

Precision Analysis of Electron Energy Deposition in Detectors Simulated by Geant4

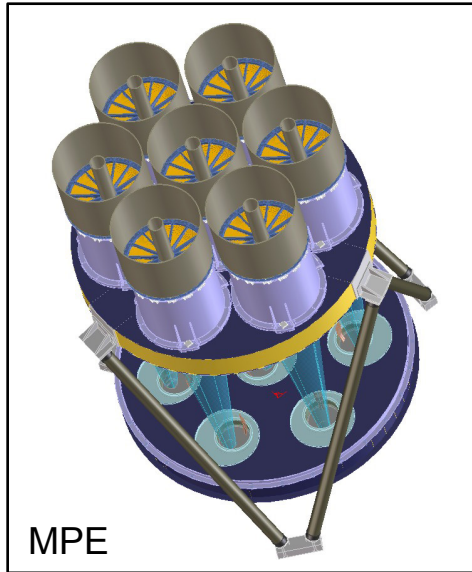
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M.G. Pia, G. Weidenspointner

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Anaheim, CA
Oct. 29 – Nov. 3, 2012

Why electrons (in) matter

- e^- are of **fundamental importance** for a multipurpose Monte Carlo tool such as Geant4
 - most detectors: measured signal is energy deposited by ionization, i.e. energy imparted on e^-
 - many applications: e^- are primary particles, or important constituents of a particle cascade
- e^- are intrinsically **difficult to simulate**
 - photons: discrete interactions
 - electrons: on microscopic level, discrete interactions, but usually a condensed transport scheme is employed to avoid IR divergence
 - ⇒ requires model for multiple scattering (continuous energy loss)
 - ⇒ Geant4: mix of continuous and discrete energy loss

eROSITA



- eROSITA:
 - extended **R**oentgen **S**urvey with an **I**maging **T**elescope **A**rray
 - launch 2014 on Russian-German mission Spectrum-X-gamma
 - energy range 200 eV to 10 keV
 - first imaging all-sky survey in 2.5 – 10 keV
 - ⇒ observation of 10^5 clusters of galaxies
 - ⇒ structure formation, dark energy, ...
 - Seven X-ray telescopes, each with a pnCCD developed at MPI HLL
 - pnCCD calibration
 - ⇒ X-ray spectral response of pnCCDs (external or on-chip optical/UV blocking filter)

