Performance Requirements

Outline

- CLIC Operation versus the Physics program assumptions
- CLIC Luminosity Spectrum Impact on Physics and Analysis
- Physics Analysis <-> Observables accuracy <->Requirements
- Performance Requirements on:
  - ✓Track momentum resolution
  - ✓Jet energy resolution and Particle Flow
  - ✓Particle Identification and Jet Flavour Tagging
- Overview: CLIC_ILD and CLIC_SiD Detector Concepts, 3 TeV

CLIC Operation vs Physics Program

CLIC will be staged in energy and should be able to operate over a range of centre-of-mass energies: √s from ~ 0.5 to 3 TeV.

The energy will be chosen according to the physics program, eg:

- Precision physics: Higgs, top studies, … at low √s ~< 0.5 TeV
- BSM physics measurements : eg
  New particles production cross sections, masses, couplings measurements at √s close to the threshold of the particles or at the highest √s value, 3 TeV.

Detectors must allow to perform physics at sub-TeV and multi-TeV energies taking into account the CLIC bunch structure and the beam induced background.

CLIC Luminosity Spectrum vs Analysis

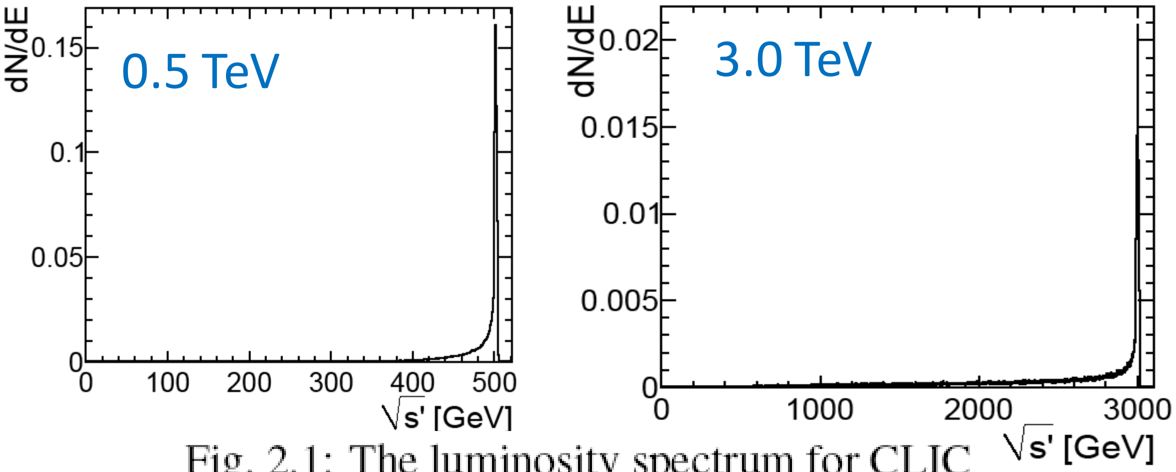


Fig. 2.1: The luminosity spectrum for CLIC

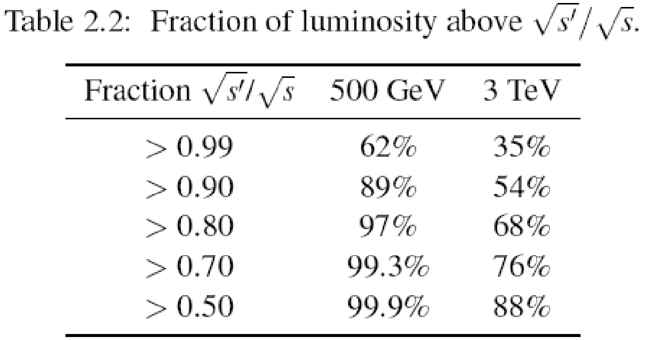
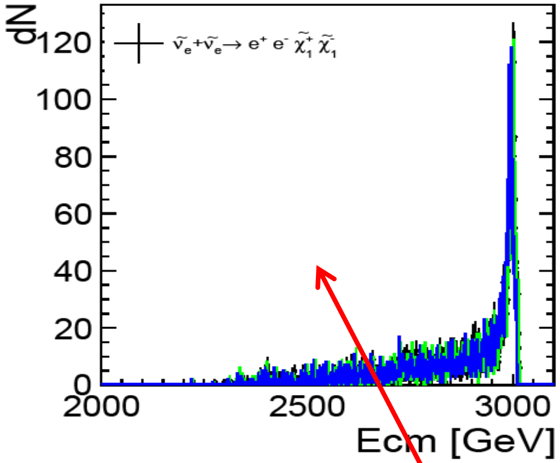


Table 2.2: Fraction of luminosity above $\sqrt{s'}/\sqrt{s}$.

Fraction $\sqrt{s'}/\sqrt{s}$	500 GeV	3 TeV
> 0.99	62%	35%
> 0.90	89%	54%
> 0.80	97%	68%
> 0.70	99.3%	76%
> 0.50	99.9%	88%



- Beamstrahlung implies

  Only a fraction of collisions at nominal energy

  At 0.5 TeV: 62% of collisions have √s'/√s> 0.99

  At 3 TeV : 35% of collisions have √s'/√s> 0.99

- Impact on physics: Reduced peak luminosity

It is relevant for a resonance study, less for the study of a process above threshold.
At √s=3 TeV, for a process with 2 TeV threshold, 75% of the luminosity is useful.
But it requires, in the analysis, eg, slepton mass determination fit, to take into account the energy dependence of the luminosity spectrum (as well as ISR).

Analysis <-> Observables Accuracy <-> Requirements

Physics analysis require accurate reconstruction of multi-lepton and multi-jet final states. The basic observables which are relevant for reconstruction of leptons and jets are:

- Track momentum resolution
- Jet energy resolution
- Particle identification and jet flavour tagging

The physics measurement accuracy (on cross sections, masses, …), taking into account the √s spread, define the measurement accuracy on tracks, jets, … and lead to the basic detector requirements.
But the performances are affected by the beam-induced background.
This leads to additional requirements essential to maintain the measurement accuracy of the basic observables.

