The International Linear Collider

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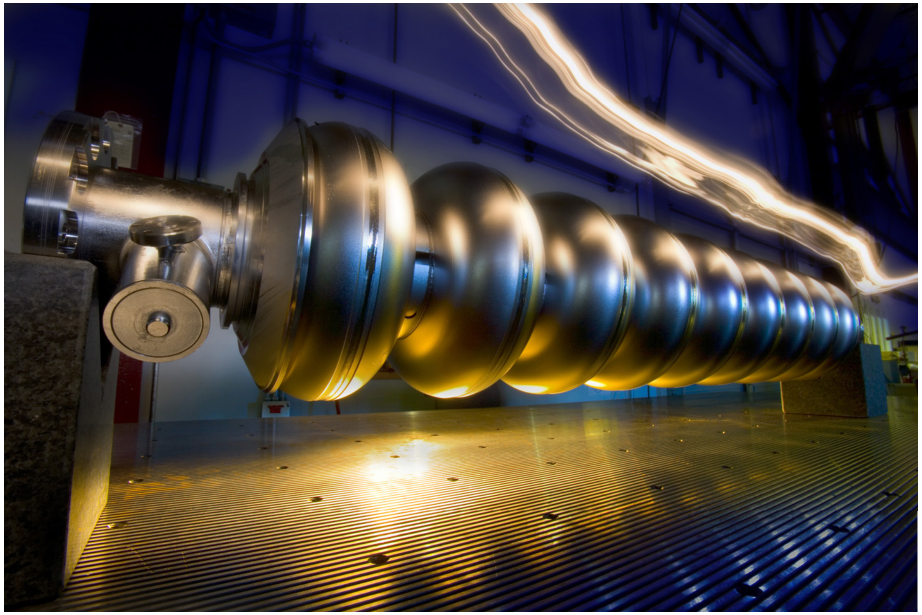
This Talk:



- ❶ Why the ILC ?
- ❷ The Machine
- ❸ Physics at the ILC
- ❹ Detectors at the ILC
- ❺ Outlook

(In this relatively short talk will try to give a flavour of ongoing ILC work)

❶ Why the ILC ?

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

The LHC

★ Will open the door to new physics !

★ Pushes the energy frontier with proton-proton collisions at 14 TeV

- *qq*, *qg* and *gg* collisions in the energy range 0.5-5 TeV

The ILC

★ 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:

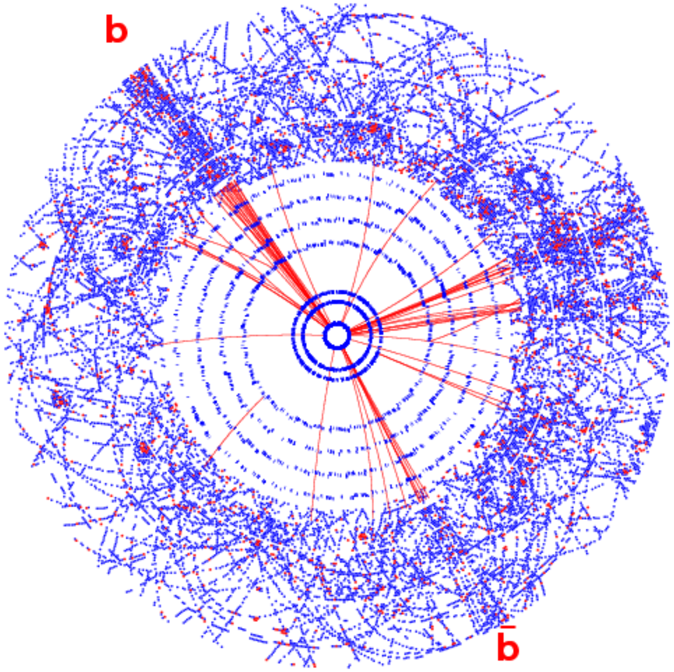
e.g. "Physics Interplay of the LHC and ILC", G. Weiglein et al., Phys. Rept. 426 (2006) 47-358

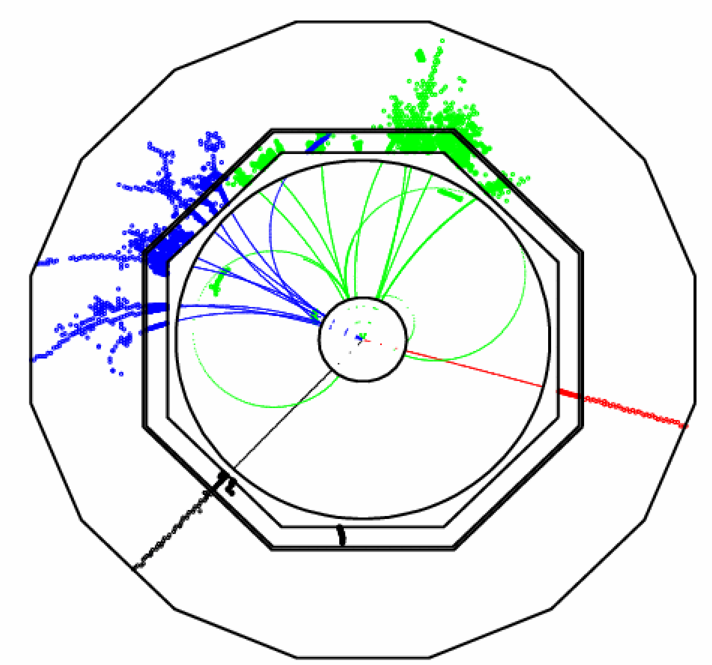
$e^+ e^-$ ≡ precision

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

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

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



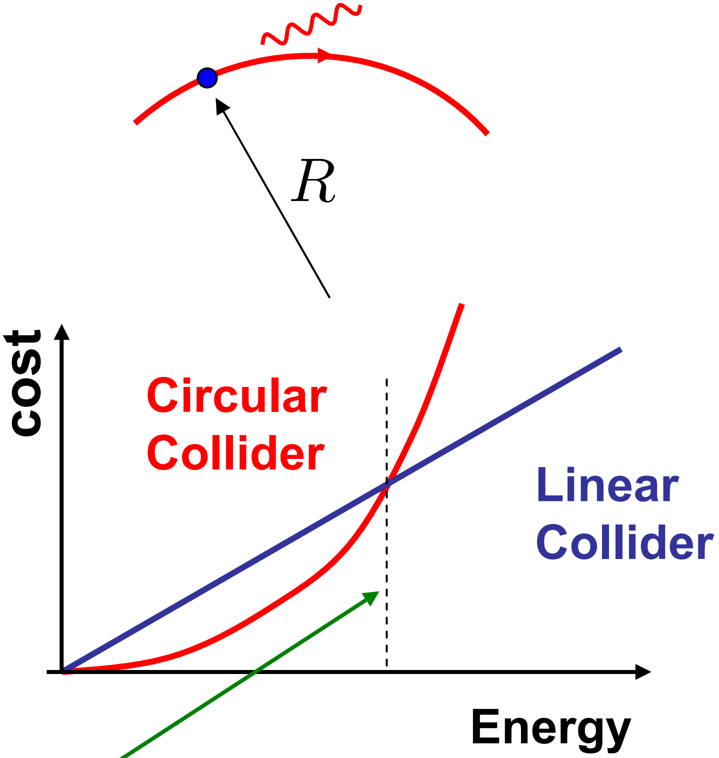


★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see $\mathrm{H} \rightarrow b\bar{b}$ and $\mathrm{Z} \rightarrow \mu^+\mu^-$ and nothing else…**

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

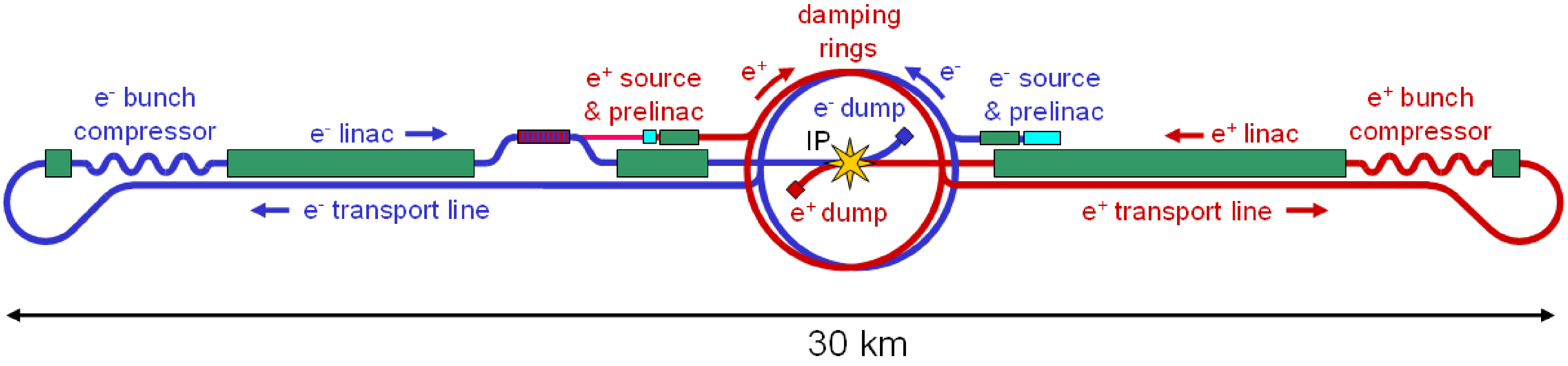
❷ ILC : the machine

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

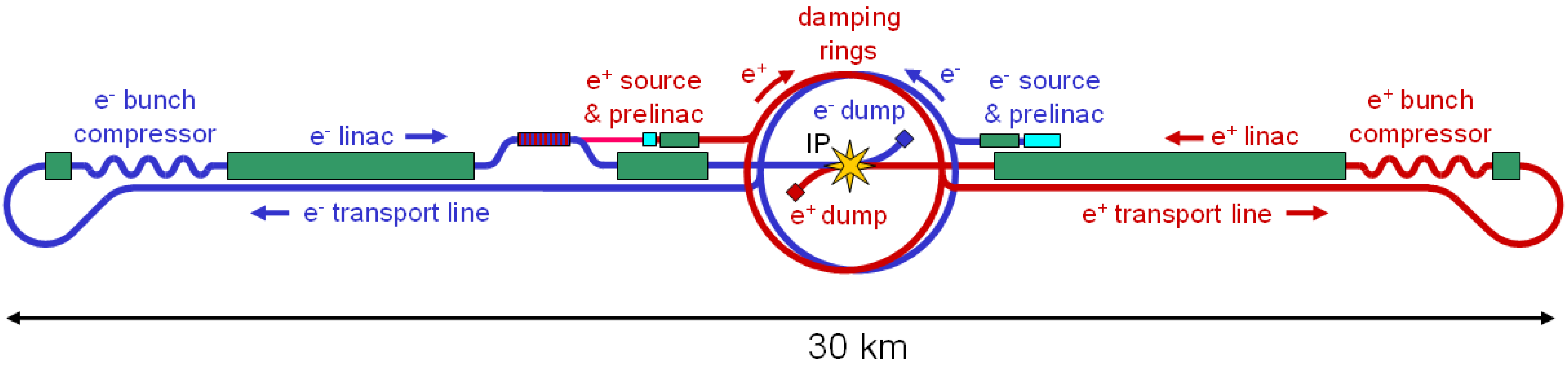
Baseline design for the ILC now exists in the form of the "The ILC Reference Design Report (2007)"

