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IMPACT IONISATION MODELS AND LGAD SENSORS FOR HGTD

5th Allpix^2 user workshop

Introduction

- This talk:
  - Introduce the High-Granularity Timing Detector in the context of the next ATLAS upgrade and the simulation of LGAD sensors
  - Focus on the **simulation of the multiplication of charges in the gain layer** and discussion of current models
- Some useful links:
  - HGTD technical design report

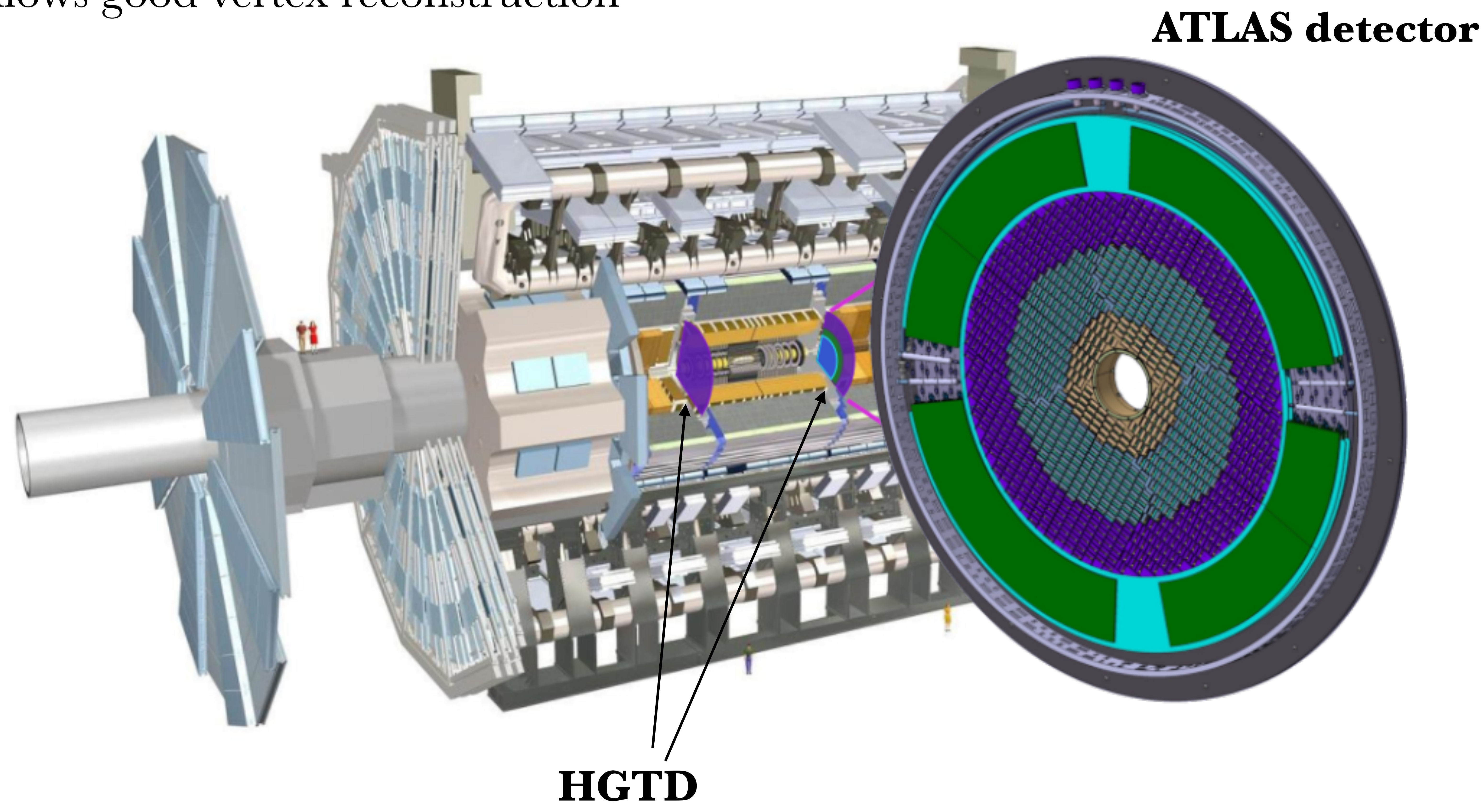
Outline

High Granularity Timing Detector

- **High-Granularity Timing Detector (HGTD)** expected to be ready for Run4 and HL-LHC phase in 2029
- Built to deal with the high pile-up density ($< \mu > = 200$ interactions per bunch crossing)
- **Track resolution** of the detector expected to be **worse than typical vertex separation** (1.6 vertices/mm) in the forward region → time measurement allows good vertex reconstruction

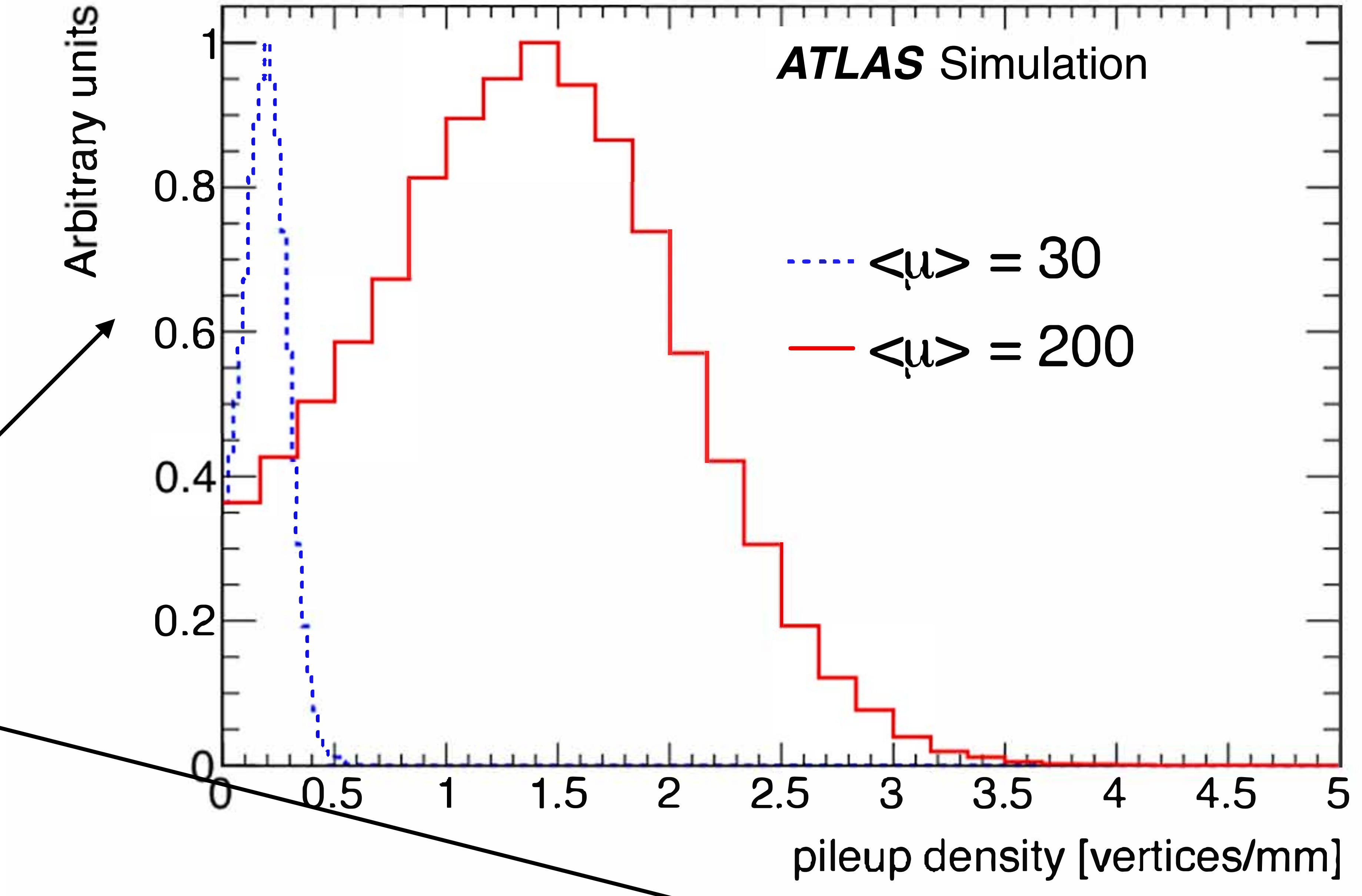
HGTD:

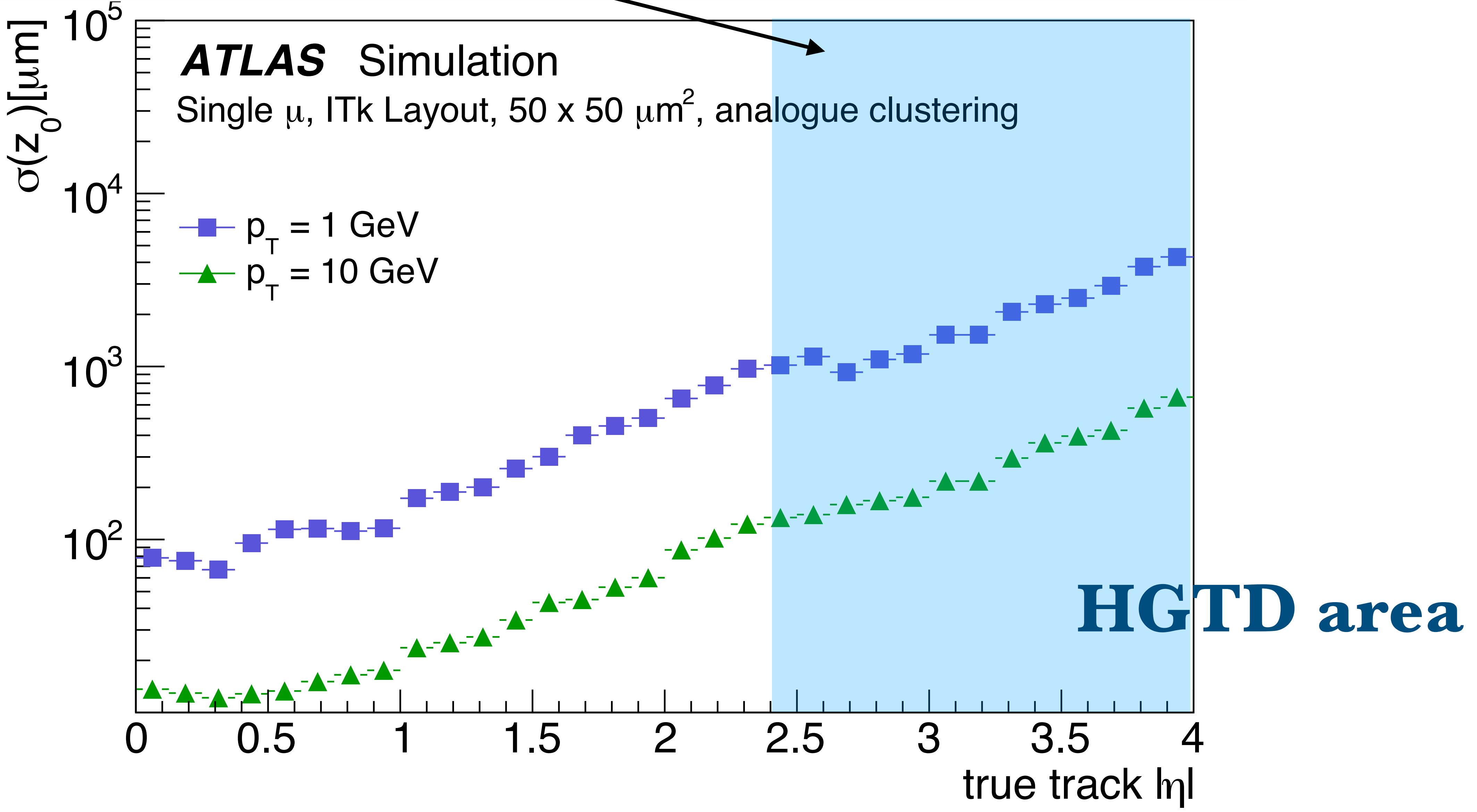
- **Two disks**, inserted between the barrel and end-cap calorimeters, coverage in $2.4 < \eta < 4$
- Consists of around 8000 modules (each module two LGADs plus custom electronics)
- Operating **temperature at -30 C°**, maximum fluency at $2.5 \times 10^{15}\ n_{eq}/\text{cm}^2$



High Granularity Timing Detector

- New Inner Tracker (ITk) of ATLAS will measure the longitudinal impact parameter z_0 of a track
- When the z_0 resolution larger than the **typical distance between two vertices** (e.g. in the **forward region** for HL-LHC) → precision timing allows these vertices to be separated
- HGTD designed to provide 30 ps time resolution on tracks at the beginning of Run4 (50 ps at the end)
- **Time measurement** will act as an additional dimension to discriminate between vertices





