RESISTIVE PLATE CHAMBER DIGITISATION FOR HIGHLY GRANULAR CALORIMETER: SDHCAL

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CALICE Collaboration

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LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

cnrs dépasser les frontières

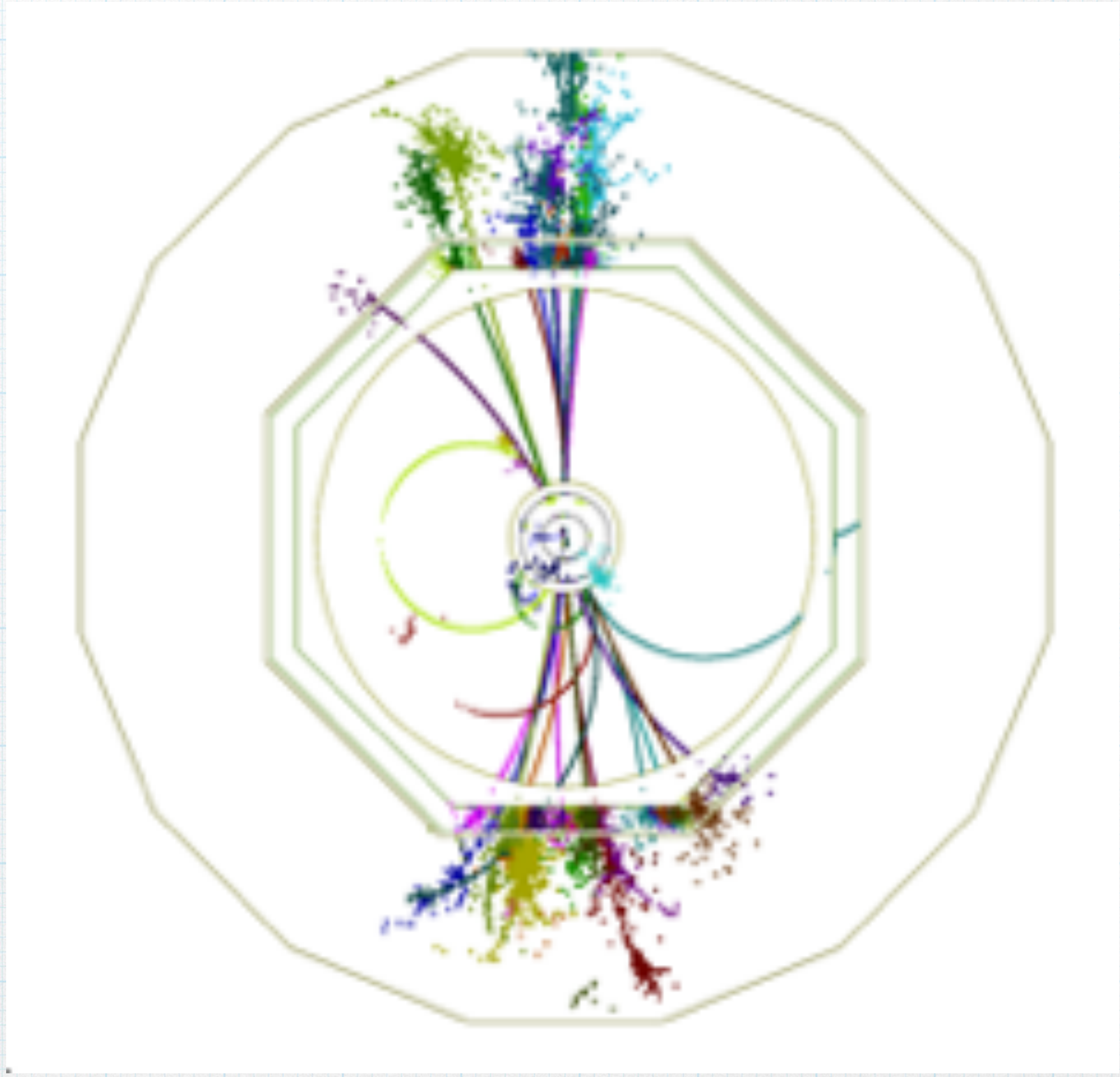
IN2P3 Les deux infinis

CALICE

Calorimeters for Particle Flow

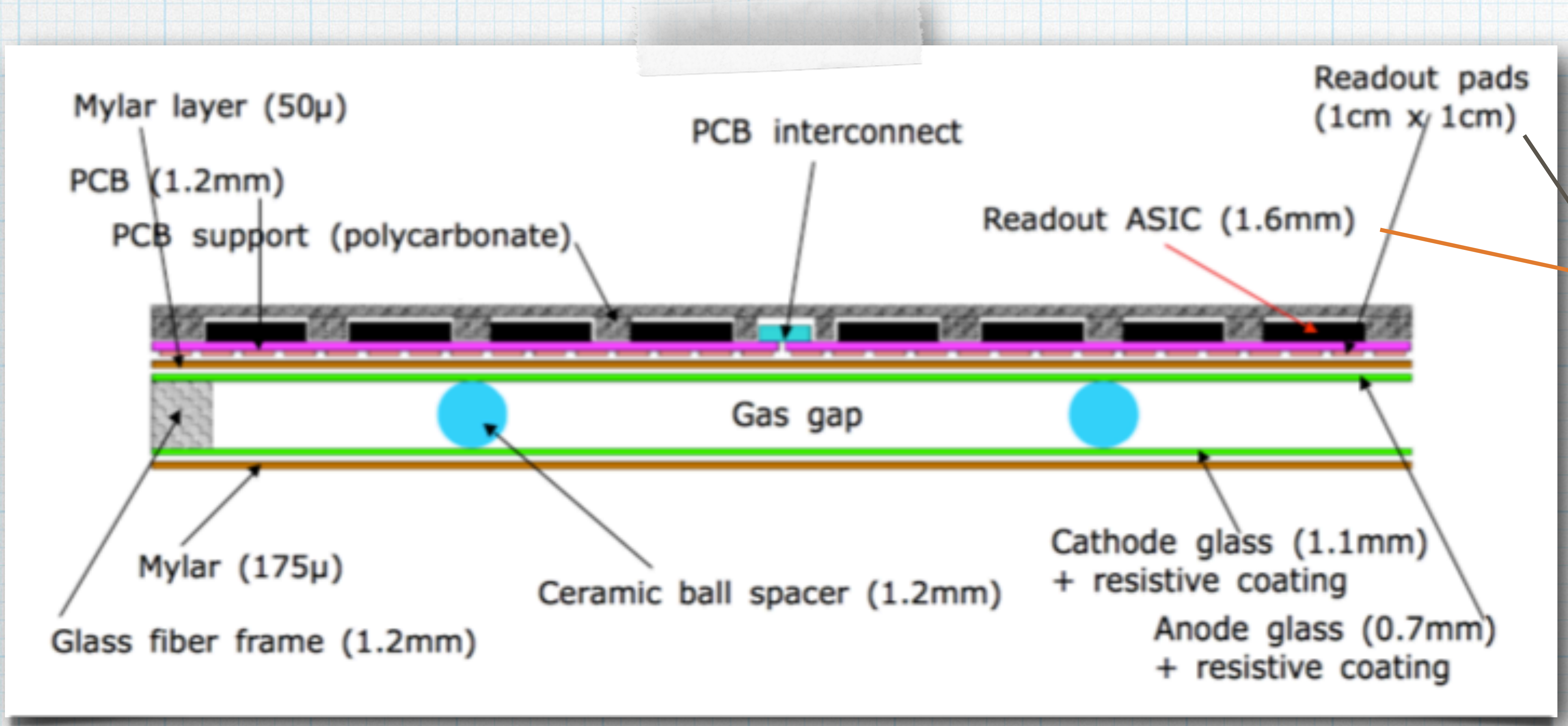
* Particle Flow analysis is an optimal way to reconstruct final states in e^+e^- collisions especially with τ, missing energy and jets...
* A Particle Flow optimized hadronic calorimeter:
  * Has to be compact, fit in the magnet with negligible dead zones
  * The active component must allow fine segmentation while keeping a reasonable intrinsic energy resolution

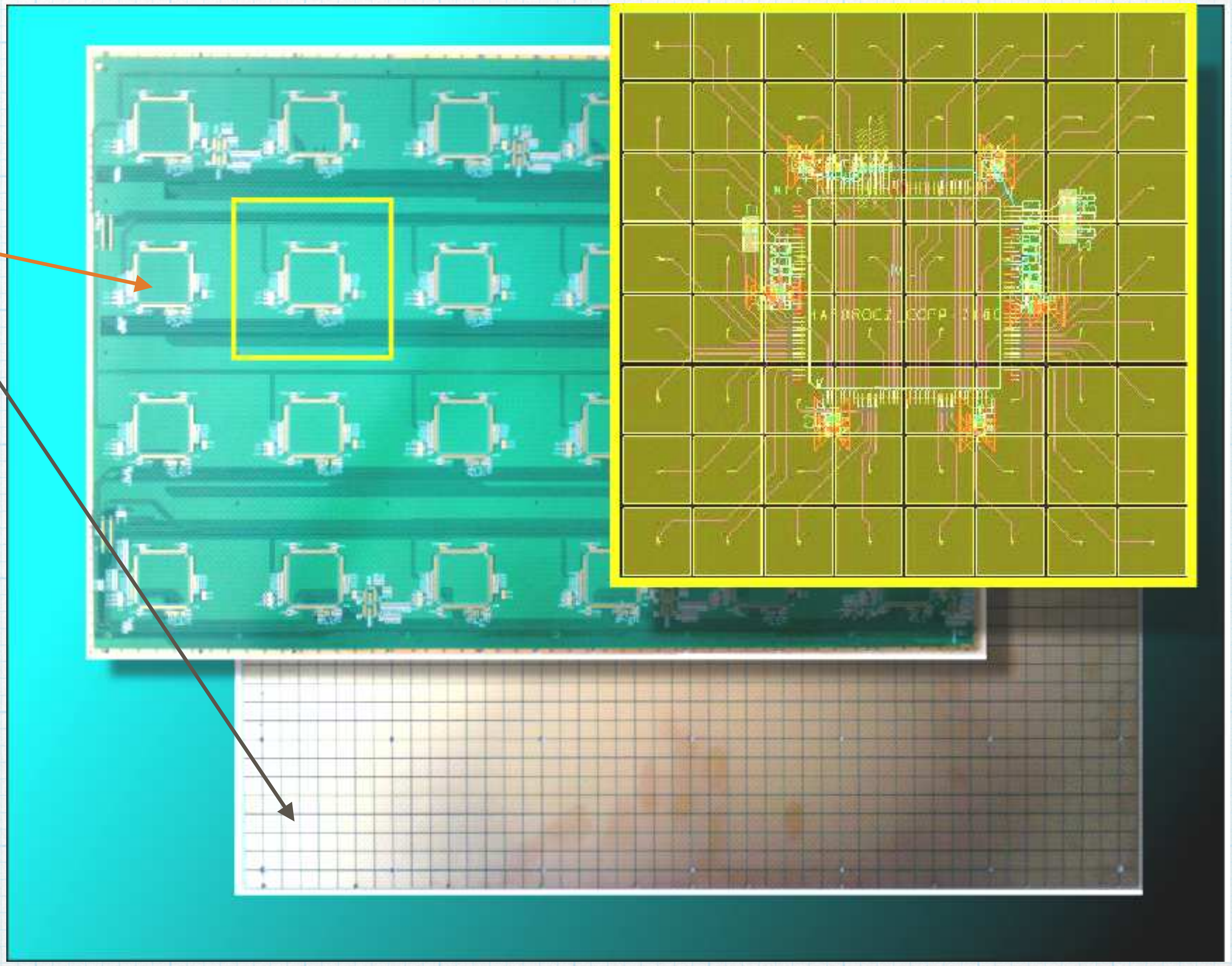
cf. talk by G. Grenier



ILD detector event display
$e^+e^- \rightarrow W^+W^- \rightarrow qqqq$

The SDHCAL Calorimeter





- SDHCAL calorimeter is a sampling calorimeter: **steel & RPC**
- SDHCAL technology:
  - Glass RPC
  - **1×1 cm²** readout pads
  - Embedded power-pulsed electronics
  - signal on the pads is recorded by HARDROC2 ASICs in a 2-bit format, corresponding to three thresholds related to the amount of induced charge → **semi digital**
  - 20 mm Stainless Steel Plates: structure of the modules and absorber
  - 50 plates, ~6λ_I

Simulation of SDHCAL: Digitisation

* Simulation in 2 steps:
    * Particle showers in the matter ➜ Geant-4
    * Simulation of the sensor response (RPC+ASIC) to Geant-4 hits ➜ Digitisation

* Digitisation is challenging:
    * High Granularity ➜ very sensitive to previous steps of simulation (Geant-4)
    * Overlapping effects: Geant-4, avalanche, charge induction, ASIC ➜ Tuning with data
    * Treat a large variety of particles: electromagnetic, hadronic, different energies ➜ universal
    * To work with both isolated tracks and dense environment

Digitisation of sDHCAL

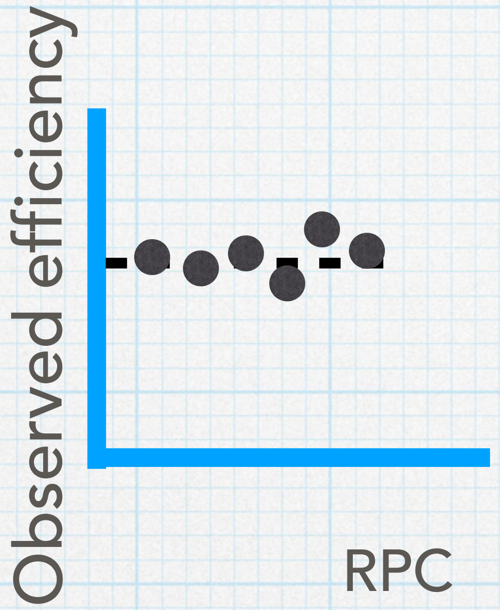
Particle$^{\pm}$ cross RPC Type/$\beta\gamma$ → (ionisation) → Initial Charges → (avalanche) → Charges → (induction, threshold) → Induced signal Distribution to pads

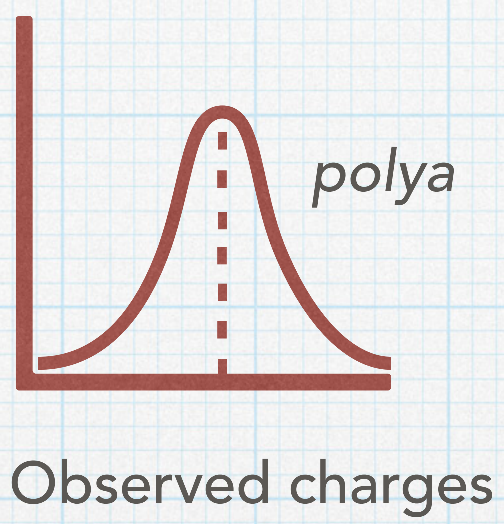
- Geant4 simulation. Interactions modelled with Geant-4 version 9.6 QGSP_BERT_HP (hadronic) & FTFP_BERT_HP (EM)
- Geant4 steps created in chambers taken as starting point

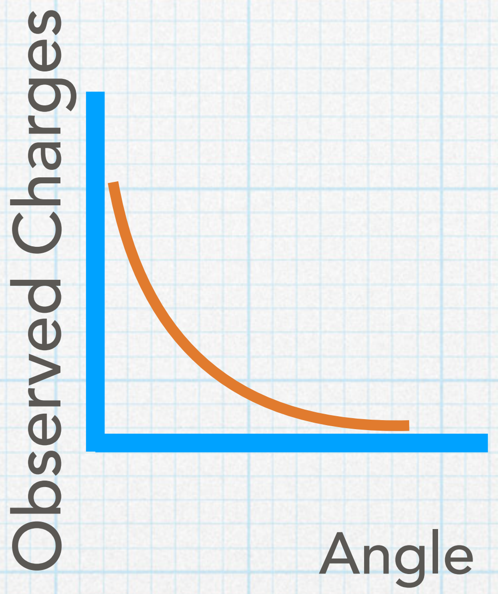
Digitisation of sDHCAL

Particle± cross RPC Type/βγ → ionisation → Initial Charges → avalanche → Charges → induction, threshold → Induced signal Distribution to pads

G4 Step preselection x







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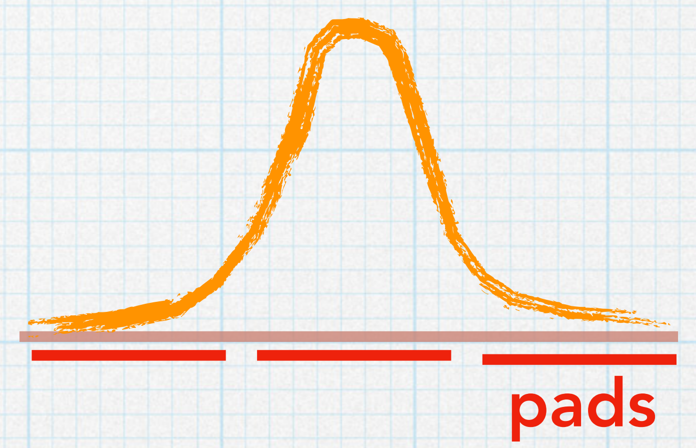
* Preselection applied to Geant4 steps based on position and length
* Screening effects induced by overlapping avalanches treated with a cut-off on the step-step distance
* For each Geant4 step, a random charge is taken from a Polya function (Avalanche modelling)
* 100 GeV muon Data from test-beam are used to tune:
  * Amplitude of the charge
  * Hit efficiency
  * Angular dependence

Digitisation of sDHCAL

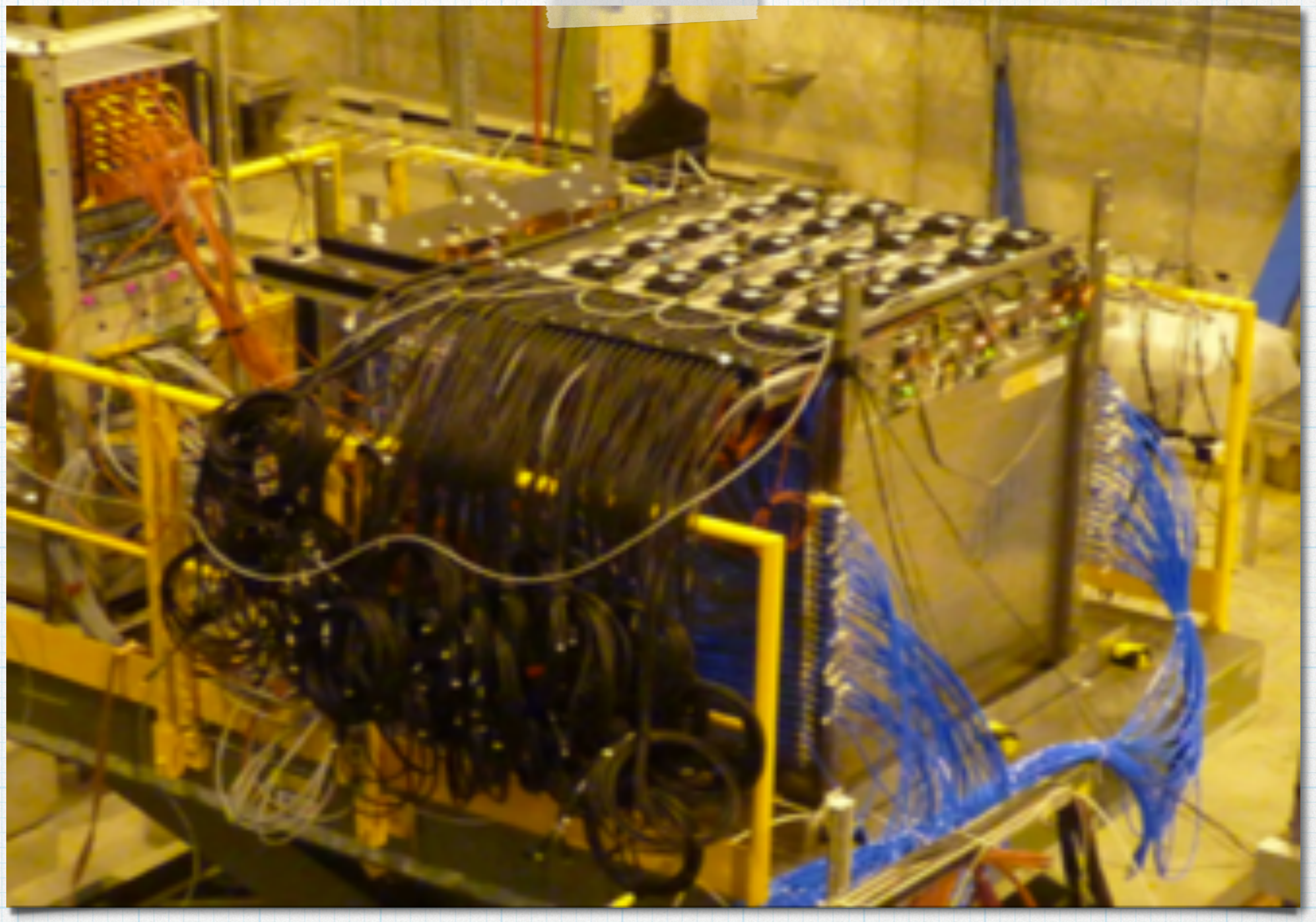
Particle± cross RPC Type/βγ → (ionisation) → Initial Charges → (avalanche) → Charges → (induction, threshold) → Induced signal Distribution to pads



