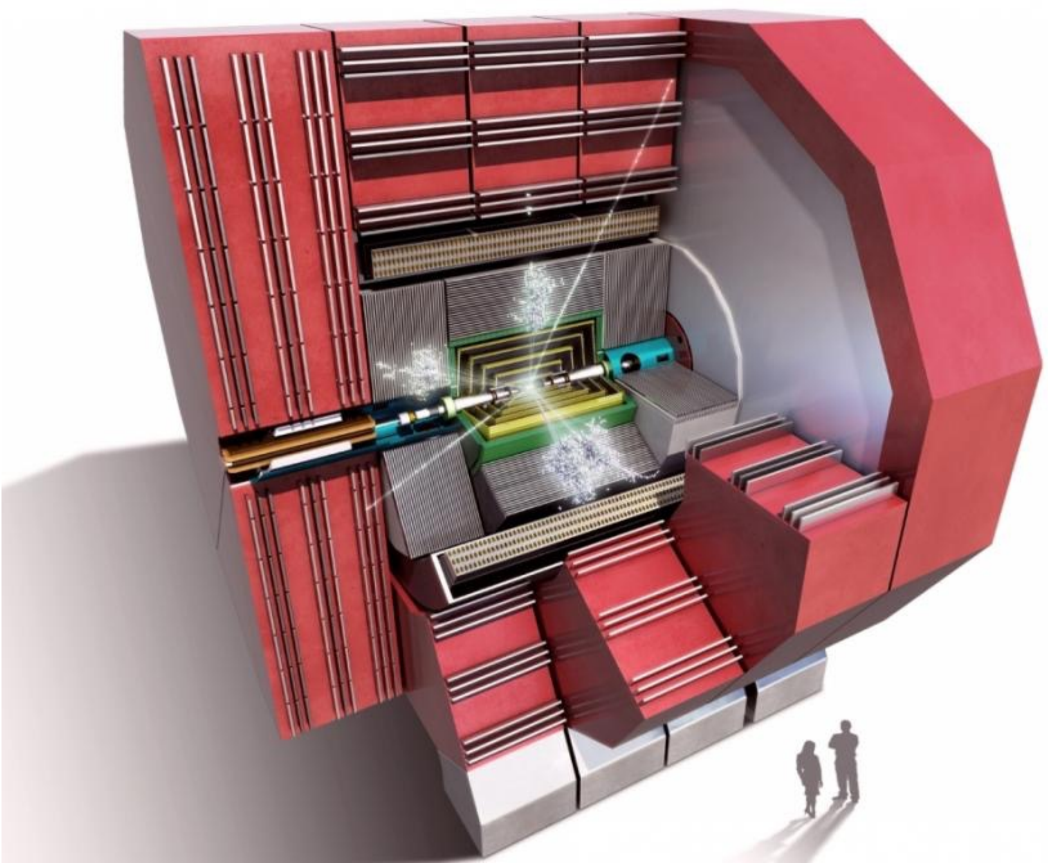
Towards a new CLIC detector model



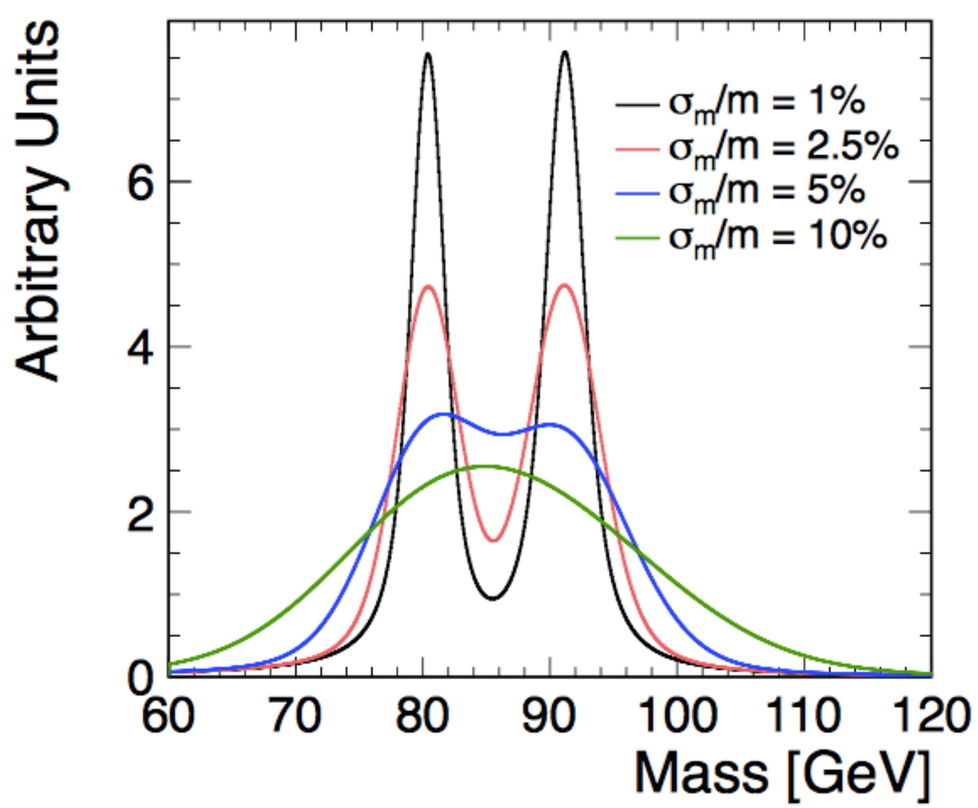
J. S. Marshall, University of Cambridge
on behalf of the CLICdp collaboration

CLIC Workshop, 30 January 2015

Detector Requirements

From the perspective of the likely physics measurements at CLIC, the requirements are:

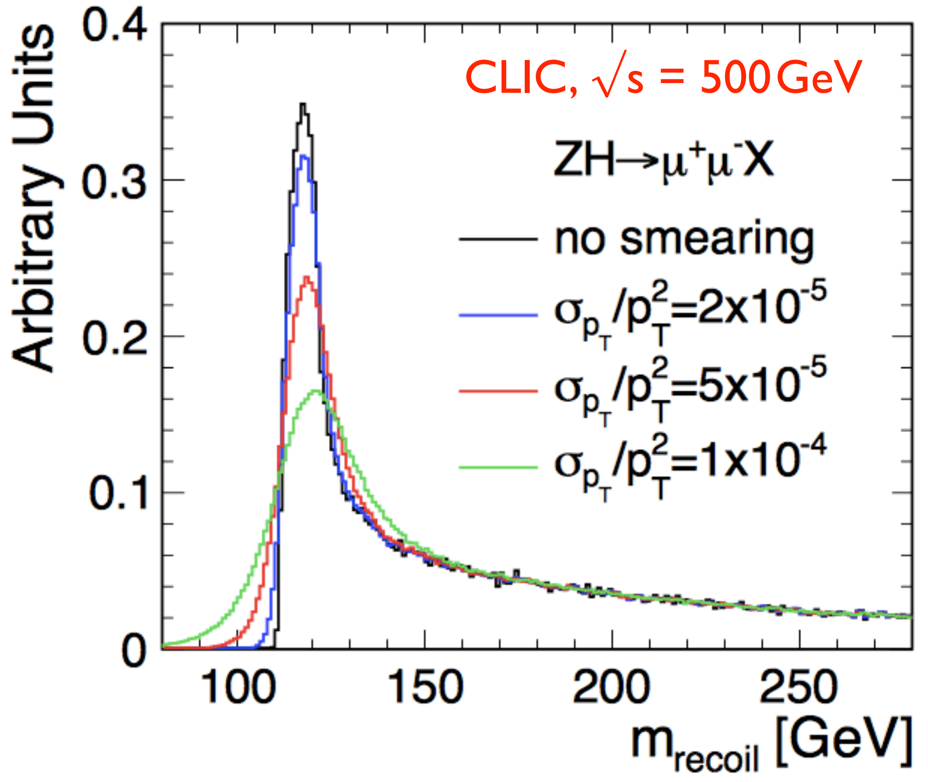
- **Jet energy resolution $\sigma_E/E \lesssim 3.5-5\%$ for jet energies in the range 50 GeV − 1 TeV**
- **Track momentum resolution $\sigma_{p_T}/p_T^2 \lesssim 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$**
- **Impact parameter resolution $\sigma_{d_0} \lesssim 5 \oplus 15\ /\ (p[\mathrm{GeV}]\ \sin^{3/2}\theta)\ \mu\mathrm{m}$**
- **Lepton identification efficiency > 95% over full range of energies**
- **Detector coverage for electrons down to very low angles**



- **Expect interesting physics processes to have multi-jet final states, with charged leptons or missing p_T**
  - Reconstruction of invariant masses of two+ jets important for event reconstruction and event id.
  - Impact of Beamstrahlung on kinematic fits means rely on intrinsic jet energy resolution of detector.
- **Aim:** discriminate between W and Z hadronic decays
- **Require:** $\sigma_E/E \lesssim 3.5\%$, providing 2.5σ W/Z separation

Detector Requirements

- **Track momentum goal motivated by Higgs mass determination via Higgsstrahlung process, $e^+e^- \rightarrow Zh$**
  - Reconstruct mass of system recoiling against pair of muons from $Z \rightarrow \mu^+\mu^-$ decays.



- **Aim:** width of reconstructed Higgs mass peak dominated by beam energy spread
- **Require:** $\sigma_{p_T} / p_T^2 \lesssim 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$

- **Tagging of charm and bottom quarks important for studies including measurements of Higgs couplings. Relies on impact parameter resolution and secondary vertex id:**

$$\sigma_{d_0} = a \oplus b / (p \sin^{3/2}\theta)$$

Point resolution of vertex detector

Multiple scattering; amount of material in inner detector

- **Aim:** Efficient heavy flavour tagging
- **Require:** $a \lesssim 5\,\mu\mathrm{m}$ and $b \lesssim 15\,\mu\mathrm{m\,GeV}$

- Efficient lepton id across wide range of momenta crucial for CLIC physics analyses. Electron id must extend to very small angles (due to *t*-channel processes or boost from Beamstrahlung).

Particle Flow Calorimetry

Jet energy resolution requirements led to adoption of particle flow calorimetry

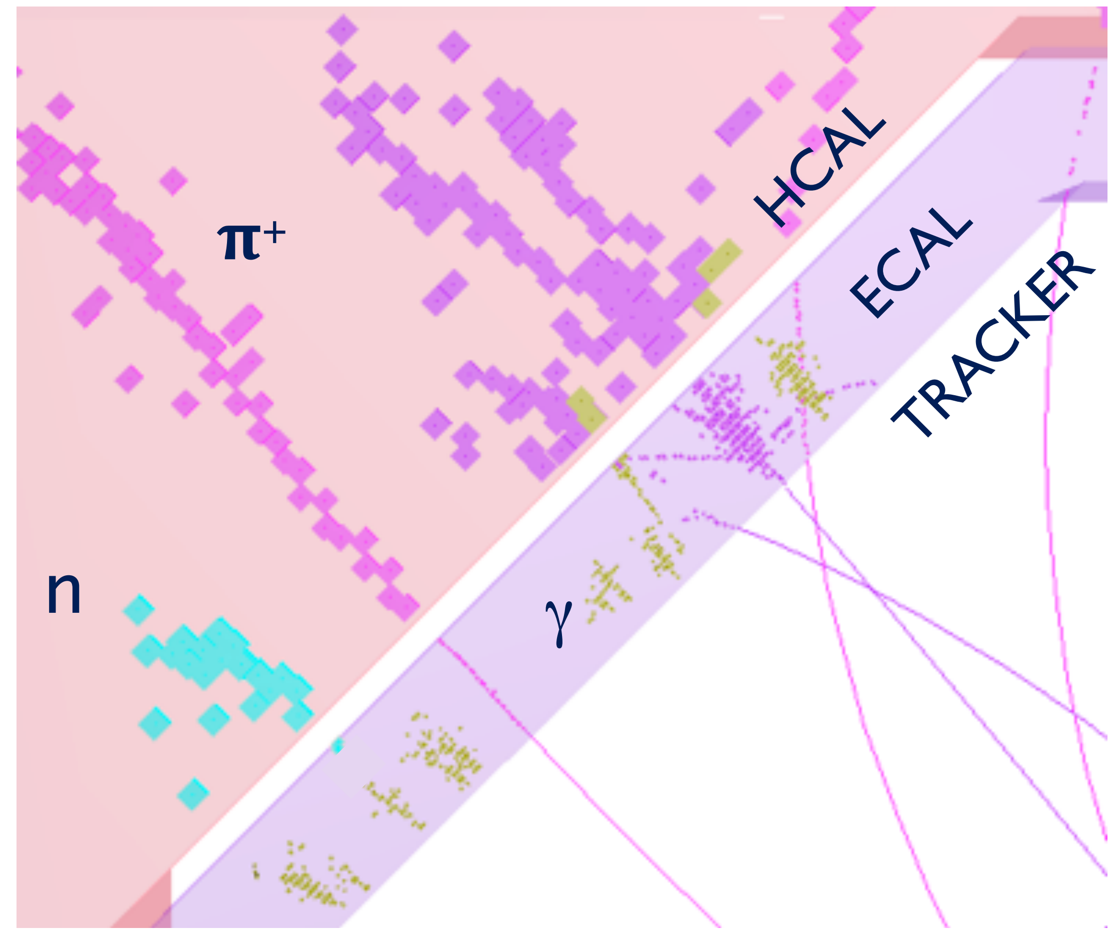
Significant impact for detector design

Typical jet composition:
- 60% charged particles
- 30% photons
- 10% long-lived neutral hadrons

Traditional calorimetry:
- Measure all energy in ECAL/HCAL
- 70% of jet energy measured in HCAL

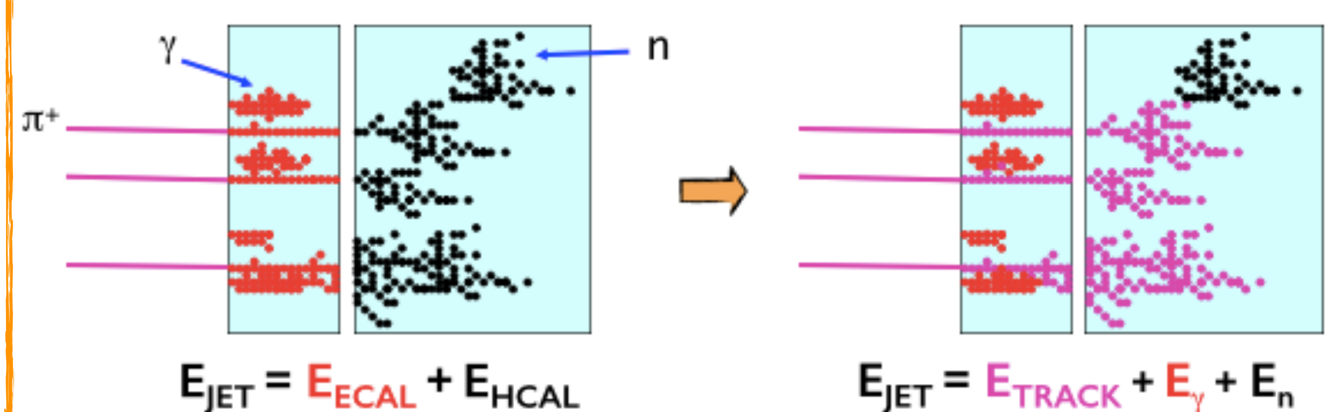
Particle Flow Calorimetry:
- Charged particle momentum: **Tracker**
- Photon energies: **ECAL**
- Only neutral hadron energies: **HCAL**

