Digital Calorimetry for Future Linear Colliders

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University of Birmingham PPE Seminar
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Overview

- The ILC
- Digital Calorimetry
- The TPAC Sensor
- Electromagnetic Shower Measurements
- Top Higgs Yukawa Coupling Measurements at the ILC
- The impact of Digital Calorimetry on the top Higgs Yukawa Coupling

The International Linear Collider

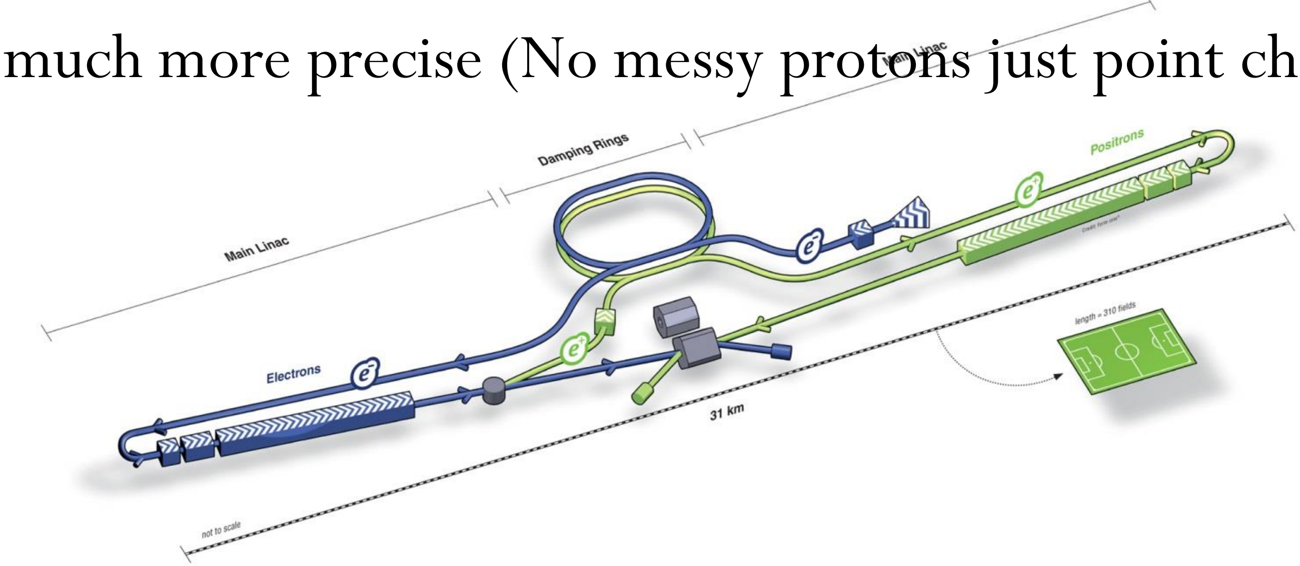
What is it?

What physics is possible?

How will we detect the particles?

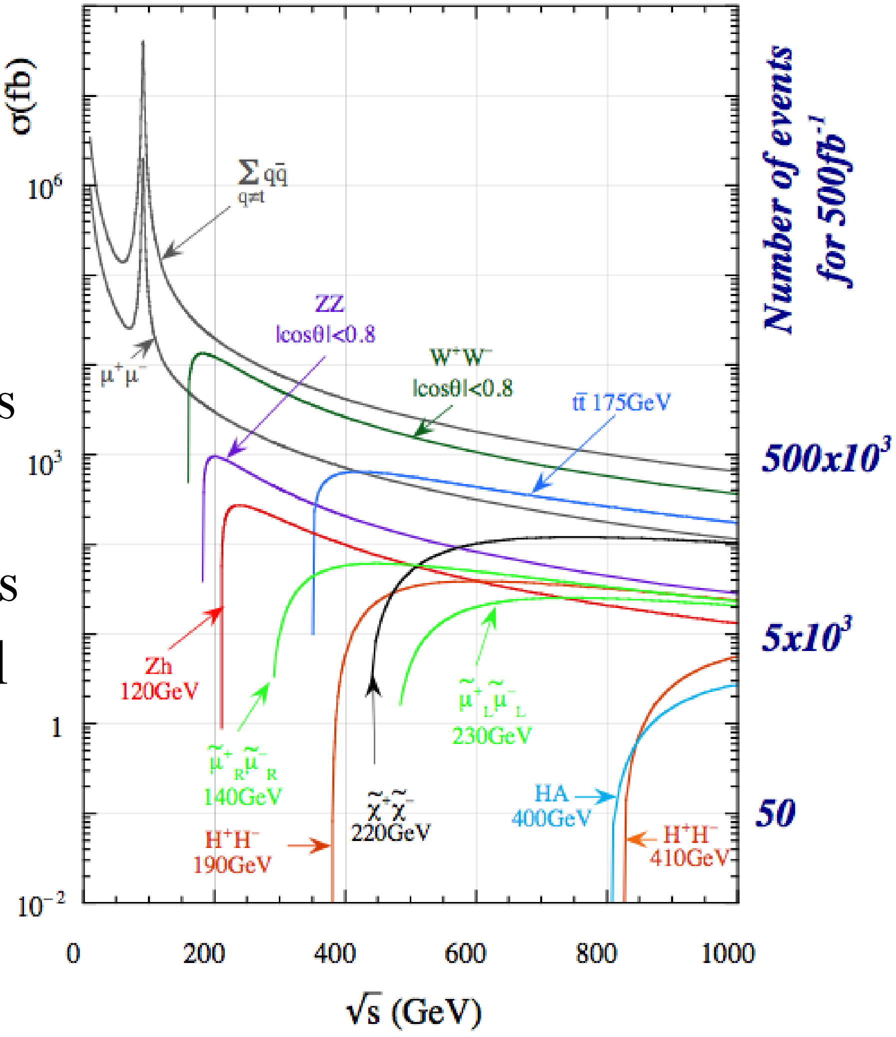
What is it?

- Proposed linear e^+e^- collider with a centre of mass energy up to 1TeV
- Currently many ideas of energies to run at but an upgradable "Higgs Factory" at 250GeV in Japan most popular
- Physics will be largely complimentary to LHC Physics
- Initial state of ILC is much cleaner so measurements can be much more precise (No messy protons just point charges)



Physics Potential

- The physics potential at the ILC is huge due to the tuneable centre of mass energy.
- Could sit at W, Z, top, Higgs resonances
- Choose regimes where cross sections of S/B are maximal

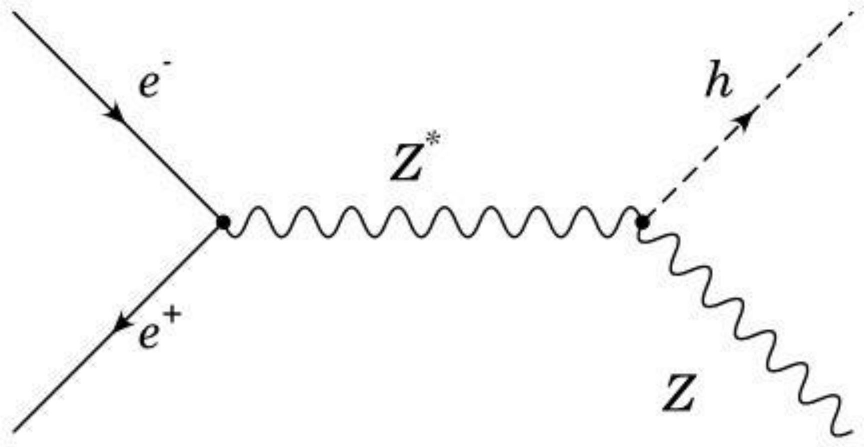


W, Z, t threshold scans

- The masses of the W and Z bosons and top quark could be measured with unprecedented accuracy at the ILC by running at centre of mass energy equal to the mass
  - W boson mass (7MeV)
  - Top quark mass (ΔMt~34MeV)
- The shape of the production cross sections would be measured by scanning the beam energy around production
- This is especially important to ttbar production as this is a major background to Higgs physics at the ILC

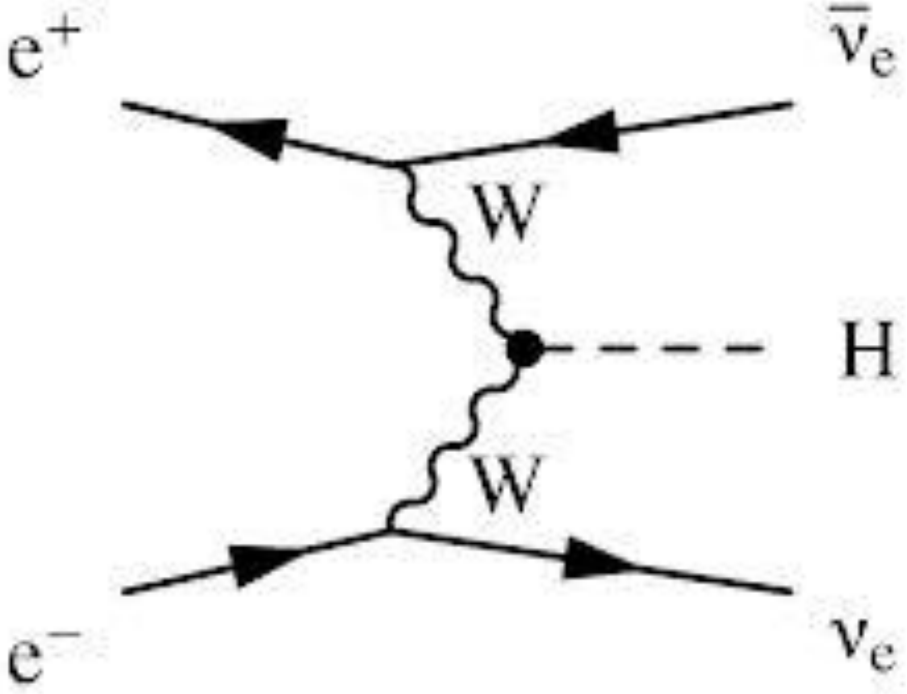
Higgs-strahlung

- A first phase at 250GeV would create huge numbers of Higgs bosons and allow an accurate measurement of its mass and coupling to the Z boson from the “Higgs-strahlung” process
- Cross section maximal around 250GeV
- Small background (no ttbar)



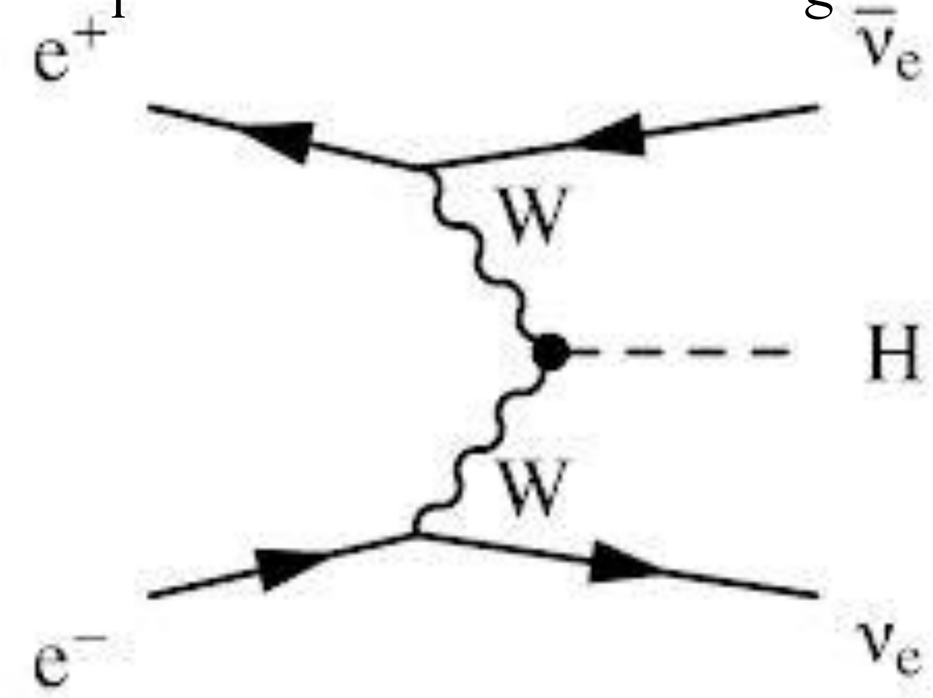
Vector Boson Fusion

- At 500 GeV the vector boson fusion production cross section of the Higgs boson becomes dominant over Higgstrahlung
- Will allow measurements of the couplings of the Higgs to the vector bosons from production and also fermions from decay



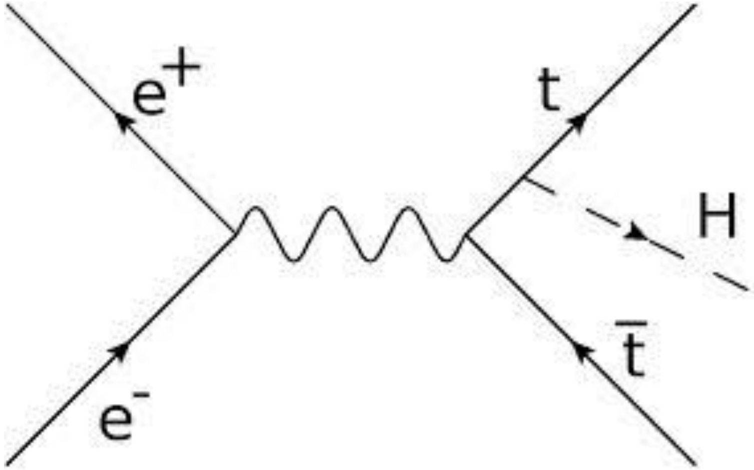
Vector Boson Fusion

- The cross section increases with energy so get more Higgs produced at 1 TeV
- ttbar background reduced
- Can improve precision with 1 TeV running



