The Timing of Hadronic Showers in a Highly Granular Scintillator-Tungsten Calorimeter

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Calorimeter for ILC

Excellence Cluster Universe

Outline

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The Motivation:
Access the TeV Scale with a Linear e^+e^--Collider

The Energy of the next Linear Collider is still unclear:
$\longrightarrow$ Depends on what LHC finds!

- Existing Concept: The ILC with 500 GeV CMS
- But maybe we need a Multi-TeV Collider (new CLIC Concept)
- The Challenge (for us): Calorimetry at such a Collider is difficult!

Key issue: Leakage

We need a very deep HCAL to contain the Showers
But: Costs of the magnet increases drastically with its radius
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Steel ($\sim 8 g/cm^3$) $\rightarrow$ consider tungsten ($\sim 19 g/cm^3$)

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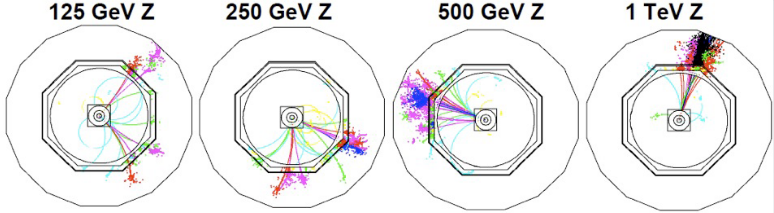

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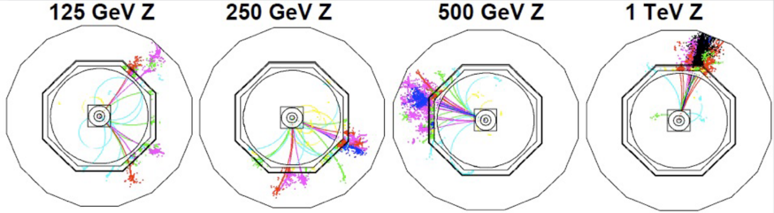

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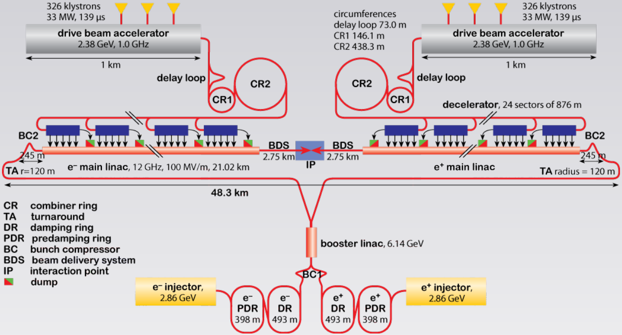

Future Linear e^+e^--Collider: Key Parameters

CMS energy:	3 TeV
Linac repetition rate:	50 Hz
Bunch train length:	156 ns
No. of bunches / pulse:	312
Bunch separation:	0.5 ns (note: 25 ns @ LHC)

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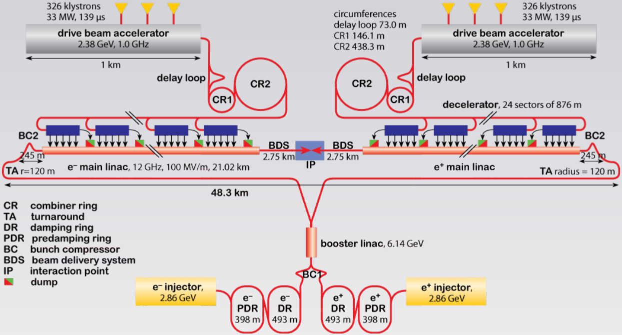

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Consequences of the Ultra-Short Bunch Separation

Background at a Multi-TeV e^+e^--Collider: $\gamma\gamma$ – Interaction

- **Source**: Beamstrahlung, Beam Focussing ⇒ Bremsstrahlung ...
- **500 GeV (ILC)**: $\gamma\gamma \rightarrow$ Leptons predominant (mainly @ low E)
- **Multi-TeV (CLIC)**: $\gamma\gamma \rightarrow q\bar{q} \rightarrow$ *Jets* CH open up (@ high E)
  ⇒ High σ for fake Jets at CLIC likely to enter Detector
  ⇒ High occurrence: ∼ 3.3 Events/BunchX , ∼13 Particles/BunchX
  ⇔ Rate of interesting physics events (e.g. $q\bar{q}$):
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4D Detector Necessary

