Modelling signal digitisation for test calorimeters: the CALICE experience

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FCC Week, 23–26/06/2023, Krakow

→ Calo5D 1st F2F, 03/12/2024, KIT

CNRS IN2P3 Les deux infinis

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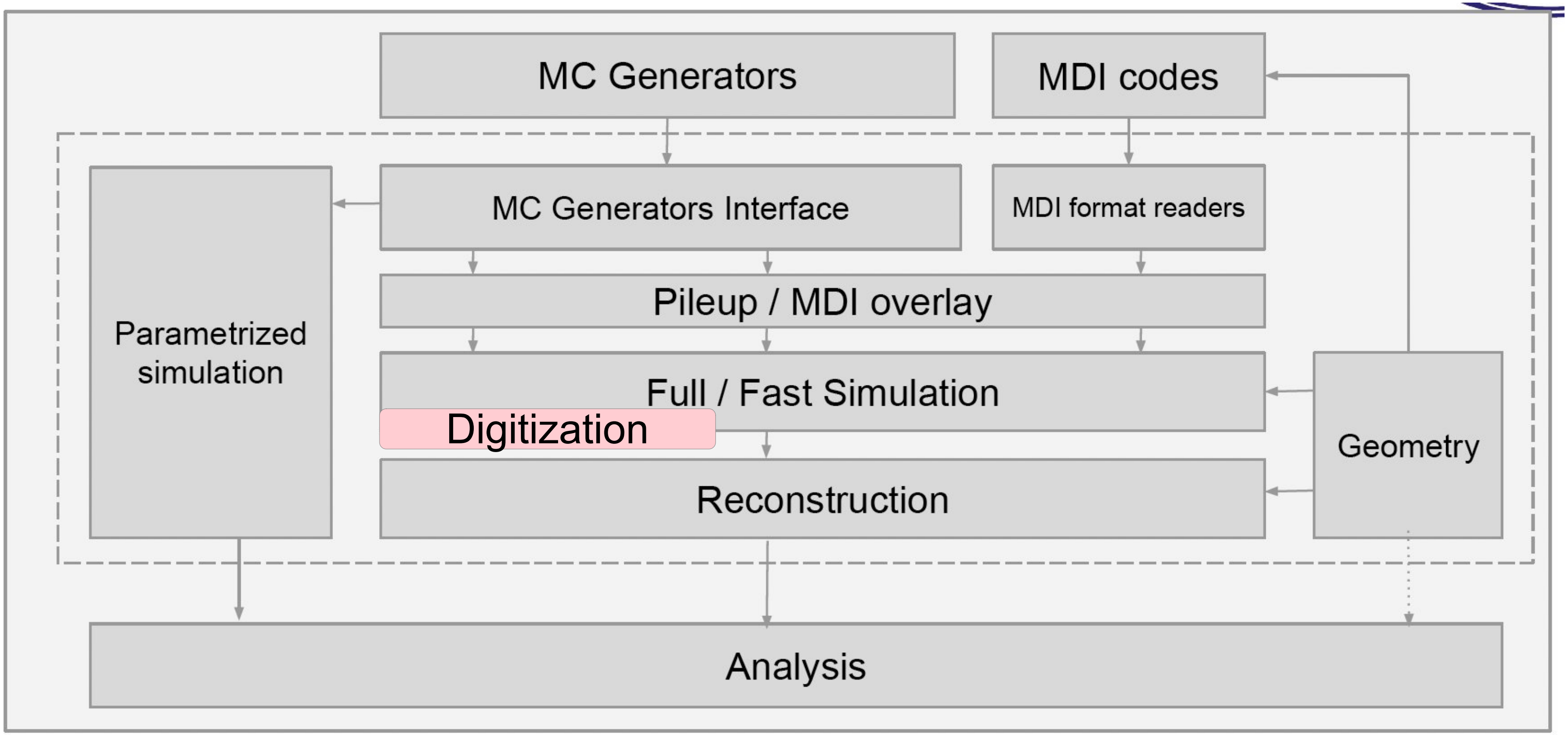
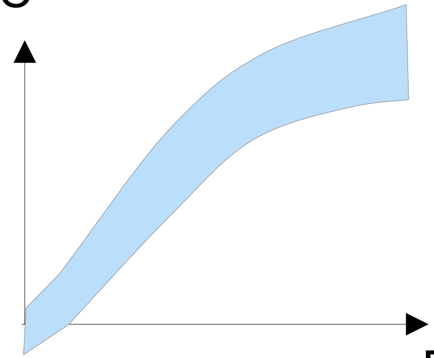
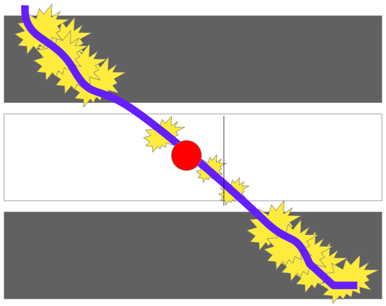
What is digitization ?



Problems:

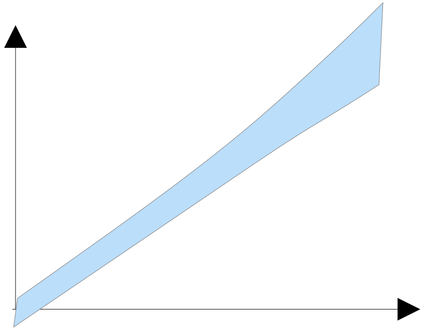


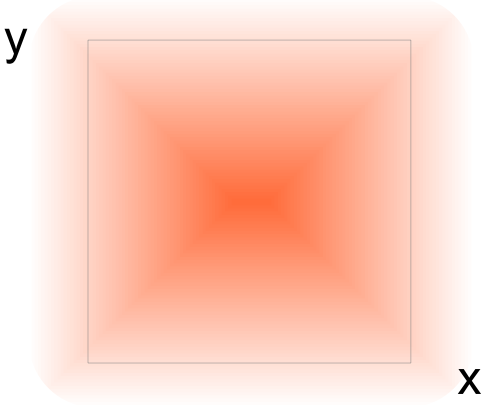
E-t :
Saturations
non-linearities
(sensor, elec)
Statistics
Noise
Thresholds



Sampling calorimeters

E-t
Physics list
Thresholds
Steps





Mapping
(in)Efficicency
X-talk

Mapping
Signal sharing

Effect

in-cell non-linear effects

- Geometric efficicency, losses

ALL

- Field / Efficiency maps
- Saturation
  - Scint: Birk's law
  - Gas
- SiPM: stat / inefficicencies
- Non-poissonian statistics
  - Si, lAr : Fano factor

Electronics non-linearities

- Energy
  - LE : (Electronics) Noises, Threshold effects
  - HE: Saturation
- Time
  - Time-slew
    (method dependant : ToA, CFD, Shaping)
  - Precision

Inter-cell

- X-talk
  - SDHCAL = multiplicity

Pile-ups

- Multiple hits
  - Time precision

Data vs Simulation (Silicon example)

IMPROVE → ← DEGRADE

Data

- Deposited energies = converted charges taken from pixels
  - Scale = Coulomb
    - Pedestal
    - MPV
    - σ_{Noise} (= ped. width)
    - S/N = MPV/σ_{Noise}
  - Trigger threshold
    - Effective Threshold
  - Charge fluctuations:
    - Physical
    - Electronics: (noise, X-talks)
  - Mishaps
    - Dead cells
    - Misalignments
  - Sources:
    - Beam params / Cosmics

Common ground

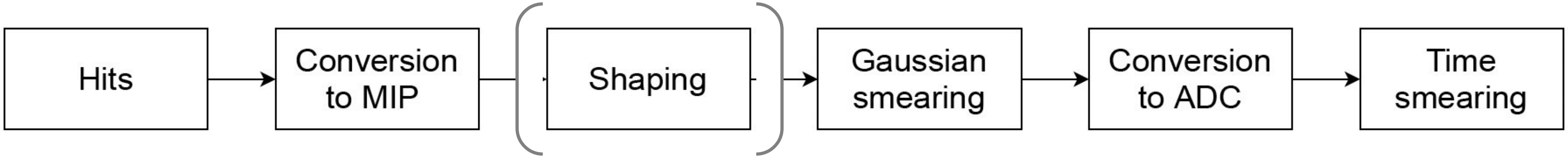
- Mip calibrated pixels
  - E/mip = (Q-ped)/ 500µm MPV
  - Common cut:
    - f_{mip} = max(Thr; n × σ_{Noise})/mip × minimal safety margin…
  - Fluctuations = digitisation
    - E_{rec} vs E_{Digi} = E_{sim}/mip ⊗ σ_{noise} / mip
      - + X-talks (%)
      - dead-cells