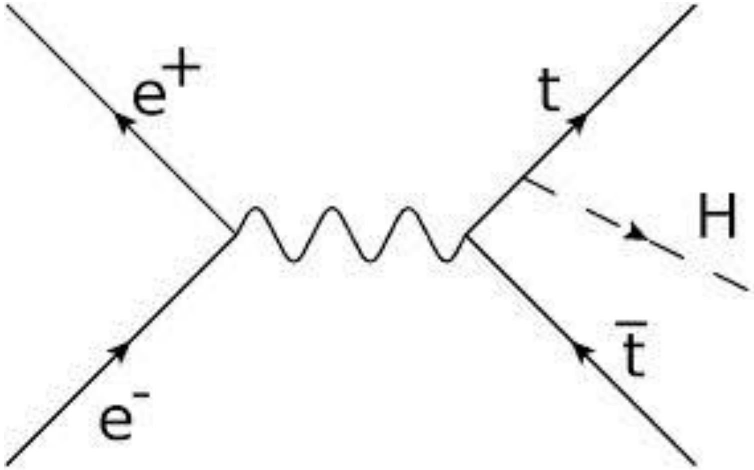
Top Higgs Yukawa Coupling

- The ttH process also becomes above threshold at approx 470GeV and could thus be studied at 500GeV
- Important as Yukawa coupling between top and Higgs is greatest due to mass of top quark
- Will allow an insight into new physics if couplings fluctuate from SM predictions

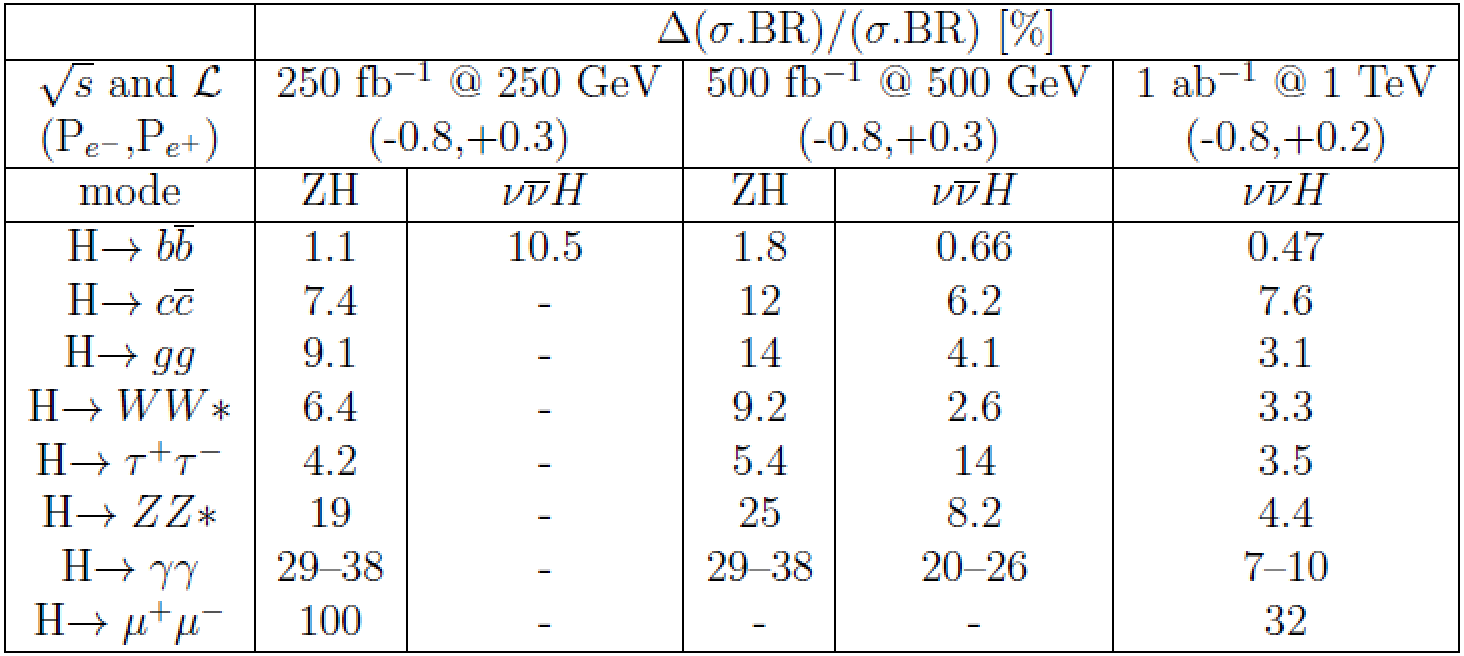


Top Higgs Yukawa

- The ttH cross section is maximal around 800GeV
- The ttbar background falls away with higher energy
- Running at 1 TeV yields a slightly worse S/N but would compliment other physics cross sections
- 800 GeV would be preferable



Results from TDR



	$\Delta(\sigma.\mathrm{BR})/(\sigma.\mathrm{BR})$ [%]				
$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-},P_{e^+})	250 fb^{-1} @ 250 GeV (-0.8,+0.3)		500 fb^{-1} @ 500 GeV (-0.8,+0.3)		1 ab^{-1} @ 1 TeV (-0.8,+0.2)
mode	ZH	$\nu\overline{\nu}H$	ZH	$\nu\overline{\nu}H$	$\nu\overline{\nu}H$
H→ $b\overline{b}$	1.1	10.5	1.8	0.66	0.47
H→ $c\overline{c}$	7.4	-	12	6.2	7.6
H→ gg	9.1	-	14	4.1	3.1
H→ $WW*$	6.4	-	9.2	2.6	3.3
H→ $\tau^+\tau^-$	4.2	-	5.4	14	3.5
H→ $ZZ*$	19	-	25	8.2	4.4
H→ $\gamma\gamma$	29–38	-	29–38	20–26	7–10
H→ $\mu^+\mu^-$	100	-	-	-	32

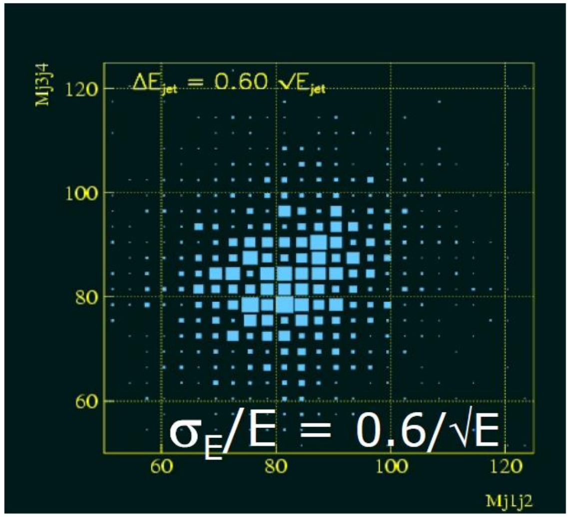
- Branching ratios extracted from the Physics volume of the TDR obtained via full scale detector models

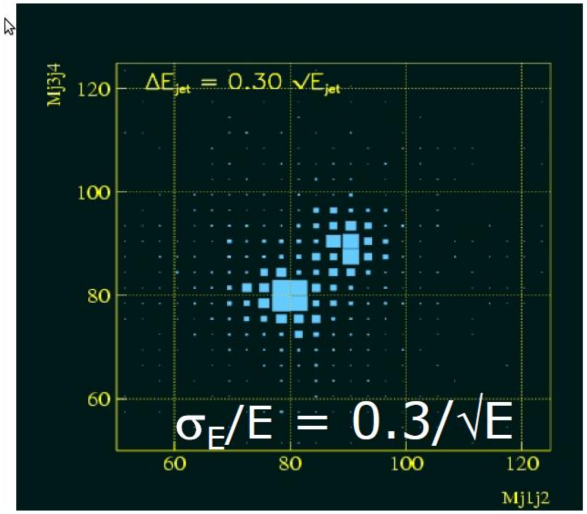
Detector Requirements

- To utilise the physics potential of the ILC the detector systems require excellent performance
- Be fully hermetic
- Must be able to handle large numbers of jets in the final states
- Accurately flavour tag jets
- Have compact calorimeter systems to get keep inside magnet
- Momentum resolution < 2x10-2 GeV/c

Detector Requirements

- Requires a jet energy resolution $\frac{E}{\sigma_E} = \frac{0.3}{\sqrt{E}}$ to untangle Z→qq and W→qq events

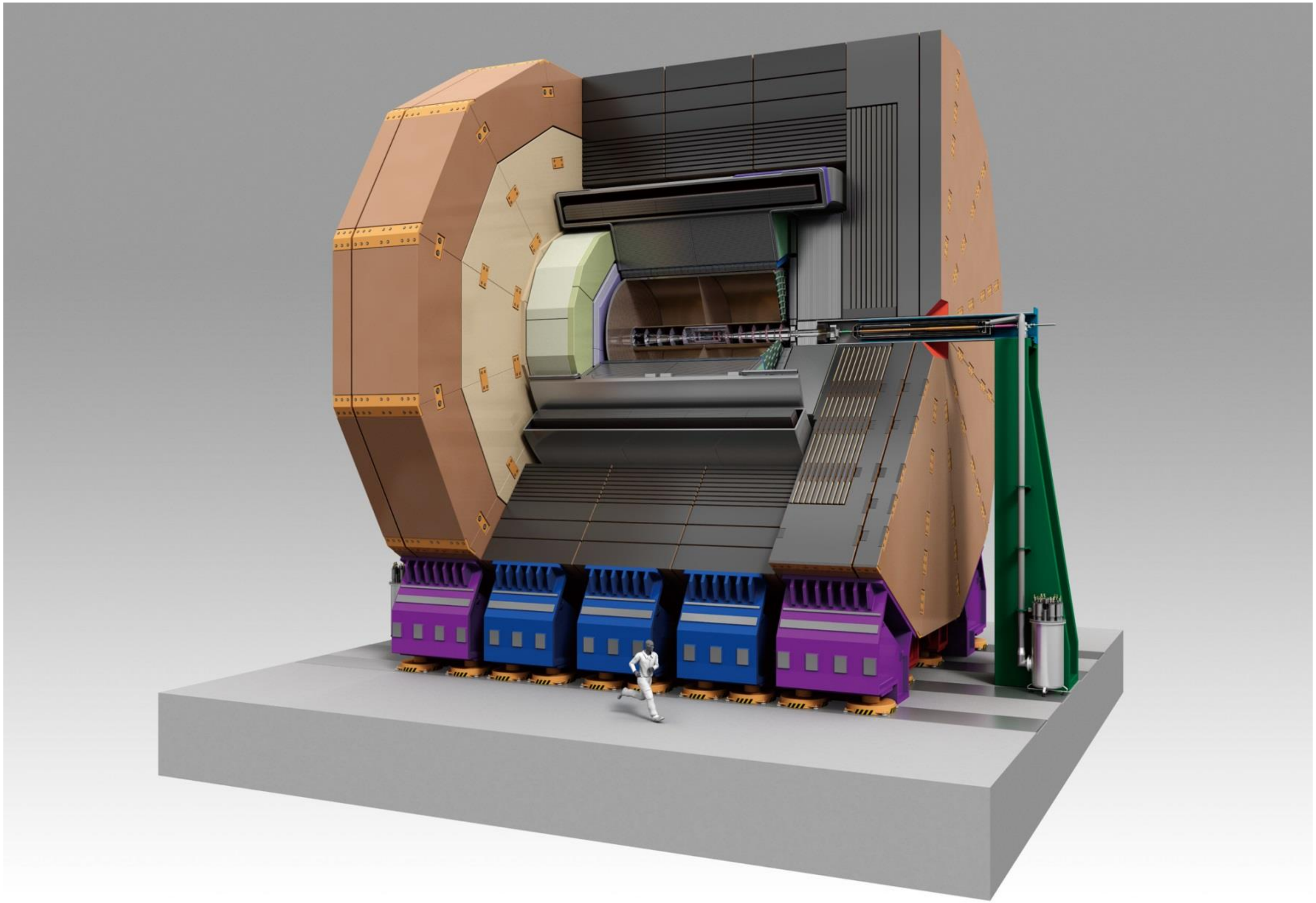




Particle Flow Algorithms

- Accepted way of doing this is to use Particle Flow Algorithms
- The entire detector is used to measure the event and every component must compliment all others
- Tracks individual particles in the jets
  - Charged particles are measured in trackers
  - Photons in ECAL
  - Neutrons hadrons in the HCAL
- Charged clusters in calorimeters are associated with tracks
- Measuring the energy this way reduces the uncertainty in the HCAL

