Review of the ILC Large Detector Concept

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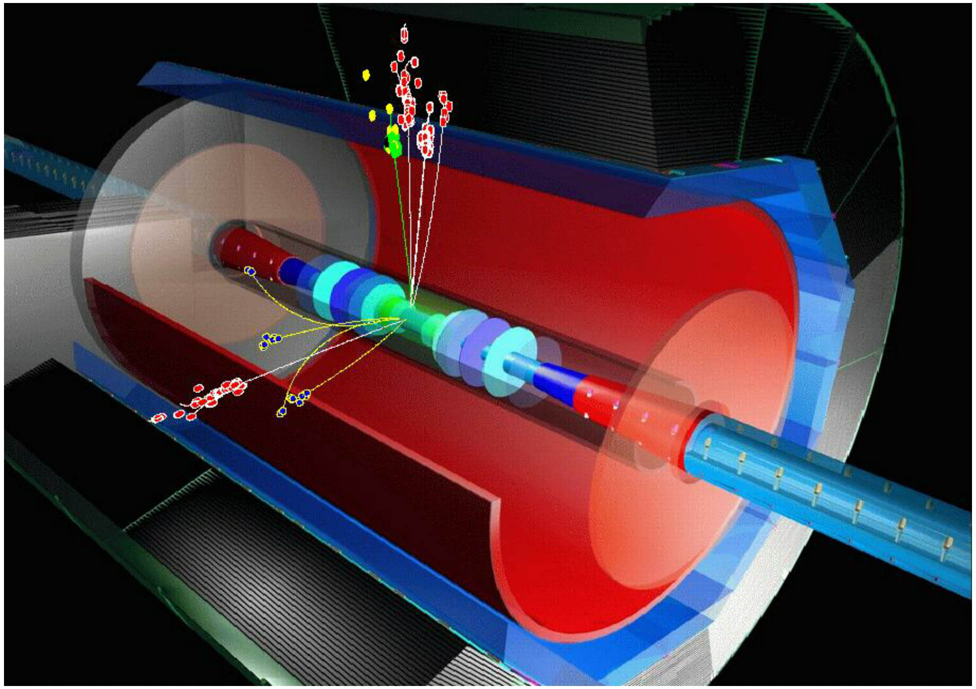
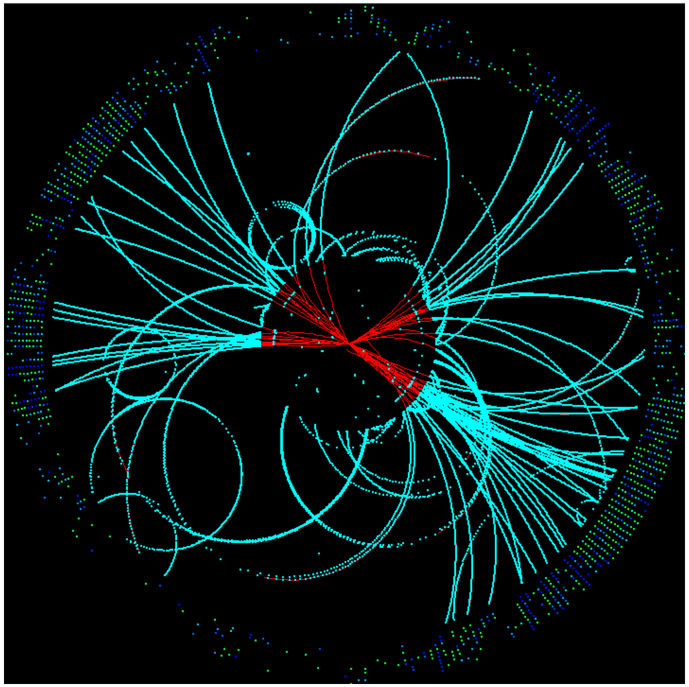


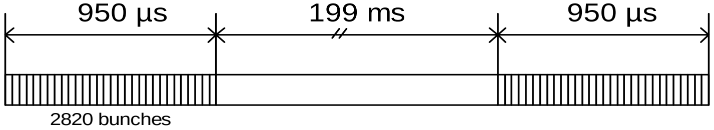


This Talk:

❶ **Machine**
❷ **ILC Physics/Detector Requirements**
❸ **The Large Detector Concept**
❹ **Cost and Optimisation**
❺ **Conclusions**

❶The Machine

- **Center-of-Mass Energy : ~ 90 – 1000 GeV**
- **Time Structure : 5 Bunch Trains/s**



Time between collisions: 337 ns

- **Luminosity : $3.4\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$ (6000xLEP)**
- **"Physics" Event Rate (fairly modest):**

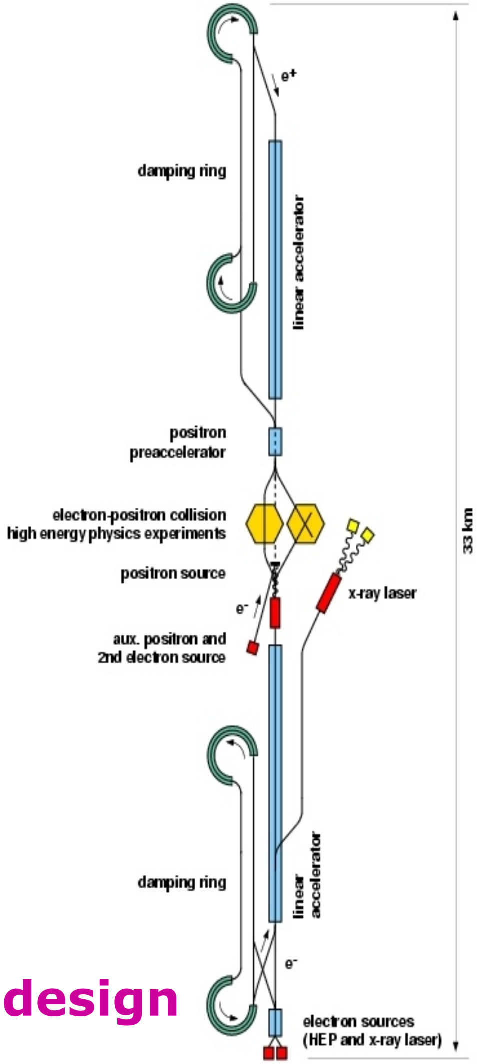
  $e^+e^-\rightarrow qq$ 330/hr $e^+e^-\rightarrow W^+W^-$ 930/hr

