EN Engineering Department

Initial (FLUKA) calculations for synchrotron radiation at TLep

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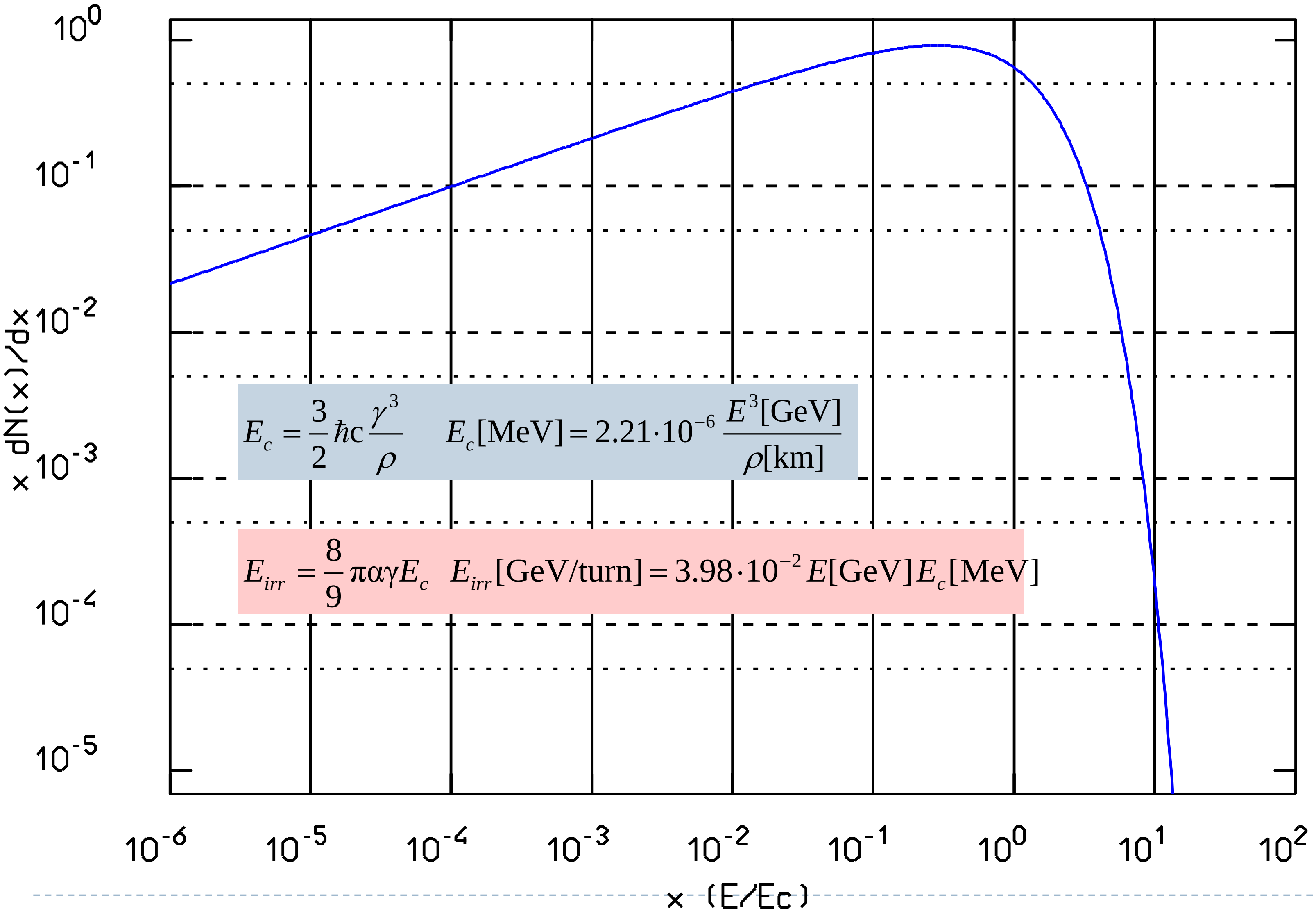
Outline

1. A few reminders about Synchrotron Radiation
2. FLUKA implementation
3. Some geometrical considerations
4. Photon attenuation and spectra for TLep
   1. Results
   2. Physical interpretation
5. Photoneutrons
6. Conclusions

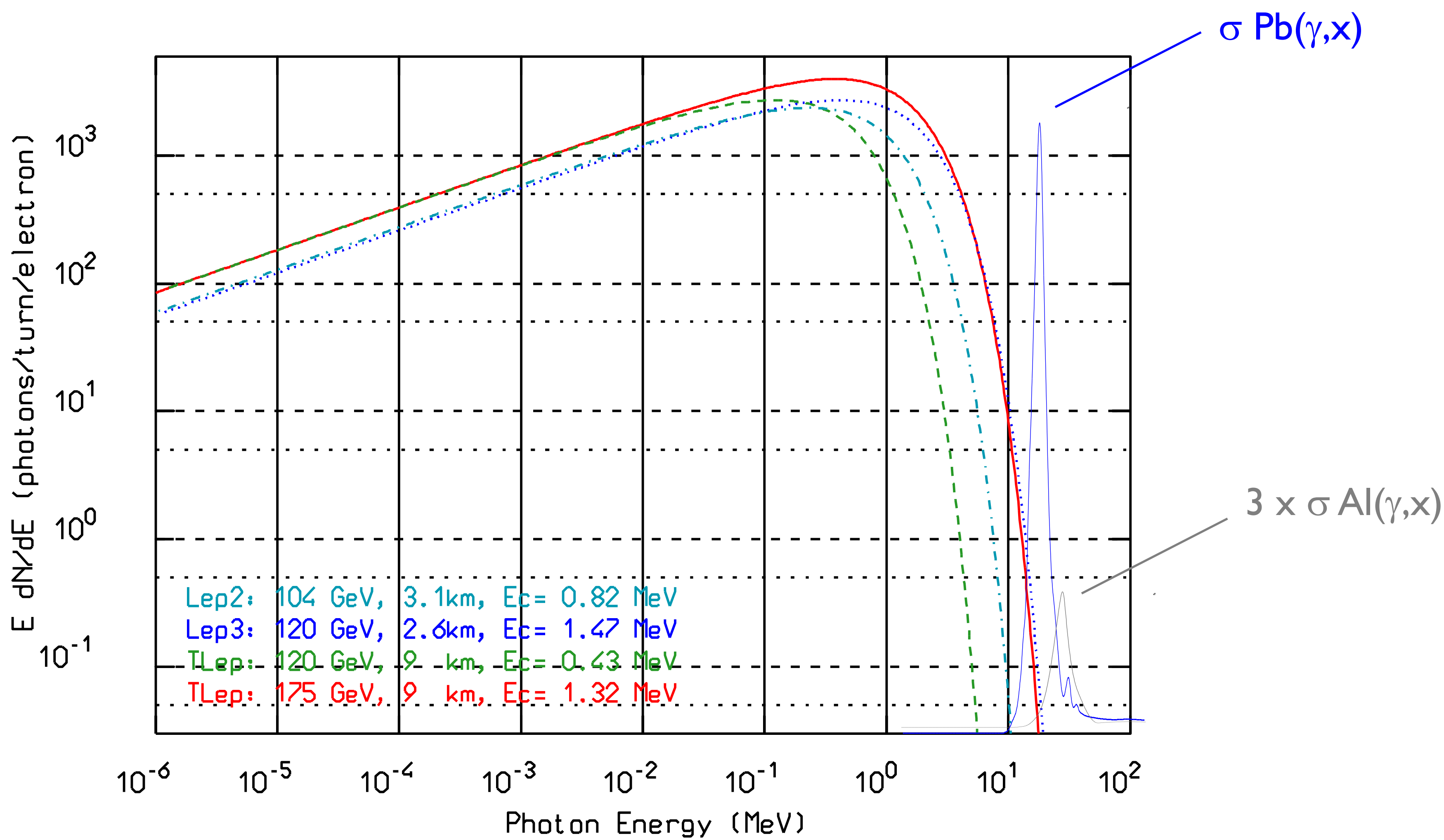
SR: generalities



$$E_c = \frac{3}{2}\hbar c \frac{\gamma^3}{\rho} \qquad E_c[\mathrm{MeV}] = 2.21\cdot 10^{-6}\,\frac{E^3[\mathrm{GeV}]}{\rho[\mathrm{km}]}$$

$$E_{irr} = \frac{8}{9}\pi\alpha\gamma E_c \qquad E_{irr}[\mathrm{GeV/turn}] = 3.98\cdot 10^{-2}\, E[\mathrm{GeV}]\, E_c[\mathrm{MeV}]$$

SR: generalities



FLUKA implementation of SR

- Sophisticated low energy photon transport including polarization effects for Compton (see next slide), photoelectric and coherent scattering, and full account for bound electron effects: already available in FLUKA since several years
- New: dedicated "generic" source for SR radiation accounting for:
  - ✓ Spectrum sampling
  - ✓ Polarization as a function of emitted photon energy
  - ✓ Angular distribution
  - ✓ Arbitrary orientation emitting particle vs magnetic field
  - ✓ Photon emission along arcs/helical paths

Compton scattering: dynamics

Klein-Nishina cross section (see for example Heitler, “The Quantum Theory of Radiation”):

$$\frac{d\sigma_{KN}}{d\Omega} = \frac{1}{4} r_e^2 \frac{k'^2}{k^2}\left[\frac{k}{k'} + \frac{k'}{k} - 2 + 4\cos^2\Theta\right]$$

