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

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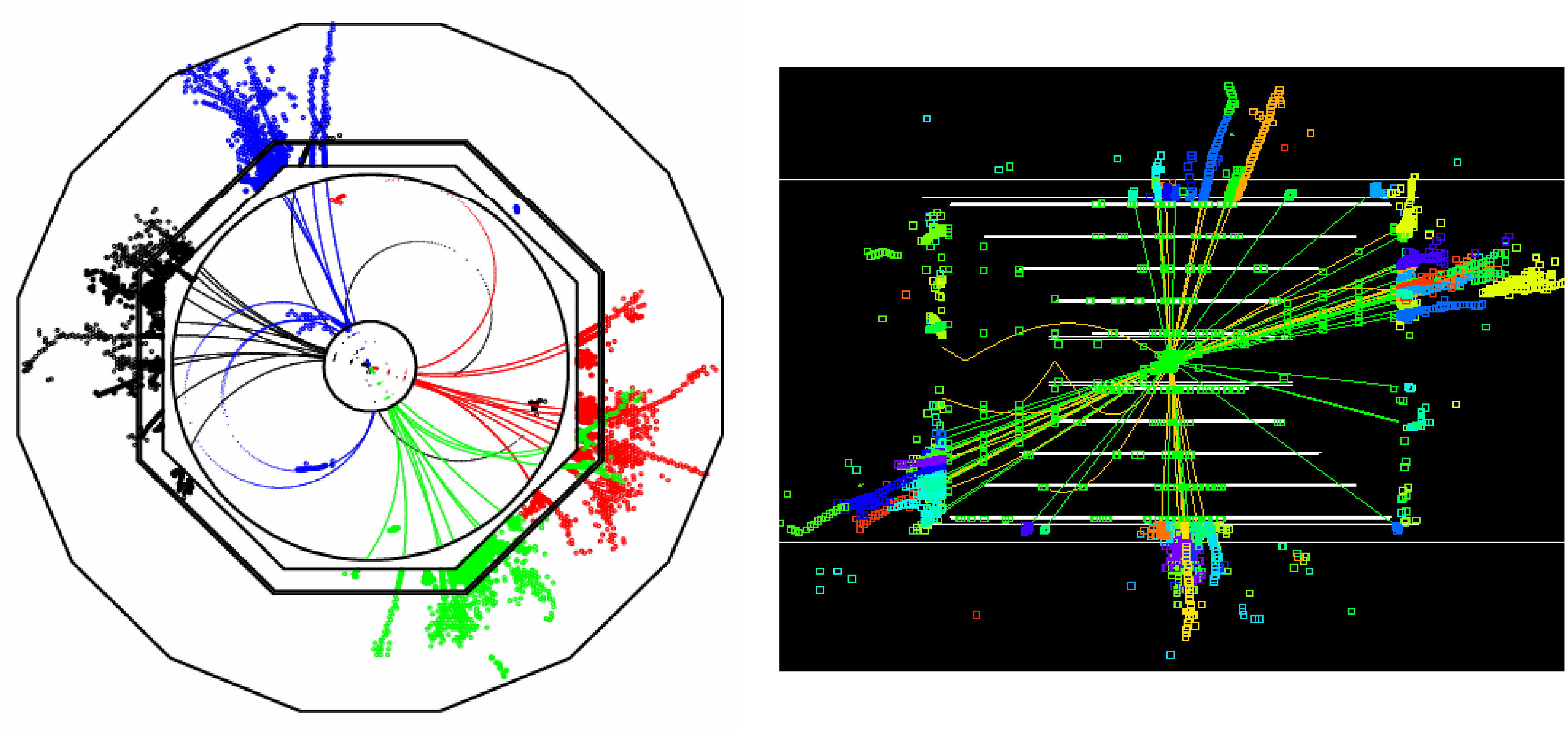


Overview

- 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

This Talk

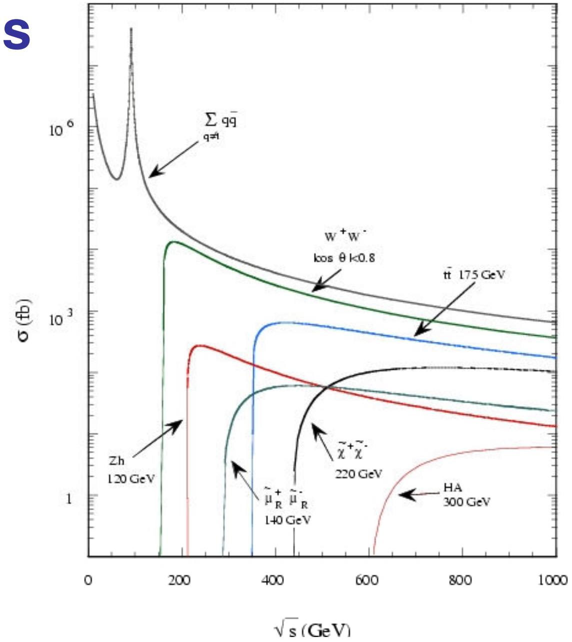
- Discuss motivation for ILC detector concepts
- Give very brief overview of ILD and SiD
- Discuss requirements for a detector at CLIC
  - Physics
  - Machine
- Discuss main issues for CLIC
  - Backgrounds
  - Vertex detector/flavour ID
  - Tracking
  - Calorimetry
  - Bunch Crossing (BX) tagging

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:

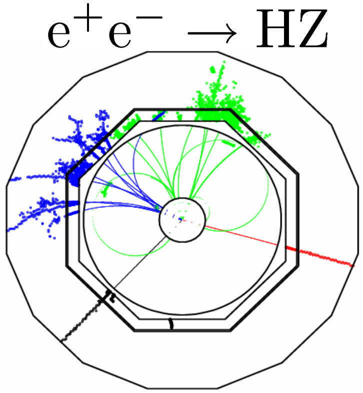
Want to design a **general purpose detector** to fully exploit physics in clean ILC environment