- Avoid accumulation of backgr. events: ∼1k per 156 ns (≙ 1 BunchTrain)
- In bunch train: Match Events with individual bunch crossings
  ⇒ Needs good time resolution in all detectors → also in calorimeters!
- Distinguish Physics and $\gamma\gamma$ Events through Energy and Timing Info
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Challenges for Calorimetry

Questions:

- Can those requirements be met?
- What is the influence of the time structure of the hadronic showers themselves? How to choose the energy integration time?
- How well does Tungsten work as an absorber for a Particle Flow HCAL? How do showers evolve?

Tungsten vs. Steel

- very different λ/X_0 ratio
  $\rightarrow$ em subshowers very short
- heavier nucleus: More neutrons in the shower
  $\rightarrow$ cause late energy depositions through nuclear excitation processes

Material	Fe	W
λ_I [cm]	16.77	9.95
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Beam tests needed to answer the questions and to take on the challenges!

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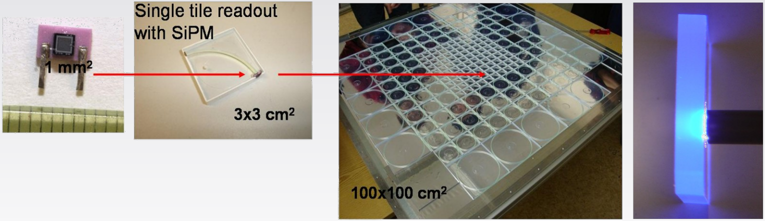
What we have: The CALICE Analog Hadron Calorimeter (AHCAL)

CALICE: Test beam program to evaluate technologies for particle flow calorimetry

- Sampling calorimeter with alternating layers of
  1. Steel absorber plates (Thickness: 2 cm)
  2. Highly granular pattern of plastic scintillator cells

  → Enable precise particle separation within the shower of a jet
- Well tested prototype: TB Runs @ CERN 06/07 and FNAL 08/09



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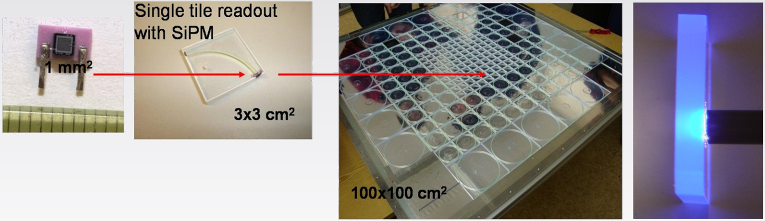

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$\Rightarrow$ The Dream: 4D Calorimetry

What is planned: CALICE TB with W Absorber and Timinig Parasite

CALICE Plans

- Buy tungsten absorber plates: Need ~5 Tons (being delivered by now)
  Note: Steel: 5-10€/kg ⇔ W: 100€/kg (size of Mars bar)
- Reuse the active CALICE Layers
- Aim: 3D Study hadron showers in a highly granular W HCAL

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Our Plans (together with the CALICE Collaboration)

- Create 1 Layer with 16 Scintillator Tiles (designed to replace 1 HCAL Layer)
- Readout with fast Digitizer → 1.25 GSa/s ≙800 ps between two measurement points (Note: 1k€per Ch)
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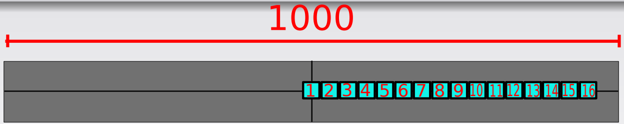

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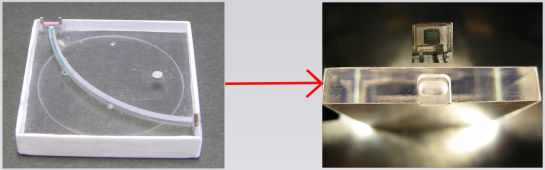
The Intrinsic Signal of Scintillator Tiles



