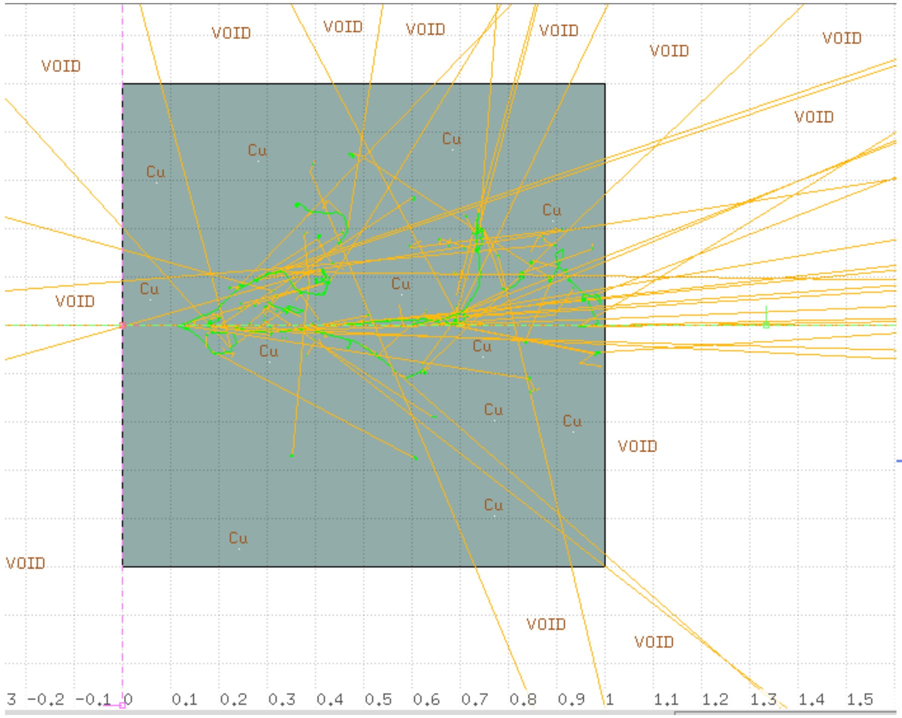
EM interactions



21st FLUKA Beginners' Course
ALBA Synchrotron (Spain)
April 8-12, 2019

Topics

- General settings
- Interactions of leptons/photons
  - Photon interactions
    - Photoelectric
    - Compton
    - Rayleigh
    - Pair production
    - Photonuclear
    - Photomuon production
  - Electron/positron interactions
    - Bremsstrahlung
  - Muon interactions
    - Bremsstrahlung
    - Pair production
    - Nuclear interactions
  - Electromagnetic dissociation

- Ionization energy losses
  - Continuous
  - Delta-ray production
- Transport
  - Multiple scattering
  - Single scattering

These are common to all charged particles, although traditionally associated with EM

E-M FLUKA (EMF) at a glance

Energy range for e^+, e^-, γ : 1 keV (100 eV for γ)- 1000 TeV
Full coupling in both directions with hadrons and low-energy neutrons
Energy conservation within computer precision
Up-to-date γ cross section tabulations from EPDL97 database

EMF is activated by default with most **DEFAULTS** options,
except: EET-TRAN, NEUTRONS, SHIELDING

To de-activate EMF:

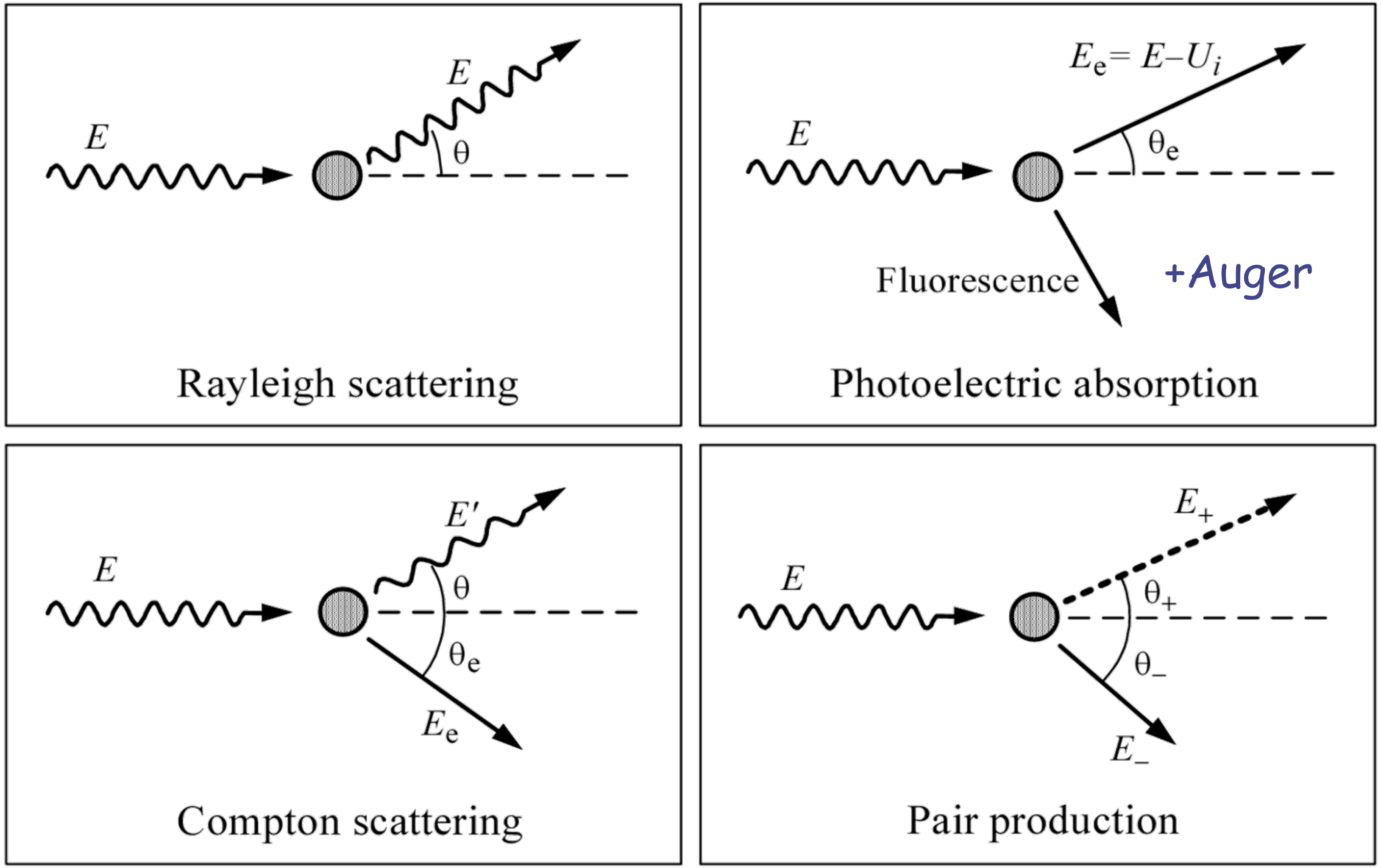
EMF	**EMF-OFF**

With EMF-OFF, E.M. energy is deposited on the spot
Consider also the **DISCARD** command

Production and transport of optical photons (Cherenkov, scintillation) is implemented.
Since it needs user coding, it is not treated further in this beginners' course.

