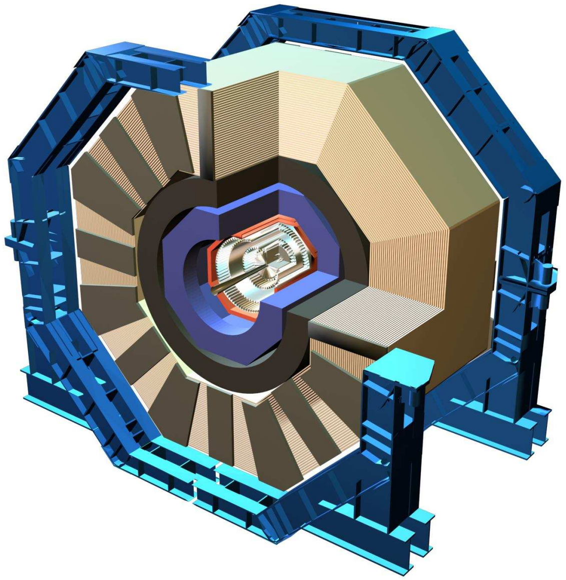
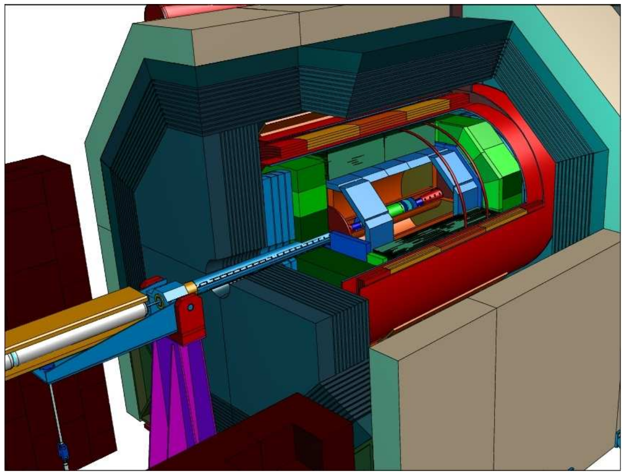
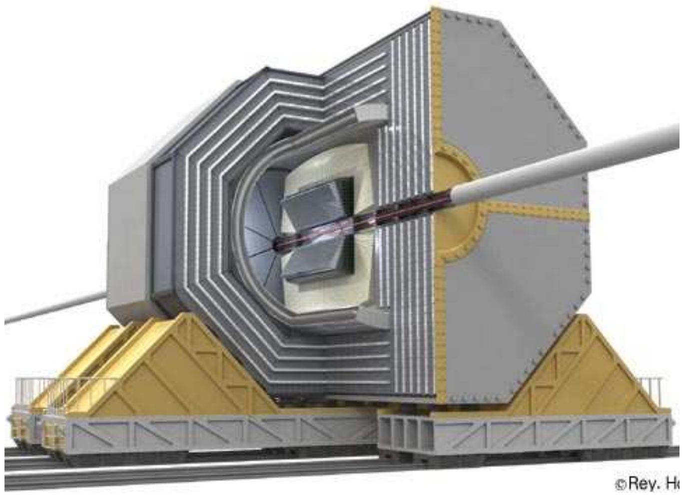
The Detector Concepts

Klaus Mönig







Introduction

- The GDE has requested costed detector concepts by the end of 2006
- These concepts should show that the required performance can be reached at a known cost
- Typical improvements wrt. LEP/SLC: factor 2-10
- The concepts should trigger a focused R&D program for detectors
- The concepts are not meant to be proto-collaborations
- Anybody should feel free to contribute to as many concepts as he likes
- Three established international concepts
  - SiD: follows from the American small detector
  - LDC: follows from the TESLA and the American large detector
  - GLD: follows from the GLC detector
- A new 4th concept based on the dream concept

Requirements for the detector

The task of ILC is precision measurements

This means

- Reconstruct all available channels
- with the highest possible efficiency
- the lowest possible systematics
- insensitive to machine-related background

Because of the environment an ILC detector is often considered “easy”

However the extreme precision requirements make the detector pretty challenging

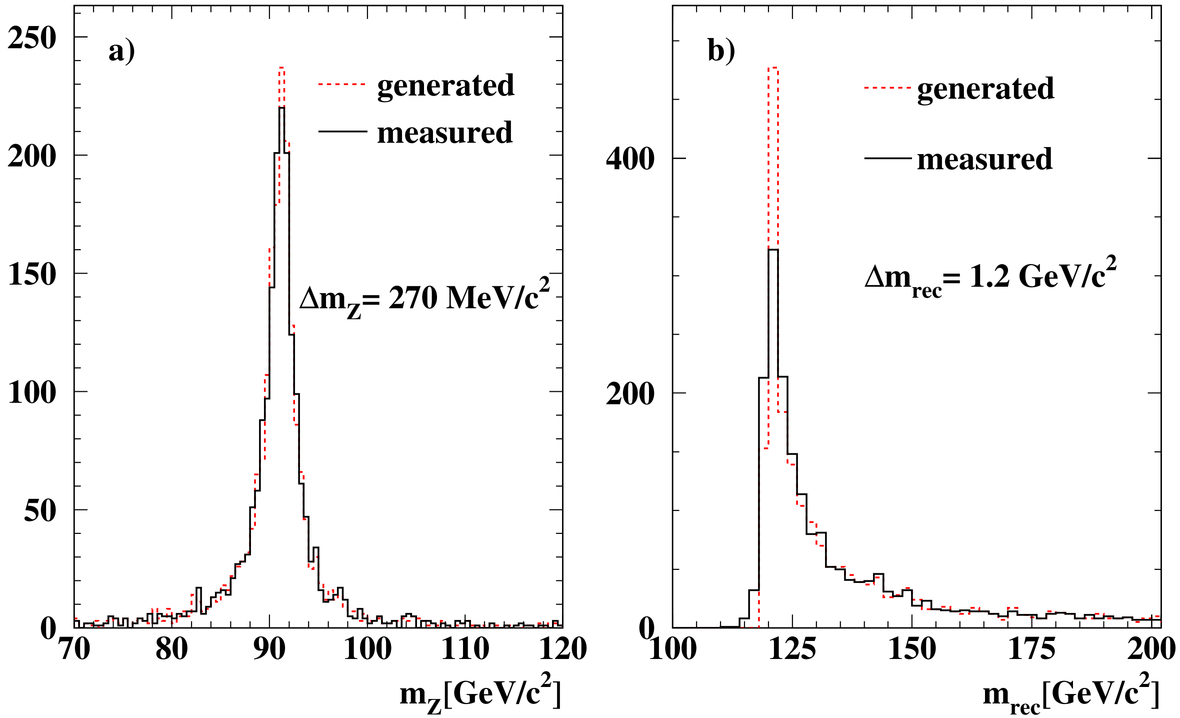
Benchmarks for the detector design

Momentum resolution

Want to reconstruct ZZH coupling from $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$ using the $\mu^+\mu^-$ recoil mass

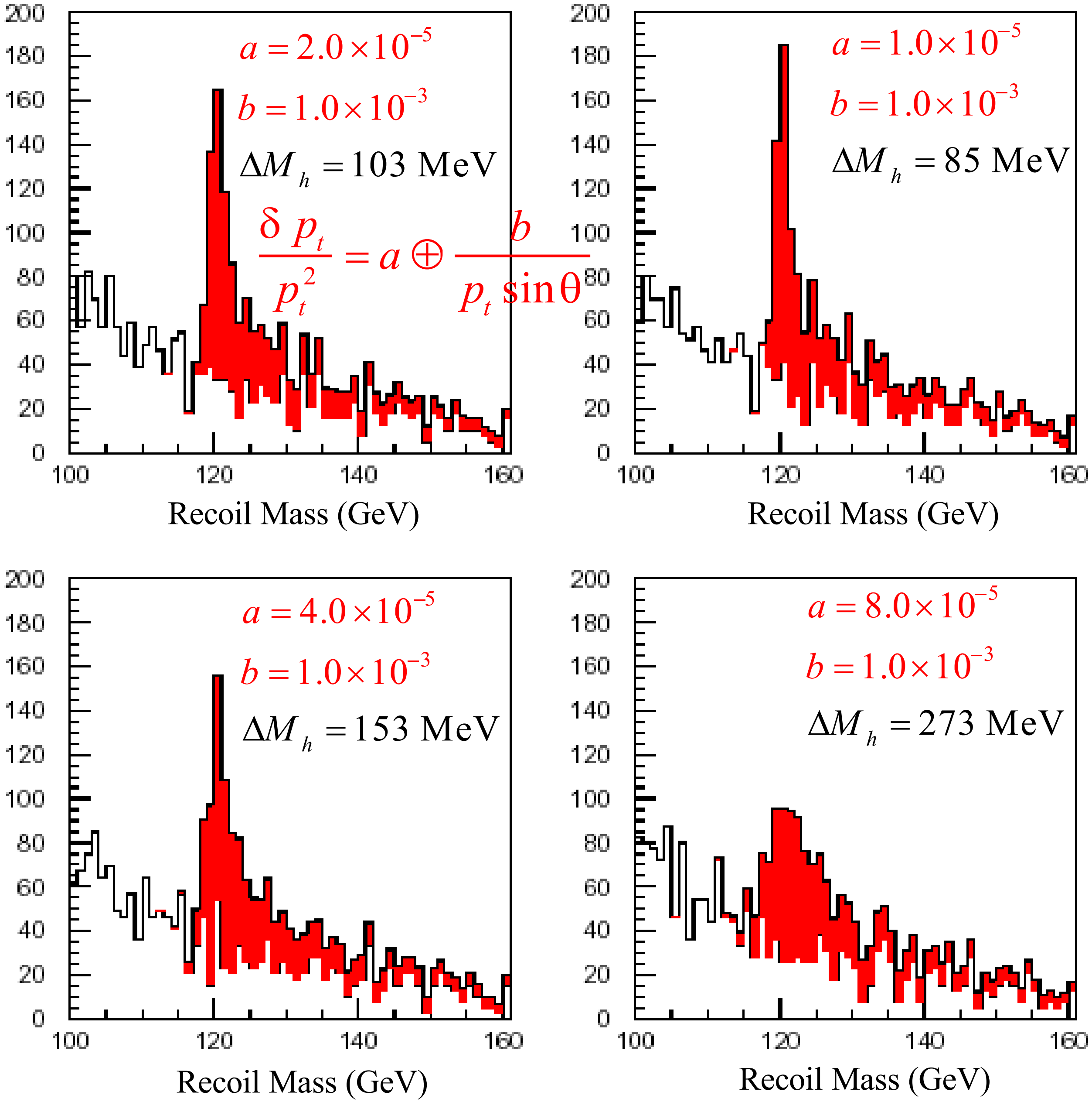
Need $\Delta\frac{1}{p} \approx 4 \cdot 10^{-5}/\,\mathrm{GeV}$ for large momenta

Generated and reconstructed $\mu^+\mu^-$ mass and recoil mass



Is a better momentum resolution useful?

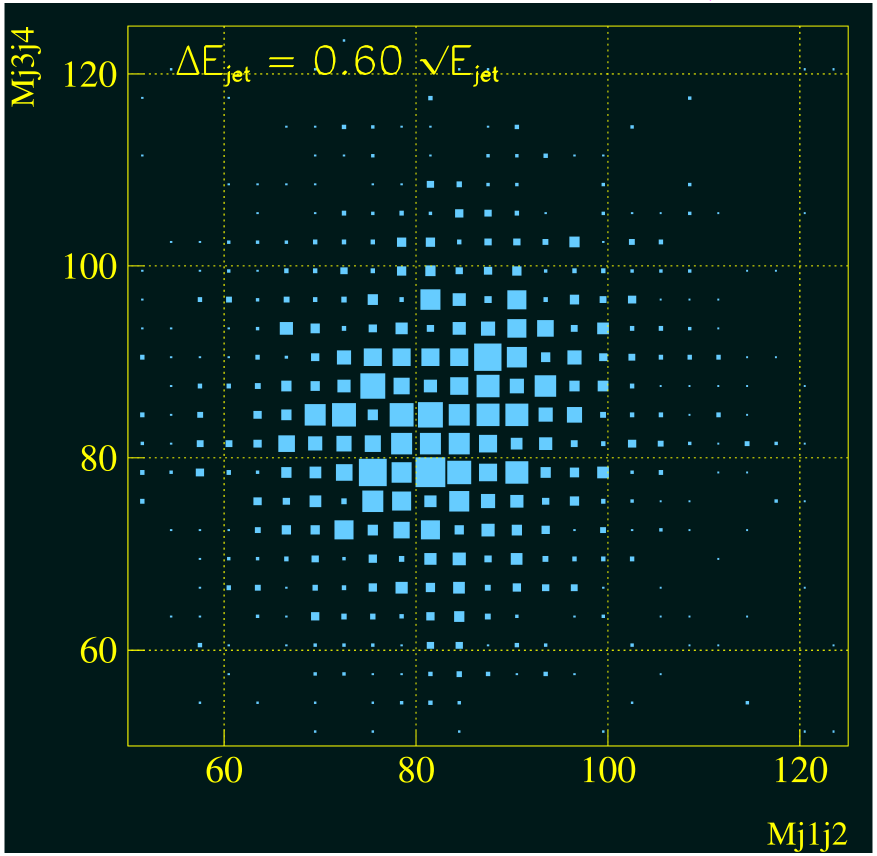
- Even better momentum resolution can give sharper signals
- However effect on physics quantities (H mass after constrained fit, H branching ratios, SUSY masses) seems modest

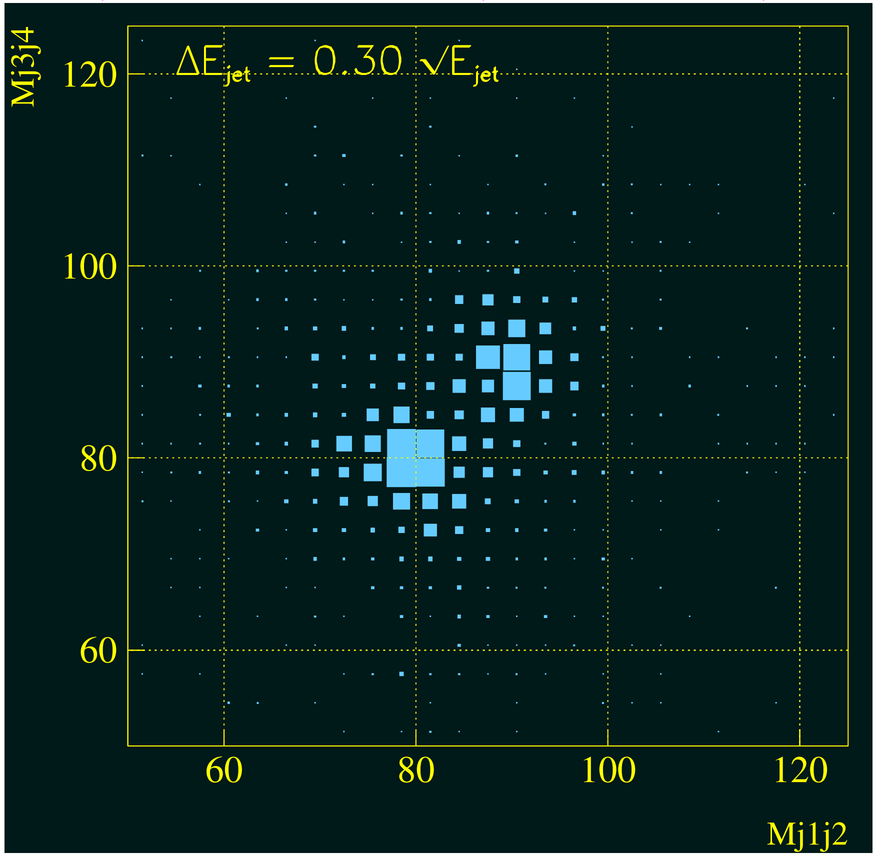


Energy flow in jets

- Some processes where WW and ZZ need to be separated without beam constraints (e.g. $e^+e^- \to \nu\nu WW$, $\nu\nu ZZ$)
- This requires a resolution of about $\Delta E/E = 30\%/\sqrt{E}$