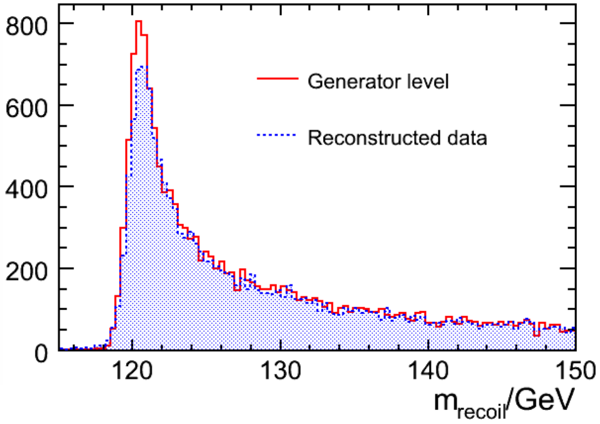
ILC Detector Requirements

- ★ **momentum: (1/10 x LEP)**

  e.g. Muon momentum
  Higgs recoil mass

$$\boxed{\sigma_{1/p} < 5\times10^{-5}\,\mathrm{GeV}^{-1}}$$

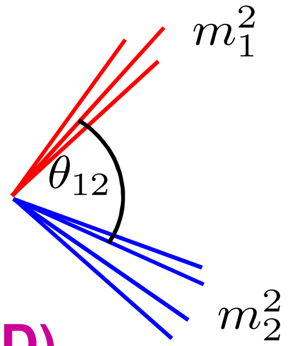


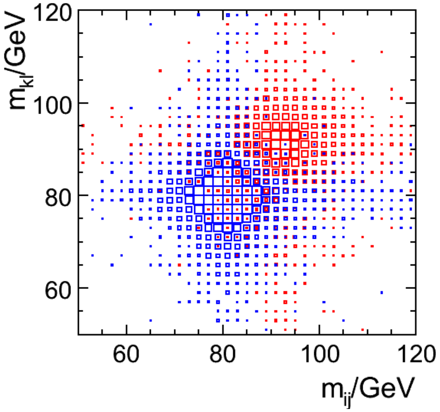


- ★ **jet energy: (1/3 x LEP/ZEUS)**

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

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

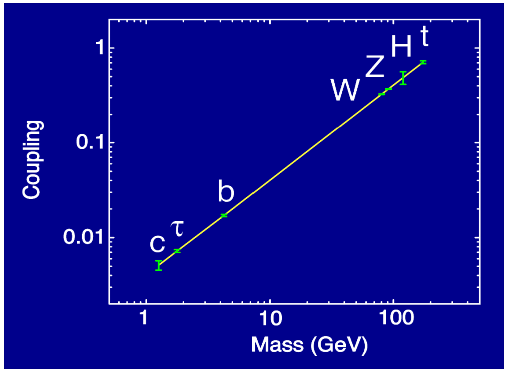




- ★ **impact parameter: (1/3 x SLD)**

  e.g. c/b-tagging
  Higgs BR

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

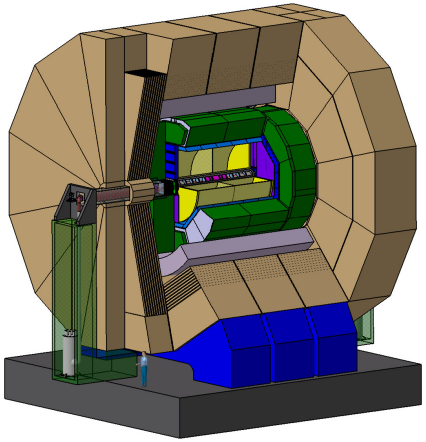


- ★ **hermetic: down to θ = 5 mrad**

  e.g. missing energy signatures in SUSY

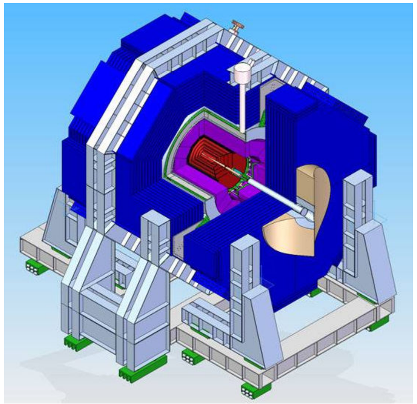
ILC Detector Concepts

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: $\boxed{\frac{\sigma_E}{E} < 3-4\%}$

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

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

but, needs study

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

But…

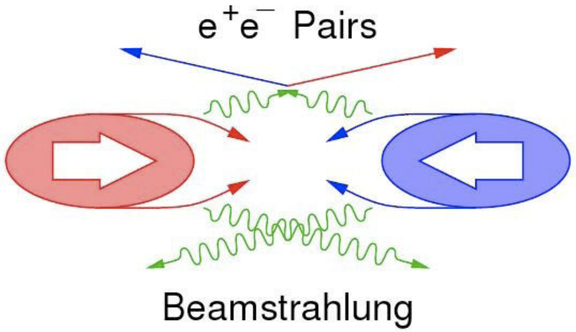
Main detector requirements driven by CLIC machine environment

From ILC to CLIC Detector Concepts

	LEP 2	ILC 0.5 TeV	CLIC 0.5 TeV	CLIC 3 TeV
$\mathcal{L}$ [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
$\mathcal{L}$/BX [cm^{-2}]	2.5×10^{26}	1.5×10^{30}	1.1×10^{30}	3.8×10^{30}
$\gamma\gamma\rightarrow X$ / 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

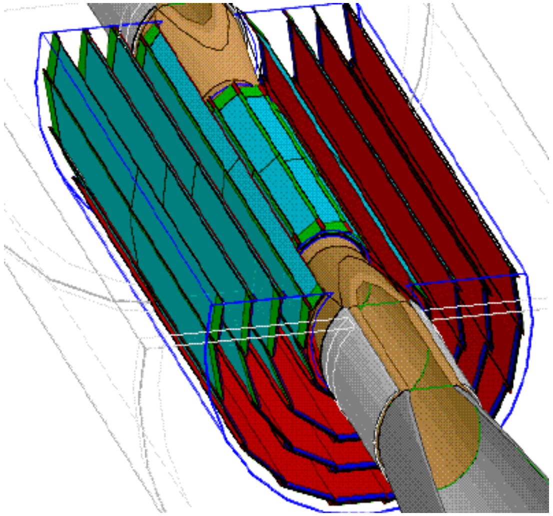


- ★ Bunch train structure:
  - ILC: BX separation 369 ns
  - CLIC: BX separation 0.5 ns
- ★ Two photon → hadrons background, at CLIC:
  - Approx three "visible" events per BX
  - Important since, sub-detectors will integrate over >1 BX (0.5 ns)

Sub-detectors: from ILC to CLIC

ILC Vertex detector

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



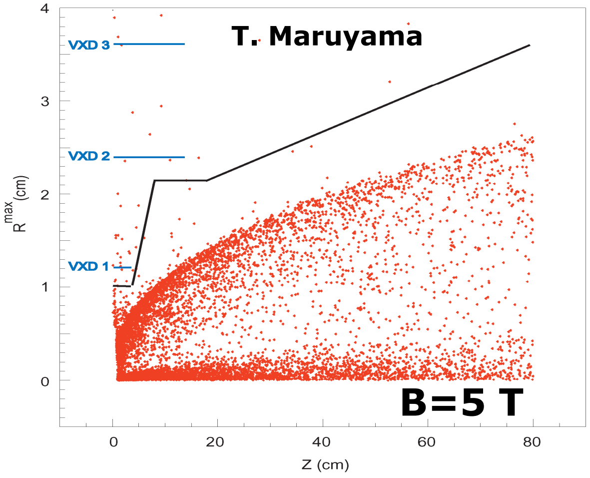
Main design considerations:

- ★ 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

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

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

- ★ 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

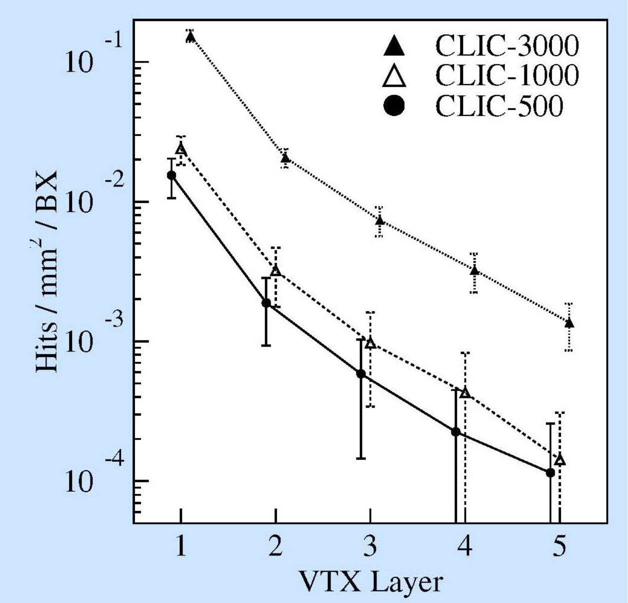
- ★ For reasonable occupancy:
  - ▪ Inner radius of CLIC VTX detector

