Model of ELectron Output Non-linearity (MELON)

Experimental spot shapes

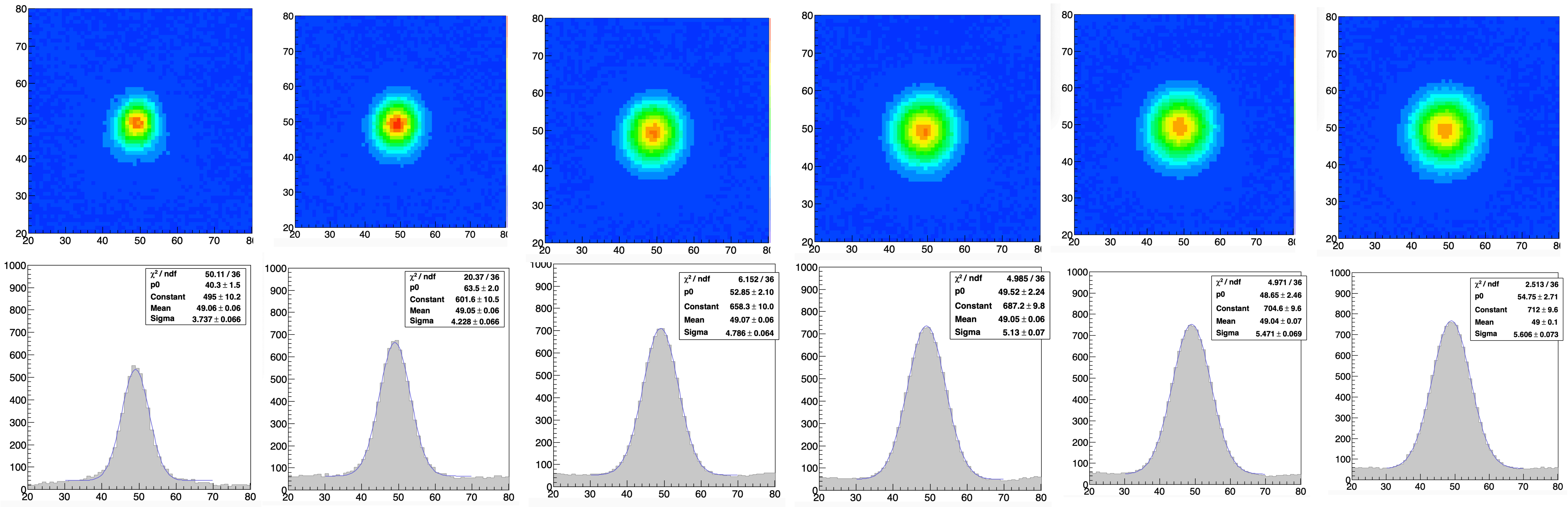
The interactions of ^{55}**Fe 6 keV** photons in the gas of an optical-readout TPC produces on the camera, **roundish spots**

In an **ideal** detector, the **light** in the spots (proportional to the released energy) is **expected to be constant**;

Since the **area of the spots** is expected to **increase** with the **distance** because of the primary electron **diffusion**, the **brightness** of the **central core** of the spots should **decrease** with the distance

Average spot shapes

Average light profile



6 cm **11 cm** **16 cm** **21 cm** **26 cm** **31 cm**

increasing distance from the GEM →

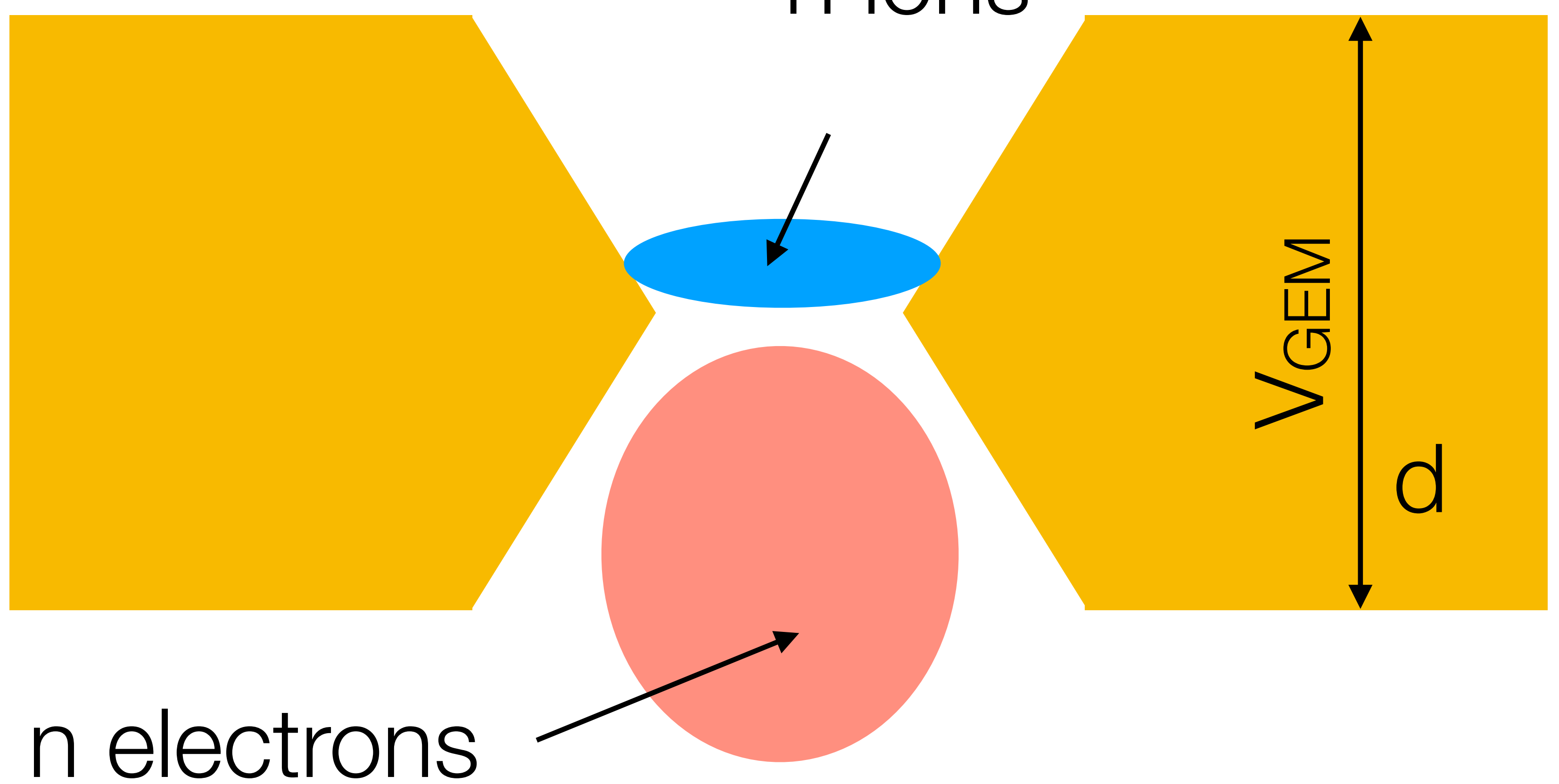
Experimental data shows a different behaviour: the **spots become larger** with a **brighter central** part as long as interaction happens **further from the GEM**

Davide Pinci - INFN Roma, Italy

A simple model

Let's suppose that during the development of the **avalanche** within the GEM channels a **significant amount of electrons** are produced.