WW-ZZ separation for $\Delta E/E = 60\%/\sqrt{E}$ and $\Delta E/E = 30\%/\sqrt{E}$

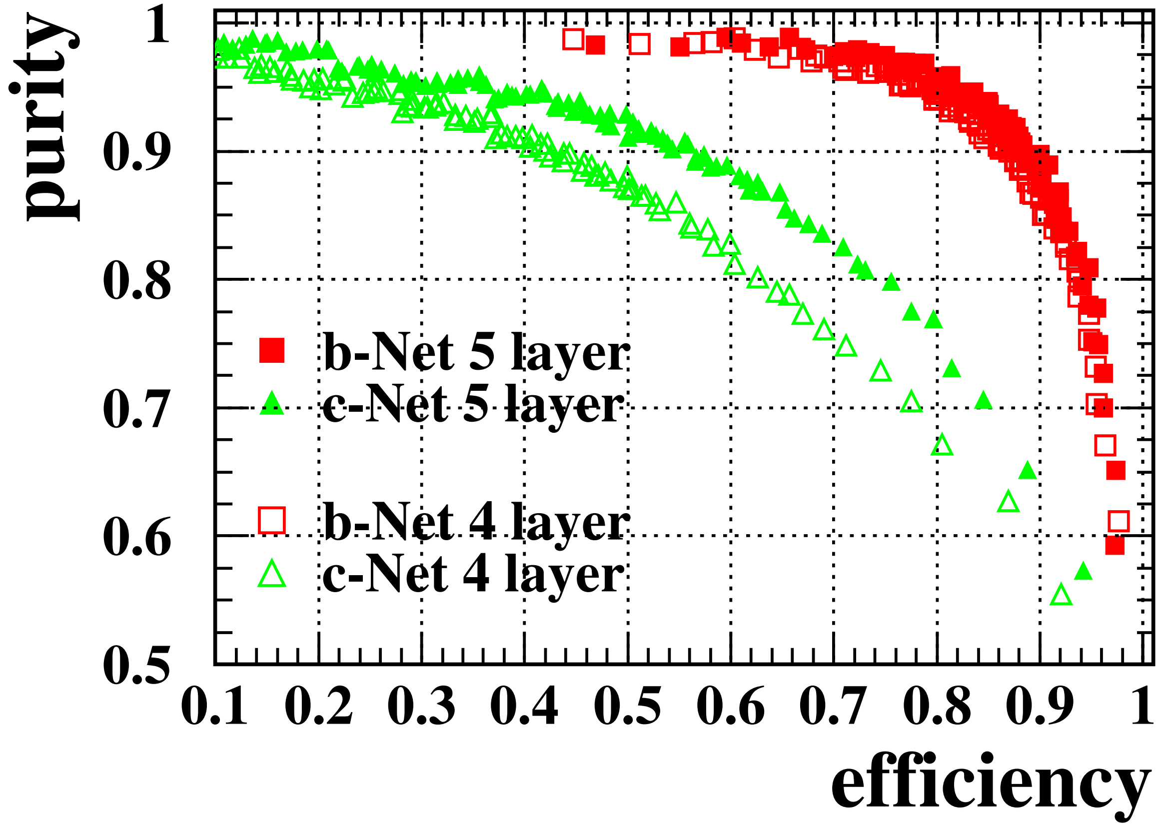




B-tagging

- Want to measure $BR(H \to c\bar{c})$ which is $< 10\%$ of $BR(H \to b\bar{b})$
- Have to tag 4-b final states ($e^+e^- \to ZHH$, $e^+e^- \to t\bar{t}H$ under huge non-b and 2-b background

Efficiency/purity for the b-tagging in the LDC



- b-tagging quite robust, but remember

$$\epsilon_{tot} \propto \epsilon_b^4$$

- c-tagging very sensitive to detector quality

Particle Flow

Particle flow is the common paradigm of the 1st three concepts

How to measure the energy of a jet?

- Classical method: Calorimetry
  - typical event: 30% electromagnetic and 70% hadronic energy
  - typical resolution: $10\%/\sqrt{E}$ for Ecal and $50\%/\sqrt{E}$ for Hcal
  - ➠ $\Delta E/E > 45\%/\sqrt{E}$ for jets
- The particle flow method
  - typical event: 60% charged tracks 30% electromagnetic and 10% neutral hadronic energy
  - tracking resolution negligible on this scale
  - ➠ $\Delta E/E = 20\%/\sqrt{E}$ for jets possible in principle

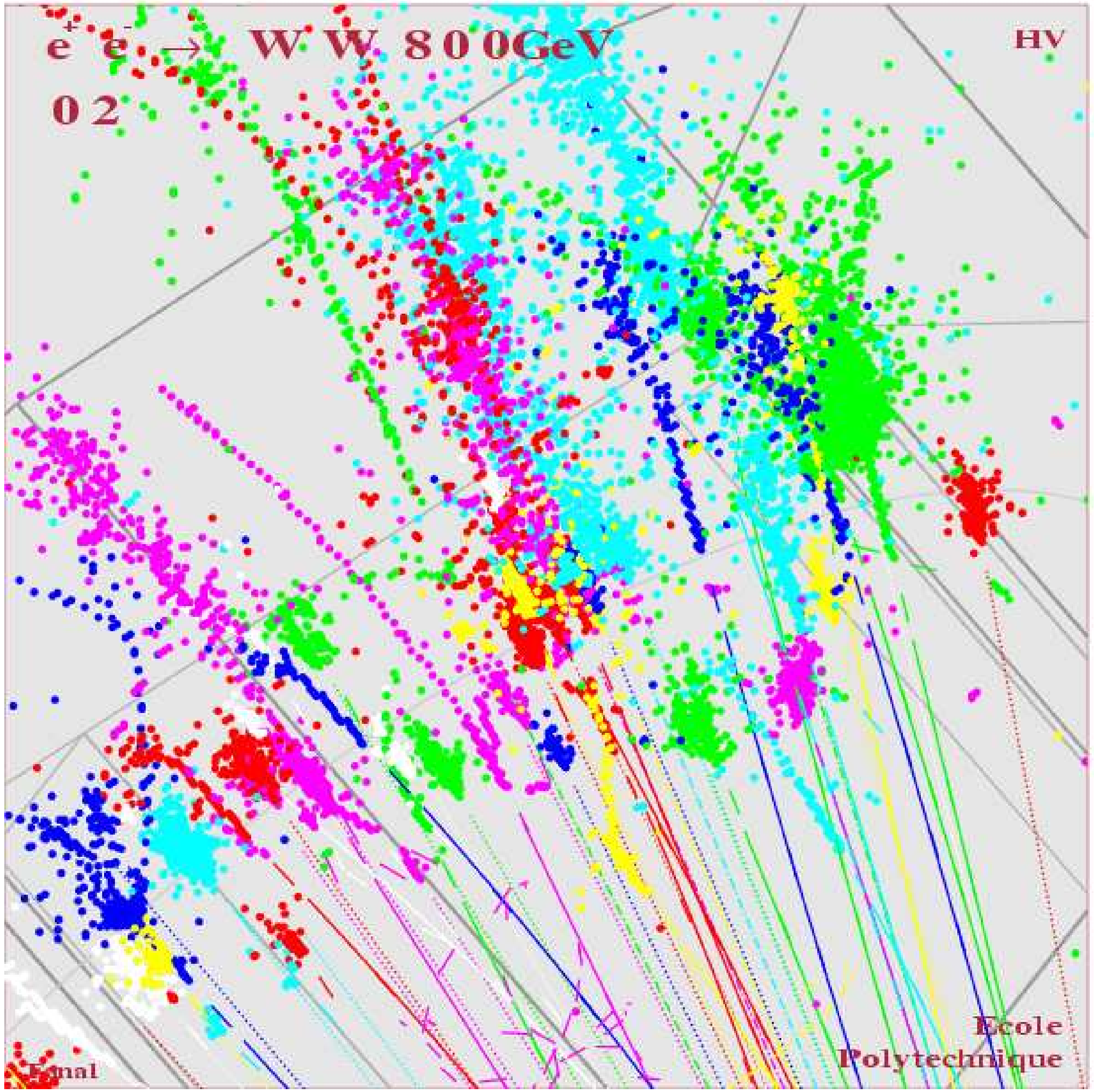
Main problem: Confusion

- At high energy jets are very narrow

➠ Tracks are very close at the calorimeter

- Need very fine granularity of calorimeter and sophisticated software to separate showers

- Energy resolution still dominated by confusion term



How to optimise the detector?

Optimisation of particle flow

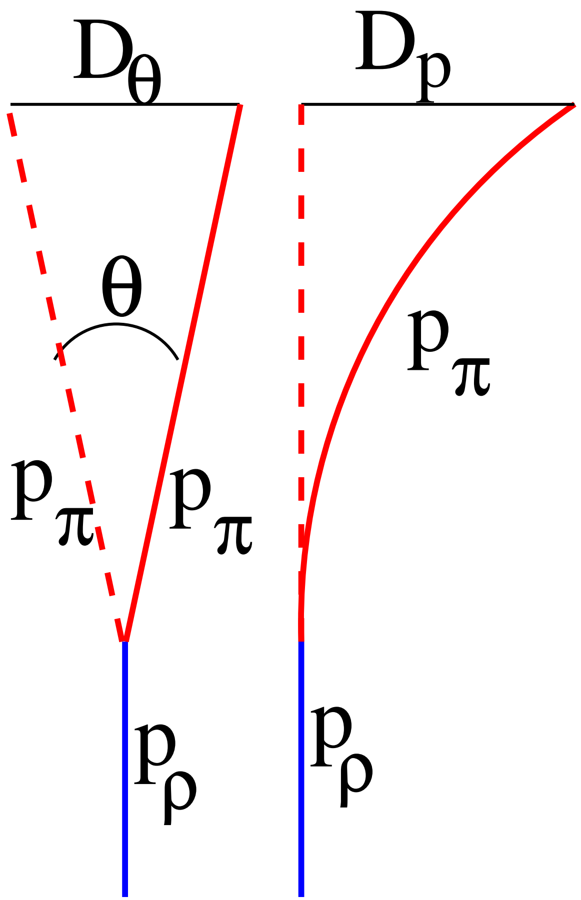
How to choose R and B-field?

- Distance between showers due to natural opening angle (D_θ) goes with R
- Distance due to magnetic deflection (D_p) goes with BR^2
- Example: symmetric ρ decay at 90°

$$D_\theta = \frac{2m_\rho R}{p_\rho} \quad D_p = \frac{0.3BR^2}{p_\rho}$$

  – ρ-mass is typical 2-particle mass in a jet
  – in the relevant parameter range D_θ and D_p are very similar

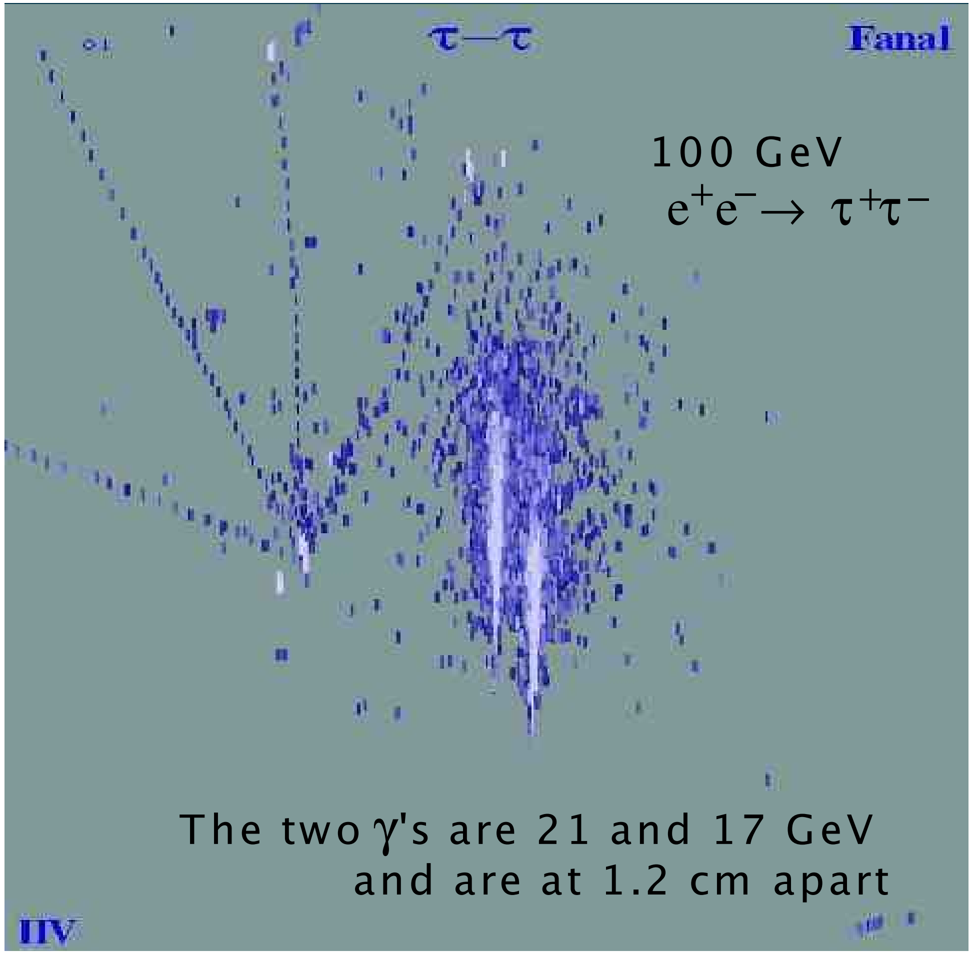
➡ No simple scaling law applies



Optimisation of the calorimeters

ECAL:

- Transverse shower size ≈ Molière Radius
  ⇒ Dense high Z material (e.g. W) with small gaps ($r_M \sim 1$cm)
- Want little hadronic showering in ECAL ⇒ large λ/X_0 ⇒ favours high Z as well
- Recent studies show that read-out resolution significantly smaller than r_M is useful ⇒ optimisation in progress



HCAL:

- Hadron showers are much more spread than electromagnetic ones
- Separation power can only be checked with sophisticated reconstruction software
- Two concepts
  - Analogue: small pads $\left(\mathcal{O}(3 \times 3\text{cm}^2)\right)$ with analogue readout
  - Digital: very small pads $\left(\mathcal{O}(1 \times 1\text{cm}^2)\right)$ with binary (or 2-bit) read-out
- Both versions are under intensive study
- The required solenoid has a thickness around 2λ