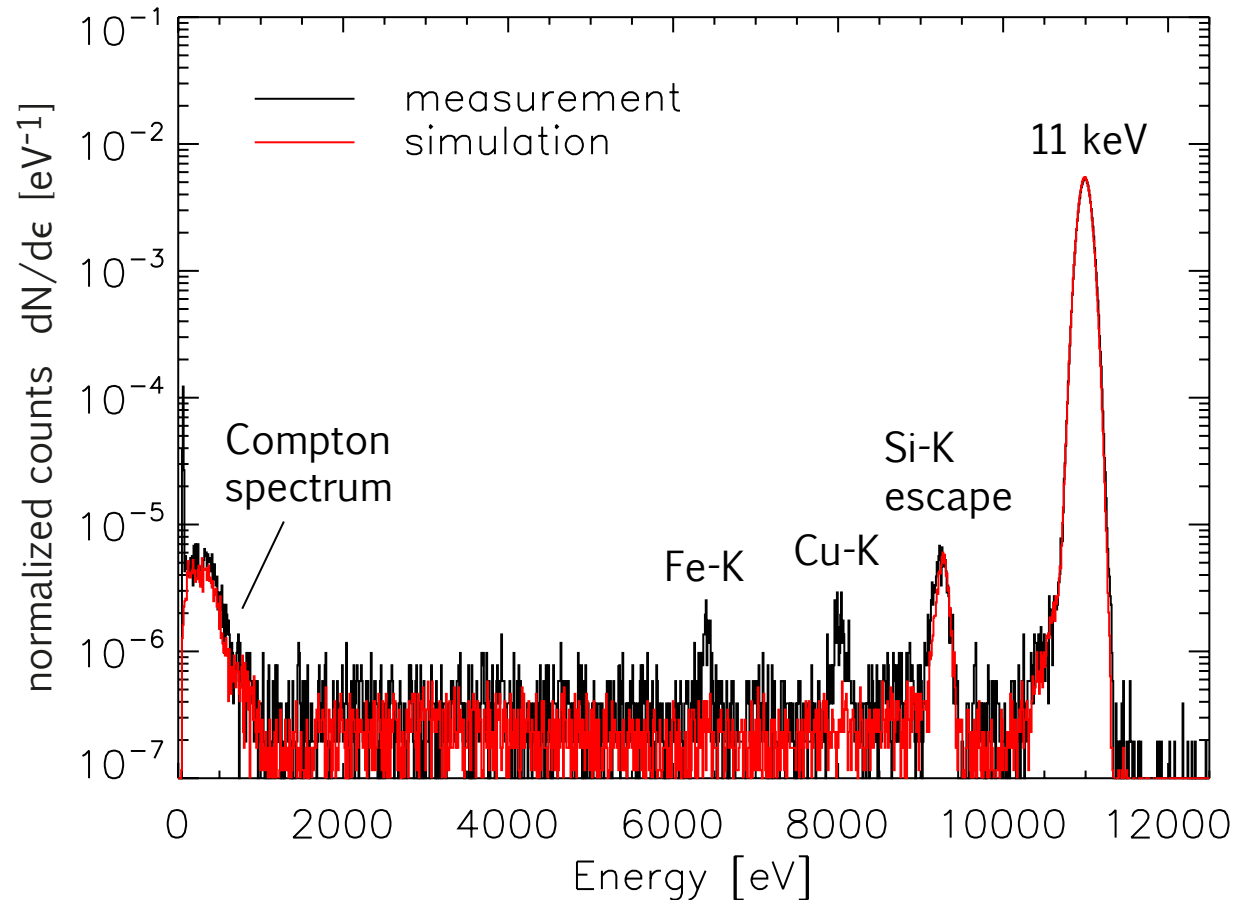
eROSITA X-ray spectral response

Measurement: BESSY II at PTB Berlin – 11 keV photons

Simulation: Geant4 version 9.2 p02 + HLLDetSim

S. Granato

good agreement



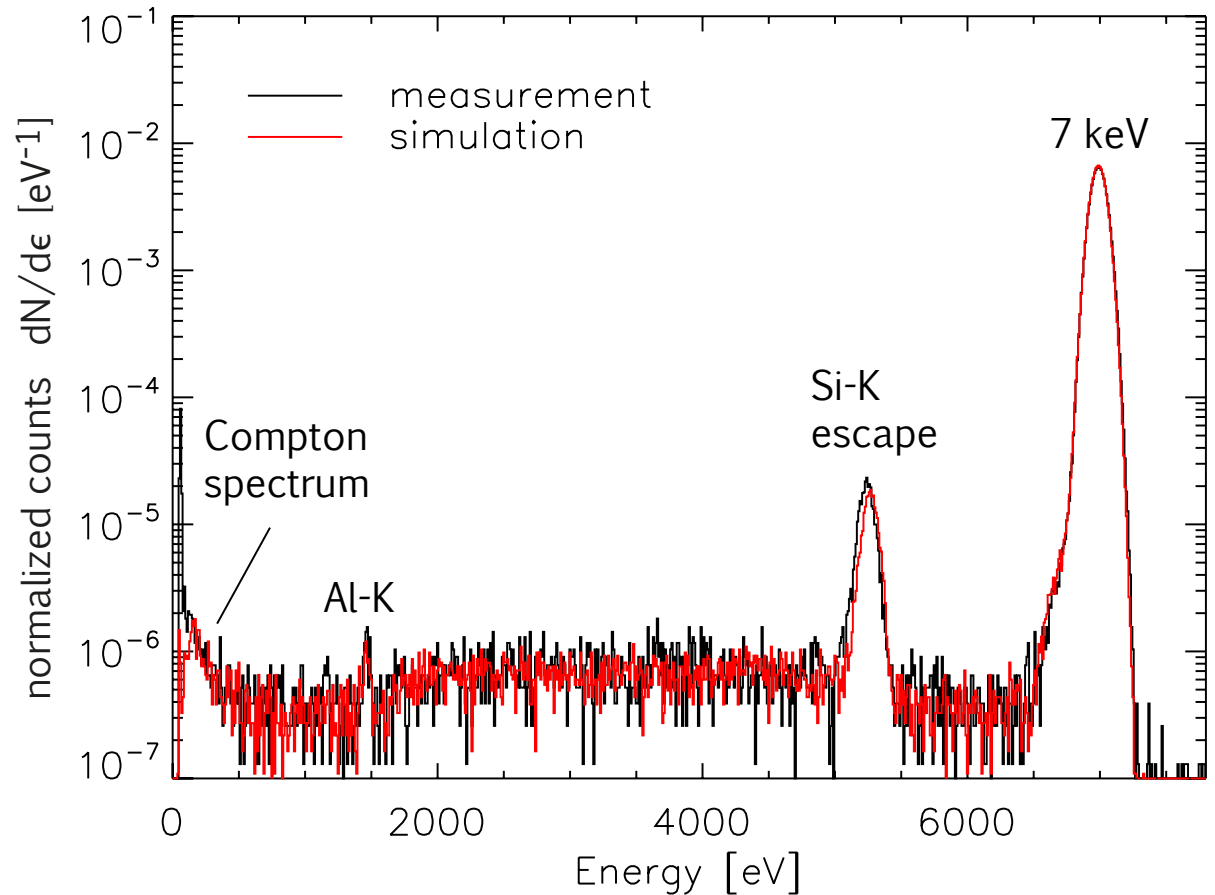
eROSITA X-ray spectral response

Measurement: BESSY II at PTB Berlin – 7 keV photons

Simulation: Geant4 version 9.2 p02 + HLLDetSim