Particle Flow requires pattern recognition
- **High-granularity calorimeters**
- **Sophisticated software algorithms**



Traditional calorimetry

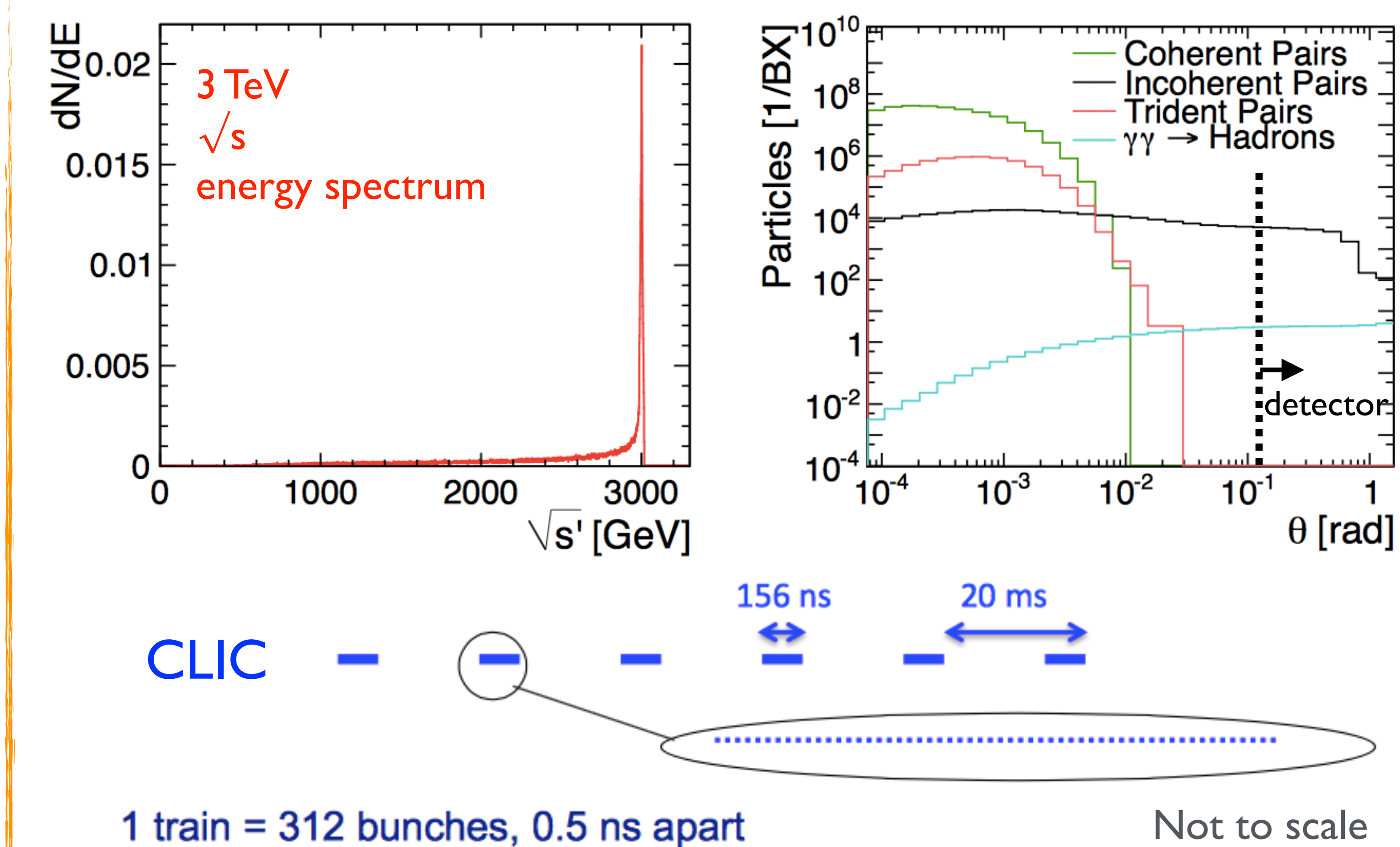
Particle flow calorimetry



CLIC Experimental Conditions

The experimental environment at CLIC will differ from that at LEP or the proposed ILC:

- **Small beam size at IP leads to Beamstrahlung.**
- **Beam related backgrounds:**
  - e^+e^- pairs, mostly low p_T
  - $\gamma\gamma \rightarrow$ hadrons, low E, $p_T \lesssim 5$ GeV
  - Beam halo muons
- **Bunch train structure drives detector timing requirements.**

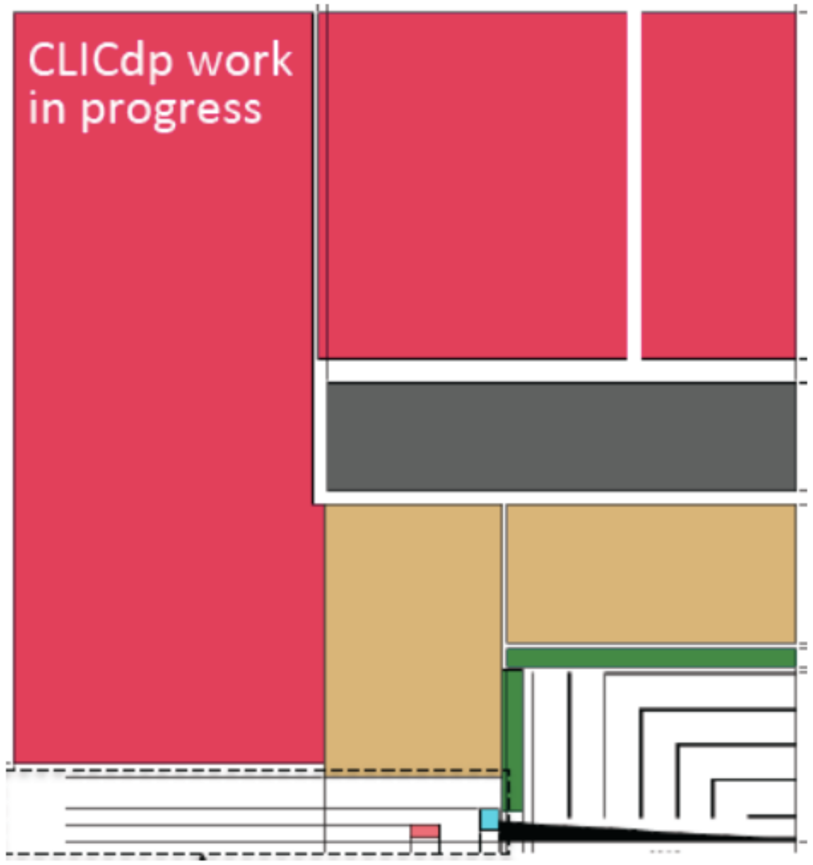


Significant beam-related backgrounds + detector integrates over multiple bunch crossings:

- High tracker occupancies ⇒ small cell sizes (beyond what is needed for spatial resolution)
- Background suppression ⇒ high-granularity calorimetry (particle flow approach advantageous)
- Background suppression ⇒ precise hit timing (10ns time-stamping in tracking, 1ns for calo hits).

CLIC Detector Concept

- **For CLIC CDR, developed two detector concepts:**
  - Starting point: validated ILC concepts **ILD** and **SiD**
  - **ILD:** TPC tracker; **SiD:** smaller Si tracker, larger B-Field
  - Optimised and adapted to CLIC conditions
  - Timing, VTX inner radius, HCAL absorber, HCAL λ_I, …
- **Now moving towards a single CLIC detector concept:**
  - Include lessons learnt so far
  - Include experience from hardware R&D
  - Some element of cost optimisation



Agreed working hypotheses

Vertex: Si double layers with spiral geometry
Tracker: all silicon, radius 1.5m, half-length 2.3m
ECAL: 25 layers, 5x5mm^2 cell sizes
HCAL: Fe absorber layers
B-Field: 4 T

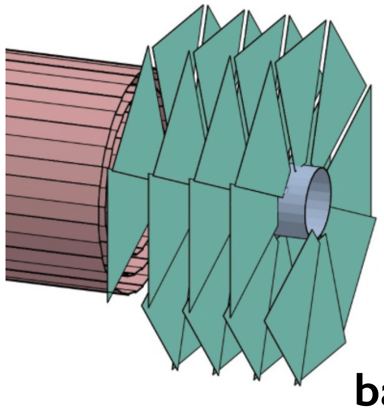
Ongoing assessments

Tracker: layout and technology options
HCAL: number of layers, cell sizes
Forward region optimisation
…

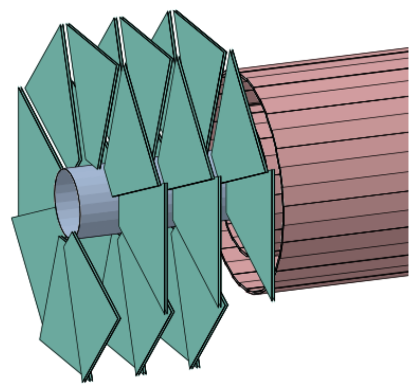
Vertex Detector Optimisation

Have settled on key parameters for vertex geometry:

- **Double layers:** as in CLIC_ILD, no adverse performance impact, benefits for support structure.
- **Spiral geometry** of endcap disks: allows for airflow into barrel, only small performance impact.
- **Inner radius:** similar to CLIC_ILD, dictated by background rates and so by the chosen B-field.
- **Material budget:** ~0.2%X_0 per layer, realistic and in line with hardware studies and CDR goal.
- **Pixel size** 25 μm and **single-point resolution** 3 μm, as in CDR.

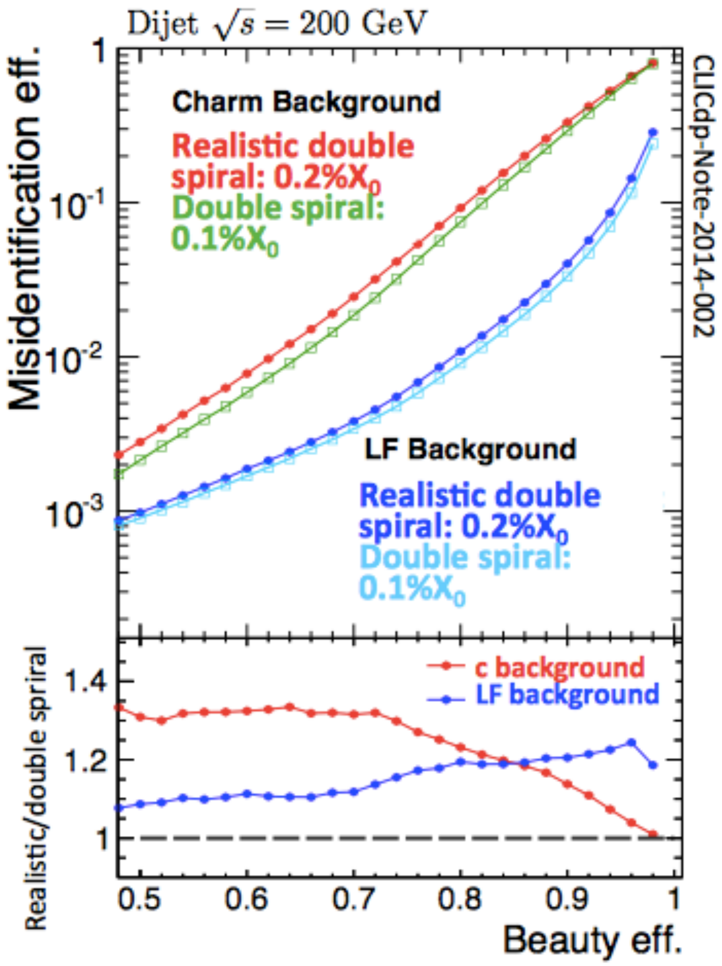


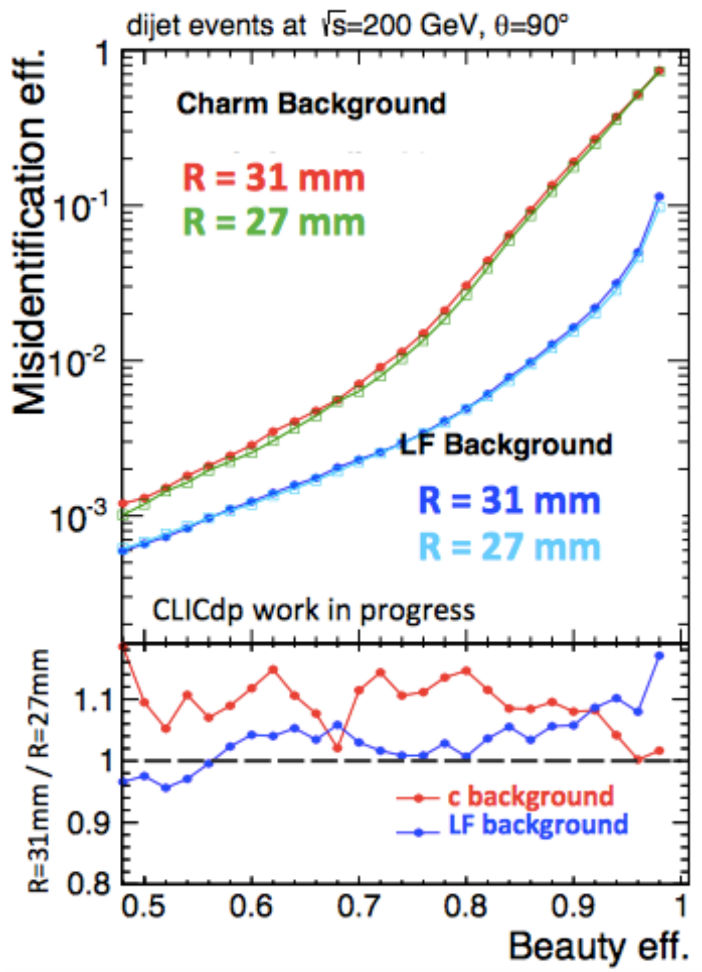
Spiral disks, 5 single layers in barrel, 4 in endcap



