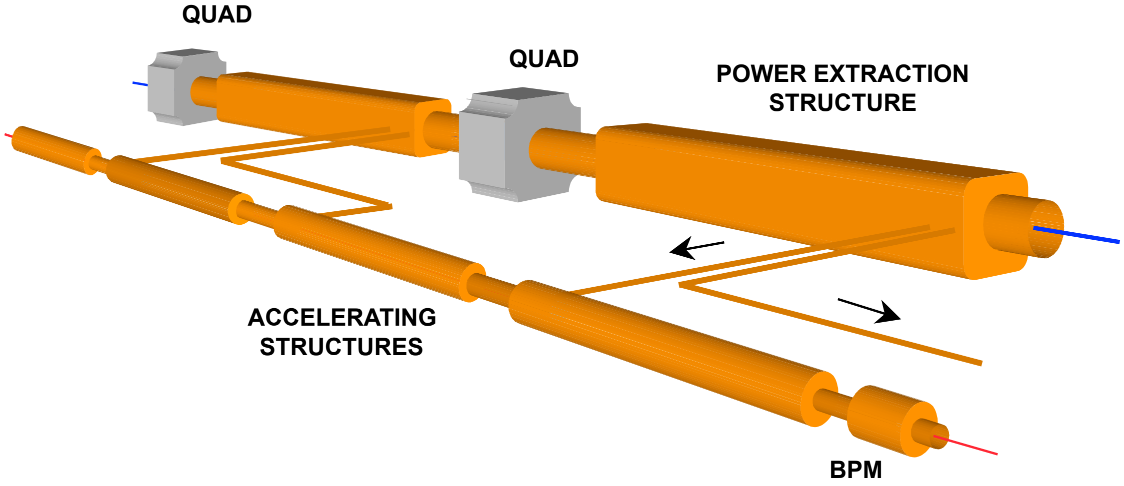


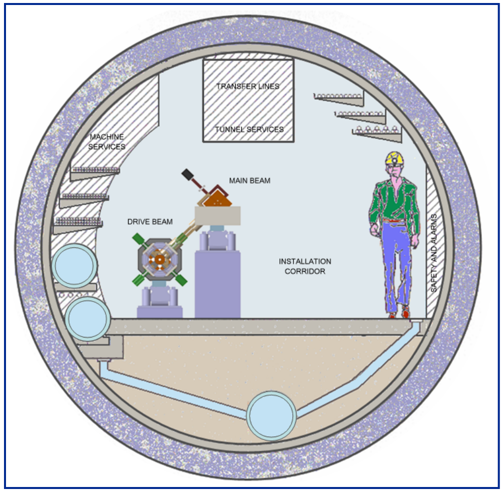
Based on SC RF Cavities
Gradient: 32 MV/m
Energy 500 GeV (upgradable to 1 TeV)
Detector studies mostly 500 GeV

Based on 2 beam acceleration scheme
Gradient: 100 MV/m
Energy 3 TeV (staging likely)
Detector studies mostly 3 TeV

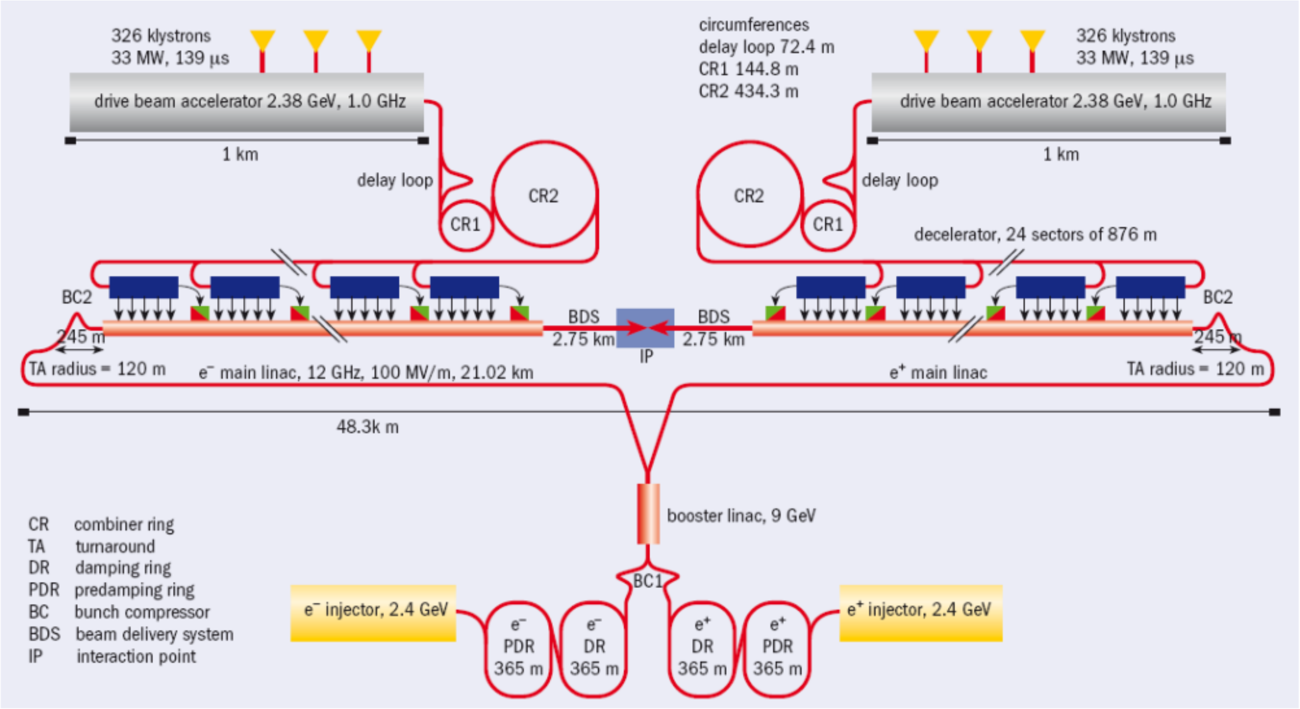
★ Potential energy reach is big CLIC selling point
  - could be the long term future of CERN
  - but very challenging accelerator (R&D <u>at least</u> 5 years behind ILC)
  - also very challenging detector environment