⇨ 31 mm

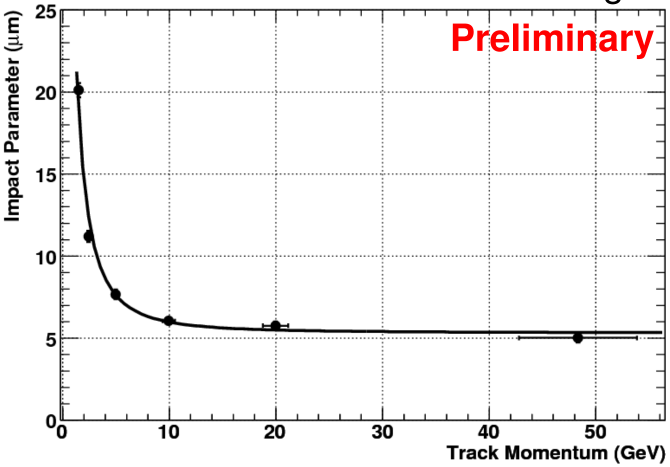
- ★ Still obtain good impact parameter resolution (depends on assumed point resolution)

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

Adrian Vogel

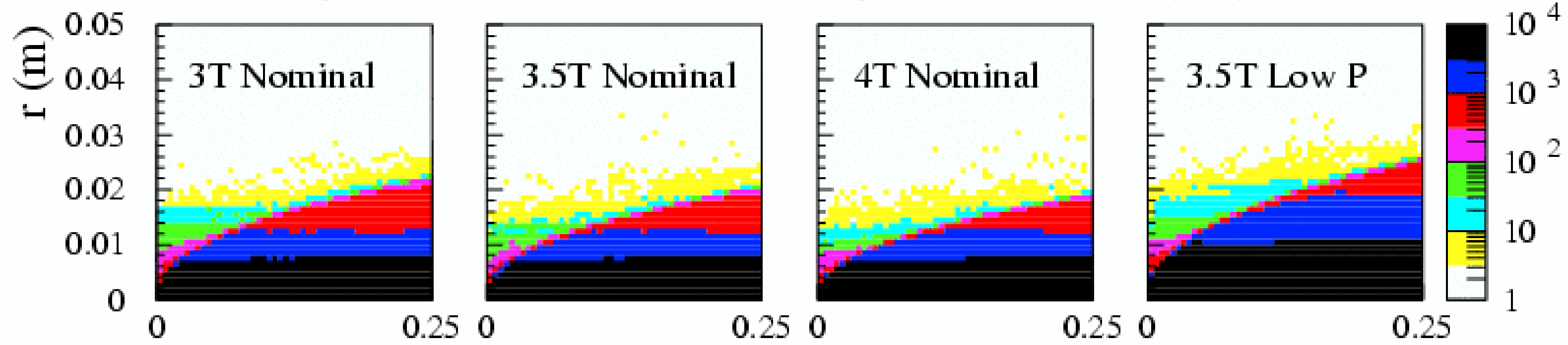


Marco Battaglia

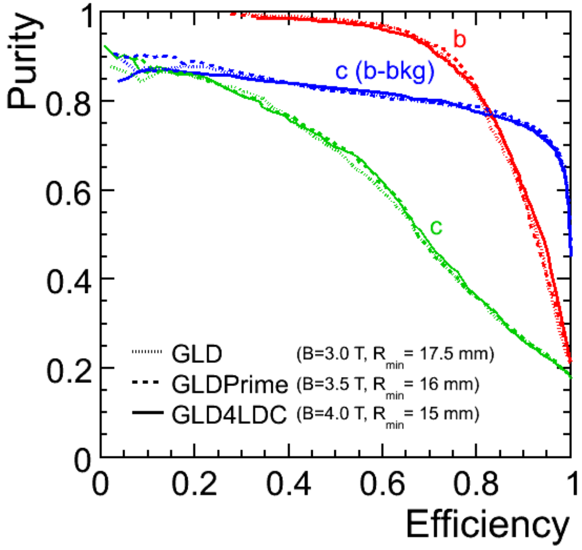


B-field and ILC Vertex detector

- ★ This question has been addressed by ILD study
- ★ But radius of pair background envelope scales roughly as √**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

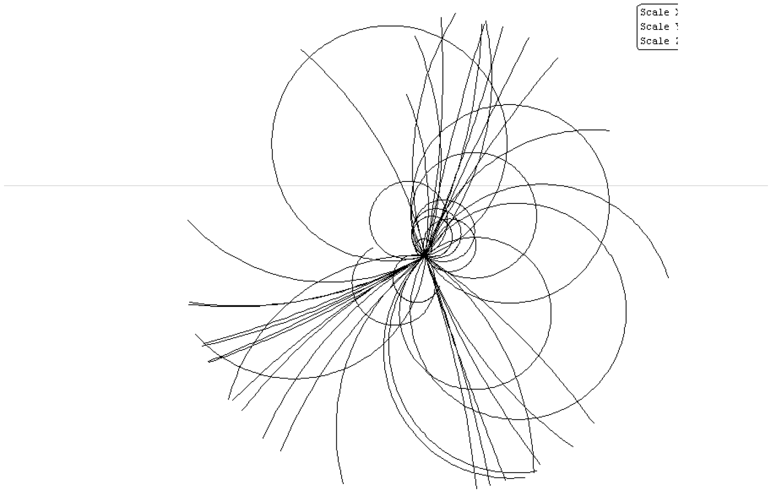
31 mm probably OK

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

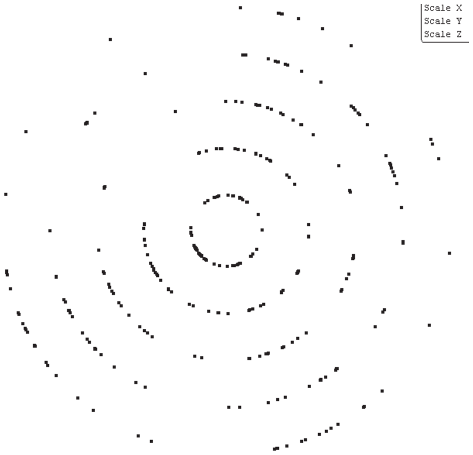
Tracking at the ILC

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: $\sigma_{1/p_{\mathrm{T}}} \sim 2\times 10^{-5}\,\mathrm{GeV}^{-1}$ (high p tracks)