➠ HCAL inside solenoid is a must

Momentum resolution

$$\Delta \frac{1}{p} \propto \frac{\delta}{R^2 B \sqrt{n}}$$

4D space for optimisation:

detector resolution – number of points – detector radius – B field

B-tagging

Critical item: IP resolution of low momentum particles

IP error from multiple scattering: $\sigma \propto \sqrt{X} r$

X: thickness (in X_0) of beampipe and 1st VXD layer,
r: radius of 1st VXD layer

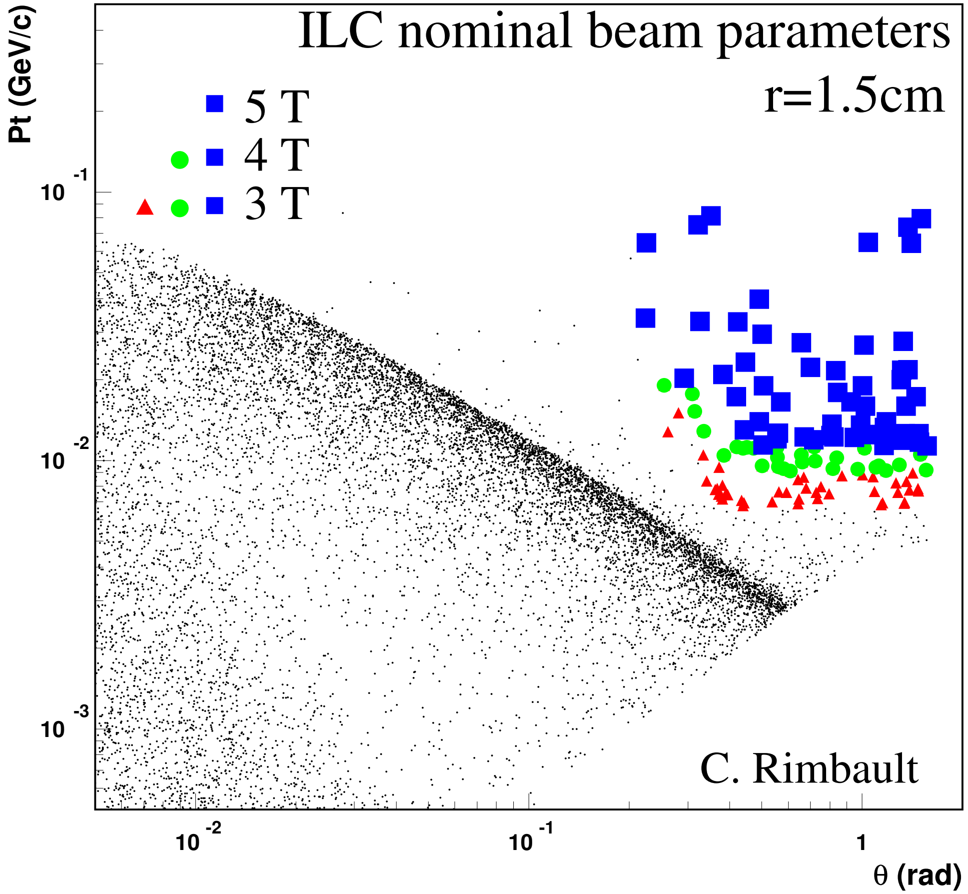
b-tagging and B-field

- Large e^+e^--pair background with small p_T from beamstrahlung
- Maximum r as function of p_T for pairs is determined by B-field

➠ Large B-field reduces background at given radius

- High background band moves to larger p_t with larger $\mathcal{L}$

VXD hits from pair background



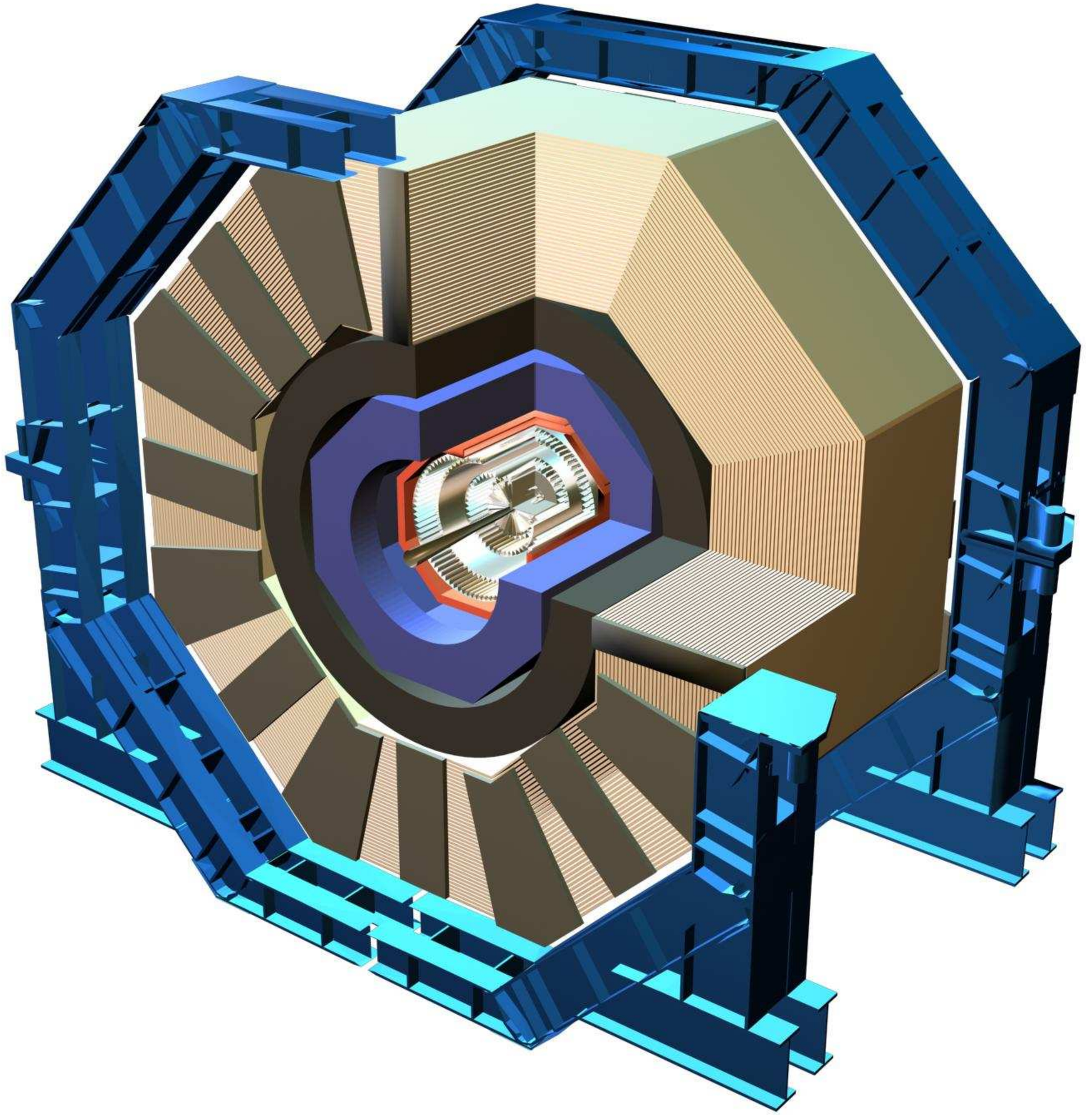
The three Detector concepts

- SiD:
  - Small radius with high field ($R = 1.3\,\text{m},\ B = 5\,\text{T},\ BR^2 = 8.5\text{Tm}^2$)
  - Few track measurements with high resolution (Si)
  - SiW calorimetry
  - $r_{\text{min}}(\text{VXD}) = 1.4\,\text{cm}$
- LDC:
  - Medium R with medium field ($R = 1.7\,\text{m},\ B = 4\,\text{T},\ BR^2 = 11.6\text{Tm}^2$)
  - Many track measurements with medium resolution (TPC)
  - SiW calorimetry
  - $r_{\text{min}}(\text{VXD}) = 1.5\,\text{cm}$
- GLD:
  - Large radius with low field ($R = 2.1\,\text{m},\ B = 3\,\text{T},\ BR^2 = 13.2\text{Tm}^2$)
  - Many track measurements with medium resolution (TPC)
  - Scintillator-W calorimetry
  - $r_{\text{min}}(\text{VXD}) = 1.7\,\text{cm}$

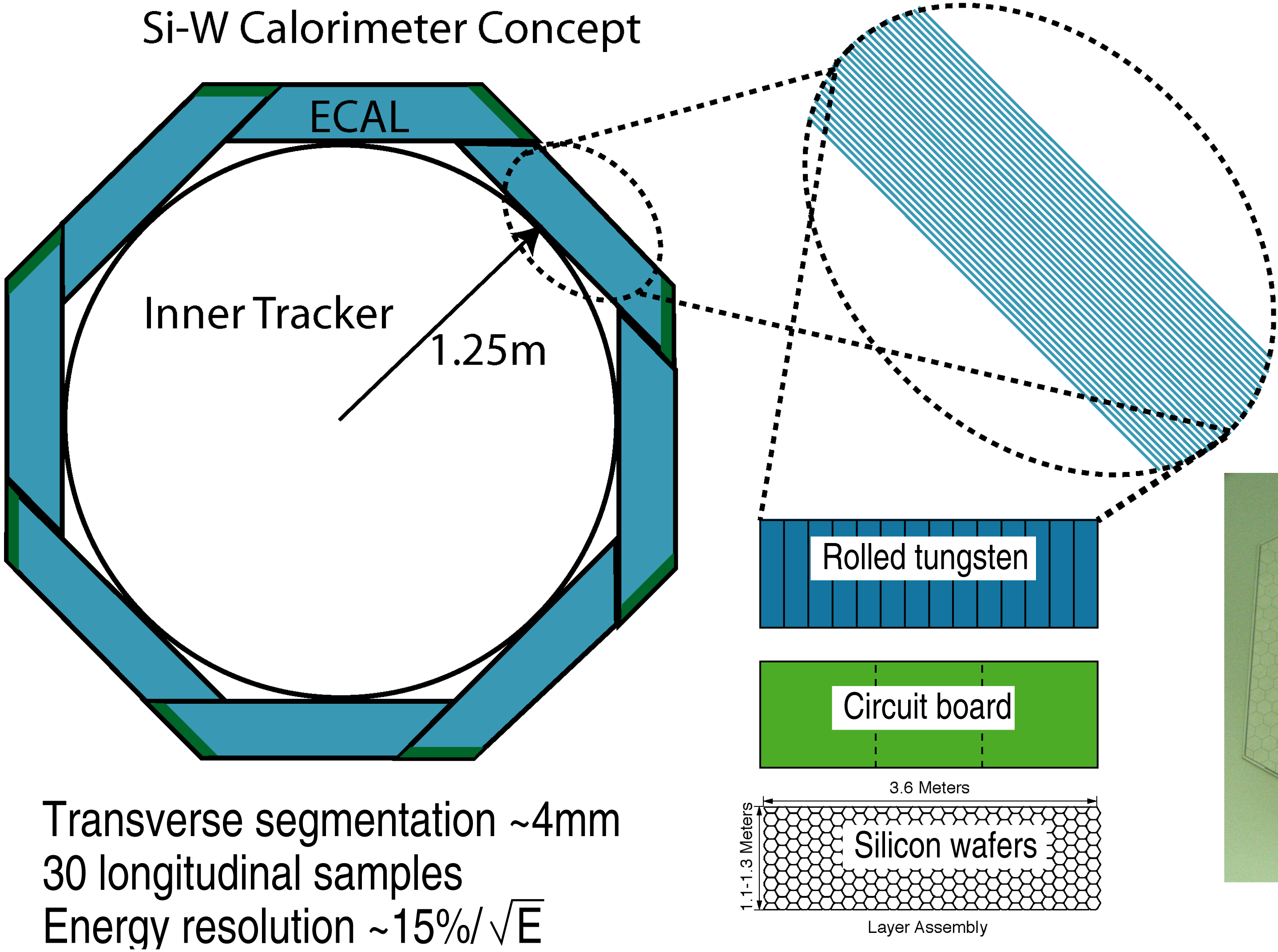
The SiD

Design philosophy

- Aim for SiW calorimeter with best possible resolution
- Keep radius small to make this affordable
- Compensate by high B-field (5 T) and very precise tracking (Si)
- Fast timing of Silicon to suppress background



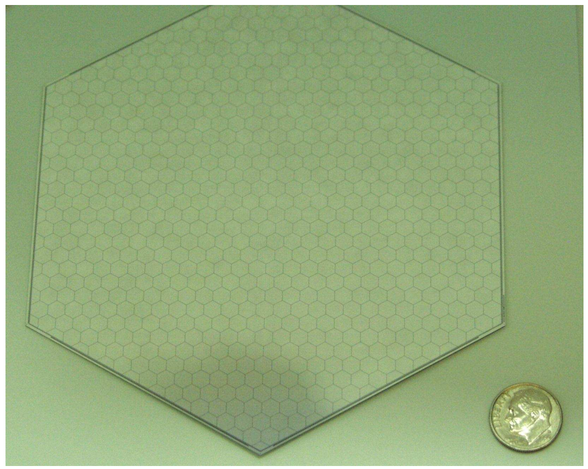
The SiD ECAL



Transverse segmentation ~4mm
30 longitudinal samples
Energy resolution ~15%/$\sqrt{E}$

Si pixel size:

- Prototype $16 mm^2$
- Readout chip $12 mm^2$
- Smaller possible if needed



Similar to LDC

The SiD HCAL

- W or stainless steel as absorber
- Different options for detector

  scintillator

  – pad size: $3 \times 3\text{cm}^2$ ➠ analogue readout needed

  – probably not cheap

  GEM

  – pad size: $1 \times 1\text{cm}^2$ ➠ digital possible

  – reliability is an issue, however first tests are positive

  – foils are expensive

  RPCs

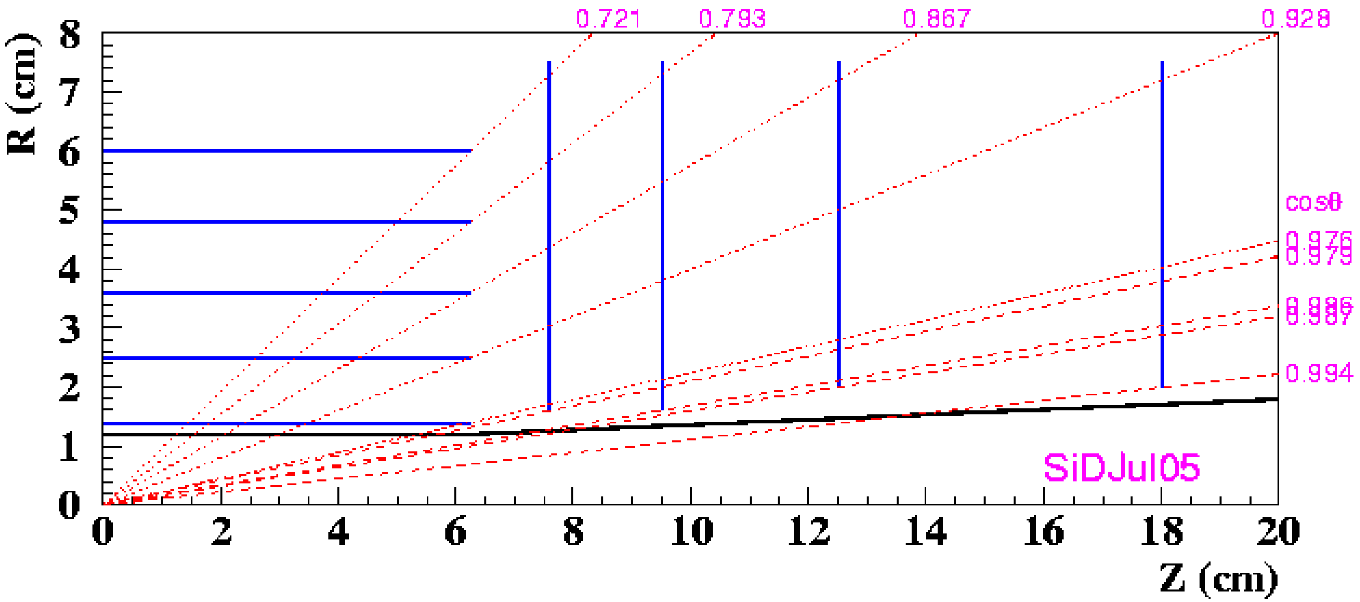
  – pad size: $1 \times 1\text{cm}^2$ ➠ digital possible