Track Momentum Resolution (1)
SM Higgs Recoil mass (500 GeV)

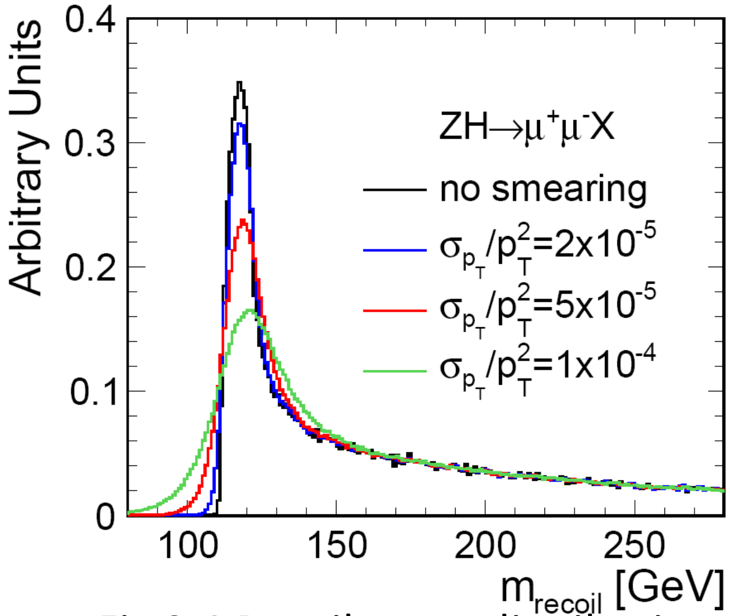
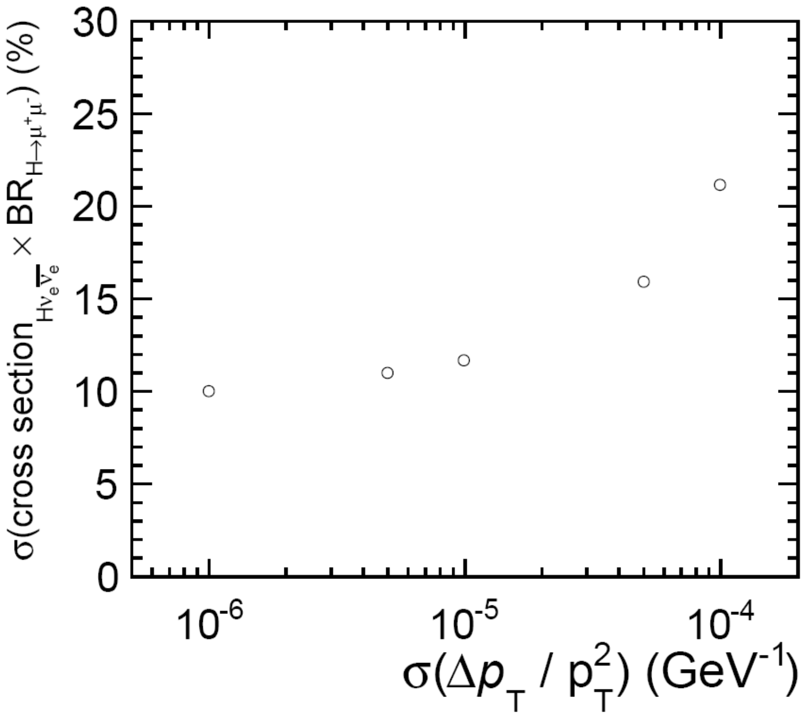


Fig 2.4:Recoil mass distribution

For the SM Higgs-strahlung process e^+e^-->Zh^0->$\mu^+\bar{\mu}X$, the Higgs mass is measured using the recoil mass to the Z, $m^2=s+m^2z-2.Ez.\sqrt{s}$.

The recoil mass width depends on the beam-spread and on the momentum resolution (plot: peak +tail.bs). The width is dominated by the beam-spread if $\sigma(1/Pt) \sim < 2.10^{-5}$ (GeV^{-1}), beyond, the momentum resolution increases the width [at LHC: $\sigma(1/Pt) \sim 2.\ 10^{-4}$].

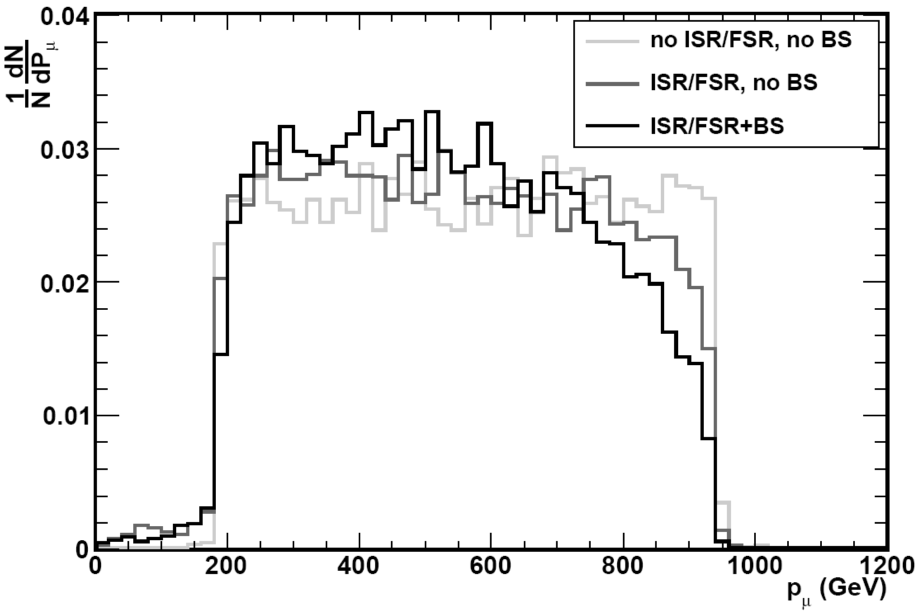
Track Momentum Resolution (2)
BR(h^0->$\mu^+\mu^-$) (3 TeV)



Cross section x Branching ration error vs σ(1/pt) : $\int L = 2ab^{-1}$

The error on the measurement of the cross section x BR(h^0->$\mu^+\mu^-$) is function of the momentum resolution (plot). The error on the cross section x BR measurement increases significantly if σ(1/Pt) > 5.10^{-5}.