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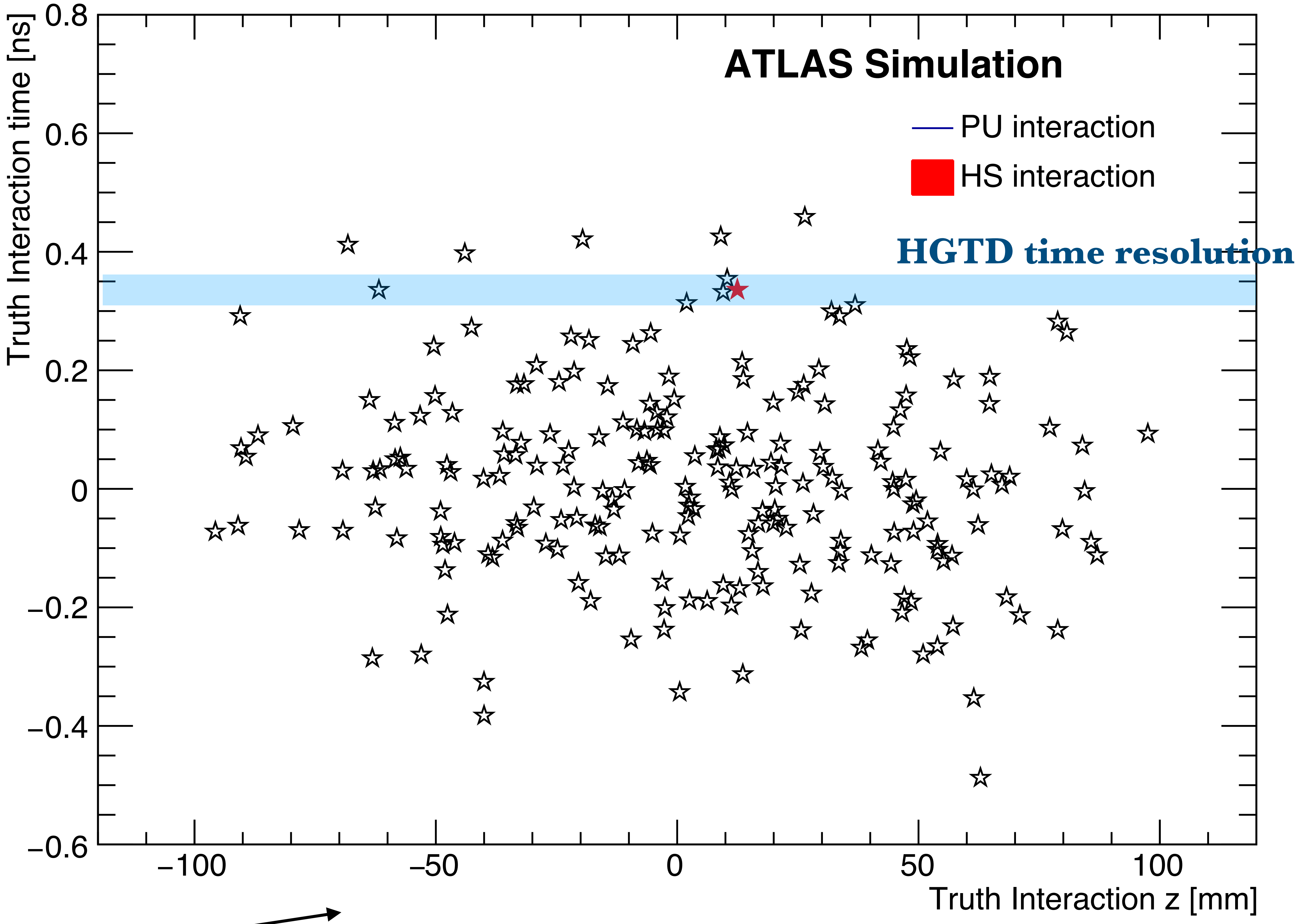
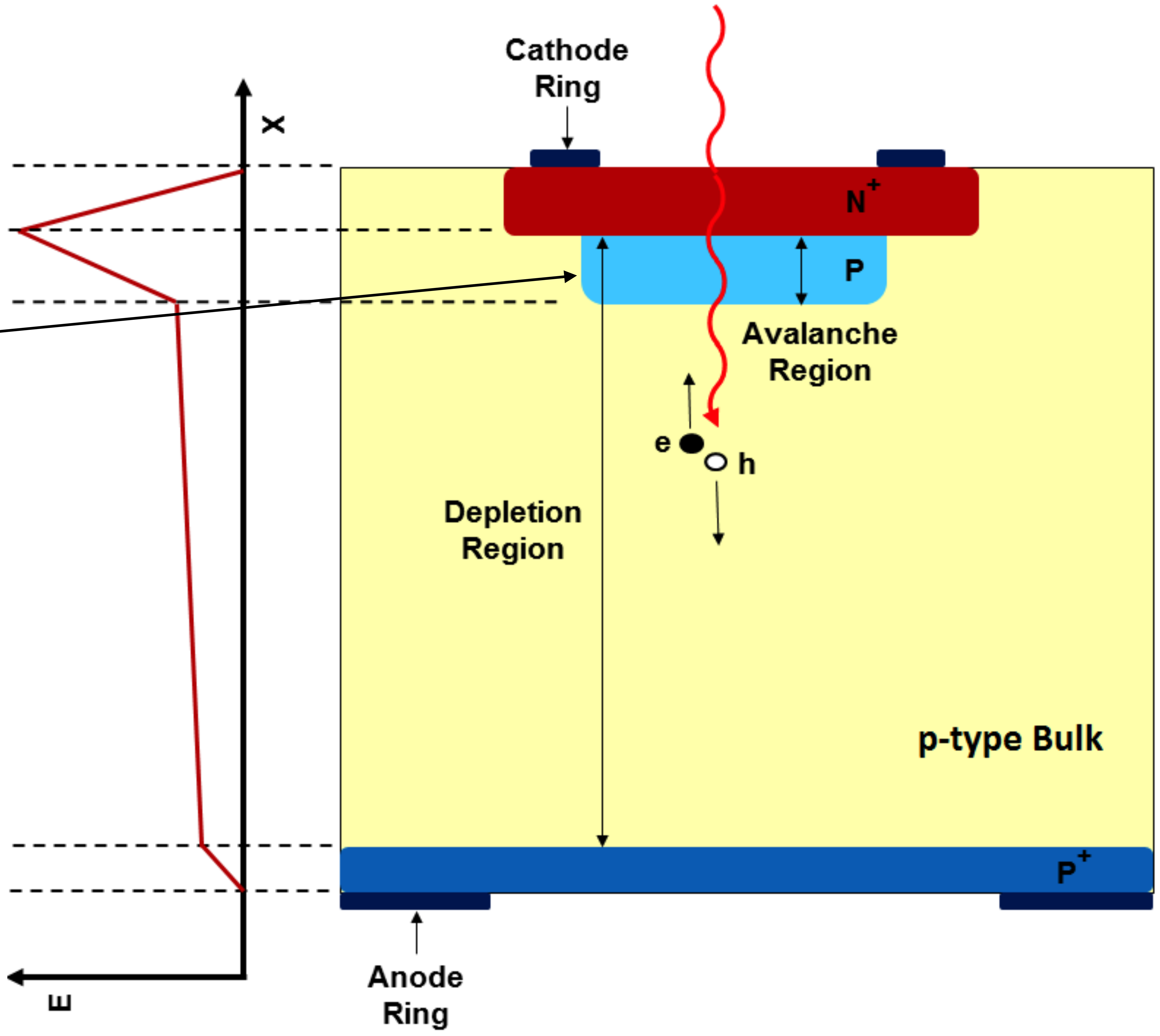


LGAD sensors

- Sensors made of 15 × 15 pads of 1.3 × 1.3 mm^2, active thickness of 50 μm
- n-on-p structure with extra p-doped gain layer
- Expected multiplication of charges in the **gain layer** to produce a gain of 10-20
- Time resolution (start - end of run):
  - Per hit: **30-50 ps**
  - Per track: 50-70 ps
- **Collected charge >4fC,** efficiency > 95% in the centre of the sensor
- Test beam campaigns at DESY and SPS to check sensor performance with the requirements



Simulation in Allpix^2

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Simulation in Allpix^2: configuration

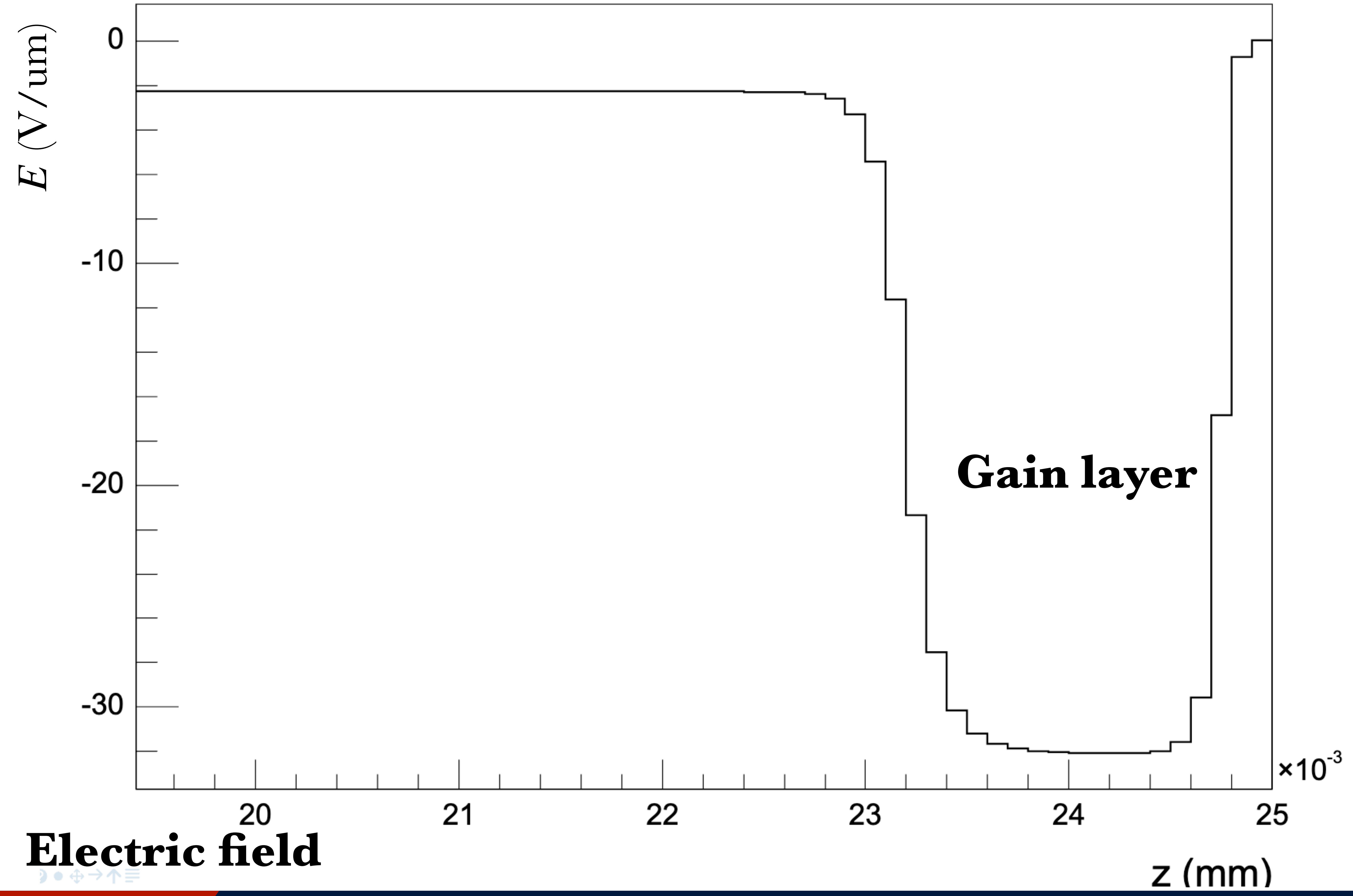
- Configuration used for the simulation in Allpix:
  - TCAD file for electric field, weighting potential obtained from two TCADs at different voltages
  - TransientPropagation module used for the propagation step, **multiplication model** chosen will be discussed later
  - **Effective simulation of electronic response**: PulseTransfer and CSADigitizer modules chosen, parameters tuned to best match the average pulse shape obtained in test beam data
  - **Threshold on output pulse** converted to match the 4fC charge threshold used in test beam

```
[Allpix]
...

[GeometryBuilderGeant4]
world_material = "air"

[DepositionGeant4]
physics_list = "FTFP_BERT_LIV"
particle_type = "e-"
number_of_particles = 1
source_energy = 5GeV
source_position = 0mm 0mm -10mm
source_type = "square"
...
max_step_length = 100nm


[ElectricFieldReader]
model = "mesh"
...

[WeightingPotentialReader]
model = "mesh"
...

[TransientPropagation]
temperature = 293K
multiplication_model = # different models
charge_per_step = 10
timestep = 1ps # for proper gain layer sampling
integration_time = 10ns
max_multiplication_level = 10

[PulseTransfer]
...

[CSADigitizer]
model = "simple"
feedback_capacitance = 1e-15C/V
rise_time_constant = 50ps
feedback_time_constant = 100ps
integration_time = 0.5e-6s
threshold = 126.68mV
ignore_polarity= true
```