  – simple, cheap

  – however slow and possible problems with cross-talk

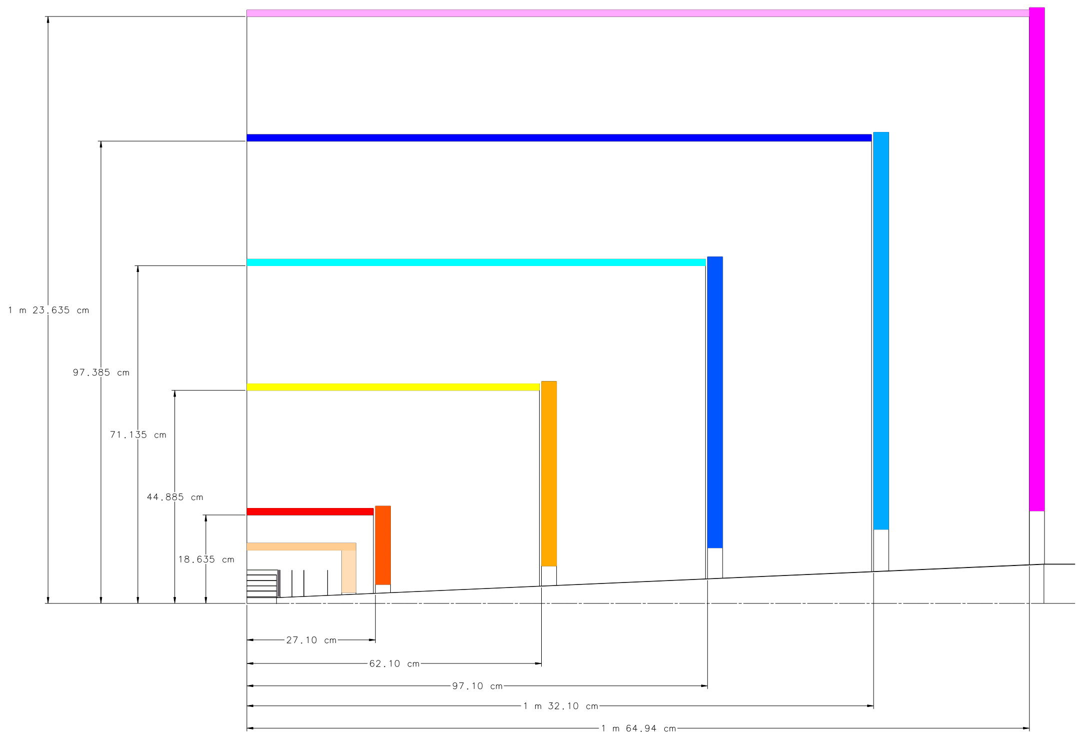
SiD tracking and vertexing

The SiD vertex detector:

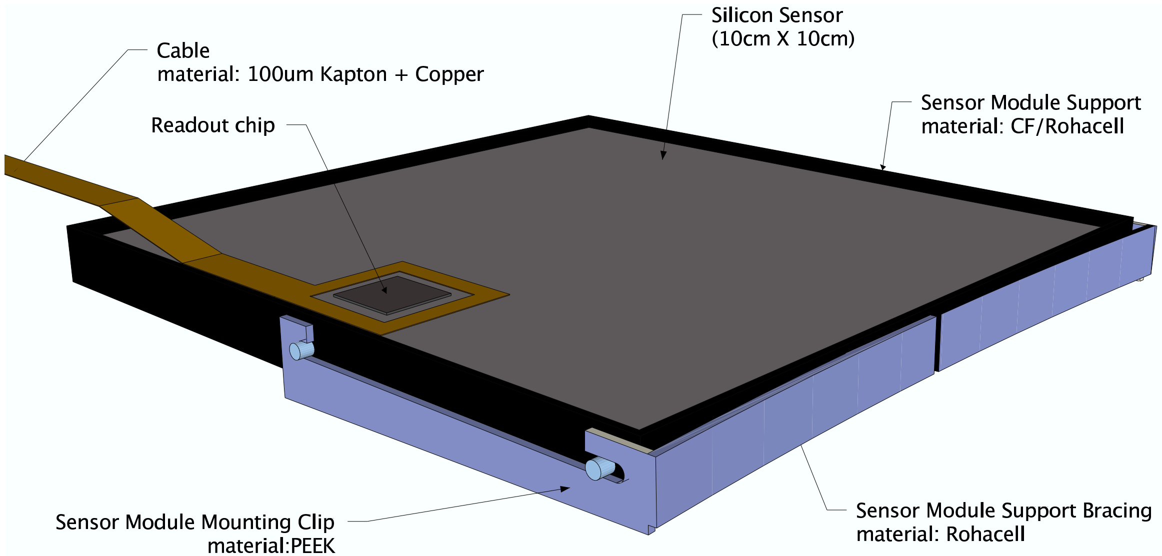


- 5 layers small pixel (e.g. CCD) and disks in endcaps
- Small inner radius (1.4 cm) due to high B-field

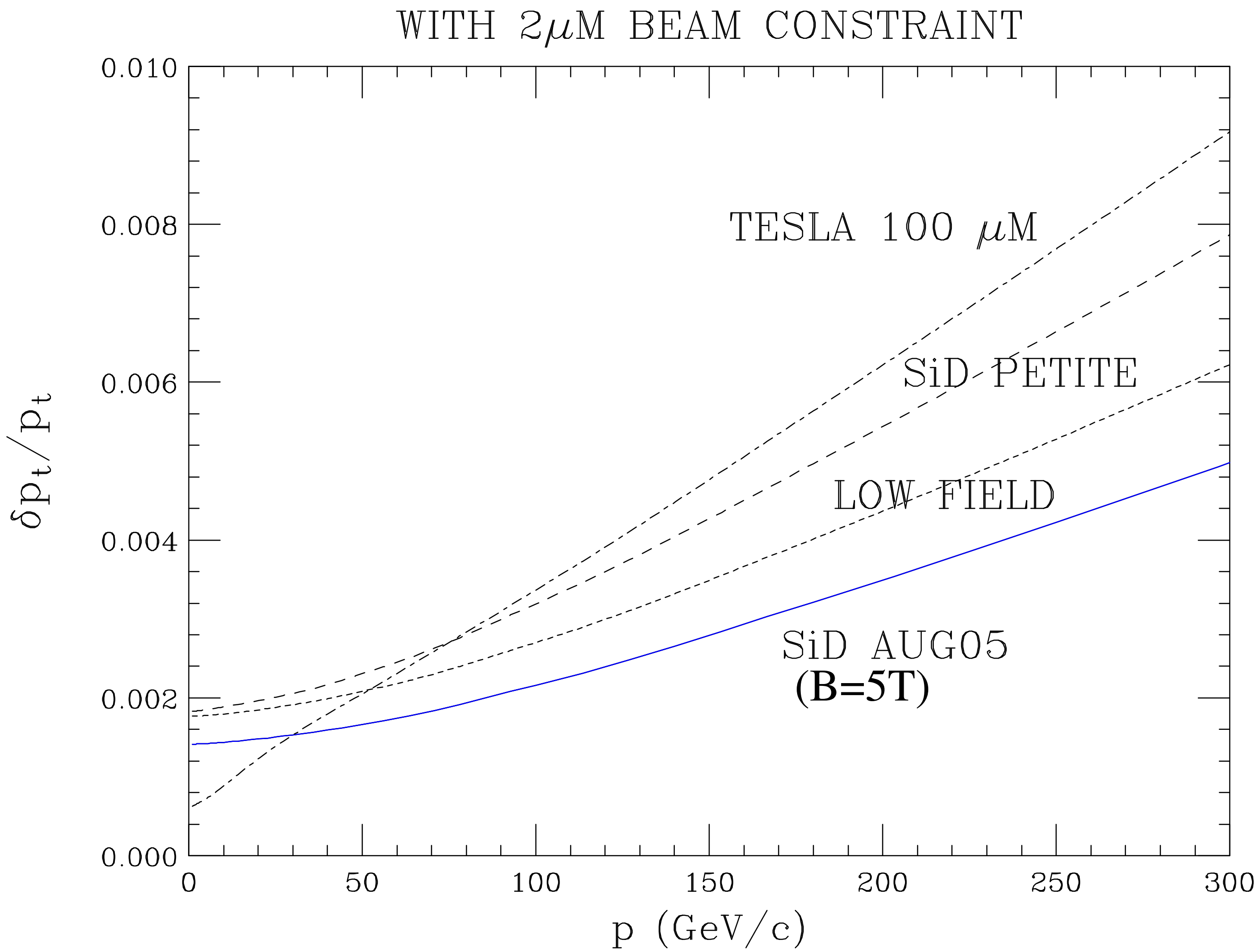
The SiD tracker:



- 5 barrel cylinders with ϕ readout only
- 4 endcap disks with r and ϕ readout
- Si modules of $10 \times 10\,\mathrm{cm}^2$

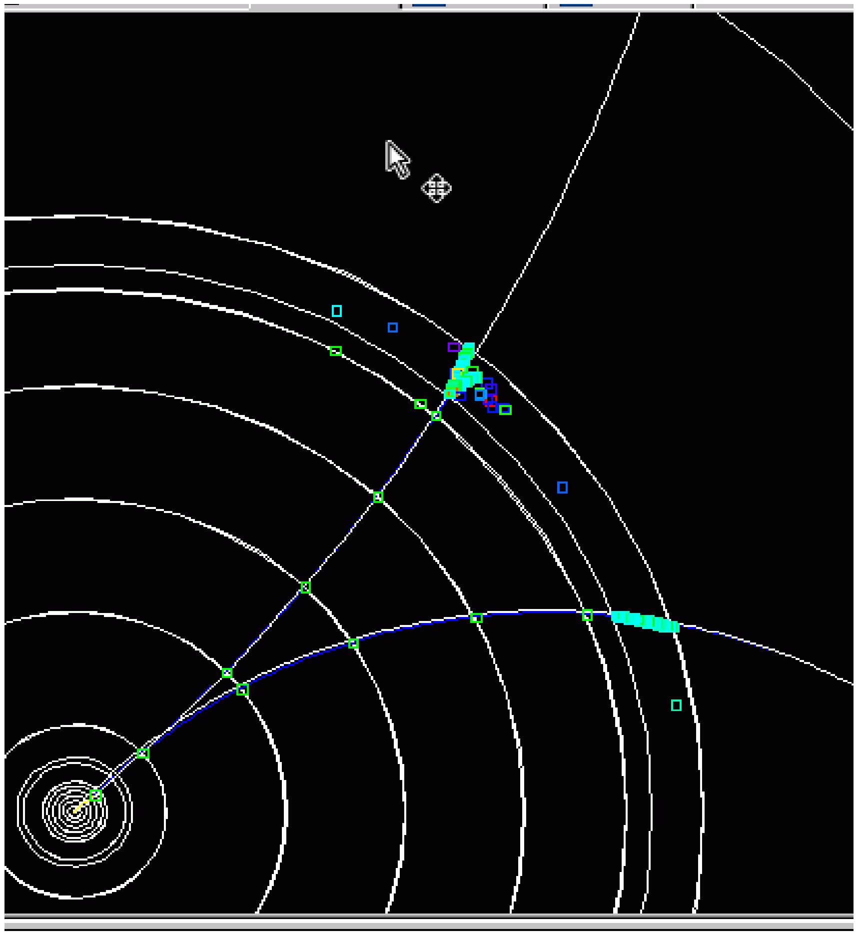


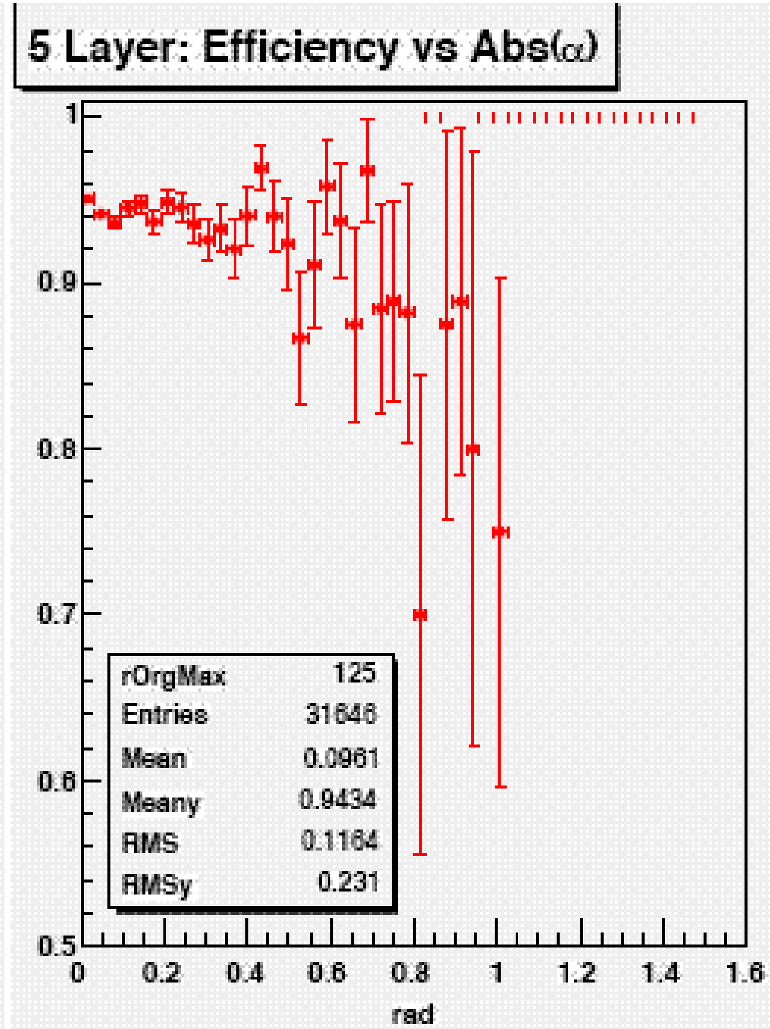
This tracking system has an excellent momentum resolution



Pattern recognition philosophy in the SiD tracker

- Find tracks in VXD only (pixels, $\epsilon \sim 95\%$ in jets)
- Extrapolate tracks outward



