UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Digital Calorimetry for Future Colliders

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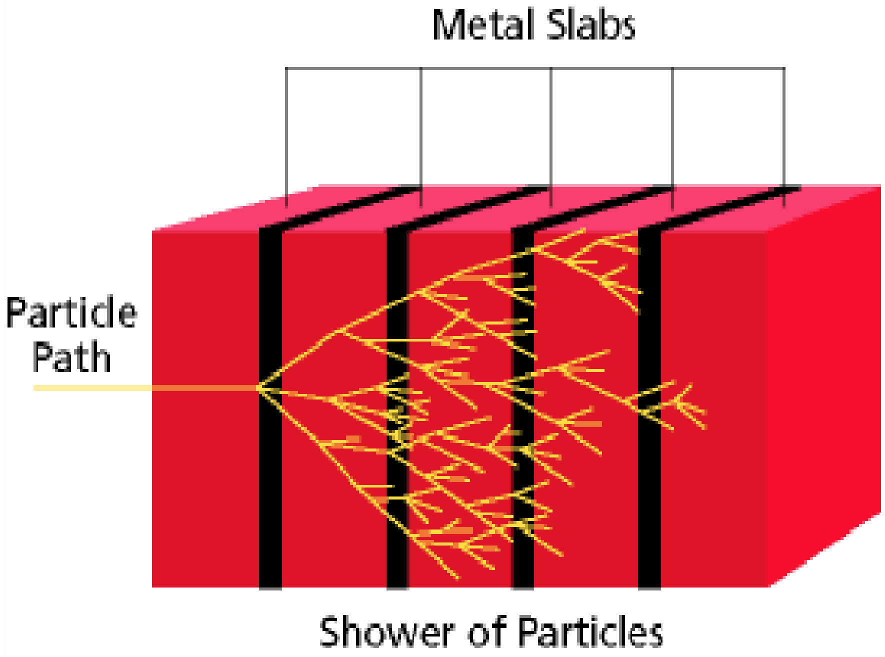
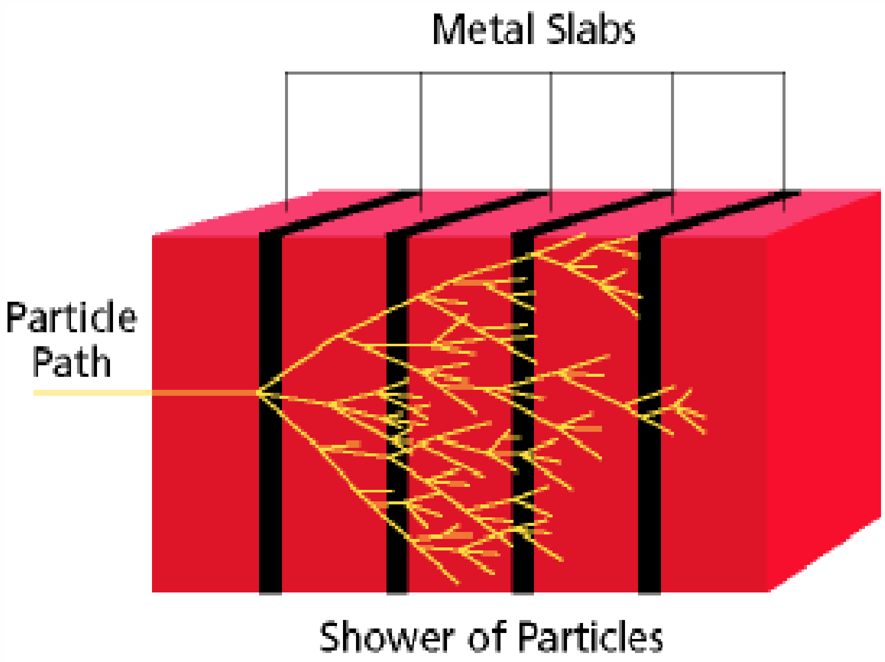
Sampling Calorimetry

- Incident particle interacts with a dense material and a shower develops
- The shower particles then deposit energy in the sensitive regions
  - Si sensors, scintillators, lAr etc…
- The sum the energy deposits and scale to the energy of incident particle



Sources of Uncertainty

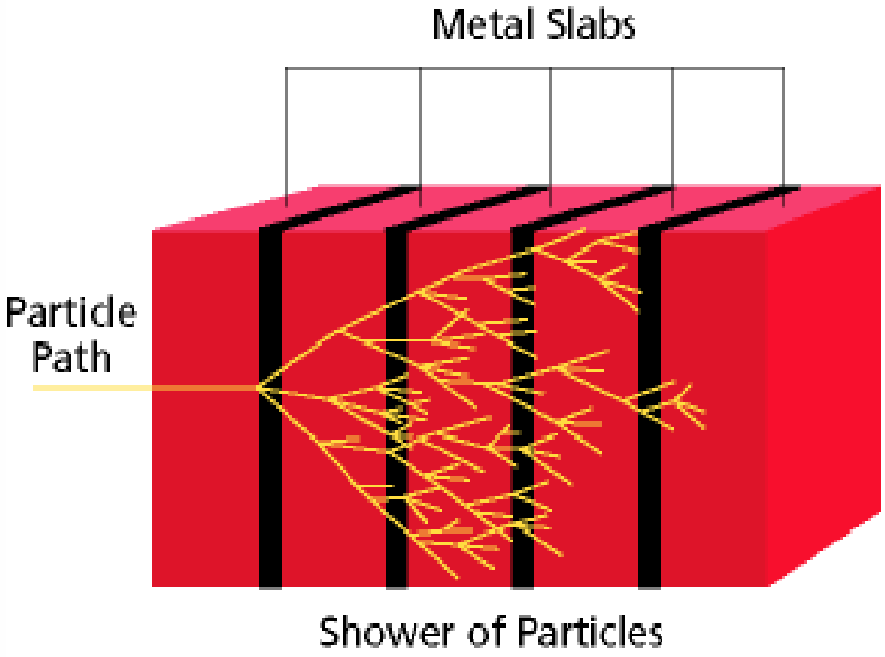
- Average number of particles in the shower is proportional to incident energy
  - fluctuations on this number
- Energy deposited in sensitive layer is proportional to number of particles
  - Fluctuations in angle
  - Particle velocity
  - Landau energy deposition