The **positive ions** slowly migrate toward the lower potential plane of the GEM, partially **shielding the GEM electric field** itself.



If $\mathbf{E_{GEM} = V_{GEM}/d}$ is the nominal electric field in the channel, we can suppose that after the production of n electron-ion pairs, the effective field becomes

$$E = E_{\mathrm{GEM}}(1 - \beta n)$$ where β is a screen scale factor

This effect **increases for large number** n_{in} **of primaries** entering the channel

Therefore, a **longer drift path** can **mitigate** this effect by **spreading the primaries** on a larger number of channels, then resulting in a **larger** effective **gain**

A simple model

In the usual **Townsend equation**

$$\frac{dn}{ds} = \alpha n$$

We can express the **dependency of** α on the electric field at the first order $\alpha = \tilde{\alpha} \cdot (E - E_{min})$

Where E_{min} is the **minimum electric field** to trigger the **avalanche**;

The **Townsend** equation becomes

$$\frac{dn}{ds} = \tilde{\alpha} \cdot (E_{\mathrm{GEM}}(1 - \beta n) - E_{min})\, n$$

By **integrating it across the single channel**, one obtains

$$c = e^{-\tilde{\alpha} V_{min}} \quad V_{min} = E_{min}/d$$

$$\beta' = \beta \frac{V_{GEM}}{V_{GEM} - V_{min}}$$

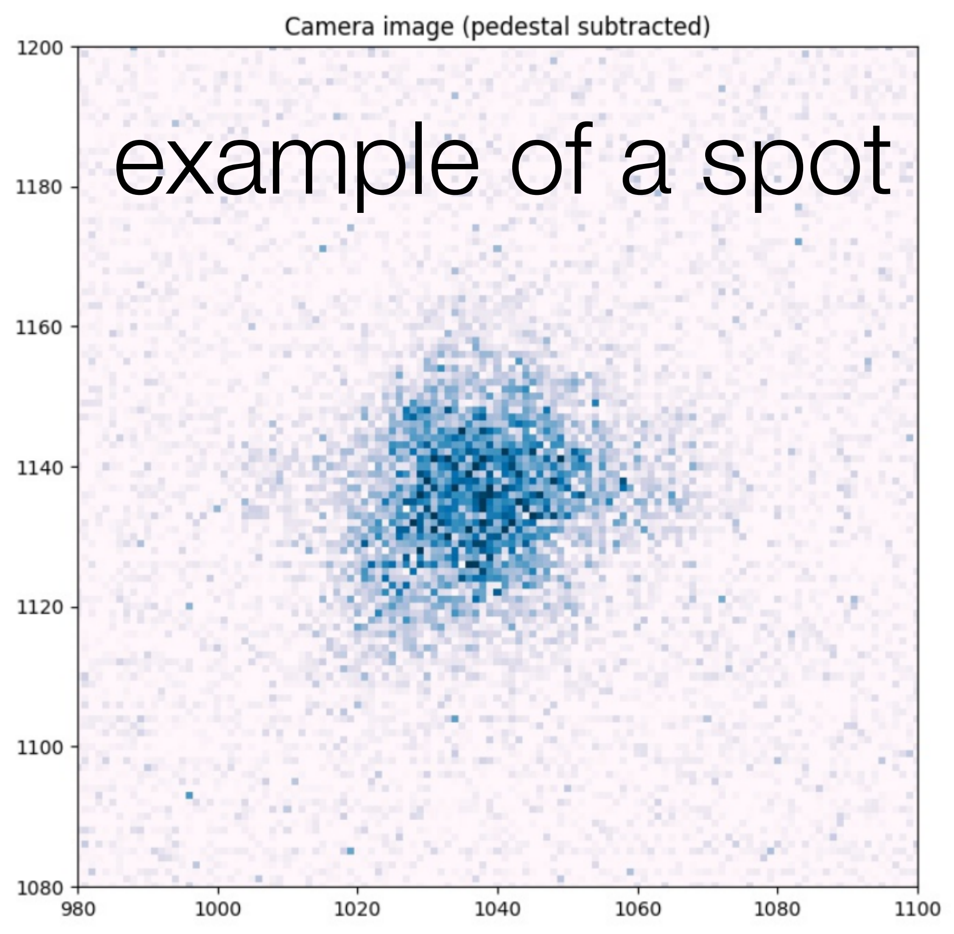
$$G = \frac{n_{out}}{n_{in}} = \frac{c\, e^{\tilde{\alpha} V_{GEM}}}{1 + \beta' n_{in}(c\, e^{\tilde{\alpha} V_{GEM}} - 1)}$$