  $e^+e^-\rightarrow tt$ 70/hr $e^+e^-\rightarrow HX$ 17/hr
- **`Backgrounds`:**

  $e^+e^-\rightarrow qq$ 0.1 /Bunch Train

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

600 hits/BX in Vertex det.
6 tracks/BX in TPC



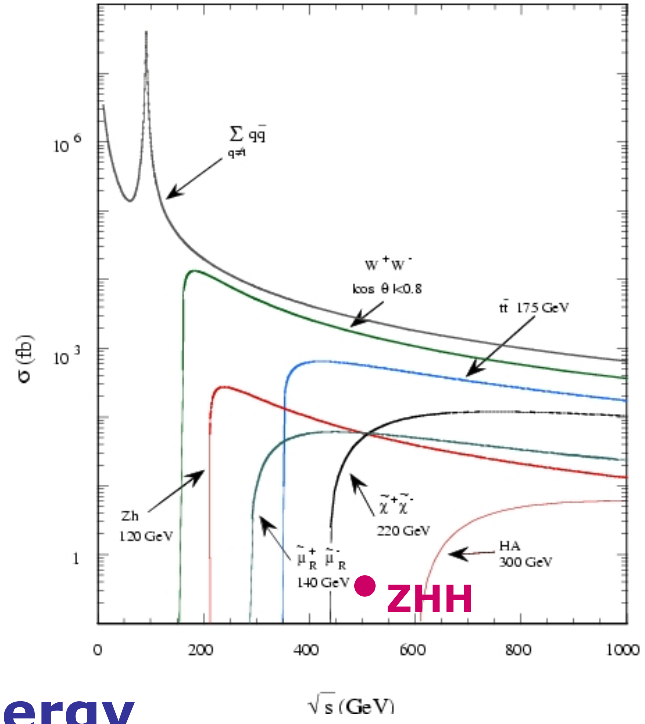
Impact on detector design:

★ **Radiation Hardness does not dictate detector design**
★ **Modest timing requirements**
★ **Must be able to cope with gamma-gamma bgd**
★ **Impact of crossing angle**

❷ ILC Physics / Detector Requirements

Precision Studies/Measurements

- ★ **Higgs** sector
- ★ **SUSY** particle spectrum
- ★ **SM particles** (e.g. W-boson, top)
- ★ and much more...



Difficult Environment:

★**High Multiplicity final states**

often **6/8 jets**

★**Small cross-sections**

e.g. $\sigma(e^+e^-\to ZHH) = 0.3$ fb

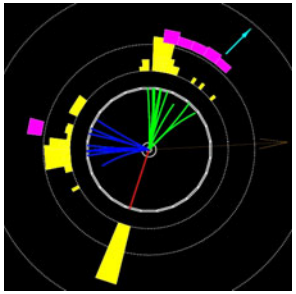
★**Many final states have"missing" energy**

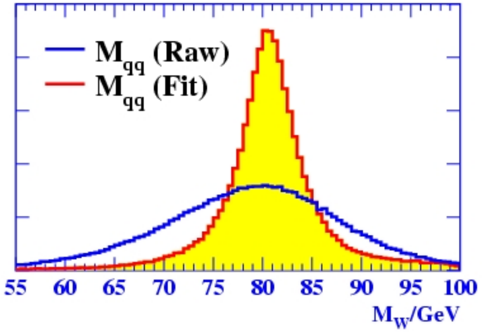
neutrinos + neutrilinos(?)/gravitinos(?) + ????

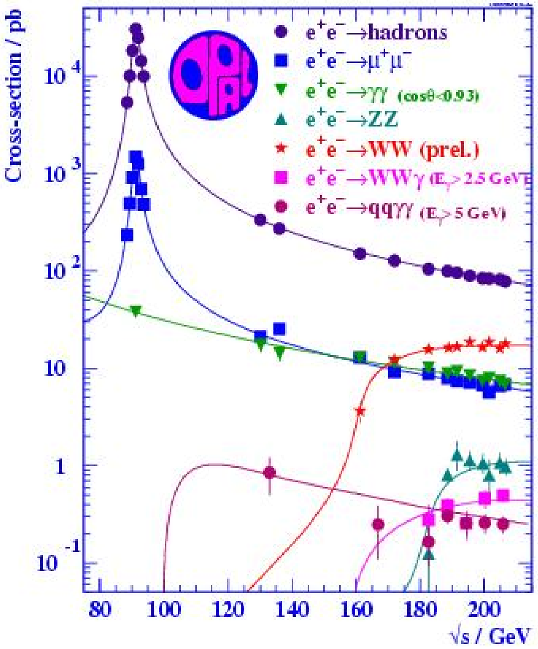
- ✸ **Detector optimized for precision measurements in difficult environment**
- ✸ **Only 2 detectors (1?) – make sure we choose the right options**

Compare with LEP

- ★ $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$ dominate
  backgrounds not too problematic
- ★ Kinematic fits used for mass reco.
  good jet energy resolution not vital







- ★ LEP Physics was "relatively" EASY

At ILC:

- ★ Backgrounds dominate 'interesting' physics
- ★ Kinematic fitting less useful (missing particles+Beamstrahlung)
- ★ Much more exposed to flaws of detector !

- ✷ Physics performance depends **critically** on the detector performance
- ✷ Stringent requirements on an ILC detector

ILC Detector Requirements

★ Momentum: $\sigma_{1/p} < 7\text{x}10^{-5}$/GeV (1/10 x LEP)

(e.g. Z mass reconstruction from charged leptons)

★ Impact parameter: $\sigma_{d0} < 5\mu m \oplus 5\mu m/p(GeV)$ (1/3 x SLD)

(c/b-tagging in background rejection/signal selection)

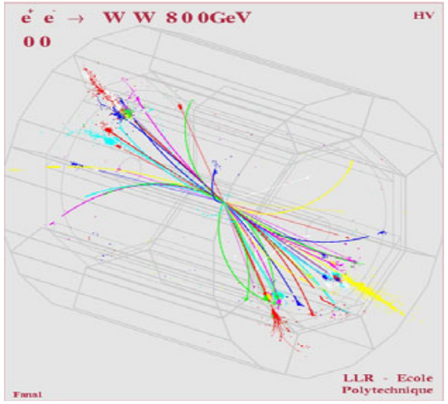
★ Jet energy : $\delta E/E = 0.3/E(GeV)$ (1/2 x LEP)

(W/Z invariant mass reconstruction from jets)

★ Hermetic down to : $\theta = 5$ mrad

(for missing energy signatures e.g. SUSY)

★ Sufficient timing resolution to separating events from different bunch-crossings



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 pattern recognition
- Good two track resolution

★ The "LARGE DETECTOR" concept is a possible design which meets these goals. Is it optimal ? Is it cost effective ?