Track Momentum Resolution (3) Slepton Mass Determination (3 TeV)



Muon dN/dP; σ/(1/Pt)=0

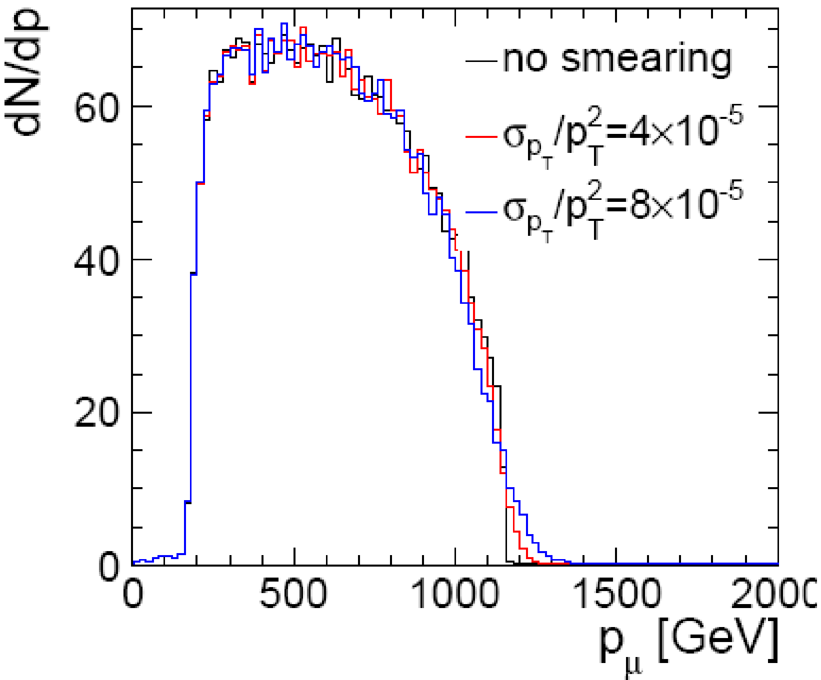


Fig 2.5: Muon dN/dP; with bs, σ/(1/Pt)=0, 4, 8x10^{-5}

The end points of the lepton momentum distribution allow to determine the Slepton an Gauginos masses. They are affected by ISR beam-spread (left) and momentum resolution (right). The higher end of the distribution is most affected by σ(P). Detailed study: σm dominated by beam spread if σ(1/Pt)< 4.10^{-5}.

Jet Energy Resolution

Good jet energy resolution is essential to discriminate hadronic decays of W± and Z^0/h^0; eg to distinguish between $\tilde{\chi}_1$± and $\tilde{\chi}_2^0$ production:
e^+e^-->$\tilde{\chi}_1$±$\tilde{\chi}_1$±-> $W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ and e^+e^-->$\tilde{\chi}_2^0\tilde{\chi}_2^0$->h(Z)h(Z)$\tilde{\chi}_1^0\tilde{\chi}_1^0$.

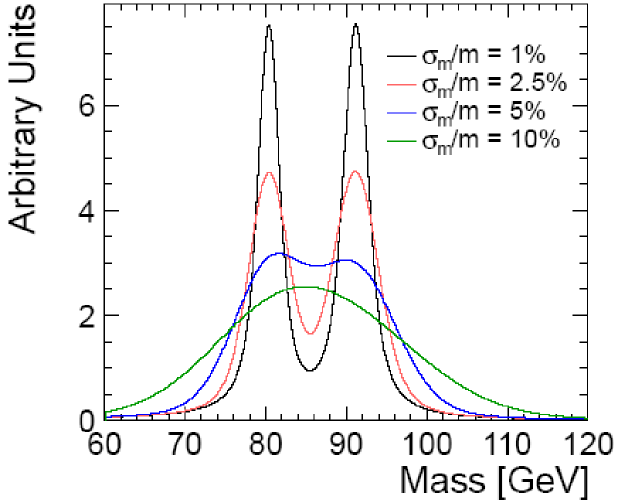
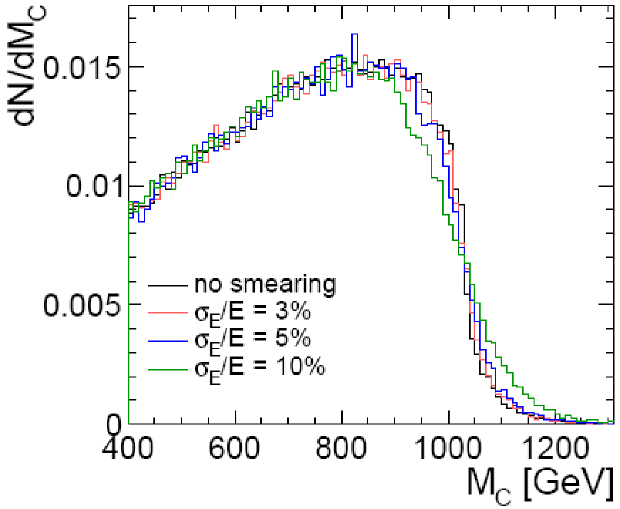