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



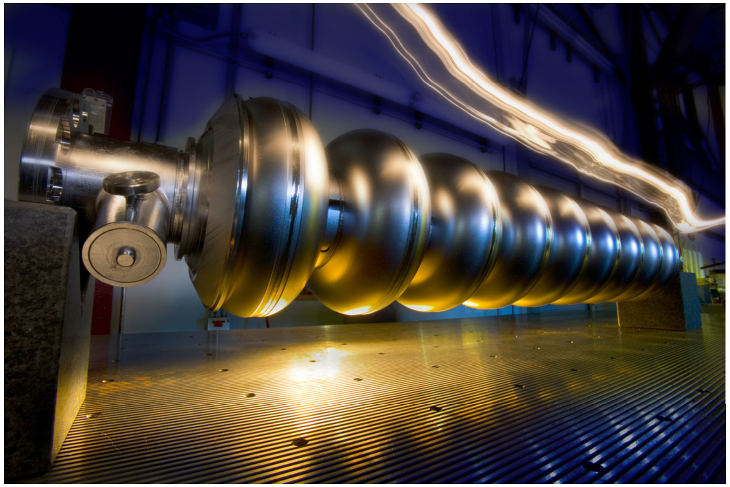
ILC Main Machine Components

- Polarized **electron source**
  - based on photocathode DC gun
- Undulator-based **positron source**
  - driven by 150 GeV electron beam
- 5 GeV electron and positron **damping rings**
  - 6.7 km circumference located at centre of ILC complex
  - provide stable low emittance beams to LINACs
- **Beam transport** from DRs to the main LINACs
- Two 11 km long main **LINACS**: acceleration to 250 + 250 GeV !
- 4.5 km long **beam delivery system**
  - brings beams into collision at 14 mrad crossing angle
- To extend to 1 TeV – add two additional 11 km LINACs

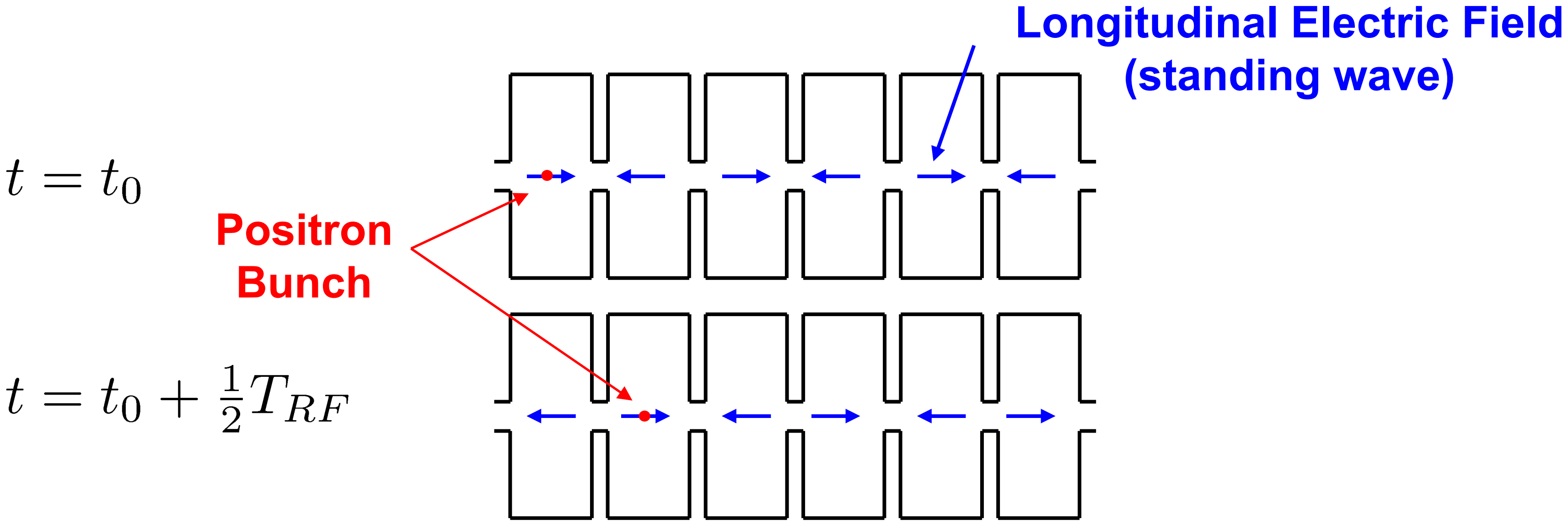


The Linear Accelerator (LINAC)

★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

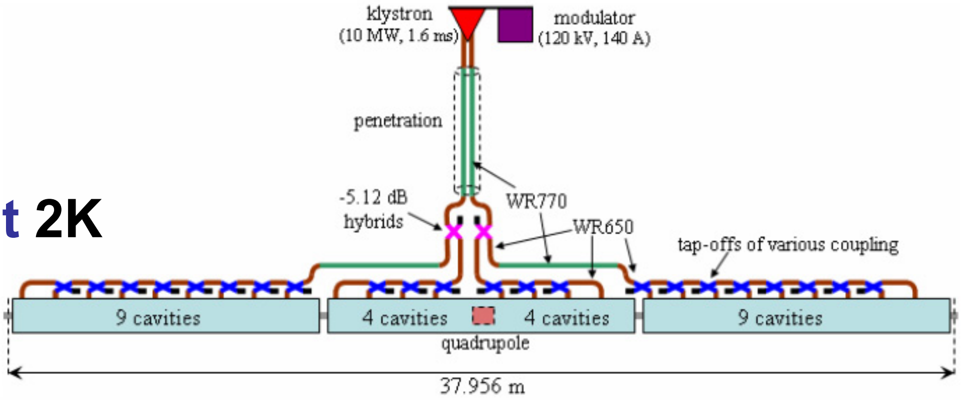


$t = t_0$

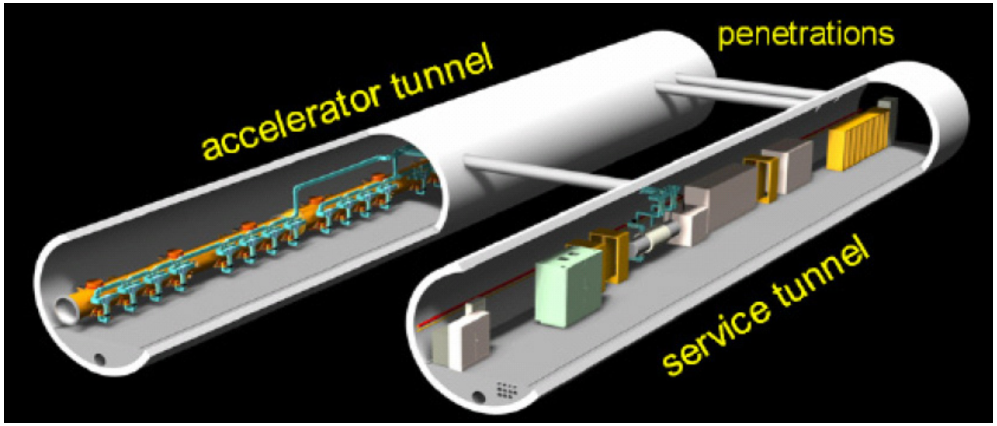
$t = t_0 + \frac{1}{2}T_{RF}$

RF Units

- ★ Cavities housed in RF Units (containing 26 cavities)
- ★ Each RF unit consists of 3 cryomodules with Helium at 2K
- ★ Each RF unit powered by 10 MW klystron



- ★ LINAC is not linear but follows "Earth's surface"
  - otherwise difficult to distribute He
- ★ Consists of two tunnels:
  - accelerator tunnel
  - service tunnel



Beam structure and Luminosity

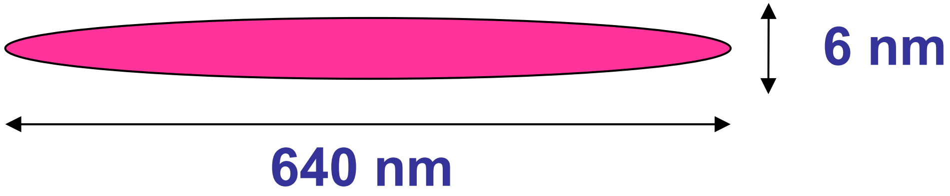
- **To achieve high luminosity is challenging:**

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

- **To reach the ILC goal of L = $2\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$ ⇨ small beam spot at the interaction point !**

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

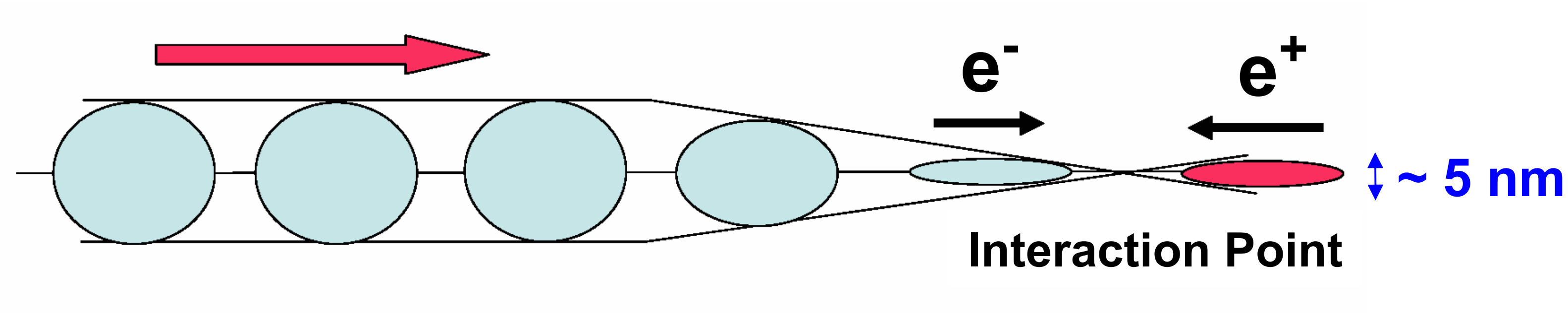
- **Working with such small beam spots has implications…**



Need highly stable, well-controlled beams

Achieving High Luminosity at the ILC

- ★ Low emittance stable beam into LINAC
  - **DAMPING RINGS** (DRs)
- ★ Contain emittance growth in LINAC
- ★ Squeeze the beam as small as possible at IP
  - **BEAM DELIVERY SYSTEM** (BDS)

