Simulation of RPC Performance for 511keV photon detection

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- *Introduction*
- *RPC for PET*
  - *Charge Deposit by 511keV photons*
  - *RPC Time Response*
  - *Comparison to MIPs*
- *Space Charge Effect*
  - *Reduction of the Multiplication with Avalanche Size*
- *Summary and Conclusions*

References

[1] M. Couceiro et al., *RPC-PET: Status and Perspectives*, NIM A 580 (2007) 915-918.

[2] L. Lopes et al., *Accurate Timing of Gamma Rays with High-Rate Resistive Plate Chambers*, NIM A 573 (2007) 4-7.

[3] D. Gonzales Diaz, *Research and Developments on Timing RPCs*, Doctoral Thesis, Santiago de Compostela, 2006.

[4] C. Lippmann and W. Riegler, *Space charge effects in Resistive Plate Chambers*, NIM A 517 (2004) 54-76.

[5] A. Mangiarotti et al., *On the deterministic and stochastic solutions of Space Charge models and their impact on high resolution timing*, Nucl. Phys. B Proc. Suppl. 158 (2006) 118-122.

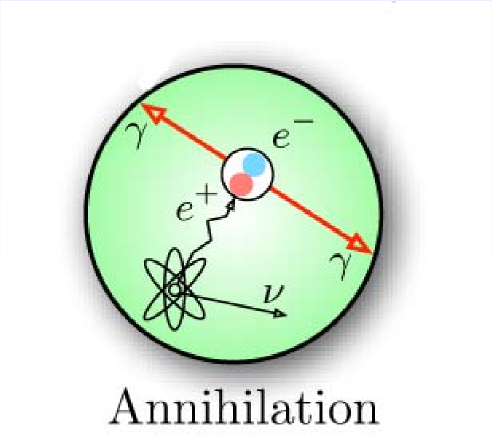
[6] C. Lippmann and W. Riegler, *Detailed Avalanche Simulations*, NIM A 533 (2004) 11-15.

[7] W. Legler, *Die Statistik der Elektronenlawinen in elektronegativen Gasen bei hohen Feldstärken und bei großer Gasverstärkung*, Z. Naturforschg. 16a (1961) 253-261.

RPC PET

- **RPCs are attractive for Positron Emission Tomography (PET) because of their [1]**
  - **Cost effectiveness and**
  - **Time resolution.**

- **511keV photons interact in the RPC material. Essentially the charge deposited by the Compton electrons is detected.**



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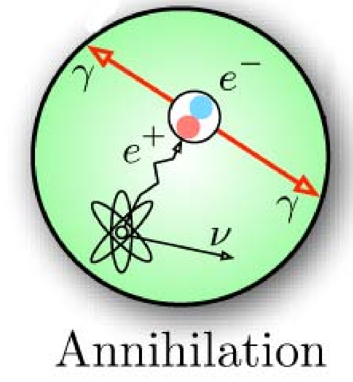

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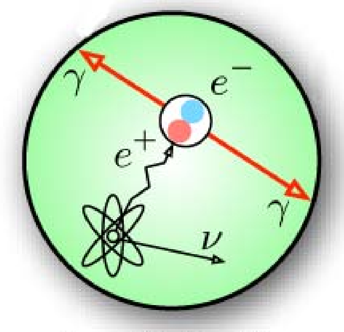

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1. Time resolution is worse for photons as compared to particle beams [2]:
   - σ ~ 90ps for 511 keV photons (single gap RPC).
   - σ ~ 50ps for particle beams (single gap RPC).
   - Possible Reason: The larger statistical variance of the primary charge that results from the photon interaction.

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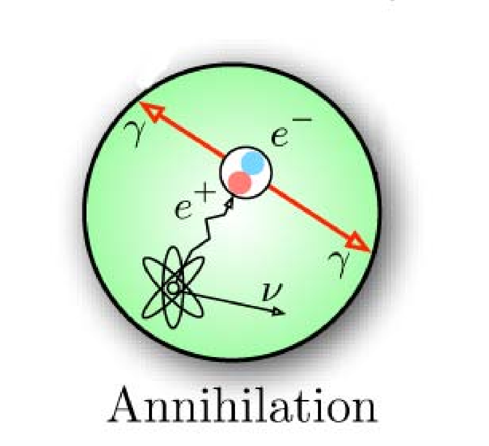

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   - Possible Reason: The <u>larger statistical variance</u> of the primary charge that results from the photon interaction.

2. Time resolution with 511 keV photons essentially independent of HV (See e.g. Fig. 8.24. In [3]).

A Simulation of RPC Performance

- **A fast simulation procedure with the following input:**
  1. **Distibution of the number of primary electrons (N) in gas gap due to the photon interactions.**
  2. **RPC Time Response data: Threshold crossing times (mean and r.m.s.) for given HV and number of primary electrons).**

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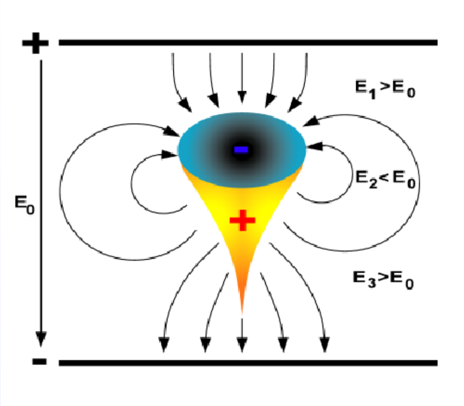
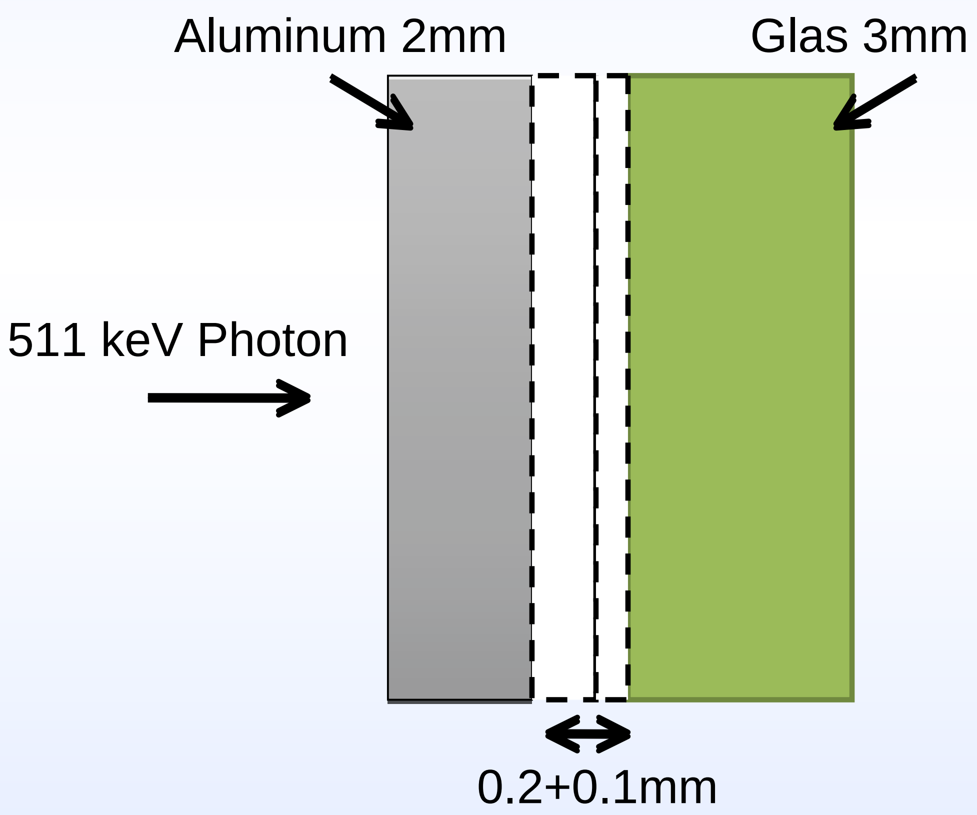
1. **The photon interaction (including secondaries) is simulated with FLUKA.**
   - **Lowest particle transport threshold for Electrons and Photons 1 keV.**

2. **The detector response is simulated with the „1.5D“ Monte Carlo [4]:**
   - **Monte Carlo Avalanche Simulation.**
   - **Contains Space Charge Effect and Diffusion.**
   - **Full Monte Carlo in longitudinal direction.**
   - **Transversal diffusion enters by assuming that space charge is situated in disks of certain transveral size.**
   - **Assumptions:**
     - **All charge deposited in one spot.**
     - **Only avalanches started in about 2/3 of the gas gap reach the threshold.**



1) FLUKA simulation of Photon Interactions

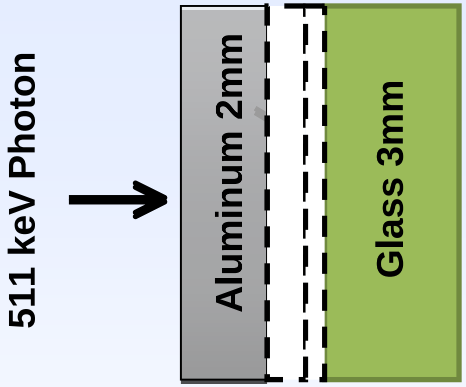
Setup similar to the one described in [2]:



The gas gap of 0.3mm is divided into two volumes of 0.2mm and 0.1mm. The reason is that only avalanches started in about 2/3 of the gas gap reach the threshold.