Direct Coupling

WLS adds additional delay to photon signal (excitation process)
⇒ Couple photomultiplier directly to the scintillator tile
(Possible through recent development of blue-sensitive SiPMs)
⇒ Needs: Modification of tile geometry to obtain uniform response to penetrating particles (actually my diploma thesis)

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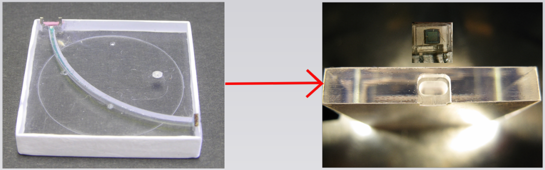

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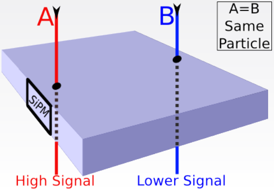

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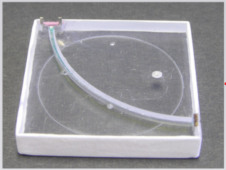

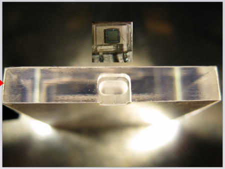

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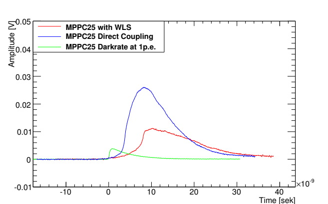
Result from the test bench:

- Position Sr^{90} on the tile (β-**Decay**)
- Record and average the signal of 500 penetrating e^{-}
- Direct Coupling: Signal is faster and fast peaking (!)



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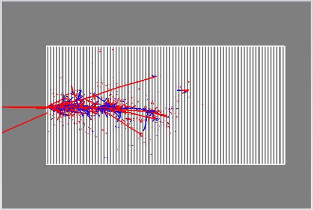
Geant4 Simulation of Our Timing Layer in the Tungsten HCAL

Simulations:

- 32 Layers W interleaved by 32 Layers of scintillator (CALICE-like)
- 200k π^- Events @ 3,5,7,10,12GeV (E_{max} of PS)



1.: Analysis of Timing Strip:

- Analyze one horizontal strip of 31 scintillator cells (size $3 \times 3 \times 0.5\ \mathrm{cm}^3$)
- Focus on time stamp and height of E depositions in these cells
- Longitudinal position flexible (here: Layer 10,20,30)
- Find start point of the hadron shower
  $\Rightarrow$ Determine strip position relative to shower start
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2.: Analysis of All active Layers (No Shower Start Finder):

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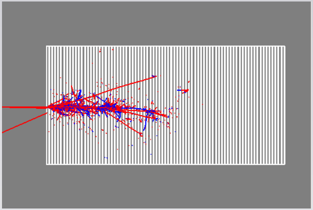

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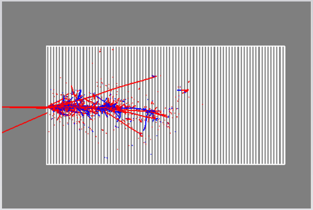

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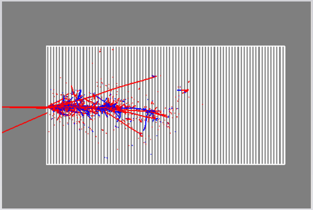

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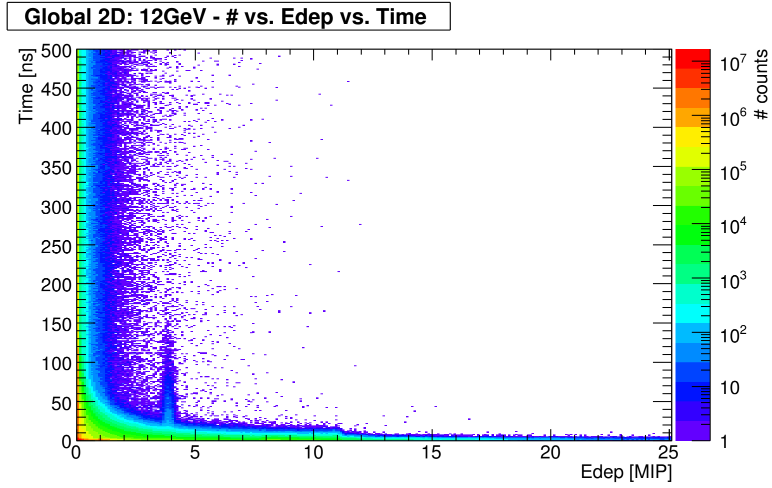
Rich Time Structure in a Tungsten Calorimeter Problem for a Timing HCAL?



