Detectors for a Future Lepton Collider
Lecture 4: Detector Design

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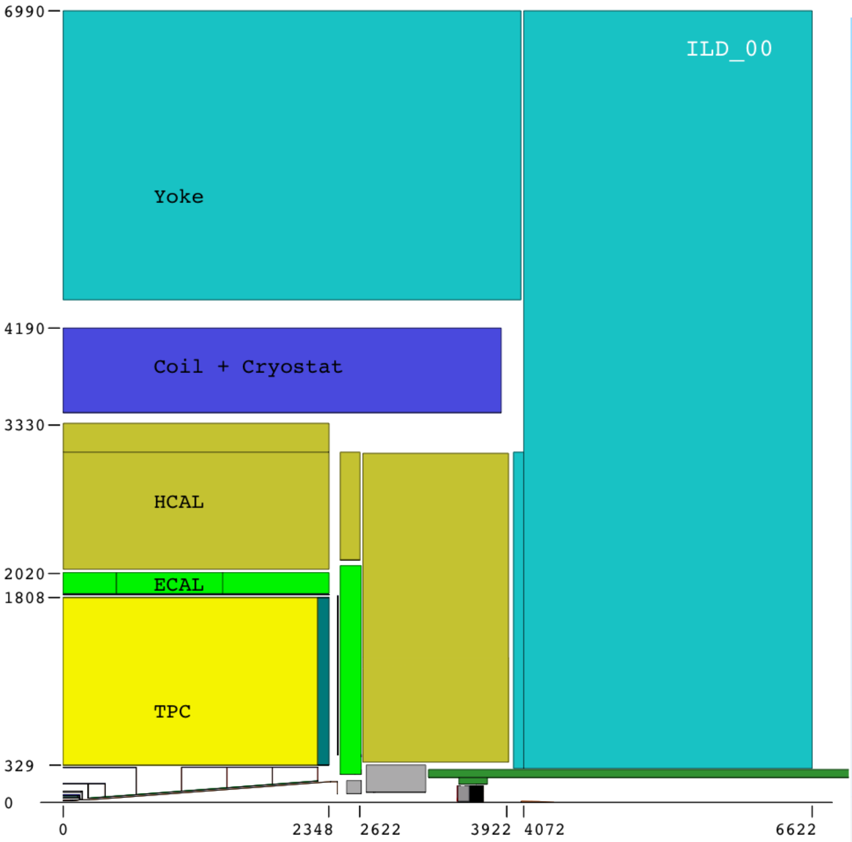
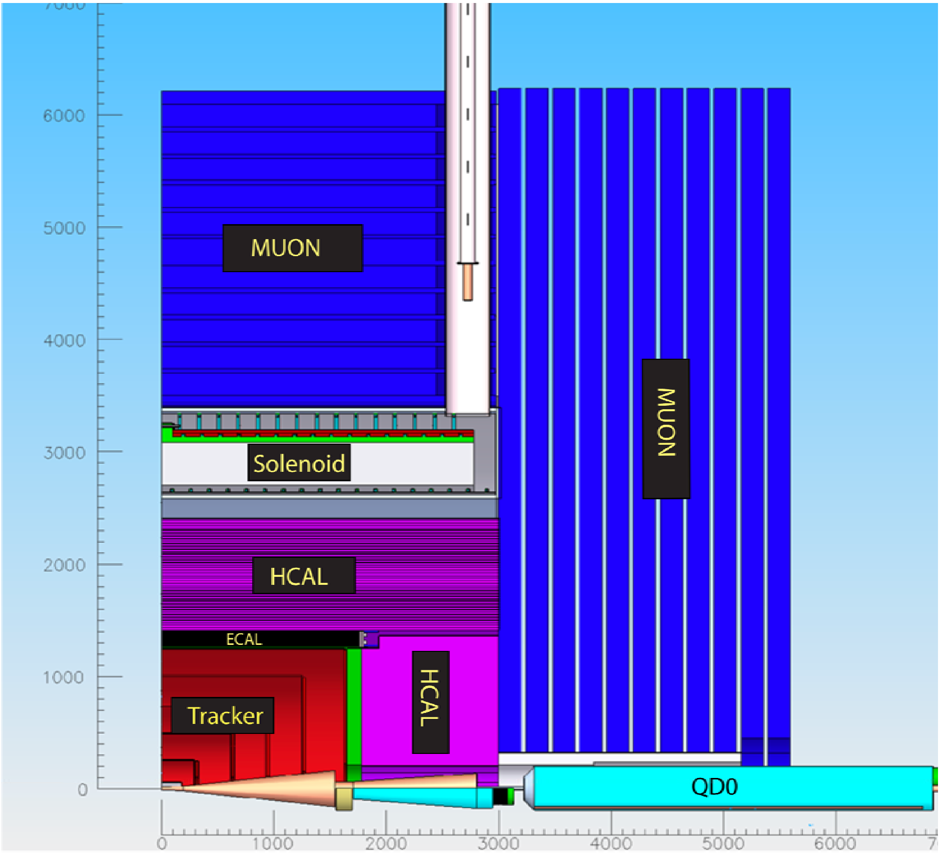




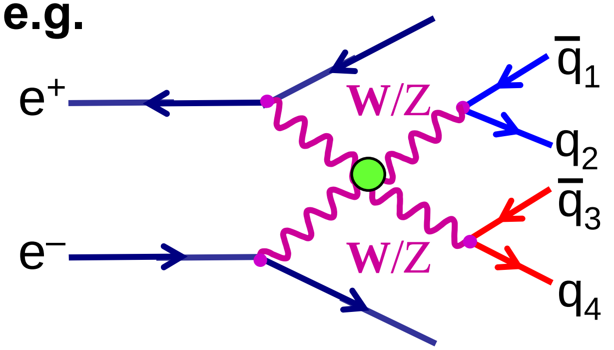
Today’s Lecture

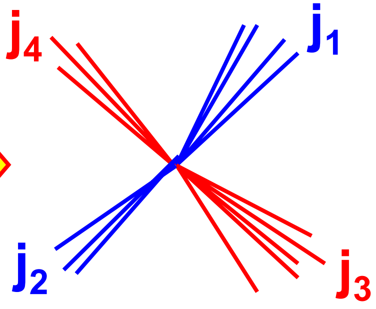
❶ Particle Flow Calorimetry Recap
❷ The Alternative to Particle Flow
❸ ILC Detector Concepts
❹ ILC Detector Design Issues
❺ Designing a detector for particle flow
❻ ILC Detector Performance Highlights
❼ From ILC to CLIC Energies
❽ Summary

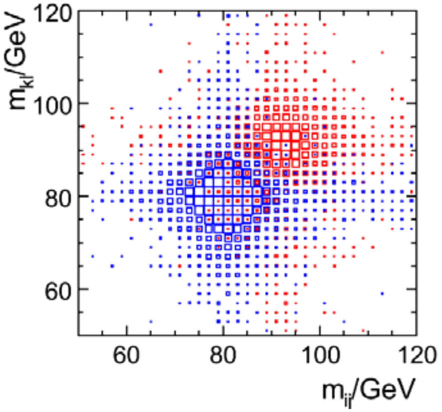
❶ Particle Flow Recap

- ★ Yesterday saw that goal for calorimetry at a future LC was to be able to cleanly separate hadronic W/Z decays
  - Potentially important for many physics processes

e.g.







⇨ **Goal: ~3.5 % jet energy resolution for 50 – 500 GeV jets**

⇨ **a new approach to calorimetry**

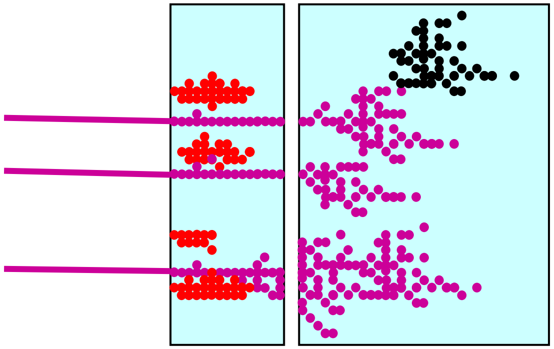
Particle Flow | **Dual Readout** | **Totally Active**

- ★ High granularity Particle Flow Calorimetry attempts to identify individual energy deposits from each particle in a jet

⇨ **Tracks + Photons in ECAL + only neutral hadrons in HCAL**

★ HCAL resolution then becomes relatively unimportant

★ But requires high granularity in ECAL/HCAL + sophisticated reconstruction



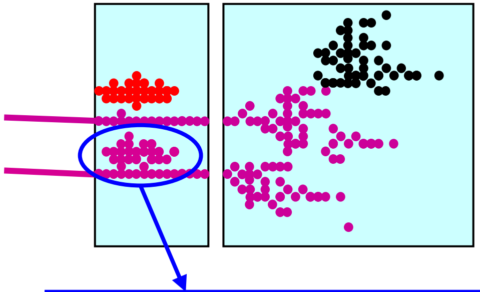
★ Avoid double counting of energy from same particle

★ Separate energy deposits from different particles

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

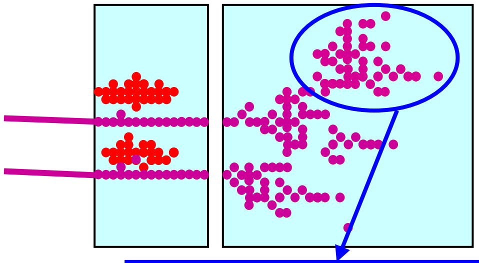
Three types of confusion:

i) Photons



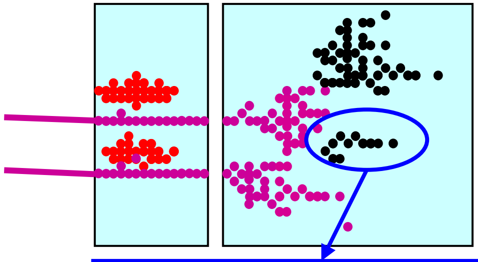
Failure to resolve photon

ii) Neutral Hadrons



Failure to resolve neutral hadron

iii) Fragments



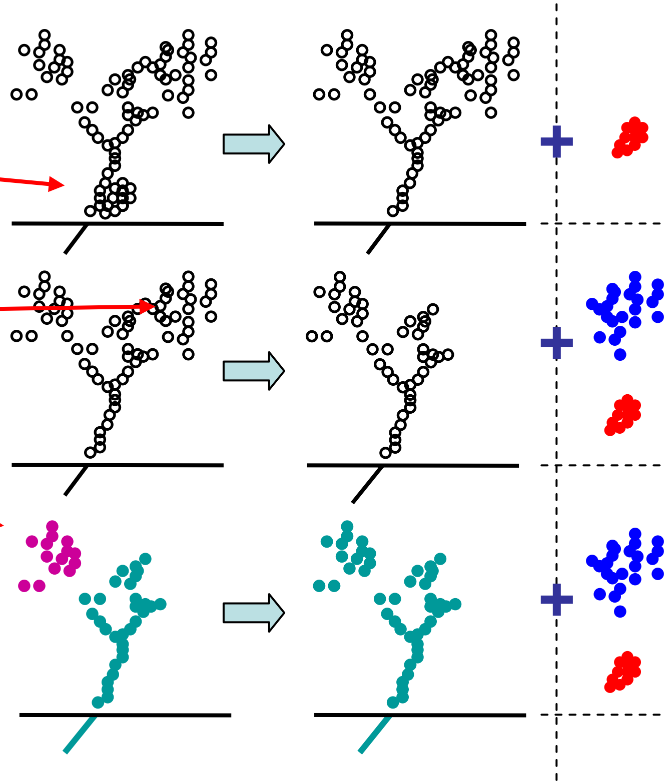
Reconstruct fragment as separate neutral hadron

Understanding Particle Flow

What drives Particle Flow performance ?

- ★ Try to use various "Perfect PFA" algorithms to pin down main performance drivers (resolution, confusion, …)
- ★ Start with full reconstruction (PandoraPFA)
- ★ Then use MC to "cheat" various aspects of **Particle Flow**

PandoraPFA options:



- **PerfectPhotonClustering**
  hits from photons clustered using MC info and removed from main algorithm
- **PerfectNeutralHadronClustering**
  hits from neutral hadrons clustered using MC info…
- **PerfectFragmentRemoval**
  after PandoraPFA clustering "fragments" from charged tracks identified from MC and added to charged track cluster
- **PerfectPFA**
  perfect clustering and matching to tracks

★ Also consider leakage (non-containment) of hadronic showers

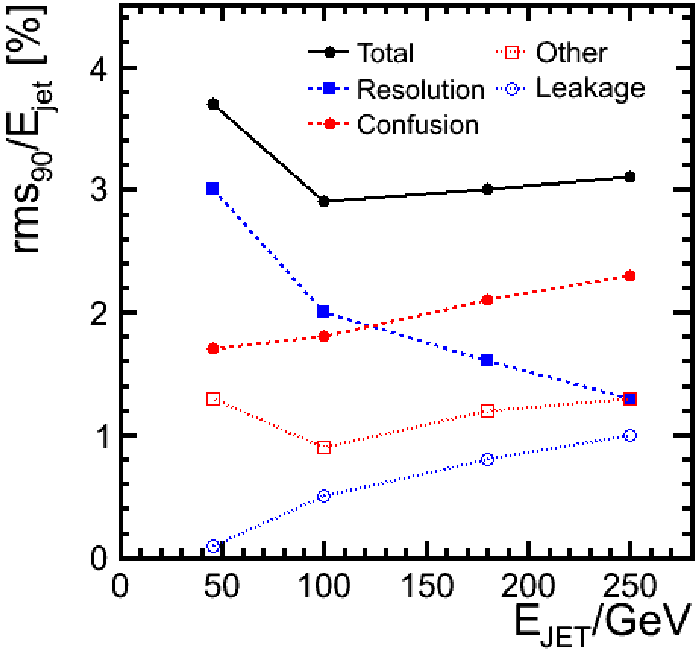
Contributions to resolution

- ★ **Answer depends on jet energy**
  - **Low energy jets: RESOLUTION**
  - **High energy jets: CONFUSION**
  - **Cross-over at ~100 GeV**
  - **For high energies CONFUSION dominates**
  - **Very high energy jets: leakage important**
- ★ **What kind of confusion ?**
  - **i) photons**