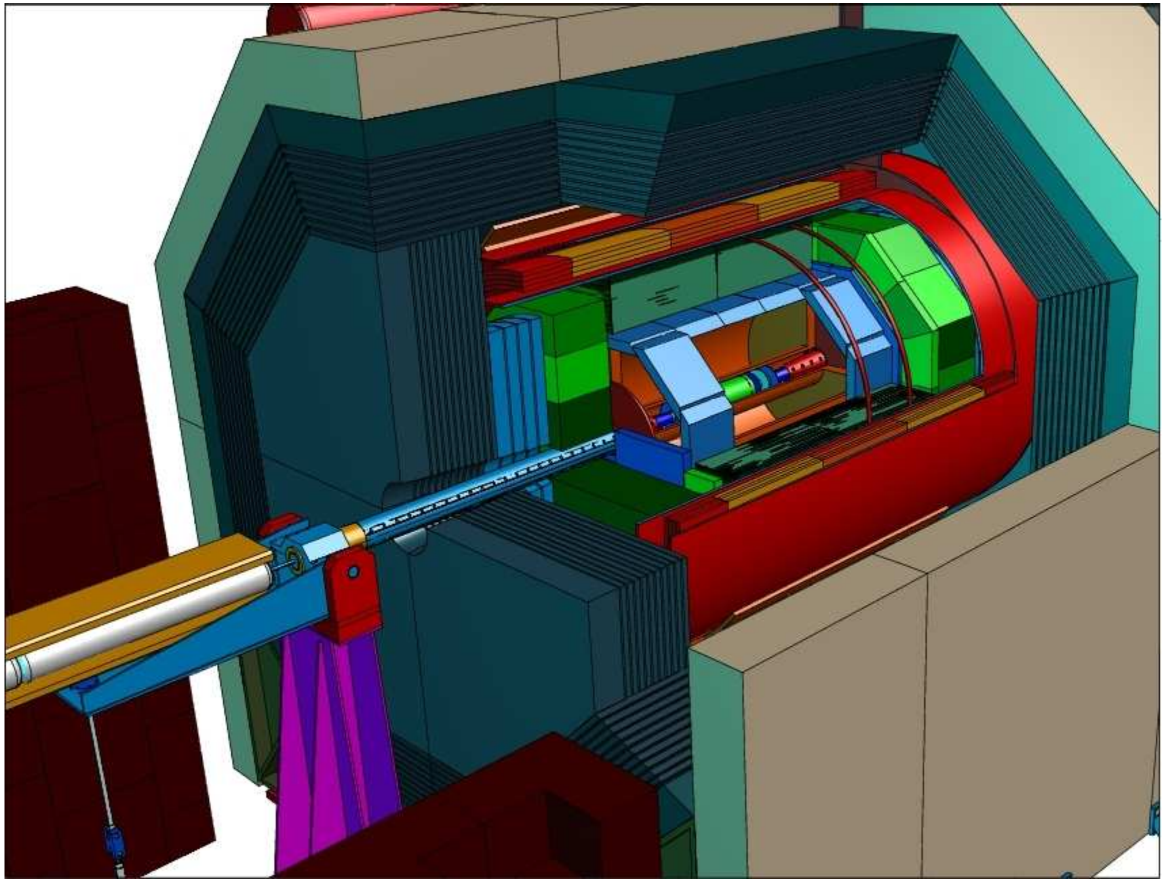


- Missing tracks (especially V^0s) can be extrapolated inwards from ECAL

The LDC

Design philosophy

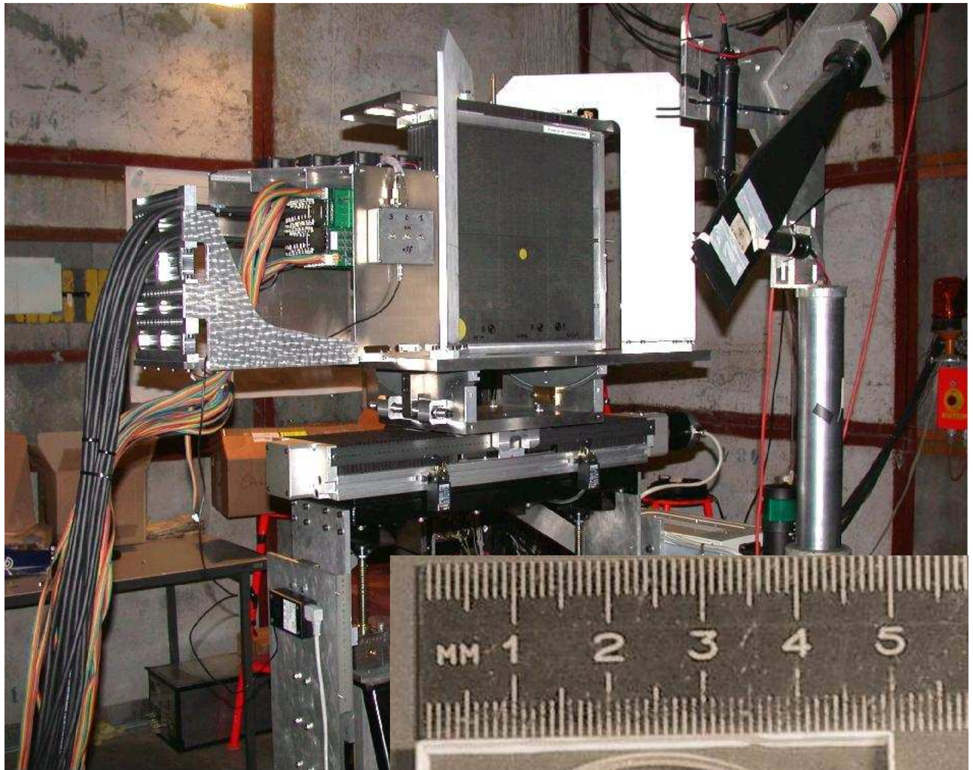
- Fine resolution calorimeter for particle flow
- Gaseous tracking for high tracking efficiency and redundancy
- Large enough radius and high enough B-field (B=4 T) to get required momentum resolution



LDC calorimetry

ECAL

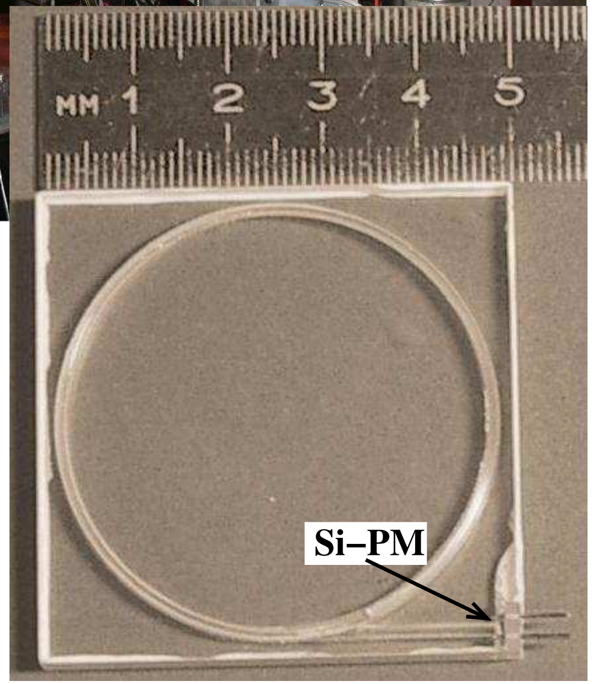
- A SiW calorimeter similar to SiD is planned
- A prototype has already been tested in the beam



HCAL

- Two options:
  (Semi-)Digital:
  - similar to SiD

  Analogue:
  - scintillating tiles, $3 \times 3\mathrm{cm}^2$ in front part, coarser in rear part
  - prototype under construction
  - common testbeam with ECAL next year



Tracking in the LDC

- Superconducting solenoid with $B = 4T$
- Vertex detector
- Main tracker: TPC

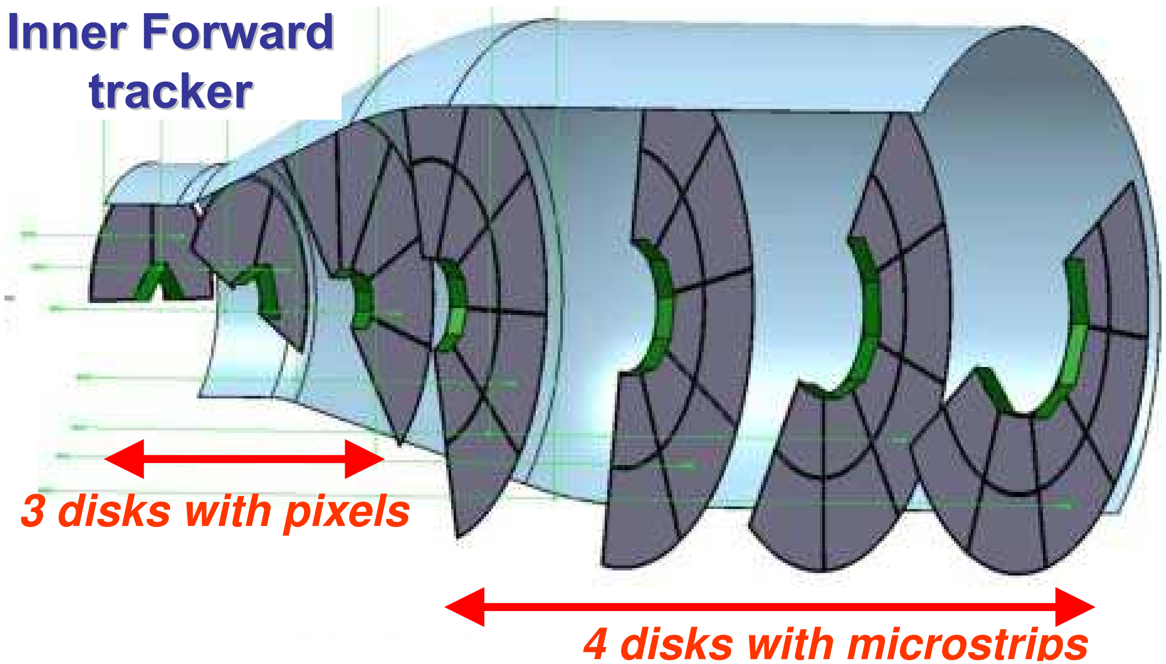
- Silicon tracker inside TPC consisting of barrel cylinders and forward disks
- Forward chamber behind TPC
- Silicon envelope possible, if needed

TPC challenges:

- To achieve required momentum resolution and background tolerance need many (> 100) pad rows
- Bunch structure prevents gating
- Large effort to solve both problems with MPGD detectors (GEM, micromegas)
- Common R&D with many institutes from LDC and GLD

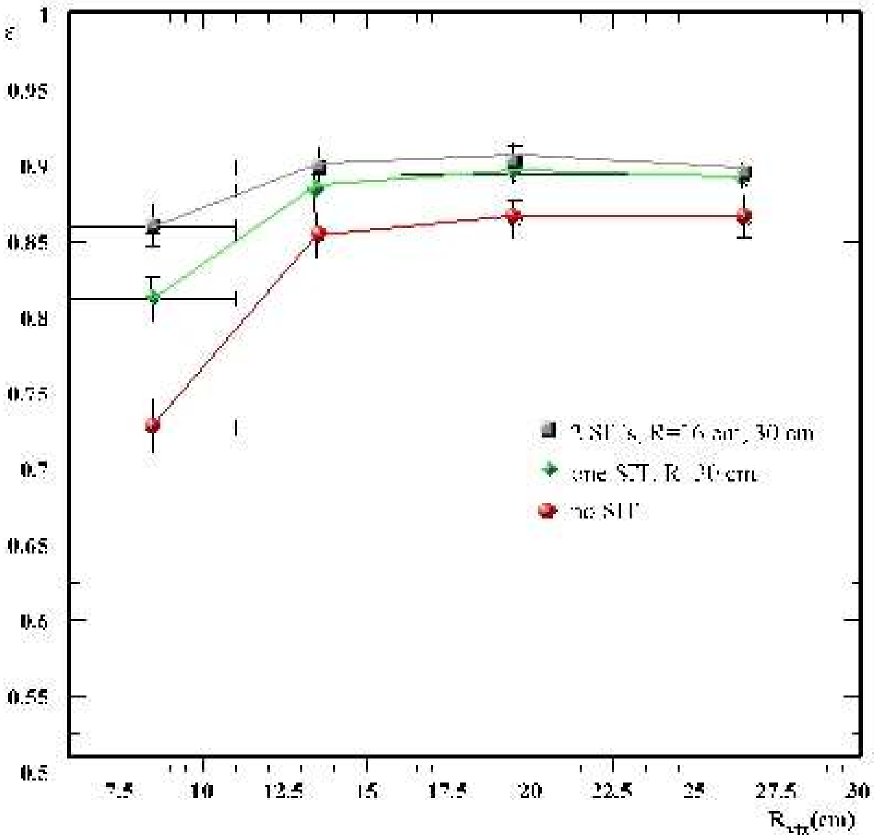
Inner silicon

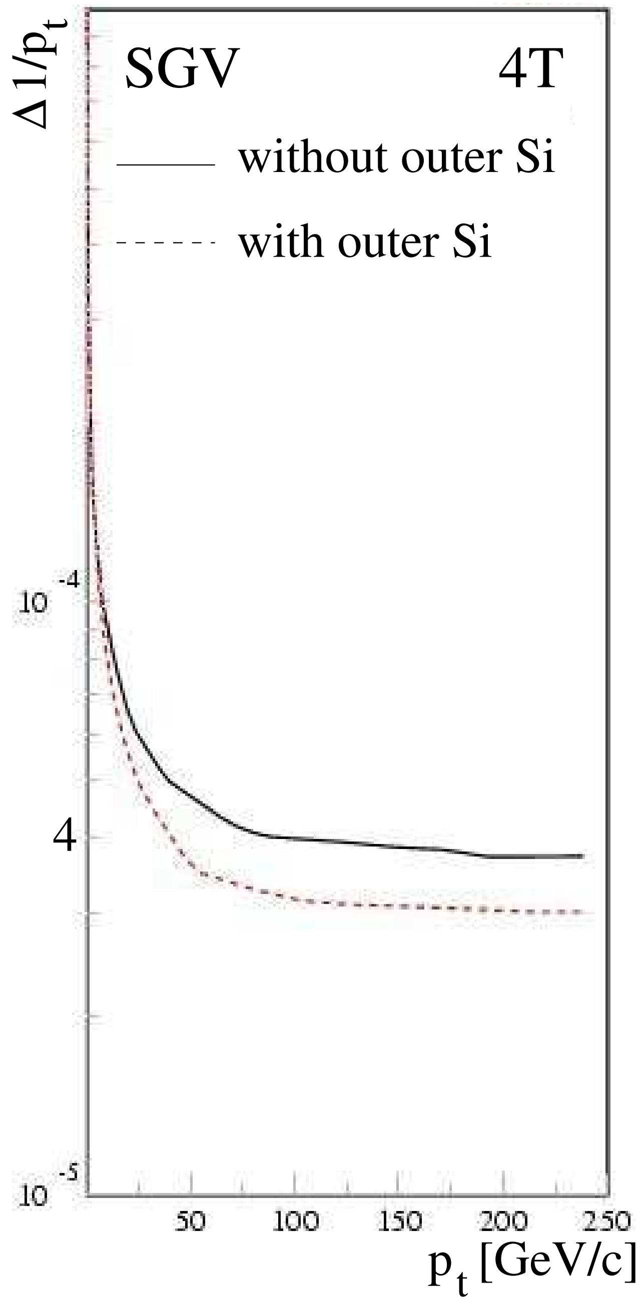
- Needed as link between TPC and VXD and for momentum resolution
- Work on design with very low systematics for beam parameter measurements



Performance of the tracking system:

- Tracking efficiency 98.8%
- Essentially independent of background
- K_s^0 rec. efficiency $\sim 90\%$ with 2-layer SIT





- Momentum resolution $\Delta\frac{1}{p} = 4 \cdot 10^{-5}/$ GeV without outer Si

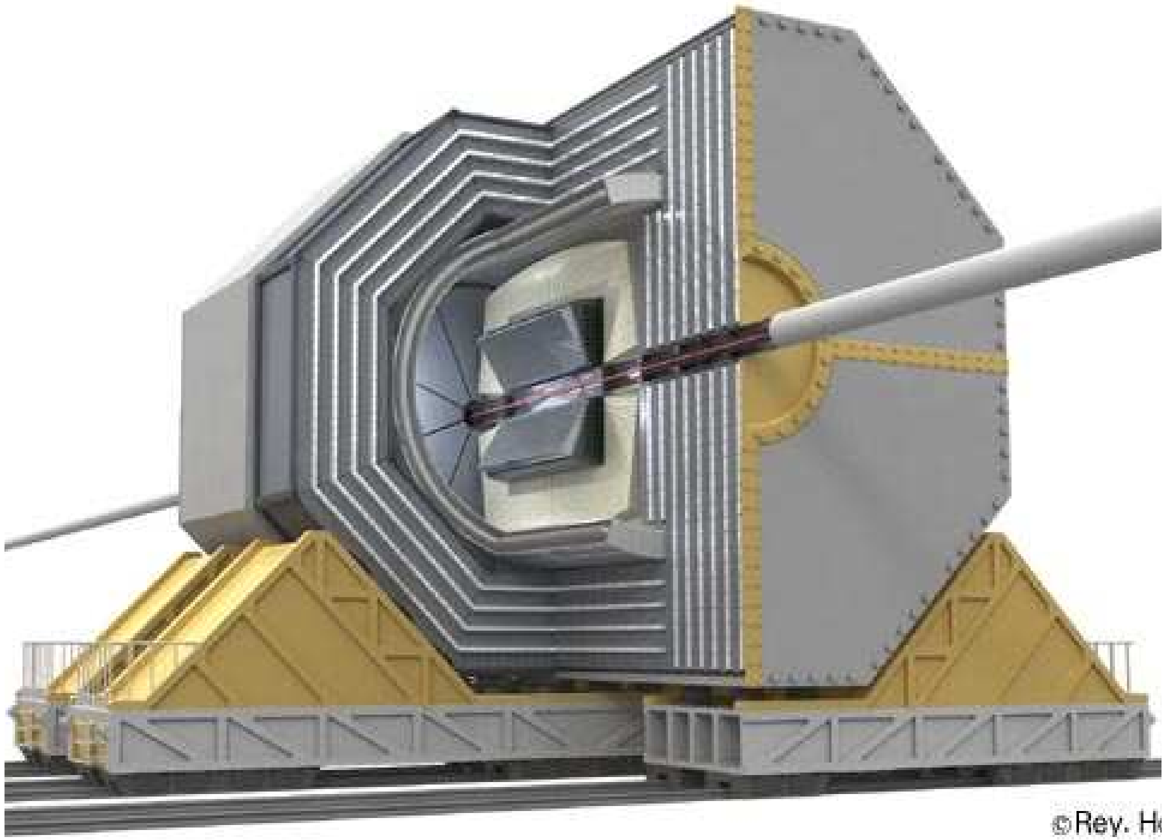
The LDC solenoid

- A prototype of the LDC solenoid exists
- It will be tested extensively by CMS in the next years
- The SiD solenoid is based on the same technology