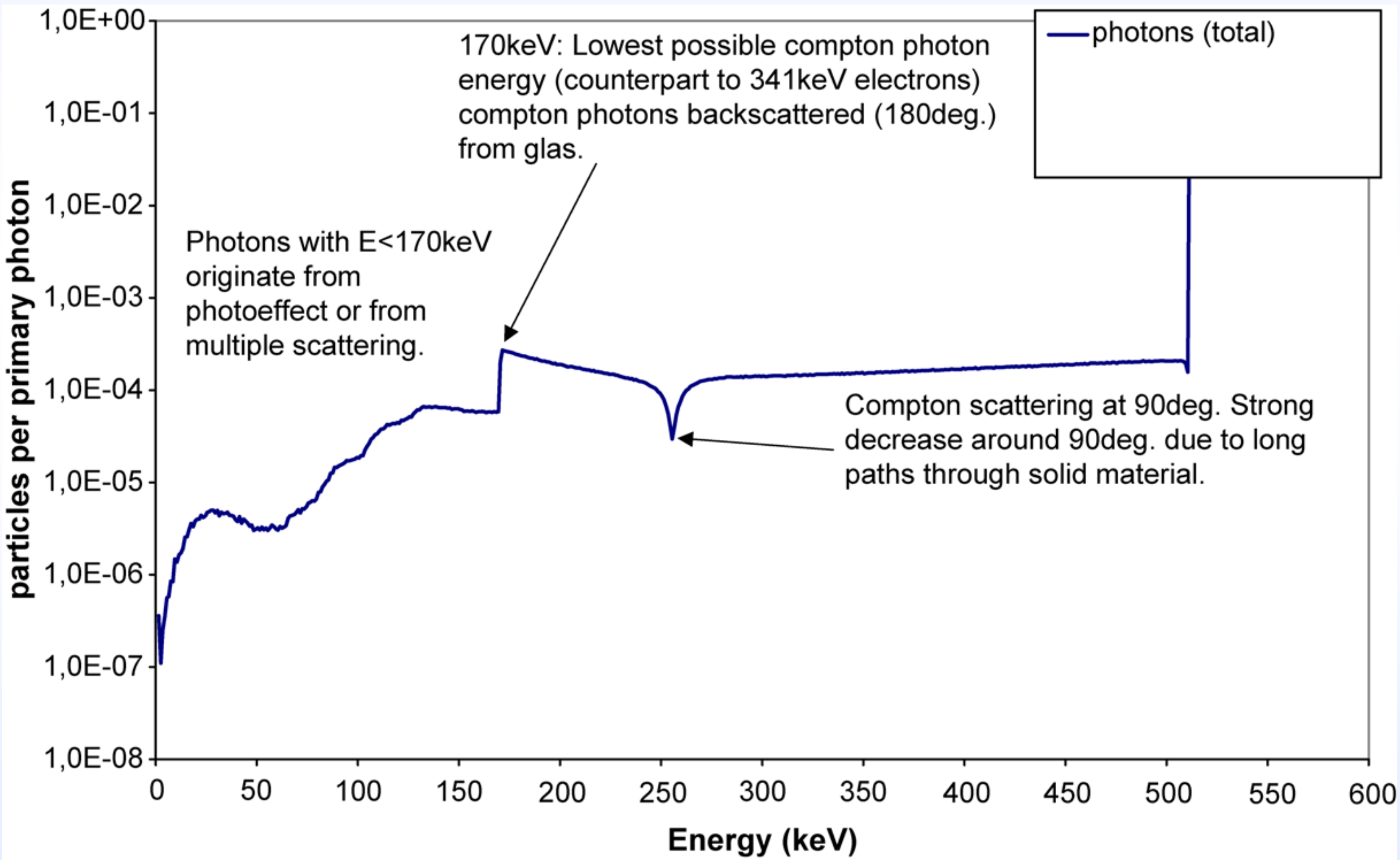
Gas mixture: $C_2F_4H_2$/ i-C_4H_{10}/ SF_6 (85/5/10)

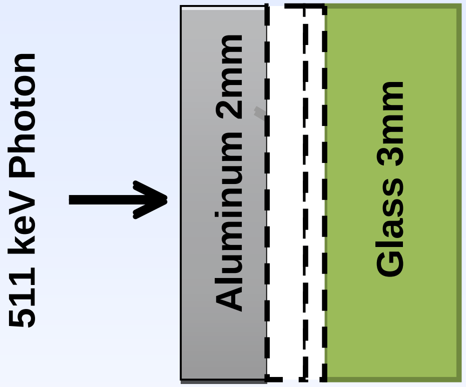
Number of interest:
Energy deposit spectrum in the two Gas volumes event by event.



Photon Interactions (1)

- **Particle currents in the gas:**





Photon Interactions (2)

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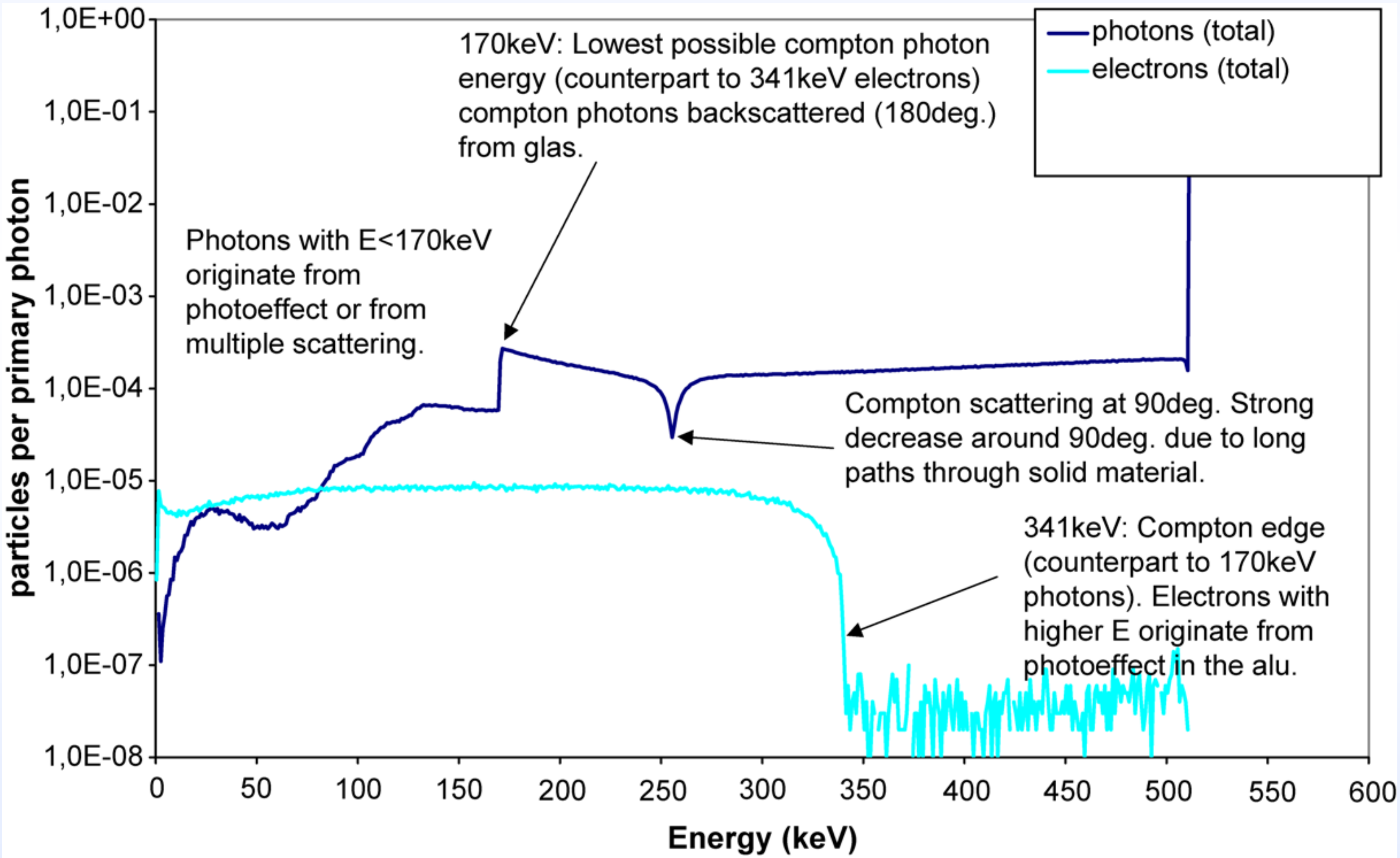
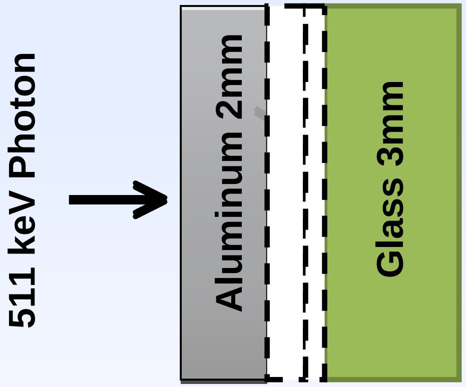
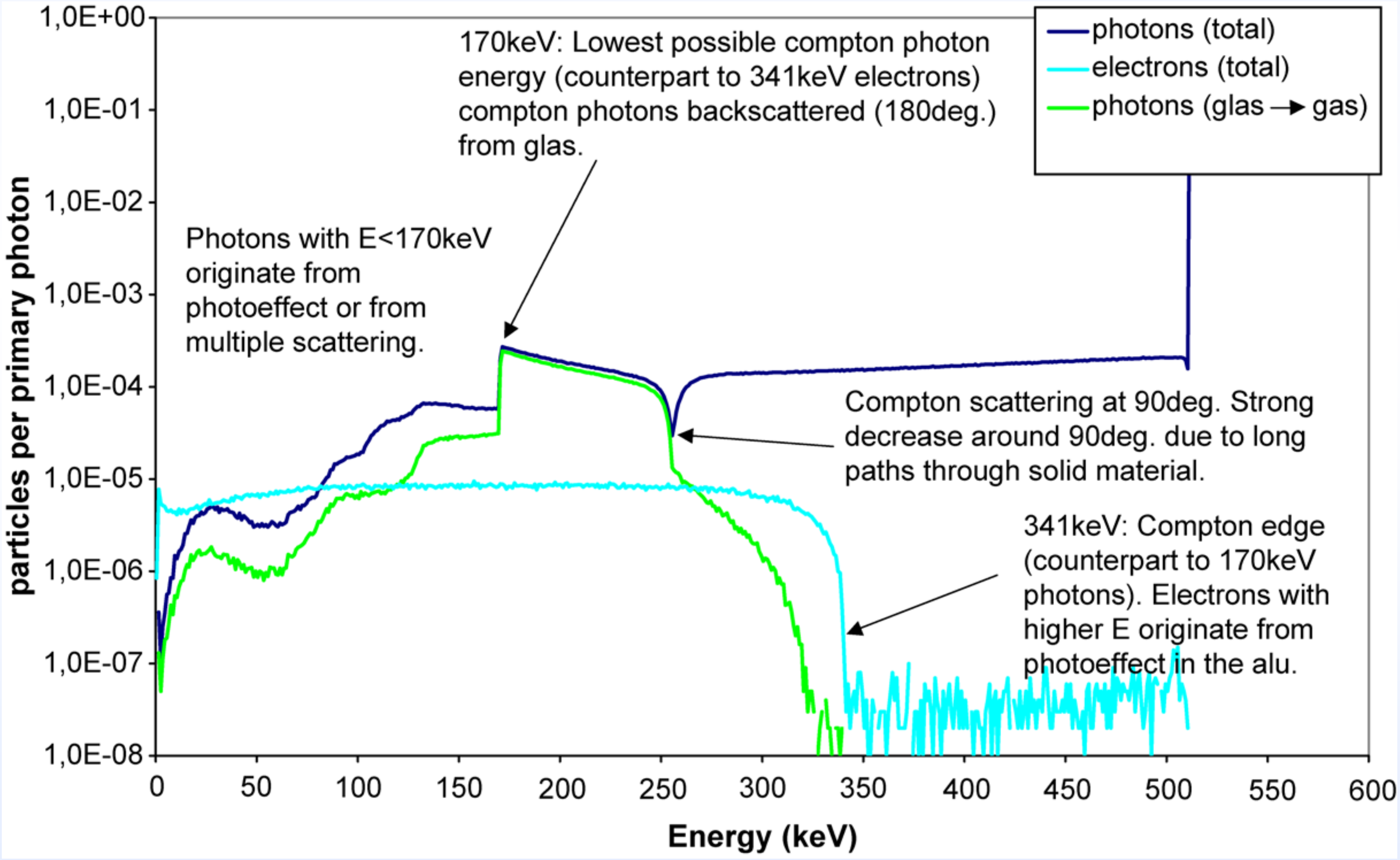
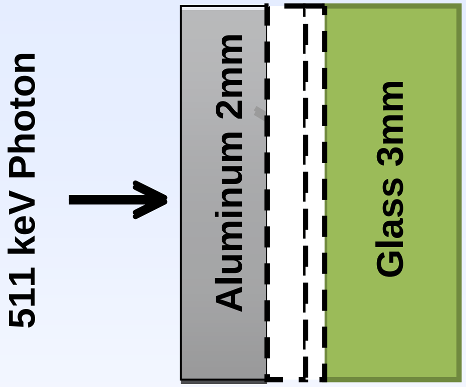