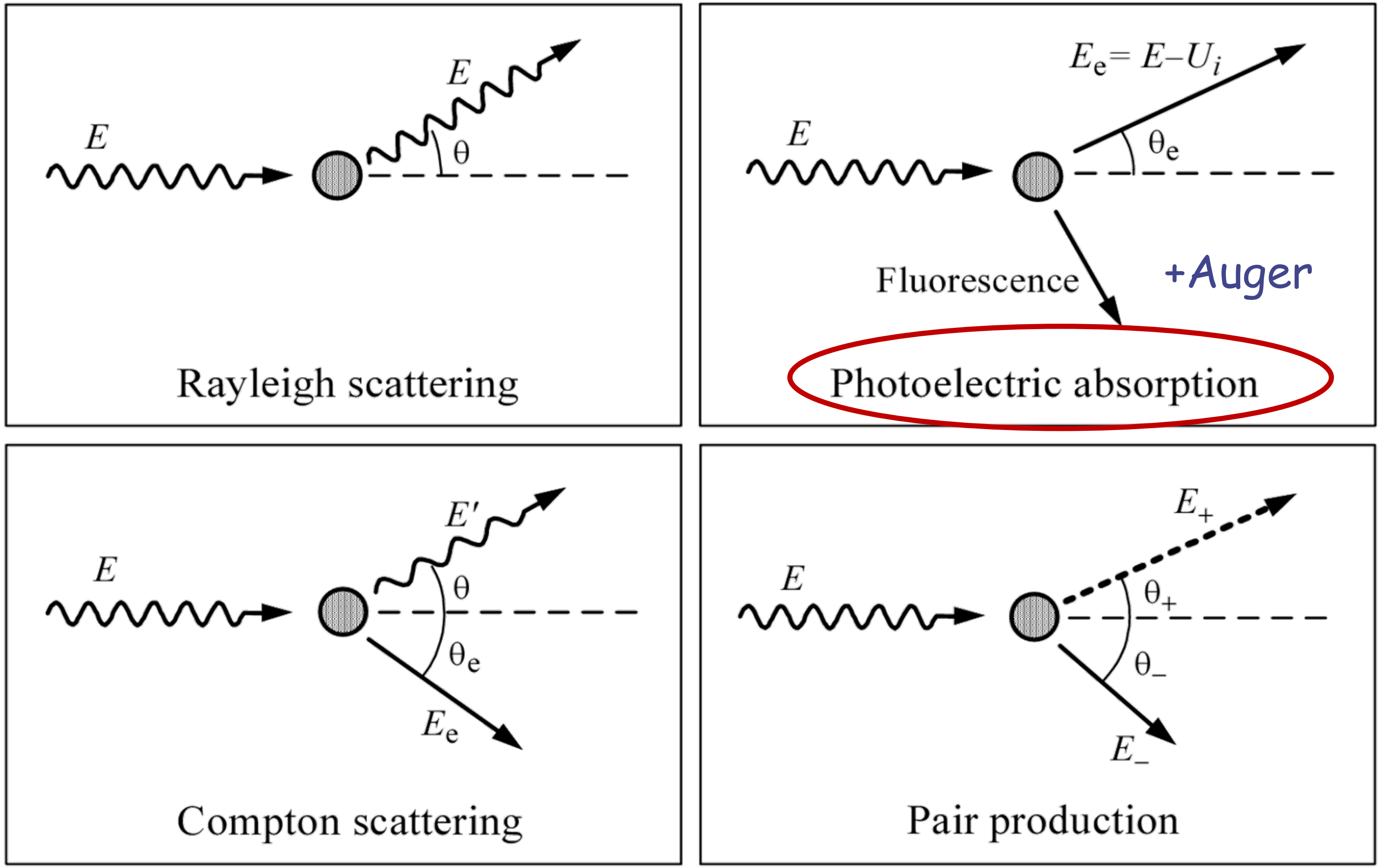
Photon interactions

Photon interactions modeled in FLUKA



+photo-nuclear processes +photo-muon production

