PROCEEDINGS OF SCIENCE

CLIC Detector

Michael Hauschild*
CERN
E-mail: michael.hauschild@cern.ch

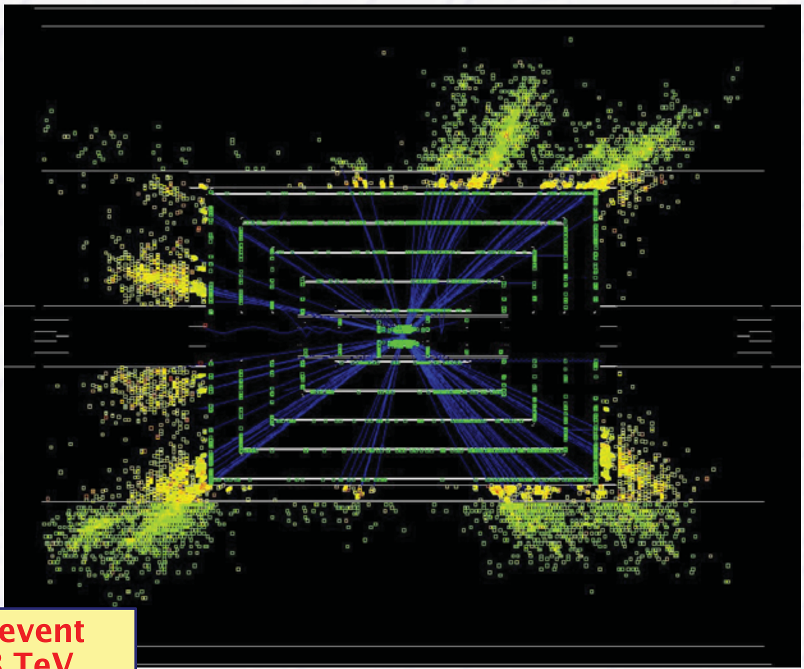
Third Linear Collider Physics School 2009 - LCPS2009
August 17 - 23 2009
Ambleside, UK

*Speaker.

PoS(LCPS2009)010

CLIC Detector

(What is the difference between an ILC and a CLIC Detector?)



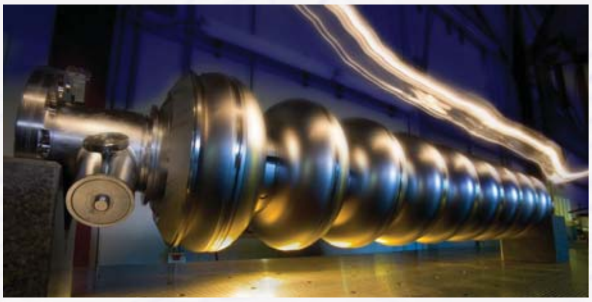
multi-jet event
at √s = 3 TeV
e^+e^- -> WW -> qqqq

Physics at the Terascale

- New physics is expected at the ~TeV scale
  - Higgs, Supersymmetrie, extra dimensions etc.
- First machine to enter the Terascale is LHC
  - LHC is a discovery machine
    - broad energy spectrum of partons in the protons give access to highest energies (enough luminosity provided)
  - LHC is not a precision machine
    - cross sections of interesting physics processes many orders of magnitude lower than physics background processes -> harsh environment, experimentally difficult
  - LHC also cannot cover full spectrum of SUSY particles (if any)
- LHC needs to be complemented by a precision e^+e^- Linear Collider
  - but at what energy?
    - is 500 GeV or 1 TeV enough? can we get sufficient physics output up to 1 TeV?
  - do we need more energy?

ILC and CLIC Technologies

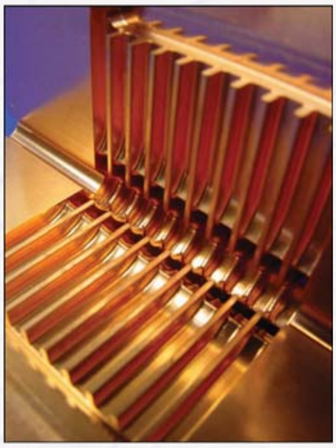
ILC



- •Based on superconducting RF cavities
- •Gradient 32 MV/m
- •**Energy: 500 GeV, upgradeable to 1 TeV**
  (possible GigaZ factory at 90 GeV or ZZ factory at ~200 GeV is also considered)
- •Detector studies focus mostly on 500 GeV

technology available

CLIC



- •Based on 2-beam acceleration scheme
  (warm cavities)
- •Gradient 100 MV/m
- •**Energy: 3 TeV**, though will probably start at lower energy (~0.5 TeV)
- •Detector study focuses on 3 TeV

feasibility still to be demonstrated

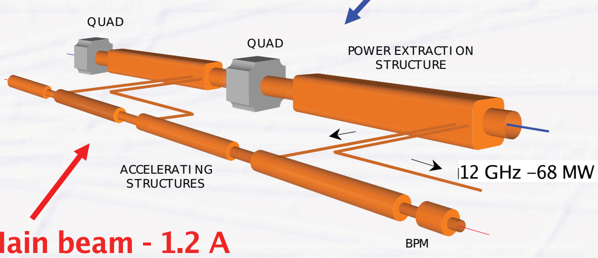
The CLIC Two Beam Scheme

Two Beam Scheme

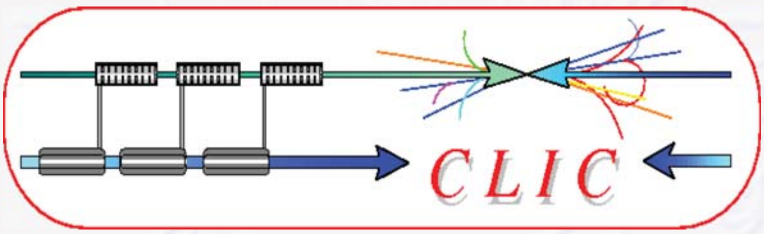
Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

Drive beam - 100 A from 2.4 GeV -> 240 MeV (deceleration by extraction of RF power)