Photon Interactions (3)

- Particle currents in the gas:





Photon Interactions (4)

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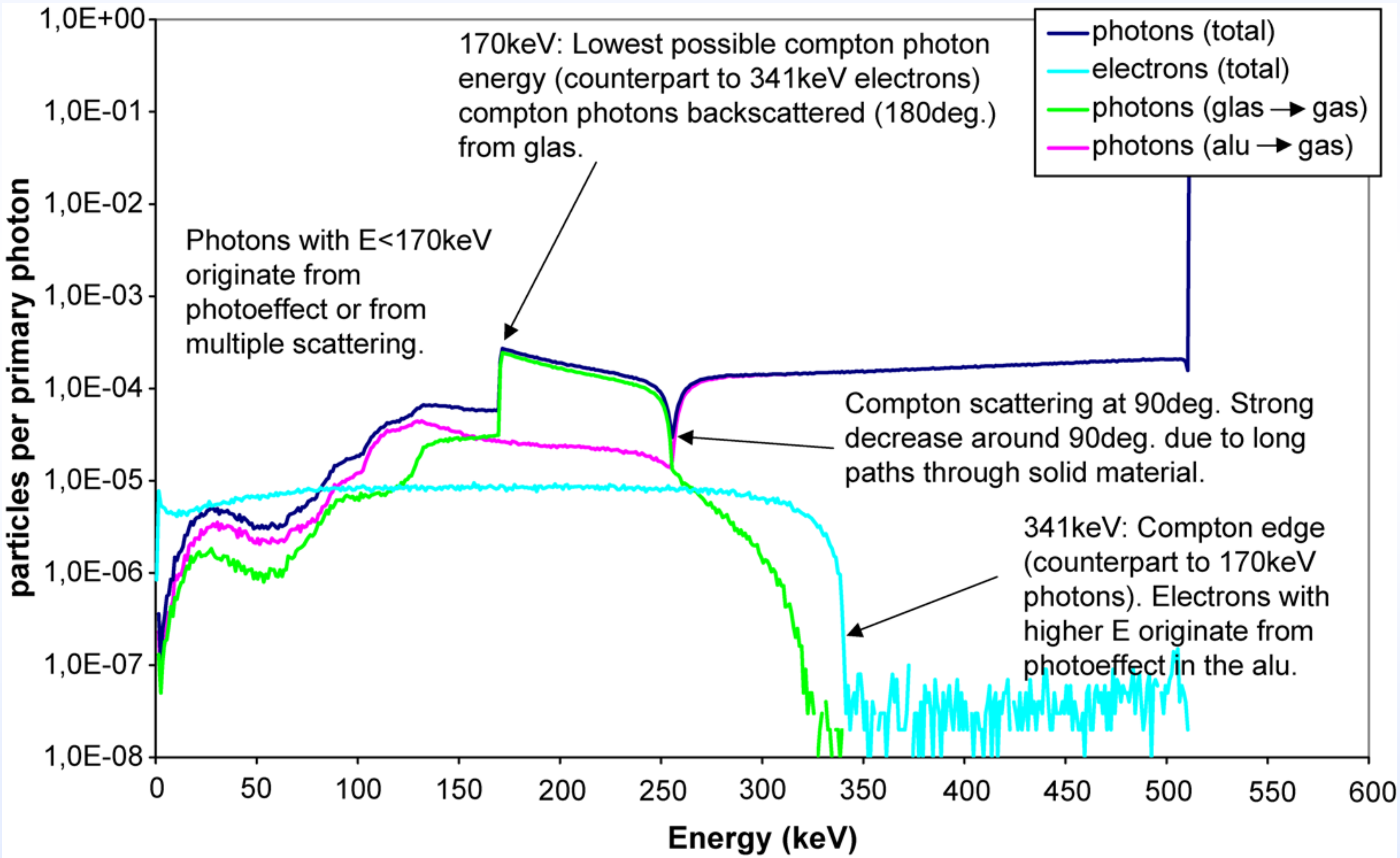
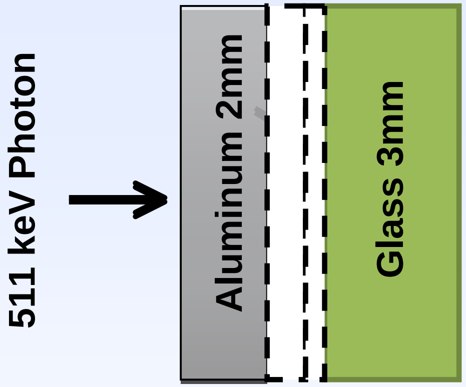
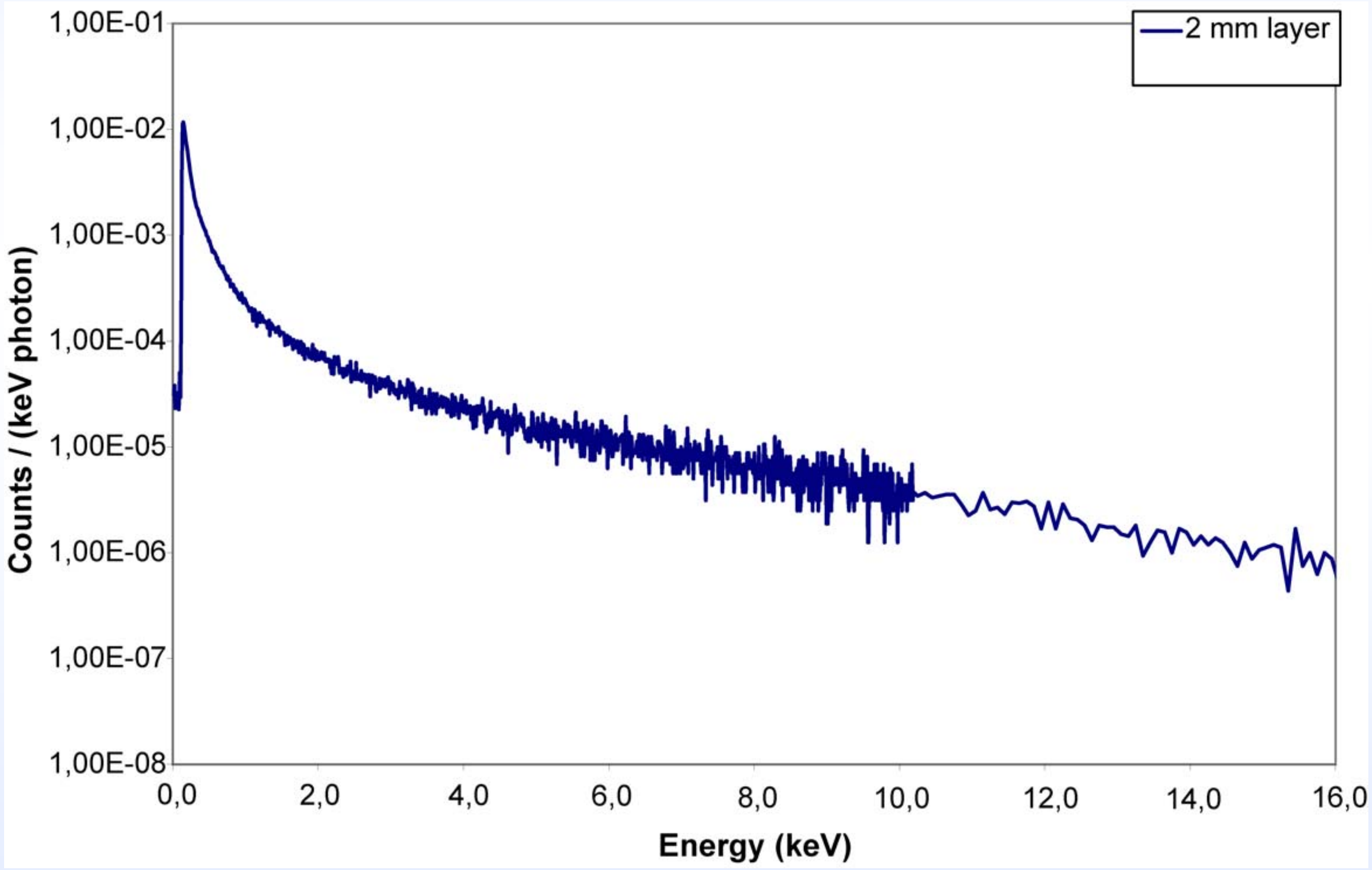




Energy Deposit

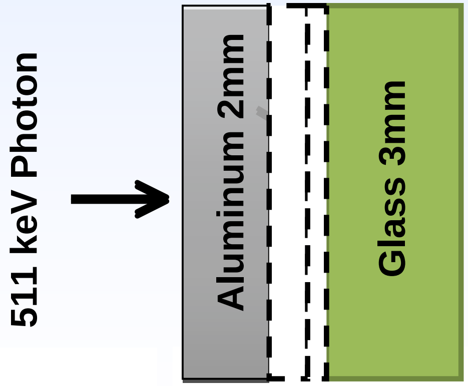
- Efficiency: 0.2% per gap.
- 0.2mm layer: Most probable=145eV.
- Number of Primary Electrons is derived by dividing by the Ionisation Potential (14.9eV).