Fig 2.6: W and Z mass for various σm/m values

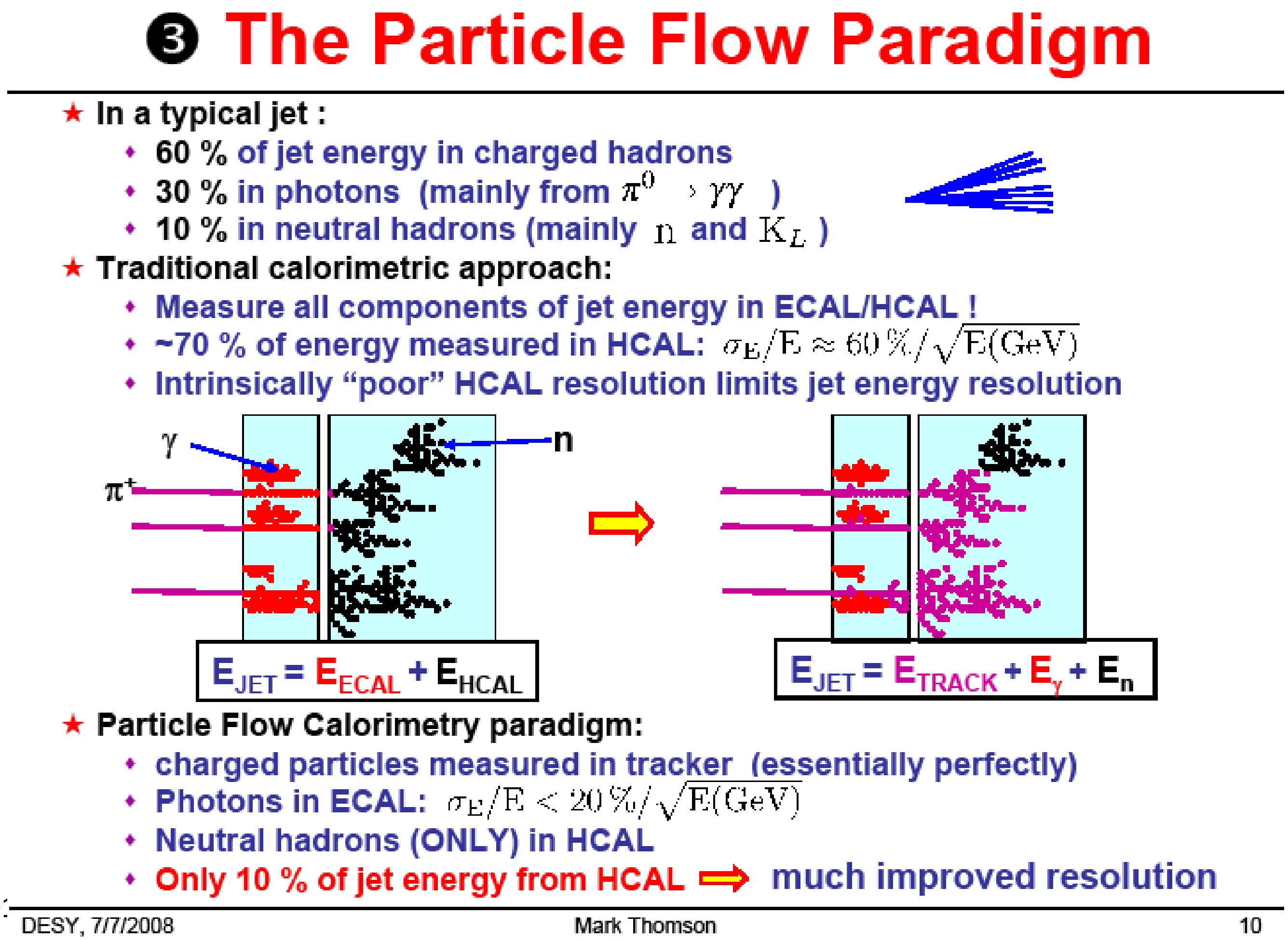


Contravariant mass Mc for various σE/E

2.5 σ W/Z separation requires σE/E=3.5%, for Ej up to 1 TeV.
Gauginos or squark masses are measured using the end points of the boson energy distributions or contravariant mass Mc. Detailed study: σm dominated by beam-spread if σE/E<5% [for LHC: σE/E ~ 10% at 100 GeV].

Particle Flow

To reach such energy resolution, studies done in context of ILC have shown that high granularity particle flow calorimetry is well suited.



❸ The Particle Flow Paradigm

- **In a typical jet :**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)
- **Traditional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL !
  - ~70 % of energy measured in HCAL: $\sigma_E/E \approx 60\,\%/\sqrt{E(GeV)}$
  - Intrinsically "poor" HCAL resolution limits jet energy resolution

γ

π^+

n

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

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

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

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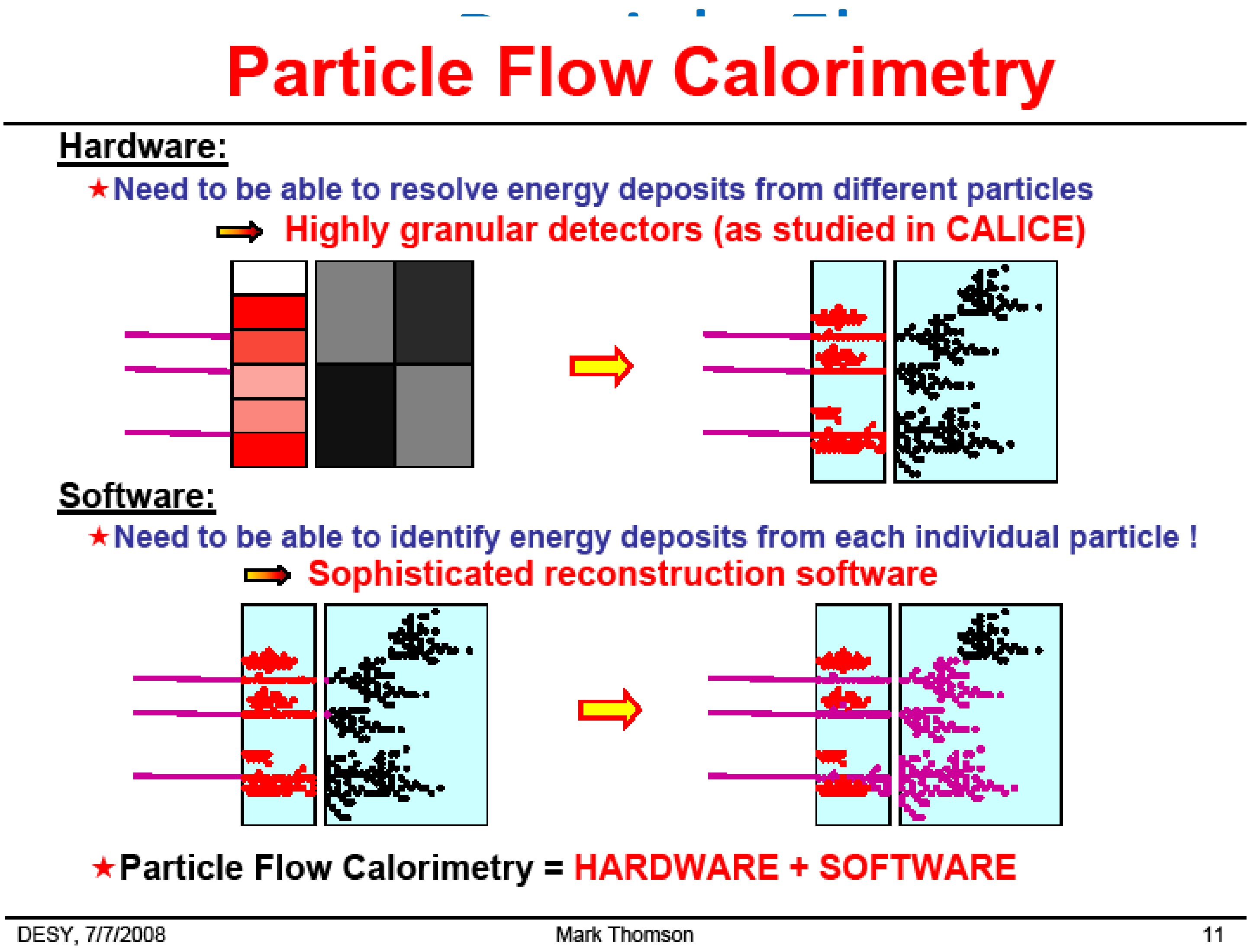

