Detectors for a Multi-TeV Collider: "what can be learnt from the ILC"

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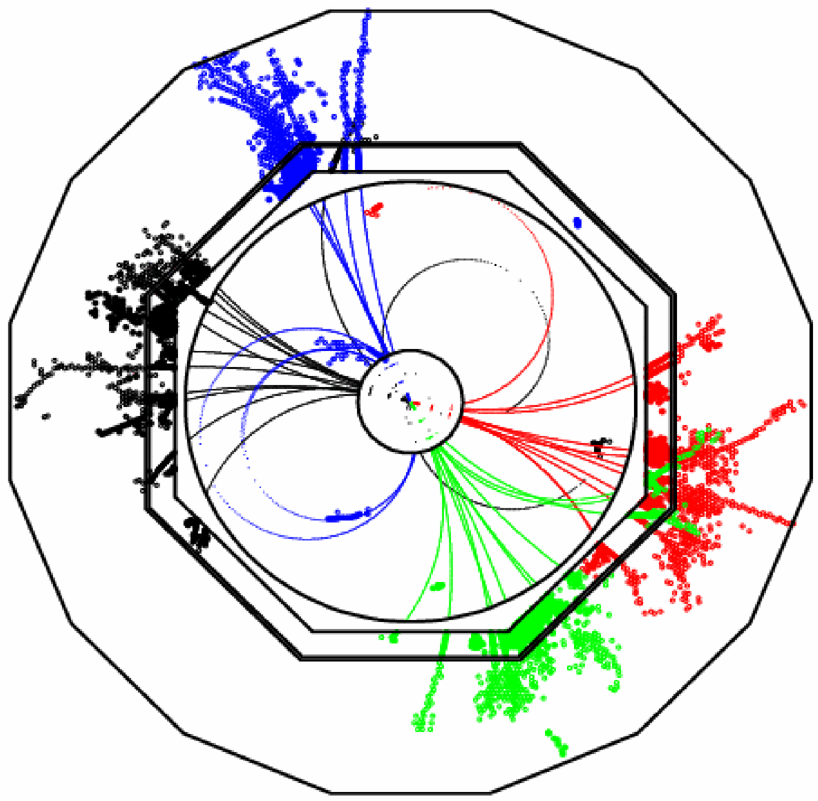
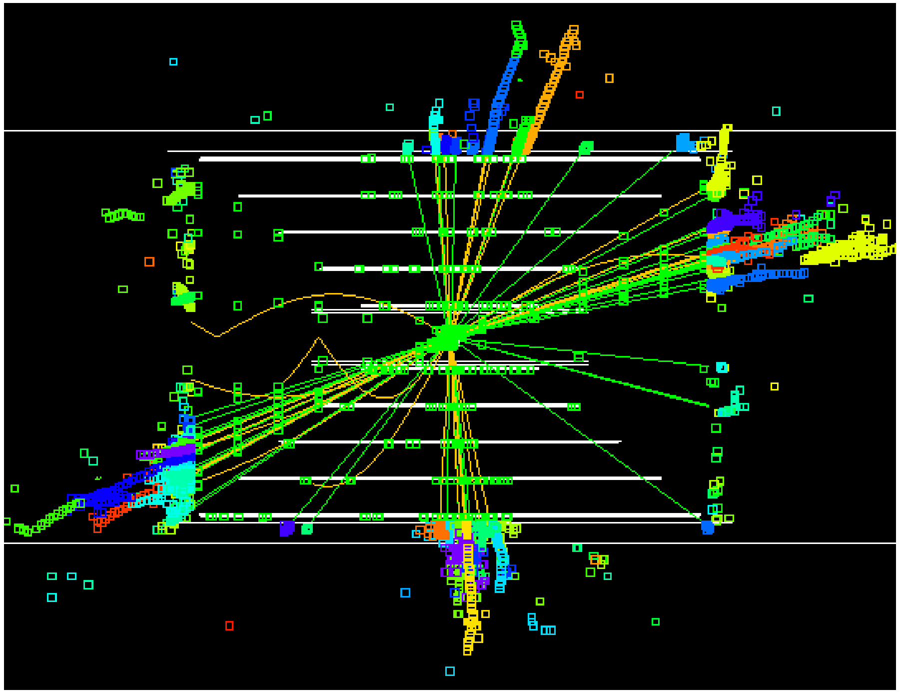




Overview

- ★ Over last 10 years extensive studies of detector concepts for the ILC
  - Recently culminated in ILC detector Letters of Intent
  - Two validated detector concepts: ILD, SiD
- ★ Initial CLIC detector studies build on these concepts…
- ★ Starting point for CLIC CDR detector

<u>This Talk</u>

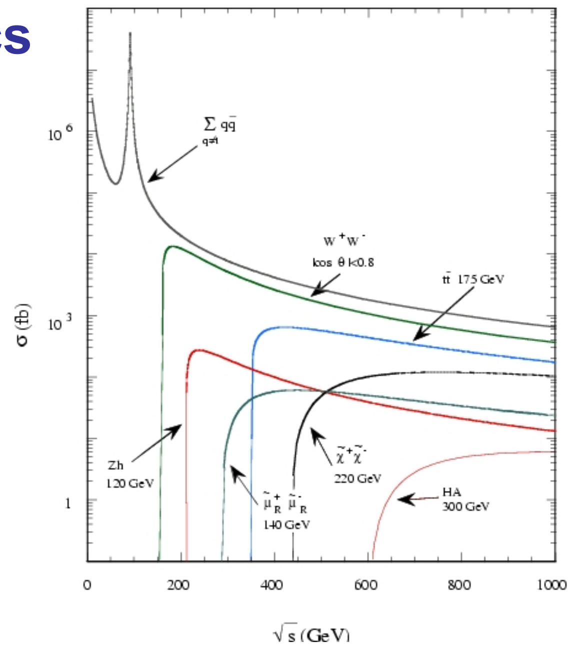
- ★ Discuss motivation for ILC detector concepts
- ★ Give very brief overview of ILD and SiD
- ★ Discuss requirements for a detector at CLIC
  - Physics
  - Machine
- ★ Discuss main issues for CLIC
  - Backgrounds
  - Vertex detector/flavour ID
  - Tracking
  - Calorimetry
  - Bunch Crossing (BX) tagging

} With reference to ILC detector concept studies

ILC Physics

- ★ Detector design should be motivated by physics
- ★ Full physics programme not fully defined until results from LHC
- ★ Nevertheless, some clear candidates:

  e.g. Precision Studies/Measurements
  - Higgs sector
  - SUSY particle spectrum (if there)
  - Top physics
- ★ Minimum detector requirements matched to "mandatory" physics programme



- ★ Radiation hardness not a significant problem, e.g. 1st layer of vertex detector : 10^9 *n* cm^{-2} yr^{-1} c.f. 10^{14} *n* cm^{-2} yr^{-1} at LHC

Bottom Line:

Want to design a **general purpose detector** to fully exploit physics in clean ILC environment