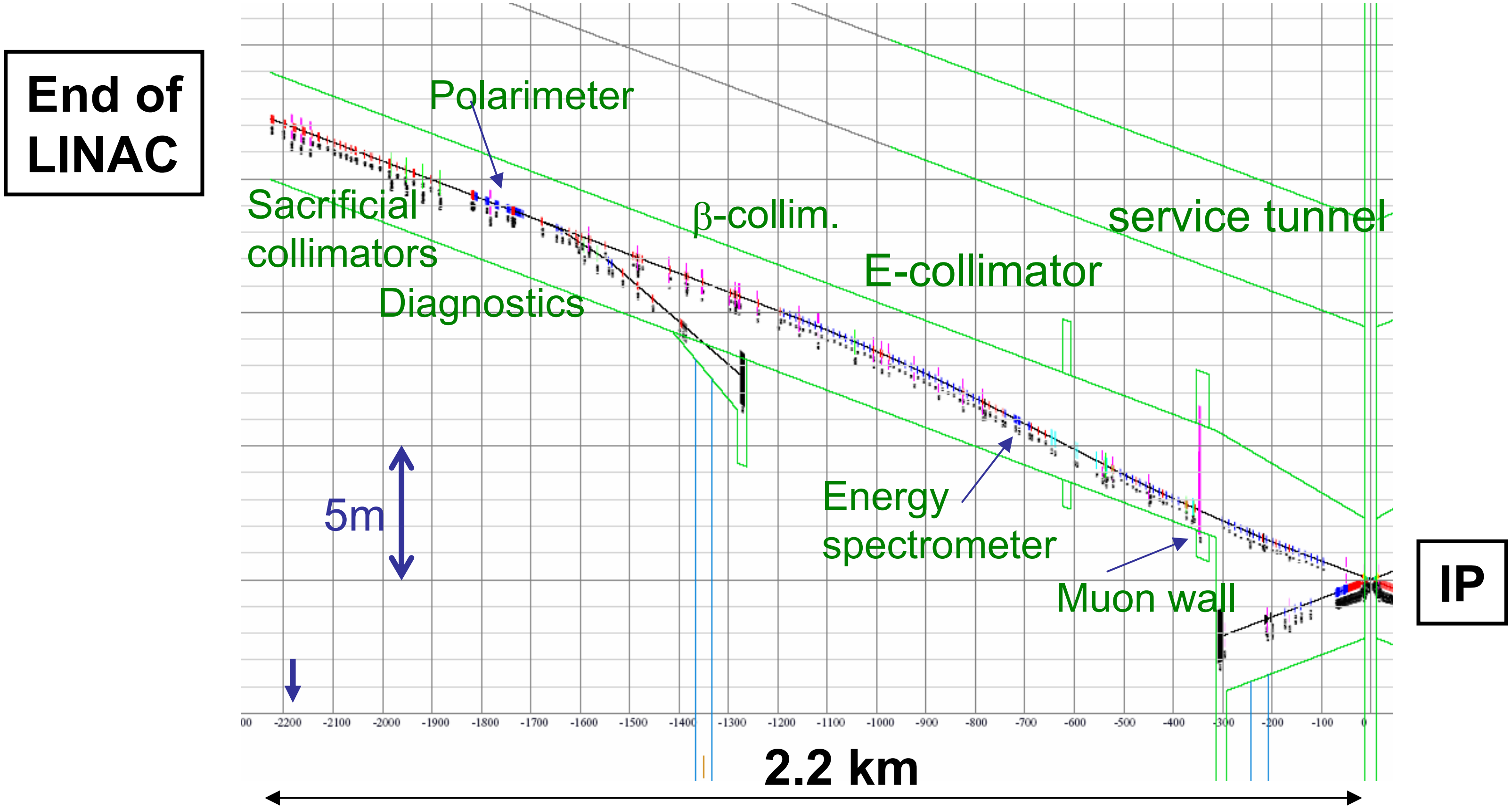


DRs and BDS are an important <u>and complex</u> part of the ILC

e.g. the BDS…

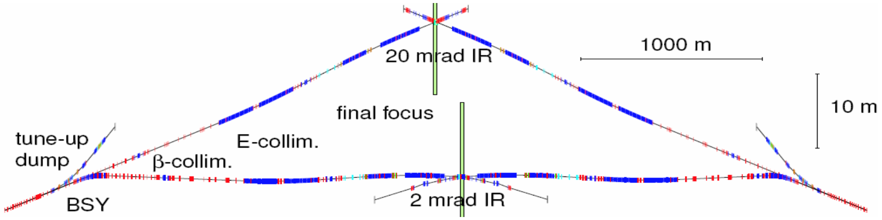
- ★ A lot happens after the LINAC in the beam delivery system:
  - cleaning the beam - collimation
  - energy and polarization measurements
  - squeezing the beam at the IP (final focus)

  } **Significant UK contributions**
- ★ Consequently it is complex and **EXPENSIVE**



The Interaction Point

- At the ILC can only bring each bunch into collision once so it is natural to have a single interaction point
- However, there is a strong case for having two complementary ILC detectors:
  - Scientific redundancy – confirmation
  - Complementarity in physics performance
  - Competition
  - Efficiency and reliability
  - Broaden scientific opportunity
- Consequently two ILC interaction regions were considered



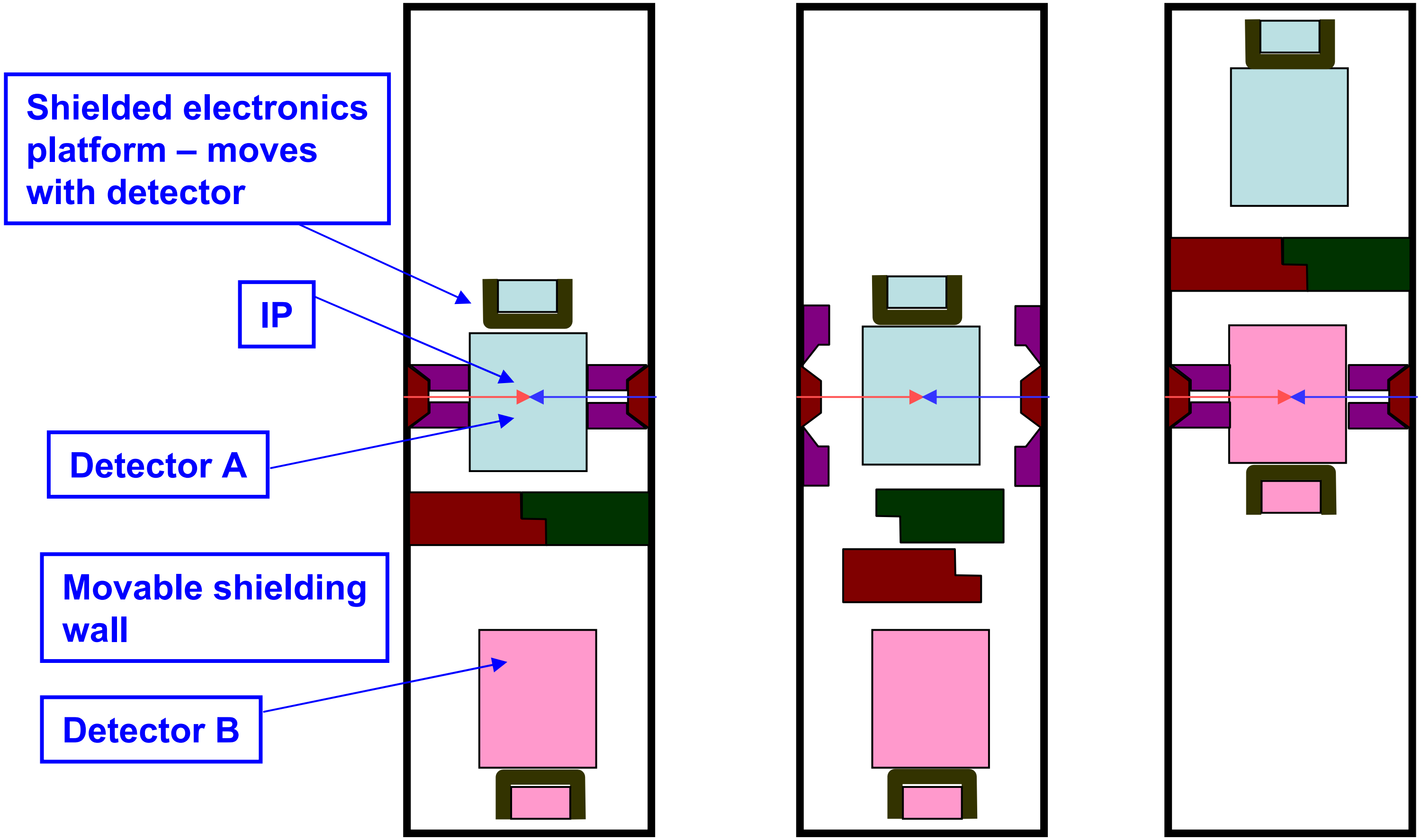
- But this requires 2 beam delivery systems – very expensive
- In reference design – there is only one Interaction Point…

BUT having two detectors is HIGHLY DESIRABLE…

Push-Pull ?

Current solution:

- One interaction region
- One detector hall
- Two **MOVEABLE detectors** (move into beam every few? months)



Shielded electronics platform – moves with detector

IP

Detector A

Movable shielding wall

Detector B

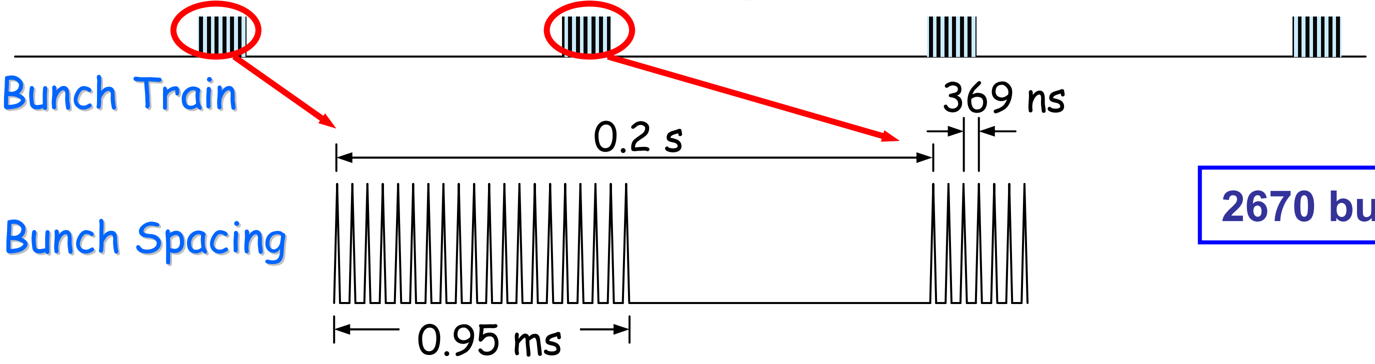
- Sensible to ask whether the push-pull scenario really feasible…
  - Currently under consideration
  - Moving ~15 kton detector not trivial !
  - However there are options…
    - Air-pads (as used in CMS installation) or Hillman Rollers

- Certainly not a "comfortable" option – but reflects strong desire for two detectors + need to keep ILC cost "low"

❸ Physics at the ILC

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

- Luminosity : ~ 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (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

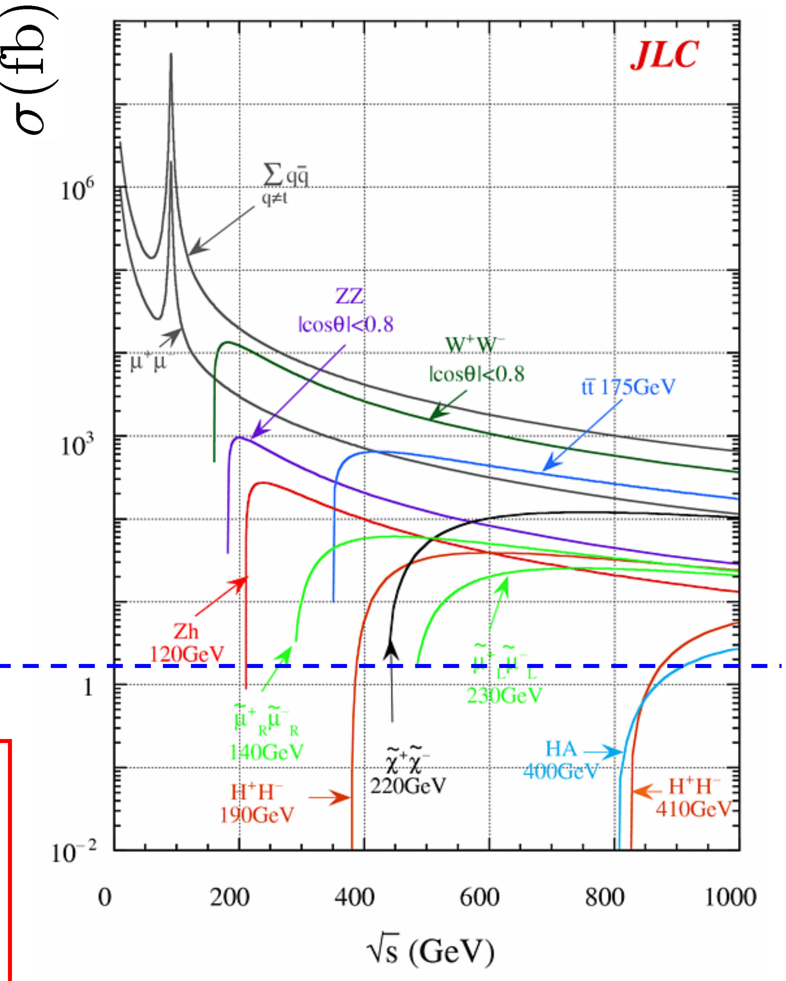
★ e^+e^- collisions at $\sqrt{s}$ = 0.2-1.0 TeV provide rich environment