Spiral disks, 3 double layers in barrel and endcap

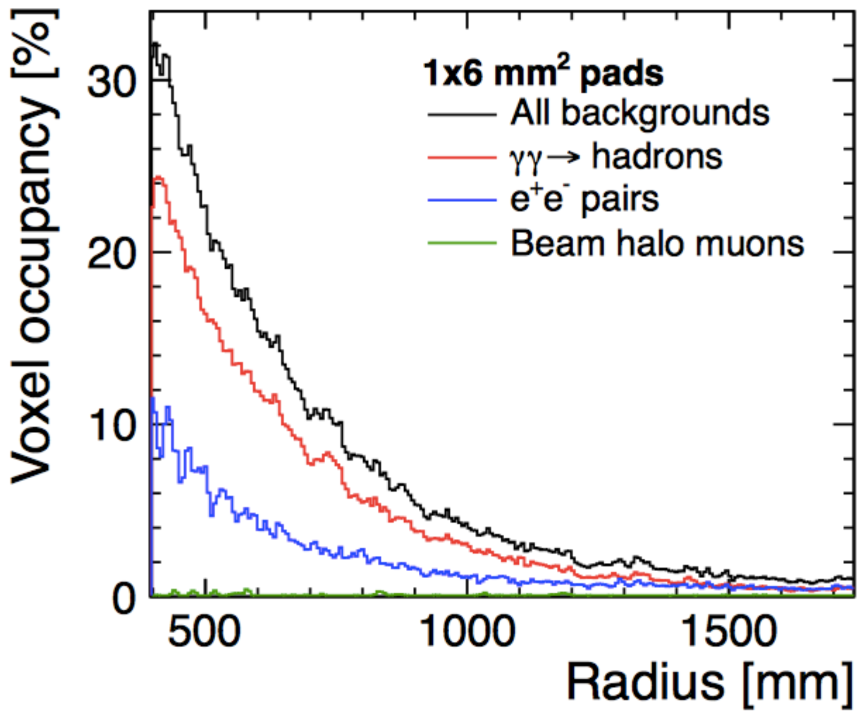
Heavy quark tagging used as performance metric

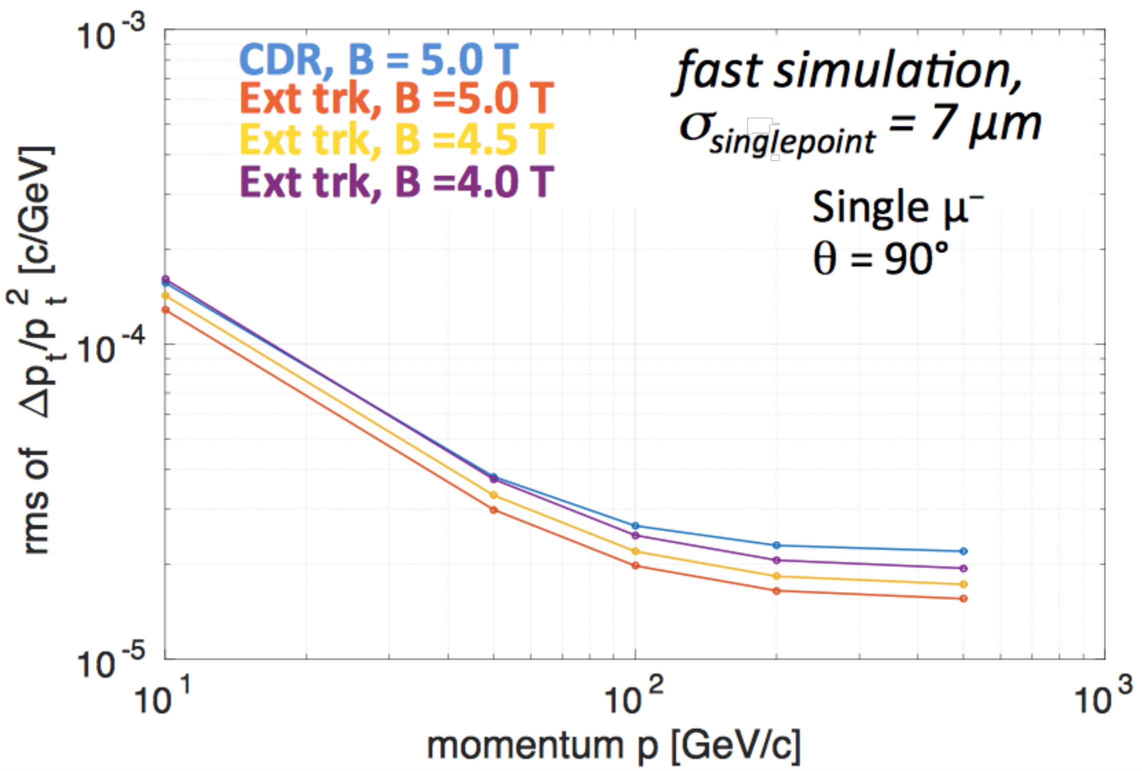




Main Tracker Optimisation

- **Studies for CLIC CDR directly addressed issue of tracker occupancies.**
- As readout time of TPC is much longer than CLIC bunch train, TPC integrates background of full train.
- Studies using default pad sizes showed inner pad rows with high total occupancy of up to 30%.
- **Immediately motivated decision to move away from a TPC and towards an all-silicon tracker.**



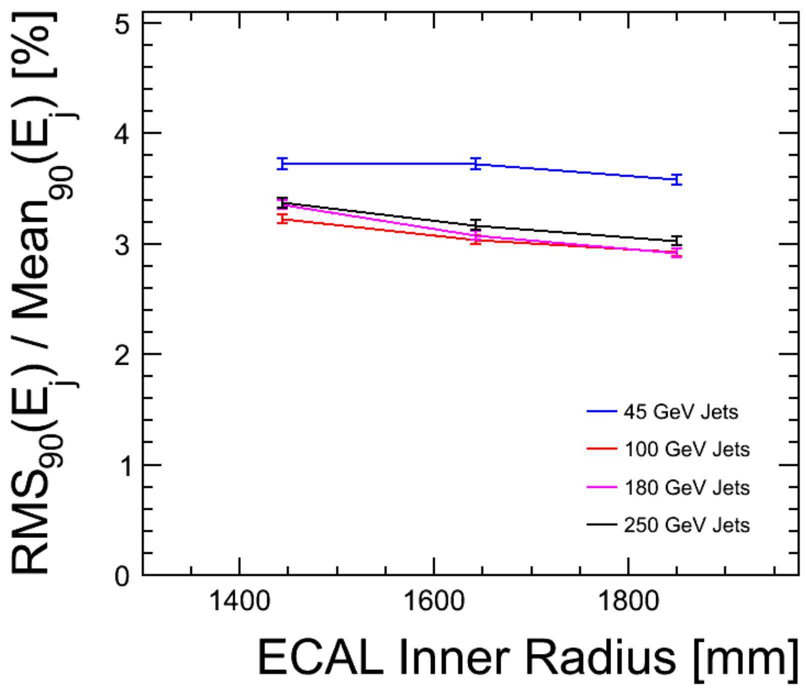


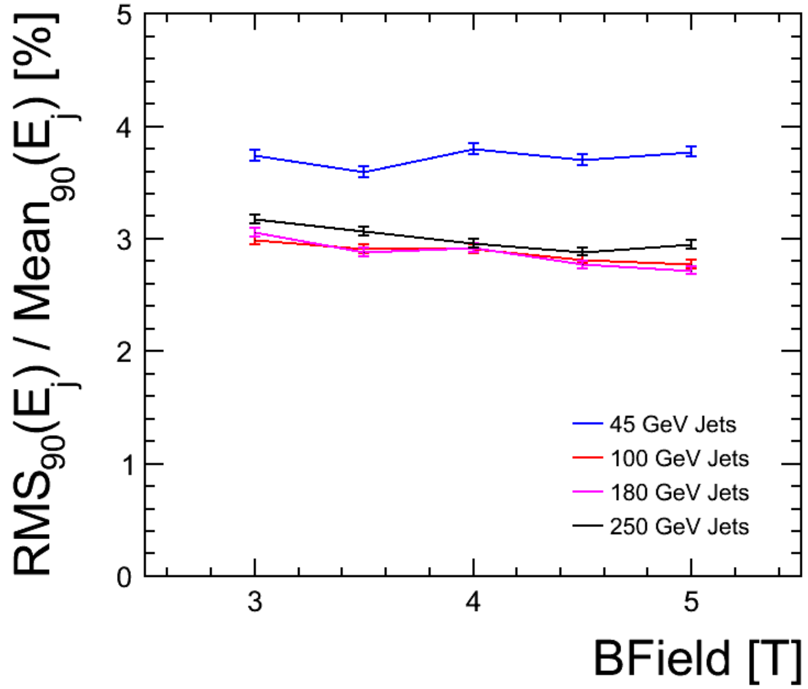
- **Larger tracker has advantages:**

$$\frac{\sigma(p_T)}{p_T^2} \propto \frac{1}{BR^2}$$

- Increase tracker radius (c.f. CLIC_SiD), **R=1.5m**
- Increase length (add disks), half-length **L=2.3m**
- Choose **B=4T** - performance still at least as good as CLIC_SiD, due to extended tracker.

Main Tracker Optimisation

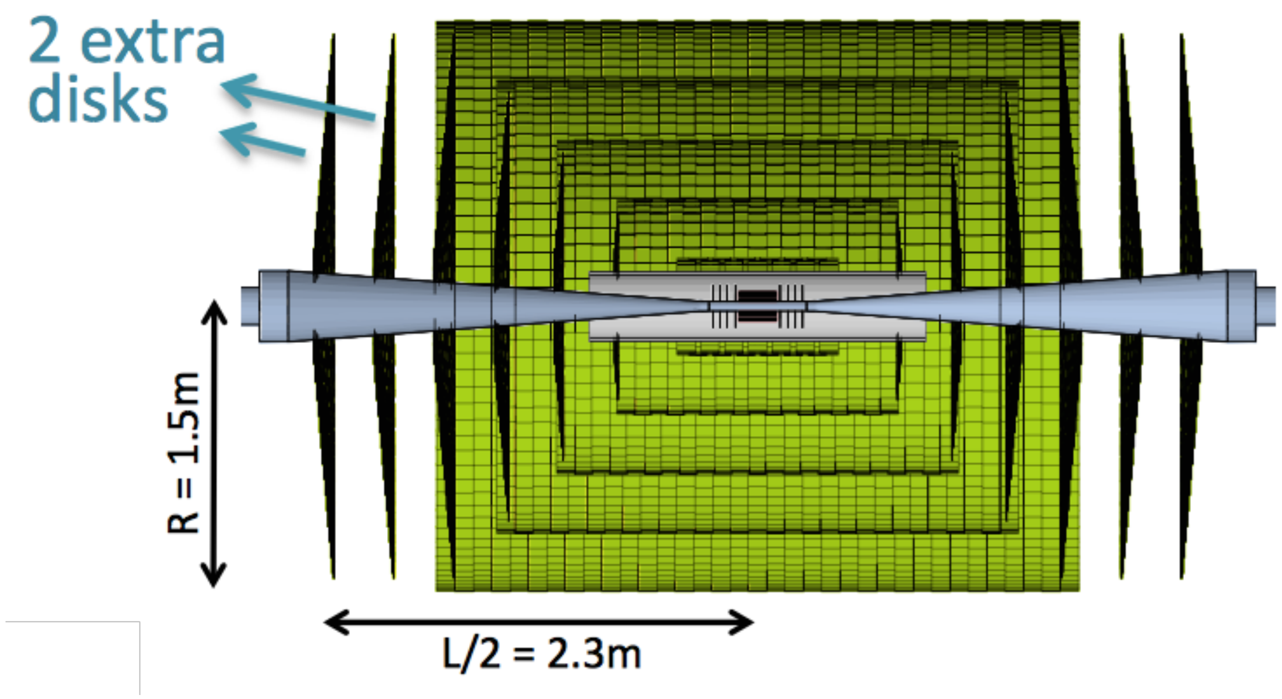




Jet energy resolutions indicate impact on PFA:

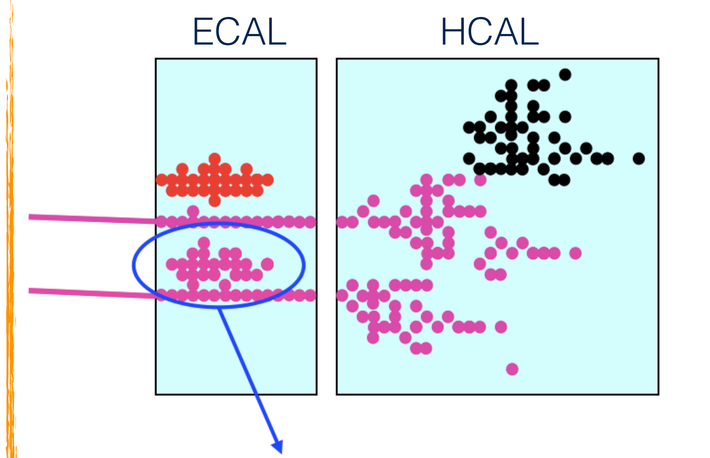
- Larger R increases particle separation in calorimeter.
- Larger B increases charged/ neutral particle separation.
- See **slight** improvement with B and R for high E jets.

- **Determination of the precise tracker layout is work in progress.**
- Ongoing development of simulation and reconstruction software.
- Studies underway to consider optimisation in terms of tracker occupancy.
- Input from hardware side required: **CLIC tracker technology working group.**

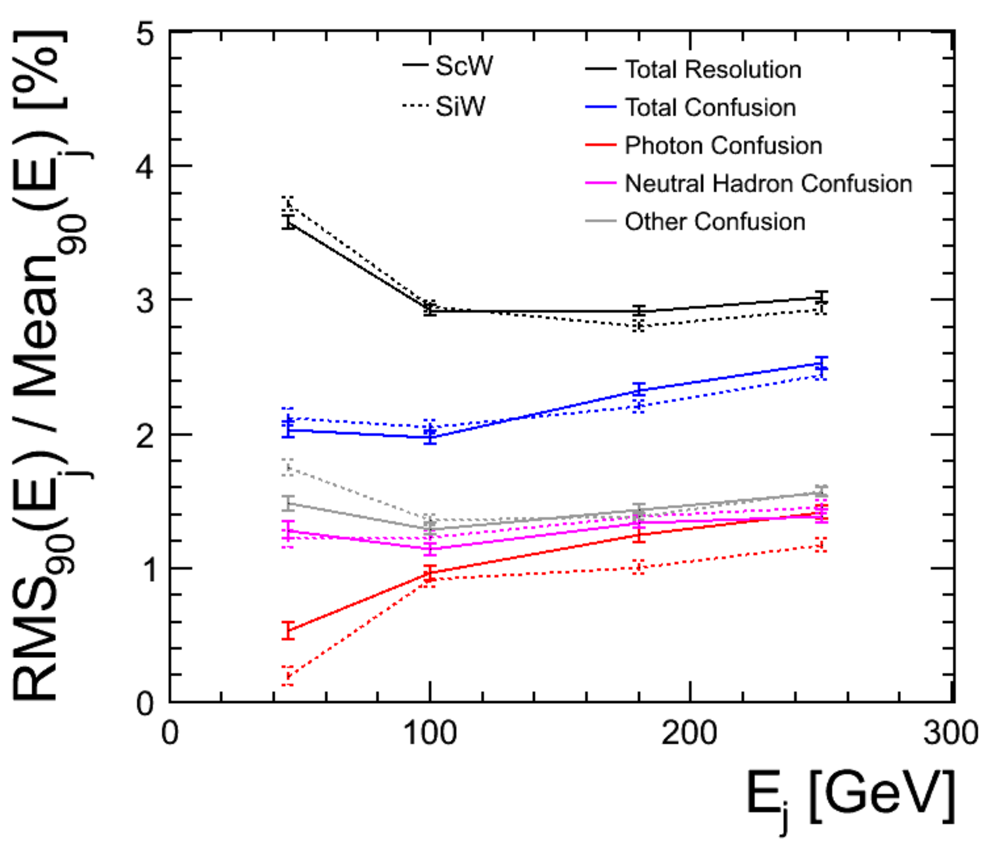


ECAL Optimisation

- **Starting point: 29 layers W absorber ($23X_0, 1\lambda_I$), 30 layers Si active medium (1 pre-sampler), divided into 5x5mm^2 pixels.**
- Particle flow means performance depends critically on pattern-recognition, not just intrinsic ECAL energy resolution.
- Granularity requirements and use of Si make ECAL expensive: consider scintillator (Sc) with SiPM readout as active medium.
- Examined wide range of ECAL models, developing detailed understanding of resulting **jet energy resolutions.**