Simulation

- Deposited Energies in “sensitive volumes”
  - Scale = absolute in MeV
    - Ped = 0
    - MPV
  - No effective cut
    - (or really low!)
  - Energy fluctuation
    - Physical
    - Electronics NONE:
      - No Noise
      - no X-talk
  - Mishaps: those modelled
    - No dead cells
    - Alignment
  - Sources
    - Match the data

Digitization: E,t space

Raw simulation ⇒ info. resembling detector output, including readout effects

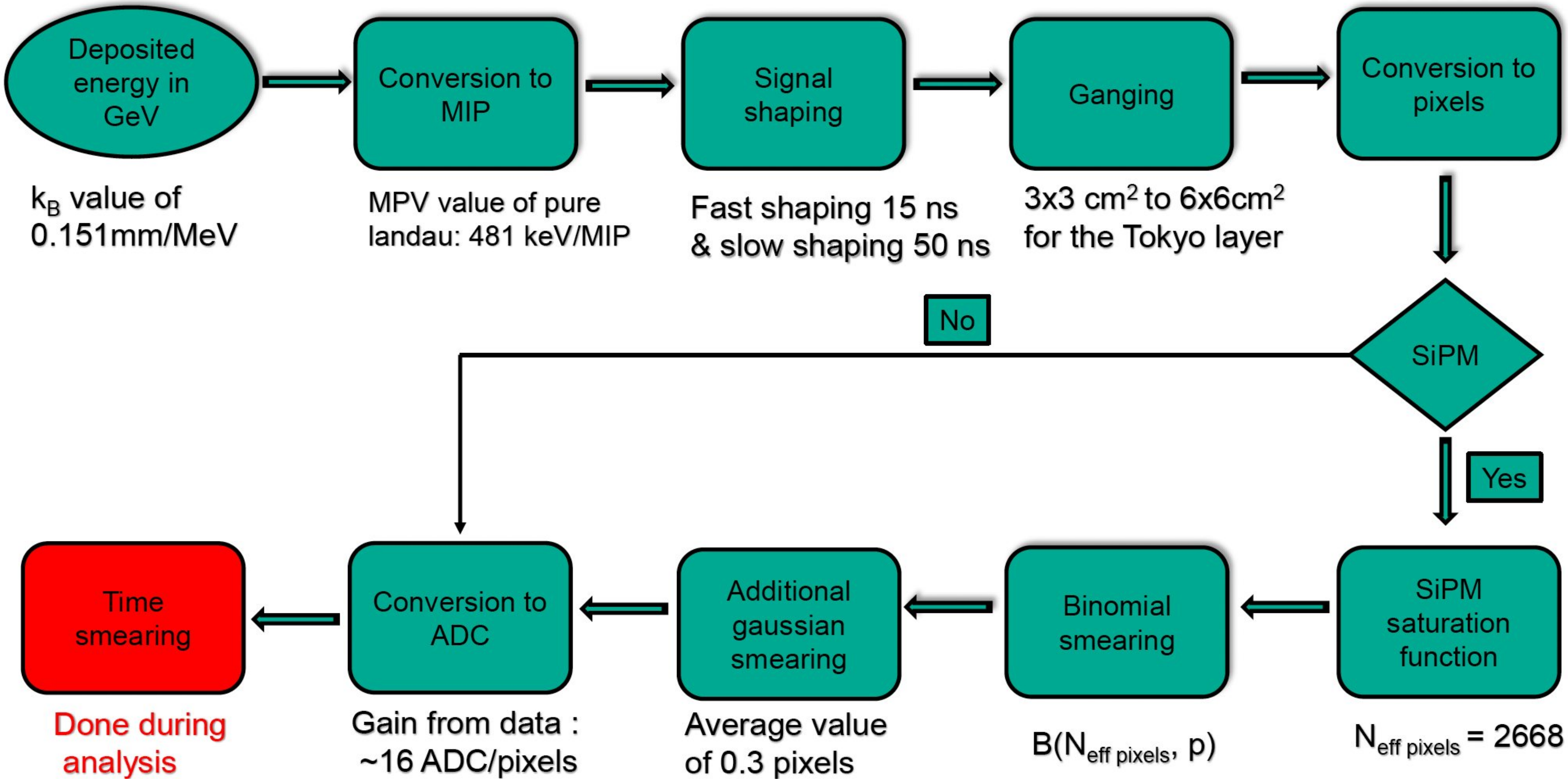


- Hits: starting point from raw simulation.
- Map energy deposited to MIP scale.
- Simulate pulse shaping in the readout electronics + saturation effects.
- Add smearing: noise term in detector cells/readout.
- Conversion to ADC, time smearing (tbd)
- (Masking at any point.)

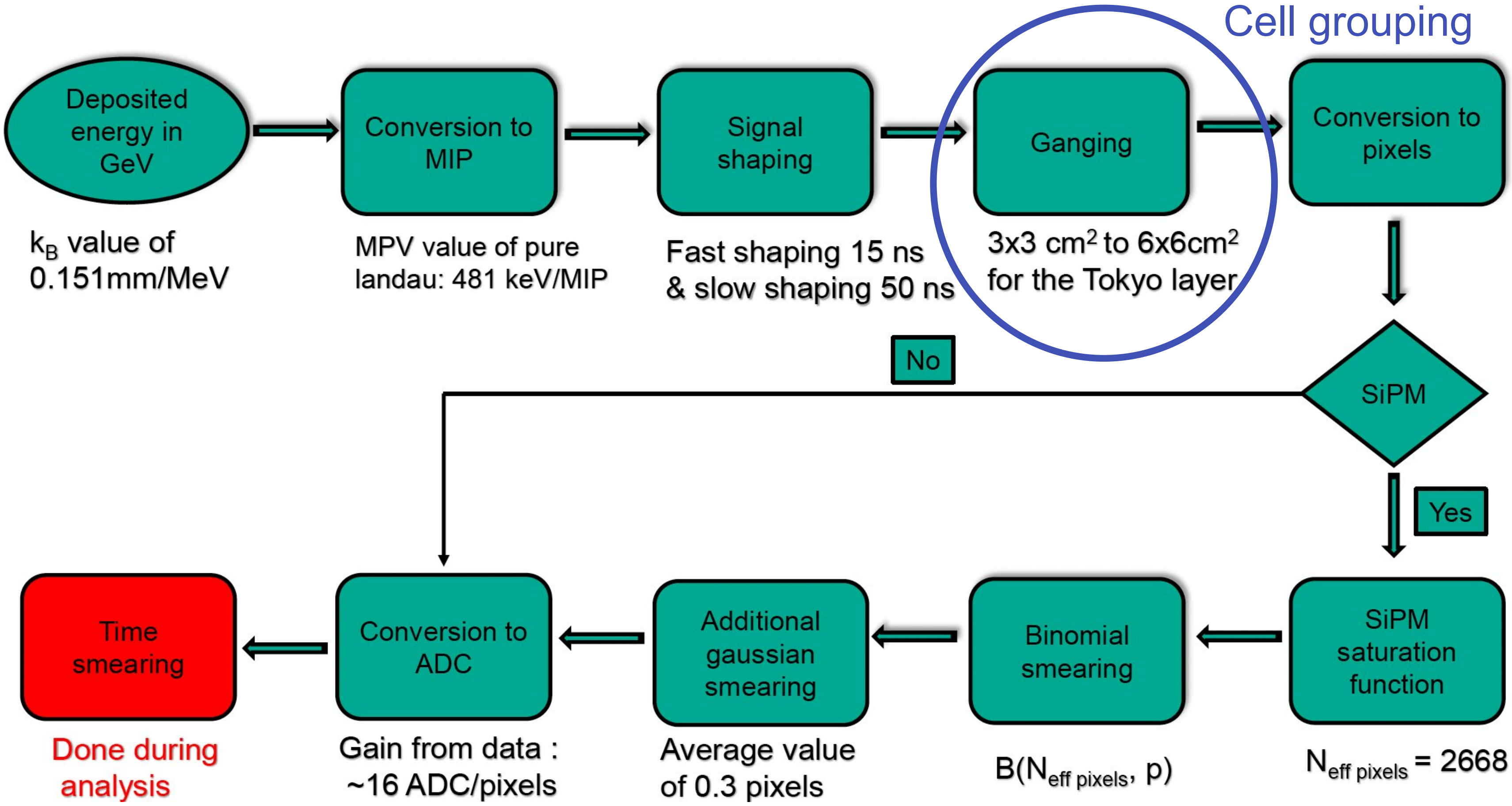
F. Jimenez, CALICE meeting, 13/10/22

AHCAL Digi

Light yield determined from data



Scint. Digi → ScECAL & AHCAL



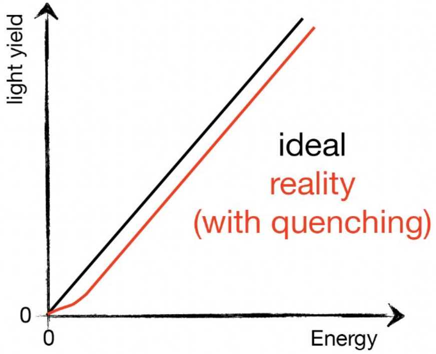
Scintillator's

Deposited energy in GeV & conversion to MIP

Simulations of energy depositions in scintillators have to account for quenching effects giving rise to non-linear light yield per unit length (dL/dx) at high ionization densities (dE/dx)