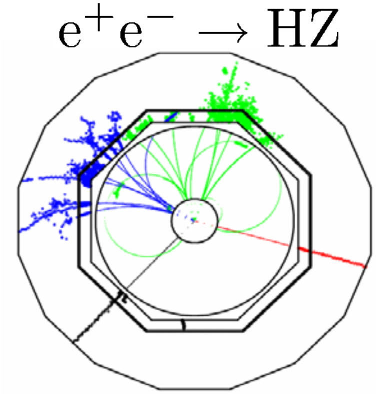
ILC Detector Requirements

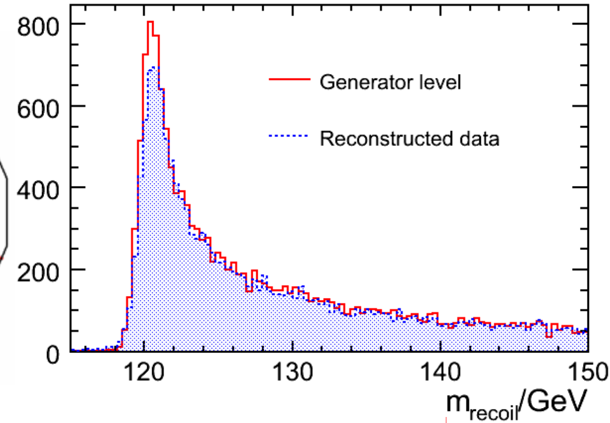
★ **momentum:** **(1/10 x LEP)**

e.g. Muon momentum

Higgs recoil mass

$$\sigma_{1/p} < 5 \times 10^{-5}\,\mathrm{GeV}^{-1}$$



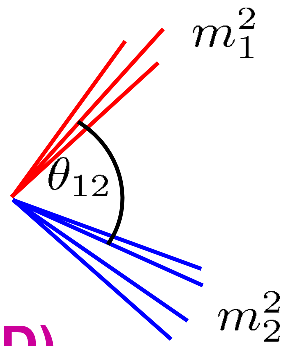


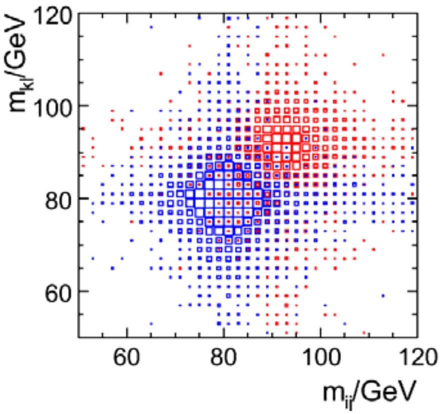
★ **jet energy:** **(1/3 x LEP/ZEUS)**

e.g. W/Z di-jet mass separation

EWSB signals

$$\frac{\sigma_E}{E} \approx 3-4\,\%$$



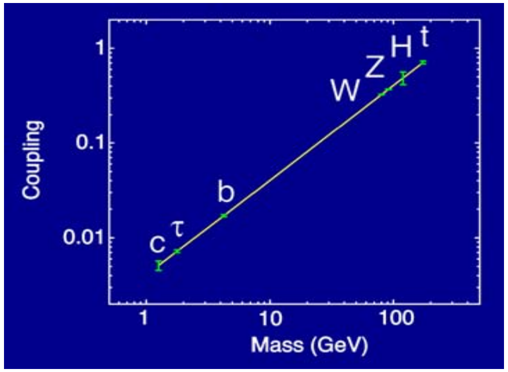


★ **impact parameter:** **(1/3 x SLD)**

e.g. c/b-tagging

Higgs BR

$$\sigma_{r\phi} = 5 \oplus 10/(p\sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$



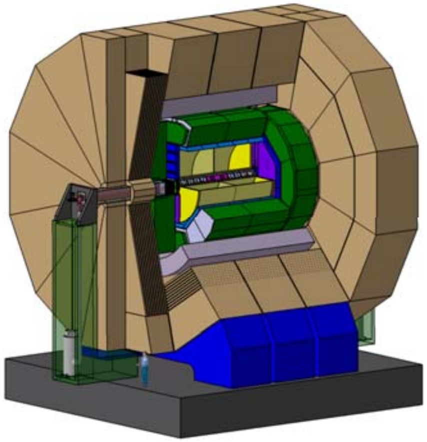
★ **hermetic:** **down to θ = 5 mrad**

e.g. missing energy signatures in SUSY

ILC Detector Concepts

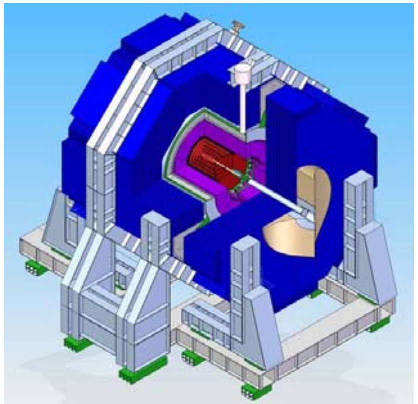
ILD: International Large Detector

"Large" : tracker radius 1.8m
B-field : 3.5 T
Tracker : TPC
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid



SiD: Silicon Detector

"Small" : tracker radius 1.2m
B-field : 5 T
Tracker : Silicon
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid



- ★ Both concepts "validated" by IDAG (independent expert review)
- ★ Detailed GEANT4 studies show ILD/SiD meet ILC detector goals
- ★ Fairly conventional technology – although many technical challenges

Represent plausible/performant designs for an ILC detector

From ILC to CLIC Detector Concepts

- ★ Detector design should be motivated by physics
- ★ On assumption that CLIC would be staged: e.g. 500 GeV → 3 TeV
  - Must meet all ILC detector goals
  - Hence ILD and SiD represent good starting points
- ★ For 3 TeV operation what are the detector goals ?
  - Less clear than for the ILC (for ILC Higgs physics helps define goals)
  - Nevertheless can make some statements:
    - ♦ Still want to separate W/Z hadronic decays

Jet energy res: $$\frac{\sigma_E}{E} < 3-4\,\%$$

    - ♦ Heavy flavour-tagging still will be important; higher boost of b/c-hadrons will help. ILC goal likely(?) to be sufficient, i.e.

$$\sigma_{r\phi} = 5 \oplus 10/(p\sin^{\frac{3}{2}}\theta)\,\mu\text{m}$$

but, needs study

    - ♦ Requirements for momentum resolution less clear, high p_T muons likely to be important…

But…

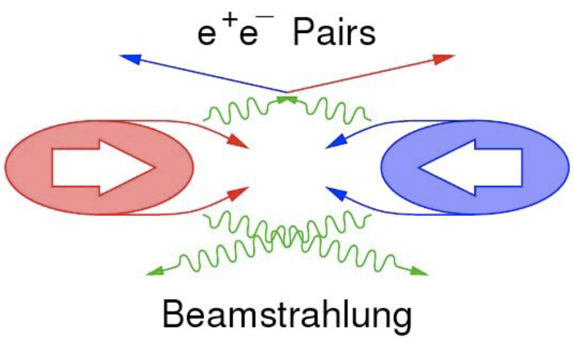
Main detector requirements driven by CLIC machine environment

From ILC to CLIC Detector Concepts

	LEP 2	ILC 0.5 TeV	CLIC 0.5 TeV	CLIC 3 TeV
L [$cm^{-2}s^{-1}$]	5×10^{31}	2×10^{34}	2×10^{34}	6×10^{34}
BX/train	4	2670	350	312
BX sep	247 ns	369 ns	0.5 ns	0.5 ns
Rep. rate	50 kHz	5 Hz	50 Hz	50 Hz
L/BX [cm^{-2}]	2.5×10^{26}	1.5×10^{30}	1.1×10^{30}	3.8×10^{30}
$\gamma\gamma\to X$ / BX	neg.	0.2	0.2	3.0
σ_x/σ_y	240 / 4 mm	600 / 6 nm	200 / 2 nm	40 / 1 nm

Note: Integrated luminosity per BX ~ same for ILC and CLIC

- ★ Beam related background:
  - Small beam profile at IP leads very high E-field;
    - Beamsstrahlung
    - Pair-background
    - Effects more significant at CLIC

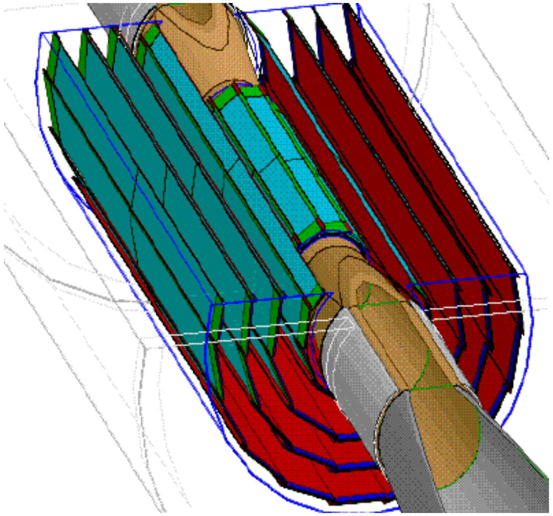


- ★ Bunch train structure:
  - ILC: BX separation 369 ns
  - CLIC: BX separation 0.5 ns
- ★ Two photon → hadrons background, at CLIC:
  - Approx three "visible" events per BX
  - Important since, sub-detectors will integrate over >1 BX (0.5 ns)

Sub-detectors: from ILC to CLIC

ILC Vertex detector

★ ILD and SiD assume **Silicon pixel** based vertex detectors (5 or 6 layers)



Main design considerations:

★ Inner radius: **as close to beam pipe as possible** for impact parameter resolution ~ 15 mm

★ Layer thickness: as thin as possible to minimize multiple scattering

$$\sigma_{r\phi} = 5 \oplus 10/(p \sin^{\frac{3}{2}}\theta)\,\mu\mathrm{m}$$

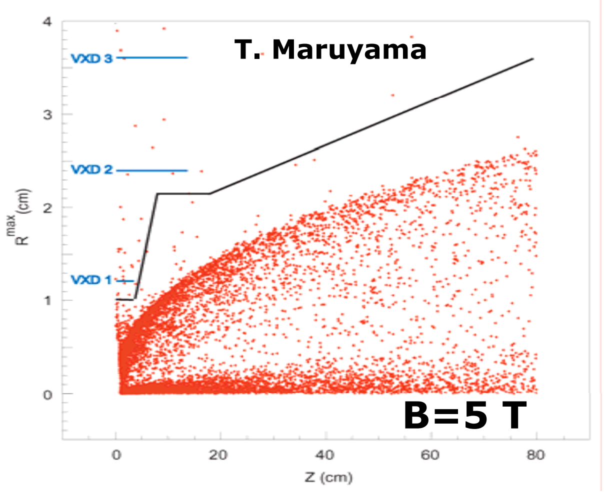
Constraints:

★ Inner radius limited by pair background depends on machine + detector B-field

★ Layer thickness depends on technology

★ Time-stamping:

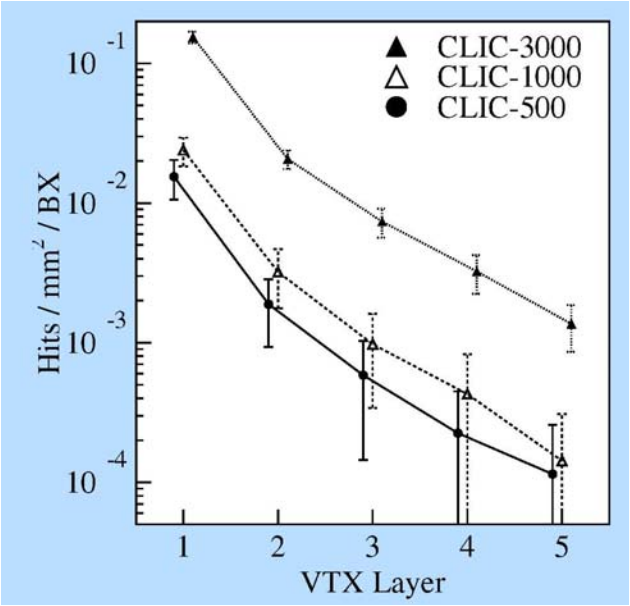
- ILD assume integrate over **~50 μs**
- SiD assume single BX time-stamping (0.3 μs)
  - **how feasible**
- faster readout, implies power consumption, cooling ⇒ **more material**



Impact of pair background at CLIC

CLIC Vertex Detector

Adrian Vogel



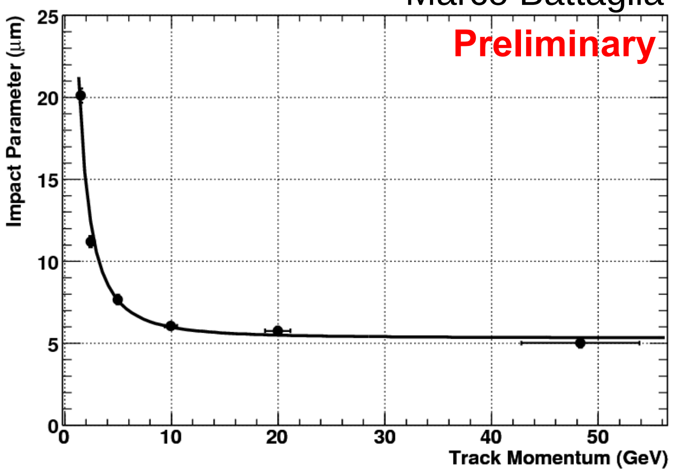
- ★ Pair background is worse at CLIC
- ★ Previously studied using full simulation at 3 TeV using ILD-like detector
- ★ Conclusions **depend on assumptions** for detector integration times:
  - used 100 BX for ILC
  - full bunch train for CLIC

⇒ CLIC VTX: O(10) × more background
CLIC TPC: O(30) × more background

- ★ For reasonable occupancy:
  - Inner radius of CLIC VTX detector

⇒ 31 mm

Marco Battaglia

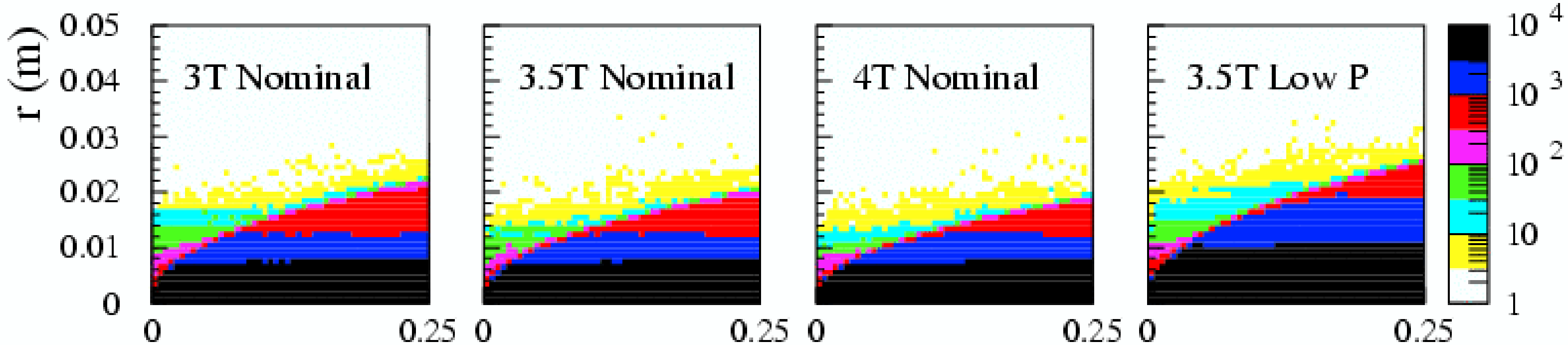


- ★ Still obtain good impact parameter resolution (depends on assumed point resolution)

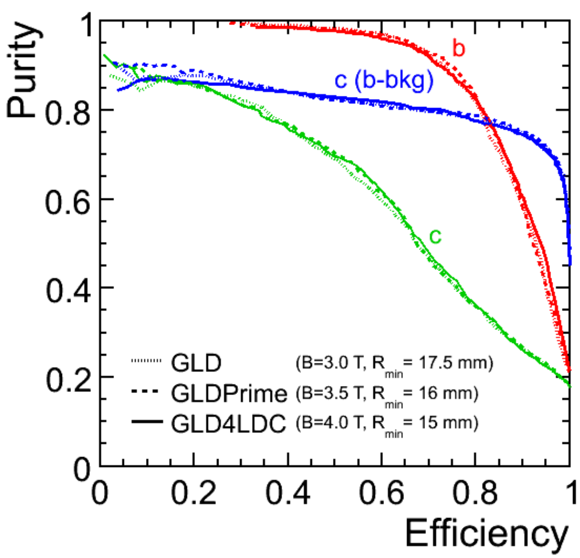
- ★ Pair background constrained by B-field, so does this argue for a higher B-field ?

B-field and ILC Vertex detector

- This question has been addressed by ILD study
- But radius of pair background envelope scales roughly as $\sqrt{B}$



- Compare flavour tagging performance for different detector models
  - Differences of **2.5 mm** in inner radius of beam pipe due to B field



- **Conclude:**
  - Differences are not large
  - Smaller inner radius of vertex detector not a strong effect
  - Earlier studies showed that going from 15 mm → 25 mm inner radius did not have a large impact on flavour tag

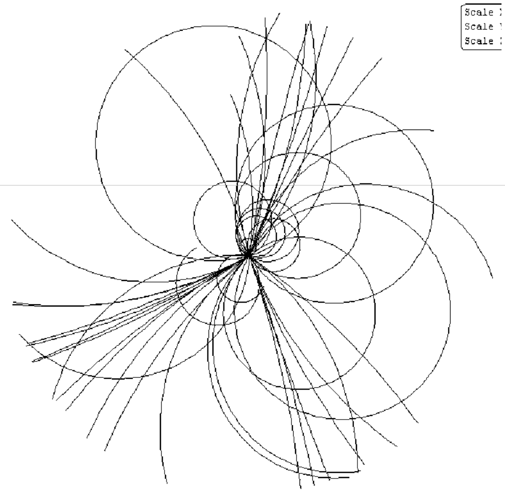
31 mm probably OK

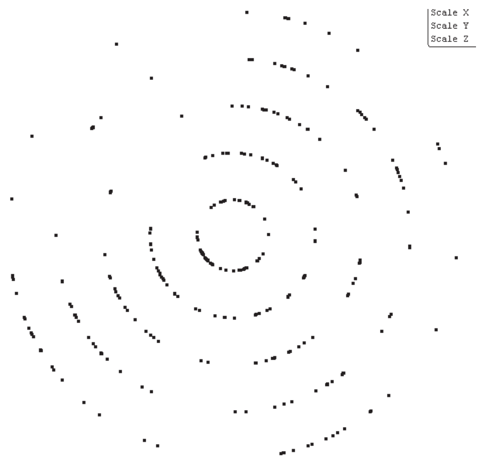
Note: Vertex charge measurements more sensitive to r_{INNER}