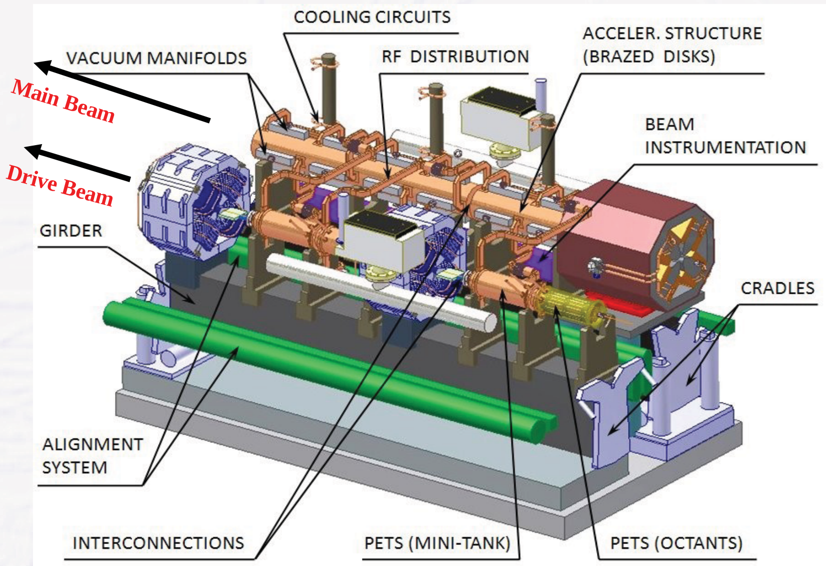


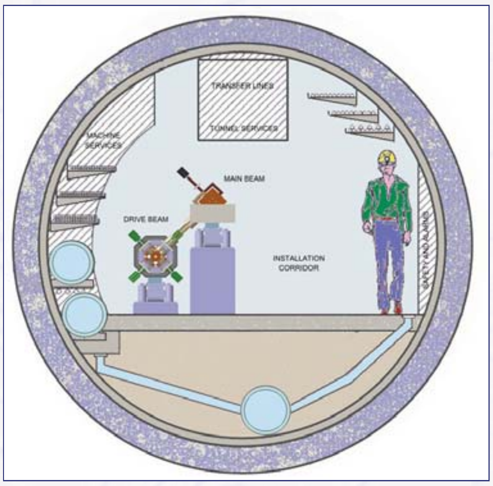
Main beam - 1.2 A from 9 GeV -> 1.5 TeV



No individual RF power sources
->
CLIC itself is basically a ~50 km long klystron...

CLIC Two Beam Module





possible CLIC tunnel scheme

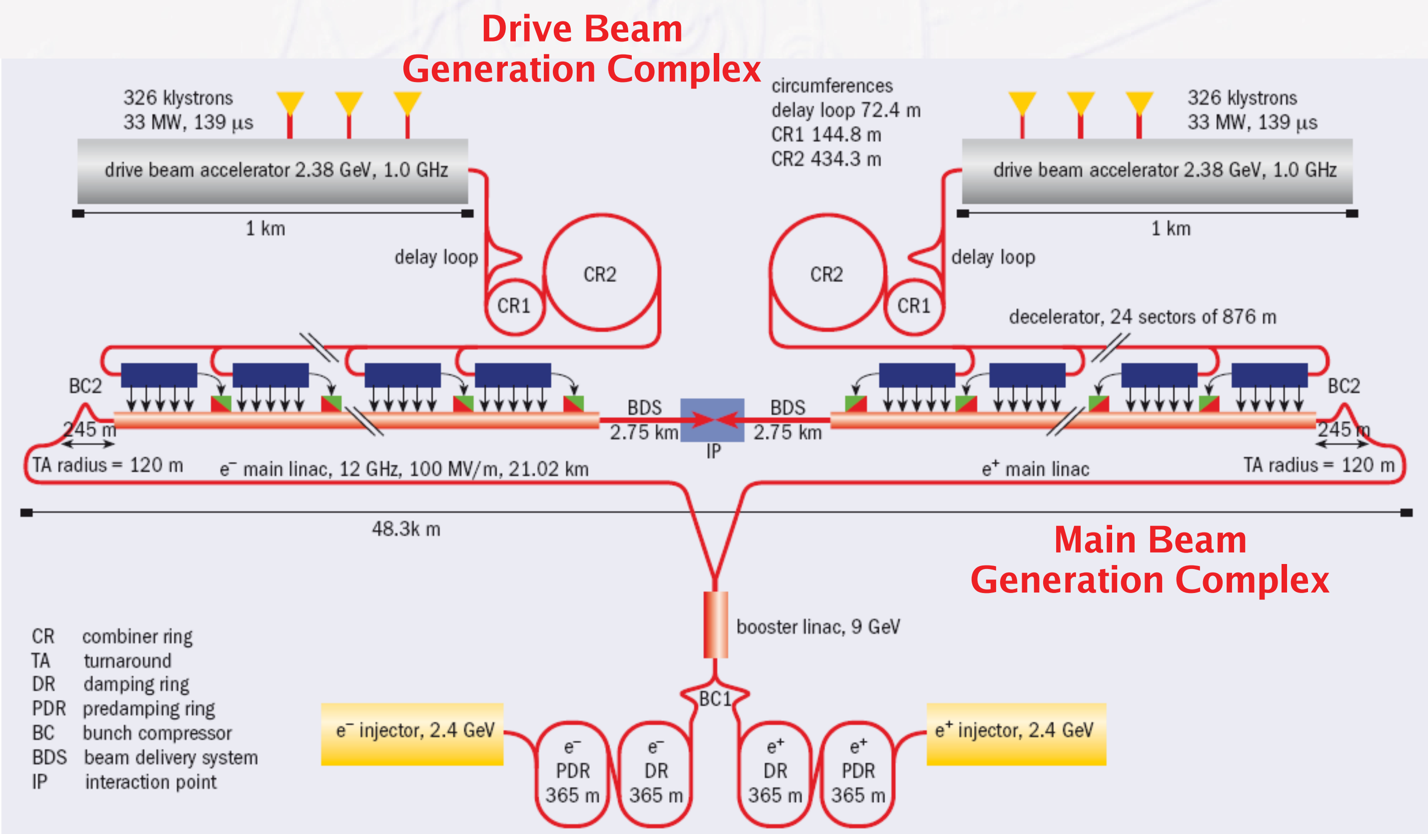
20760 modules (2 meters long)

71460 power production structures PETS (drive beam)

143010 accelerating structures

(main beam)

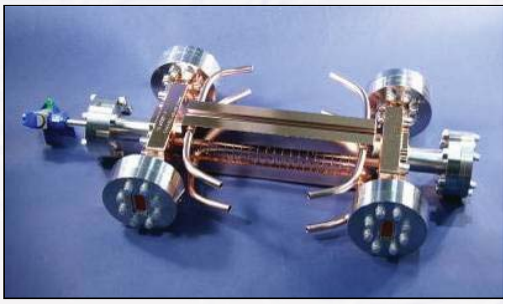
CLIC 3 TeV Overall Leyout

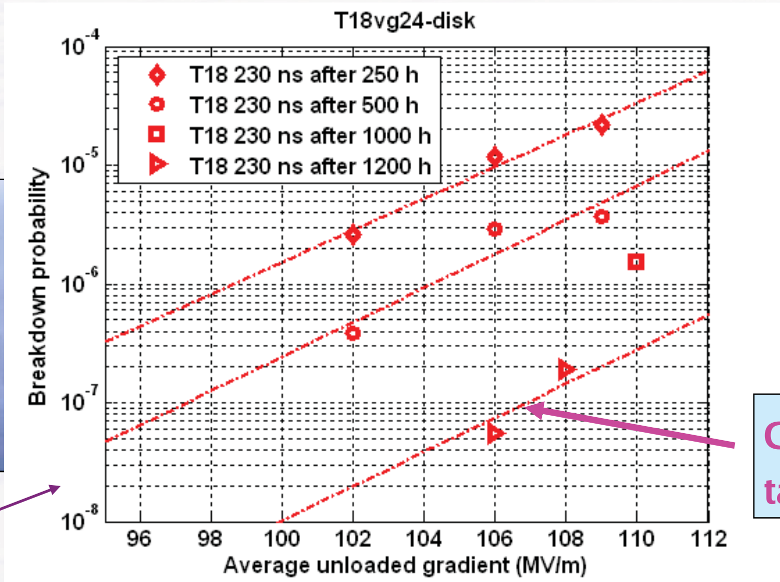


Breakdown Rate

- Major problem over last years
  - breakdown and damage of accelerating structure at high gradients and long pulse length
  - need to keep breakdown rate (damage) as low as possible