- Birks' law describes this effect with:

$$\frac{dL}{dx} = \frac{\left(S * \frac{dE}{dx}\right)}{1 + k_B * \frac{dE}{dx}}$$



- The AHCAL simulations use the Geant4 implementation of Birks' law with a Birks coefficient of k_B= 0.151 mm/MeV https://agenda.linearcollider.org/event/4776/contributions/19855/attachments/16078/26247/CALICE_Birks.pdf

MC Production and AHCAL Digitization | Olin Pinto, 30/06/2020

Alexander Tadday - CALICE Meeting 23.09.2010

"Digi in G4"
- Birk's law
- (Light tracking)

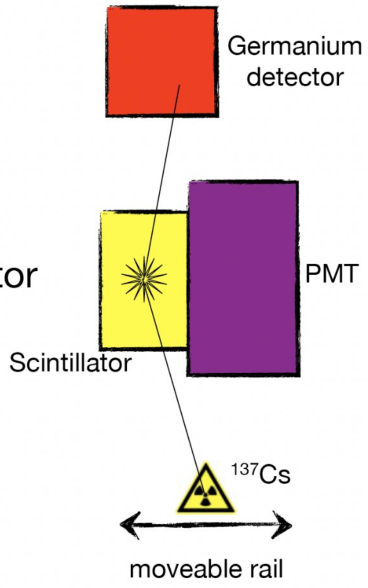
Depends on
- **Scintillator type**
- **Simulation step size**

Experimental Setup (MPIK Heidelberg)

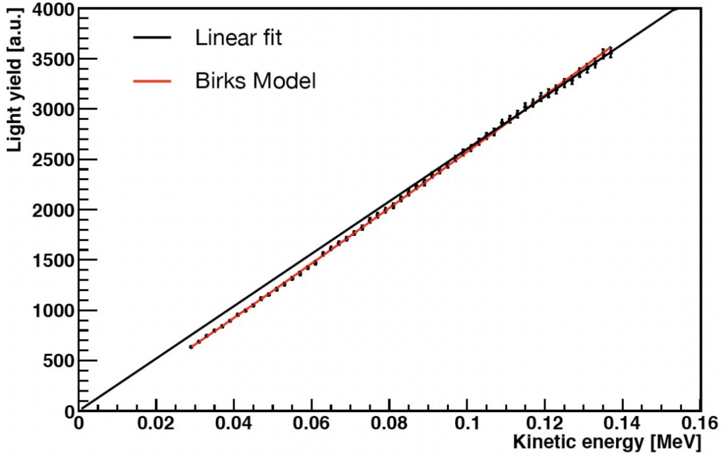
- PMT measures light yield
- Germanium detector measures Energy of Compton scattered photon E_{Ge}

$$\boxed{E_{e^-} = 662\,keV - E_{Ge}}$$

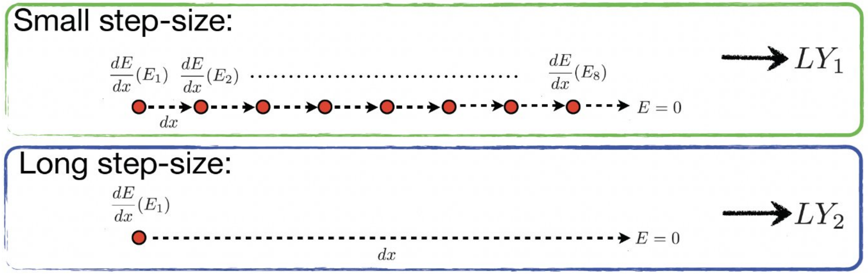
- Coincidence trigger PMT and Ge-detector
- Measured energy range of electrons ~ 30 - 140 keV
- Thanks to Christoph Aberle and Stefan Wagner for the ability to use the setup
- Detailed setup description in [1]



Alexander Tadday - CALICE Meeting 23.09.2010



Fit function: $$LY \approx \sum_{i=1}^{R/\delta x} \frac{S \cdot \frac{dE}{dx}(E_i)}{1 + kB \cdot \frac{dE}{dx}(E_i)} \delta x$$



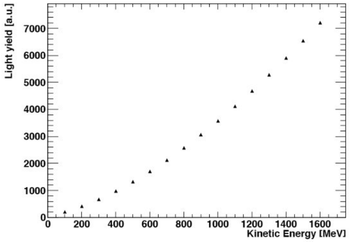
AHCAL Scint.

Data generation

Particle type *(e.g. proton)*
kB = 0.0151 cm/MeV
S = 29807 a.u.

GEANT4
small step-size (α, ρ)
large production cut P_{cut}

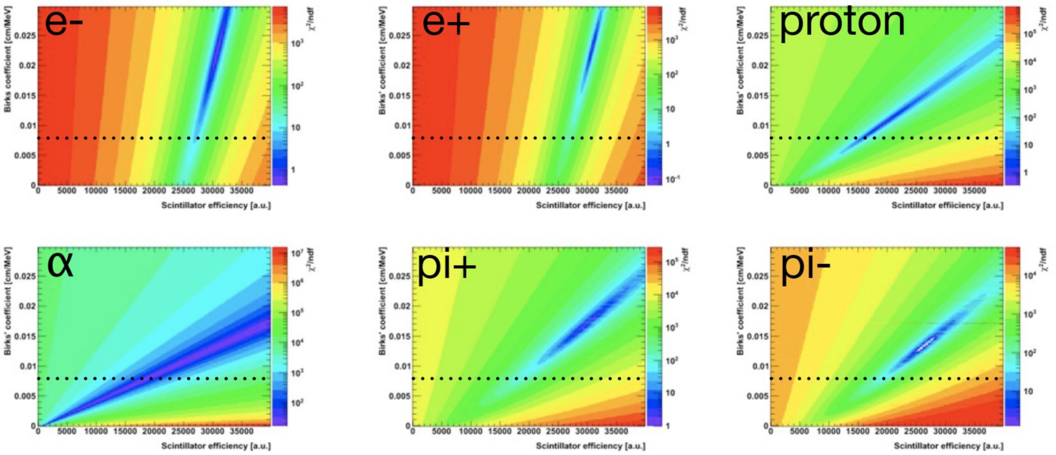
"artificial" data set



GEANT4
default α, ρ, P_{cut}

chi squared distribution

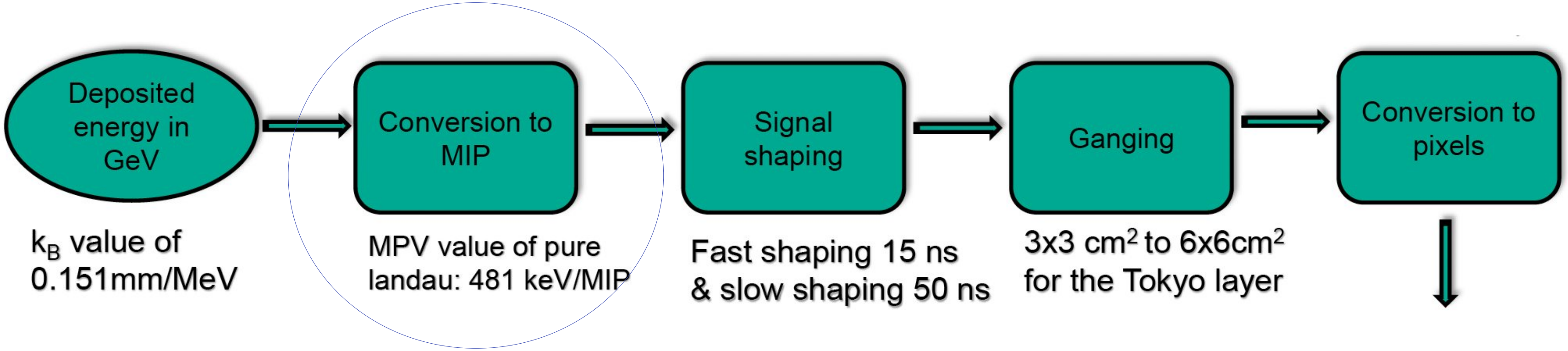
Alexander Tadday - CALICE Meeting 23.09.2010