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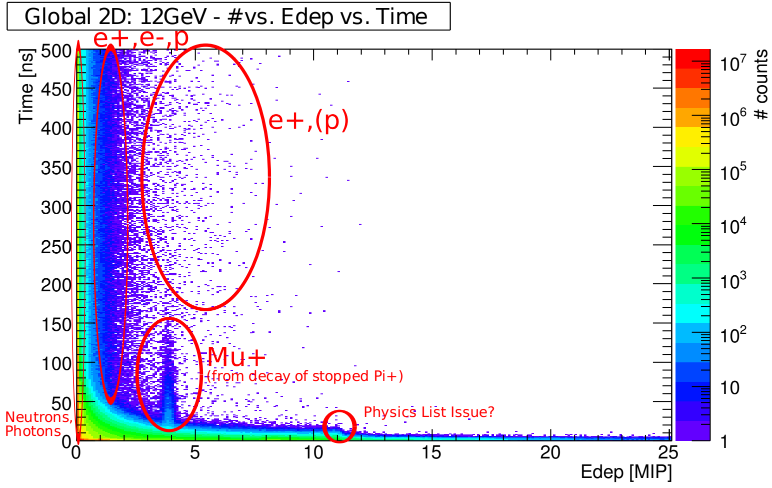

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Hit Probability of Timing Strip

Positioning of the Timing Strip

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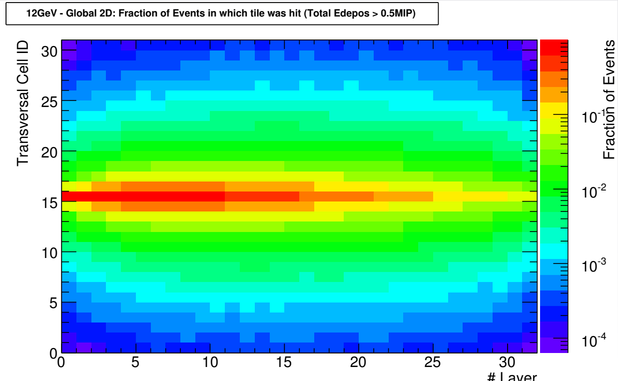
- During 95% of the time → timing strip at Layer 30 → low statistics
- Need about 200k Events or more!
- Luckily: On the last day we get to choose the position



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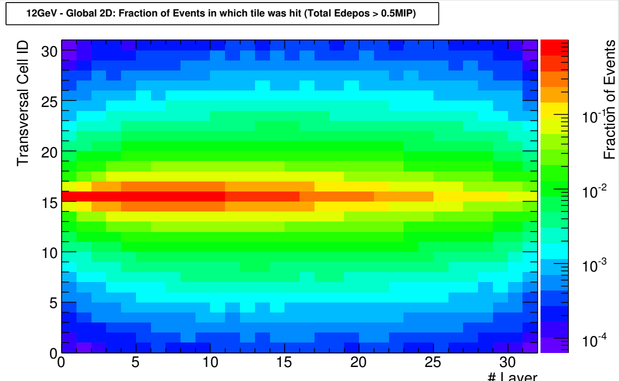

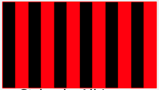

Timing of Hadronic Showers - Mean Time of Energy Deposition

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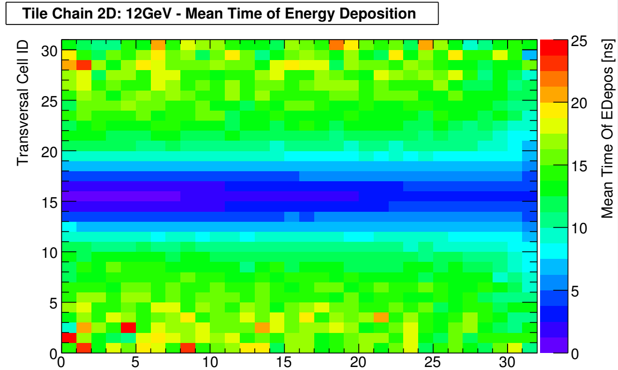