Failure to separate photons from nearby charged hadrons: **"photon confusion"**



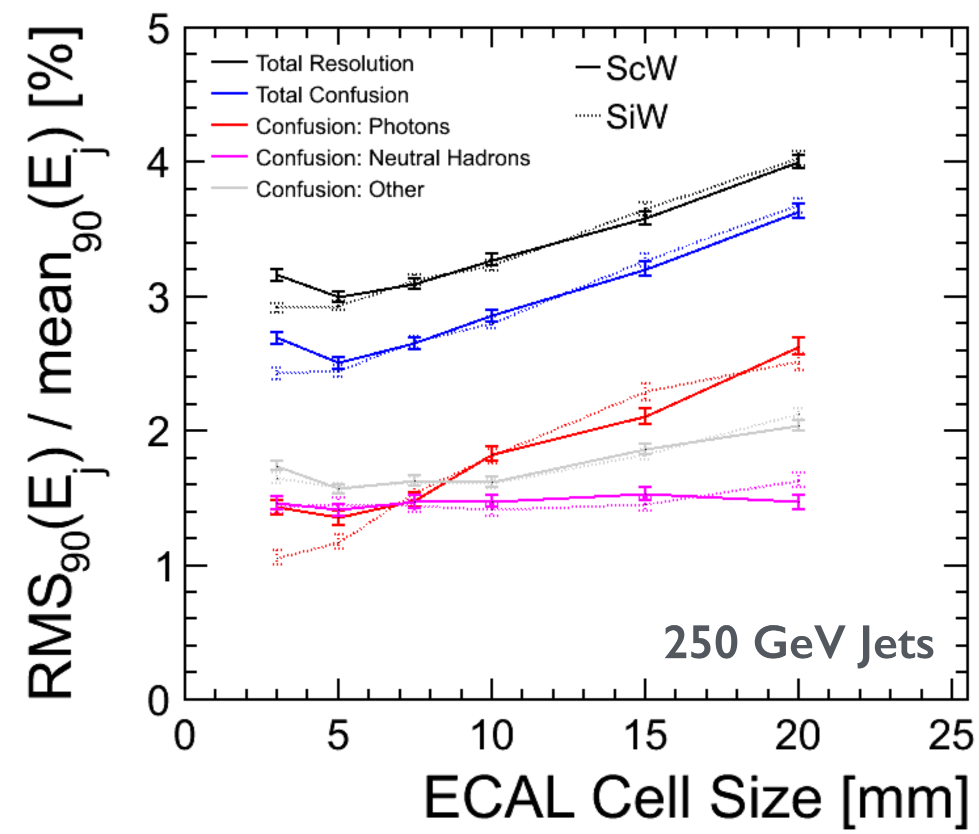
Jet energy resolution:

Total resolution

Total confusion

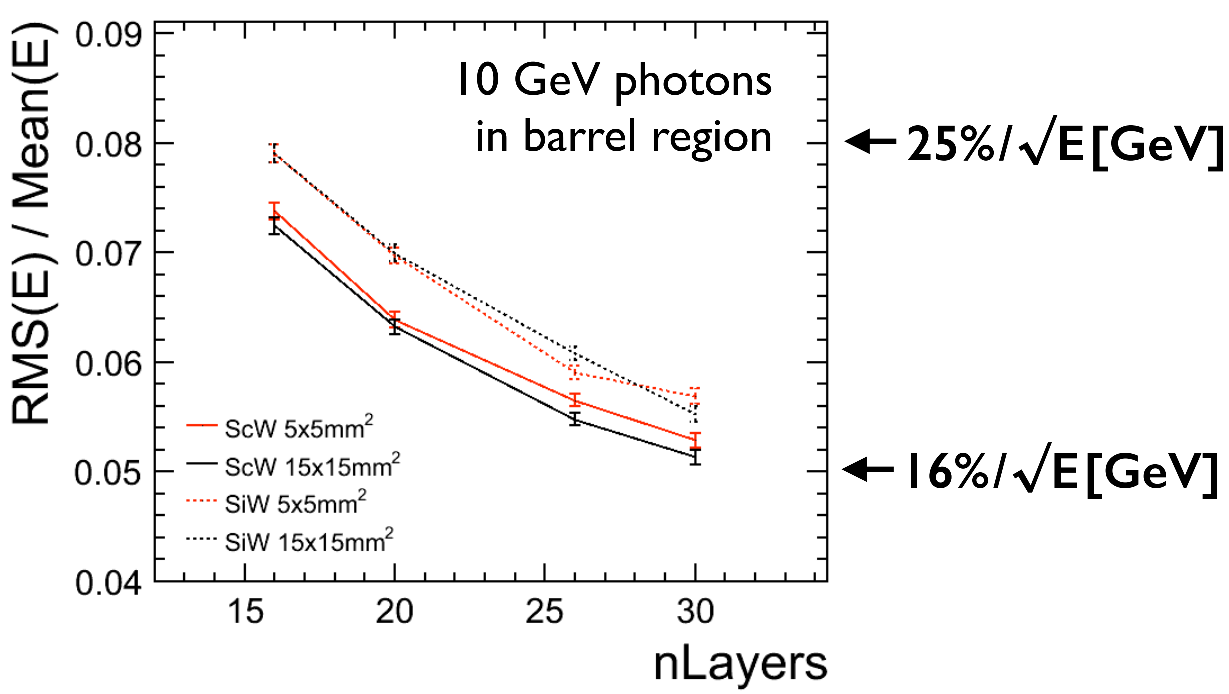
Photon **Other**

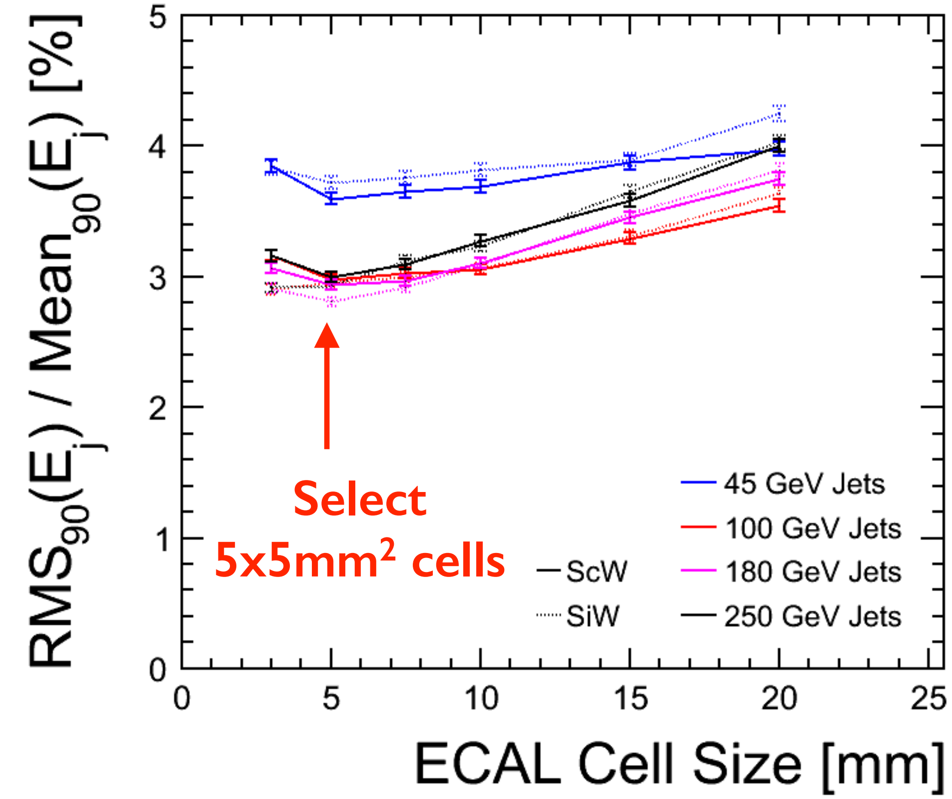
Neutral hadron

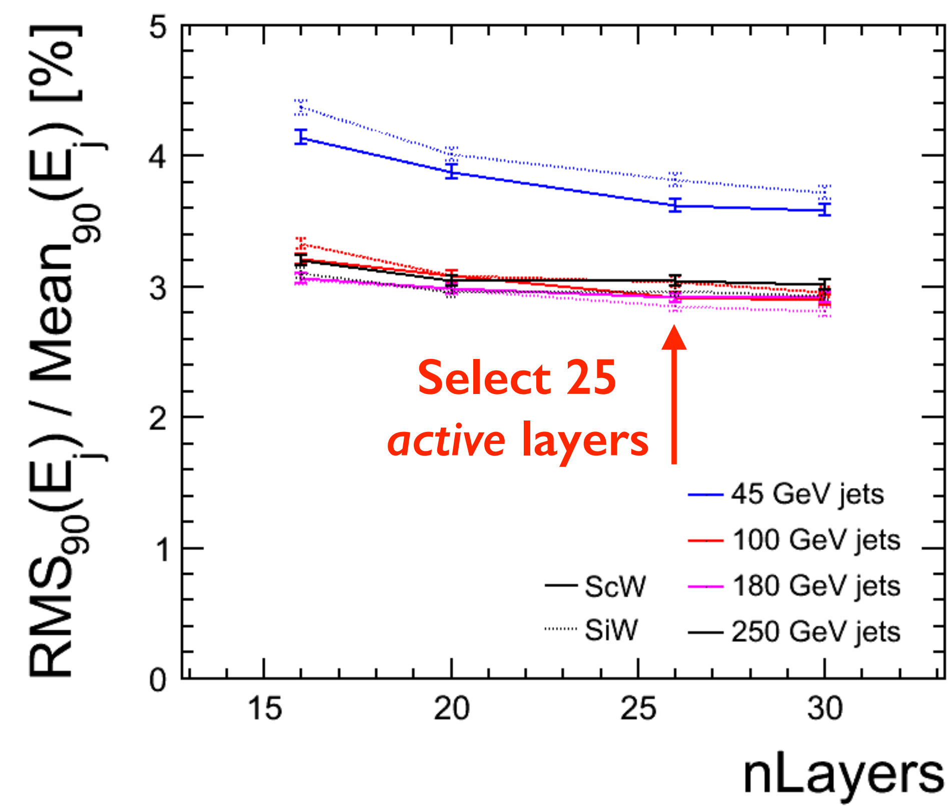


ECAL Optimisation

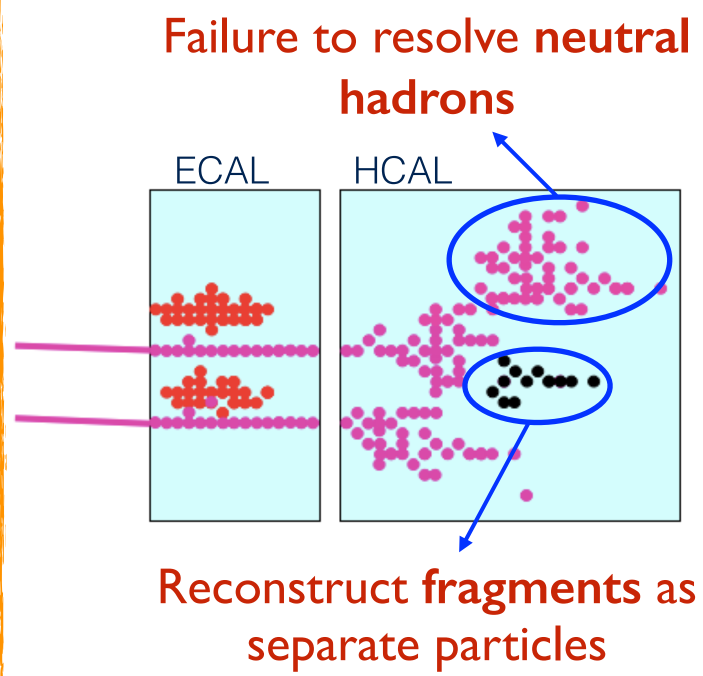
- Sc (2mm thick; Si 0.5mm) offers better intrinsic E resolution. Side-mounted MPPC affects performance for small Sc cells.
- With same size cells, SiW and ScW yield similar performance. Cost arguments not yet conclusive, so **stick with Si.**
- **Performance vs. nLayers:** very flat, change mostly due to varying intrinsic E-resolution.
- **Performance vs. ECAL cell size:** intuitive and driven by photon confusion.

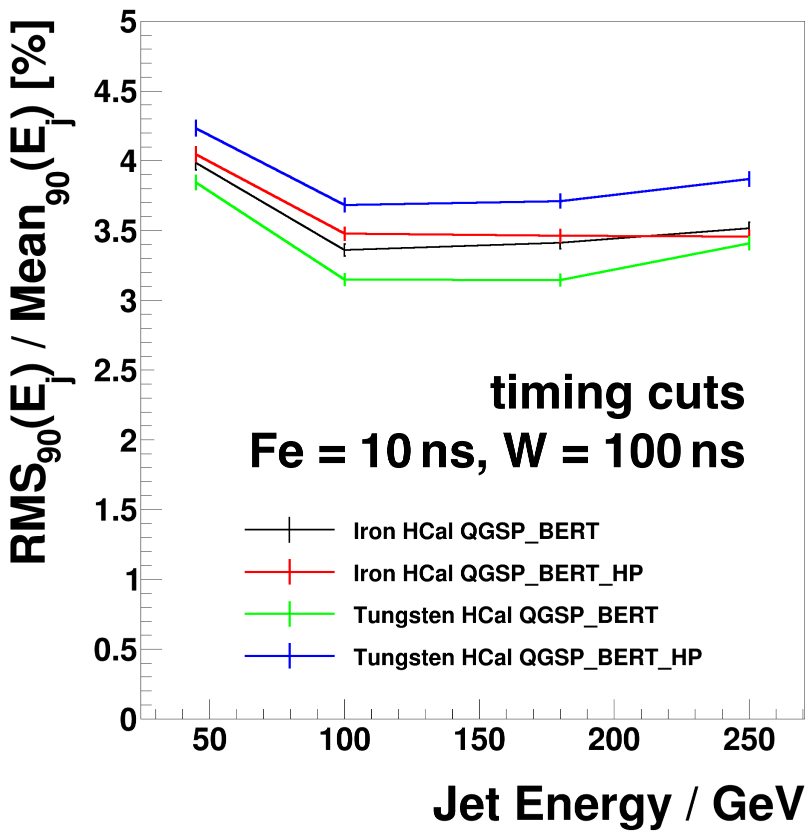


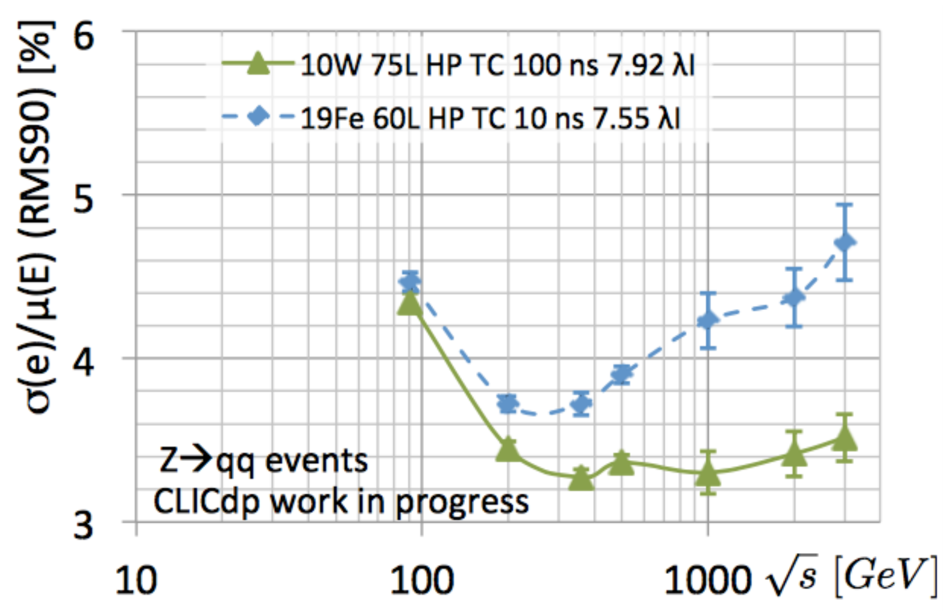




- **Starting point: barrel 75 W layers, endcap 60 Fe layers ($7.5\lambda_I$), scintillator active layers divided into $3\text{x}3\text{cm}^2$ cells.**
- Transverse and longitudinal granularity needed to resolve neutral hadrons and minimise creation of fake fragment particles.
- Some uncertainty with cell digitisation and ensuring use of optimal hadronic energy estimator for each detector model.
- Must use appropriate readout time windows. Careful calibration required, with consideration of software compensation.