it won’t be easy…





Drive Beam Generation Complex



Main Beam Generation Complex

From ILC to CLIC Detector Concepts

- Detector design should be motivated by physics
- On assumption that CLIC would be staged: e.g. 500 GeV → 3 TeV
  - Must meet all ILC detector goals
  - Hence **ILC detectors** represent good starting point for CLIC
- **For 3 TeV operation what are the detector goals ?**
  - Less clear than for the ILC (for ILC Higgs physics helps define goals)
  - Nevertheless can make some statements:
    - Still want to separate W/Z hadronic decays

Jet energy res: $\boxed{\frac{\sigma_E}{E} < 3-4\,\%}$

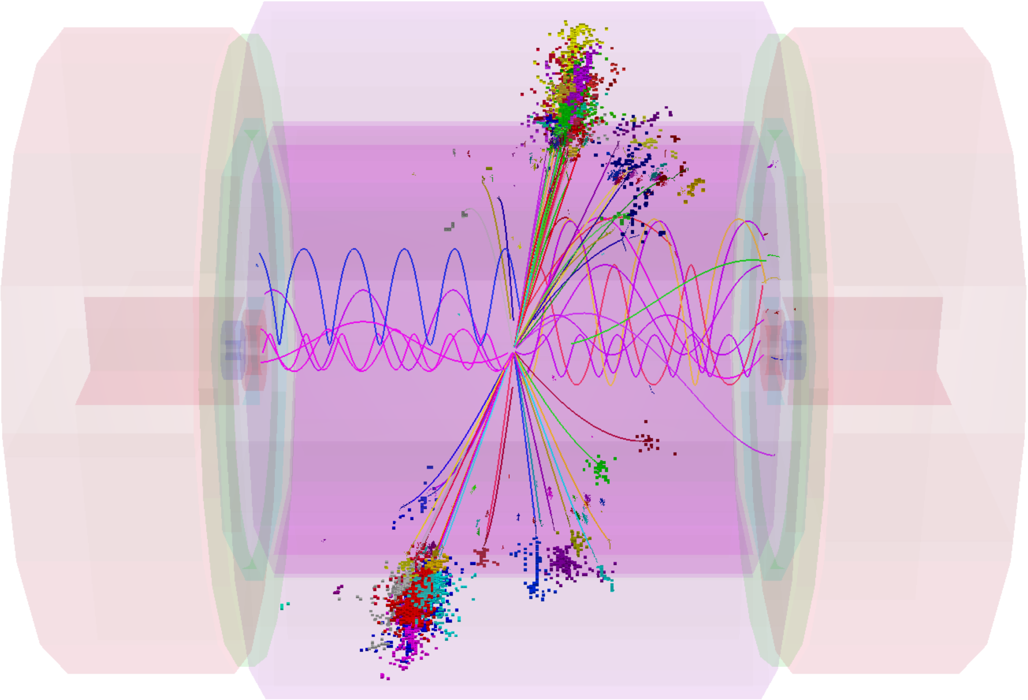
    - Heavy flavour-tagging still will be important; higher boost of b/c-hadrons will help. ILC goal likely(?) to be sufficient, i.e.