* Charges are distributed to the pads
* Modelled with an analytical function (double Gaussian)

Test Beam data used to tuned digitiser parameters

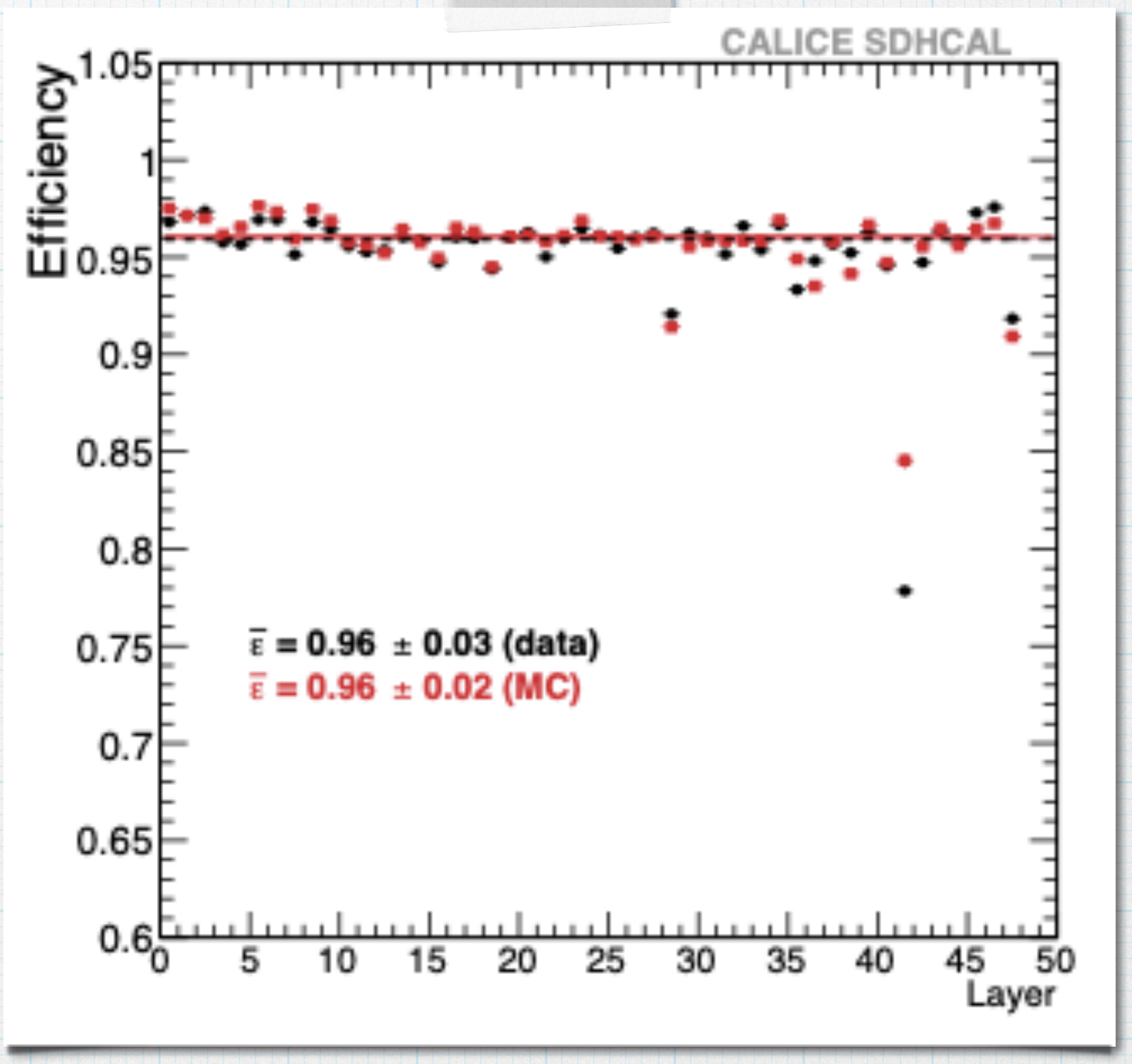
* Use of the SDHCAL technological prototype:
  * 48 Layers (48 GRPC)
  * 1 m2 layers
  * Gas mixture : 93%TFE ; 5%CO2 ; 2%SF6
  * HV about 6.9 kV à avalanche mode
  * 9216 pads (1 cm2) per chamber
  * 442k channels
  * 144×48 ASICs: Hardroc 2 (64 ch)
* Test beam campaigns:
  * 2012, 2015, 2016, 2017, 2018 at CERN PS and SPS
  * Exposed to hadron, muon, electron beams
* Use of power-pulsing:
  * Based on (S)PS spill structure
  * First test of the power pulsing with such a detector



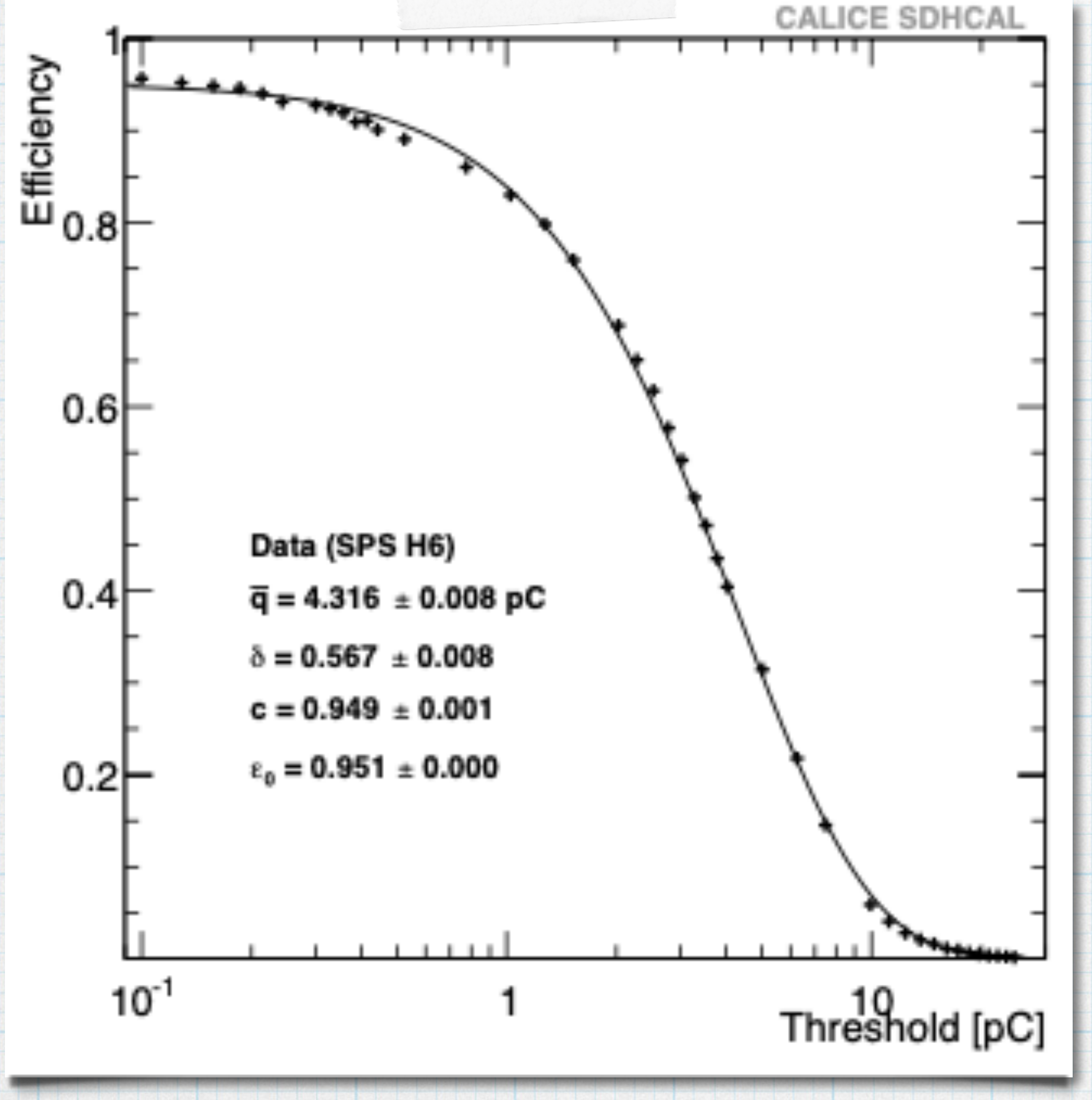
Inputs of the digitisation: efficiency

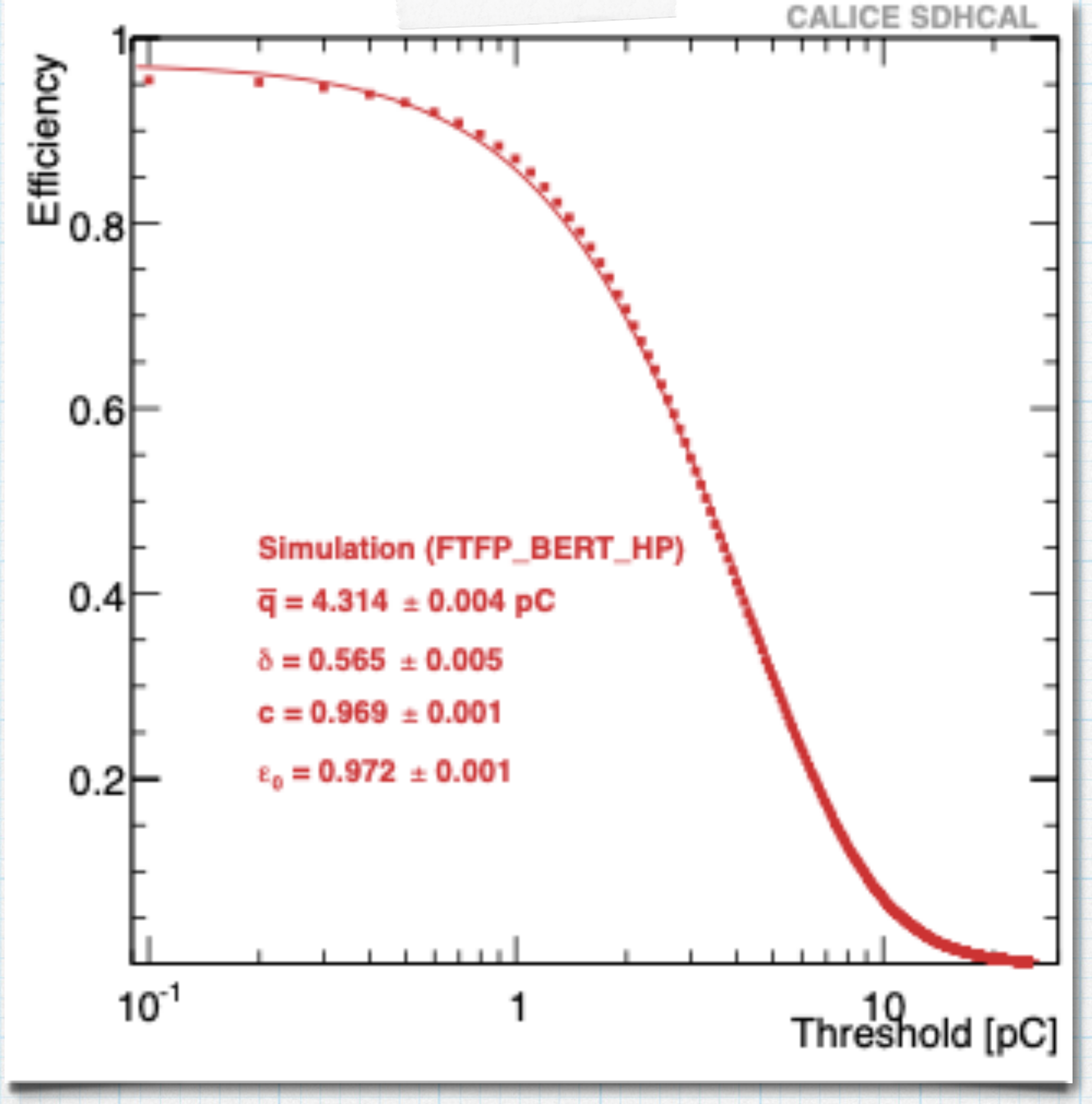
* Efficiency is measured with test beam muons
* It reflects non homogeneities of the detector (RPCs, ASICS)
* Quantifies the probability to reach the first threshold

Random selection of hits in the digitisation performed based on this efficiency



Inputs of the digitisation: polya parameters





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

- Induced charge distribution modelled by a Polya
- Polya parameters extracted from test beam data
- Digital calorimeter: use of a threshold scan

Parameter	Data	Simulation	Digitizer input
$\bar{q}$	$4.316 \pm 0.008\,pC$	$4.314 \pm 0.004\,pC$	$4.580\,pC$
δ	0.567 ± 0.008	0.567 ± 0.005	1.120

Random charge produced from the polya function

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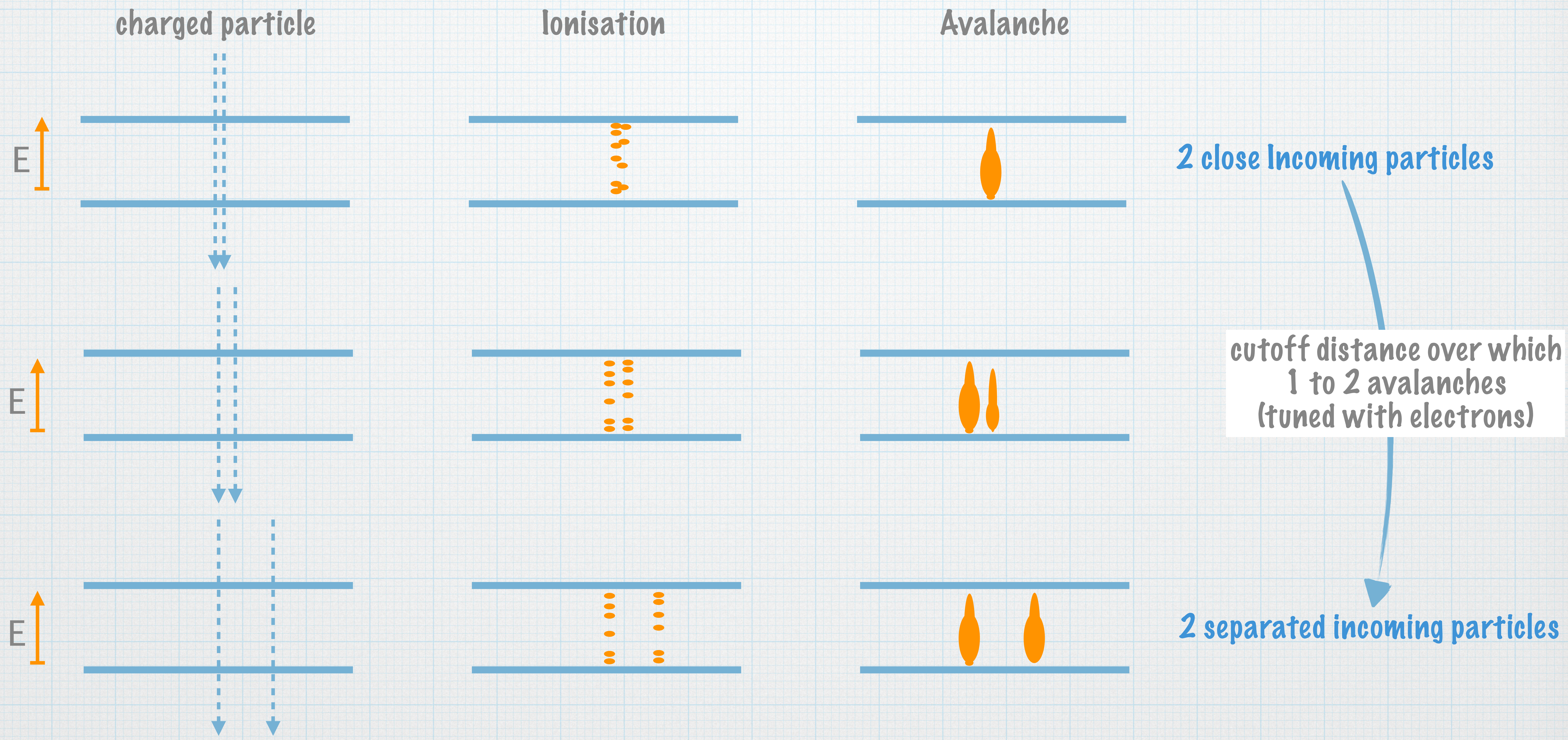
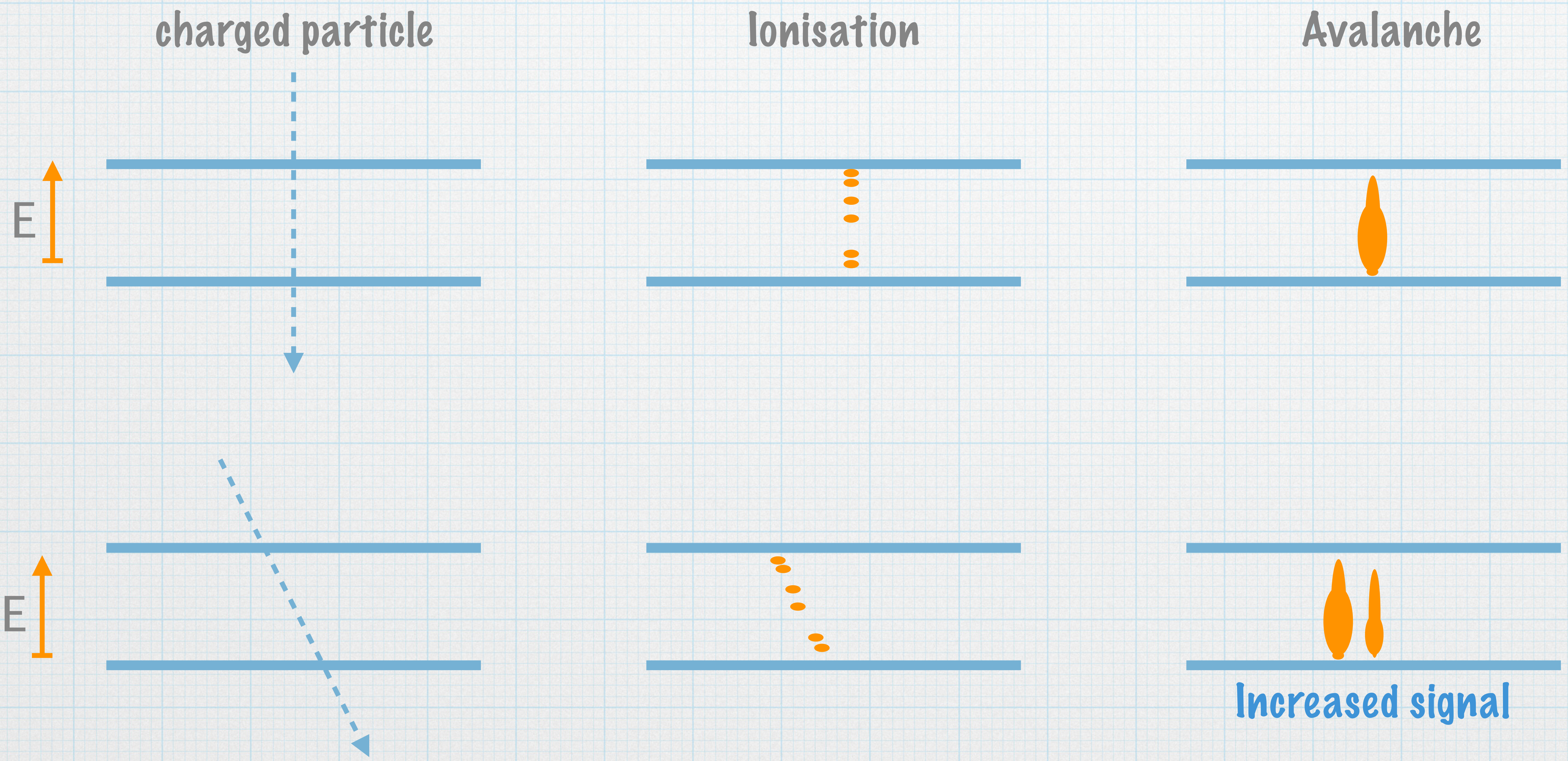
Inputs of the digitisation: overlapping hits