High power test of
CERN (design)
KEK (machined)
SLAC (brazed)
structure





CLIC target

Improvement by RF conditionning

CLIC Bunch Spacing

- CLIC study started at CERN about ~20 years ago
  - major revision of CLIC parameters made in summer 2007
- Basic changes
  - 30 GHz -> 12 GHz RF frequency
    - close to old NLC frequency (11.424 GHz)
      - easier to adapt NLC work and experience
    - lower frequency allows more relaxed alignment tolerances
  - 150 MV/m -> 100 MV/m
    - reduces breakdown rate and surface damages in RF accelerating structures
    - 50 km long LINAC allows 2 x 1.5 TeV = 3 TeV CM energy (was 5 TeV)
  - 0.5 ns bunch spacing, 312 bunches (= 156 ns bunch trains), 50 Hz (3 TeV)
    - optimized for maximum luminosity
    - was subject of various changes in the past:
      0.667 ns -> 0.267 ns -> 0.667 ns -> 0.5 ns
- Aim for feasibility and conceptional design report in 2010

detector challenge

ILC + CLIC Parameters

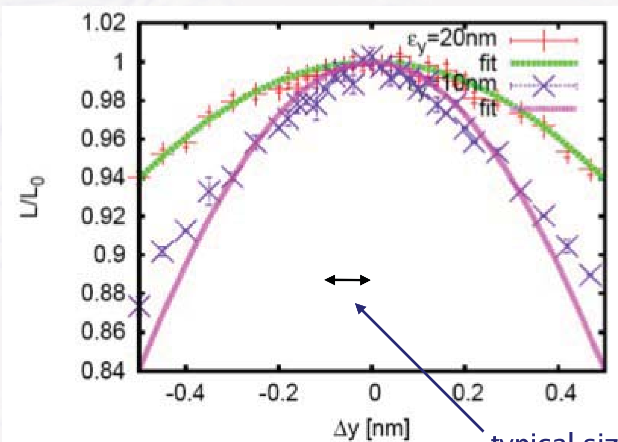
Luminosity at
500 GeV similar to ILC

Center-of-mass energy	ILC 500 GeV	CLIC 500 GeV	CLIC 3 TeV
Total (Peak 1%) luminosity [·10^{34}]	2(1.5)	2.3 (1.4)	5.9 (2.0)
Repetition rate (Hz)	5	50	
Loaded accel. gradient MV/m	32	80	100
Main linac RF frequency GHz	1.3	12	
Bunch charge [·10^9]	20	6.8	3.7
Bunch separation (ns)	370	0.5	
Beam pulse duration (ns)	950μs	177	156
Beam power/beam (MWatts)		4.9	14
Hor./vert. IP beam size (nm)	600 / 6	200 / 2.3	40 / 1.0
Hadronic events/crossing at IP	0.12	0.2	2.7
Incoherent pairs at IP	1 ·10^5	1.7·10^5	3·10^5
BDS length (km)		1.87	2.75
Total site length km	31	13	48
Total power consumption MW	230	130	415

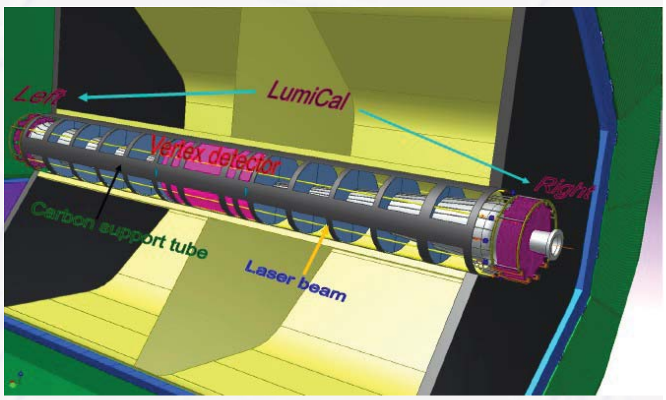
Crossing Angle 20 mrad (ILC 14 mrad)

Precise alignment/stability

- Extremely small beam sizes require unprecedented beam focusing stability
  - how to link left-arm and right-arm?
    - LumiCal could measure via Bhabha scattering
  - last quadrupole (at +/- 3.5 m) alignment requirements
    - ILC: < 4 μm (x,y), < 100 μm (z)
    - CLIC: more severe...



typical size of 1 atom



Main CLIC –ILC differences

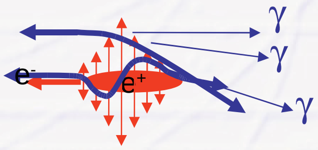
- Higher energy -> more dense particle jets (independent on machine concept)
  - need tracker with better double track resolution
    - TPC with good double hit resolution (GEMs, MicroMegas) reconsidered again as CLIC main tracker as alternative to full Si tracker
  - need calorimeters with larger thickness and higher granularity
    - Particle Flow concept requires to identify individual calorimeter EM and hadronic clusters
    - alternatively: forget particle flow, build calorimeter with (hardware) compensation = DREAM concept
- Much shorter bunch spacing: 0.5 ns (CLIC) vs 337 ns (ILC)
  - need 'time-stamping': identification of tracks from individual bunch crossings
    - if no time-stamping -> overlay of physics events with hadronic background from beamstrahlung
  - general time structure also has consequences for pulsed electronics
- Smaller beam sizes + higher E -> more (severe) background
  - need to move innermost layers further out

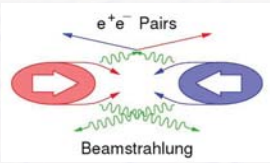
CLIC Detector Study

- CLIC detector study has started in 2008 at CERN
  - starting point: existing SiD and ILD concepts and simulations
  - have to modify/adjust concepts to CLIC needs
- CLIC detector = "90% ILC detector" + "10% CLIC specifics"
  - CLIC is profiting a lot from ongoing ILC detector R&D and design studies
  - but ILC also profits from CLIC studies
    - CLIC detector = "extreme" ILC detector -> win –win situation for both communities
    - common work on Particle Flow Algorithms
    - engineering studies (push –pull), also foreseen at CLIC
- Aim
  - prepare addenda for ILC LoIs end of 2010
    - "SiD-like concept" @ CLIC @ 3 TeV
    - "ILD-like concept" @ CLIC @ 3 TeV
    - 4th concept?