Different possibilities to combine results:
- *Common kB, S for all particles*
- *Particle specific kB, but common S*

······ current kB
0.007943cm/MeV

AHCAL Scintillator’s



Deposited energy in GeV & conversion to MIP

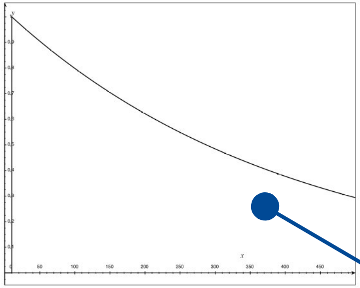
MIP2GeV is extracted from simulation by projected 40 GeV muons perpendicular on the AHCAL tile

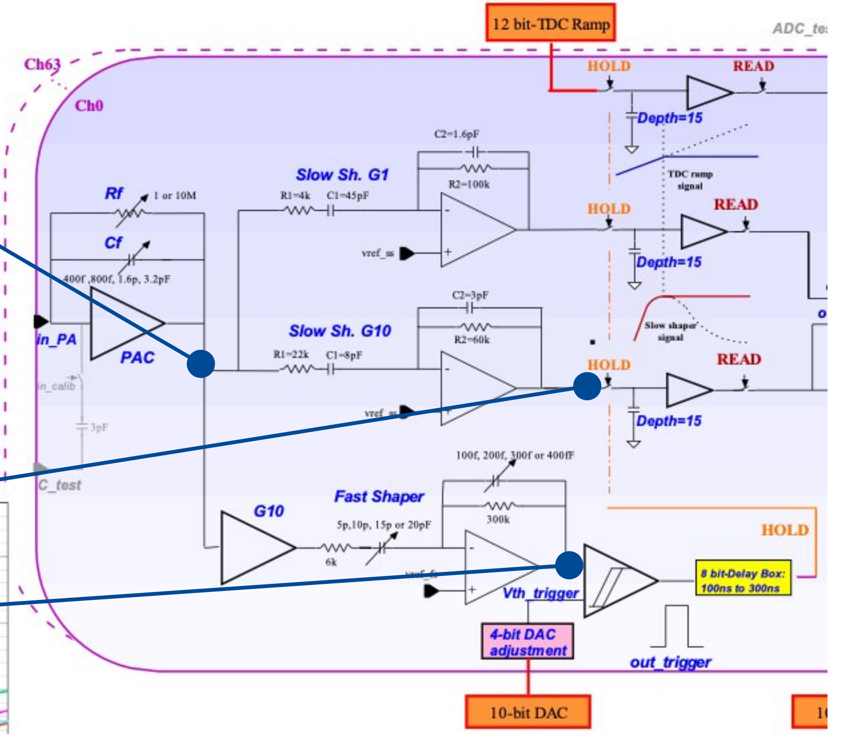
- The MIP distribution is fitted with Landau and the position is centered around unity
- The MPV value used as the **MIP2GeV factor**. The value is **481keV/MIP**

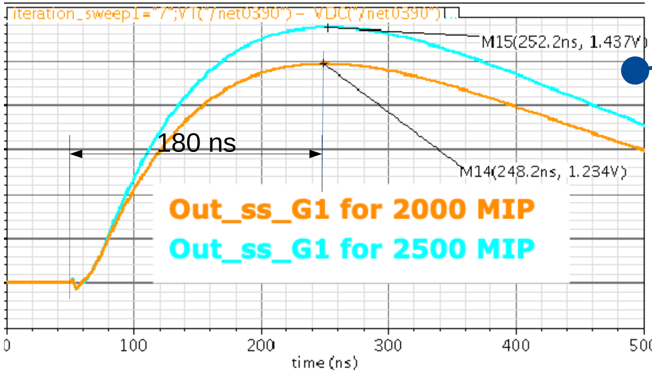
Shaping of the SKIROC2

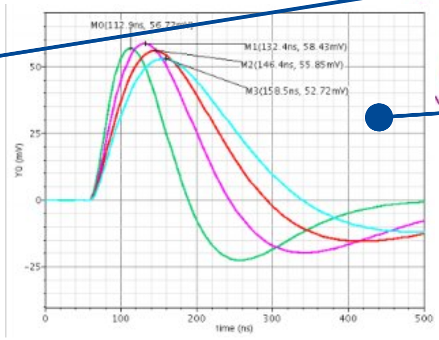
Signal path in each channel:

- 1 pre-Amp =
  - integrator with $\tau_i \sim 0.4\text{–}32\ \mu s$
- Fast Shaper
  - CR-RC$^{(1\sim2)}$ with τ_i and $\tau_d \sim 30\text{–}120$ ns
- Slow Shapers
  - CR-RC$^{(1\sim2)}$ with τ_i and $\tau_d = 180$ ns







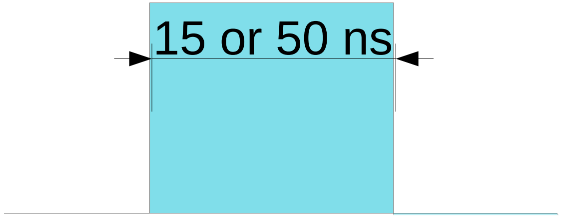


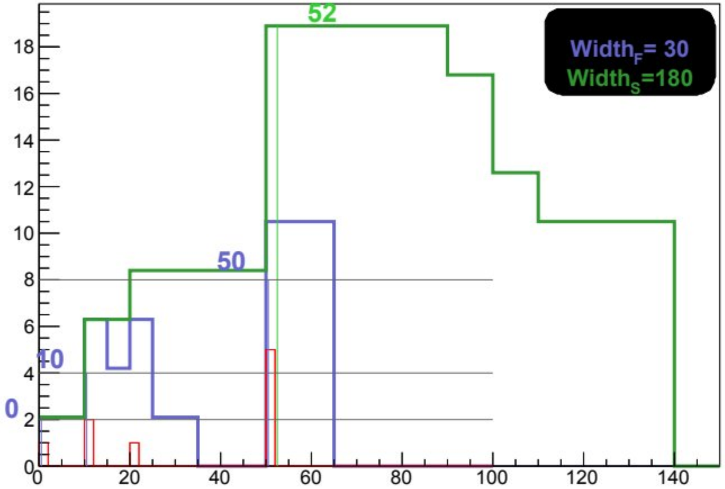
Scint : Signal shaping

Simulating Spiroc2E timestamping and energy measurement

- The energy sum of the sub-hits in a cell are integrated over a sliding time window of 50ns
- The 15ns (fast shaper) is introduced to know if the energy deposited in the cell go over threshold
- Then the energy is integrated over 50 ns (slow shaper)
- MIPThr of 0.5 in the ASIC has currently been ignored in this step. Such a cut should be present after all smearing

Equivalent to a «Heaviside shaping»





SiPM effects

Ecell / MIPs → Ecell / photon (pixel)

- Using Light Yield values from data
- Cell wise

Saturation function:

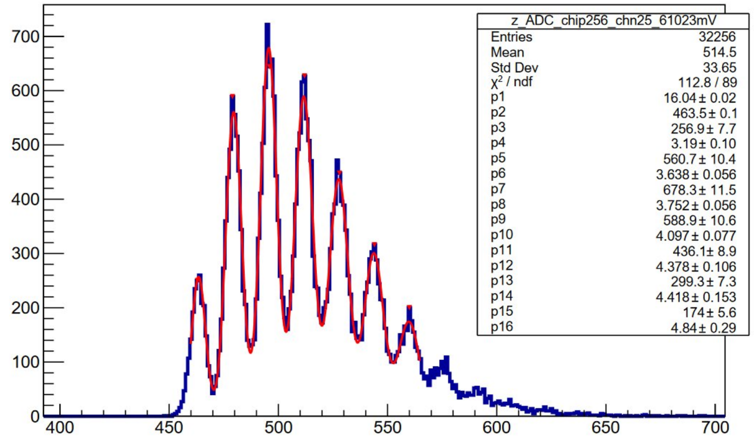
Amplitude of the hit not saturated

$$A^{sat}[pixels]_i = N_{effpixels} * (1 - exp(\frac{-A^{nosat}[pixels]_i}{N_{effpixels}}))$$