★ 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 light Higgs

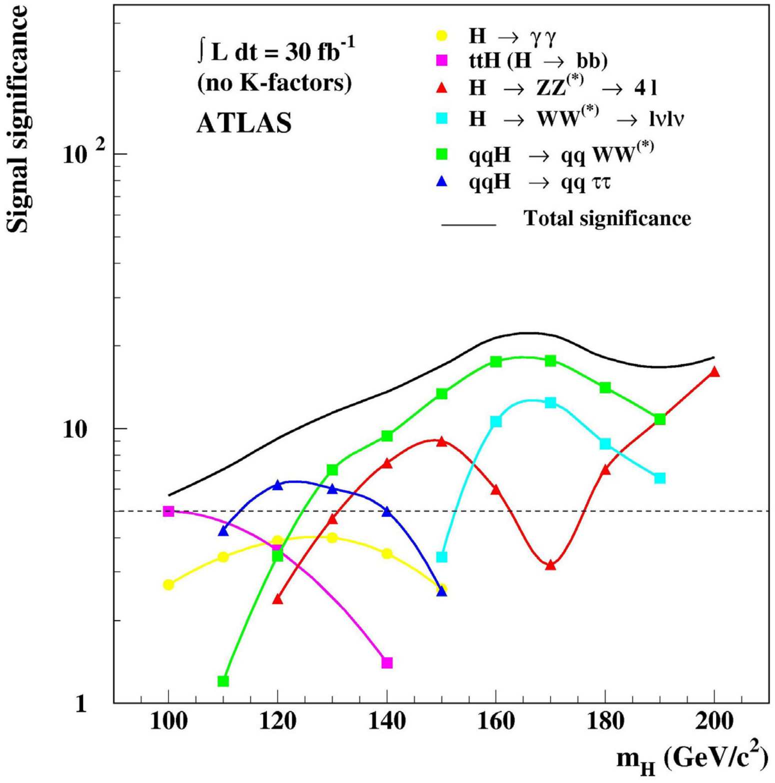
The LHC

★ If the Higgs exists, it will be discovered at the LHC independent of its mass

★ But LHC only has sensitivity in at most a few channels

★ How do you know it is the Higgs ?

★ What kind of Higgs - SM ? SUSY ?



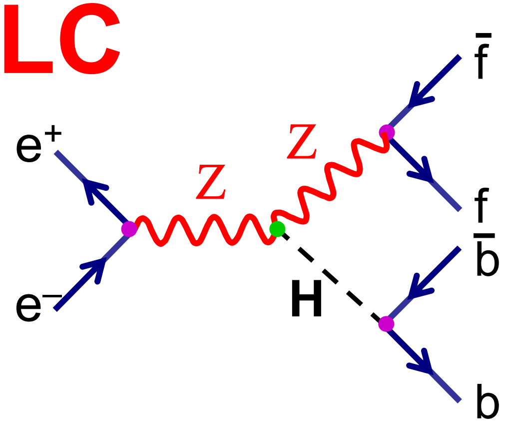
The ILC

★ Precise measurements in ALL decay channels - “easy” to select events

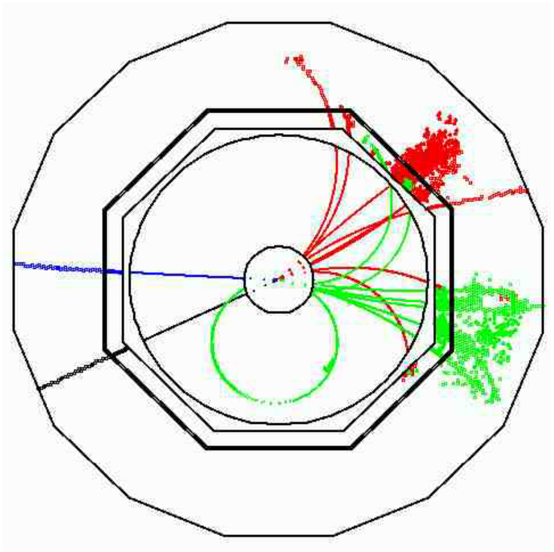
★ Determine nature of the Higgs

The Higgs at the ILC

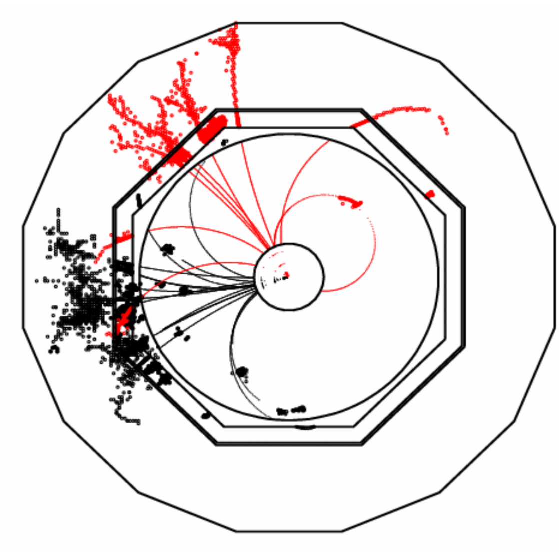
e.g. light Higgs produced by Higgsstrahlung



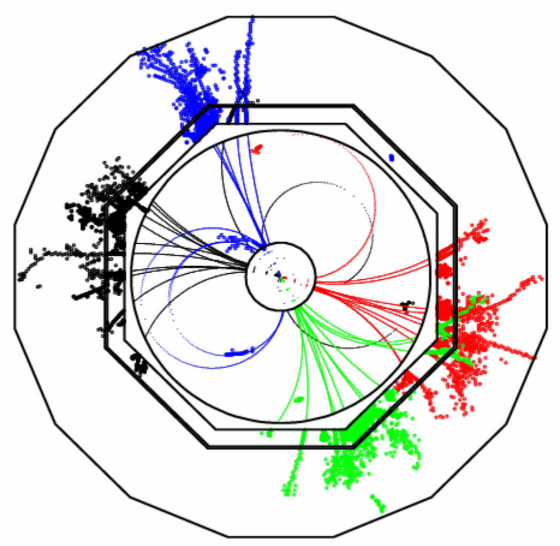
★ Very clean events



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



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



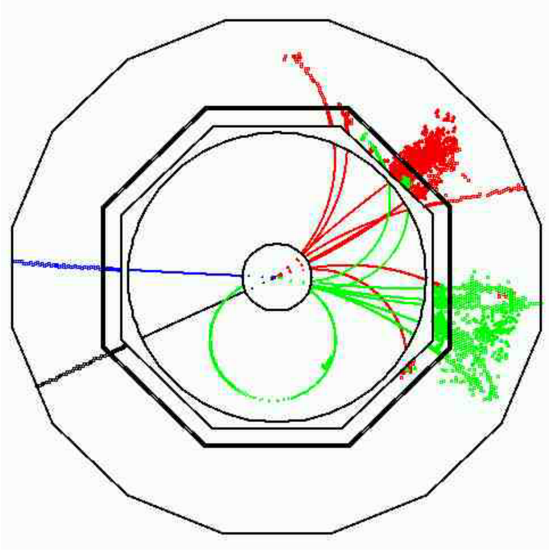
$HZ \rightarrow b\bar{b}q\bar{q}$

★ Relatively simple to select and identify in all decay topologies

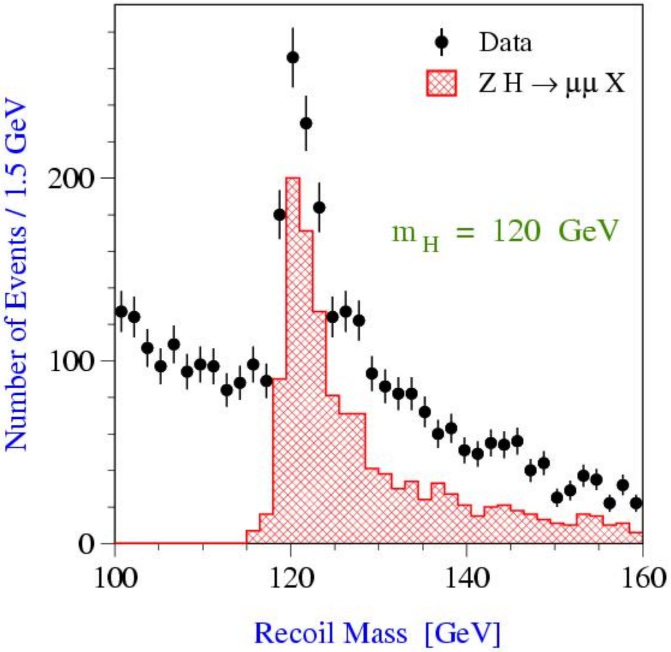
★ Would accumulate **O(10^5)** events (larger than LEP2 WW sample)

The Higgs at the ILC cont.

★ **Model-independent studies:**
- mass
- absolute branching ratios
- total width
- spin
- top Yukawa coupling
- self-coupling

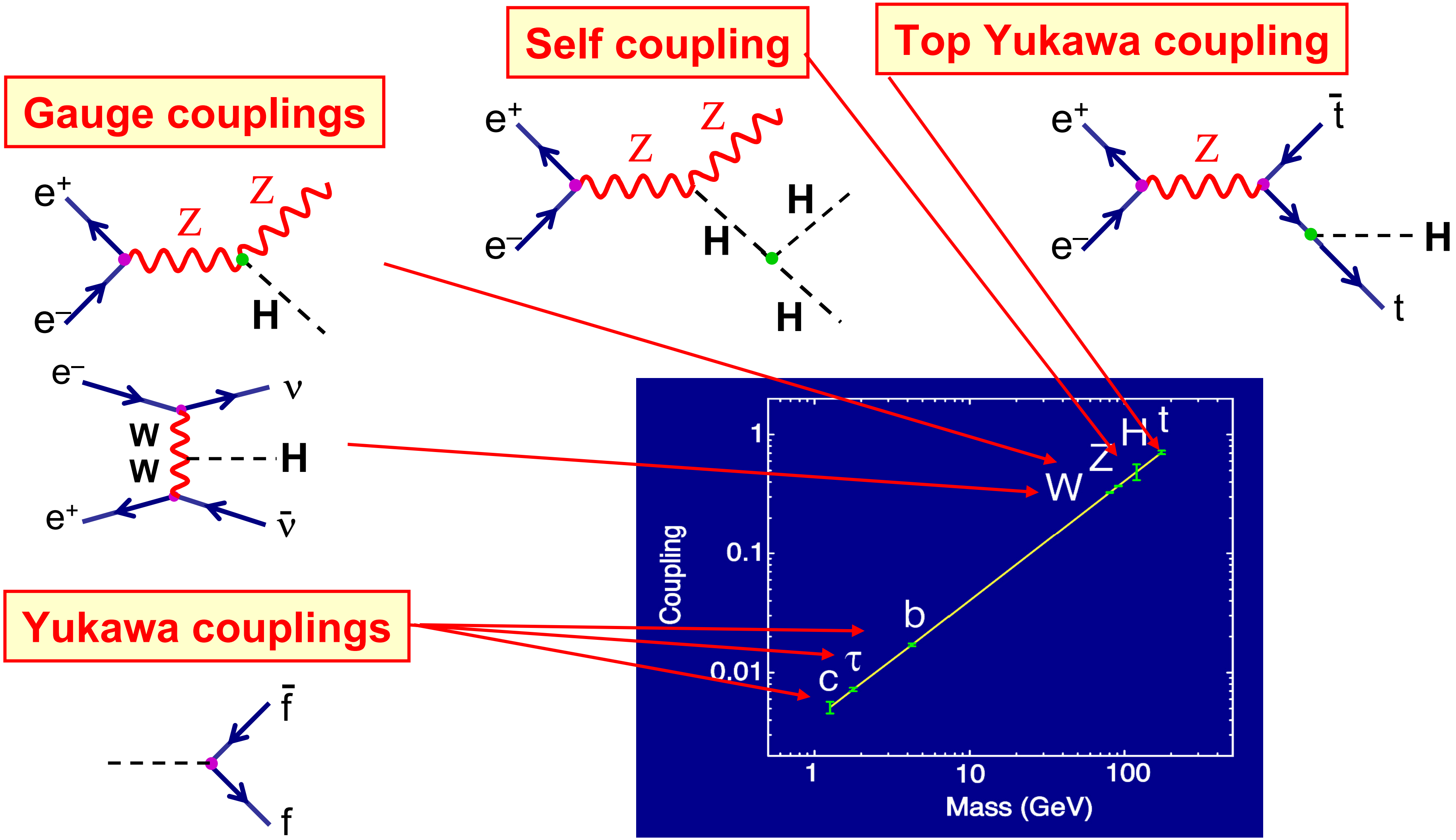


e.g. in $e^+e^- \to HZ$ have model-independent measurement of Higgs mass by measuring recoil against identified $Z \to \mu^+\mu^-$ decays