Particle Flow Calorimetry

Hardware:

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

⇨ Highly granular detectors (as studied in CALICE)

Software:

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

⇨ Sophisticated reconstruction software

★Particle Flow Calorimetry = HARDWARE + SOFTWARE

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Energy deposit identification => Electron, muon, photon, pion identification is part of PFA

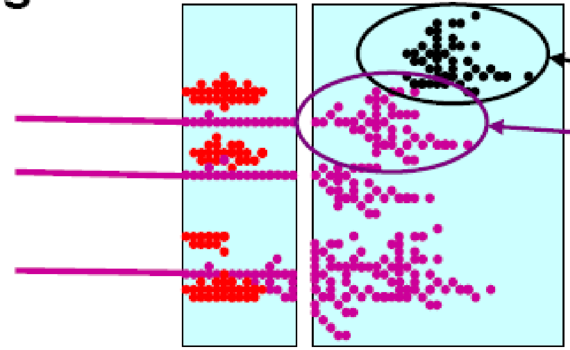
Particle Flow Challenge

Particle Flow Reconstruction (PFA)

Reconstruction of a Particle Flow Calorimeter:

- ★ Avoid double counting of energy from same particle
- ★ Separate energy deposits from different particles

e.g.



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

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

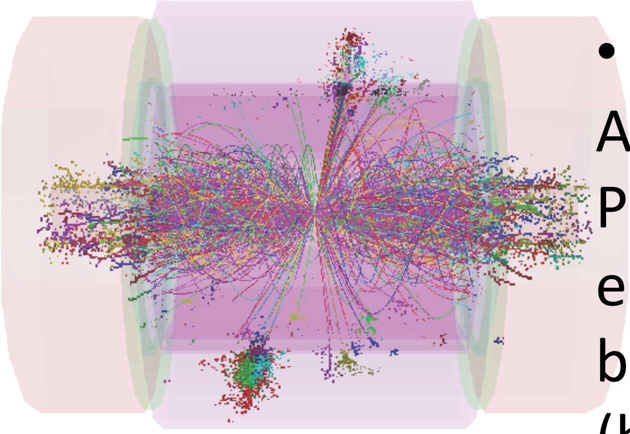
The confusion, is closely correlated with the detector granularity , it sets strong requirements on ECAL, HCAL granularity. (more in PFA talk: John Marshall)

PFA challenge with γγ->hadrons

CLIC bunch train composed of 312 bunches with 0.5 ns separation.
γγ->hadrons produce ~ 5000 particles, <P>=1.5 GeV, <Pt>=0.9 GeV, total calorimetric energy deposit 19 TeV

$\Rightarrow$ Jet structure and jet energy resolution spoiled by these hadrons

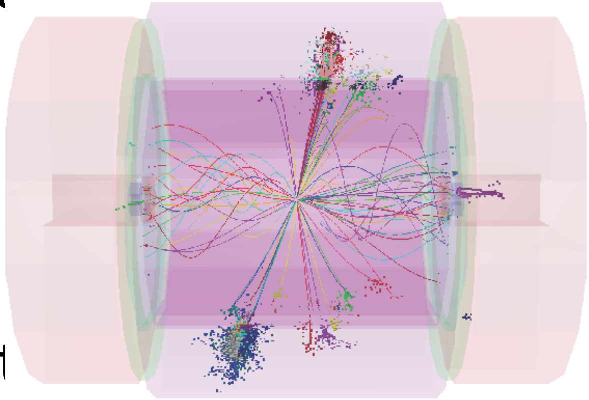
$\Rightarrow$ To remove them requires:



e^+e^-->H^+H^-->$t\bar{b}b\bar{t}$

- Detector hits time stamping
- Multi-hit storage/readout

After reconstruction Pt/timing cuts applied to eliminate hits which do not belong to the physics event (background reduction talk: M. Thomson).



Particle ID and Jet Flavour Tagging

All analysis require lepton identification or/and jet flavour tagging to define the event topology.

High event selection efficiency requires:

- High particle ID efficiency over the full momentum range, ε(ID)>95%
- High efficiency/purity b and c tagging to identify Z^0/h^0 : => good impact parameter resolution

$$\sigma_{d_0}^2 = a^2 + \frac{b^2}{p^2 \sin^3 \theta} ,$$

ILC requirements + CLIC studies: (Talk D. Dannheim)

- a < 5 μm :depends on the VTX point resolution
- b < 15 μm/GeV :depends on the VTX layout and material budget

[at LHC : a=20 and b=100 μm/GeV]

Physics performances: (Talk J. Strube)

Basic Requirements Summary

Accurate lepton and multi-jet final states reconstruction require:

- Track momentum resolution $\sigma(1/Pt) \sim 2.10^{-5}$
- Good calorimeter coverage, with minimum leakage
- Jet energy resolution allowing to separate W and Z^0/h^0 Di-jets:
  $\sigma E/E \sim 3.5 - 5$ % over the range 1 TeV to 50 GeV.
- Lepton ID efficiency, > 95 % over full energy range
- Good jet flavour tagging efficiency, it implies:
  impact parameter resolution: a< 5 µm, b< 15 µm /GeV.

Performance must be maintained in presence of beam-induced background => additional requirements:

- Detector hits time stamping
- Multi-hit storage/readout capability.