Saturated amplitude of the hit

Number of effective pixels, which in our case is 2668 pixels

- Smeared with a binomial distribution to model the statistical process of photon detection
  - The number of fired pixels *p* is random from B(N_{eff} pixels, *p*), which has input parameters:
    - the number of effective pixels of the SiPMs(Neffpixels) and the probability p that a pixel is fired



Additional gaussian smearing:

- 0.3 pixels (average value).
- estimated from the width of the pedestal (zeroth peak in LED measurements)

Silicon ECAL

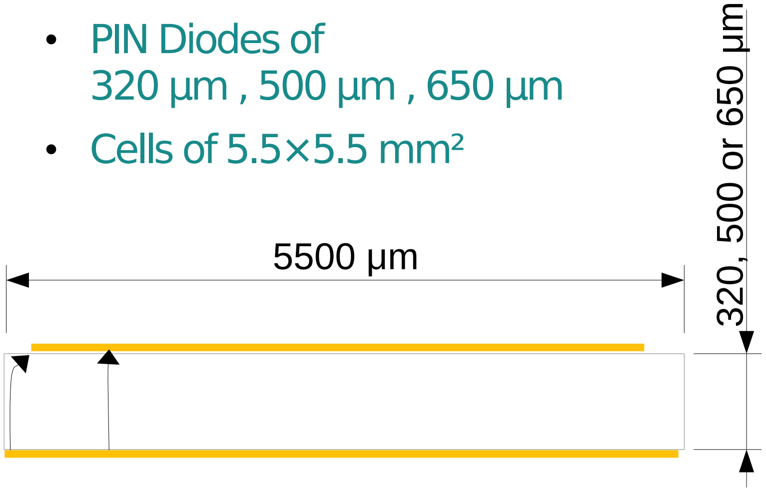
Prototype:

– 15 layers of 18×18 cm²

– Silicon sensors:

  • PIN Diodes of
    320 µm , 500 µm , 650 µm

  • Cells of 5.5×5.5 mm²



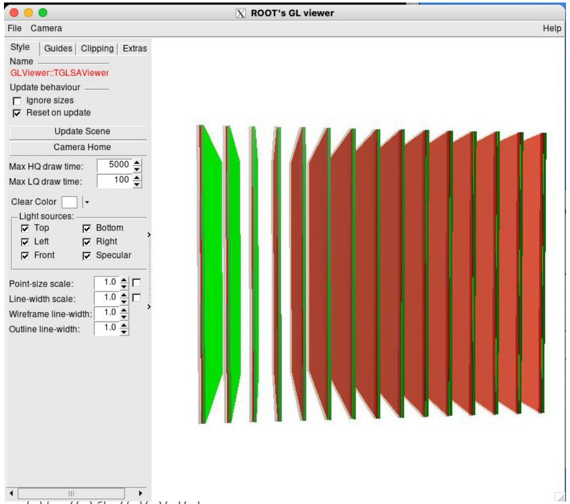
Simulation

– Gaps between wafers

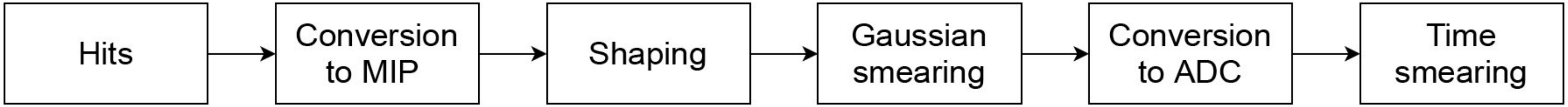
– No-gaps between cells

  • Charge collections ~ 100%

    – To be evaluated with dedicated simulation (GarField++, …) and data

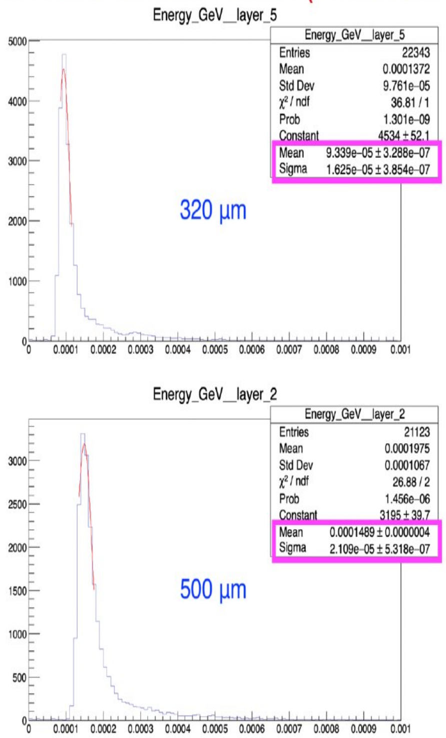


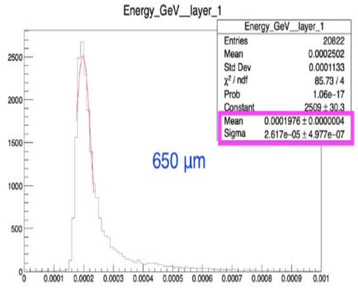
Silicon ECAL Digi



- Hits: starting point from raw simulation.
- Map energy deposited to MIP scale.

Conversion to MIP scale (electrons @ 3 GeV)





- Conversion per layer (different layers Si thickness)

Pulse shaping

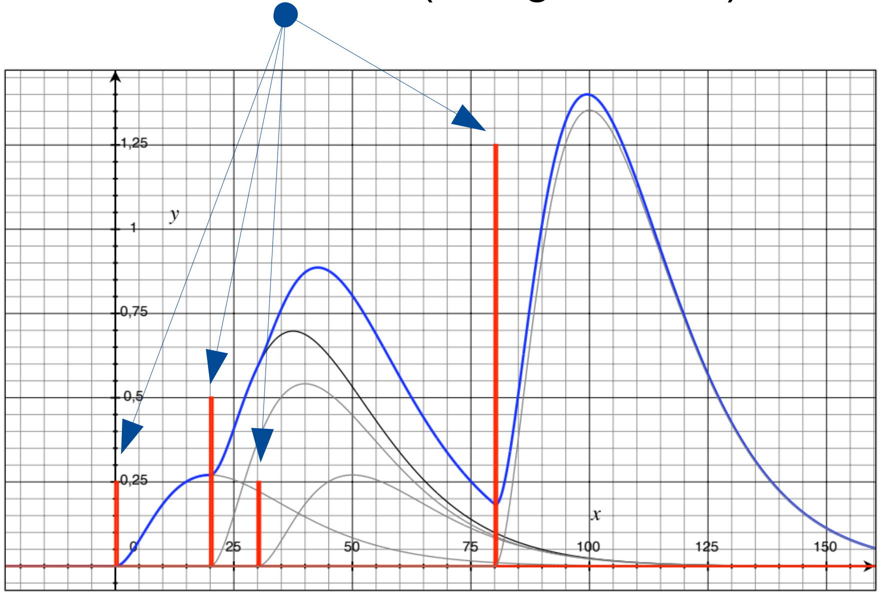
n^{th} order CR–RC filter

– Linear response to step function

$$s(t,A)=\begin{cases} 0 & x\text{-}t<0 \\ \frac{A}{n!}\left(\frac{x\text{-}t}{\tau_i}\right)^n \exp\left(-\frac{x\text{-}t}{\tau_i}\right) & x\text{-}t>0 \end{cases}$$

- Ignores exp. tail
- Ignores saturation effects (≥~2000 mips)

Sub-Hits (in a given cell)

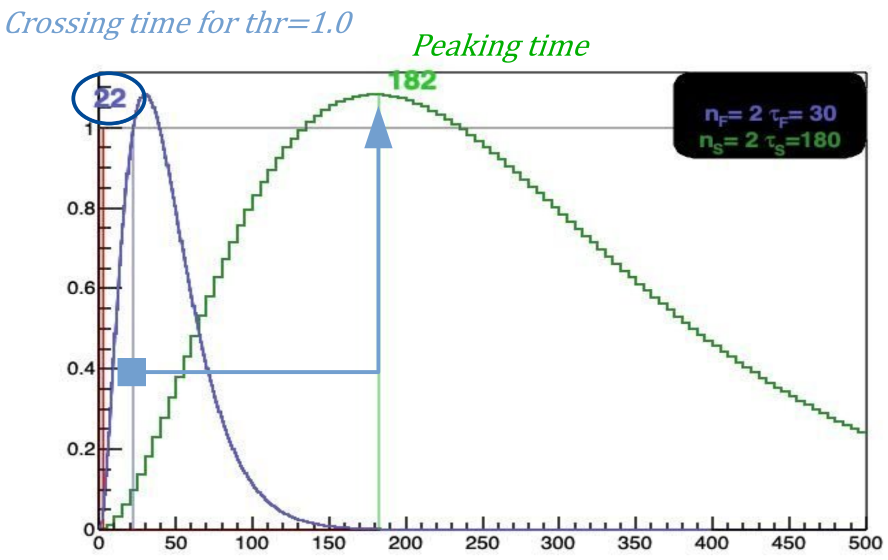


Example of pulse shape output of CR-$(CR)^2$ filter with a nτ=20 ns from 4 inputs, at 0, 20, 30 and 80 ns, with relative amplitudes of 1,2,1 and 5.