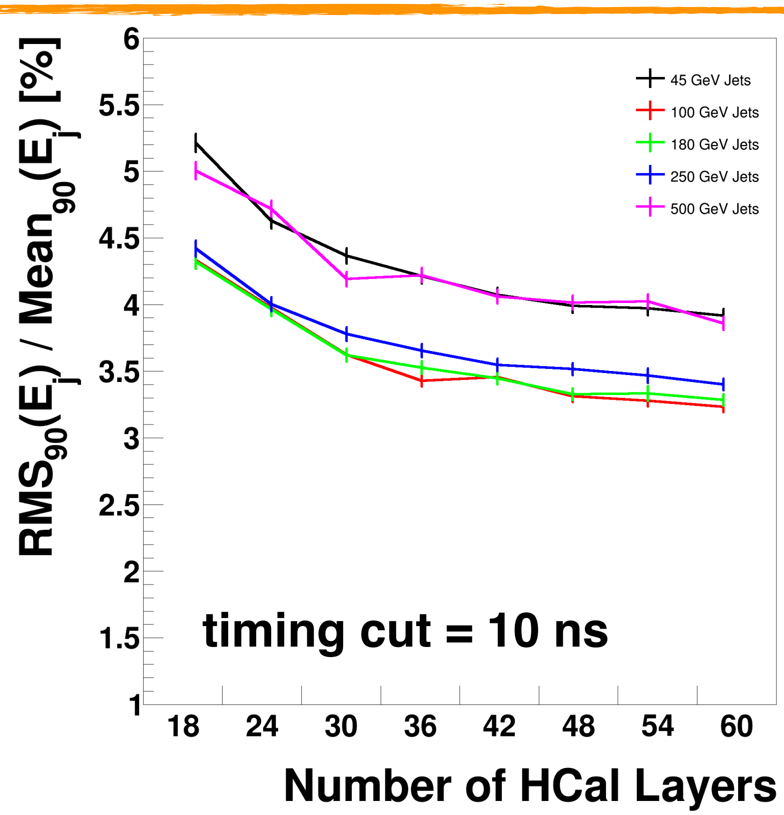


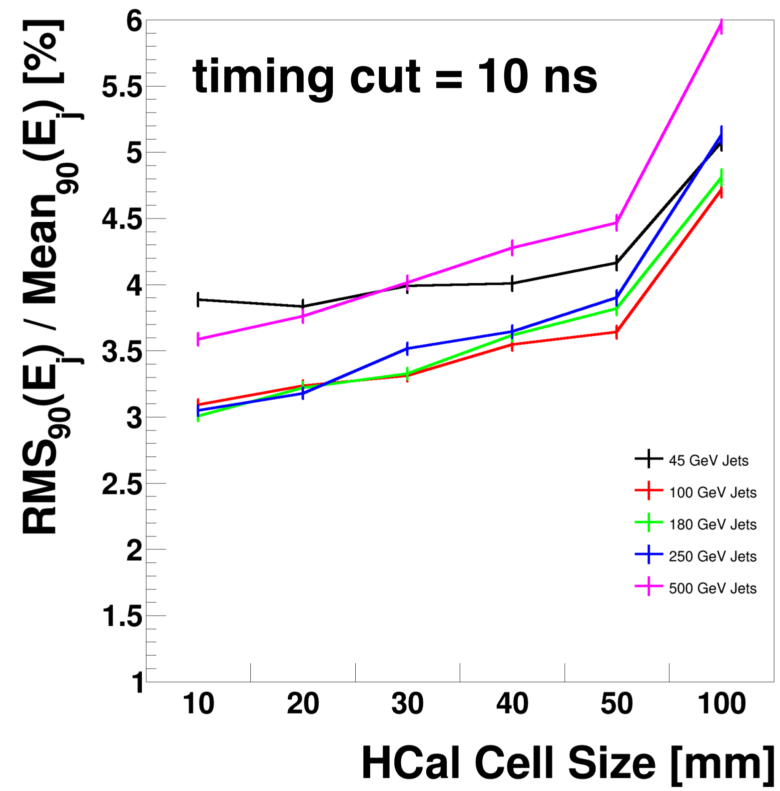


- **Use Fe absorber:** cheaper, easier, similar performance
- Some questions remain: **parallel studies ongoing**

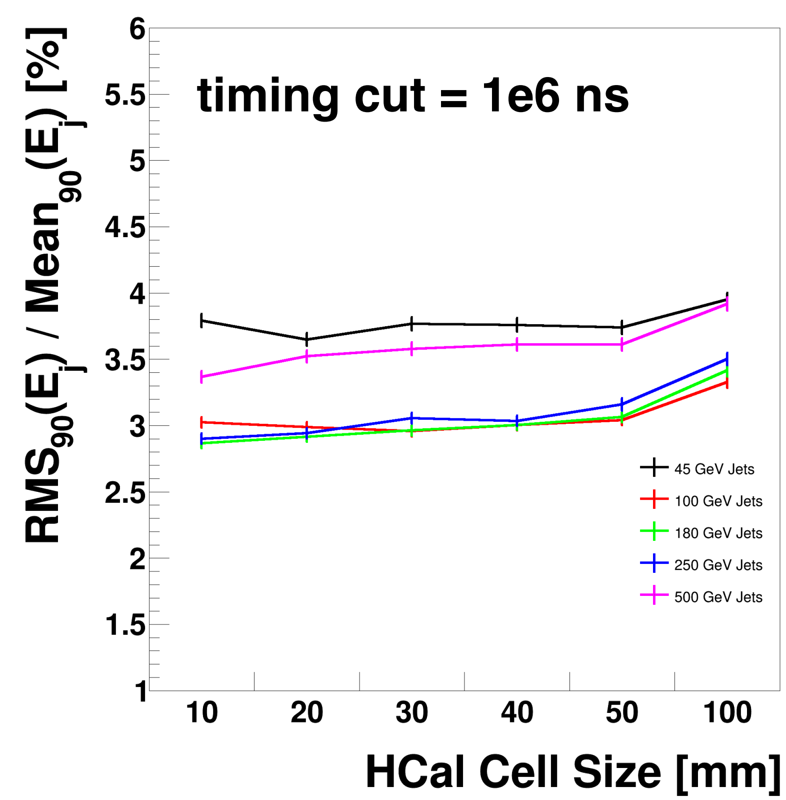
HCAL Optimisation

- **Performance vs. nLayers:** not too steep; should be able to use fewer active layers.
- **Performance vs. cell size:** trends clear, but concern about the impact of timing cuts.
- **Studies ongoing to better understand:**
  - impact of **timing cuts** on the pattern recognition and intrinsic E-resolution.
  - **confusion terms** associated with creation of fake neutral hadron particles.





Relax timing cuts in cell digitisation

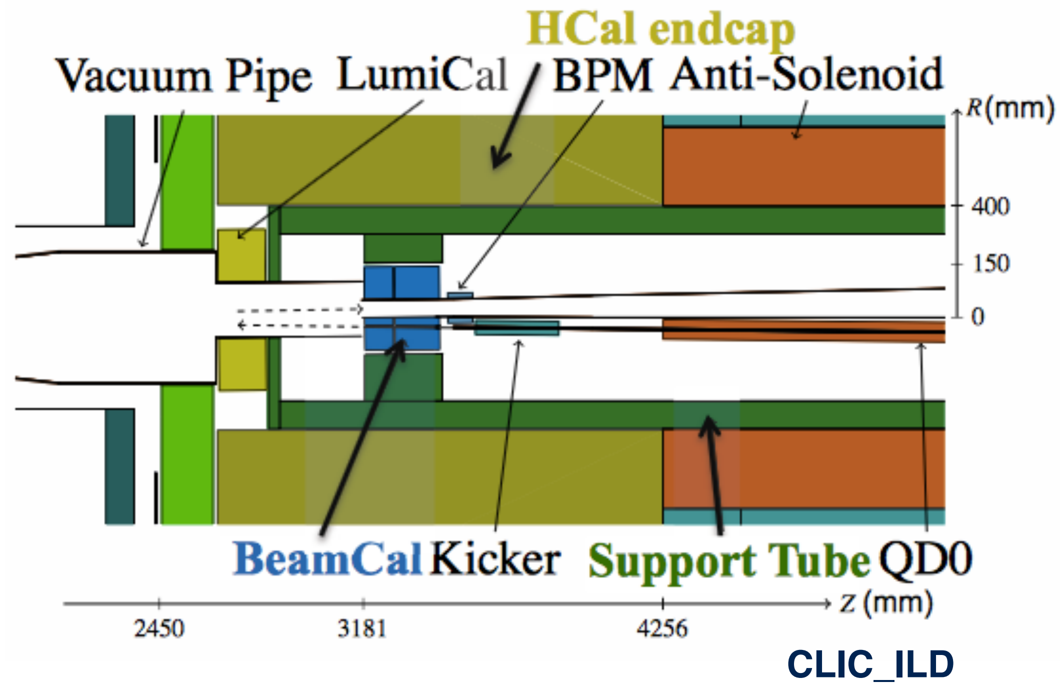


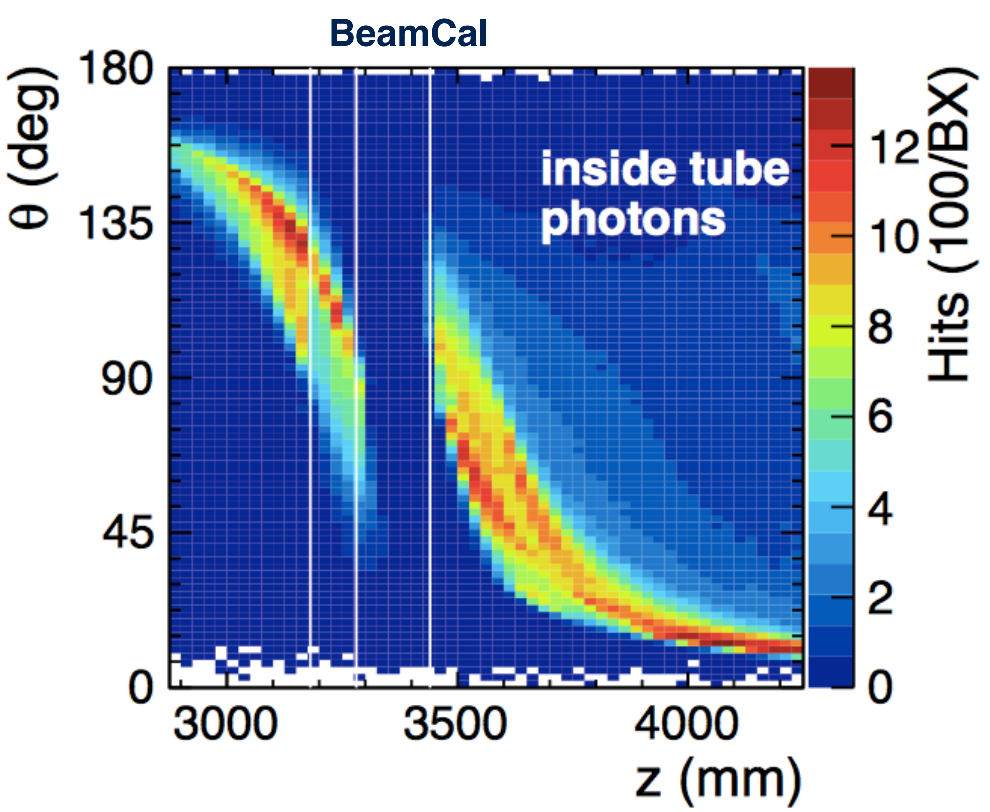
Forward Region Optimisation

- **Study benefits of increased HCAL endcap coverage,** including impact of $\gamma\gamma \rightarrow$hadron pile-up.
- Examine jet energy resolutions to find coverage beyond which backgrounds mean no further gain.

- **Incoherent pairs shower in BeamCal,** creating secondary particles that pass through support tube into HCAL endcap.
- Proposal: PE-W support tube (performance vs. engineering compromise), and possible reduction of cell size (<30x30mm^2) in high-occupancy region.

- **Ongoing discussion:** is there space (from detector point of view) for final focusing quadrupoles?
- Depends on gains from increasing HCAL coverage and how much shielding is required.
- Option under study: make Fe endcap yokes thinner.





Summary

Aim to finalise new CLIC detector model by mid 2015:

will be used for the next round of physics sensitivity studies

- **Current status of key detector parameters:**

  Vertex: Si double layers with spiral geometry

  Tracker: full Si, R=1.5m, L/2=2.3m

  ECAL: 25 active layers, 5x5mm^2 cell sizes

  HCAL: Fe absorber layers

  B-Field: 4 T

- **Ongoing assessments:**

  Tracker: layout and technology options

  HCAL: number of layers, cell sizes

  Forward region: calorimeter coverage, support tube shielding, QD0 location

Many thanks to all those who contributed to this talk!