    (γ merged into charged had. shower)
  - **ii) neutral hadrons**

    (K_L/n merged into charged had. shower)
  - **iii) charged hadron fragments**

    (fragments of charged had. reconstucted as neutral hadron)
- ★ **At high energies ii) is the largest contribution, e.g. for 250 GeV jets**

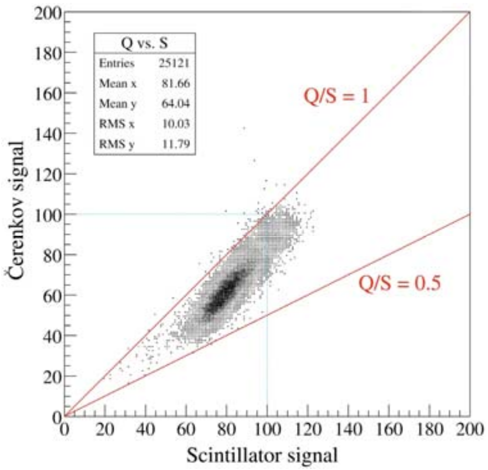


Total Resolution	**3.1 %**
Confusion	**2.3 %**
i) Photons	**1.3 %**
ii) Neutral hadrons	**1.8 %**
iii) Charged hadrons	**0.2 %**

Not insignificant

Largest single contribution, but remember, enters in quadrature

❷ The Alternative to PFlow

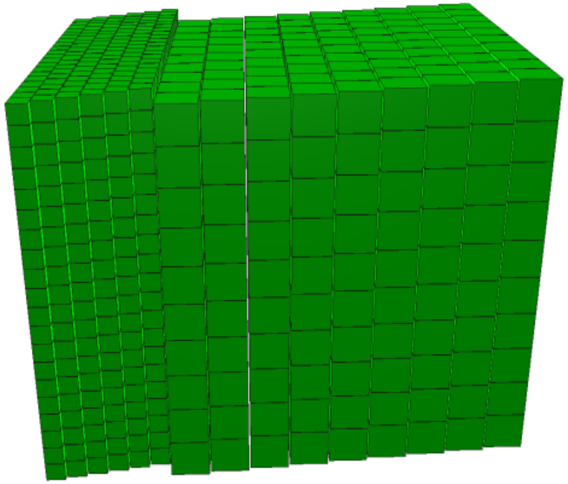


- ★ **Dual/Triple readout calorimetry**
- ★ **Measure all components of hadronic shower**
  - **Measure EM component: Cerenkov light**
  - **Measure "slower" hadronic component: scintillation signal**
  - **Measure thermal neutron component: from timing (triple readout)**
- ★ **Effectively, measure shower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

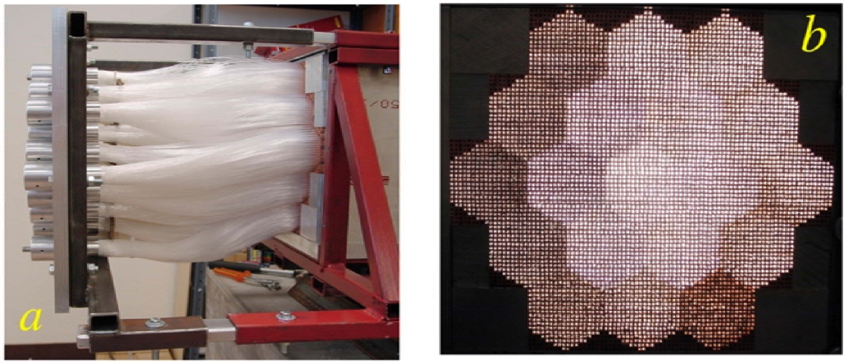
$$\boxed{\frac{\sigma_E}{E} < \frac{30\,\%}{\sqrt{E[\text{GeV}]}} \oplus ?}$$

<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 ?**
  - **But needs significant R&D programme**

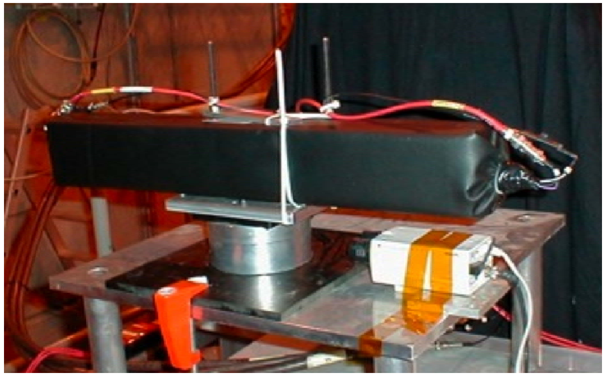


Dual/Triple Readout R&D



DREAM Calorimeter (Wigmans et al.)

- Fibre/Cu calorimeter
  - Cerenkov light in fused-silica fibres
  - Scintillation light in plastic fibres
  - No longitudinal segmentation
- Concept demonstrated in test beam
- Prototype too small to fully demonstrate resolution due to leakage, but results very promising



Crystal R&D

- To date primarily single crystal tests
  - Plenty of options

A realistic alternative to Particle Flow ?

- Clearly a very nice idea !
- **Can it be turned into a collider calorimeter system ?**
- Not clear at this stage
  - Requires a lot of R&D
  - Engineering may be non-trivial
  - What about calibration/constant term?
- Clearly worth pursuing R&D, but not currently the ILC baseline

$$\boxed{\frac{\sigma_E}{E} = \frac{\alpha\,\%}{\sqrt{E/\mathrm{GeV}}} \oplus \beta\,\%}$$

❸ ILC Detector LoIs

- Development of potential detectors for the ILC has two main strands:

Detector Concept Groups

- e.g. ILD and SiD
- Overall system design
- Physics reach

⟺

Sub-Detector R&D Groups

- e.g. CALICE
- Detector R&D

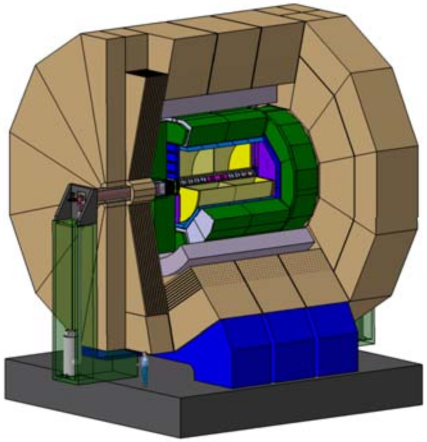
- Concepts and R&D **Tightly coupled**
  - e.g. to develop a detector optimised for particle flow calorimetry can't work on the calorimeters in isolation
    - No longer primarily interested in single particle response
    - Particle Flow Reconstruction depends on whole detector
- In **2009** the detector groups each produced a detector "Letter of Intent"
  - Not an LoI in the usual sense (difficult without an approved project)
  - Reviewed by an international panel of experts (IDAG)
  - Two concepts "Validated": **ILD** and **SiD**
- Extremely valuable in pushing the detector concepts forward

In this lecture will discuss motivation behind these detector designs
Will concentrate on ILD studies, but much applies equally to SiD

LC Detector Concepts

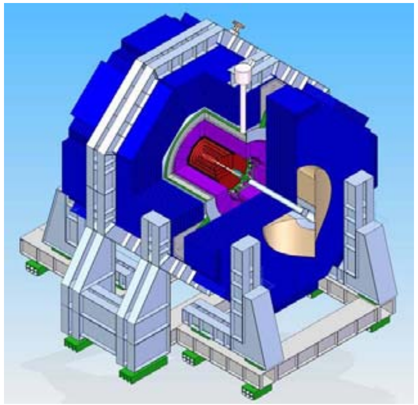
- ★ Both **ILD** and **SiD** designed for Particle Flow Calorimetry
- ★ Designed for **ILC** energies, but form basis of **CLIC** detector studies

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
Muon : integrated in Yoke

SiD: Silicon Detector

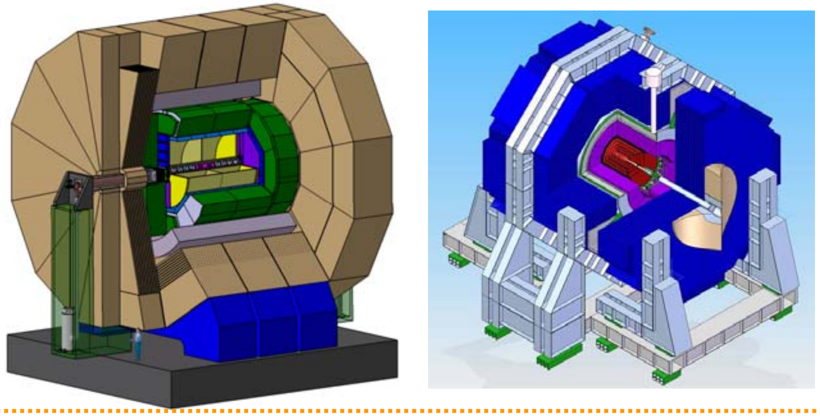


"Small" : **tracker radius 1.2m**
B-field : **5 T**
Tracker : **Silicon**
Calorimetry : high granularity particle flow
ECAL + HCAL inside large solenoid
Muon : integrated in Yoke

- ★ Studied with: detailed **GEANT 4 models** (inc. some gaps/dead regions etc)
  : **full reconstruction** chain (no MC cheat information used)

❹ ILC Detector Design/Optimisation

Detailed detector models



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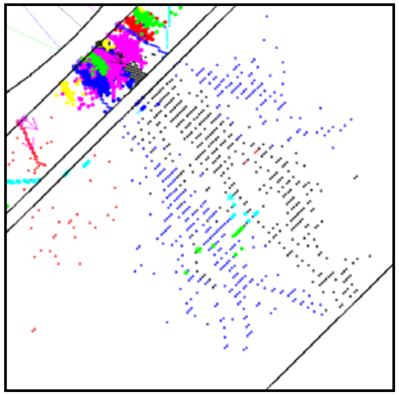
“Realistic” PFlow Reco.



- ★ Have tools to investigate design of a Particle Flow Detector
- ★ First consider **overall detector design issues** for the ILC
- ★ Then consider specific issues for CLIC

★In both cases need to consider:

① The detector performance goals

② The machine environment

③ Cost

- Size
- Magnetic Field

} Major cost drivers

④ Sub-detector technological options

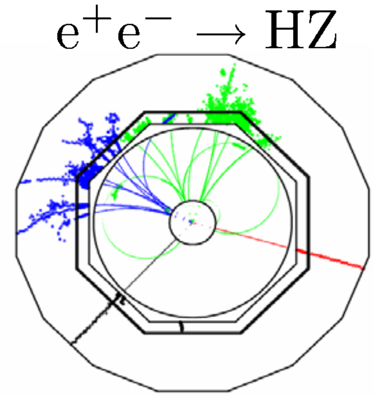
① Performance goals

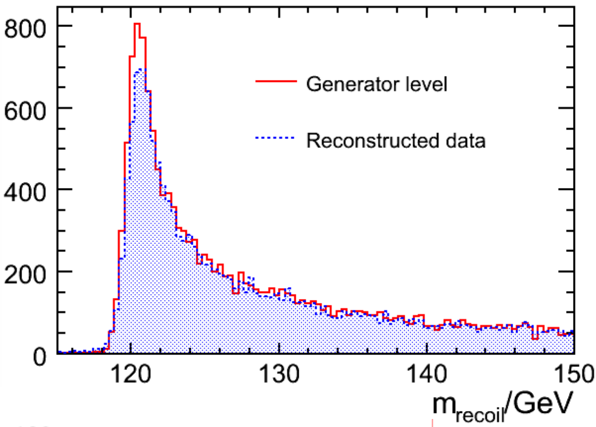
- ★ **momentum: (1/10 x LEP)**

  e.g. Muon momentum

  Higgs recoil mass

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



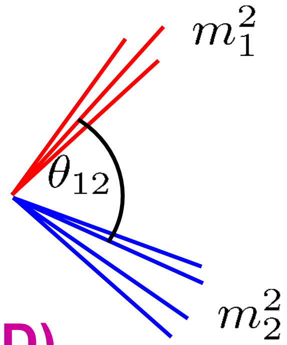


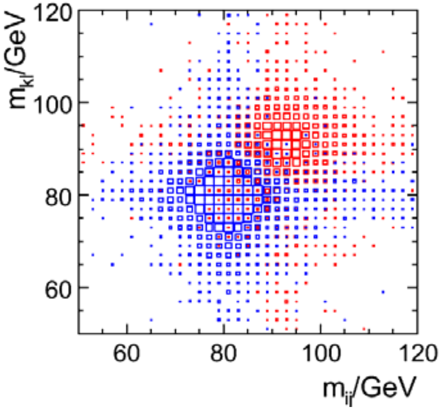
- ★ **jet energy: (1/3 x LEP/ZEUS)**

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

  EWSB signals

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



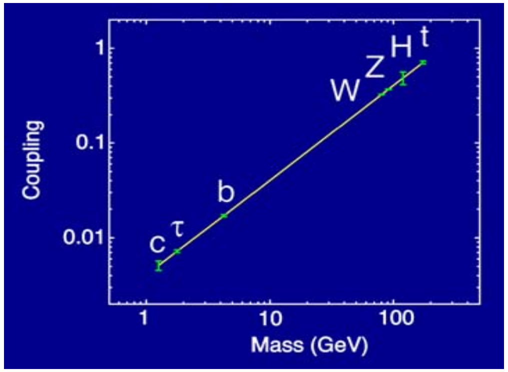


- ★ **impact parameter: (1/3 x SLD)**

  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**

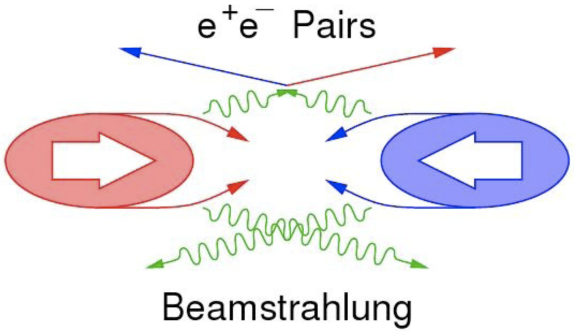
  e.g. missing energy signatures in SUSY