Implementation for each channel

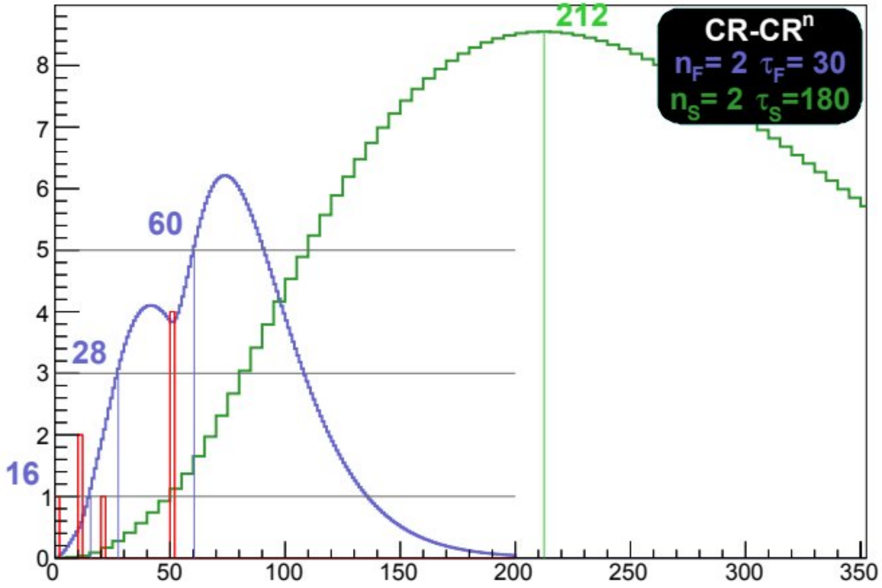
Shaping by histograms:

- bin ~ time resolution
  - 1 ns ns for FS
  - 5 ns for SS



Multiple hits

- Time slew effect
- Peaking time

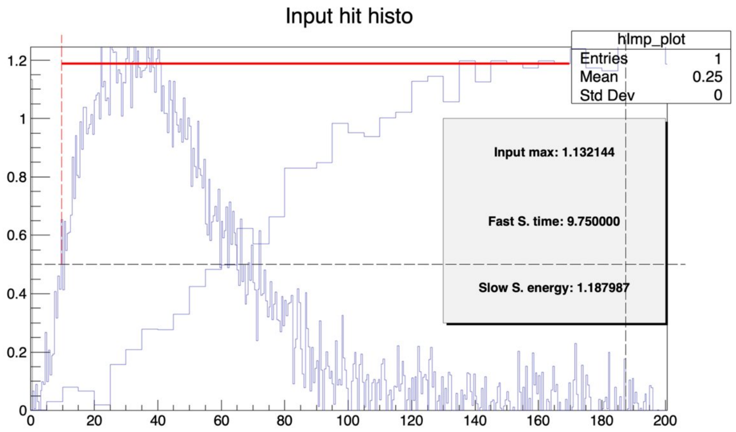


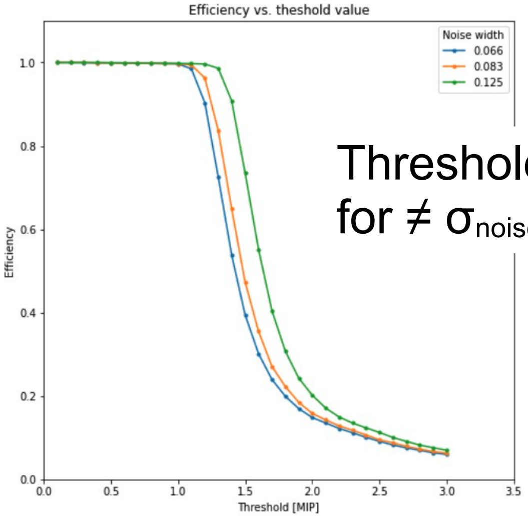
SiW-ECAL digitizer by shaping

SiW-ECAL digitizer by shaping

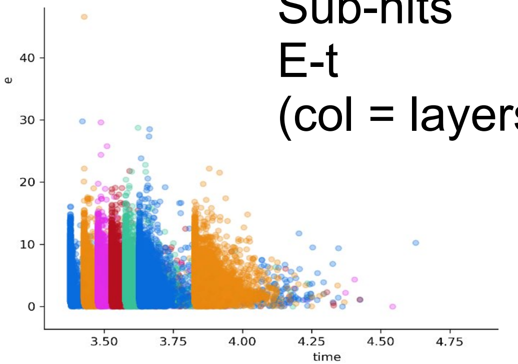
- Shaping processor properly implements noise and a realistic time binning

  Example: Threshold 0.5 MIP, delay 180 ns
- Shapers with noise MIP/12 and MIP/20

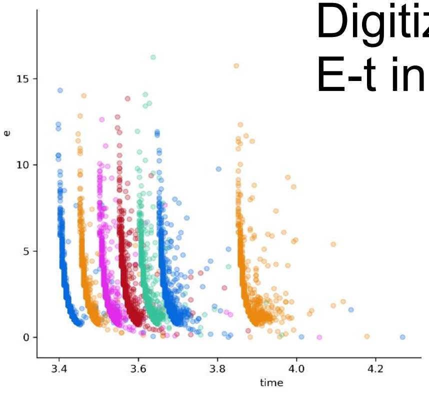




Thresholds scan for ≠ σ_{noise}



Sub-hits E-t (col = layers)



Digitized E-t in cells

Conclusions

Summary

- Digitization links MC to exp. Data
- Very sensor Specific
  - Silicon < Scint ≪ Gas RPC
  - Amplitude, Time
  - Geometry
- Electronics :
  - Standard: Gain,
  - Next / On-going precision timing
- Precision of description
  - Gaps, ineff. maps
- Only possible with (lot of) dedicated BT data

Big, Cursed & politically sensitive work

- The more advanced, the less performant
- Simplistic / Incomplete digitization yields better results… until compared with data !
  - Why invest ?

→ Technology comparisons review committee task must be done with prototypes & Sim+Digi.

Signal collection in Silicon

See presentation on W. Riegler's presentation

Programs:

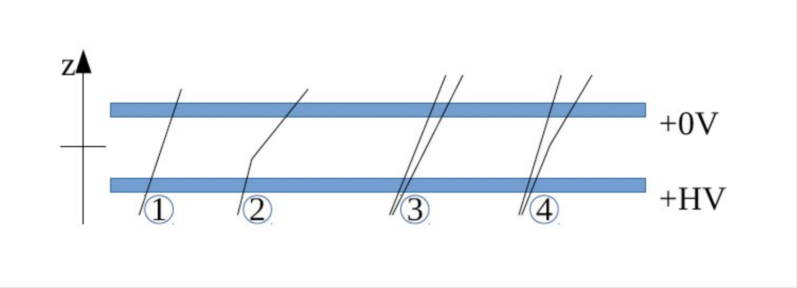
- Garfield / Garfield ++
  - Finite Element Electrostatic calculations
    ESIPAP'2021 paper
- Magboltz and Heed
  - Heed ionisation :
    https://arxiv.org/abs/physics/9912042
- AllPix² (Strasbourg's VTX people)
  - On-going PhD of Elio SACCHETTI (IPHC):
    - Framework with
      GEANT4
      + Charge propagation
      + Spice simulation of ASIC

First task:

- Get the $\overline{E}$ field (ie.e doping profile)