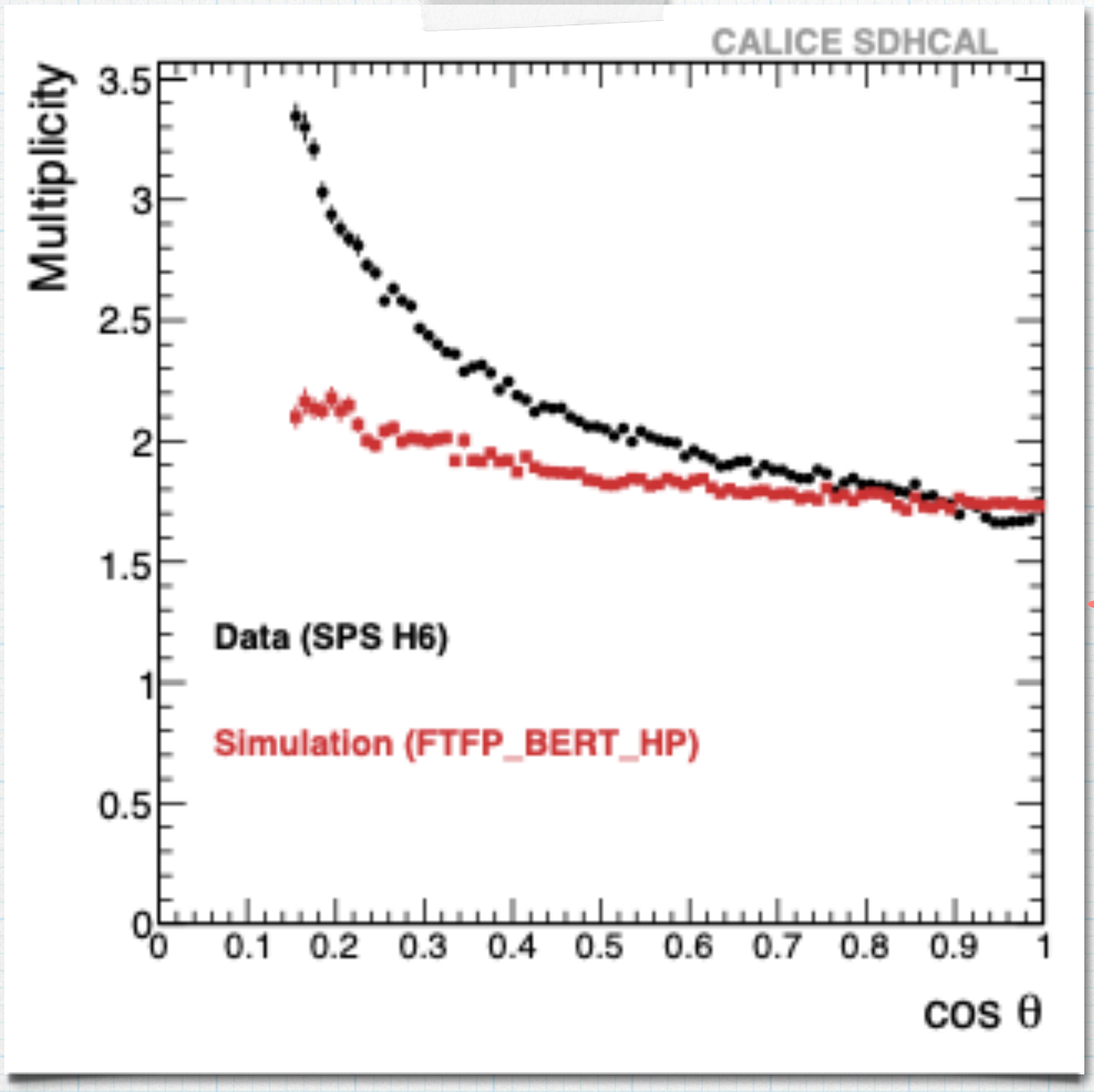
Inputs of the digitisation: angular dependence



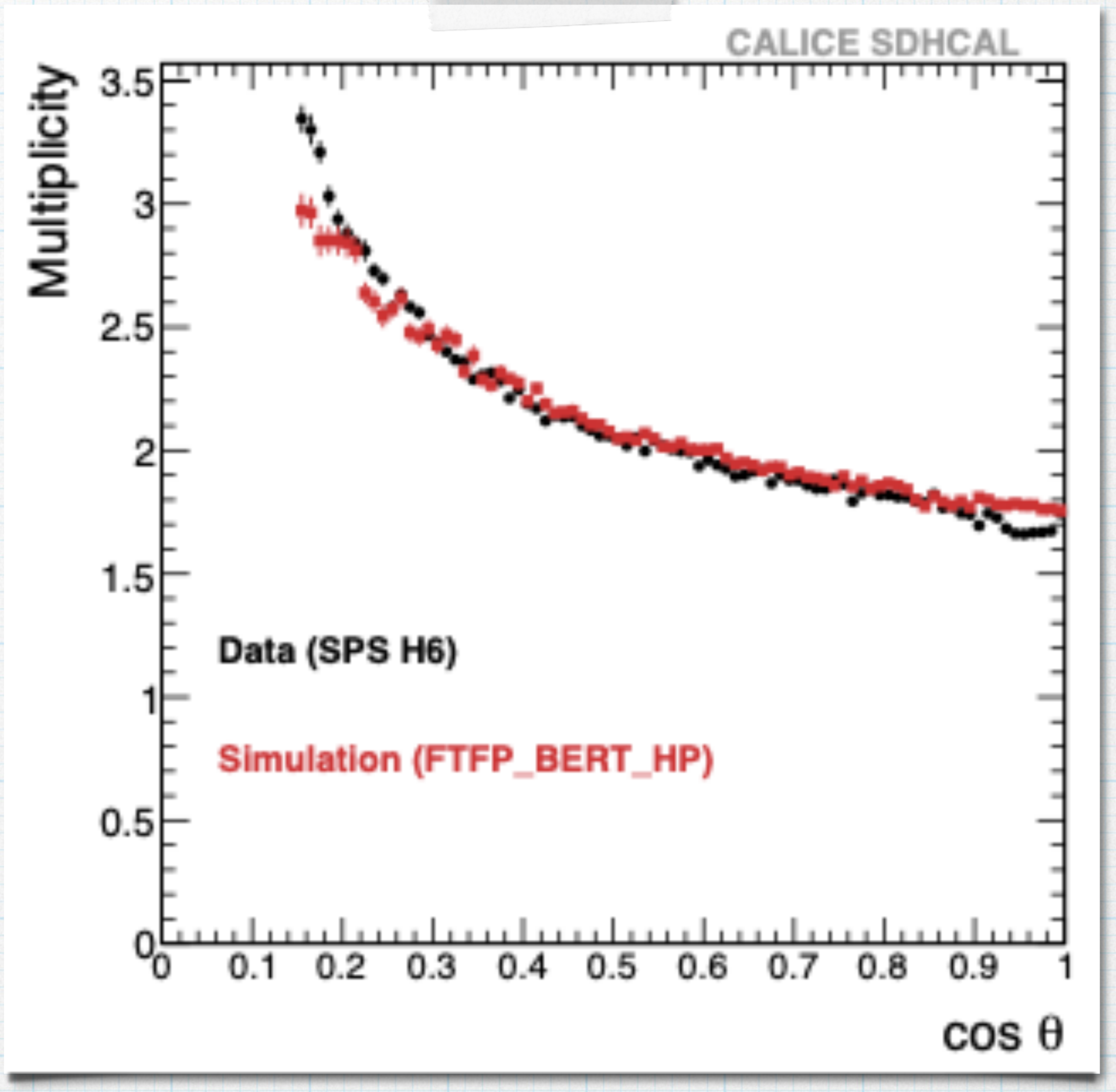
Incoming particle normal to RPC

Incoming particle with angle

Inputs of the digitisation: angular dependence



Step angle correction



* Amplitude of avalanches depends on the angle of the incoming particle
* Dependence of amplitude & efficiency measured using test beam muons with different angles.

Correction applied to hit amplitude function of Geant-4 step angle

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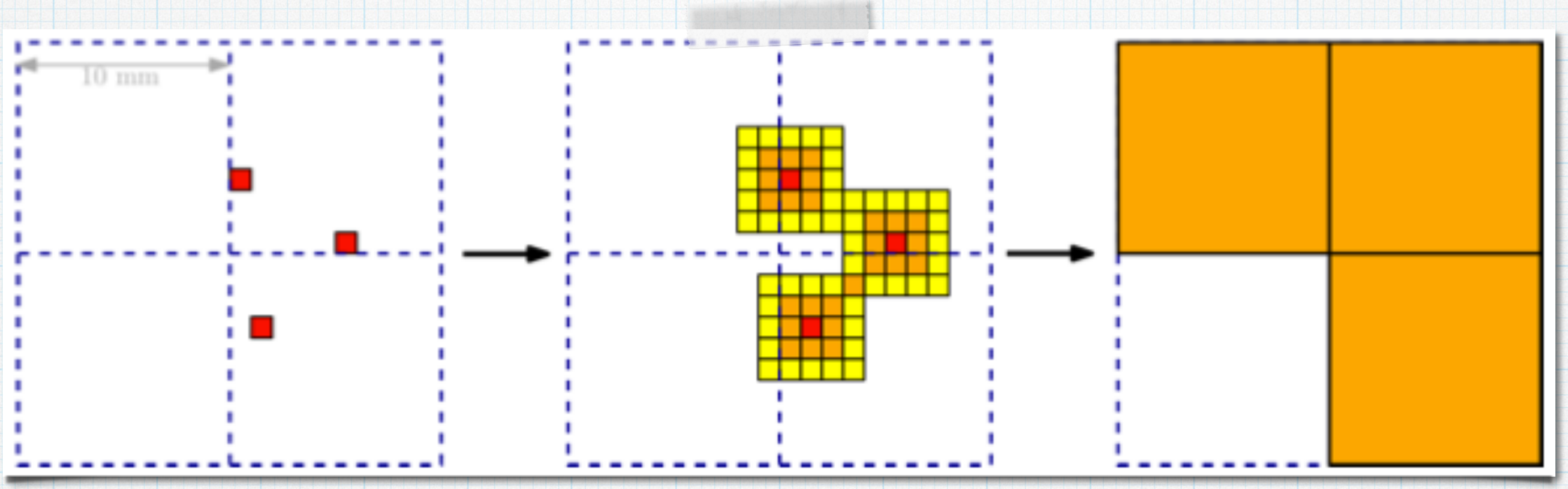
Charge collection



* Charges are distributed to the pads
* For each step (avalanche), fraction of charges seen by a pad is modelled with a sum of gaussian weights
* Charges accumulated on the Pads
* Parameters tuned with muon test beam data

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

$$N = \int_{-r_{max}}^{+r_{max}} \int_{-r_{max}}^{+r_{max}} \sum_{j=0}^{n} \alpha_j e^{\frac{(x_0-x)^2+(y_0-y)^2}{2\sigma_j^2}} dxdy$$

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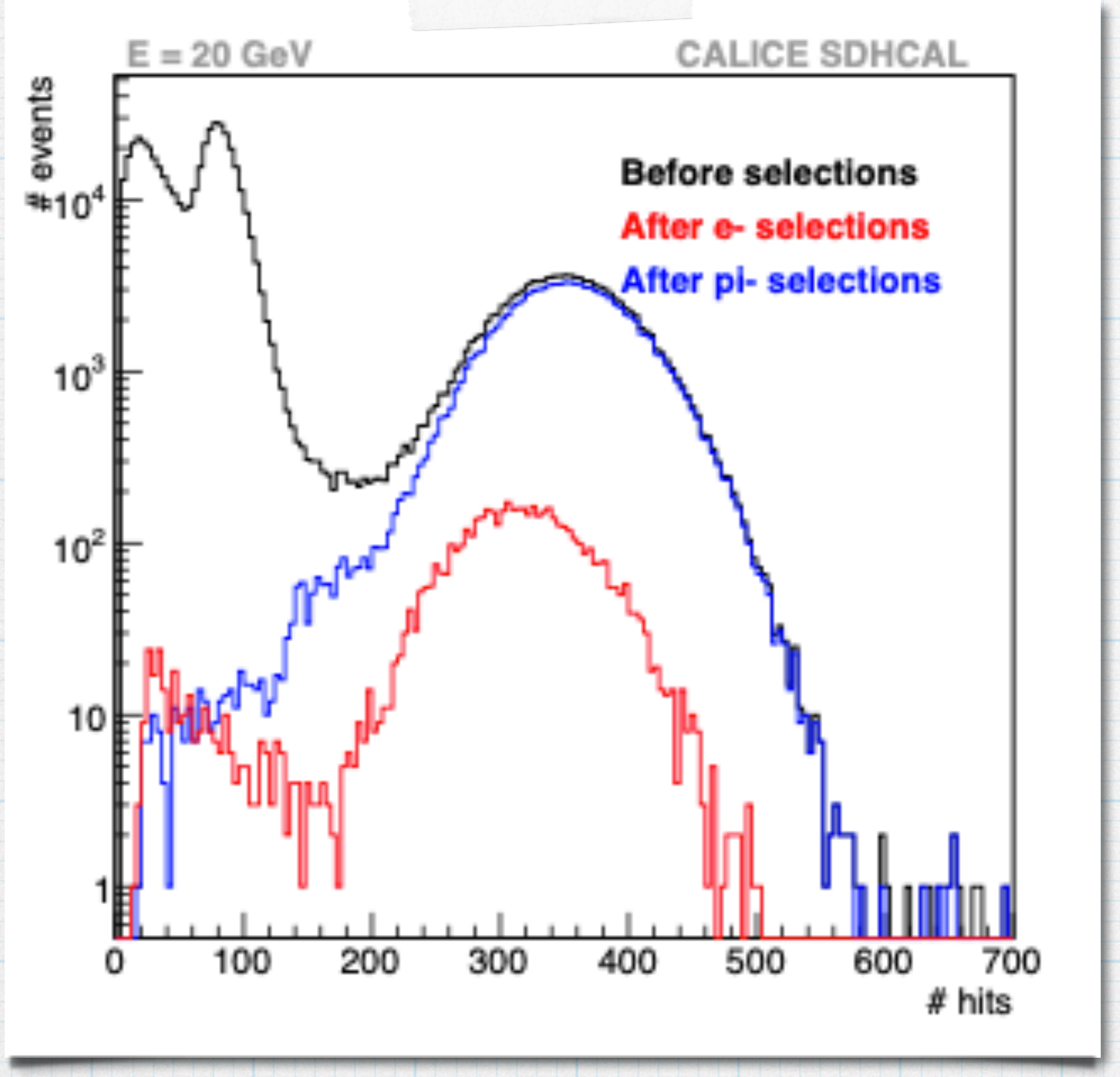
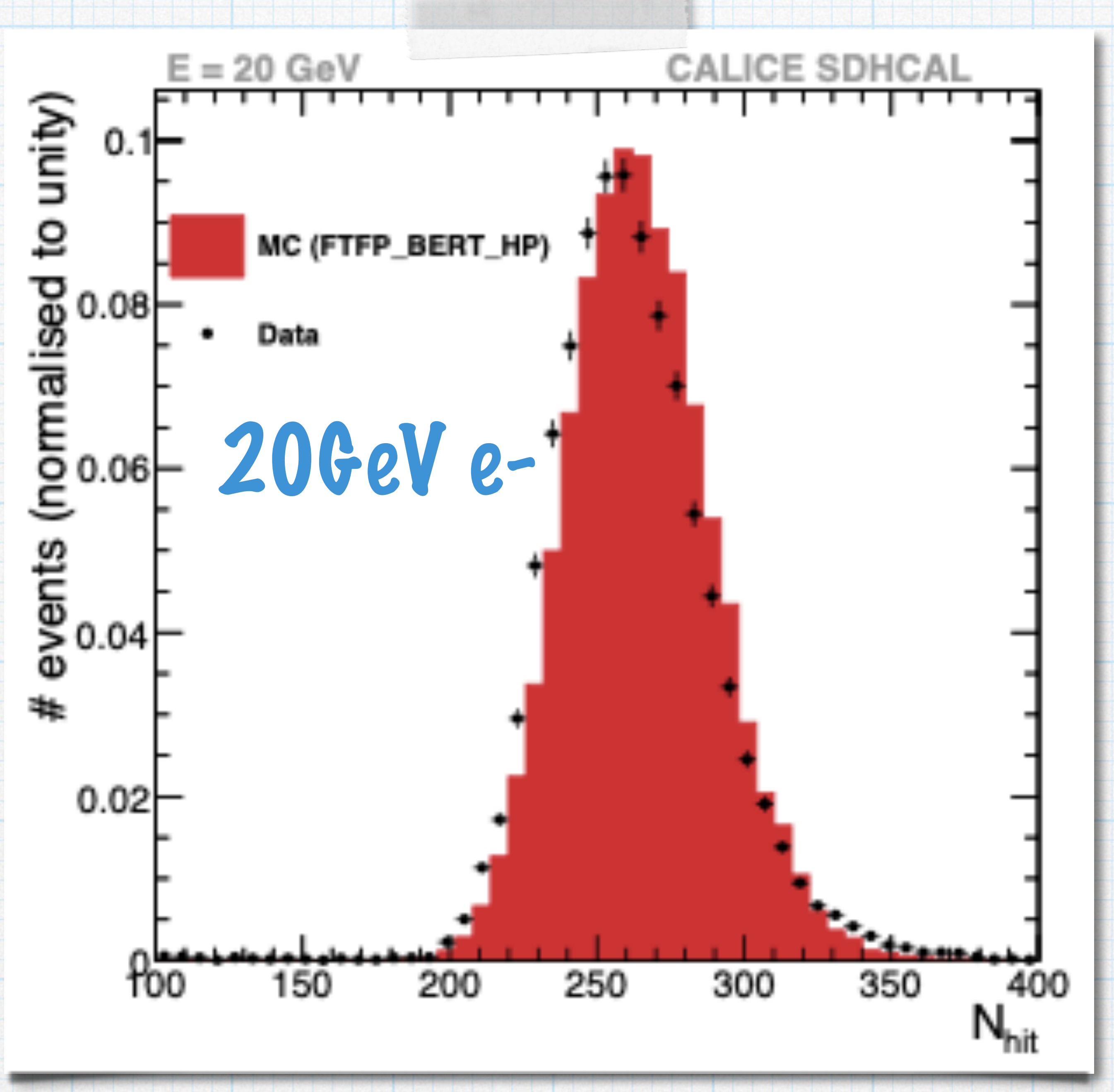
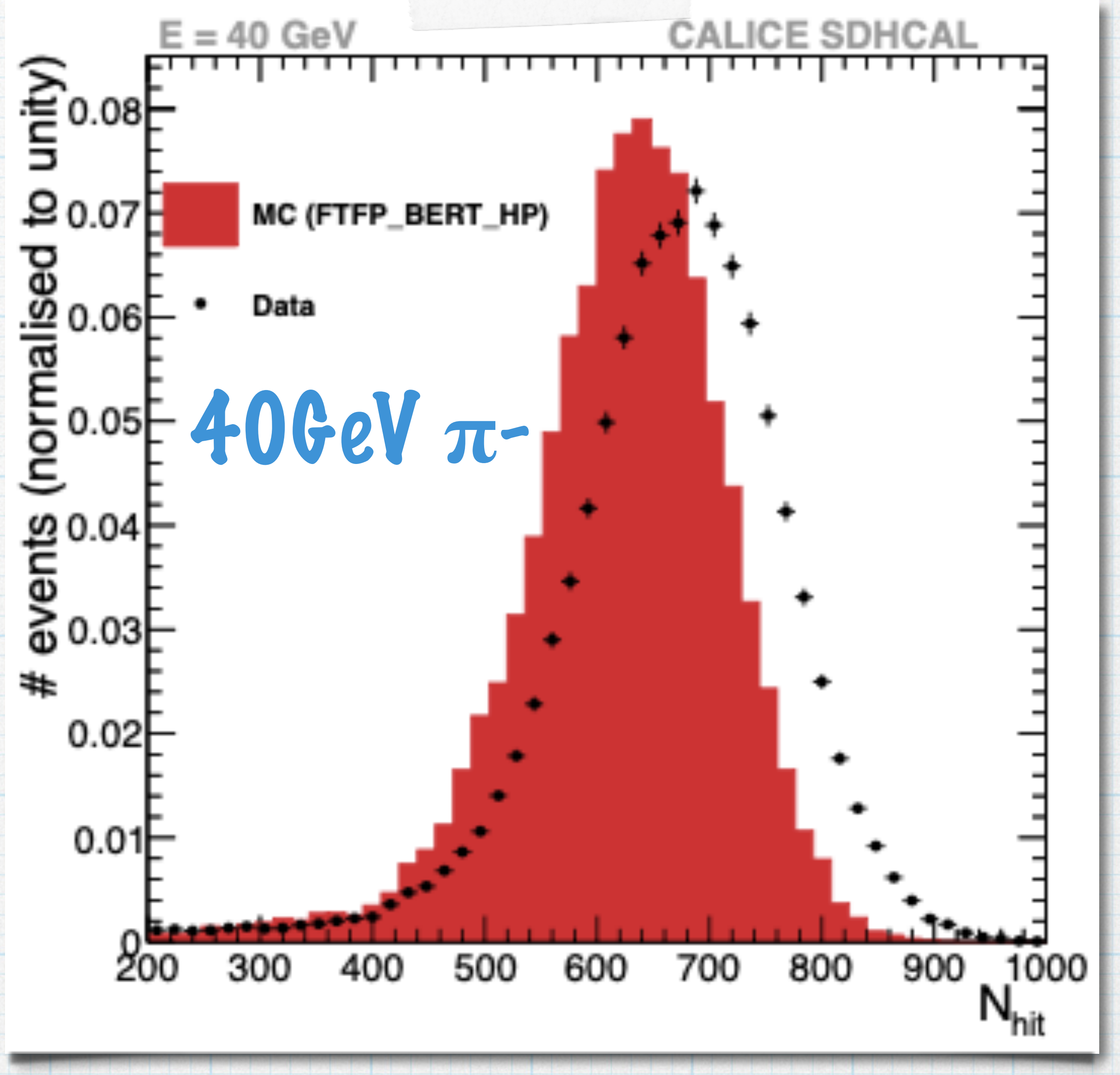
Comparison of simulation to Data