Sources of Uncertainty

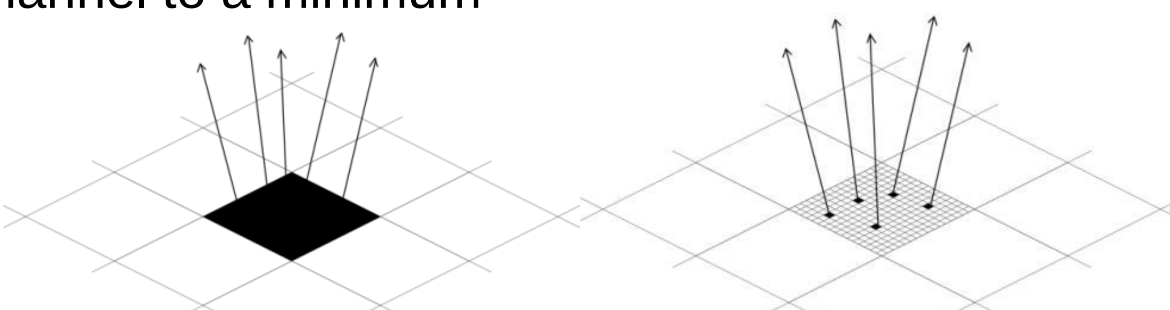
- Average number of particles in the shower is proportional to incident energy
  - fluctuations on this number
- Energy deposited in sensi[redacted] layer [redacted]roportional to nu[redacted]cles
  - Fluc[redacted]in angle
  - F[redacted]e v[redacted]
  - Landau energy deposition

Remove this uncertainty by just counting number of particles



Digital Calorimetry: The Concept

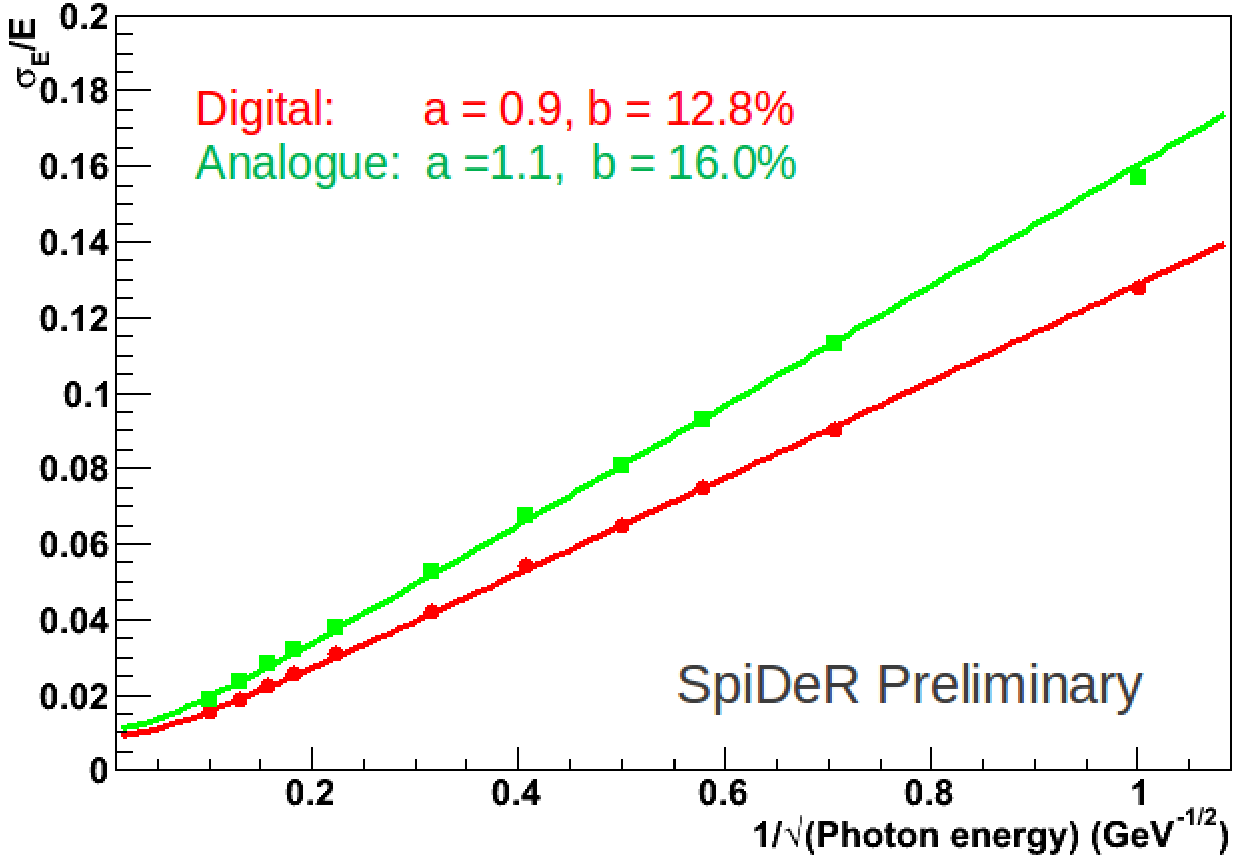
- Dates back to c.2005 work within CALICE
- Make a pixelated calorimeter to count the number of particles in each sampling layer
- Ensure that the particles are small enough to avoid multiple particles passing through a single pixel to avoid undercounting and non-linear response in high particle density environments
- Digital variant of ILD ECAL would require 10^{12} channels
- Essential to keep dead area and power consumption per channel to a minimum