$$\boxed{\sigma_{r\phi} = 5 \oplus 10/(p\sin^{\frac{3}{2}}\theta)\,\mu\text{m}}$$

    - Requirements for momentum resolution less clear, high p_T muons likely to be important…

CLIC Detector Concepts

- ★ Modified versions of ILC detector concepts
  - Vertex detector further out (r_{min} = 30 mm)
  - Thicker HCAL (8 λ_I)
    - but HCAL is in solenoid – need to keep “thin”
    - hence currently assume Tungsten as absorber
- ★ Full Geant4 simulations of: **CLIC ILD CDR** and **CLIC SiD_CDR**

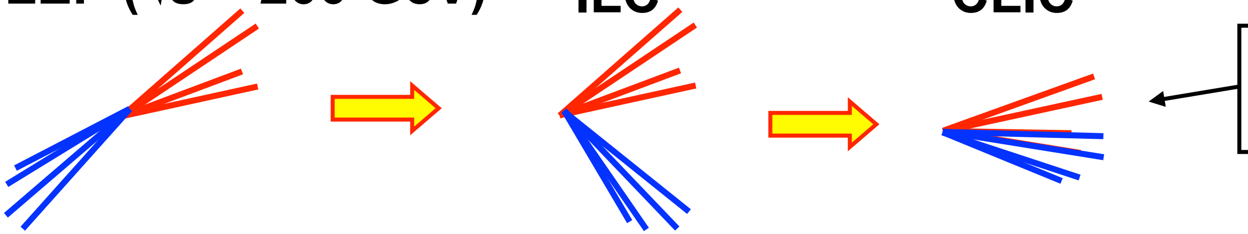


e.g. reconstructed event in CLIC_ILD_CDR

- ★ Currently evaluating performance

e.g. Particle Flow at CLIC

★On-shell W/Z decay topology depends on energy:



LEP (√s = 200 GeV) **ILC** **CLIC**

Particle flow reco. might help here

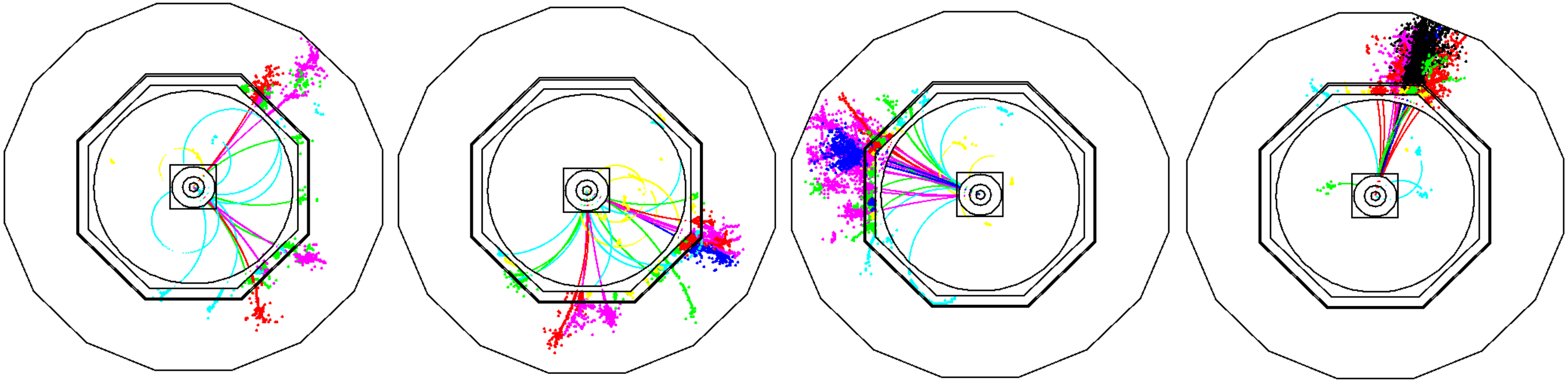
√s = 200 GeV **√s = 0.5-1.0 TeV** **√s = 3.0 TeV**

★A few comments:

- Particle multiplicity does not change
- Boost means higher particle density
- PFA could be better for "mono-jet" mass resolution

More confusion

★PandoraPFA + ILD$^+$ performance studied for:

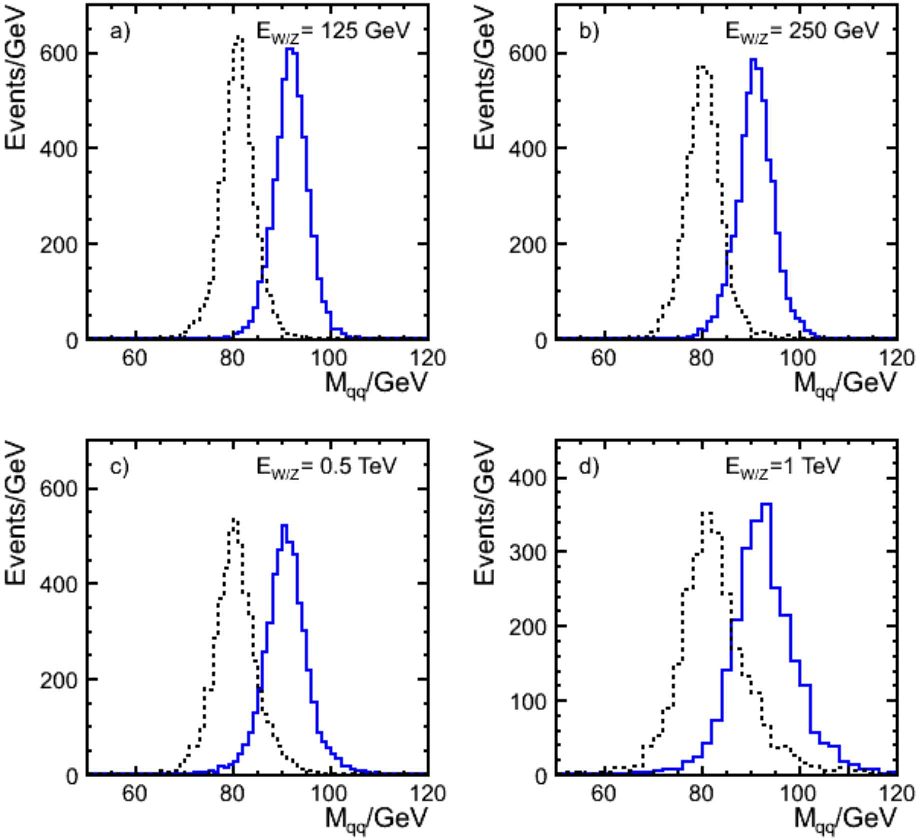


125 GeV Z **250 GeV Z** **500 GeV Z** **1 TeV Z**

W/Z Separation

★ **Studied W/Z separation using CLIC_ILD (8 λ_I HCAL) samples of**

$$e^+e^- \rightarrow WW \rightarrow u\bar{d}\nu\mu \qquad e^+e^- \rightarrow ZZ \rightarrow d\bar{d}\nu\bar{\nu}$$



ILC-like energies

Clear separation

CLIC-like energies

There is separation, although less clear for 1 TeV bosons

- **Current PandoraPFA gives good W/Z separation for 0.5 TeV bosons**
- **Still fair separation for 1 TeV bosons**
- **Particle Flow works at a 3 TeV collider**

CLIC Jet Energy Performance

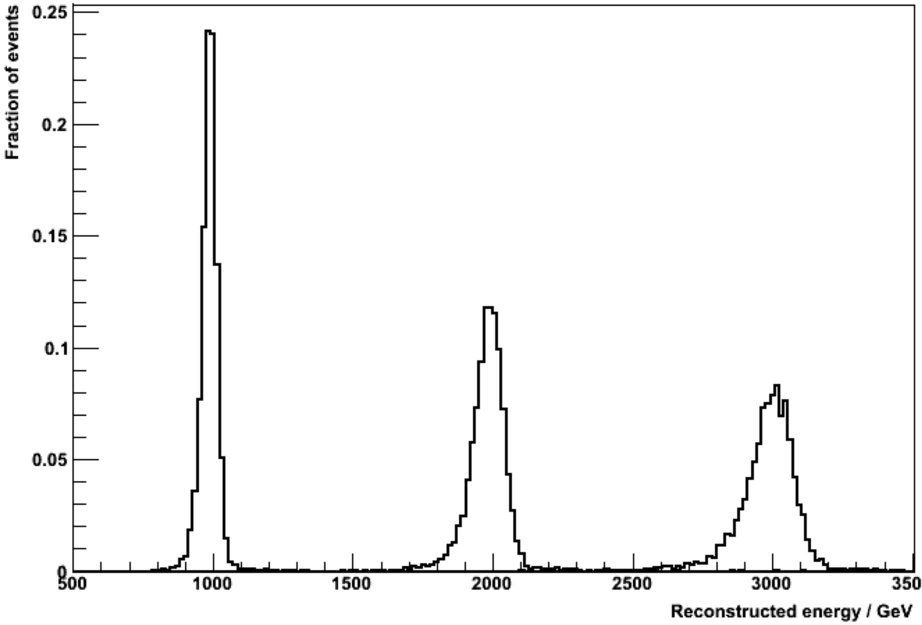
★ Now tested for jets in range 45 GeV – 1.5 TeV