❸The Large Detector Concept

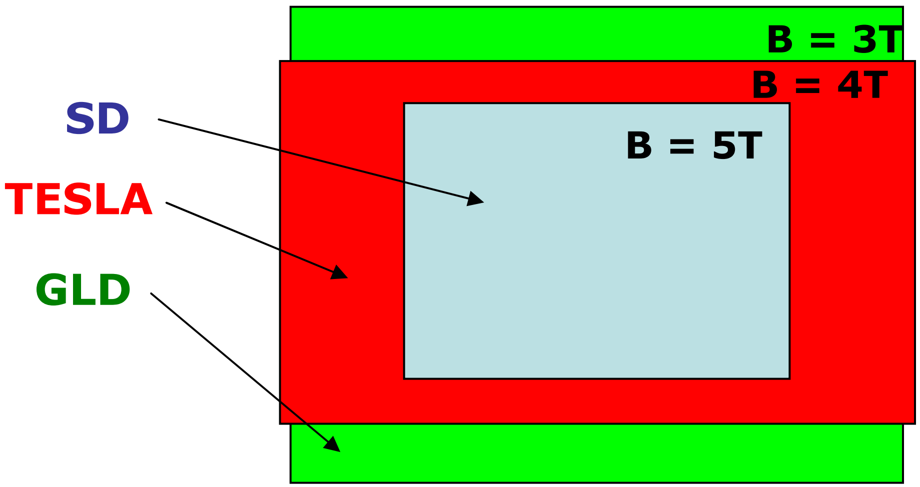
What is the Large Detector concept ?

- ★ **the descendant of the TESLA TDR/US LD concepts**
- ★ **SIZE : "not small and not huge"**

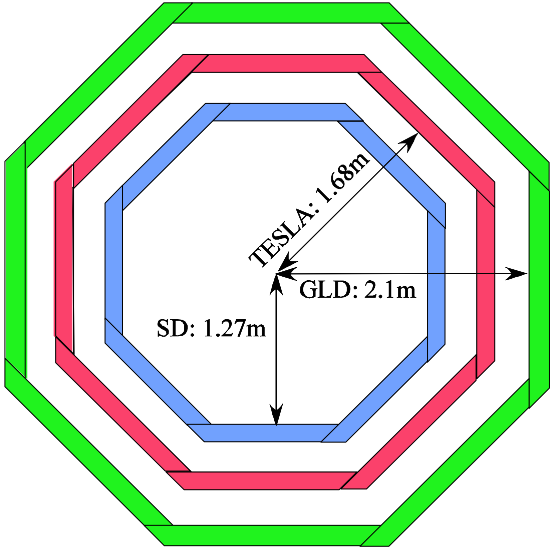
Compare:

- ★**Small Detector : SD**
- ★**Large Detector: e.g. TESLA**
- ★**Huge/Truly Large Detector: GLD**

Tracker



ECAL

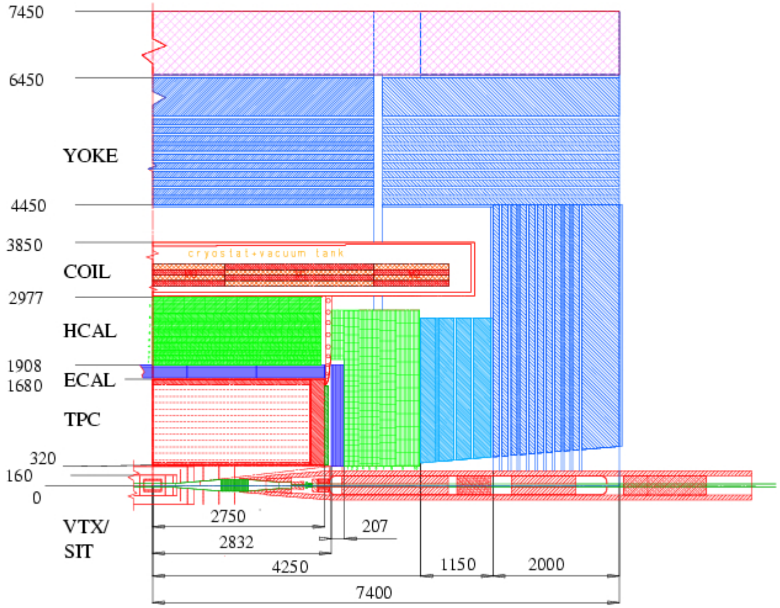


(TESLA TDR Detector a bit long…?)

General Features of Large Detector Concept

- ★ **Large gaseous central time projection chamber (TPC)**
- ★ **High granularity ECAL (SiW generally favoured)**
- ★ **High granularity HCAL (inside coil favoured)**
- ★ **Precision microvertex detector (first layer close to IP)**
- ★ **SC Solenoid with B ~ 4 T**

e.g. TESLA TDR concept:



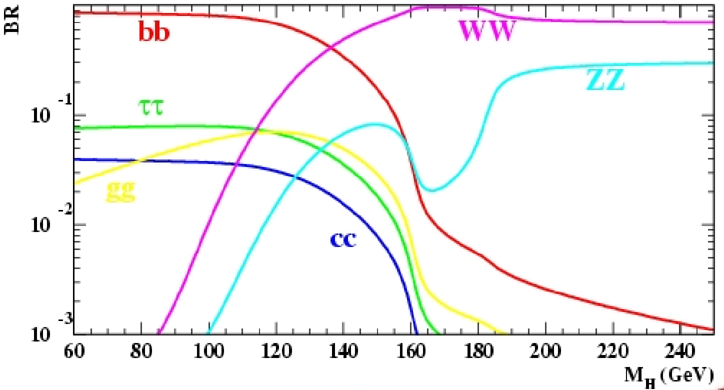
Will briefly review main features of:
- ★**Vertex detector**
- ★**Tracking**
- ★**Calorimetry ECAL/HCAL**

Won't have time to cover forward CALORIMETERS

Vertex Detector

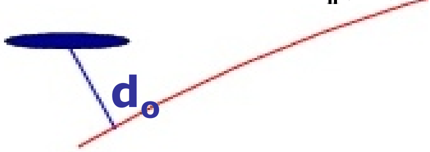
★ Requirements driven by heavy flavour tagging