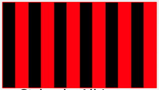

Strips in All Layers

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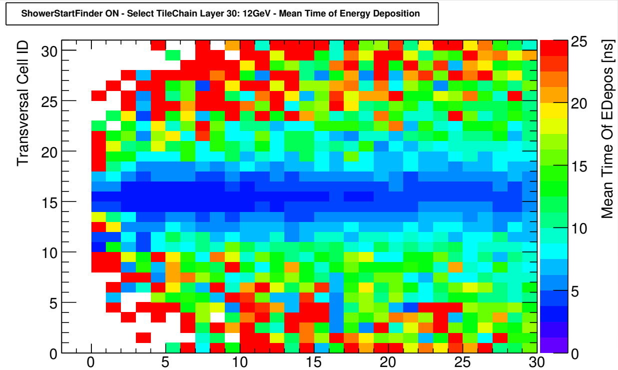

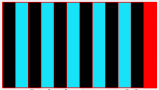

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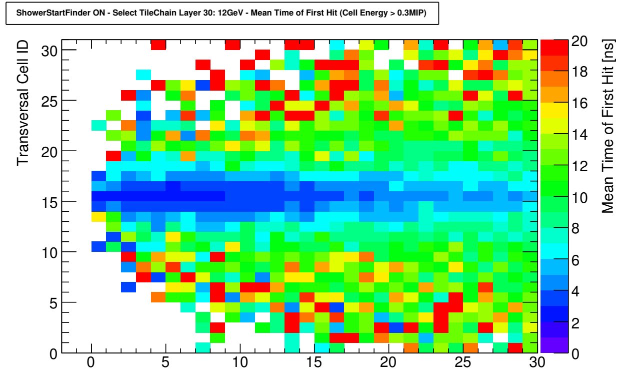

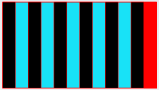

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Time of FH shows:
Hadronic showers are slow
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$\sim$ 10 ns outside shower core

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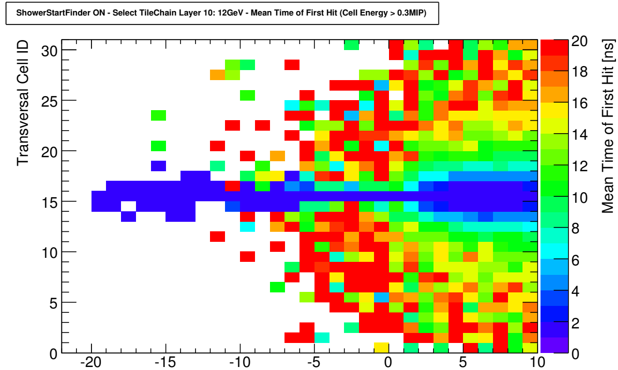
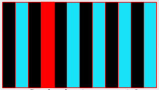


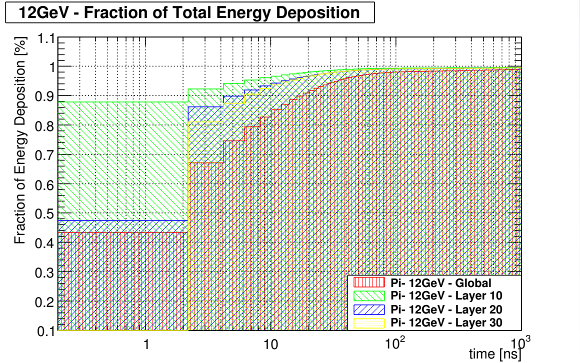


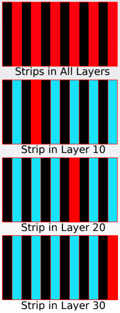
Challenge:
Use Time of FH to match Event with bunchX
$\rightarrow$
integrate shower over a certain time

Integration Time: Time to Collect Full Energy

Important Result of Simulation Study

- Time resolved fraction of the total E deposition per event
- Significant fraction of event energy arrives late
  $\Rightarrow$ Dependent on position in HCAL and the projectiles' energy
- So far we have only simulations $\rightarrow$ might be uncorrect as never tested
  Now it ist time to prove those results!!