Let $\vec{e}$ be the polarization vector of the incident photon, and $\vec{e}'$ that of the scattered one:

$$\cos\Theta = \vec{e}\cdot\vec{e}'$$

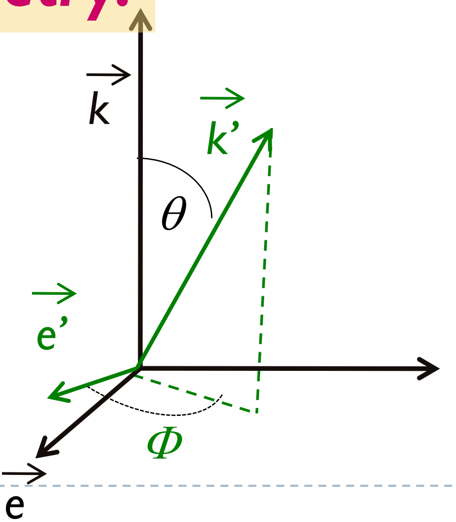
Split σ into the two components, ⊥ and || to $\vec{e}$ respectively (actually with $\vec{e}' \perp$ to the plane *(e,k')*, or contained in the plane *(e,k')*):

Important polarization effects breaking the azimuthal symmetry!

$$\frac{d\sigma_{\perp}}{d\Omega} = \frac{1}{4} r_e^2 \frac{k'^2}{k^2}\left[\frac{k}{k'} + \frac{k'}{k} - 2\right]$$

$$\frac{d\sigma_{||}}{d\Omega} = \frac{1}{4} r_e^2 \frac{k'^2}{k^2}\left[\frac{k}{k'} + \frac{k'}{k} + 2 - 4\sin^2\vartheta\cos^2\Phi\right]$$

$$\cos^2\Theta = 1 - \sin^2\vartheta\cos^2\Phi$$



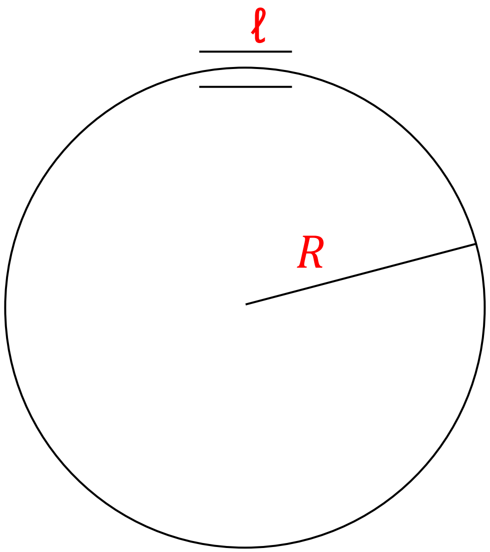
Tlep: parameters for the calculations

- E = 175 GeV, R = 9000 m
- E_{crit}= 1.32 MeV, ΔE=9.2 GeV/turn, dE/ds=1.63 keV/cm
- P = 9.2 I[mA] MW, dP/ds=1.6 I[mA] W/cm

- Simplified geometry, cylindrical Al beam pipe and (Pb) shielding
- SR photons generated and tracked above 100 eV (99.999% of the total power), average energy of the photons <E>=430 keV (E>100 eV)

A decrease of ~ 15% in R (eg Holzer talk) → a corresponding increase in E_c, power, and likely a factor a few in photoneutron production

Synchrotron Radiation Interception



R accelerator bending radius

ℓ dipole length

r vacuum chamber radius

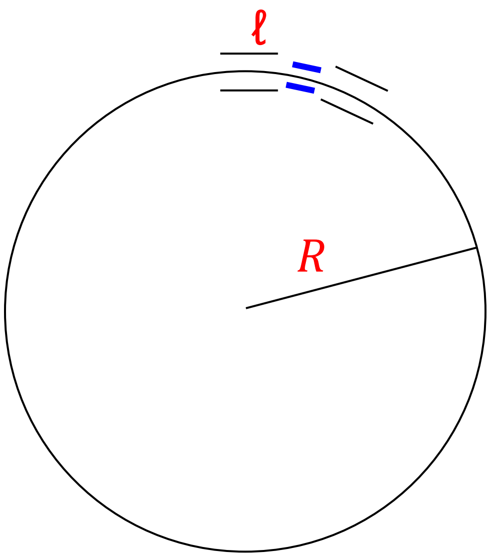
SR hitting inside the same dipole only if $\ell > \sqrt{2\,r\,R}$

for R= *9 km and* r= *4.5 cm* ℓ > *28.5 m*

for R= *3.1 km and* r= *6.5 cm (LEP2)* ℓ > *20 m*

totally escaping (→ hitting downstream elements) for shorter dipoles

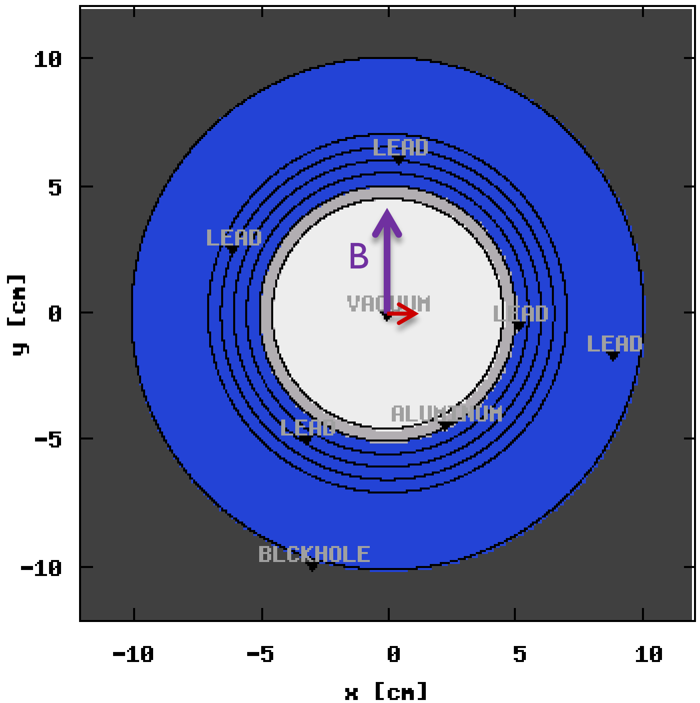
Pb shielding in the interconnects ?



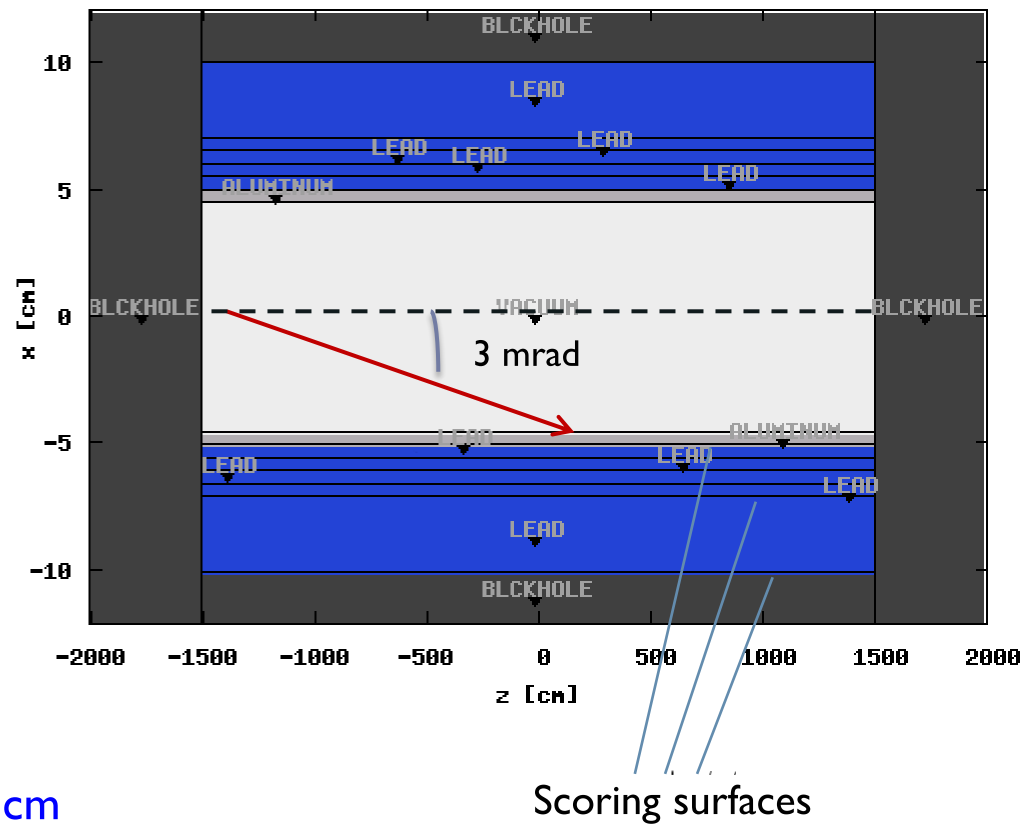
For the time being: impact angle as for "curved" geometry (eg, very short magnets, or very long curved ones)