S. Granato

good agreement



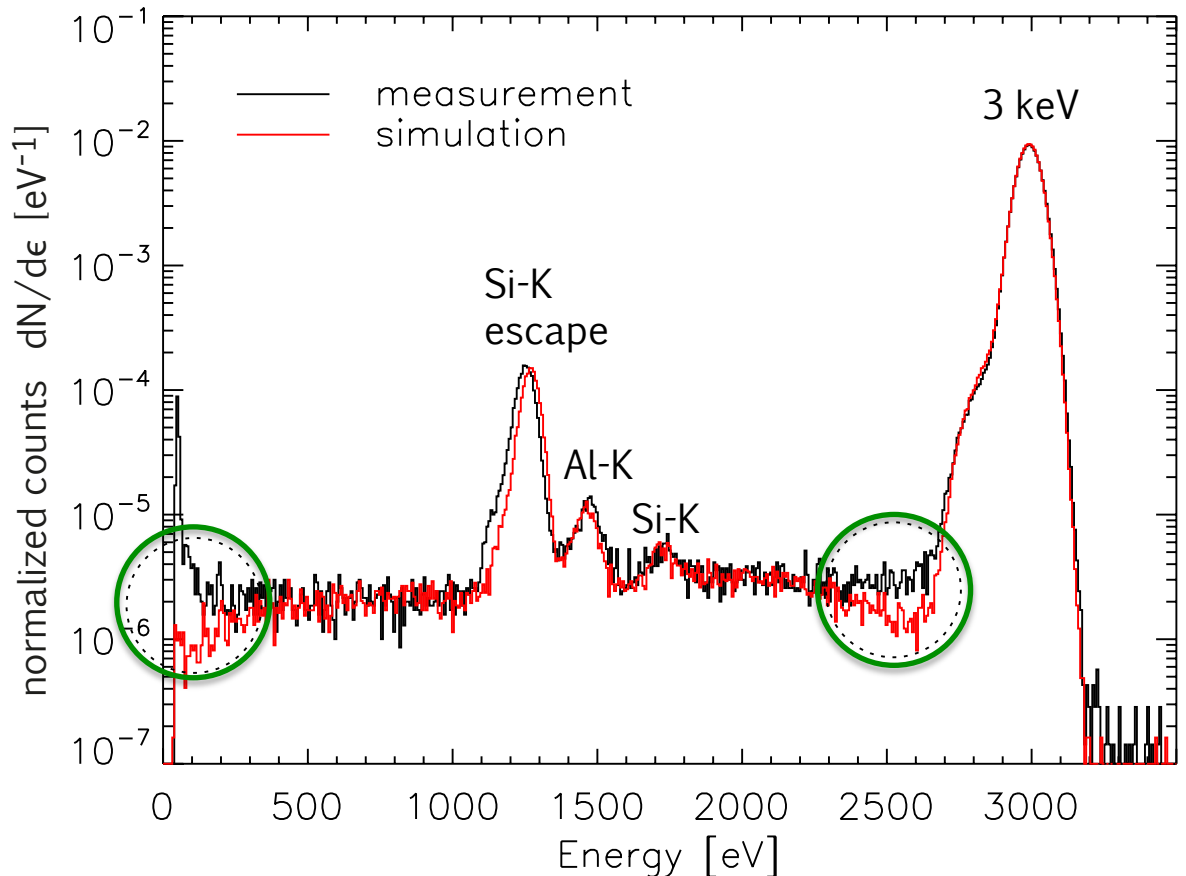
eROSITA X-ray spectral response

Measurement: BESSY II at PTB Berlin – 3 keV photons

Simulation: Geant4 version 9.2 p02 + HLLDetSim

S. Granato

overall good agreement,
but deviations due to
low energy e^-
generated close to
volume boundaries
(photon absorption
length $3 \mu\text{m}$)