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- Test beam data with electrons or pions are selected
- Comparison of total number of hits
  - Better for electrons than pions
  - Better for high energy electrons w.r.t. low energy electrons
  - Better for low energy pions w.r.t. high energy pions
- Simulation combines Geant-4 and digitiser modelings

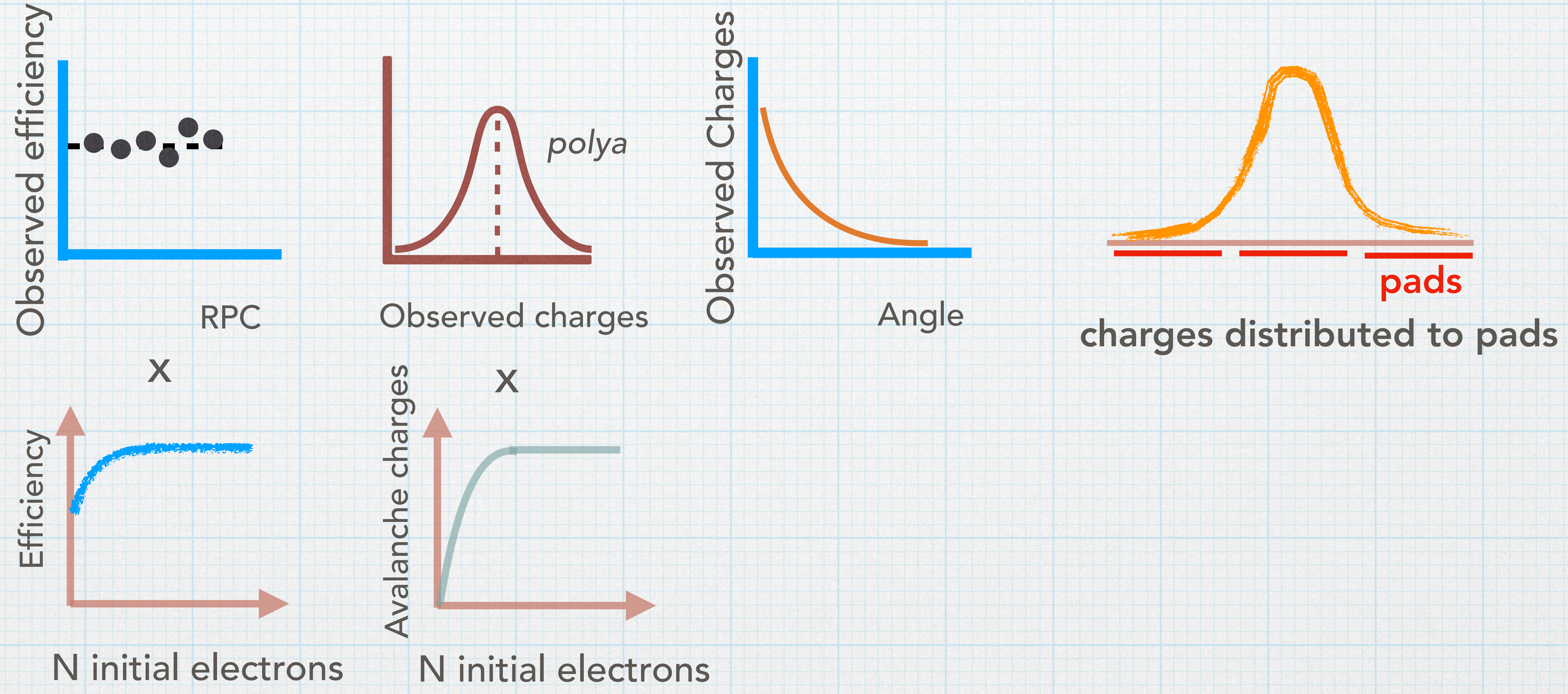
Possible improvements of RPC digitisation

* Screening effects due to overlap of avalanches treated with a cut-off ➜ possibility to apply a non linear combination of avalanches
* Charge distribution modelled with gaussian weights ➜ possibility to use better distribution functions
* Data tuning of the digitisation done with high energy muons, not function of energy deposit ➜ possibility to add dependence to ionisation

Digitisation of sDHCAL

Particle± cross RPC Type/βγ → ionisation → Initial Charges → avalanche → Charges → induction, threshold → Induced signal Distribution to pads

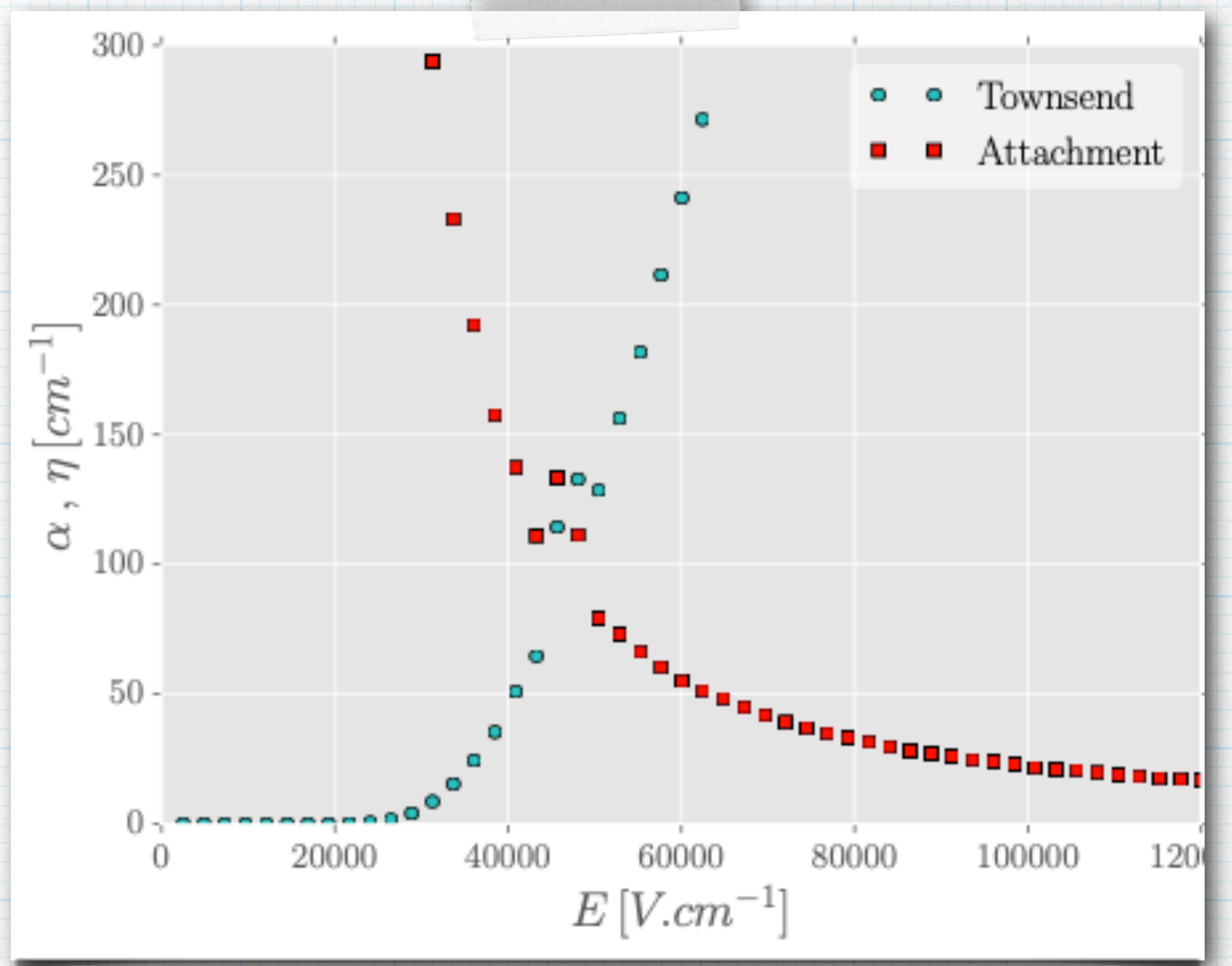
G4 Step preselection x

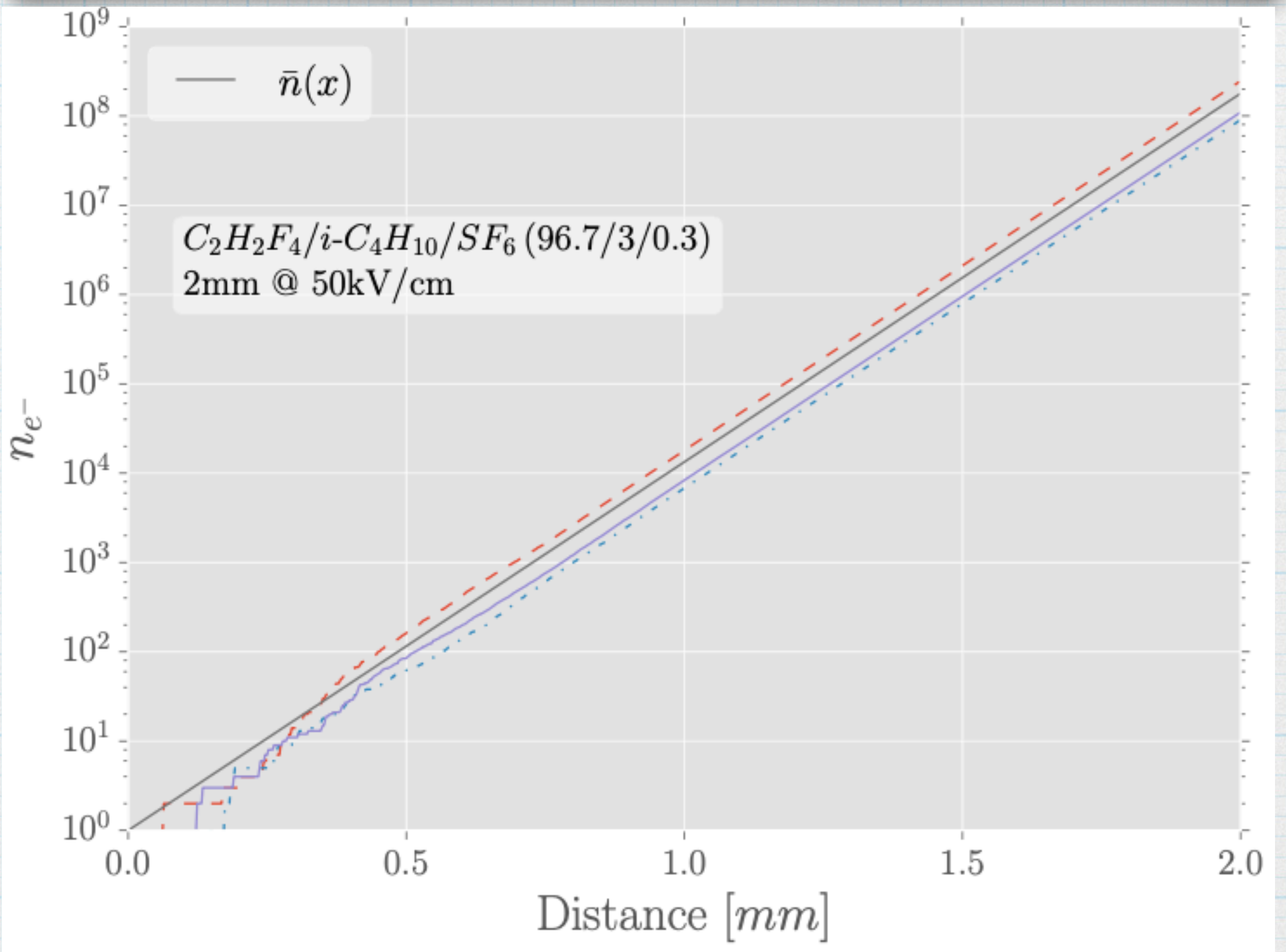


- Add a dependence of the efficiency/signal to the initial number of charges (Ionisation correction)
- Initial numbers of charges given by Geant-4 deposited energy (ionisation) in the hit

Ingredient: amplification modelling

* Monte Carle simulation of the avalanche:
  * Follow the evolution of the number of electrons and ions as a function of time and position
  * Take into account the changes in the magnetic field
* Simulation account for:
  * **Multiplication and absorption probabilities from Magboltz**
  * Diffusion
  * Space charge effect
  * Induced charge