Photon interactions modeled in FLUKA

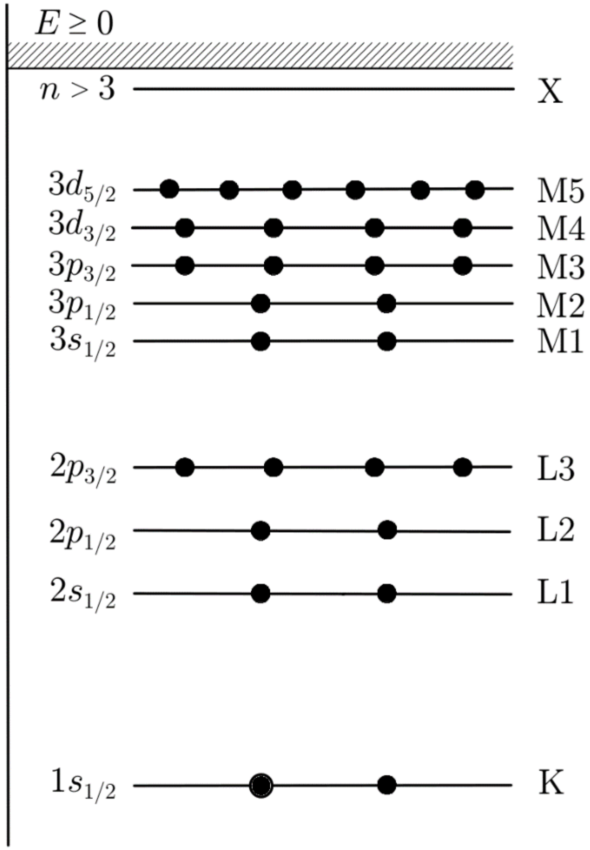


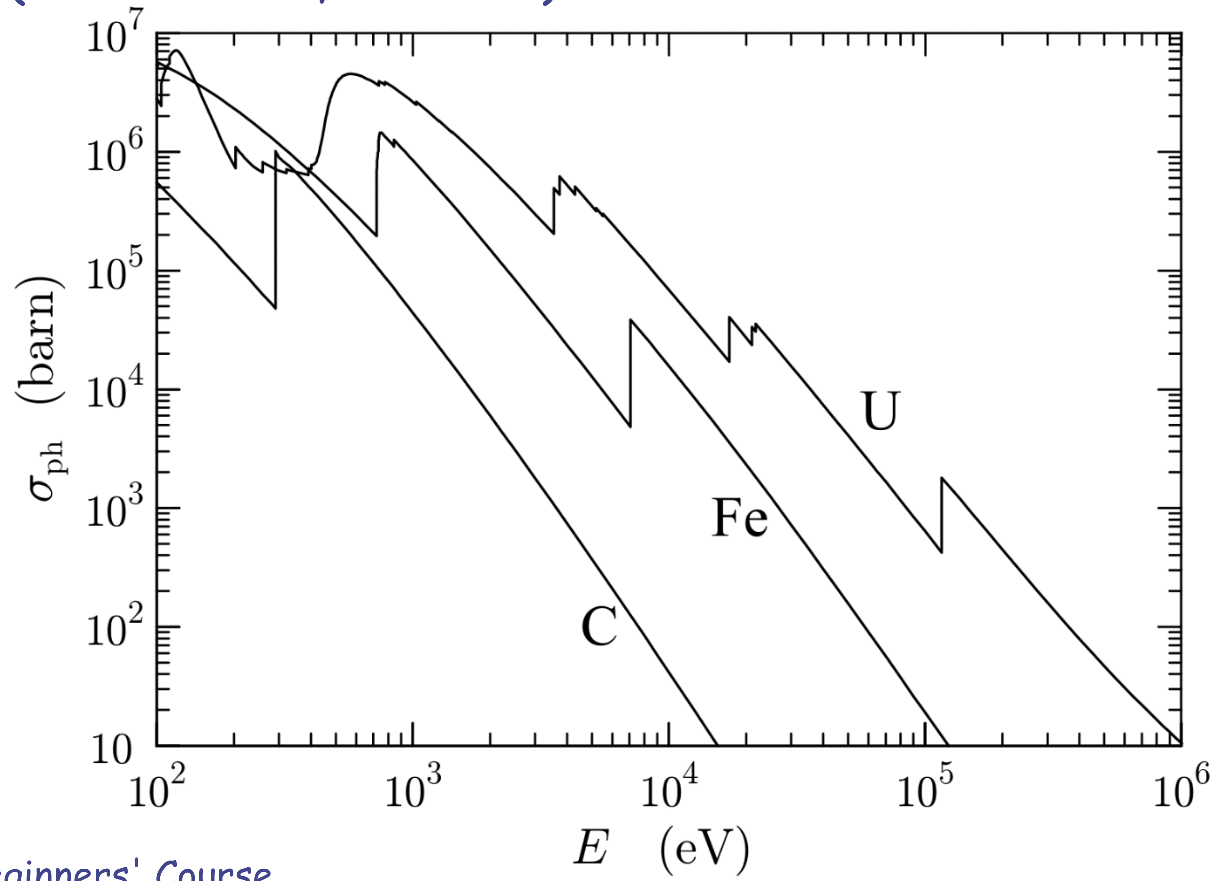
+photo-nuclear processes +photo-muon production