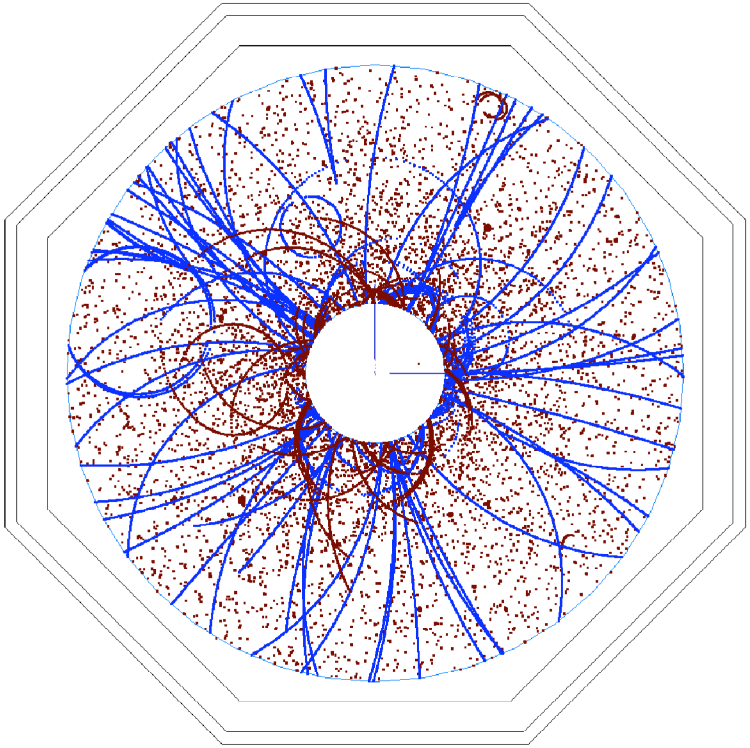
What is the best option for CLIC ?

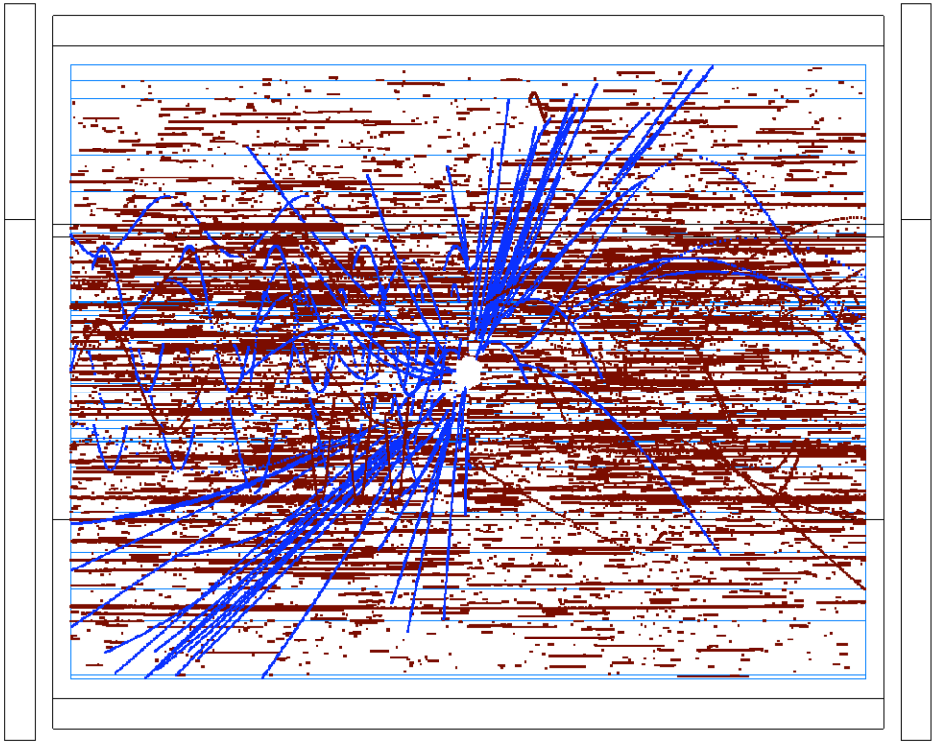
- Robustness to background/Pattern recognition ?
- Two track separation ?

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

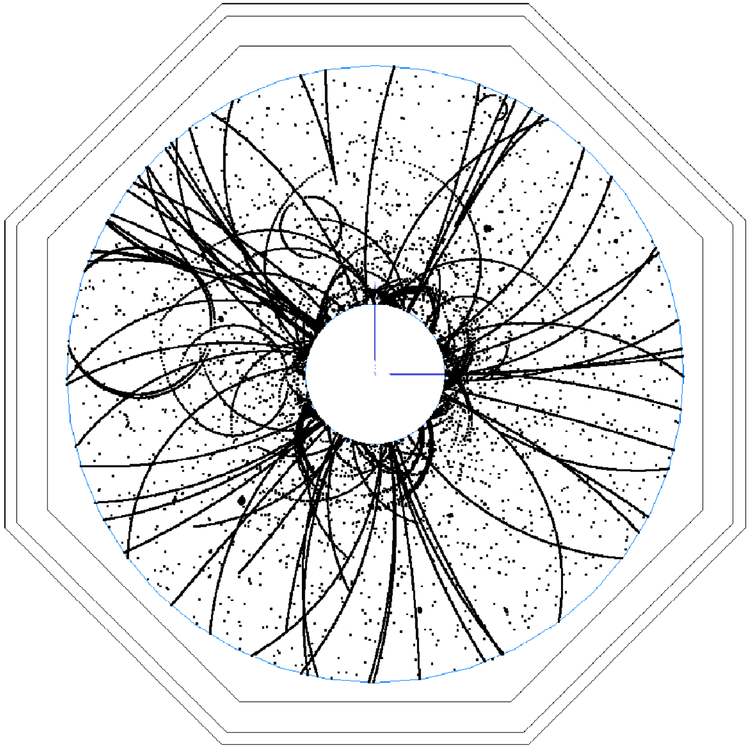


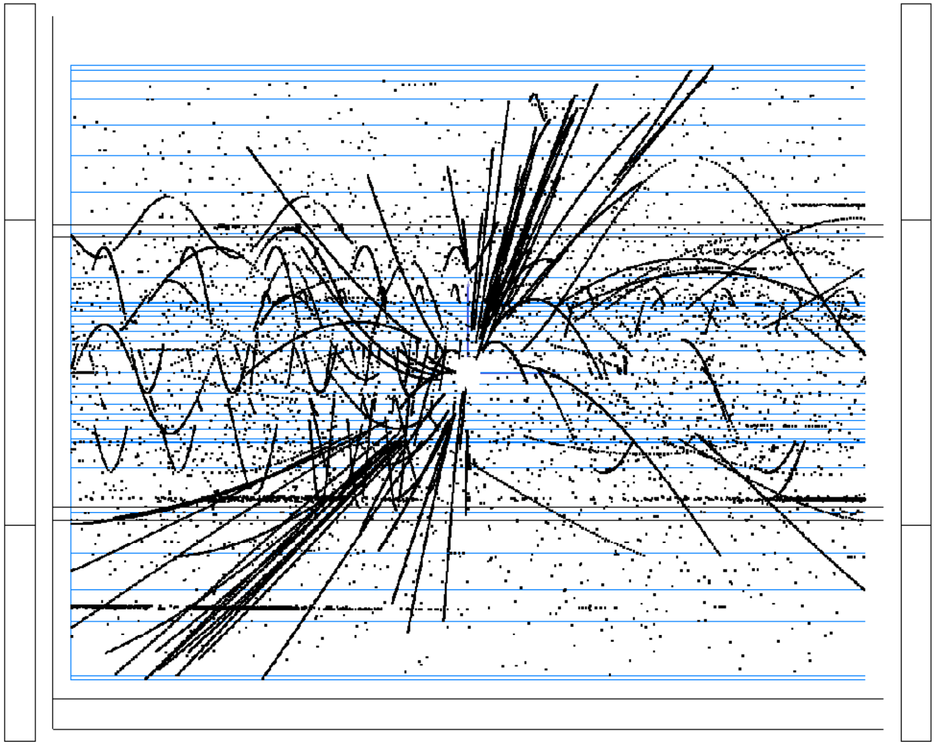


- Effective removal of large fraction of background hits

	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:

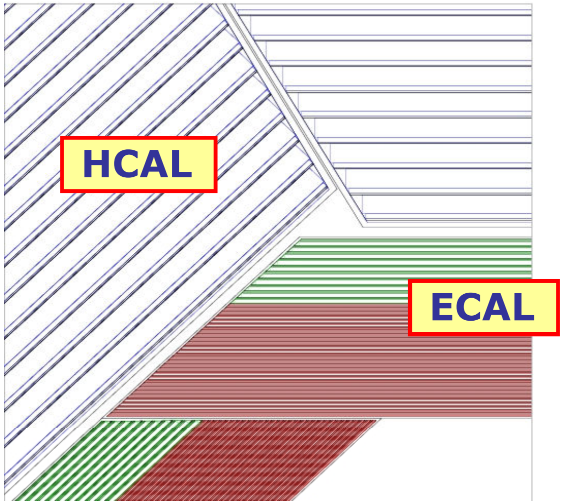
- ✓ May provide some time stamping capability
- ✘ Pattern recognition in dense CLIC track environment not proven (SiD studies assumed single BX tagging)

★ 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/λ_{had} = 1/25, $R_{Mol.}$ ~ 9mm
  - → 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:

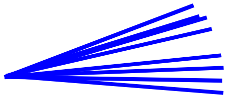
★ Technologically feasible (although not cheap)

★ Ongoing test beam studies (CALICE collaboration)

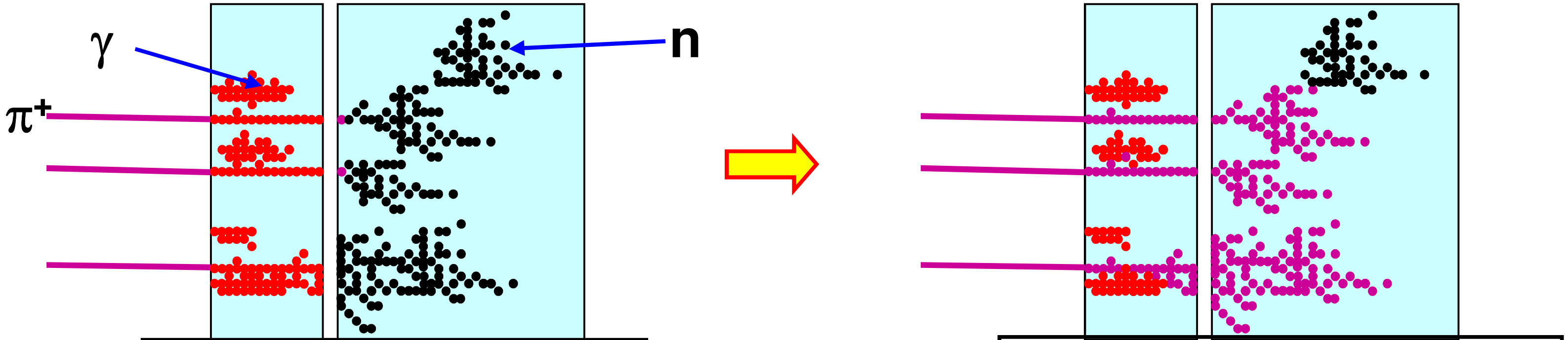
*Other ILD calorimetry options being actively studied, e.g. RPC DHCAL, Scintillator strip ECAL

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: $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically "poor" HCAL resolution limits jet energy resolution



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

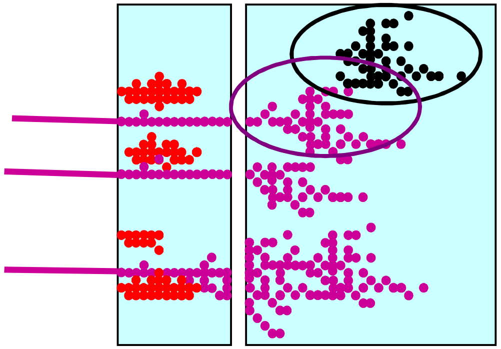
$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - 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)

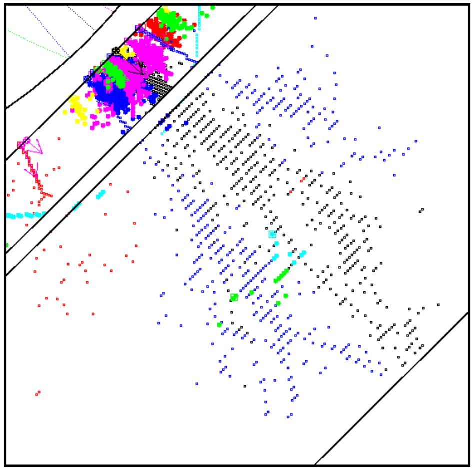


Level of mistakes, "confusion", determines jet energy resolution <u>not</u> the intrinsic calorimetric performance of ECAL/HCAL