International Large Detector



International Large Detector

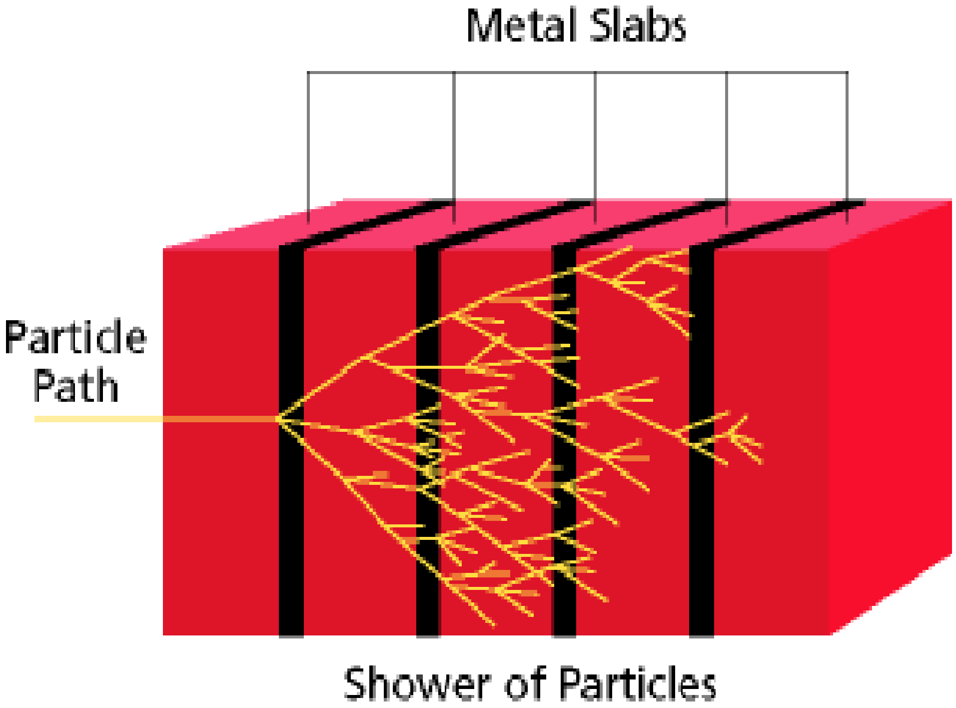
- Typical onion layer detector
- VTX→Trackers→Calorimeters→Magnets→Muons
- The dimensions and components of the ILD have been finalised for the TDR
  - e.g. Trackers will be TPC, ECAL absorber material will the tungsten
- The technologies have not been as R&D effort is still ongoing
- Most of the technologies in TDR now have a working prototype

International Large Detector

- An example of the range of choices can be highlighted using the Electromagnetic Calorimeter
- Has to be constructed of W to keep calorimeter small
- There are currently two readout technologies deemed to have demonstrated the properties required to enter the TDR
  - Silicon wafers → expensive but have excellent results
  - Scintilator strips → cheaper but results not quite as good
- Also a hybrid of the two
- Digital readout calorimeter which will use silicon wafers but will be much cheaper

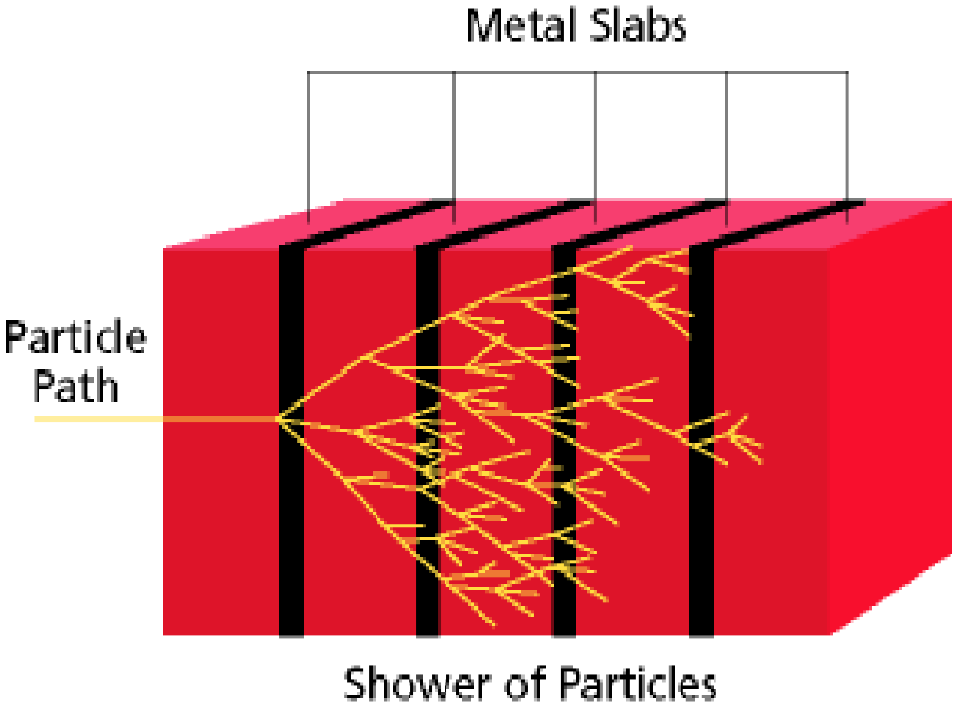
Digital Calorimetry

Sampling Calorimetry



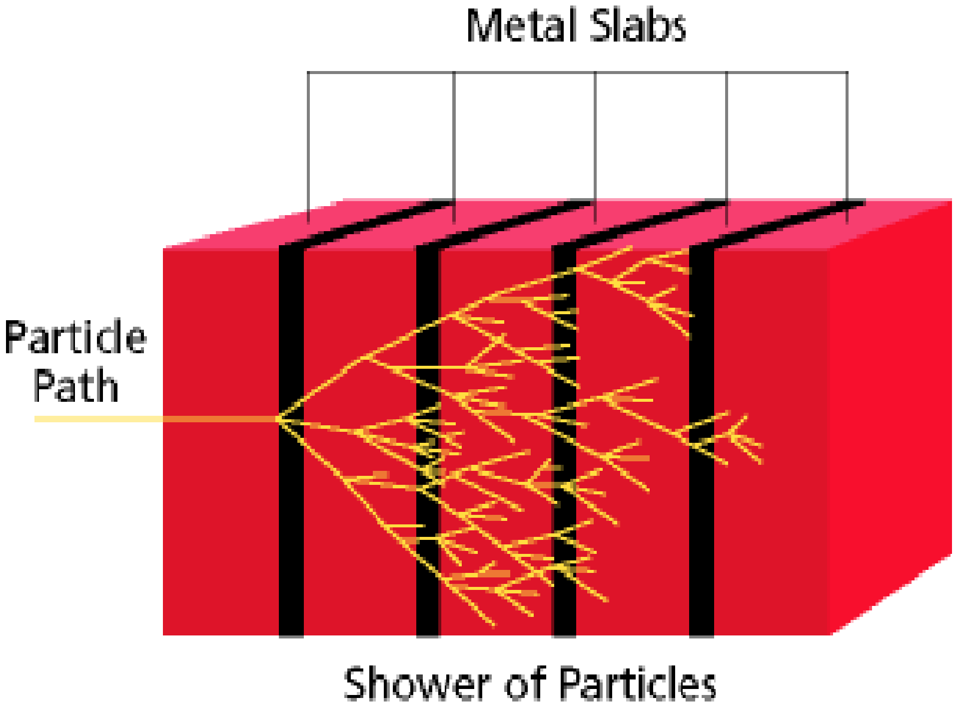
- Incident particle interacts with a dense material and a shower develops
- The shower particles then deposit energy in the sensitive regions
    - Si sensors, scintiallots, lAr etc…
- The sum the energy deposits and scale to the energy of incident particle

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
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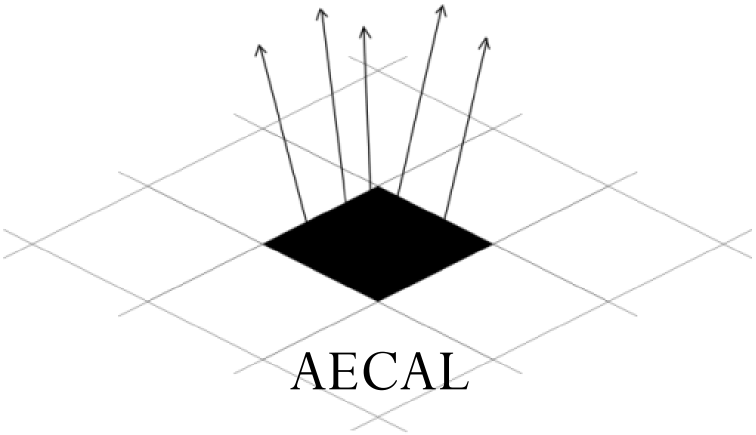
- Energy deposited in sensitiv[illegible]ver i[illegible] proport[illegible]umber of particle[illegible]
  - Fluct[illegible]ons i[illegible]gle
  - Particle velocity
  - Landau energy deposition

Remove this uncertainty by just counting number of particles

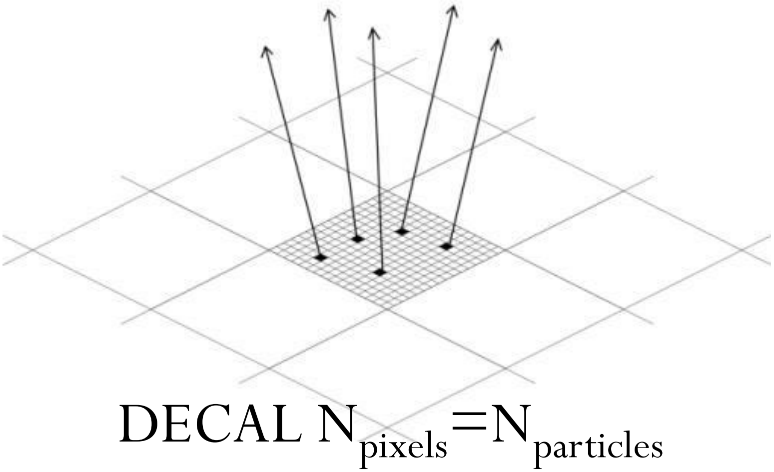
Digital Calorimetry: The Concept

- Make a pixelated calorimeter to count the number of particles in each sampling layer
- Have digital readout
- 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