The GLD

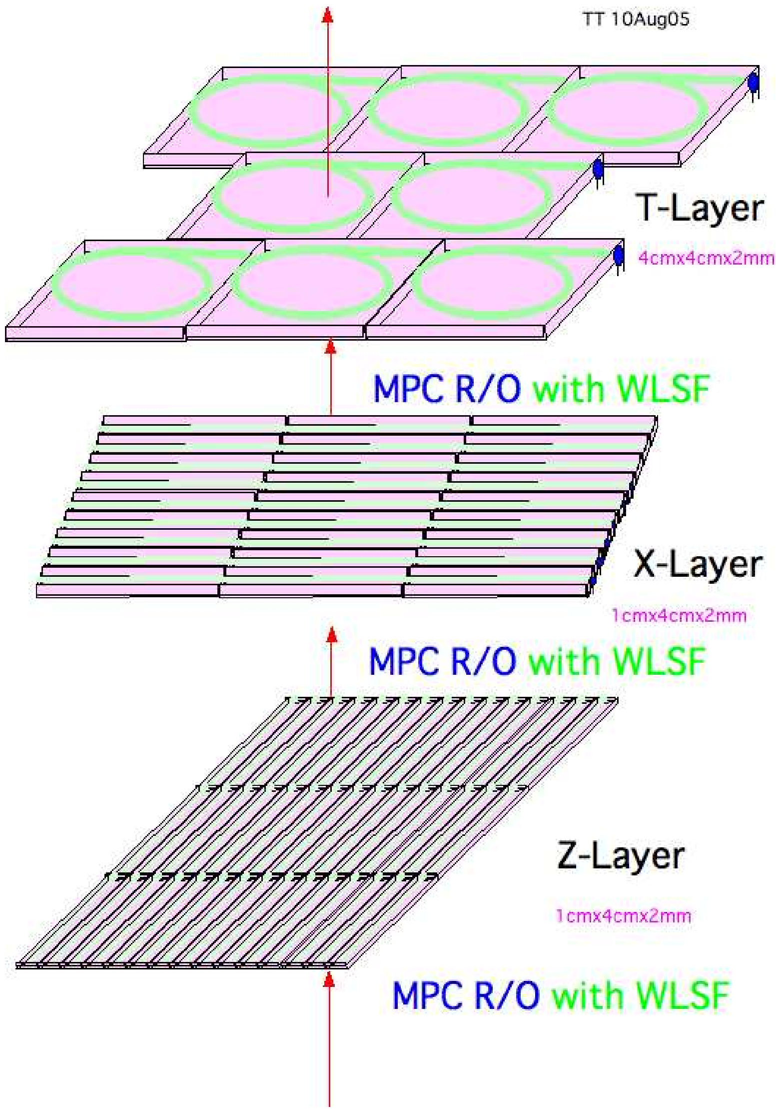
Design philosophy

- Large radius for particle flow optimisation
- Gaseous tracking for high tracking efficiency and redundancy
- Fine grained Scintillator-tungsten calorimeter
- Moderate B-filed (3 T)



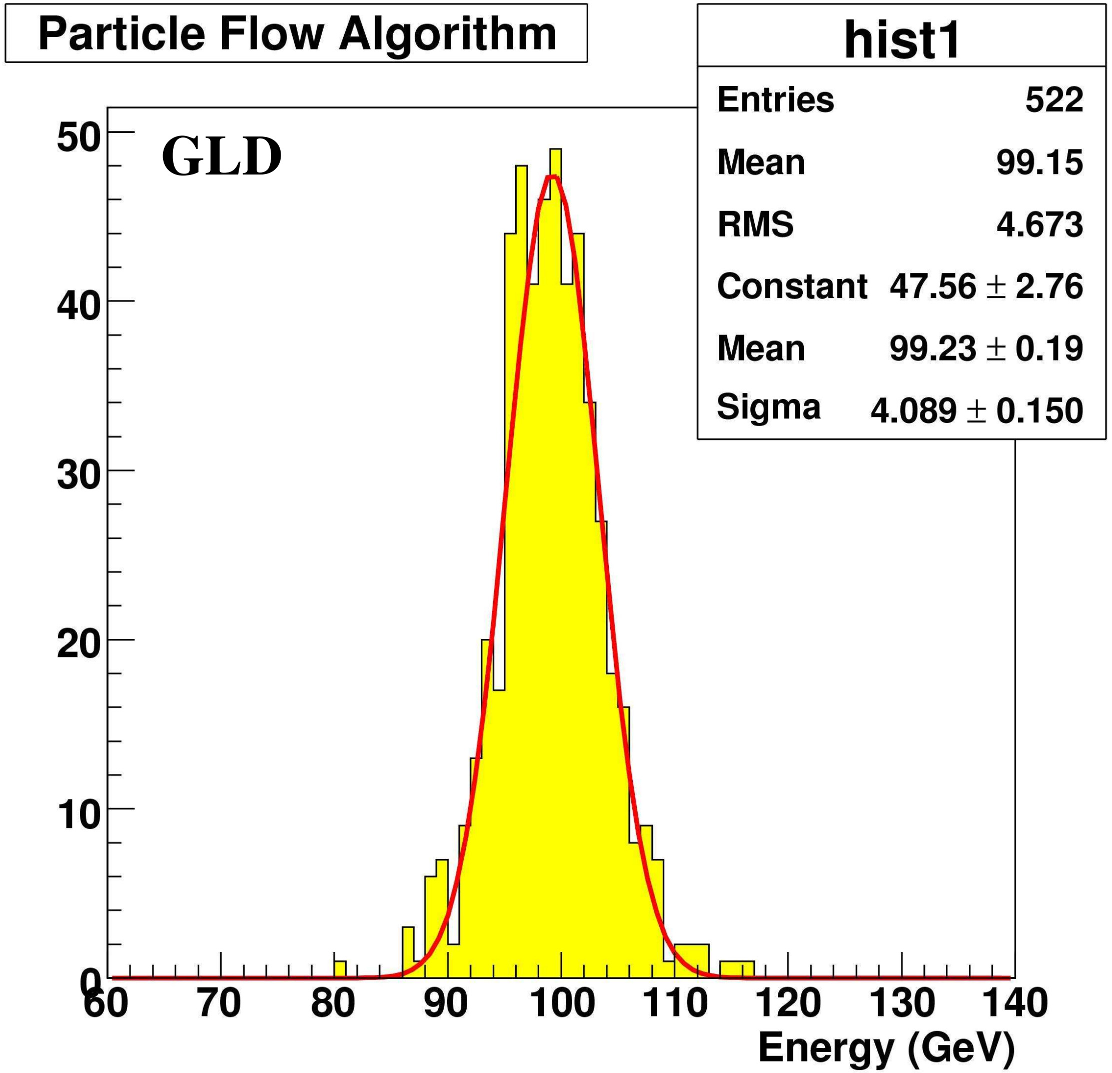
The GLD calorimeter

- SiW too expensive for the GLD radius
- Current baseline $4 \times 4\,\text{cm}^2$ pads interleaved with $1 \times 4\,\text{cm}^2$ strips for Ecal and Hcal
- Few Si layers for Ecal are discussed
- Digital Hcal is an option



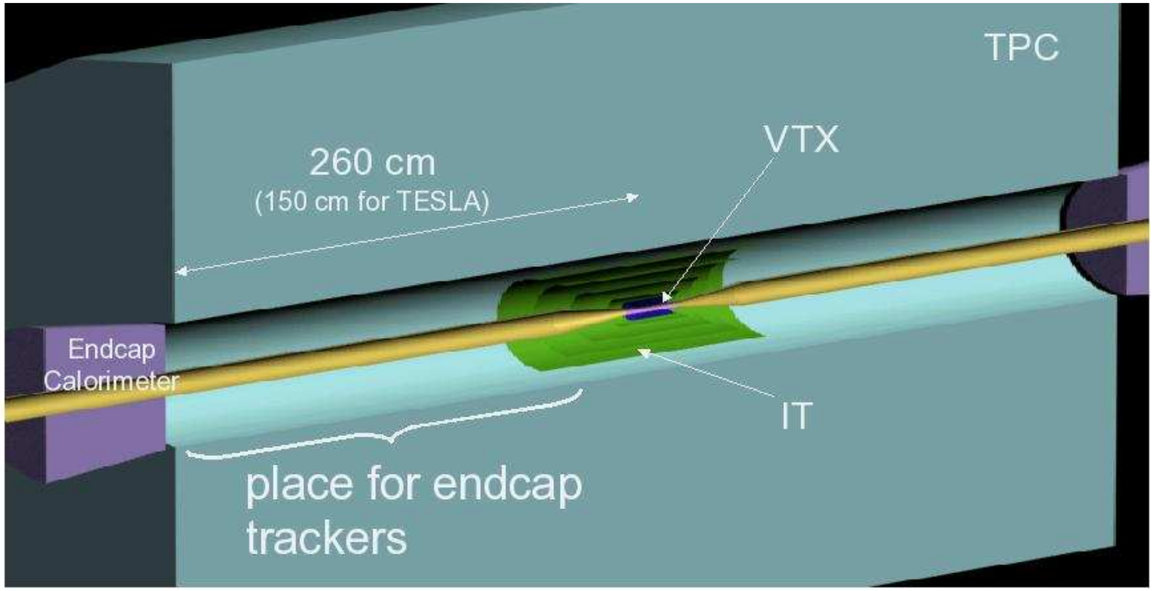
Particle flow studies

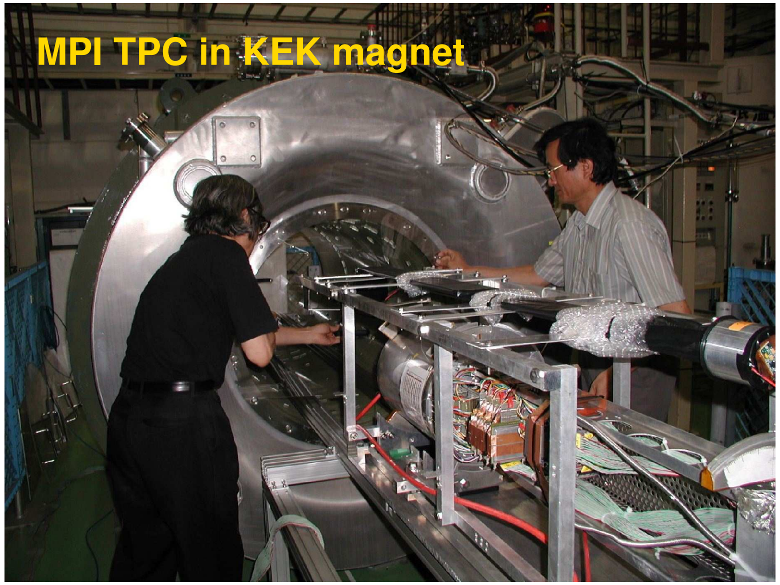
- $\Delta E/E = 40\%/\sqrt{E}$ reached in $Z \rightarrow q\bar{q}$ events
- At present no difference between $4\times4\,\mathrm{cm}^2$ pads and $1\times1\,\mathrm{cm}^2$ pads
- Not completely understood why
- Similar results from other concepts

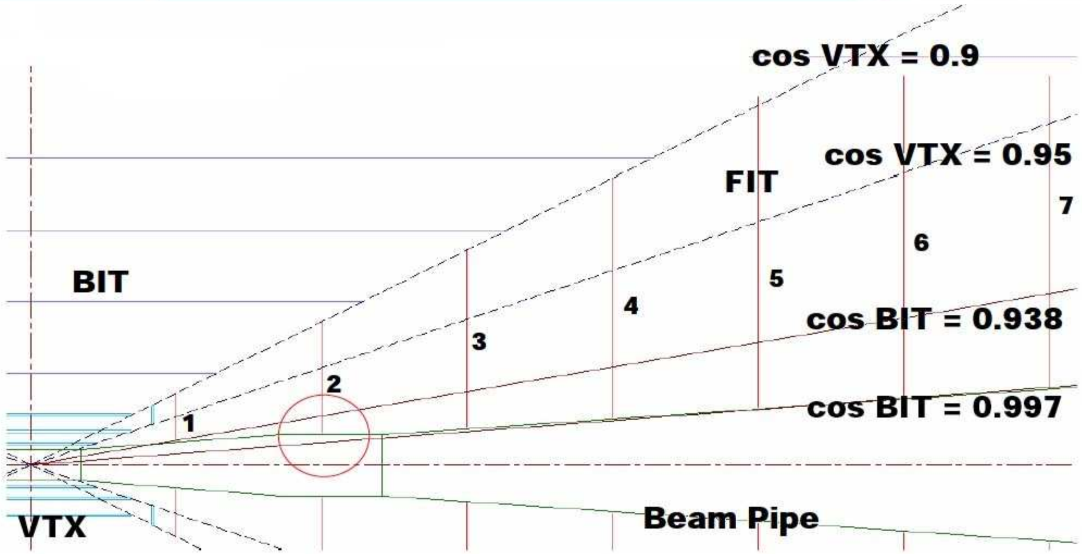


GLD tracking

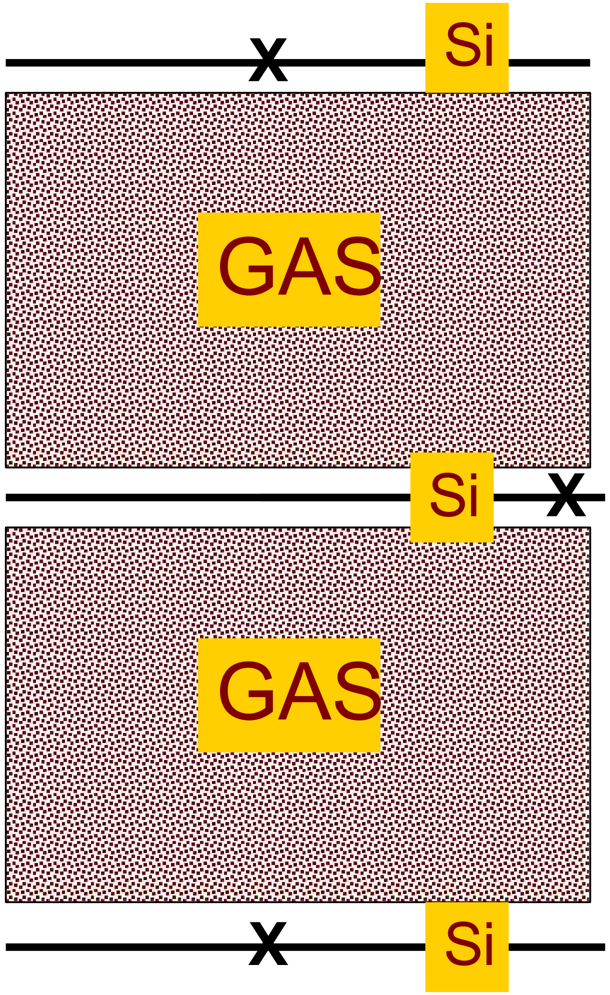
- GLD baseline tracking is very similar to LDC: TPC with inner Si tracking
- Close collaboration with LDC groups on TPC R&D
- A small-cell jetchamber is kept as backup