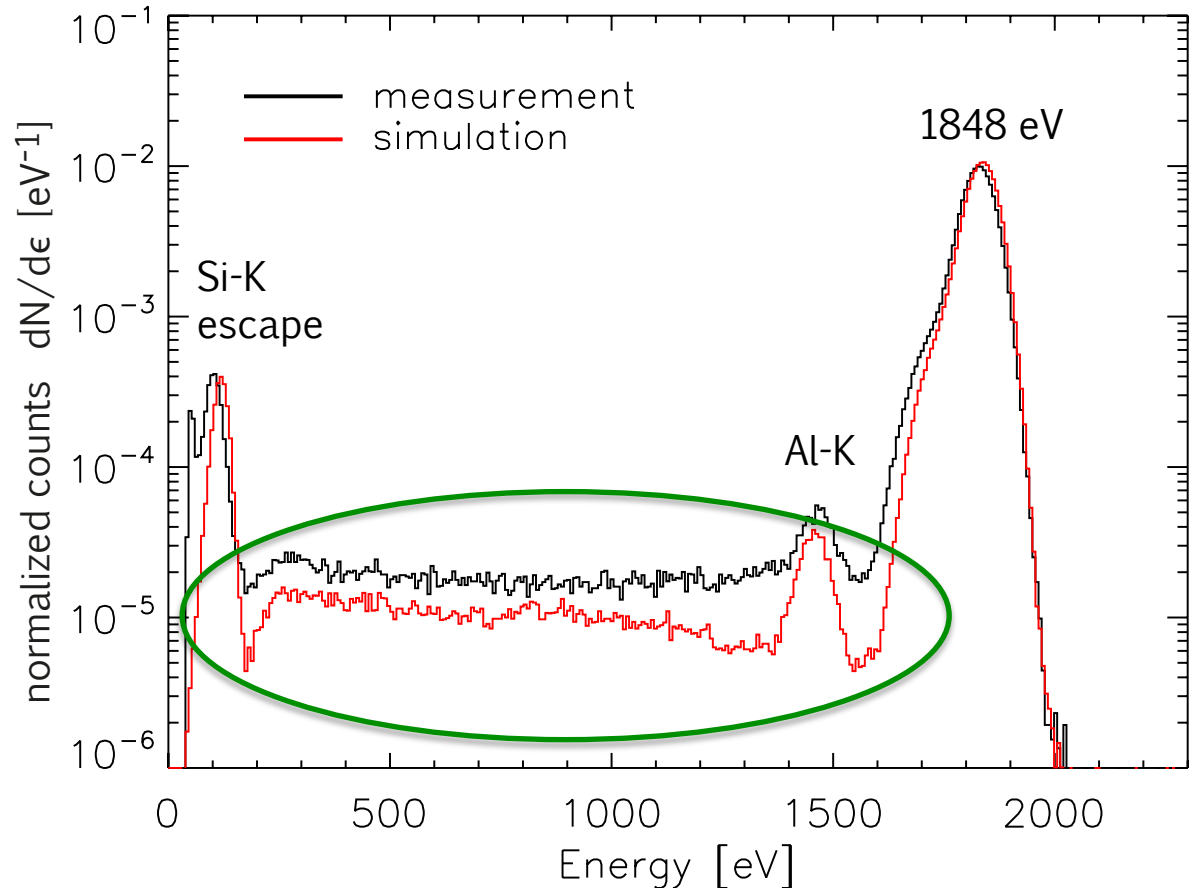
eROSITA X-ray spectral response

Measurement: BESSY II at PTB Berlin – 1.848 keV photons

Simulation: Geant4 version 9.2 p02 + HLLDetSim

S. Granato

No good agreement,
problems due to
low energy e^-
generated close to
volume boundaries
(photon absorption
length $< 2 \mu\text{m}$)



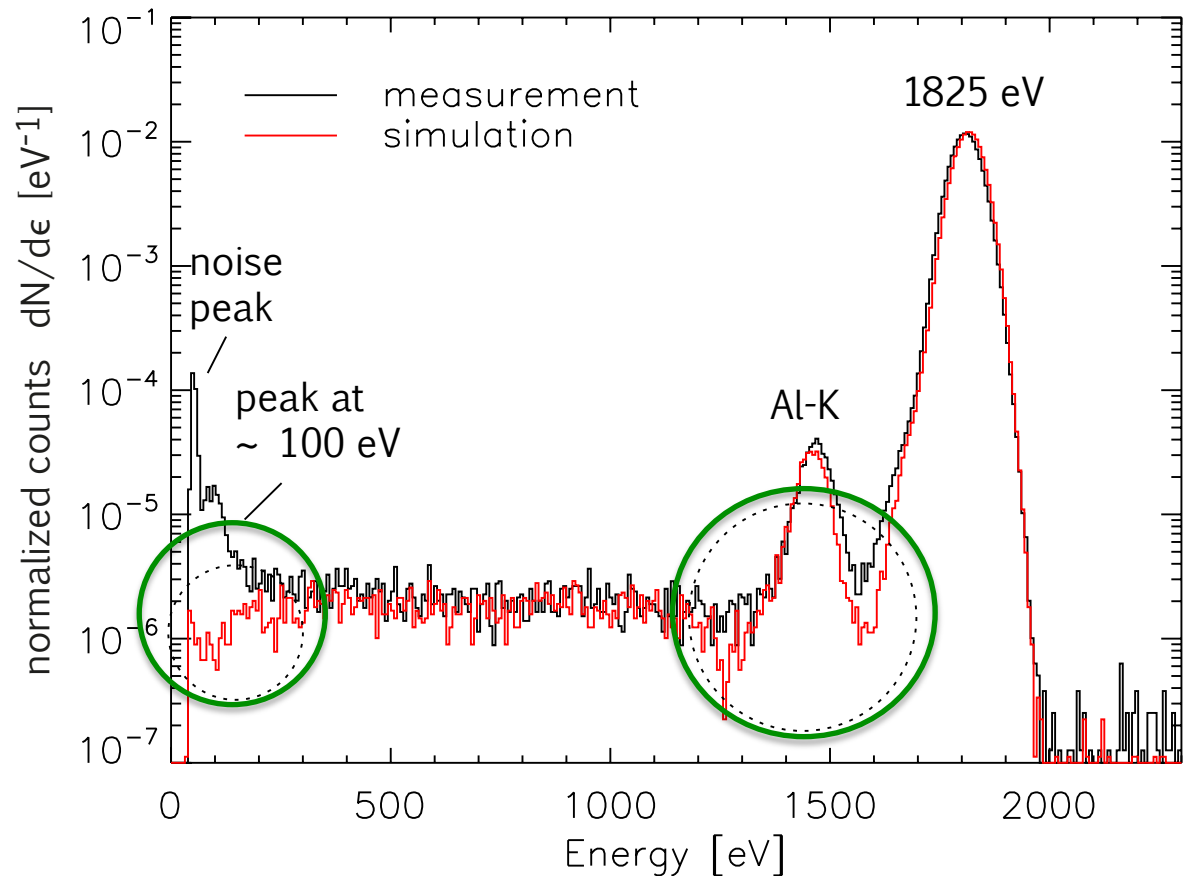
eROSITA X-ray spectral response

Measurement: BESSY II at PTB Berlin – 1.825 keV photons

Simulation: Geant4 version 9.2 p02 + HLLDetSim

S. Granato

overall good agreement,
but deviations due to
low energy e^-
generated close to
volume boundaries
(photon absorption
length $< 20 \mu\text{m}$)