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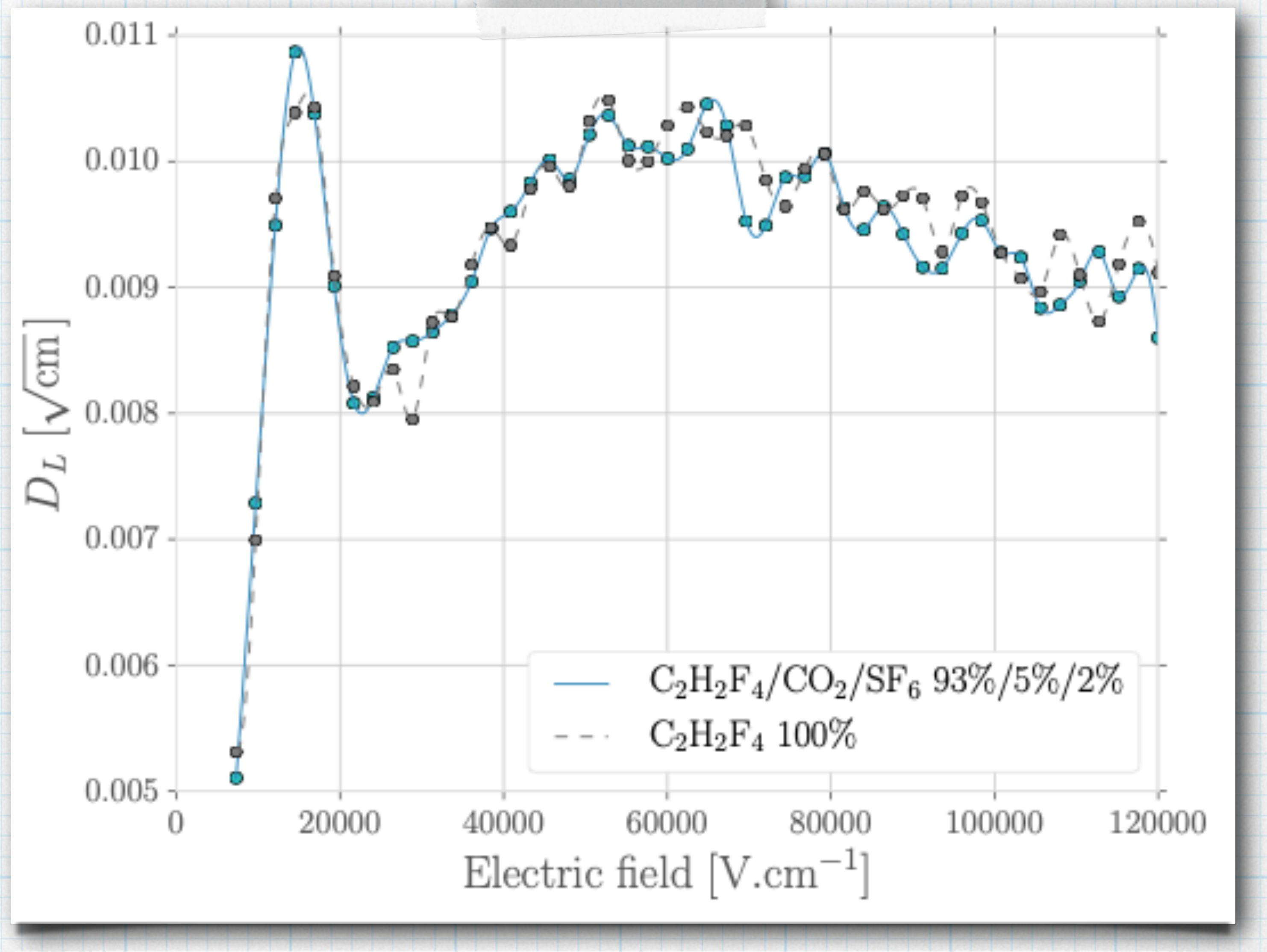
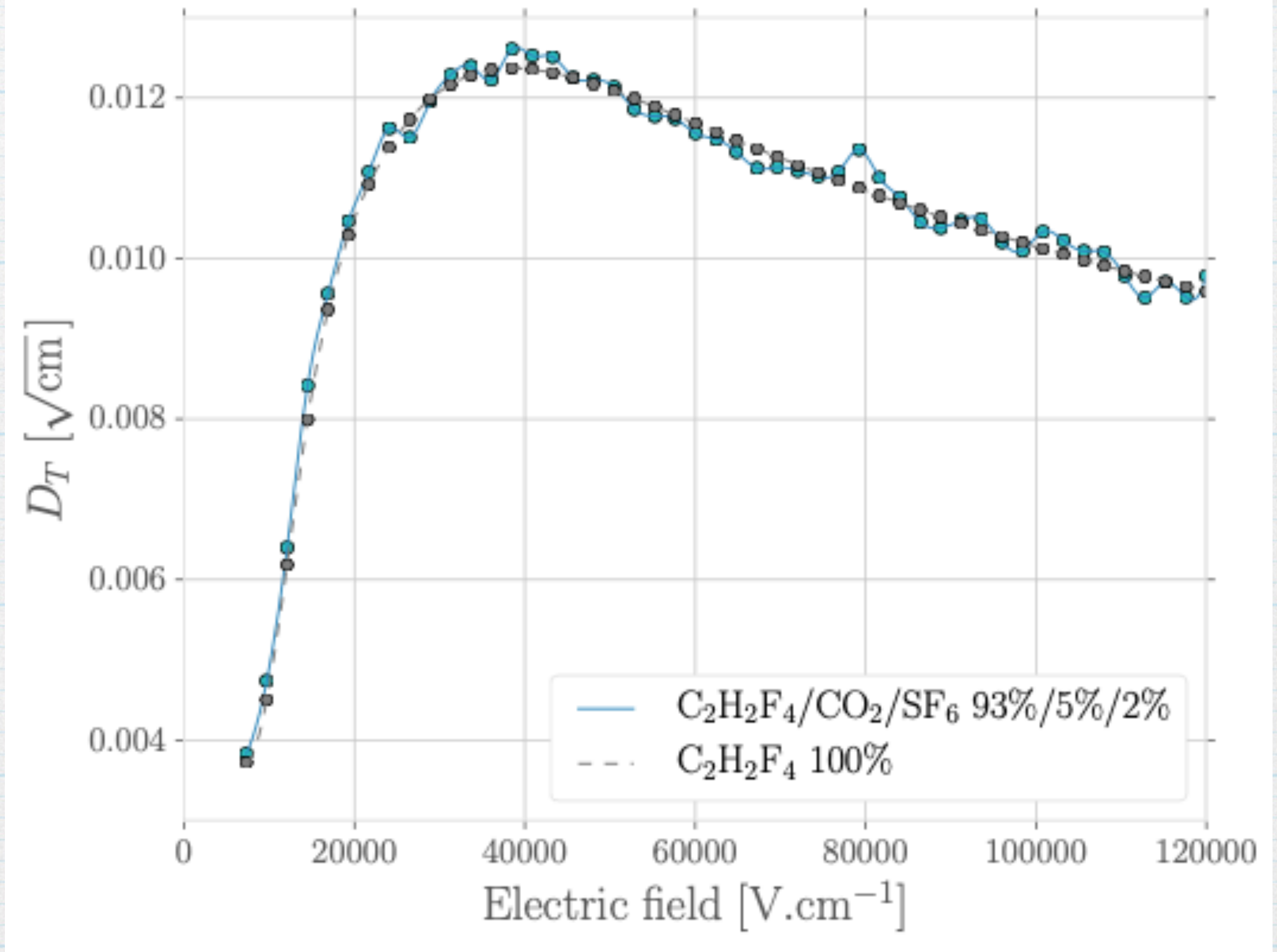
  * Multiplication and absorption probabilities
  * Diffusion computed with Magboltz 9
  * Space charge effect
  * Induced charge





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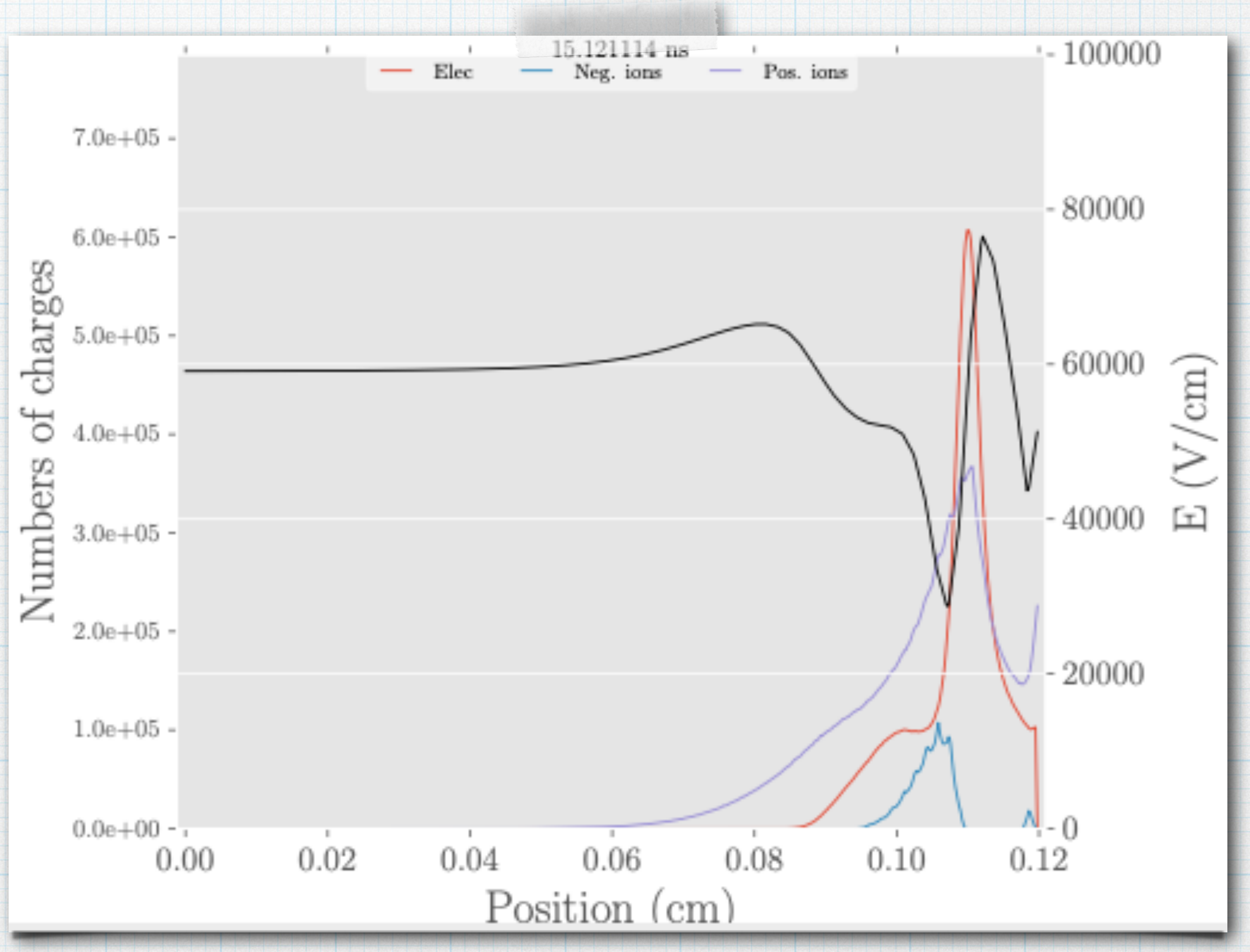
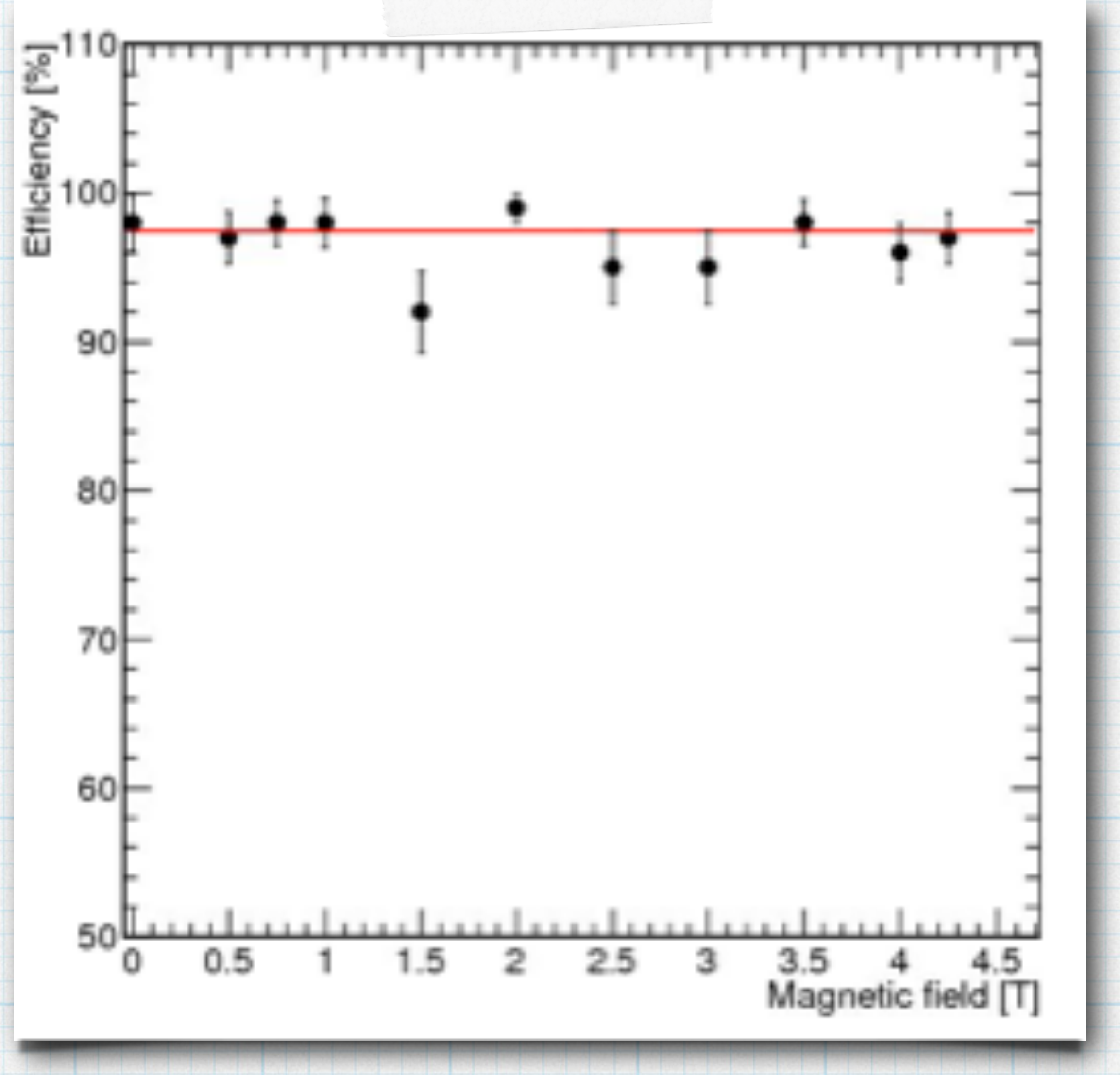
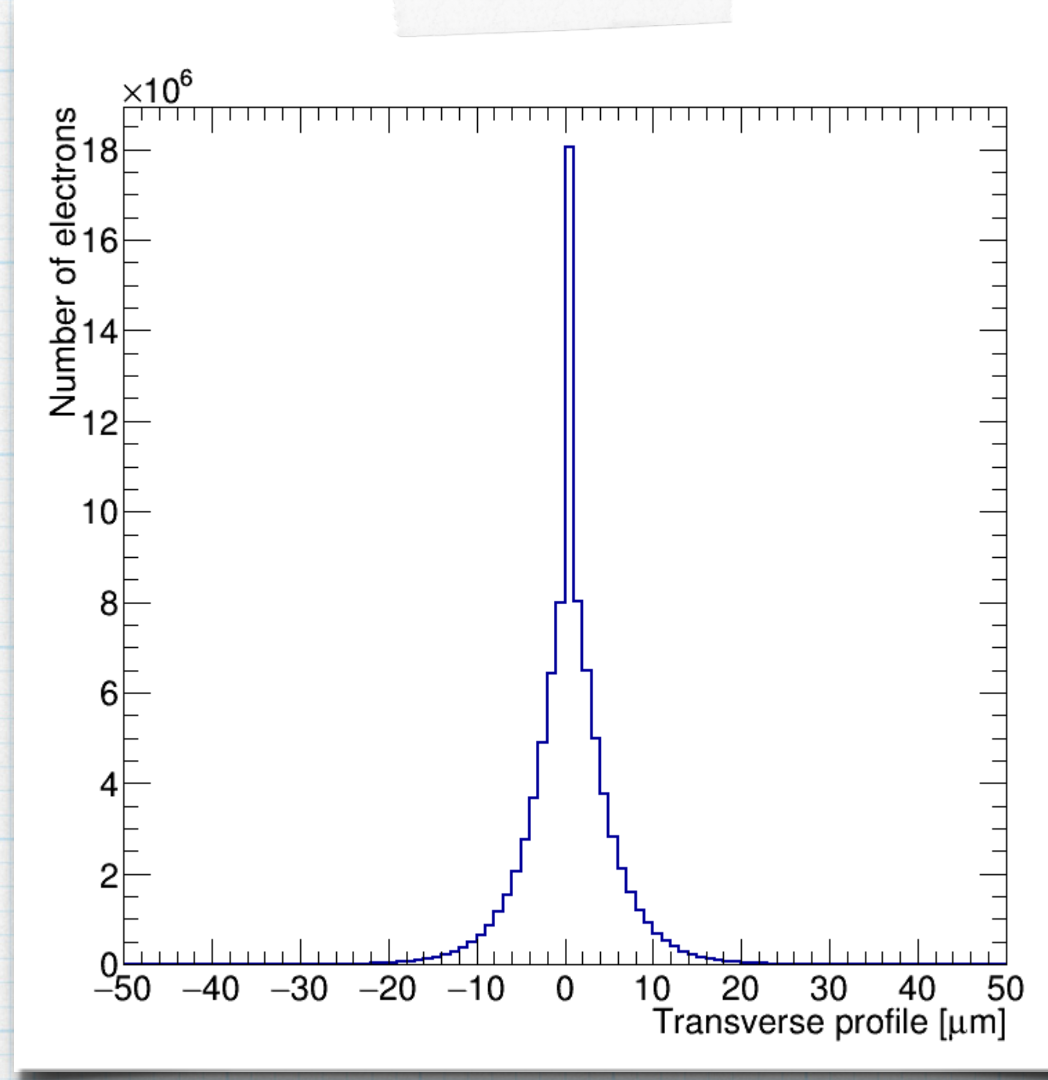
* Monte Carle simulation of the avalanche:
  * Follow the evolution of the number of electrons and ions as a function of time and position
  * Take into account the changes in the magnetic field
* Simulation account for:
  * Multiplication and absorption probabilities
  * Diffusion
  * Space charge effect: computing the influence of the avalanche on the electric field at each position & time
  * Induced charge

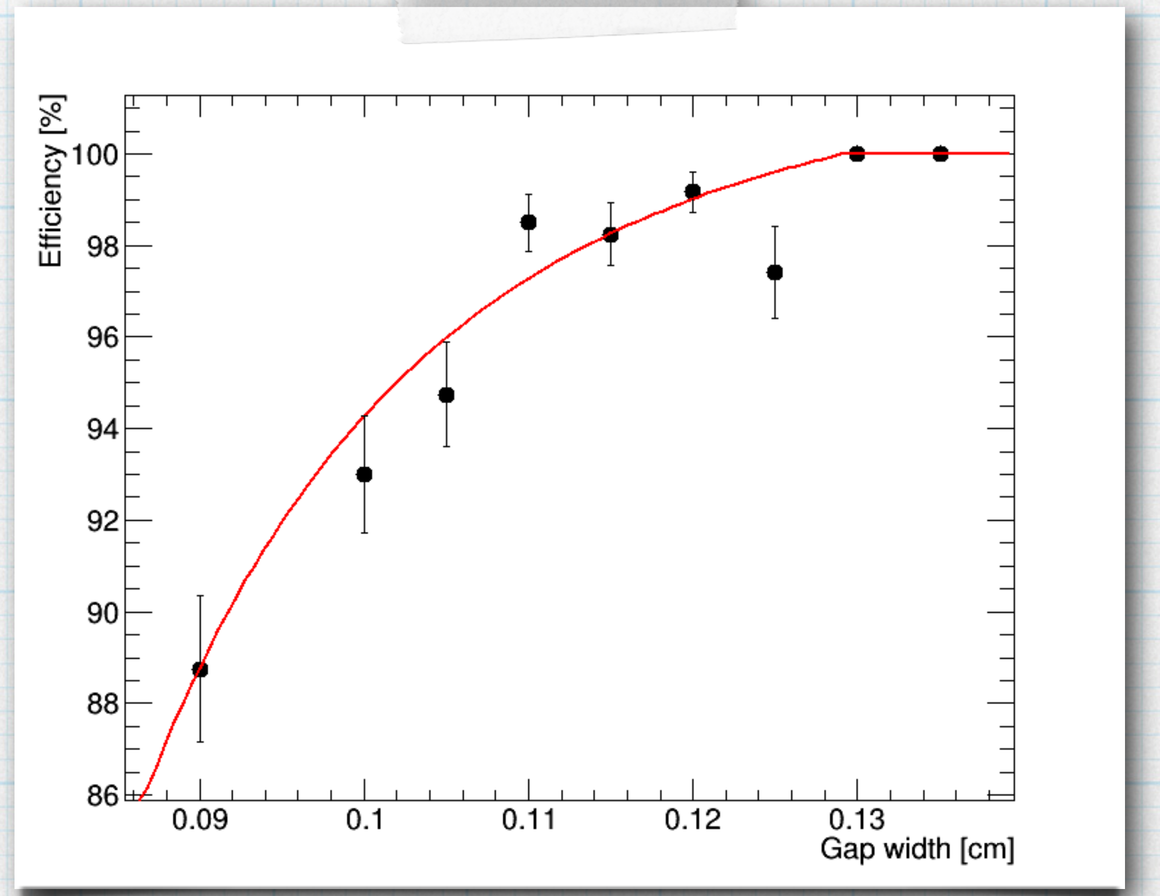


Ingredient: amplification modelling

* Modeling of avalanches can be used for many purposes:
  * Hit by Hit modelling of the amplitude
  * Hit by Hit Modeling of the efficiency
  * Time resolution
  * Impact of magnetic fields
  * Impact of gap width non-uniformities
* Next slides it will be used only to correct from amplitude and efficiency extrapolation from high energy muons (test beam) to other particles