② The Machine Environment

	LEP 2	ILC 0.5 TeV	CLIC 0.5 TeV	CLIC 3 TeV
L $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	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 $[\mathrm{cm}^{-2}]$	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 μm	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

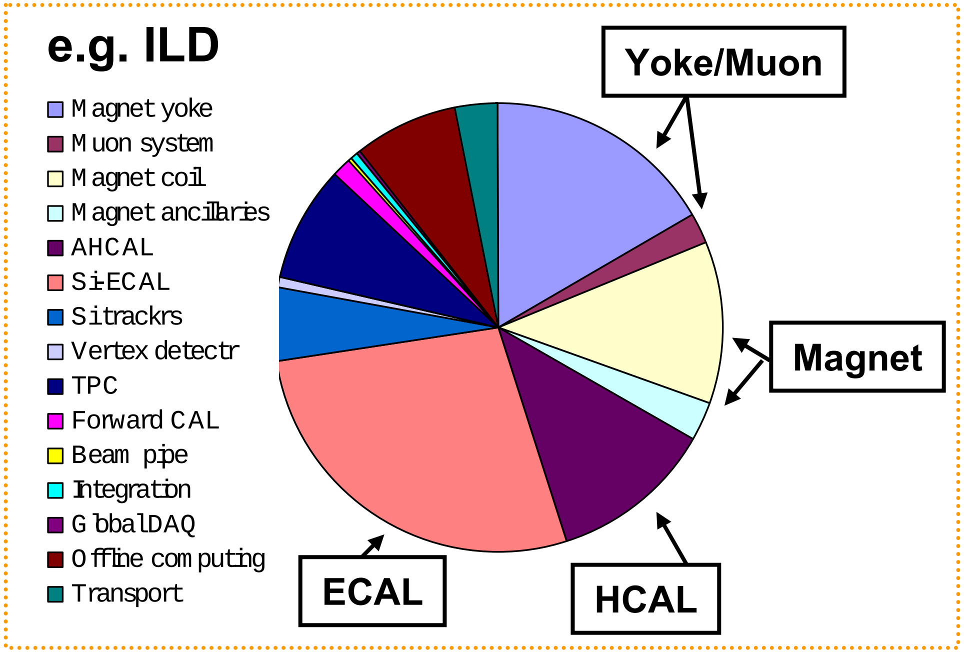


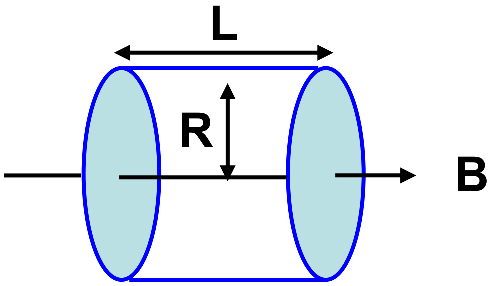
- ★ Bunch train structure:
  - ILC: BX separation 369 ns
  - CLIC: BX separation 0.5 ns
- ★ In addition, two photon → hadrons background is significant at CLIC:
  - Approx three "visible" events per BX
  - Important since, sub-detectors will integrate over >1 BX (0.5 ns)

③ Cost

- ★ Both ILD and SiD assume high granularity particle flow calorimetry to achieve the challenging ILC jet energy goal
- ★ **Major impact** on overall detector design
  - ▪ ECAL and HCAL granularity is all important – not cheap
  - ▪ ECAL and HCAL inside solenoid

    ⇨ large solenoid
- ★ Detector costs largely driven by:
  - ♦ Calorimeters
  - ♦ Solenoid and Yoke


e.g. ILD



- ▪ Cost of calorimeters scales with active area

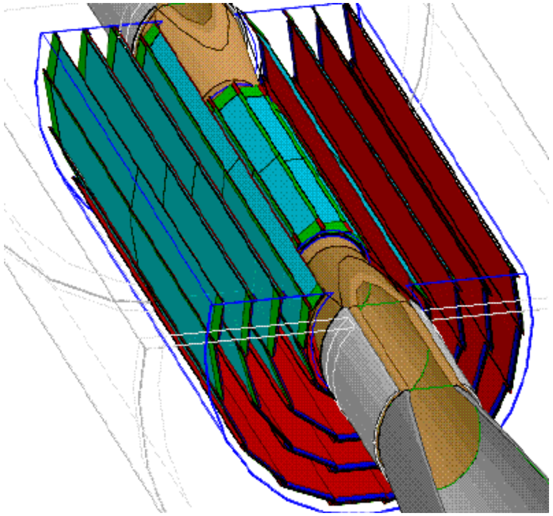
$$\$\$\$ \propto N_{\text{layers}} \times (2RL + R^2)$$

- ▪ Cost of solenoid scales with stored energy

$$\$\$\$ \propto (B^2 R^2 L)^{0.66}$$

- ▪ Interested in performance dependence on: **B**, **R** and, to a lesser extent **L**

④ Sub-detectors: Vertex Detector



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

Main design considerations:

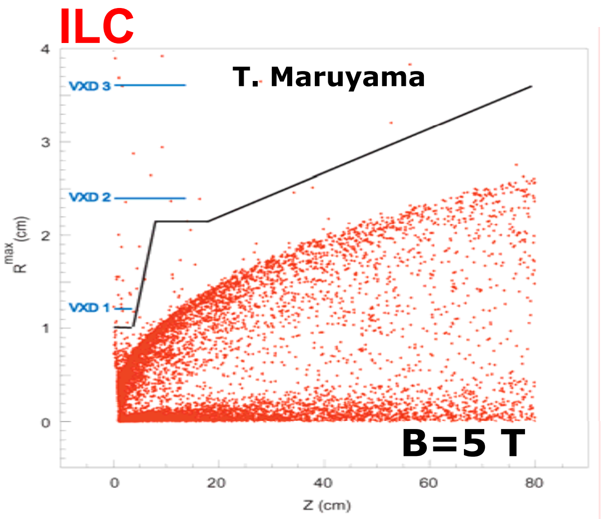
★ Inner radius: as close to beam pipe as possible for impact parameter resolution ~ 15 mm

★ 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 (Machine):

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



Constraints (Technology):

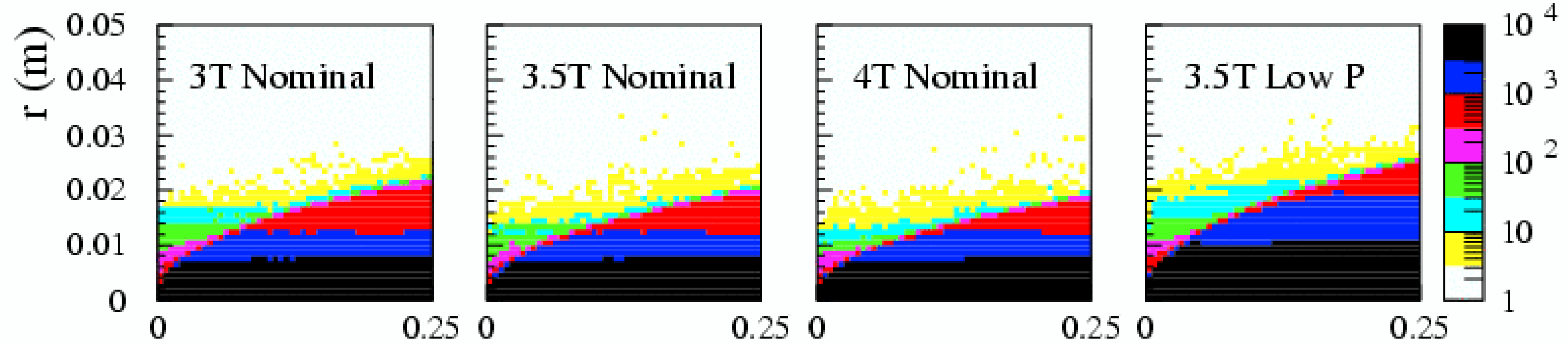
★ Layer thickness depends on technology

★ 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

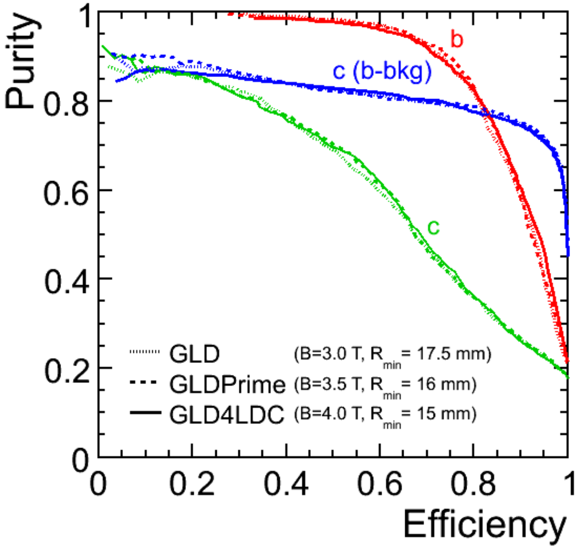
Impact on overall design: B-field

- ★ Might expect increased **B-field** to help… go to lower inner radii
- ★ At ILC radius of pair background envelope scales roughly as **√B**



ILD
LoI

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



- ★ Differences in flavour tag perf. are not large

★ **Conclude:**

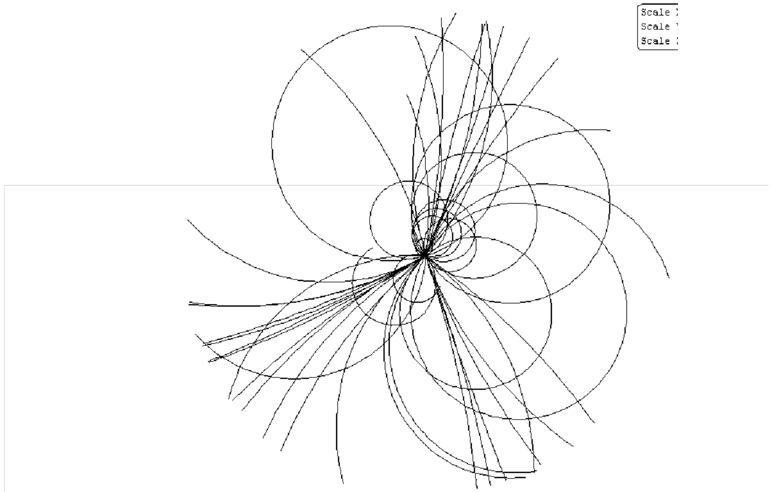
- **Technology is main driving factor in the Vertex detector design**
- Many options (see Marco’s 2nd lecture)
- **Impact of B-field not large**

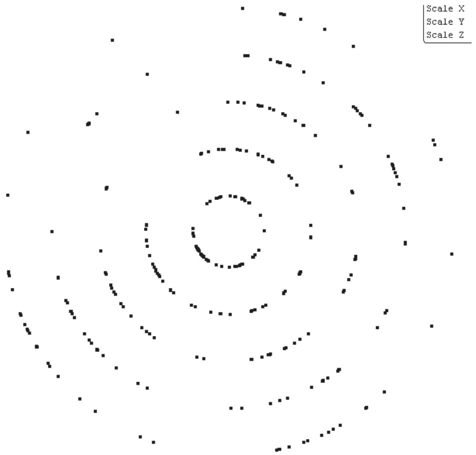
Note: Vertex charge measurements likely to be more sensitive to r_{INNER}

Sub-detectors: Central Tracker

Two main options:

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





- ♦ Large number of samples
- ♦ Few very well measured points

★ Detailed studies in the **ILD** and **SiD** LoIs show that both result in:

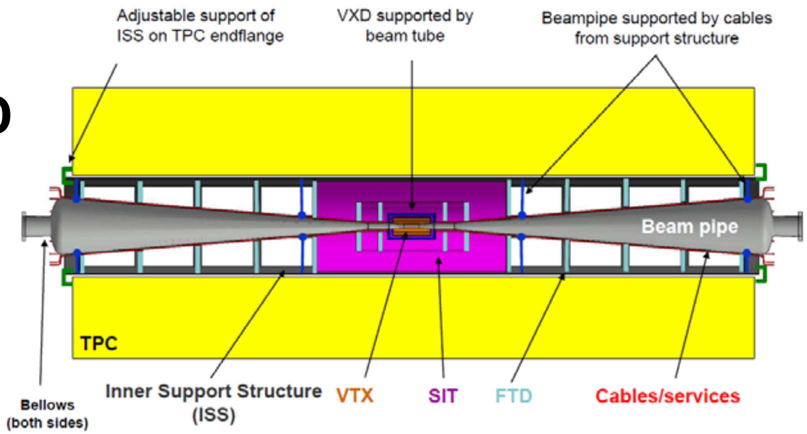
- Very high track reconstruction efficiency
- Excellent momentum resolution: $\sigma_{1/p_T} \sim 2\times10^{-5}\,\mathrm{GeV}^{-1}$ (high p tracks)

★ Tracker optimisation issues are well understood, playoff between:

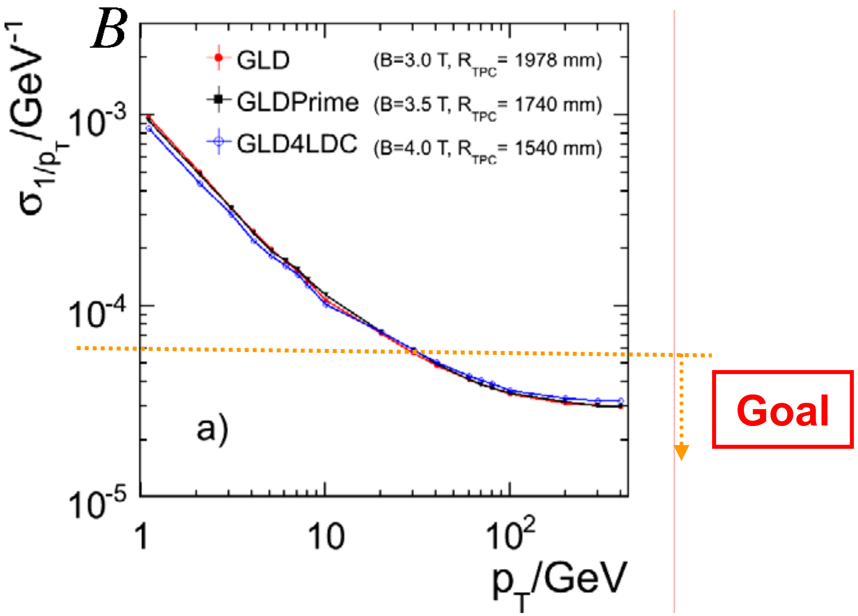
- lever arm – tracker radius
- point resolution
- B-field

- ★ LC tracking systems augment central tracker with Si inner tracking layers and forward tracking disks.