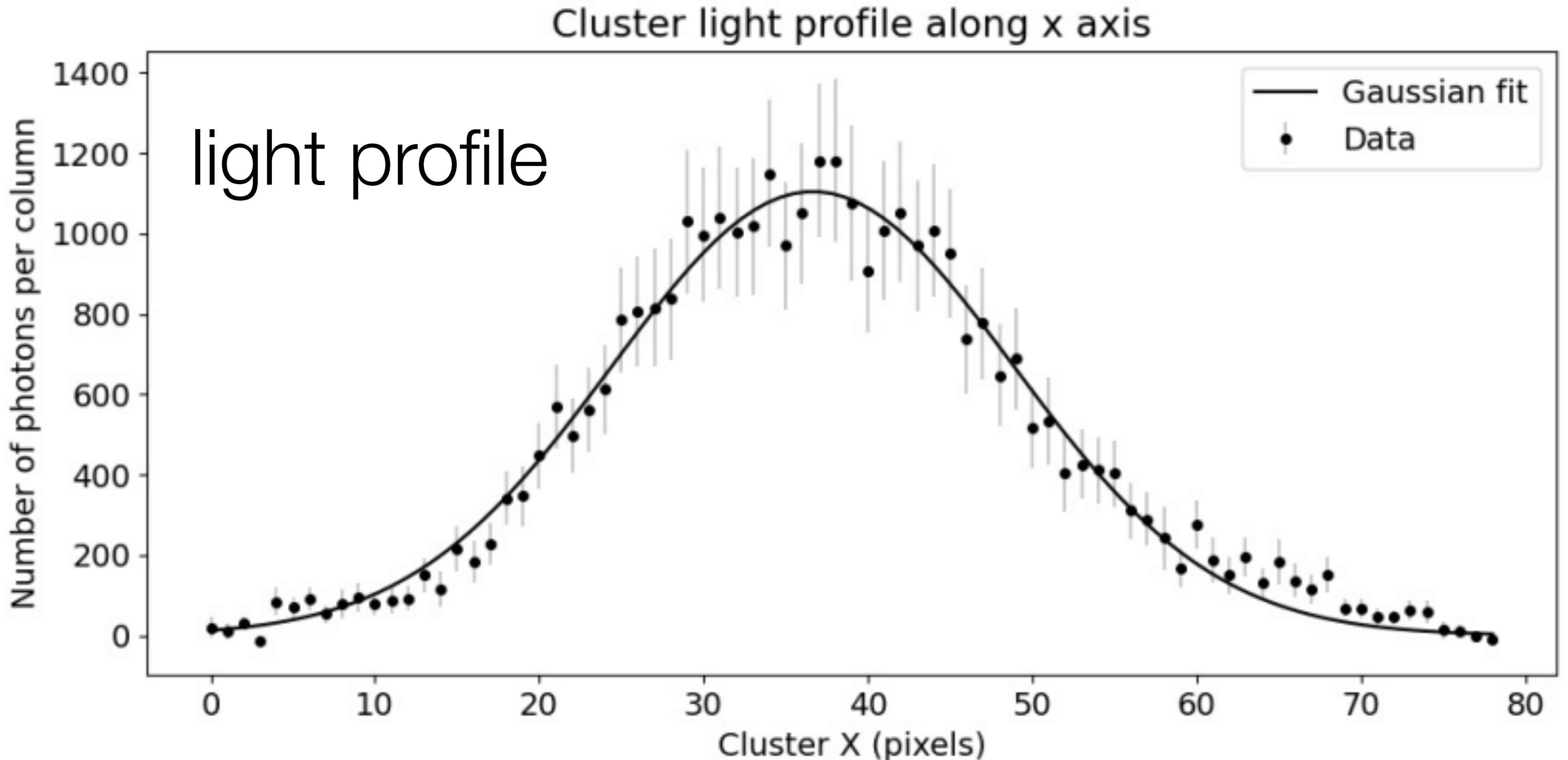
A simple model: the meaning of β

$$G = \frac{c\,e^{\tilde{\alpha}V_{GEM}}}{1 + \beta' n_{in}(c\,e^{\tilde{\alpha}V_{GEM}} - 1)}$$

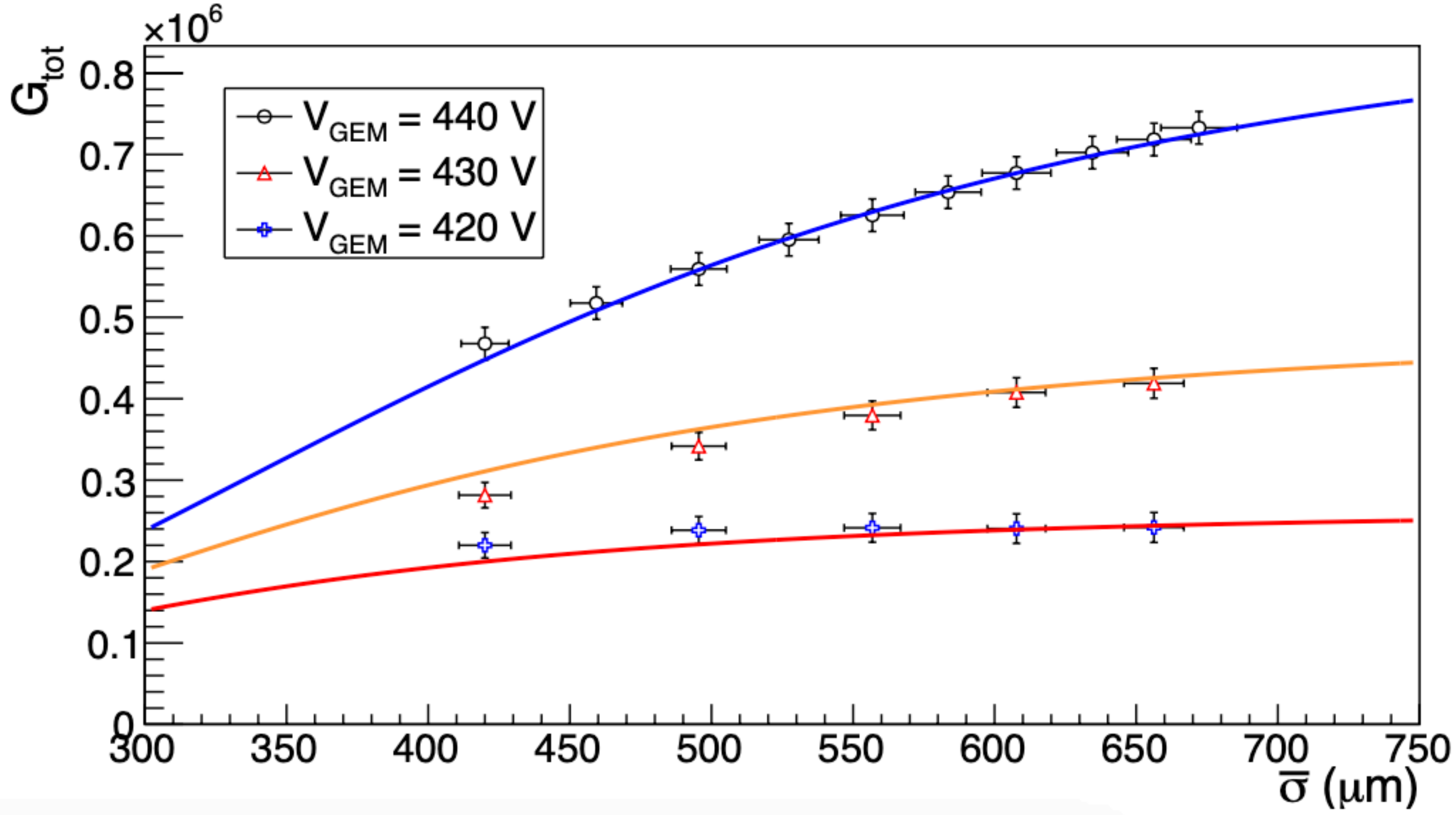
- if $\beta' n_{in} \simeq 0 \rightarrow$ **negligible** screen effect $G = \tilde{G} = c\,e^{\tilde{\alpha}V_{GEM}}$ (typical exponential behaviour);
- if $\beta' n_{in} \simeq 1 \rightarrow$ **total** screen effect $G = 1$ (no gain at all);

- once the values of β, c **and** $\tilde{\alpha}$ are **fitted on data**, this simple modelization, allows to **simulate the avalanche process** in a GEM for **any** n_{in} (i.e. energy release and charge diffusion) value;
- To evaluate those parameters, the **above formula** was used to fit the behaviour of the gain for **three sets of experimental data** taken with all the three GEMs operating at the same voltage drops: **440V**, **430V** and **420V** as a function of the sigma of the gaussian describing the spot light profile





A simple model: an analytical fit



- The **analytical fit** is based on the simplistic assumptions of a **spherical electron cloud** with an **uniform electrons distribution**;
- It also allows to evaluate the values of the **non-saturated gains** at the different V_{GEM}

$$\tilde{G}(\mathrm{V_{GEM}} = 440\mathrm{V}) = 135 \pm 12$$
$$\tilde{G}(\mathrm{V_{GEM}} = 430\mathrm{V}) = 105 \pm 10$$
$$\tilde{G}(\mathrm{V_{GEM}} = 420\mathrm{V}) = 90 \pm 8$$