Analogue: 5mm pitch   Digital: 50um pitch

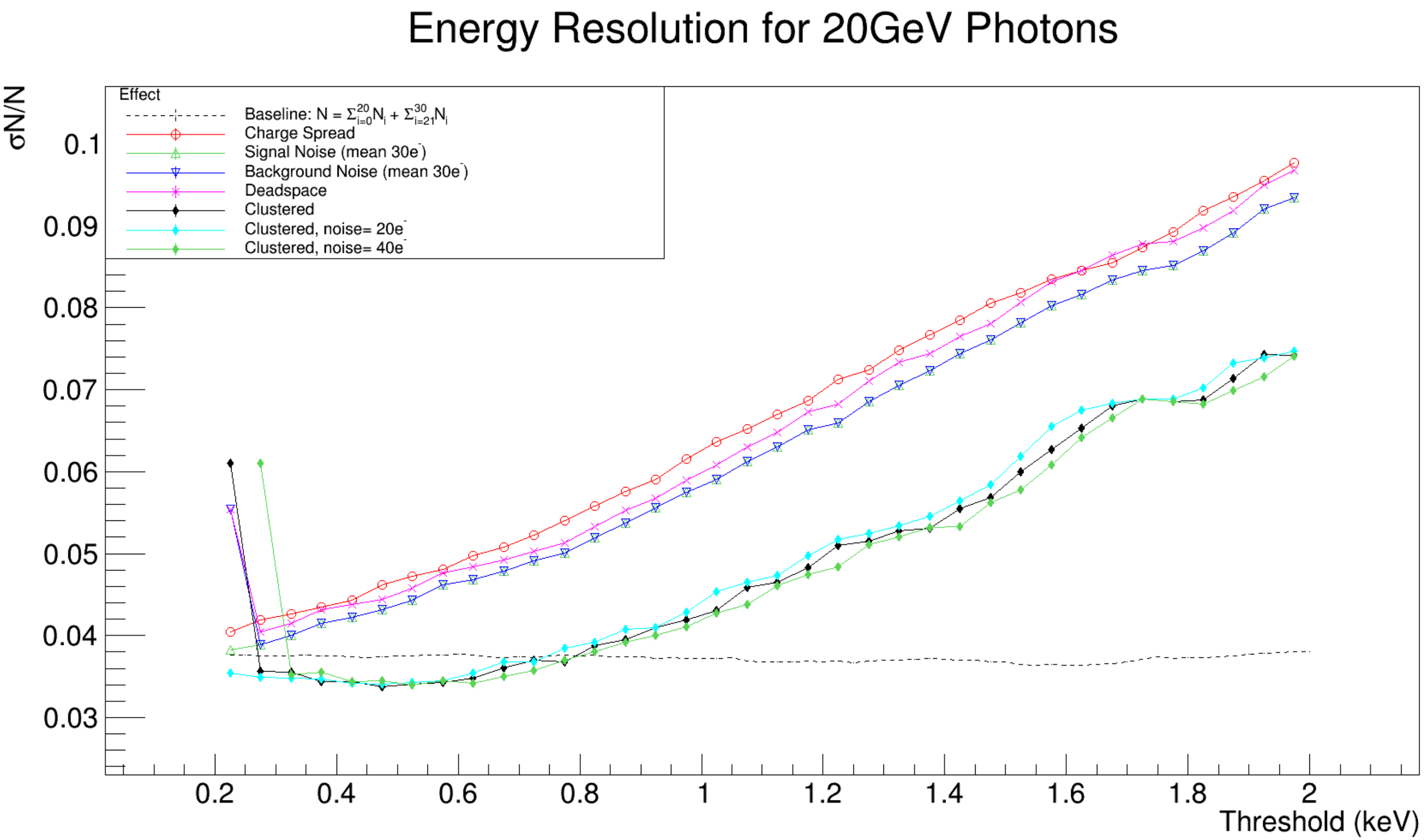
ILD (D)ECAL Simulated Energy Resolution

Full Mokka G4 simulation with 20 layers 0.6 & 10 layers 1.2

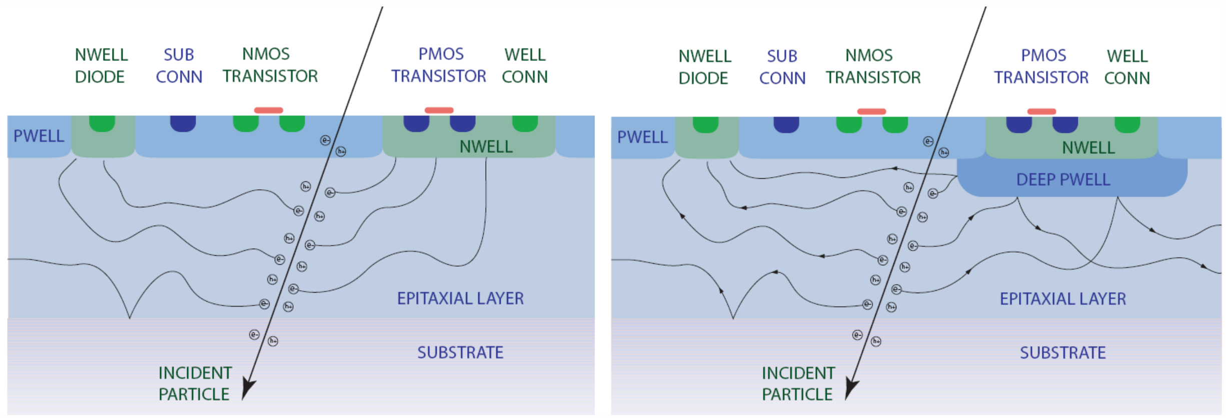


DECAL Simulations with added realism

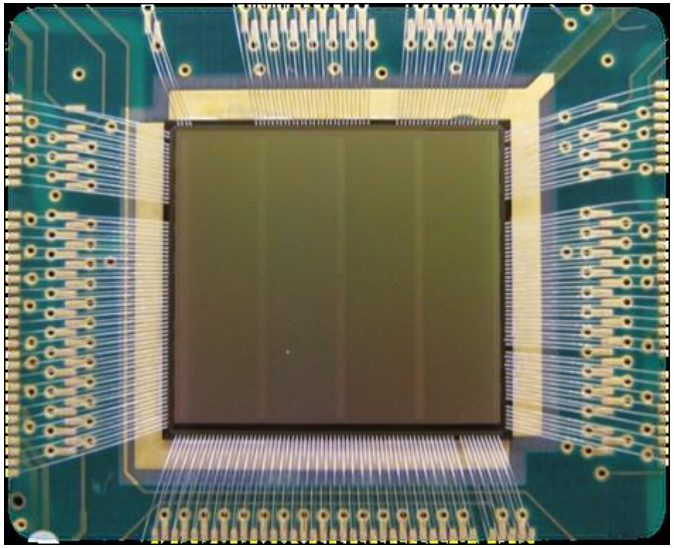
Original work by Anne-Marie Magnan (now on CMS) and resurrected by current PhD student Alasdair Winter