e^- and X-rays at volume boundaries

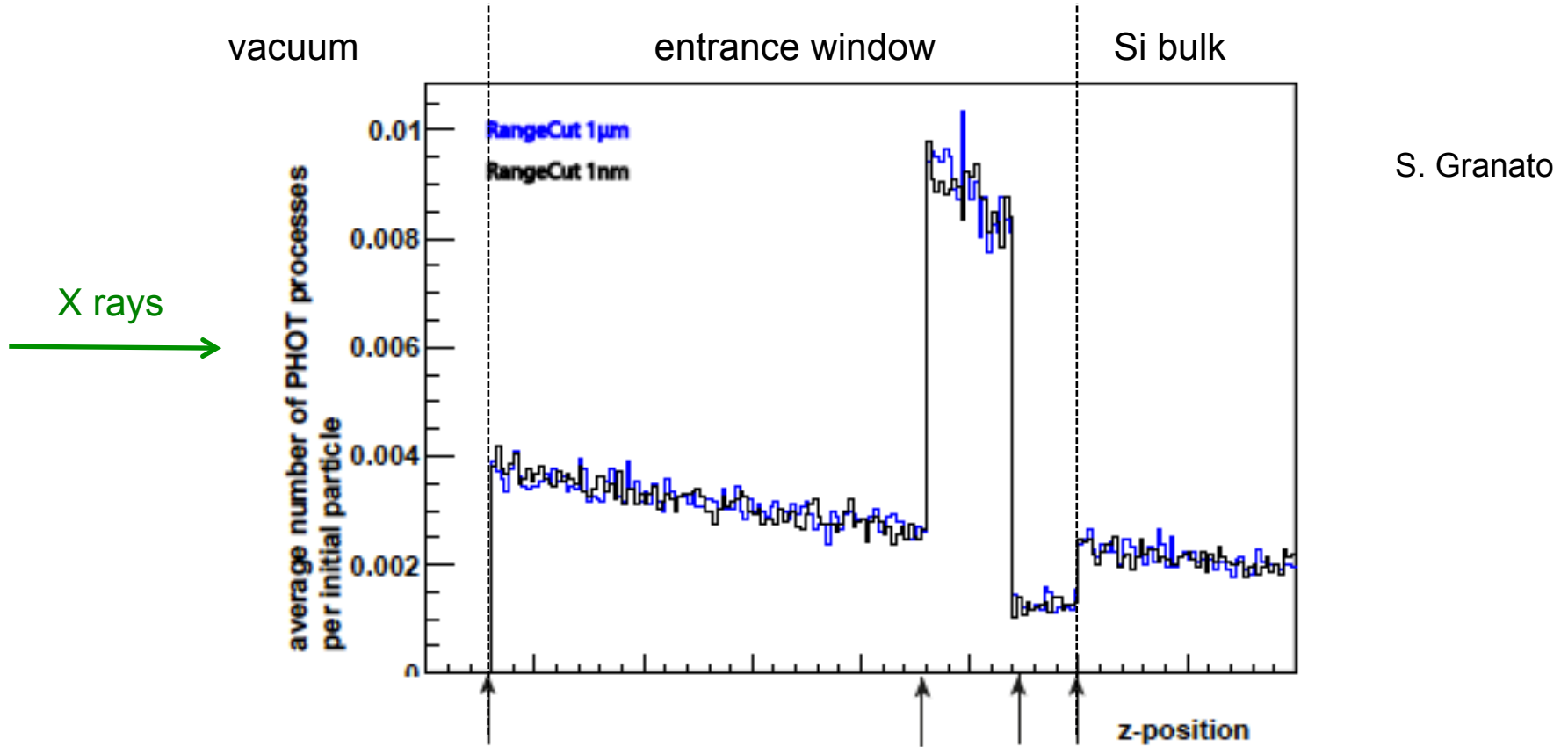
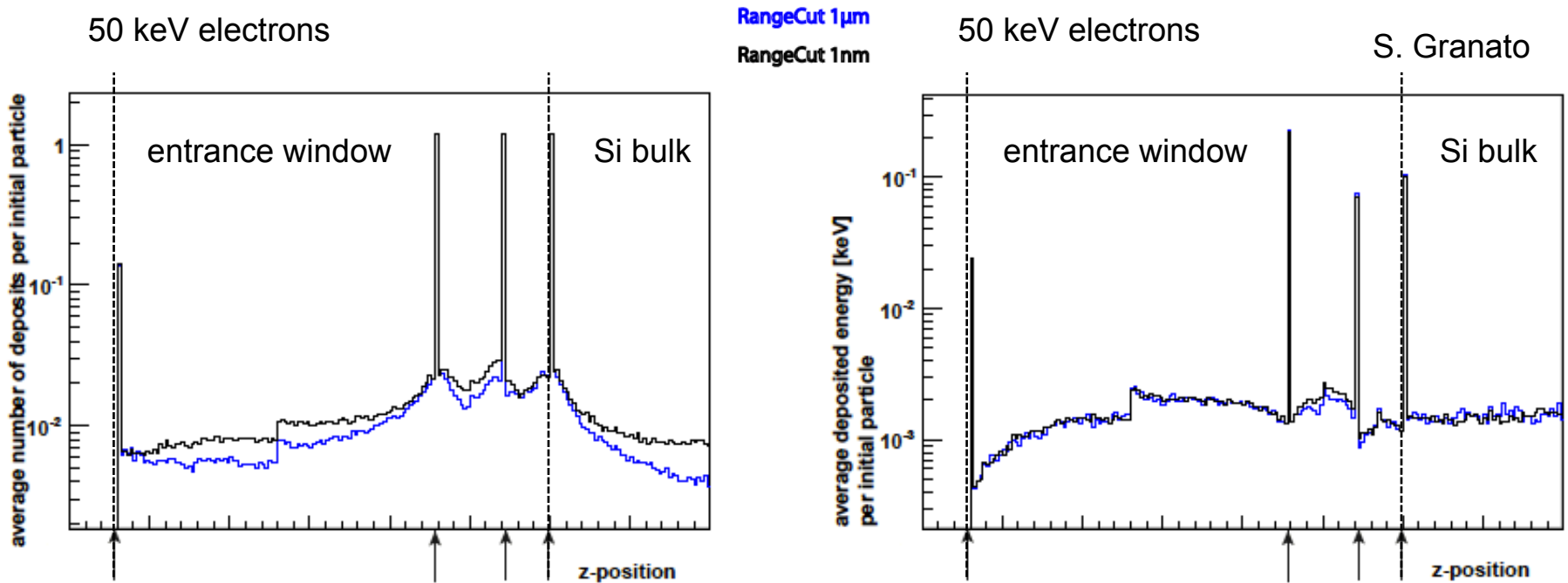


Photo-electric effect: expected behaviour at volume boundaries

e⁻ and X-rays at volume boundaries



(a) number of energy deposits vs. z-position

(b) deposited energy vs. z-position

Electron energy loss by ionization:
pronounced discontinuities / spikes at volume boundaries

Origin unknown...