Photoelectric effect

Absorption of a photon by a target atom, electron ejected, inner-shell vacancy left behind.

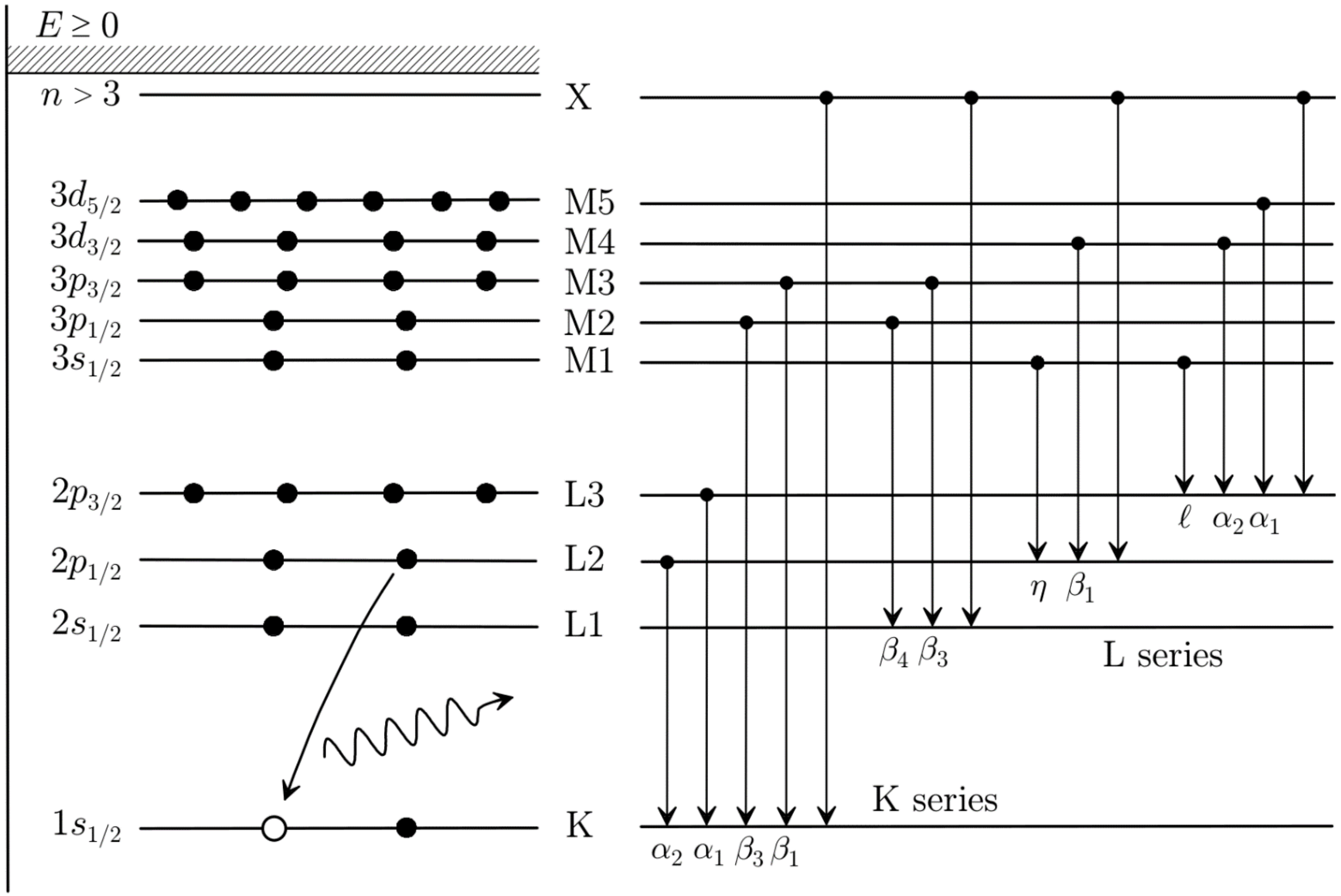
Source: Evaluated Photon Data Library (Cullen et al., EPDL97).





