The Tesla Detector

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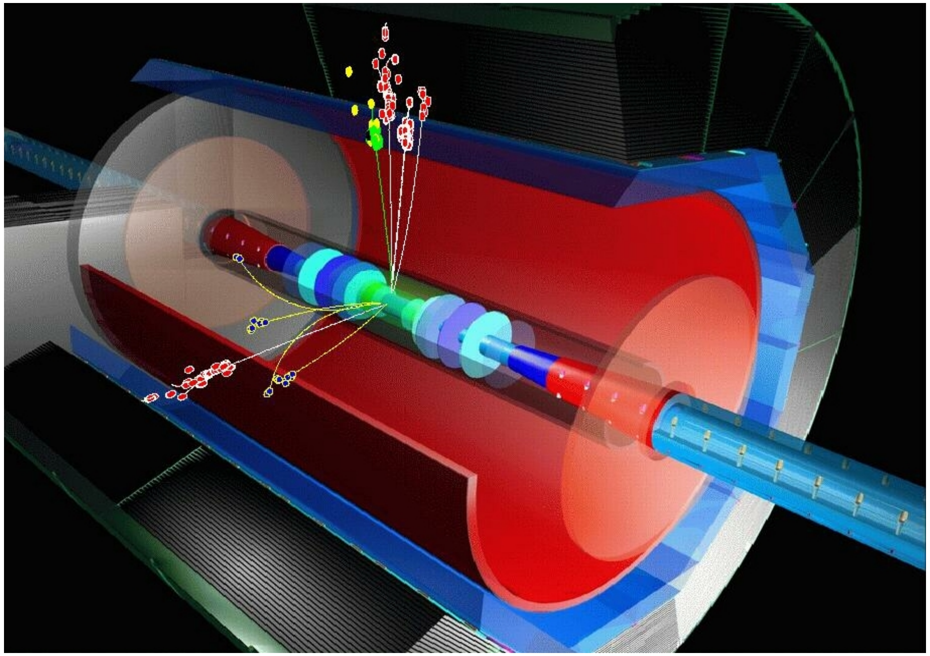
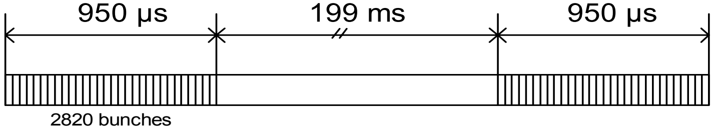


- ★ Requirements
- ★ Basic Concept
- ★ Developments

The TESLA Accelerator

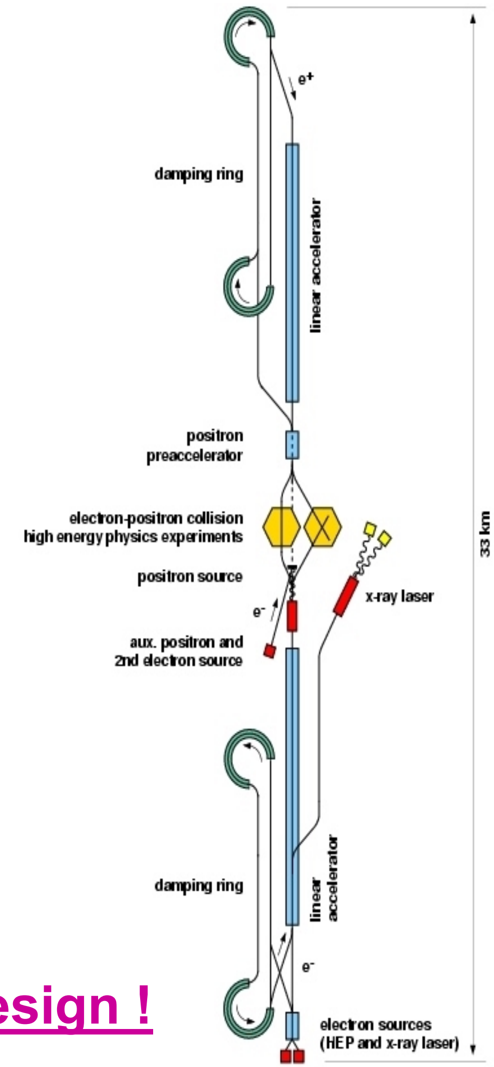
- **Center-of-Mass Energy : 90 – 800 GeV**
- **Time Structure : 5 Bunch Trains/s**



Time between collisions: 337 ns

- **Luminosity : 3.4×10^{34} cm^{-2}s^{-1}** (6000xLEP)
- **Event Rates :**
  - $e^+e^-\to qq$ 330/hr $e^+e^-\to W^+W^-$ 930/hr
  - $e^+e^-\to tt$ 70/hr $e^+e^-\to HX$ 17/hr
- **`Backgrounds`:**
  - $e^+e^-\to qq$ 0.1 /Bunch Train
  - $e^+e^-\to\gamma\gamma\to X$ 200 /Bunch Train
  - 600 hits/BX in Vertex det.
  - 6 tracks/BX in TPC

★ **Radiation Hardness does not dictate detector design !**



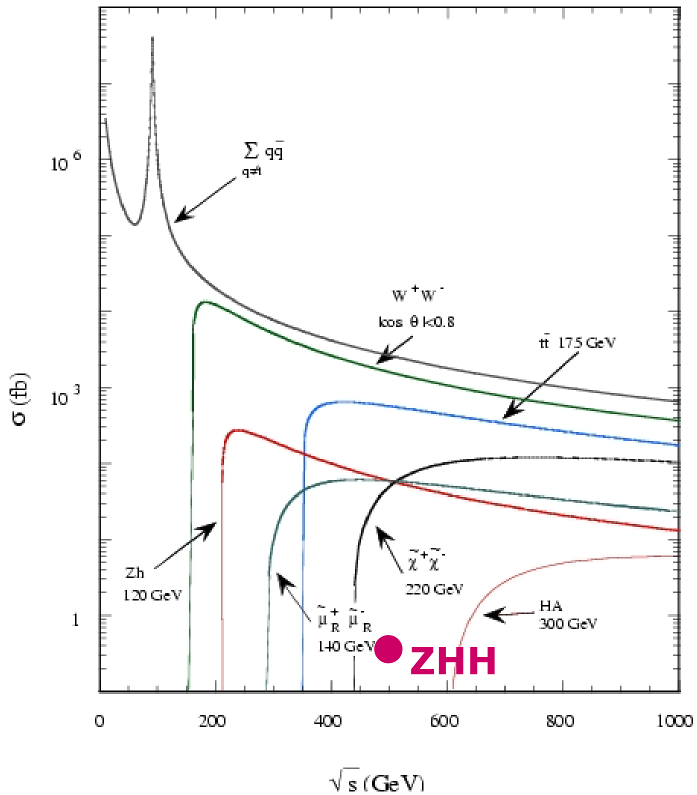
Linear Collider Physics

Precision Studies/Measurements

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

★ **High Multiplicity final states**
often **6/8 jets**

★ **Small cross-sections**
e.g. $\sigma(e^+e^- \to ZHH) = 0.3$ fb



✸ **Require High Luminosity**

✸ **Detector optimized for precision measurements in difficult environment**

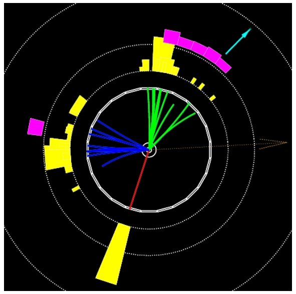
Compare with LEP

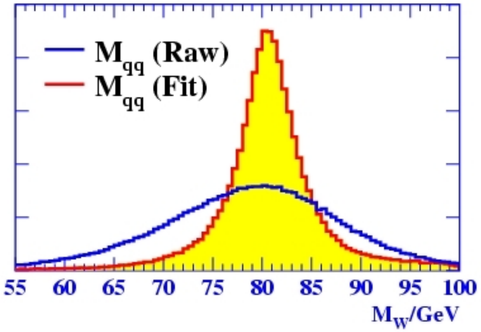
★ $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$ dominate

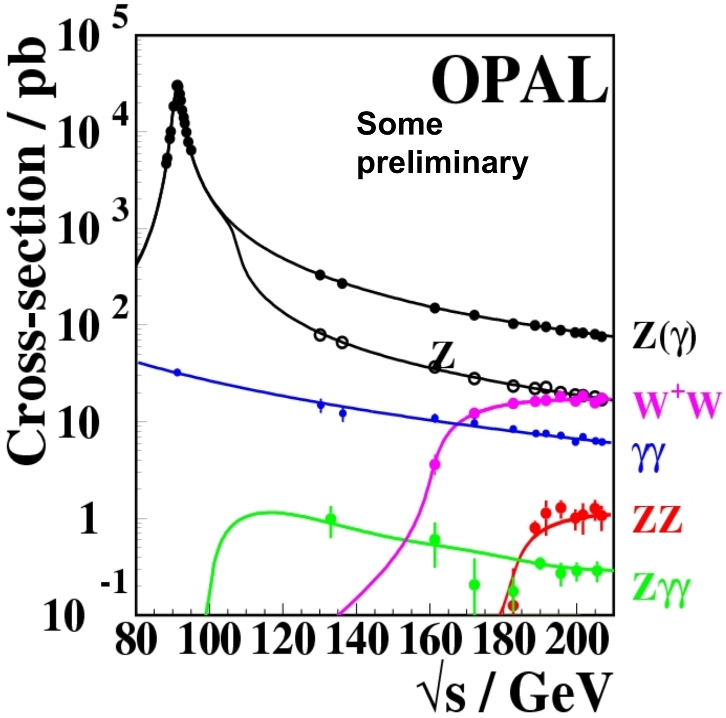
backgrounds not too problematic

★ Kinematic fits used for mass reco.