★ 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 %

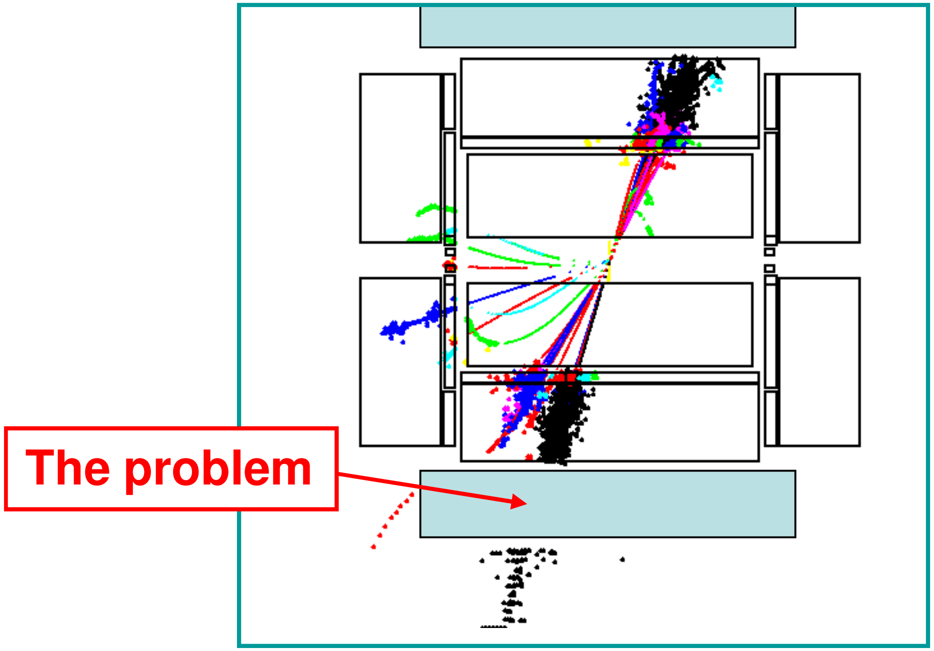
Goal < 3-4 %

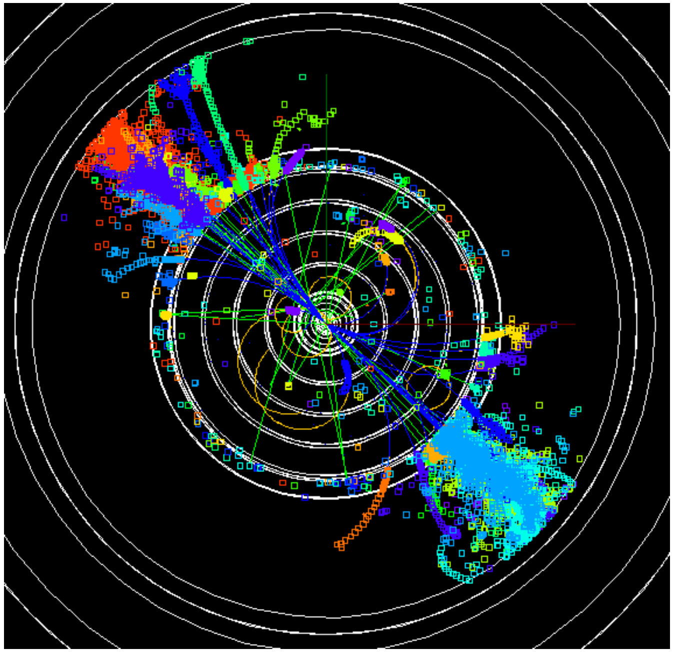


- ♦ ILD/PandoraPFA meets ILC goal for all relevant jet energies
- ♦ SiD/IowaPFA getting close: difference = smaller detector + software

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



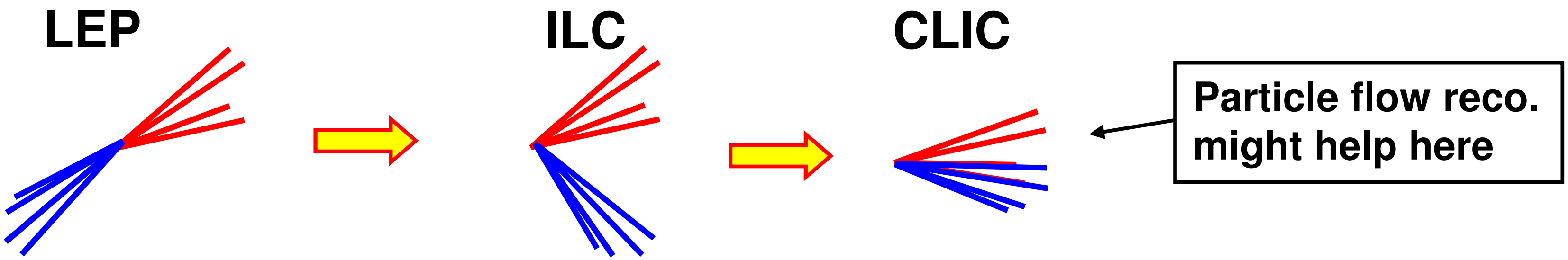


- ★ Probably need ~8 λ_I HCAL for CLIC energies
  - but needs to be inside Solenoid for PFA – cost/feasibility
    - e.g. for current ILD concept ⇨ **7.4m** diameter solenoid !
  - compact structures e.g. Replace steel with Tungsten as HCAL absorber?
  - partially instrumented solenoid ?

In principle, can PFA deliver at CLIC energies ?

W/Z Separation at CLIC

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

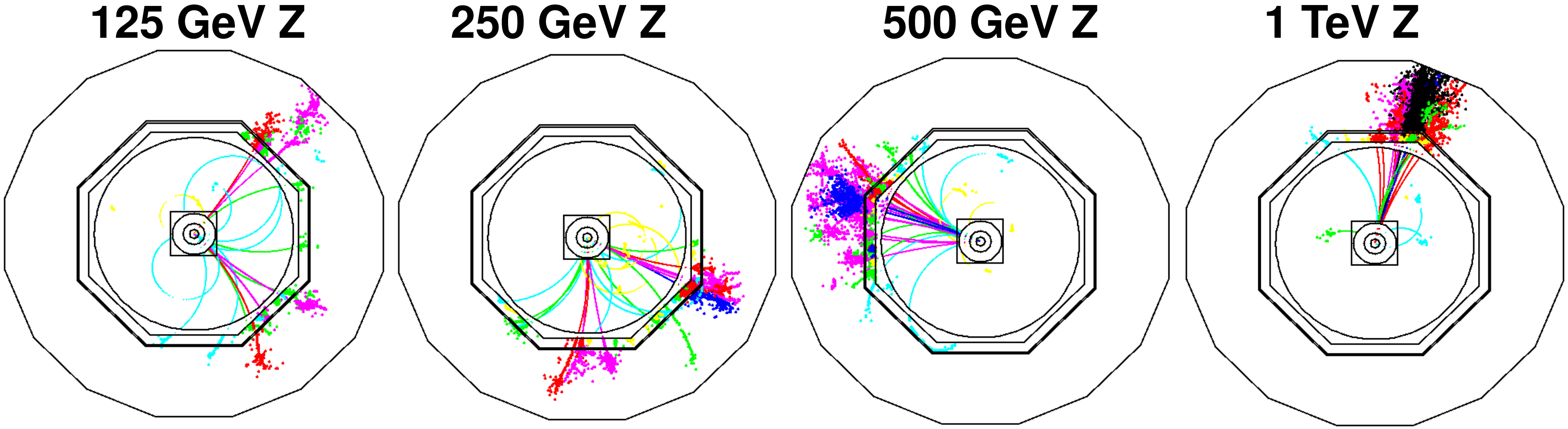


Particle flow reco. might help here

- A few comments:
  - Particle multiplicity does not change
  - Boost means higher particle density
  - PFA could be better for "mono-jet" mass resolution