CLIC Detector Concepts Overview

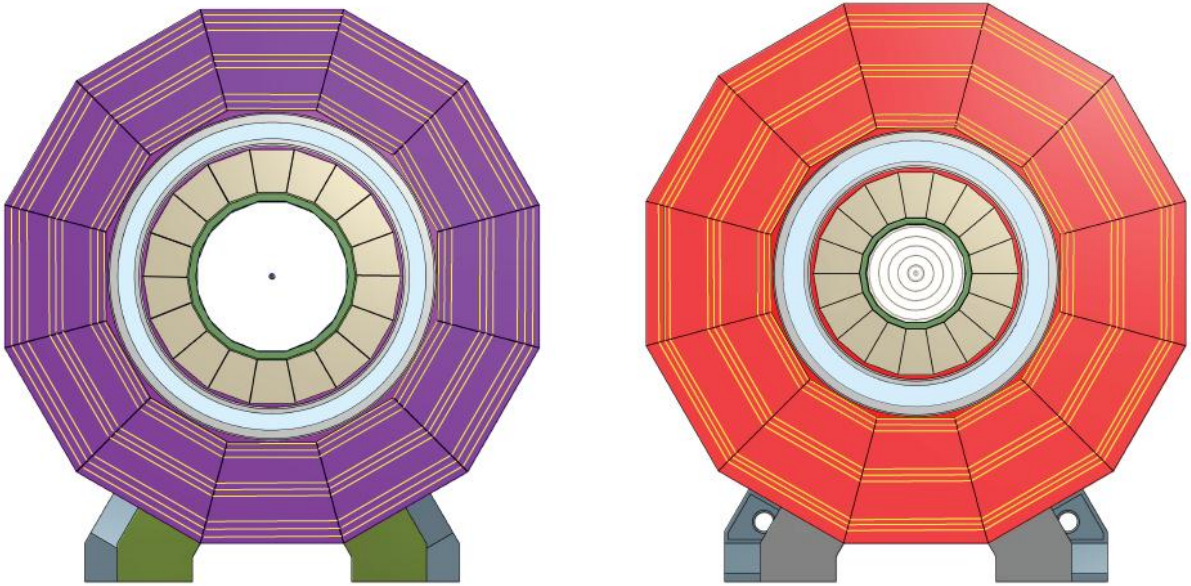


Fig. 3.2: Transverse cross section of CLIC_ILD (left) and CLIC_SiD (right).

System	CLIC_ILD	CLIC_SID
VTX+Tracker	TPC, Radius=1.8m	Silicon, Radius=1.2m
ECAL	W/Si	W/Si
HCAL Barrel	W/Scint	W/Scint
HCAL Endcap	Steel/scint	Steel/Scint
Solenoid: B-Field	4 T	5 T

CLIC Detector Concepts Overview

CLIC detector requirements:

- At ~ 0.5 TeV, same as for ILC + modifications to mitigate the effects of the CLIC bunch structure. Beam induced backgrounds much smaller than at 3 TeV
- At 3 TeV, need optimization to take into account the increase in energy and the effects of the CLIC bunch structure and beam induced background.

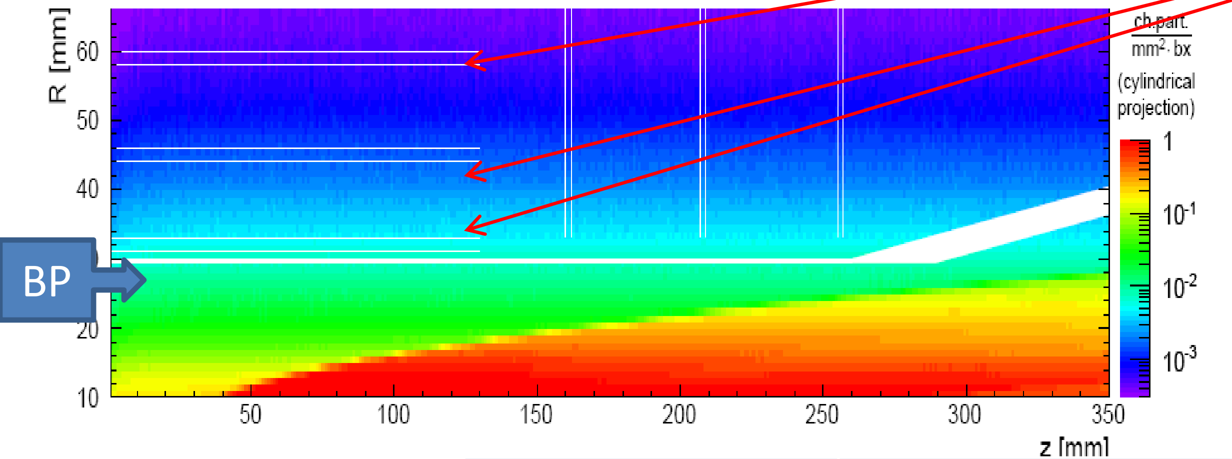
Start with ILD/SiD LoI validated detectors + modifications (3 TeV):

- Beam pipe and vertex detector layout and location to account for increased background.
- Increased HCAL depth to account for increased jet energies.
- Forward region layout to cope with increased background, 20 mrad crossing angle and QD0 location.
- Solenoid design modified to account for larger HCAL

CLIC Detector Concepts
Beam Pipe and VTX

VTX elements layout designed to match impact parameter requirements:

- Remain outside the incoherent pair background region, but as close to the beam line as possible (Fig 4.8: Density of hits from incoherent pairs)
- Low occupancy: Not > 3.10^{-2} at R=31mm for 20x20 µm pixels
- Low number of radiation length

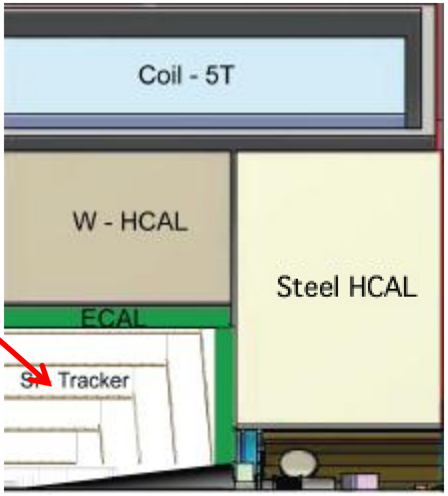


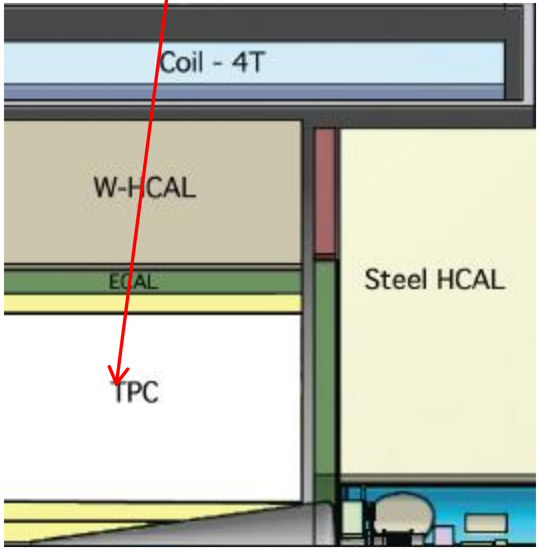
Main parameters	CLIC_ILD (B=4T)	CLIC_SID (B=5T)
Inner radius (mm)	31	27
Outer radius (mm)	60	77(barrel), 169 (disks)
Max. Z (mm)	125(barrel) 257(disks)	99(barrel), 830(disks)
Barrel layers	3 double layers	5 single layers
Forward layers	3 double layers	7 single layers