- ★ **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

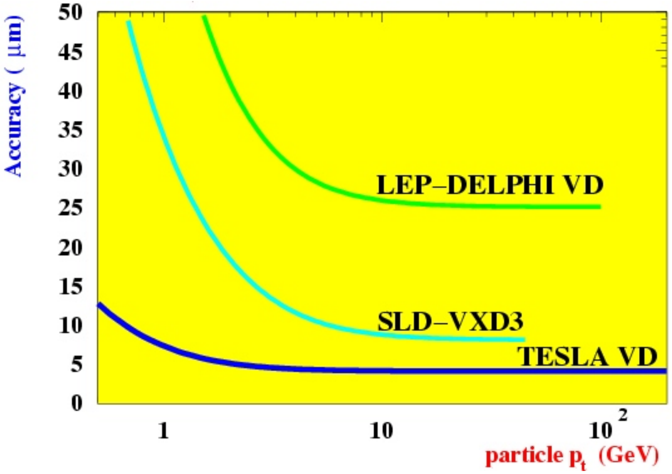


Aim for significant improvement compared to previous detectors

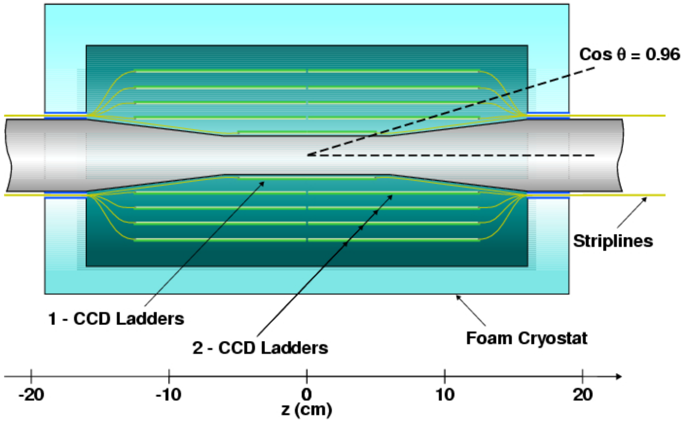
$\sigma_{d0} \sim a \oplus b/p_T(\mathrm{GeV})$

Goal: a<5mm, b<5mm

a: point resolution, b : multiple scattering



Vertex Detector – conceptual design



"Generic" VTX Detector

- **5 Layer Silicon pixel detector**
- **Pixel size ~20x20μm**
- **Space point resolution: < 5μm**
- **1 Gpixels !**

Main design considerations:

★**Inner radius: as close to beampipe as possible, ~15 mm (1/2 SLD) for impact parameter resolution**

★**Layer Thickness: 0.1 %X_0 (1/4 SLD) suppression of γ conversions, minimize multiple scattering,…**

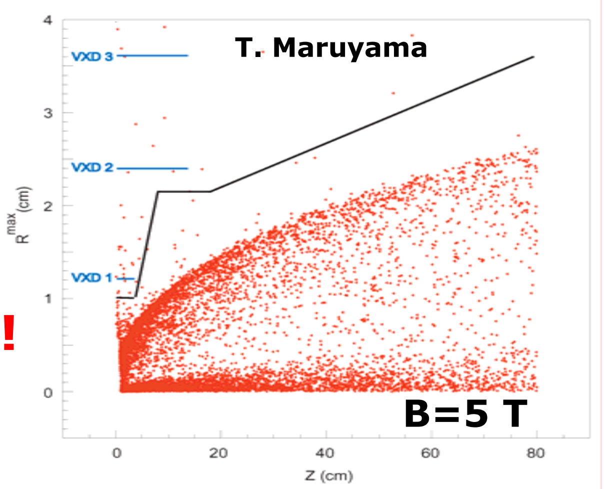
Constraints:

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

★ **Layer thickness depends on Si technology**

★ **Design driven by machine + technology !**

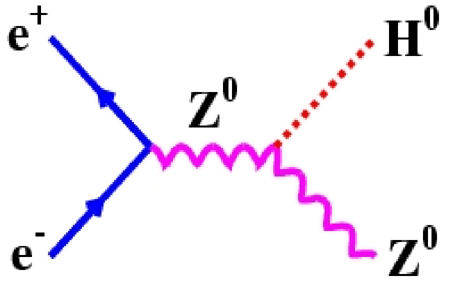
★ **although higher B helps as pairs constrained to smaller radii**



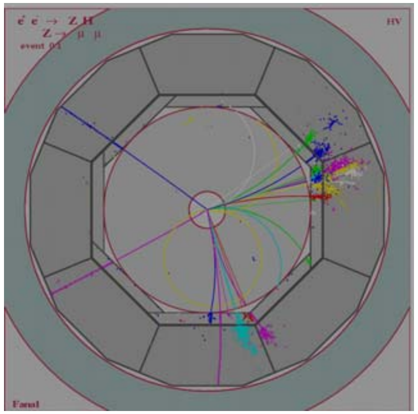
Central Tracking

- **Required momentum resolution driven by reconstruction of Z mass in $Z \rightarrow \mu^+\mu^-$ decays**

Classic Key process



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



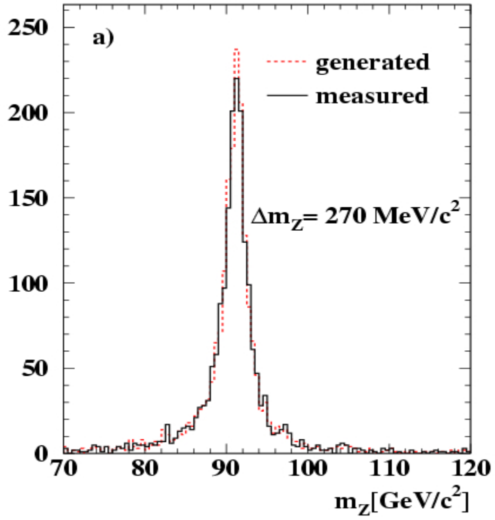
$\mu^+\mu^-$ angular distribution

⇨ Spin, CP,...

