Status of Silicon Charge Detector Simulation in HerdSoftware

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The Silicon Charge Detector

A **Silicon micro-strip** device that will measure with precision the impinging particle charge |Z|.
Basic requirements are:

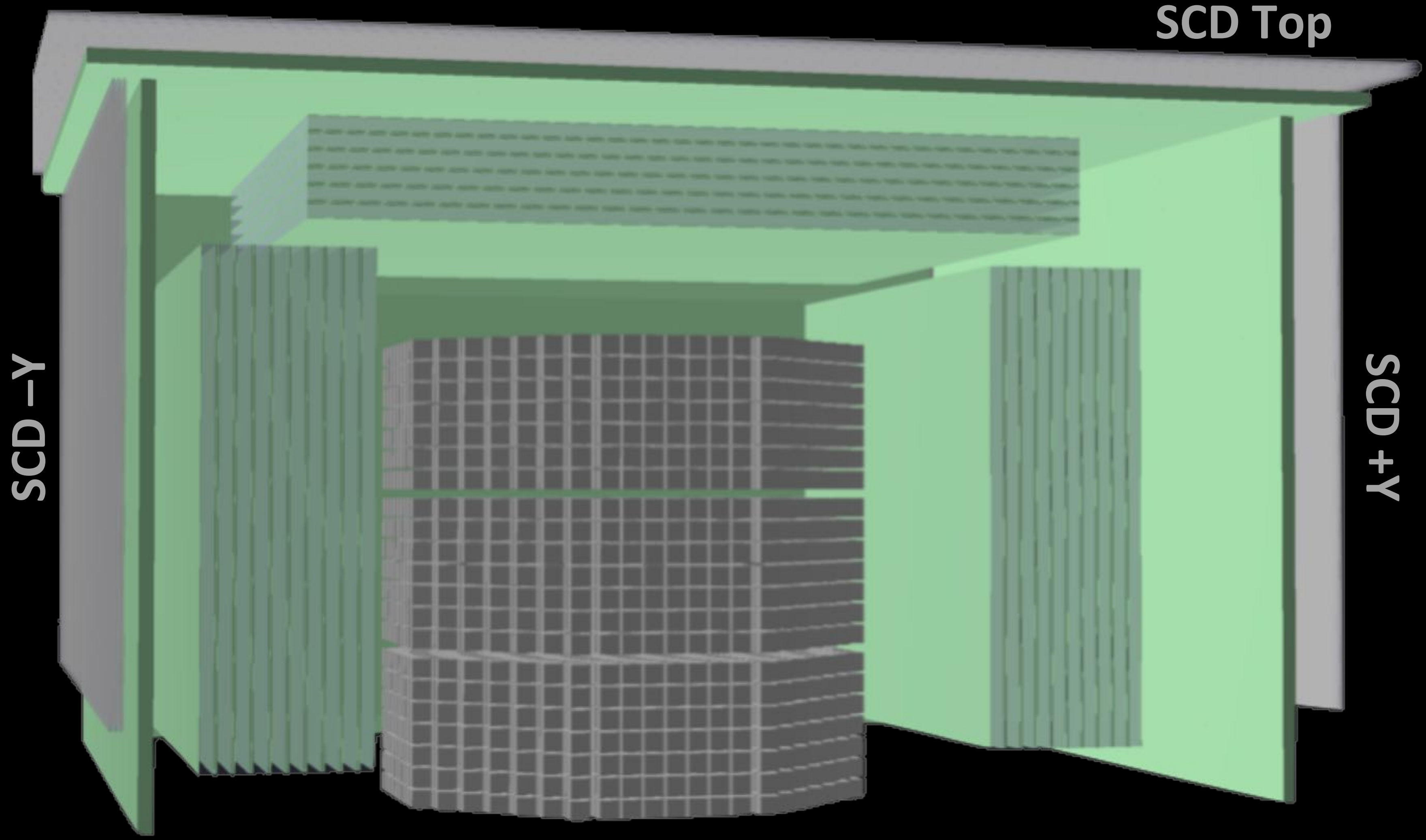
1) Enough charge resolution: measured by dE/dx technique. The detector should have enough thickness/active layers to have a charge resolution $\Delta Z<0.3$ up to at least charge $Z=26$.

2) Low interaction level: high-Z nuclei have large cross sections. To avoid early charge-change interactions that can make our life difficult (top-of-the instrument corrections), the SCD should be the "first" detector on top of PSD. Active and passive materials should be reduced to a minimum.

3) Low backsplash effect: interactions in the calorimeter may provide a lot of backscattered secondary particles extra-hits. The segmentation of the SCD should be enough to minimize the charge resolution worsening due to this effect.

Additionally, the tracking capabilities of the SCD can help overall HERD reconstruction, eventually we would need to investigate that.

Current Layout of SCD in HerdSoftware



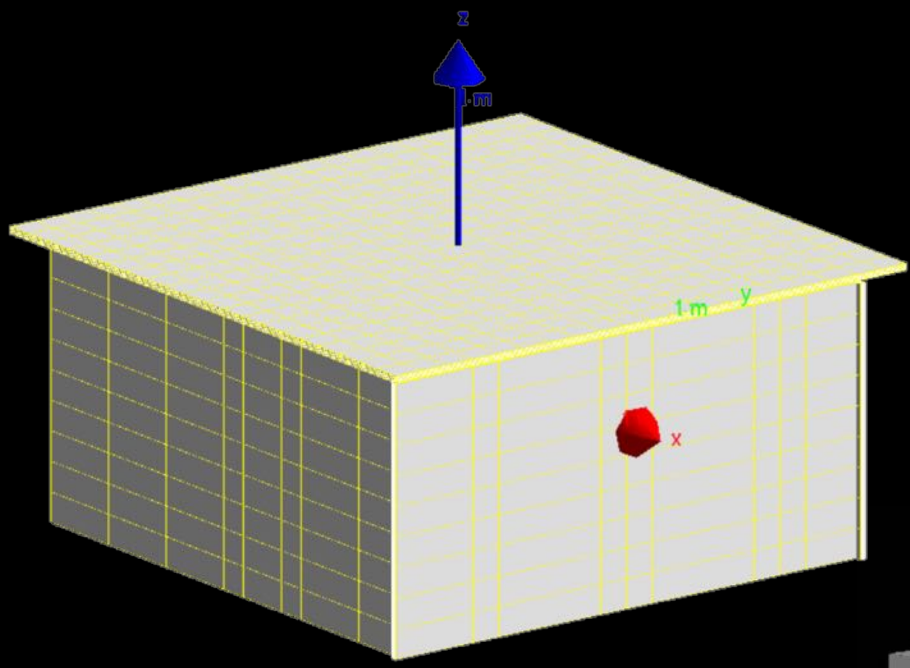
V. Formato, SCD Meeting 11/05/2020

Current Layout of SCD in HerdSoftware

Each side is composed by 8 layers of 150 μm silicon detectors:

Geometry (number of planes, thicknesses, gaps, support structures) is decided in **G4 production**.
This design above is too light and thin, but it is **good for basic estimations** of performances.

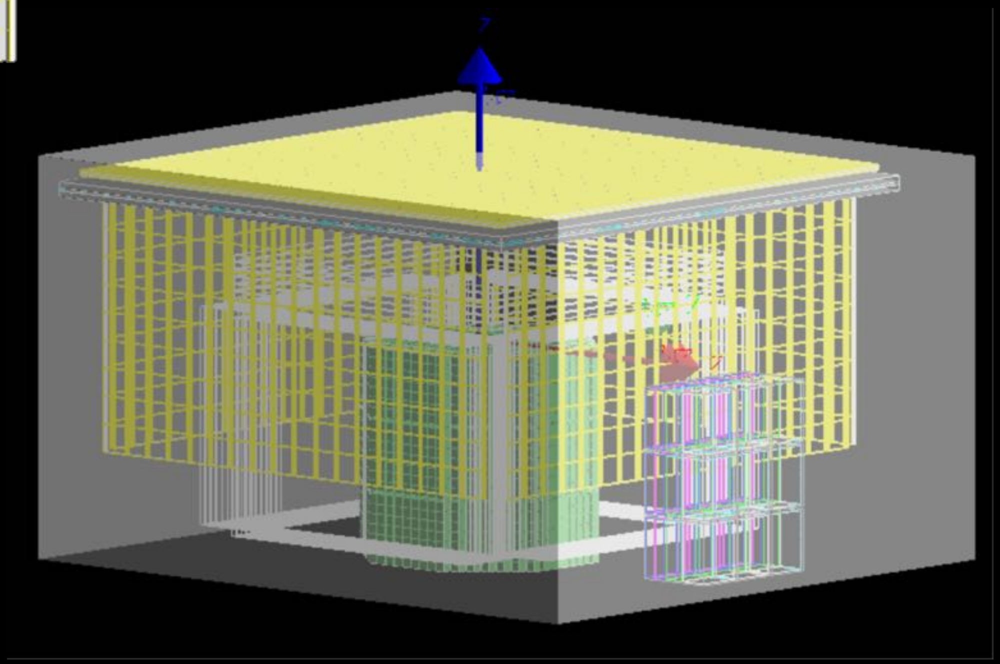
New Features in HerdSoftware Relevant for SCD



N. Mori, Analysis Meeting 05/01/2021

Additional foam as supporting structure filling the SCD space (reference material is polyurethane with ρ=0.2 g/cm^2).

Additional anti-meteorite shield (for now Aluminium 1 mm thick).



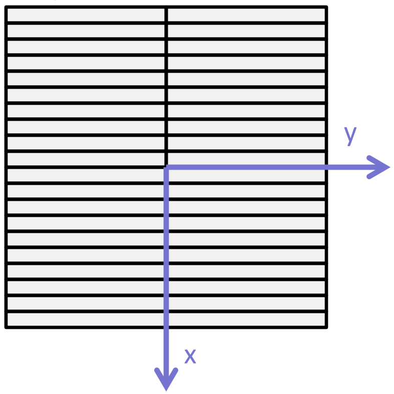
Not using this for now, but quite important (top-of-the-instrument corrections, charge resolution, …).

Current Layout of SCD in HerdSoftware

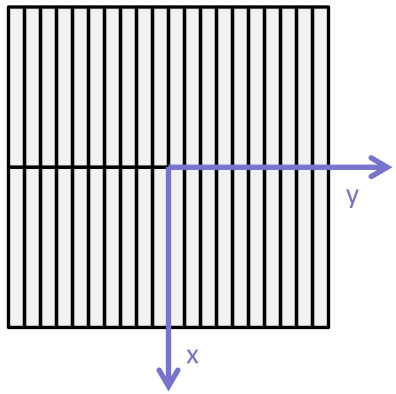
SCD Wafer: 9.5×9.5 cm^2

SCD Top: 20×20 wafers, 190×190 cm^2, 2×20 ladders

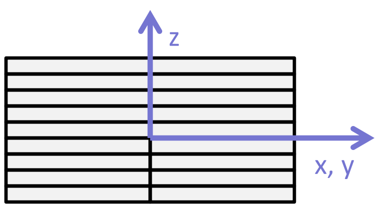
Layer 0,2,4,6



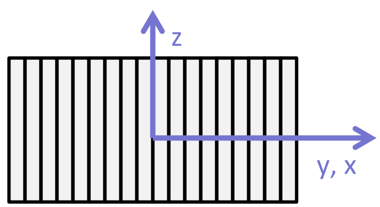
Layer 1,3,5,7



SCD Sides: 9×18 wafers, 98×175 cm^2, 2×9 and 1×18 ladders



Layer 0,2,4,6



Layer 1,3,5,7

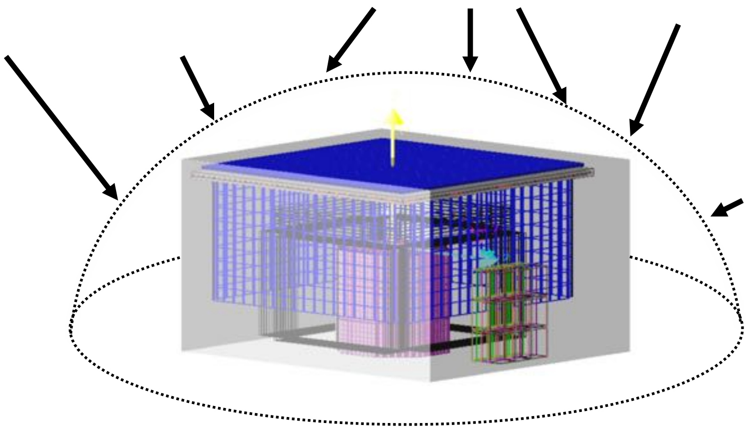
896 ladders of 9 or 10 wafers
8284 wafers
75.7 m^2 active area

With 50 μm pitch, 1900 strip/wafer:
1.7M readouts, with 0 floating strips
850k readouts, with 1 floating strips
600k readouts, with 2 floating strips
430k readouts, with 3 floating strips

With 200 μm pitch, 475 strip/wafer:
430k readouts, with 0 floating strips
210k readouts, with 1 floating strips
140k readouts, with 2 floating strips
100k readouts, with 3 floating strips

Wafer sizes, number of layers, placement can be changed in **G4 production**.
Ladder association (bonding), strip implantation, readout pattern can be changed later on, in **digitization**.