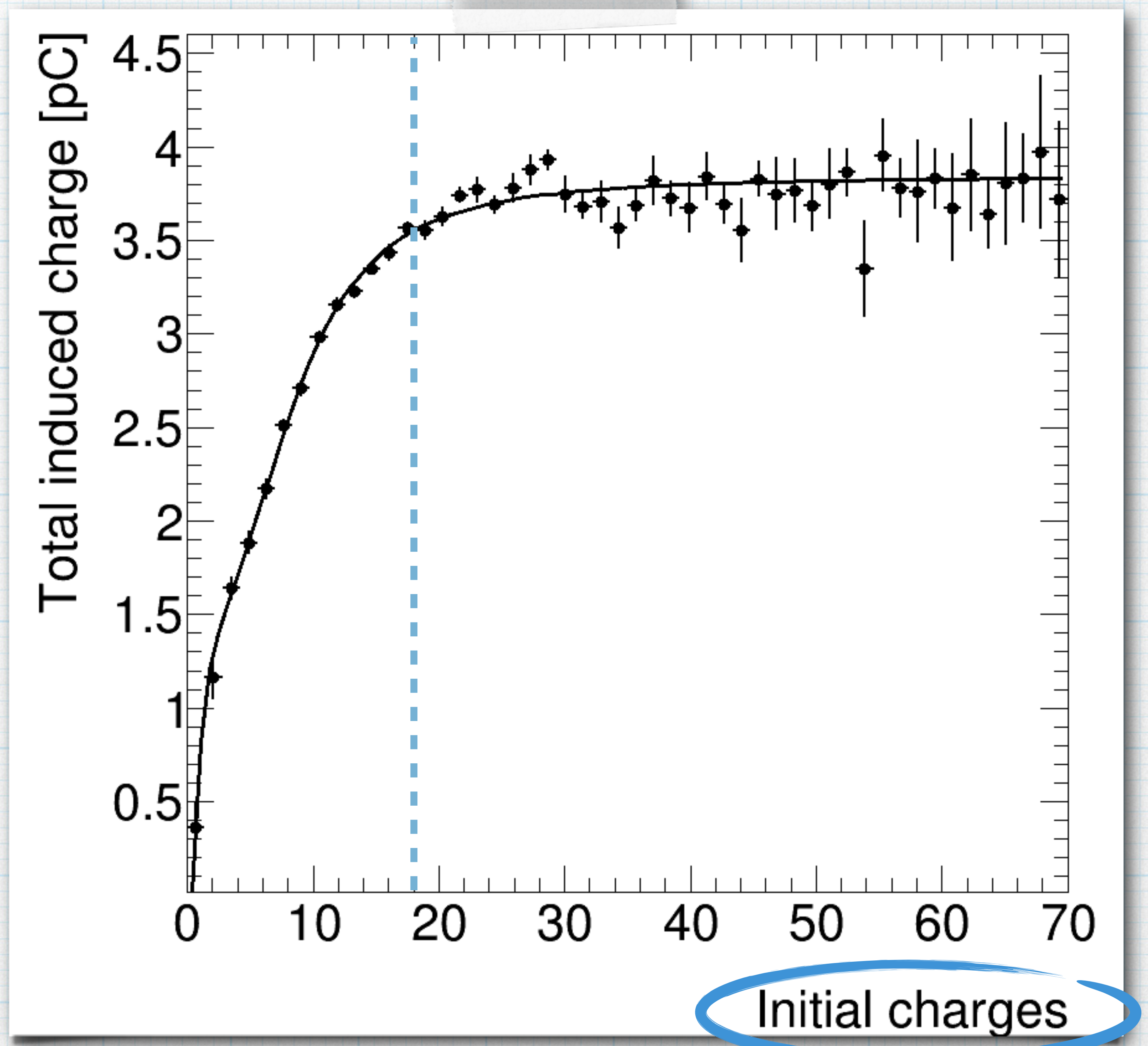




Ingredient: amplification modeling

* Test the amplitude of the avalanche and the efficiency (probability to have an avalanche)
* Clear saturation effect due to screening: no dependence to Ne>20 electrons
* Significant drop in amplitude (efficiency) if number of initial electrons < 20 (10)
* Use of 2D simulation of 32050 avalanches that required about 8500 CPU hours
* Amplitude and efficiency modelled with an analytical function that is injected in the digitiser
* Number of ionisation charges not provided by Geant4: use deposited energy given by Geant4 and another simulation to get the number electrons

typical ionisation by 100 GeV muons as used in test-beam



Geant-4 Energy / 29.8 eV

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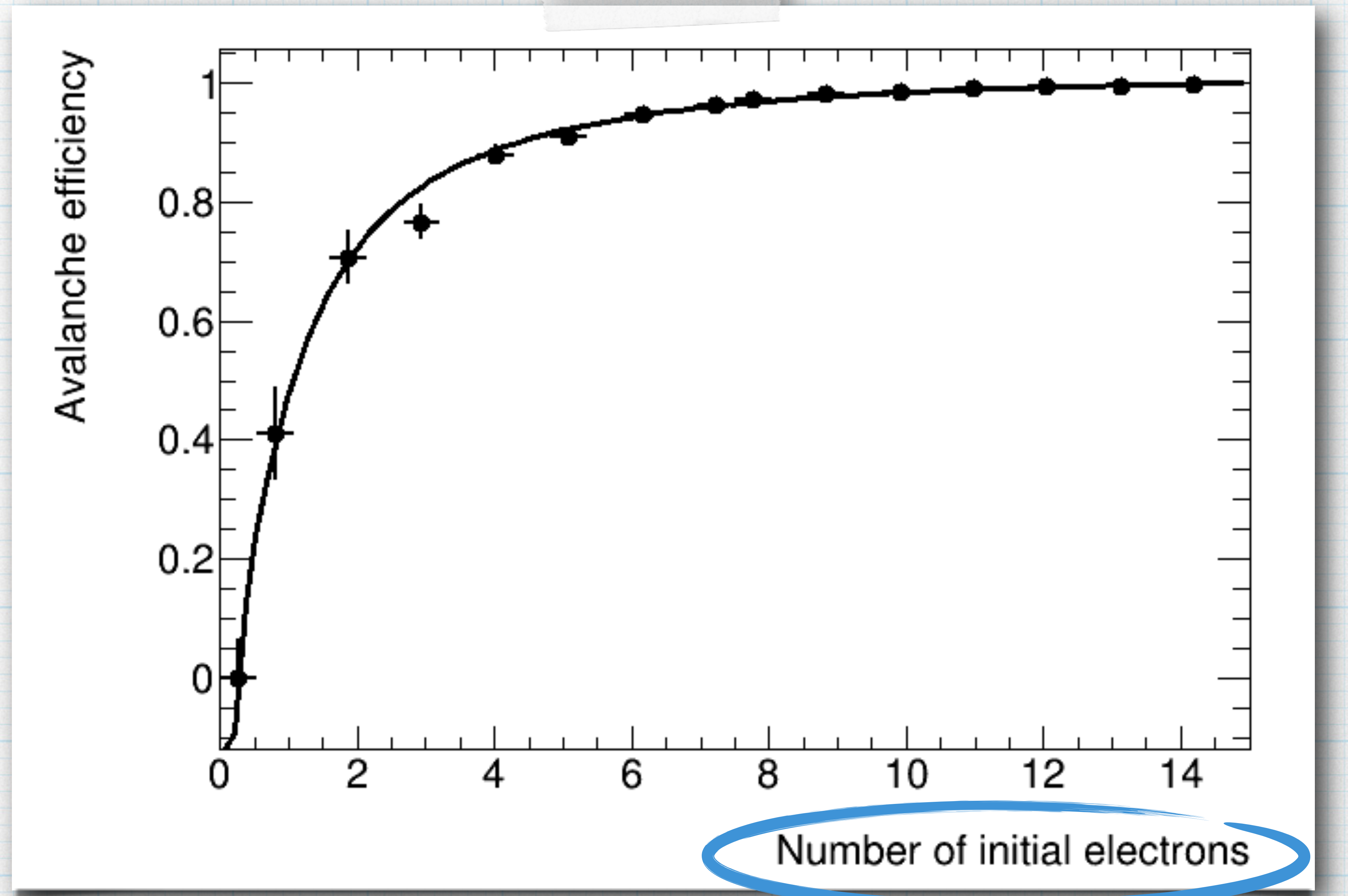
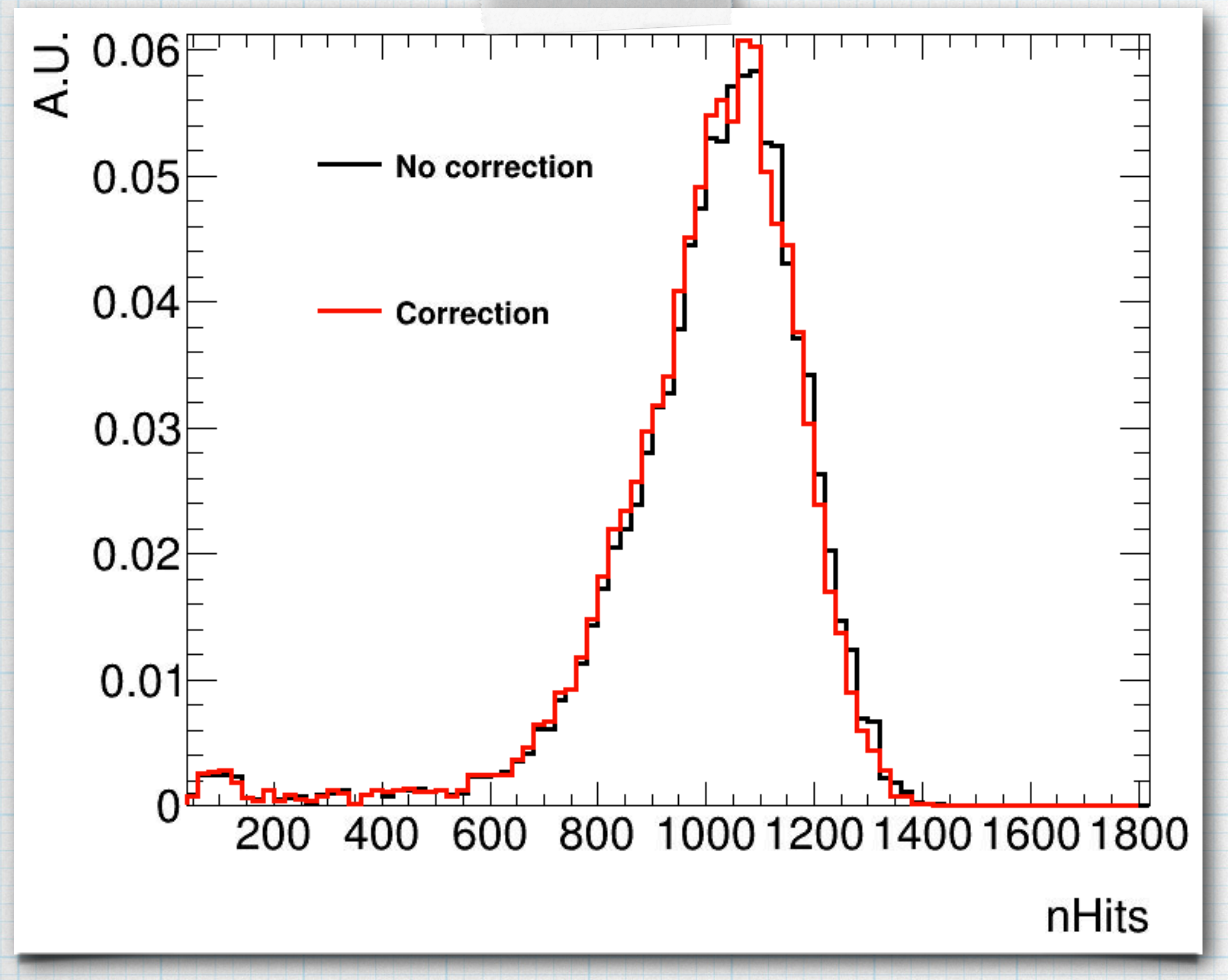
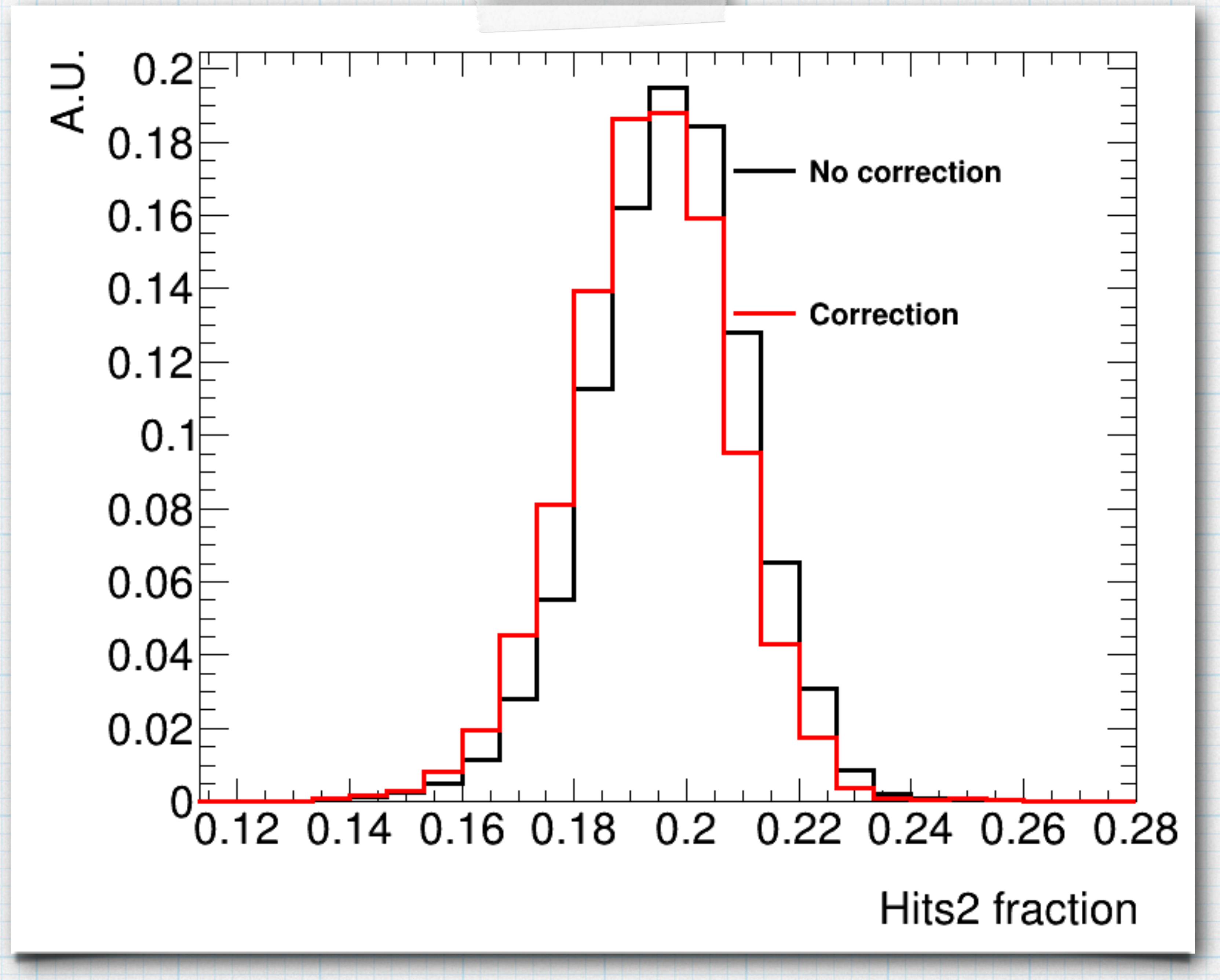


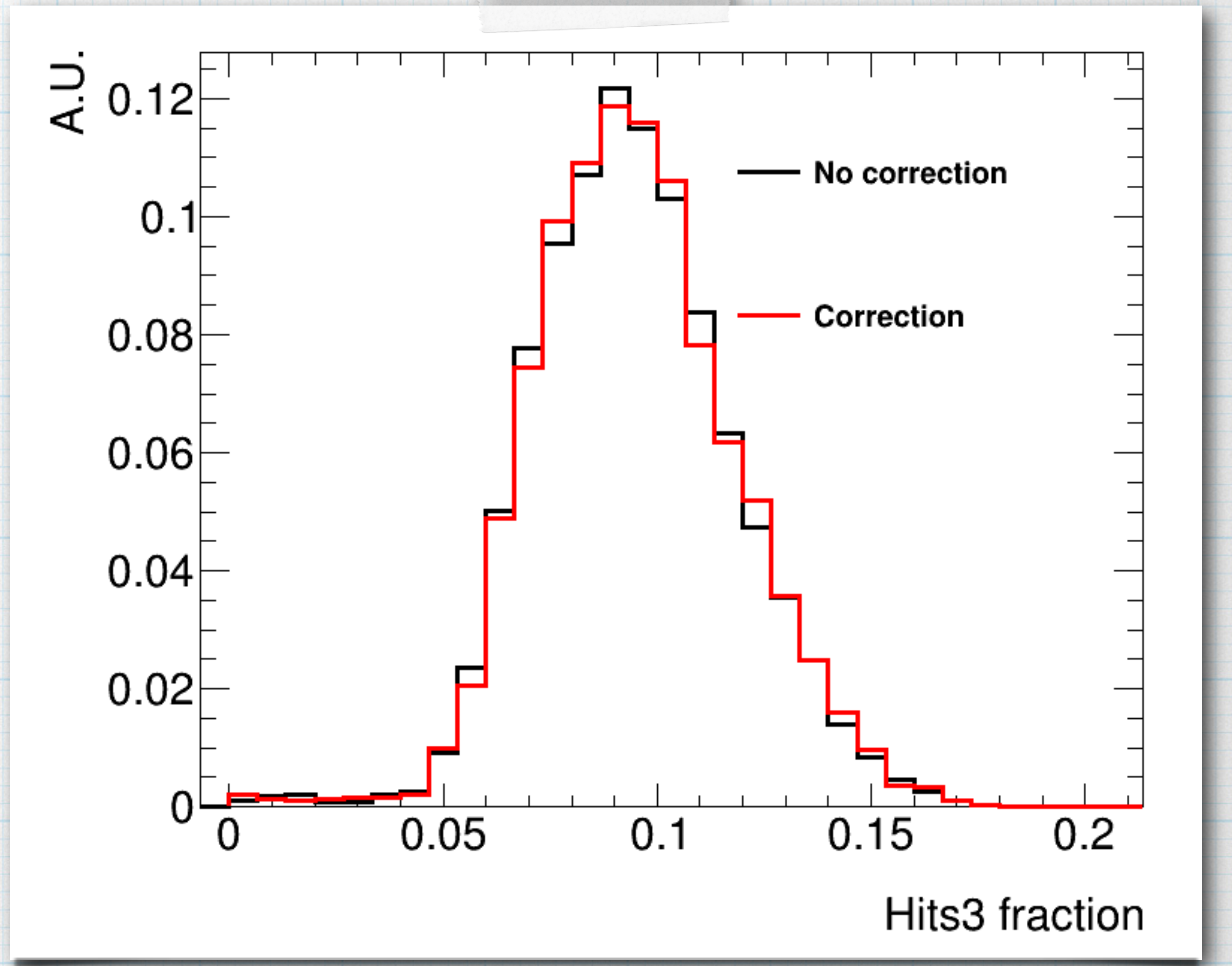
Geant-4 Energy / 29.8 eV

Impact on number of Hits (70 GeV π)