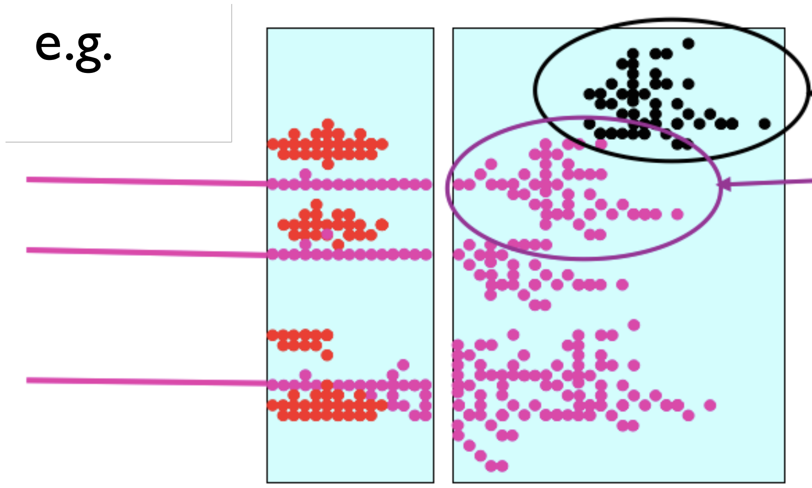
Spare Slides

Particle Flow: "Confusion"

The challenge for fine granularity particle flow algorithms:

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

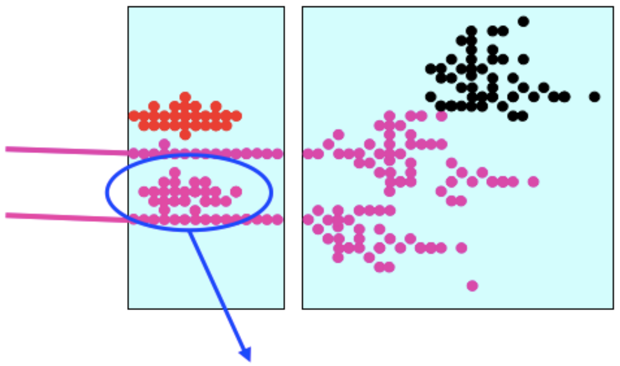
e.g.



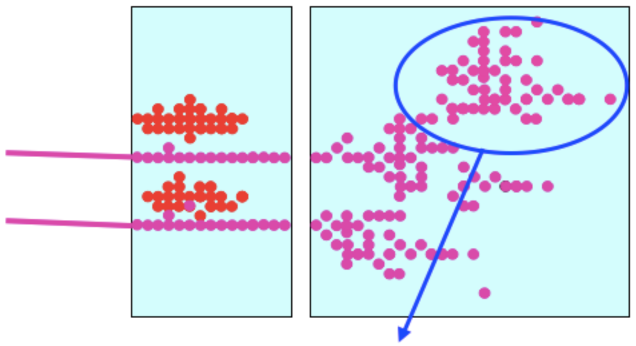
If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution, not intrinsic calorimetric performance

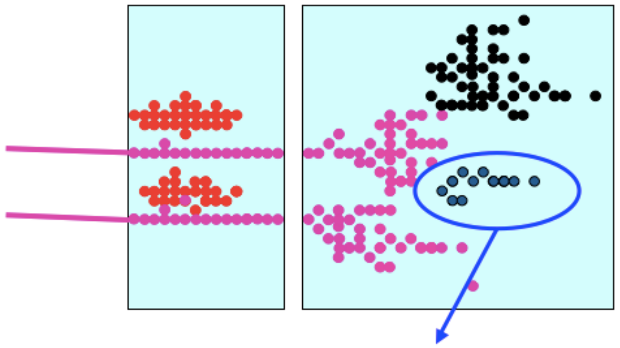
Three basic types of confusion:



Failure to resolve photons



Failure to resolve neutral hadrons

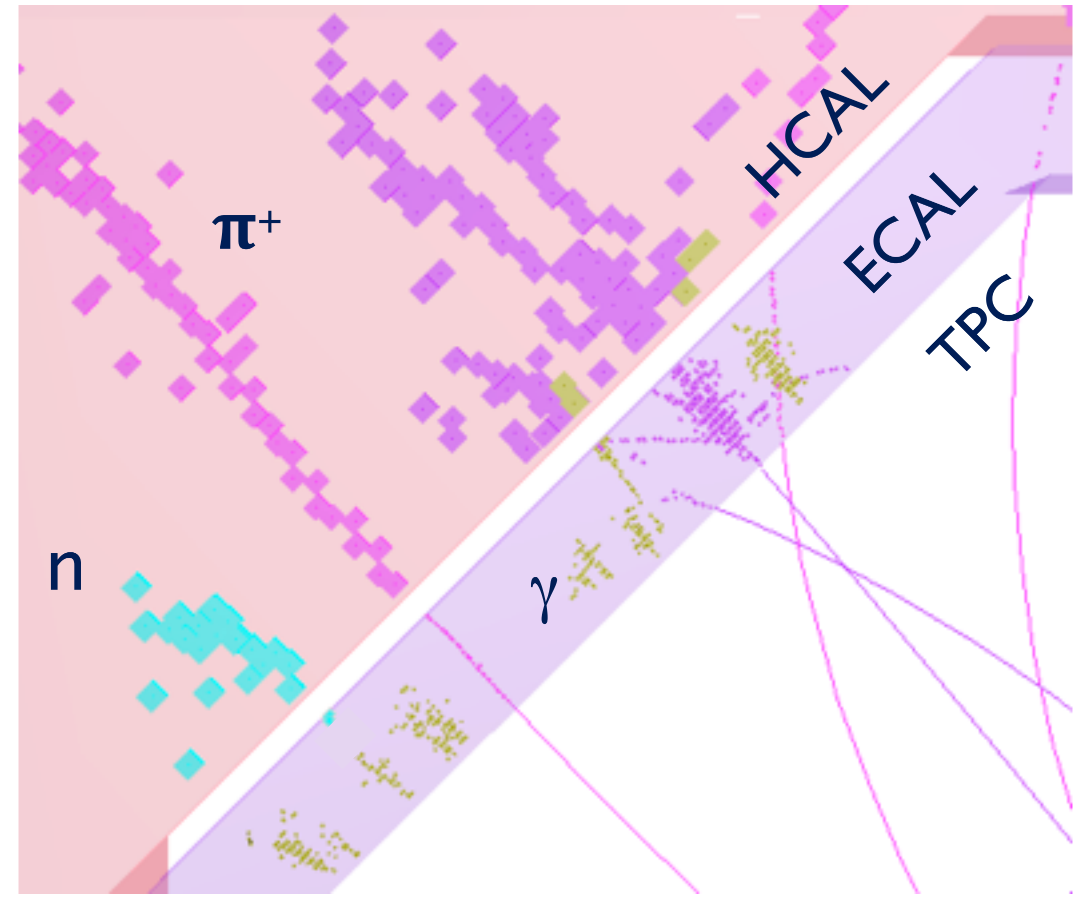


Reconstruct fragments as separate neutral hadrons

Particle Flow: Calorimeter Design

ECAL requirements:

- Minimise transverse spread of EM showers:
  - Small Molière radius & transverse segmentation
- Longitudinally separate EM/Hadronic showers:
  - Large ratio λ_I/X_0
- Identification of EM showers
  - Longitudinal segmentation.



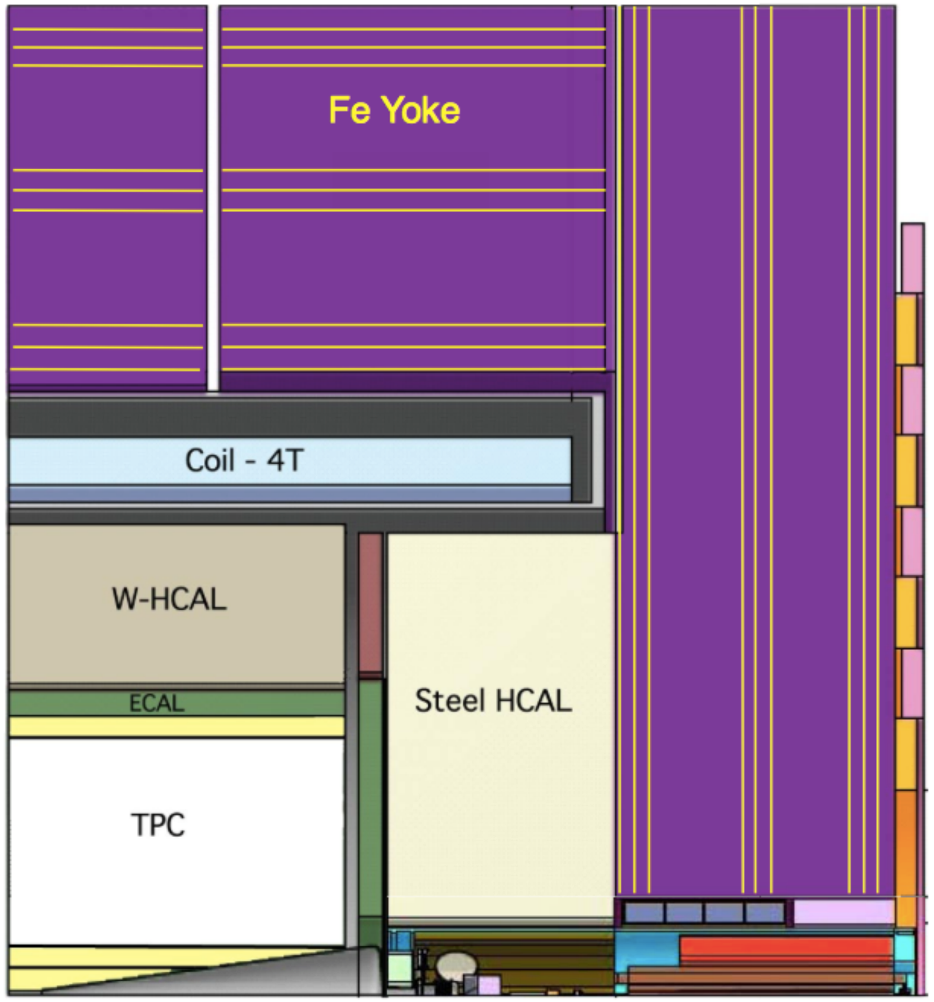
HCAL requirements:

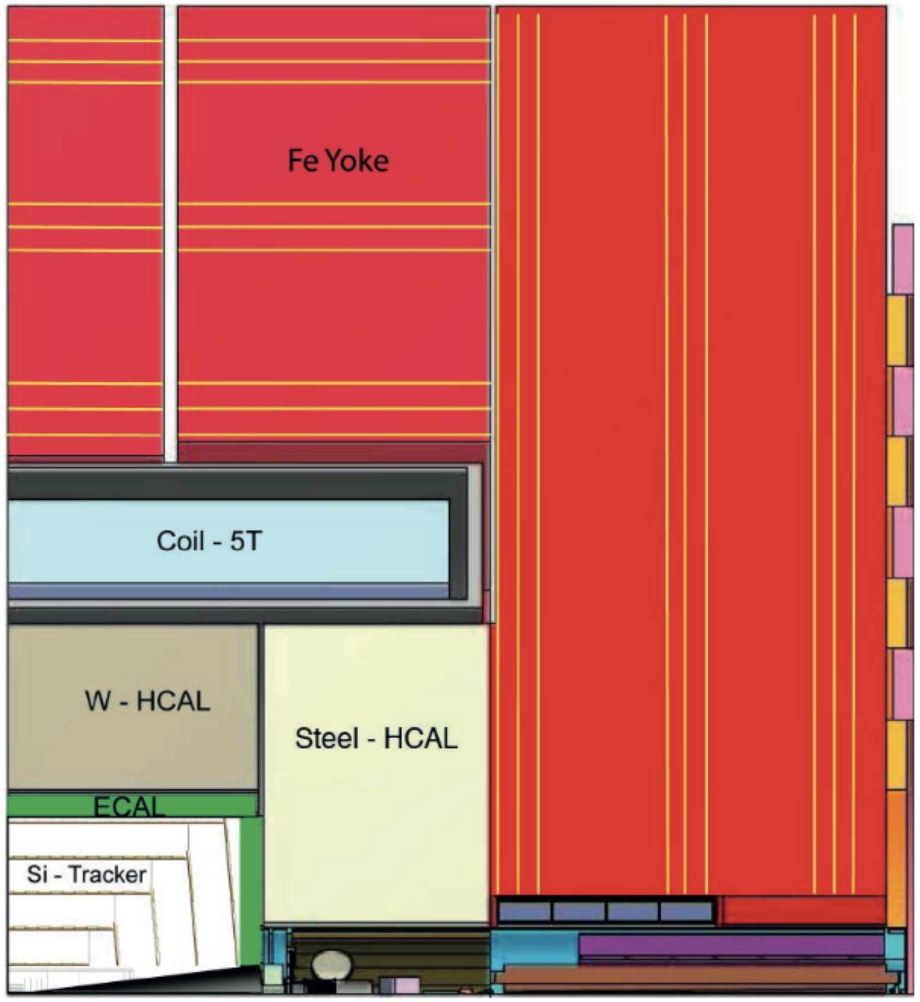
- Fully contain hadronic showers:
  - Small λ_I
- Resolve hadronic shower structure:
  - Longitudinal and transverse segmentation
- HCAL will be rather large:
  - Cost and structural properties important

Suitable absorber materials:

Material	X_0/cm	ρ_M/cm	λ_I/cm	λ_I/X_0
Fe	1.76	1.69	16.8	9.5
Cu	1.43	1.52	15.1	10.6
W	0.35	0.93	9.6	27.4
Pb	0.56	1.00	17.1	30.5