Tlep Idealized geometry

Transverse cut

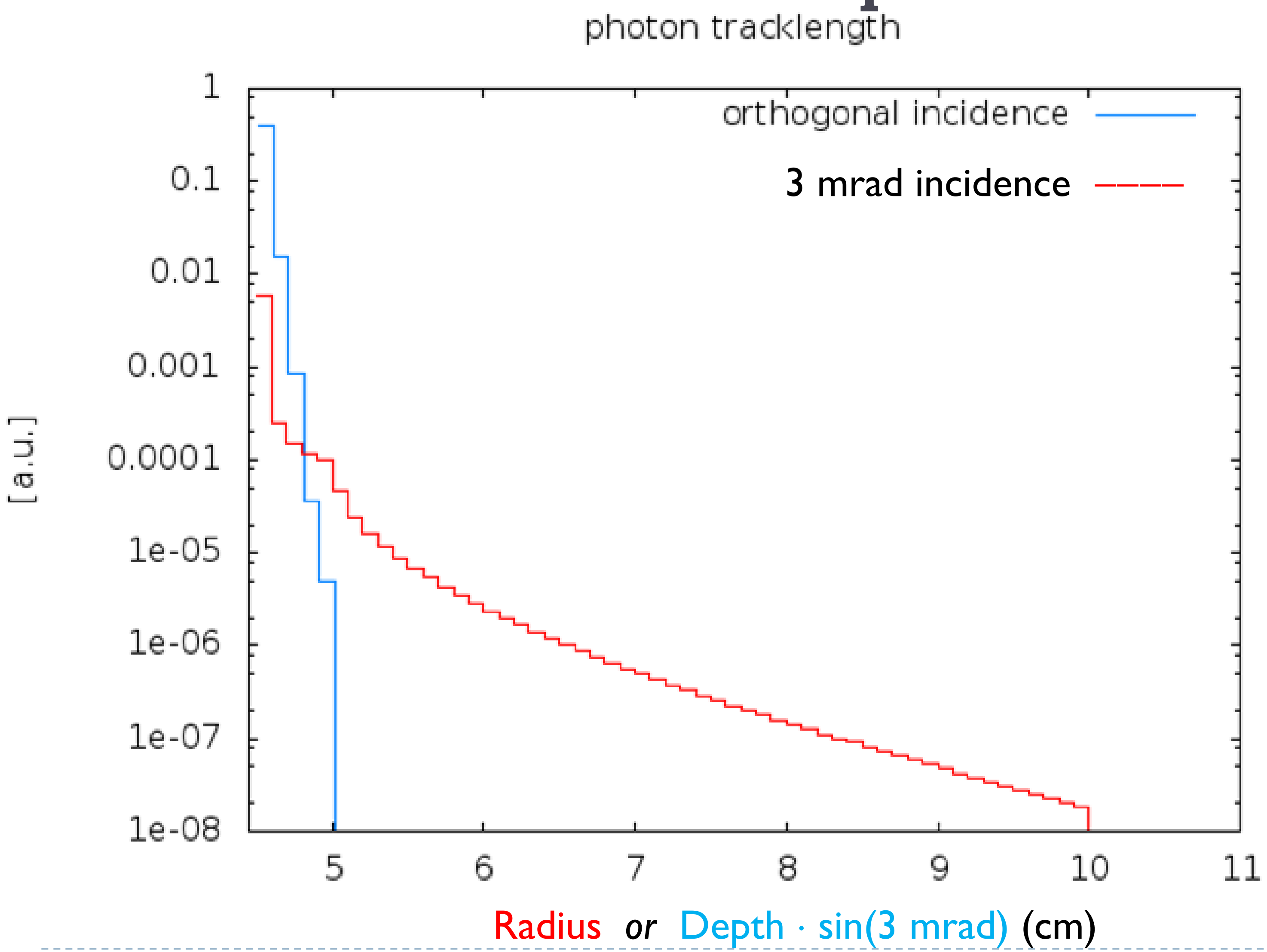


Longitudinal view

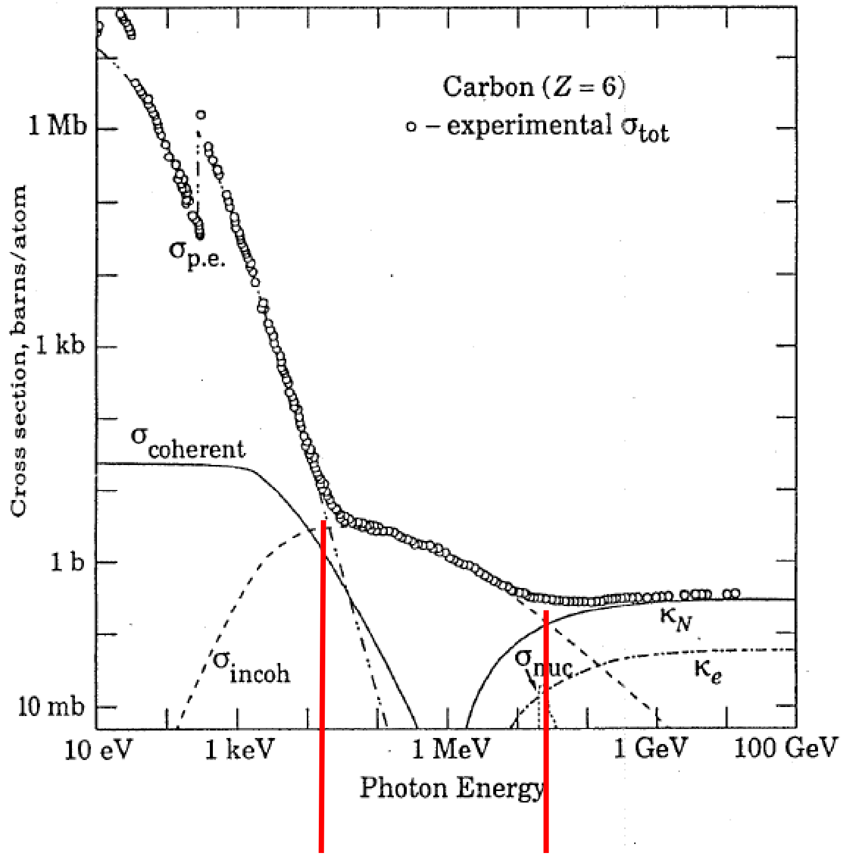


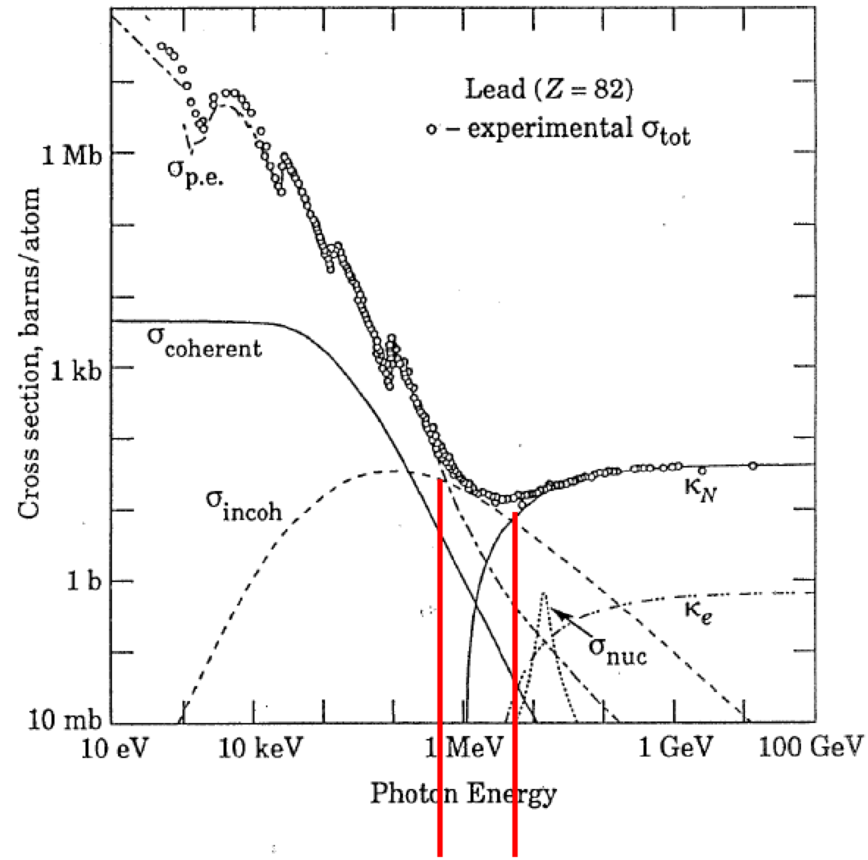
- ❑ Vacuum pipe: round R = 4.5 cm
- ❑ Aluminum pipe: thickness = 0.5 cm
- ❑ Lead shielding: thickness = 5.0 cm

How different is the attenuation vs the equivalent line-of-sight?



Photon cross sections:



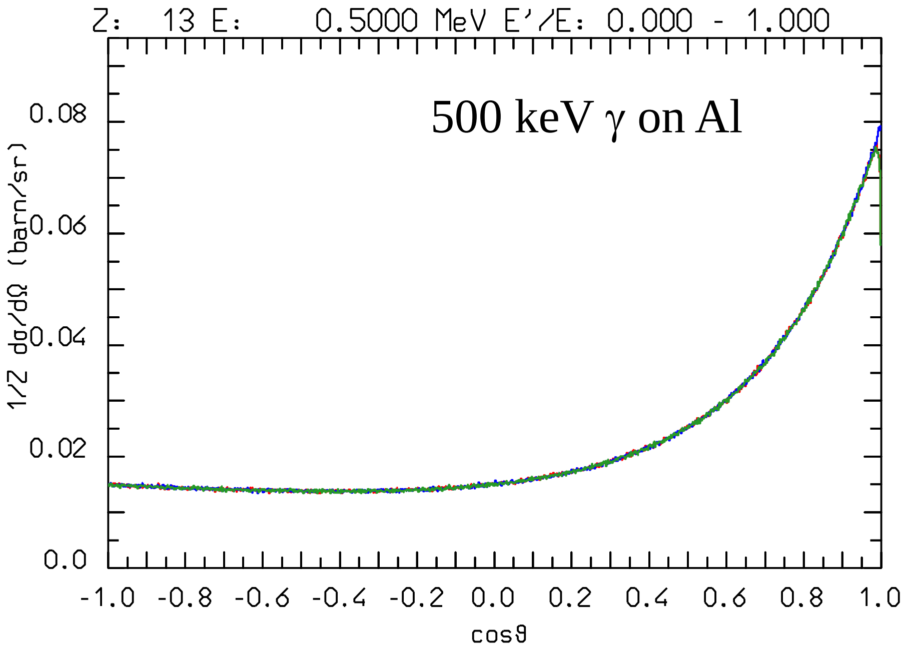


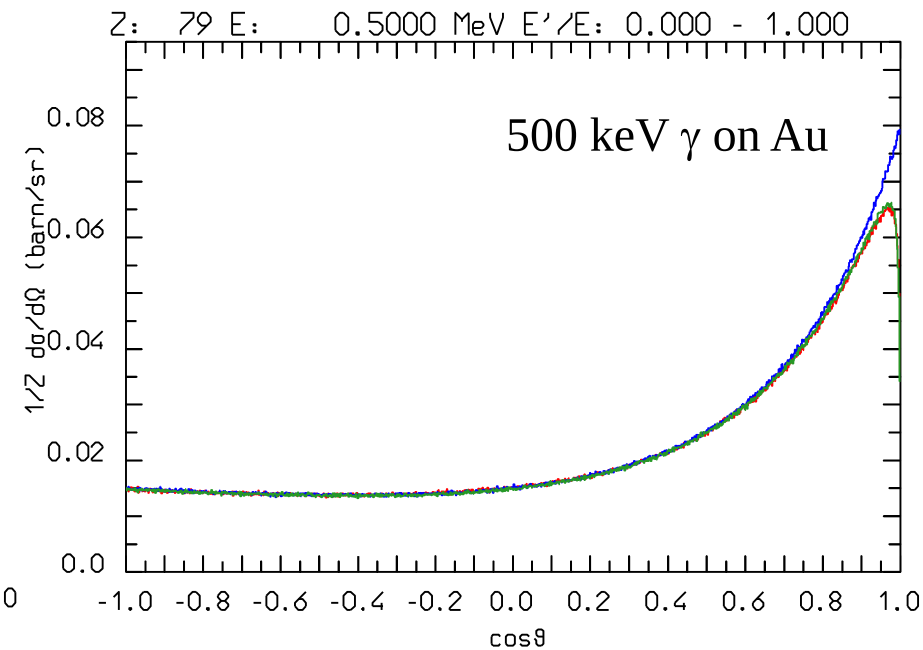
Photoelectric dominated | Compton dominated | Pair dominated

Photoelectric dominated | Compton dominated | Pair dominated

$\sigma_{p.e.}$=photoelectric cross section; σ_{incoh}=Compton cross section;
$\sigma_{coherent}$=Rayleigh cross section; σ_{nuc}=photonuclear cross section;
κ_N=pair production cross section, nuclear field;
κ_e=pair production cross section, electron field

Compton ang. distr.: examples

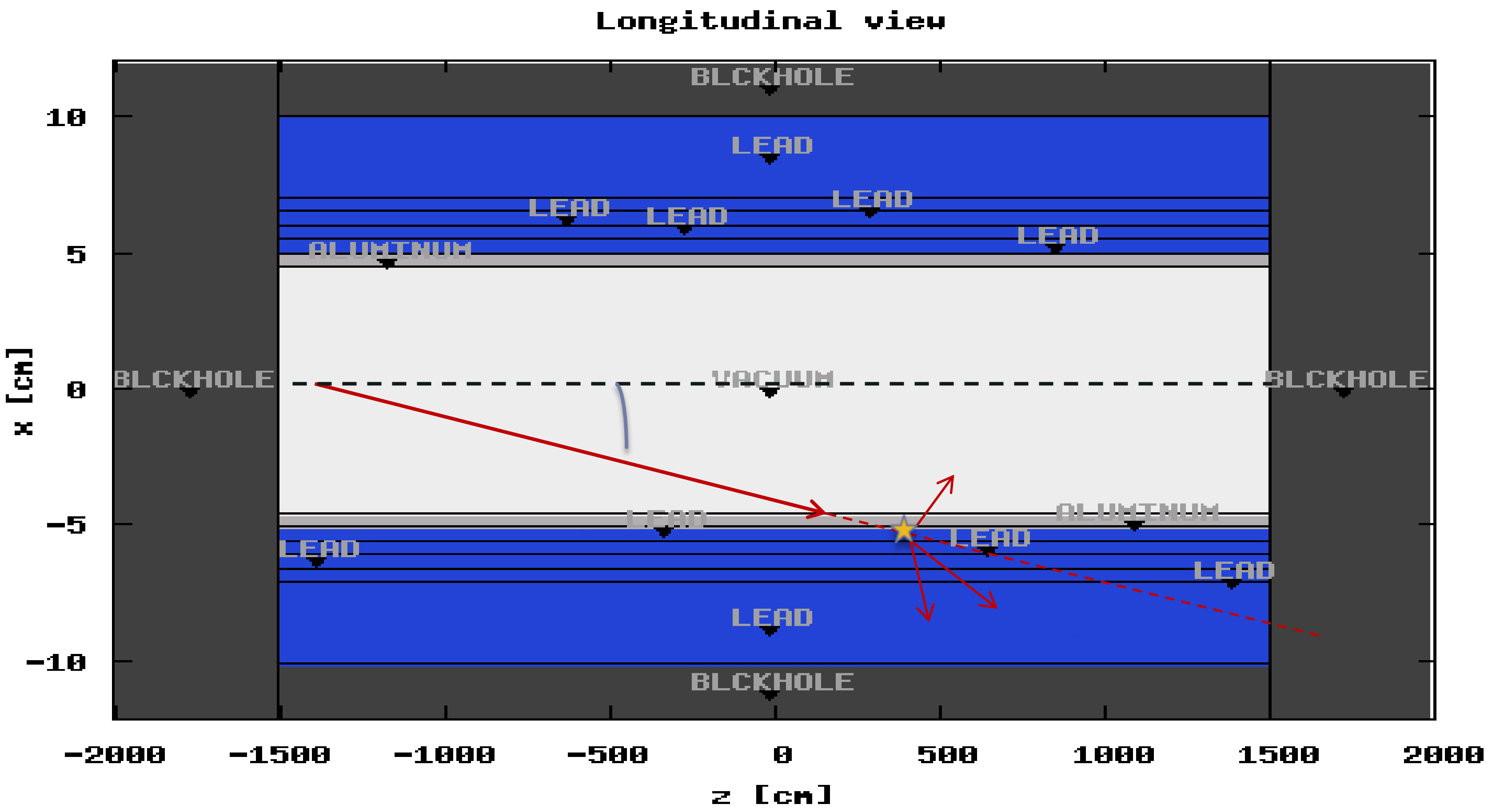




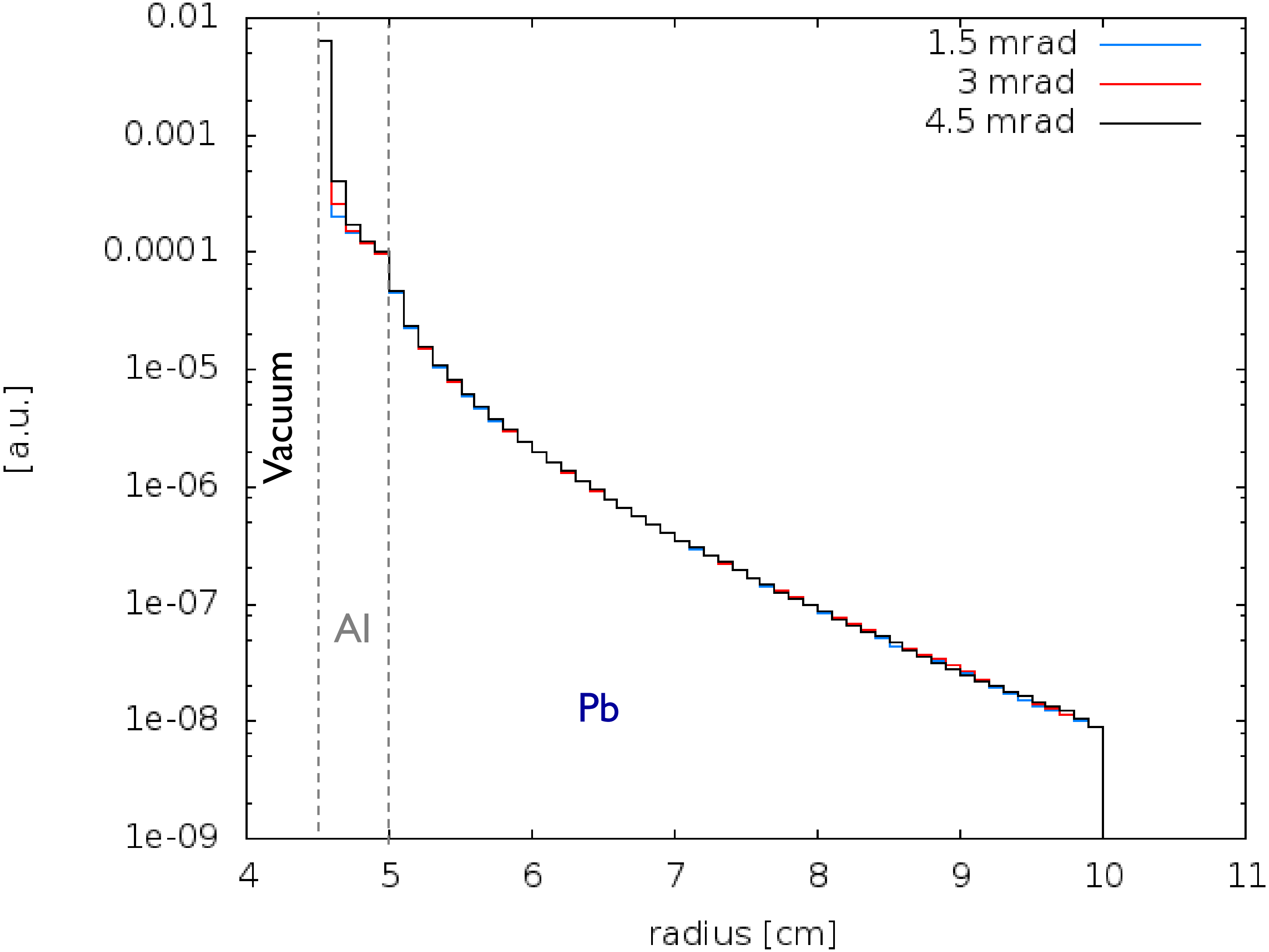
blue = free electron
green = binding with form factors
red = binding with shells and orbital motion