ILD



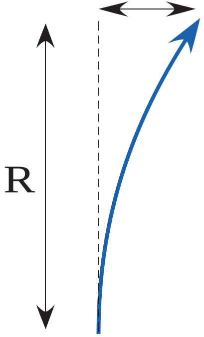
- ★ Performance studied in full simulation/reconstruction
  - e.g. compare
    - B= 3.0 T, R_{TPC} = 2.0 m
    - B= 3.5 T, R_{TPC} = 1.7 m
    - B= 4.0 T, R_{TPC} = 1.5 m
  - Differences small
  - Meet ILC goal

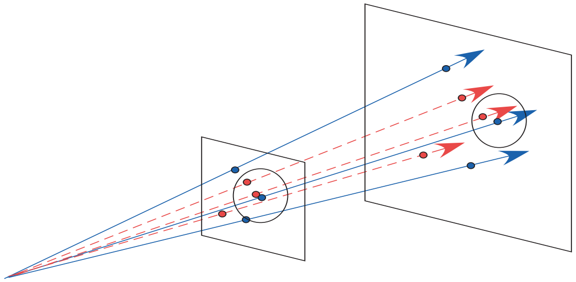


- ★ Not a strong constraint on **B** and **R**
- ★ Assumed TPC/Si point resolutions more important

Sub-detectors: Calorimetry

- ★ **Particle Flow Calorimetry** lives or dies on ability to separate energy deposits from individual particles.
  - **Large detector** – spatially separate particles
  - **High B-field** – separate charged/neutrals
  - **High granularity ECAL/HCAL** – resolve particles





Might expect "figure-of-merit": $\frac{BR^2}{\sigma}$

Separation of charge/neutrals

Calorimeter granularity/R_{Moliere}

- ★ Argues for: **large** + **high granularity** + ⇧ **B**
- ★ Cost considerations: **small** + **lower granularity** + ⇩ **B**

Particle Flow Calorimetry drives overall detector design

Detector Optimisation and Particle Flow

- ★ Would like to optimise the overall detector for particle flow performance wrt cost

However:

- ★ High granularity particle flow calorimetry is a relatively new concept
- ★ Not that well understood
  - ♦ complex interplay between hardware and reconstruction
  - ♦ not easy to "guess" dependencies on B, R, granularity
- ★ In two years Particle Flow reconstruction software has become sufficiently powerful/realistic:
  - ▪ can now investigate Particle Flow Calorimetry in detail

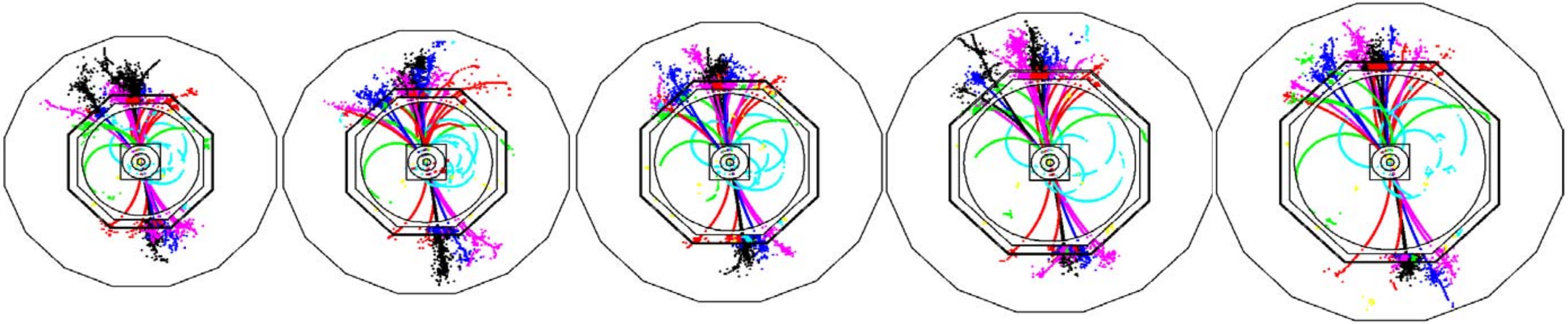
⚠ Interpretation: observing effects of detector + imperfect software

❺ Optimising for Particle Flow

Cost drivers:

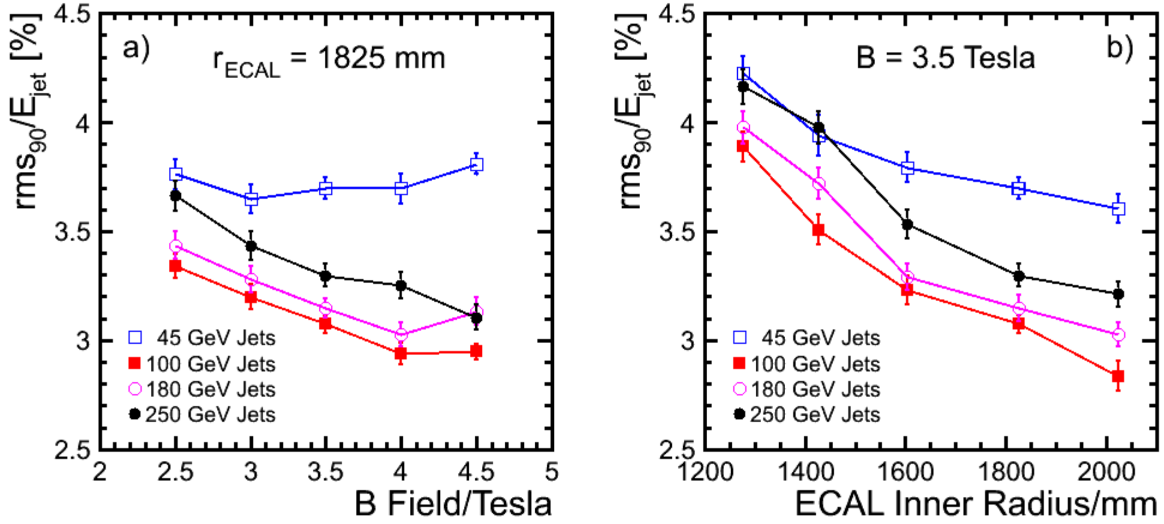
- Calorimeters and solenoid are the main cost drivers of an ILC detector optimised for particle flow
- Most important detector design considerations are:
  - B-field
  - R : inner radius of ECAL
  - L : length, equivalently aspect ratio L/R
  - HCAL thickness : number of interaction lengths
  - ECAL and HCAL segmentation
- Study jet energy resolution as a function of these cost critical issues

★e.g. vary ECAL radius and B-field



B vs R

- **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 ↑

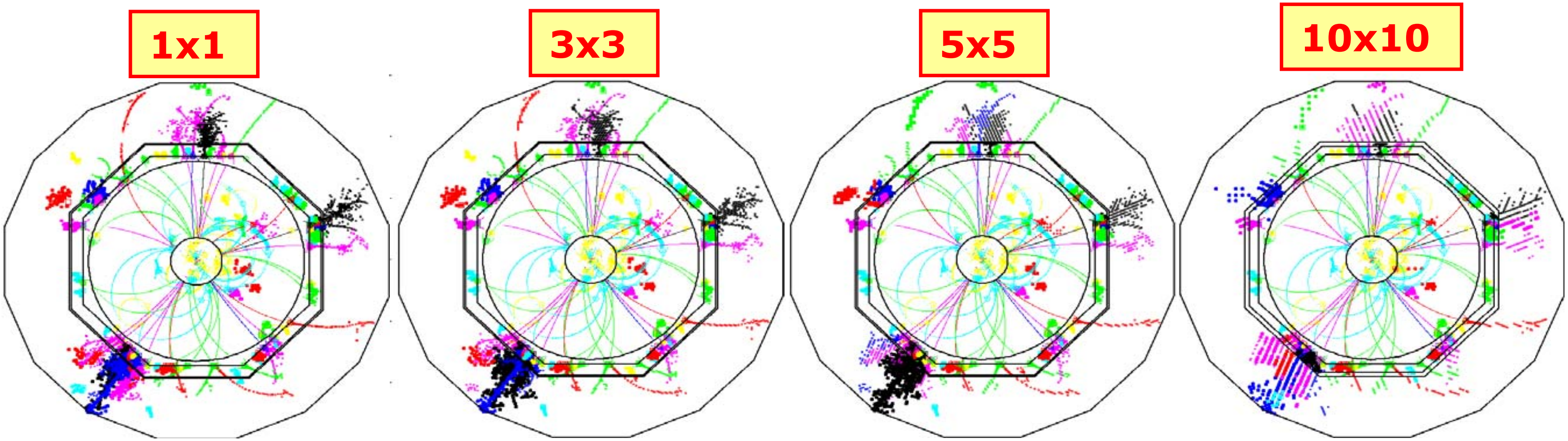
- Confusion $\propto$ **$B^{-0.3}$ R^{-1}** (**1/R** dependence "feels right", geometrical factor !)

Conclusions:

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

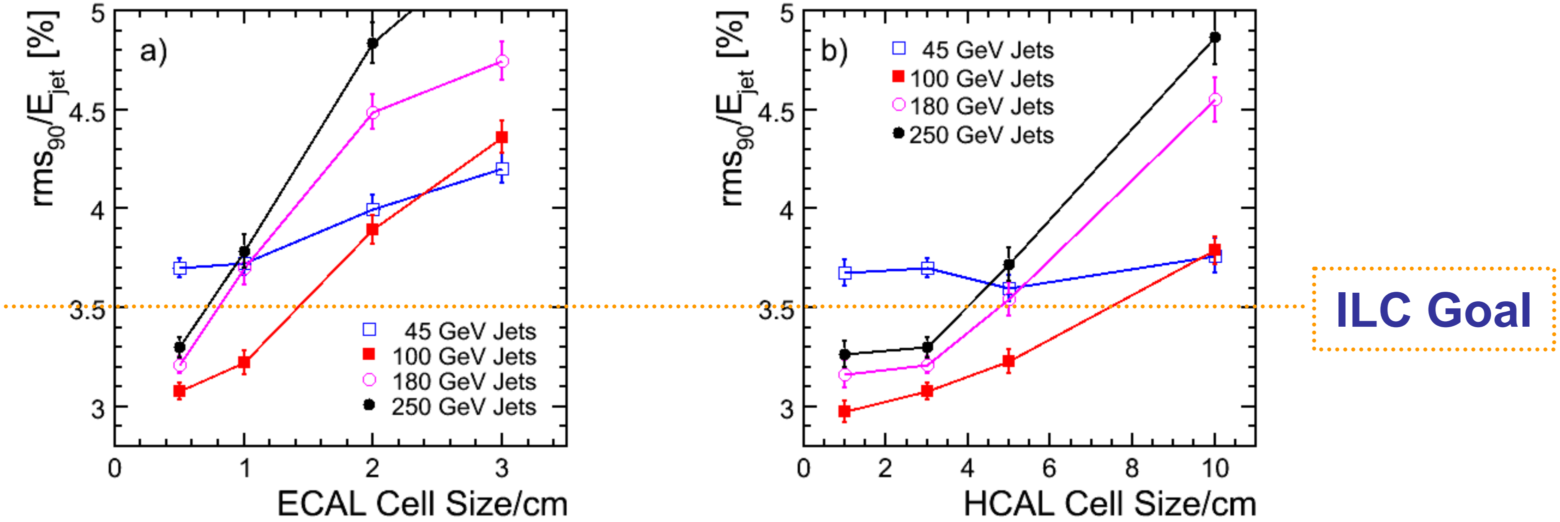
ECAL/HCAL Segmentation

- ★ Assumed particle flow reconstruction requires very highly segmented ECAL and HCAL
- ★ What does this mean ?
- ★ In ILD detector model vary ECAL Si pixel size and HCAL tile size
  - e.g. HCAL tile size [cm^2]



- ★ "By eye" can see that pattern recognition becomes harder for **10x10 cm^2**
- ★ Dependence of jet energy resolution on segmentation obtained with full particle flow reconstruction

★ In ILD detector model vary ECAL Si pixel size and HCAL tile size



ILC Goal

★ ECAL Conclusions:

- Ability to resolve photons in current PandoraPFA algorithm strongly dependent on transverse cell size
- Require at least as fine as 10x10 mm^2 to achieve 4.0 % jet E resolution
- Significant advantages in going to 5x5 mm^2
- For 45 GeV jets resolution dominates (confusion relatively small)