Comparison of Glas and Alu Interactions

- Mean energy deposit in glas-first case is 10% higher due to smaller absorption in glas.

1)



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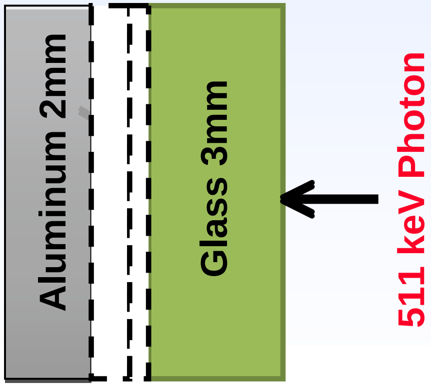

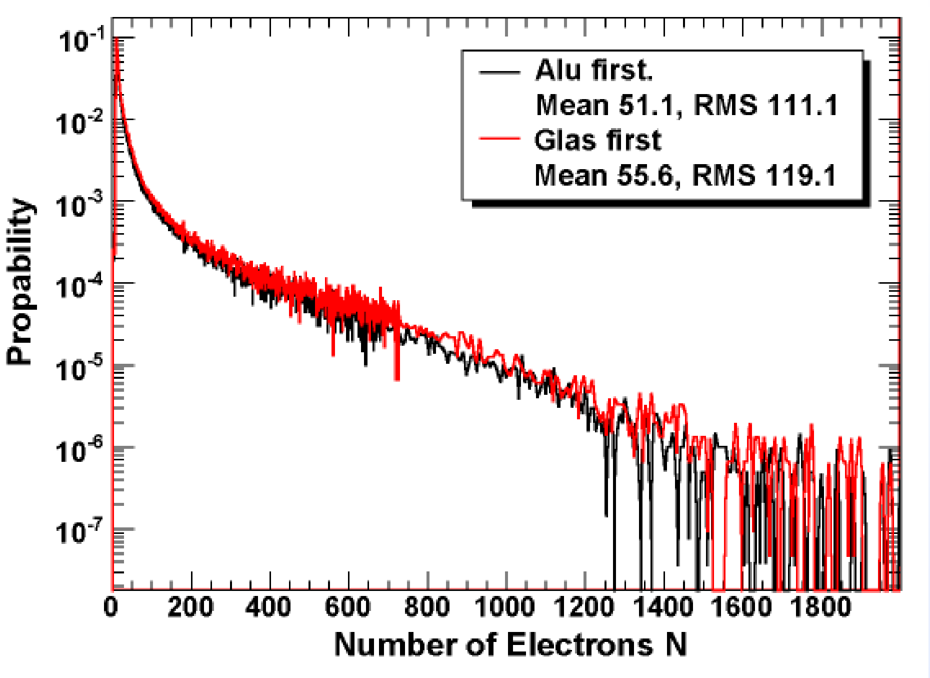

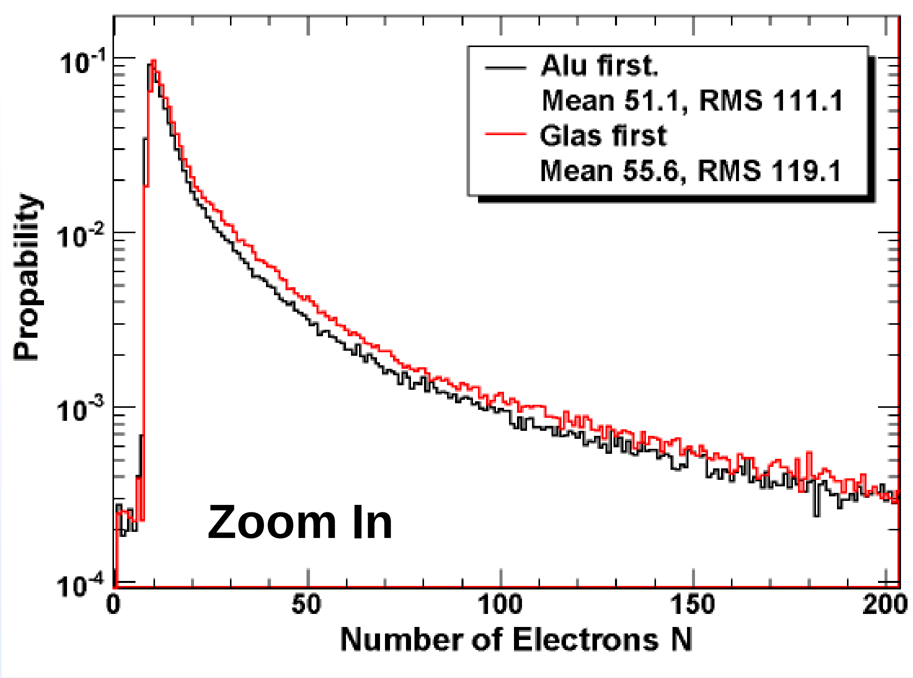

2) Monte Carlo Simulation of RPC Response

- **Simulate 5000 events for each setting:**
  - **HV = 2.6, 2.8, 3.0, 3.2kV (Electric fields 8.67, 9.33, 10.0, 10.67 kV/mm)**
  - **Number of primary electrons = 1, 2, 4, 10, 30, 60, 100, 250, 500, 1000, 2000, 10000.**
  - **Avalanches always start at anode with given number of electrons.**
  - **Save threshold (20fC) crossing time (mean and r.m.s.) for each event.**

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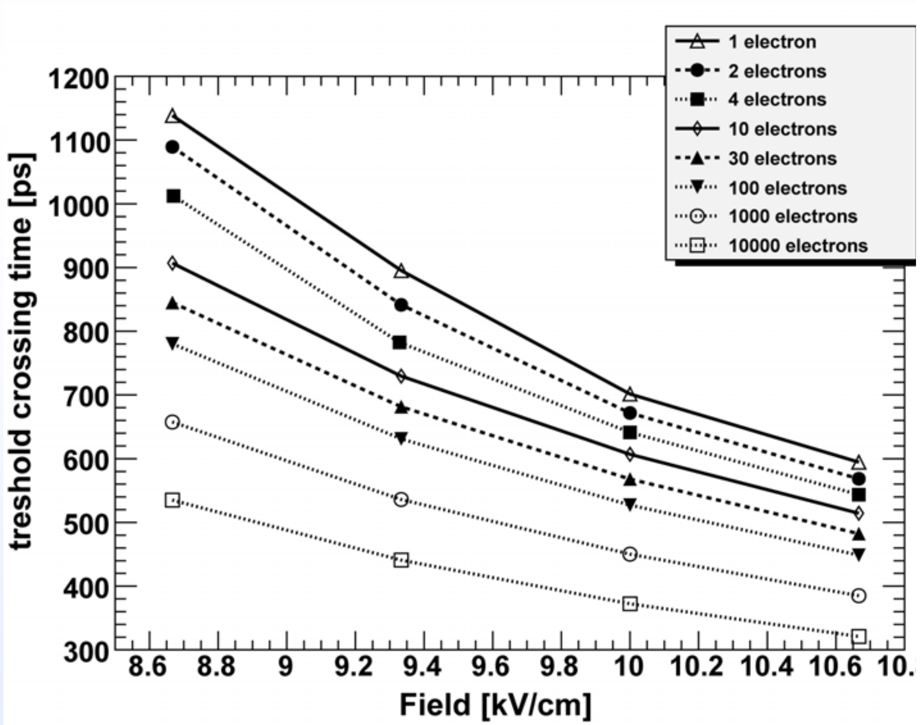
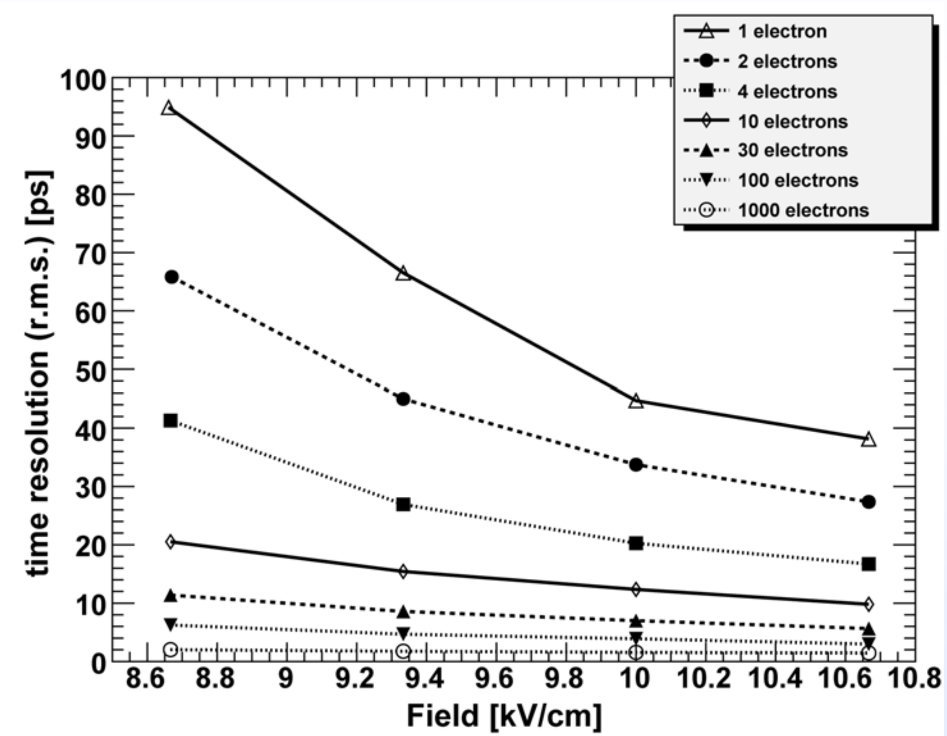
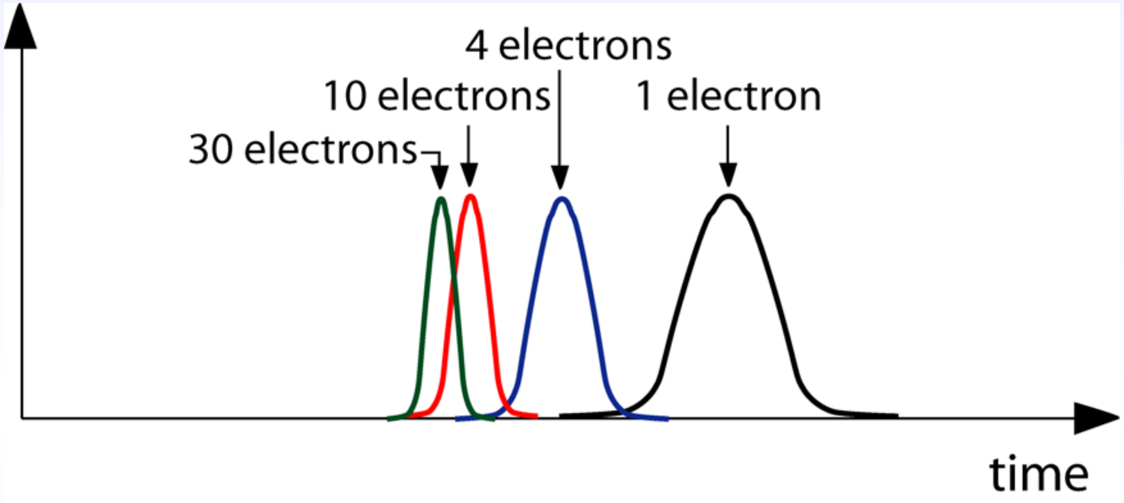