Higgs couplings

- ★ **Can measure all Higgs couplings**



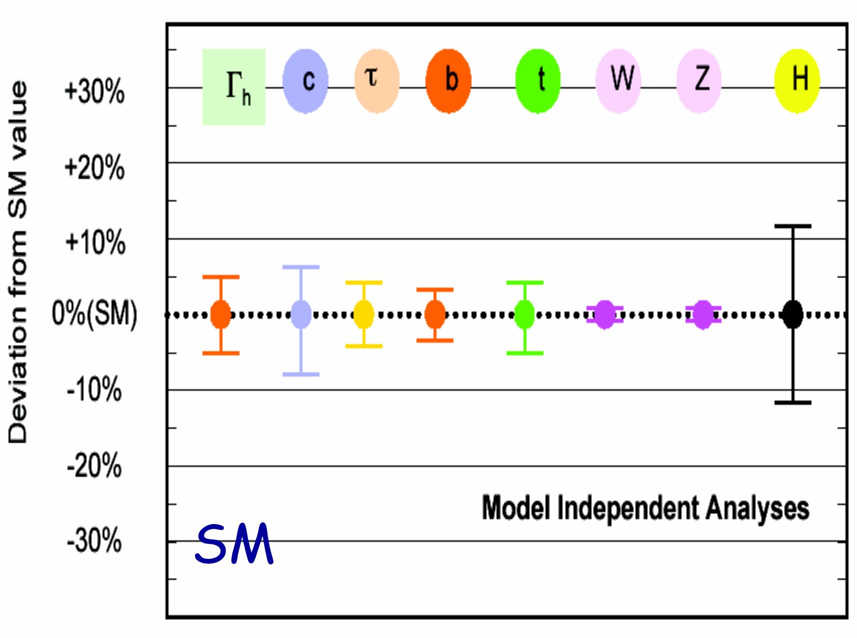
Gauge couplings

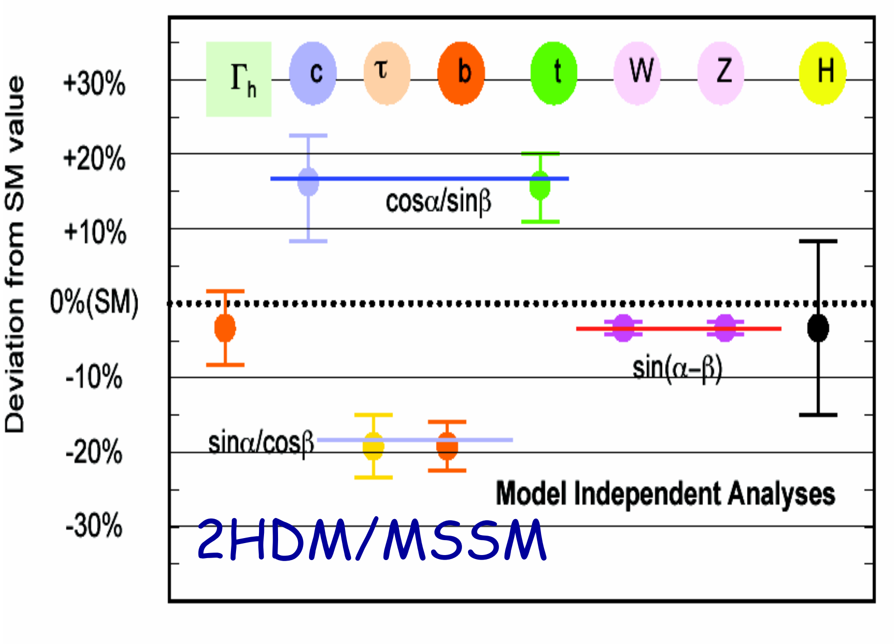
Self coupling

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**

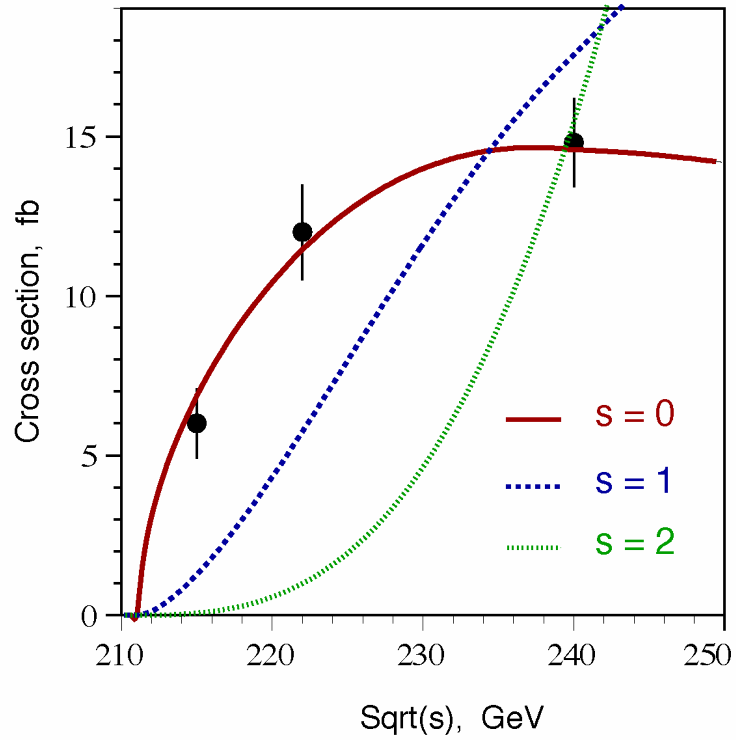




- **Very powerful !**

+Higgs spin

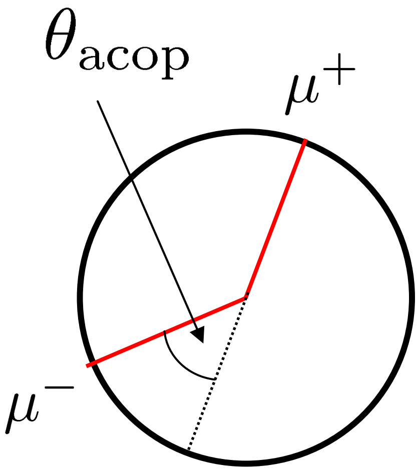
- ★ **At the ILC can determine the spin of ANY Higgs it can produce by studying running the accelerator close to production threshold**

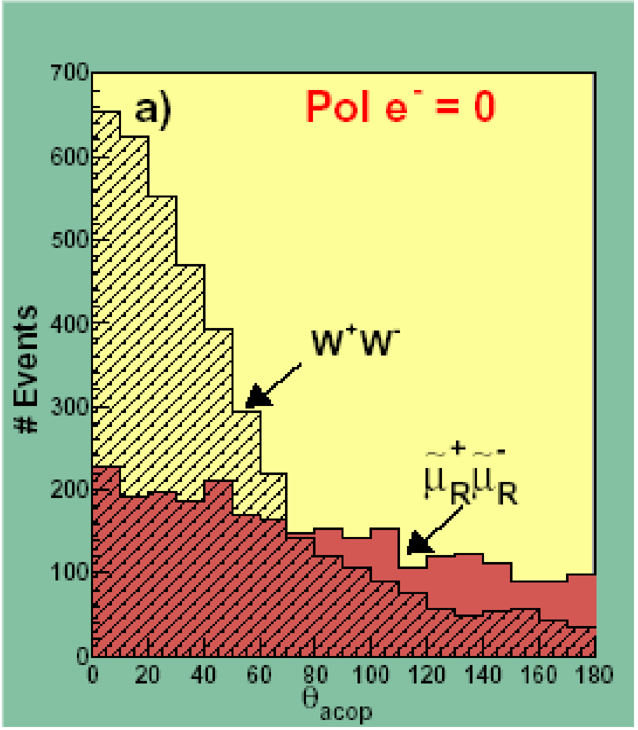


SUSY at the ILC

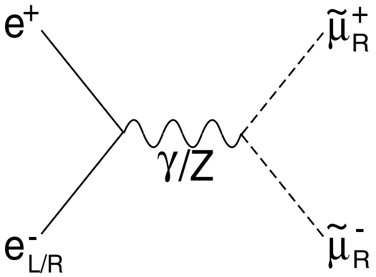
- ★ **If TeV scale SUSY is realised in nature the ILC complements the LHC in pinning down its nature (the subject of an entire talk)**
- ★ **Here use SUSY to illustrate a neat feature of the ILC – polarization**

e.g. study smuon pair production by looking at “acoplanarity” distribution of the decay muons

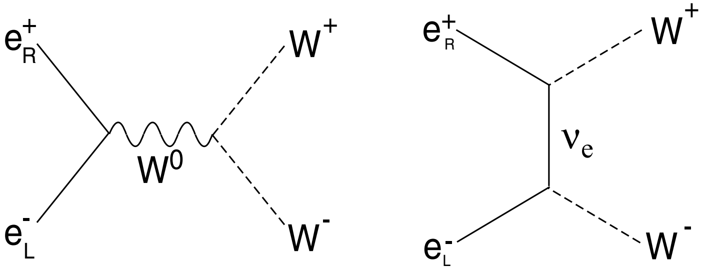




signal

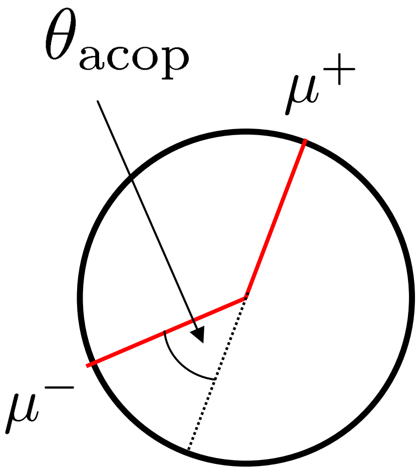


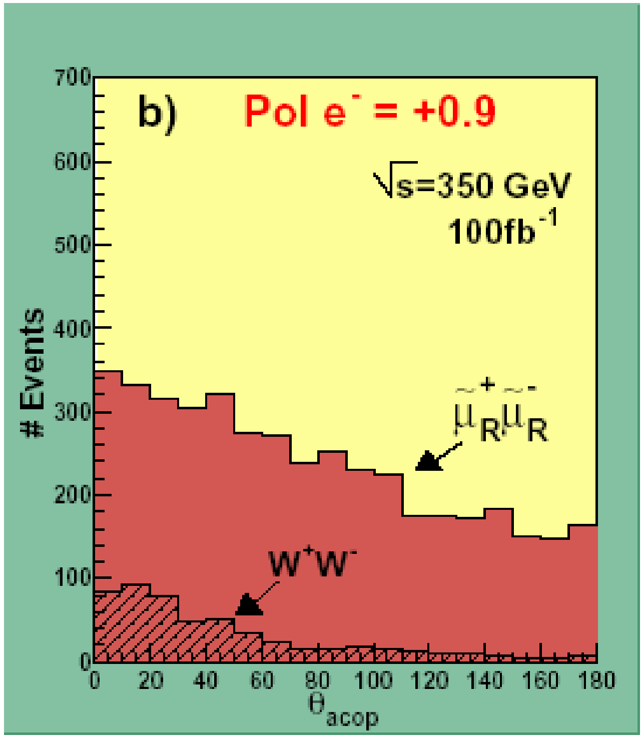
SM background



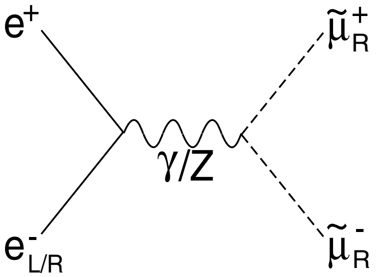
with 90% electron polarization

- **Suppress Standard Model background by running ILC with predominantly the "wrong" helicity electrons e^-_R**