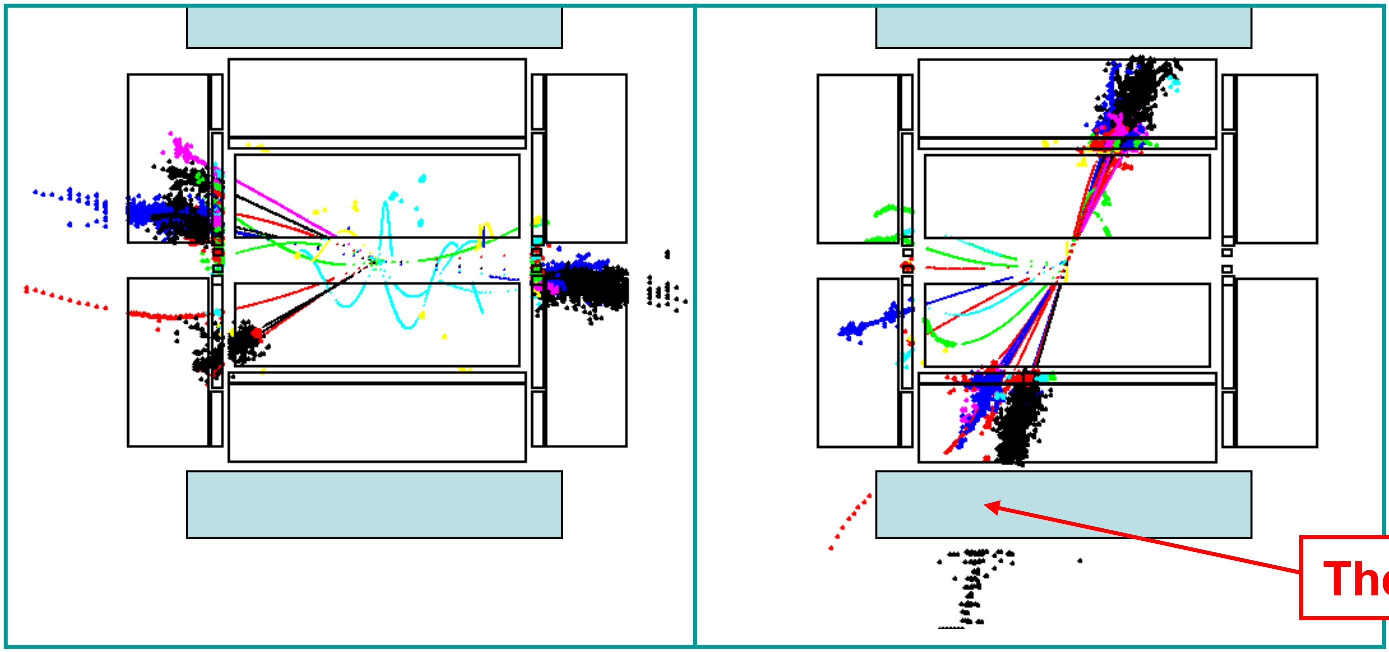
★ HCAL Conclusions:

- For current PandoraPFA algorithm and for Scintillator HCAL, a tile size of 3×3 cm^2 looks optimal
- May be different for a digital/semi-digital RPC based HCAL

HCAL Depth

- ★ Determines solenoid radius
  - significant impact on cost
- ★ How important is HCAL leakage ?
  - vary number of HCAL layers
- ★ What can be recovered using MUON chambers as a “Tail catcher”
  - Impact limited by thick (~2 λ_I) solenoid
  - Included in particle flow reconstruction
  - Simple energy estimator (digital) + some estimate for loss in coil

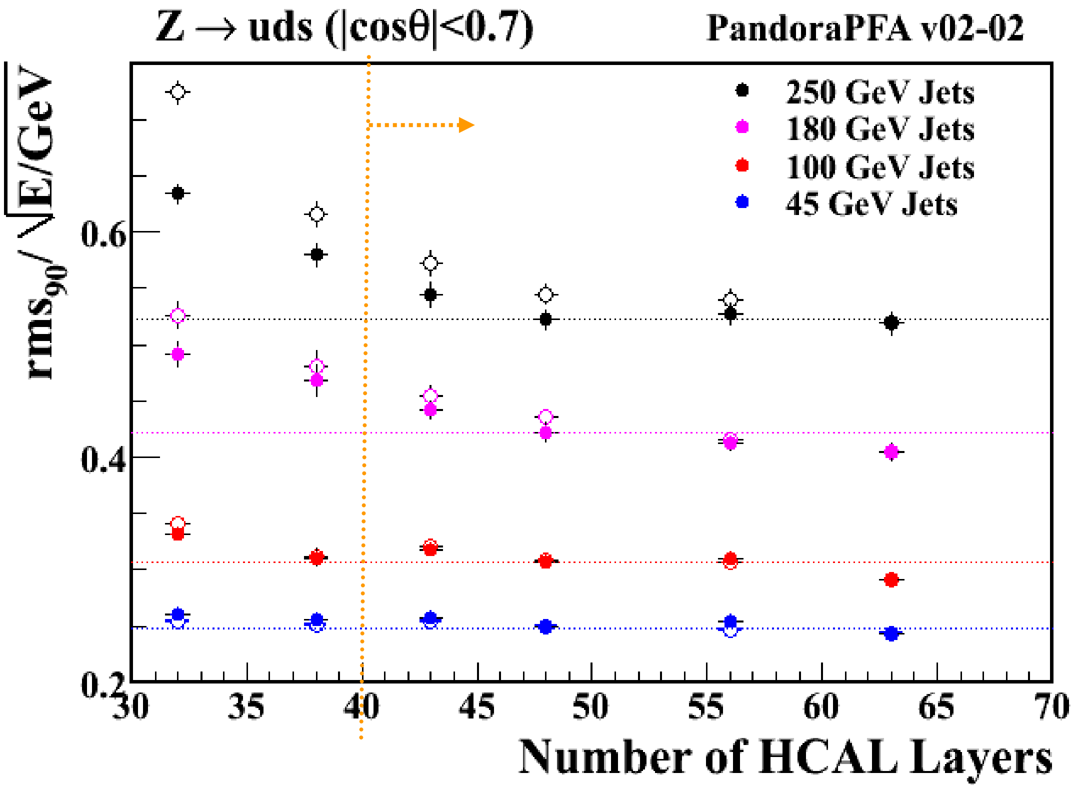
e.g.



The problem

HCAL Depth

- **Open circles** = no use of muon chambers as a "tail-catcher"
- **Solid circles** = including "tail-catcher"



HCAL Layers	λ_I	
	HCAL	+ECAL
32	4.0	4.8
38	4.7	5.5
43	5.4	6.2
48	6.0	6.8
63	7.9	8.7

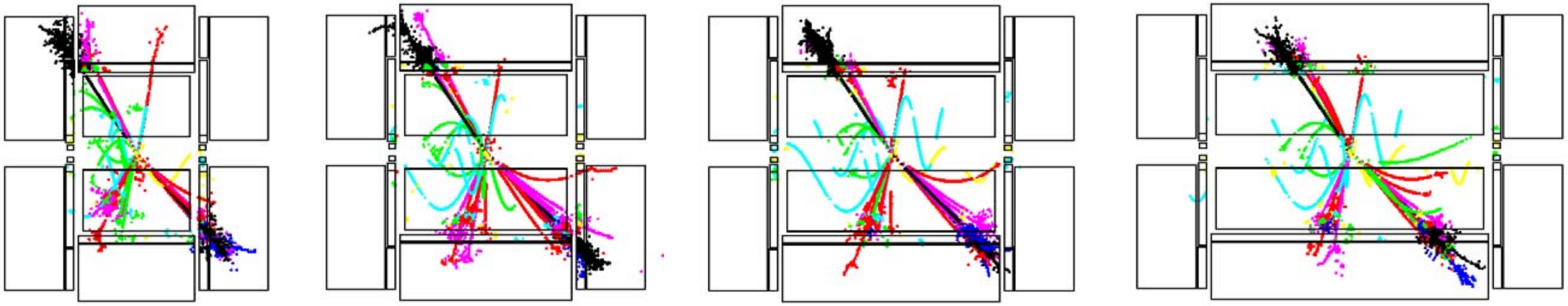
ECAL : λ_I = 0.8
HCAL : λ_I includes scintillator

★ Little motivation for going beyond a 48 layer (6 λ_I) HCAL
★ Depends on Hadron Shower simulation
★ "Tail-catcher": corrects ~50% effect of leakage, limited by thick solenoid

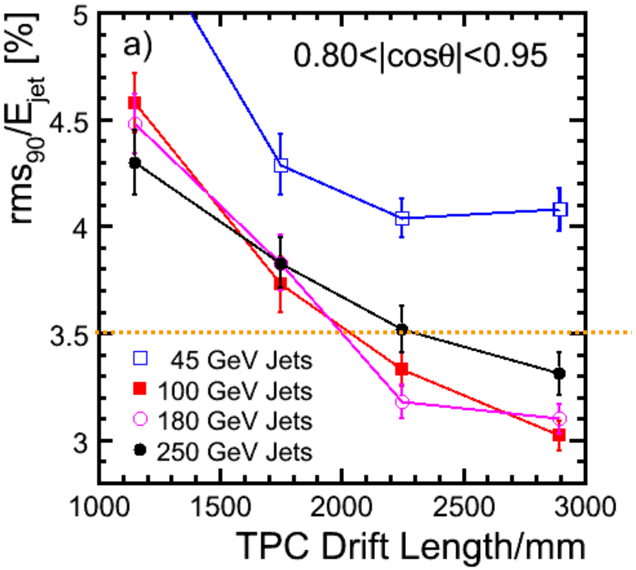
For 1 TeV machine "reasonable range" 5 λ_I - 6 λ_I

Detector Aspect Ratio

- ★ What aspect ratio is optimal ?



- ★ For “end-cap” jets find



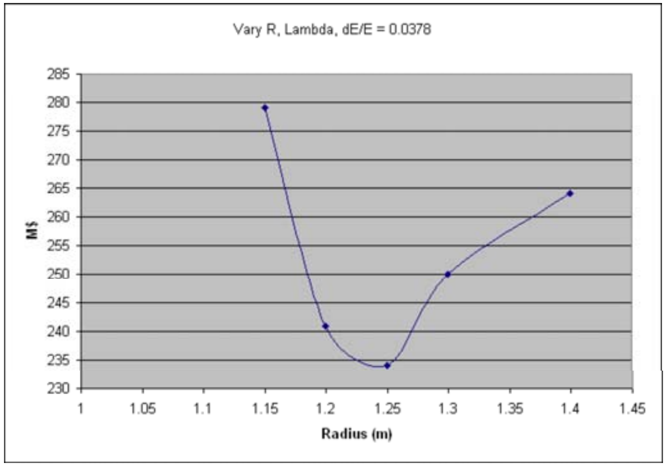
- ★ As expected performances improves with larger **L**
- ★ But diminishing returns in going from **2.2 m → 2.9 m**
- ★ Conclude for ILD **L = 2.2 m** is reasonable, c.f. **R = 1.8 m**

How to optimise the detector ?

- ★ Now have some understanding of how detector performance depends on various global parameters
- ★ However, need to fold in cost
- ★ Ideally would like to determine cost optimised parameters for a given level of performance

e.g. from SiD LoI

- ♦ Fix jet energy resolution = 4 %
  vary R and B
- ♦ Give excel a cost model and…



- ★ In my opinion, this is extremely hard to justify unless you know relative costs of parts rather well, e.g. Silicon for ECAL, solenoid, …
- ★ At these stage very large uncertainties (i.e. factors of a few)
- ★ ILD chose detector parameters to give desired performance whilst being “cost conscious”
- ★ As real costs are better understood, things will evolve…

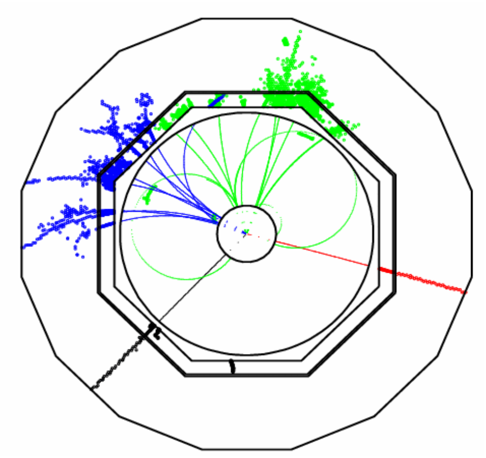
❻ Physics Performance

- ★ Ultimate test of detector is physics performance
- ★ Studied for several “benchmark” processes (see Marco’s first lecture)
- ★ These were chosen to test different aspects of the ILC detectors
  - ♦ momentum reconstruction
  - ♦ flavour-tagging
  - ♦ jet-energy resolution
  - ♦ forward tracking
- ★ All studied with full GEANT4 simulation and full reconstruction
- ★ Large MC productions of full SM data sets ~50M events