(related to multiple scattering algorithm?)

Validation of Geant4 with Sandia electron data

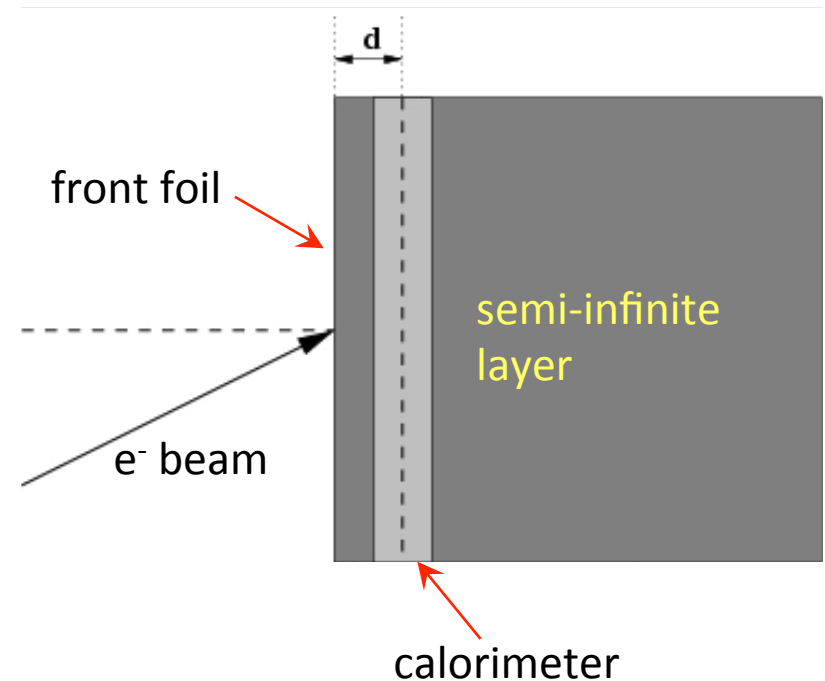
- **validation** of Geant4 requires adequate experimental data
- to our knowledge: no suitable experimental electron data for energies below 25 keV
- BUT: Sandia National Laboratory precision data for 25 keV – 1 MeV e^- , for various incidence angles and materials
 - ⇒ **reference for validation of electron transport models**
 - SAND79-0414, Lockwood et al., 1987a
Calorimetric Measurement of Electron Energy Deposition in Extended Media – Theory vs Experiment
⇒ validate energy deposition as a function of depth
 - SAND80-1968, Lockwood et al., 1987b
Electron Energy and Charge Albedos – Calorimetric Measurement vs Monte Carlo Theory
⇒ validate electron backscattering and total energy deposition

Validation of Geant4 with Sandia electron data

- status report
- work is ongoing
- current work based on and extends
A. Lecher, M.G. Pia and M. Sudhakar, 2009, TNS 56, pp. 398 ff.
*Validation of Geant4 Low Energy Electromagnetic Processes
against Precision Measurements of Electron Energy Deposition*
- same analysis procedure for consistency

Simulation configuration

- **Geometry:** as in experiment
- **e⁻/γ physics:**
 - low energy EEDL/EPDL (“Livermore”)
 - low energy Penelope
 - standard
- **Multiple scattering models:**
 - Urban
 - Goudsmit-Saunderson
- **Secondary e⁻ production threshold:**
 - 250 eV (low energy, Penelope)
 - 1 keV (standard)
- **Step limitation:**
 - 1, 10, 1000 μm
 - no limitation
- **Geant4 versions** (with latest patches)
8.1, 9.1, 9.2, 9.3, 9.4, 9.5, 9.6-β



Sandia79:

- calorimeter placed at different depths
- all volumes same material

Sandia80:

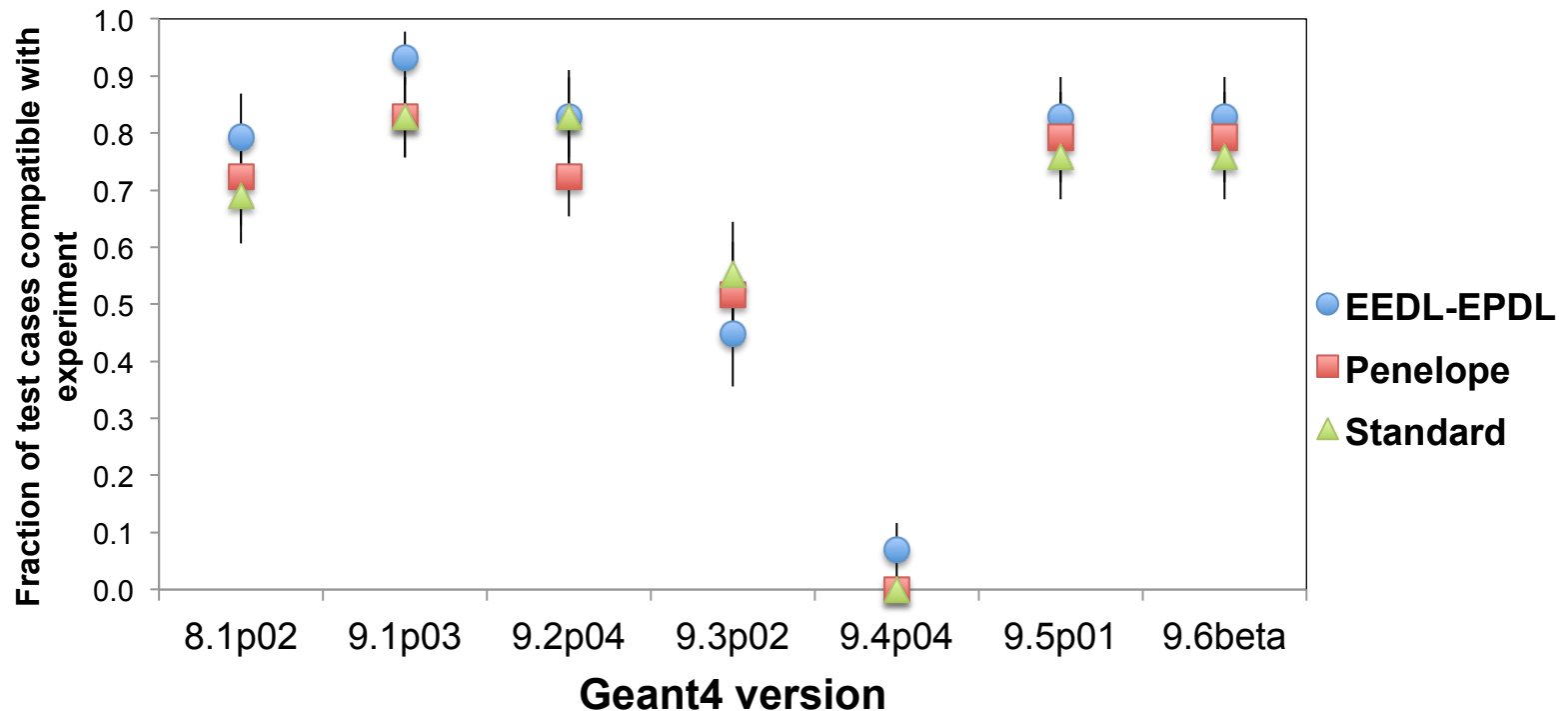
- single sensitive volume

Validation analysis

- **Compatibility** of simulation with experiment:
 - χ^2 test
 - χ^2 test case: target material, beam energy, beam incidence angle
 - significance of χ^2 test: $\alpha = 0.01$
 - **Efficiency** of a Geant4 physics model:
 - fraction of test cases in which simulation is compatible with experiment
- $$\epsilon_{G4model} = \frac{N_{\alpha>0.01}}{N_{tot}}$$
- **Significance** of difference in accuracy between models or versions:
 - categorical analysis

Total energy deposition

- Single volume of single-element material – simplest possible test case!
- Used default settings for all models (Geant4 optimized parameters)



⇒ highest efficiency (best version): Geant4 9.1

⇒ Geant4 9.4: very poor,

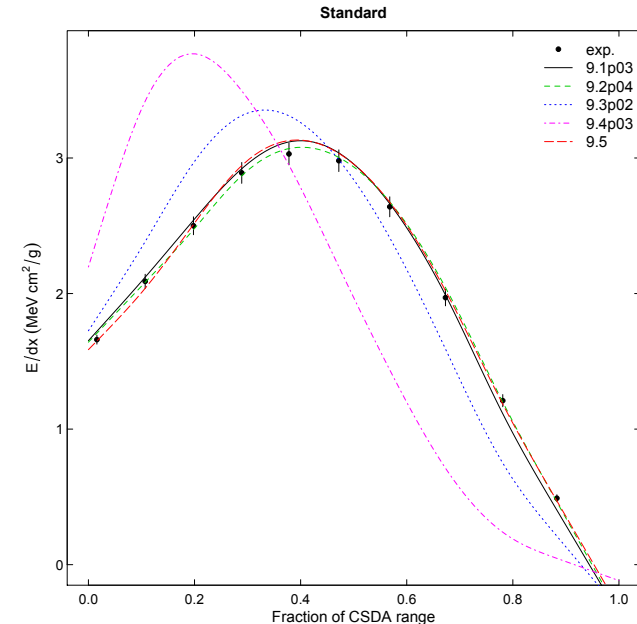
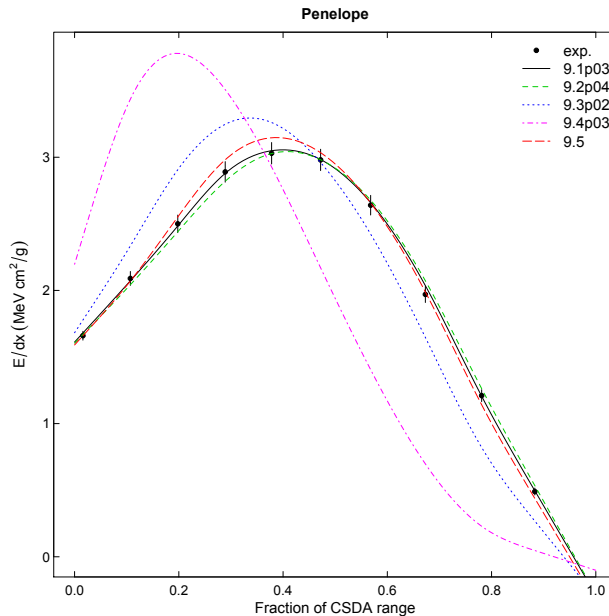
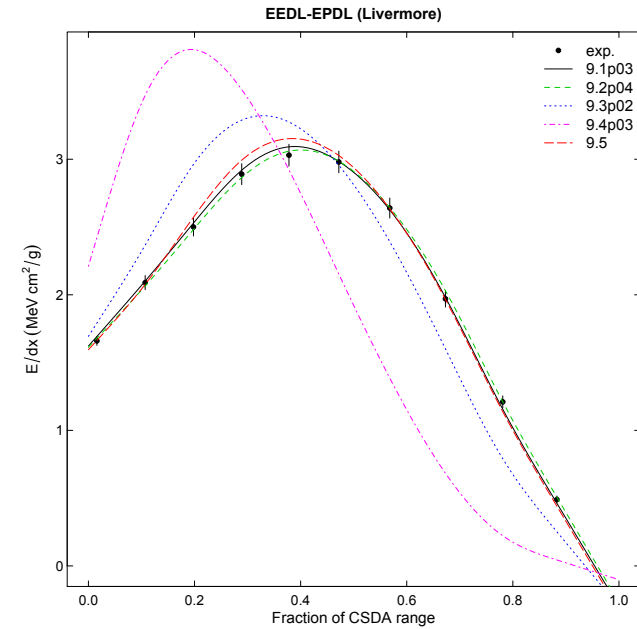
dependence on step limitation...!