Tracking at the ILC

Two options:

- ILD: Time Projection Chamber
- SiD: Silicon tracker (5 layers)





- Large number of samples
- Few very well measured points

★ LoI studies show that both result in :

- Very high track reconstruction efficiency
- Excellent momentum resolution: $\sigma_{1/p_T} \sim 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ (high p tracks)

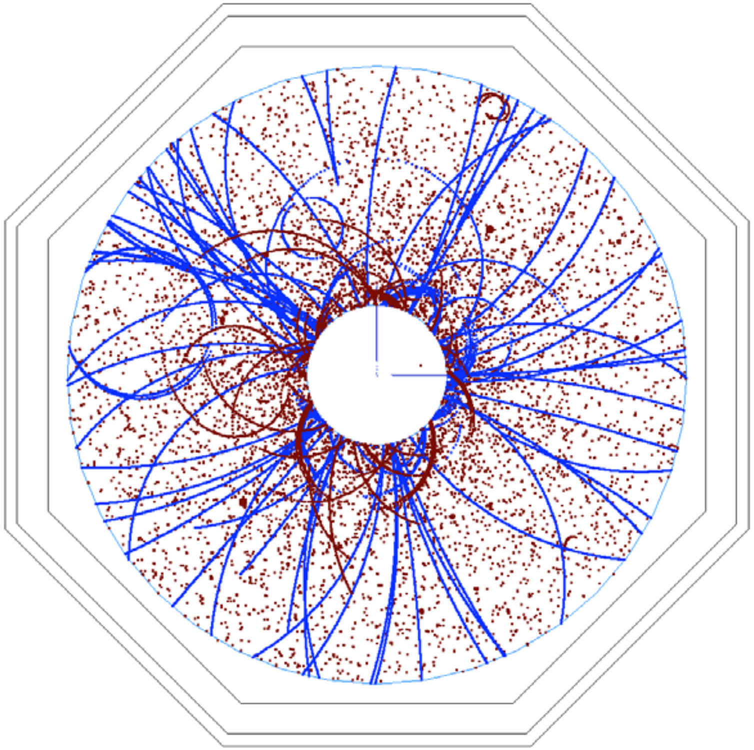
What is the best option for CLIC ?

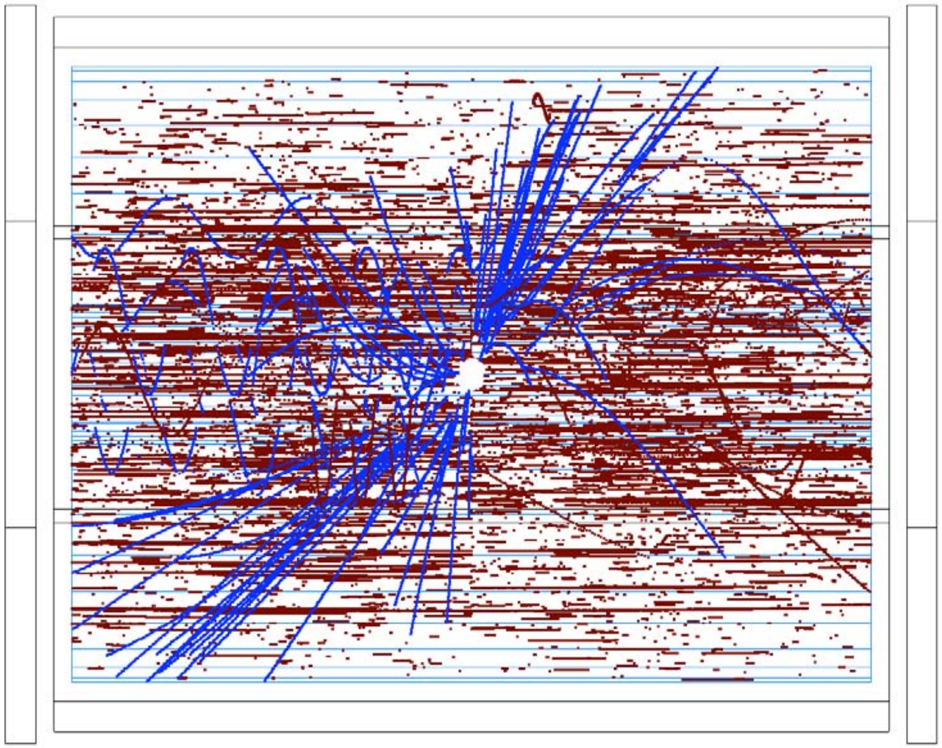
- Robustness to background/Pattern recognition ?
- Two track separation ?

Background: TPC

- For TPC, conservatively take drift velocity to be **4 cm μs^{-1}**
- Therefore fill TPC with **150 BXs** of background shifted in **z**
- Superimpose on fully-hadronic top-pair events at 500 GeV
- Main issue "micro-curlers", low energy e^+e^- from photon conversions
- Removed using dedicated patrec software

150 BXs of pair background



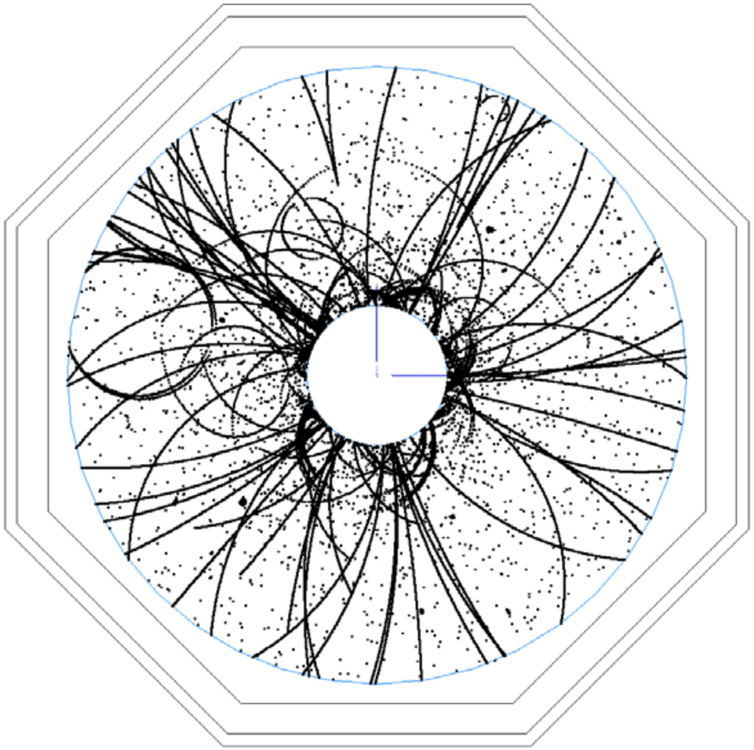


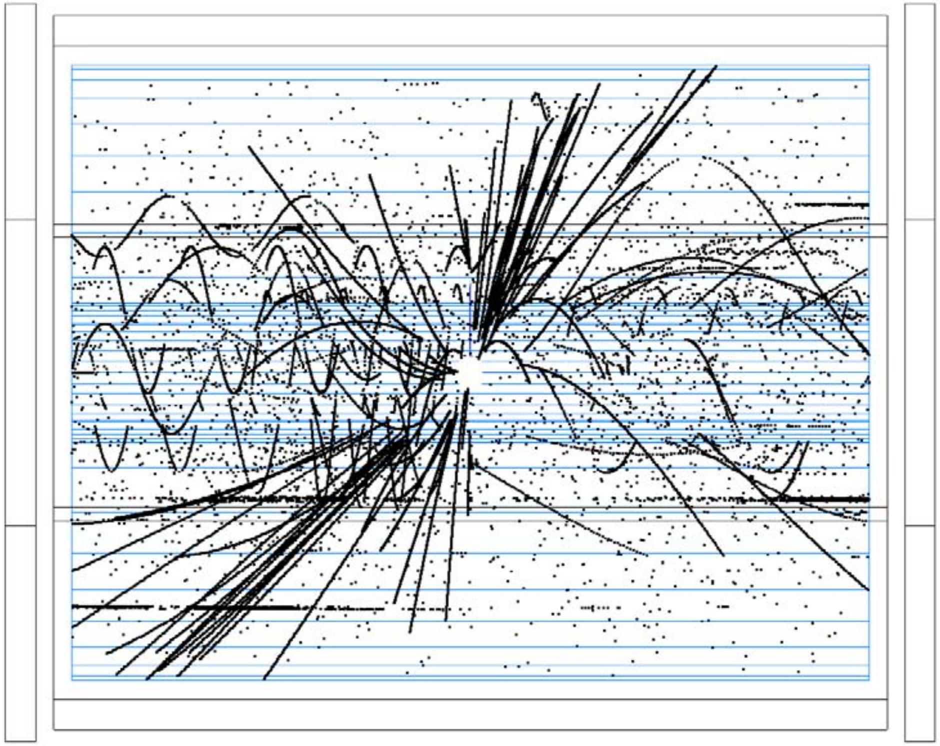
★ **Effective removal of large fraction of background hits**