good jet energy resolution not vital







At TESLA:

★ Backgrounds dominate 'interesting' physics

★ Kinematic fitting much less useful (Beamstrahlung)

✸ Physics performance depends critically on the detector performance (not true at LEP)

✸ Stringent requirements on a TESLA detector

TESLA Detector Requirements

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

(e.g. 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)

(invariant mass reconstruction from jets)

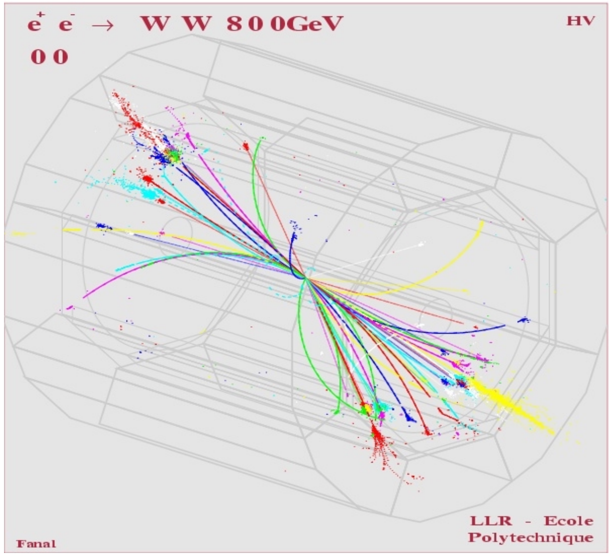
★ **hermetic down to :** θ = 5 mrad

(for missing energy signatures e.g. SUSY)

★ **Radiation hardness not a significant problem**

1st layer of vertex detector : 10^{9} n cm^{-2} yr^{-1}

c.f. 10^{14} n cm^{-2} 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

The TESLA Detector Concept

★Large Gaseous central tracking chamber (TPC)

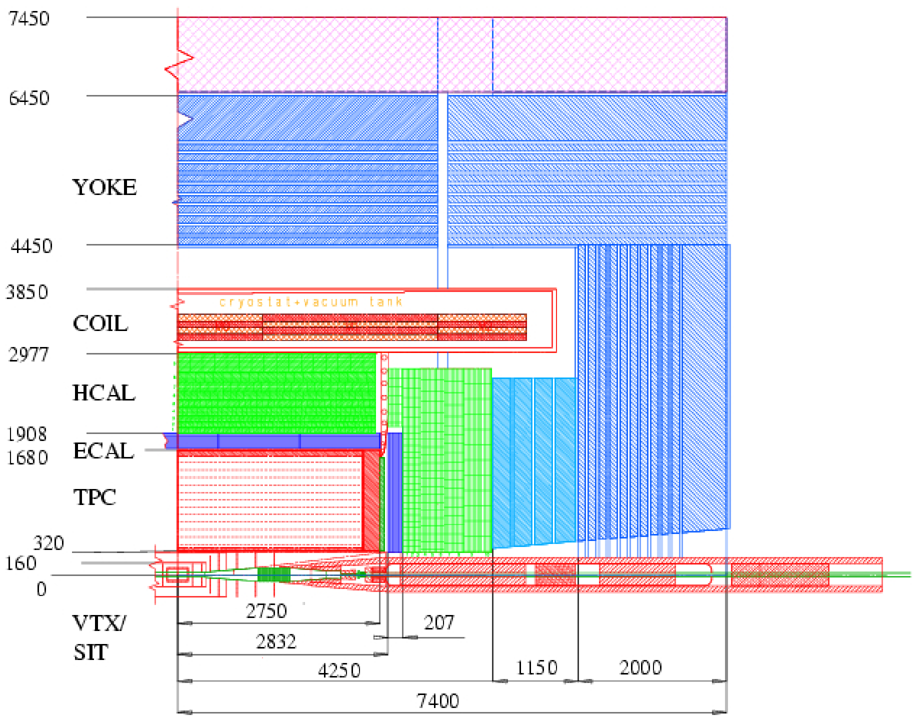
★High granularity SiW ECAL

★High granularity HCAL

★Precision microvertex detector

4 T Magnetic Field

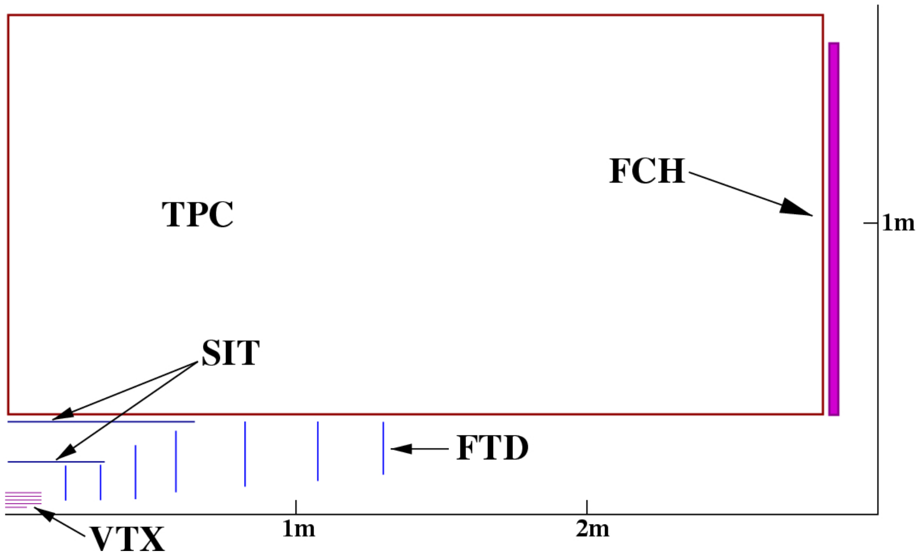
★ ECAL/HCAL inside coil



✷ No hardware trigger, deadtime free continuous readout for the complete bunch train (1 ms)

✷ Zero suppression, hit recognition and digitisation in front-end electronics

Overview of Tracking System



Barrel region:
Pixel vertex detector (VTX)
Silicium strip detector (SIT)
Time projection chamber (TPC)
Silicon envelope SET ?
Forward region:
silicon disks (FTD)
Forward tracking chambers (FCH)
(e.g. straw tubes, <u>silicon strips</u>)

TDR approach

Requirements:

- ★ Efficient track reconstruction down to small angles
- ★ Independent track finding in TPC and in VTX+SIT (7 points)
  alignment, calibration
- ★ Excellent momentum resolution $\sigma_{1/p} < 7 \times 10^{-5}$ /GeV
- ★ Excellent flavour-tagging capability