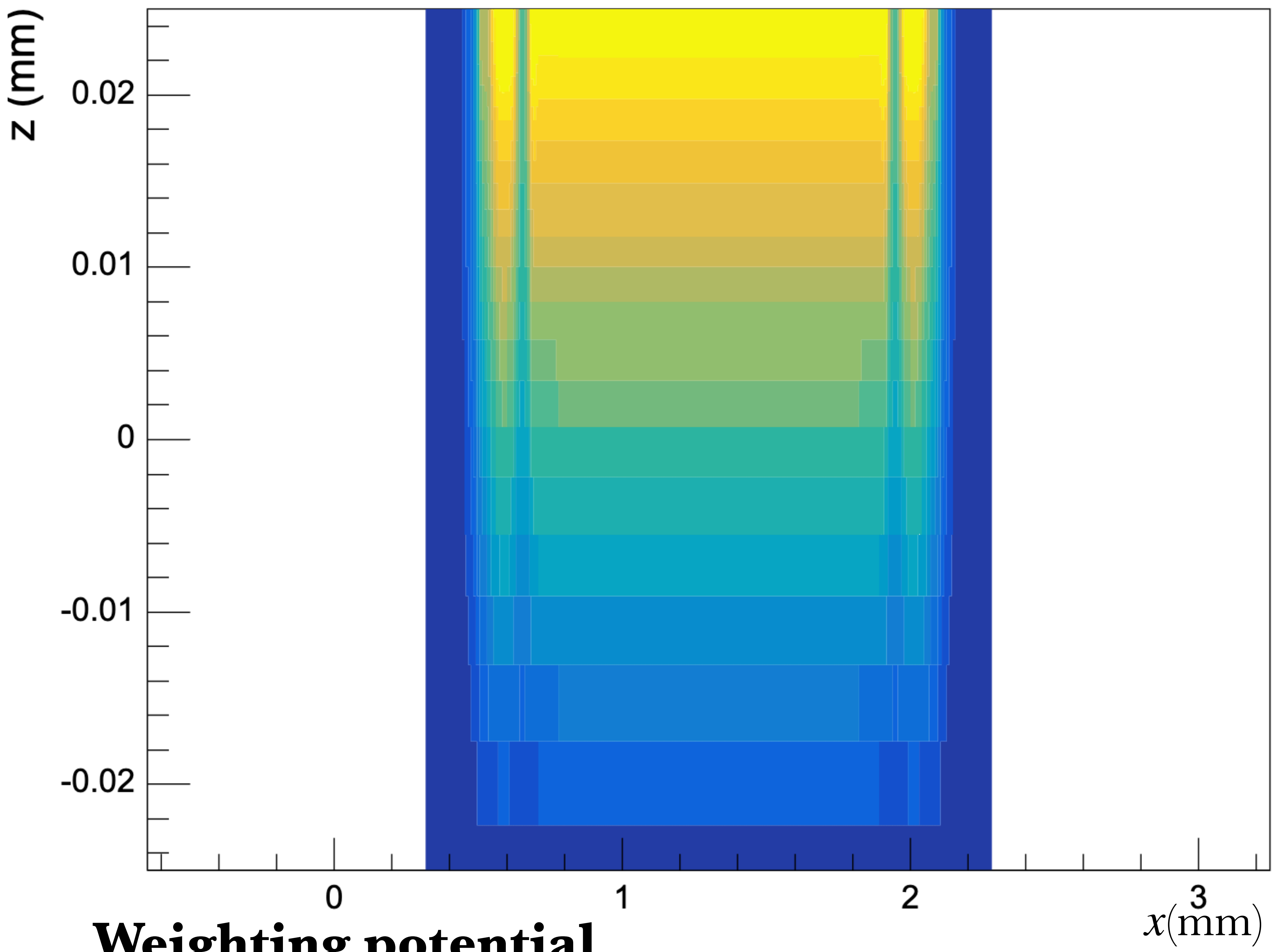
Configuration file

Electric field and weighting field potential

- **TCAD output** for different bias voltages used to simulate **electric field** in the sensor (very limited in inputs available, due to constraints from the vendors)
- Two voltages (30V difference) used to create a weighting potential file also used as input in the simulation as described in the manual
- Electric field projection along thickness axis is shown below (32 V/um max for about 1 um GL)



Electric field



Weighting potential

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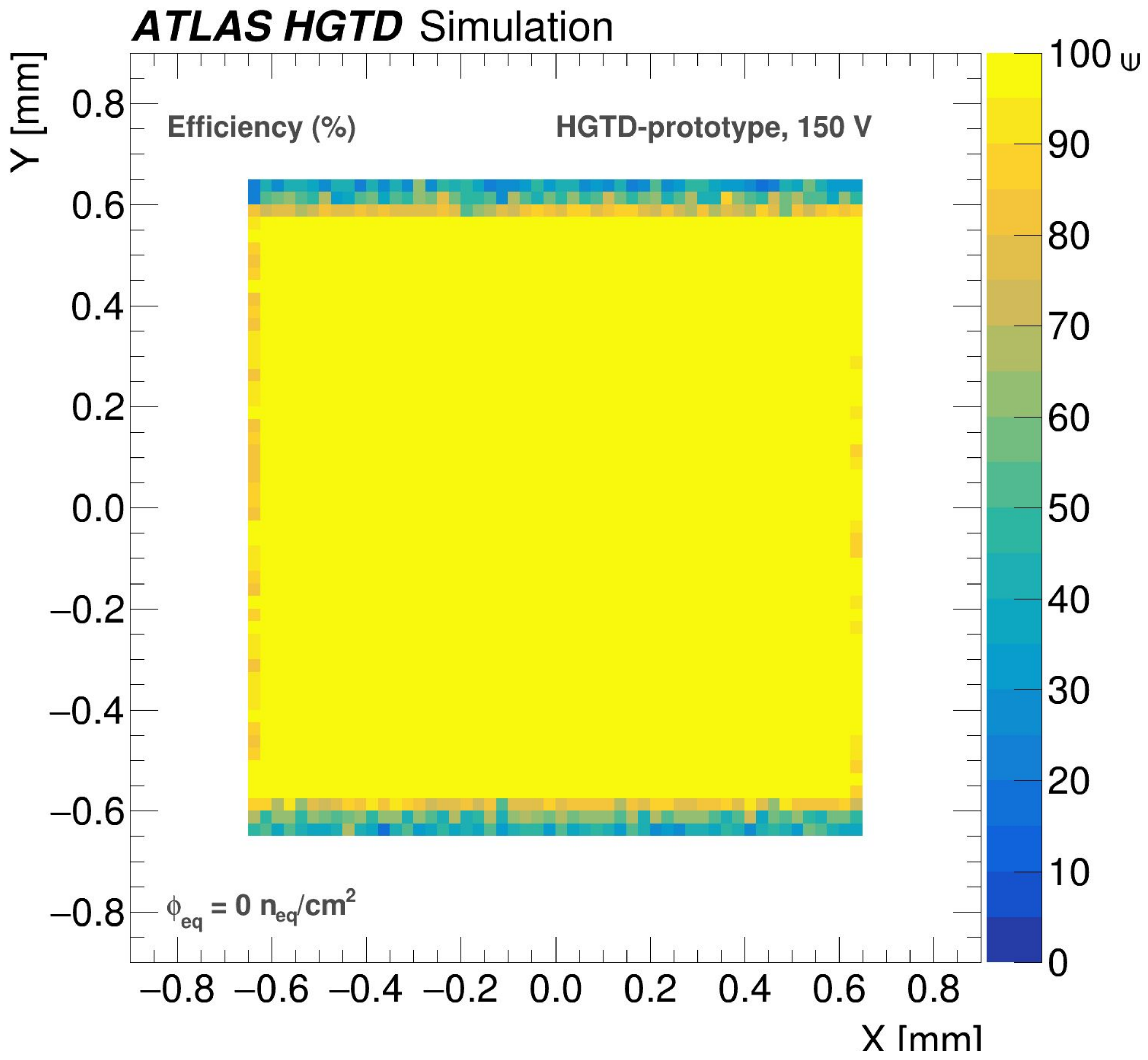
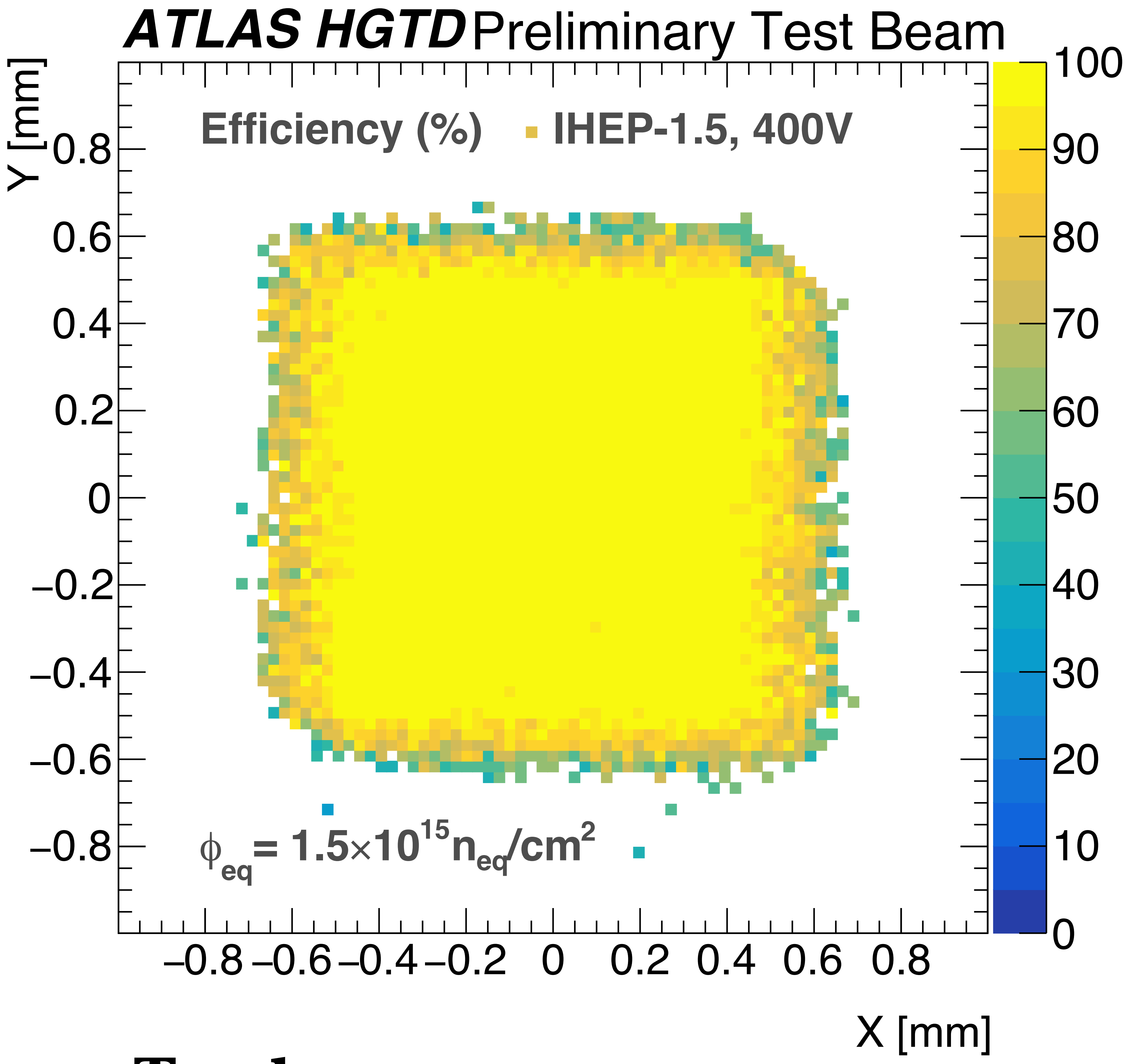
Simulation in Allpix^2: goals

- Simulated data passed through **Corryvreckan for tracking**, and sensor simulated with telescope to obtain **efficiency maps**

- Goal is being able to **reproduce test beam data** (comparing low level information like collected charge and extrapolating on high level observables like efficiency and time resolution)



Simulation



Test beam

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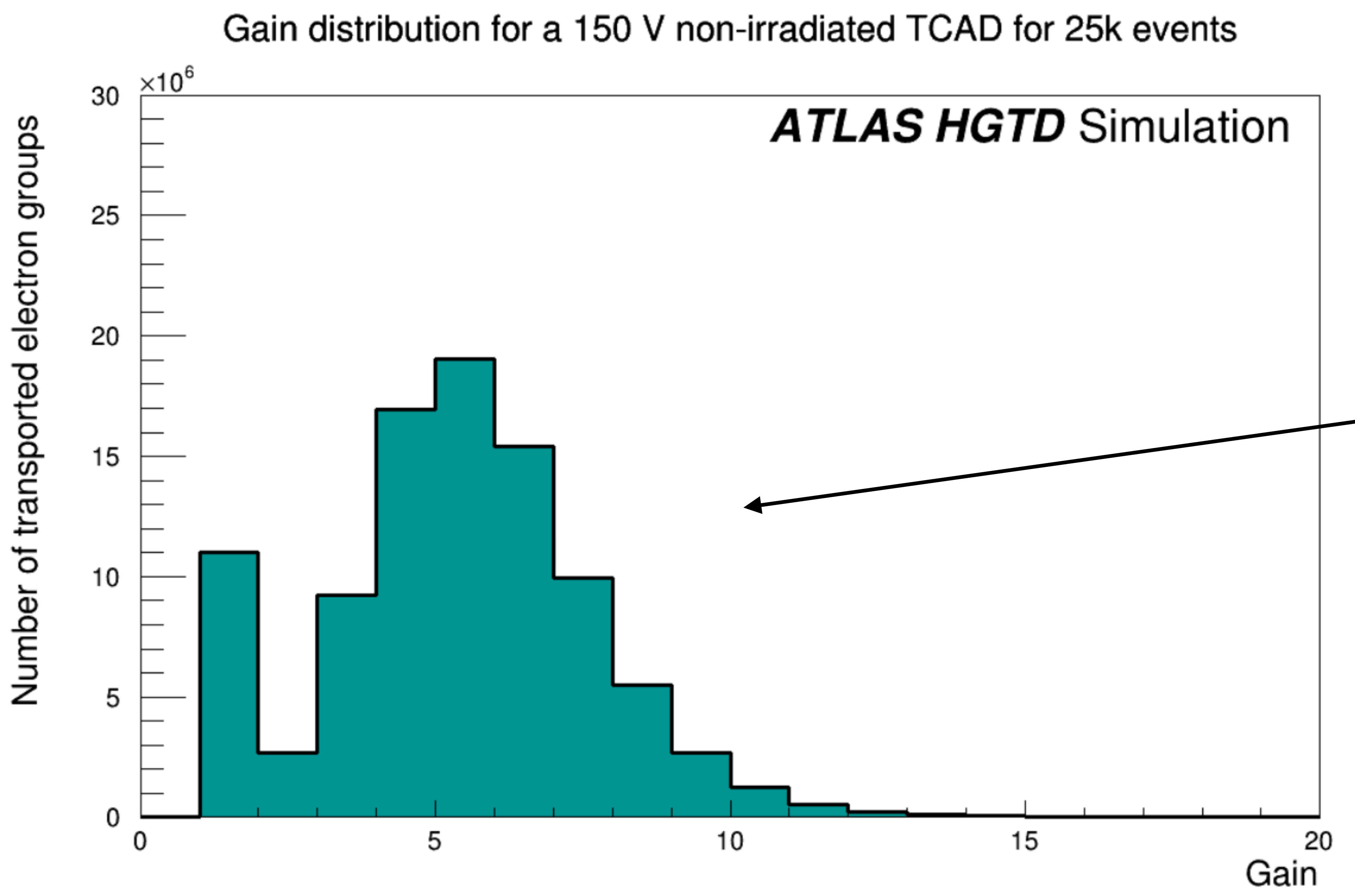
Data comparison