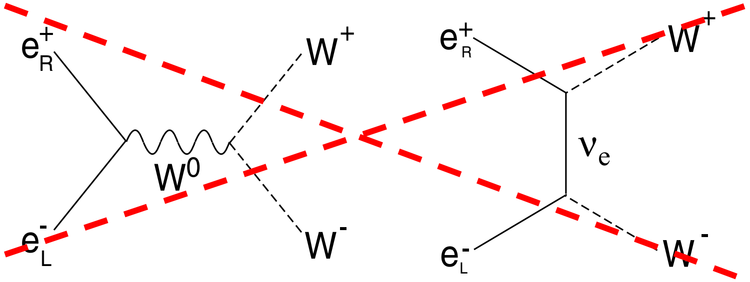




signal



SM background



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)

❹ The ILC Detector(s)

ILC Detector Concepts:

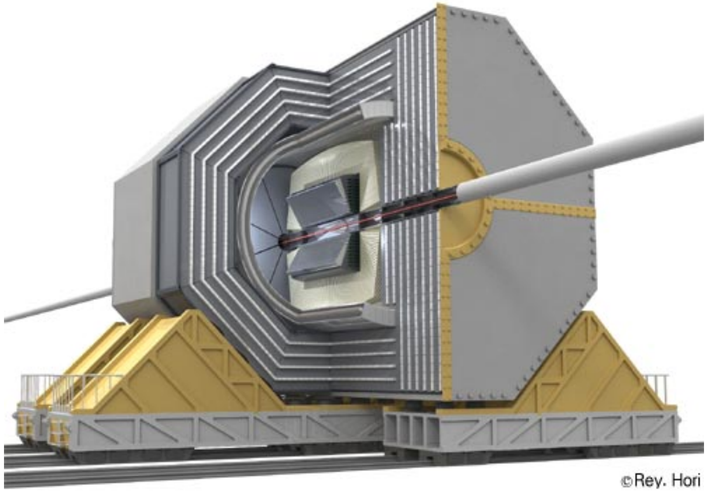
★ The design of the ILC detectors is a very active area of research

★ Design work centred around 4 detector "concepts"

★ Each will contribute to an ILC detector conceptual design report

★ Concepts ultimately form basis for TDRs/collaborations etc.

GLD : Global Large Detector



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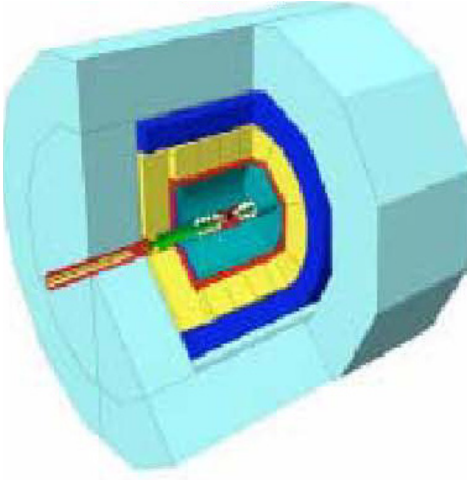
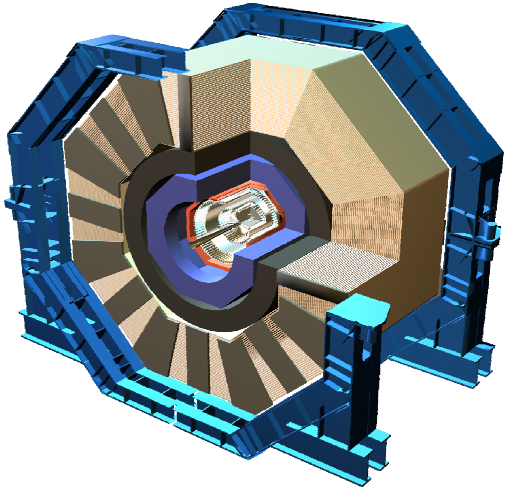
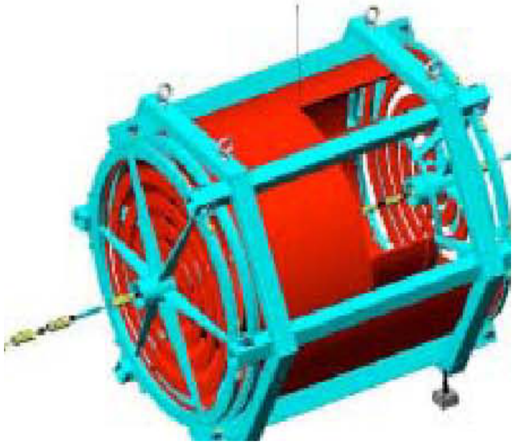
LDC : Large Detector Concept



SiD : Silicon Detector

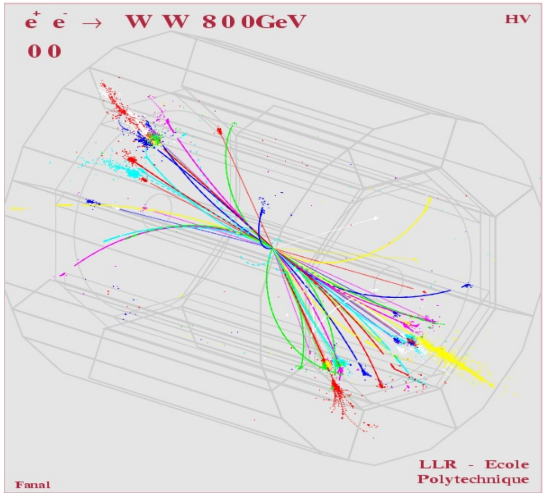


4th



ILC Detector Requirements

- **momentum:** $\sigma_{1/p} < 7\times10^{-5}/\text{GeV}$ (1/10 x LEP)
  (e.g. mass reconstruction from charged leptons)
- **impact parameter:** $\sigma_{d0} < 5\mu\text{m} \oplus 5\mu\text{m}/p(\text{GeV})$ (1/3 x SLD)
  (c/b-tagging in background rejection/signal selection)
- **jet energy:** $\sigma_E/E = 0.3/\sqrt{E(\text{GeV})}$ (1/2 x LEP)
  (invariant mass reconstruction from jets)
- **hermetic down to :** $\theta = 5$ mrad
  (for missing energy signatures e.g. SUSY)
- Radiation hardness not a significant problem, e.g. 1st layer of vertex detector : $10^9\ n\ \text{cm}^{-2}\ \text{yr}^{-1}$ c.f. $10^{14}\ n\ \text{cm}^{-2}\ \text{yr}^{-1}$ at LHC

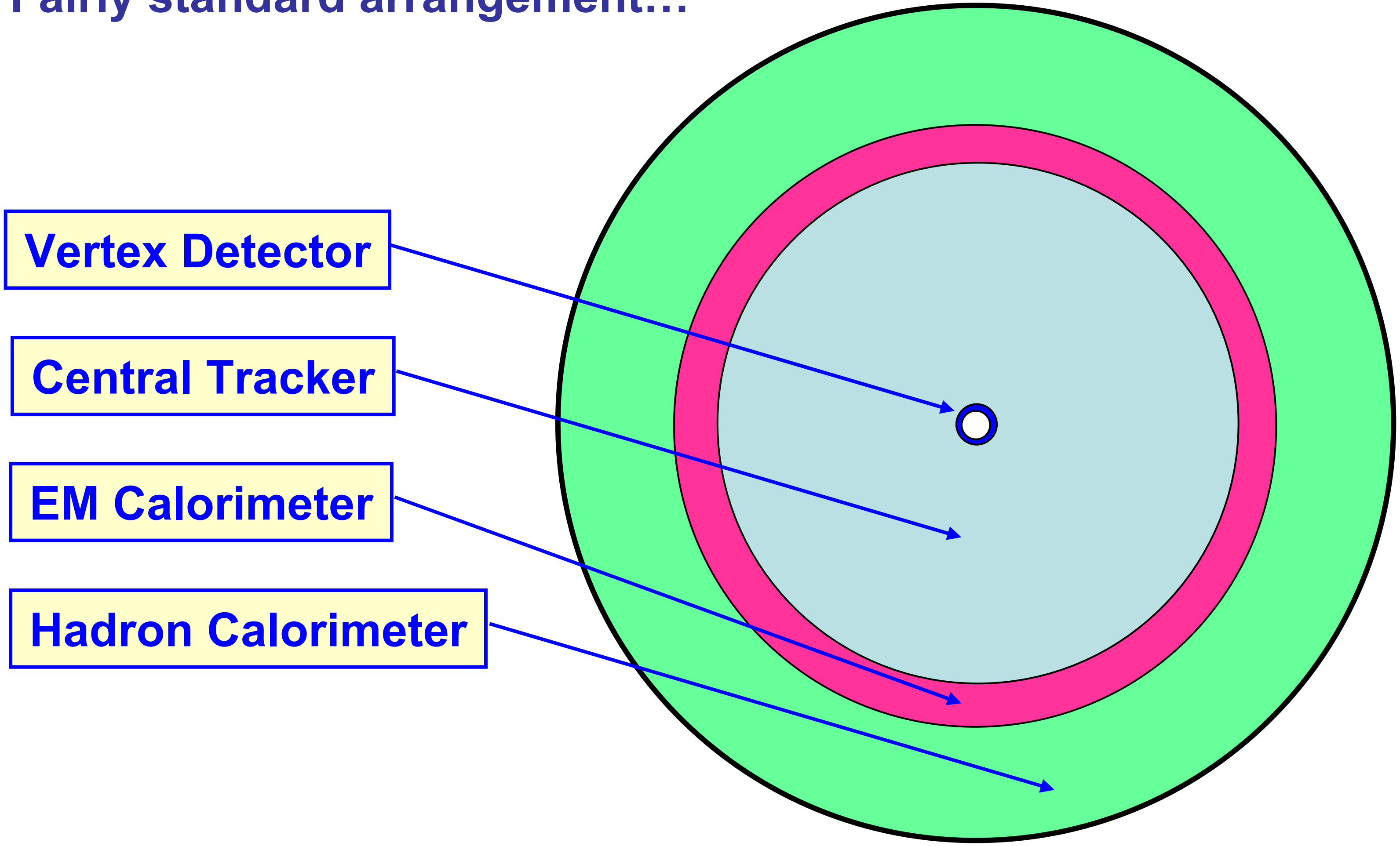


Must also be able to cope with high track densities due to high boost and/or final states with 6+ jets, therefore require:

- High granularity
- Good two track resolution

Detectors at e+e- colliders

★ **Fairly standard arrangement…**



Vertex Detector

Central Tracker

EM Calorimeter

Hadron Calorimeter

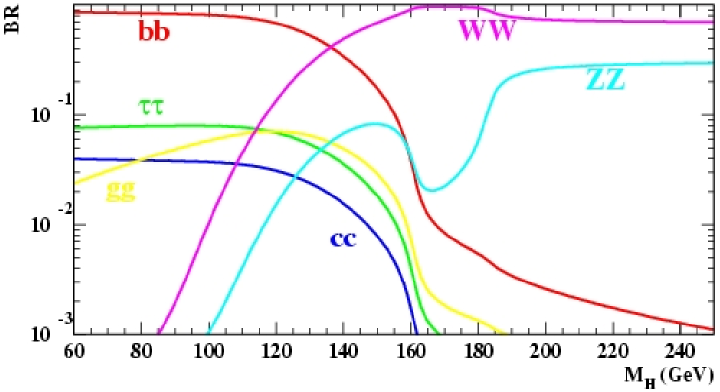
Vertex Detector

★ Important for many physics analyses

e.g. couplings of a low mass Higgs

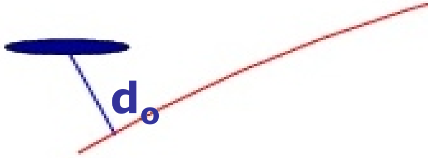
Want to test $g_{Hff} \sim m_f$

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

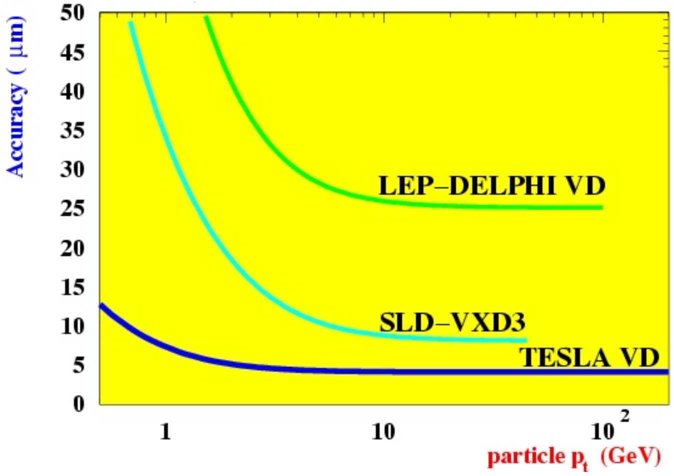


Aim for significant improvement compared to previous detectors

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

Goal: a<5mm, b<5mm

a: point resolution, b : multiple scattering

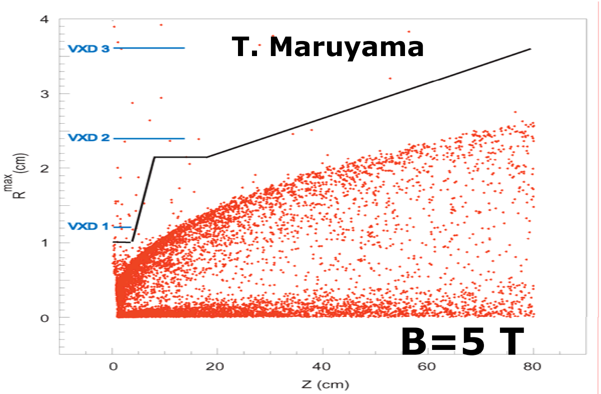


Main design considerations:

- 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:

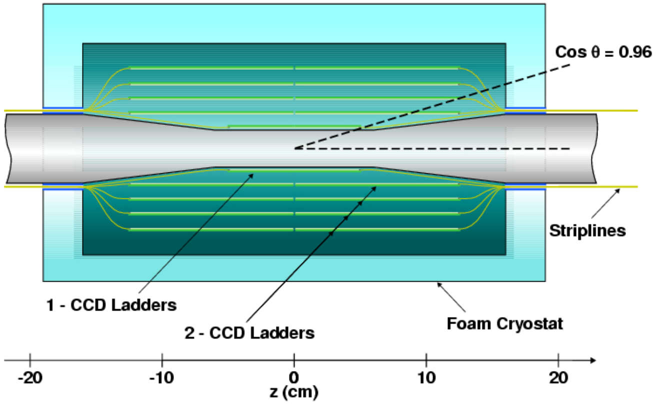
- Inner radius limited by e^+e^- pair bgd.
  depends on the machine + B field
- Layer thickness depends on Si technology



Ultimate design driven by machine + technology !

e.g. LDC Baseline design:

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

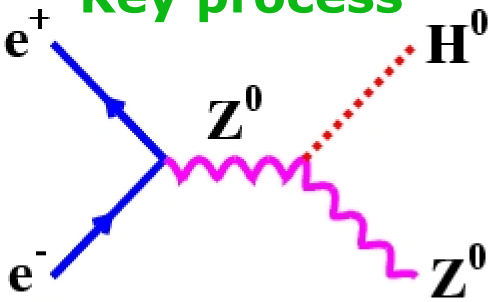


Ultimate design depends on worldwide detector R&D

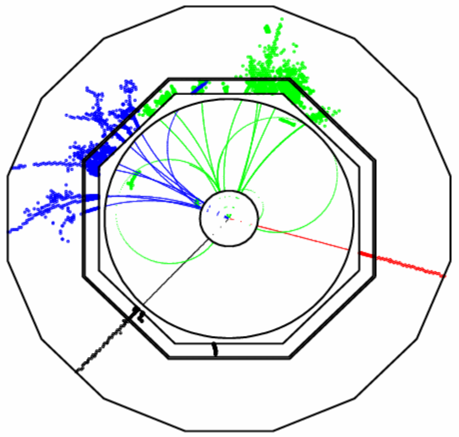
(Major UK contribution : LCFI)

Tracking : Momentum Resolution

Key process



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



Recoil mass to μ+μ-

⇨ M_H σ_{ZH} , g_{ZHH}

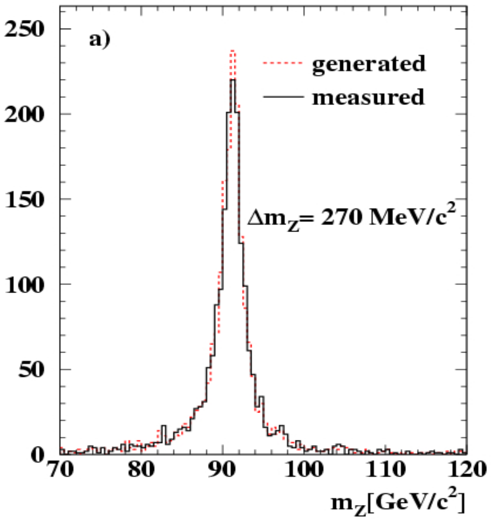
$\mu^+\mu^-$ angular distribution

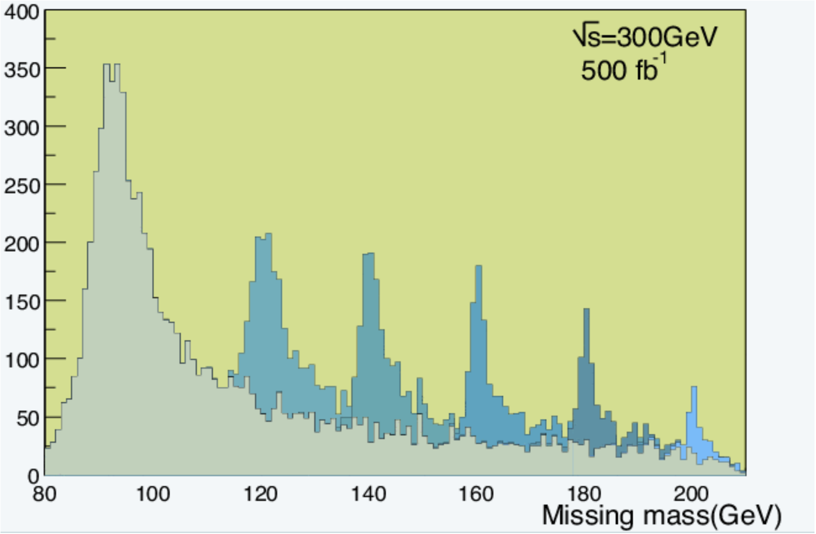
⇨ Spin, CP,...

- **Measurements depend on lepton momentum resolution**

goal: $\Delta M_{\mu\mu} < 0.1 \times \Gamma_Z$ ⇨ $\sigma_{1/p} < 7\times10^{-5}$ GeV^{-1}

- ♦ **Use μμ mass to select Z**
- ♦ **Recoil mass gives m_H**

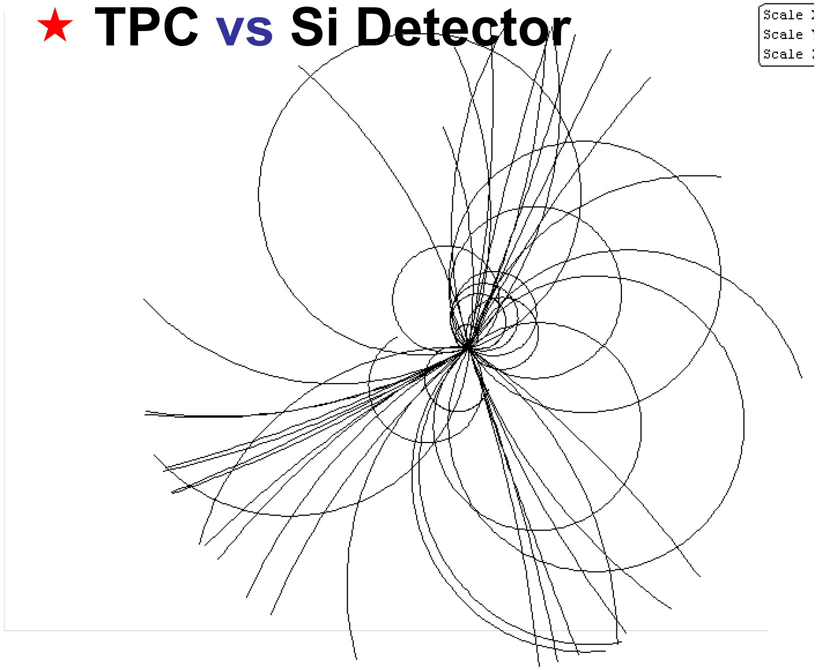


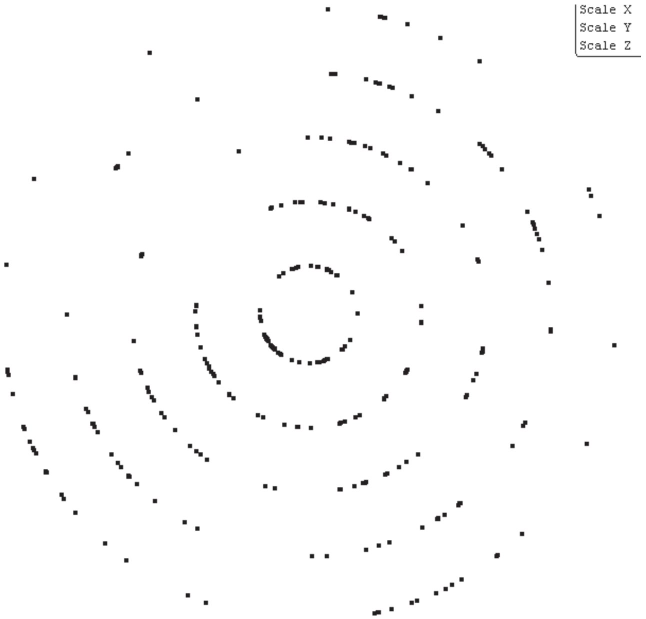


Two main tracker options

i) Gaseous Time Projection Chamber (e.g. ALEPH)
ii) Si Tracker (e.g. ATLAS)

★ **TPC** vs **Si Detector**





★ Large number of samples

★ Relatively few samples but very well measured

★ Both options being studied in detector concept groups
- TPC : GLD, LDC, 4th
- Si : SiD

Calorimetry at the ILC

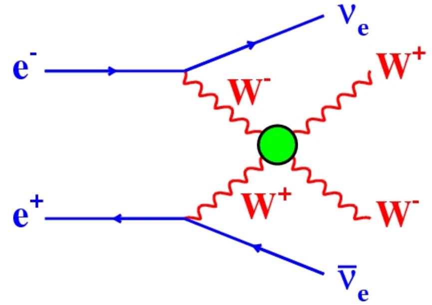
Jet energy resolution:

THIS IS HARD !