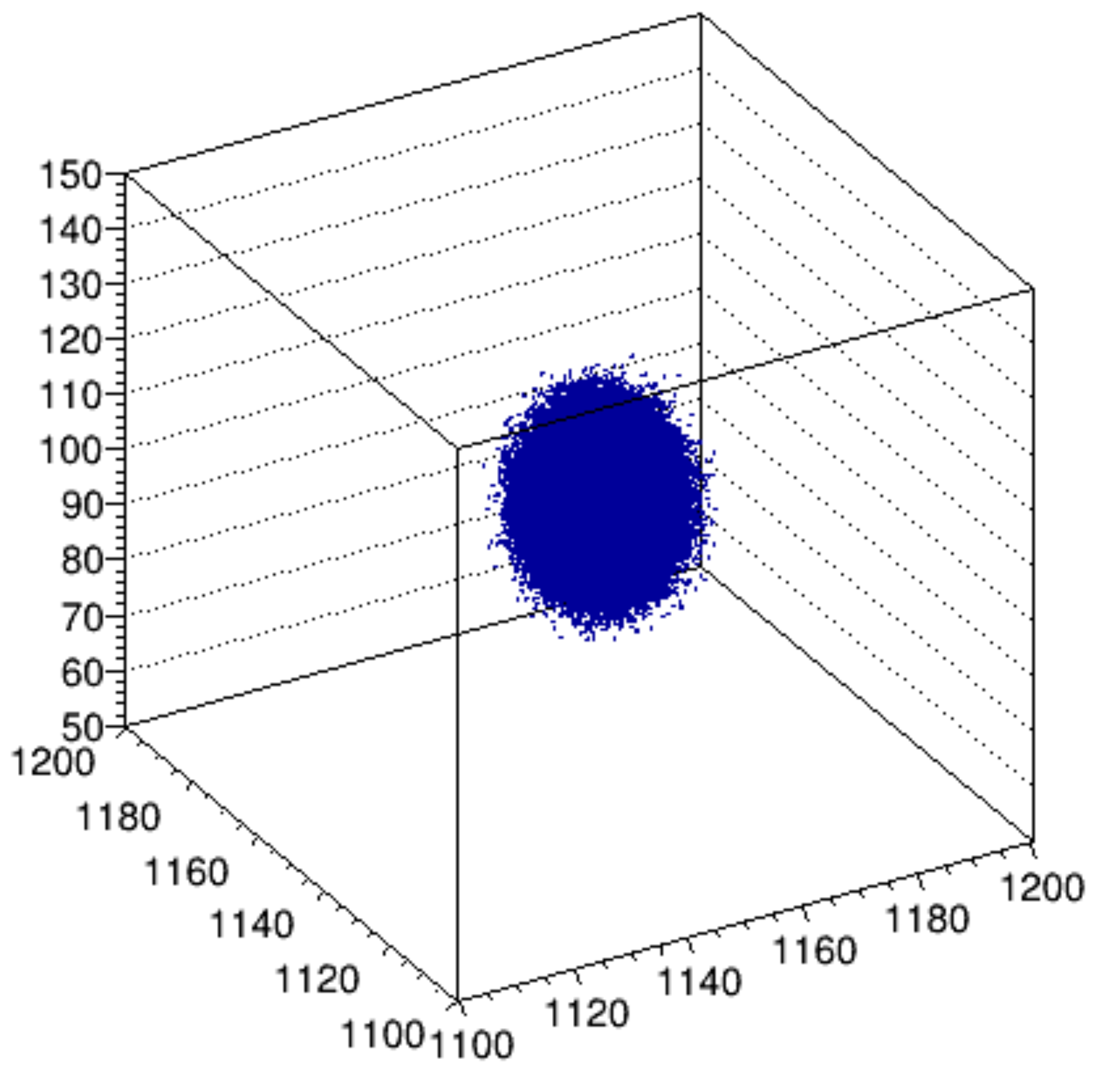
- In the **real life** this is not the case and the **charge** are distributed according to **triple gaussian distribution** because of the **longitudinal** and **transverse** diffusion (that can be different);

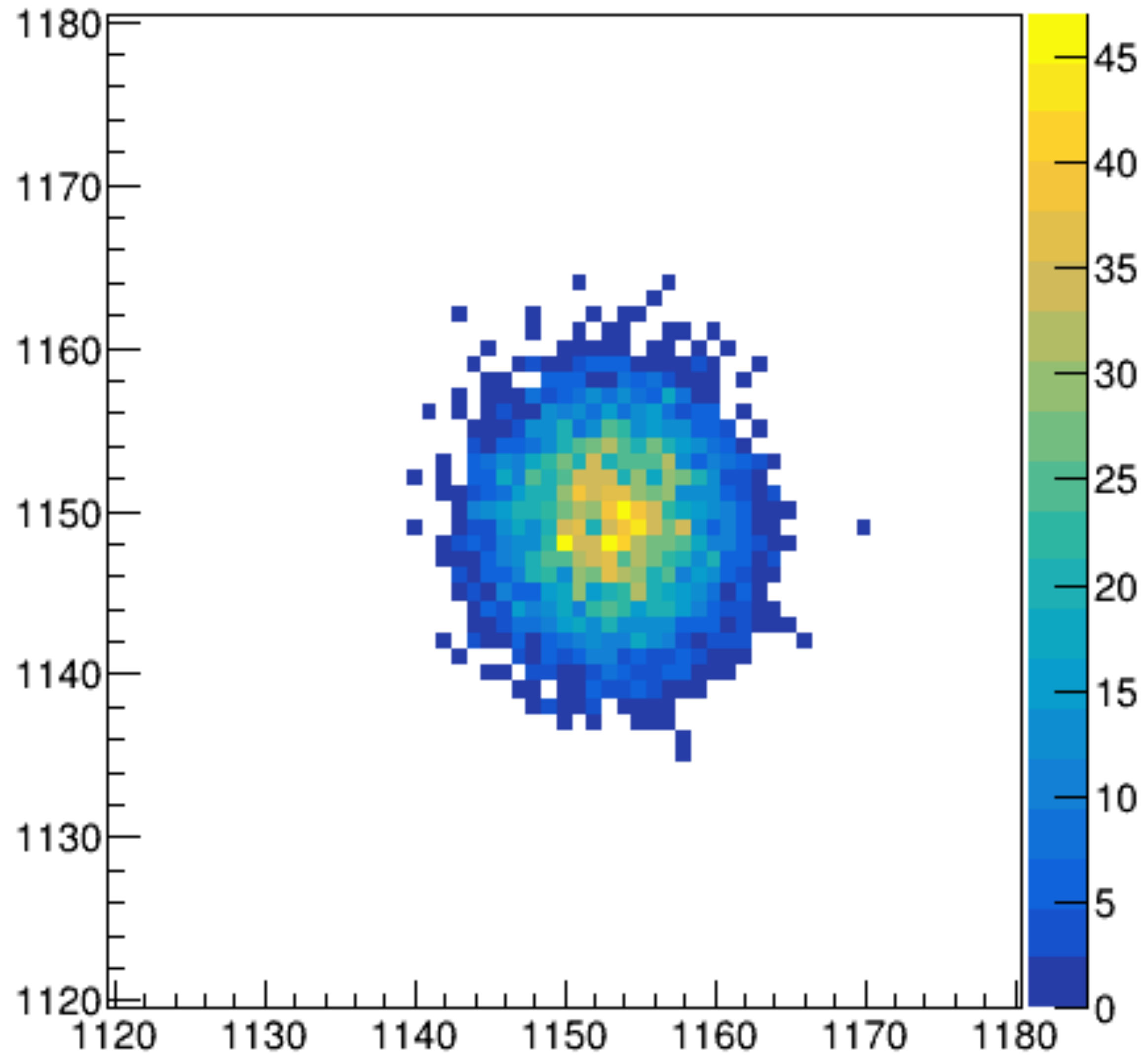
From the analytical to the numerical

- We developed an **custom-MC:**
  - **production, drift** and **diffusion** of the primary electrons in gas (GEANT4);
  - at the GEM stack entrance, the cloud is split into (0.1 mm)^3 **voxels**;
  - for each voxel, according to the number n_{in} of primaries, evaluate the number of exiting electrons n_{out};

$$n_{out} = n_{in} \frac{c\, e^{\tilde{\alpha} V_{GEM}}}{1 + \beta' n_{in} (c\, e^{\tilde{\alpha} V_{GEM}} - 1)}$$