Recoil mass to μ+μ-

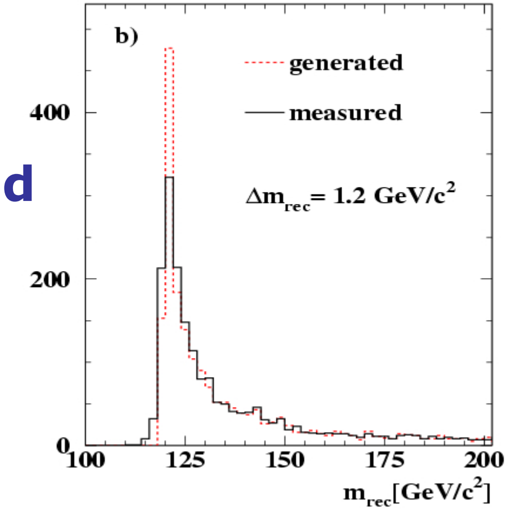
⇨ M_H σ_{ZH}, g_{ZHH}

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



⇦rejection of background

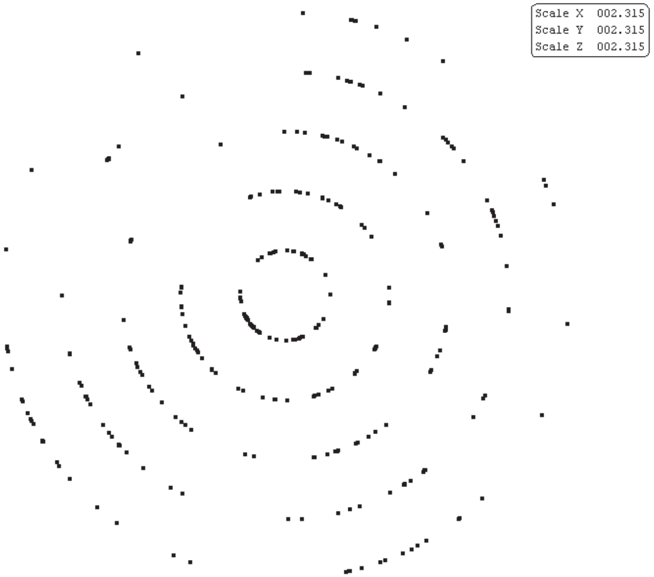
good resolution for ⇨ recoil mass



TPC or Si Tracker ?

- ★ **Two favoured central tracker technologies:**

  TPC and Si Detector

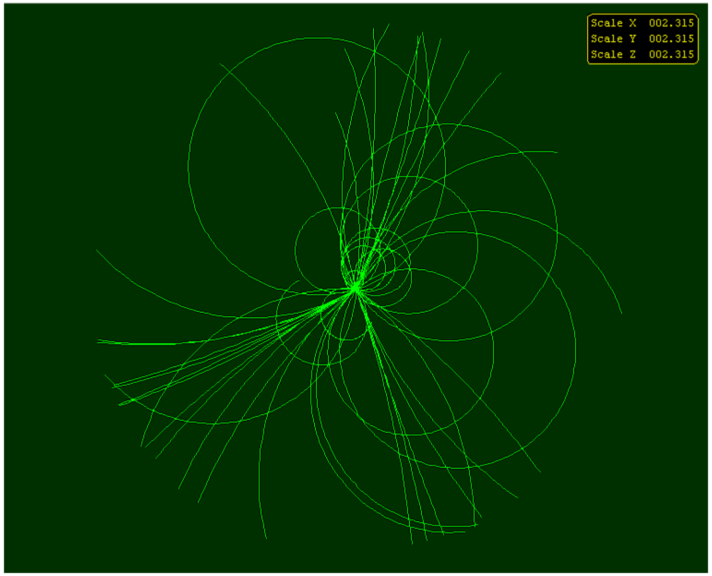


- ★ **Large number of samples vs. smaller number of high precision points granularity**
- ★ **PATTERN RECOGNITION in Si Det looks non-trivial + plenty of additional tracks from two-photon bgnd.**
- ★ **LD Concept adopts a TPC - used successfully in ALEPH/DELPHI**

Motivation for a TPC

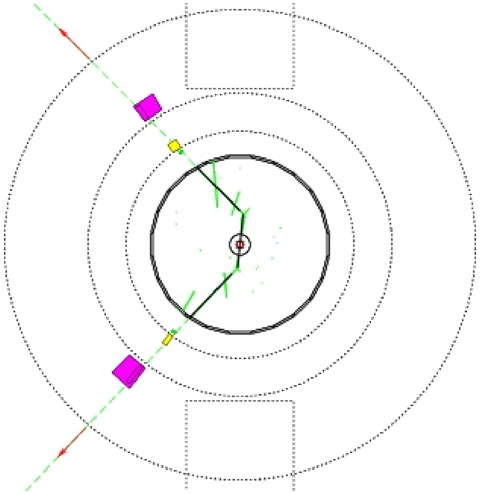
Advantages of a TPC:

- ★ Large number of 3D space points
  - good pattern recognition in dense track environment
- ★ Good 2 hit resolution
- ★ Minimal material
  - little multiple scattering
  - little impact on ECAL
  - conversions from background γ
- ★ dE/dx gives particle identification
- ★ Identification of non-pointing tracks
  - aid energy flow reconstruction of V^0
  - signals for new physics



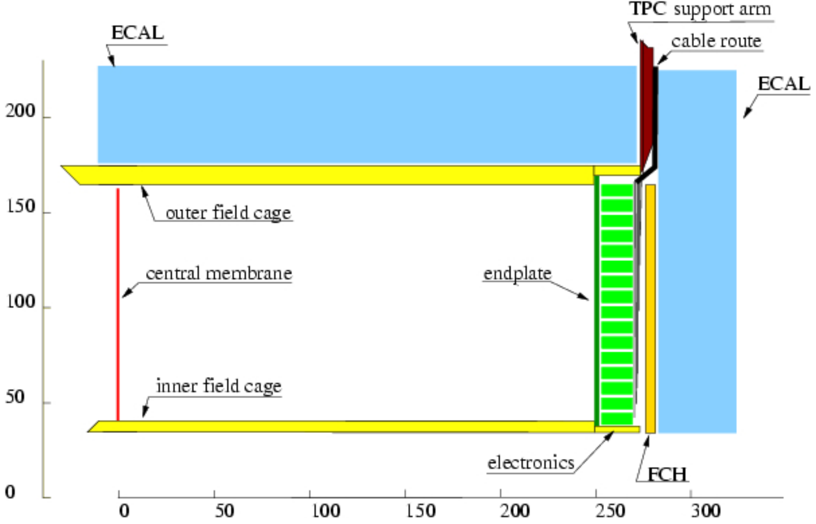
e.g. Reconstruction of kinks

GMSB SUSY: $\tilde{\mu} \to \mu + \tilde{G}$



\+ Large WORLDWIDE R&D effort suggests that a TPC for an ILC detector is viable

e.g. TESLA TPC Conceptual Design



★Readout on 2x200 rings of pads

★Pad size   2x6mm

★Hit resolution: $\sigma < 140\ \mu m$

ultimate aim $\sigma < 100\ \mu m$

✦ May be able to do even better ?
- smaller R/lower B-field ?