Time Response for different Primary Electron Numbers

- **Fixed Number of Electrons (schematic plot):**



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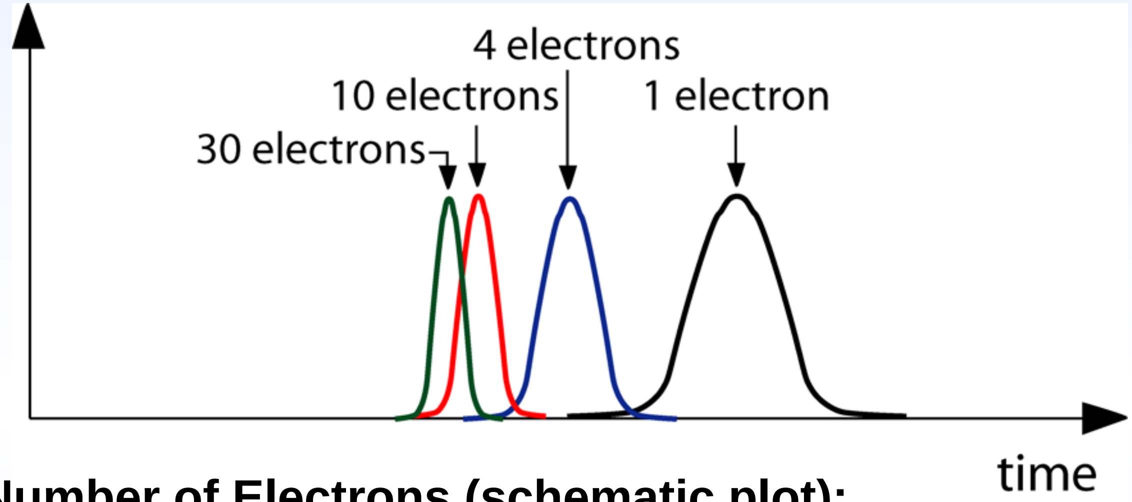
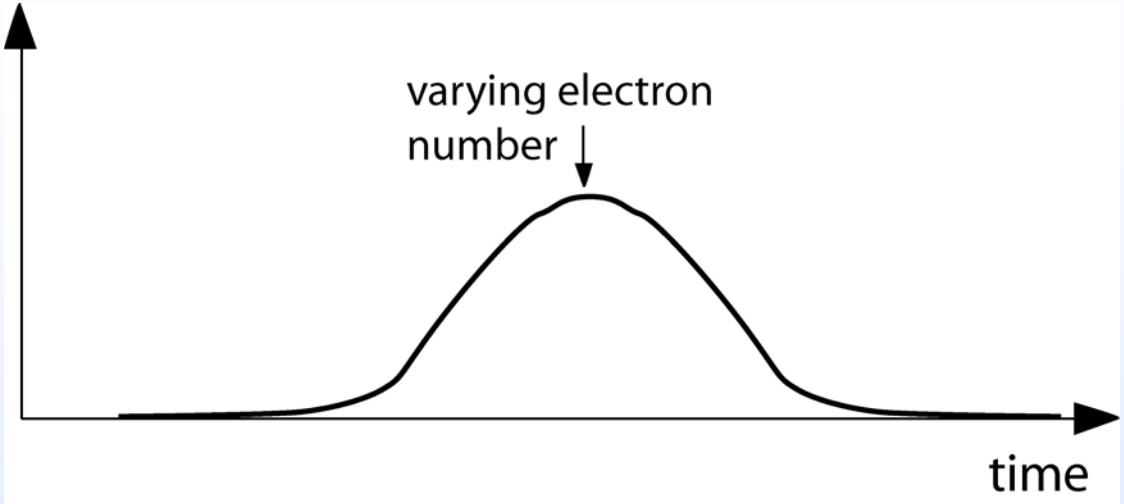
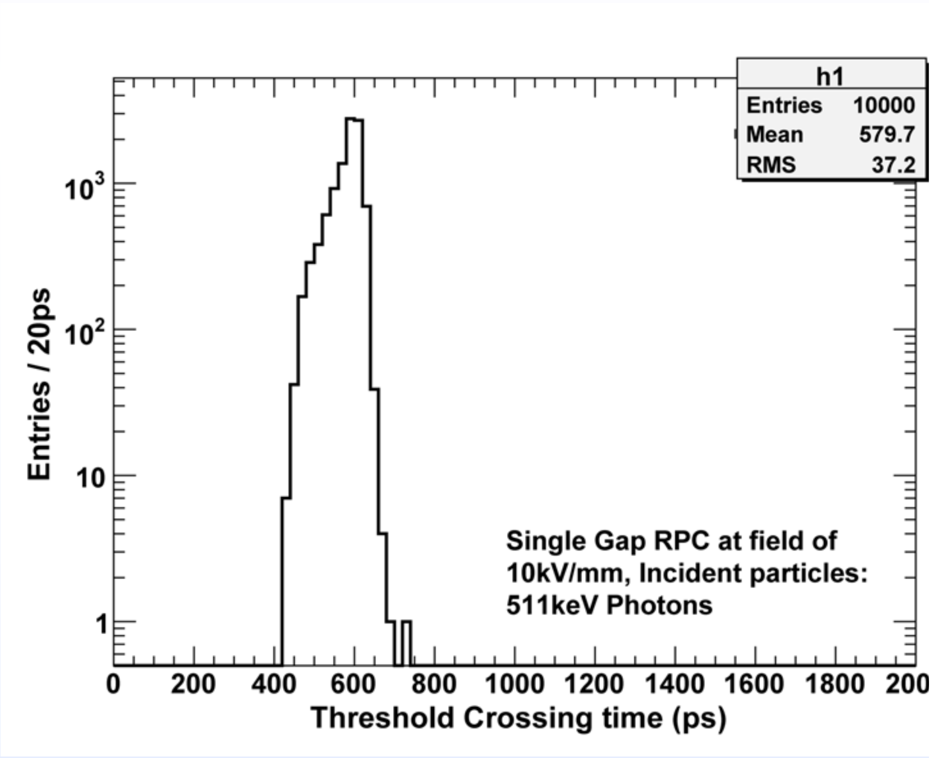


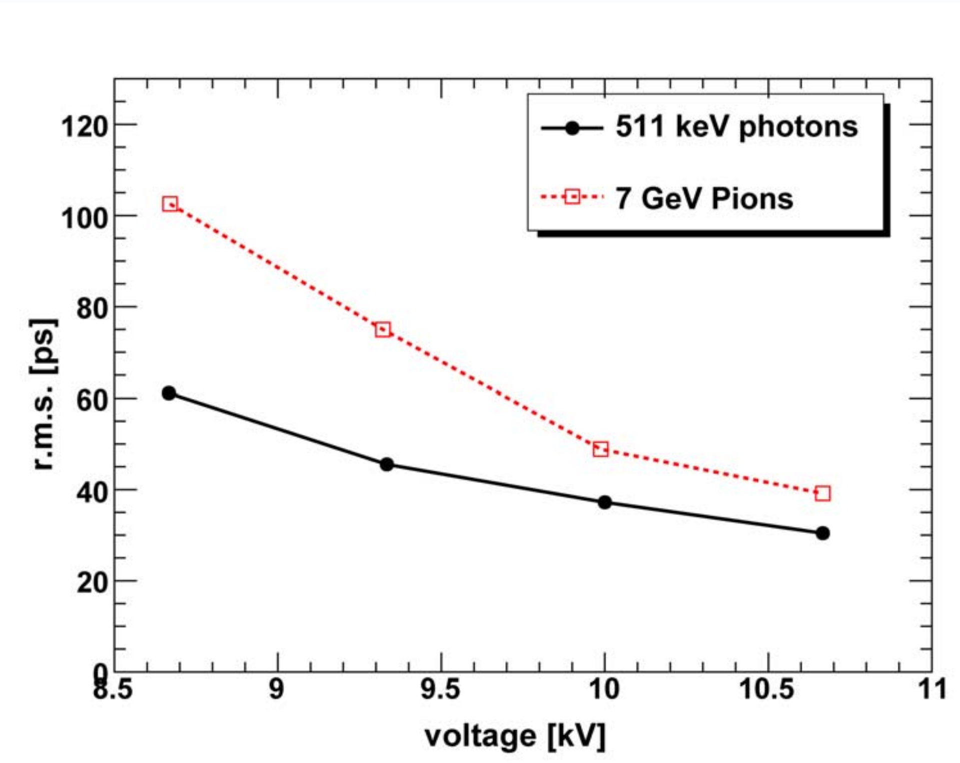
- **Varying Number of Electrons (schematic plot):**