Beamstrahlung

unavoidable at Linear Colliders in general: small beam sizes -> large beamstrahlung



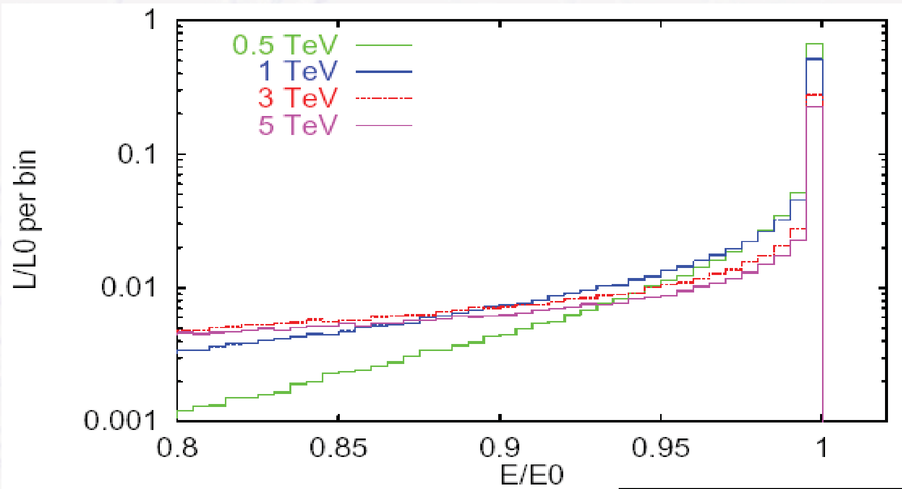


more severe at CLIC because of higher energy and smaller beamsizes

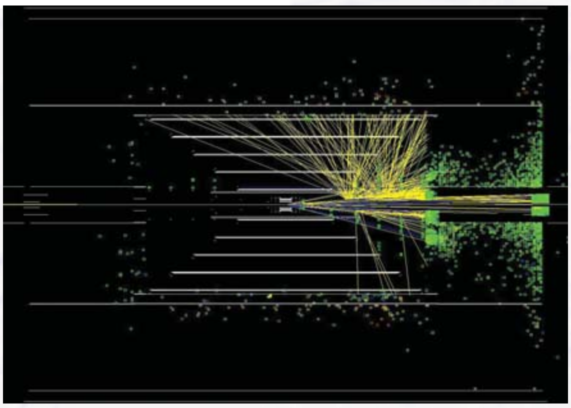
Parameter	Symbol	CLIC 3 TeV	CLIC 1 TeV	CLIC 0.5 TeV	ILC 0.5 TeV	NLC 0.5 TeV	Unit
Transverse horizontal emittance	$\gamma\epsilon_x$	660	660	660	8000	3600	nm rad
Transverse vertical emittance	$\gamma\epsilon_y$	20	20	20	40	40	nm rad
Nominal horizontal IP beta function	β^*_x	4	20	15	20	8	mm
Nominal vertical IP beta function	β^*_y	0.09	0.1	0.1	0.4	0.11	mm
Horizontal IP beam size before pinch	σ^*_x	40		142	640	243	nm
Vertical IP beam size before pinch	σ^*_y	1		2	5.7	3	nm
Beamstrahlung energy loss	δ_B	29	11	7	2.4	5.4	%
No. of photons / electron	n_γ	2.2	1.2	1.1	1.32	1.3	-
No. of pairs (p_T^{min}=20MeV/c, Î¸$_{min}$=0.2)	N_{pairs}	45	17.1	11.5			-
No. of coherent pairs	N_{coh}	38	0.07	0.0001			10^7
No. of incoherent pairs	N_{incoh}	0.44	0.09	0.05			10^5
Hadronic events / crossing	N_{hadron}	3.23	0.29	0.1			-

- CLIC 3 TeV beamstrahlung ΔE/E = 29% (~10 x ILC at 500 GeV)
  - 3.8 x 10^8 coherent pairs per BX (dispappear in beam pipe)
  - 4.4 x 10^4 incoherent pairs per BX (suppressed by strong solenoid field)
  - 3.2 hadronic events per BX (from $\gamma\gamma$ -> hadrons)

CLIC Luminosity Spectrum

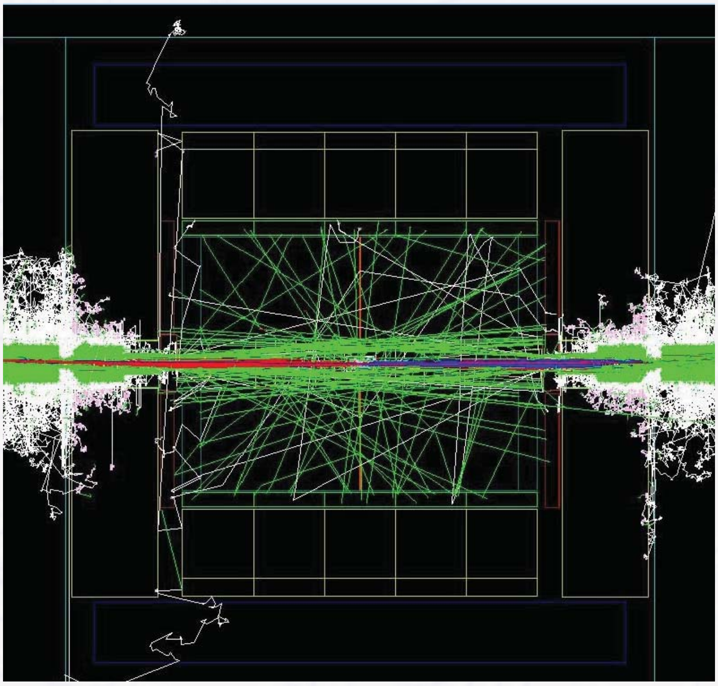


- **Due to beamstrahlung**
  - only 1/3 of the luminosity is in the 1% top centre-of-mass energy bin
  - many events with large forward or backward boost + many back-scattered photons/neutrons



Lessons Learnt from ILC

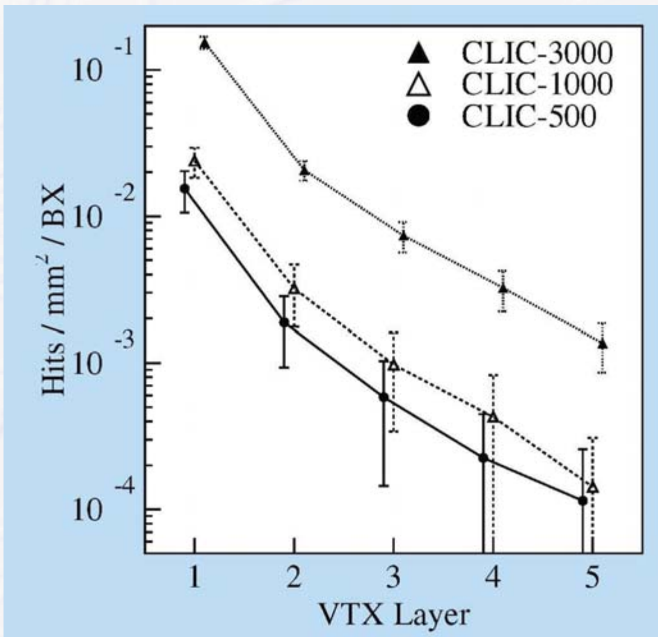
- Dominant background
  - pair production
  - Innermost vertex layer (r = 1.5 cm) has 0.04 hits/mm²/BX
  - critical level of neutrons (radiation damage) at small radii of HCAL end-cap
- Most backgrounds can be controlled by careful design
- Full detector simulation needed to avoid overlooking effects