	Top (p_T>1 GeV)	Background
Raw hits	**~8,600**	**~265,000**
After	**~8,500**	**~3,000**

★ **By eye – clear that this should be no problem for PatRec**

★ **In practice, negligible impact on track reconstruction efficiency.**





Tracking at CLIC

★ At this stage it is not clear which is the best option for CLIC

TPC:

✓ Excellent pattern recognition capabilities in dense track environment

✘ Integrates over all bunch-train: 312 BXs ~ 1cm drift

Silicon:

✓ May provide some time stamping capability

✘ Pattern recognition in dense CLIC track environment not proven (SiD studies assumed single BX tagging)

★ Silicon Tracker is probably the safest option for now – but a TPC is certainly not ruled out

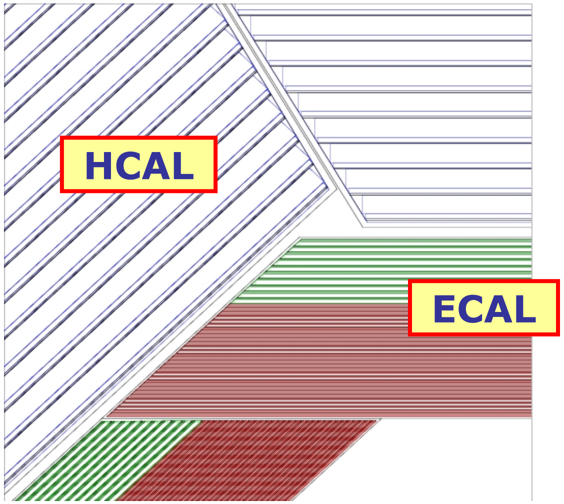
Needs a detailed study with full CLIC background/BX structure

Calorimetry at the ILC

★ ILD and SiD concepts designed for particle flow calorimetry, e.g. ILD*

ECAL:

- SiW sampling calorimeter
- Tungsten: $X_0/\lambda_{had} = 1/25$, $R_{Mol.} \sim 9$mm
  - → Narrow EM showers
  - → longitudinal sep. of EM/had. showers
- longitudinal segmentation: 30 layers
- transverse segmentation: 5x5 mm^2 pixels



HCAL:

- Steel-Scintillator sampling calorimeter
- longitudinal segmentation: 48 layers (6 interaction lengths)
- transverse segmentation: 3x3 cm^2 scintillator tiles

Comments:

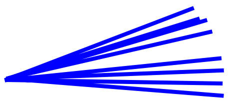
★ Technologically feasible (although not cheap)

★ Ongoing test beam studies (CALICE collaboration)

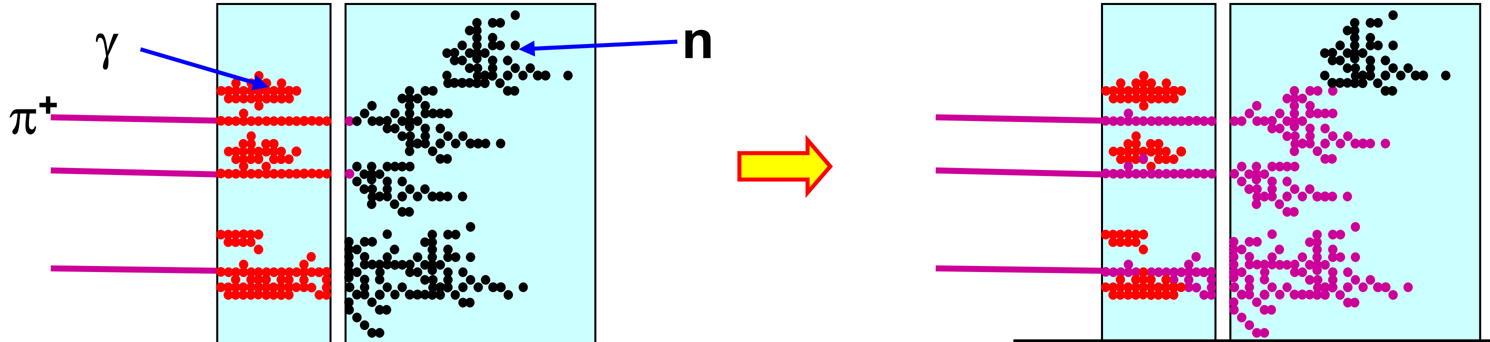
*Other ILD calorimetry options being actively studied, e.g. RPC DHCAL, Scintillator strip ECAL

Particle Flow Calorimetry

- **In a typical jet :**
  - **60 % of jet energy in charged hadrons**
  - **30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)**
  - **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: $\sigma_E/E \approx 60\,\%/\sqrt{E(\mathrm{GeV})}$**
  - **Intrinsically "poor" HCAL resolution limits jet energy resolution**



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

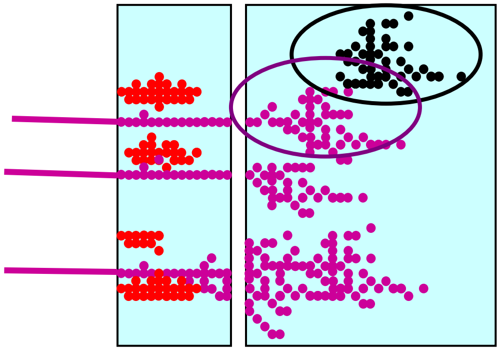
$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

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

Particle Flow Algorithms

Reconstruction of a Particle Flow Calorimeter:

- ★ Avoid double counting of energy from same particle
- ★ Separate energy deposits from different particles
- ★ Performance depends on hardware + reconstruction software (Particle Flow Algortithm)

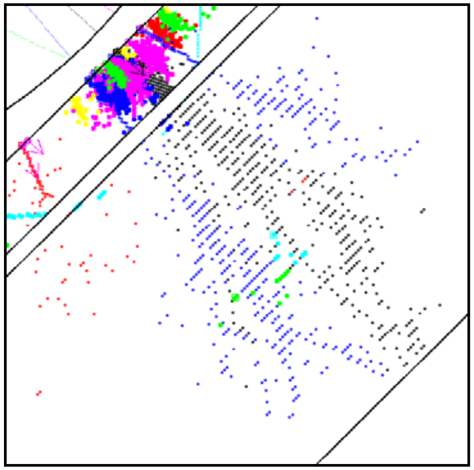


Level of mistakes, "confusion", determines jet energy resolution not the intrinsic calorimetric performance of ECAL/HCAL

★ Principle of Particle Flow Calorimetry now demonstrated; it can deliver at ILC energies

E_{JET}	σ_E/E (rms_{90})	
	ILD	SiD
45 GeV	3.7 %	5.5 %
100 GeV	2.9 %	4.1 %
180 GeV	3.0 %	4.1 %
250 GeV	3.1 %	4.8 %