* Full simulation of 70 GeV pions with and without the ionisation correction





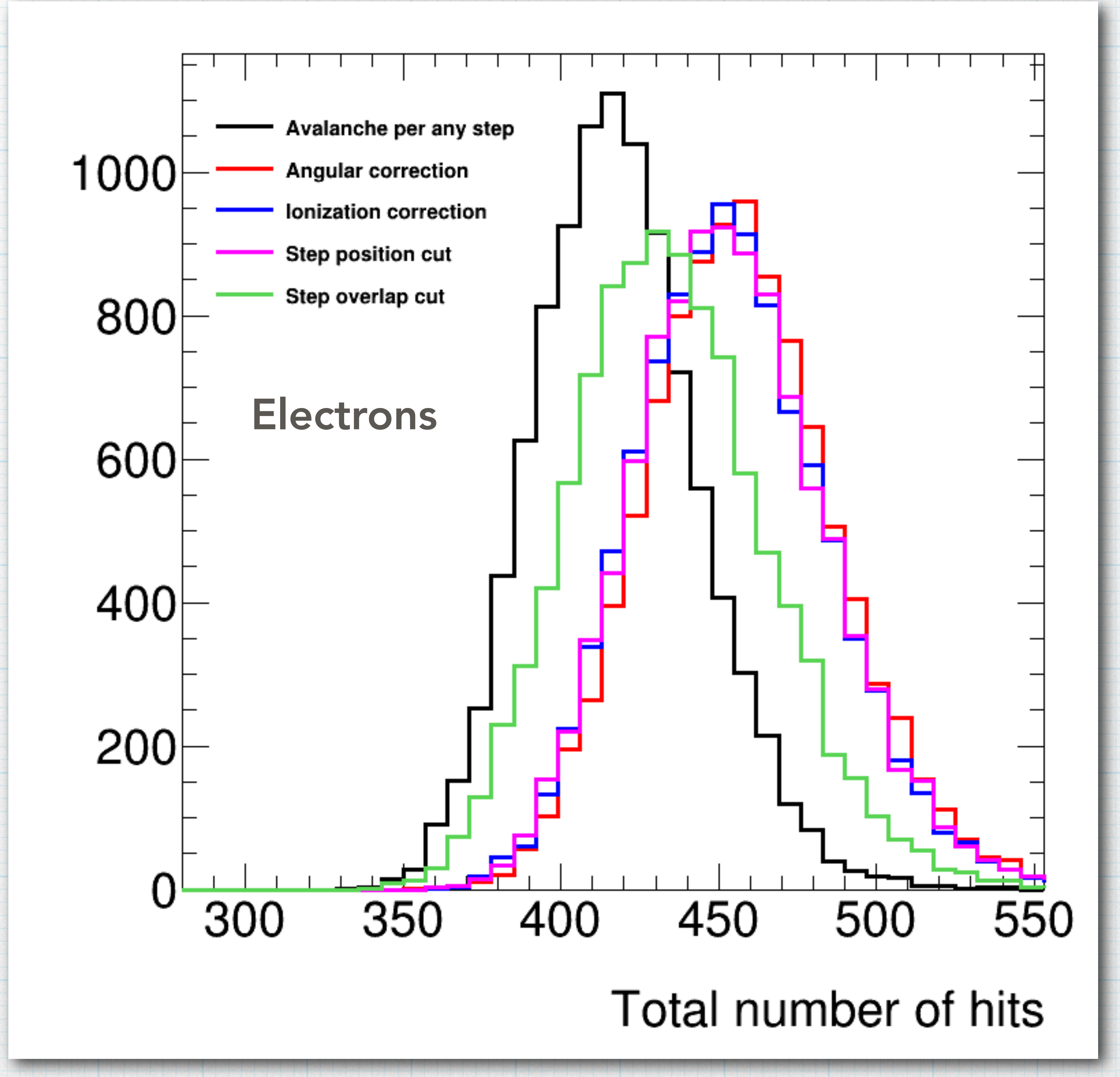


* Impact on number of Hits, mainly on threshold 2
* Impact on total number of Hits does not explain discrepancies observed with data

Steps of the digitisations

* Check impact of the digitisation steps on Number hits (first threshold)
* Digitization steps applied sequentially:
  * One avalanche per G4 step
  * Angular correction
  * Ionisation correction
  * Step position selection
  * Step overlap suppression

* Digitiser refined with Ionisation correction, does not explain discrepancies
* Overlap correction & Charge distribution have a strong impact on the number of hits and is a good candidate for refinement

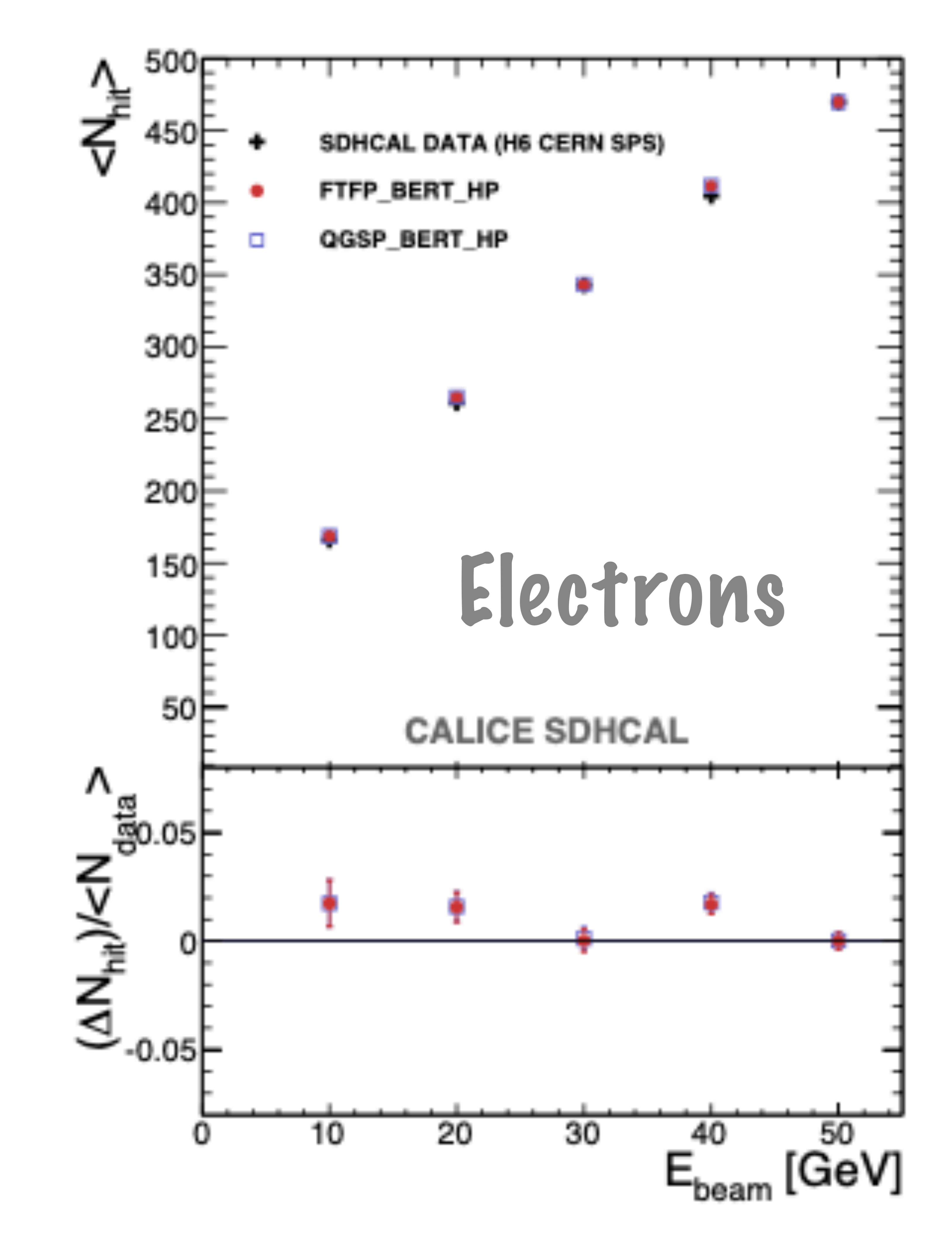


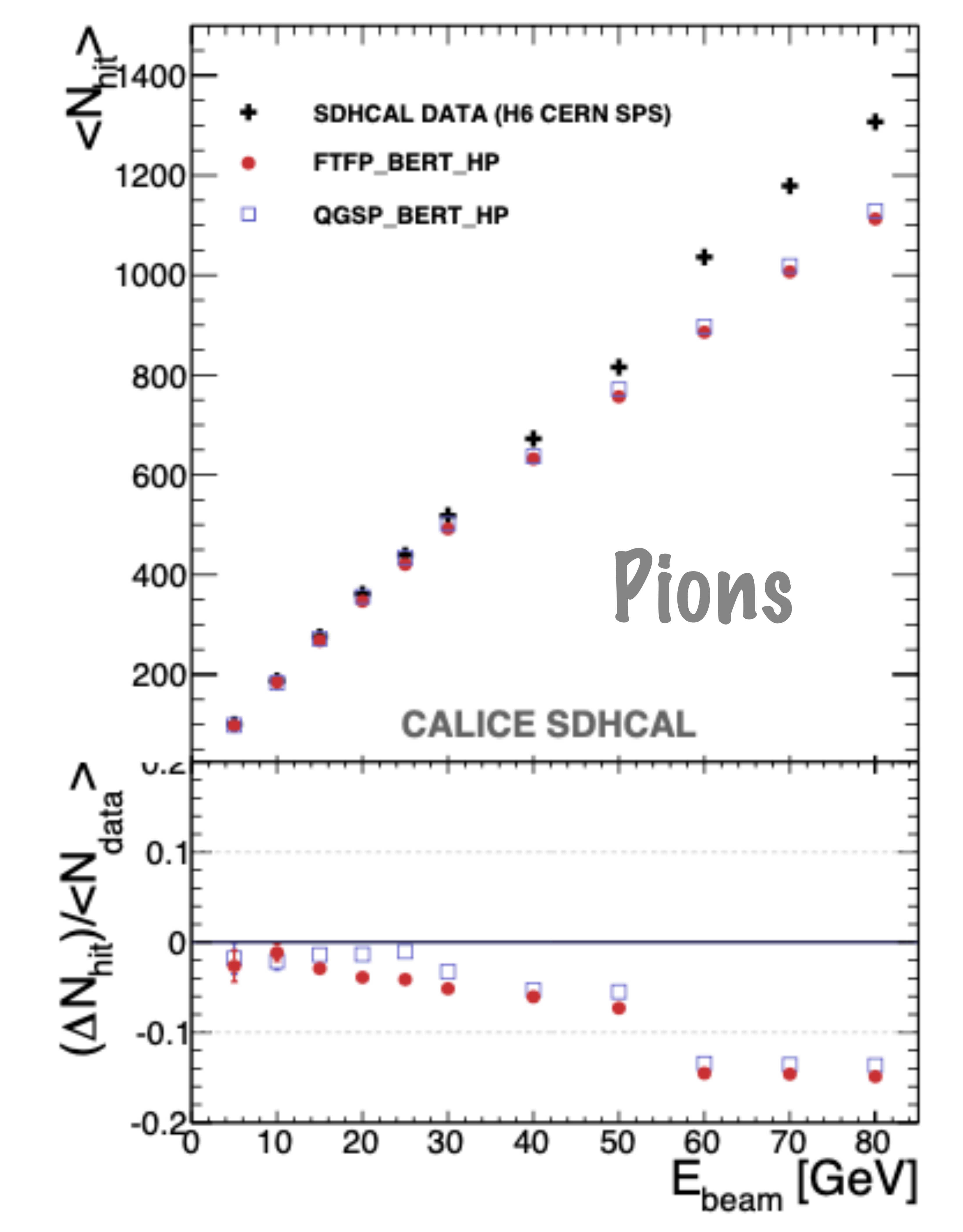
Summary

* Digitisation of RPC based high granular calorimeter is **challenging**:
    * Requires good modelling of both isolated and overlapping hits
    * Large number of (overlaping) effects
* **Geant-4** models provide digitiser inputs: some **mismodeling** in the hadronic showers will have a strong effect on the simulation
* **Digitiser model implemented** and tested with SDHCAL prototype:
    * **Reasonable description** of electrons data and pions below 40 GeV despite its complexity
    * Several **improvements** identified, some already implemented

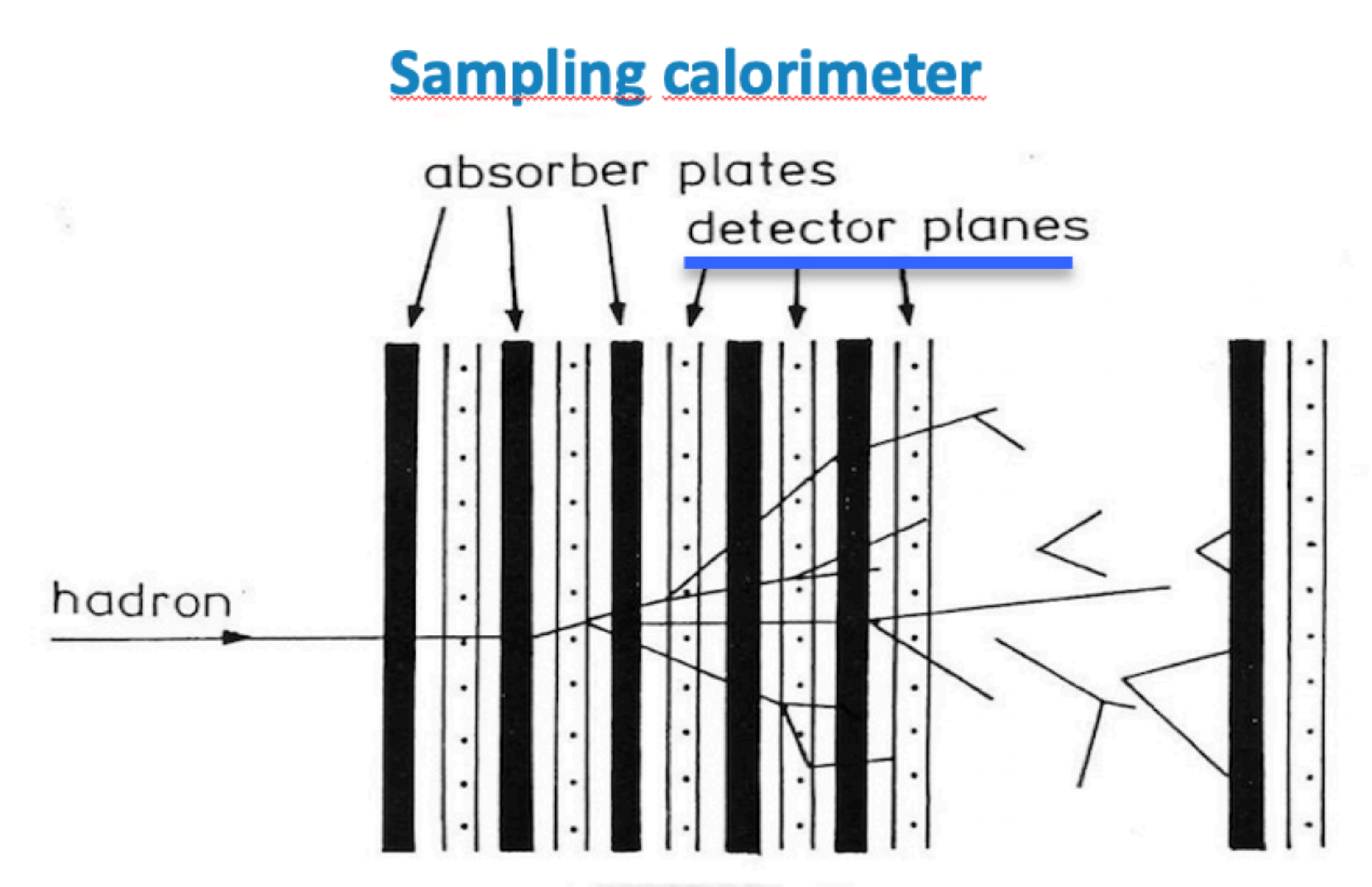
Additional Material

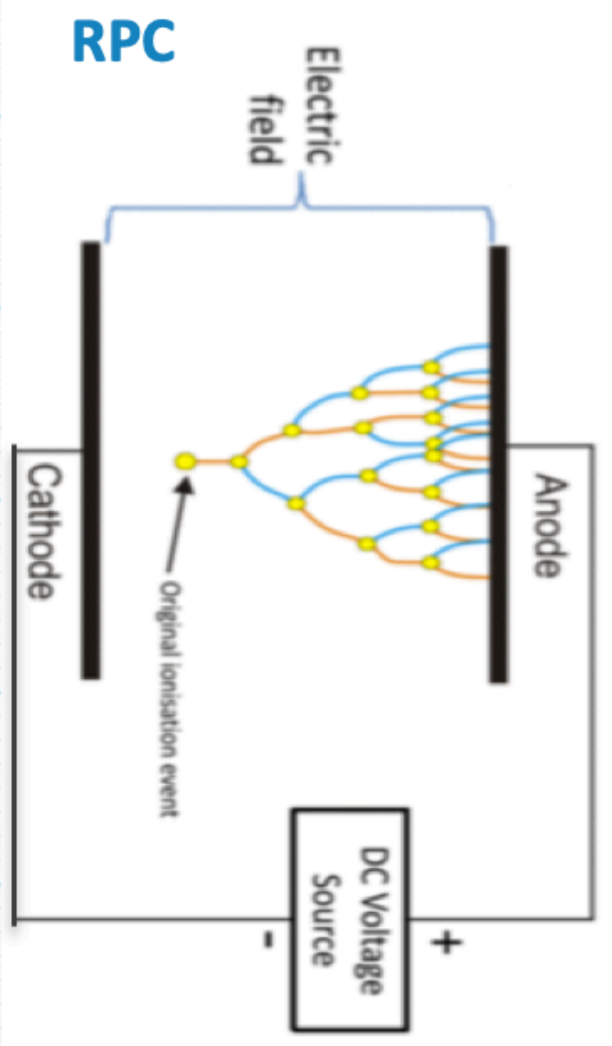
Data/MC comparisons





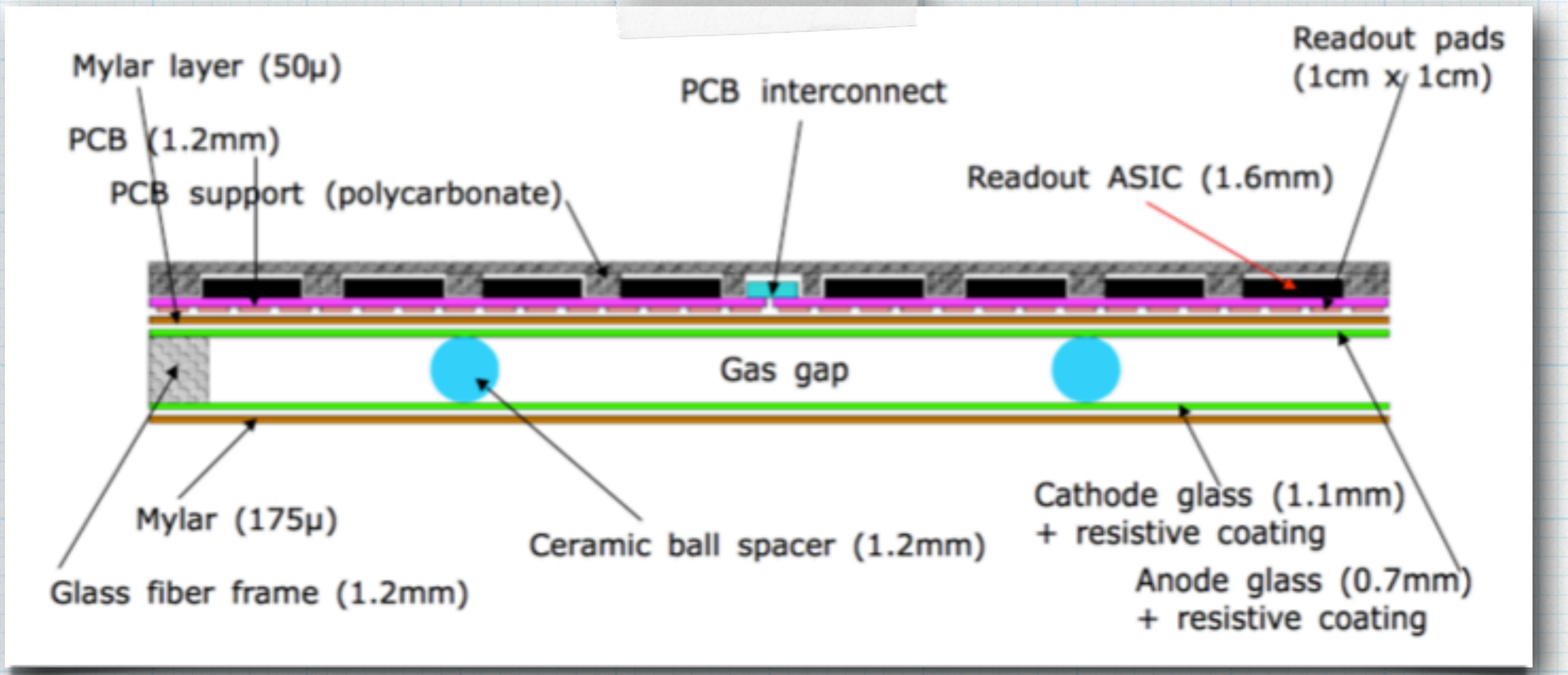
The SDHCAL Calorimeter





- Advantages of Resistive Plate Chambers:
  - High efficiency, Low background, Linearity ➔ Energy resolution
  - Well contained avalanches ➔ granularity, energy resolution
  - Not expensive, robust, ...
- Requires good modelling of the detector response ➔ simulation, digitisation