  - per **each** final **electron**, a random number of **photons** with average **0.07** is produced;
  - photons are then **geometrically propagated** and the **optical system** response is evaluated: **vignetting**, **QE**, **sensitivity**
  - Signal is then **convolved** with sensor thermal **noise**

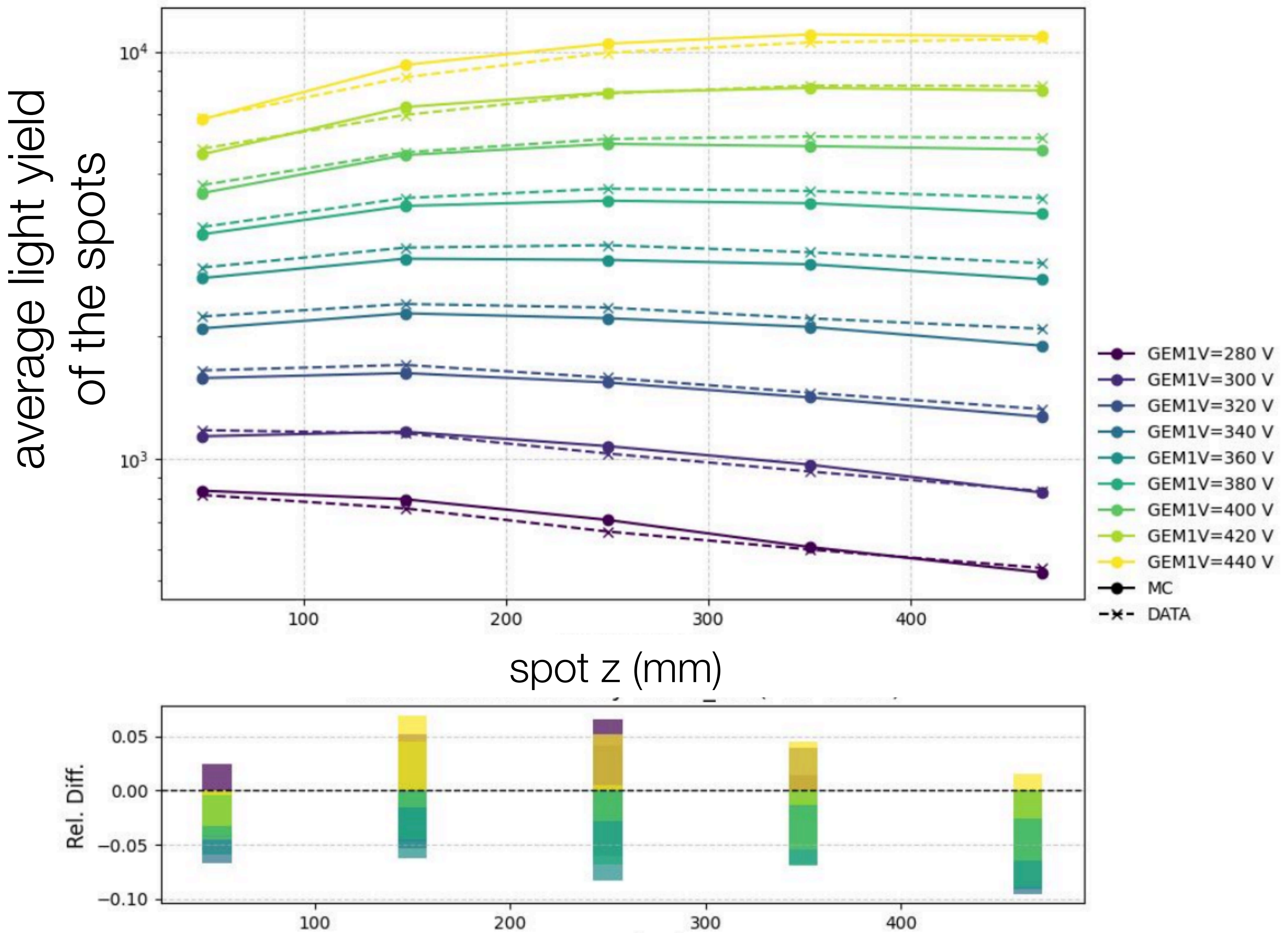




Comparison with experimental data

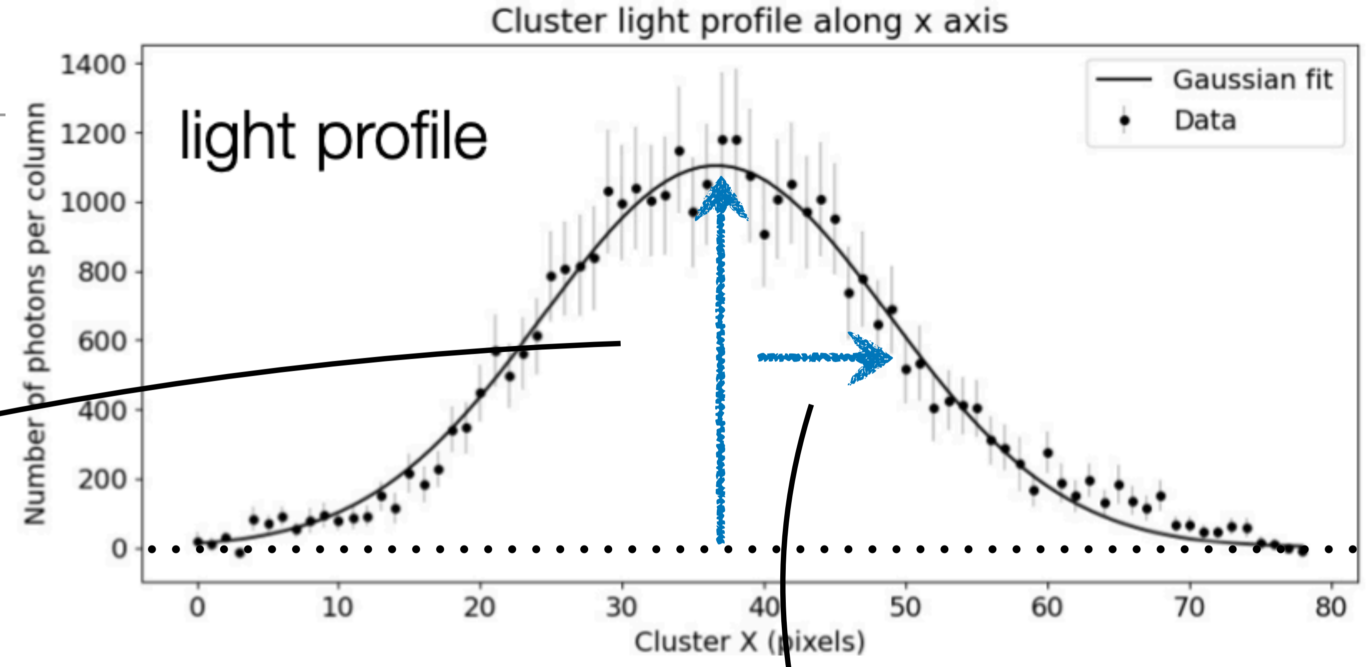
- To evaluate the **reliability** of this custom-MC, we took **three sets** of data by illuminating the TPC with the **^{55}Fe source**, in different ***z* positions**;
- By **varying** the voltage drop on the first **V_{GEM1}**, **different** amounts of **charges** on the **GEM3** were obtained;