- Only time to show a few highlights…

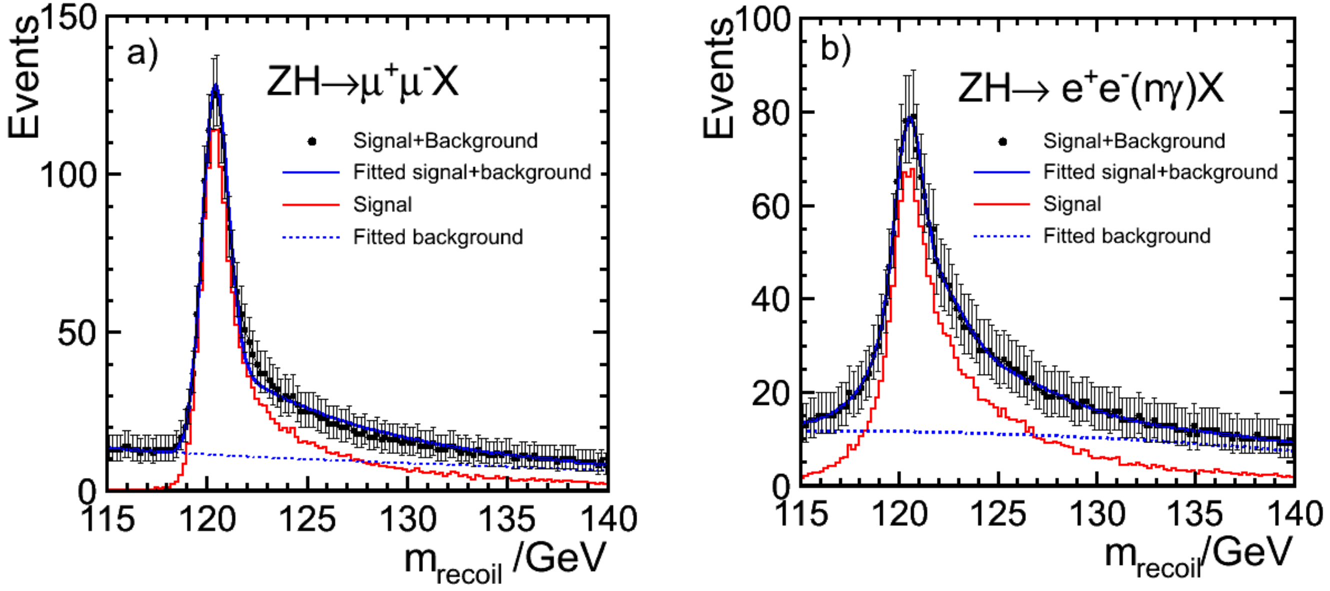
Higgs Recoil Mass at $\sqrt{s}$ = 250 GeV

- ★ **Model independent** determination of Higgs mass from Higgs-strahlung events at $\sqrt{s}$ = 250 GeV
- ★ Measure four-momentum of Z from its decays to $e^+e^-/\mu^+\mu^-$
- ★ Determine Higgs four momentum from recoil mass assuming $\sqrt{s}$ = 250 GeV for underlying e^+e^- collision
- ★ Resolution limited by:
  - momentum resolution
  - beamstralung
  - +bremsstrahlung for electron final state



- ★ Select events using **only** information from di-lepton system

(250 fb^{-1})



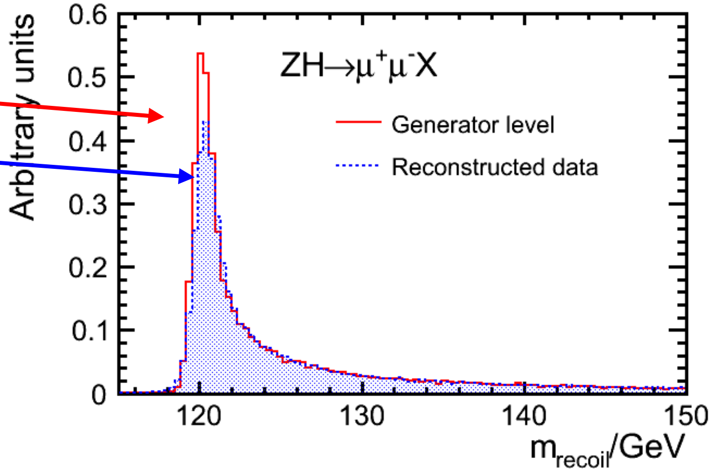
Model independent results:

Pol(e^-,e^+)	Channel	$\sigma(m_H)$	Cross-section	
-80 %, +30%	$\mu\mu$X	36 MeV	±0.39 fb	(3.3 %)
	eeX	72 MeV	±0.61 fb	(4.8 %)
	ee(nγ)X	74 MeV	±0.47 fb	(4.0 %)

⇒ $\sigma(m_H)$ = 32 MeV

Relation to detector performance

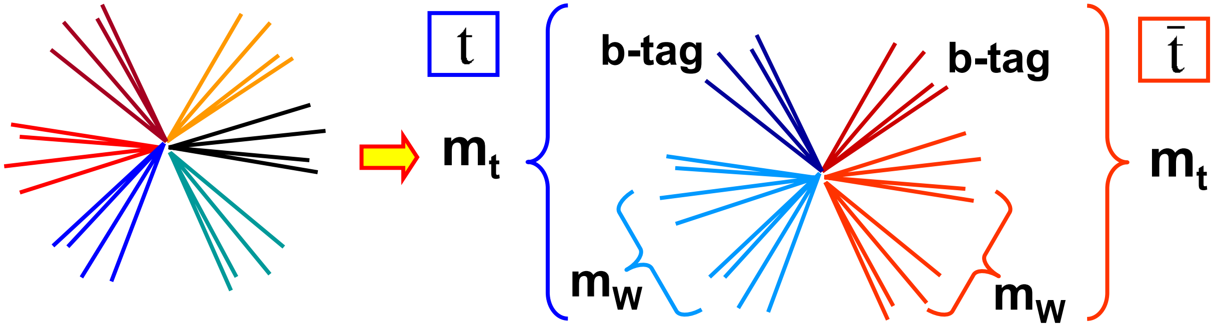
- This is a benchmark analysis for **momentum resolution**
- Width of $\mu\mu$X recoil mass peak:
  - **560 MeV** for perfect resolution
  - **650 MeV** after reconstruction
- For ILD momentum resolution, luminosity spectrum still dominates !
  - **560 MeV** vs **330 MeV**



ILD momentum resolution well matched to ZH requirements

Top production at $\sqrt{s}$ = 500 GeV

- ★ **At $\sqrt{s}$ = 500 GeV** top mass determined from direct reconstruction of final state
- ★ Fully-hadronic $t\bar{t} \rightarrow (bq\bar{q})(\bar{b}q\bar{q})$ and semi-leptonic $t\bar{t} \rightarrow (bq\bar{q})(\bar{b}\ell\nu)$
- ★ Main analysis issue is that of jet combinatorics

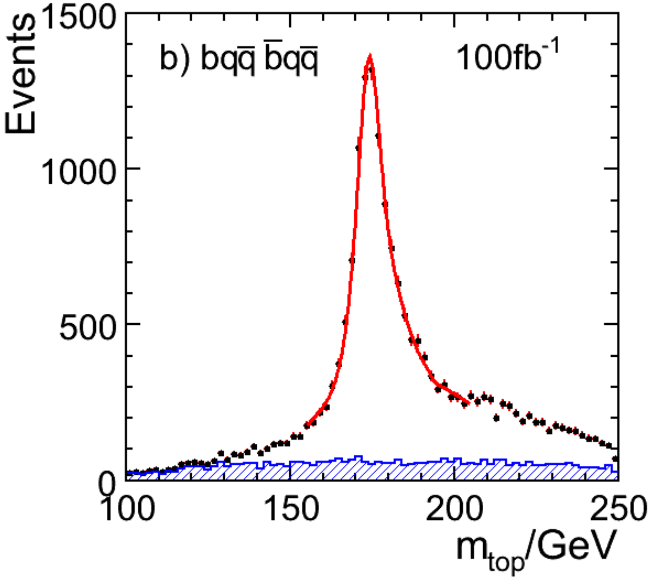


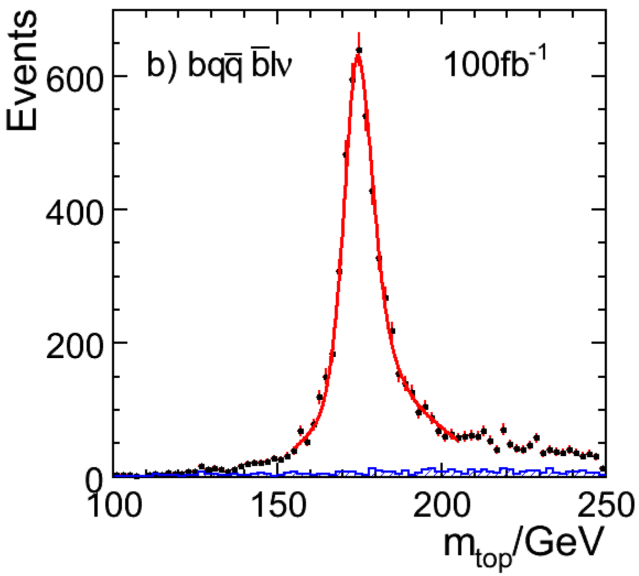
Use:

- b-tagging
- Invariant masses

Flavour-tagging
Jet Energy

- ★ Final mass distribution from kinematic fit using selected jet association





500 fb^{-1}

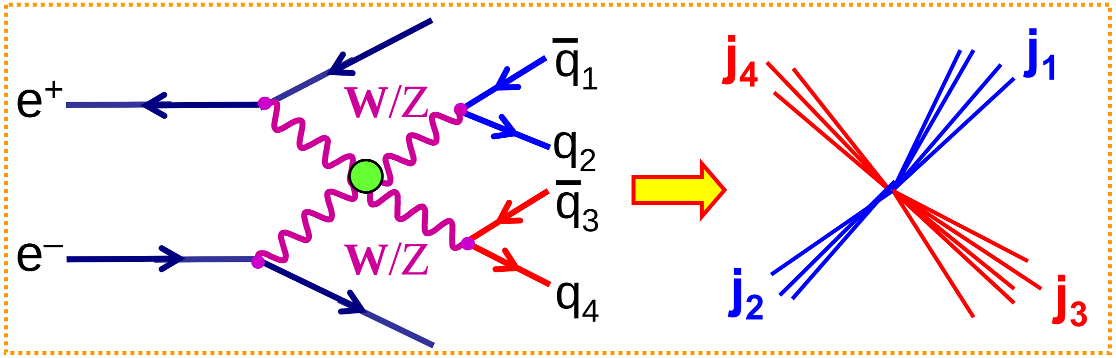
↓

$$\boxed{m_t\ :\ \pm 30\,\mathrm{MeV}}$$

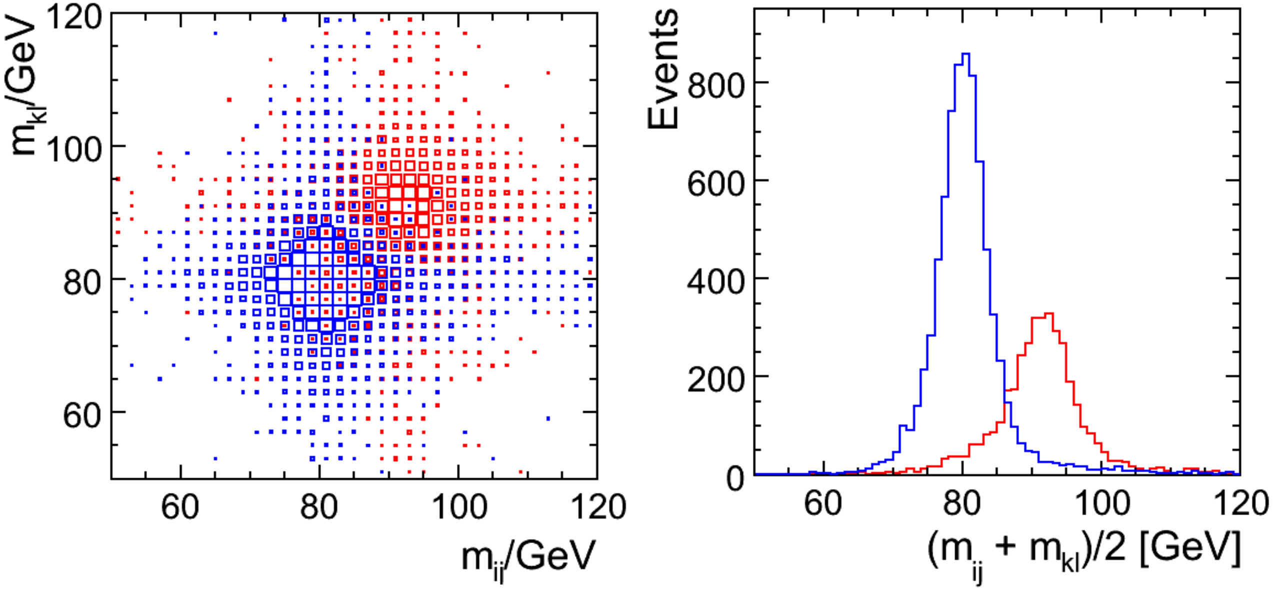
(no systematics)

and finally…WW-scattering at √s = 1 TeV

- ★ **Study** $\mathrm{W^+W^-} \rightarrow \mathrm{W^+W^-}$ **and** $\mathrm{W^+W^-} \rightarrow \mathrm{ZZ}$ **in** $\mathrm{e^+e^-} \rightarrow \nu\overline{\nu}\mathrm{W^+W^-}$ **and** $\mathrm{e^+e^-} \rightarrow \nu\overline{\nu}\mathrm{ZZ}$



- ★ **jets + missing energy**
- ★ **"Classic" benchmark for jet energy resolution**
- ★ **At 1 TeV clear separation is obtained between W and Z peaks with ILD**