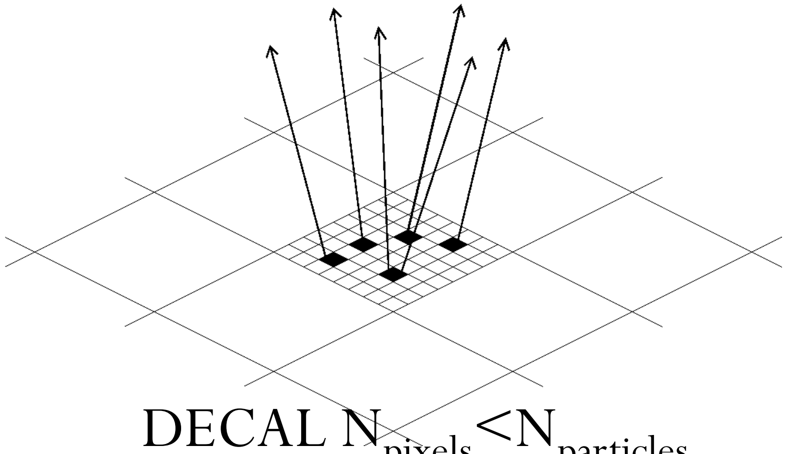
Digital Calorimetry: The Concept



AECAL

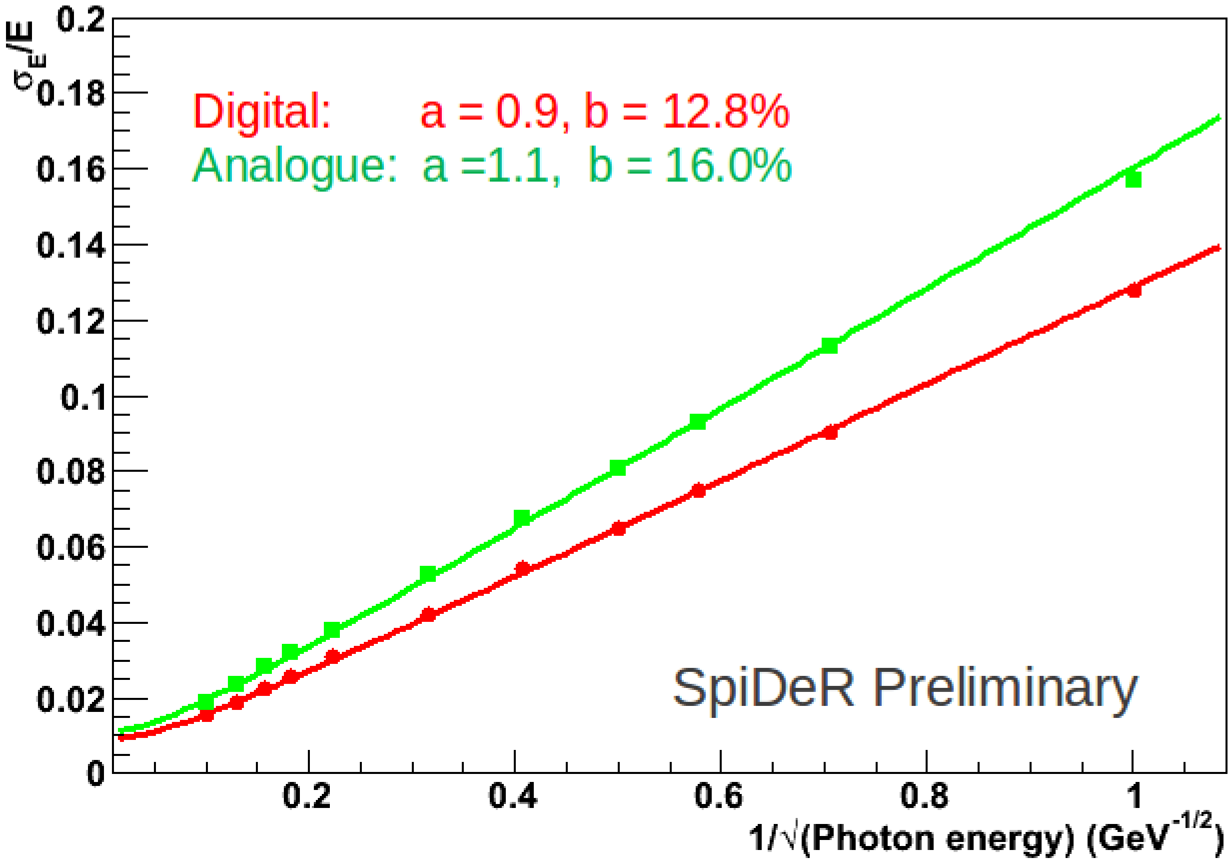


DECAL $N_{pixels}=N_{particles}$



DECAL $N_{pixels}<N_{particles}$

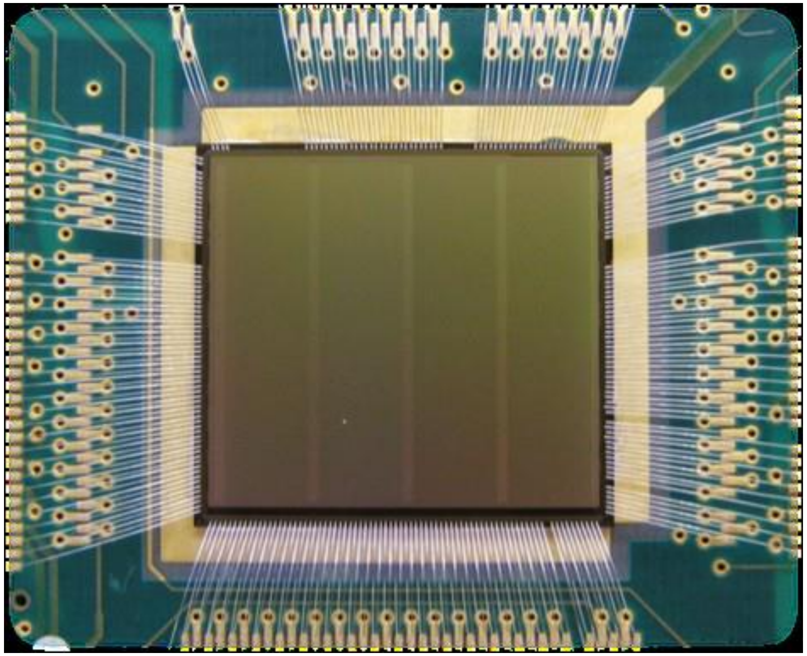
Energy Resolution Comparison



Simulation: 20 layers 0.6 & 10 layers 1.2

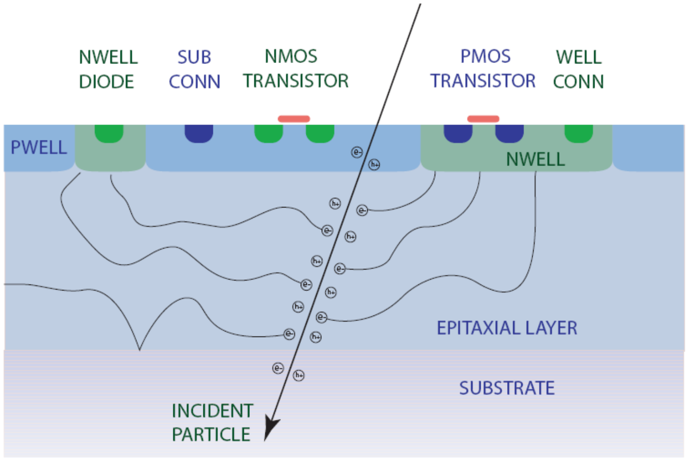
TeraPixel Active Calorimeter Sensor

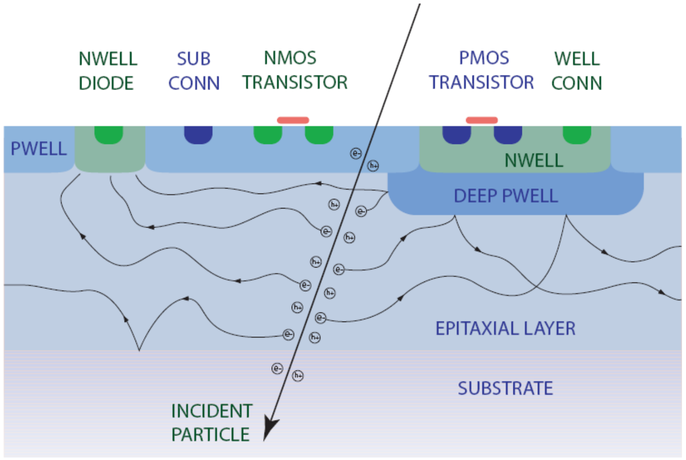
TPAC Sensor



- CMOS sensor
- 168x168 pixel grid
- 50x50 micron pitch
- 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)

INMAPS Process





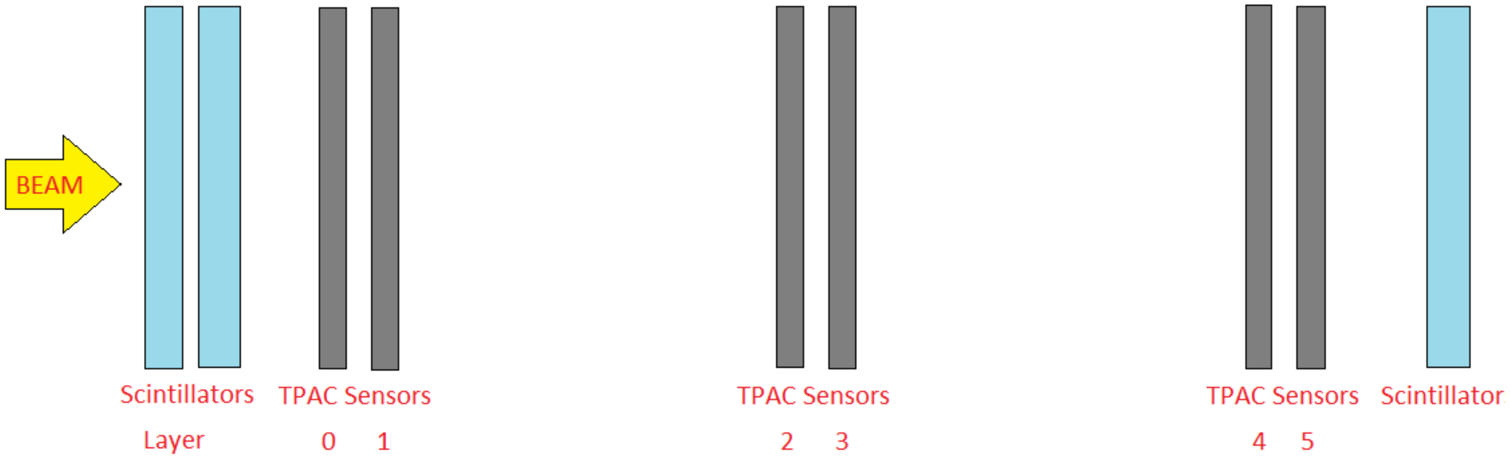
- CMOS architecture causes parasitic charge collection at N-wells reducing pixel efficiency
- INMAPS uses a deep P-well which inhibits the parasitic collection and increases signal at diodes
- Allows the use of full CMOS

Beam Testing of the TPAC Sensor

Overview

- TPAC Beam tests conducted at
  - CERN 20-120 GeV pions
  - DESY 1-5 GeV electrons
- Aim: to study the response of MIPs and particles showers

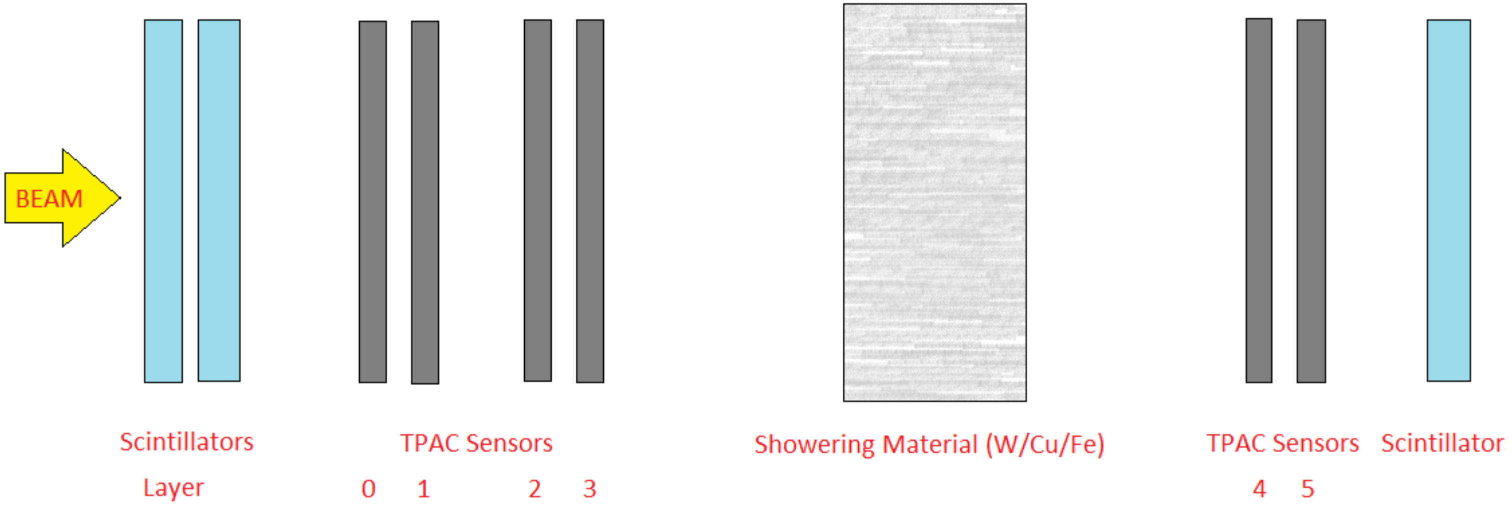
Experimental Setup



<u>Tracking Mode</u>

- Triggered with PMTs either side of the sensors
- Outer sensors fixed
- Inner sensors have thresholds scanned and studied the sensor efficiency

Experimental Setup



Showering Mode

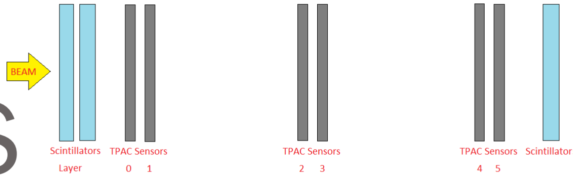
- Triggered with PMTs either side of the sensors
- Tracks found in the first four sensors
- Projected through material and properties of shower measured downstream