10% beam crossing in ILD detector at 500 GeV

Extrapolation ILC -> CLIC

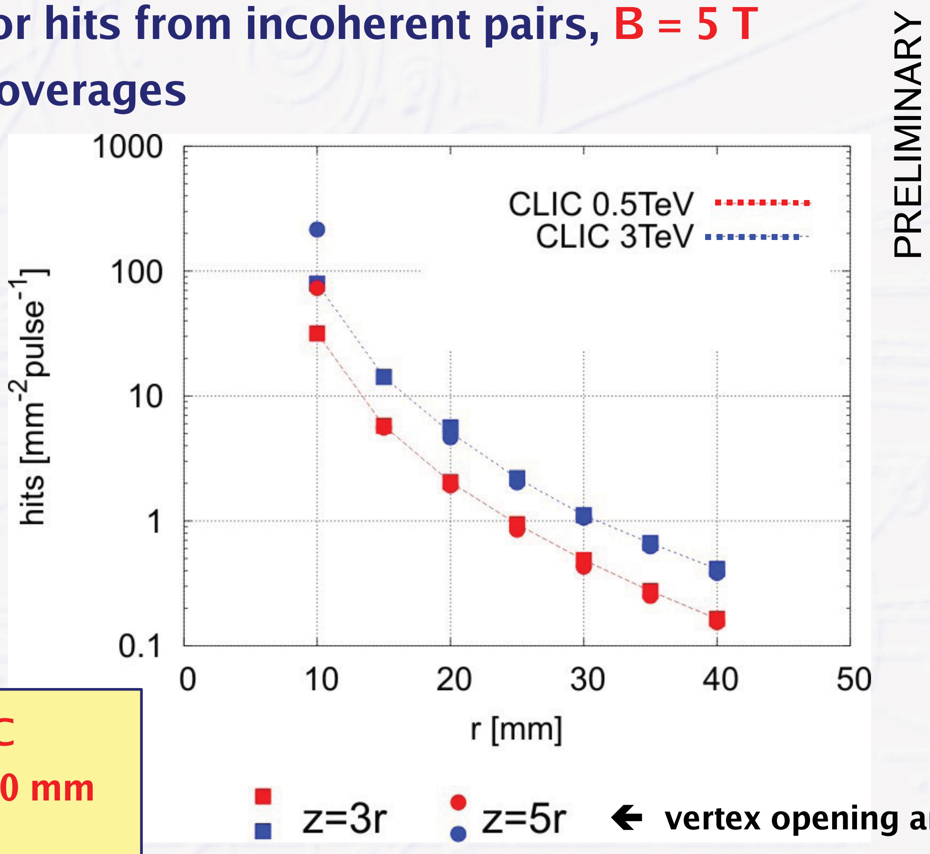
- Full LDC detector simulation at 3 TeV
  - simulation of e^+e^- pairs from beamstrahlung
- Conditions
  - ILC: 100 BX used (1/20 bunch train)
  - CLIC: 312 BX used (full bunch train)
- Conclusions (compared to ILC)
  - CLIC VTX
    - O(10) times more background
  - CLIC TPC
    - O(30) times more background



CLIC Vertex Detector

Vertex detector hits from incoherent pairs, B = 5 T
two angular coverages

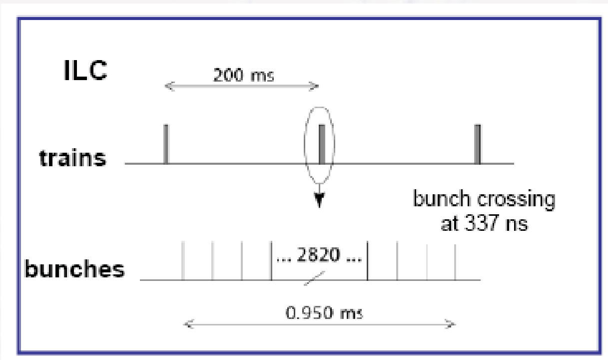
for
312 BX

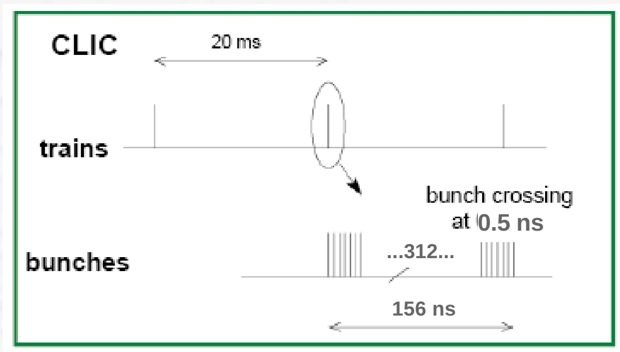


← vertex opening angle

inner radius of CLIC vertex det. at r = ~30 mm (15 mm for ILC)

CLIC Time Structure

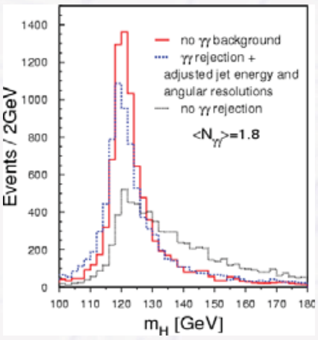




- **Bunch Spacing**
  - ILC: 337 ns, enough time to identify events from individual BX
  - CLIC: 0.5 ns, extremely difficult to identify events from individual BX
    - need short shaping time of pulses
    - power cycling with 50 Hz instead 5 Hz at ILC
    - larger power dissipation? does silicon tracker need to be cooled? (not cooled in SiD)

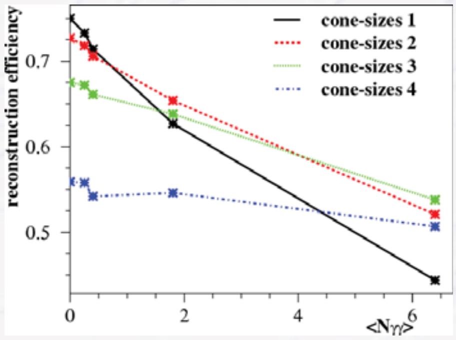
Why Time Stamping?