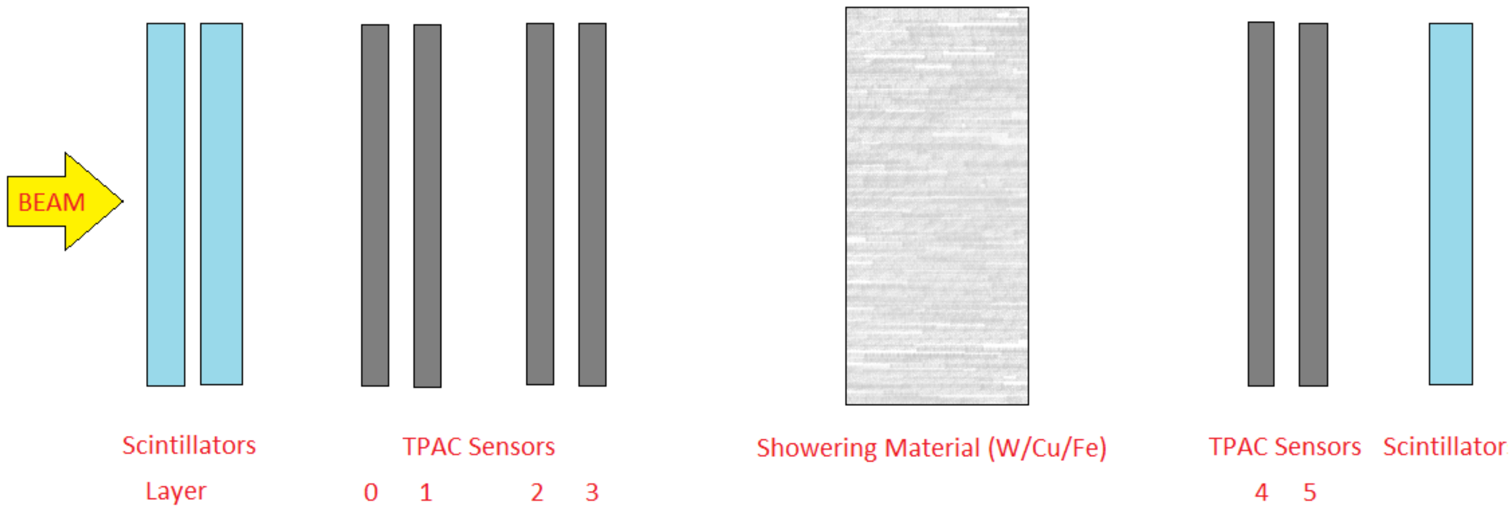
TPAC Sensor



- CMOS MAPS
- 168x168 pixel grid
- 50x50 um pitch
- 12-18 um epi layer
- Digital readout
- Low noise
- Utilise the INMAPS process
- Collect charge by diffusion to signal diodes
- Sampled every 400 ns (timestamp)
- Readout every 8192 timestamps (bunch train)