SCD Acceptance



Generation from a hemisphere of radius 2 m with center on the calorimeter bottom (A_{Gen} = 79 m^2sr):

- SCD Single-Side Acceptance (8 planes) = 6.7 m^2 sr
- SCD Top Acceptance (8 planes) = 14.8 m^2 sr
- **At least one side or top = 28.3 m^2 sr**
- At least one side or top (for L > 0.5 λ_I) = 2.0 m^2 sr (for protons @ 10 GeV/n)

A specific trigger for SCD calibration: if we can realize an additional **high-threshold trigger**, such that we have signal for Z≫1 particles, we may collect **a lot of high-Z** events still keeping a manageable trigger rate, since Z>2 are quite rare. These events will be mostly outside CALO and can be used for:

1. A **high-Z precise calibration** (without backsplash) for SCD and other detectors;

2. To measure the **relative abundances of super-rare elements** with Z>26 for which we will have a huge exposure (possibly beating Super-TIGER, CALET, ...). Of course this implies that the dynamic range of SCD should be reasonable (we may profit of capacitive coupling for low-gain measurement);

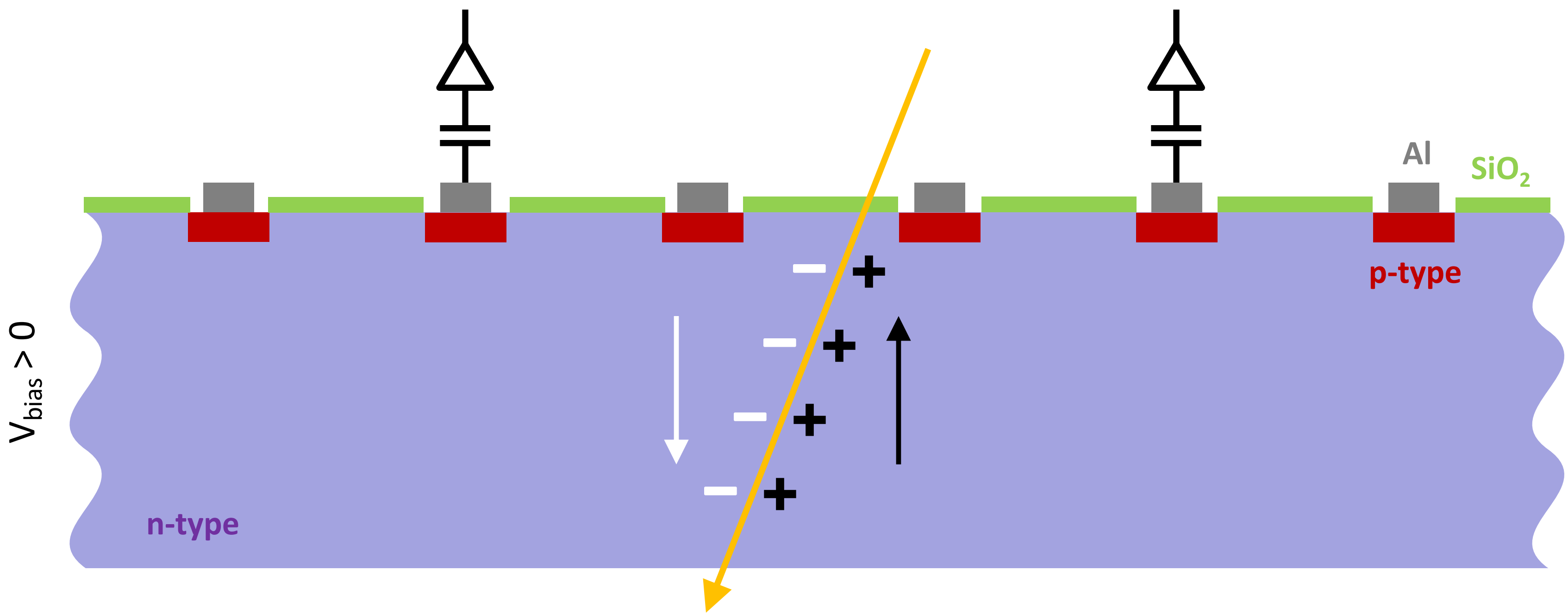
3. To measure **ion spectra at low energy with high statistics** in two ways:
   1. up to about 30 GV using the geomagnetic cutoff;
   2. up to few GeV using the energy deposit itself.

What Happens Inside the Silicon Detector

Ionization
- Particle energy deposition (~ 80 keV for Z=1 MIP in 300 µm, straggling)
- Production of e/h pairs (E_i = 3.6 eV, Fano factor)
- Production of δ-rays ($d\sigma/dT \approx k\, Z^2/T^2$)

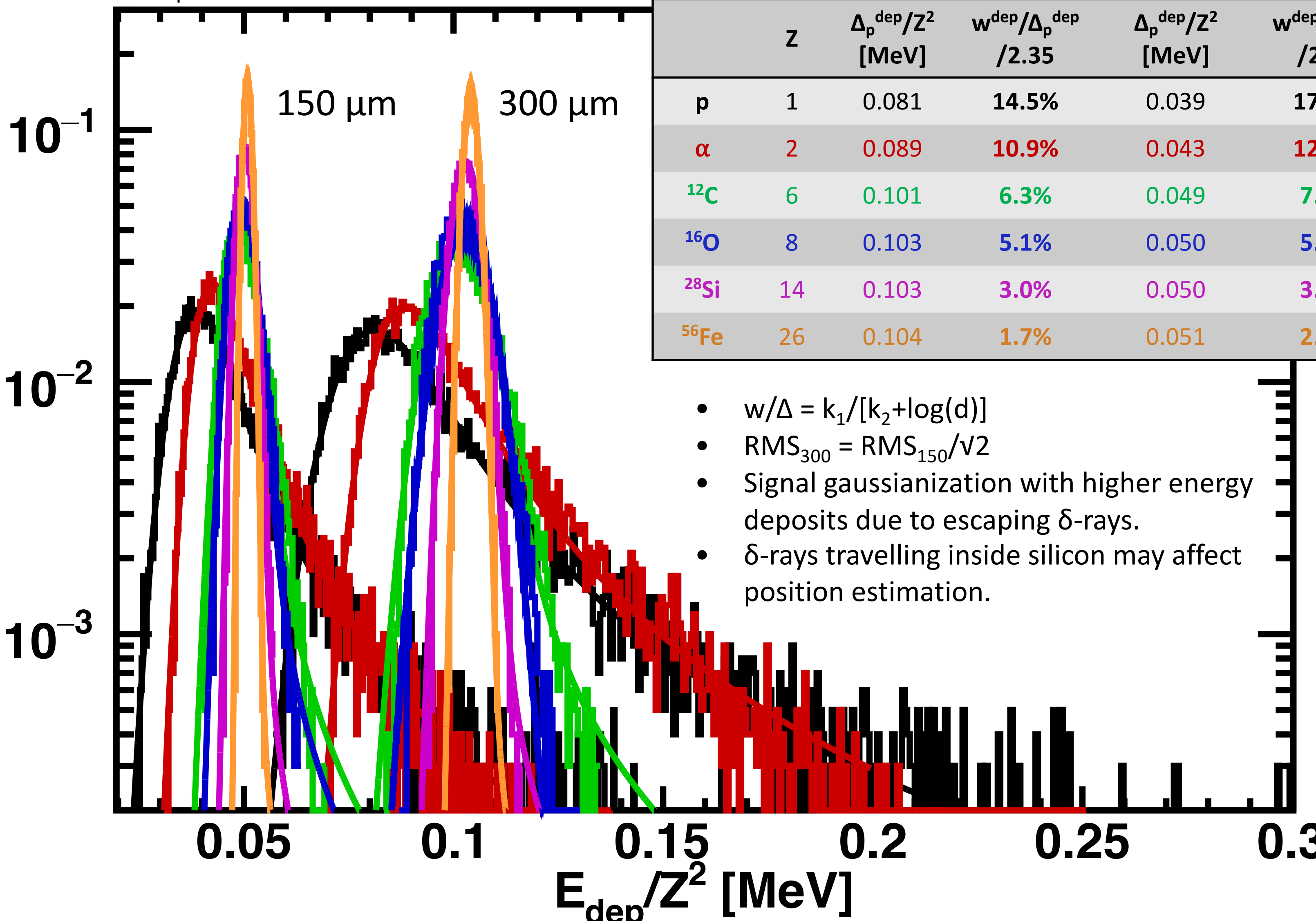
Propagation of e/h pairs in Silicon
- Charge drift due to electric field ($\mathbf{v}(x) = \mu \mathbf{E}(x)$)
- Thermal diffusion ($\sigma^2 = 2Dt$)
- Carriers absorption, space charge effects, …
- Induction of current on electrodes (Ramo's theorem, …)
- Other effects (carriers absorption, saturation for high-Z, …)

Readout electronics
- Amplifier and shaping
- Digitization (eV to ADC)
- Noise generation
- Response non-linearities, cross-talk



Ionization: Energy Deposit and δ-rays

$E_{dep} = \sum E_{ion}^{i} < E_{loss}$



		d = 300 µm		d = 150 µm	
	Z	Δ_p^{dep}/Z^2 [MeV]	w^{dep}/Δ_p^{dep} /2.35	Δ_p^{dep}/Z^2 [MeV]	w^{dep}/Δ_p^{dep} /2.35
p	1	0.081	**14.5%**	0.039	**17.0%**
α	2	0.089	**10.9%**	0.043	**12.3%**
^{12}C	6	0.101	**6.3%**	0.049	**7.0%**
^{16}O	8	0.103	**5.1%**	0.050	**5.7%**
^{28}Si	14	0.103	**3.0%**	0.050	**3.6%**
^{56}Fe	26	0.104	**1.7%**	0.051	**2.0%**

- $w/\Delta = k_1/[k_2+\log(d)]$
- $RMS_{300} = RMS_{150}/\sqrt{2}$
- Signal gaussianization with higher energy deposits due to escaping δ-rays.
- δ-rays travelling inside silicon may affect position estimation.

For an **accurate description a δ-rays** a 10 µm range production threshold for electrons is set in G4 for SCD.

Propagation of e/h Pairs: Drift-Diffusion

In approximation charge is "collected" (not correct but ok) at the strip.

$$v(x) = \mu E(x) \quad \text{Drift}$$

$$\sigma(x) = \sqrt{2Dt(x)} \quad \text{Diffusion}$$

$$D = \frac{kT}{e}\mu \quad \text{Einstein relation}$$

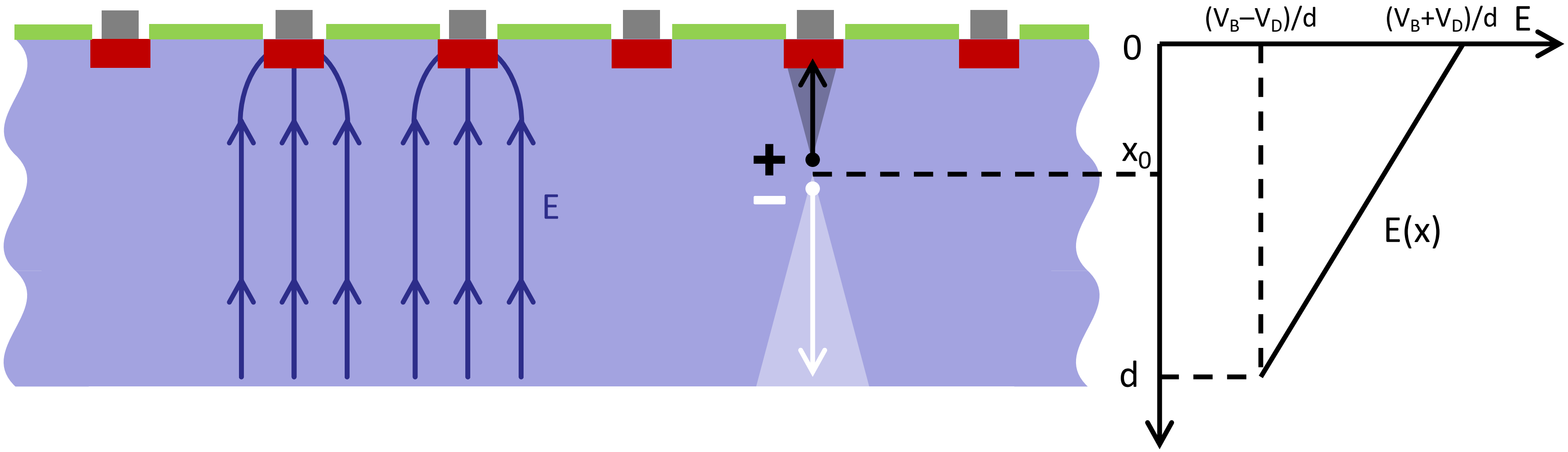
Assuming a uniform electric field (no effect in proximity of strips) → e/h trajectories are **straight lines**.

$$E(x) = \frac{V_B + V_D}{d} - \frac{2V_D x}{d^2}$$

V_D = Intrinsic Voltage (includes intrinsic bias + depletion voltage)
V_B = Bias Voltage (> V_D, «overbias»)

$$\sigma = \sqrt{2D\int_{x_1}^{x_2}\frac{\mathrm{d}x}{v(x)}} = \sqrt{2\frac{kT}{e}\int_{x_1}^{x_2}\frac{\mathrm{d}x}{E(x)}}$$

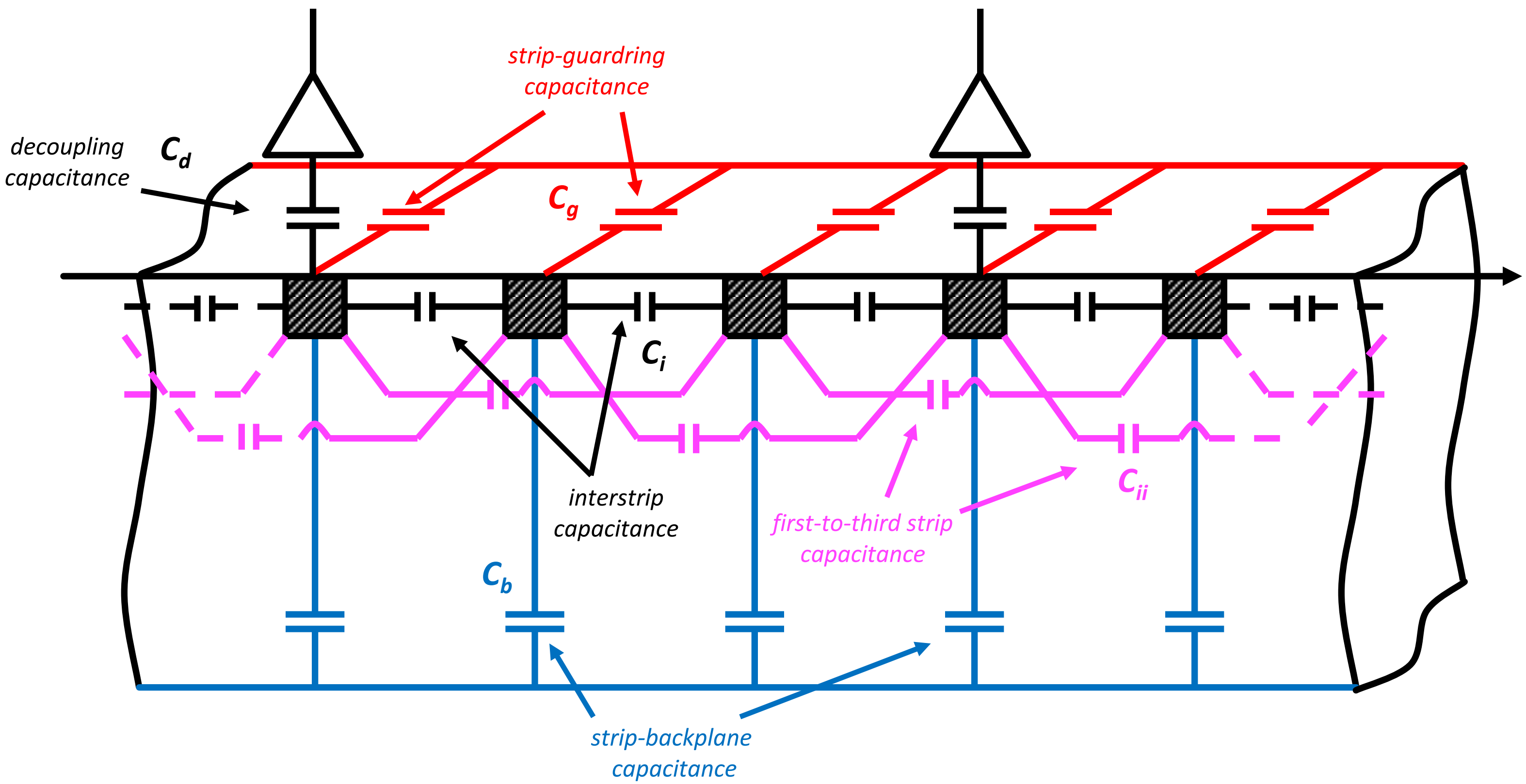
Dependence from e/h different mobility disappears



We use this simple approximation, controlled by 2 parameters V_D and V_B (and sensor thickness).
However drift-diffusion in our case **is not very important** (for d = 150 μm, $\sigma \lesssim 5$ μm).