- Overlay of physics events with background events from several bunch crossings
  - ➨ degradation of physics performance
- Main background sources from beamstrahlung
  - ➨ e^+e^- pairs from beamstrahlung photons
    - low p_T, can be kept inside beam pipe with high magnetic field, B > 3 T
  - ➨ hadrons from 2-photon collisions (beamstrahlung photons)
    - can have high p_T, reach main tracker and confuses jet reconstruction
    - typically ~O(1) hadronic background event per BX with p_T > 5 GeV tracks



Higgs mass reconstruction from HZ ➔ $b\bar{b}q\bar{q}$

reconstruction of H ➔ $\tau^+\tau^-$

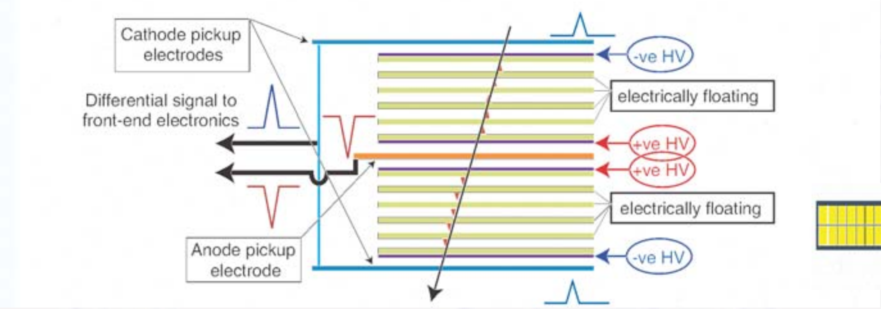


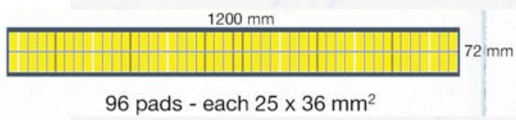
Time Stamping

- Ideal detector would be capable to identify particles from individual bunch crossings in all detector components
  - ➨ not realistic, most detectors don't have 0.5 ns resolution or better
- Way out
  - ➨ add a few dedicated time stamping layers
    - Fast silicon pixel layers for tracking
    - TOF layer with high granularity in front or inside calorimeters
      - ALICE Multigap RPCs have time resolutions of <100 ps

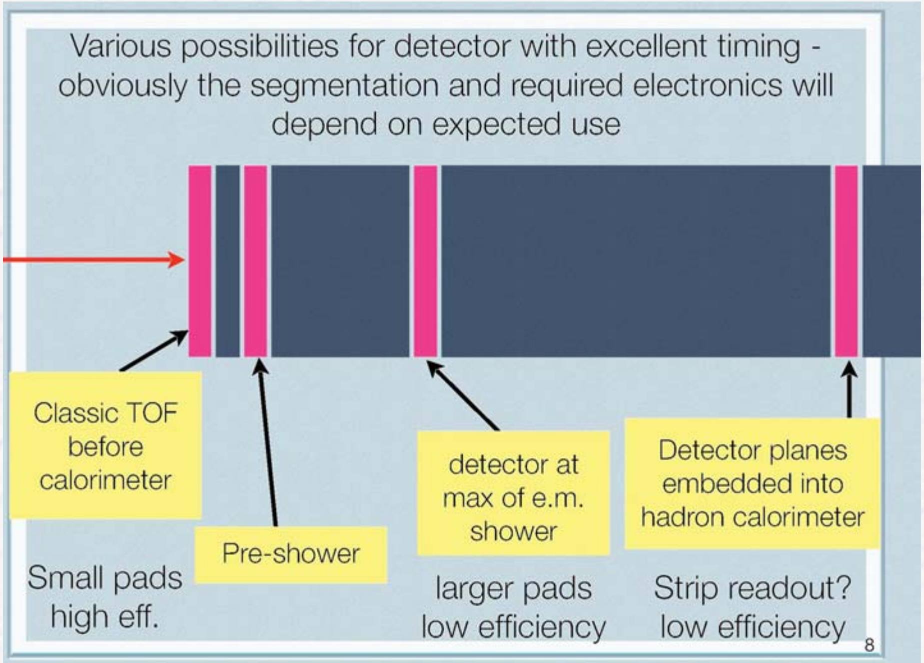
ALICE-TOF has 10 gas gaps (two stacks of 5 gas gaps) each gap is 250 micron wide

Built in the form of strips, each with an active area of 120 x 7.2 cm^2, readout by 96 pads





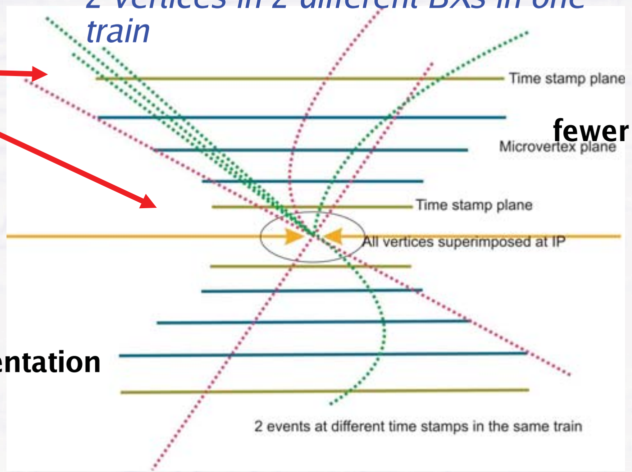
Time Stamping - Calorimeters



- **Fast TOF available already today**
  - **need to optimize for CLIC**
    - **granularity, segmentation, material, electronics (type/power)**
    - **how fast do we really need? faster electronics -> higher power consumption**

Time Stamping - Tracking

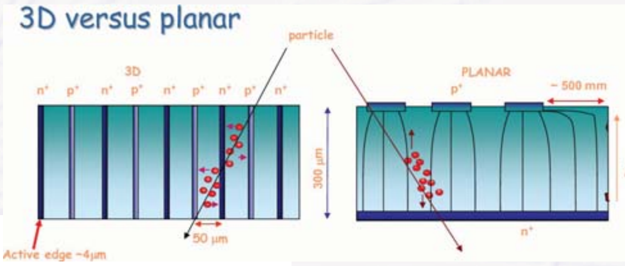
- **Limitations**
  - **time stamping requires fast detector/electronics**
  - **but cannot affort too many channels/pixels (high power consumption)**
- **Basic idea**
  - **have few time stamping layers**
    - **fast, larger pixels, less spatial resolution, fewer channels**
    - **Hybrid pixel, 0.3 x 0.3 mm²**
  - **+ "standard" tracker layers**
    - **"slow", small pixels, many channels, precise**
    - **Monolithic sensor pixel, 0.02-0.05 mm segmentation**
    - **integrate over full bunch train (156 ns)**
- *2 vertices in 2 different BX's in one train*