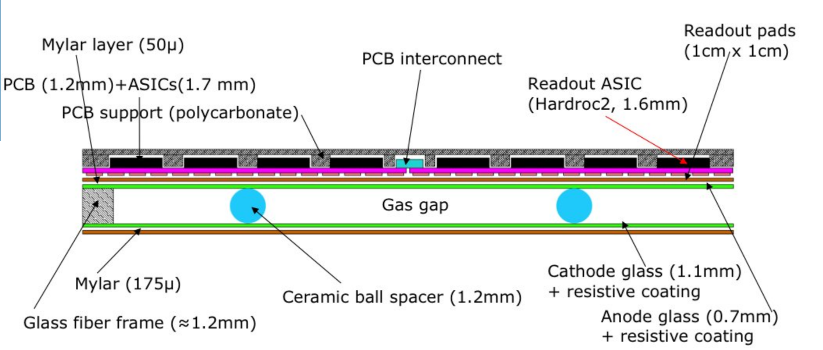
Extras

SDHCAL



Simulation output

- steps list inside RPC gas gaps
- deposited energy from these steps
- occurrence time of each step
- entrance and exit point positions of each step



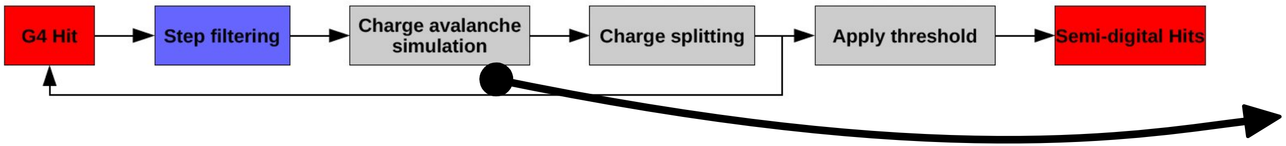
Glass resistive plate chambers

- Glass electrodes separated by 1.2 mm gas gap
- Glass resistivity $\approx 10^{12}\,\Omega m$
- Gas mixture : 93 % TFE, 5 % CO_2, 2 % SF_6
- High voltage : 6.9 kV $\rightarrow$ avalanche mode
- Transverse segmentation : 1 cm^2
- Thresholds : 0.114, 5.0, 15.0 pC

SDHCAL Digi, A. Steen, may 2016
https://agenda.linearcollider.org/event/7072/contributions/35082/attachments/28589/43096/sdhcal-digit.pdf

SDHCAL

Digitizer method



Charge avalanche simulation

- Charge randomly chosen in Polya distribution :

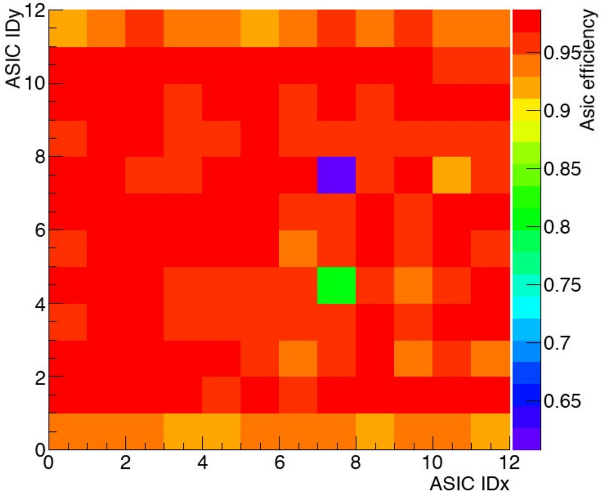
$$P(q) = \frac{1}{\Gamma(\delta+1)}\left(\frac{1+\delta}{\bar{q}}\right)^{\delta+1} q^{\delta}\, e^{[-\frac{q}{\bar{q}}(1+\delta)]}$$

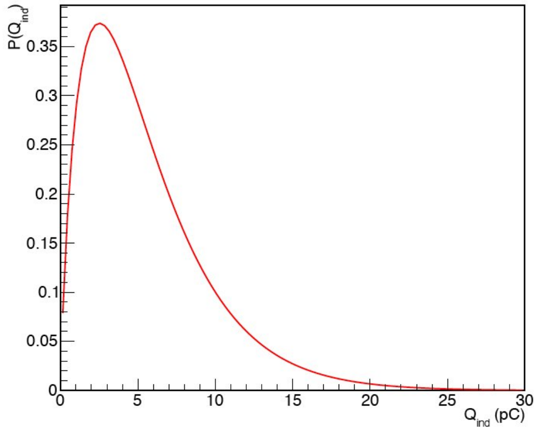
- Length charge correction :

$$Q_{Corrected} = \begin{cases} Q_{ind}\left(\frac{d_s}{d_{gap}}\right)^{\kappa} & \text{if } \frac{d_s}{d_{gap}} > 1 \\ Q_{ind} & \text{otherwise} \end{cases}$$

Step filtering

- Step occurrence time $< 1000\ ns$
- Step length $> 1\ \mu m$
- Efficiency map
- Charge screening (d_{cut} tuned with electromagnetic showers)

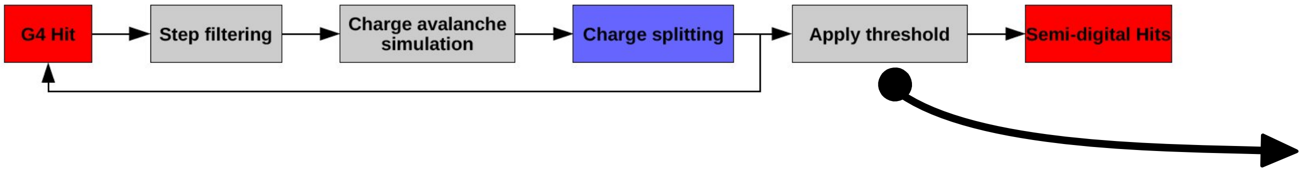




SDHCAL Digi, A. Steen, may 2016

https://agenda.linearcollider.org/event/7072/contributions/35082/attachments/28589/43096/sdhcal-digit.pdf

SDHCAL Digi : Amplification



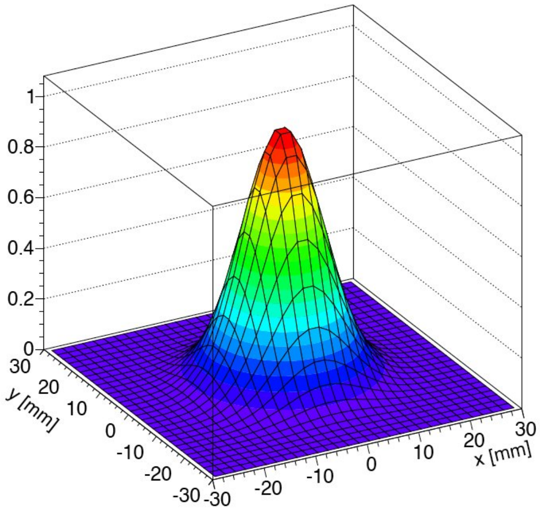
Threhsolds

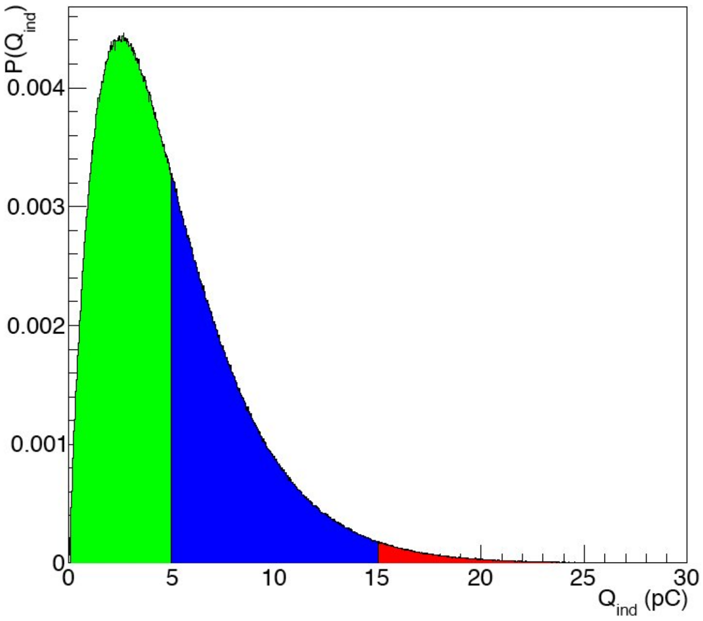
- Threhsolds 2 and 3 tuned with muon data to reproduce efficiency related to threshold 2 and 3