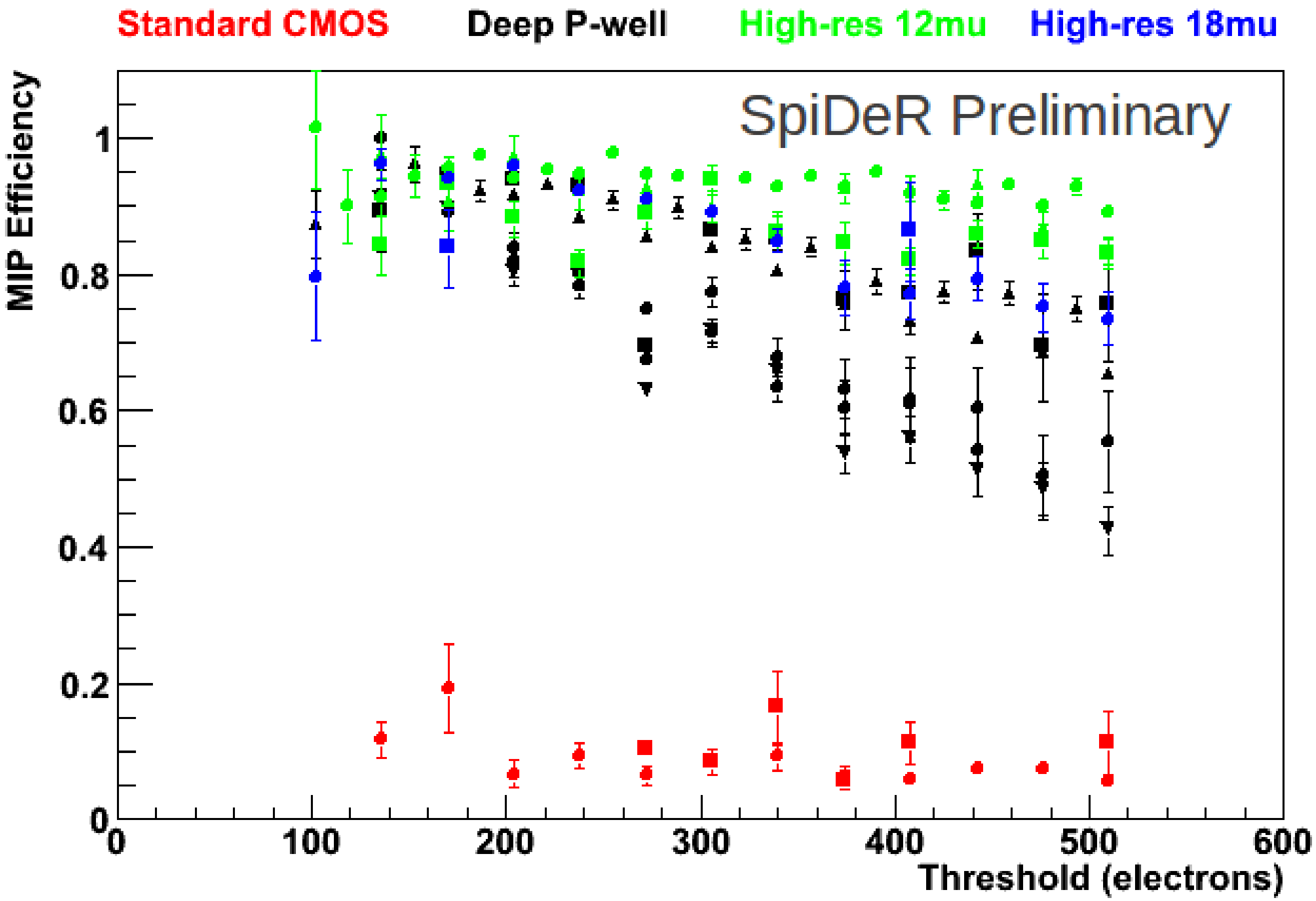
Note: 1cm2 sensor size so not all shower contained

Experiments

- Many many properties of the TPAC sensor studies
  - Noise
  - Electrical characteristics
  - Cluster sizes and shapes
  - Track reconstruction
  - Shower Multiplicites
  - Core density in the showers
- Due to time constraints just going to focus on two of these

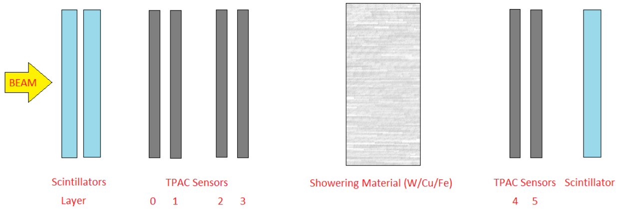
Pixel Efficiencies to MIPS

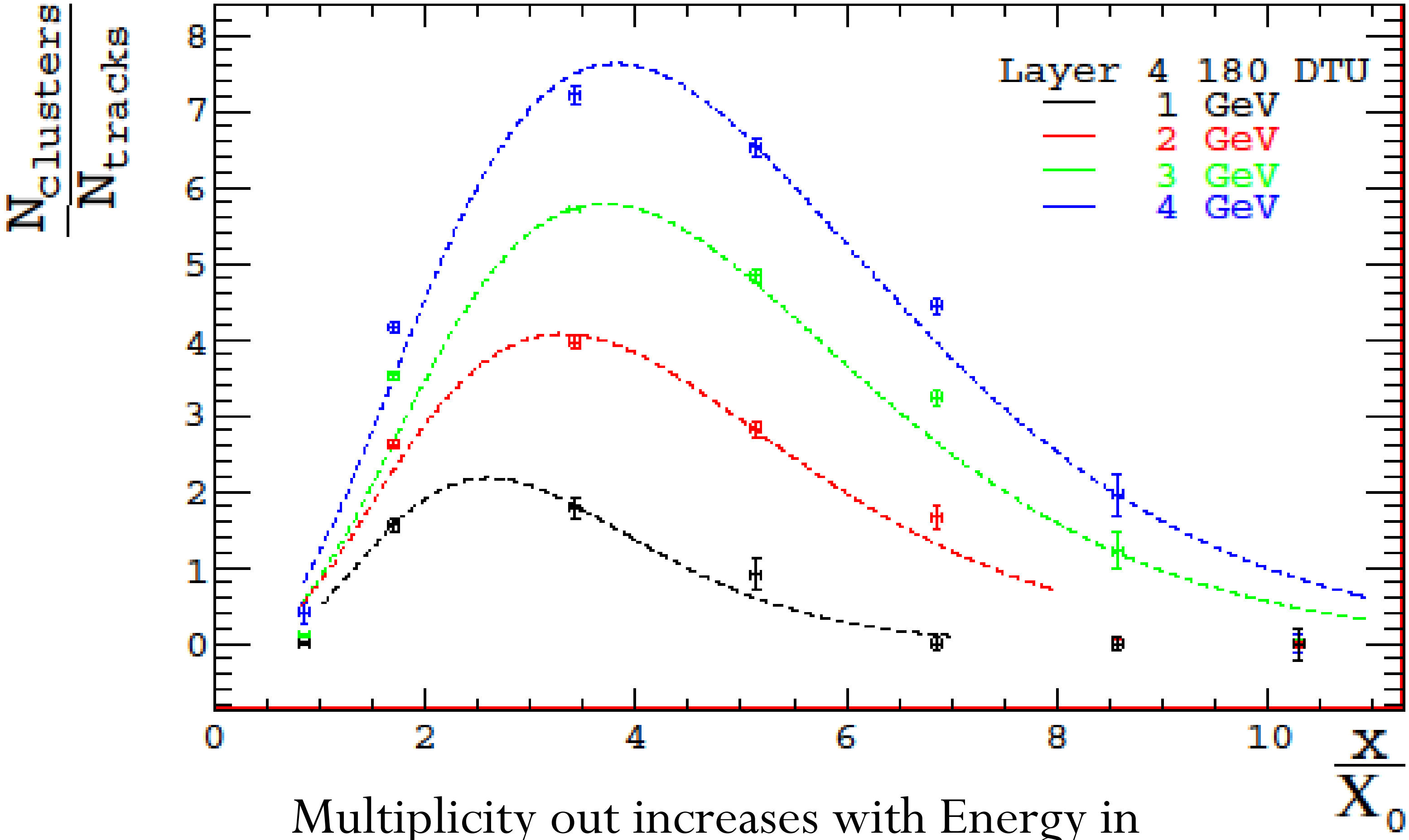




INMAPS vastly increases the efficiency over standard CMOS

Shower Multiplicities





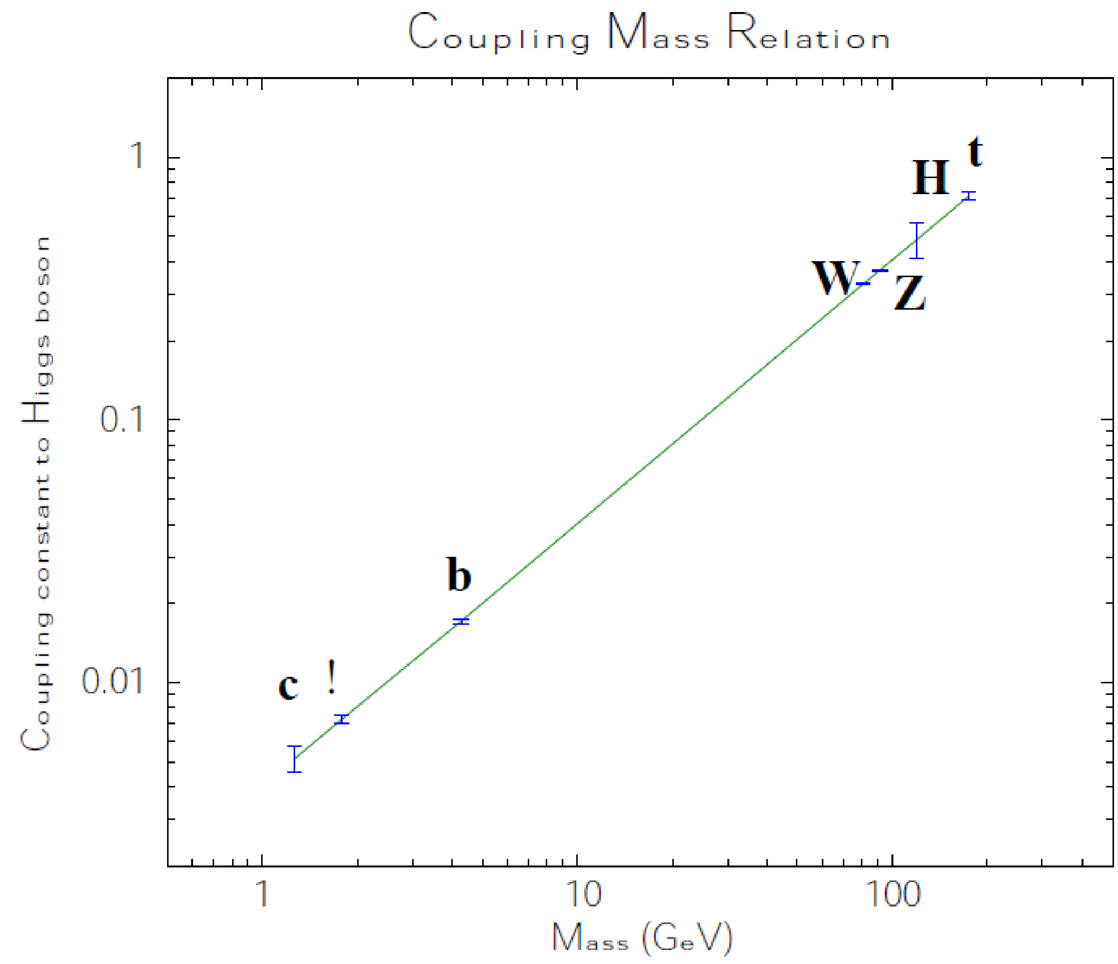
Multiplicity out increases with Energy in

Demonstrates DECAL concept to be valid…

But what is the impact on the physics?

Top Higgs Yukawa Coupling

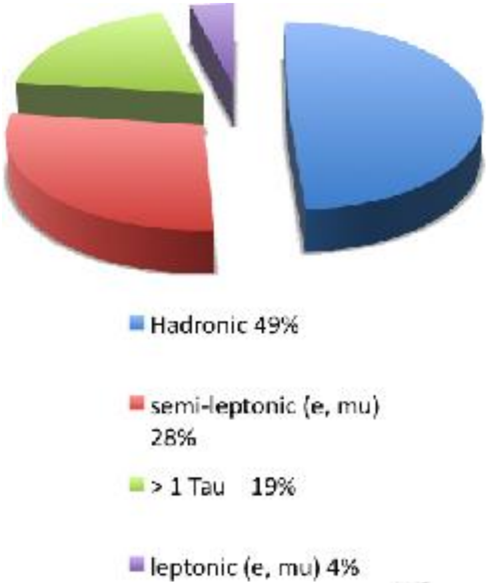
Top Higgs Yukawa Coupling

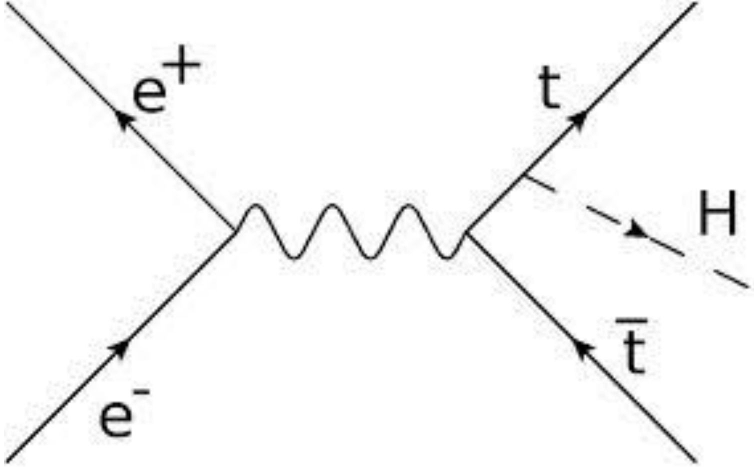


- Fermion coupling to Higgs dependent on mass
- $g_{ffH}=m_f/v$
- Top quark has greatest mass so coupling should be the strongest
- BSM predicts fluctuations < 10% in the couplings