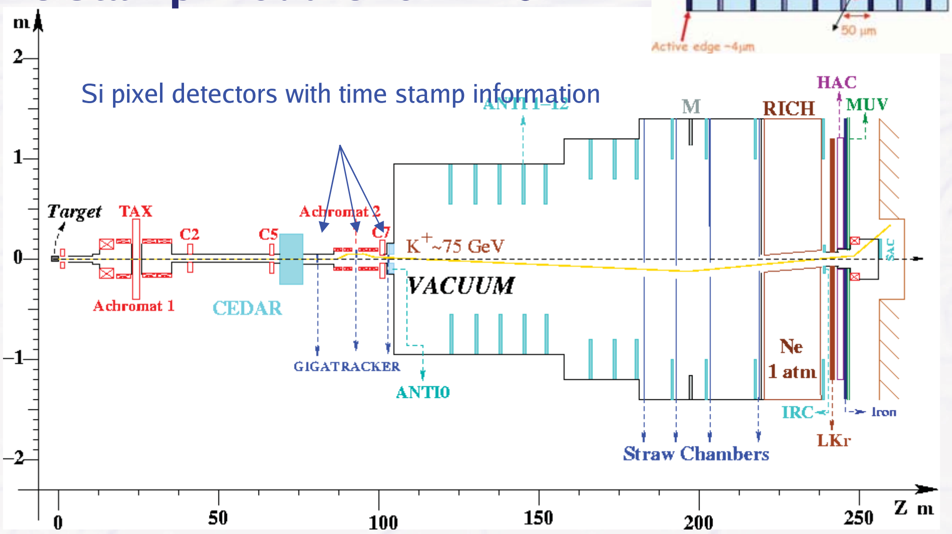


- **Similar concept as for trigger**
  - **fast + course detectors give triggers**
  - **slow + precise detectors used for reconstruction**

Time Stamping - Prospects

- Preliminary results on 130 nm Front End circuits encouraging
  - time resolution < 100 ps for 300 µW power on 0.3 x 0.3 mm ^{2} pixel
- Fast sensors also encouraging
  - can reach 1 or 2 ns in 3-D silicon
- Proposal to build demonstrator time stamp module for NA62

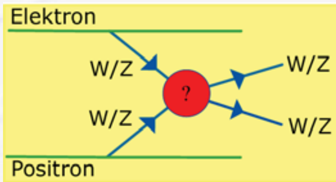


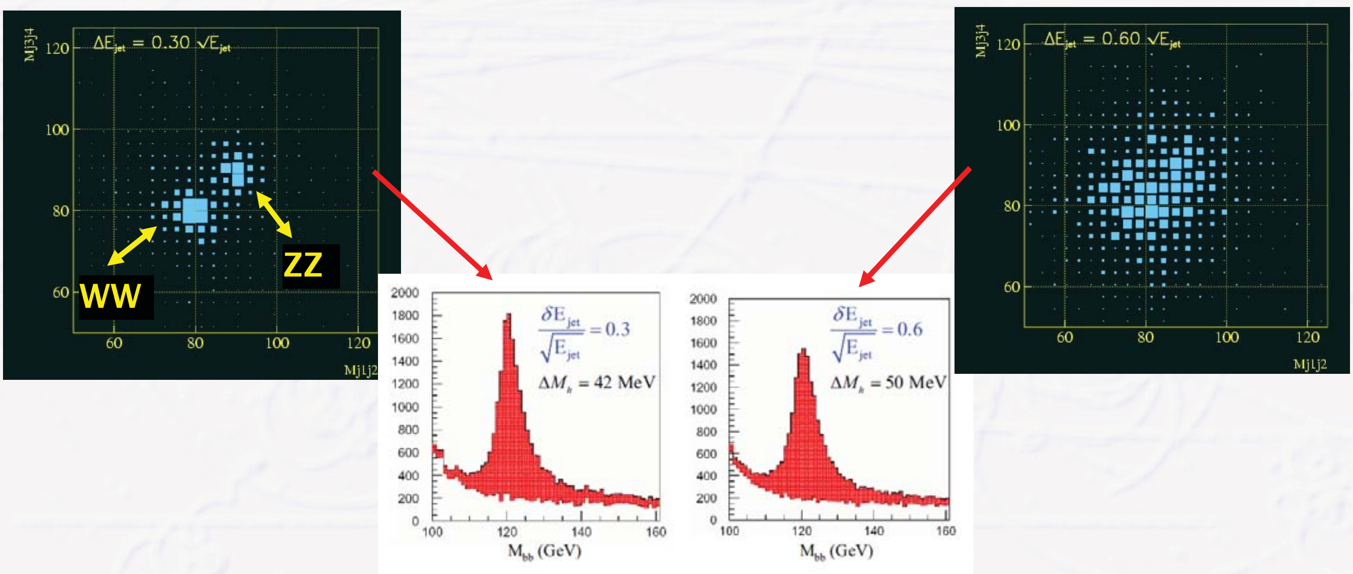


measurement of rare Kaon decays: $K^+ \rightarrow \pi^+ \nu \nu$

Jet Energy Resolution (ILC + CLIC)

- Need enough resolution to separate Z and W decaying into jets: $e^+e^- \rightarrow \nu\nu$ + WW/ZZ → jets
- Improvement of $\Delta E/E$ from $60\%/\sqrt{E}$ to $30\%/\sqrt{E}$
  - equivalent to ~40% luminosity gain in ΔM_h
    - similar luminosity gain in $\Delta BR(H \rightarrow WW^*)$, Δg_{hhh}

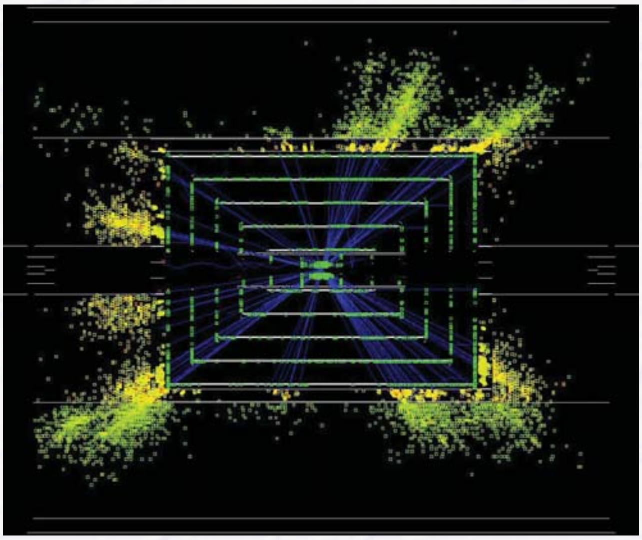




Jet Multiplicities

Jet Multiplicity

$\sqrt{s}$ (TeV)	0.09	0.20	0.5	0.8	3.0
$< N_{Jets} >$	2.8	4.2	4.8	5.3	6.4
	LEP1 90 GeV	LEP2 200 GeV	ILC 500 GeV	ILC 800 GeV	CLIC 3 TeV



multi-jet event
at √s = 3 TeV
e^+e^- -> WW -> qqqq

Distance of Leading Particles in Jets

Spatial distance neutral – charged hadrons

(J.J. Blaising)