⇒VTX layout
Talk D.Dannheim

CLIC Detector Concepts
Tracking System

Barrel Tracker	CLIC_ILD	CLIC_SiD
Technology	TPC+Silicon strips	Silicon strips
Inner radius	329	230
Outer radius	1808	1239
Max. Z	2250	578 to 1536
Max. samples	2(Si), 224(TPC),1(Si)	5





Forward Tracker	CLIC_ILD	CLIC_SiD
Technology	Silicon strips	Silicon strips
Inner radius	47 to 218	207 to 1162
Outer radius	320	1252
Max. Z	1868	1556
Max. samples	5	4

Technology and performance talks : M. Stanitzki (SiD) and J. Timmermans (ILD)

CLIC Detector Concepts
ECAL and HCAL in High B Field

ECAL	CLIC_ILD, B=4 T	CLIC_SiD, B=5 T
Absorber/Active elements	Tungsten/Si pads	Tungsten/Si Pads
Sampling layers	30 (20 × 2.1, 10 × 4.2)	30 (20 × 2.5, 10 × 5)
Cell size	5.1x5.1	2.5x2.5
X_0 and λI	23 and 1	26 and 1

- To minimize leakage HCAL depth increased:

  Jet energy resolution studies => 7.5 λ_I

- To maintain reasonable solenoid radius

  Tungsten used as absorber in barrel

HCAL	CLIC_ILD	CLIC_SiD
Absorber(B/F)	Tungsten/Steel	Tungsten/Steel
Sampling layers(B/F)	75x10mm/60x20	75x10mm/60x20
Cell size	30x30/30x30	30x30
λI (B/F)	7.5/7.5	7.5/7.5

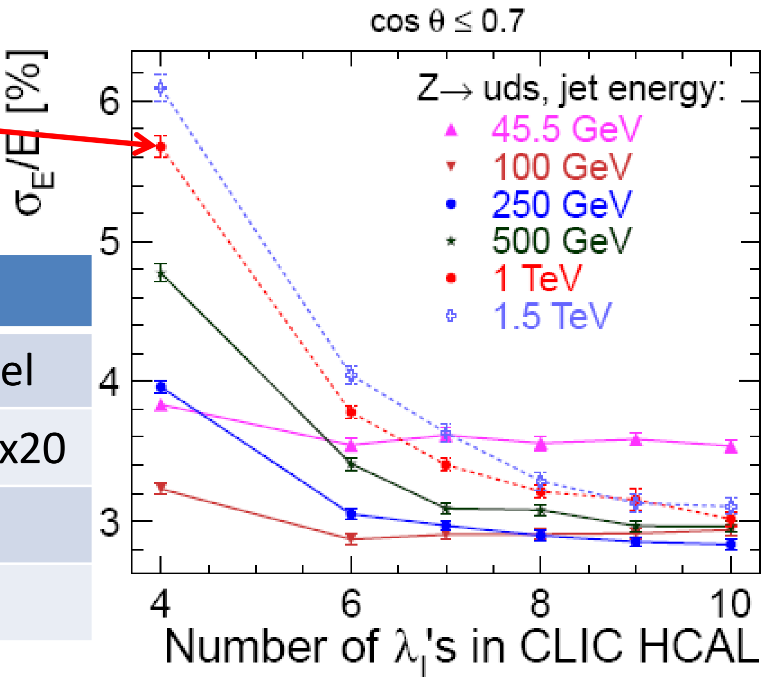


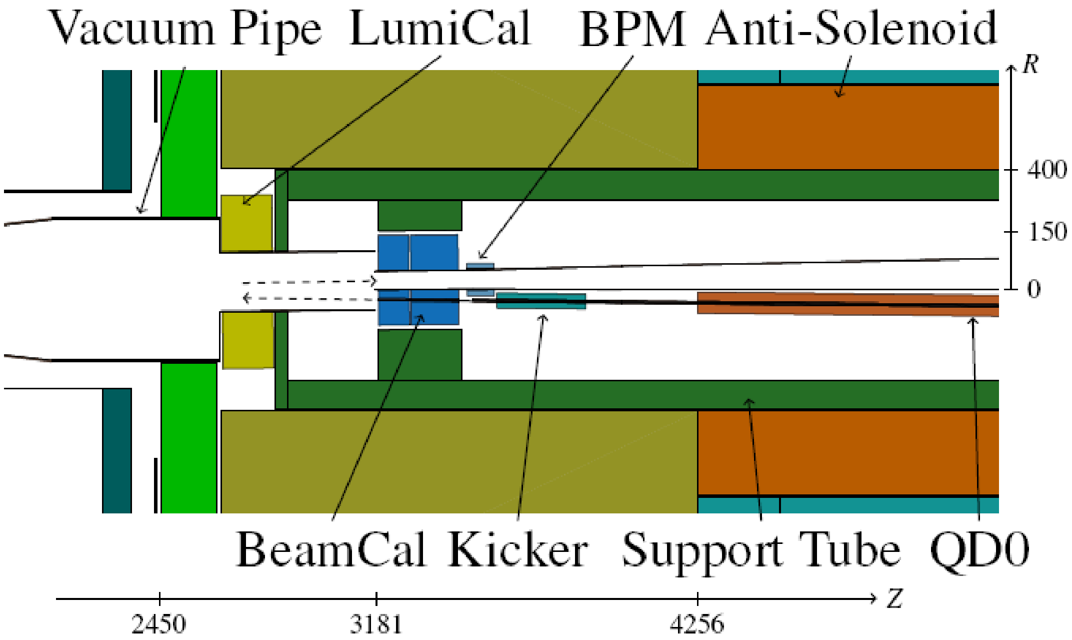
Fig 6.2

Technology and Performance talk: F. Sefkow

CLIC Detector Concepts
Very Forward Region

CLIC beam crossing angle is 20 mrad, (ILC: 14 mrad) => modifications of the design of the very forward region components:

- LumiCal (40-100 mrad) : luminosity measurement
- BeamCal (10- 40 mrad) : electron detection
- Beam position monitor
- Beam Kicker: intra train feedback
- Final focus quadrupole: QD0
- Anti-Solenoid: field compensation
- Shielding masks: protect upstream detectors and BPM, Kicker, …