Capacitive Net Approximation

In some approximation, the silicon sensor is equivalent to a circuit:

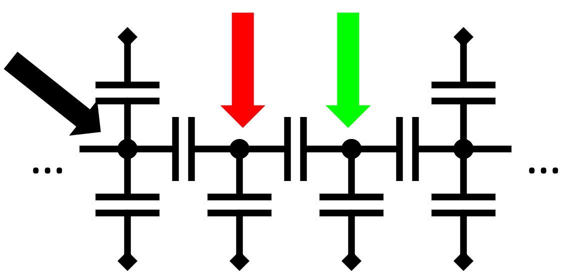


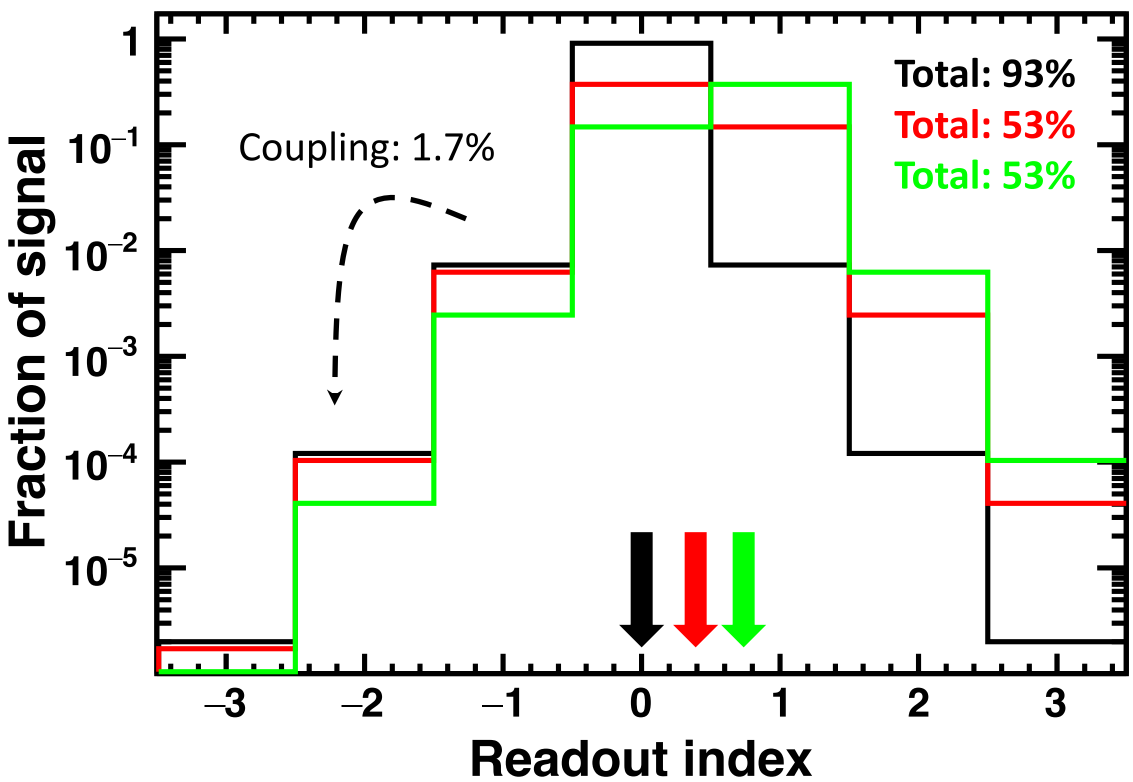
This can be modeled with SPICE, calculated with TCAD, or directly measured.
We implemented the use of **tables** describing the readout signal
as function of the signal injected on different locations.

A Capacitive Net Example

To make some test I assumed capacitances of $C_{IS} \sim C_{bck} \sim$ pF/cm, $C_{IS2} \sim 0.1C_{IS}$, $C_{dec} \sim 10\ C_{IS}$
(I followed E. Barberis NIM A 342 (1994), but they derive numbers for double-sided 300 μm sensors …)

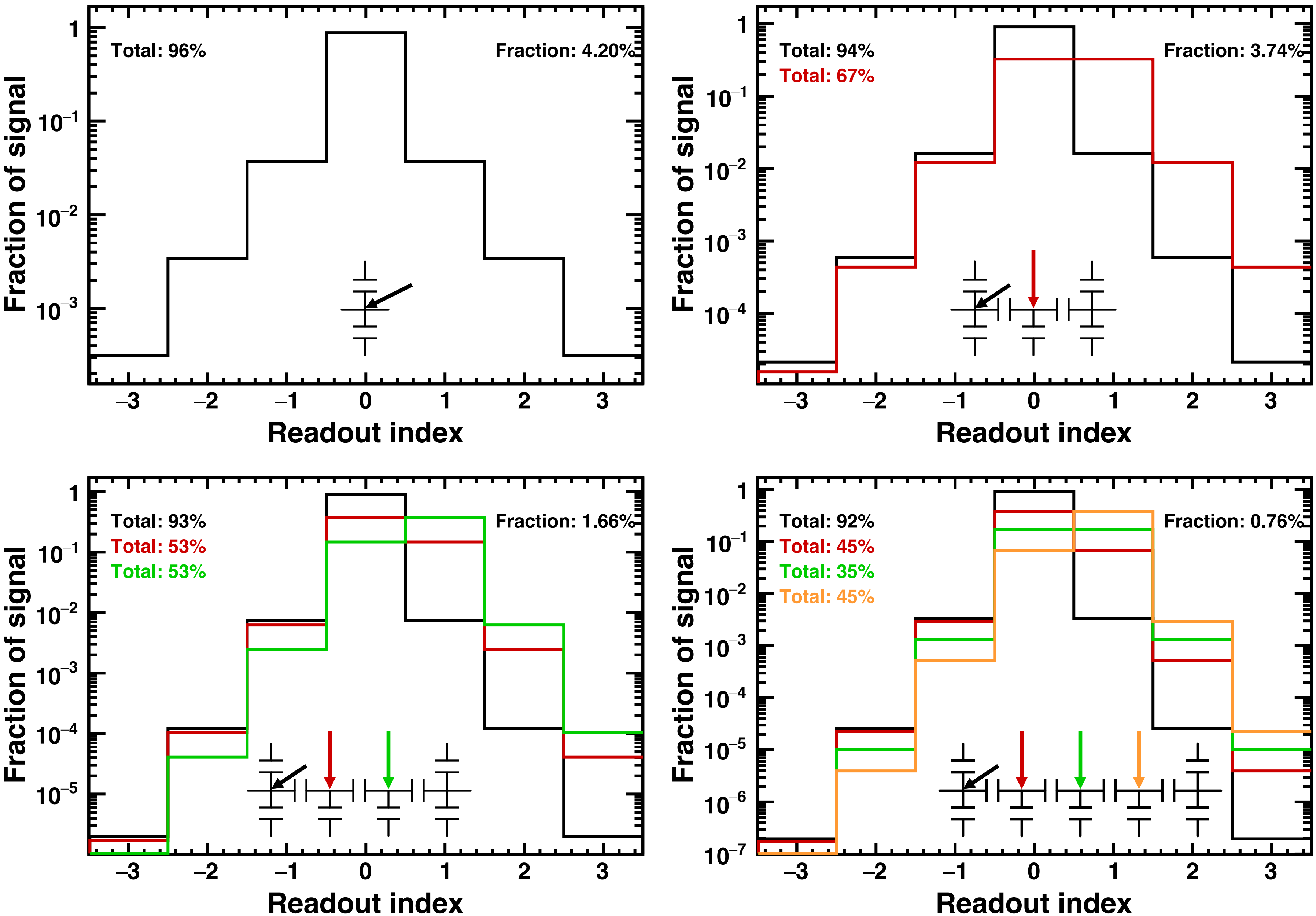
Thickness: 150 μm
Pitch: 50 μm
Width: 10 μm
N. Floating: 2



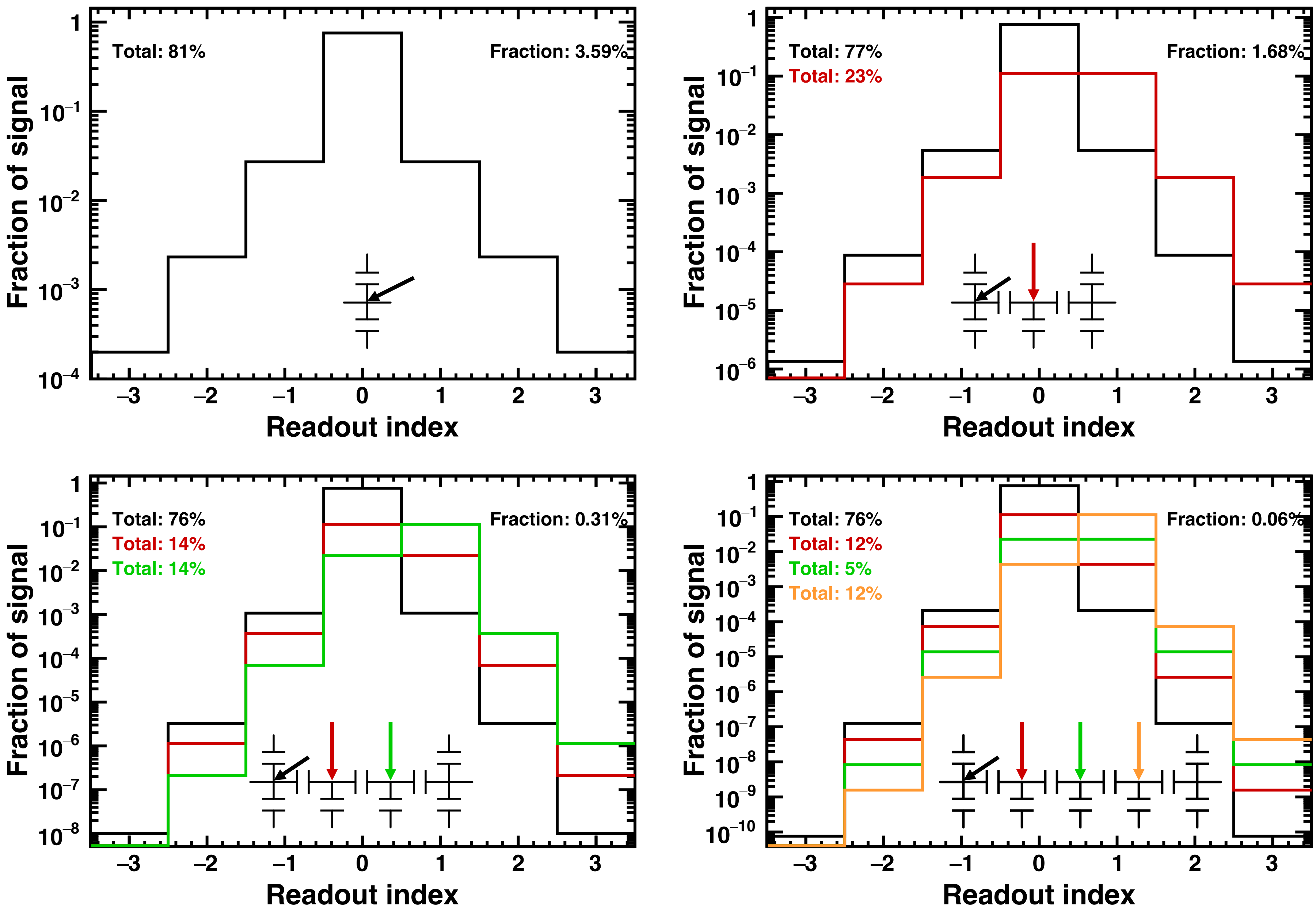


Energy loss: amount of signal lost for energy deposit in between strips with respect to readout (~57%).
Coupling: ratio of contiguous strips outside of the signal region (~1.7%) (→ low gain channels).

Examples of Capacitive Net for 50 µm Implantation Pitch



Examples of Capacitive Net for 200 µm Implantation Pitch



Analysis

We stopped development to fully test the simulation up to this stage, to check if everything is ok before adding too many effects (noise, track reconstruction, …).

We did a production at CNAF for p, α, ^{12}C, ^{16}O, ^{18}Si and ^{56}Fe at several energy point (10, 100, 1000, 10000 GeV/n) generated from an hemisphere of 2m. We simulated SCD, PSD_v2, CALO_v2, and TRD, but no CSS and no the extra material on top (nor foam, nor meteorite shield).

Using the flexibility of HerdSoftware, from the same simulation files we produced SCD digitized data using different configurations (different pitch, different number of floating strips, different capacitive nets).

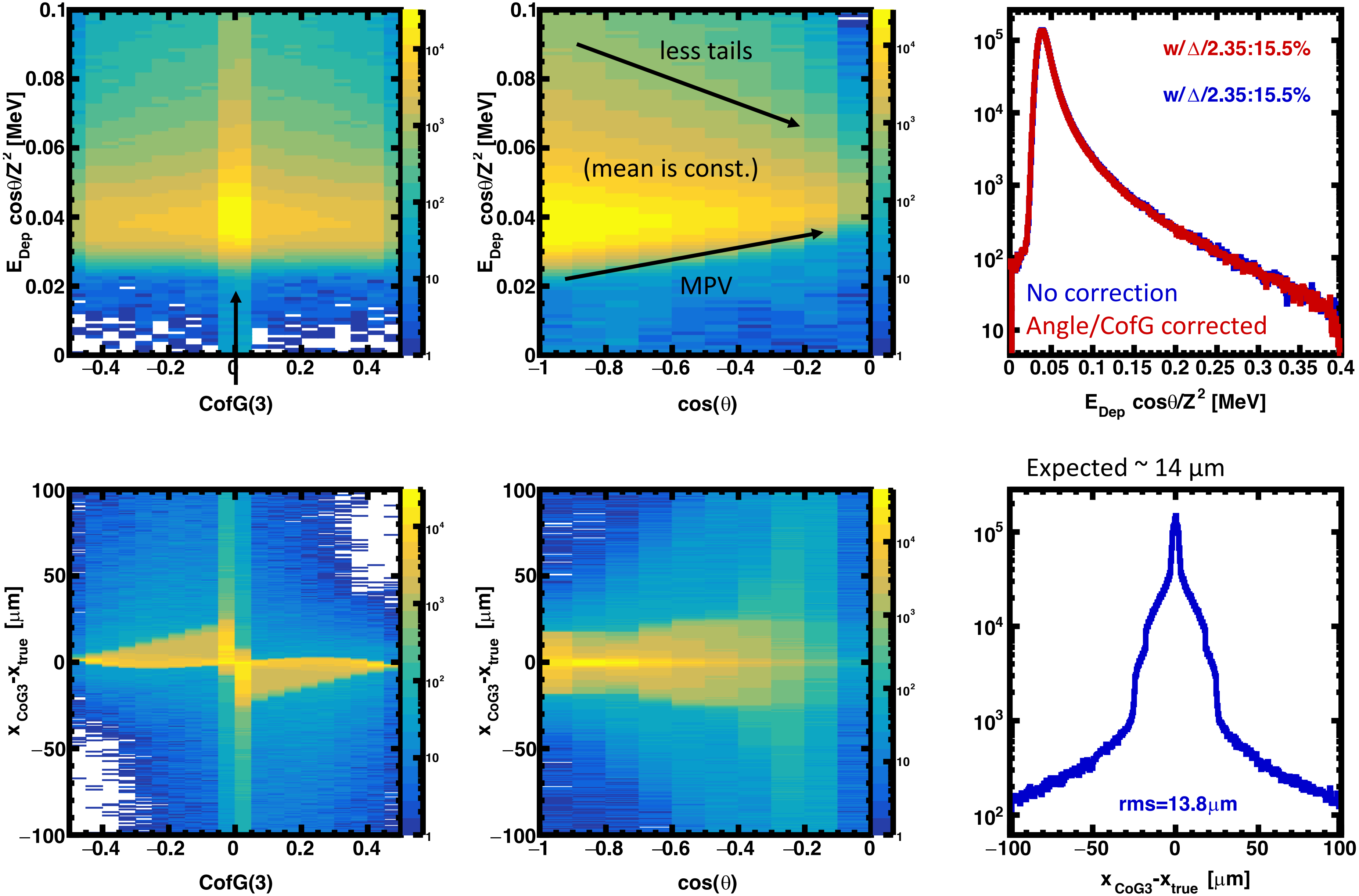
Eventually, we did an analysis program that creates clusters starting from strip signal. Then it evaluates which clusters are closer to the passing primary particle. Then we evaluated the performances in terms of charge resolution and spatial resolution.