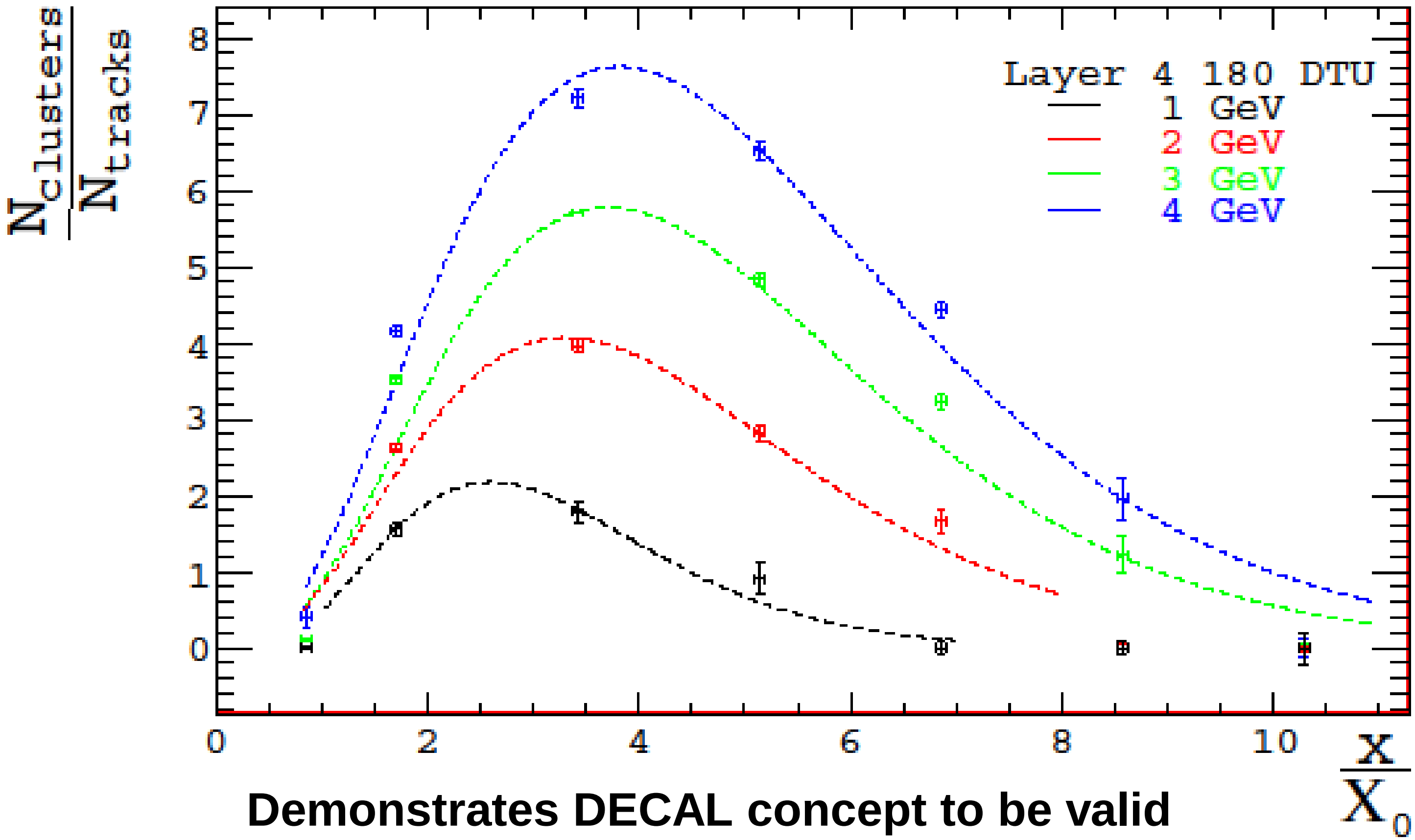
Experimental Validation of DECAL Concept



Showering Mode

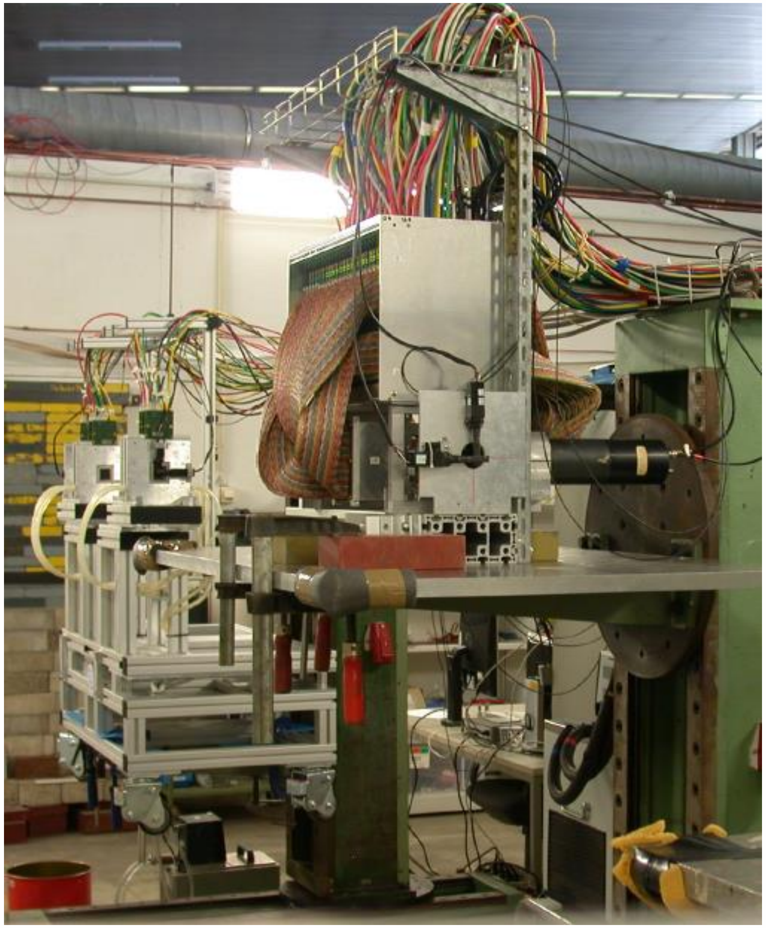
- 1-5 GeV e+ at DESY in Feb/March 2010
- Triggered with PMTs either side of the sensors
- Tracks found in the first four sensors
- Projected through material and properties of shower measured downstream

Shower Multiplicities: DESY Testbeam



Demonstrates DECAL concept to be valid
Further results can be found
http://etheses.bham.ac.uk/4515/1/Price13Phd1.pdf