ILD

E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	3.1 %
180 GeV	3.0 %
250 GeV	3.3 %

CLIC_ILD

E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	2.9 %
250 GeV	2.8 %
500 GeV	3.0 %
1 TeV	3.2 %
1.5 TeV	3.2 %



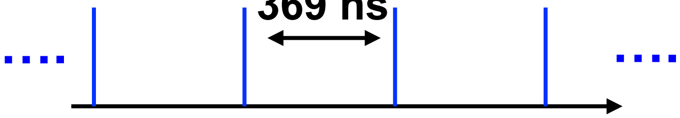
Jet Energy Resolution better than 3.6 % over whole range

❼ CLIC Physics Environment

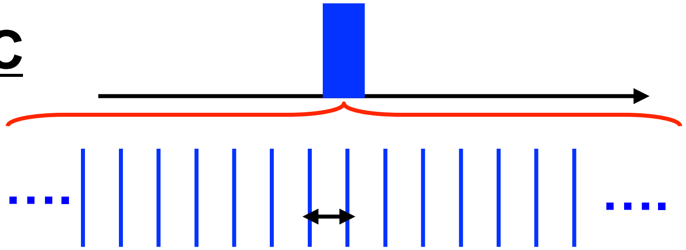
- ★ An ILC detector will work at 3 TeV
- ★ However the CLIC machine environment is very different to ILC

	LEP 2	ILC 0.5 TeV	CLIC 0.5 TeV	CLIC 3 TeV
L [cm^{-2}s^{-1}]	5×10^{31}	2×10^{34}	2×10^{34}	6×10^{34}
BX/train	4	2670	350	312
BX sep	247 ns	369 ns	0.5 ns	0.5 ns
Rep. rate	50 kHz	5 Hz	50 Hz	50 Hz
L/BX [cm^{-2}]	2.5×10^{26}	1.5×10^{30}	1.1×10^{30}	3.8×10^{30}
$\gamma\gamma\to X$ / BX	neg.	0.2	0.2	3.0
σ_x/σ_y	240 / 4 mm	600 / 6 nm	200 / 2 nm	40 / 1 nm

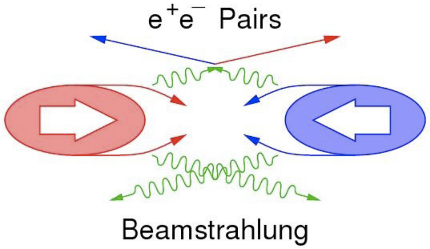
ILC



CLIC



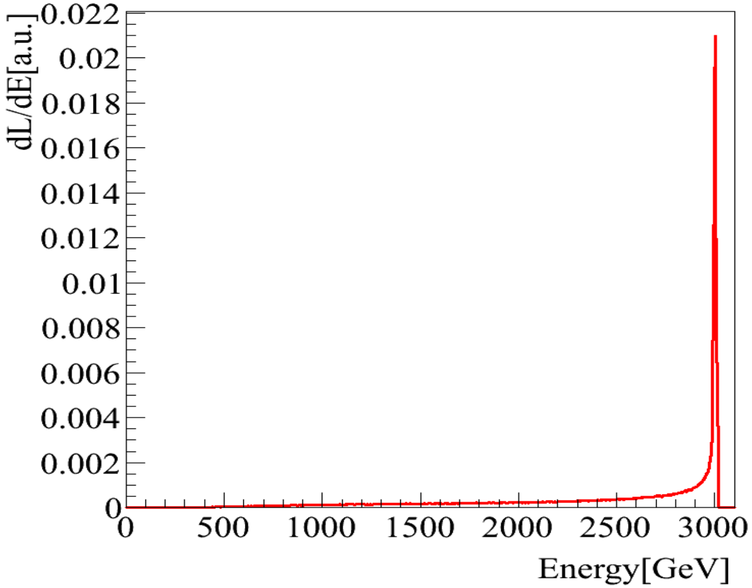
- ★ Time stamping will be an issue
- ★ Single BX ID will not be possible…
- ★ + very small bunch sizes lead to large backgrounds