Single Layer Performance: 10 GeV Protons, 50 μm Pitch, No Floating Strips

No request on CALO, all layers together.

Expected ~ 15%

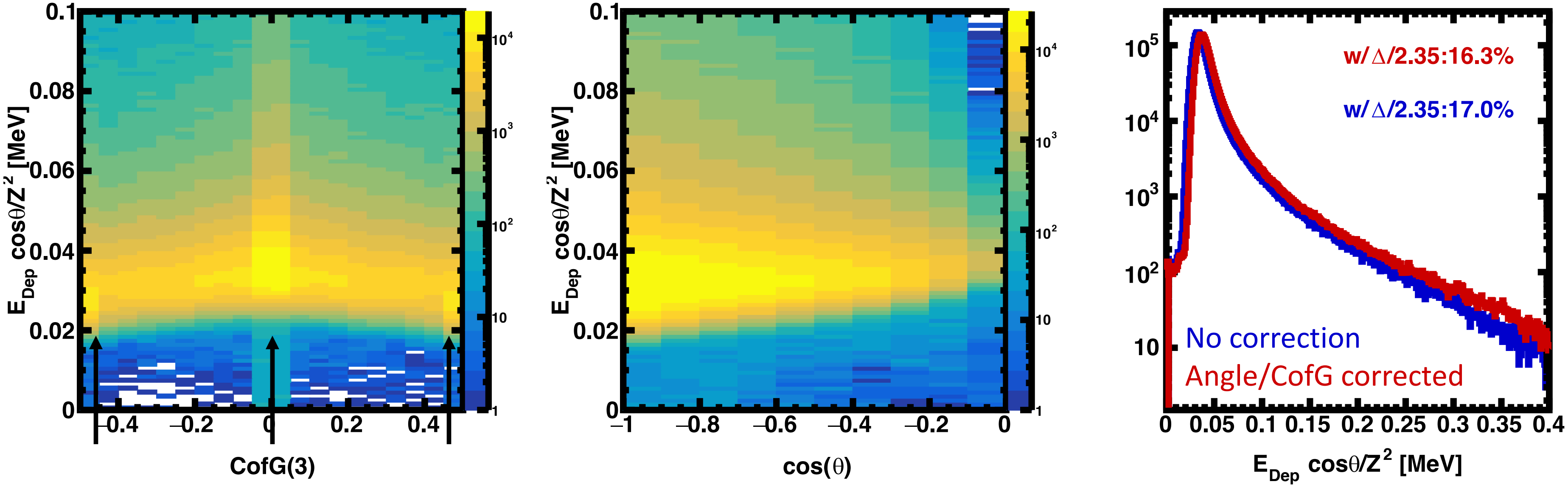
Expected ~ 14 μm



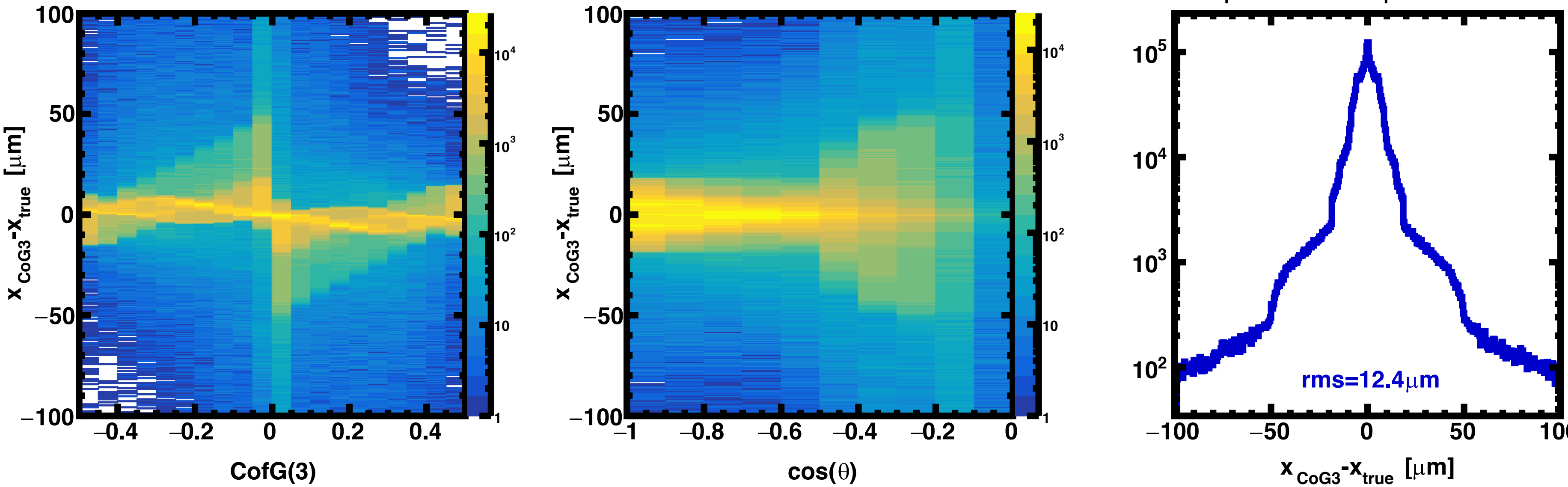
Single Layer Performance: 10 GeV Protons, 50 μm Pitch, 1 Floating Strip

No request on CALO, all layers together.

Expected ~ 15%

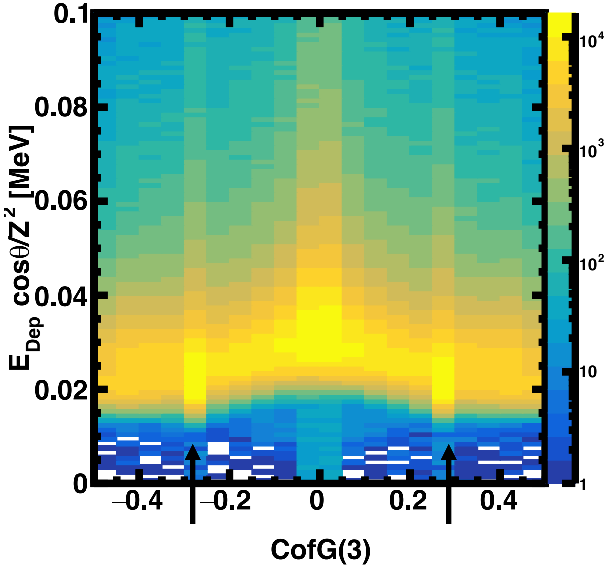


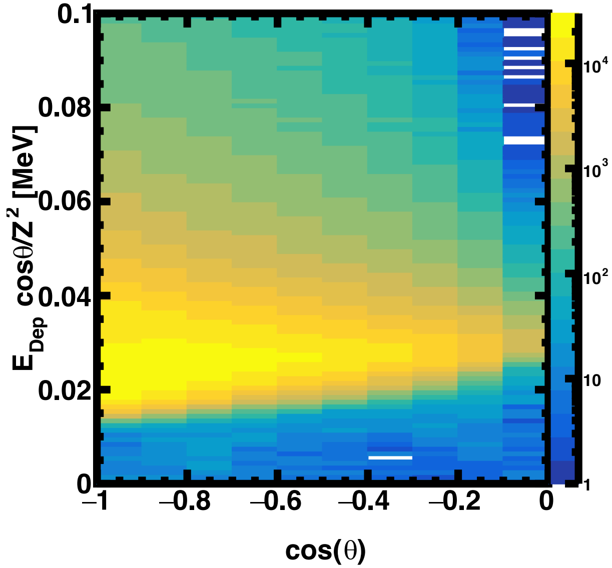
Expected ~ 14 μm



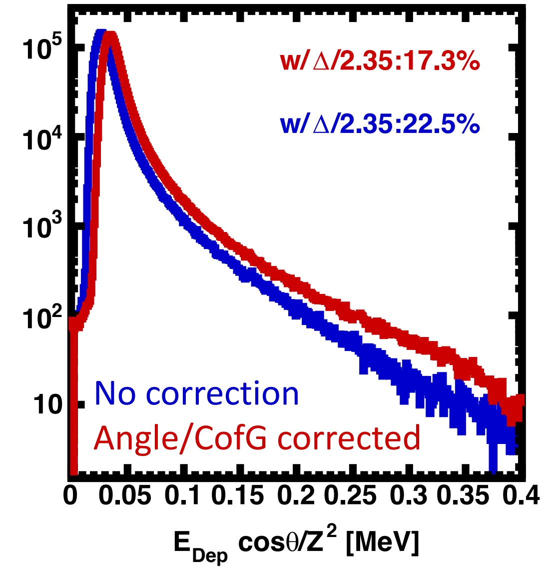
Single Layer Performance: 10 GeV Protons, 50 µm Pitch, 2 Floating Strips

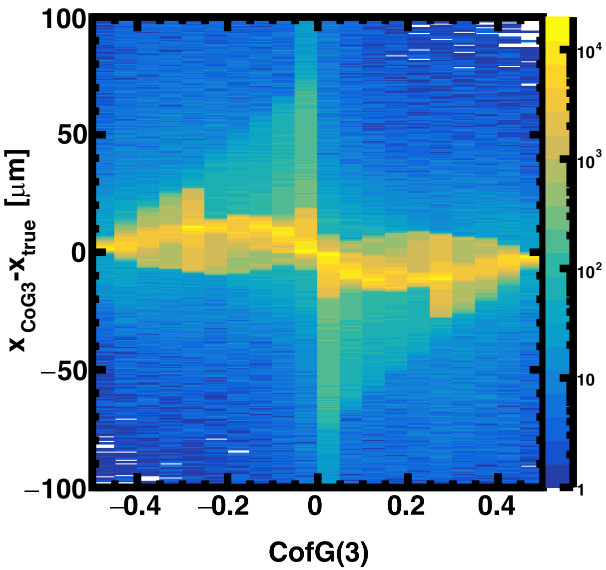
No request on CALO, all layers together.

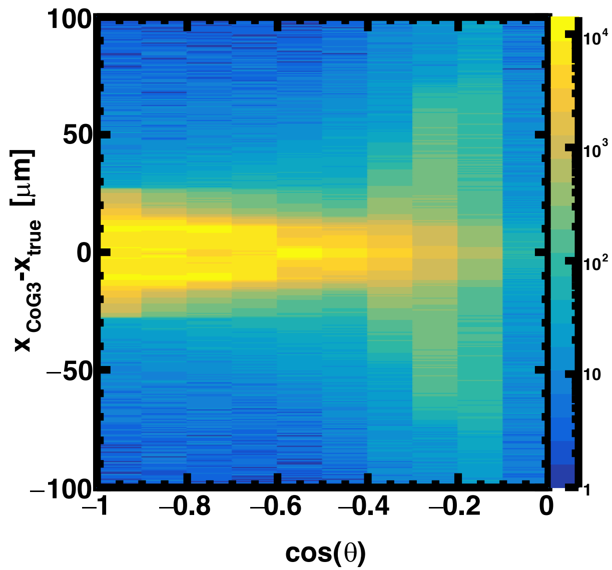




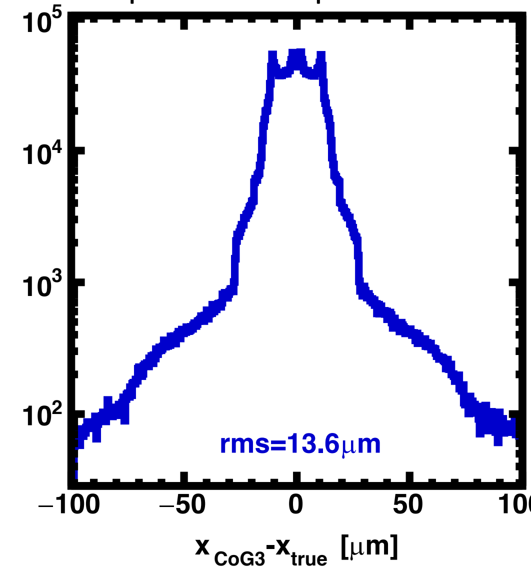
Expected ~ 15%







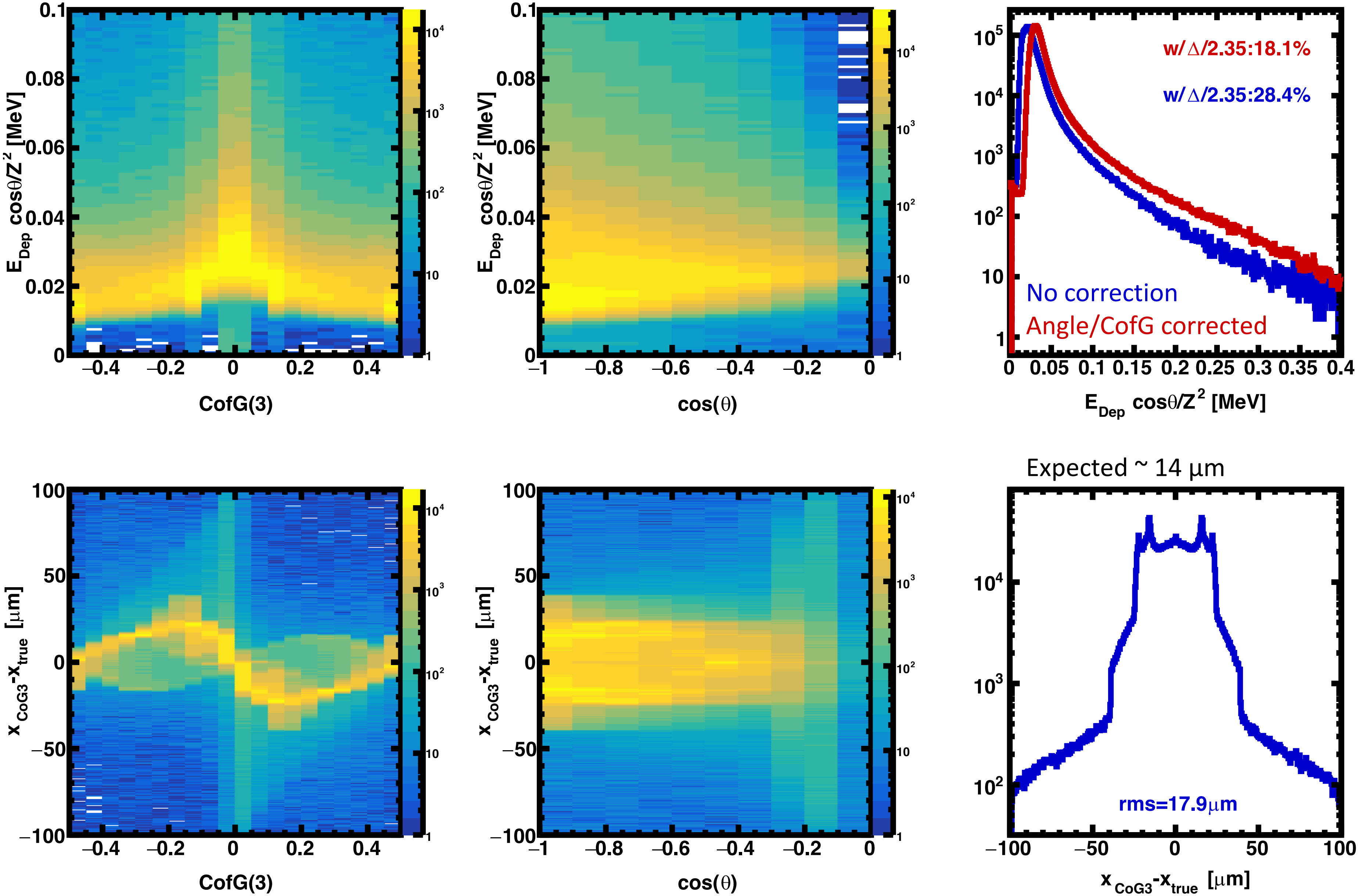
Expected ~ 14 µm



Single Layer Performance: 10 GeV Protons, 50 μm Pitch, 3 Floating Strips

No request on CALO, all layers together.