- Sources of difference between data and simulation :
  - **Gain simulation**: gain models not very flexible (plus our input electric fields are limited and not perfectly matching tested sensors) → gain can be quite different with consequences on all simulated quantities (time resolution, efficiency etc etc)
  - **Electronics**: we don't have the electronic response of the ASIC (for now): just implemented matching the average pulse shape → this data-driven approach probably also not very flexible



Example from our experience:

- **Gain underestimated** (5-6 instead of 10-20 expected) **with Okuto or Massey models**
- Had to compensate with ad-hoc correction factor → bad approx in the edges of the sensor
- **Next part of the talk on gain models!**

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Gain simulation

Gain simulation models

- **Impact ionisation models are empirical parameterisations** of the expected gain as function of the **electric field** strength E in the sensor and the **temperature** T

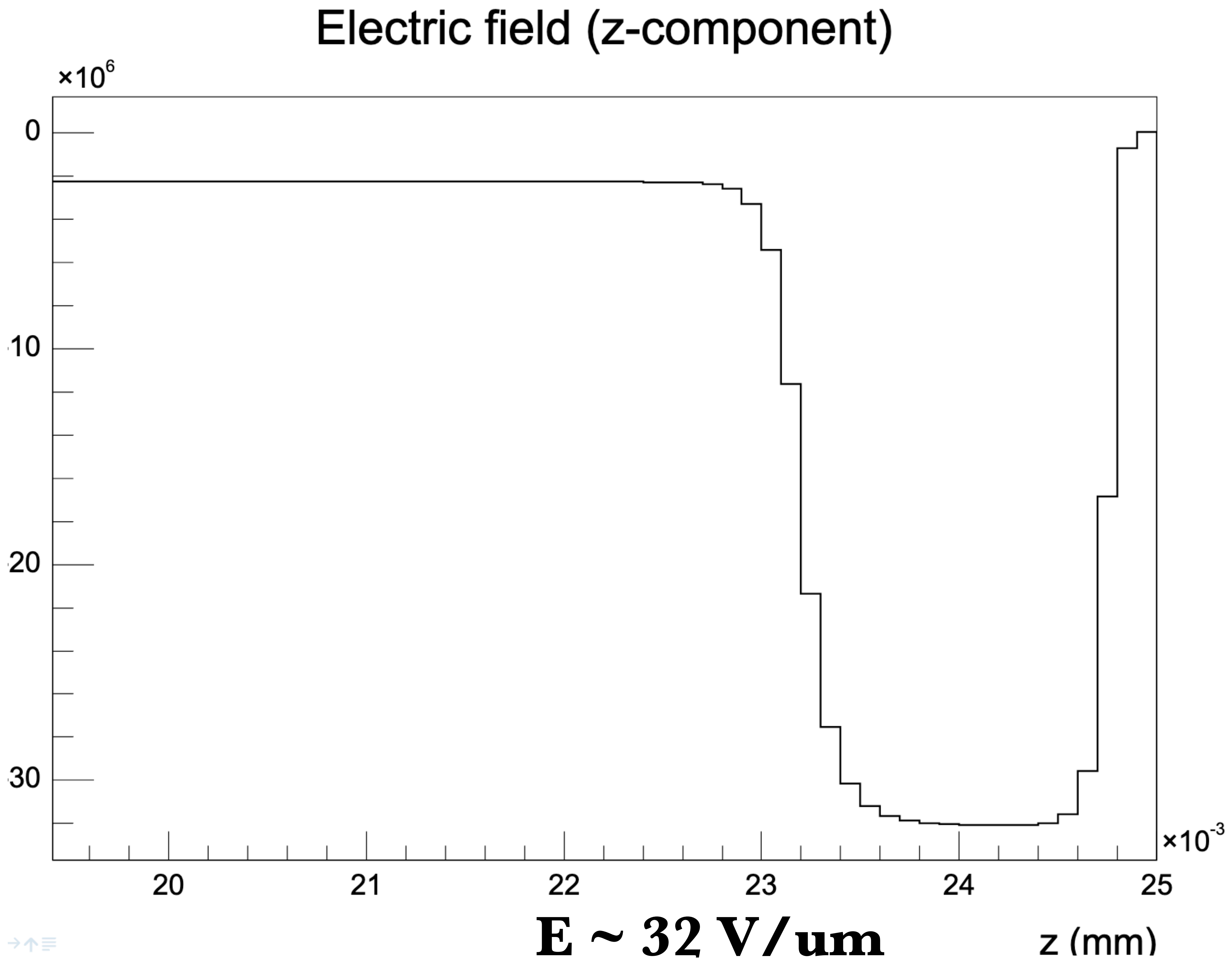
- In general the gain g after a given step in the simulation is expressed as:

$$g = e^{\alpha_{n,p}(E,T)l}; E > E_{thr}$$

where l is the step length of the simulation and $\alpha_{n,p}$ **is the impact ionisation coefficient** (model dependent) for electrons or holes

- In Allpix the probability to create a number of charges n per step is implemented drawing a random number u from a uniform distribution as: $n = \dfrac{\ln(u)}{\ln(1-1/g)}$

- **Step size** in the propagation **has to be sufficiently small** to sample the gain layer (1 um)



E ~ 32 V/um

Gain comparison

Models have different dependence on E and T, either through parameterisation formula or through different values of the parameters (A, B found fitting data):

- **Okuto-Crowell**:

  $\alpha(E,T) = A(T)Ee^{-\left(\frac{B(T)}{E}\right)^2};\ A(T), B(T)$ linear in T

- **Massey**:

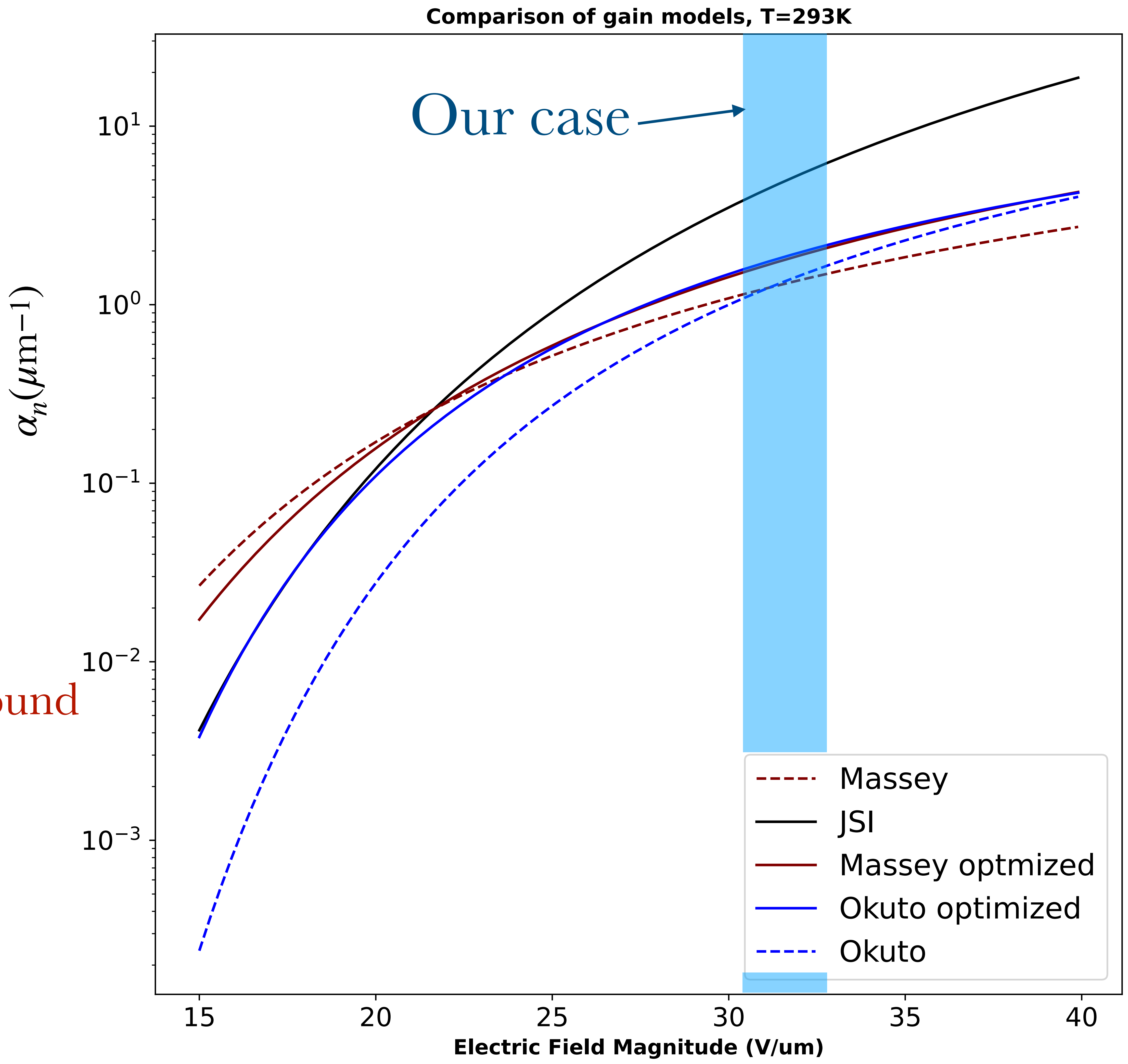
  $\alpha(E,T) = Ae^{\frac{-B(T)}{E}};\ B(T)$ linear in T

- **JSI model** (Howard et al, JINST 17 P10036) :

  $\alpha(E,T) = A(T)e^{\frac{-B(T)}{E}};\ A(T), B(T)$ linear in T

- **Optimised models** (RD50**,** E. Currás Rivera, M. Moll,10.1109/TED.2023.3267058): model parameters updated on LGADs