The physical explanation

The first scattering effect: after a Compton interaction the photon loses "memory" of the initial, grazing, incidence because of the much larger scattering angle

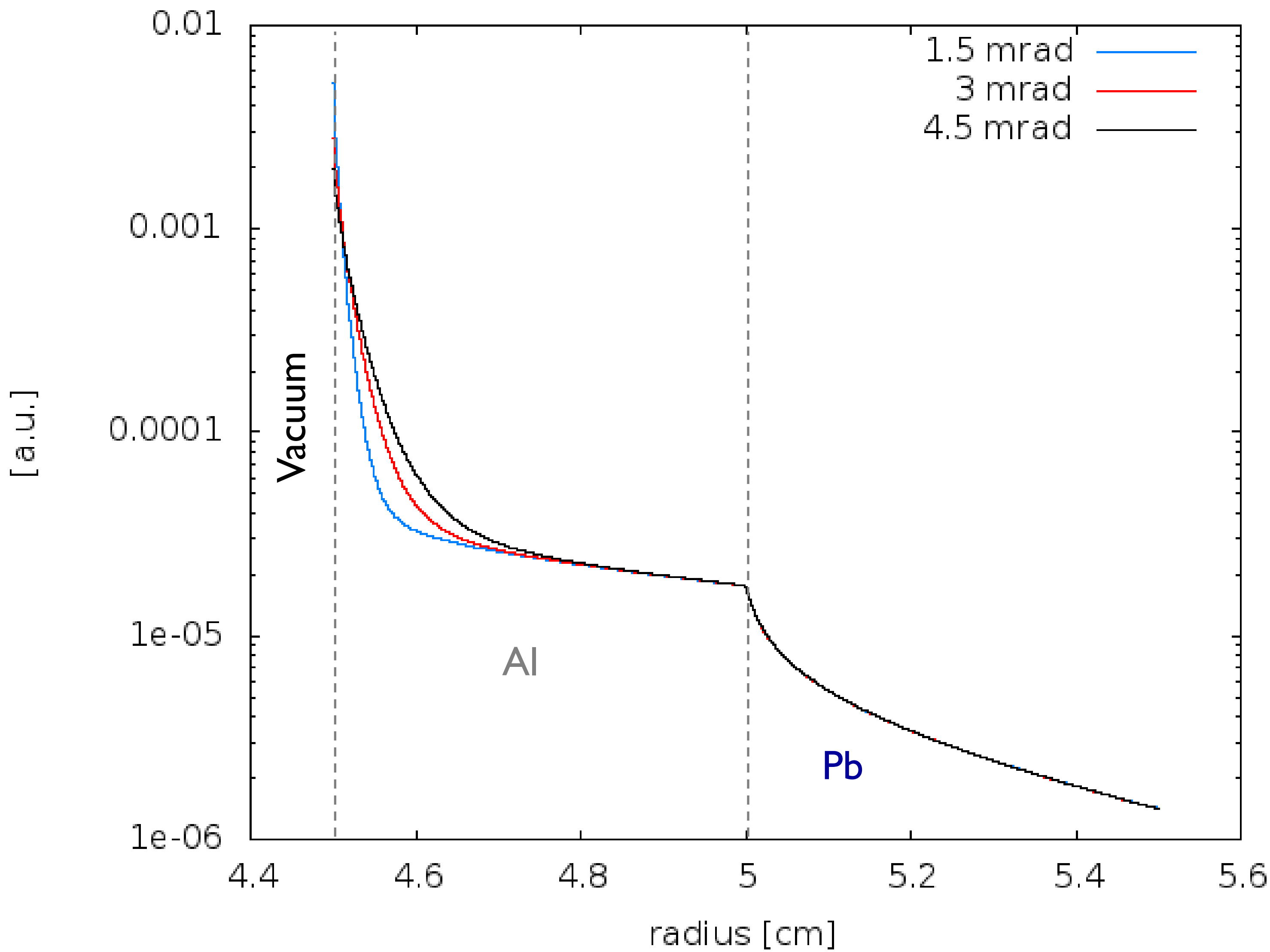


Photon fluence attenuation for 3 angles

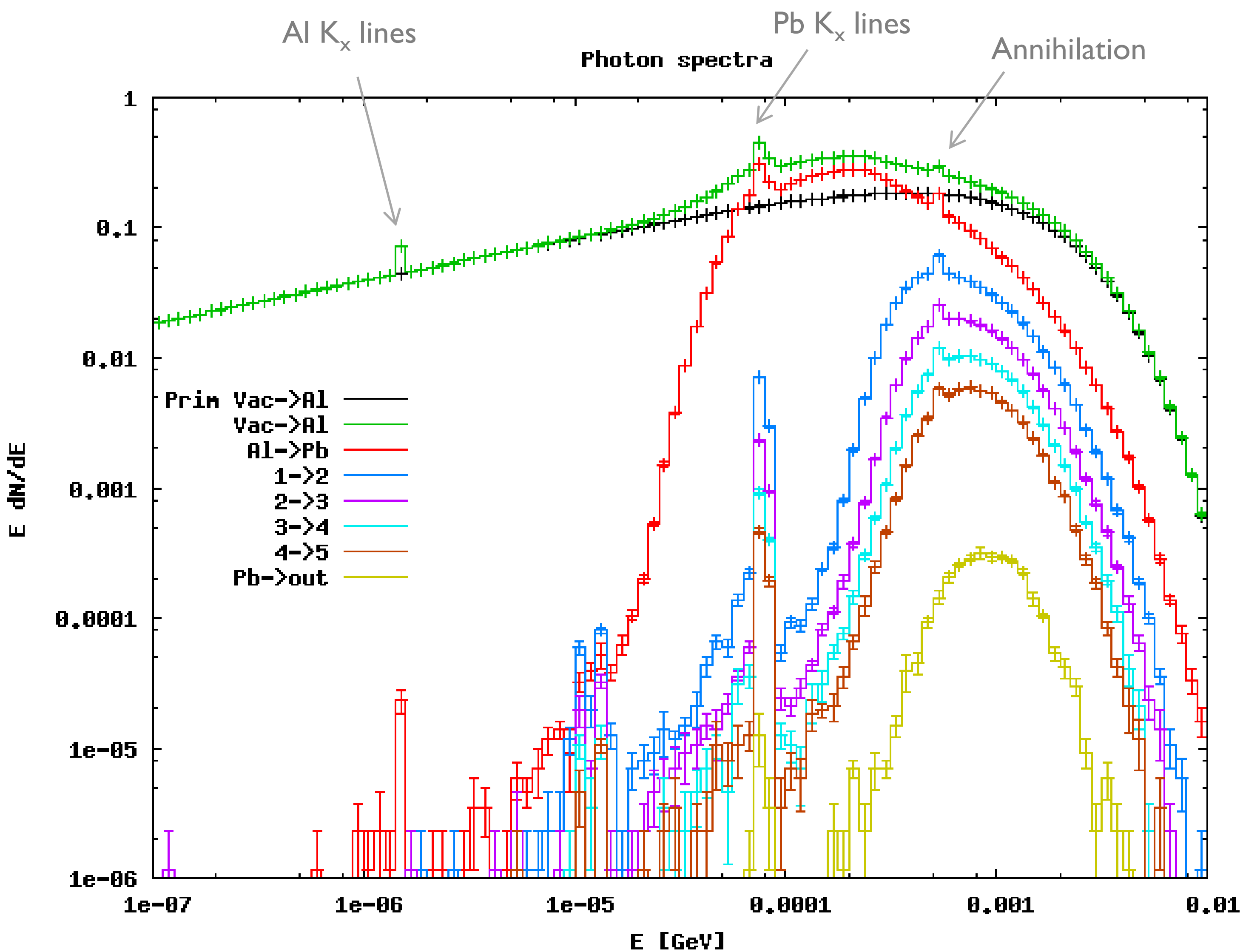


As expected, after a few mm the memory of the initial incidence angle is lost

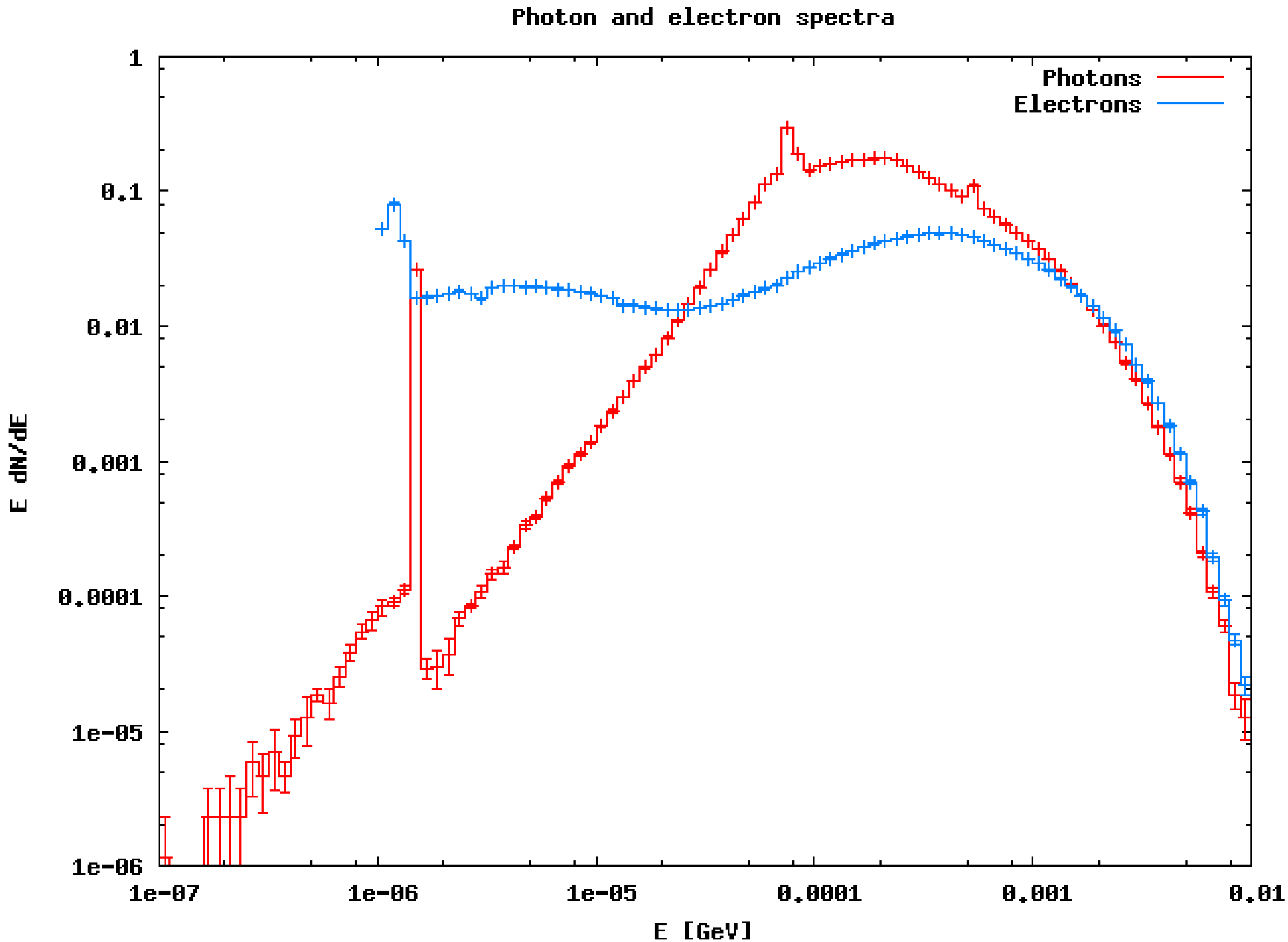
Photon fluence attenuation curves for 3 angles