Distance, Δ, at the 1. layer of HCAL

	Njet, Ecm, B	Δ (cm) MPV barrel	Δ (cm) RMS barrel	Δ (cm) MPV endcap	Δ (cm) RMS endcap
$\nu\nu H^0$	2J, 0.5 GeV,4T	8.0	3.6	9.7	4.4
$t\bar{t}$	4/6J, 0.5 GeV,4T	6.4	2.8	8.6	6.7
$\nu\nu H^0$	2J, 3.0 TeV, 4T	3.8	2.6	2.6	2.4
$t\bar{t}$	4/6J, 3.0 TeV, 4T	1.0	1.1	1.7	0.9
$t\bar{t}$	4/6J, 3.0 TeV, 5T	1.4	1.2	1.9	1.0

- at 3 TeV neutral - charged particle separation only ~ 1 cm
- cluster of neutral and charged hadrons will overlap in HCAL
- neutral hadron reconstruction (with PFA) only by subtraction

CLIC Calorimetry

- Higher energy -> deeper hardronic shower
  - need deeper HCAL ($\geq 8\ \lambda_i$)
    - want to keep HCAL inside coil
    - cannot increase coil radius too much
  - need heavy absorber (tungsten?) to limit thickness
- 2 general concepts
  - based on Particle Flow Algorithm (as ILC)
    - highly segmented (~25 mm²) ECAL
    - segmented HCAL
    - does it work at 3 TeV???
  - based on Dual (Triple) readout
    - homogeneous ECAL
      - based on crystals
    - sampling HCAL
      - based on fibres

Particle Flow Algorithm:
- Method and engineering difficult, but conventional
- Limited in energy-range to a few hundred GeV

Dual (Triple) readout:
- Method and engineering difficult and non-proven
- Not limited in energy range

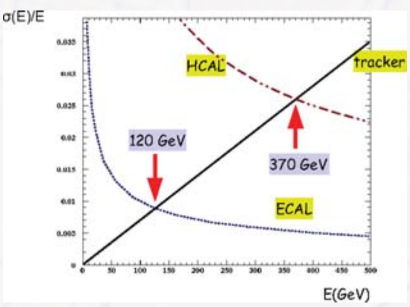
Particle Flow

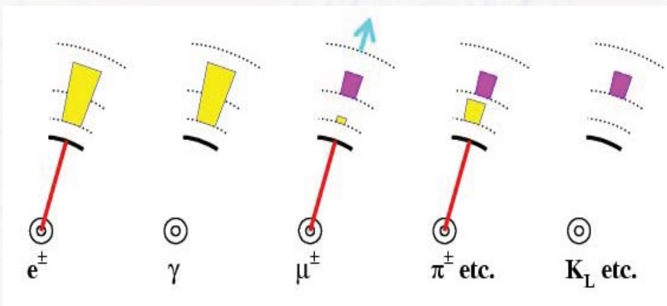
- Many physics signatures have complicated multi-jet final states >6 jets (6.4 jets per event at 3 TeV)
  - good jet energy resolution required (2x better than at LEP)
    - LEP: $\sigma(E_{jet}) \approx 60\%/\sqrt{E_{jet}}$ ILC/CLIC: $\sigma(E_{jet}) \approx 30\%/\sqrt{E_{jet}}$
  - use combined information of tracker, ECAL + HCAL to obtain better jet energy resolution
- "Particle Flow" concept (simple but challenging)

$$\sigma^2(E_{jet}) = \sigma^2_{charged\ particles} + \sigma^2_{photons} + \sigma^2_{neutral\ hadrons} + \sigma^2_{confusion} + \sigma^2_{threshold}$$

keep these as small as possible ($\sigma^2_{confusion}$, $\sigma^2_{threshold}$)

contributions to E_{jet}: 60% tracker, 30% ECAL, 10% HCAL

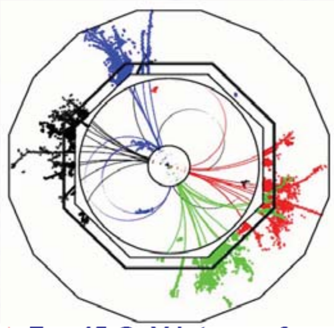




Particle Flow Performance

- Performance depends largely also on software algorithms
  - "software compensation"

from Mark Thompson, CALICE-UK, Cambridge



several algorithms are being developed
today best performing:
PandoraPFA (M. Thompson)

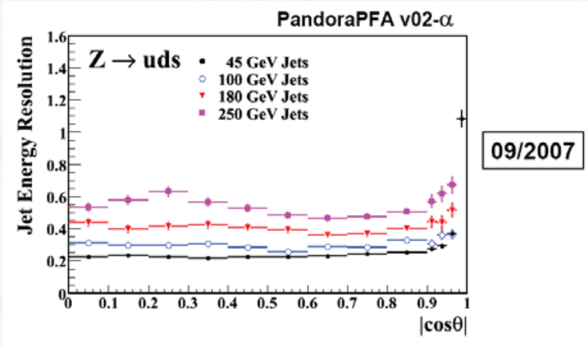
PandoraPFA v02-α

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.227	3.4 %
100 GeV	0.287	2.9 %
180 GeV	0.395	2.9 %
250 GeV	0.532	3.4 %

★ For 45 GeV jets, performance now equivalent to

23 % / √E

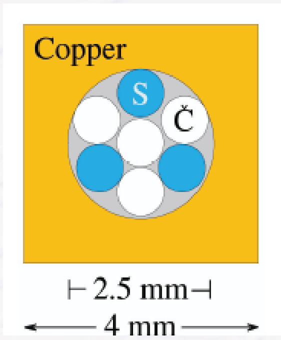
energy range > 100 GeV still problematic
but … work in progress !



- Does PFA work for CLIC at 3 TeV?
  - higher energies
  - particle separation in HCAL ~ few cm only

PFA Alternative: the 4th Concept

- DREAM concept (Dual REAdout Module)
- Basic idea
  - have calorimeter with absorber and two types of fibers to measure EM and hadronic shower separately
    - clear fibers: sensitive to EM shower only via Čerenkov light
    - scintillating fibers: sensitive to both EM and hadronic shower
    - Triple Readout: sensitive to neutrons in late scintillating signal
  - hardware compensation
    - good energy resolution but still a sampling calorimeter (separate absorber + detector)
    - sampling fluctuations degrade resolution



- Can one do even better?
  - have fibers both acting as absorber and detector
    - get 'quasi-homogeneous"calorimeter
  - need to find/develop heavy materials to be use as fibers

Summary of CLIC Challenges + R&D

- Time stamping
  - most challenging in inner tracker/vertex region
  - trade-off between pixel size, amount of material and timing resolution
- Power pulsing and other electronics developments
  - in view of CLIC time structure
- Hadron calorimetry
  - dense absorbers to limit radial size (e.g. tungsten)
  - PFA studies at high energy
  - alternative techniques, like dual/triple readout
- Background
  - innermost radius of first vertex detector layer
  - shielding against muon background more difficult at higher E
- Alignment and stability

Tentative long-term CLIC Scenario