Result: RPC Performance for 511keV Photons

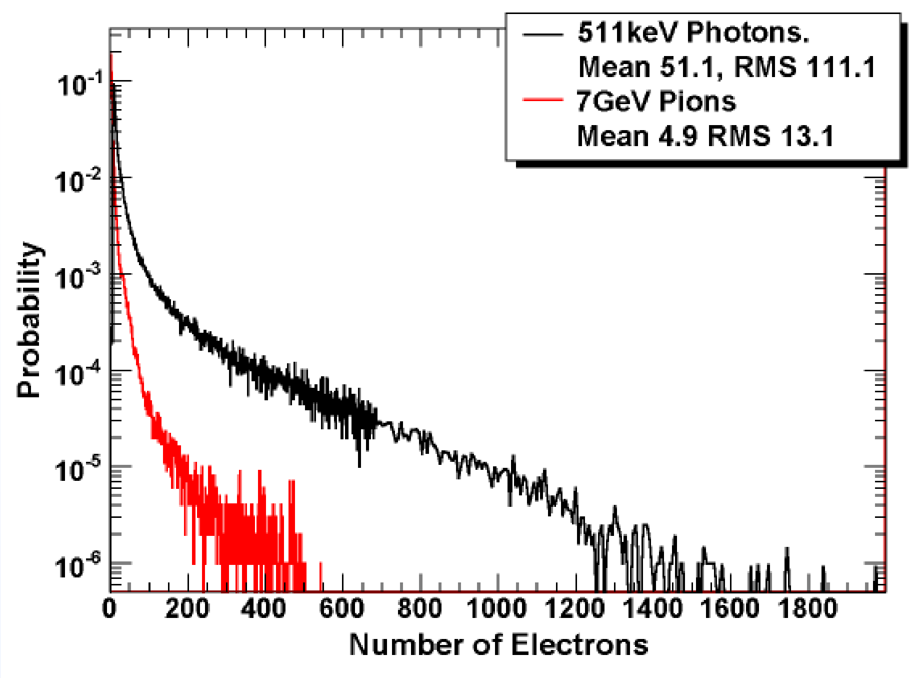
- Simulated time resolution is better for photons than for MIPs. This is contradicting the measurements.
- Simulated time resolution improves with increasing HV (as expected). This is also contradicting the measurements.

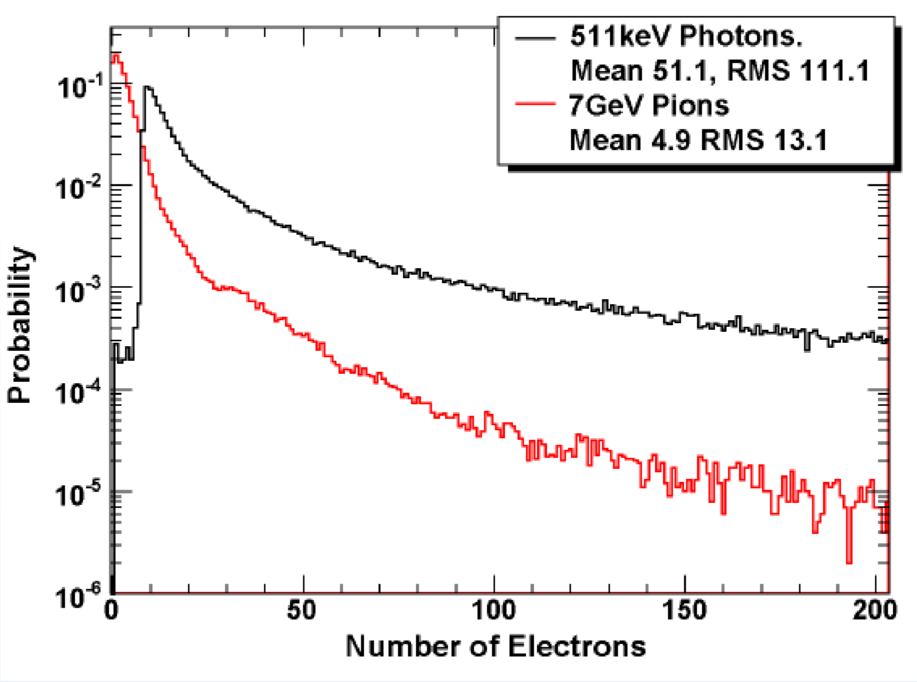




A Closer Look to the Distribution of the Primary Electron Number

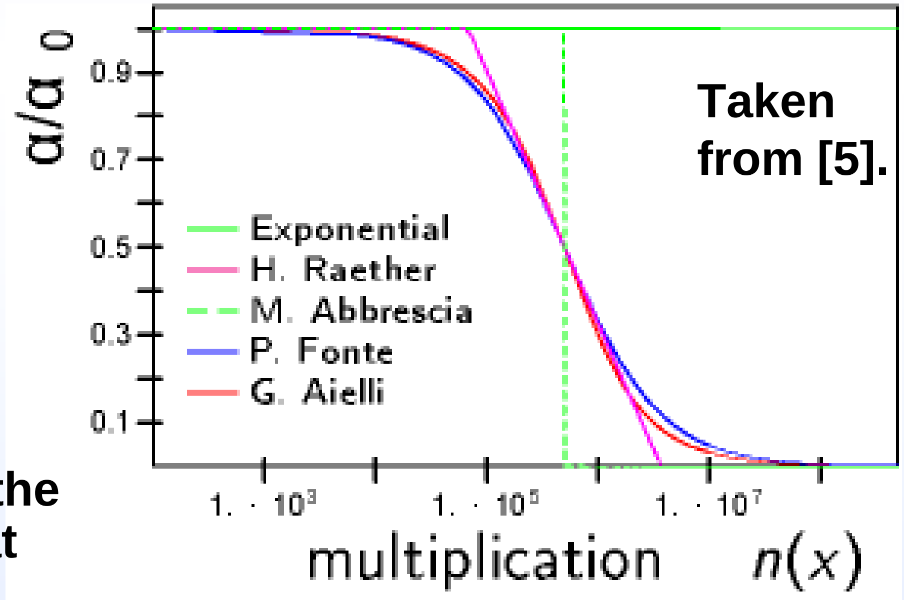
- **Distribution of Primary Electron Number (N) for Particles:**
  - **Most Probable Value of 1 with long tail.**
  - **<u>N<10 is very likely</u>!**
- **Distribution of N for Photons:**
  - **Most Probable Value of 9 to 10 with long tail.**
  - **<u>N<9 is rather unlikely</u>!**
- **However at N<10 the variation of threshold crossing time is strongest!**
- **Thus, a better timing resolution must be expected for Photons.**





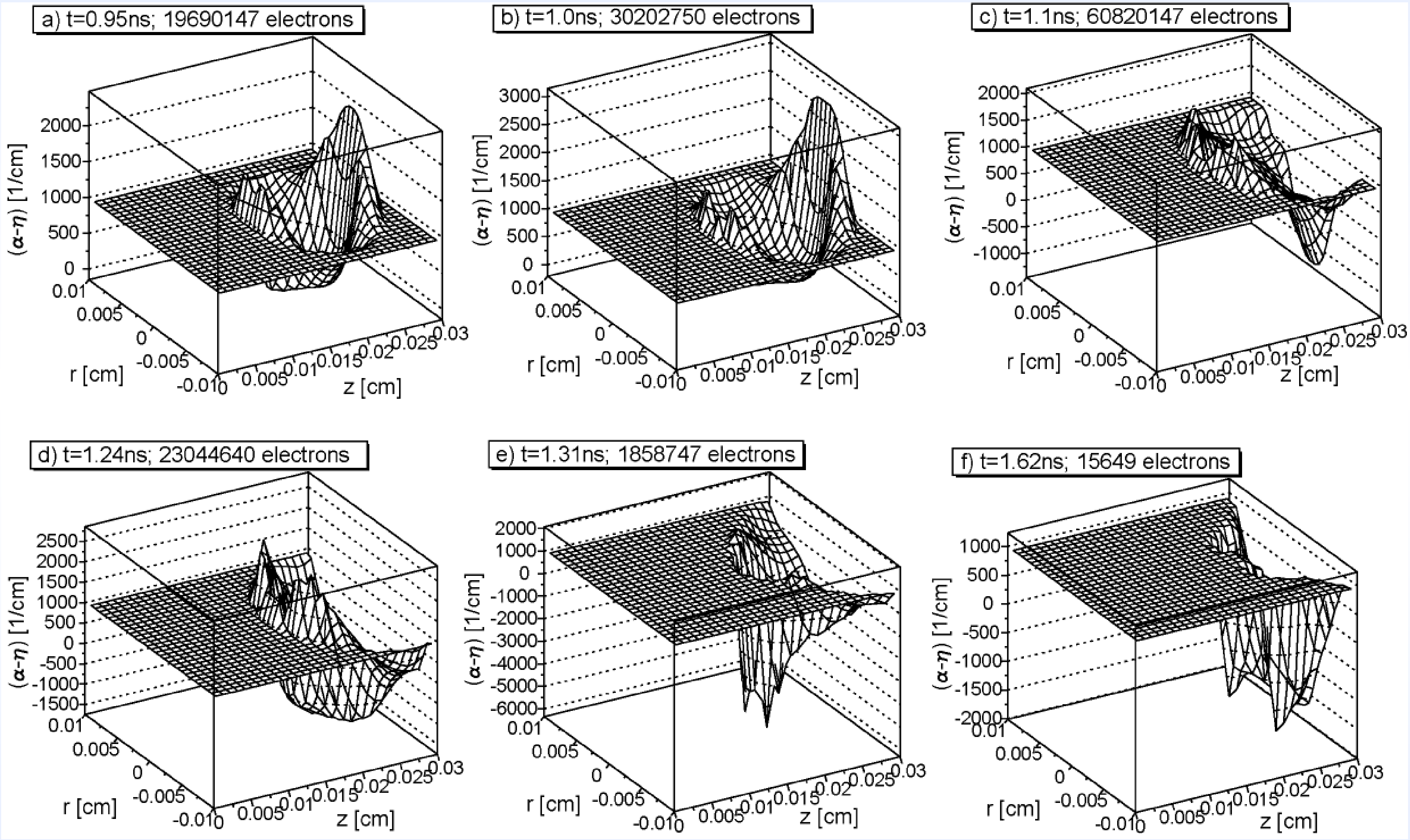
Multiplication Coefficient in the Presence of a Strong Space Charge Effect (1)

- **Different analytic models for RPC response assume a weakening of the effective Townsend coefficient by the Space Charge Effect: $\alpha=\alpha(n)$.**
- **The different approaches were compared in RPC2005 (A. Mangiarotti [5]).**
- **In these models the space charge effect takes effect only at rather large avalanche sizes.**
- **In RPC2003 it was however shown that the space charge effect is already present at the threshold level [6].**
- **What dependency is calculated by the detailed 2D simulation (presented at RPC2003 [4,6])?**



Taken from [5].