ALICE FoCal: SPS and DESY test beams



- ALICE Forward Calorimeter (FoCal) require highly granular to separate showers
- Mixture of MAPS and pad sensors proposed
- Protoype used 24 layers of MAPS interweaved with 1.5mm W
- Tested at DESY and SPS in 2012
- Results here are from Martijn Reicher's thesis

ALICE FoCAL: Results

Results in Martijn's thesis further demonstrate the validity of a DECAL

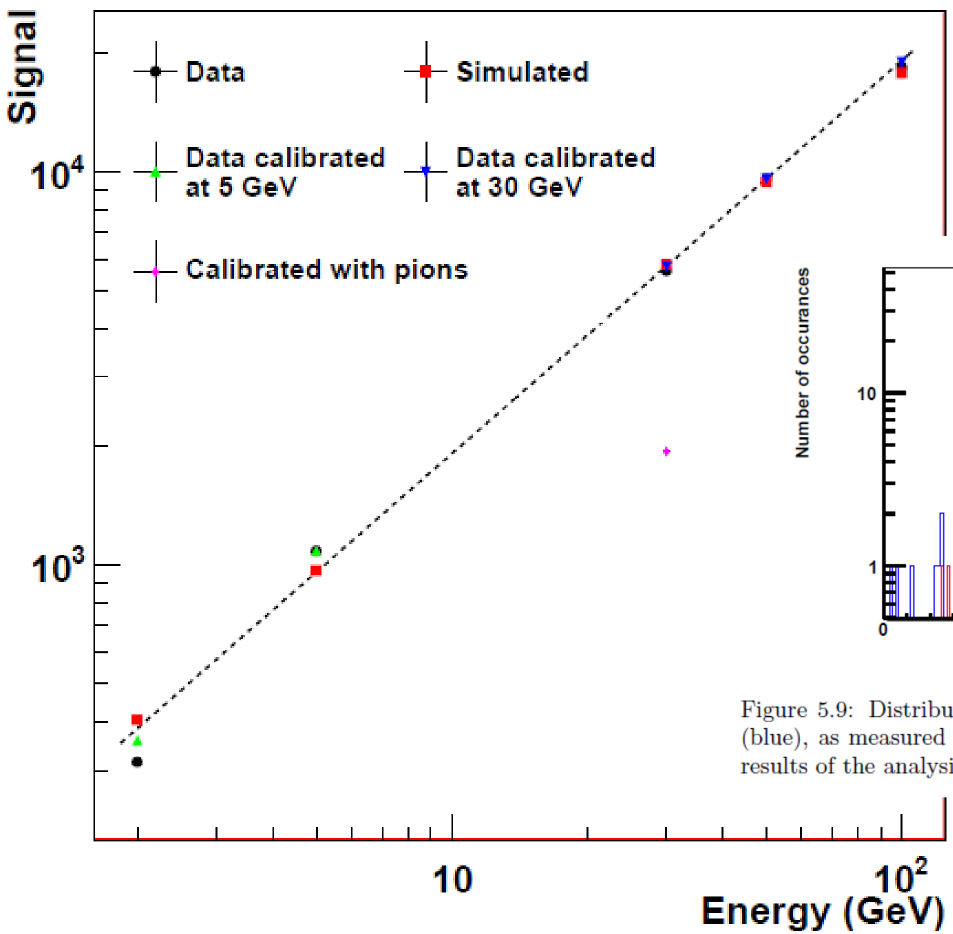


Figure 5.23: A comparison of signals from DESY and SPS, after correcting for the different calorimeter constructions. The dotted line indicates a linear fit to the raw data points which passes through the origin.

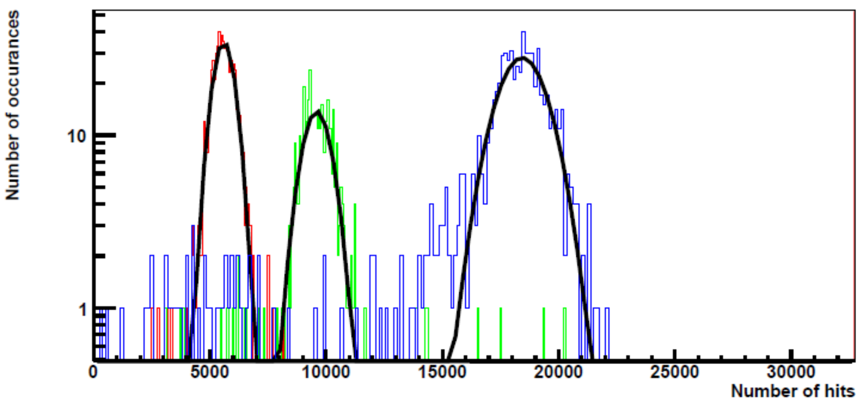
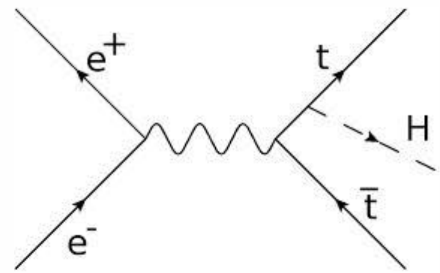
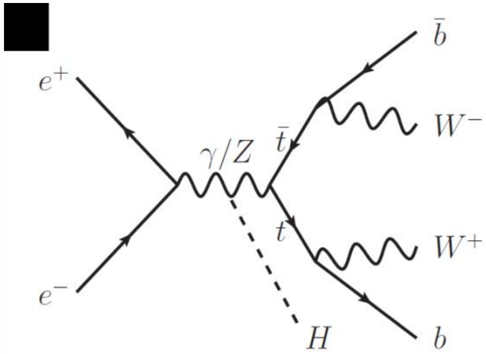