Expected ~ 15%

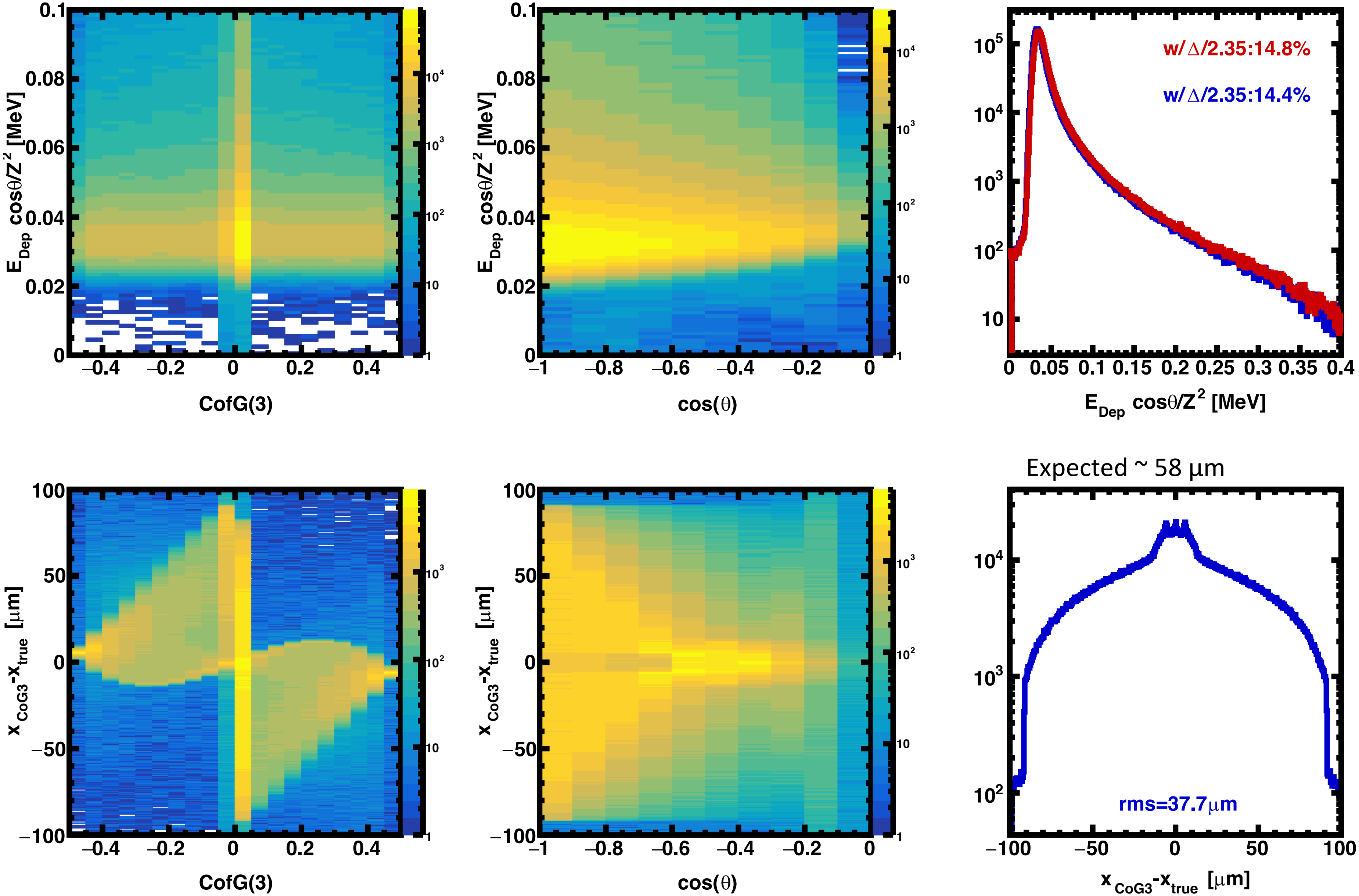


Single Layer Performance: 10 GeV Protons, 200 μm Pitch, No Floating Strips

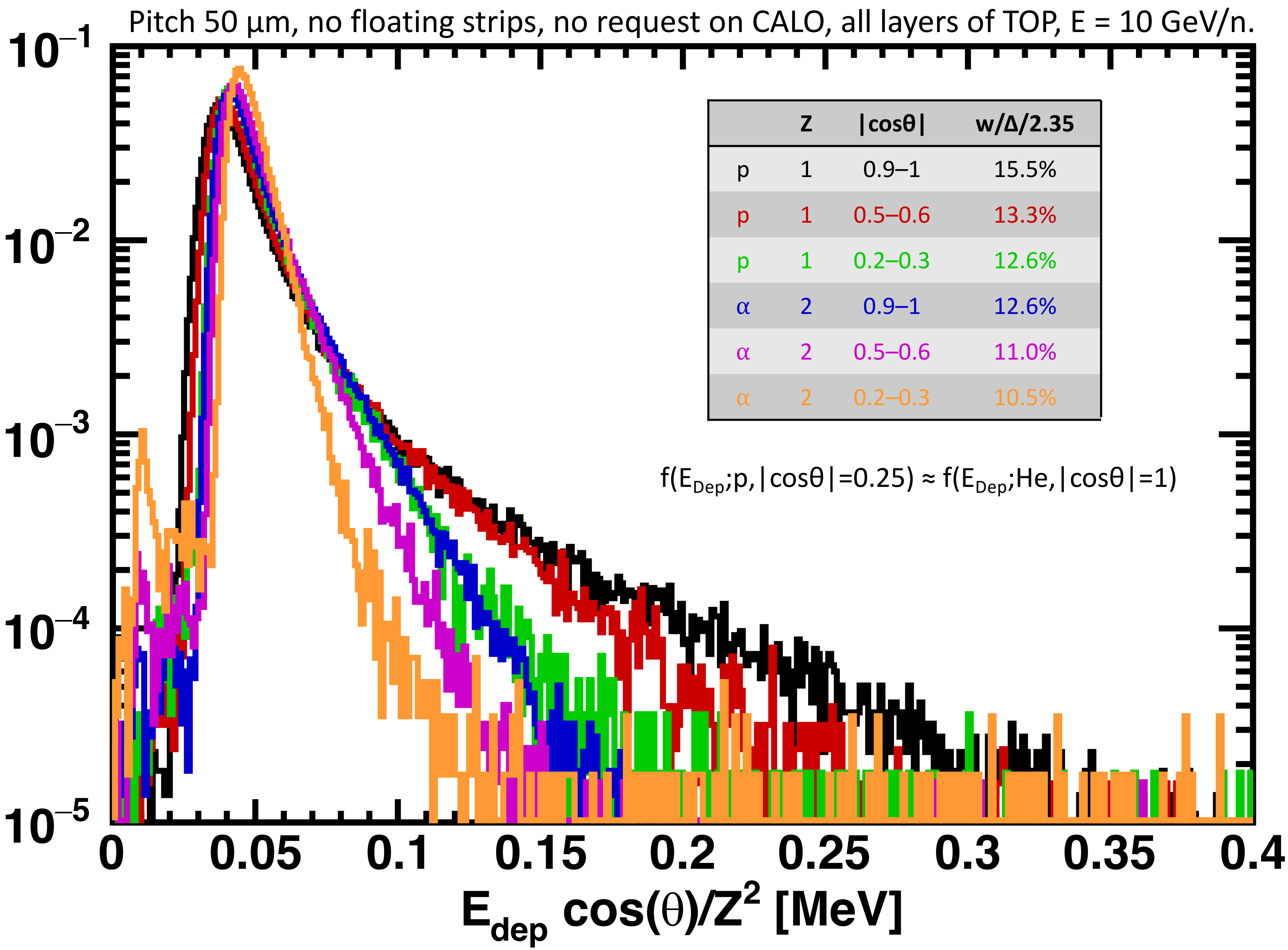
No request on CALO, all layers together.