Top Higgs Yukawa Coupling: Signal

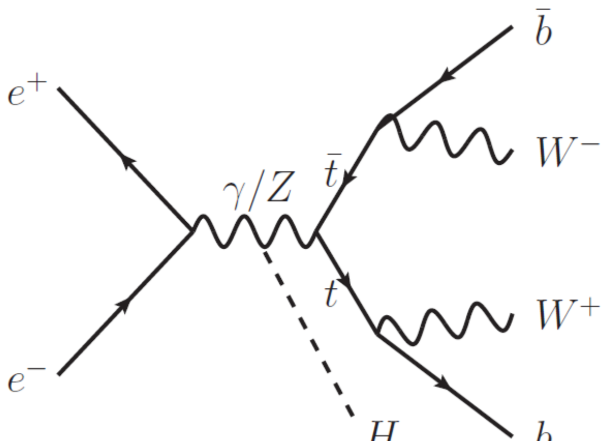
- Assume t→bW 100%
- W→qq, lv
- H→bb, WW, ZZ etc.
- MH=126 GeV so H→bb dominates
- Leads to three possible final states
- Fully hadronic
- Semileptonic
- Fully leptonic

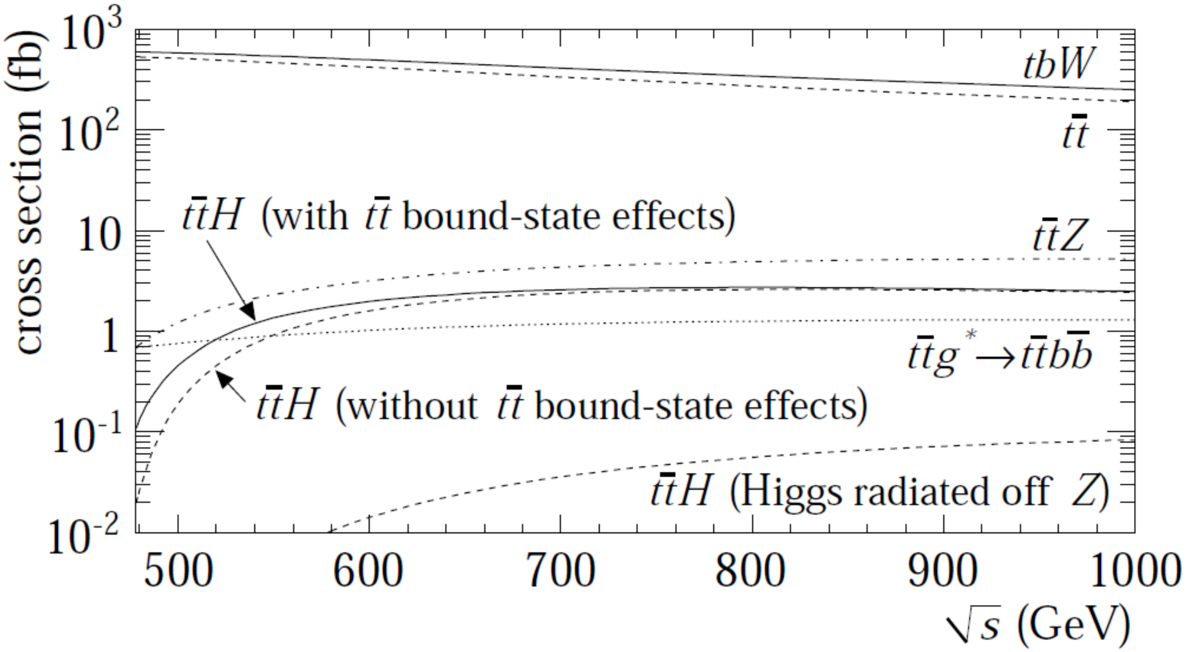




Top Higgs Yukawa Coupling: Backgrounds

- Main backgrounds arise from
  - $e^+e^- \rightarrow$ ttbb
  - $e^+e^- \rightarrow$ ttZ
  - $e^+e^- \rightarrow$ tt
- Also contribution from
  - H → other
  - Higgs-strahlung

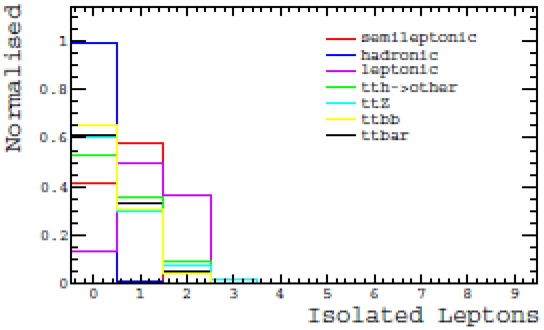




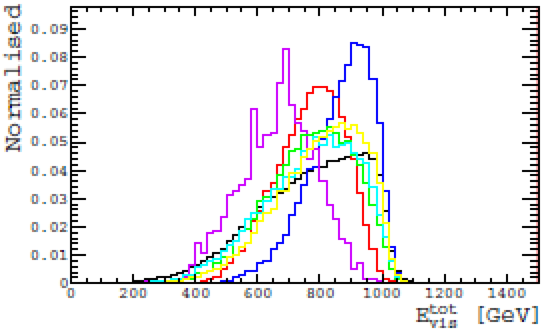
Analysis

- The strength of the coupling is related to the cross section of the process
- If we count the number of events we see we can calculate the coupling strength
- Just focused on the semi leptonic channel
- Full scale detector simulations using the conventional ECAL performed for the TDR
- Utilised a trained MVA to select the signal and reject the background
- Variables which were used in the selection
    - Total visible energy, properties of reconstructed neutrinos, number of isolated leptons, number of jets, flavour of jets, particle multiplicity and reconstructed masses

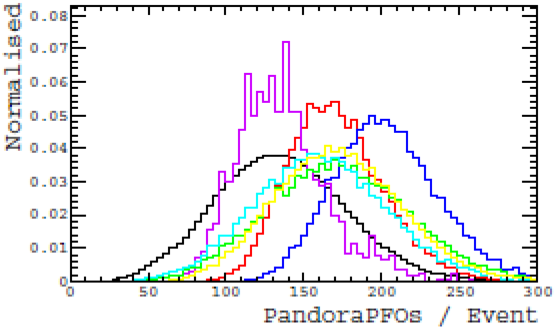
Variables



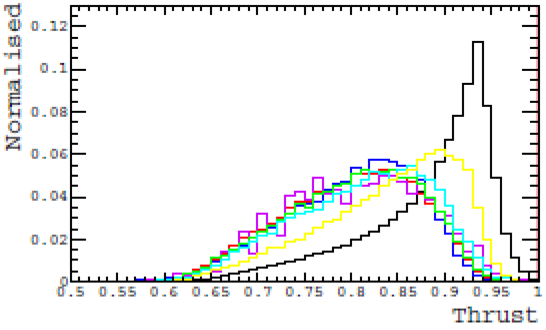
(a) Number of isolated leptons



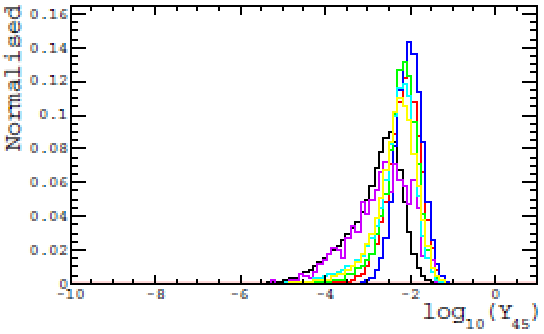
(b) Total visible energy



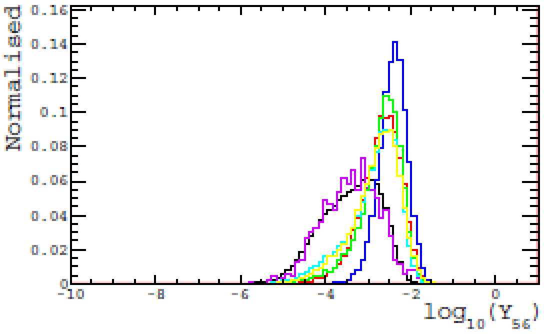
(c) Number of PandoraPFOs



(d) Thrust of event

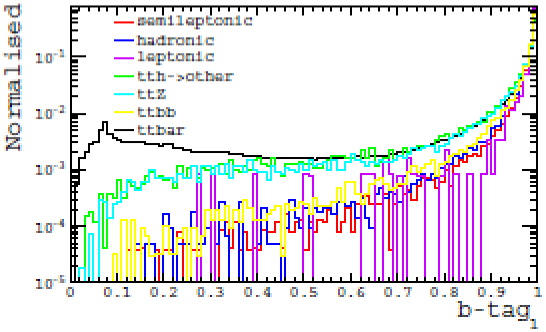


(e) Y_{45}

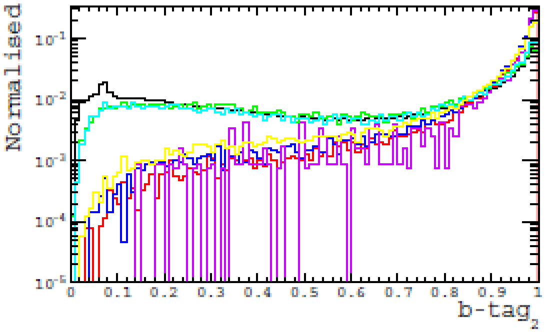


(f) Y_{56}

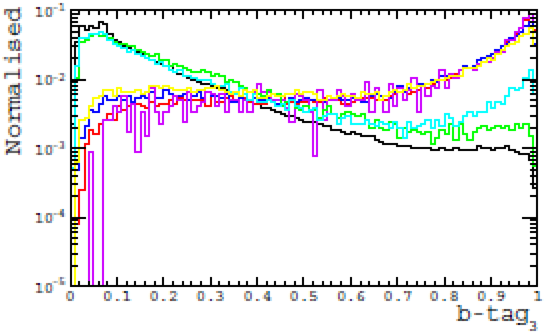
Flavour Tagging Information



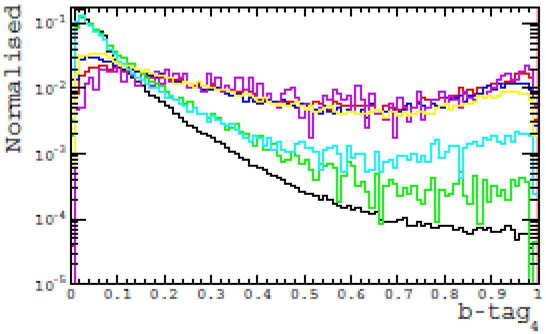
(a) Largest b-tag in an event



(b) Second largest b-tag in an event

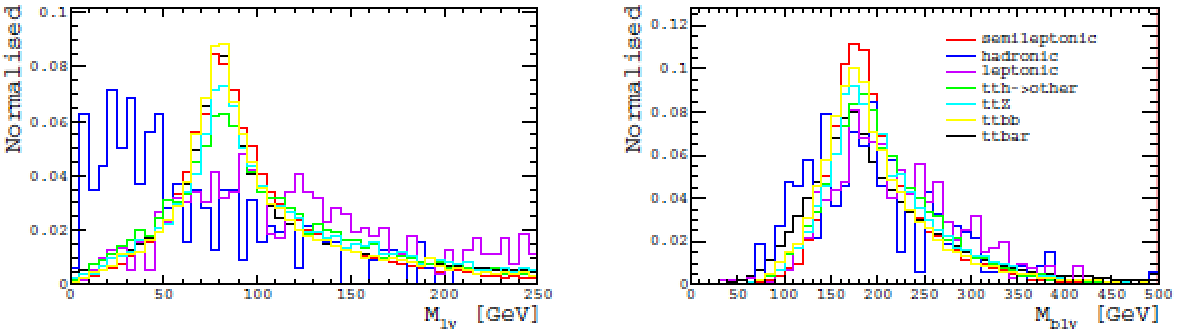


(c) Third largest b-tag in an event

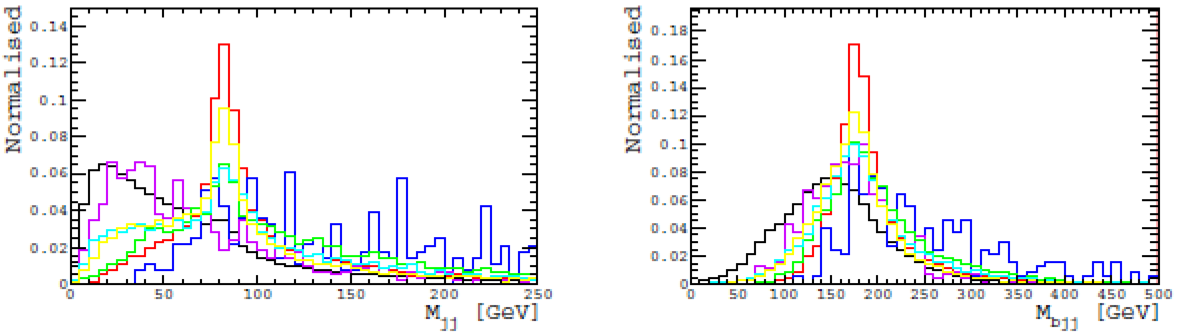


(d) Fourth largest b-tag in an event

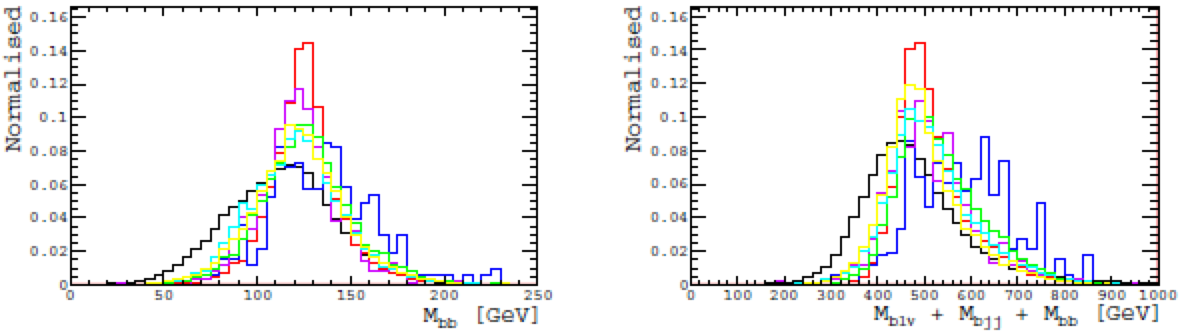
Rec Mass



(a) Reconstructed mass of leptonic W boson (b) Reconstructed mass of leptonic top quark