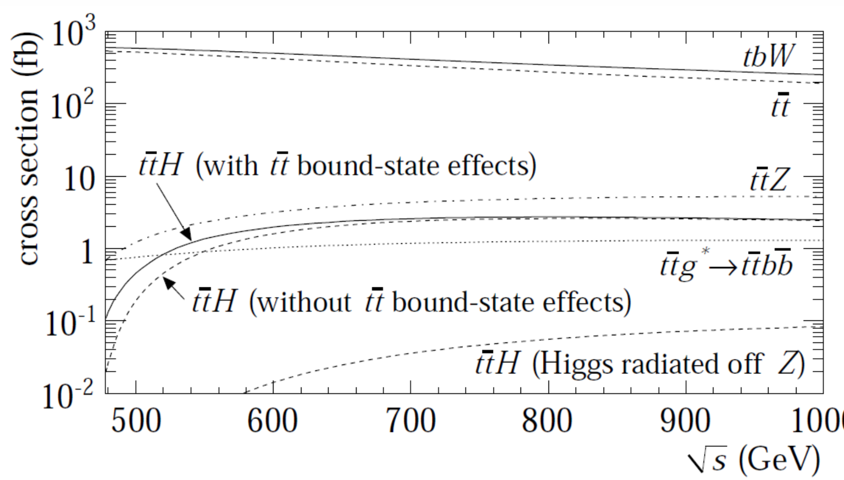
Figure 5.9: Distribution of hit pixels for e^+ at 30 GeV/c (red), 50 GeV/c (green) and 100 GeV/c (blue), as measured at SPS as in figure 5.7. In addition cuts on the shower position based on the results of the analysis of figure 5.8 are applied.

Top Higgs Yukawa Coupling: ILC @ 1 TeV

- Samples created for the ILC TDR in 2012
- Studied the semi-leptonic final state
  - ttH->lvbbjjbb
- Main backgrounds considered
- TMVA analysis led to measurement on coupling uncertainty of 4.3%
- Changed the ILD SiW ECAL for a DECAL with MAPS to evaluate impact on this







Impact on Jet energy resolution

Conventional ECAL

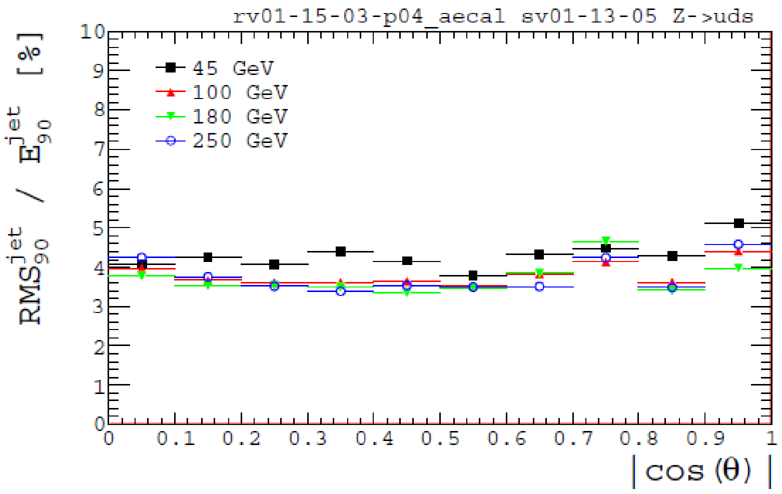


Figure 6.3: Jet energy resolution ($\frac{RMS_{90}}{E_{90}}$) as a function of angle from the beamline for the Z→uds events at centre of mass energies of 91, 250, 360, and 500 GeV for the AECAL using iLCSoft v01-13-05 and reconstruction v01-15-03-p04_aecal.

DECAL

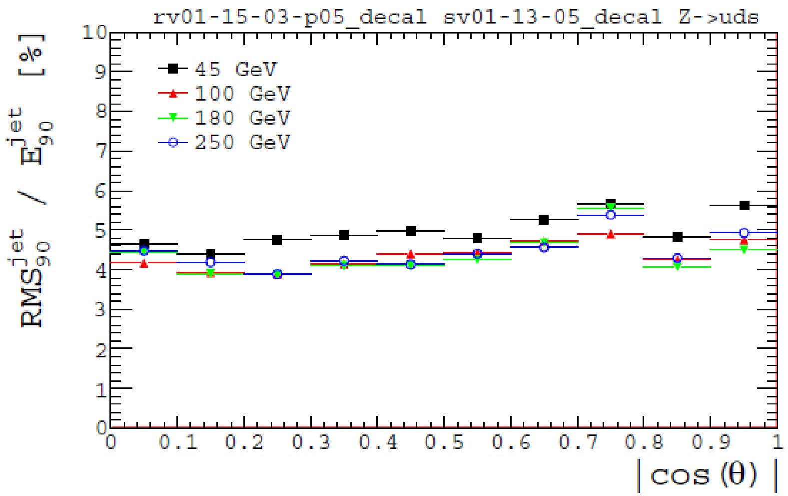
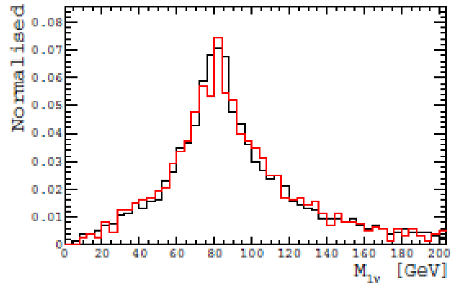


Figure 6.4: Jet energy resolution ($\frac{RMS_{90}}{E_{90}}$) as a function of angle from the beamline for the Z→uds events at centre of mass energies of 91, 250, 360, and 500 GeV for the DECAL using iLCSoft v01-13-05_decal and reconstruction v01-15-03-p05_decal.