Goal < 3-4 %

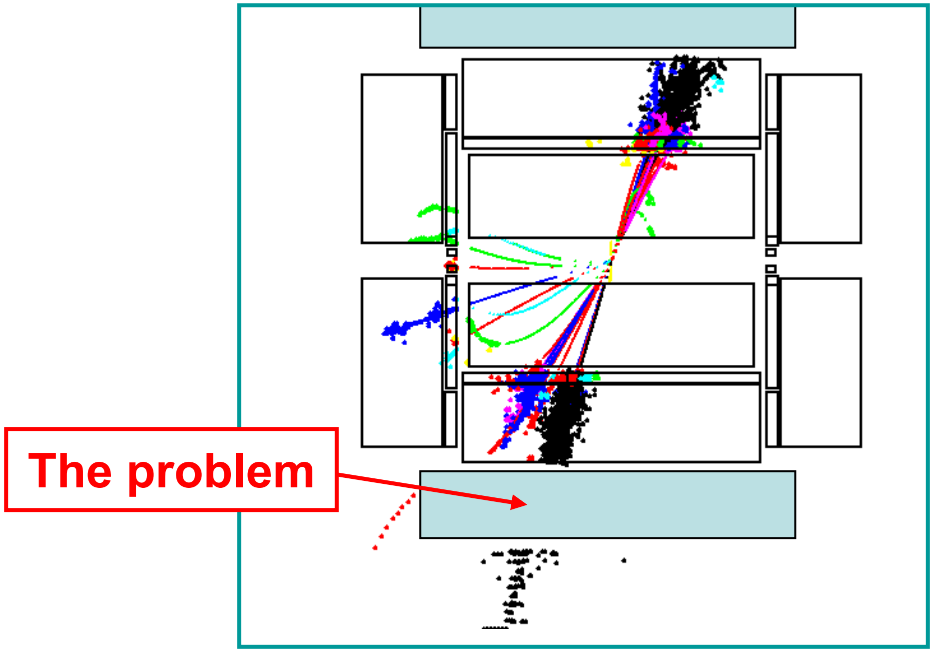


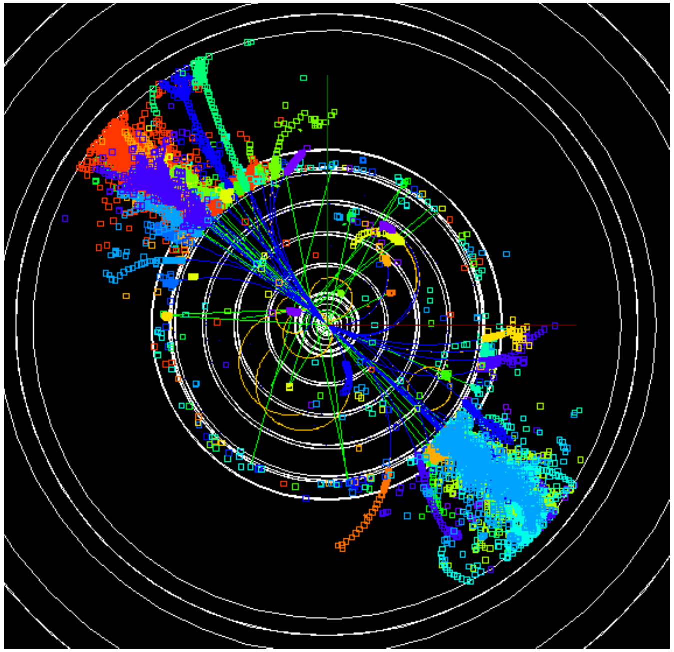
- ILD/PandoraPFA meets ILC goal for all relevant jet energies
- SiD/IowaPFA getting close: difference = smaller detector + software

PFA at CLIC ?

★ At a Multi-TeV collider, leakage of hadronic showers is a major issue

★ HCAL in **ILD** (6 λ_I) and **SiD** (4 λ_I) concepts too thin to contain **1 TeV** showers





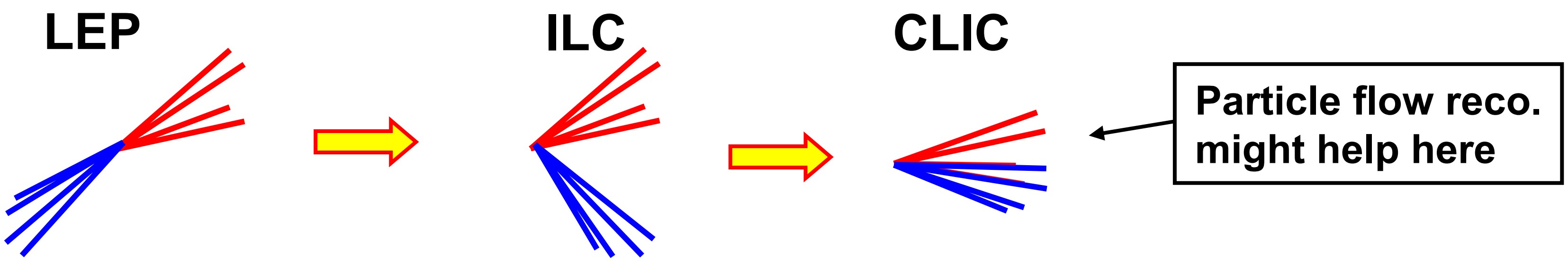
★ Probably need ~8 λ_I HCAL for CLIC energies

- but needs to be inside Solenoid for PFA – cost/feasibility
  - e.g. for current ILD concept ⇨ **7.4m** diameter solenoid !
- compact structures e.g. Replace steel with Tungsten as HCAL absorber?
- partially instrumented solenoid ?

In principle, can PFA deliver at CLIC energies ?

W/Z Separation at CLIC

★ On-shell W/Z decay topology depends on energy:



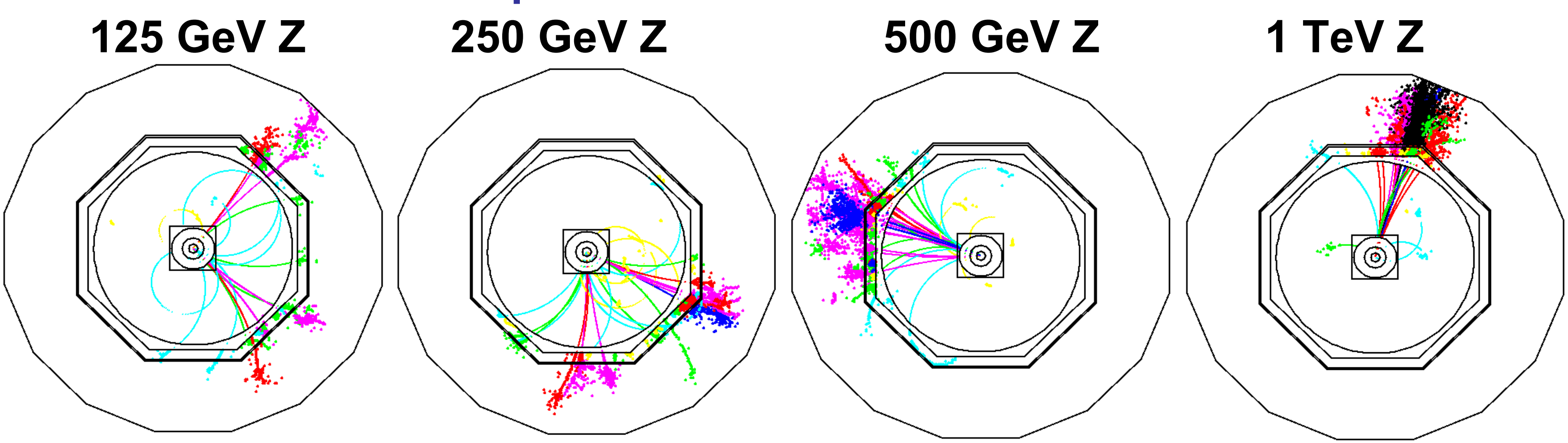
★ A few comments:

- Particle multiplicity does not change
- Boost means higher particle density

} More confusion

- PFA could be better for "mono-jet" mass resolution

★ PandoraPFA + ILD⁺ performance studied for:



Jet Energy Resolution

- Is an ILD-sized detector suitable for CLIC ?
- Defined modified ILD+ model:
  - B = 4.0 T (ILD = 3.5 T)
  - HCAL = 8 λ_I (ILD = 6 λ_I)
- Jet energy resolution

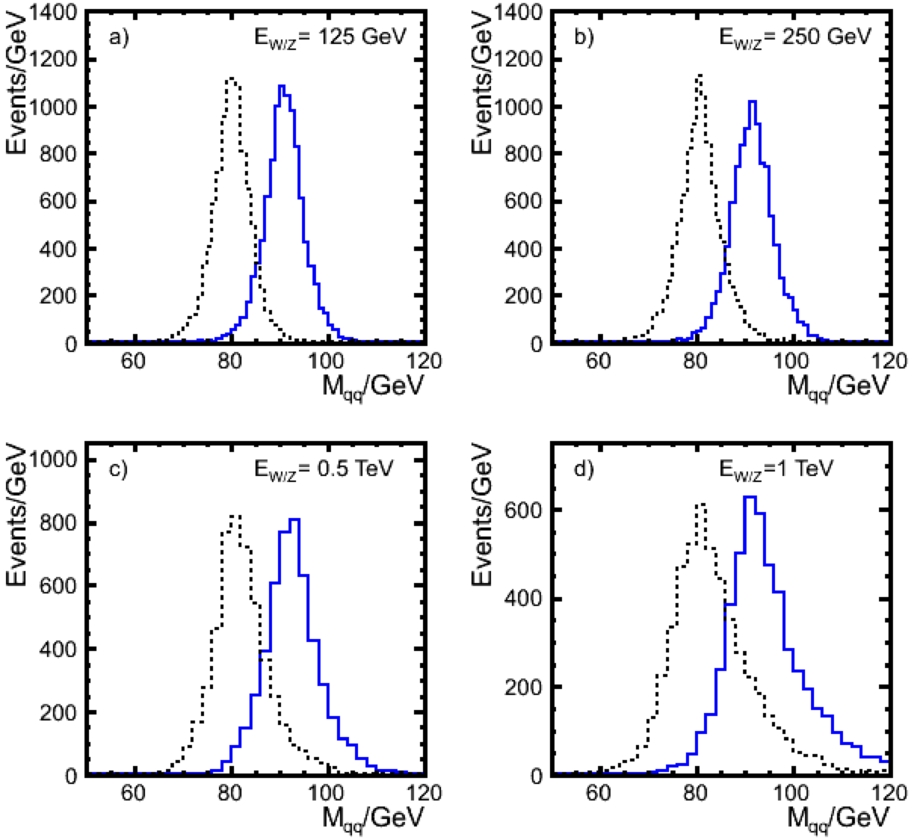
E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	28.7 %	2.9 %
180 GeV	37.5 %	2.8 %
250 GeV	44.7 %	2.8 %
375 GeV	71.7 %	3.2 %
500 GeV	78.0 %	3.5 %