Parameters found on LGADs

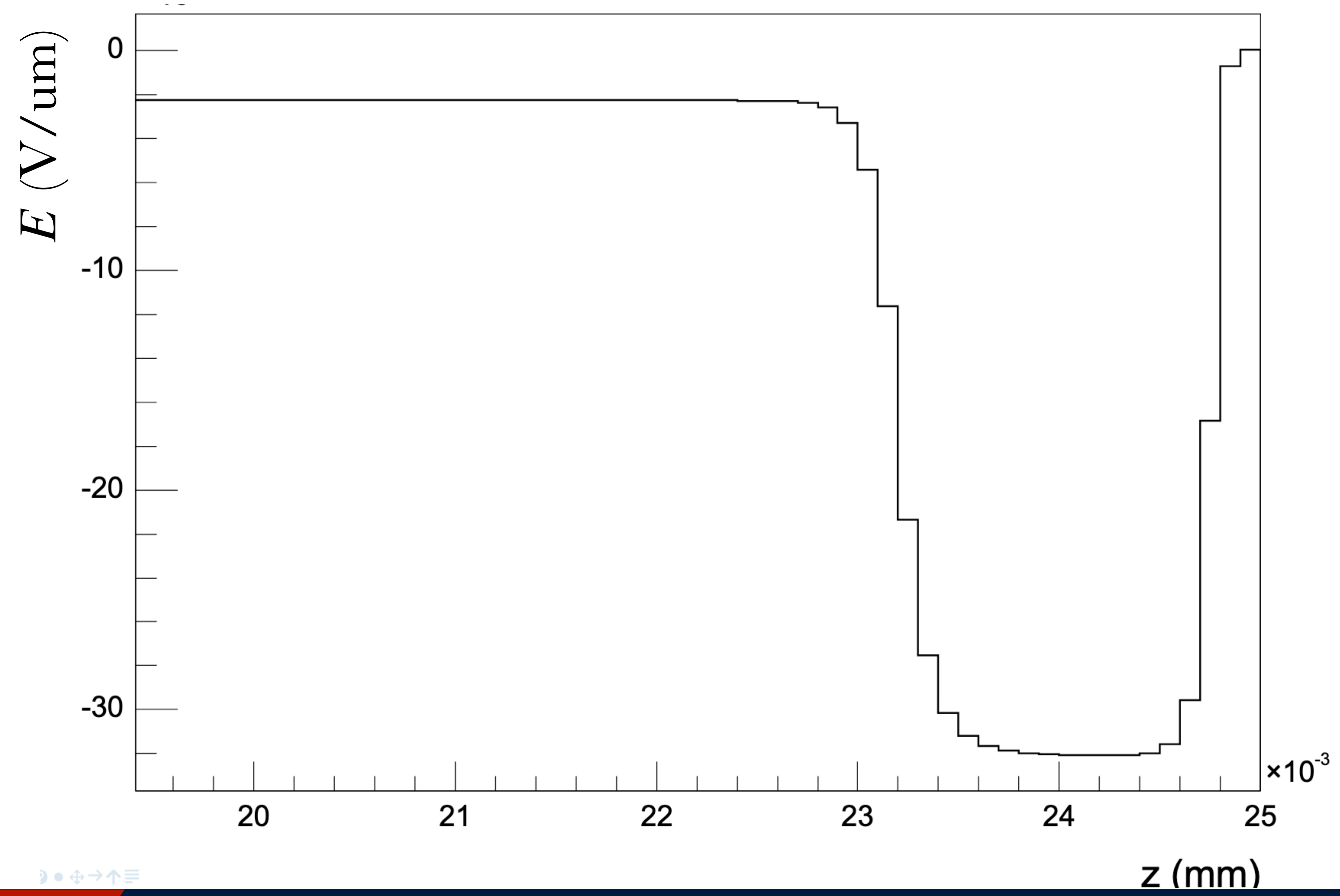


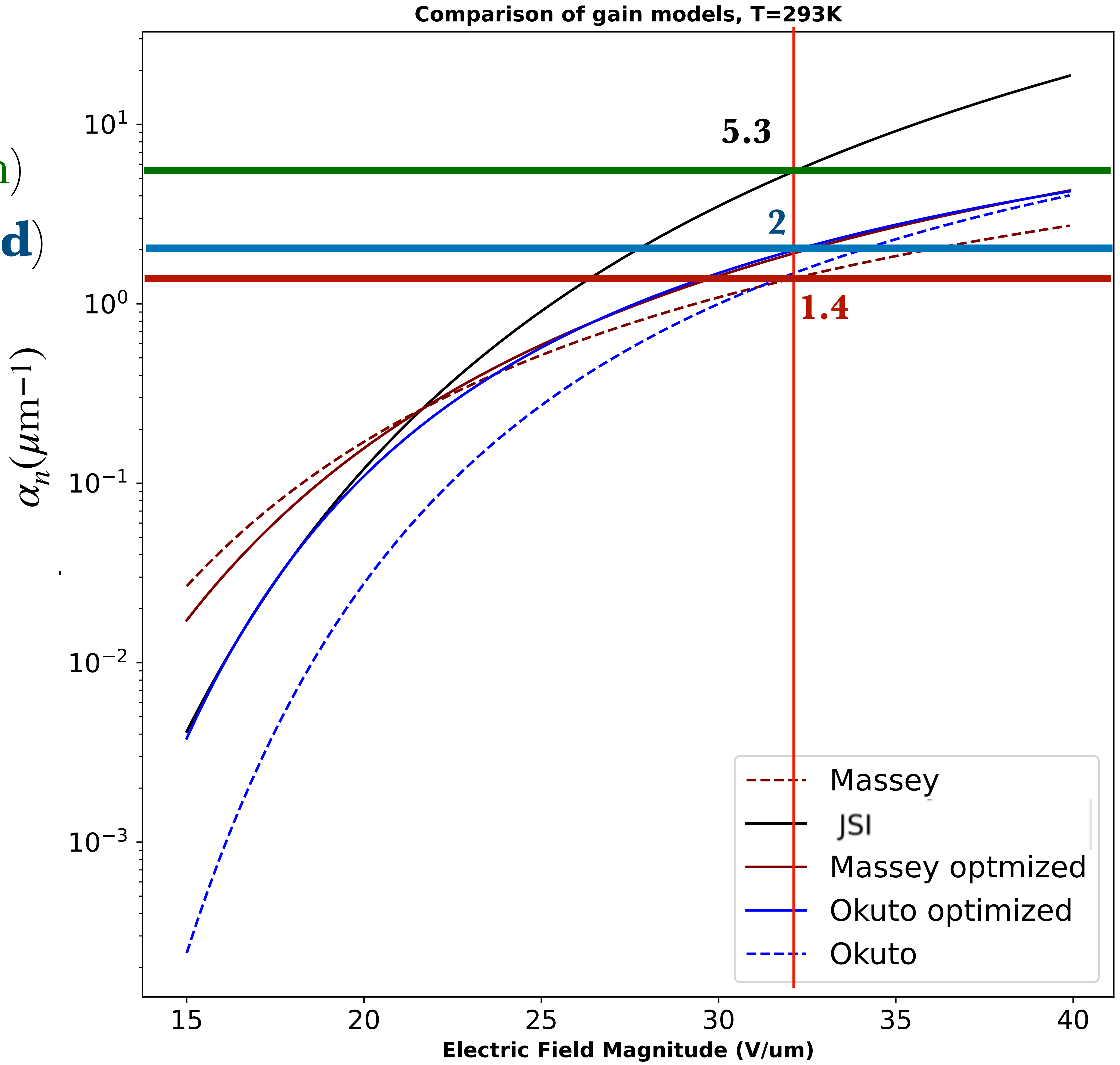
Some calculations

Same (simplified) calculations to understand the difference between these models in our case:

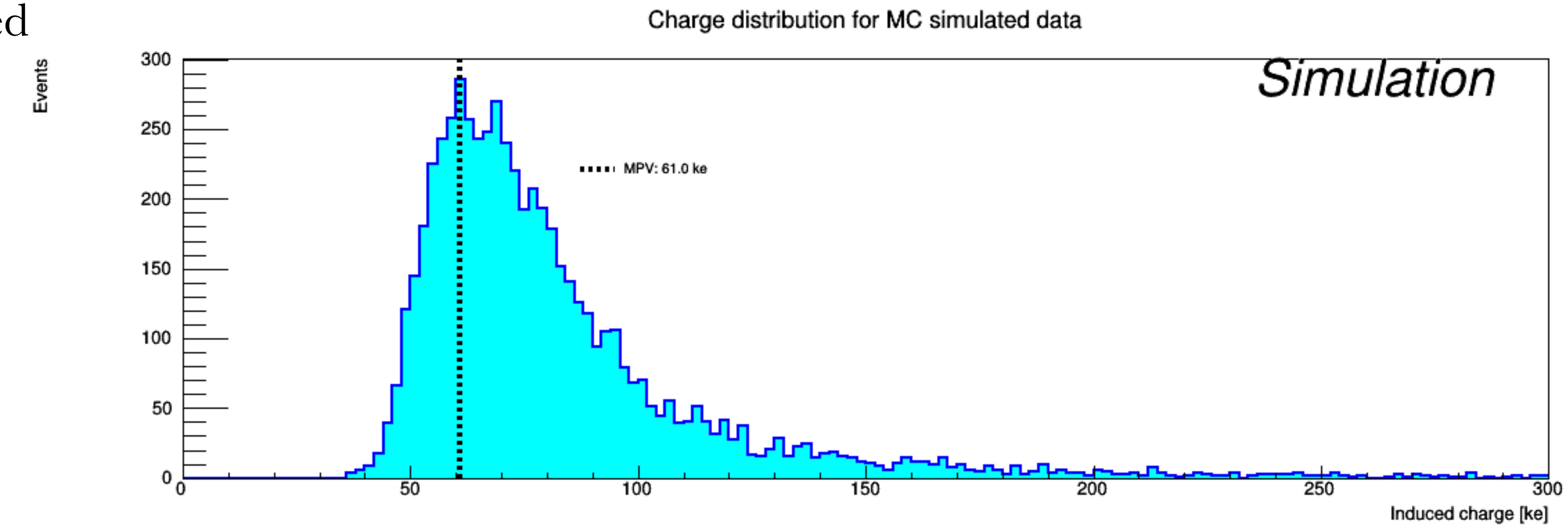
$$g = e^{\alpha(E,T)l}$$

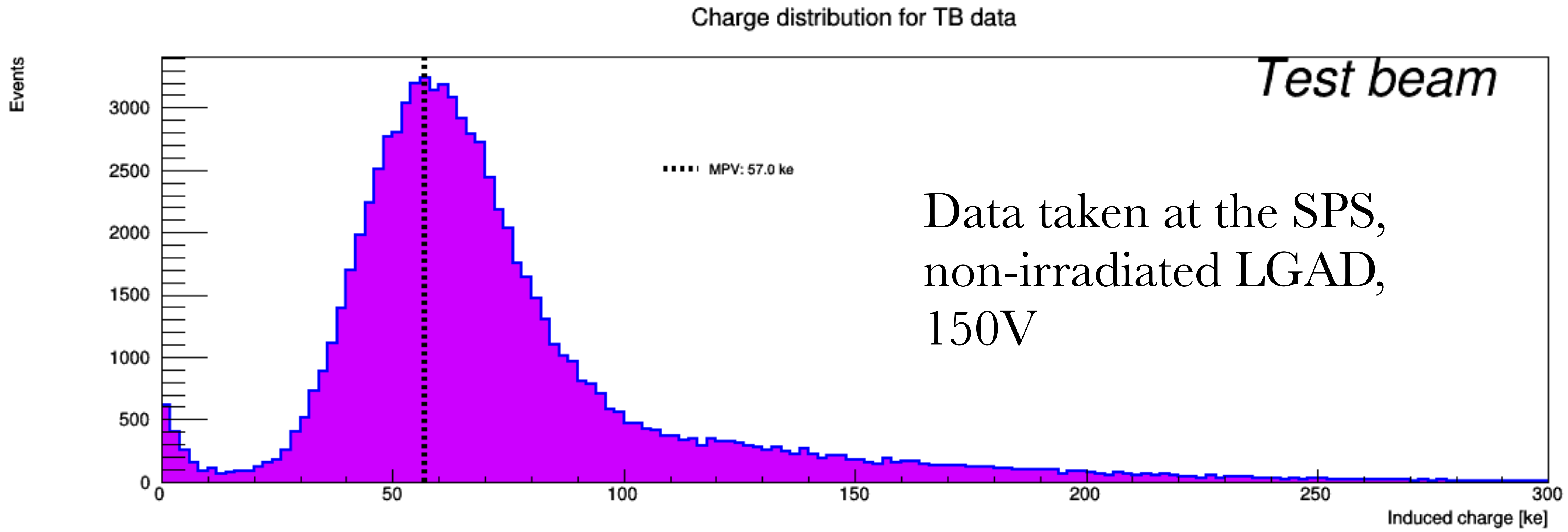
- Choosing $l = 0.1$ um as a step, 10-12 steps in the gain layer with E=32 V/um
- Coefficients α at 32 V/um:
  - JSI model $\alpha = 5.3\ um^{-1}$ $\rightarrow e^{0.1*5.3}$ ^10 ~ 200 (too high)
  - **Okuto optimised**: $\alpha = 2\ um^{-1}$ $\rightarrow e^{0.1*2}$ ^10 ~ 10 (**expected**)
  - Okuto: $\alpha = 1.4\ um^{-1}$ $\rightarrow e^{0.1*1.4}$ ^10 ~ 5 (too low)