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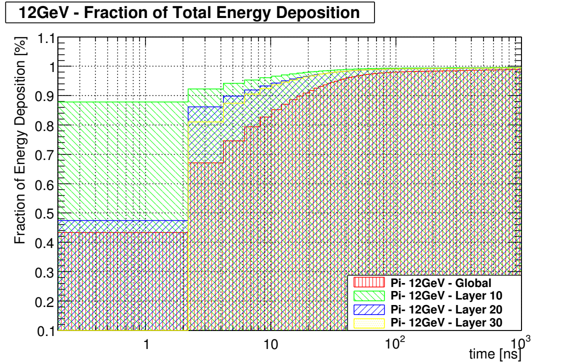

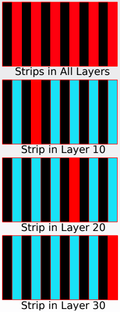

Integration Time: Time to Collect Full Energy

Important Result of Simulation Study

- Time resolved fraction of the total E deposition per event
- Significant fraction of event energy arrives late
  $\Rightarrow$ Dependent on position in HCAL and the projectiles' energy
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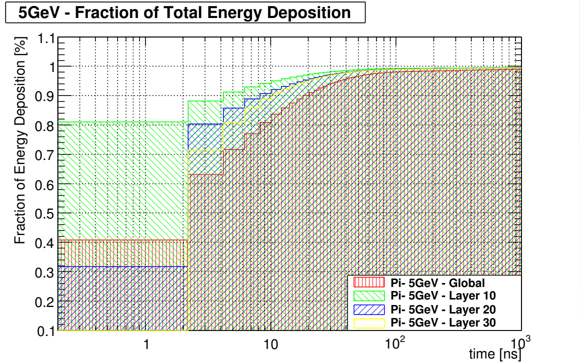

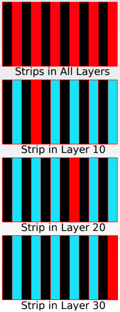

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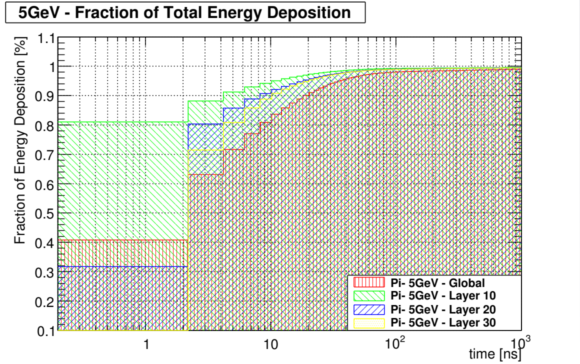
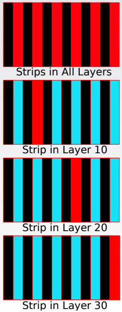




Outline

1. Motivation: CLIC, CALICE and Shower Timing
2. The Shower Timing Experiment
3. The Physics Case - Simulation Studies
4. Summary and Conclusion

Summary and Conclusion

Timing at a Multi-TeV Collider

- For a Multi-TeV LC, leakage is a serious concern for the calorimeters
  $\Rightarrow$ A dense absorber is attractive: Tungsten!
- CLIC has extremely high bunch crossing rates (2 GHz) and considerable hadronic background from $\gamma\gamma$ interactions
  $\Rightarrow$ Time stamping of signals is crucial for background rejection

Summary and Conclusion

Timing at a Multi-TeV Collider

- For a Multi-TeV LC, leakage is a serious concern for the calorimeters
  ⇒ A dense absorber is attractive: Tungsten!
- CLIC has extremely high bunch crossing rates (2 GHz) and considerable hadronic background from $\gamma\gamma$ interactions
  ⇒ Time stamping of signals is crucial for background rejection