- Meet "LC jet energy resolution goal [~3.5%]" for 500 GeV ! jets

W/Z Separation

★ Studied W/Z separation using ILD+ MC

$$e^+e^- \to WW \to u\bar{d}\nu\mu$$
$$e^+e^- \to ZZ \to d\bar{d}\nu\bar{\nu}$$



ILC-like energies

Clear separation

CLIC-like energies

There is separation, although less clear

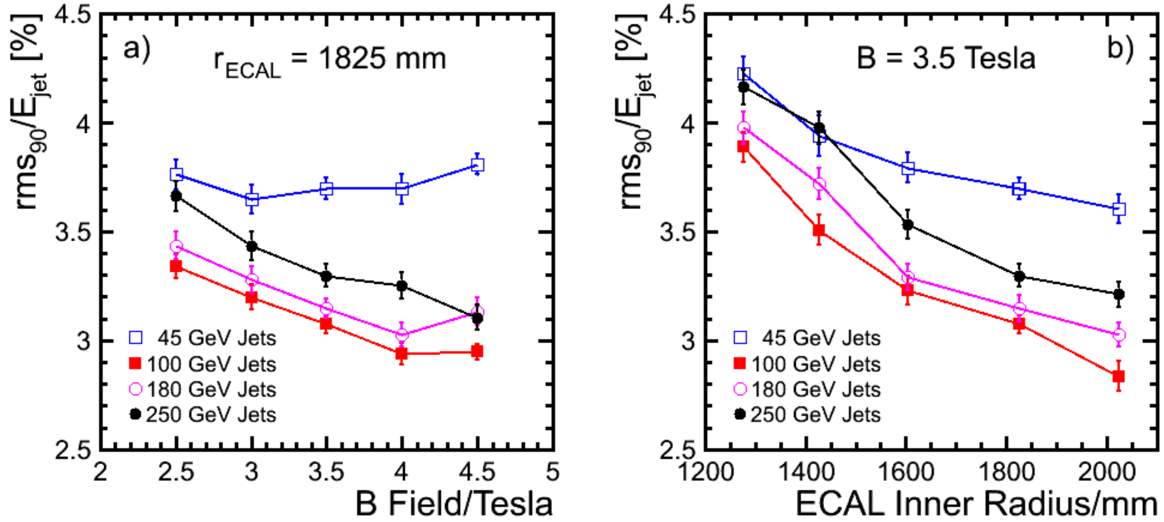
- Current PandoraPFA/ILD+ gives good W/Z separation for 0.5 TeV bosons
- Less clear for 1 TeV bosons – but PFA not optimized for CLIC energies

★ (Perhaps surprisingly) PFlow calorimetry looks promising for CLIC

PFA Detector Design Issues

★ Assuming a high granularity PFlow detector for CLIC, there are some important design considerations e.g. B-field, ECAL inner radius

★ Empirically find (PandoraPFA/ILD)



$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{R}{1825}\right)^{-1.0} \left(\frac{B}{3.5}\right)^{-0.3} \left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution | Tracking | Leakage | Confusion

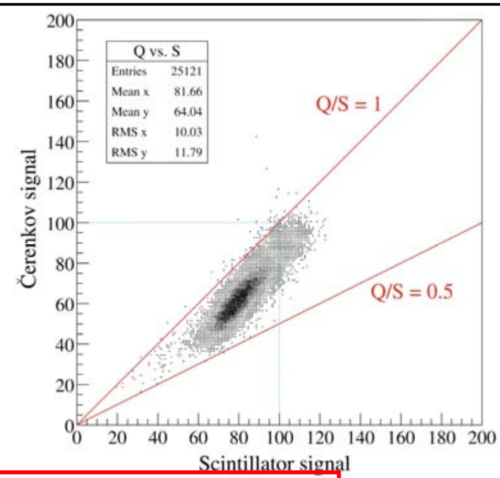
♦ Confusion ∝ $B^{-0.3}$ R^{-1} (1/R dependence “feels right”, geometrical factor !)

Conclusions:

Detector should be fairly large
Very high B-field is less important

The Alternative to PFlow

- ★ Dual/Triple readout calorimetry
- ★ Measure all components of hadronic shower
  - Measure EM component:
    Cerenkov light
  - Measure "slower" hadronic component:
    scintillation signal
  - Measure thermal neutron component:
    from timing (triple readout)

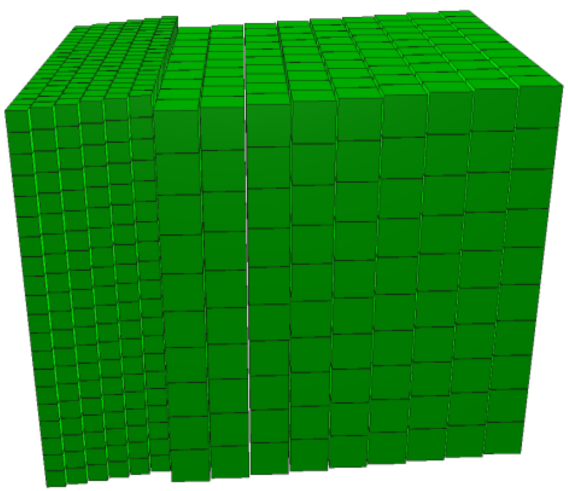


- ★ Effectively, measure shower fluctuations
- ★ In principle, can give <u>very good</u> resolution

$$\frac{\sigma_E}{E} \sim \frac{20\%}{\sqrt{E[\mathrm{GeV}]}} \oplus ?$$

<u>Possible implementation:</u>

- ★ Totally active crystal calorimeter (ECAL + HCAL)
  - ECAL: ~100,000 5×5×5 cm^3 crystals, e.g. BGO
  - HCAL: ~50,000 10×10×10 cm^3 crystals
  - Readout: 500,000 Si photo-detectors
- ★ GEANT4 simulations: 22%/√E
- ★ It could be the "ultimate" calorimeter, but…
  - Feasible ? Cost ?
  - Scintillation signal slow (c.f 0.5 ns)
  - Needs significant R&D programme