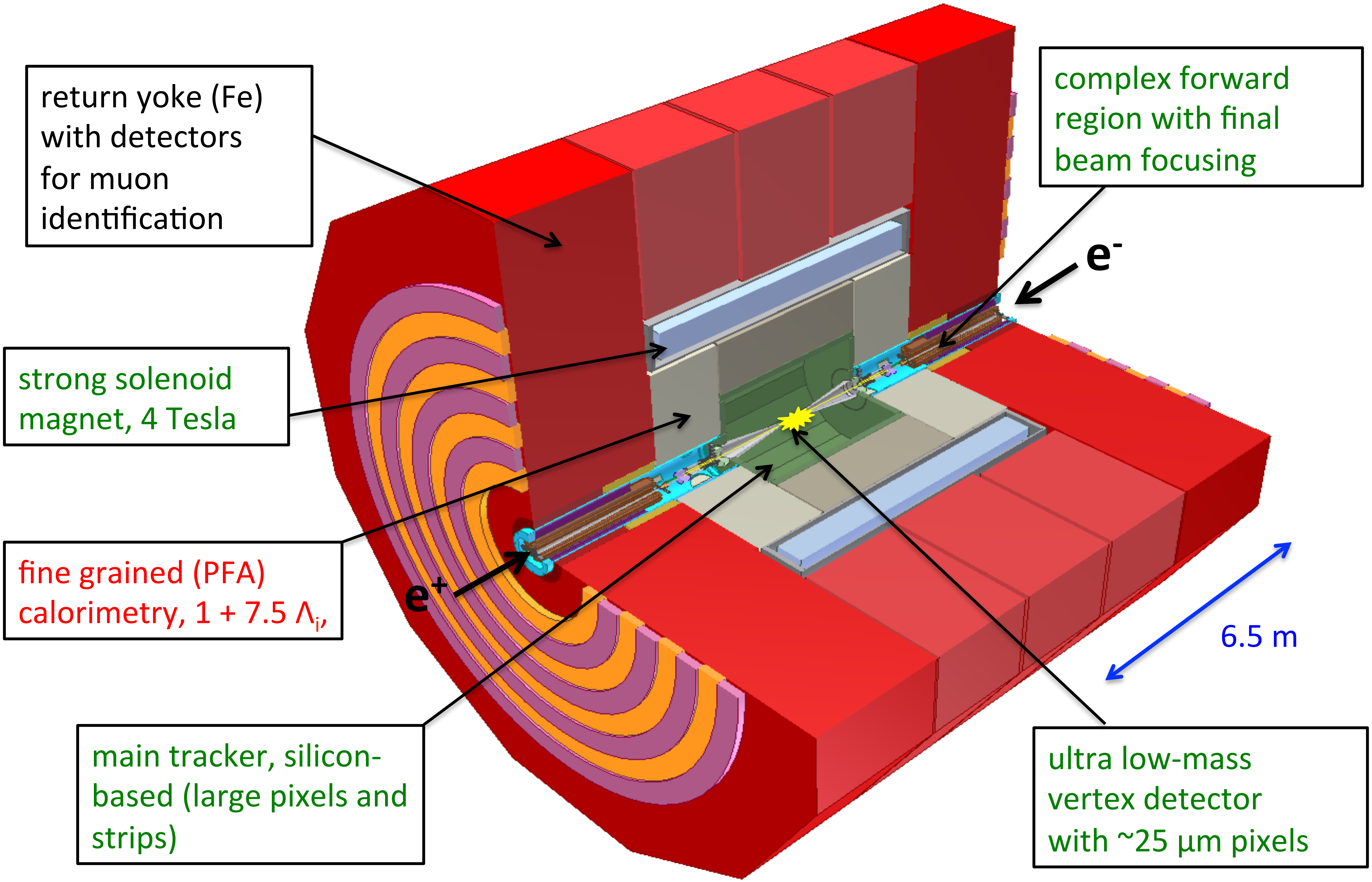
CLIC_ILD and CLIC_SiD





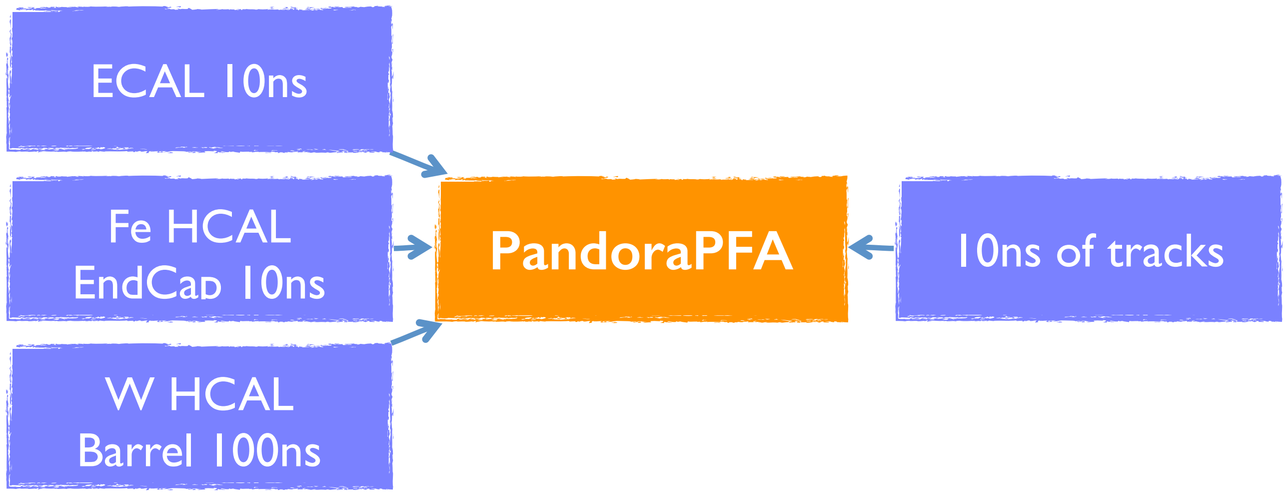
	B-Field [T]	VTX r_{min} [mm]	TRACKER	TRK z_{max} [m]	ECAL r_{min} [m]	ECAL ΔR [mm]	HCAL Absorber	HCAL λ_I	Overall H [m]	Overall L [m]
CLIC_ILD	4	31	Si + TPC	2.3	1.8	172	W / Fe	7.5	14.0	14.0
CLIC_SiD	5	27	Si	1.6	1.3	135	W / Fe	7.5	12.8	12.8

CLIC Detector Concept 2015



Slide courtesy of L. Linssen

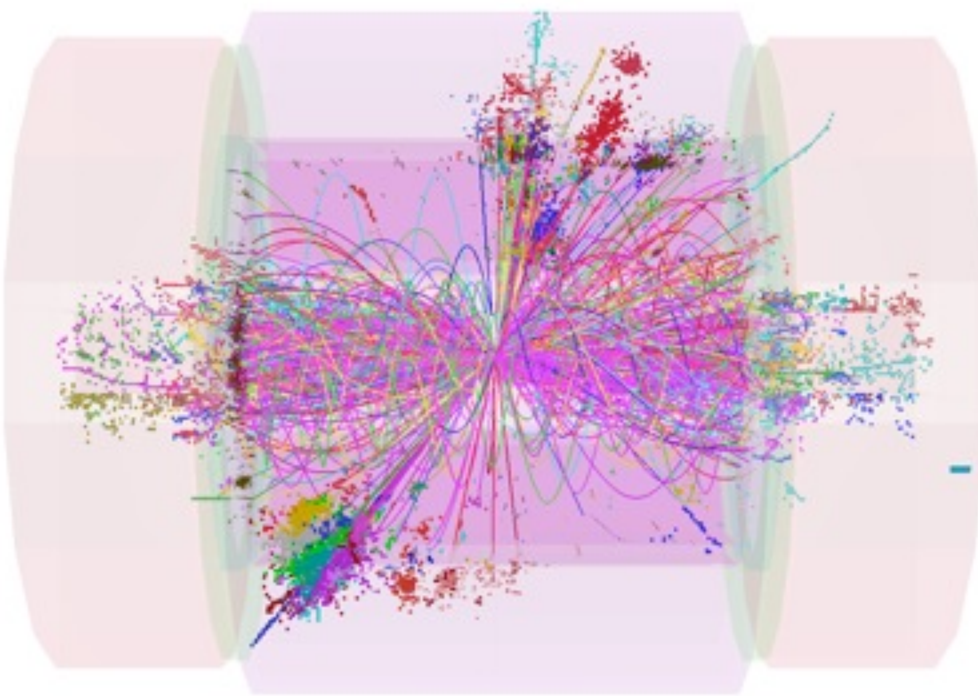
1. CLIC 3TeV input to reconstruction:



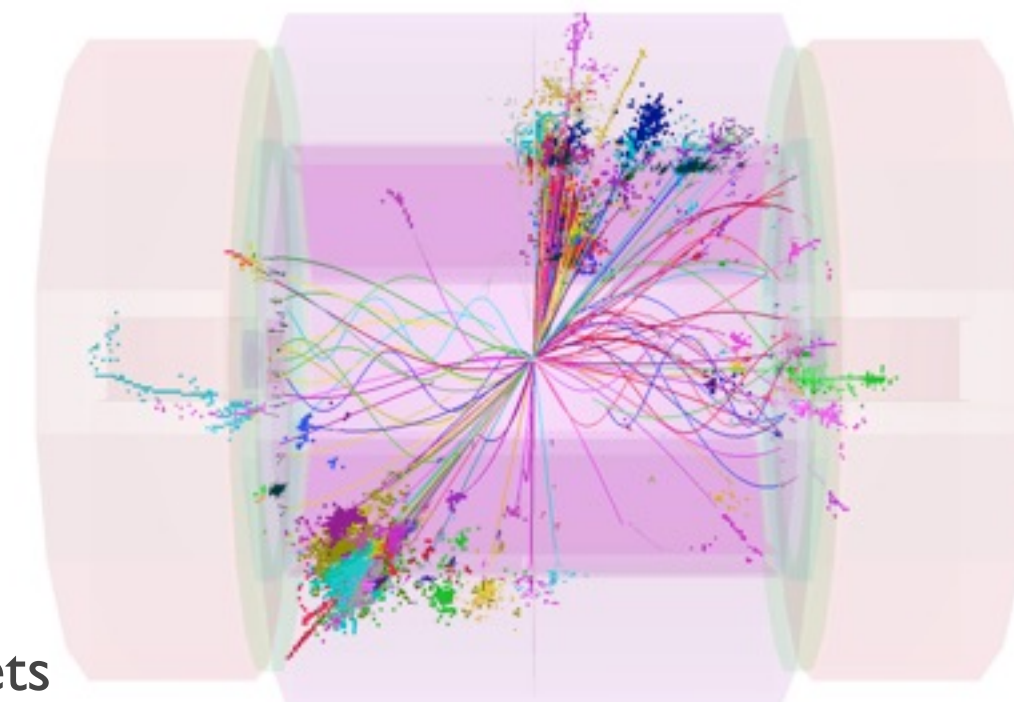
Subdetector	Reco Window	Hit Resolution
ECAL	10 ns	1 ns
Fe HCAL EndCap	10 ns	1 ns
W HCAL Barrel	100 ns	1 ns
Si Detectors	10 ns	$10/\sqrt{12}$
TPC (CLIC_ILD)	Entire train	n/a

2. Reconstructed particles, bkg energy 1.2TeV:

3. Selected particles, bkg energy 85GeV:

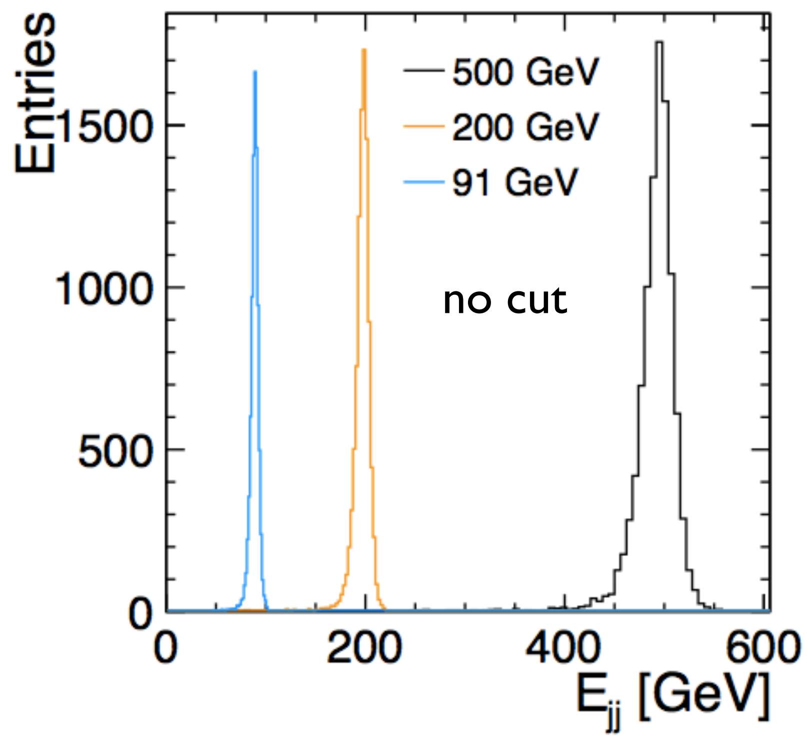


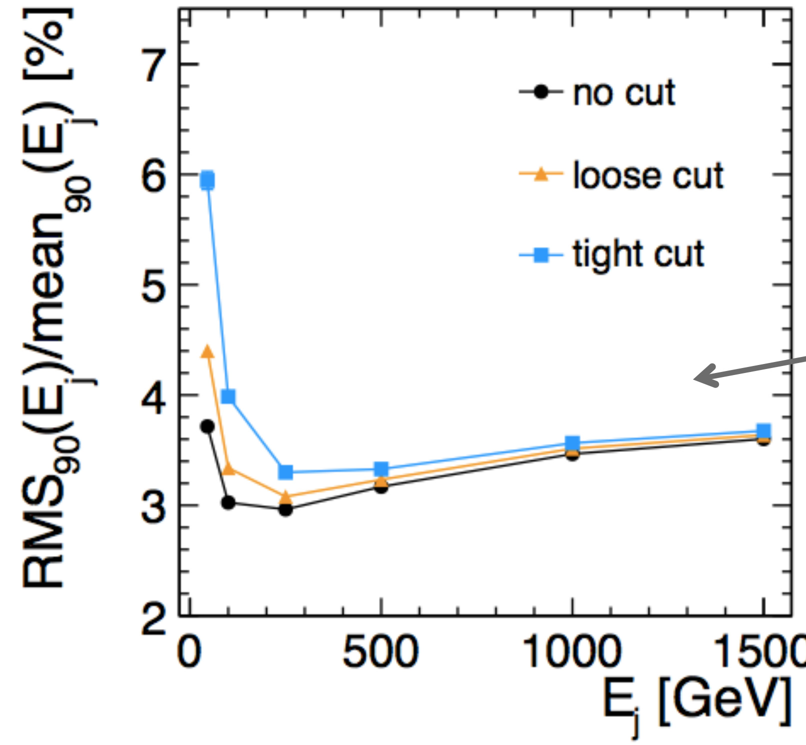
Apply timing and p_T cuts to reject background PFOs