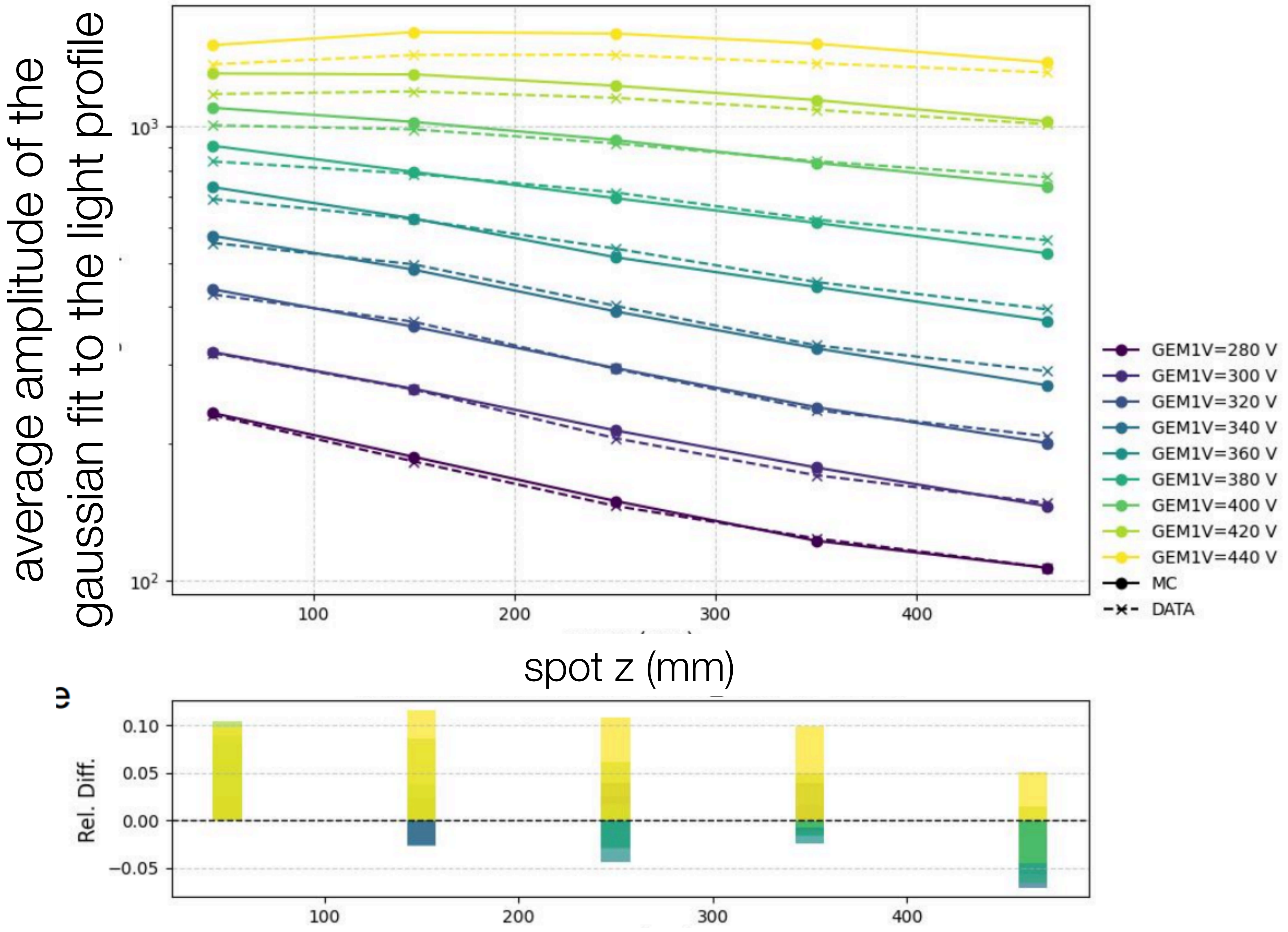
  - **Simulated** and **experimental** data were then **reconstructed** and **analysed** with the **same algorithms**
  - This plot shows the behaviour of the **average** spot **light yield** as a function of the **drift path**
  - Over **two orders of magnitude** an agreement better than **10%** was found