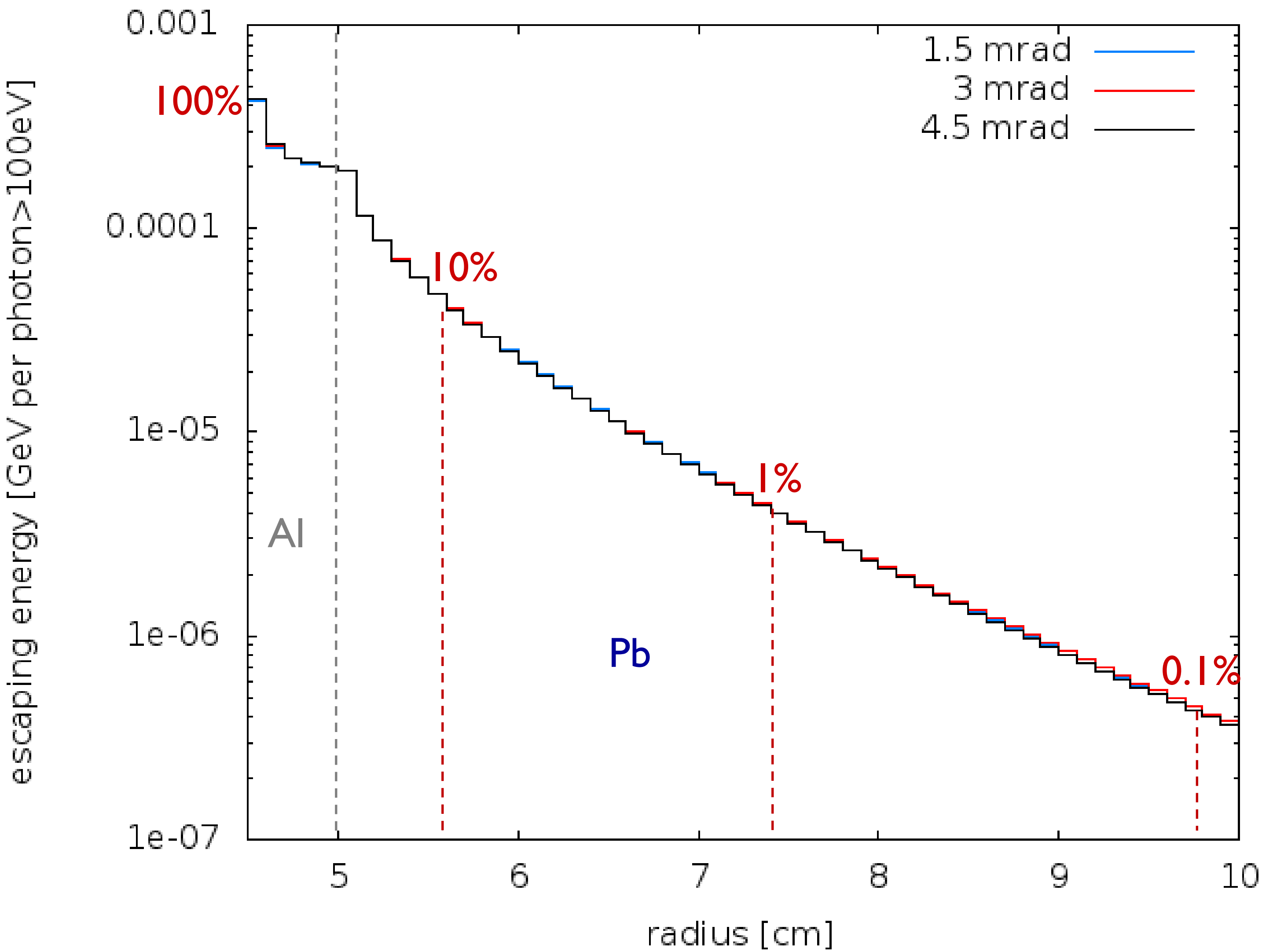
Photon spectra at various depths



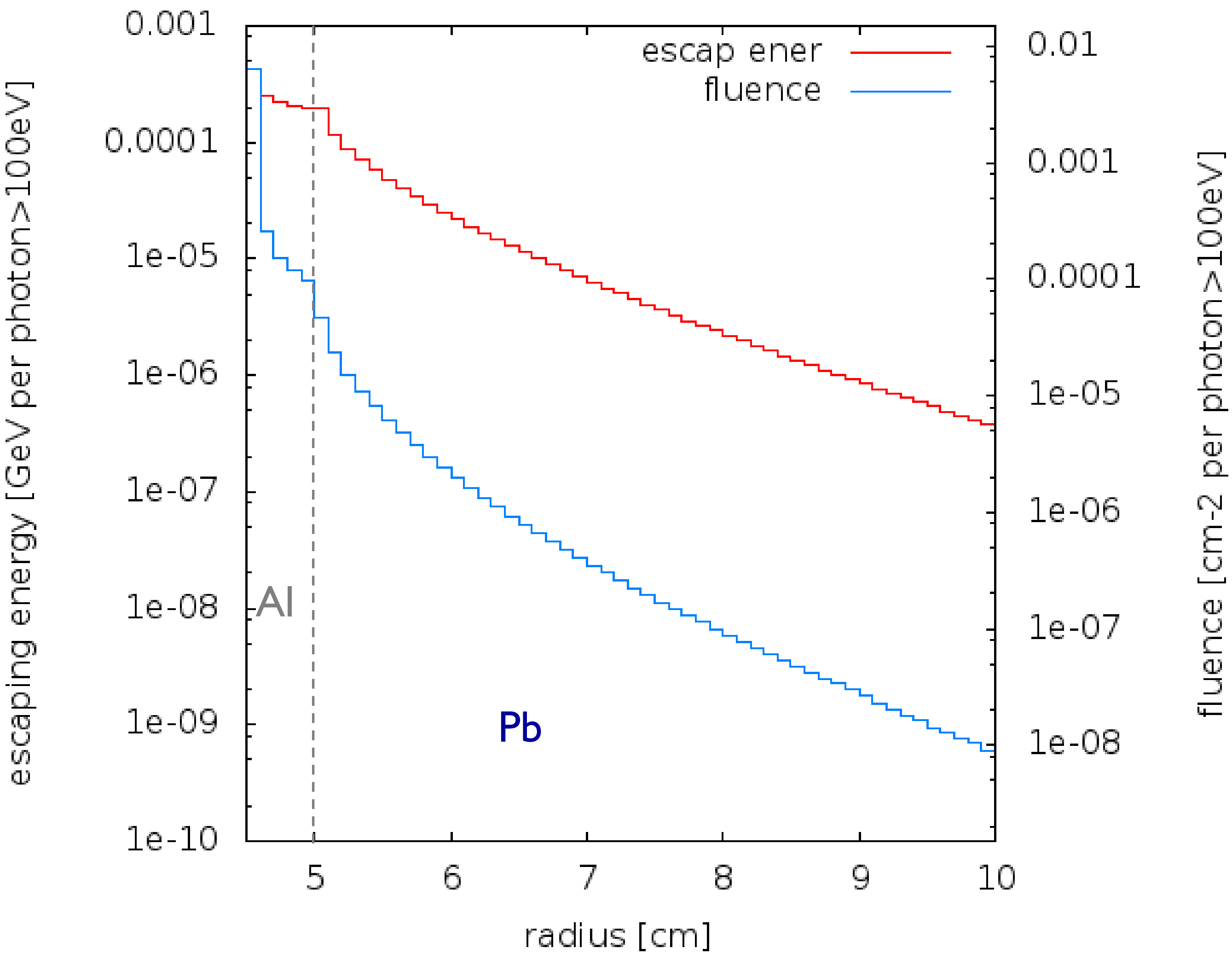
Backscattered photon and electron spectra



Power attenuation: escaping energy as a function of radius



Escaping energy vs fluence as a function of radius



Remarks, after 5 cm of Pb:

- Power and fluence are not yet exponentially attenuated
- The escaping power is decreasing slower than the photon fluence