- Drift velocity ~5cm μs^{-1} (for ArC0$_2$-CH$_4$ (93-2-5)%)
- Total Drift time ~ 50μs
  - i.e. integrate over 160 BX

★Background ⇨ 80000 hits in TPC   (less with other gas mixtures)

★~10^9 3D readout voxels (1.2 MPads+20MHz sampling)

⇨0.1% occupancy

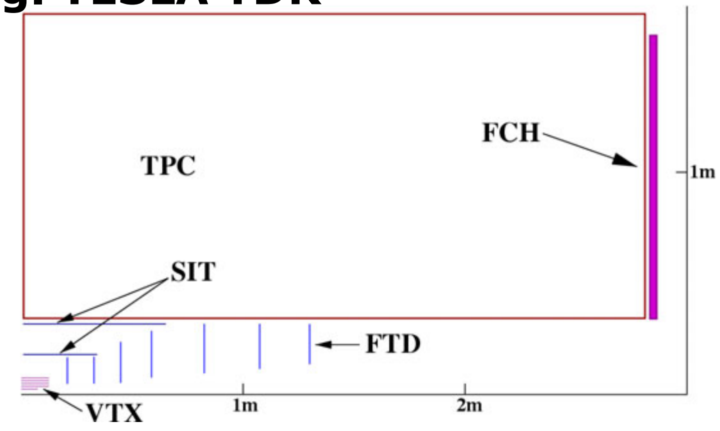
★No problem for pattern recognition/track reconstruction even when taking into account background !

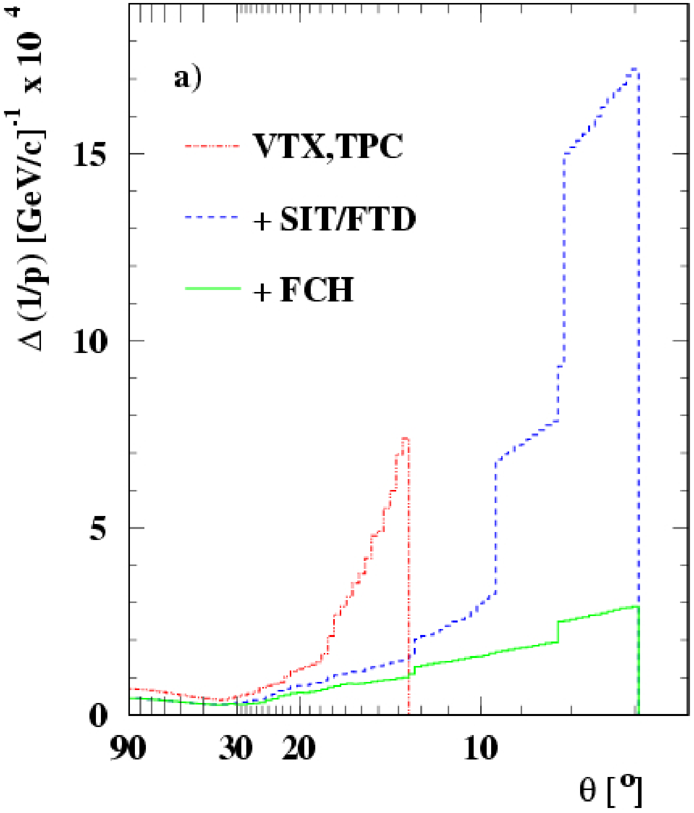
- verified using full simulation in Brahms and LEP-derived tracking !
- very interesting to see if Si Det can do as well

Tracking = VTX + TPC +……

- ★To achieve good momentum resolution need to augment VTX/TPC particularly in the ENDCAP/far forward region
  - ✦ Favoured solution(?) – **Si** strips behind TPC end-planes
    - care not to introduce "too much" material in front of ECAL endcaps

e.g. TESLA TDR





TPC : $\sigma(1/p) = 2.0 \times 10^{-4}$ GeV^{-1}
+VTX: $\sigma(1/p) = 0.7 \times 10^{-4}$ GeV^{-1}
+SIT : $\sigma(1/p) = 0.5 \times 10^{-4}$ GeV^{-1}

- ★Forward tracking is IMPORTANT
  - needs carefully revaluation in LD studies !

Calorimetry at the ILC

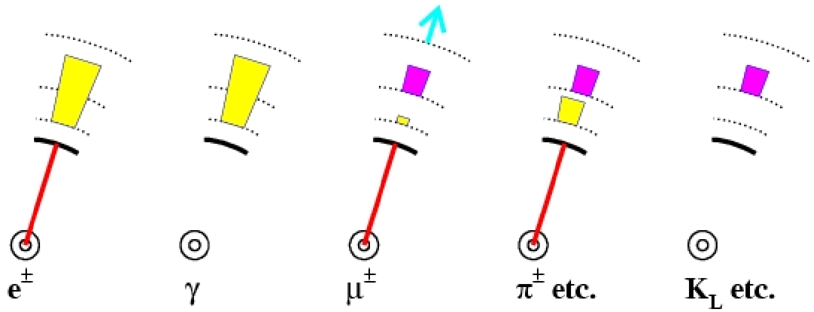
- ★ Much **ILC** physics depends on reconstructing invariant masses from jets in hadronic final states
- ★ Kinematic fits won't necessarily help – **Unobserved particles (e.g. ν)**, + (less important ?) Beamstrahlung, ISR
- ★ Aim for jet energy resolution ~ Γ_Z for "typical" jets
  - the point of diminishing return
- ★ Jet energy resolution is the key to calorimetry

The visible energy in a jet (excluding ν) is:

60 % charged particles : 30 % γ : 10 % K_L,n

The Energy Flow/Particle Flow Method

- 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

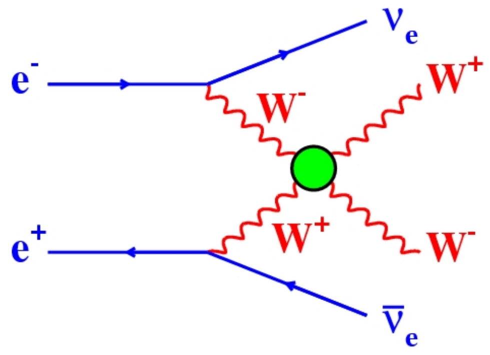
THIS ISN'T EASY !