Simulation of SDHCAL: Digitisation



* When a charged particle crosses the gas gap, several gas molecules are ionized
* Ions and electrons are then accelerated by the strong electric field
* Avalanche is the result of multiple ionisations by electrons
* signal on the pads is recorded by HARDROC2 ASICs in a 2-bit format, corresponding to three thresholds related to the amount of induced charge
* In avalanche mode, charges can be modelled by a Polya distribution

Digitisation will model these steps

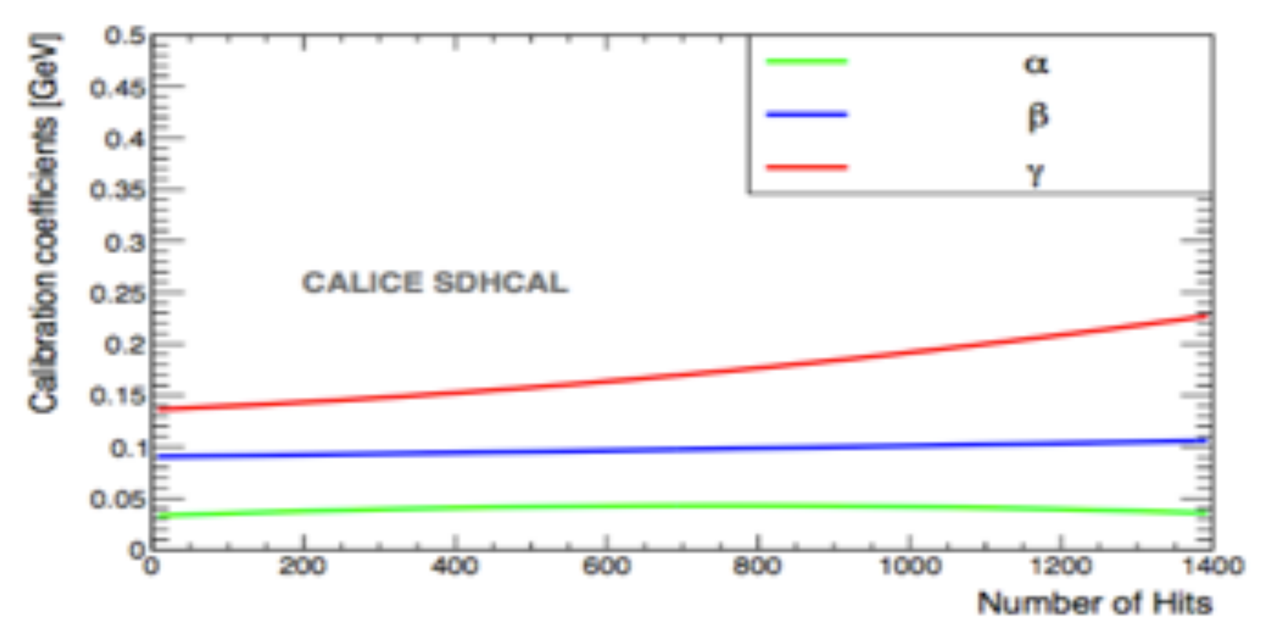
Energy Reconstruction in SDHCAL

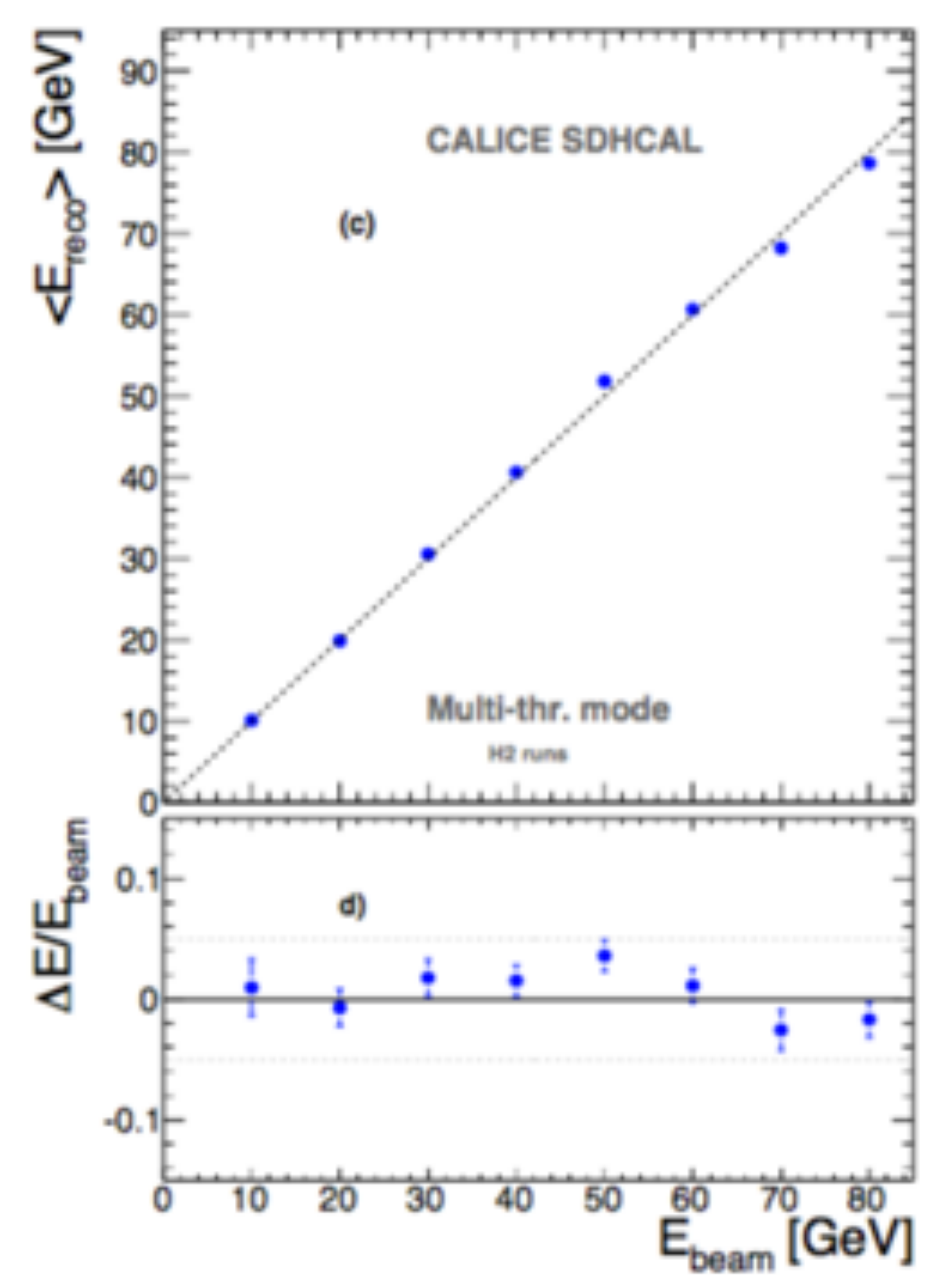
- Use the number of Hits by thresholds to exploit the shower density information

$$E_{reco} = \alpha N_1 + \beta N_2 + \gamma N_3$$

- with α, β, γ (Nhit)
- Factors measured in test beam by minimizing
-

$$\chi^2 = \sum_{i=1}^{N} \frac{(E^i_{beam} - E^i_{reco})^2}{\sigma_i^2}$$



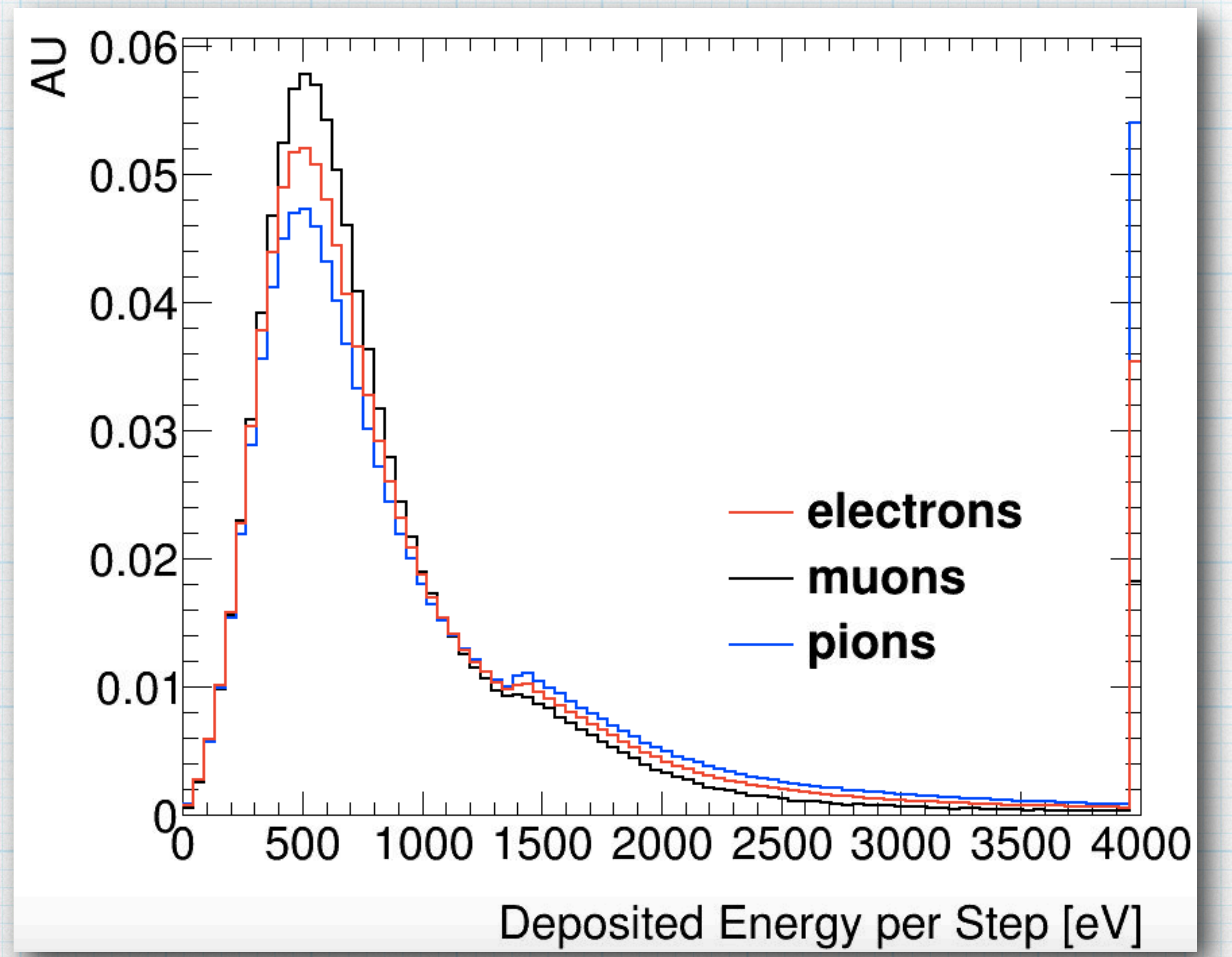


Avalanche correction

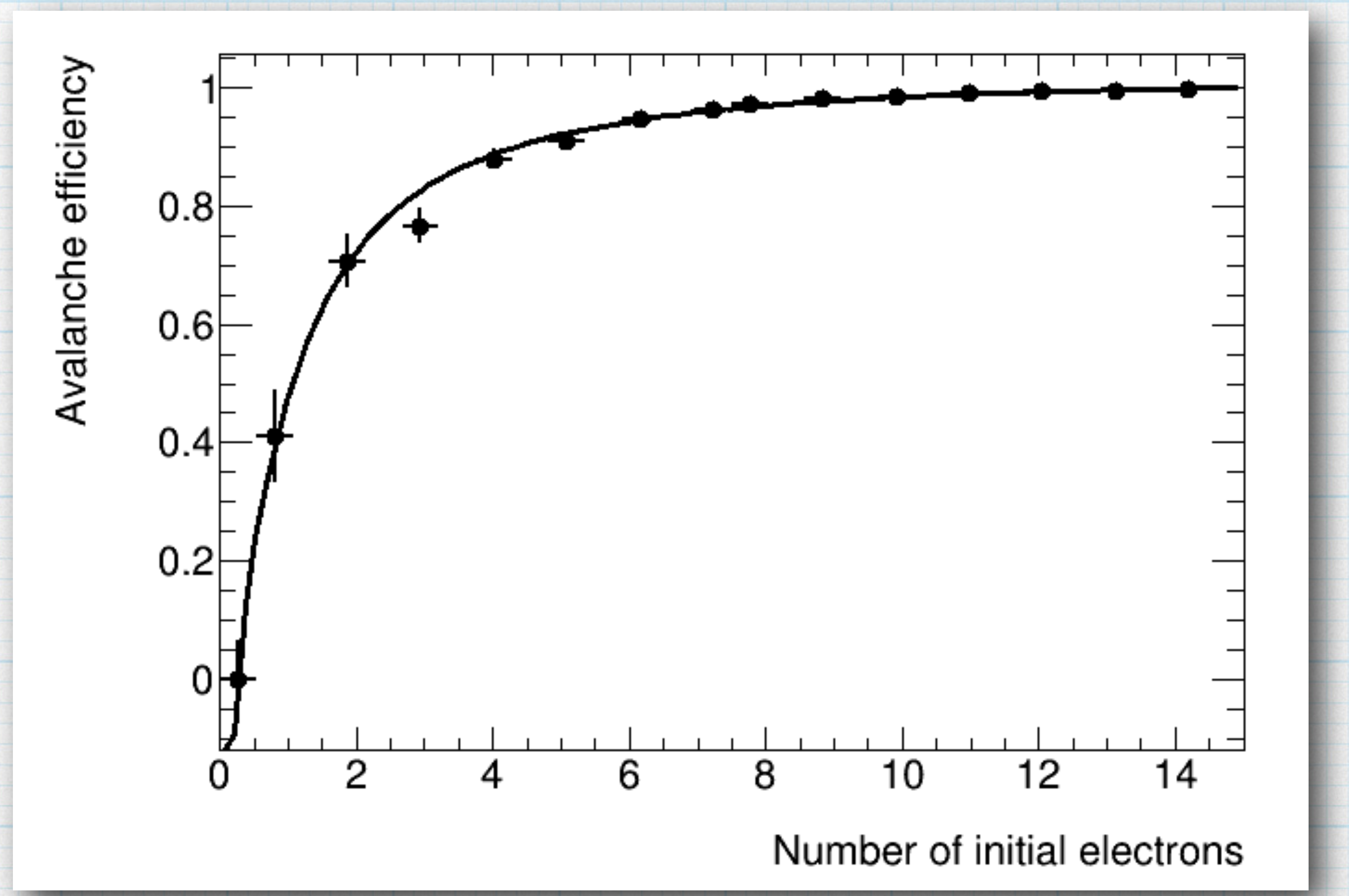
Geant 4 output (step by step)

Heed

Avalanche efficiency modeling



/ 29.7 x

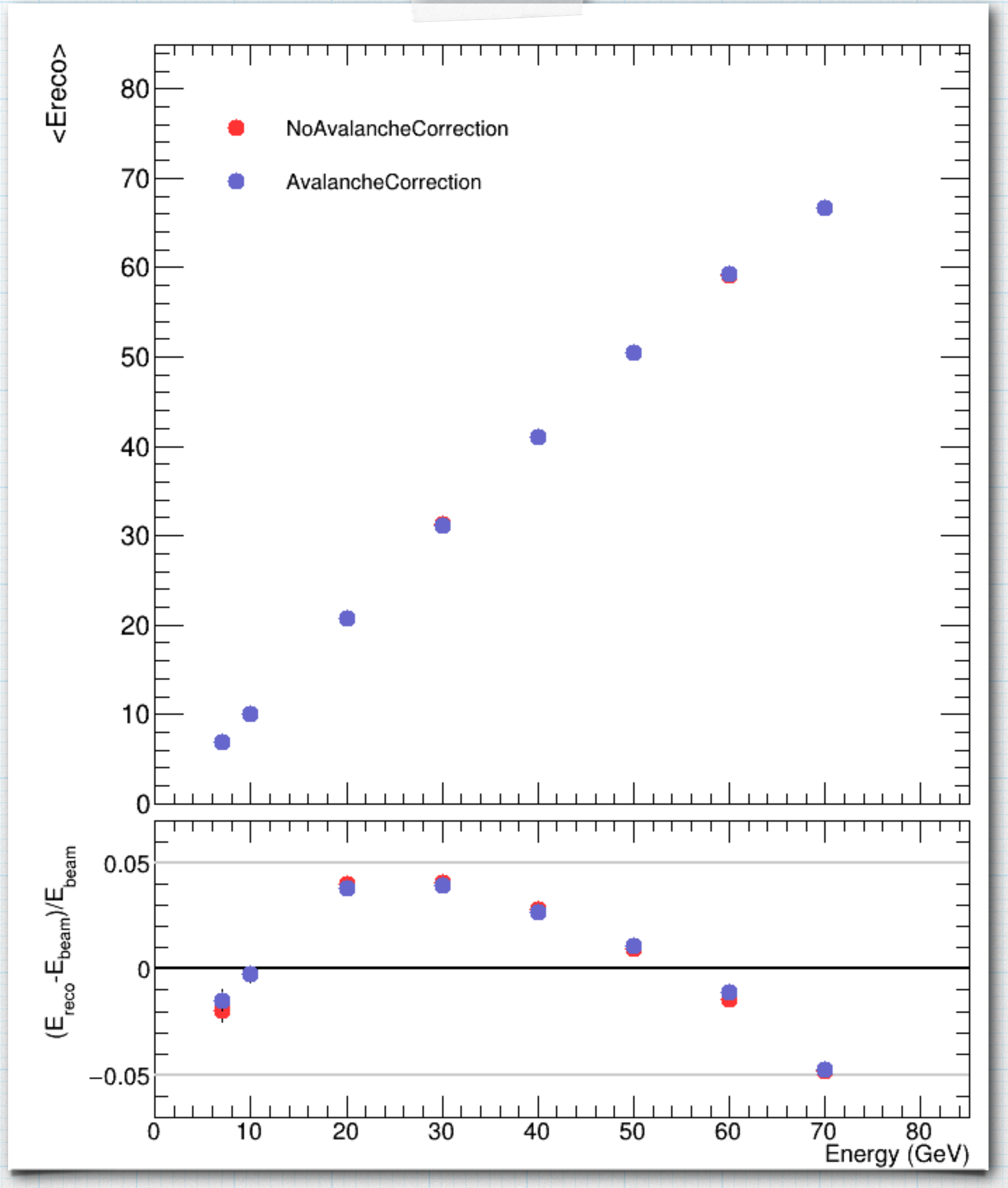


0 energy steps removed from this plot

Probability that an avalanche does not vanish

Impact on linearity (π)

* Using full simulation of pions from 7 to 70 GeV
* Energy reconstructed using the full simulated samples
* Linearity is slightly improved but small effect



Input Parameters

Parameter name	Value
l_{min}	0.001 mm
d_{cut}	0.5 mm
$\bar{q}$	4.58 pC
δ	1.12
n	2
r_{max}	30 mm
α_0	1.0
σ_0	1.0 mm
α_1	0.00083
σ_1	9.7 mm
κ	0.4
T_1	0.114 pC
T_2	5.4 pC
T_3	14.5 pC

JINST 11 (2016) 6 P06014

Dependence to ionisation

* Avalanche modeled with a **data-tuned Polya (100 GeV muons)** for each Geant4 step that passes the selection → assumes that MIPs are universal, i.e., same modelling applied for high and low energy charged particles crossing RPC

* sDHCAL is a calorimeter: a large spectrum of particle type/energies will induce a signal

* Can we use Geant4 step properties to refine the polya modelling