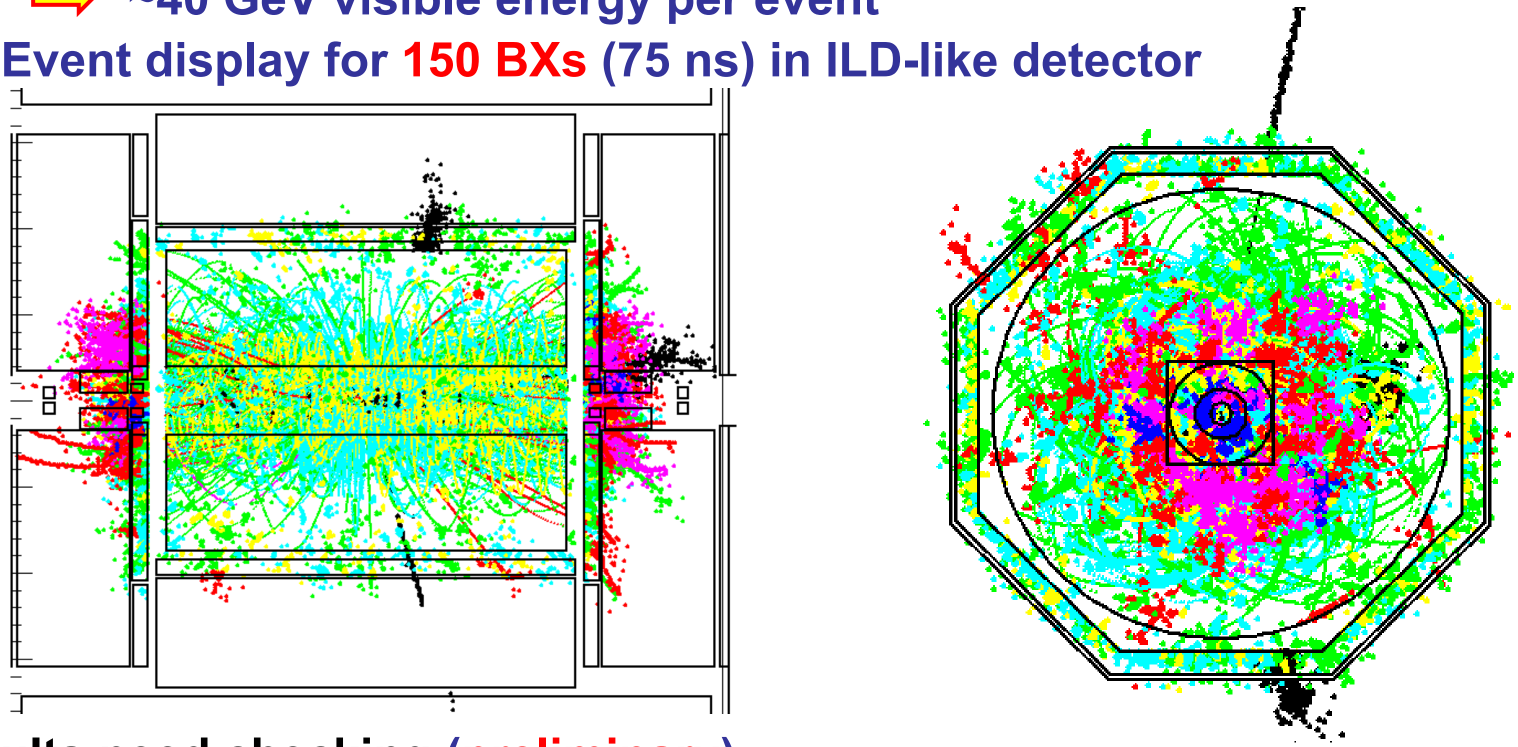
The Importance of BX tagging

Two-photon → hadrons background

- ★ Preliminary studies (Battaglia, Blaising, Quevillon) indicate significant two photon background for 3 TeV CLIC operation
- ★ Approx 40 particles per BX $(p_T > 0.15\,\mathrm{GeV}\ ,\ |\cos\theta| < 0.98)$

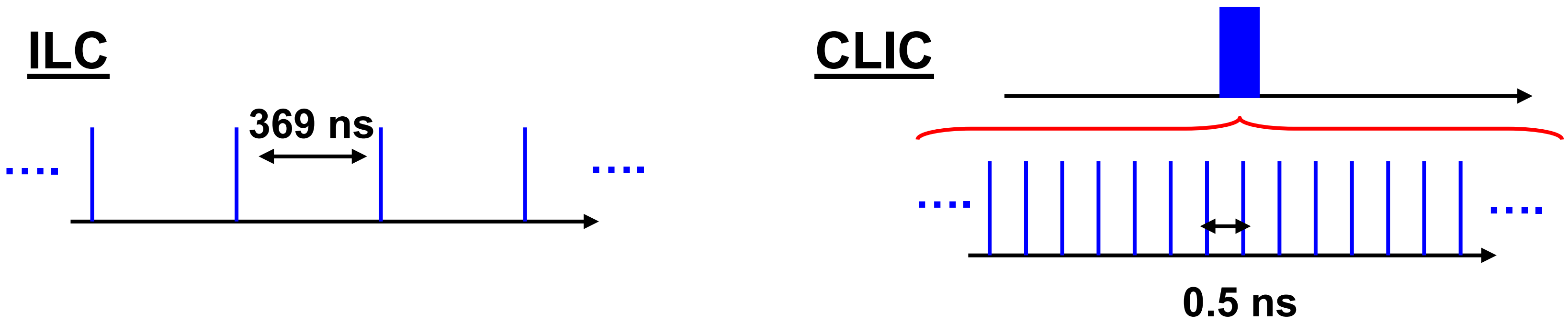
  ⇨ ~40 GeV visible energy per event

e.g. Event display for 150 BXs (75 ns) in ILD-like detector



- ★ Results need checking (preliminary)
- ★ With 0.5 ns BX – will inevitably integrate over multiple BXs, how many?
- ★ CLIC at 3 TeV may look rather different to the ILC environment
- ★ In addition, there is also the pair background…

BX Tagging



- Reconstruction study with ILD (conservative assumptions) shows that at the ILC BX-tagging is not likely to be a significant issue
- At CLIC, physics performance likely to depend strongly on BX-tagging capability.
- First studies **(Battaglia,Blaising,Quevillon):** suggest **~25 ns or better**
- This is challenging… and places constraints on detector technologies

This is an important issue which need careful study

Summary/Conclusions

- ★ ILC detector concepts are now well studied
  - meet the ILC goals
- ★ ILC concepts useful starting point for a possible CLIC detector
  - particle flow calorimetry looks promising
- ★ Argument for very high B-field not that compelling
  - 4 T probably sufficient – needs proper study
- ★ CLIC machine environment is much more challenging
  - backgrounds (pairs/$\gamma\gamma \rightarrow$hadrons)
  - time structure – inevitably integrate over multiple BXs

- ★ Detailed simulation studies of background/impact on physics are essential
- ★ Need to understand the physics environment at CLIC
  - detector requirements may be very different from ILC

Fin

Backup Slides

ILC Background Studies

- ★ IF one assumes single BX tagging capability then background is not an issue
- ★ For ILD studies conservatively? assume 30 μs / 125 μs integration times for VTX layers (0,1) and (2,3,4,5) respectively
- ★ Therefore VTX integrates over 83/333 BXs
- ★ Superimpose on fully-hadronic top-pair events at 500 GeV

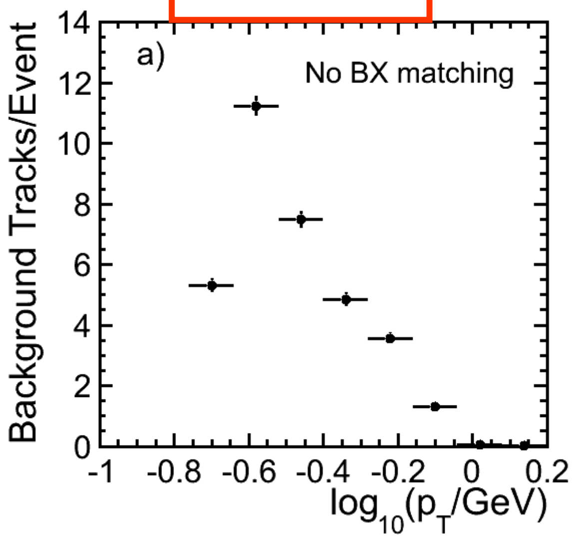
⇨ 200,000 background hits per event !

- ★ Also consider finite cluster size of background hits (~10 pixels)
- ★ Significantly increases occupancy →

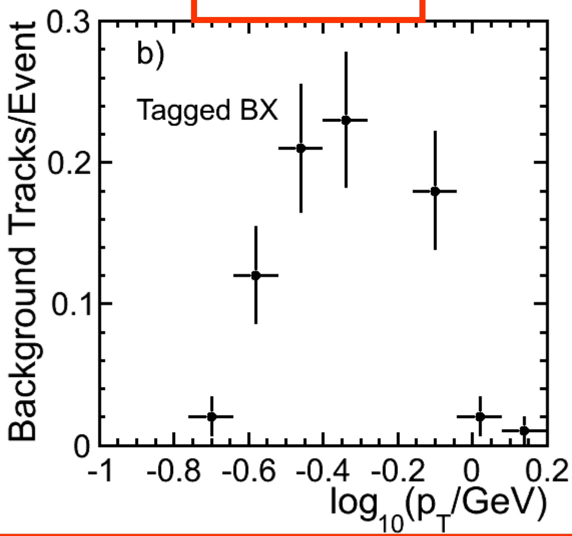
layer	Occ.
0	3.3 %
1	1.9 %
2	0.4 %
3	0.3 %
4	0.08 %
5	0.06 %

- Combinatorics produce fake "ghost" tracks
- In addition to some real electron/positron background tracks
- **Large combinatoric background challenges pattern recognition**
- From **83/333 BXs** overlayed on $e^+e^- \rightarrow t\bar{t} \rightarrow 6\ \mathrm{jets}$:
  reconstruct ~34 "ghost" tracks/event (~1/3 are genuine)
- Rejected by requiring at least **1 SIT hit** or **>10 TPC** associated hits

34/event



1/event



Left with ~0.5 GeV per event (mixture of real tracks/combinatorics)