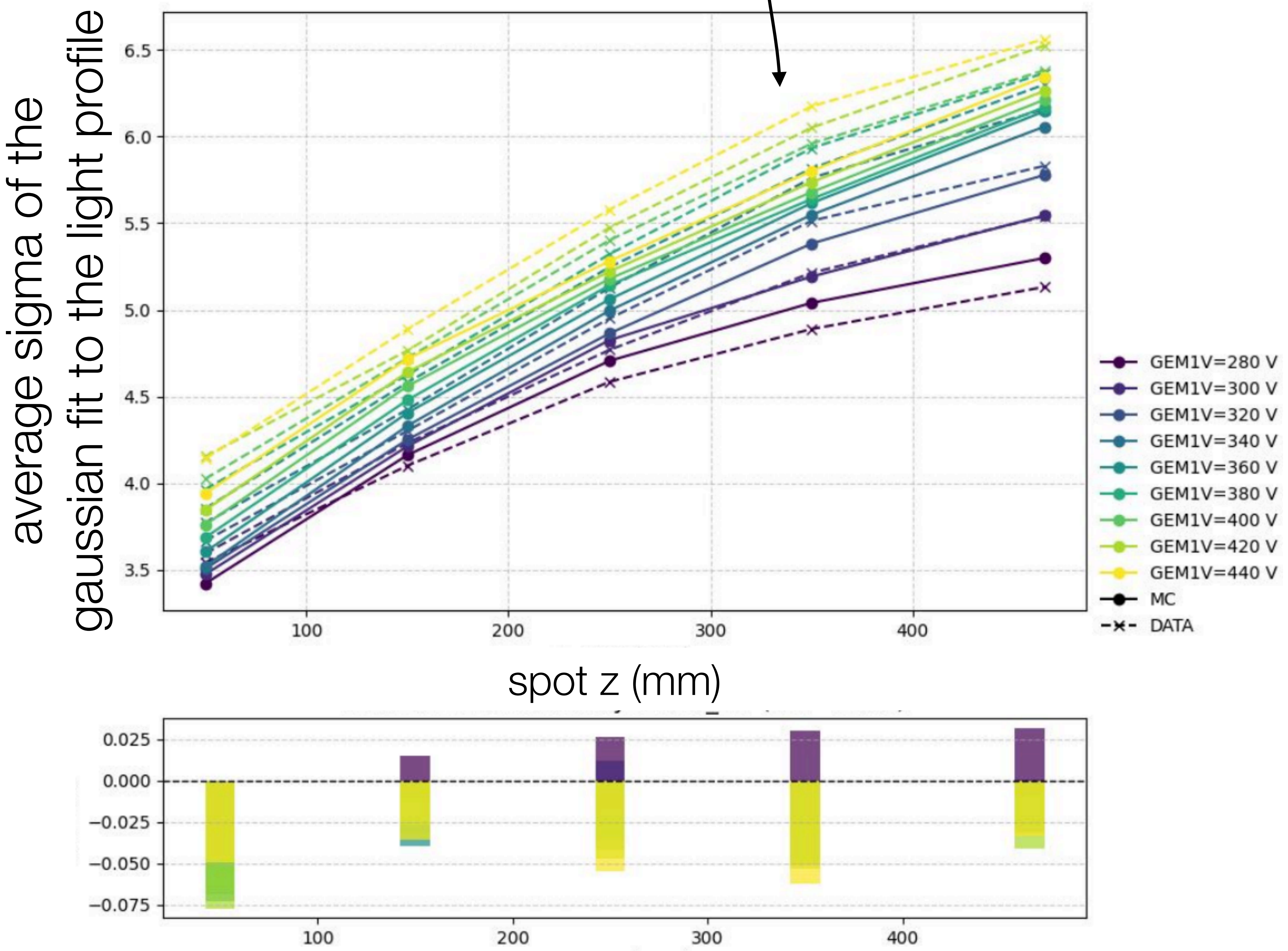


Comparison with experimental data

Other **variables** were analised to cross check the capability of this algorithm of reproducing the **spot shapes** and **hit distribution**



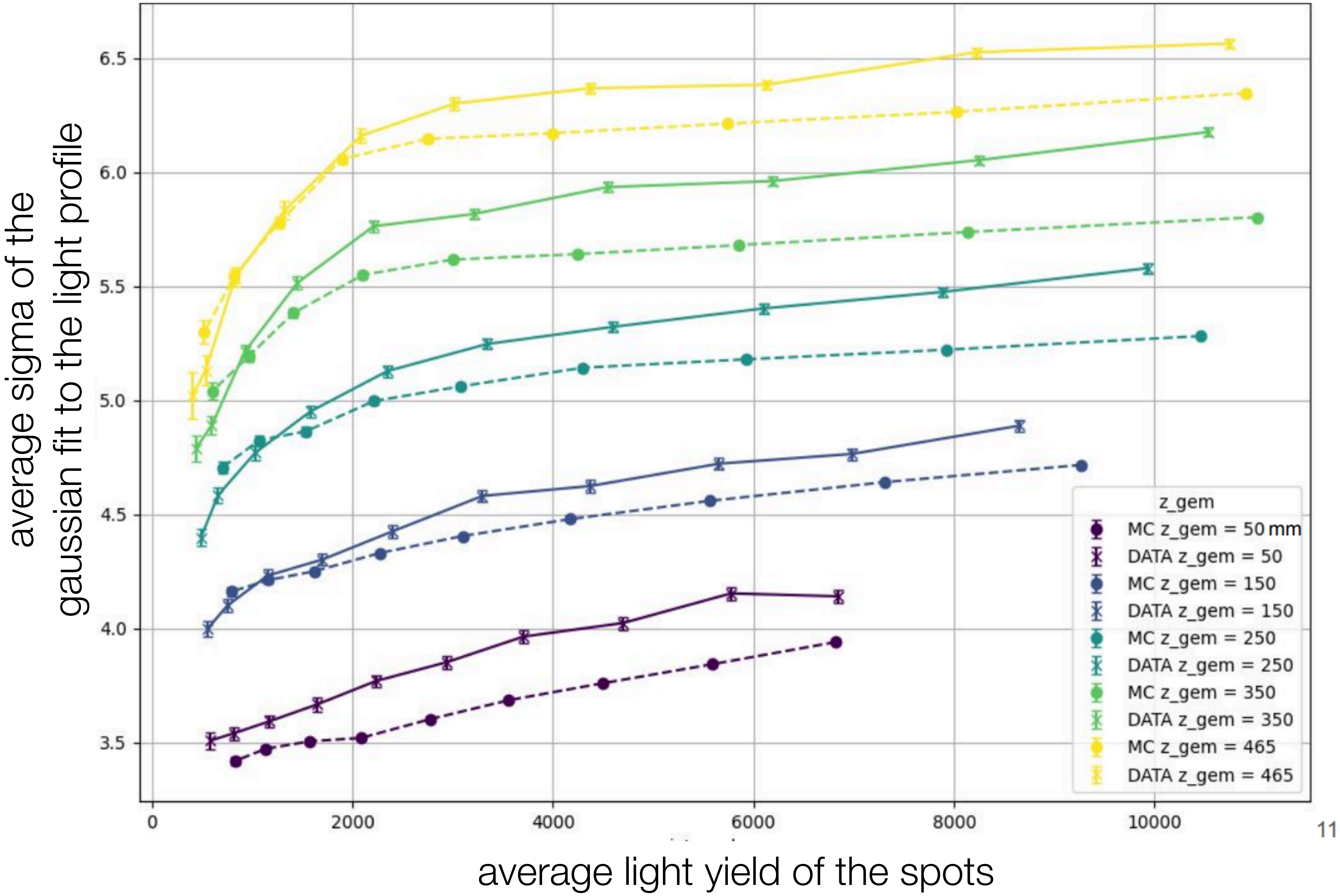




Comparison with experimental data

- This algorithm is also capable of reproducing an "**instrumental effect**": even if in principle the **width** of the light profile is **only** expected to be due to the **diffusion**, a **sigma increasing** with the gain was **measured**;

- The **analysis** of the **simulated events** showed that this was mainly due to some **inefficiencies** to properly **reconstruct the borders of the spots**, leading to a lower evaluated sigma;