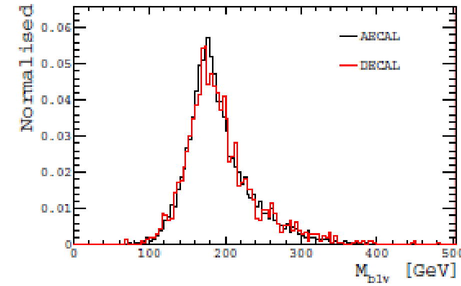
ECAL calibrated with Z->uds dijet events.
Resolution marginally degraded with DECAL **BUT** the geometry not optimised for DECAL. Just changed sensitive region

Impact on reconstructed mass

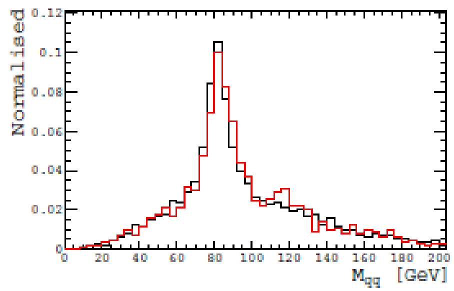
- Reconstructed mass of W, t and H candidates unchanged between (D)ECALs
- All other variables in the MVA also largely uneffected
- Introduction of DECAL at ILD does not impact on the measurements of top Yukawa coupling



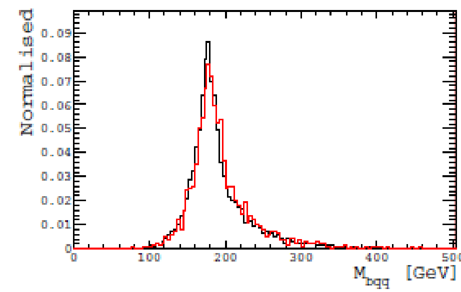
(a) Leptonic W boson candidate



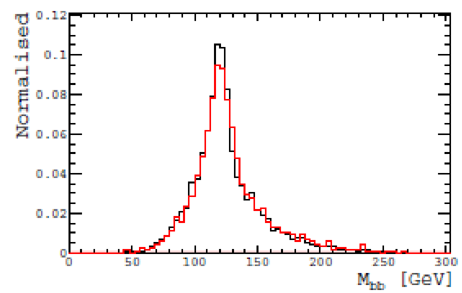
(b) Leptonic top quark candidate



(c) Hadronic W boson candidate



(d) Hadronic top quark candidate



(e) Higgs boson candidate

DECAL at the FCC-hh?

- New funding started July 2016 to investigate reconfigurable, radiation hard, HR-CMOS MAPS for tracking and DECAL purposes for future HEP experiments and Medical Physics
- The University of Birmingham
  - P. Allport (PI), P. Newman, N. Watson, L. Gonella, K, Nikolopoulos, T. Price, A, Winter
- Rutherford Appleton Laboratory
  - F. Wilson, R. Turchetta, D. Das, S. Worm, S. McMahon, Z. Zhang, P. Phillips
- The University of Sussex
  - F. Salvatore

Geant4 Modelling

- We currently have a stand alone Geant4 model and a setup in Mokka for the ILD detector to evaluate shower properties and influence design choices of our sensor
- We believe that an (analogue) SiW geometry has been / will be implemented within FCCSW(?) If so, rather than studying a DECAL with non optimal geometry could be nice to create at this relatively early stage an optimised DECAL.
  - With effort from us (me) potentially
- Use of DELPHES to study impact on physics of the DECAL
  - Note: single particle resolution will always be worse for DECAL than LAr so would need to implement PFA within DELPHES

Physics Studies

- The HEP group at UoB were involved in the Higgs and EWSB Physics Report for FCC workshop (arXiv:1606.09408)
- Continue with physics studies of very rare Higgs boson decays probing the light quark Yukawa couplings
  - UoB leading contribution in pioneering papers on probing the couplings of Higgs boson to light quarks with ATLAS (arXiv:1607.03400, arXiv:1501.03276)
  - Two MSc student that will study this in the context of FCC starting in September
- In order to understand the origin of EWSB we would also like to study Vector Boson Scattering

Other Considerations

- Radiation Hardness
  - Forward region of FCC-hh detectors Si not an option
  - Barrel region of 10^{14} n_{eq}/cm^2 makes Si and MAPS feasible
  - Depleted CMOS currently under development (HV/HR) with results up to 10^{15} n_{eq}/cm^2 presented recently by other groups
- Cost
  - Cost of MAPS needs to decrease to make affordable but over 20 years this is expected to fall dramatically.
  - A cost of 30 cents / cm^2 would mean an ECAL of ~$10M.
- Pile Up
  - Need to evaluate shower properties, widths, multiplicity etc.
  - average occupancy and particle density at entrance
- Deployment
  - Complimentary technology to as a pre-shower / tracker
  - seamless transition from tracker to ECAL possible with same technology in second detector?

In Conclusion

- Hopefully I have convinced you that a DECAL is feasible at a future collider
- We are developing a new sensor aimed at digital electromagnetic calorimetry with readout structures to match HL-LHC / FCC-hh
- We want to perform physics studies in the context of FCC-hh and compare with conventional methods
- Still lots to do and think about
- But also a lot of time before FCC-hh detector design choices are made so makes sense to look at all options.

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We want to work in collaboration with you!!!

Any questions?*

*only nice easy ones allowed