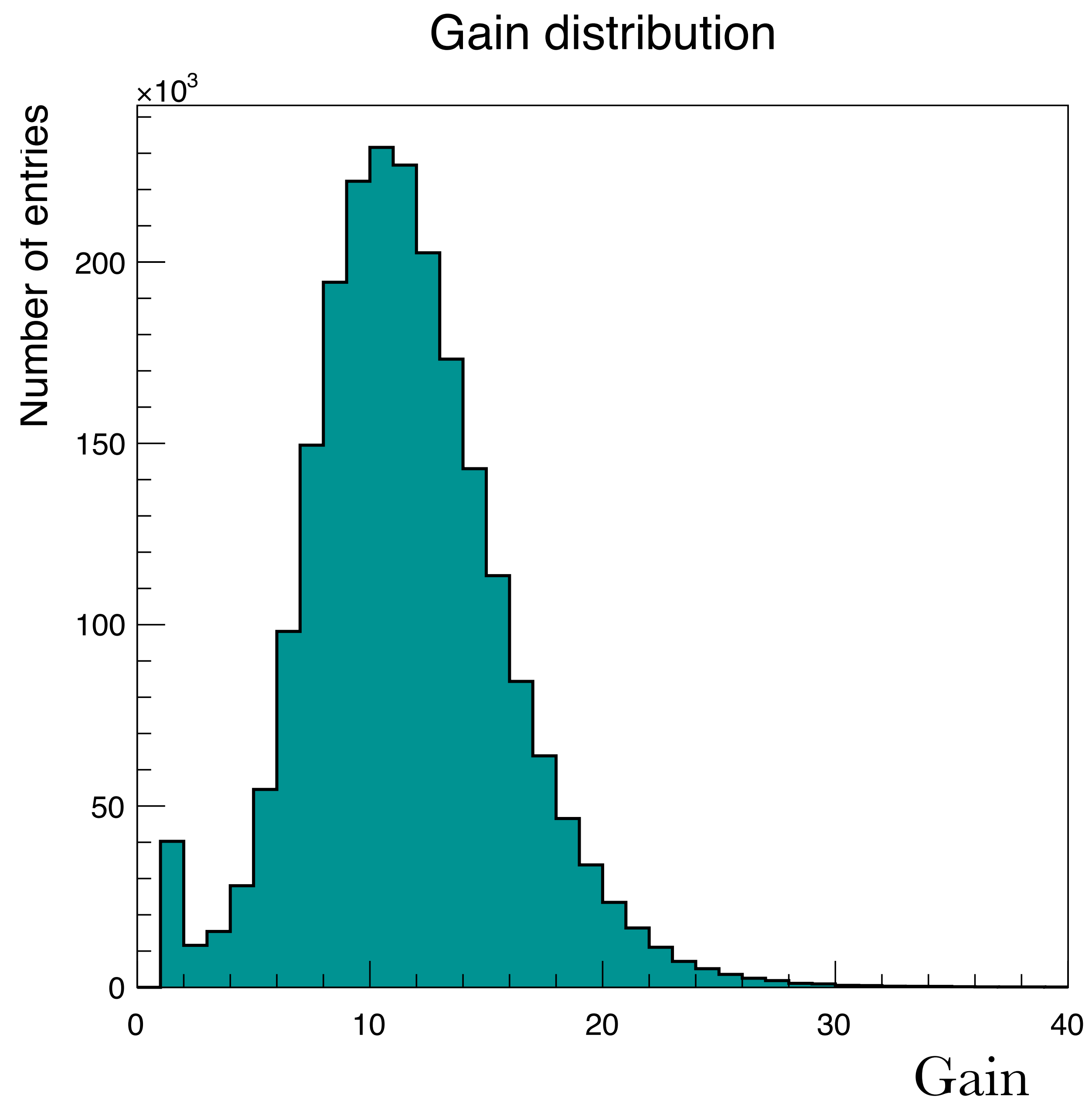




- Okuto optimised model chosen for our case, gain looks as expected:
  - **Collected charge distribution between TB and simulation:** MPV different by less than 5%, compared to a factor two with other models
  - Residual differences might be explained by differences between the electric field of the TCAD and the sensor under test



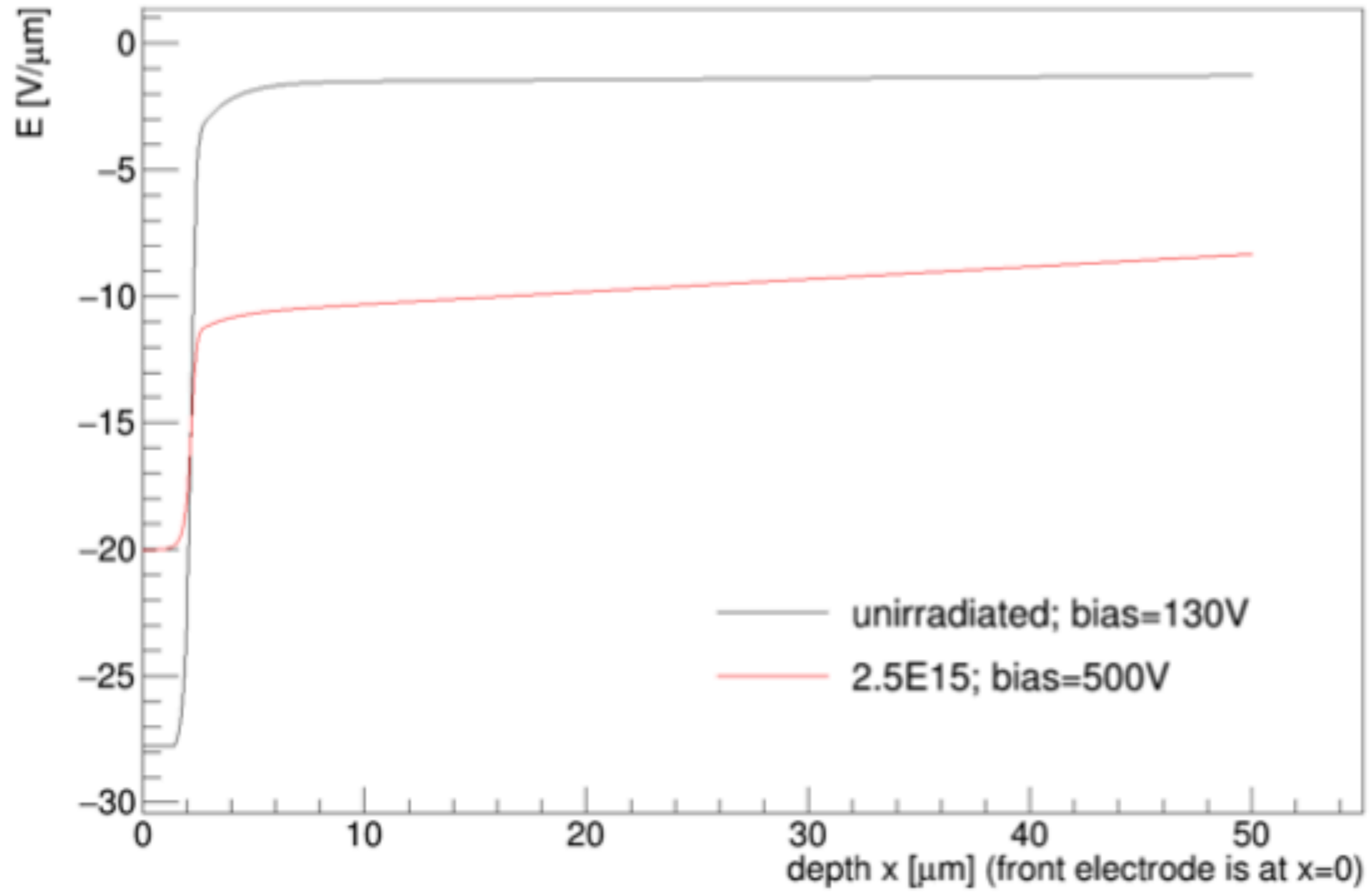




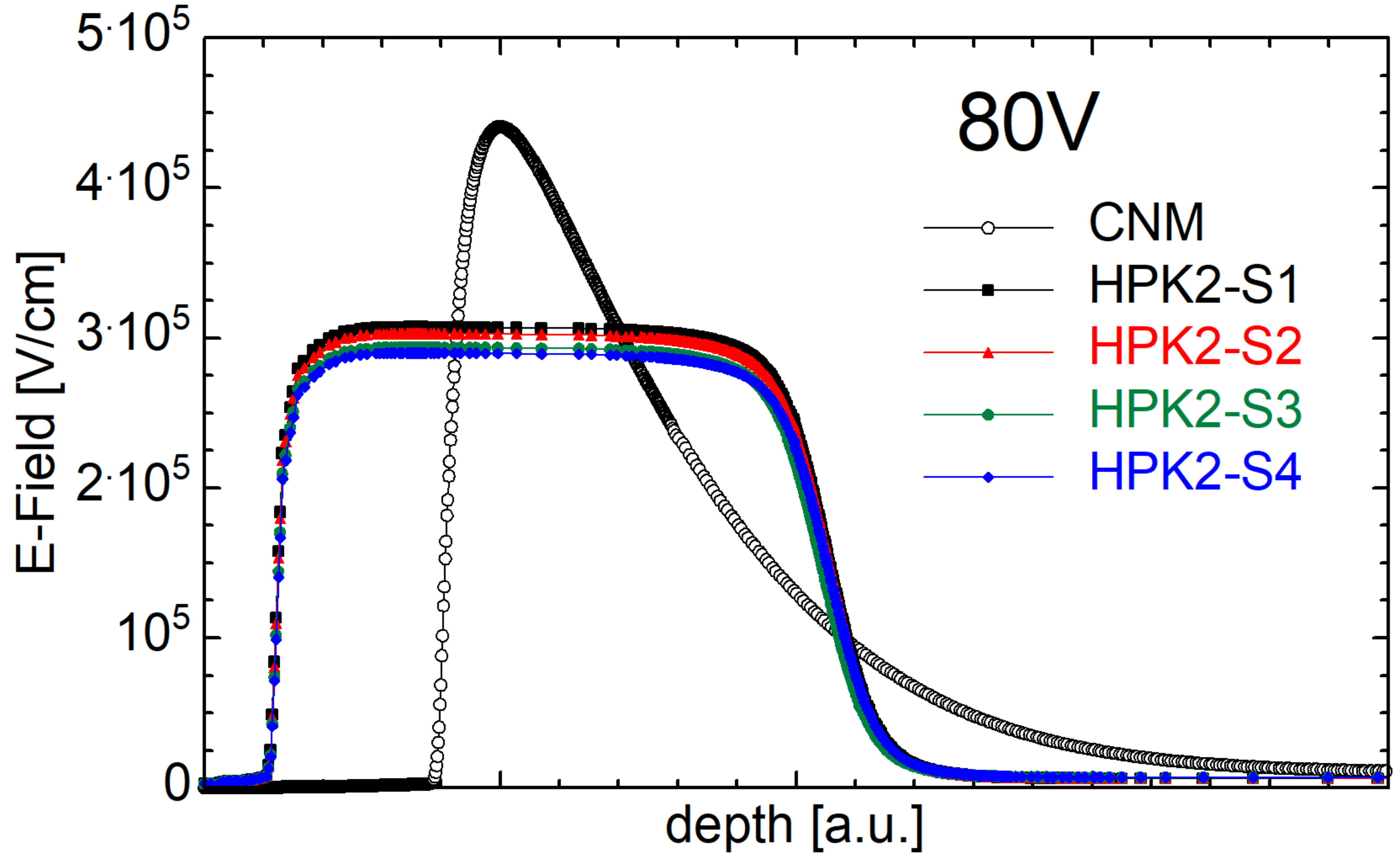
- JSI vs RD50 optimised models as a case study:
  - **Both** sets of parameters have been **found on LGADs** (differently than original Massey/Okuto-Crowell papers)
  - JSI electric field in the GL around 27 V/um
  - RD50 electric field in the GL higher, and around our TCAD values
  - **Two models are quite different** for E> 20V/um

- Small differences between the simulated electric field and the sensor under test can result in very different gain due to the exponential formula

- More complex effects like charge screening might affect the gain in the simulation



Howard et al, JINST 17 P10036



E. Currás Rivera, M. Moll,10.1109/TED.2023.3267058

Conclusions and next steps

Conclusions:

- **Models are not very flexible**: they reproduce well the data used for fit performed to obtain their parameters, but fail to be extended to a general case
- Limited availability of TCAD inputs vs tested sensors increases difficulty of precise benchmarks with data
- Effect of radiation is not included in the models

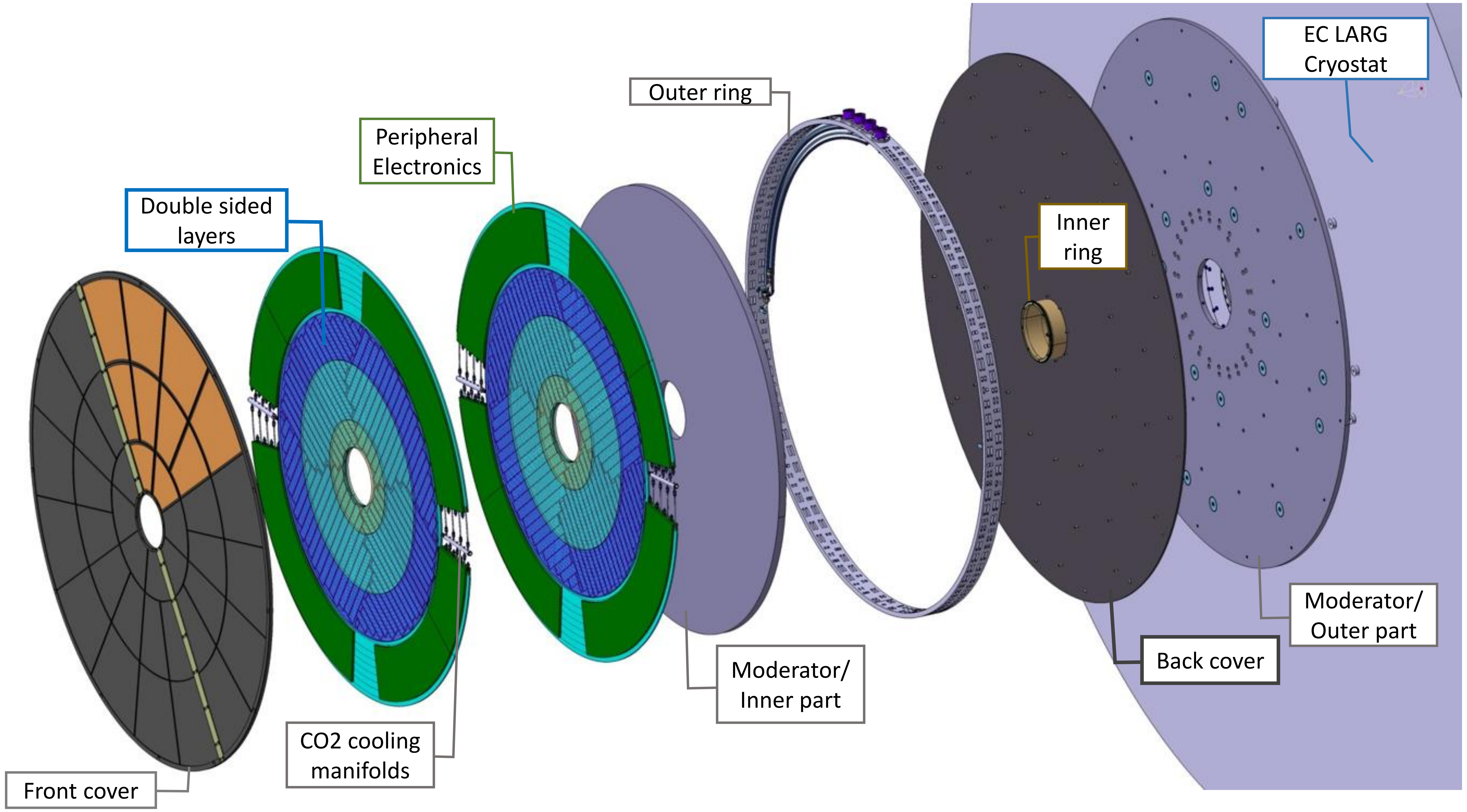
Next steps in our studies:

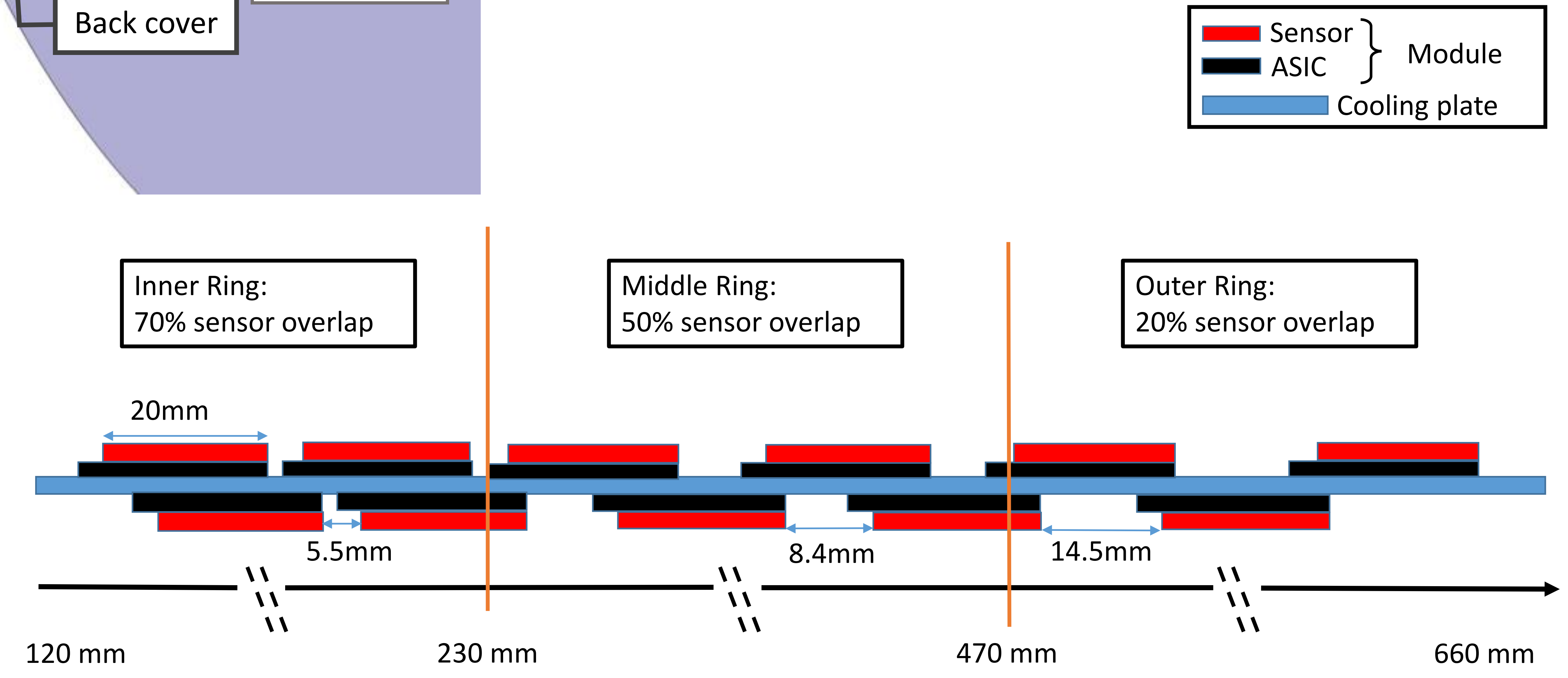
- Time performance studies and benchmark with data
- Working towards understanding the **gain simulation for irradiated sensors**

Thank you!

Back-up

HGTD geometry





Optimised model from RD50

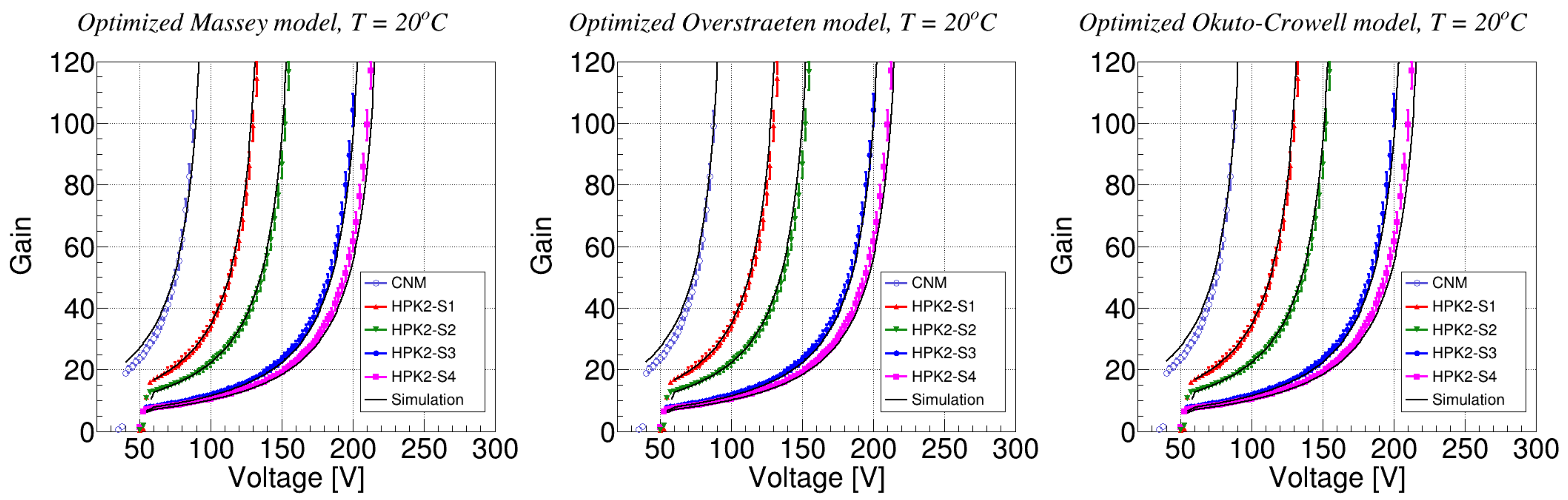
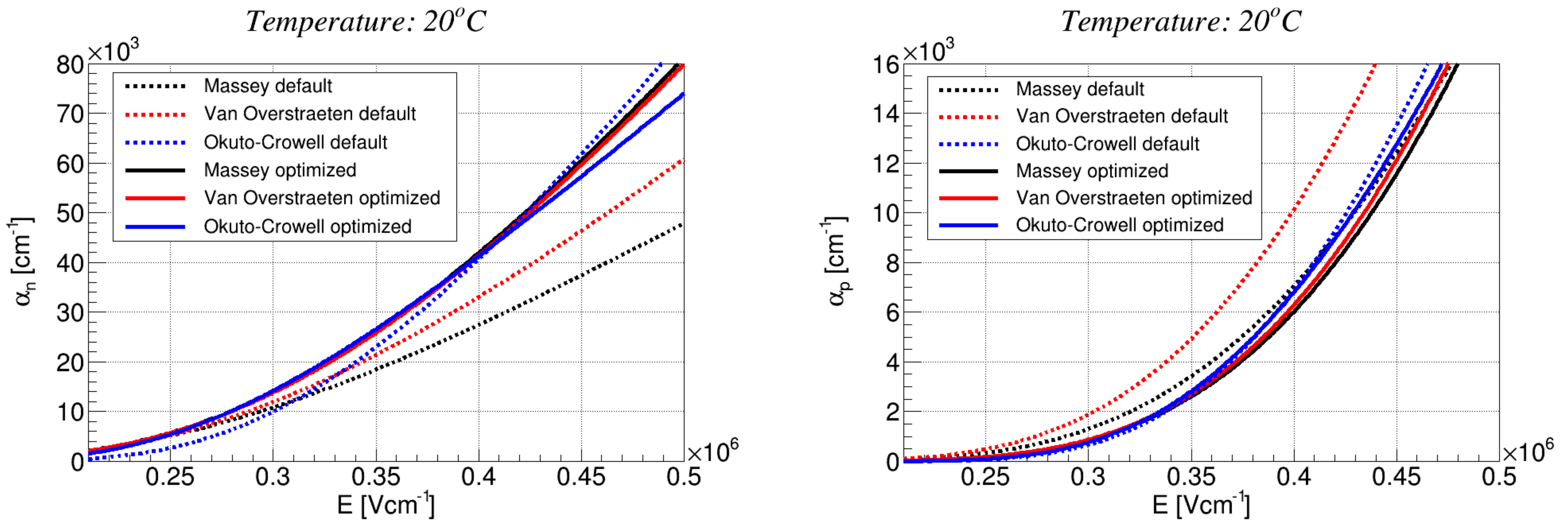


Figure 10: Agreement between the measured and simulated gain, at $20\,^oC$, after the optimization of the parameters for the three models indicated in the figure titles.



E. Currás Rivera, M. Moll,10.1109/TED.2023.3267058

Optimised model from RD50

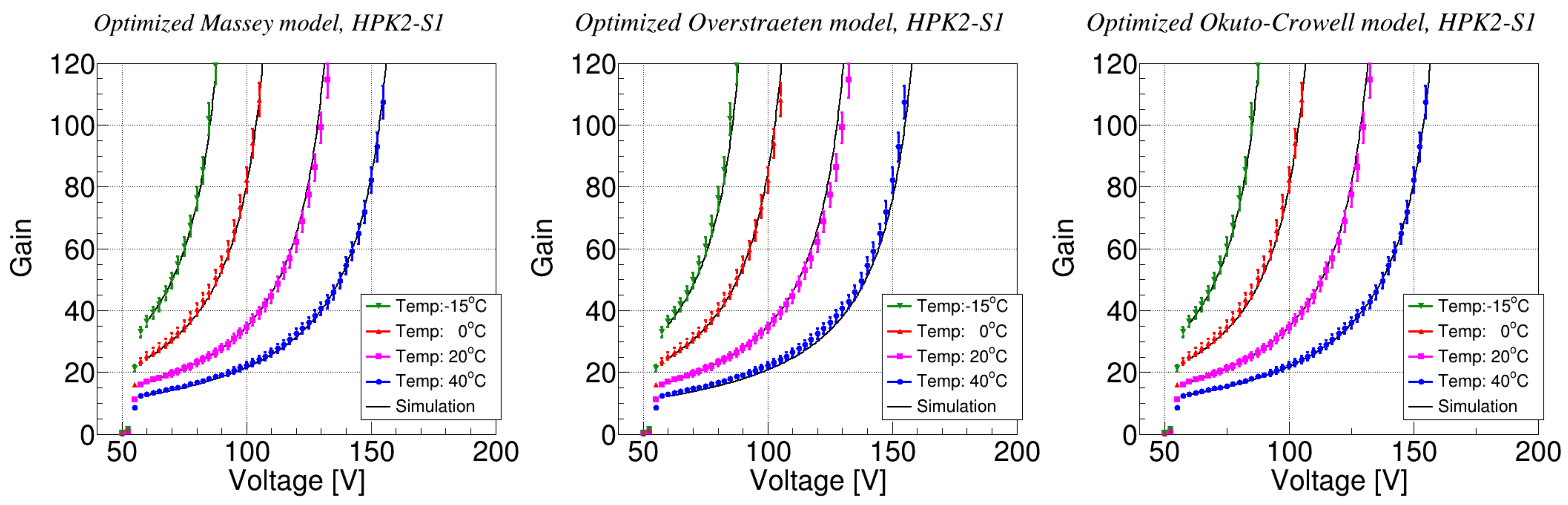
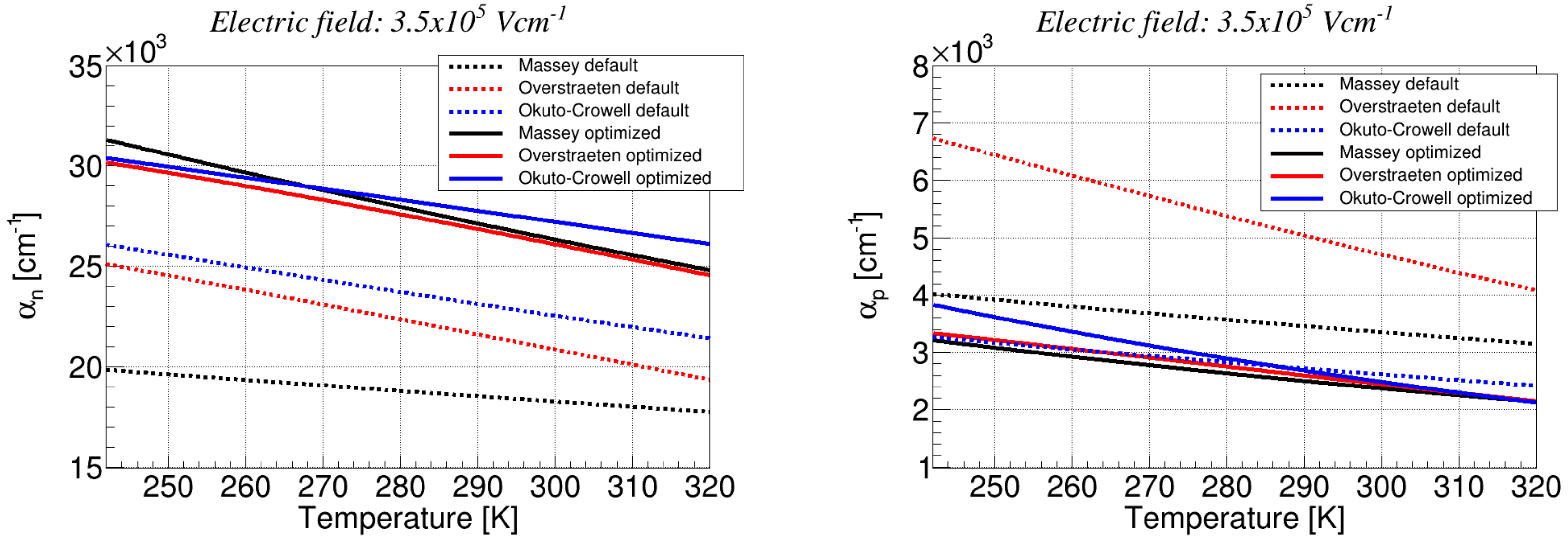


Figure 12: Measured and simulated gain of the HPK2-S1 LGAD at different temperatures, after the optimization of the parameters for the three models indicated in the titles of the three plots.