- ★ **Limits on anomalous couplings similar to earlier fast simulation studies**

❼ From ILC to CLIC

- ★ 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…

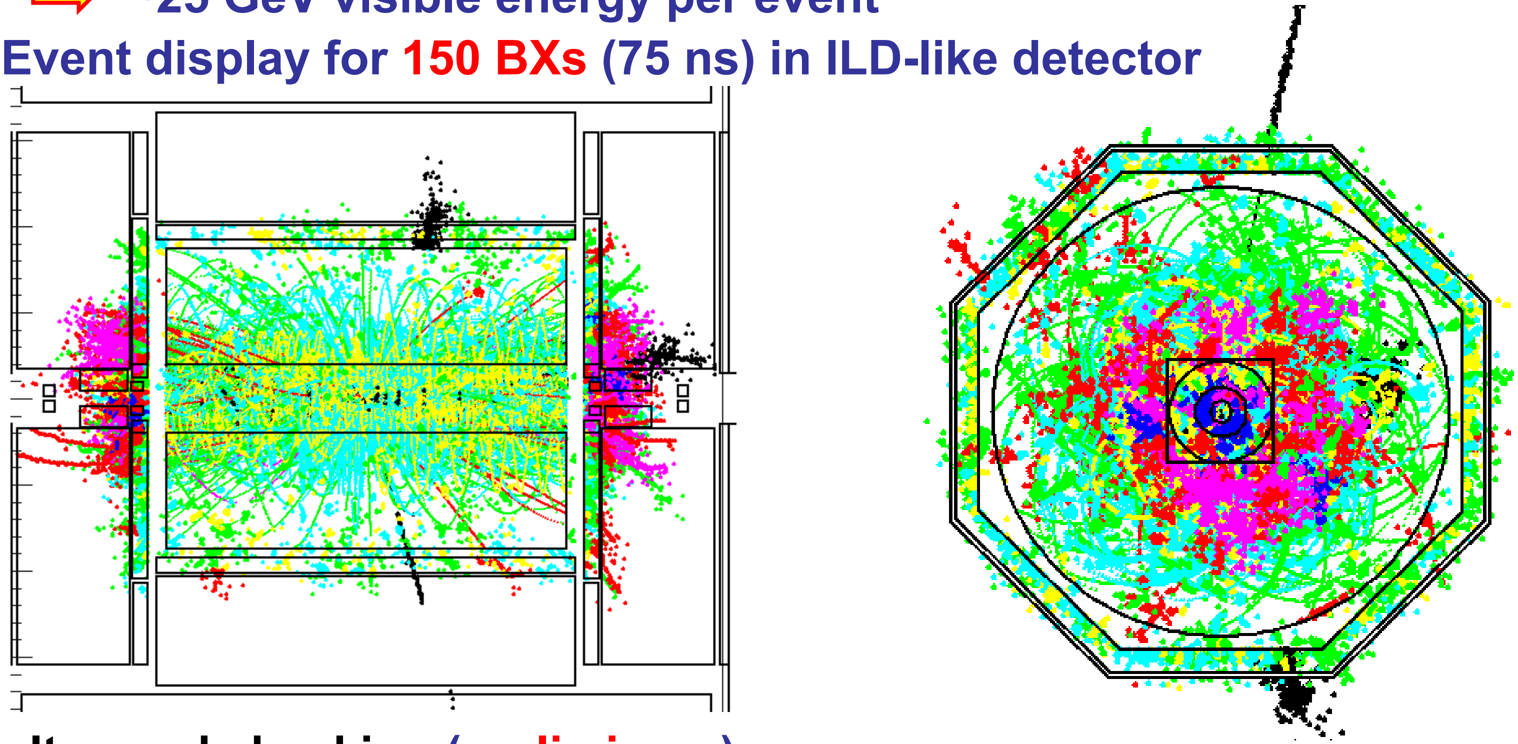
Main detector requirements driven by CLIC machine environment

Two-photon → hadrons background

- ★ Preliminary studies (Battaglia,Blaising,Quevillon) indicate significant two photon background for 3 TeV CLIC operation
- ★ Approx 13 particles per BX $(p_T > 0.15\,\mathrm{GeV}\;,\; |\cos\theta| < 0.98)$

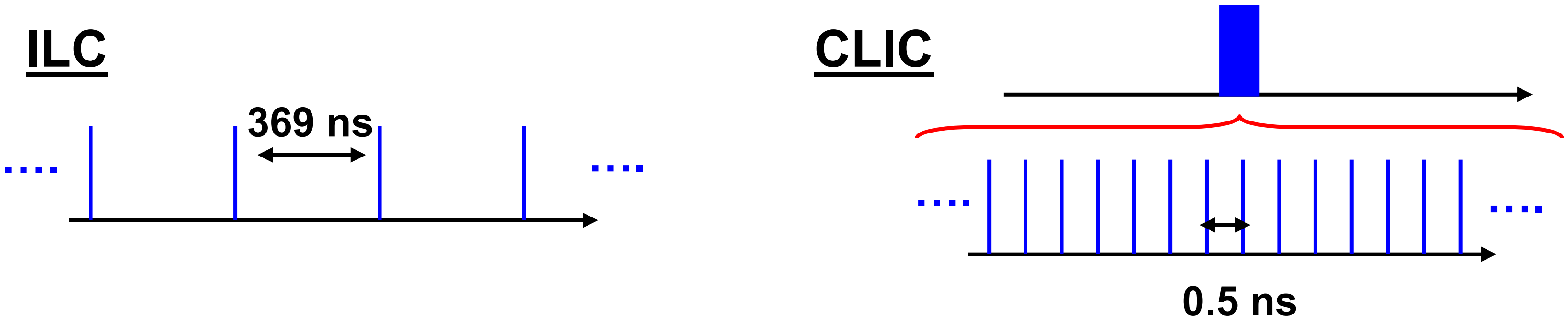
  ⇨ ~25 GeV visible energy per event

  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: suggest **~25 ns or better**
- This is challenging… and places constraints on detector technologies

This is an important issue which need careful study

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

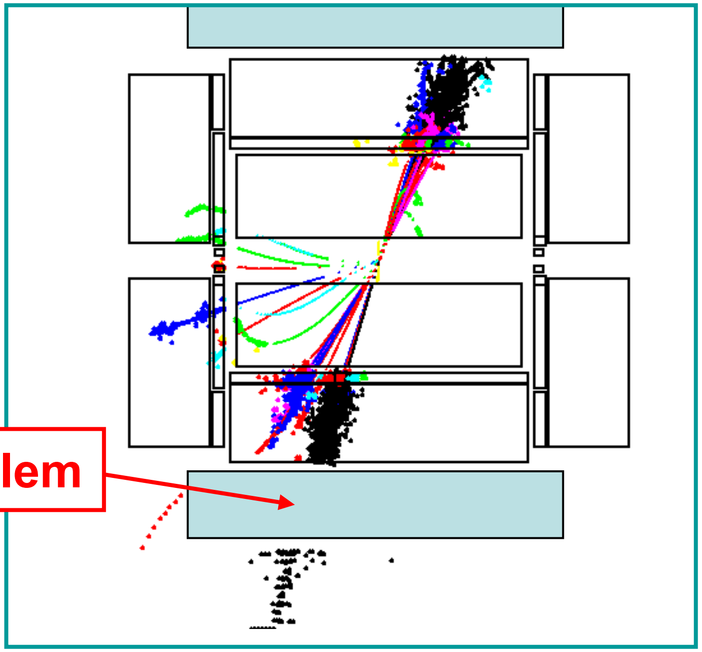
✘ Pattern recognition in dense CLIC track environment not proven
(SiD studies assumed single BX tagging)

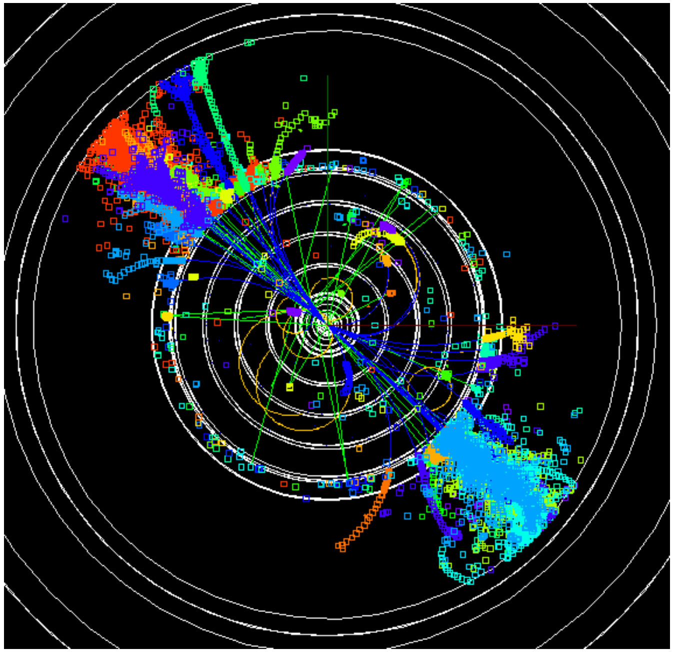
★ Silicon Tracker is probably the safest option for now – but a TPC is certainly not ruled out

Needs a detailed study with **full** CLIC background/BX structure

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



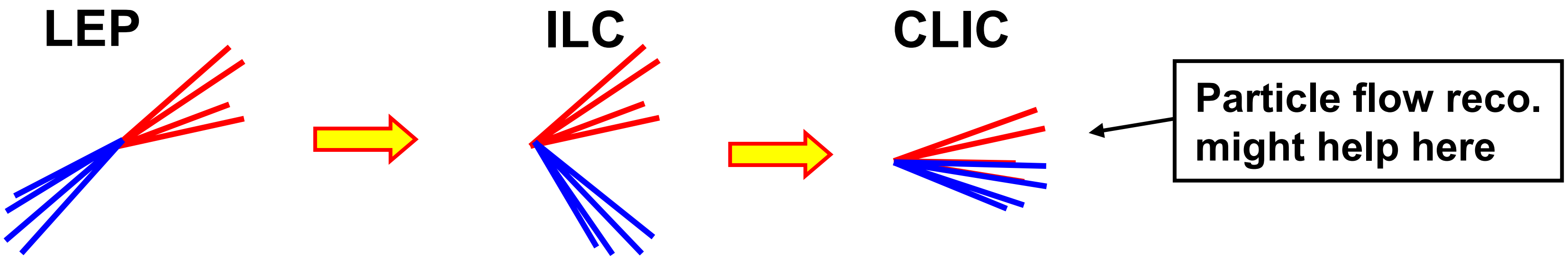


- ★ Probably need ~8 λ_I HCAL for CLIC energies
  - but needs to be inside Solenoid for PFA – cost/feasibility
    - e.g. for current ILD concept ⇨ **7.4m** diameter solenoid !
  - compact structures e.g. Replace steel with Tungsten as HCAL absorber?
  - partially instrumented solenoid ?

But can PFA deliver at CLIC energies ?

W/Z Separation at CLIC

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



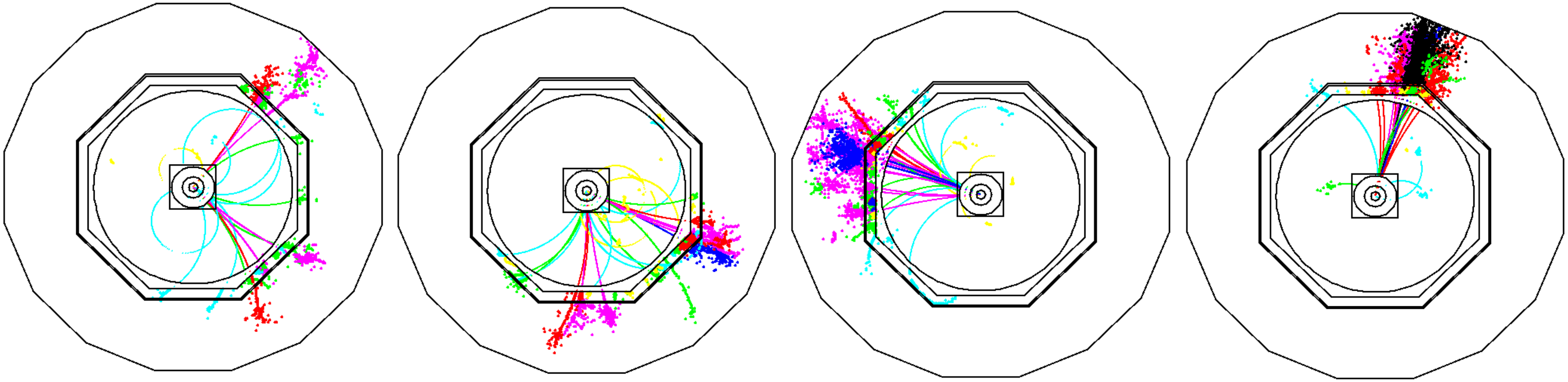
Particle flow reco. might help here

★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:



125 GeV Z **250 GeV Z** **500 GeV Z** **1 TeV Z**

PandoraPFA/ILD 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**)
- ★ Effect on 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	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %
375 GeV	81.4 %	3.6 %
500 GeV	91.6 %	4.1 %

⇒

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 %

NOTE:

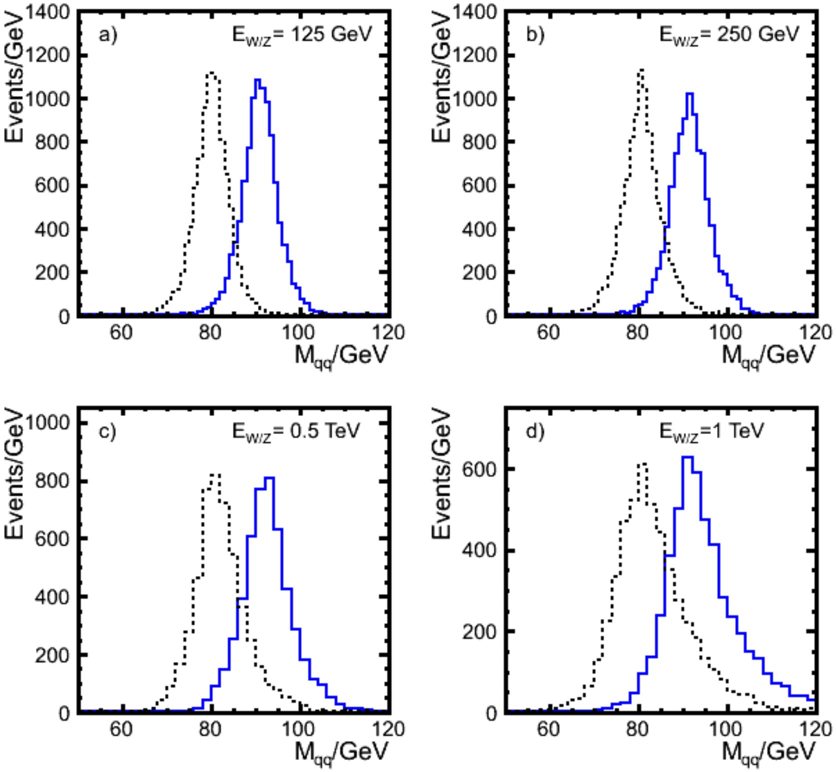
- ★ Meet "LC jet energy resolution goal [3.5%]" for 500 GeV ! jets
- ★ Importantly, PFA is still working for 500 GeV jets
  - ★ **Raw calo. energy : 5.2 %**
  - ★ **PandoraPFA : 3.5 %**

Looks promising…

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

Conclude:

- **Performance almost certainly good enough for 500 GeV W/Zs**
- **Would like better performance for 1 TeV W/Z**
- **Remember, PandoraPFA not tuned for very high energy jets…**

★ **(Perhaps surprisingly) PFlow calorimetry looks promising for CLIC**

❽ Summary/Conclusions

- ★ Over last two years our understanding of particle flow calorimetry has increased enormously NIM 611 (2009) 24-40
- ★ **ILC** detector concepts are now well established: **ILD** and **SiD**
  - ▪ particle flow calorimetry has major impact in determining overall detector design
  - ▪ meet the ILC detector goals
  - ▪ physics performance demonstrated using full simulation/reconstruction
- ★ **ILC** concepts are a good starting point for a possible **CLIC** detector
  - ▪ no obvious show-stoppers
  - ▪ particle flow calorimetry looks promising
- ★ However **CLIC** machine environment is much more challenging
  - ▪ time-stamping requirements at CLIC ???