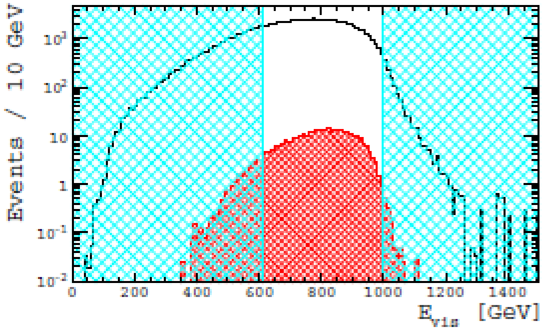
c) Reconstructed mass of hadronic W boson (d) Reconstructed mass of hadronic top quark



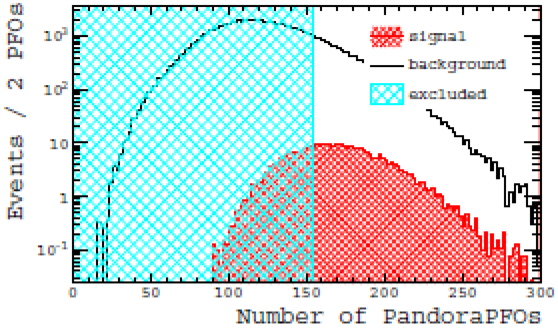
(e) Reconstructed mass of Higgs boson (f) Total reconstructed mass of the events

Cut based

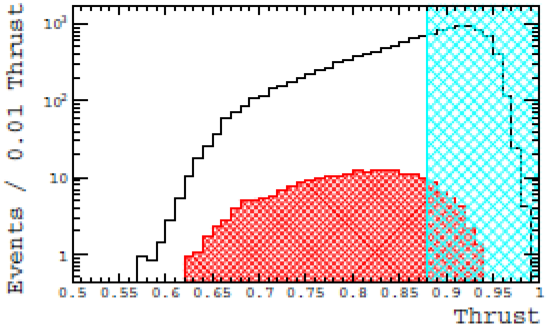
- A simple cut based analysis shows excellent background reduction due to the different shapes of the tt distributions
- Harder to remove ttZ ttbb
- Overall sig = 5.4 and uncertainty on coupling = 9.6%



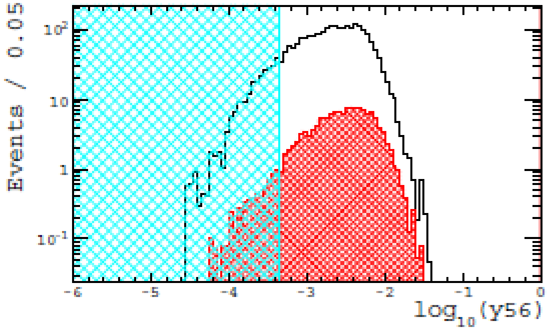
(a) Total visible energy



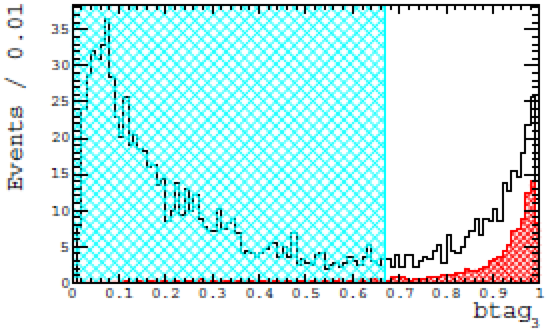
(b) PandoraPFOs per event



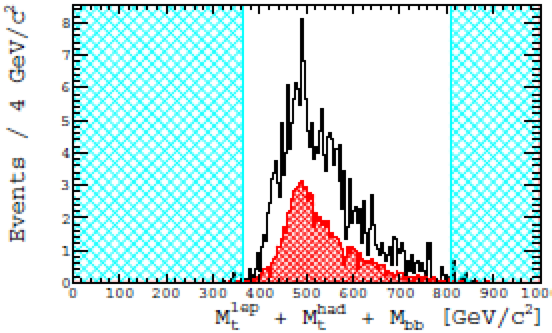
(c) Thrust of event



(d) $\log_{10}(Y_{56})$



(e) Third largest b-tag



(f) Total reconstructed mass of event

TMVA

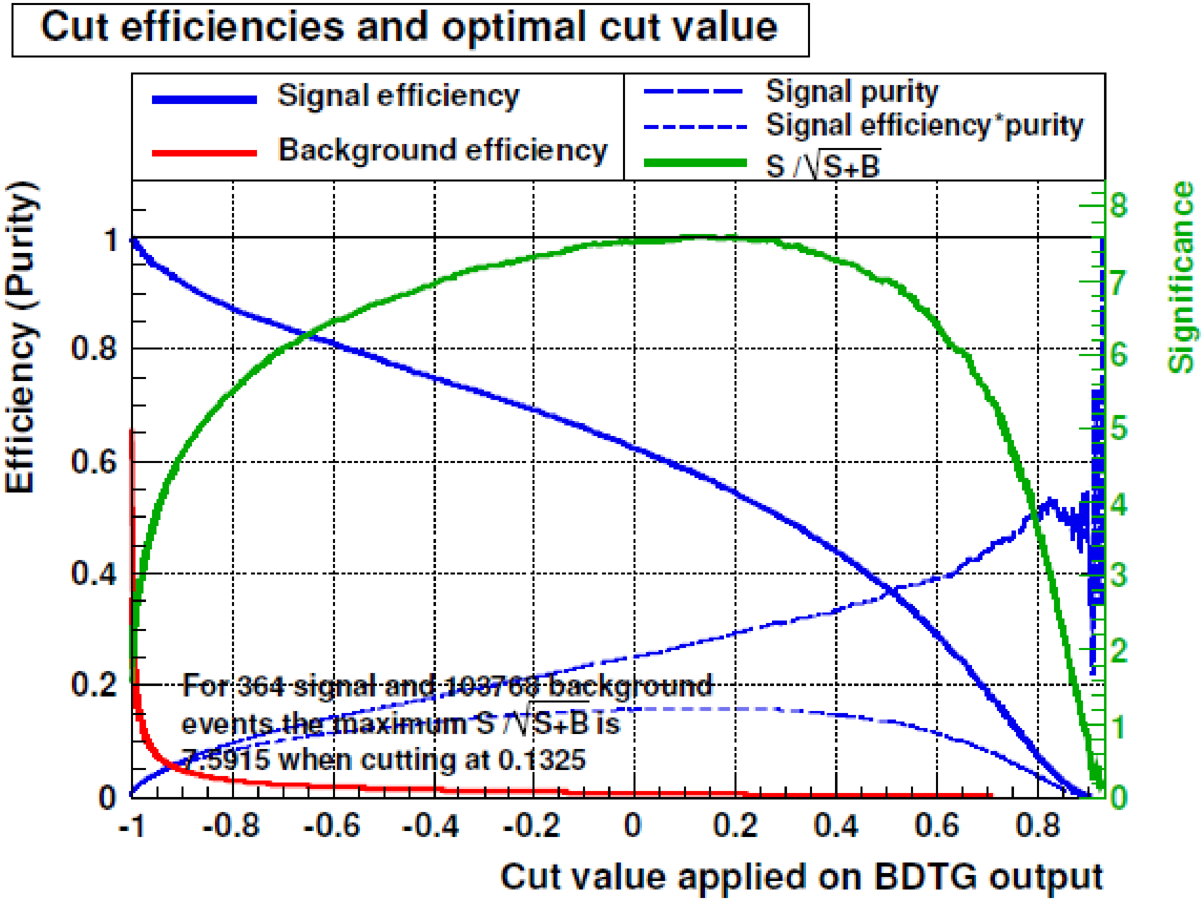


Figure 5.15: The response of the multivariate training showing the efficiency of the signal and combined background; signal purity, and significance against the BDTG value.

- TMVA analysis yields a significance of 7.6 of signal to background
- This equates to an uncertainty on the measurement of the coupling of 6.9%

Combined analysis

- When the results of the semi leptonic analysis (performed by me) and the hadronic decay (as performed by Tomohiko Tanabe at KEK) were combined an uncertainty on the coupling was found to be 4.3%
- When compared to the SiD analysis (as performed at CERN) the two detectors were in excellent agreement
- A joint paper us currently being written
- A measurement at this precision could rule out some BSM which predict the existance of multiple Higgs bosons
- Further reading can be found in the ILC TDR or here http://www-flc.desy.de/lcnotes/ (my note…)

Impact on the coupling measurement from the DECAL

DECAL Model

- To evaluate the impact of the DECAL on the physics potential I ran some simulations to compare with the TDR results
- Kept all of the parameters of the detector fixed except for the readout of the ECAL except
  - Cell sizes reduced to 50x50 microns
  - Sensitive thickness to 12 microns to match TPAC sensor
  - Conversion factors from deposited energy to incident energy re-evaluated
  - Digital readout turned on

Impact on Jet energy resolution

Conventional ECAL

Z→uds dijet events

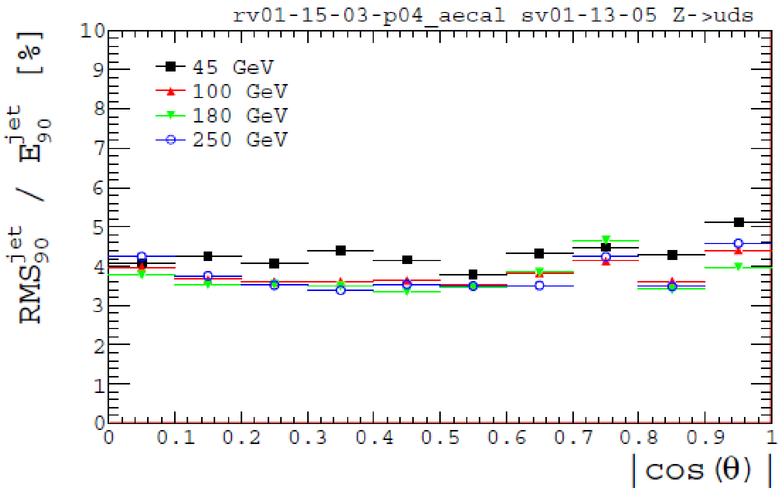


Figure 6.3: Jet energy resolution ($\frac{RMS_{90}}{E_{90}}$) as a function of angle from the beamline for the Z→uds events at centre of mass energies of 91, 250, 360, and 500 GeV for the AECAL using iLCSoft v01-13-05 and reconstruction v01-15-03-p04_aecal.

DECAL

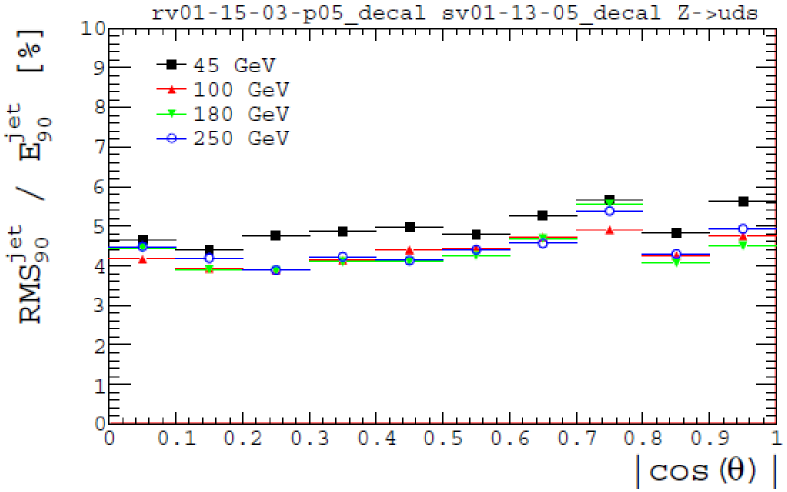
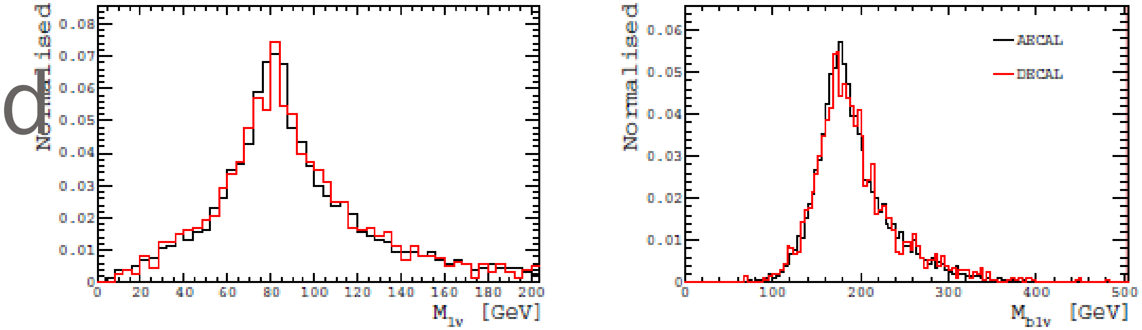


Figure 6.4: Jet energy resolution ($\frac{RMS_{90}}{E_{90}}$) as a function of angle from the beamline for the Z→uds events at centre of mass energies of 91, 250, 360, and 500 GeV for the DECAL using iLCSoft v01-13-05_decal and reconstruction v01-15-03-p05_decal.