Jet energy resolution:

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

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

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

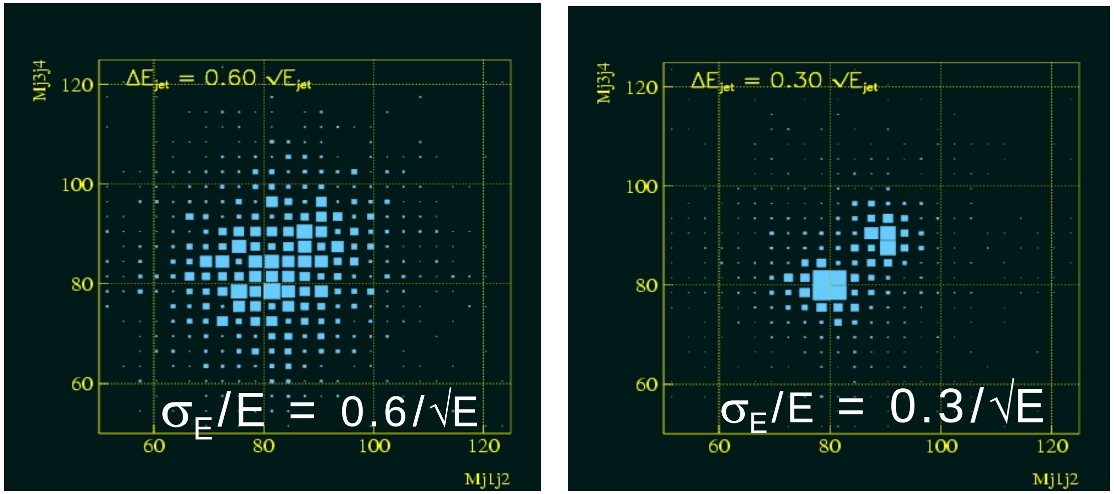


Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states

Often-quoted Example:

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

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



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

★**Best resolution achieved for TESLA TDR : $0.30\sqrt{E_{jet}}$**

Component	Detector	Frac. of jet energy	Particle Resolution	Jet Energy Resolution
Charged Particles($X^{\pm}$)	Tracker	0.6	$10^{-4}\ E_X$	neg.
Photons(γ)	ECAL	0.3	$0.11\sqrt{E_\gamma}$	$0.06\sqrt{E_{jet}}$
Neutral Hadrons(h^0)	HCAL	0.1	$0.4\sqrt{E_h}$	$0.13\sqrt{E_{jet}}$

morgunov

★ **In addition, have contributions to jet energy resolution due to "confusion" = assigning energy deposits to wrong reconstructed particles (double-counting etc.)**

$$\sigma_{jet}^2 = \sigma_{x^{\pm}}^2 + \sigma_{\gamma}^2 + \sigma_{h^0}^2 + \sigma_{confusion}^2 + \sigma_{threashold}^2$$

★ **Single particle resolutions not the dominant contribution to jet energy resolution !**

granularity more important than energy resolution

Calorimeter Requirements

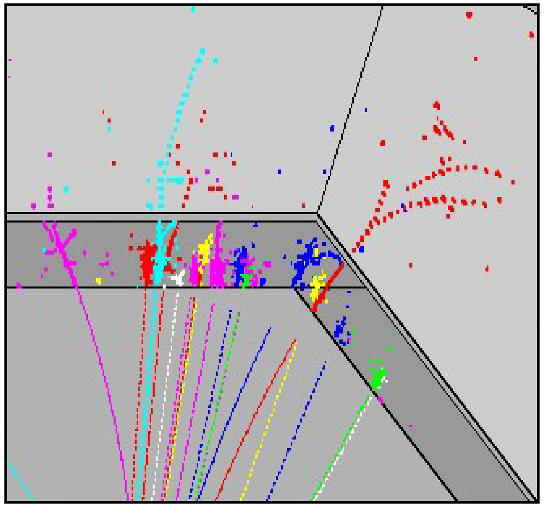
- Excellent energy resolution for jets – i.e. high granularity
- Good energy/angular resolution for photons – how good ?
- Hermeticity
- Reconstruction of non-pointing photons

Energy flow drives calorimeter design:

★ Separation of energy deposits from individual particles
  - small X_0 and $R_{Moliere}$: compact showers
  - high lateral granularity : $O(R_{Moliere})$

★ Discrimination between EM and hadronic showers
  - small X_0/λ_{had}
  - longitudanal segmentation

★ Containment of EM showers in ECAL



★ **SiW** sampling calorimeter is a natural (if costly) choice

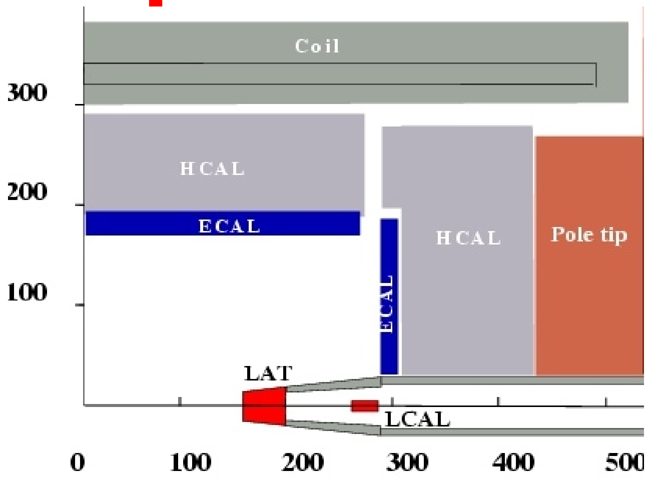
(successfully used in ALEPH/OPAL luminosity detectors)

- Tungsten is great ! X_0 $/\lambda_{had}$ = 1/25, $R_{Moliere}$ ~ 9mm

  EM showers are short/Had showers long

  + narrow EM showers

Calorimeter Concept



- ★ ECAL and HCAL inside coil
  - can we get away with some/all of HCAL beyond coil ?
- ★ SiW ECAL can meet design requirments
  - BUT it is far from cheap
  - shouldn't exclude other ideas (yet)

Tesla TDR SiW ECAL:

- Lateral segmentation: 1cm^2 matched to R_{Moliere}
- Longitudinal segmentation: 40 layers $(24\,X_0,\ 0.9\lambda_{\text{had}})$
- Achieves Good Energy Resolution:

$$\sigma_E/E = 0.11/\sqrt{E(\text{GeV})} \oplus 0.01$$

Some COMMENTS/QUESTIONS:

- R_{Moliere} ~ 9mm for solid tungsten
  - gaps between layers increase effective R_{Moliere}
  - an engineering/electronics issue
- R_{Moliere} is only relevant scale once shower has developed
  - in first few radiation lengths higher/much higher lateral segmentation should help
- + Many optimisation issues !