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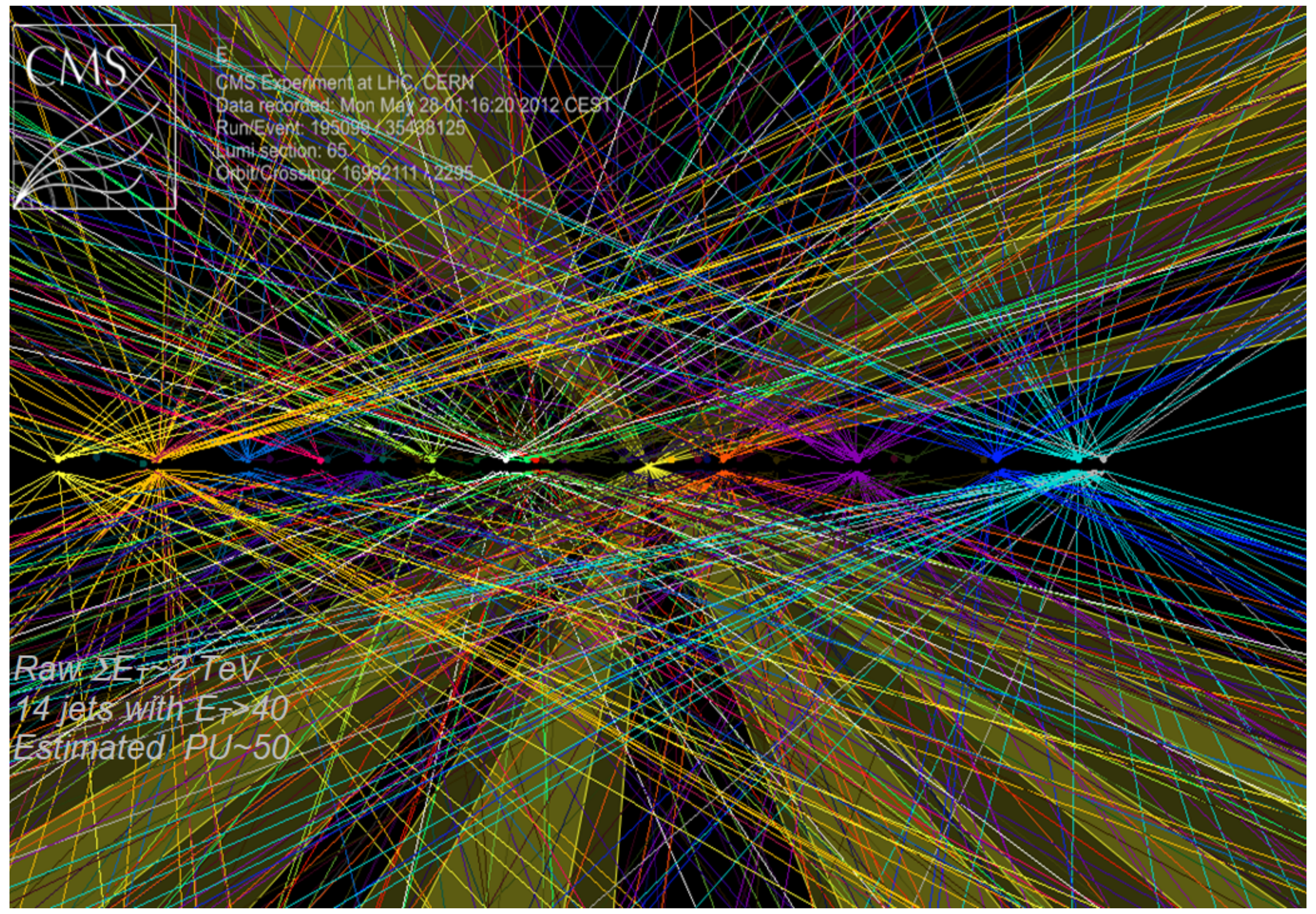
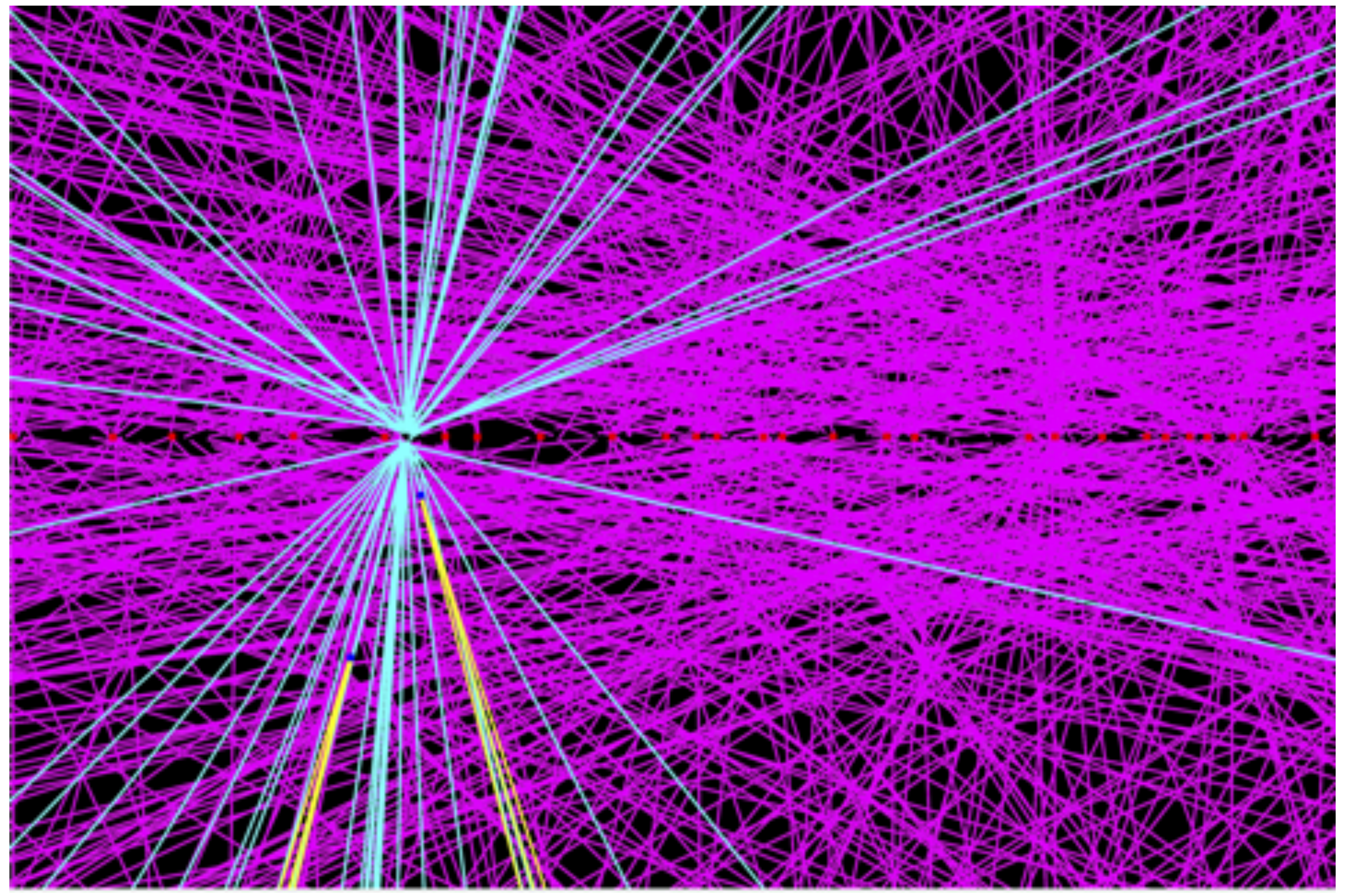
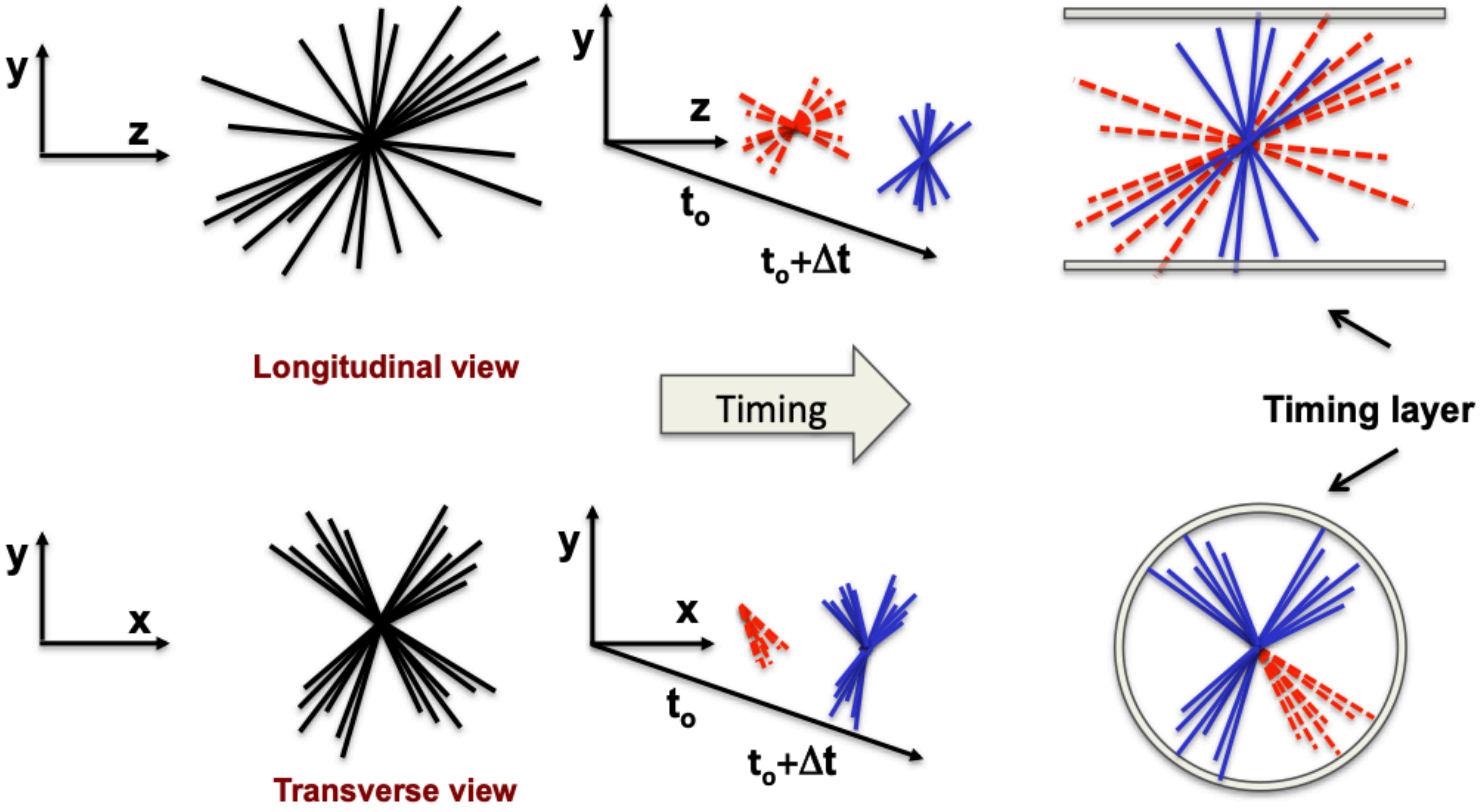
4D tracking



Mu = 50



Mu = 200



From: LGAD and 3D as Timing Detectors