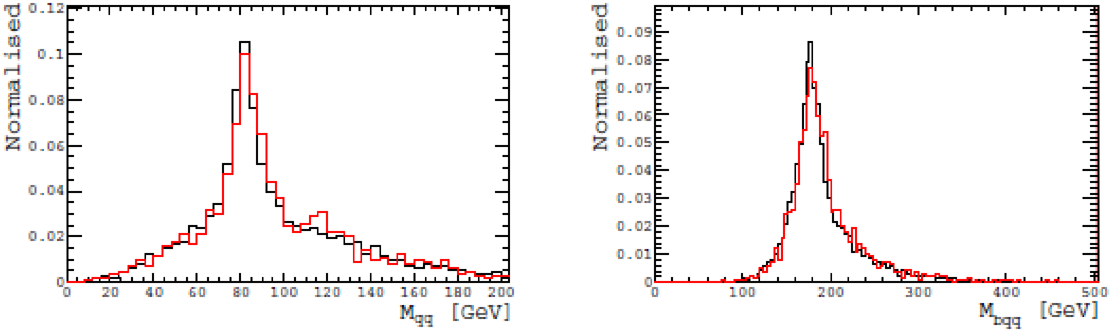
Resolution marginally degraded with DECAL

Impact on reconstructed mass

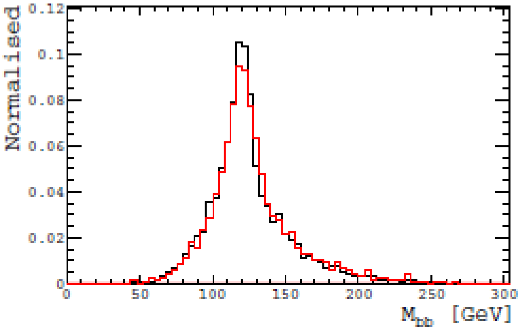
- DECAL = Red
- ECAL = Black
- Can see a slight overestimation in the DECAL over the ECAL in the masses



(a) Leptonic W boson candidate (b) Leptonic top quark candidate



(c) Hadronic W boson candidate (d) Hadronic top quark candidate



(e) Higgs boson candidate

Treatment of Backgrounds

- Only focused on the variables which lead to the greatest increase in the significance from previous analysis
- Thrust of event
- Flavour tag information
- Reconstructed masses

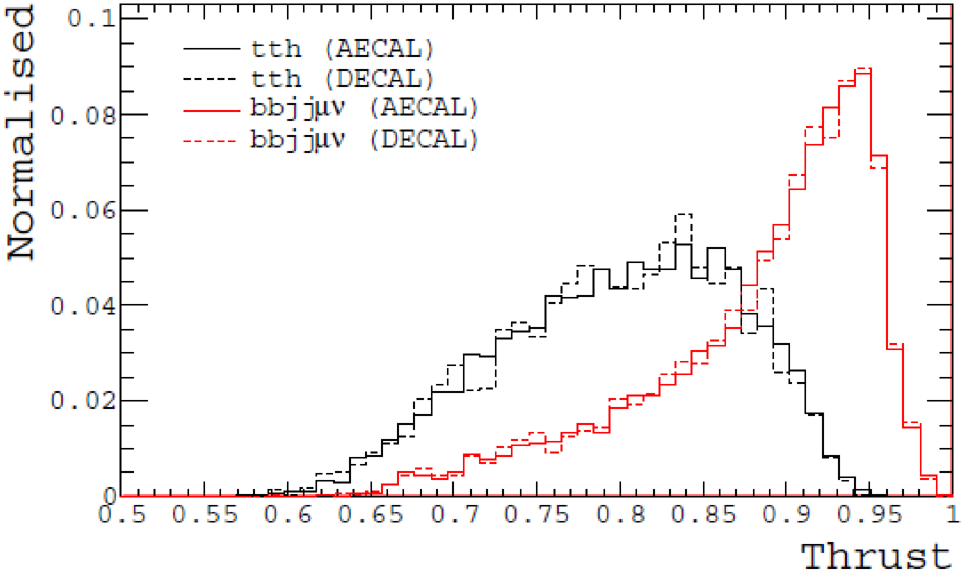


Figure 6.10: The calculated thrust of the event for both the semileptonic $t\bar{t}H$ (black) a the $t\bar{t}$ channel including four jets and one muon (red) for the AECAL (solid lines) a DECAL (dashed lines).

Treatment of Backgrounds

- Only focused on the variables which lead to the greatest increase in the significance from previous analysis
- Thrust of event
- Flavour tag information
- Reconstructed masses

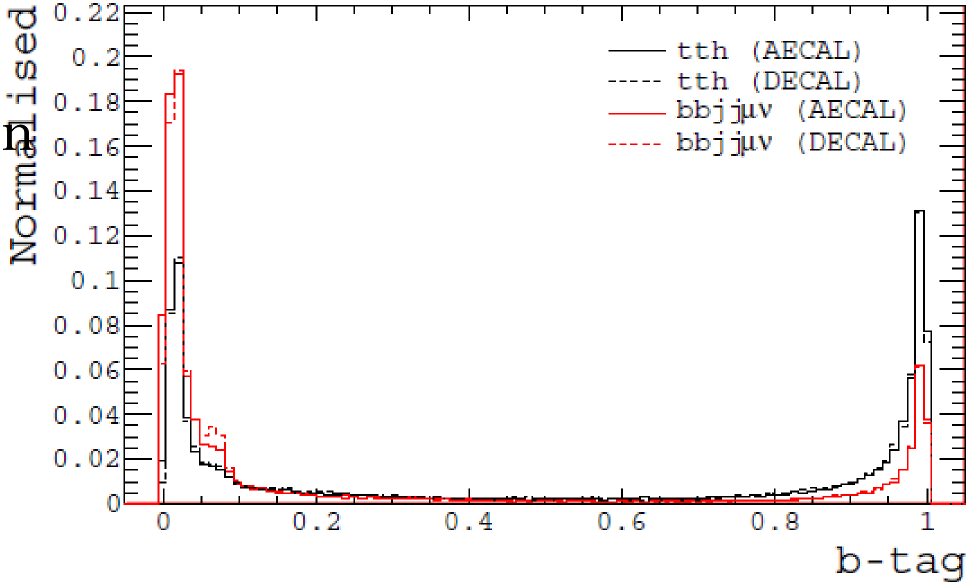
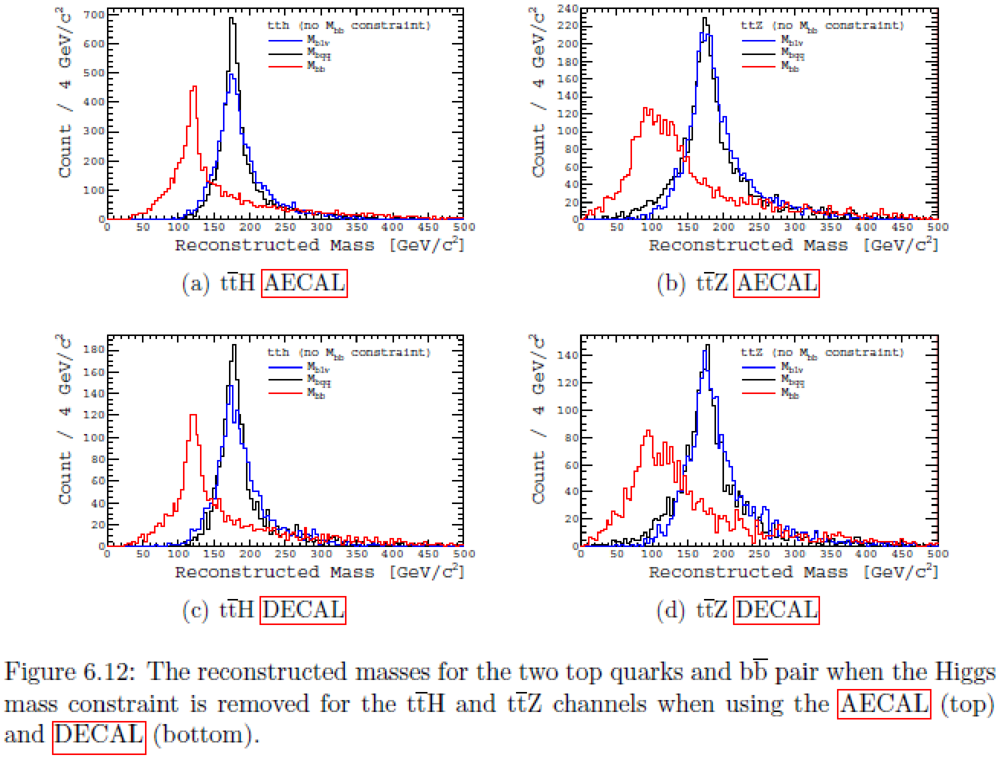


Figure 6.11: The b-tag values of all the jets in an event for both the semileptonic $t\bar{t}H$ (black) and the $t\bar{t}$ channel including four jets and one muon (red) for the AECAL (solid lines) and DECAL (dashed lines).

Treatment of Backgrounds

- Only focused on the variables which lead to the greatest increase in the significance from previous analysis
- Thrust of event
- Flavour tag informatio
- Reconstructed masses



(a) $t\bar{t}H$ AECAL (b) $t\bar{t}Z$ AECAL

(c) $t\bar{t}H$ DECAL (d) $t\bar{t}Z$ DECAL

Figure 6.12: The reconstructed masses for the two top quarks and $b\bar{b}$ pair when the Higgs mass constraint is removed for the $t\bar{t}H$ and $t\bar{t}Z$ channels when using the AECAL (top) and DECAL (bottom).

Treatment of Backgrounds

- Only focused on the variables which lead to the greatest increase in the significance from previous analysis
- Thrust of event
- Flavour tag information
- Reconstructed masses

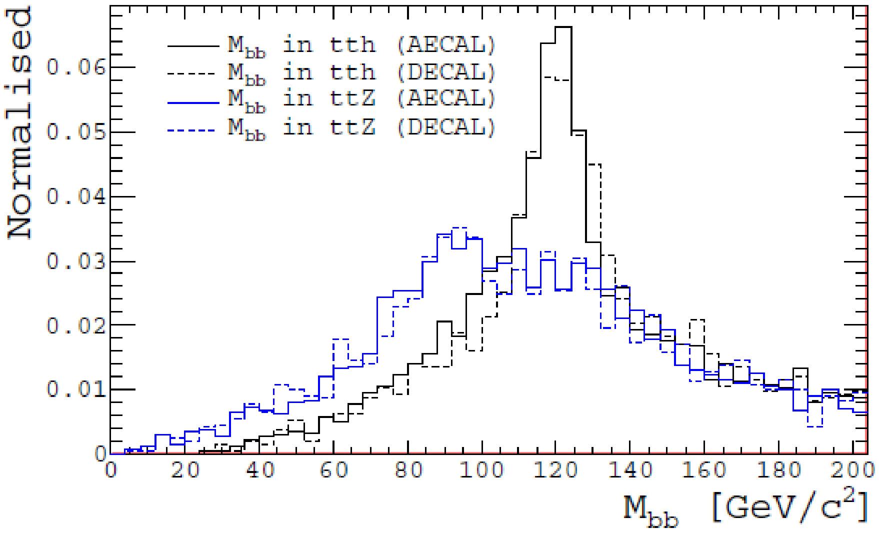


Figure 6.13: The reconstructed mass of the $b\bar{b}$ system when the Higgs mass constraint is removed for the $t\bar{t}H$ (black) and $t\bar{t}Z$ (blue) samples for the AECAL (solid lines) and DECAL (dashed lines).

Impact of DECAL

- Observe a slight overestimation in reconstructed masses
- Distributions of main variables to cut down backgrounds seem unchanged
- Applying the original analysis should yield very similar results for both the ECAL and the DECAL
- This is an excellent result for the reconstruction of events using a DECAL as the main parameters of the detector were optimised for the conventional ECAL.

Conclusions

- With the discovery of the Higgs boson we need a linear collider to accuratley measure its properties
- A DECAL offers the potential to reduce the uncertainty closer to the intrinsic resolution at a reduced cost to the overall machine
- The TPAC sensor show technology works and that we can observe the differing behaviour of the e/m showers even when only sampling a small region of the shower
- The ILC will be able to measure the couplings of the Higgs boson to the top quark with < 5% uncertainty
- The introduction of the DECAL does not appear to impact on this value

Any Questions??

(… only easy ones please….)