Atomic de-excitation

Fluorescence vs Auger emission



Next: angular distribution of emitted electron and deexcitation via fluorescence / Auger emission.

Photoelectric effect

Detailed treatment of	Fluorescence
Photoelectron	Angular distribution
Approximate	Auger effect
Effect of photon	Polarization

Fluorescence (and Auger) after photoelectric is activated only with a subset of DEFAULTS: CALORIMEtry, EM-CASCA, ICARUS, PRECISIOn

CPU time vs. precision in small granularity

To activate/deactivate it:

```
EMFFLUO        Flag     Mat1     Mat2     Step
```

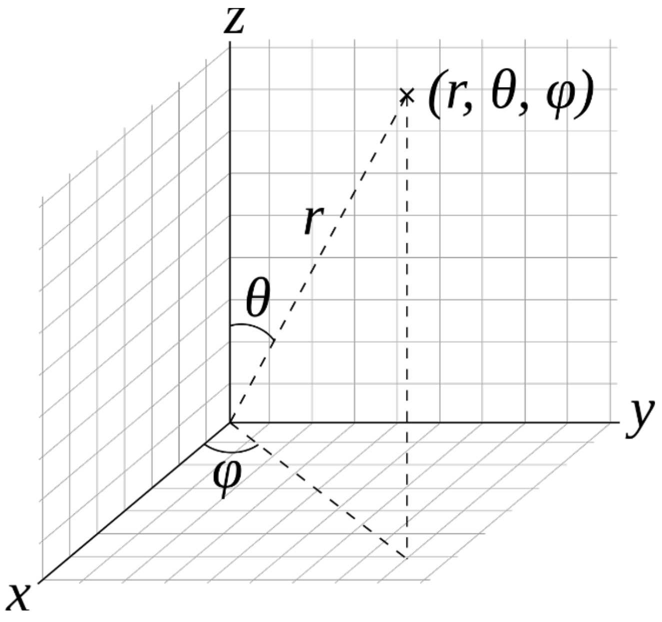
Flag > 0: Activate   Flag < 0: De-activate