Best at LEP (ALEPH):
$\sigma_E/E = 0.6(1+|\cos\theta_{Jet}|)/\sqrt{E(GeV)}$

ILC GOAL:
$\sigma_E/E = 0.3/\sqrt{E(GeV)}$

★ **Jet energy resolution directly impacts physics sensitivity**

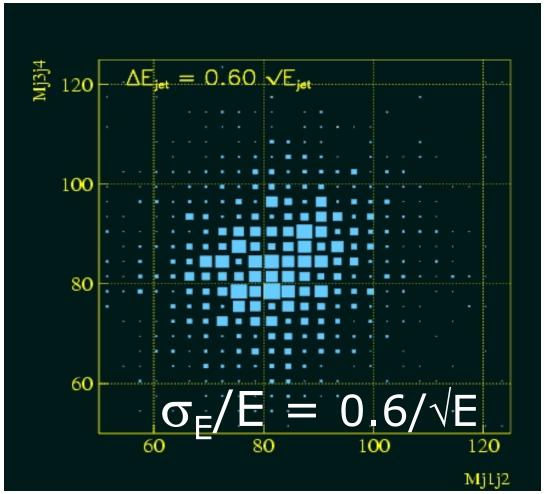


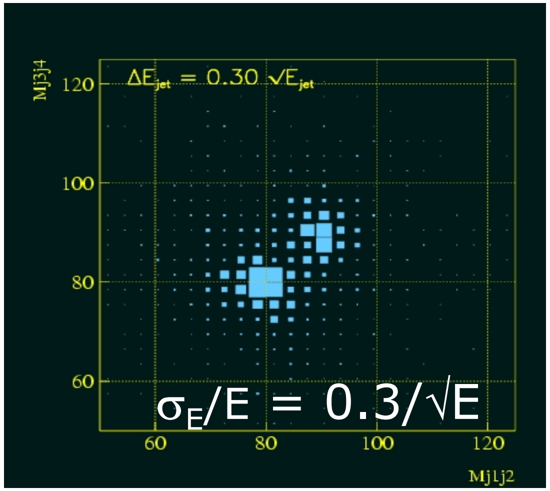
Often-quoted Example:

If the Higgs mechanism is not responsible for EWSB then QGC processes important

$e^+e^- \to \nu\nu WW \to \nu\nu qqqq$, $e^+e^- \to \nu\nu ZZ \to \nu\nu qqqq$

Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states





★ **EQUALLY applicable to any final states where want to separate** $W \to qq$ and $Z \to qq$!

- ★ **Want** $\boxed{\sigma_E/E \approx 30\%/\sqrt{E(\mathrm{GeV})}}$

- ★ **Very hard - not possible (?) to achieve this with a traditional approach to calorimetry**

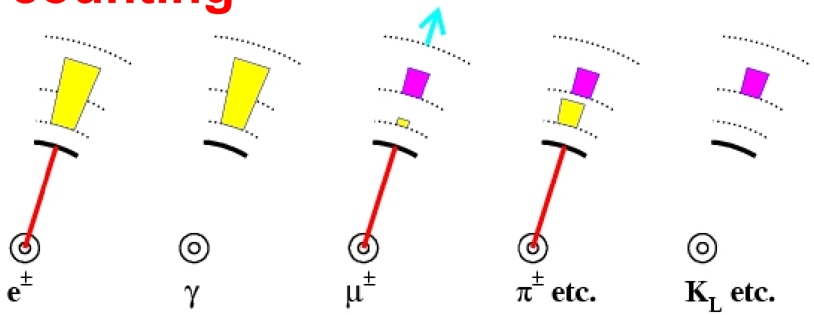
Limited by typical HCAL resolution of $> 50\%/\sqrt{E(\mathrm{GeV})}$

⇨ **a new approach to calorimetry**

The Particle Flow Paradigm

The Particle Flow Analysis (PFA):

- Reconstruct momenta of individual particles avoiding double counting



Charged particles in tracking chambers

Photons in the ECAL

Neutral hadrons in the HCAL (and possibly ECAL)

★ Need to separate energy deposits from different particles

★ Not calorimetry in the traditional sense

Main Issue:

★ NOT calorimetric performance !

- ♦ 60 % of jet energy in charged hadrons ("perfectly measured")
- ♦ 30 % in photons - typical ECAL res. Easily sufficient
- ♦ 10 % in neutral hadrons - 60%/√E(GeV) HCAL res. sufficient

★ Confusion rules

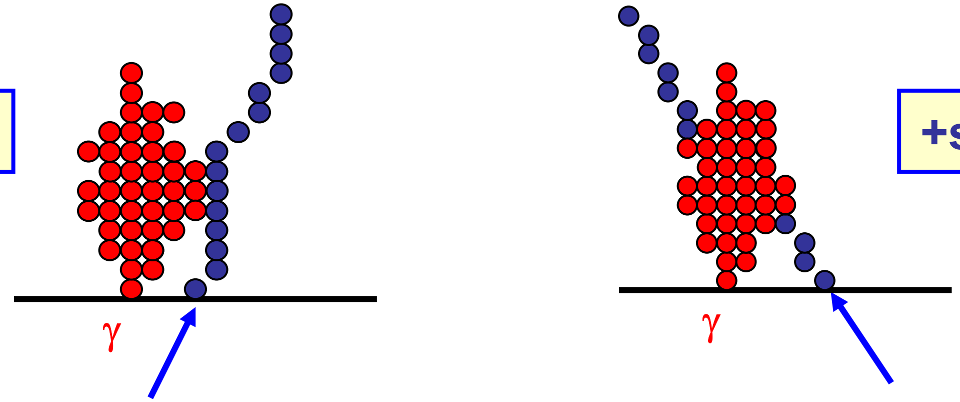
- ♦ Particle flow lives and dies on ability to correctly separate energy deposits from different particles

Practical PFA Calorimetry

- ★ How to separate energy deposits + avoid double counting

e.g.

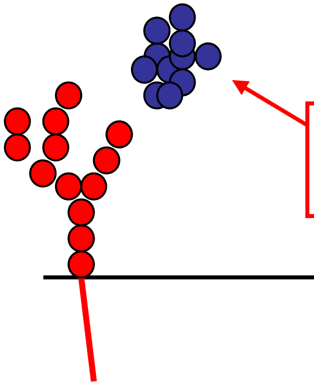
- ★ Need to separate “tracks” (charged hadrons) from photons



granularity

+software

- ★ Need to separate neutral hadrons from charged hadrons

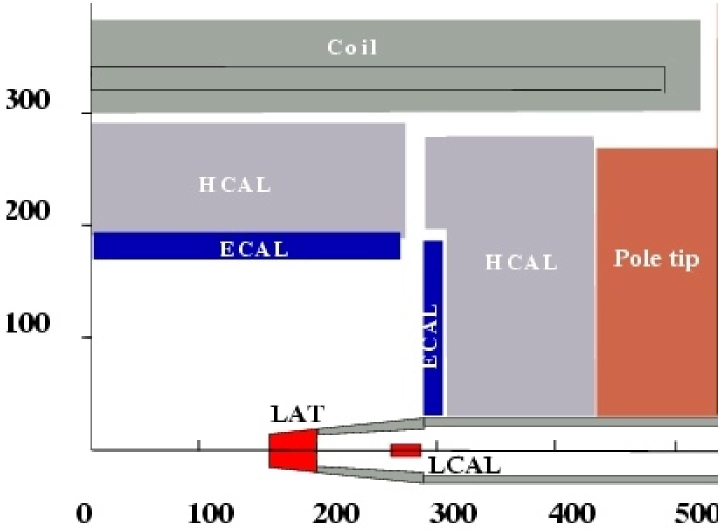


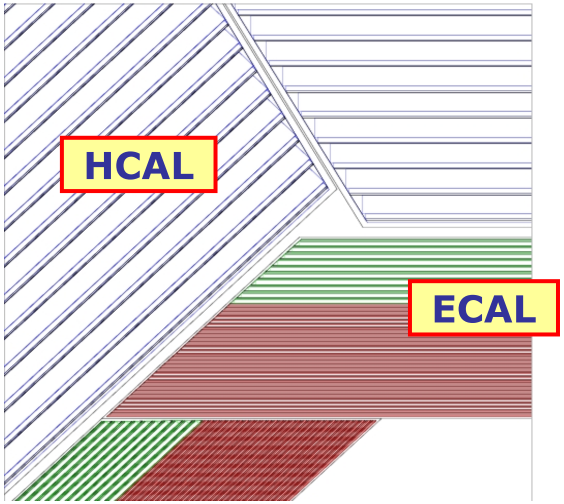
Isolated neutral hadron or fragment from shower ?

⇨ **granularity more important than energy resolution**

e.g. LDC/SiD Calorimetry

ECAL and HCAL inside coil





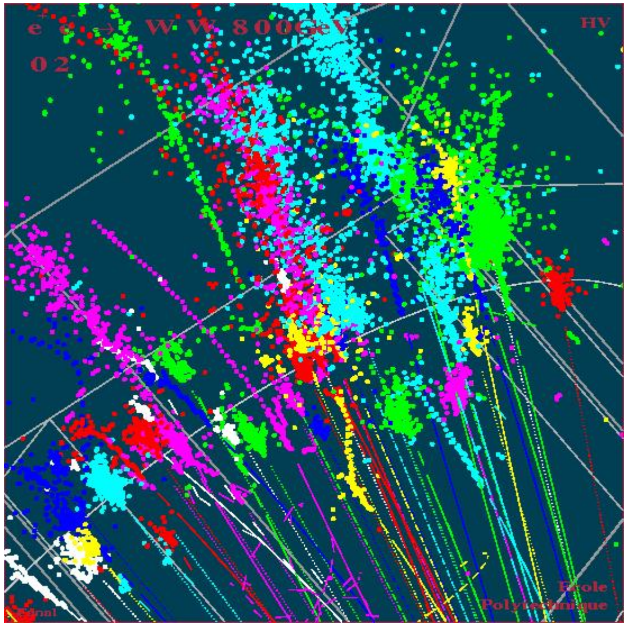
ECAL: silicon-tungsten (SiW) calorimeter:

- Tungsten : $X_0\ /\lambda_{had}$ = 1/25, $R_{Moliere}$ ~ 9mm
  (gaps between Tungsten increase effective $R_{Moliere}$)
- Lateral segmentation: ~1cm^2 matched to $R_{Moliere}$
- Longitudinal segmentation: 30 layers (24 X_0, 0.9λ_{had})
- Typical resolution: $\sigma_E/E = 0.15/\sqrt{E(\text{GeV})}$

Very high longitudinal and transverse segmentation

(Major UK contribution : with CALICE collaboration)

+Calorimeter Reconstruction



- ★ **High granularity calorimeters –** **<u>very different</u>** **to previous detectors (except LEP lumi. calorimeters)**
- ★ **“Tracking calorimeter” – requires a new approach to ECAL/HCAL reconstruction**

- **ILC calorimetric performance = HARDWARE + SOFTWARE**
- **Development of full ILC reconstruction chain progressing rapidly (including PFA reconstruction)**

Confident that Particle Flow Calorimetry can give desired performance

★ **Although ILC detector performance goals are challenging:**

- **momentum:** $\sigma_{1/p} < 7\mathrm{x}10^{-5}/\mathrm{GeV}$ **(1/10 x LEP)**
- **impact parameter:** $\sigma_{d0} < 5\mu\mathrm{m} \oplus 5\mu\mathrm{m}/p(\mathrm{GeV})$ **(1/3 x SLD)**
- **jet energy:** $\sigma_E/E = 0.3/\sqrt{E(\mathrm{GeV})}$ **(1/2 x LEP)**

believe we have the detector conceptual designs to achieve them

★ **Current emphasis on:**
- **Detailed sub-detector R&D**
- **Detector optimisation**

How to build them
Test beam

What to build
Performance per $

❺ Outlook

- ★ Hopefully have given a flavour of the ongoing ILC work
- ★ Work towards realising the ILC is progressing rapidly
  - UK very active in ILC community (machine+detectors)
- ★ Machine design "frozen" : Reference Design Report 2007

"How much ?"

6.7 Billion ILC Units
13,000 person-years

1 ILC Unit = 1 US 2007$ (= 0.83 Euro = 117 Yen)

- ★ Detector design progressing well
- ★ By 2010 aim to have:
  - Machine Engineering Design Report
  - Detector Engineering Design Report(s)
- ★ At that point it is down to political will (when, where, how)…

Dear Hilary, Gordon, …
….

- ★ Could have first ILC physics by 2020

End