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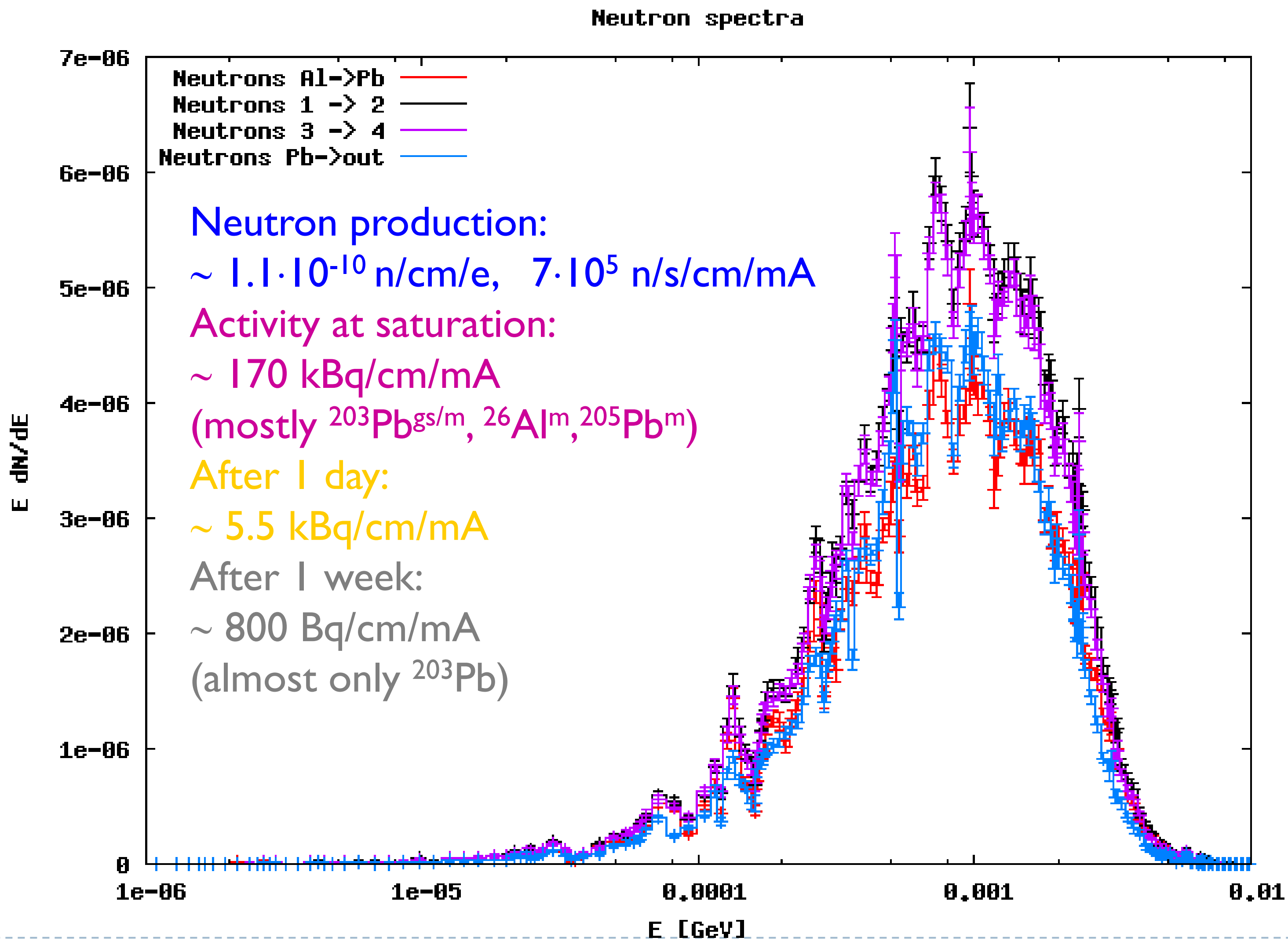
Neutron spectra at various depths

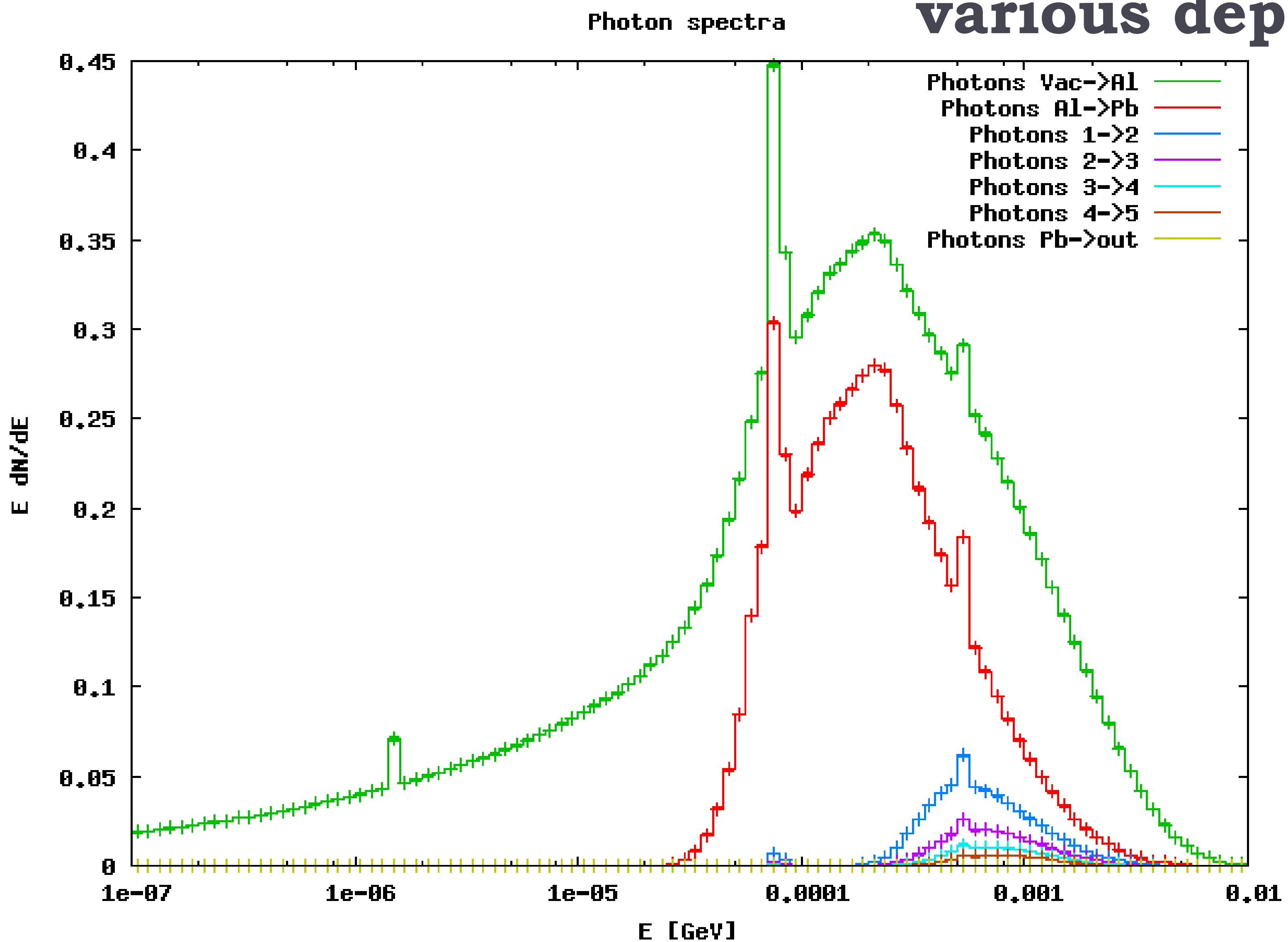


Conclusions

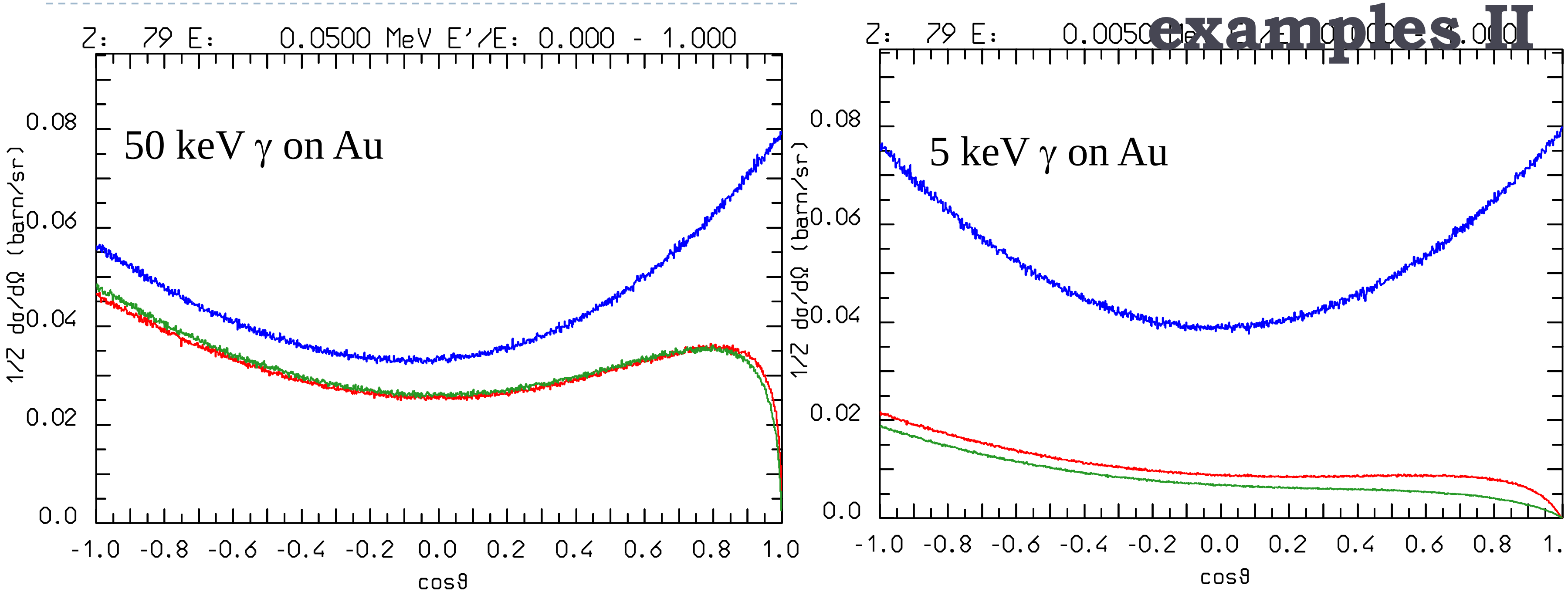
- **SR calculations possible** with full generality
- Some **minimal layout specs** (dipole length, curved or straight, beam pipe radius) **required** in order to start devising a **shielding strategy**, maybe possible to **intercept** most of **SR** at **interconnections?**
- Specs about the **"tolerable" escaping power** levels required as well
- As expected the **attenuation curve** is **insensitive to the incidence angle** and (unfortunately) far from naïve line-of-sight approximations
- **Photoneutron** production and associated activation (relatively) **minor**, it will change steeply with E_c