Expected ~ 15%

Expected ~ 58 μm

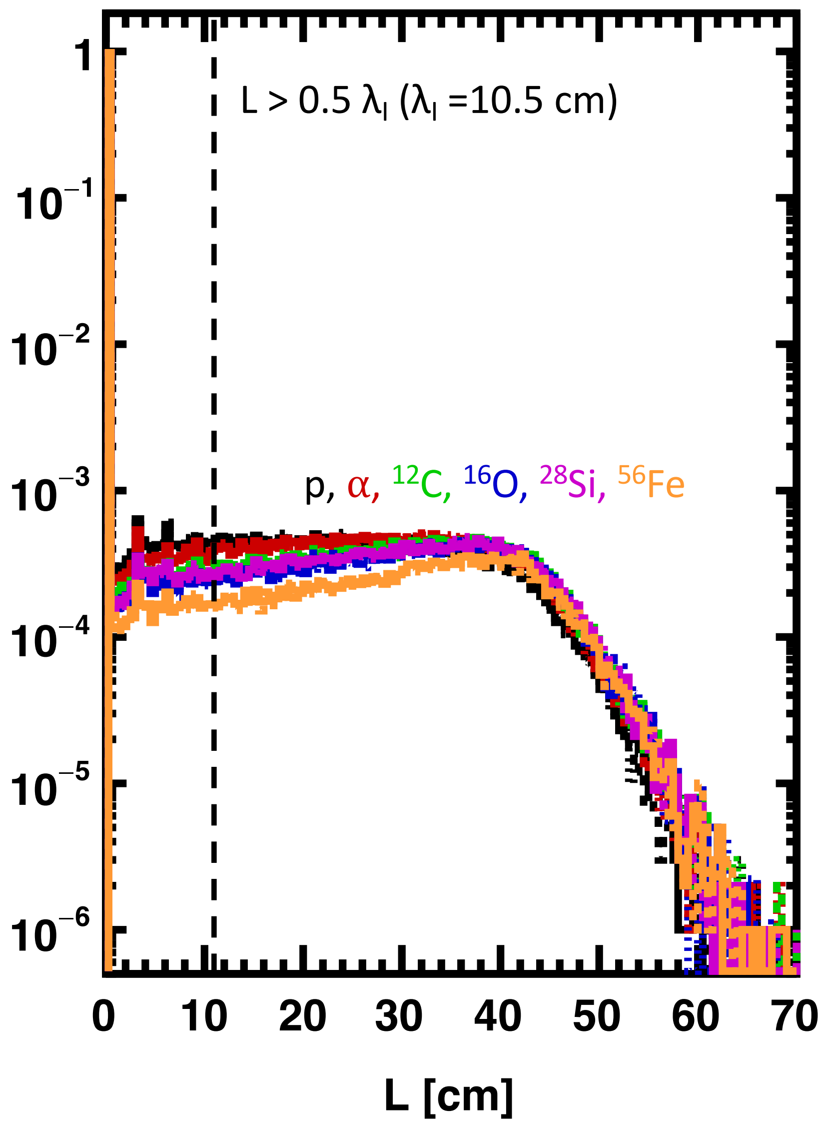


Single Layer E_{Dep} Dependence from $\cos\theta/Z^2$

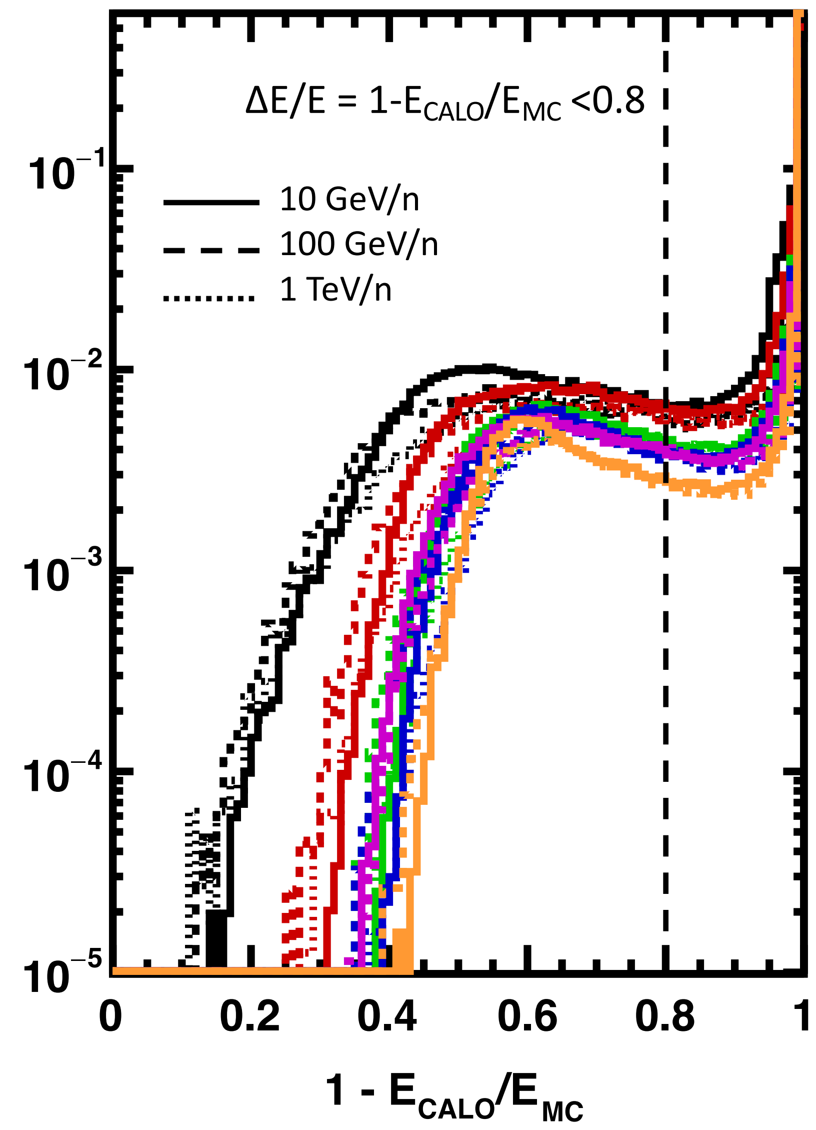


CALO Selection

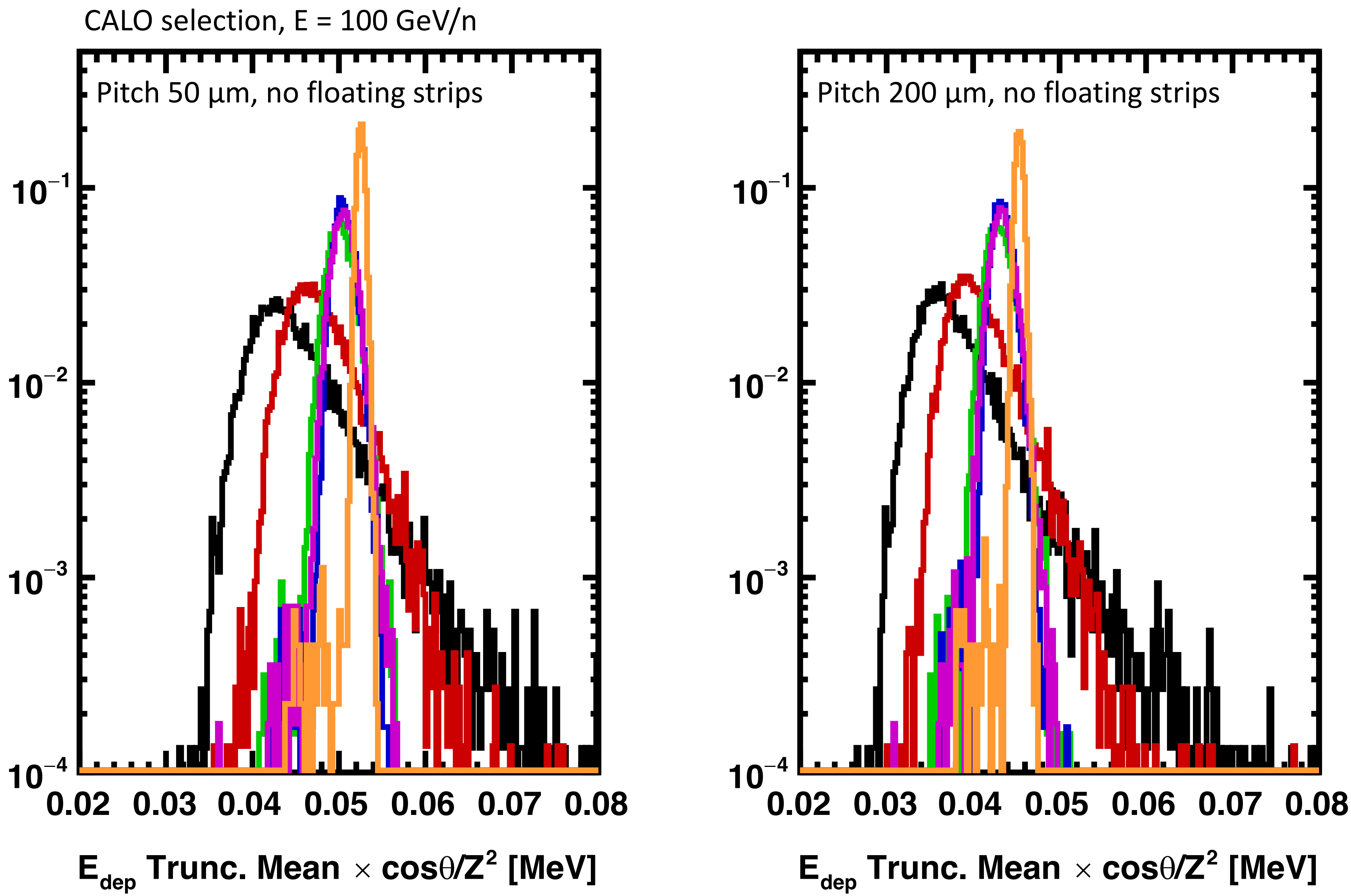
Length in CALO after interaction.



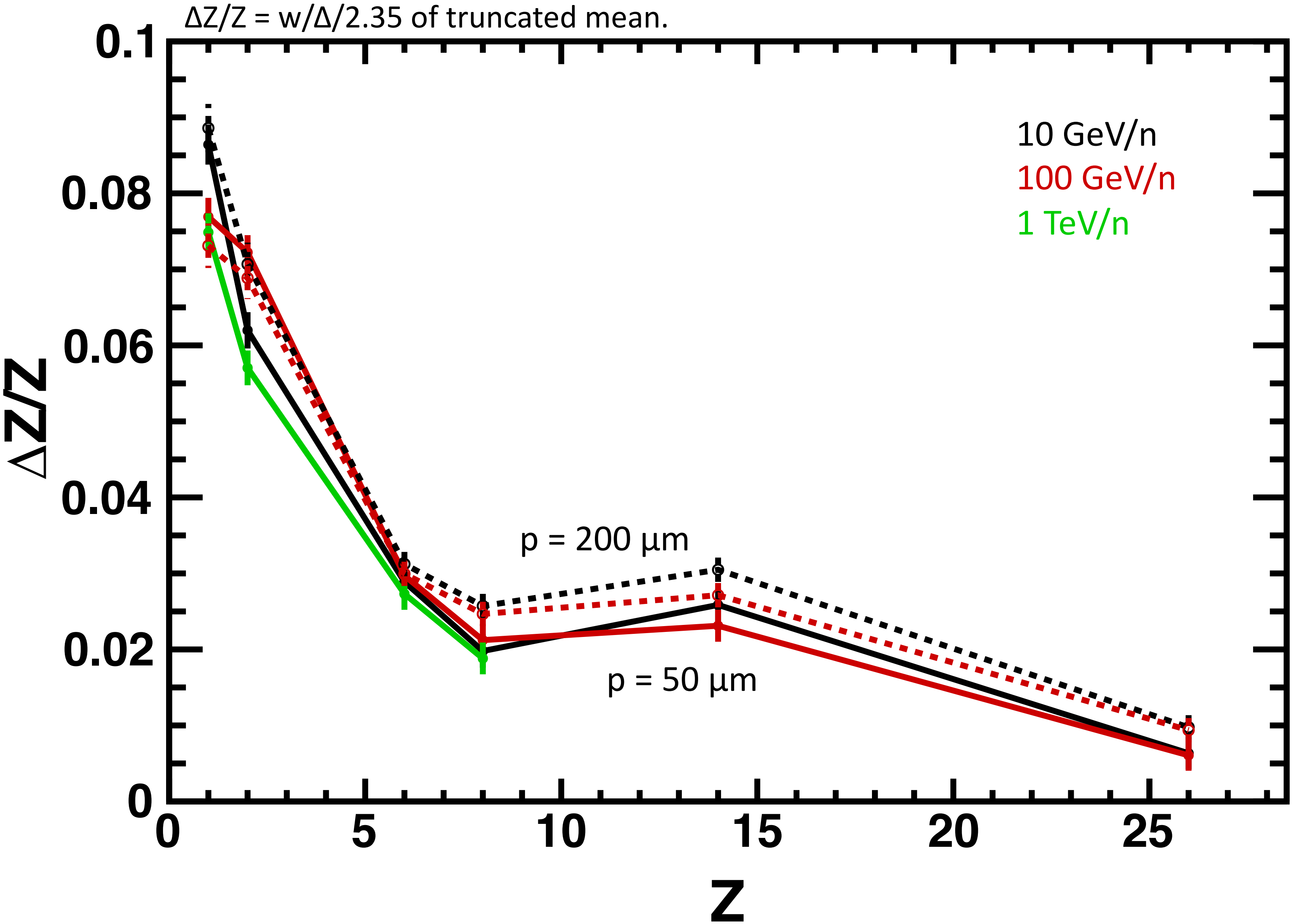
Energy resolution.



Single Side (up-to-8 Layers) Resolution



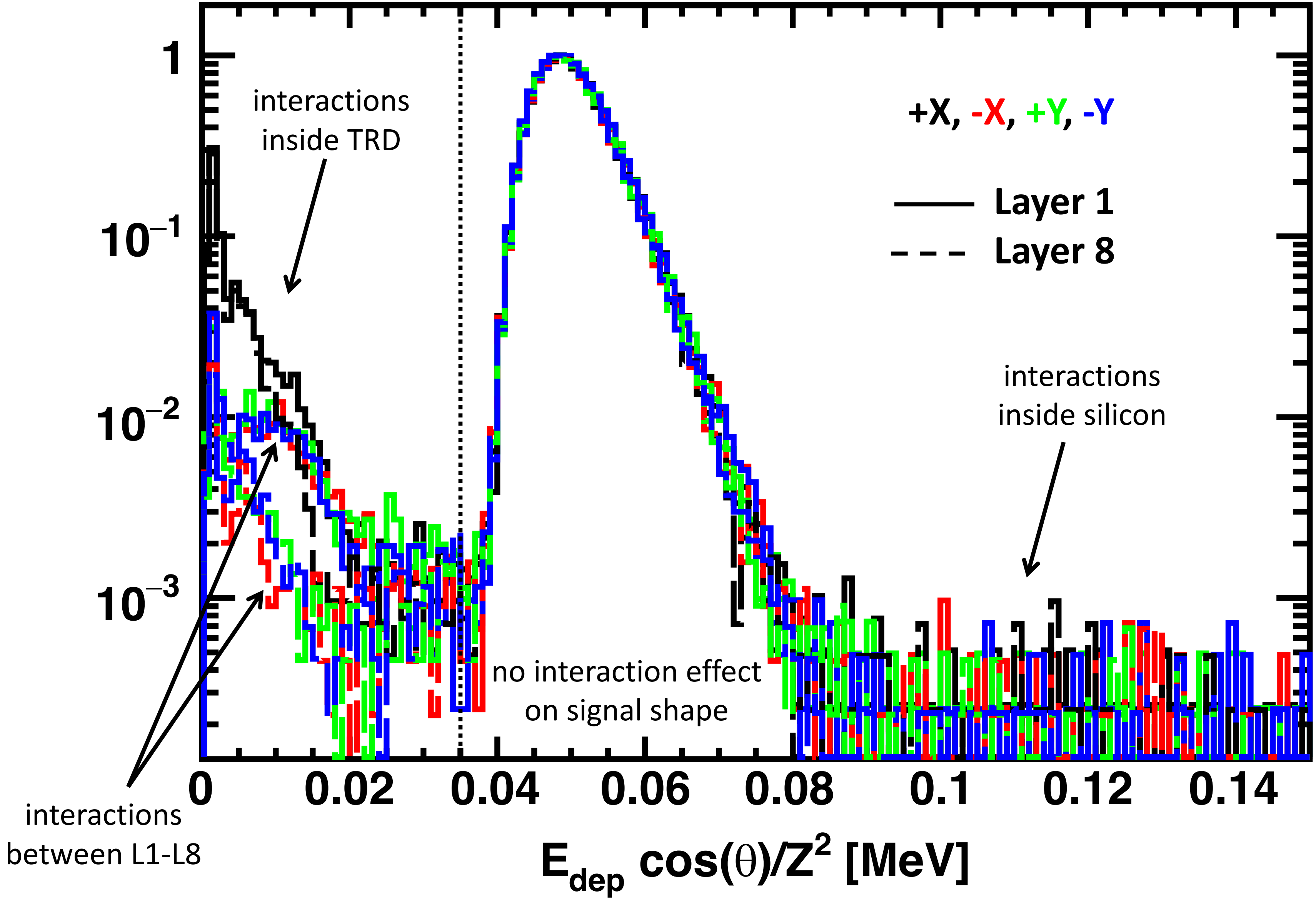
Single Side (up-to-8 Layers) Resolution



No big effect from backsplash observed up to 1 TeV/n. Higher energies still under processing.

Interactions in SCD and TRD for ^{12}C @ 10 GeV/n

No CALO selection. The interaction prob. is ~ 6% on TRD side and ~ 1% from L1 to L8.



Conclusions

A series of algorithms to simulate the digitization for a Silicon Strip Detector in HerdSoftware have been introduced. A few more steps are needed to have a full simulation/reconstruction chain (noise creation algorithm and connection to the already present clusterization and tracking algorithms in HerdSoftware).

This simulation scheme is simple and computationally inexpensive, but is based on many simplifications, and has not a big predictive power. However can be improved with results of detailed simulations, laboratory data and/or test beam data.

First estimation of performances in terms of spatial resolution, energy deposit resolution, and interaction level show a reasonable performance using 8 layers of 150 μm (both for 50 and 200 μm pitch).

Charge evaluation requires a calibration procedure to take into account signal dependencies of E_{Dep} from impact position and angle, and other effects. A possible extension of the trigger to acquire Z>2 particles could help the study of these effects in detail in the case of flight data.

Backup

Ionization

$$k = \frac{\xi}{W_{\max}}$$

Vavilov parameter

$$\xi = \frac{K}{2}\frac{Z}{A}\frac{z^2}{\beta^2}\rho x \qquad \xi[\mathrm{MeV}] = 0.1535\frac{K}{2}\frac{Z}{A}\frac{z^2}{\beta^2}X[\mathrm{g/cm^2}]$$

Landau width

$$W_{\max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma\frac{m_e}{M} + \left(\frac{m_e}{M}\right)^2} \overset{m_e\gamma \ll M}{=} 2m_e c^2\beta^2\gamma^2$$

Maximum energy transfer to e^-

For Silicon below 1 mm Silicon, β≈1, and impinging nuclei, **k is below 0.1**, corresponding to **Landau regime**.