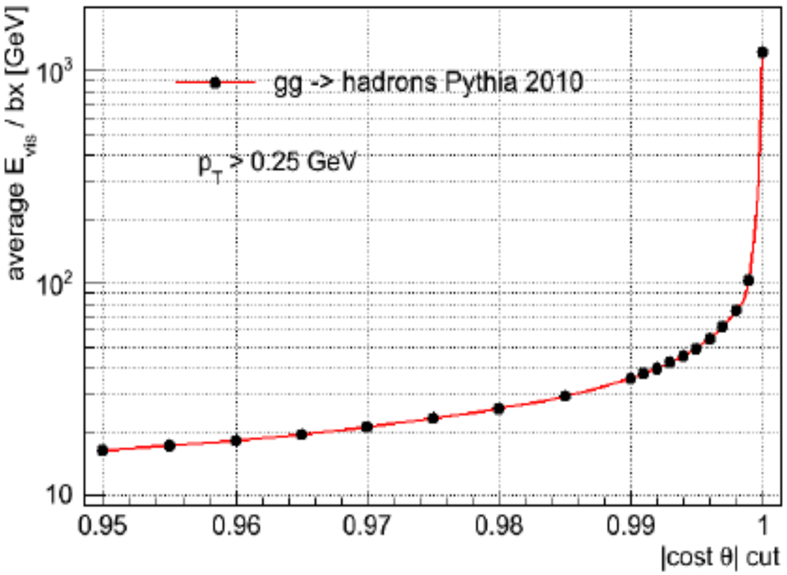
Pile-up

- ★ **Small beams/high fields result in significant production of real (and virtual) photons**

Beamsstrahlung



"Mini-jet" Background



Only 30 % of energy within 1% of 3 TeV

15 TeV of energy in 150 ns bunch-train !!!!

Time-stamping is a (the) major detector issue at CLIC

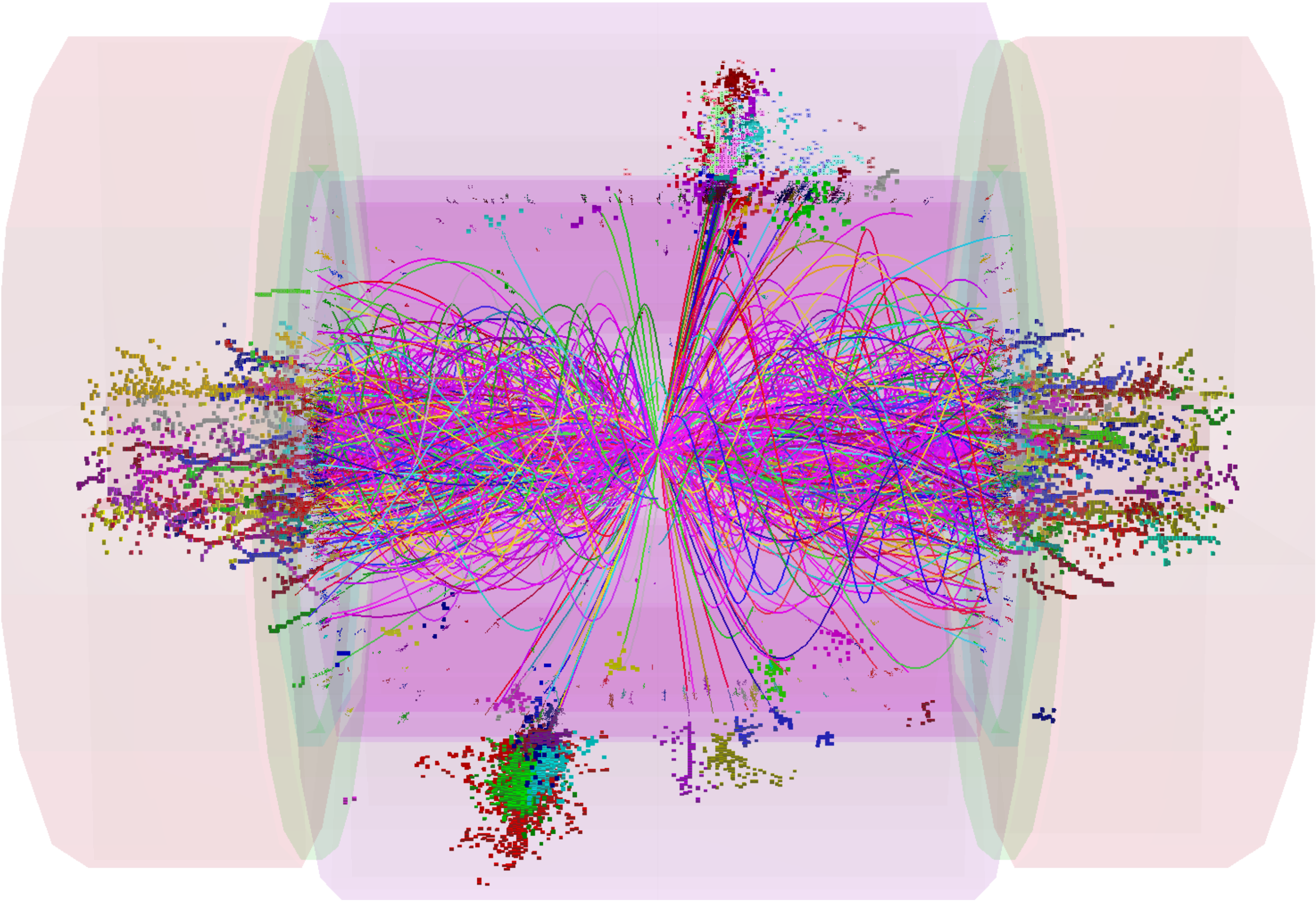
Physics at CLIC ?