Warning: check consistency with production/transport thresholds

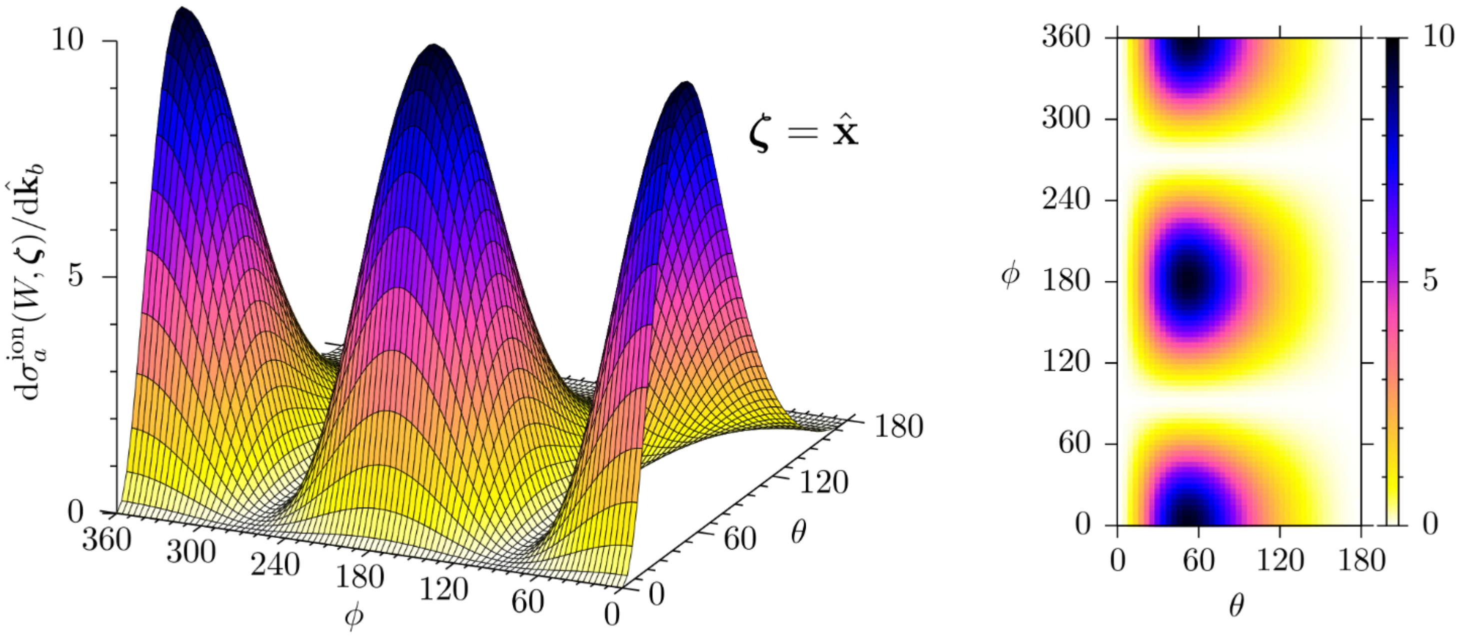
Effect of polarization

The polarization of the incoming photon breaks the azimuthal symmetry in the angular distribution of the emitted electron.