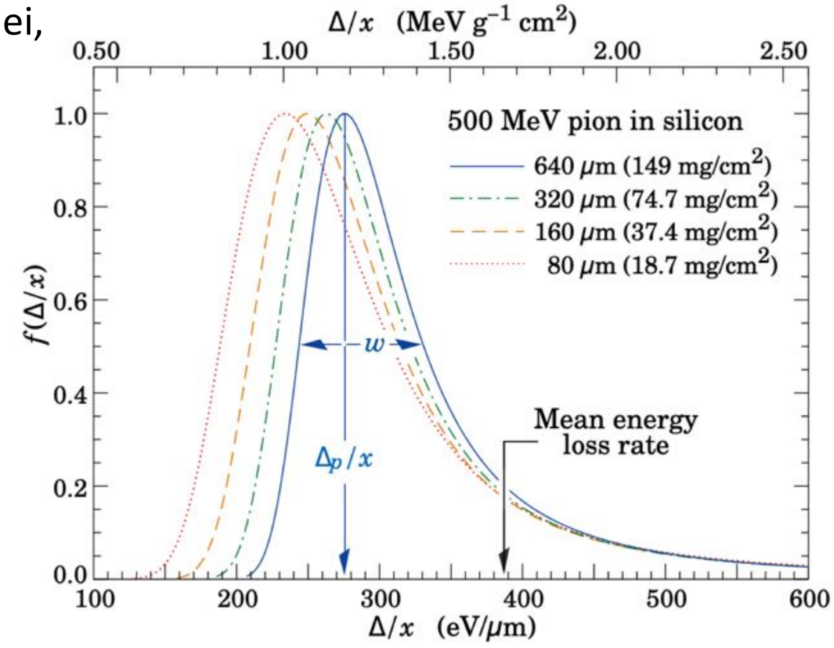
Landau most probable energy loss:

$$\Delta_p = \xi\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + 0.2 - \beta^2 - \delta(\beta\gamma)\right]$$

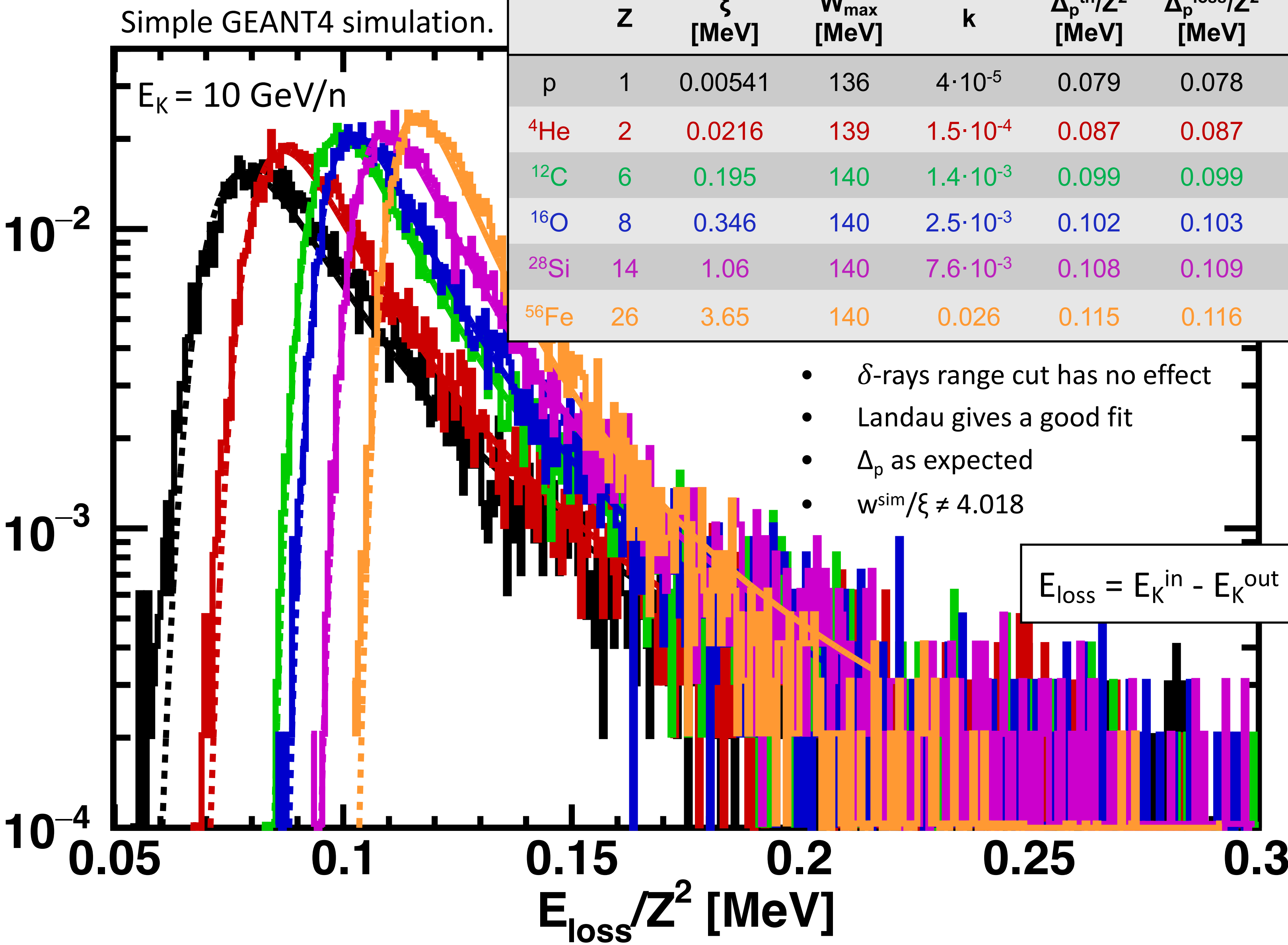
Landau full-width at half maximum (FWHM):

$$w_L \sim 4.018\xi$$

Ionization cylinder is ≈ 1 µm.



Ionization: Energy Loss

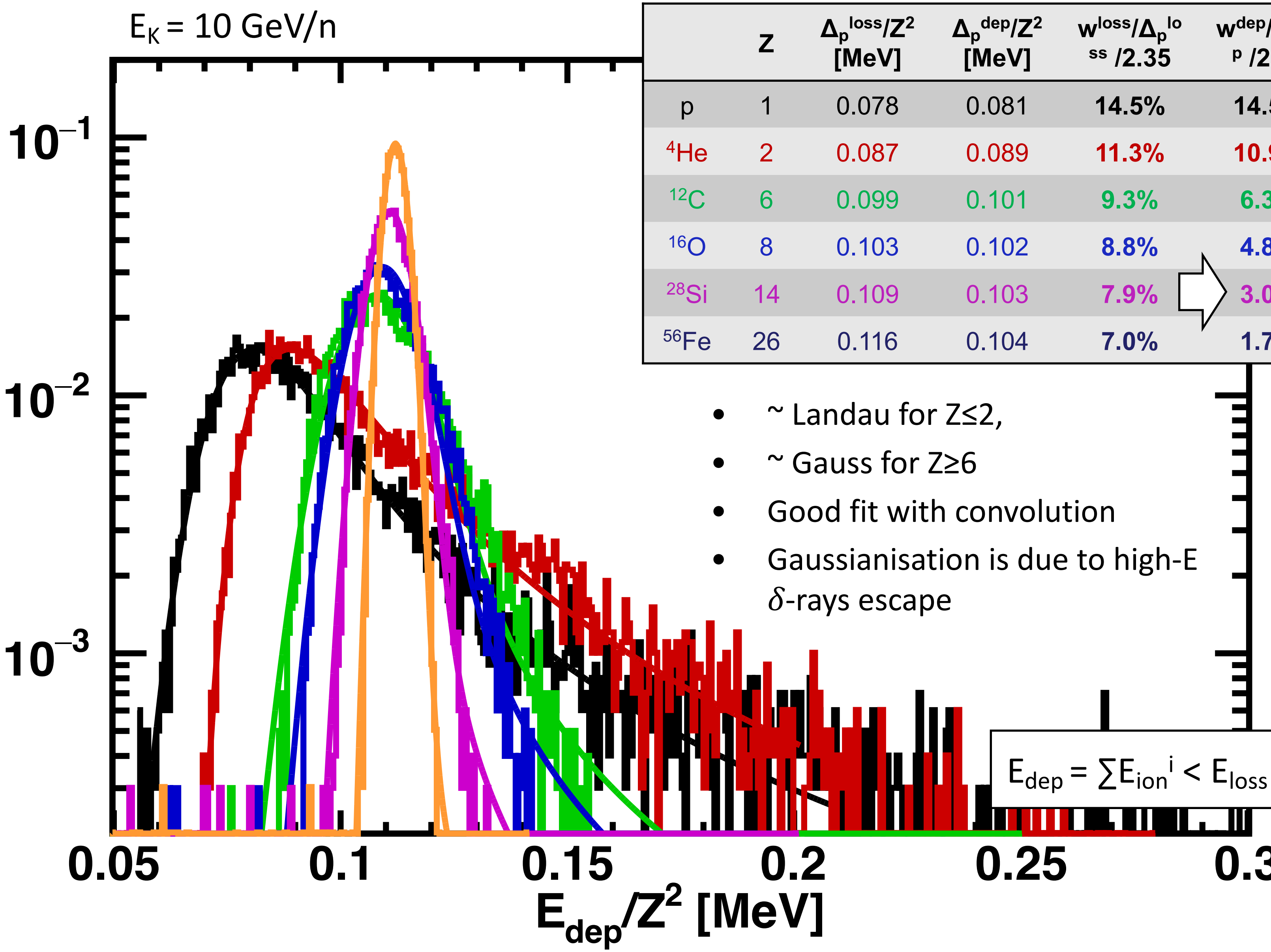


	Z	ξ [MeV]	W_{max} [MeV]	k	Δ_p^{th}/Z^2 [MeV]	Δ_p^{loss}/Z^2 [MeV]	w^{loss}/ξ
p	1	0.00541	136	$4\cdot10^{-5}$	0.079	0.078	4.92
^{4}He	2	0.0216	139	$1.5\cdot10^{-4}$	0.087	0.087	4.26
^{12}C	6	0.195	140	$1.4\cdot10^{-3}$	0.099	0.099	4.00
^{16}O	8	0.346	140	$2.5\cdot10^{-3}$	0.102	0.103	3.91
^{28}Si	14	1.06	140	$7.6\cdot10^{-3}$	0.108	0.109	3.74
^{56}Fe	26	3.65	140	0.026	0.115	0.116	3.55

- δ-rays range cut has no effect
- Landau gives a good fit
- Δ_p as expected
- $w^{sim}/\xi \neq 4.018$

$$E_{loss} = E_K^{in} - E_K^{out}$$

Ionization: Energy Deposition



	Z	Δ_p^{loss}/Z^2 [MeV]	Δ_p^{dep}/Z^2 [MeV]	w^{loss}/Δ_p^{loss} /2.35	w^{dep}/Δ_p^{dep} /2.35
p	1	0.078	0.081	**14.5%**	**14.5%**
^{4}He	2	0.087	0.089	**11.3%**	**10.9%**
^{12}C	6	0.099	0.101	**9.3%**	**6.3%**
^{16}O	8	0.103	0.102	**8.8%**	**4.8%**
^{28}Si	14	0.109	0.103	**7.9%**	**3.0%**
^{56}Fe	26	0.116	0.104	**7.0%**	**1.7%**

- ~ Landau for Z≤2,
- ~ Gauss for Z≥6
- Good fit with convolution
- Gaussianisation is due to high-E δ-rays escape

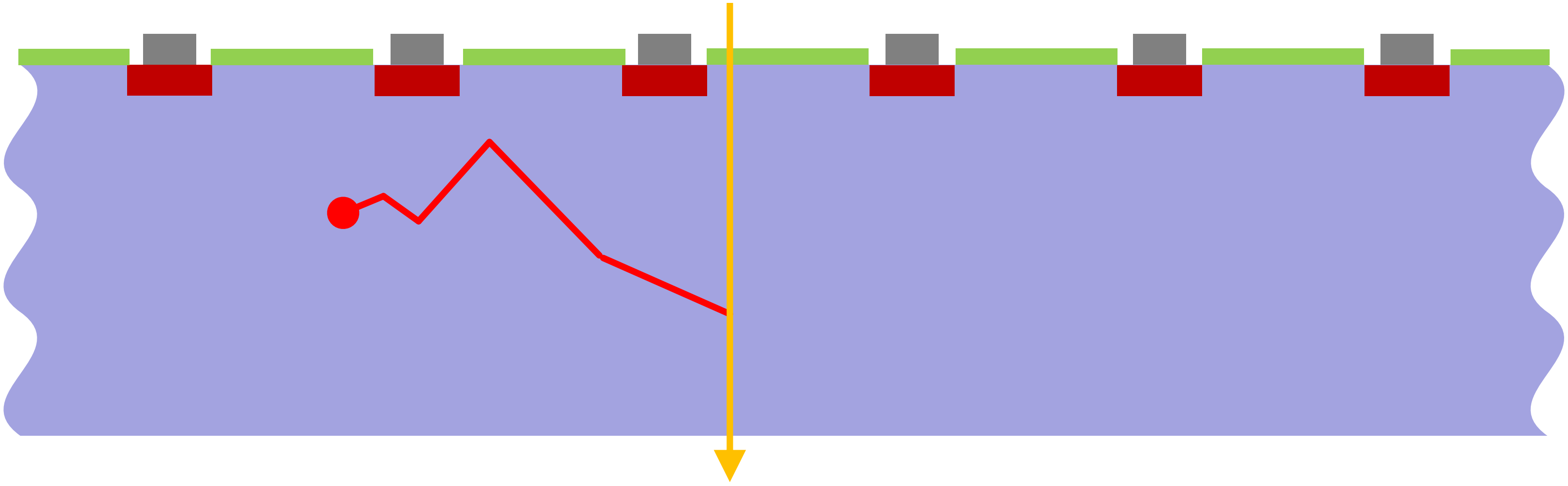
$E_{dep} = \sum E_{ion}^i < E_{loss}$

Ionization: Stepping

→ We need high-energy δ-rays escaping from active material to have observe the signal gaussianization for high-Z (100 keV electrons can escape 100 µm Silicon) → Xi'an presentation.

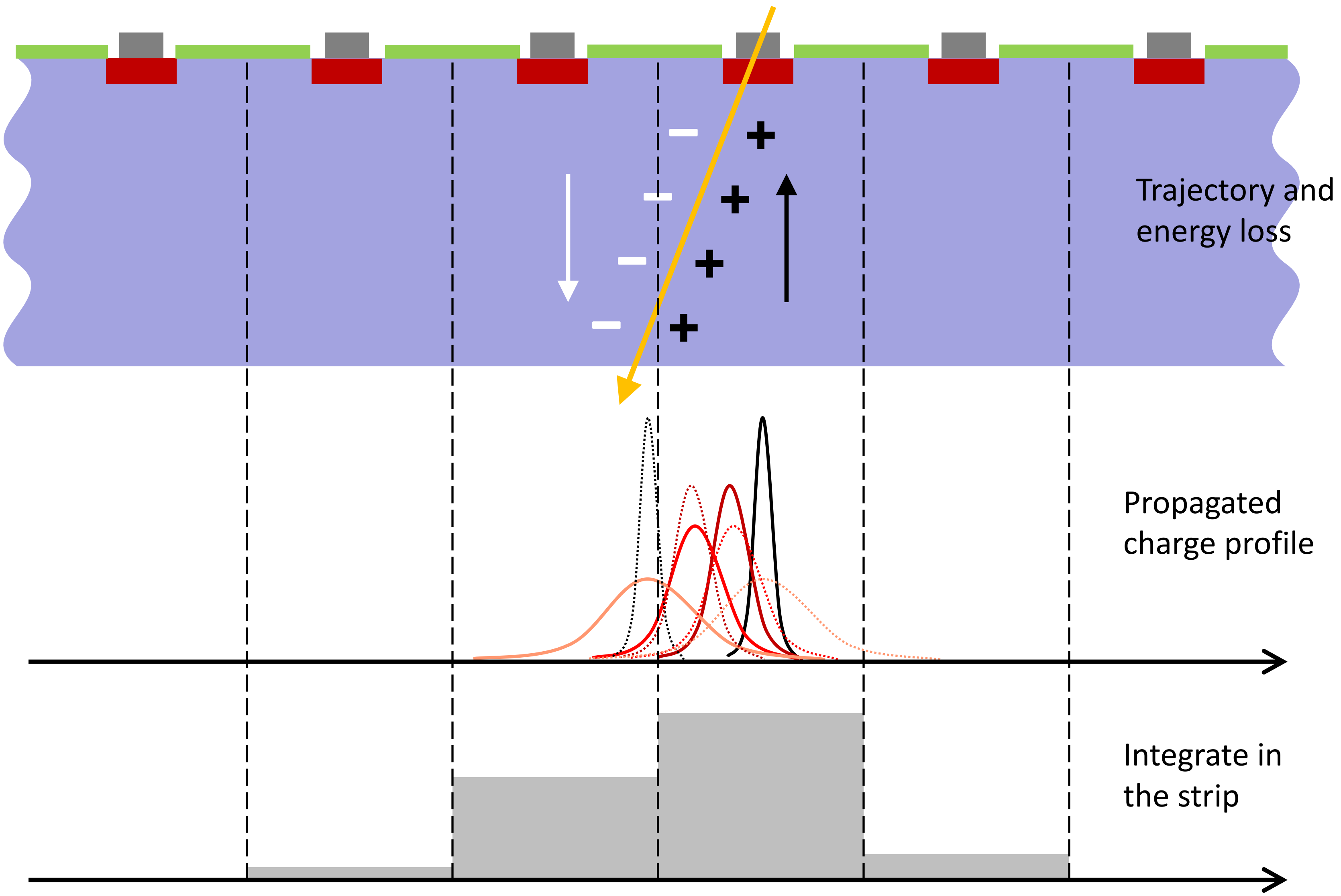
→ δ-rays of moderate energy may produce an important energy deposit that can change charge profile and coordinate evaluation. As an example a vertical MIP particle in 300 µm of Si deposits about 80 keV, a 50 keV electron emitted horizontally can travel about 16 µm giving a deviation of about 4 µm.