The Effective Townsend Coefficient within the Avalanche [4]



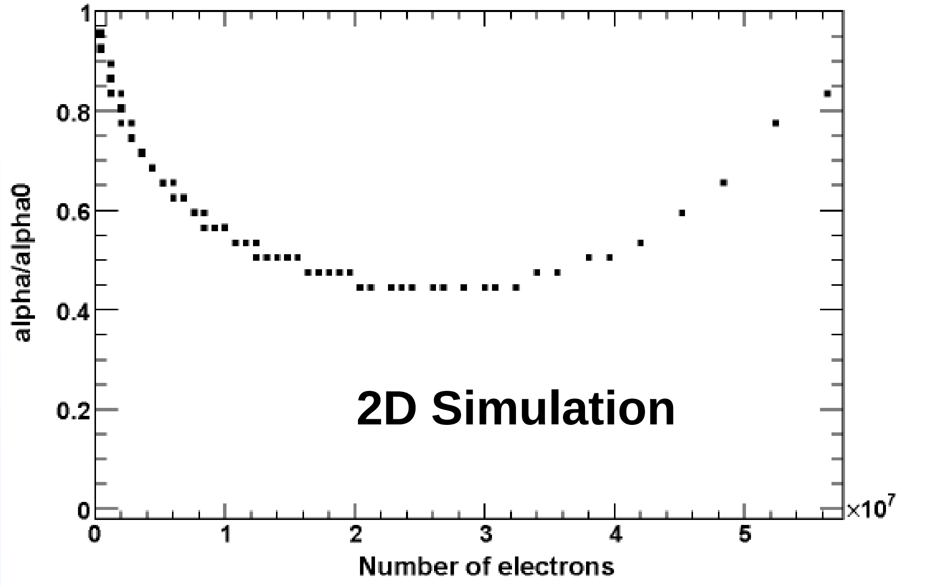
The effective Townsend Coefficient ranges from +3000/cm to –6000/cm!

2D simulation

Multiplication Coefficient in the Presence of a Strong Space Charge Effect (2)

- **We calculate the mean effective Townsend coefficient in the avalanche using the 2D Monte Carlo:**
  - **Contains longitudinal and transversal Space Charge Effect and Diffusion.**

- **We find that the effective Townsend coefficient decreases rapidly!**



Multiplication Coefficient in the Presence of a Strong Space Charge Effect (3)

- **We calculate the mean effective Townsend coefficient in the avalanche using the 2D Monte Carlo:**
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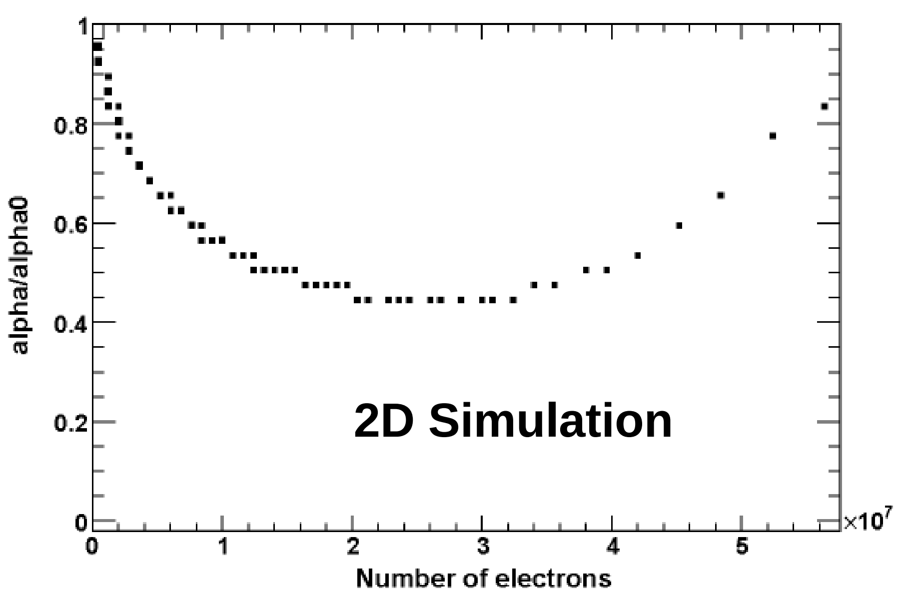
- **We find that the effective Townsend coefficient decreases rapidly!**

- **This is backed also by an early measurement [7].**



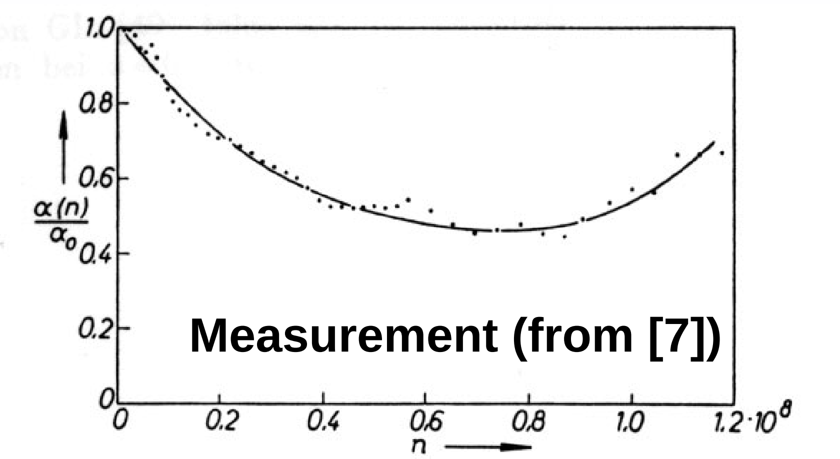
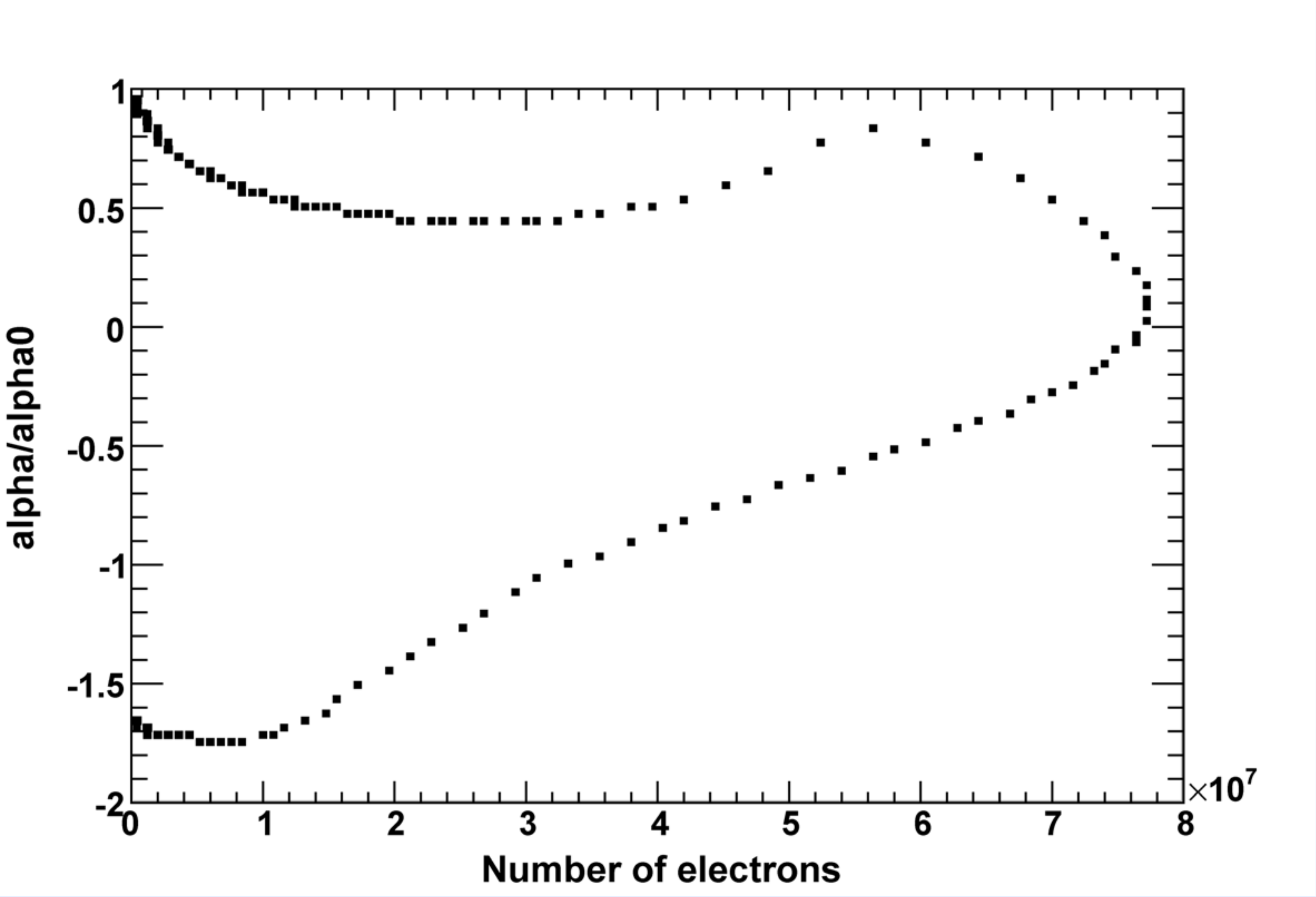


Abb. 6. Durch Raumladung geschwächter Ionisationskoeffizient $\alpha(n)$. Ermittelt aus einer Statistik in Methylal nach Schlumbohm [8] (Versuchsdaten im Text).