More confusion

- 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

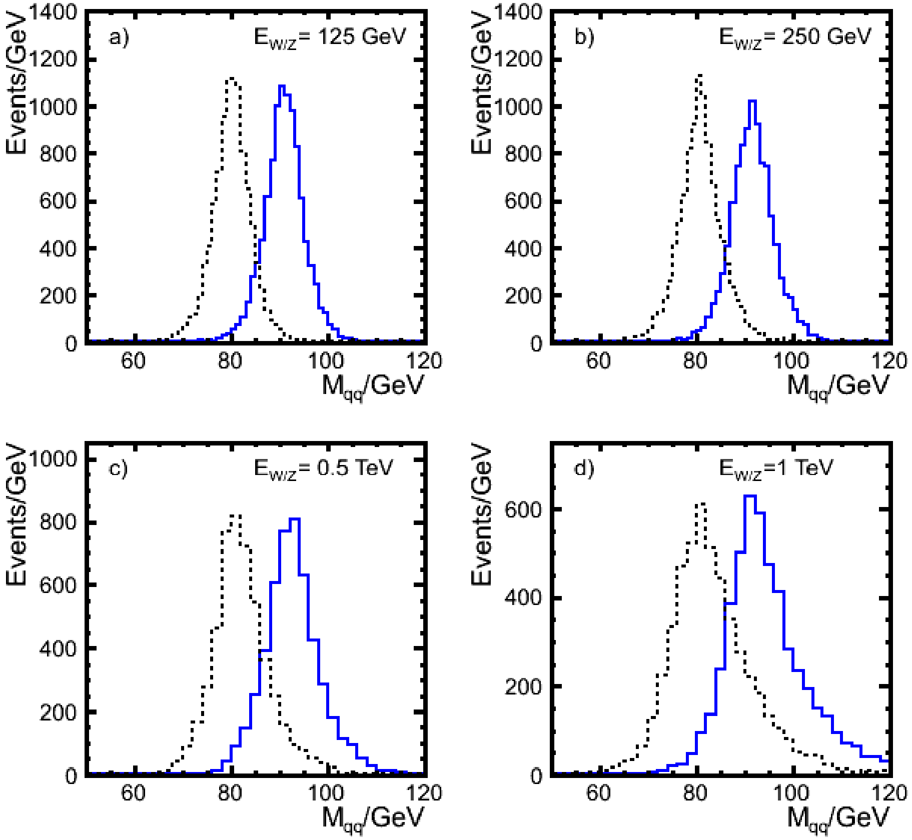
E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	28.7 %	2.9 %
180 GeV	37.5 %	2.8 %
250 GeV	44.7 %	2.8 %
375 GeV	71.7 %	3.2 %
500 GeV	78.0 %	3.5 %

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

W/Z Separation

★ Studied **W/Z** separation using **ILD⁺** MC

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



ILC-like energies

Clear separation

CLIC-like energies

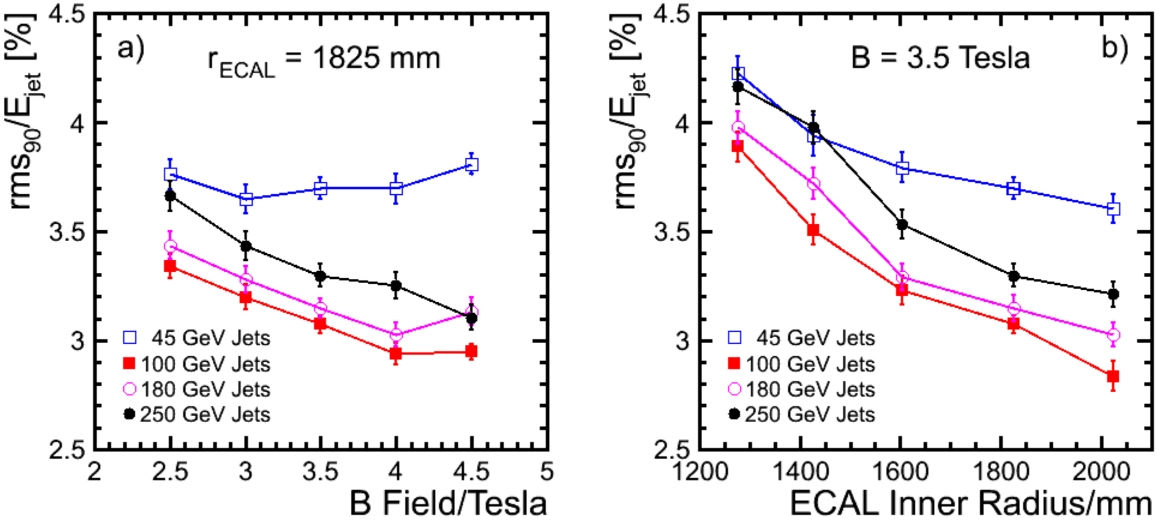
There is separation, although less clear

- 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)



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

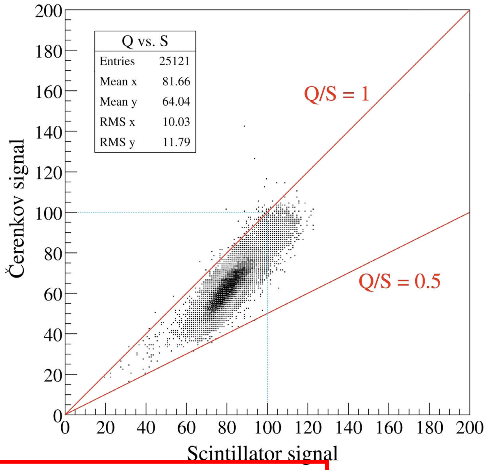
- ♦ **Confusion ∝ $B^{-0.3}$ R^{-1} (1/R dependence "feels right", geometrical factor !)**

Conclusions:

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

The Alternative to PFlow

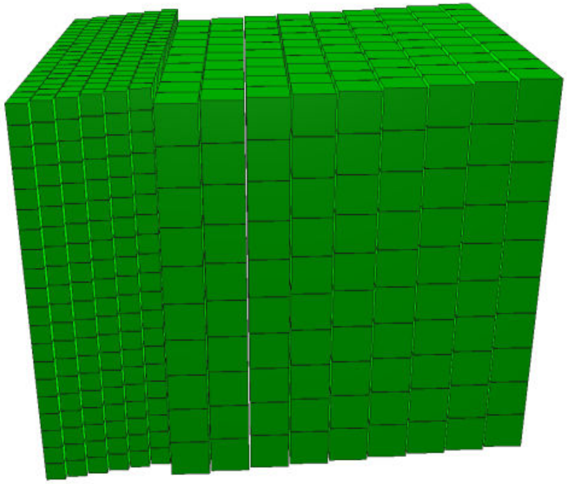
- ★ Dual/Triple readout calorimetry
- ★ Measure all components of hadronic shower
  - Measure EM component: Cerenkov light
  - Measure “slower” hadronic component: scintillation signal
  - Measure thermal neutron component: from timing (triple readout)
- ★ Effectively, measure shower fluctuations
- ★ In principle, can give very good resolution



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

Possible implementation:

- ★ 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



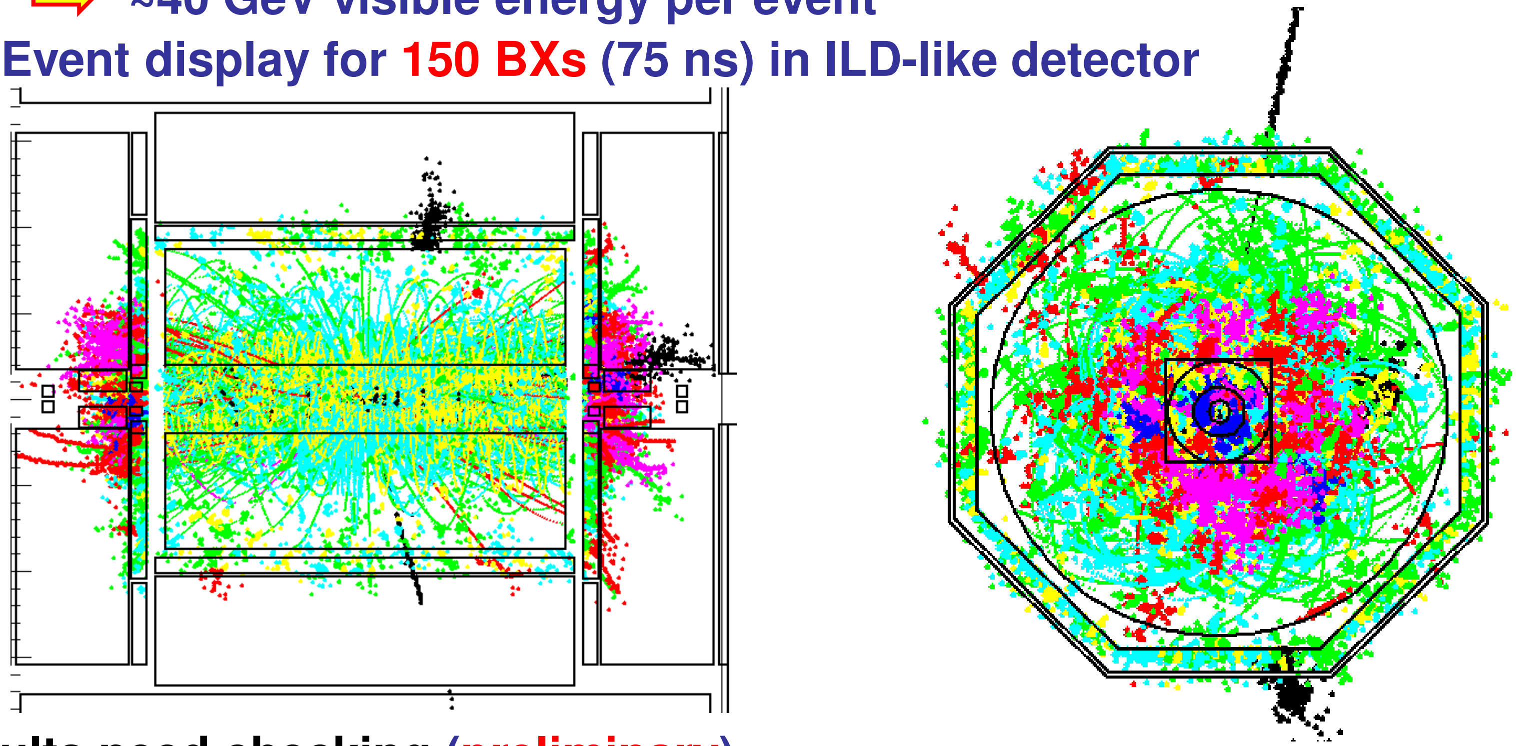
The Importance of BX tagging

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

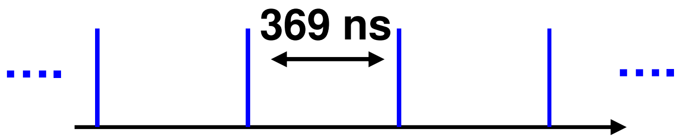
e.g. Event display for **150 BXs** (75 ns) in ILD-like detector



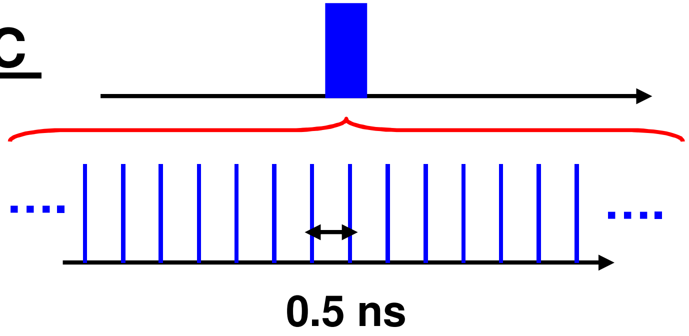
- ★ **Results need checking** (preliminary)
- ★ With 0.5 ns BX – will inevitably integrate over multiple BXs, **how many?**
- ★ CLIC at 3 TeV may look rather different to the ILC environment
- ★ In addition, there is also the pair background…

BX Tagging

ILC



CLIC



- 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 !

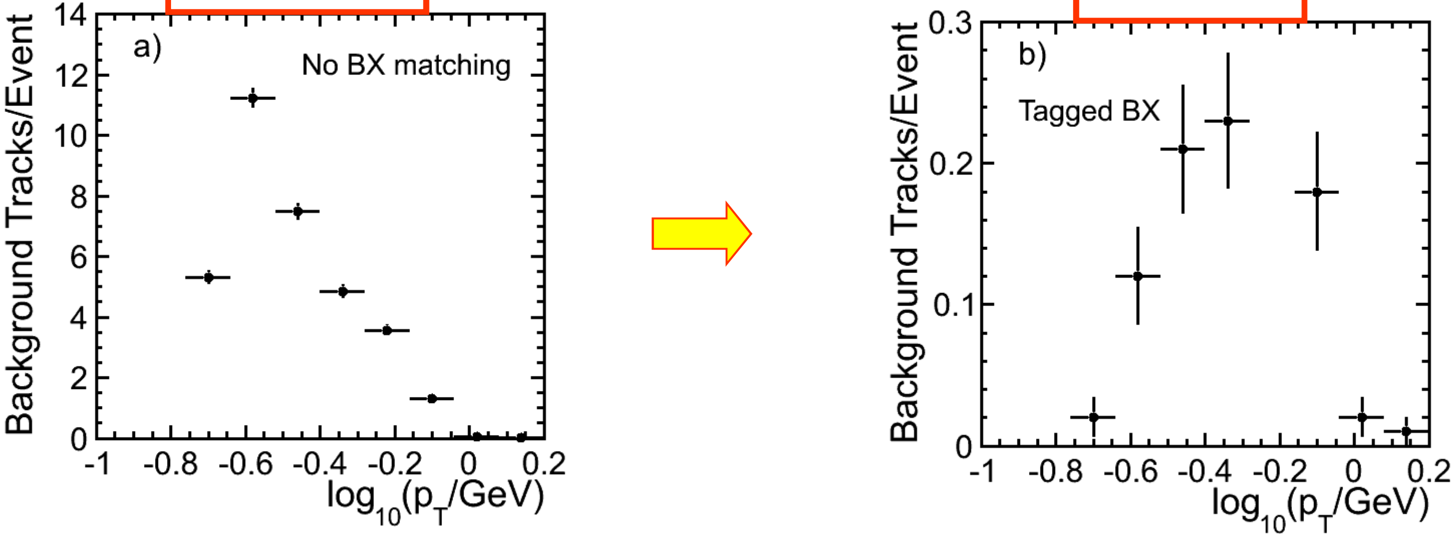
- ★ Also consider finite cluster size of background hits (~10 pixels)
- ★ Significantly increases occupancy →

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 $e^+e^- \to t\bar{t} \to 6\,\text{jets}$:
  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)