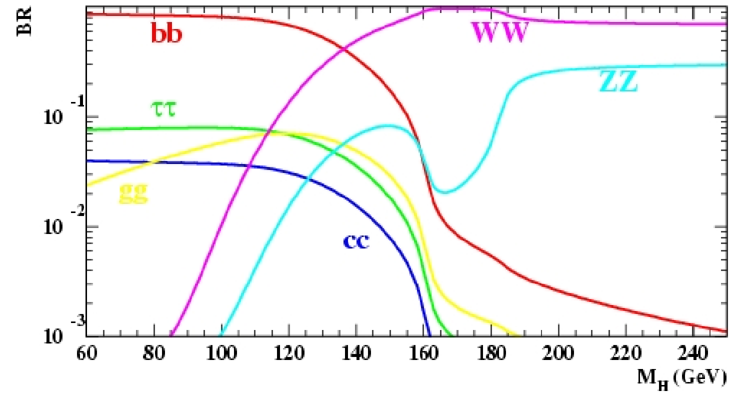
Quark-Flavour Identification

★ **Important for many physics analyses**

e.g. couplings of a low mass Higgs

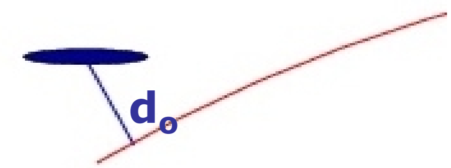
Want to test $g_{Hff} \sim m_f$

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

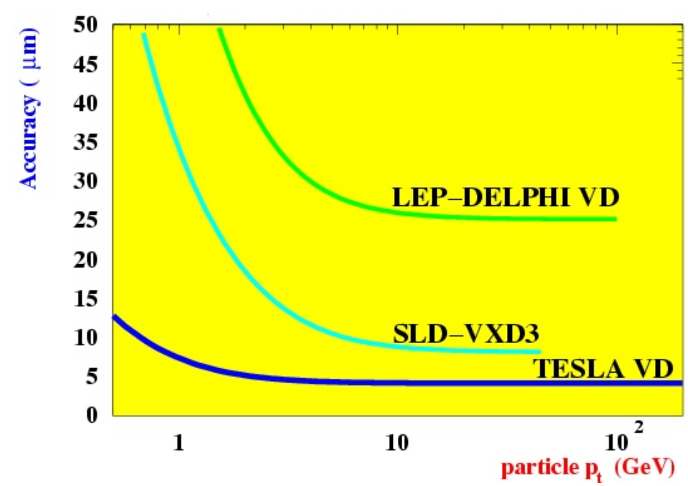


Aim for significant improvement compared to previous detectors

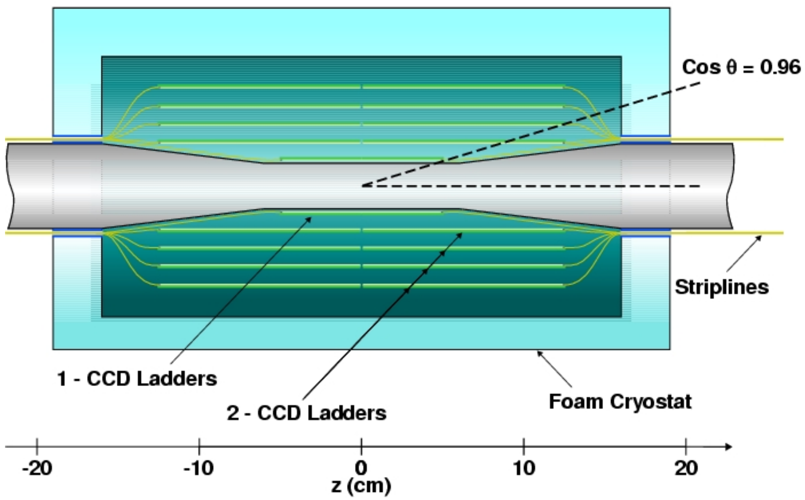
$\sigma_{d0} \sim a \oplus b/p_T(\mathrm{GeV})$

Goal: a<5mm, b<5mm

a: point resolution, b : multiple scattering



Vertex Detector – conceptual design



5 Layer **Silicon pixel detector**

Pixel size 20x20μm

Space point resolution: < 5μm

1 Gpixels !

★**Inner radius: 15 mm** **(1/2 SLD)**

as close to beampipe as possible – charm tagging

★**Layer Thickness: 0.1 %X_0** **(1/4 SLD)**

suppression of γ conversions – ID of decay electrons

minimize multiple scattering

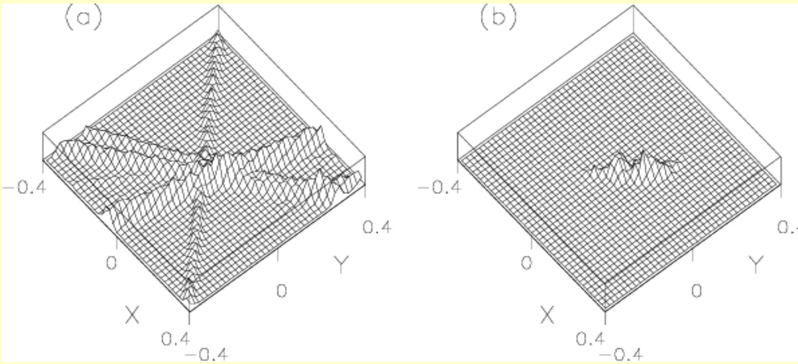
★ **Many current technologies + future developments**

– very active area of R&D

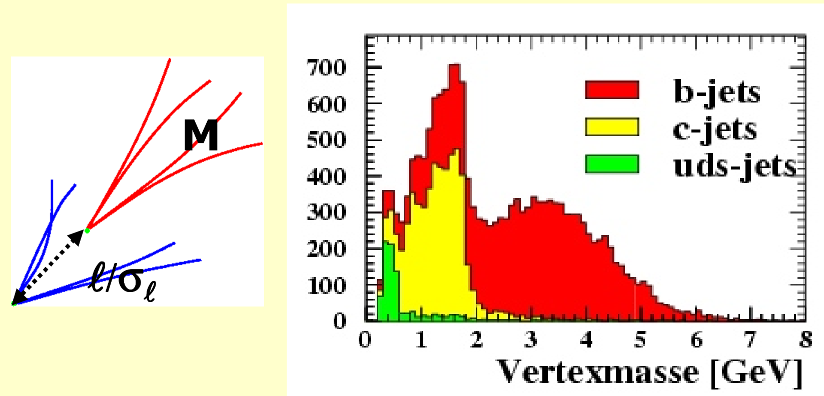
Flavour Tagging

- **Powerful flavour tagging techniques (from SLD and LEP)**

e.g. topological vertexing



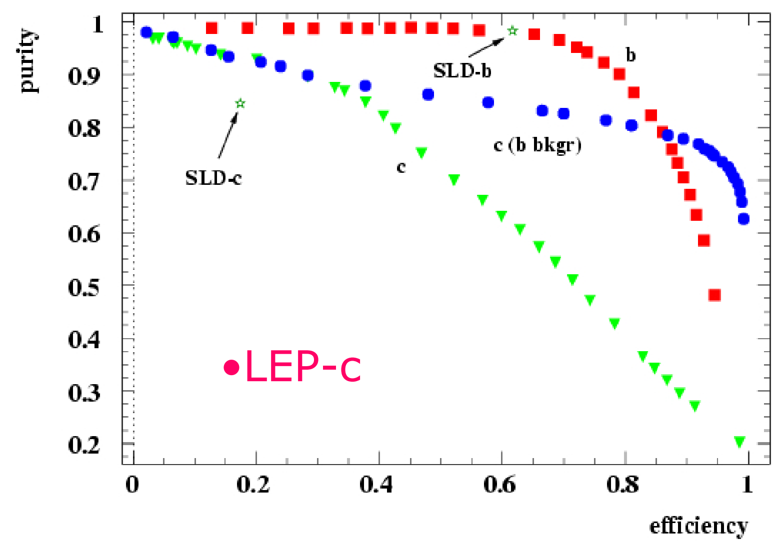
e.g. vertex mass



Expected resolution in r,ϕ and r,z
$\sigma \sim 4.2 \oplus 4.0/p_T(\text{GeV})\ \mu m$

★ **Combine information in ANN**

- **charm-ID**
  significant improvement compared to SLD

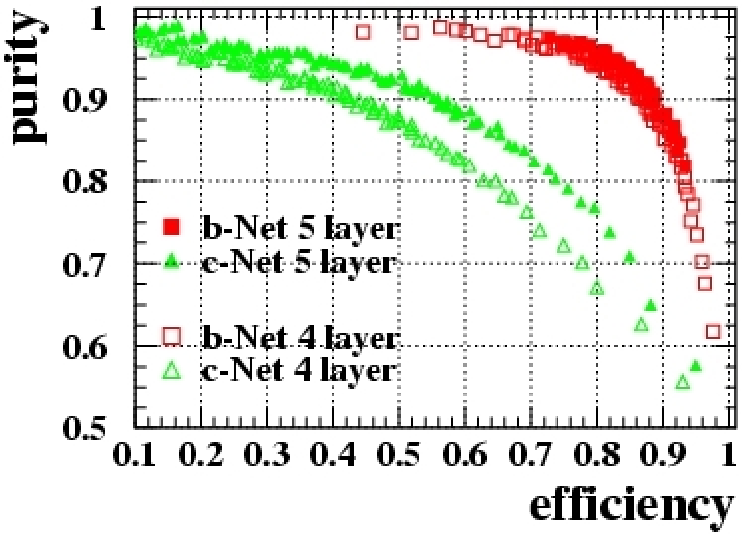


Flavour Tagging : Recent Studies

★ Inner layer at **1.5cm** is very important, e.g. $e^+e^- \rightarrow Z^* \rightarrow ZH$

ZH→llbb, ZH→llcc, ZH→llgg

If inner layer is removed (event-wise) charm tagging degraded by 10%



Future Optimization

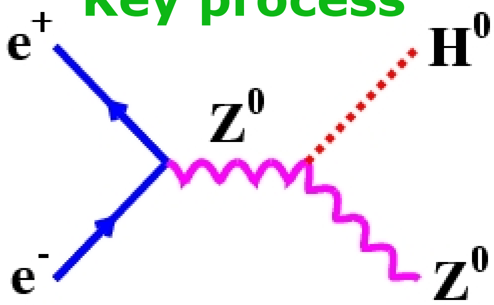
★ Optimize for physics performance:
- charm tag
- vertex charge
- charge dipole
- conversion ID