Evolution of the Mean Effective Townsend Coefficient

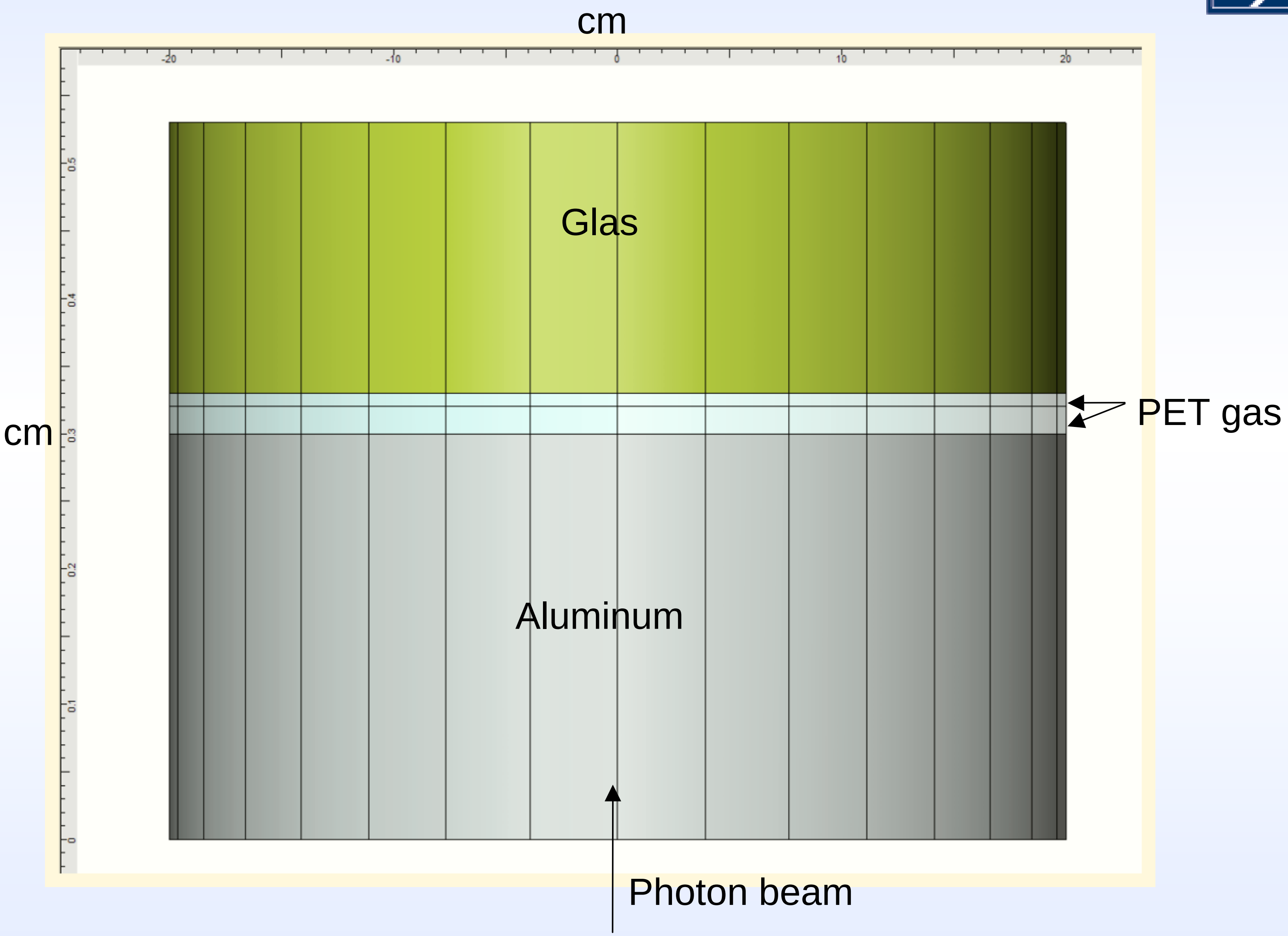
- **In the final stage of the avalanche strong attachment dominates!**

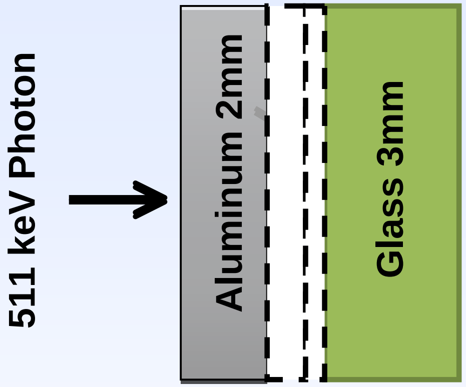


Summary and Conclusions

- **Timing RPCs (with ~0.3mm gaps) are attractive as photon detectors for PET.**
- **We simulated 511keV photon interactions and secondaries production in a single gap RPC (0.3mm gap) using FLUKA.**
- **We simulated the RPC time response to 511keV photons.**
- **The simulated time resolution of ~37ps (at 10kV/mm) does not confirm the measured results, which are much worse (~90ps).**
- **The fact that the measured time resolution does not change with HV indicates that the detector intrinsic resolution is dominated by other effects.**
- **The decrease of the effective Townsend coefficient (due to the space charge effect) with growing avalanche size starts already at the threshold level, different from what is widely assumed in analytic models.**

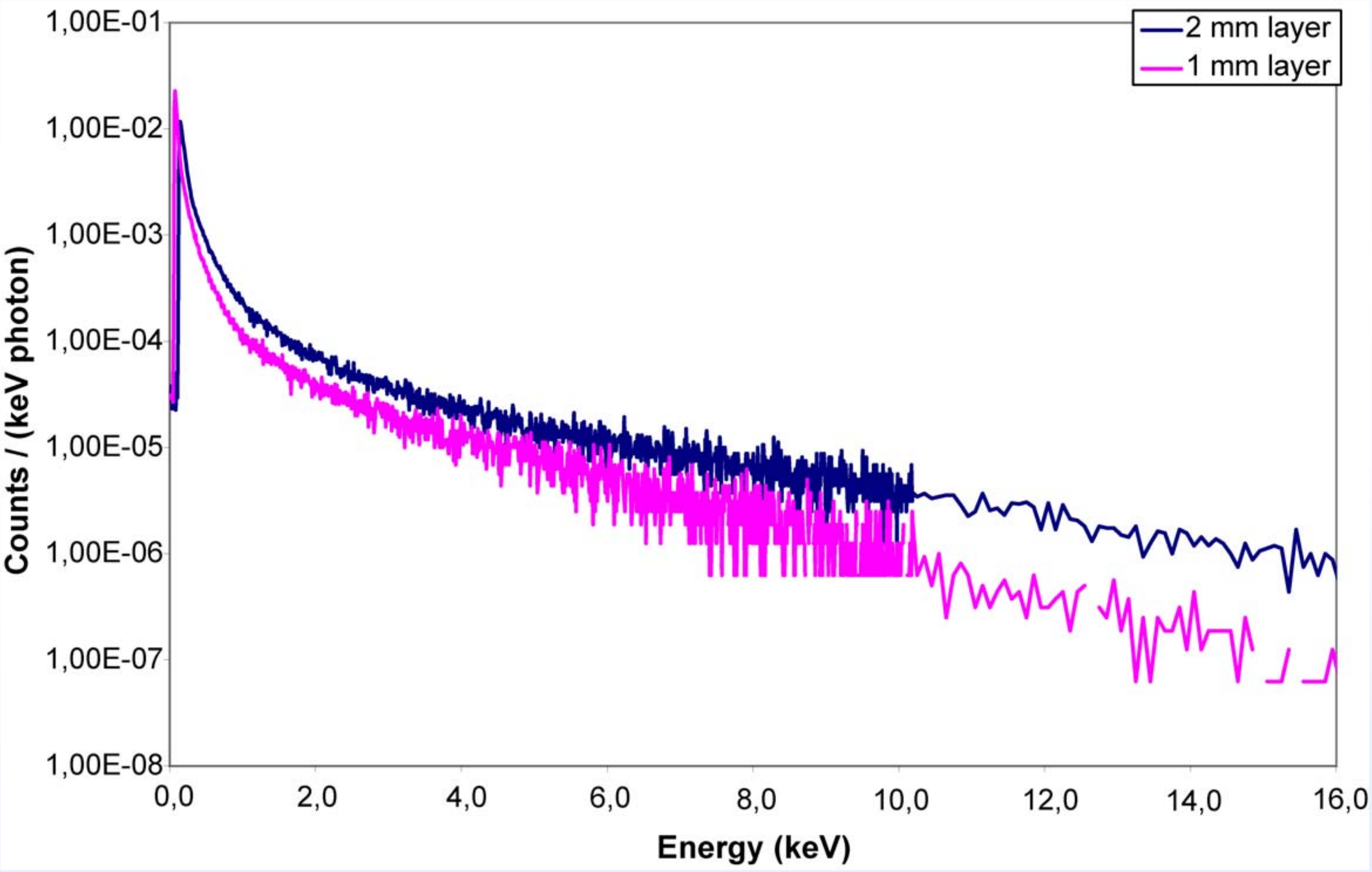
FLUKA simulation





Energy Deposit (2)

- 0.2mm layer: Most probable=145eV
- 0.1mm layer: Most probable=75eV



Slide Added after the workshop (on March 14, 2008)

- **After discussions at the workshop it turns out that the following statements should be added:**
  - **The plot on slide 23 has log scale on the X axis.**
  - **The plots on slides 25/26 have linear scale.**
  - **This makes them hard to compare ....**
- **In the conclusions (slide 28) we should thus conclude:**
  - **The development of the effective Townsend coefficient (due to the space charge effect) with growing avalanche size differs from what is widely assumed in analytic models, becoming strongly negative in the final stage of an avalanche.**