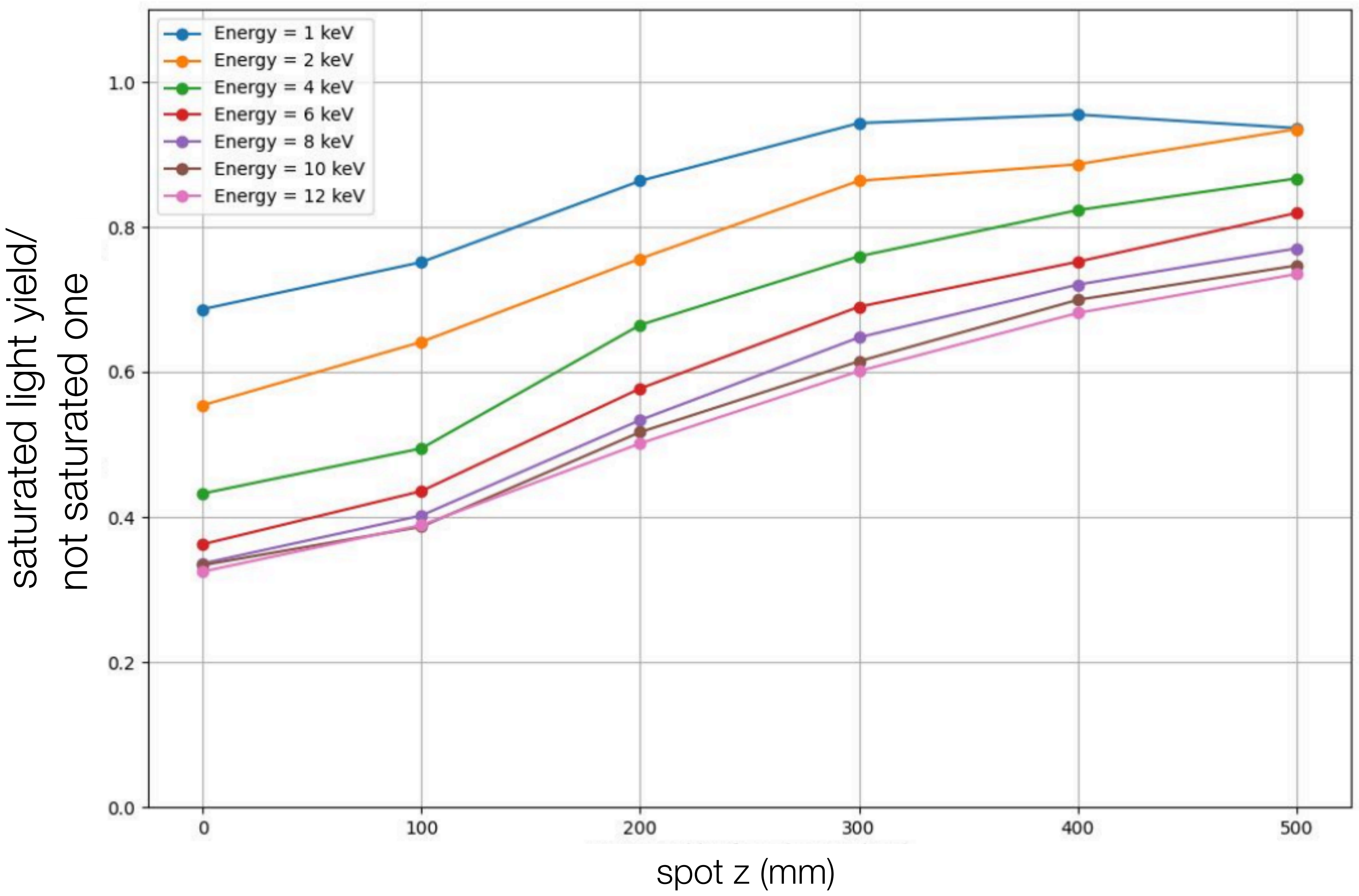


Davide Pinci - INFN Roma, Italy

Evaluation of the saturation values

- Once the **free parameter** of the model are **fitted**, we can also evaluate the **light yield suppression** for spots produced by **photons of different energies**;

- It is interesting to see that already for **1 keV interactions**, the signal decreases to **70%** for event close to the GEM stack;



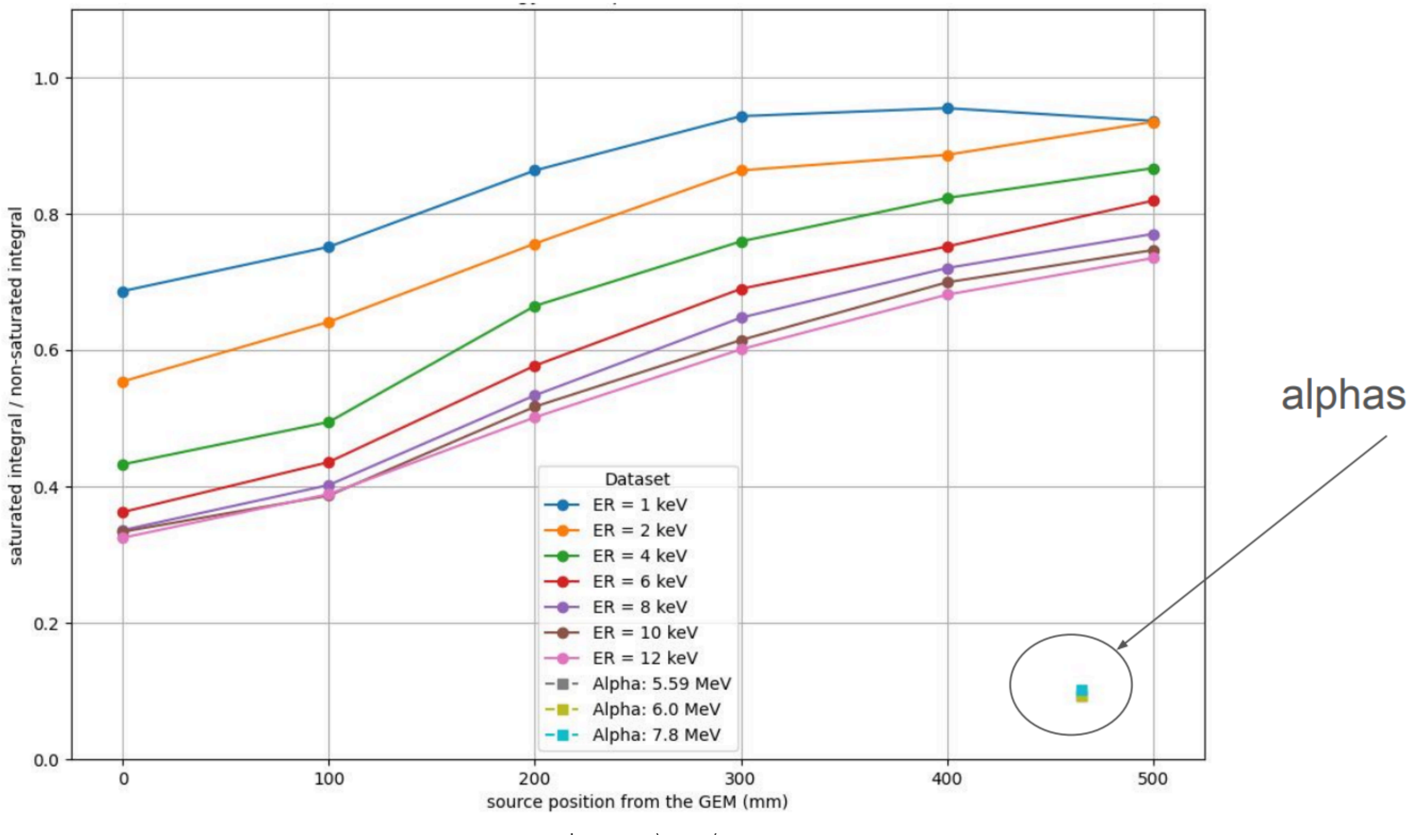
Evaluation of the saturation values

And alphas…

- Once the **free parameter** of the model are **fitted**, we can also evaluate the **light yield suppression** for spots produced by **photons of different energies**;

- It is interesting to see that already for **1 keV interactions**, the signal decreases to **70%** for event close to the GEM stack;

- **5-8 MeV** alphas have a signal **suppression** of a factor of **10**



Conclusion

The **gain** of the **GEM depends** on the number of **secondaries created** within the channels;

Therefore, it depends on:

- **ionization density**;
- **diffusion**;
- **nominal gain** of the channel;

A **simple model** based on a **modified Townsend equation** was developed and was then **used within a more general algorithm** (MELON) simulating **all steps** from the **energy deposit** to the formation of the optical **signal on the sensor**;

From a comparison with experimental data, this model resulted of **being able to reproduce** X rays spots with **5%-10% precision;**

It is then used by the CYGNO collaboration to **evaluate the detector response**;

It can also provide the basis **to correct** for this **non-linear response** if, for example, ***z*** can be **reconstructed**


Thank you!