- ★ Can one make “high” precision measurements at CLIC ?
- ★ Looks tough…

Recent Work

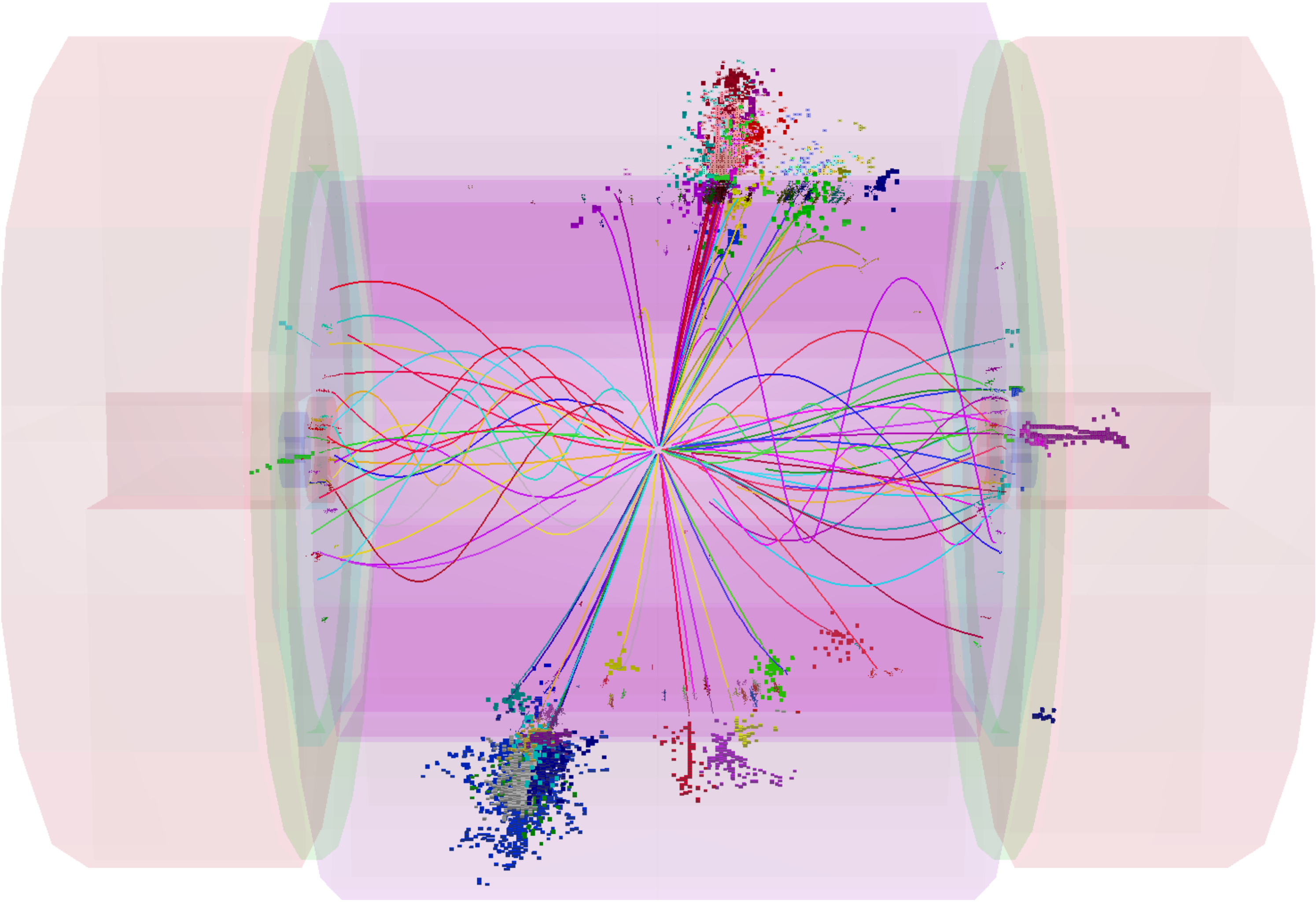
- ★ Full Geant 4 simulation of ILD detector concept with pile-up
  - ▪ Significant fraction of bunch-train simulated
  - ▪ Full reconstruction, assuming **10 ns integration times**
  - ▪ Full study of mitigation of background using calorimeter timing…

Reconstructed CLIC event with “pile-up”



1.4 TeV of background !

After timing cuts at cluster level



0.1 TeV of background

Looks feasible

The challenge: ~10 ns time-stamping

❽ Outlook, Politics, and Conclusions

★ Have given a flavour of the current status of the LC + detectors

★ ILC Machine design "fixed" : Reference Design Report 2007

"How much ?"