★ Minimize inner radius

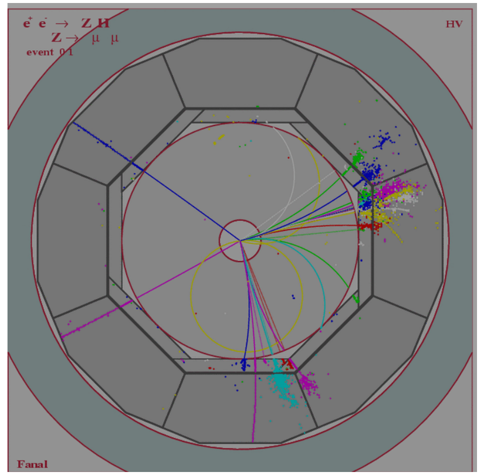
★ Minimize material

Momentum Resolution

Key process



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

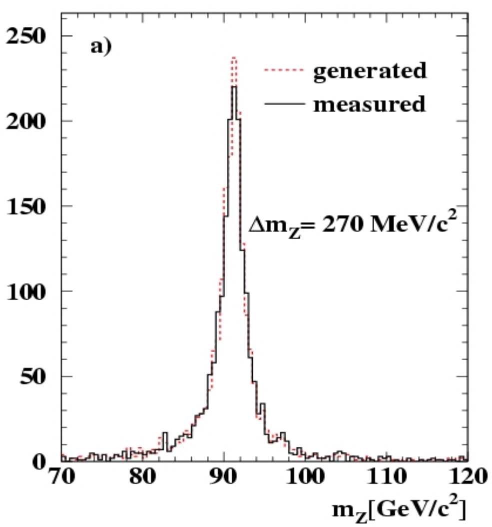


Recoil mass to $\mu^+\mu^-$
⇨ M_H σ_{ZH} , g_{ZHH}

$\mu^+\mu^-$ angular distribution
⇨ Spin, CP,...

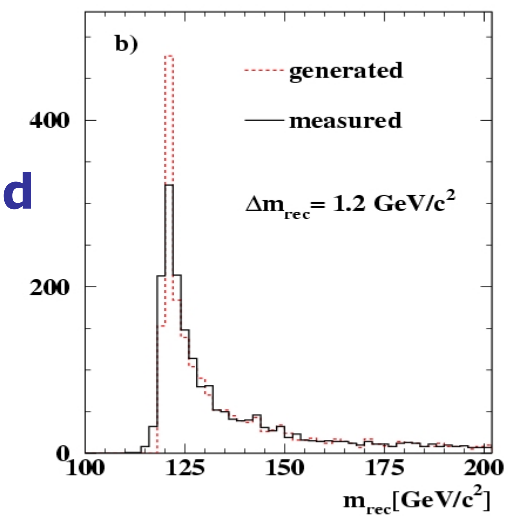
★ **Measurements depend on lepton momentum resolution**

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

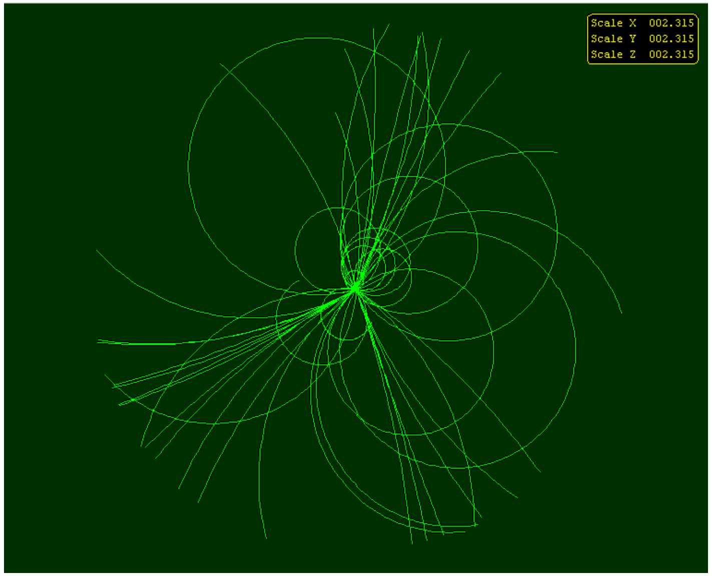


⇦rejection of background

good resolution for ⇨ recoil mass



Motivation for a TPC

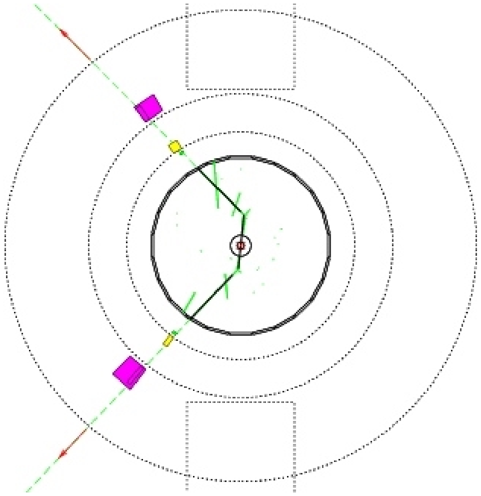


Advantages:

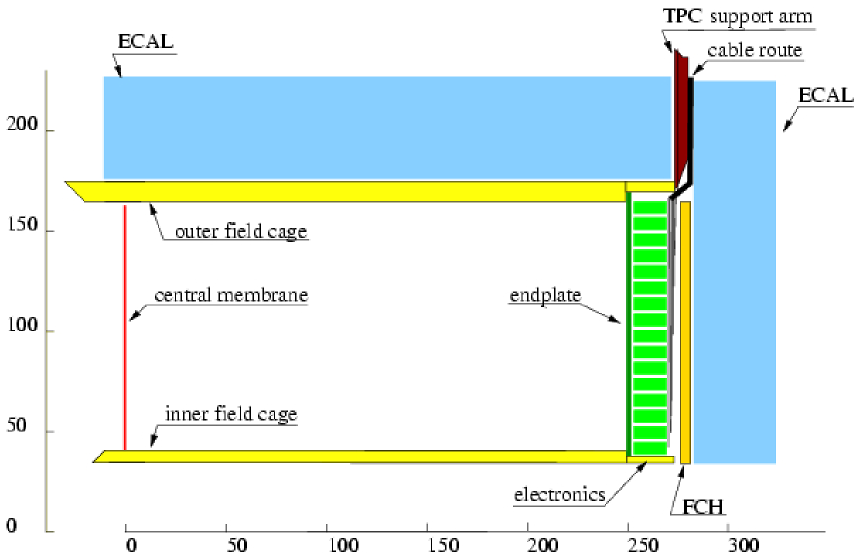
- ★ Large number of 3D space points
  - good pattern recognition in dense track environment
- ★ Good 2 hit resolution
- ★ Minimal material
  - little multiple scattering
  - little impact on ECAL
  - conversions from background γ
- ★ Good timing – few ns
  - separate tracks from different bunches
- ★ 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: $\tilde{\mu} \rightarrow \mu + \tilde{G}$



TPC Conceptual Design



- ★ **Readout on 2x200 rings of pads**
- ★ **Pad size 2x6mm**
- ★ **Hit resolution: σ < 140 μm**

  ultimate aim σ ~100 μm

Drift velocity ~ 5cm μs^{-1}

$ArC0_2$-CH_4 (93-2-5)%

Total Drift time ~ 50μs = 160 BX

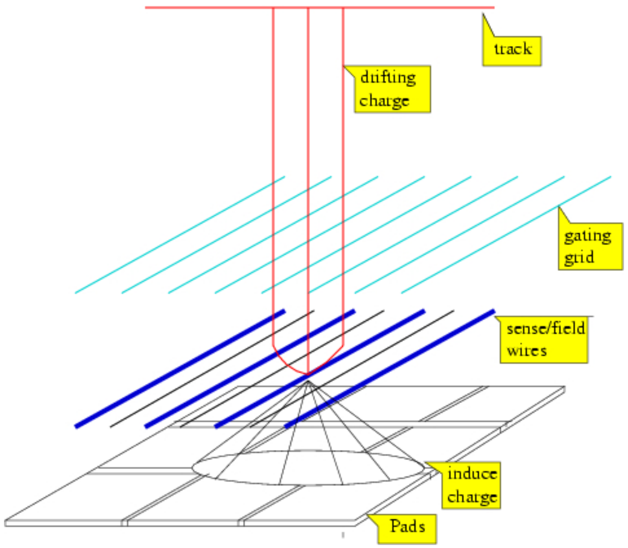
Background ⇨ 80000 hits in TPC

$8x10^8$ readout cells (1.2 MPads+20MHz)

⇨0.1% occupancy

No problem for pattern recognition/track reconstruction

Gas Amplification



Previous TPCs used multiwire chambers not ideal for TESLA.

resolution limited by:

- **ExB effects**

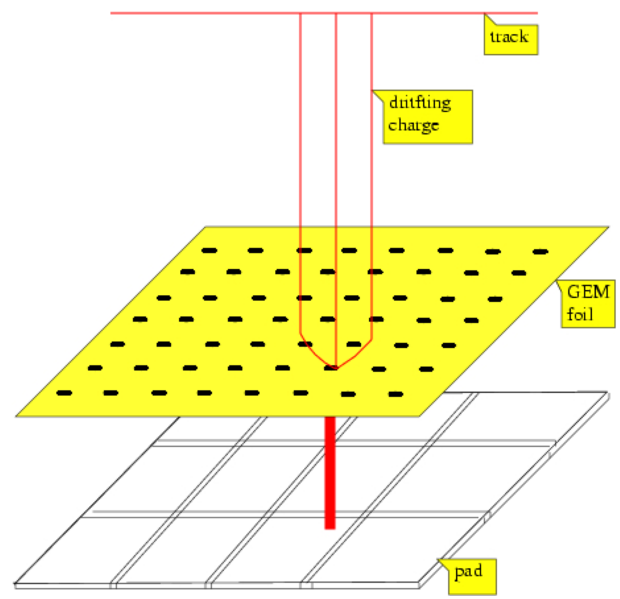
  angle between sense wires and tracks
- **Strong ion feedback – requires gating**
- **Thick endplanes – wire tension**

Gas Electron Multipliers or MicroMEGAS

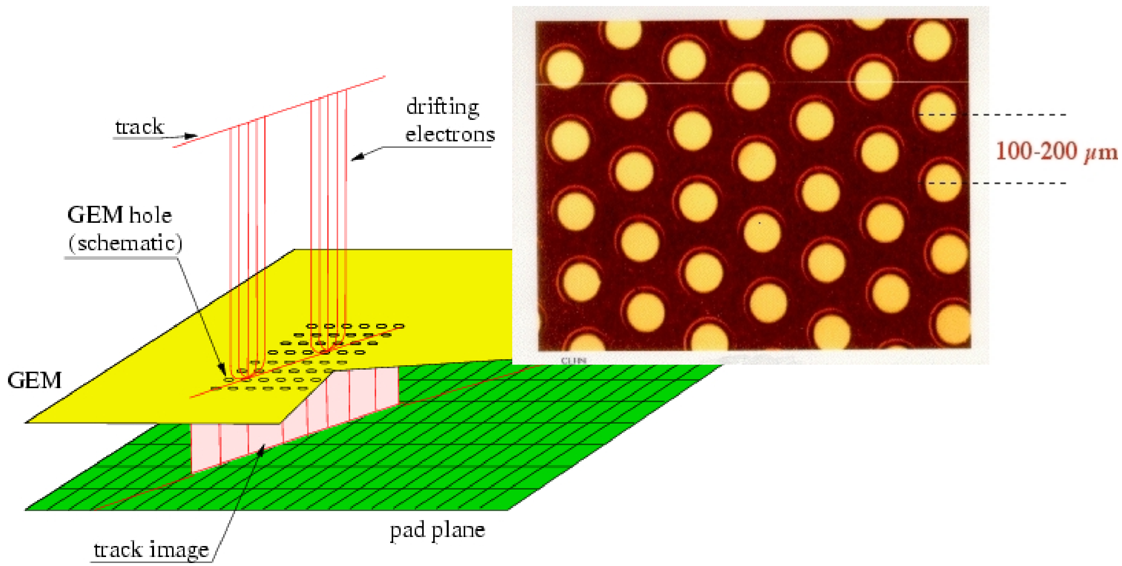
- **2 dimensional readout**
- **Small hole separation ⇨**

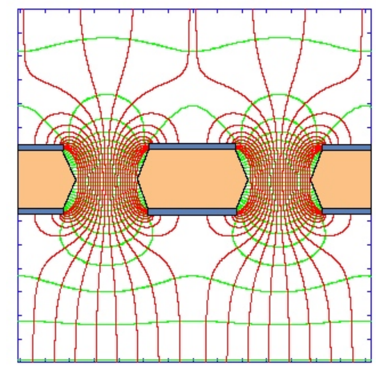
  reduced ExB effects ⇨

  improved point resolution
- **Natural supression of ion feedback**
- **No wire tension ⇨ thin endplates**



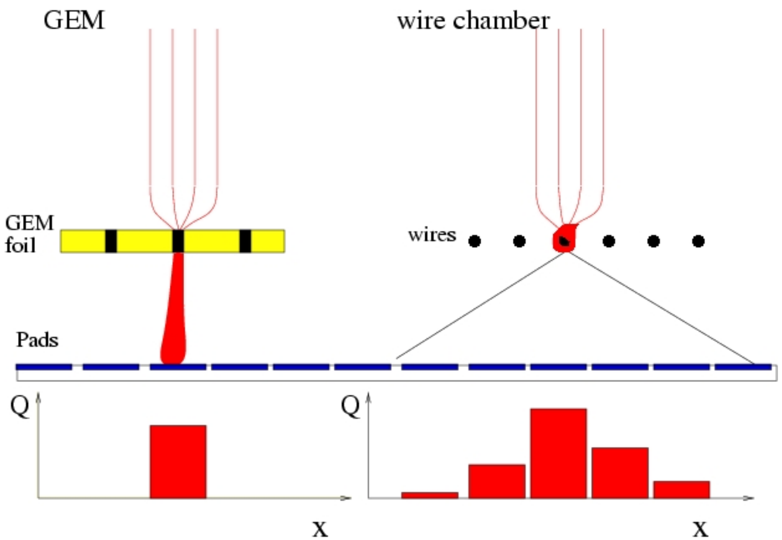
e.g. GEMs





- ★ **High electric field strength in GEM holes ~ 40-80kV/cm**
- ★ **Amplification occurs between GEM foils (50 μm)**
- ★ **Ion feedback is suppressed : achieved 0.1-1 %**
- ★ **Limited amplification (<100) - use stack of 2/3 GEMs**

GEM Point Resolution



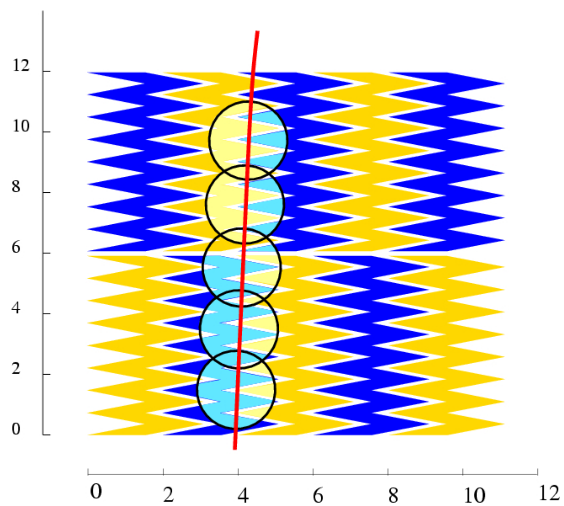
Wire Chamber readout :

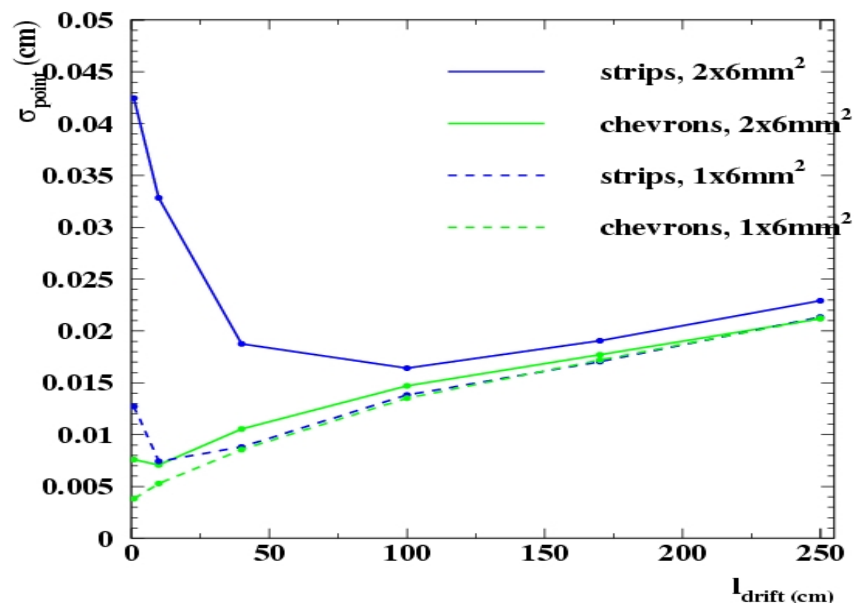
- Readout induced charge on pads
- Charge induced on several pads
- Improved point resolution

GEM readout :

- Induced charge too small
- Readout charge on pads
- Limits resolution to pad size

Improve point resolution using chevron/diamond pads





Recent progress

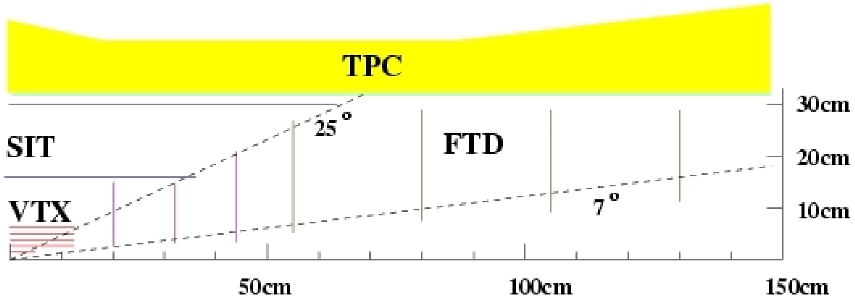
No change in basic concept, but much R&D:

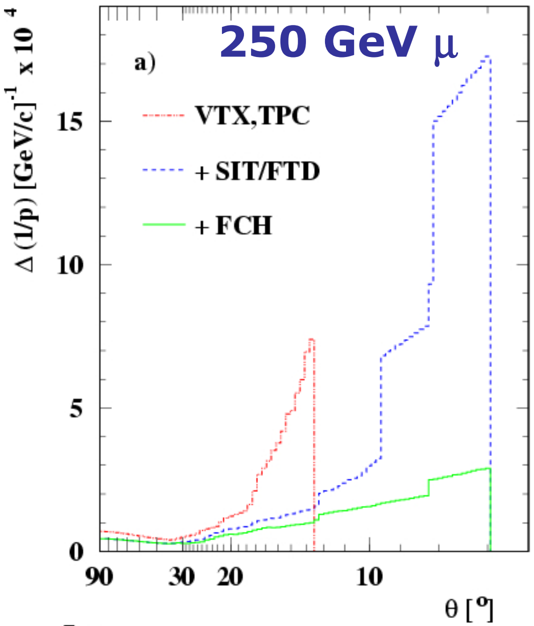
- **operation in high magnetic fields**
- **ion feedback,**
- **pad shapes,**
- **gas studies,**
- **simulation work – ultimately allow optimization**
- **and much more....**

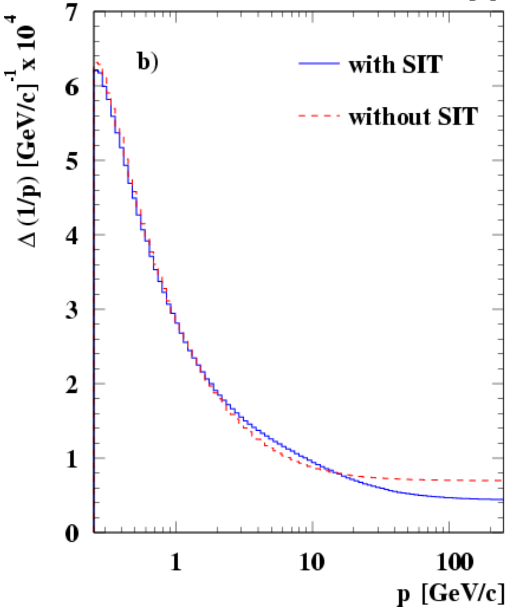
Aachen, Carleton, DESY/Hamburg, Karlsruhe, Krakau, LBNL, MIT, Montreal, MPI-München, NIKHEF, Novosibirsk, Orsay, Saclay, Rostock,Victoria

So far so good. A TPC remains a viable option for the TESLA detector

Intermediate Tracking Chambers







- At low angles TPC/VTX momentum resolution is degraded

Tracking Improved by:

SIT: 2 Layers of SI-Strips $\sigma_{r\phi} = 10\ \mu m$

FTD: 7 Disks

3 layers of Si-pixels $50 \times 300 \mu m^2$

4 layers of Si-strips $\sigma_{r\phi} = 90 \mu m$

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

Calorimetry at TESLA

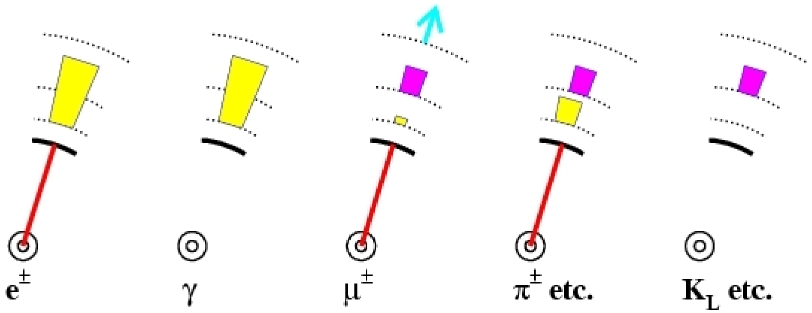
- ★Much TESLA physics depends on reconstructing invariant masses from jets in hadronic final states
- ★Kinematic fits don't help – Beamstrahlung, ISR
- ★Jet energy resolution is of vital importance

The energy in a jet is:

60 % charged particles : 20 % γ : 10 % K_L,n : 10 % ν

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)

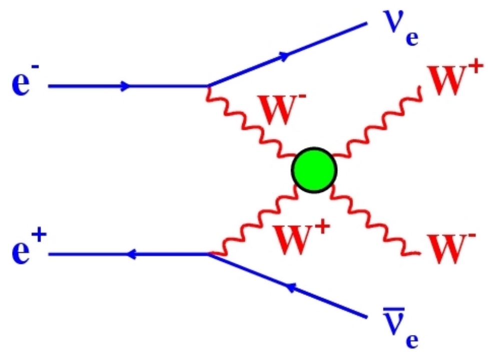
★need to separate energy deposits from different particles

Jet energy resolution:

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

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

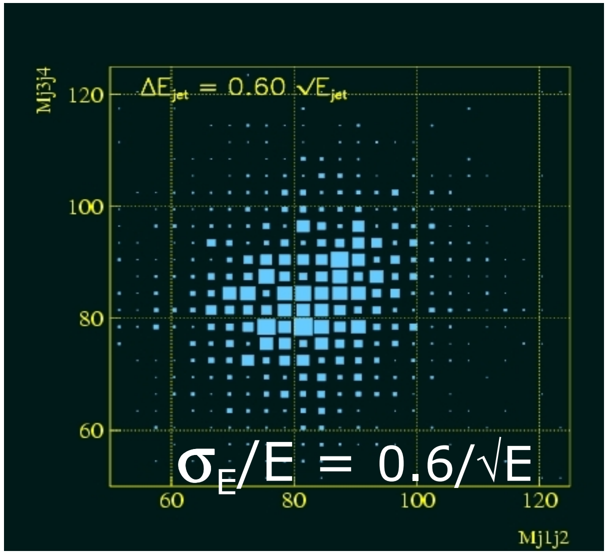
★ **Jet energy resolution directly impacts physics sensitivity**

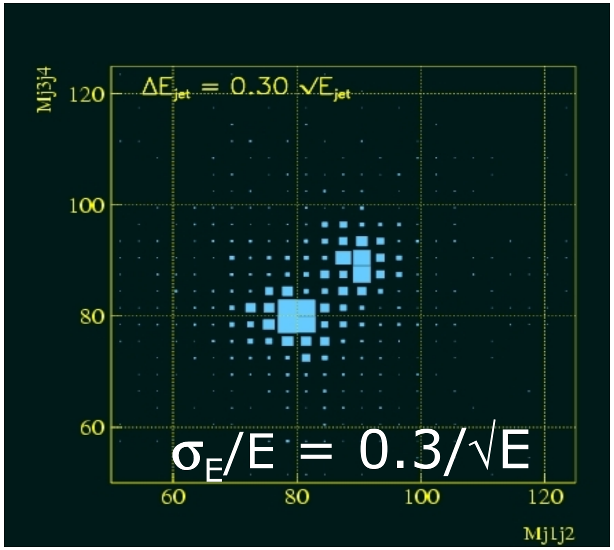


If the Higgs mechanism is not responsible for EWSB then QGC processes important

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

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





Calorimeter Requirements

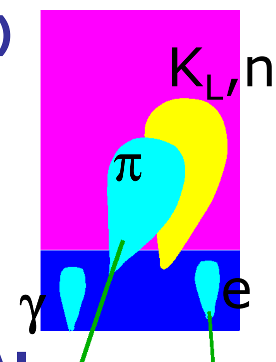
- **Excellent energy resolution for jets**
- **Good energy/angular resolution for photons**
- **Hermeticity**
- **Reconstruction of non-pointing photons**

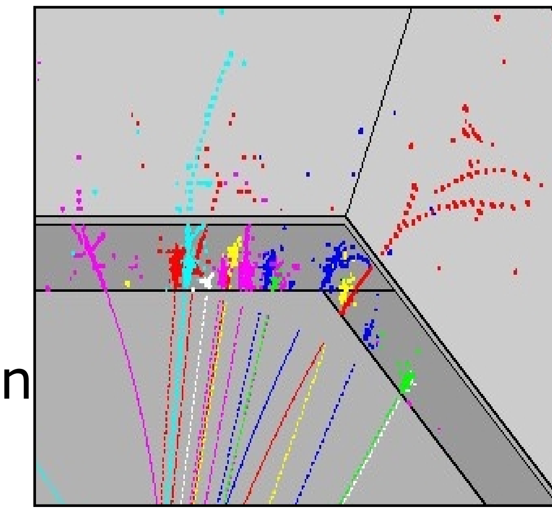
Energy flow drives calorimeter design:

★ **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**

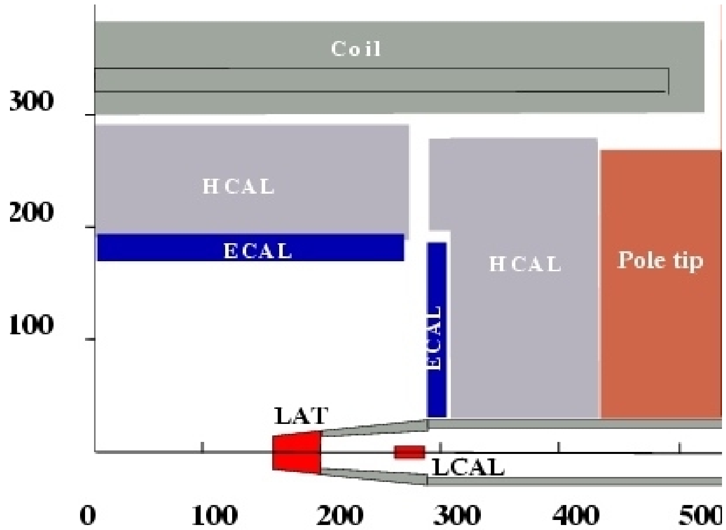


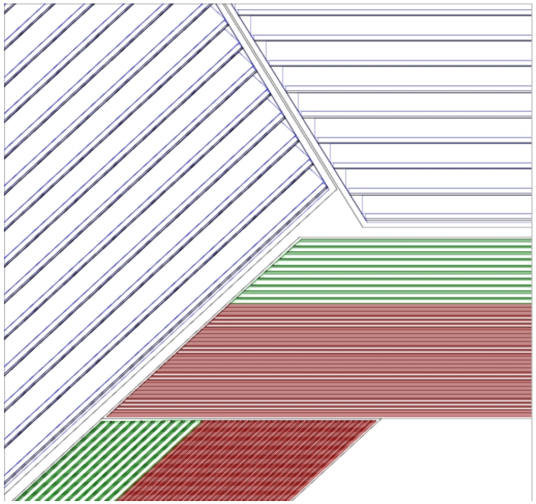


granularity more important than energy resolution

Calorimeter Concept

ECAL and HCAL inside coil





ECAL: silicon-tungsten (SiW) calorimeter:

- **Tungsten : $X_0 / \lambda_{had} = 1/25$, $R_{Moliere} \sim 9mm$**
  (gaps between Tungsten increase effective $R_{Moliere}$)
- **Lateral segmentation: $1cm^2$ matched to $R_{Moliere}$**
- **Longitudinal segmentation: 40 layers (24 X_0, 0.9λ_{had})**
- **Resolution: $\sigma_E/E = 0.11/\sqrt{E(GeV)} \oplus 0.01$**

$$\sigma_\theta = 0.063/\sqrt{E(GeV)} \oplus 0.024 \text{ mrad}$$

Hadron Calorimeter

Highly Segmented – for Energy Flow

- **Longitudinal: 9-12 samples**
- **4.5 – 6.2 λ (limited by cost - coil radius)**
- **Would like fine (1 cm^2 ?) lateral segmentation**
- **For 5000 m^2 of 1 cm^2 HCAL = $5x10^7$ channels – cost !**

Two Options:

★ **Tile HCAL (Analogue readout)**

Steel/Scintillator sandwich

Lower lateral segmentation

5x5 cm^2 (motivated by cost)

★ **Digital HCAL**

High lateral segmentation

1x1 cm^2

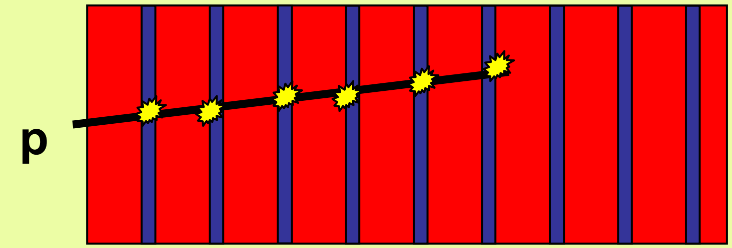
digital readout (granularity)

RPCs, wire chambers, GEMS…

The Digital HCAL Paradigm

- **Sampling Calorimeter:**

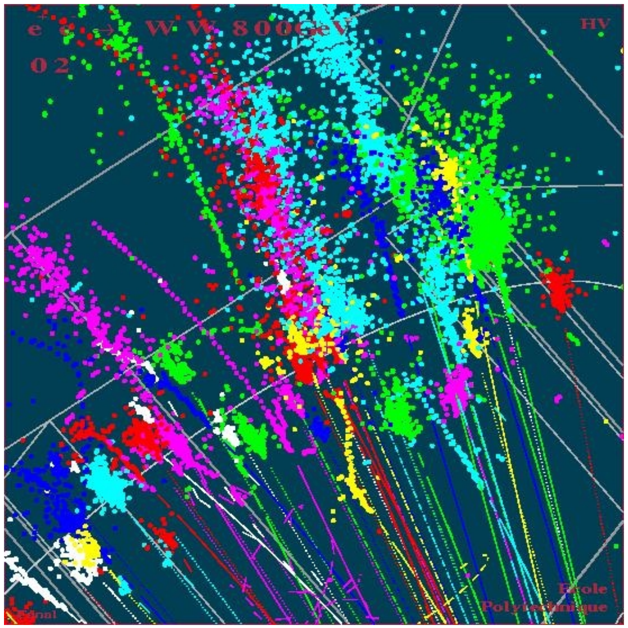
  Only sample small fraction of the total energy deposition



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

Calorimeter Reconstruction

- **High granularity calorimeter – <u>very different</u> from previous detectors**



- **`Tracking calorimeter'**
  - **Requires new approach to reconstruction**
  - **Already a lot of excellent work on powerful energy flow algorithms**
  - **Still room for new ideas/ approaches**

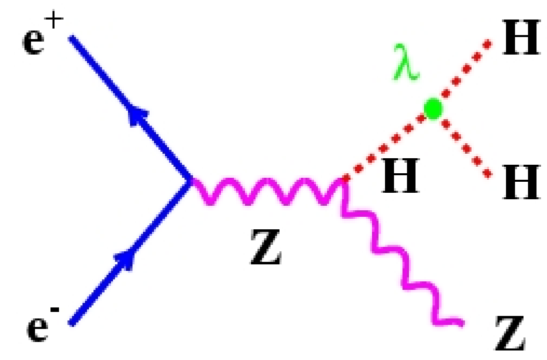
A number of ongoing studies....

- **Highly segmented digital HCAL favoured**

Calorimeter performance

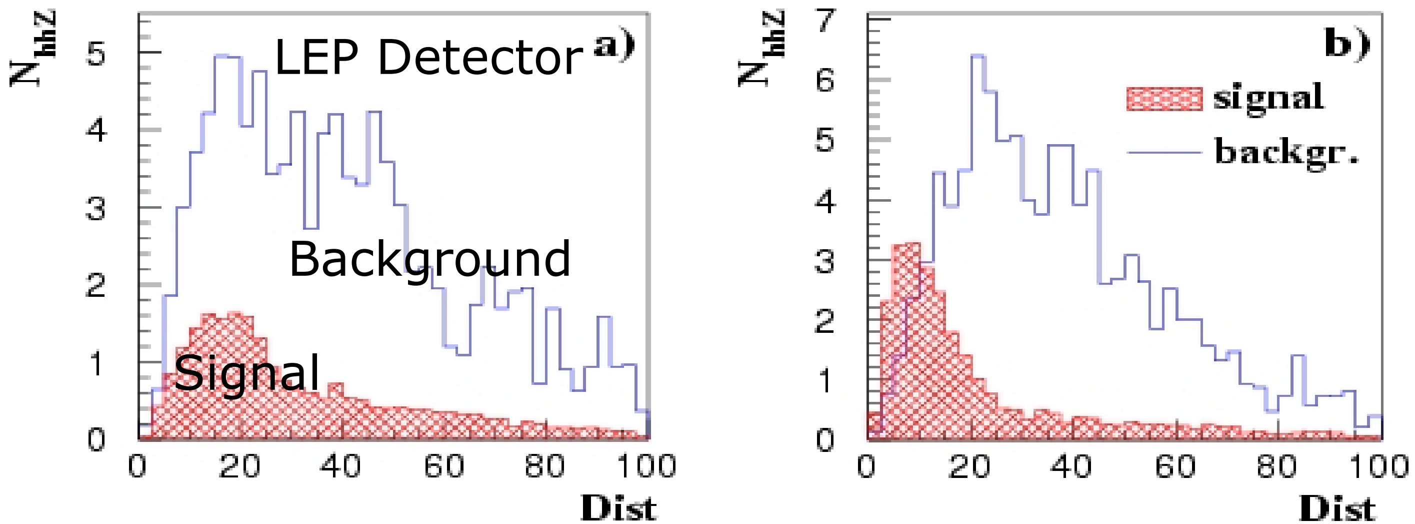
e.g. measurement of trilinear HHH coupling via $e^+e^- \rightarrow ZHH \rightarrow qqbbbb$

- ★Probe of Higgs potential
- ★Small cross-section
- ★Large combinatoric background
- ★6 jet final state