Road to a first Shower Timing Experiment

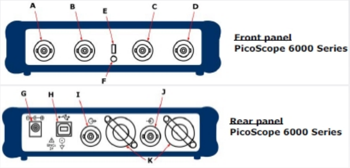
- Simulations for Tungsten have very large uncertainties: Needs to be improved by test beams
  ⇒ Timing is definitely a crucial open issue
- A full study requires a completely instrumented W HCAL
  ⇒ Still a long way till we might get there!
- Wide range of measurements possible with a single strip of scintillator tiles with time-resolved readout
  ⇒ Particularly powerful in combination with shower start information through Sync with CALICE HCAL

Outline

backup

backup

Readout Options: PicoScope 6403 (already tested)



PicoScope 6403 Stats

- 4 Channel Readout @ 1.25 GSa/Sec
- 1 GSa buffer memory (shared)
- Rapid Shot: Aquire Signals with up to 1 MHz repetition rate
- External Trigger
- Size of an external HDD

PicoScope 6403 Stats

- 8-bit vertical resolution (ADC)
- clipping of very high signals can distort measurement
- 350 MHz Bandwidth

Vertical Dynamic Range

Aquire Signals from $\sim 20\,\mathrm{MIP}$ down to $1-2\,\mathrm{p.e.}$
$\Rightarrow$ not achievable with 8-bit

Option 1: Two Run Modes

- High dynamic range mode (28 MIP): Quantify high E depositions @ $t < 10\,\mathrm{ns}$
- Low dynamic range mode (5.5 MIP): Quantify low E depositions @ $t > 10\,\mathrm{ns}$

$\rightarrow$ Problem: Signals $> 15\,\mathrm{MIP}$ can distort the measurement in Low dynamic range mode
$\rightarrow$ External Pre-Clipping might be an option

Option 2: Use Logarithmic Amplifier

$\rightarrow$ Problem: Signal is convoluted with Amplifier Error
$\rightarrow$ Need 16 of them

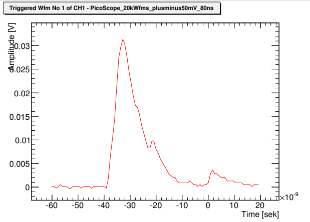
Physics Mode using CALICE Trigger

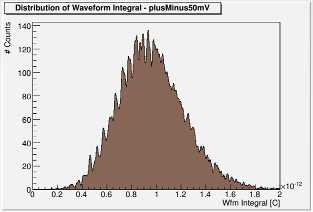
Synch. with CALICE trigger → event-based shower start finding
⇒ obtain timing information relative to the shower start

Run Mode and Requirements of Synchronisation

- Required Time Window per Event: 2 μs
- Aquire <3000 Events @ a trigger rate < 10 kHz and transfer and save the data before the next spill arrives ($\sim$ 60 MB per Spill)

→ Achieved in <8 seconds!!!





Time resolution (1.25 GSa/Sec) sufficient to resolve single pixel peaks in the Waveform Integral Distribution of tile penetrating electrons

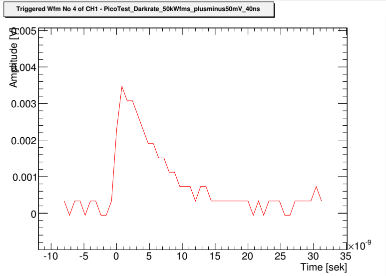
Calibration Mode

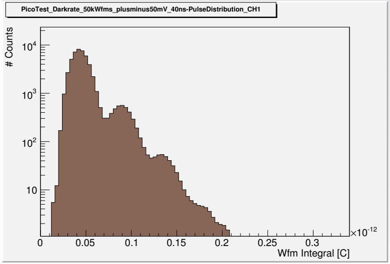
SiPM Gain monitoring through SiPM darkrate

Run Mode and Requirements of Synchronisation

- Short Time Window: 40 ns
- Take calibration data between spills and/or runs

→ up to 1000 darkpulses between spills is realistic





Additional temperature sensors allow gain-temperature correlation

Readout Options: Struck VME Digitizer SIS3305 (to be tested)

SIS 3305 Stats

- 8 Channel Readout @ 1.25 GSa/Sec
- 1 GSa buffer memory (shared)
- 2 GHz Bandwidth
- 10-bit vertical resolution (ADC)
- Trigger in/out

SIS 3305 Stats

- to be tested
- can the required signal caption rate be achieved?
- can be delivered till autumn?