6.7 Billion ILC Units
13,000 person-years

1 ILC Unit = 1 US 2007$

- Design currently being "refined" with cost control in mind
- Full ILC **TDR** in 2012
- Confident that the ILC can be built – no major technical issues

★ CLIC is at a much early stage (but significant CERN funding)

- CLIC CDR in 2011 – to go to council late this year
- Full **TDR** in 2015/2016 (dependent on machine R&D)
- Feasibility ?

★Designs of detector concepts and related R&D progressing well
strong connection with hardware R&D, e.g. CALICE, LCTPC, …

Current Political Landscape

End 2007 "Black December":

- ★STFC : "withdraws from ILC"
- ★USA : budgetary crisis means large cuts to ILC (and other project funding)

Two years ago things looked rather bleak for the ILC…

Somewhere in Swindon, December 2007

The Current situation (mixed, but real hope):

Europe:

- ★ France, Germany maintaining significant funding for ILC
- ★ CERN: entering the game in major way
- ★ Cooperation between ILC/CLIC

UK:

- ★ less said the better…

USA:

- ★ not much better – too many republicans in office…

Asia:

- ★ Japan leads the way – both in terms of research and political will
- ★ China – now involved in ILC detector R&D

2012 is a possible decision time for future of HEP: the ILC will be ready

European Strategy for HEP

“Personal view”

- ★ Highly likely date for European Strategy for HEP will move to early 2012
  - Allow input of “run 1” LHC data

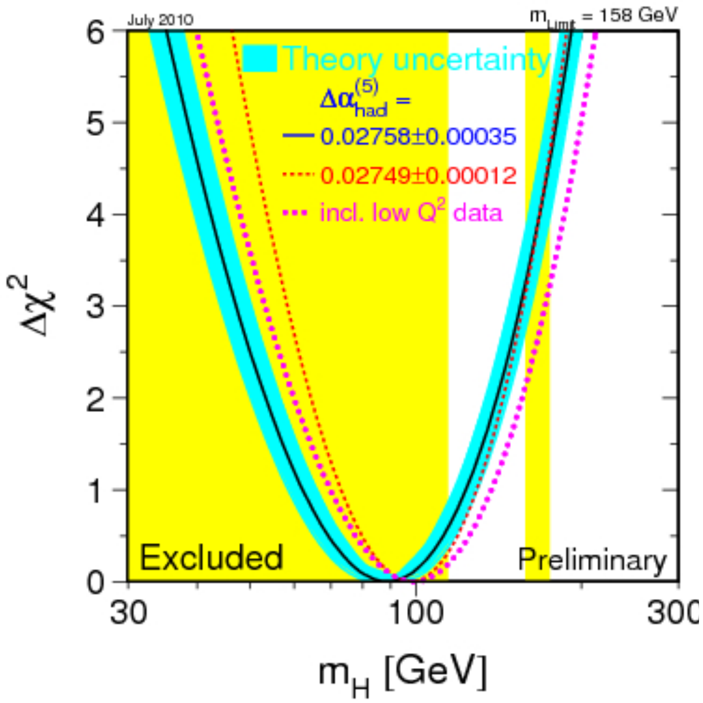
- ★ By this time:
  - we will almost certainly know if the Higgs exists
  - either will have hints of SUSY or MSSM will be in trouble

- ★ What does this mean for the ILC:
  - if nothing discovered… very hard to make the case
  - if discover a low mass Higgs (and/or low scale SUSY) this will
  - provide massive impetus to the ILC project

- ★ What does this mean for the CLIC:
  - highly dependent on what LHC sees
  - if nothing, CLIC may be left as the only (currently) realistic option for the future…

Closing Remark

★ If a **low mass Higgs is discovered at the LHC**, the scientific argument for building the ILC is overwhelming, I believe there is a realistic chance that the ILC project could move forward rather rapidly



Precision measurements: (blue band)

$$m_{\rm H} < 154\,{\rm GeV}\ \ 95\,\%\ {\rm C.L.}$$

+direct limits (LEP): (yellow exclusion)

$$m_{\rm H} < 184\,{\rm GeV}\ \ 95\,\%\ {\rm C.L.}$$

★ "Can be ~90 % confident that the ILC will be the next major project in HEP"

Please don't quote me on this

THE END