- Use jet-jet invariant masses to extract signal

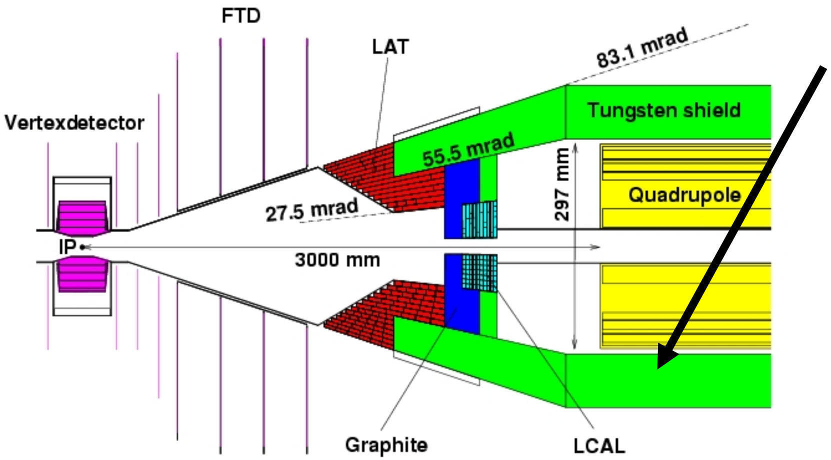
$$Dist=((M_H - M_{12})^2 + (M_Z - M_{34})^2 + (M_H - M_{56})^2)^{1/2}$$



★ Good jet energy resolution give ~5σ signal

Forward Calorimeters

Forward region geometry determined by need to suppress beam related background



TDR version of mask
L* = 3 m

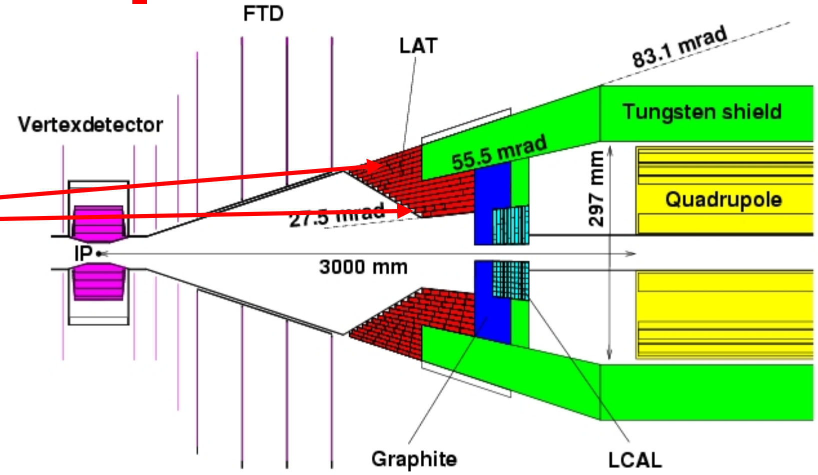
LAT: Luminosity monitor and hermeticity
SiW Sampling Calorimeter
aim for $\Delta\mathcal{L}/\mathcal{L} \sim 10^{-4}$ require $\Delta\theta = 1.4$ mrad

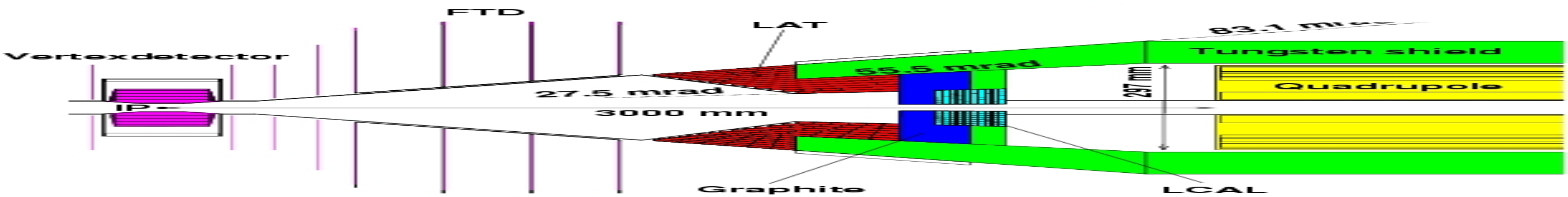
LCAL: Beam monitoring and fast luminosity
$\sim 10^4$ e^+e^- pairs/BX
Need radiation hard technology:
SiW or Diamond/W Calorimeter, Scintillator Crystals

Recent Developments

★TDR version of LAT not suitable for a precision lumi measurement:

- Shower leakage
- Difficulty in controlling inner acceptance to ~1μm

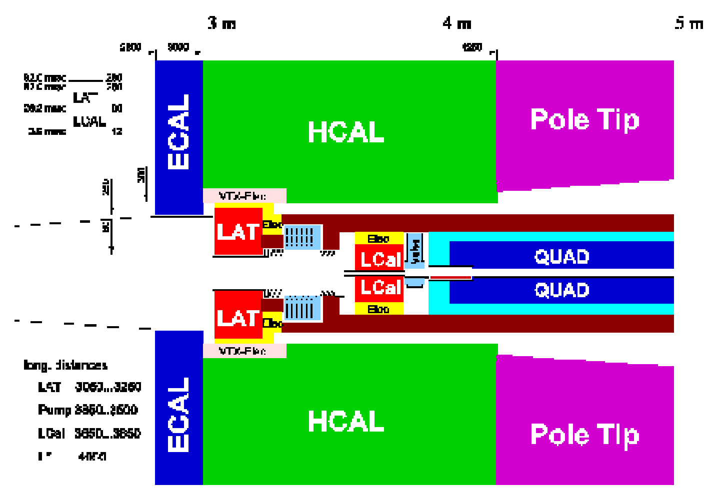




New L* = 4-5 m version currently being studied.

More space – better for lumi

<u>Forward region is in a state of flux</u>



Detector Optimization

Current concept of TESLA detector essentially <u>unchanged</u> from TDR

Time to think again about optimizing detector design, e.g.

TRACKING CHAMBERS:

- ★ **Study Effect of reducing TPC length (Ron Settles)**
- ★ **Optimize Number of SIT Layers.**

CALORIMETERS:

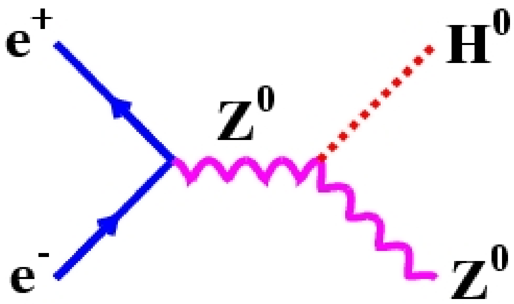
- ★ **Continue evaluation of digital vs analog HCAL**
  - **beware simulation of hadronic showers**
- ★ **Calorimeter segmentation**
- ★ **HCAL active medium**
- ★ **Alternative designs LCCAL**

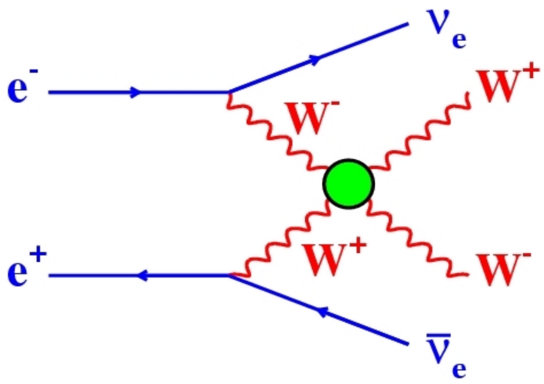
+ OTHER/NEW IDEAS……

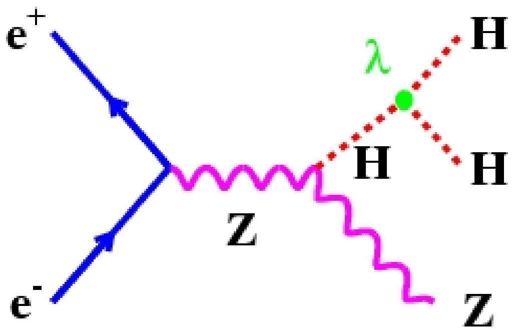
Need to consider detector as a whole

Detector Performance Goals

★ <u>Optimize</u> design of detector performance using key physics processes, e.g.







★ VERY DIFFICULT !

★ Need unbiased comparison
- Same/very similar reconstruction algorithms
- Common reconstruction framework
- Same Monte Carlo events

★ Use state of the art reconstruction

★ TIME TO **<u>START</u>** : propose looking at TPC length
- Relatively simple – reconstruction unchanged (?)

Conclusion

★ Physics at a linear collider places strict requirements on the TESLA detector

★ 2 years later - the TDR design still looks good

★ Time to start thinking about optimizing the detector design for the rich physics potential of TESLA

★ Remain open to new ideas..... (e.g. see Jim Brau's talk)

Many Thanks to:

Chris Damerell, Thorsten Kuhl, Pascal Gay, Markus Schumacher, Ron Settles, Henri Videau