Energy deposition profiles

- Layers of single-element material – second simplest possible test case!
- Used default settings for all models (Geant4 optimized parameters)

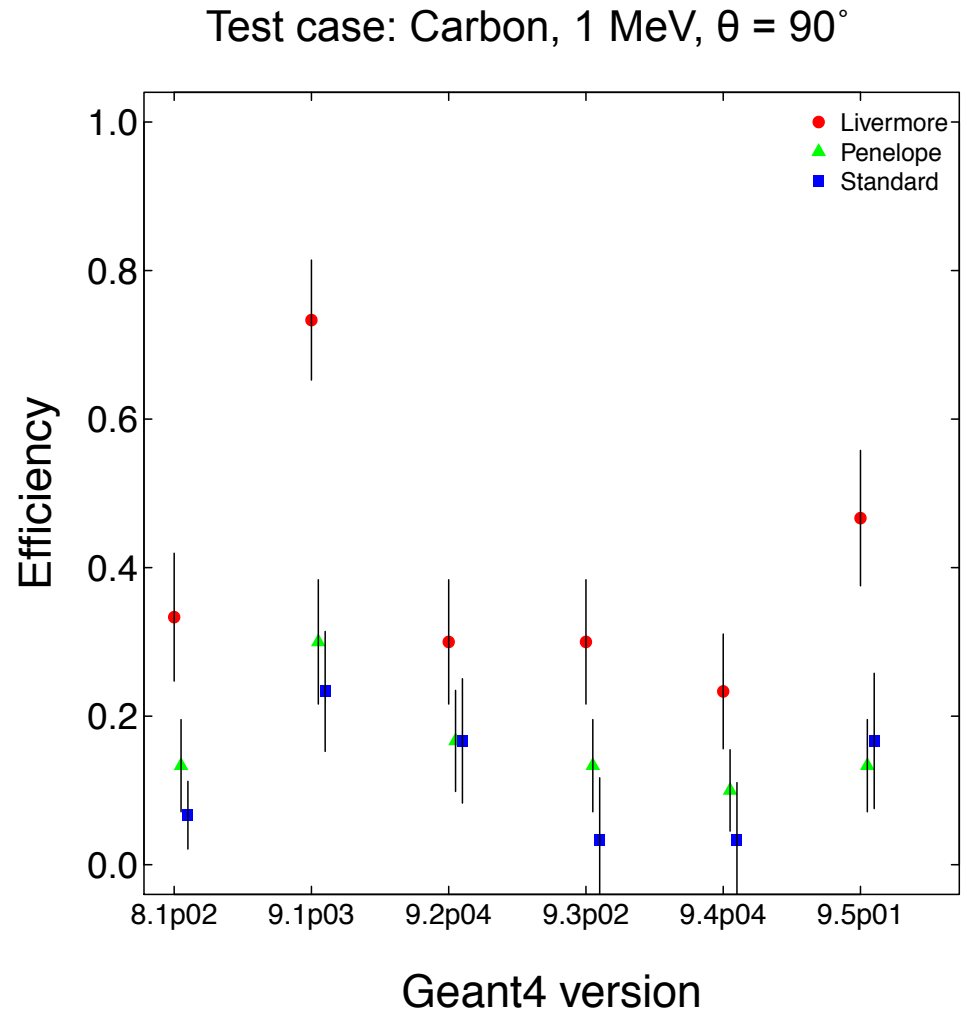
⇒ Best Geant4 version: 9.1

Test case: Carbon, 1 MeV, $\theta = 90^\circ$



Energy deposition profiles

- Most accurate Geant4:
 - version 9.1
 - “Livermore” model
- equivalence of Geant4 versions and models:
 - 9.1 and 9.5:
p-value = 0.008
 - “Livermore” and Penelope:
p-value = 0.002
 - “Livermore” and standard:
p-value < 0.001



Note: Geant4 9.6- β similar to 9.5

Conclusions

- Accuracy of e^- energy deposition in Geant4 depends on:
 - use case
 - software version
 - physics model
- Best choice for low energy electrons:
Geant4 version 9.1 with “Livermore” model
- Final results will be published soon in TNS – stay tuned...