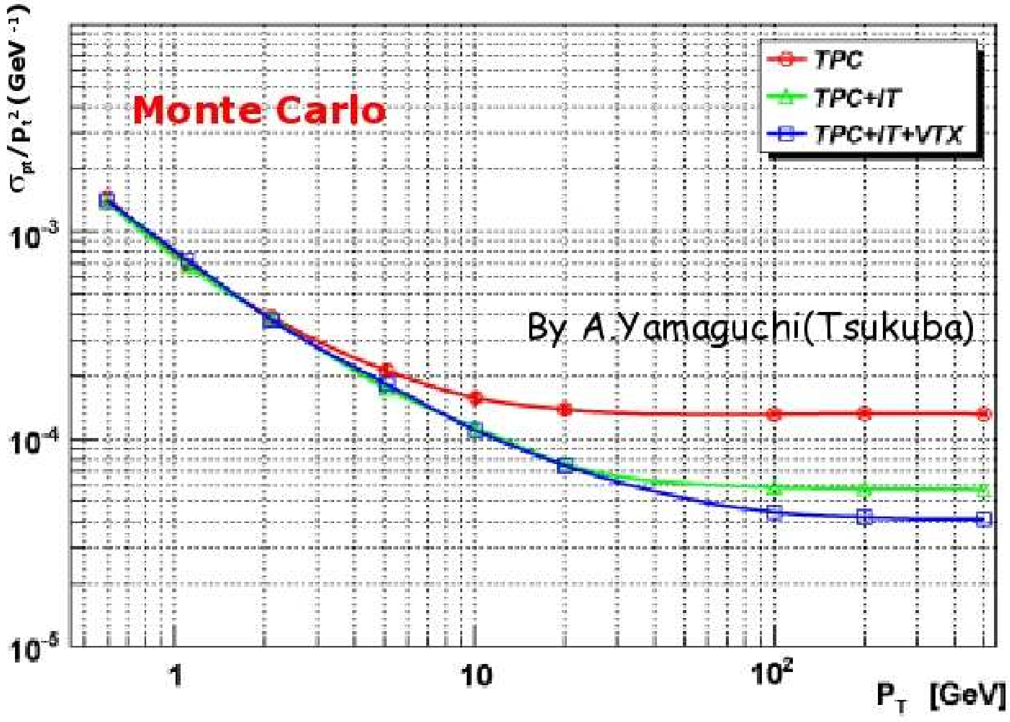






With this tracking system the required momentum resolution of $\Delta\frac{1}{p} = 5 \cdot 10^{-5}/\,\mathrm{GeV}$ is reached





If needed it can be improved with a Si-TPC hybrid solution ("club-sandwich")

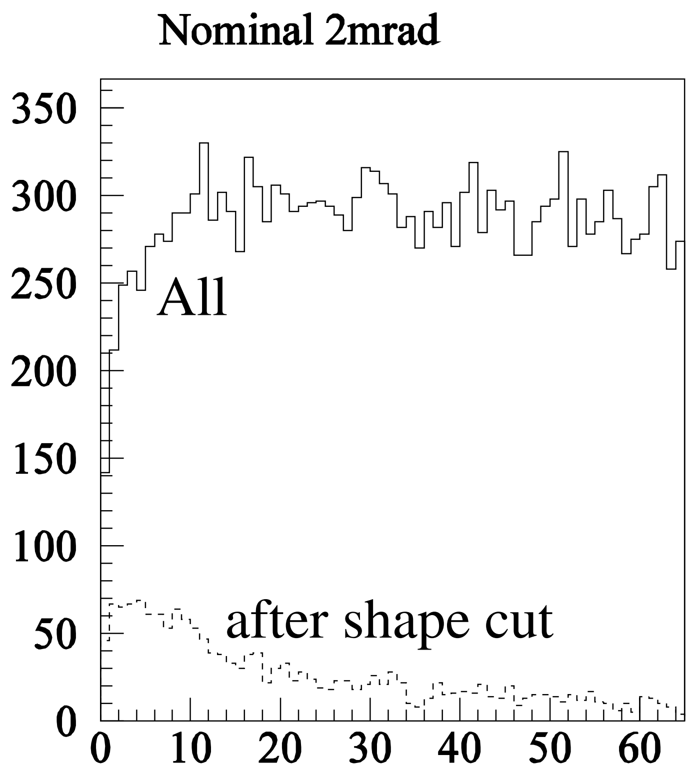
Vertex detectors in the three concepts

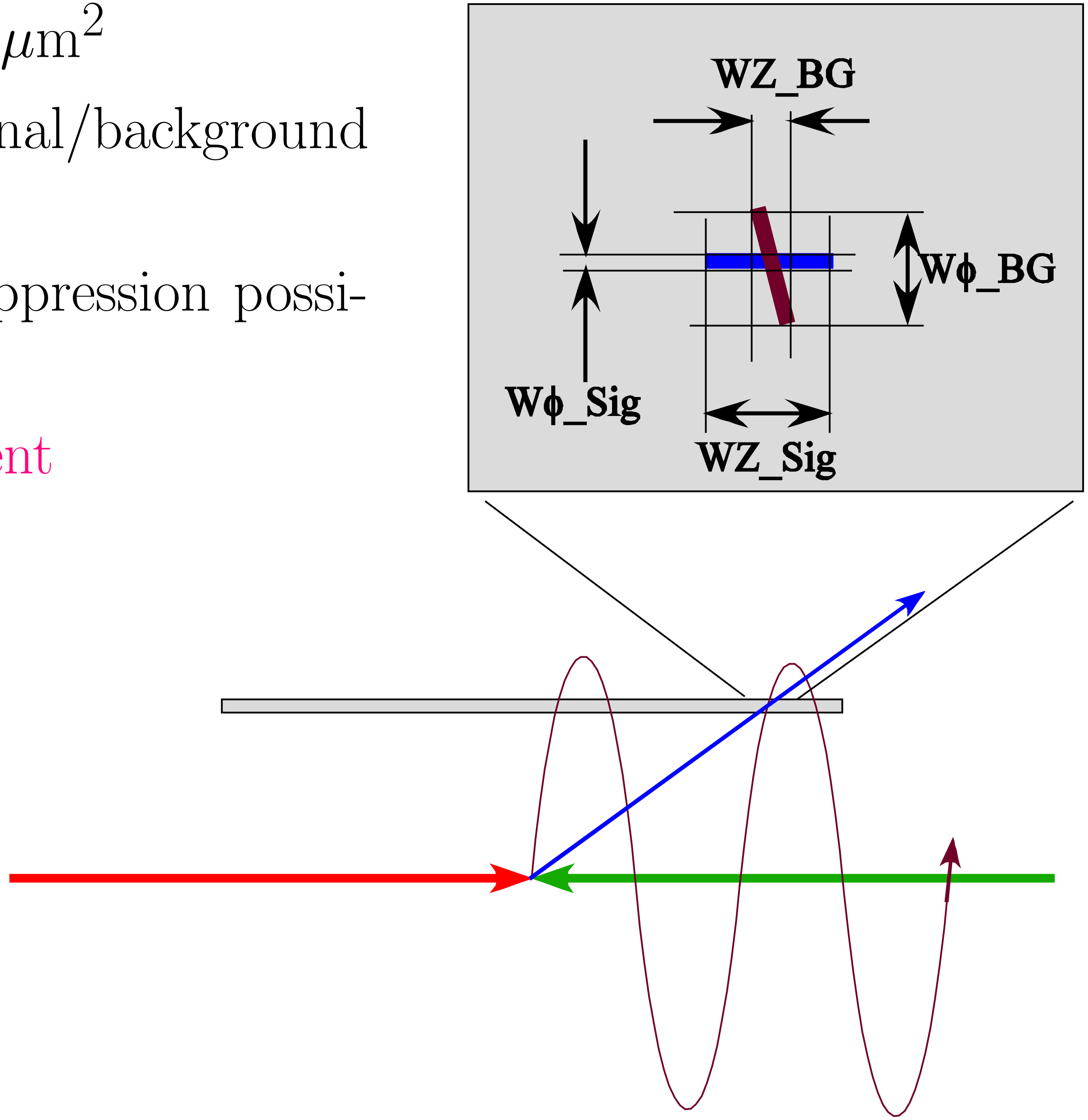
- Vertex detectors are very similar in the concepts
- Only difference: inner radius/background due to B-field
- Common challenges:
  - very precise and thin detectors to reach physics requirements
  - fast readout to reduce background (20 frames/train needed)
  - electromagnetic interference for readout during train
- Many technologies under study: CCD, CMOS, Depfet...
- Decision can only be taken later

New idea from GLD team: fine pixels

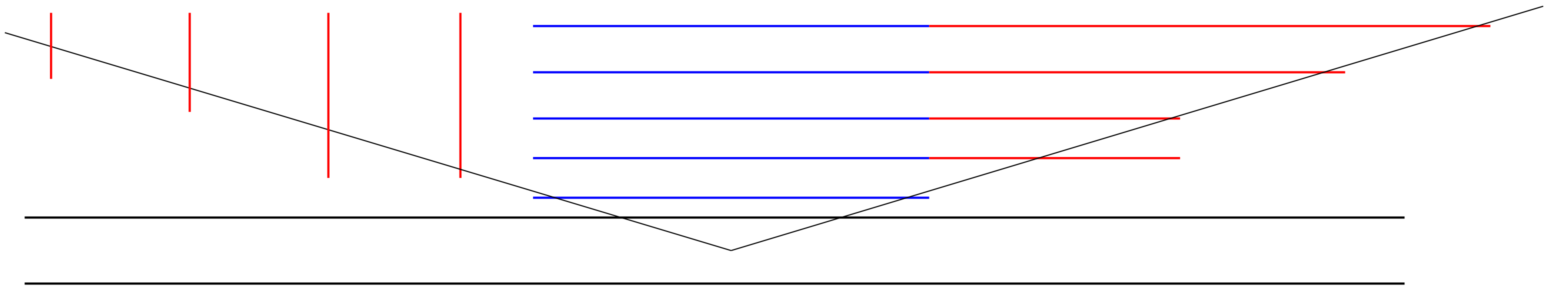
- Very small pixels $\sim 5 \times 5\mu m^2$
- Cluster shapes allows signal/background separation
- Factor 20 background suppression possible

➡ One readout/train sufficient





Common optimisation problem: VXD forward region



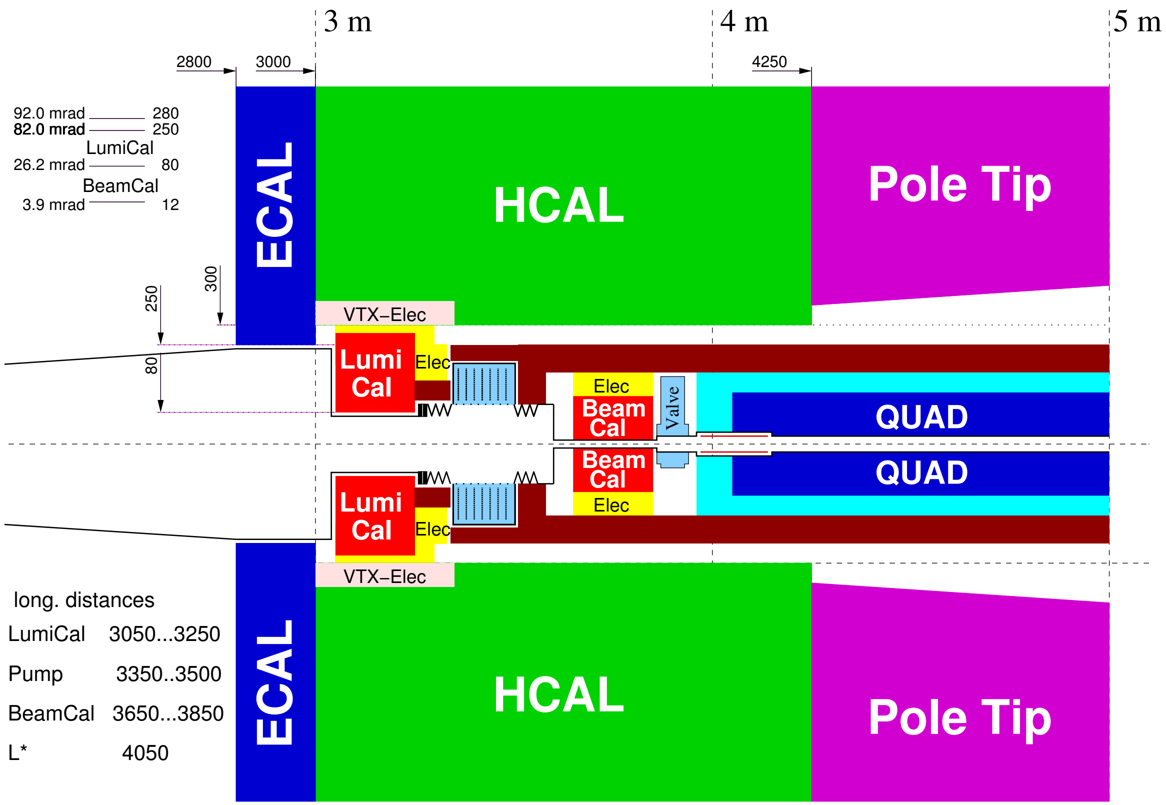
- Two option: Long cylinders or disks
- Advantage disks:
  - less silicon
  - larger crossing angle ⇒ less material and better measurement precision
- Advantage cylinders:
  - in disk solution tracks have to cross readout electronics and cables from barrel cylinders
- Need careful comparison of both options

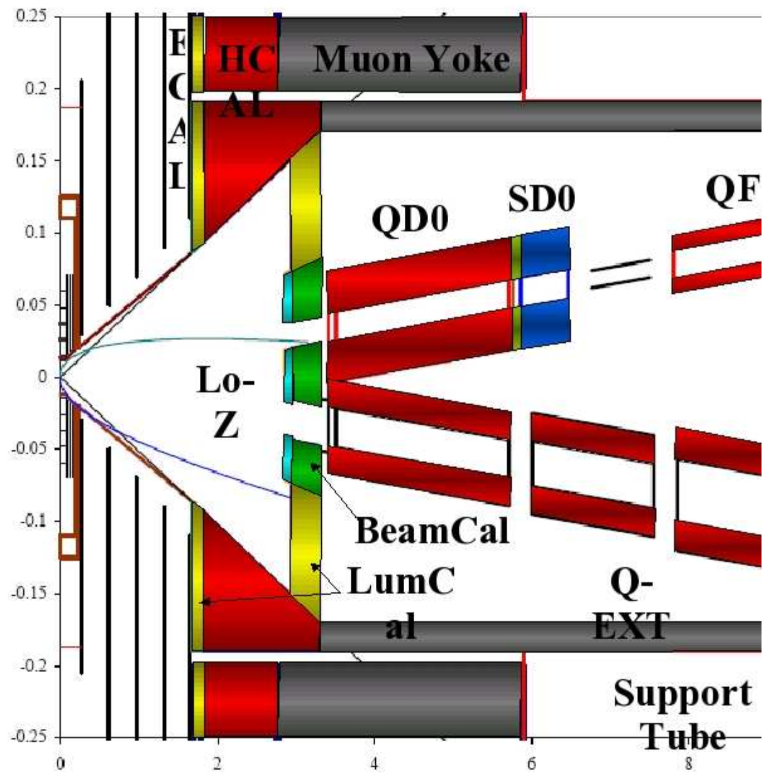
The forward region in the three concepts