Concluding remarks:

- ★ **Calorimetry is central to a future linear collider detector**
- ★ I hope that I have convinced you that it is an important and interesting subject…

Fin

Backup: Hadron shower simulation

- ★ Modelling of hadronic showers far from perfect, so:
  - Can we believe PFA results ?
  - Need a dedicated PFA test beam demonstration? [is this even possible?]
- ★ Have tried to address this by comparing **PandoraPFA/ILD** performance for 5 very different Geant4 physics lists…

Physics List	Jet Energy Resolution				
	45 GeV	100 GeV	180 GeV	250 GeV	
LCPhys	3.74 %	2.92 %	3.00 %	3.11 %	← Default
QGSP_BERT	3.52 %	2.95 %	2.98 %	3.25 %	
QGS_BIC	3.51 %	2.89 %	3.12 %	3.20 %	
FTFP_BERT	3.68 %	3.10 %	3.24 %	3.26 %	
LHEP	3.87 %	3.15 %	3.16 %	3.08 %	← ~GHEISHA
χ^2	23.3 / 4	17.8 / 4	16.0 / 4	6.3 / 4	
rms	4.2 %	3.9 %	3.5 %	2.5 %	

- ★ Only a weak dependence < 5 % (but need to connect to **CALICE** studies)
  - **NOTE:** 5 % is on the **total**, not just the **hadronic confusion term**

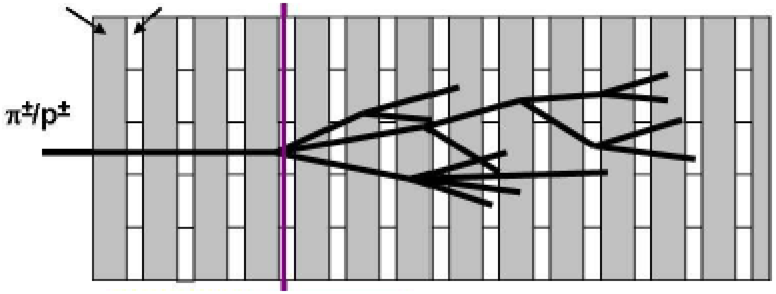
e.g.

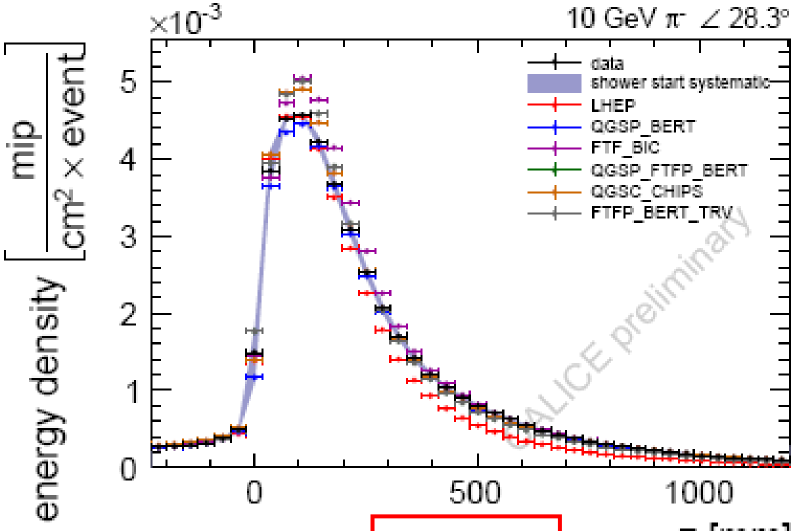
Total Resolution	3.11 %	×1.05 →	Total Resolution	3.27 %
Conf: neutral hads	1.80 %	×1.14 →	Conf: neutral hads	2.05 %
Other contributions	2.54 %	×1.00 →	Other contributions	2.54 %

Study suggests **Particle Flow** is rather robust to hadronic modelling

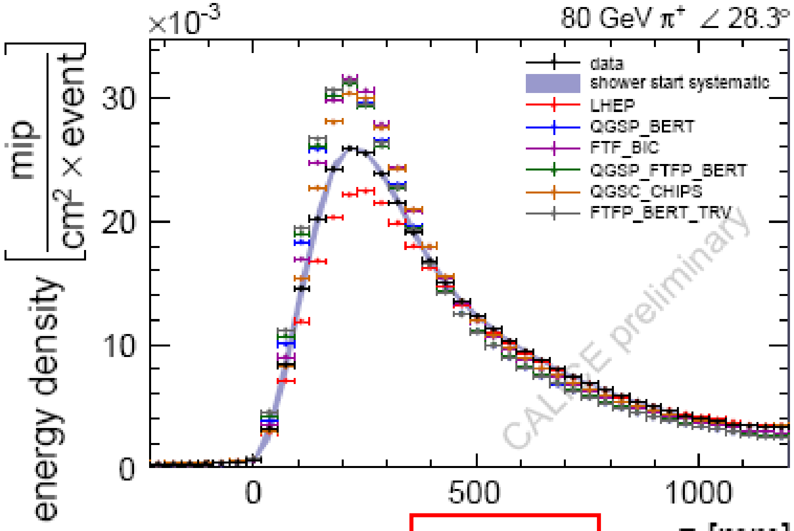
Backup: Hadron showers in CALICE

- In addition to technology demonstration, CALICE aims to study in detail hadronic shower development
- Studies in Scintillator HCAL already fairly advanced
  - compare to different hadronic shower models in GEANT4
  - e.g. longitudinal hadronic shower profile (from shower start)



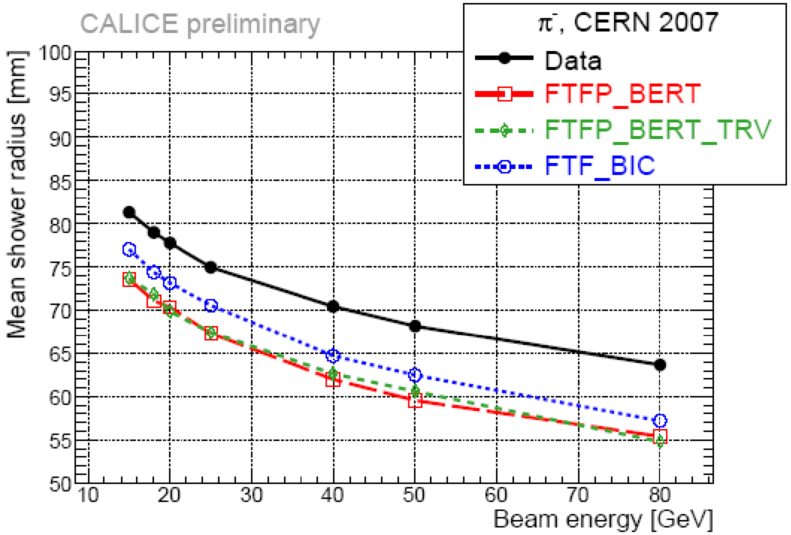


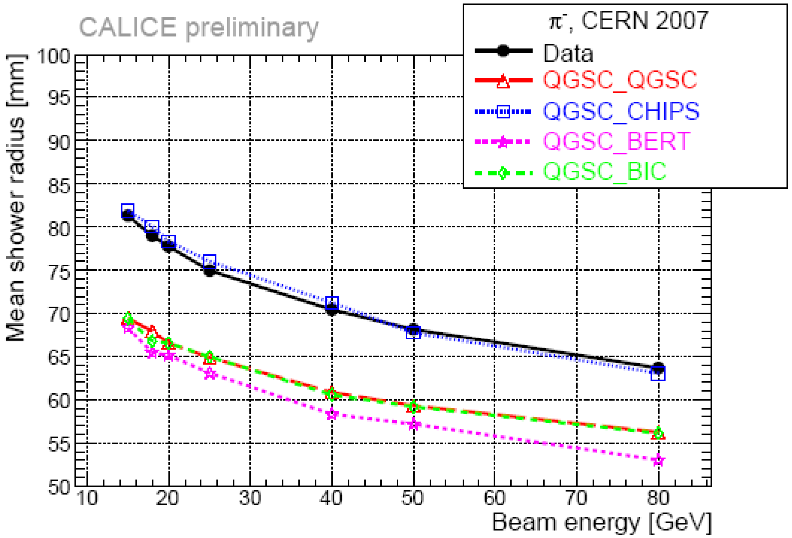
10 GeV

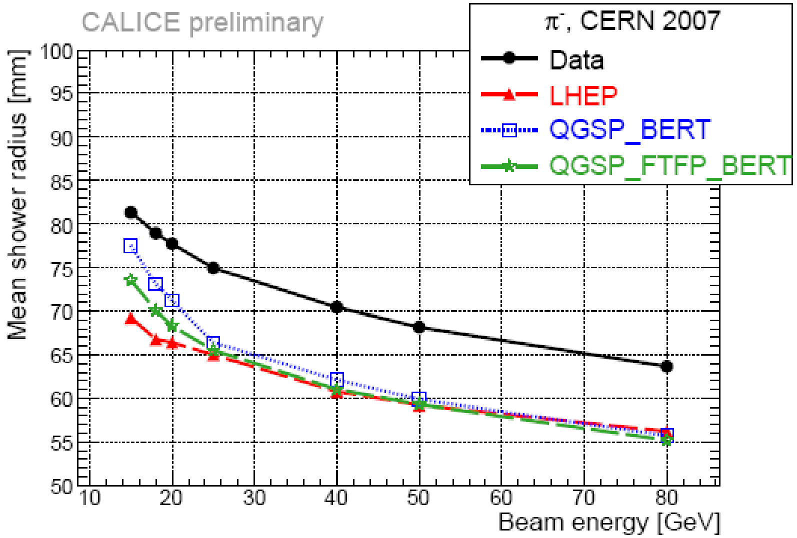


80 GeV

- e.g. **transverse hadronic shower profile**







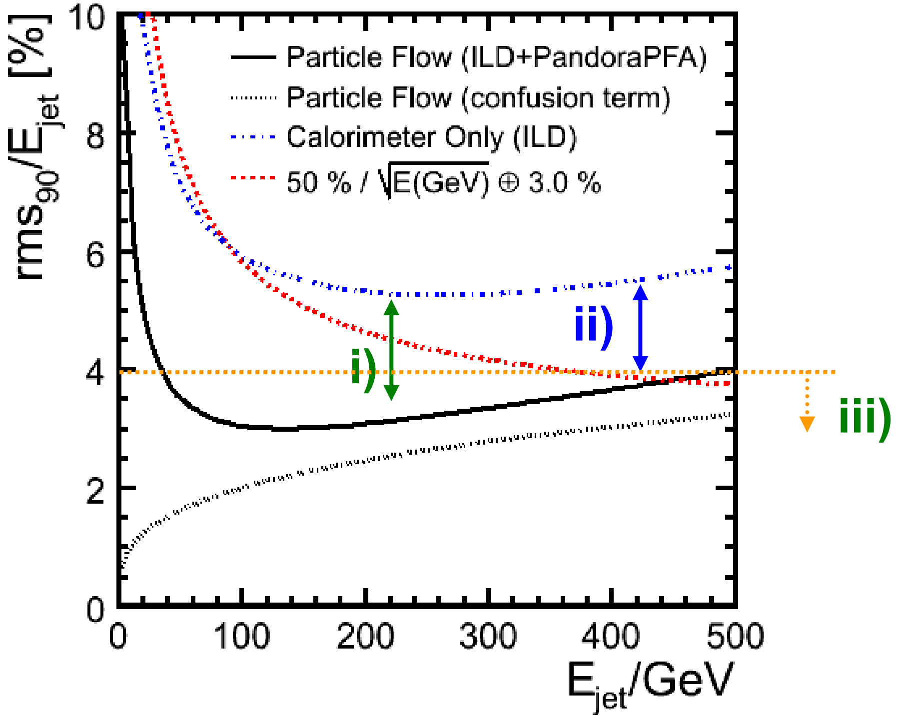
★ **No hadronic shower model gives perfect fit to longitudinal and transverse shower profiles**

★ **But, at this level of detail, differences are not huge**

★ **Finer detail PFlow-oriented studies are ongoing**

Backup: PFA vs Conventional Calorimetry

- ★ ILD/SiD intended for PFA, but also good conventional calorimeters
  - ♦ ECAL ~15%/√E; HCAL ~55%/√E
- ★ Interesting to compare PFA and pure energy sum with ILD



Comments:

i) PandoraPFA: PFA ALWAYS wins over purely calorimetric
  - ▪ adding information should not make things worse !

ii) PandoraPFA: effect of leakage clear at high energies

iii) PandoraPFA/ILD: Resolution better than 4 % for E_{JET} < 500 GeV