Hadron Calorimeter

Highly Segmented – for Energy Flow

- **Longitudinal: ~10 samples**
- **~5 λ_{had} (limited by cost - coil radius)**
- **Would like fine (1 cm² ?) lateral segmentation (how fine ?)**
- **For 5000 m² of 1 cm² HCAL = 5x10⁷ channels – cost !**

Two(+) Options:

★ **Tile HCAL (Analogue readout)**

Steel/Scintillator sandwich

Lower lateral segmentation

5x5 cm² (motivated by cost)

★ **Digital HCAL**

High lateral segmentation

1x1 cm²

digital readout (granularity)

RPCs, wire chambers, GEMS…

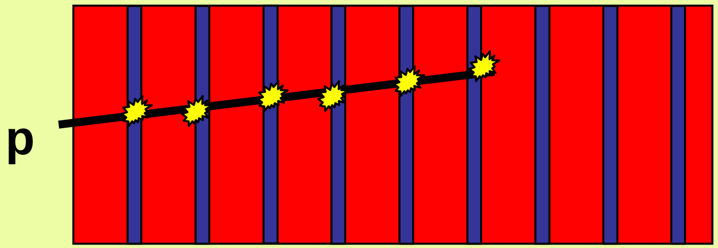
★ **Semi-Digital option ?**

★ **OPEN QUESTION**

The Digital HCAL Paradigm

- **Sampling Calorimeter:**

  Only sample small fraction of the total energy deposition



- **Energy depositions in active region follow highly asymmetric Landau distribution**

❹ Cost and Optimisation

$$$€€€¥¥¥£££:

In Large Detector Concept two main cost drivers:

- ★ **SiW ECAL**
  - **driven by the total area of Silicon**
  - **i.e. ECAL radius, length and number of layers**
- ★ **Solenoid**
  - **cost scales roughly as total stored energy U**
  - **pdg quotes 50 M$ $(U/GJ)^{0.66}$**

    (take with generous pinch of salt, based on pre-1992 data, but ~OKish for CMS)
  - $U \propto B^2 R^2 L$ **($R = R_{coil}$, $L = L_{coil}$)**
  - **playoff between solenoid volume and field**

OPTIMISATION:

- ★ **Physics argues for:**

  large + high granularity + higher field
- ★ **Cost considerations:**

  small + lower granularity + lower field
- ★ **What is the optimal choice and how to find it ?**

  (hopefully easier than finding Amphitheatre Carnot)

Sub-detector Optimisation

Different requirements for different sub-detectors:

- ★ **VTX : design driven by heavy flavour tagging, machine backgrounds, technology**
  : higher B-field helps – get closer to IP
- ★ **Tracker : design driven by σ_p, PATREC, track separation, + R&D**
  : probably OK for all reasonable Radii, B-field

(TRACKER does influence on size and therefore cost)

- ★ **ECAL/HCAL : single particle σ_E not the main factor ➡ jet energy resolution ! Impact on particle flow drives calorimeter design**

★ **For VTX and TRACKER can learn a lot independent of rest of detector design. NOT TRUE for ECAL/HCAL need to consider entire detector**

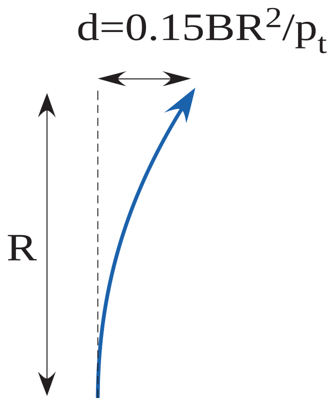
★★ **For LD concept "optimisation" of SIZE and CALORIMETRY (i.e. PARTICLE FLOW) appear to be the main issues**

Aside : Size versus Particle Flow

For Particle Flow want:

- Larger radius ECAL
  - larger transverse separation of energy deposits
- Higher Field
  - sweep tracks away from clusters
- High granularity
  - resolve nearby energy deposits

Comment : on useful (?) Figure of Merit:



- Often quoted F.O.M. for jet energy resolution:

  BR^2/σ ($R=R_{ECAL}$; σ = resolution)

  i.e. transverse displacement of tracks/“granularity”
- Does this work ?
  - compare **OPAL/ALEPH** (W→qq no kinematic fit)

	BR^2	BR^2/σ	$\sigma_E/\sqrt{E}$	R^2/σ
OPAL	2.6 Tm²	26 Tm	0.9	60 m
ALEPH	5.1 Tm²	160 Tm	0.6	110 m

- **No !** Things aren’t that simple….
  - my guess is that **R^2/σ** is more appropriate (even this doesn’t account for neutral hadrons)

Desperately need full simulation studies !

❺ Conclusions

- The **LD** concept still looks like an attractive option for an **ILC** detector !
- However, current designs <u>not really optimised</u>
- Size, COIL and ECAL (Si area) most important cost issues
- Particle flow is probably the major design issue beyond vital detector R&D
- + COIL is imporant – need to get the real experts involved when trying to optimise cost/perfomance

<u>Personal optimisation hit-list (cf. TESLA TDR design):</u>

- Investigate reducing TPC length (guess too long in TESLA TDR)
  - reduce Si area, but more "forward" tracks
- TPC outer radius (i.e. optimal size tracking/pflow/cost)
- Vary (i.e. reduce) number of **ECAL** layers
- Investigate smaller pad sizes in first ECAL layers ?
- Can some/all of **HCAL** be places outside coil ?
- Digital vs. Analog **HCAL**
- Don't forget impact of non-zero crossing angle

<u>Final words:</u>

★ Full simulation studies preferable – this is a tricky business !

★ Vital to include backgrounds in optimisation of LD and comparison with other concepts

★★ There is a lot of extremely interesting work to be done over the next few years…… it should be fun !