Similar in all three concepts

Detailed design for LDC and 0/2 mrad crossing angle exists

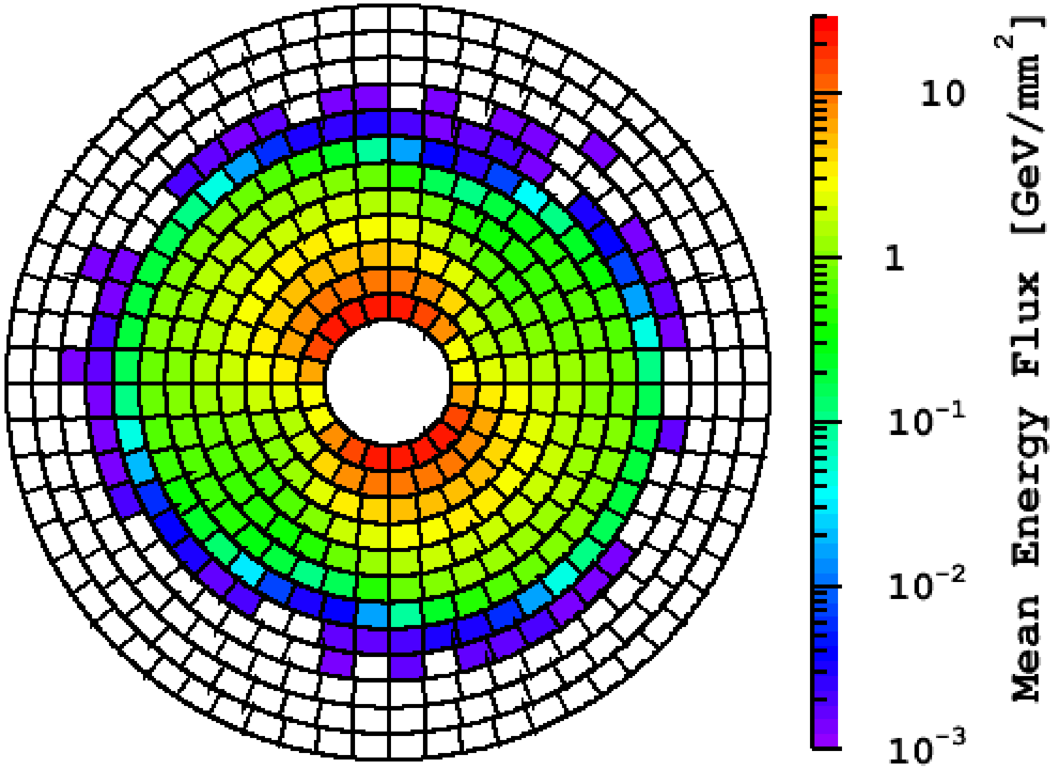
Also preliminary SID design for 14/20 mrad available



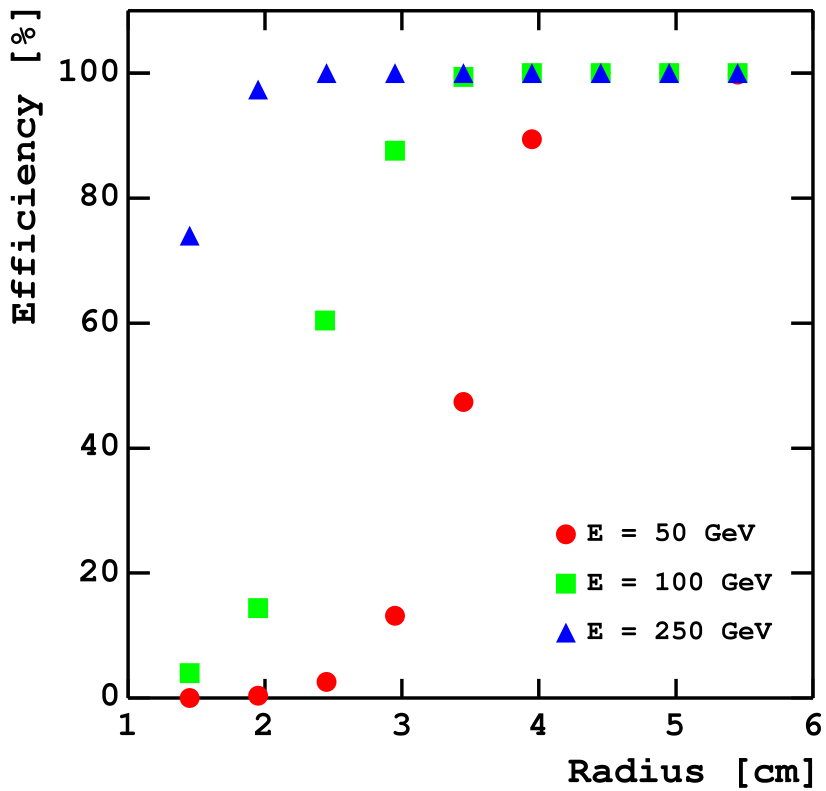


- The forward region serves simultaneously as a mask and as a veto device
- The challenge is to find electrons under a huge pair backgrounds
- With a fine grained calorimeter this works in most parts for 0/2 mrad
- For 20 mrad crossing angle further optimisation is needed

Energy deposited in BeamCal for zero crossing angle



Reconstruction efficiency for electrons in BeamCal



The 4th concept

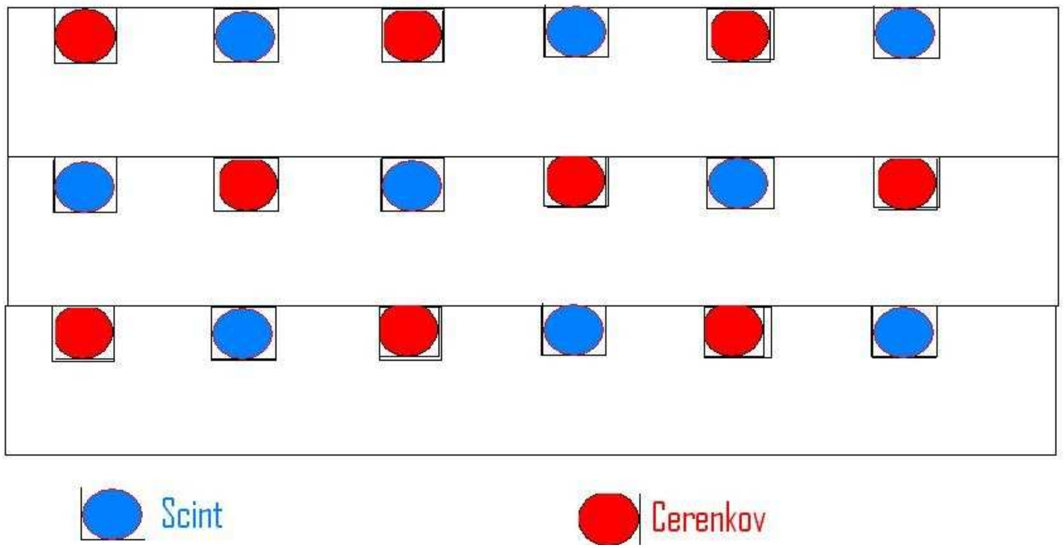
The 4th concept is based on the dual (or triple) readout approach

- Standard scintillation light readout measures the total energy
  However bad resolution due to fluctuation of em-component
- The em component is measured is measured separately with clear fibres, sensitive only to Cerenkov light

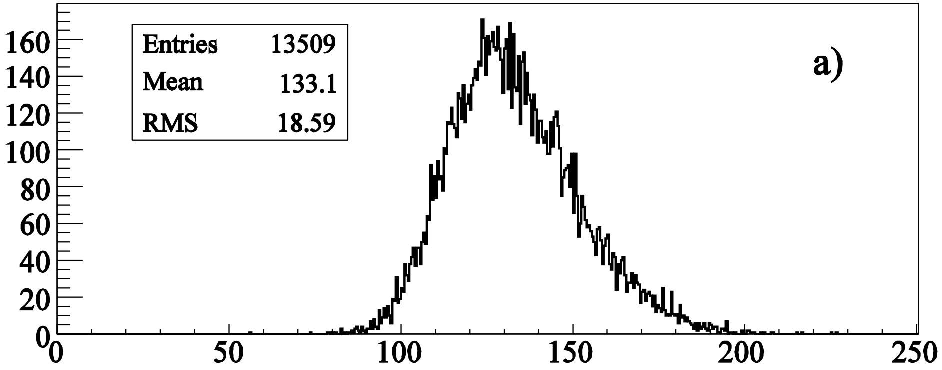
➠ can disentangle the two components

- Further improvement maybe possible by measuring the low-energy neutron component using timing (However large volume filled by neutrons!)

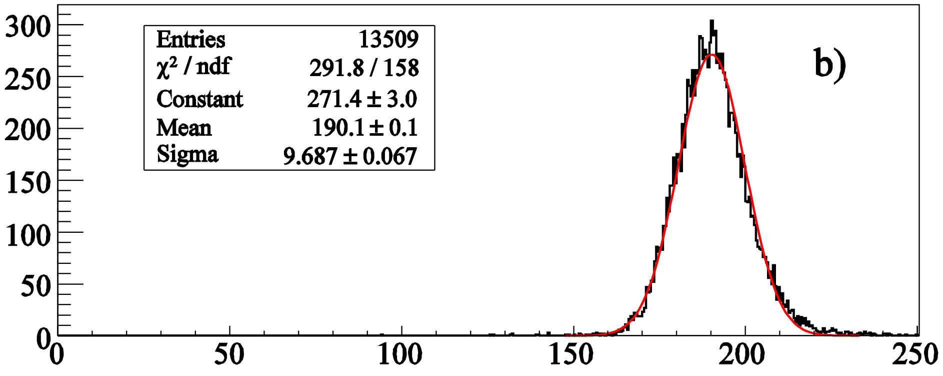
Layout of an ILC calorimeter cell



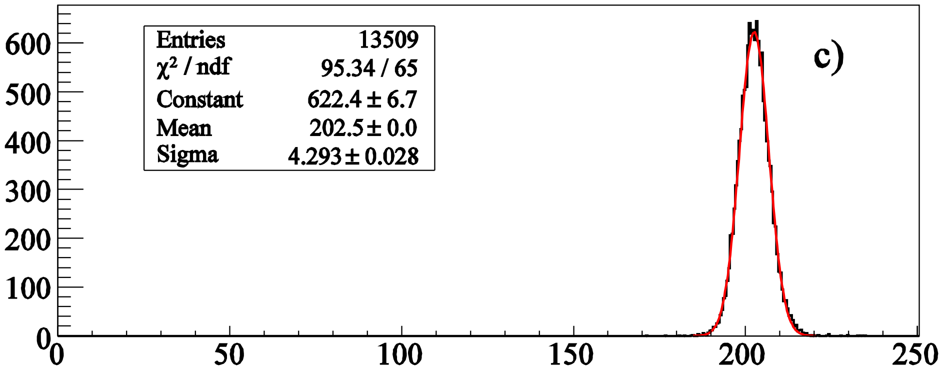
Results from a 200 GeV π^- beam



Scintillating fibres



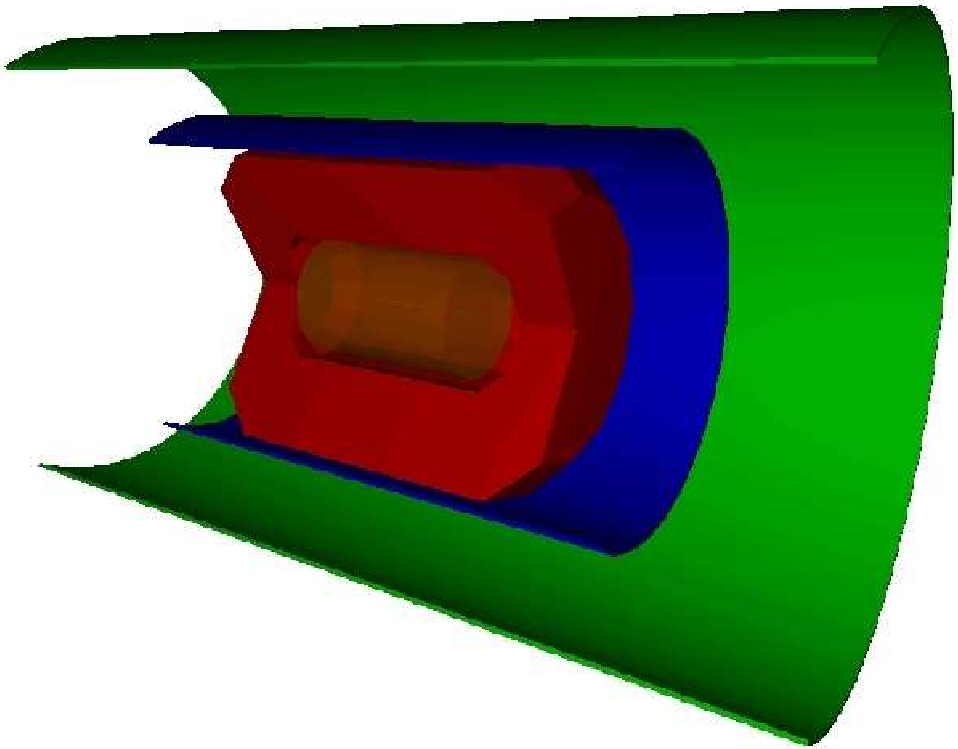
Scintillating fibres
+ Cerenkov



+ leakage correction
using beam energy

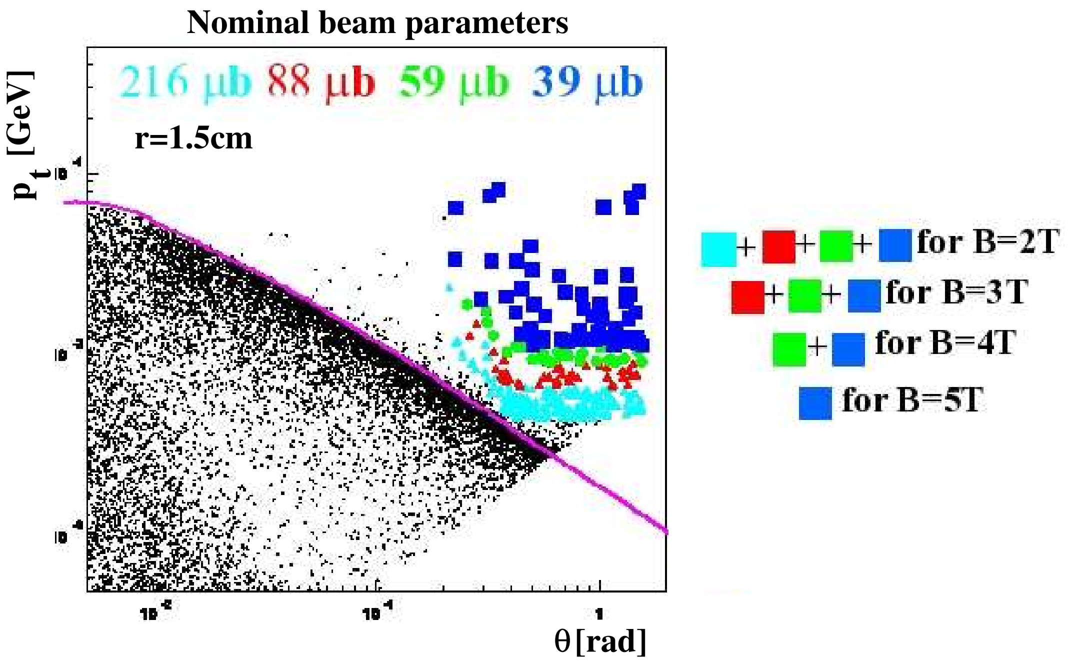
The whole detector concept

- With $\Delta E/E = 20\%/\sqrt{E}$ jet energies can be measured calorimetrically
- This requires a low field around $B = 2\,\mathrm{T}$
- The inner tracking is copied from GLD/LDC
- Muons are remeasured outside the calorimeter with a dual-solenoid concept



Possible problems with the 4th concept

- The B-field deflects charged particles
  ➠ Invariant mass of jets get increased and jet axis gets is shifted
- The low B-field increases the VXD background
  ➠ 3 cm inner radius may be needed



The 4th concept still has to prove that it fulfils the physics requirements

Conclusions

- Three concept studies based on the particle flow approach going on
- A 4th concept based on the dream approach is starting
- All aim for a costed concept by the end of 2006
- The present designs seem to meet the requirements, but further optimisation and simulation work is needed
- It is too early to make comparisons since the level of optimisation and approximations in the analysis is too different
- All are open for new manpower
- More information at

http://physics.uoregon.edu/~ lc/wwstudy/concepts/