Charge spreading

$$R_i = \frac{\int_{a_i}^{b_i} \int_{c_i}^{d_i} \sum_{j=0}^{n} \alpha_j e^{\frac{(x_0-x)^2+(y_0-y)^2}{\sigma_j^2}} dxdy}{N}$$

- Charge in pad i incremented by $R_i Q_{corrected}$





SDHCAL Digi : Tuning

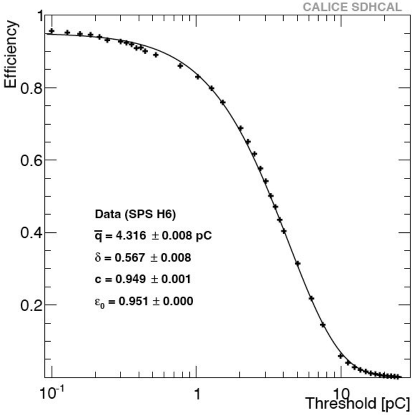
Digitizer parametrisation : threshold scan

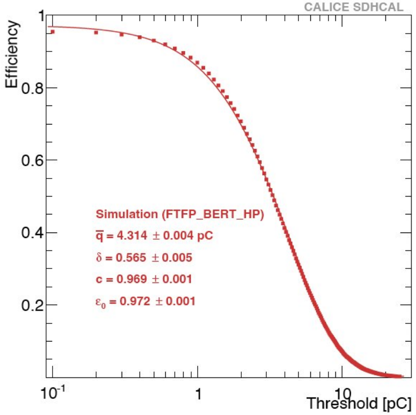
Threshold scan method :

- $\sim$ 20 dedicated muon runs
- Threshold variation in few chambers
- Efficiency reconstructed with tracks from other layers
- Fit the curve to extract $\bar{q}$ and δ parameters

$$\epsilon(q) = \epsilon_0 - c\int_0^q P(q')dq'$$

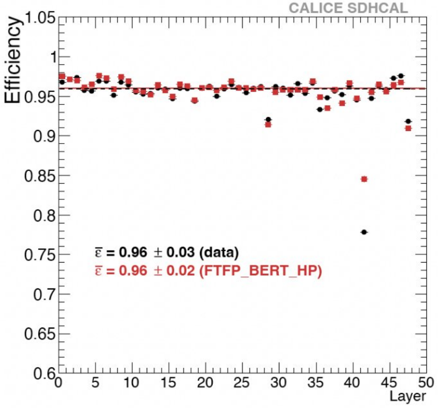
Polya parameter	Digitizer input value
$\bar{q}$	4.58 pC
δ	1.12



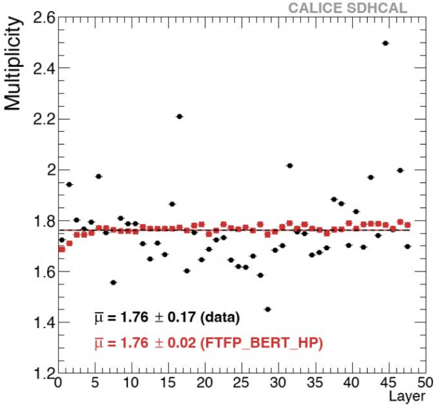


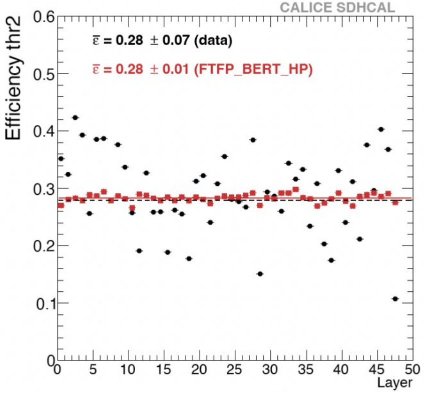
Lengthy dedicated BT μ runs with thr. scan

Efficiency

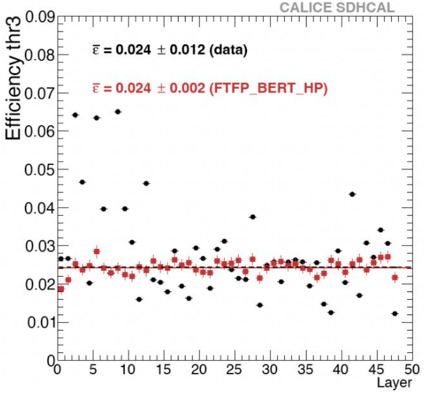


Multiplicity





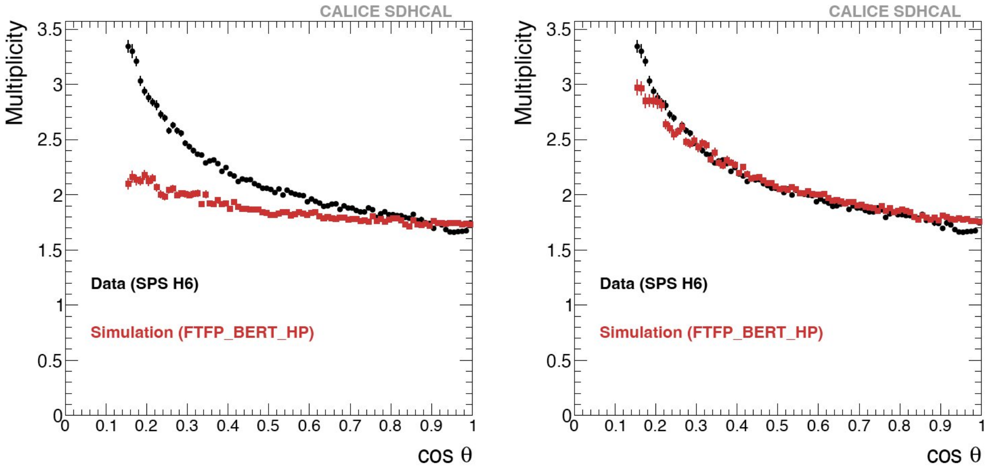
Efficiency Thr2

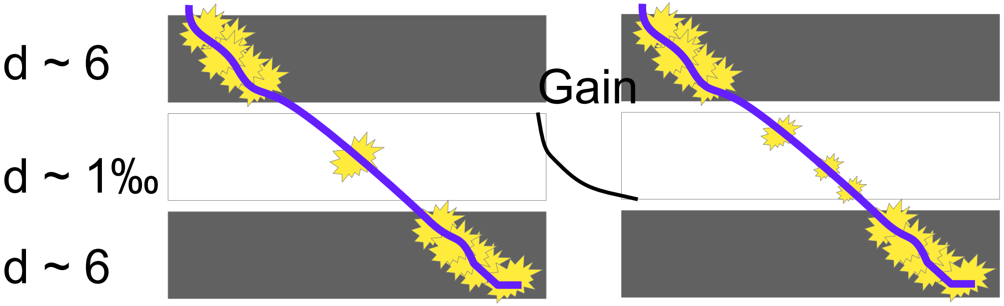


Efficiency Thr3

SDHCAL Digi: results

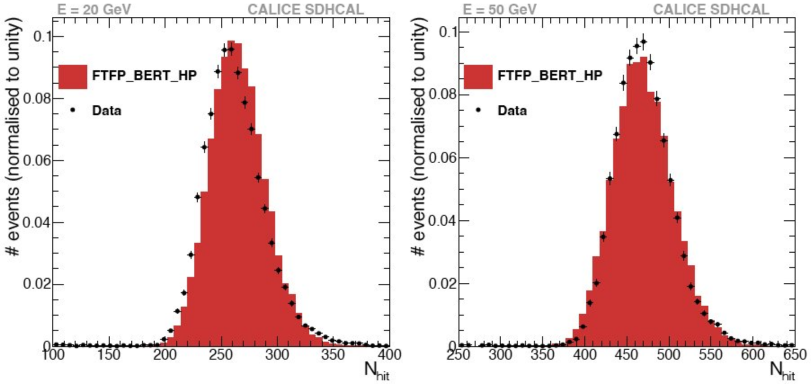
Improved parametrization & Step length





Electromagnetic showers

- Digitizer parameter tuned with EM showers (d_{cut})
- EM shower selection :
  $N_{tracks} = 0$ & $P_{start<5}$ & $N_{layers} < 30$
- Selection efficiency $\geq 98\,\%$
- Relative deviation $< 3\%$



Comparison with Had. Shower complex:

- Clustering, Shower profiles, Beam contamination …
- Physics list