$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8$ jets

CLIC Jet Energy Resolution

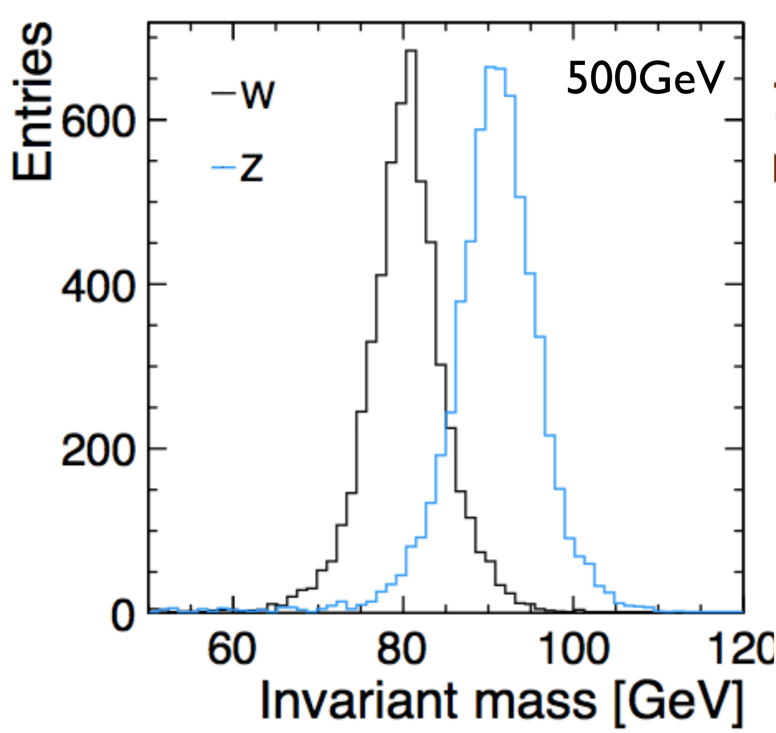


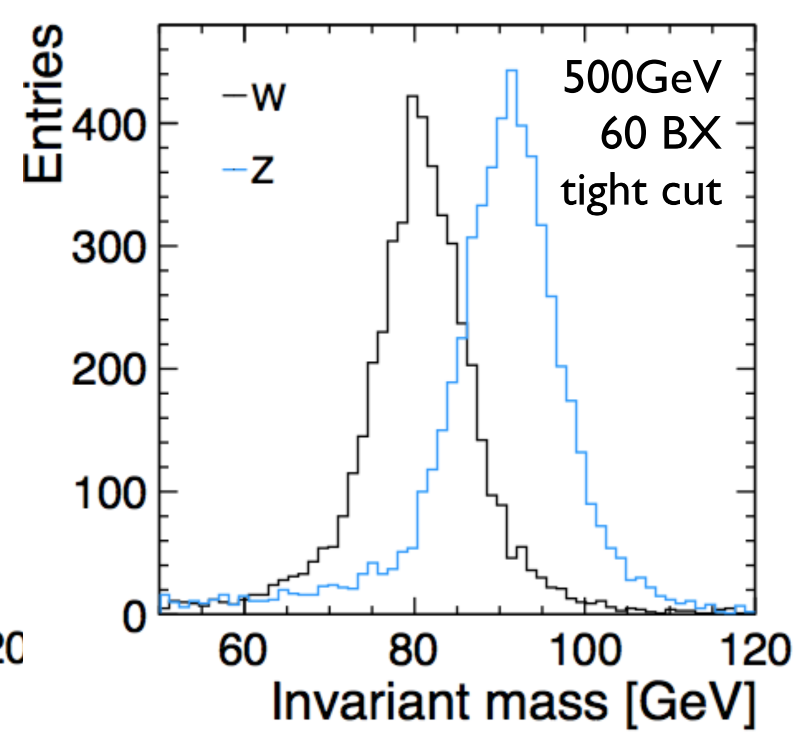


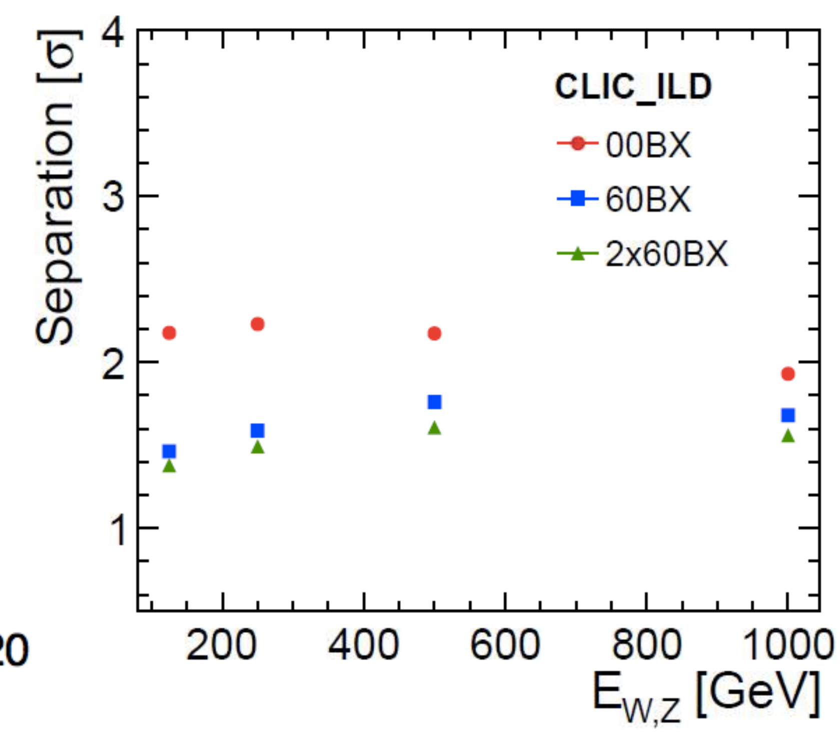
Jets in barrel region only, $|\cos(\theta)| < 0.7$

No cuts: resolution better than ~3.7% for all energies considered

CLIC_ILD







ECAL: Parameterised Jet Energy Resolution

ECAL Energy Resolution

HCAL Energy Resolution

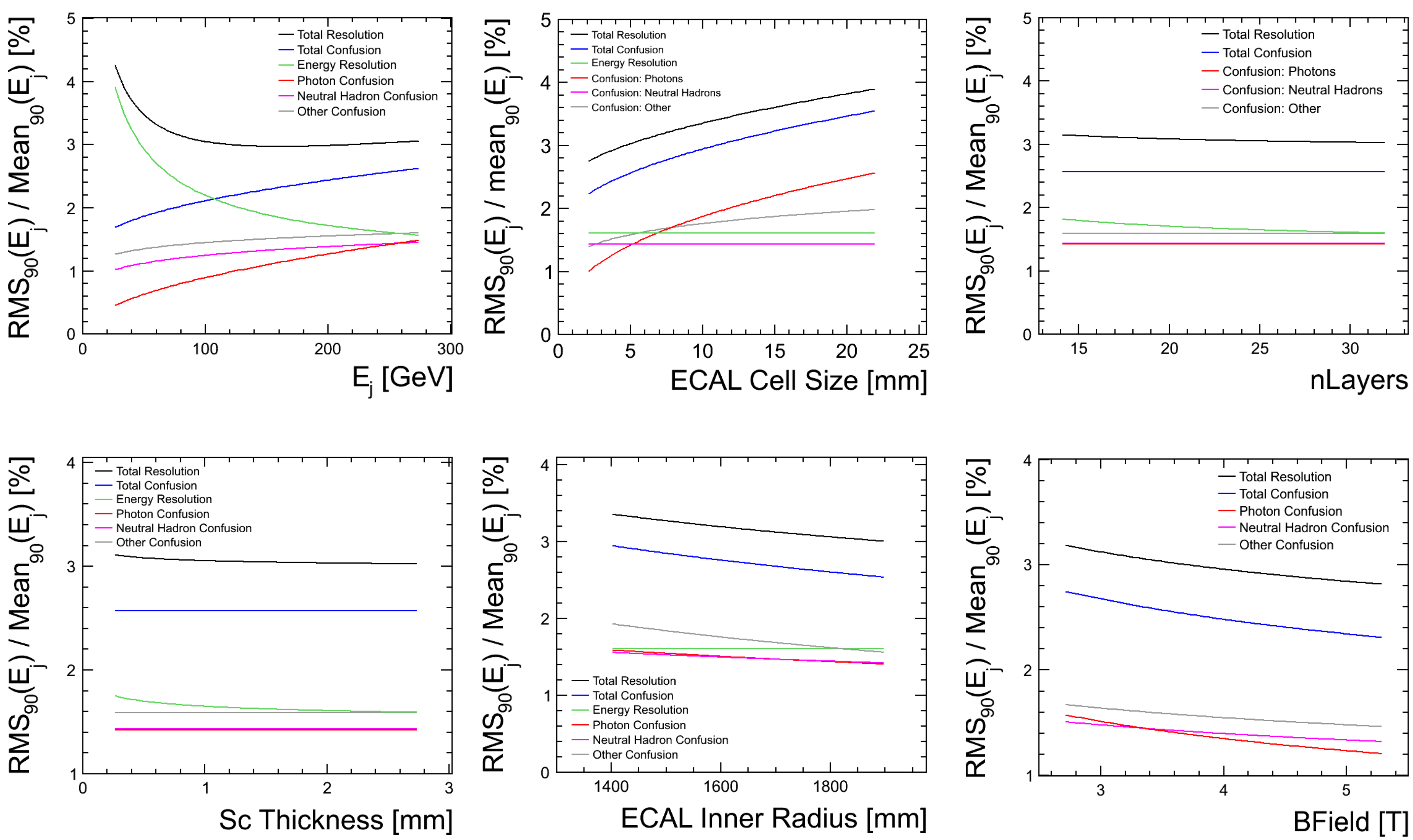
Leakage/Tracking

$$\left(\frac{\sigma_E}{E}\right) =$$

$$\left(\frac{100\%}{E}\right)\left(\left(0.30E\left(\frac{0.154}{\sqrt{0.30E/\mathrm{GeV}}}\oplus 0.0200\right)\left(\frac{t}{2\text{ mm}}\right)^{-0.14}\left(\frac{L}{30\mathrm{lyr}}\right)^{-0.50}\right)\oplus\left(0.10E\left(\frac{0.55}{\sqrt{0.10E/\mathrm{GeV}}}\right)\right)\oplus(0.0086E)\right)\oplus$$

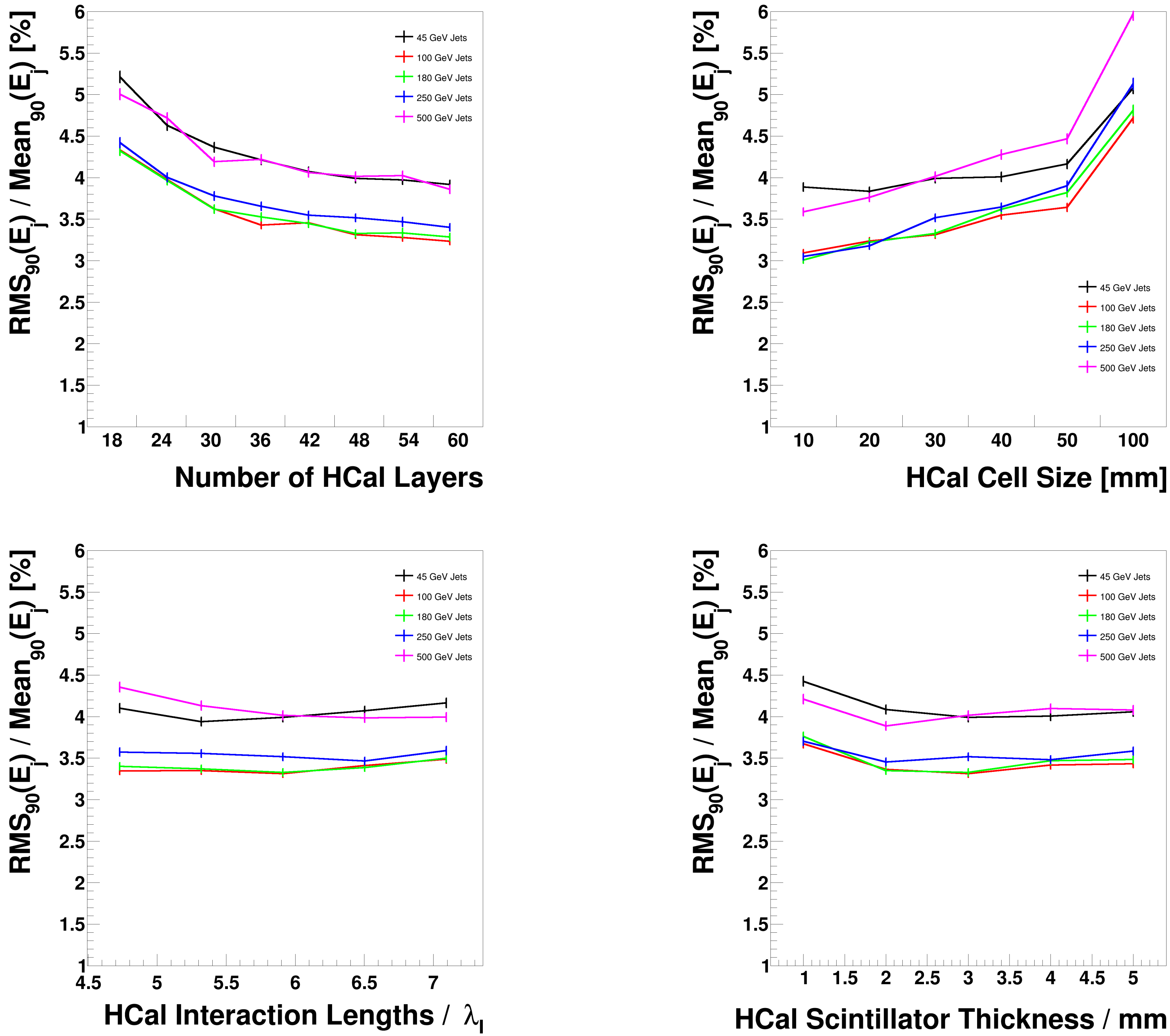
$$\left(2.11\left(\frac{E}{100\mathrm{GeV}}\right)^{0.20}\left(\frac{R}{1853\mathrm{mm}}\right)^{-0.50}\left(\frac{C}{5\mathrm{mm}}\right)^{0.20}\left(\frac{B}{3.5\mathrm{T}}\right)^{-0.25}\right)$$

Confusion



ILD_o1_v05

HCAL Optimisation: Summary Plots



Slide courtesy of S. Green

LC Vertex Detector Requirements

- efficient tagging of heavy quarks through precise determination of displaced vertices:

$$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot \mathrm{GeV}^2/(p^2 \sin^3\theta)}$$

$$a \sim 5\ \mu m, \quad b \sim 10\text{-}15\ \mu m$$

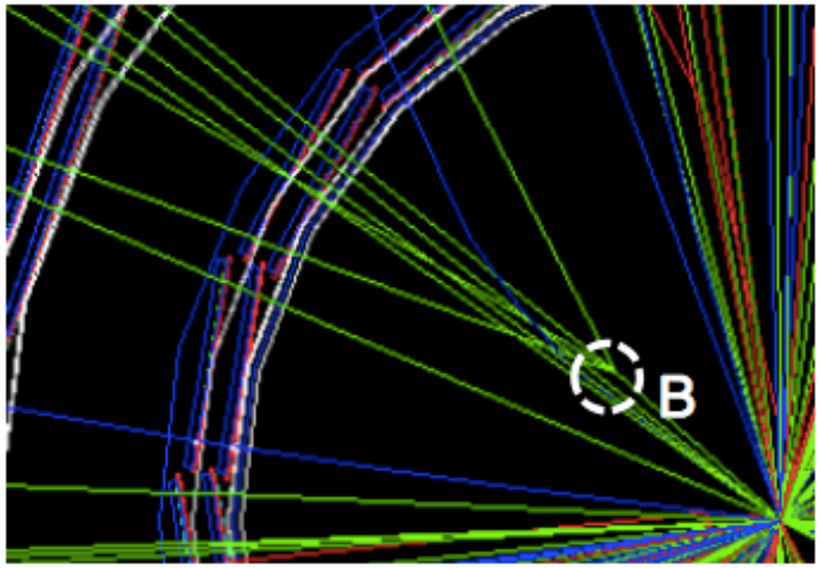
→ good single point resolution: $\sigma_{SP} \sim 3\ \mu m$

→ small pixels <~25x25 μm^2, analog readout

→ low material budget: $X \lesssim 0.1\text{-}0.2\%\ X_0$ / layer

→ corresponds to ~100-200 µm Si, including supports, cables, cooling

→ low-power ASICs (~50 mW/cm^2) + gas-flow cooling



- 20-200 ms gaps between bunch trains → trigger-less readout, pulsed powering
- B = 4-5 T → Lorentz angle becomes important

- few % maximum occupancy from beam-induced backgrounds → sets inner radius
- moderate radiation exposure (~10^4 below LHC!):
  - NIEL: < $10^{11}\ n_{eq}/cm^2/y$
  - TID: < 1 kGy / year

- for CLIC: Time stamping with ~10 ns accuracy, to reject background
  → high-resistivity / depleted sensors, readout with precise time stamping

Slide courtesy of D. Dannheim