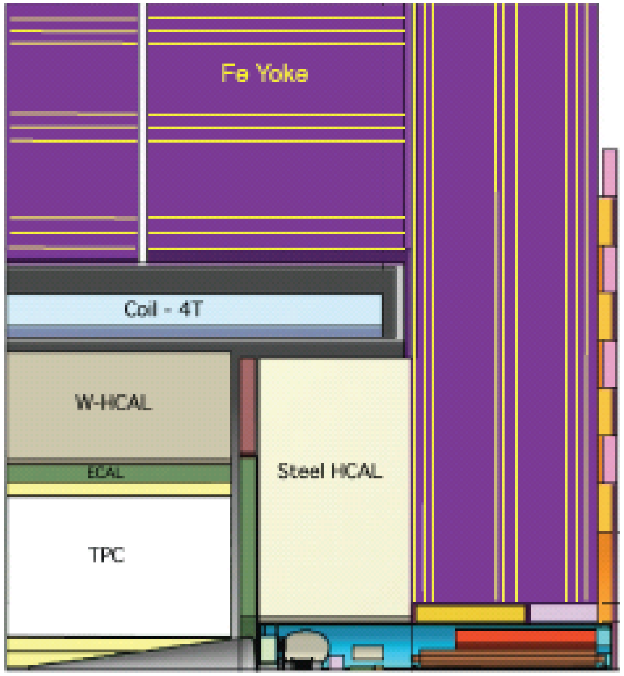


Details in talk: K. Elsener

Fig 3.3

CLIC Detector Concepts
Solenoid and Muon System

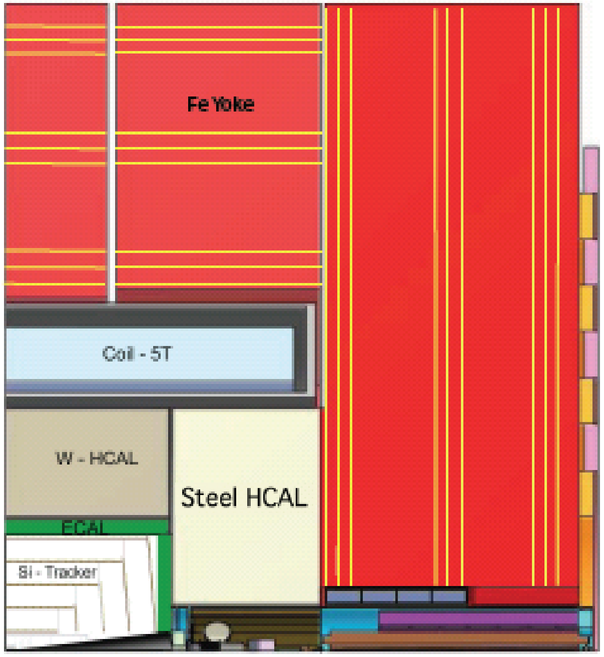
Coil+cryostat	CLIC_ILD	CLIC_SiD
Field	4T	5T
Coil Free bore/Thickness	3426/864 mm	2744/966 mm
Yoke material/thickness	Steel/2586 mm	Steel/3086 mm
Muon layers	9	9



Technology talk: H. Gerwig

For the CDR two GEANT4 models defined

Physics benchmark studies with full reconstruction and overlaid beam induced background

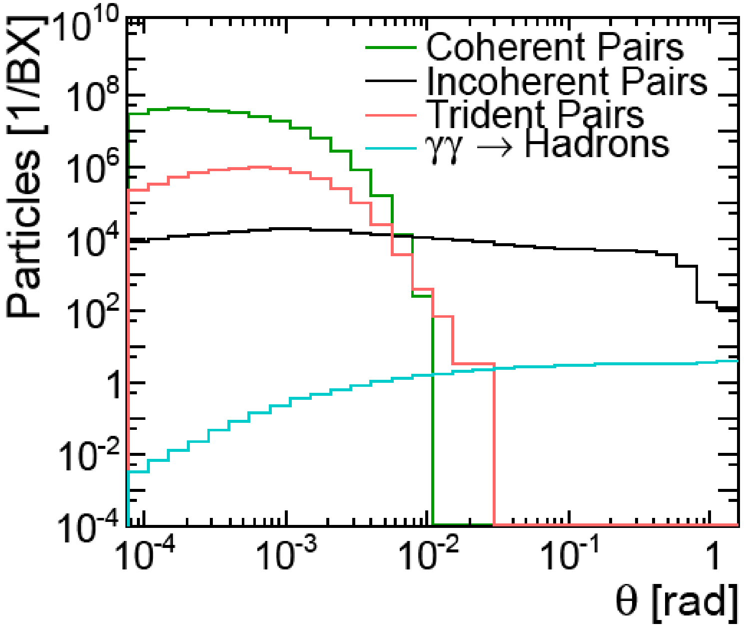


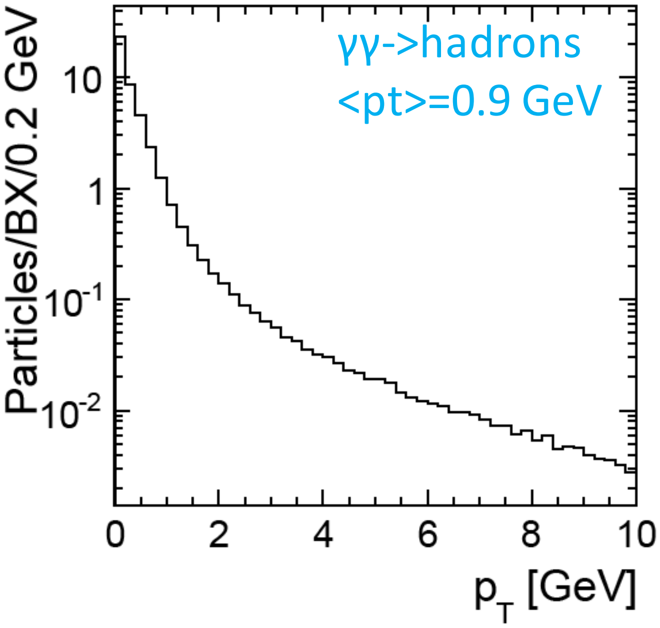
Thanks

Impact of Beam Induced Backgrounds (Daniel)

- Coherent pairs : produced at small angle, end up in beam pipe
- Incoherent pairs : produced at larger angle, affect VTX inner layers
- γγ->hadrons : affect tracking, calorimeters and observables
- Beam halo muons: impact on physics observables << γγ->hadrons

pt>5 GeV cut removes γγ->hadrons; ok for physics with leptons, not with jets, because it would bias the jet energy resolution.





Particle Flow

To reduce the background requires to:
time stamp the detector hits and to apply timing cuts to eliminate the hits which do not belong to physics event.
But there is a basic limitation to the time stamping window related to the time for the showers to develop and to the signal integration.