→ δ-rays of even lower energy may bias inclined tracks.



Propagation of e/h Pairs: Drift-Diffusion

Schematically:

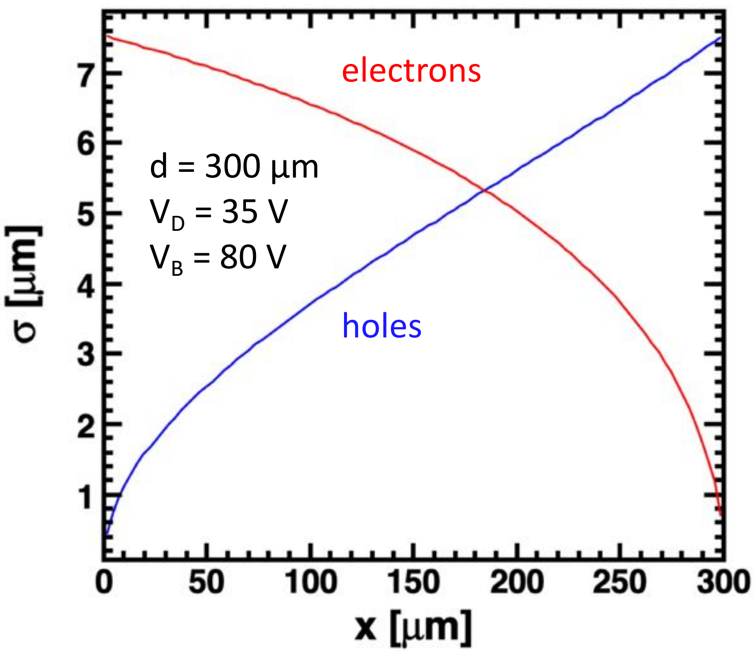


Propagation in Si: Simple Drift-Diffusion Scheme

$$\sigma_h = d\sqrt{-\frac{kT}{e}\frac{1}{V_D}\log\left(1-\frac{2V_D}{V_B+V_D}\frac{x}{d}\right)}$$

$$\sigma_e = d\sqrt{\frac{kT}{e}\frac{1}{V_D}\log\left(\frac{V_B+V_D}{V_B-V_D}-\frac{2V_D}{V_B-V_D}\frac{x}{d}\right)}$$

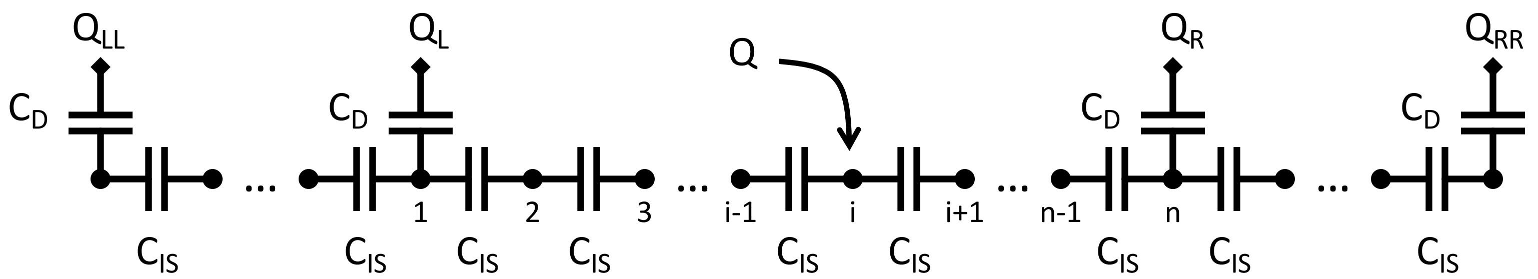
$$\sigma_{\max} = d\sqrt{\frac{kT}{e}\frac{1}{V_D}\log\left(\frac{V_B+V_D}{V_B-V_D}\right)}$$



This is an approximation. Drift-diffusion should take into account:
- The real shape of the electric field (it is not uniform nearby the strips)
- The trajectory of charges in the electric field (mobility dependence on electric field, …)
- The effect of charges migration on the electric field, and viceversa (saturation for high ionization? …)
- Other effects (carriers trapping, …).

Also charge collection is a misleading concept. Movement of charge in silicon induces signal on the electrodes. This current can be estimated via the Ramo's theorem (by the use of a weighting field, …). This is important if we need to have a time dependent signal (detailed simulation of the readout, …).

Equivalent Circuit: Charge Coupling



$$Q_{LL,RR} = \frac{1}{1 + n\frac{C_D}{C_{IS}}} Q_{L,R} = \epsilon Q_{L,R}$$

Spectator strips take a fix amount of the closest strip.
They represent a **"low gain" channel** of the nearby strip.
This is actually very useful for fighting saturations.
Extending the capacitive net we can find a similar relation for more far away strips (Q_L, $Q_{LL} = \varepsilon Q_L$, $Q_{LLL} = \varepsilon Q_{LL} = \varepsilon^2 Q_L$, …).

$$\frac{Q_L + Q_R}{Q} = \frac{1}{1+\epsilon}$$

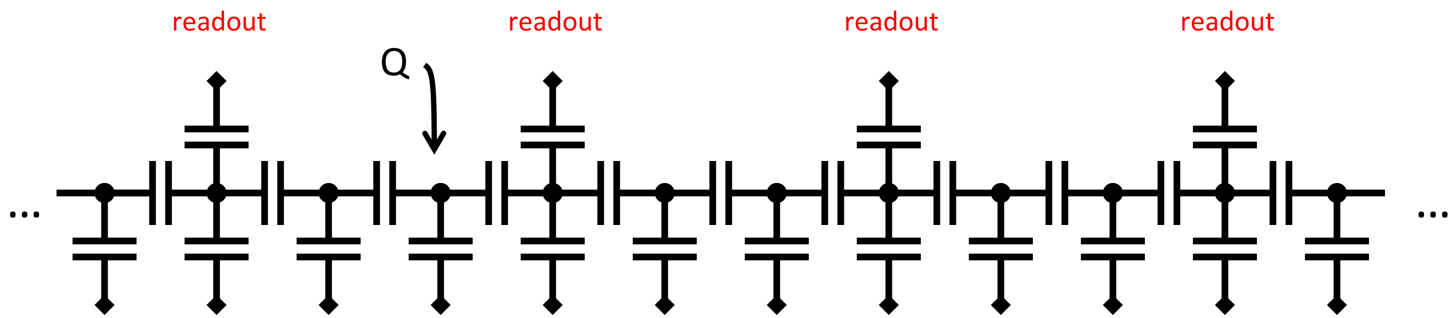
A small fraction of the signal goes to external strips (however in this case there is no charge loss: $Q = Q_{LL} + Q_L + Q_R + Q_{RR}$)

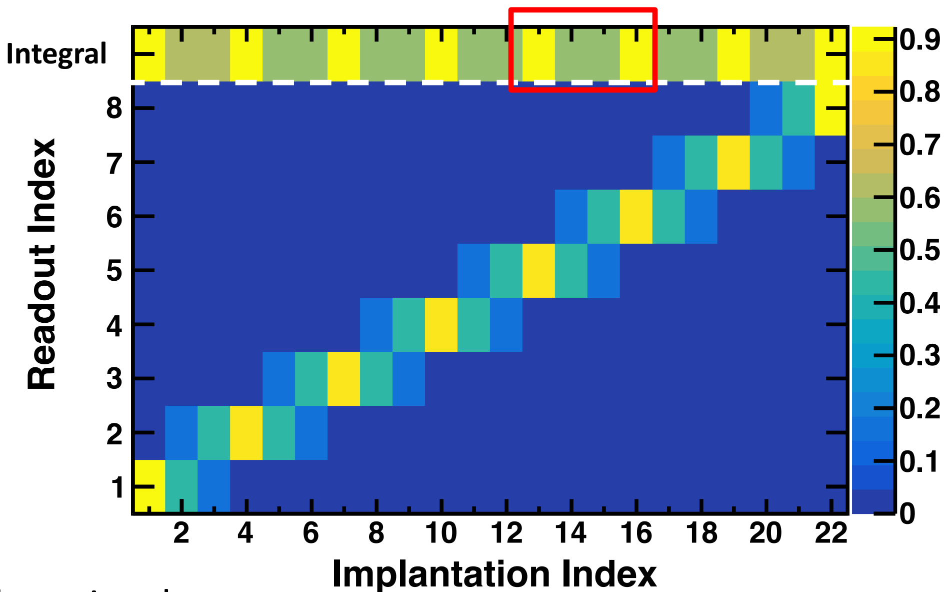
$$\frac{Q_R}{Q_R + Q_L} = \frac{1 + i(1+\epsilon)\frac{C_D}{C_{IS}}}{2 + n(1+\epsilon)\frac{C_D}{C_{IS}}} \xrightarrow{C_D \gg C_{IS}} \frac{i}{n}$$

Signal is distributed **proportionally** to the energy deposit location.

With $C_D \gg C_{IS}$, position determination is better, and there is no "leakage" of charge.
However, some "leakage" is an advantage for charge/position determination.

Equivalent Circuit: Charge Loss





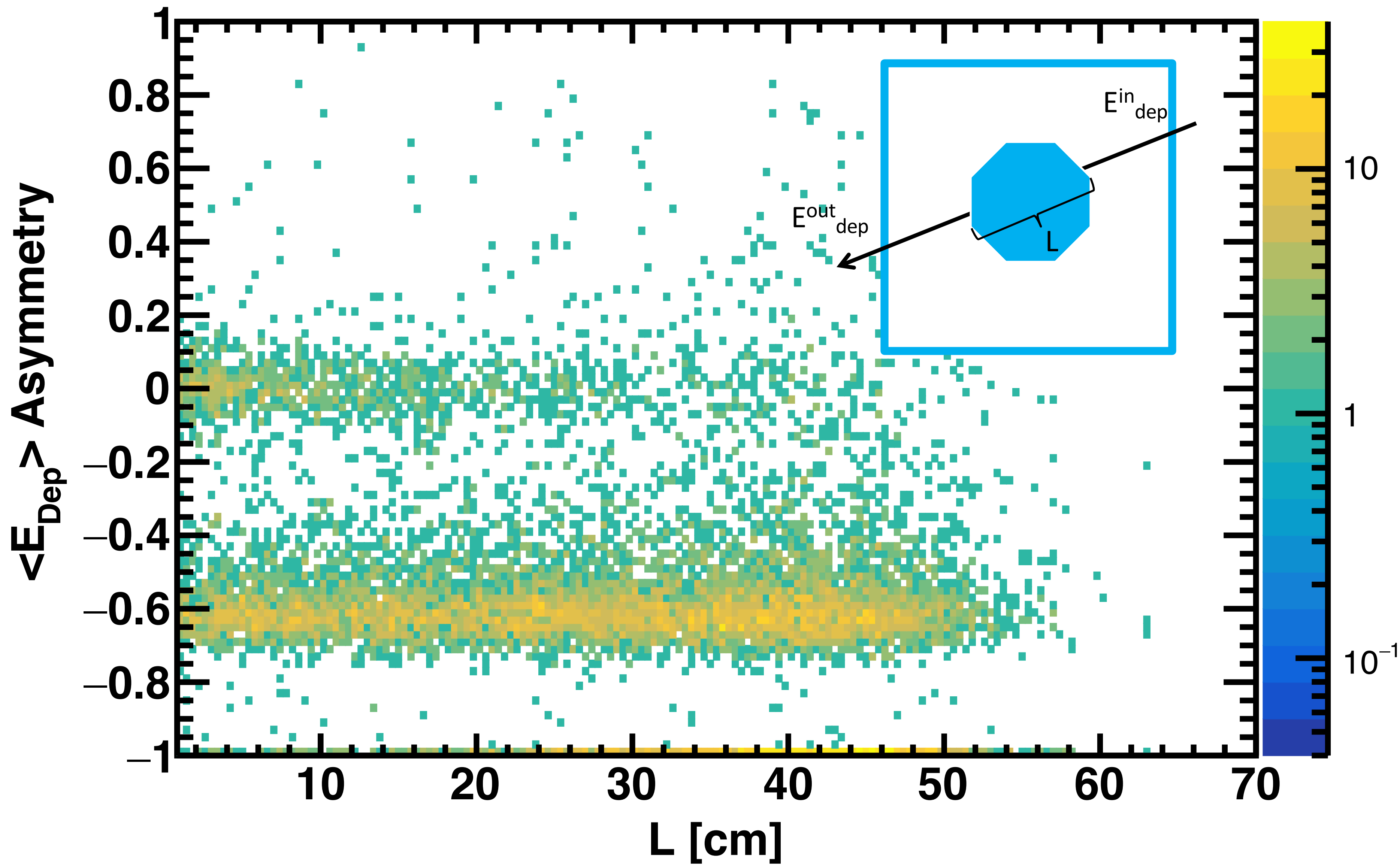
The system can be generically solved with a software (Spice, …).

Main feature is that the presence of C_B gives a **charge loss**, an apparent total signal dependence on position (depends on C_B/C_{IS} and C_B/C_D).

Charge loss is problematic:
-Smaller total signal when far away from readout signal
-Requires accurate correction (calibration and reconstruction)
-Can be minimized with $C_B \ll C_{IS}$ (and $C_B \ll C_D$)

Note that charge losses can be caused also by other things, like the electric field shape in the silicon and, in that case, can be improved with higher bias voltage.

Possible Use of SCD for Verification of Interactions



This can be compared, in bins of geomagnetic cutoff, with flight data.