Backup Slides

Photon spectra at various depths



Compton ang. distr.: examples II



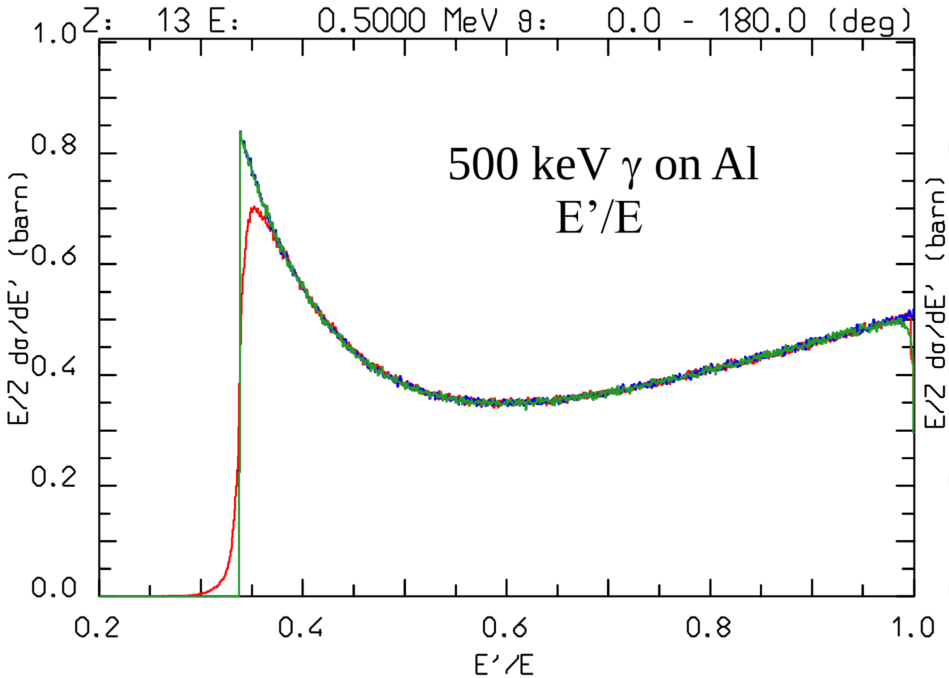
blue = free electron

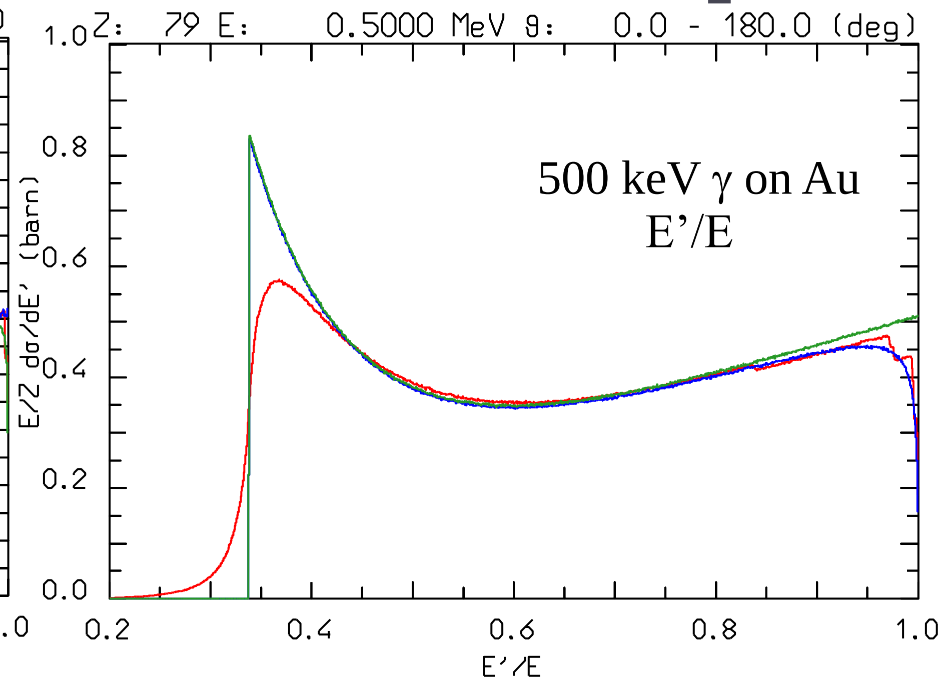
green = binding with form factors

red = binding with shells and orbital motion

Effects visible only at ***cos**θ* close to 1. The ***S(q,Z)*** approximation is still very good at 50 keV,

Compton profile: examples

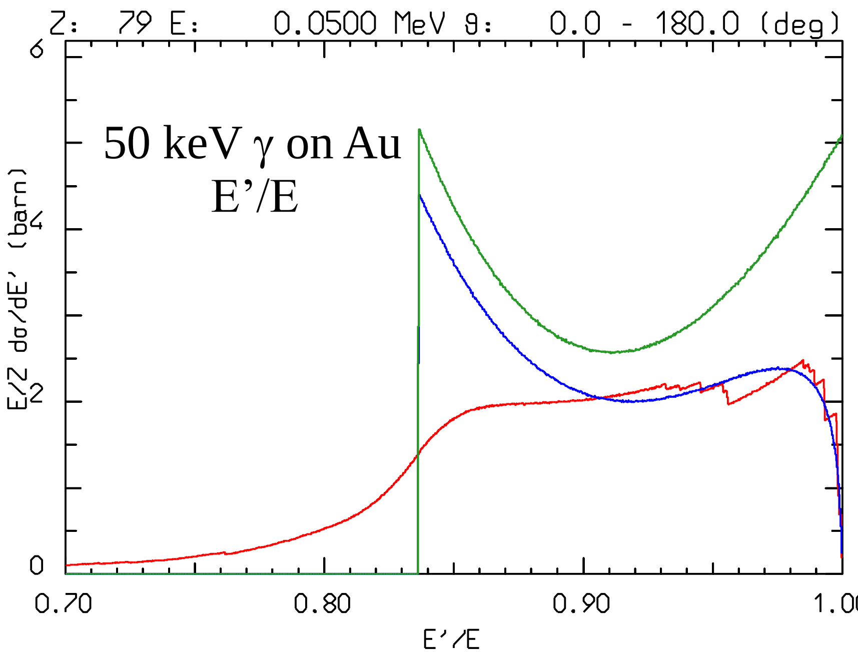


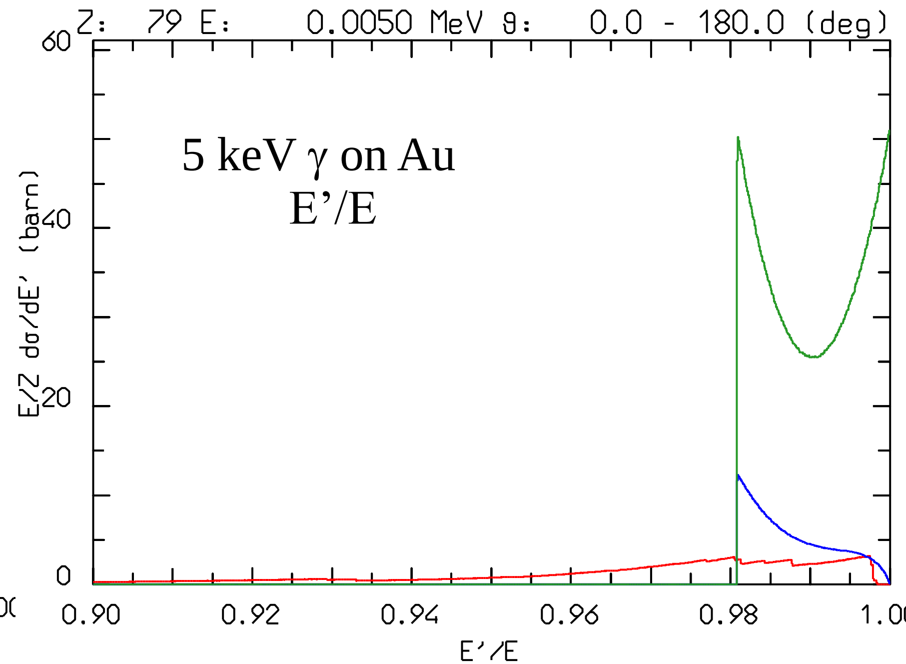


green = free electron
blue = binding with form factors
red = binding with shells and orbital motion

Larger effect at very low energies, where, however, the dominant process is photoelectric.
Visible: shell structure near E'=E, smearing from motion at low E'

Compton profile: examples II





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Larger effect at very low energies, where, however, the dominant process is photoelectric.
Please note that the actual cross section goes down again at low energies!!
Visible: shell structure near E'=E, smearing from motion at low E'