E.g. for polarization along the x axis (theta=90°, phi=0° or 180°) we have

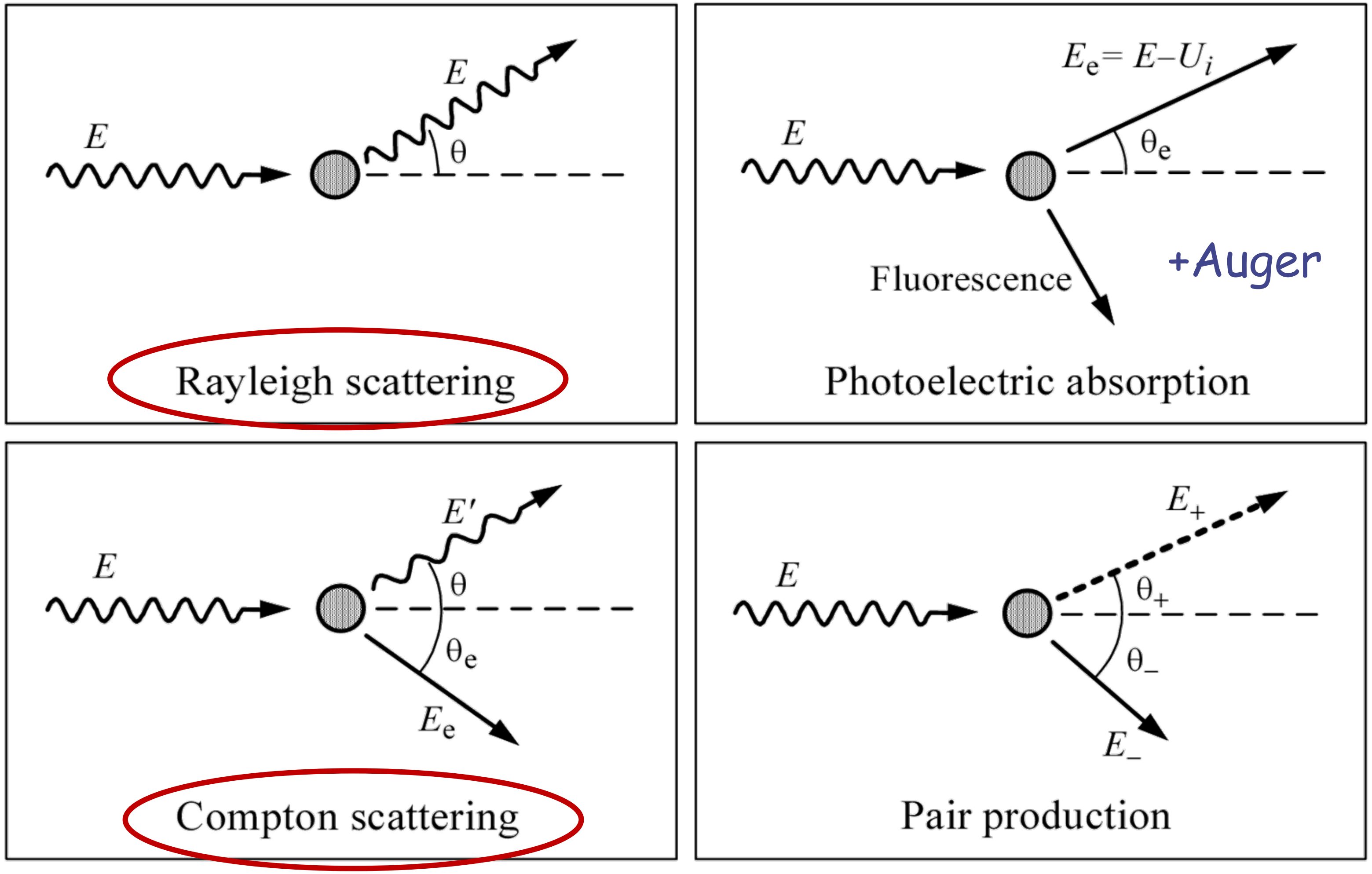


L. Sabbatucci, F. Salvat / Radiation Physics and Chemistry 121 (2016) 122–140



Card POLARIZA discussed below

Compton and Rayleigh scattering



+photo-nuclear processes

+photo-muon production

Compton and Rayleigh scattering

- Klein-Nishina cross section: free target electron at rest.
- Account for atomic bonds using inelastic Hartree-Fock form factors (very important at low E in high Z materials)
- NEW : Compton with atomic bonds and orbital motion (as better alternative to form factors)
  - Atomic shells from databases
  - Orbital motion from database + fit
  - Followed by fluorescence
- Account for effect of incoming photon polarization

Inelastic Form Factors, Compton profile and Rayleigh scattering are activated only with a subset of DEFAULTS. To activate/deactivate:

```
EMFRAY  Flag    Reg1    Reg2    Step
```

Look in the manual for further details

Compton scattering

KN: free e⁻ at rest

Incoh. scatt. function: binding via form factor

FLUKA: accounting for atomic shell binding energies and e⁻ orbital motion

Ref: T. Boehlen *et al.*, *J Instrum* **7** P07018 (2012)

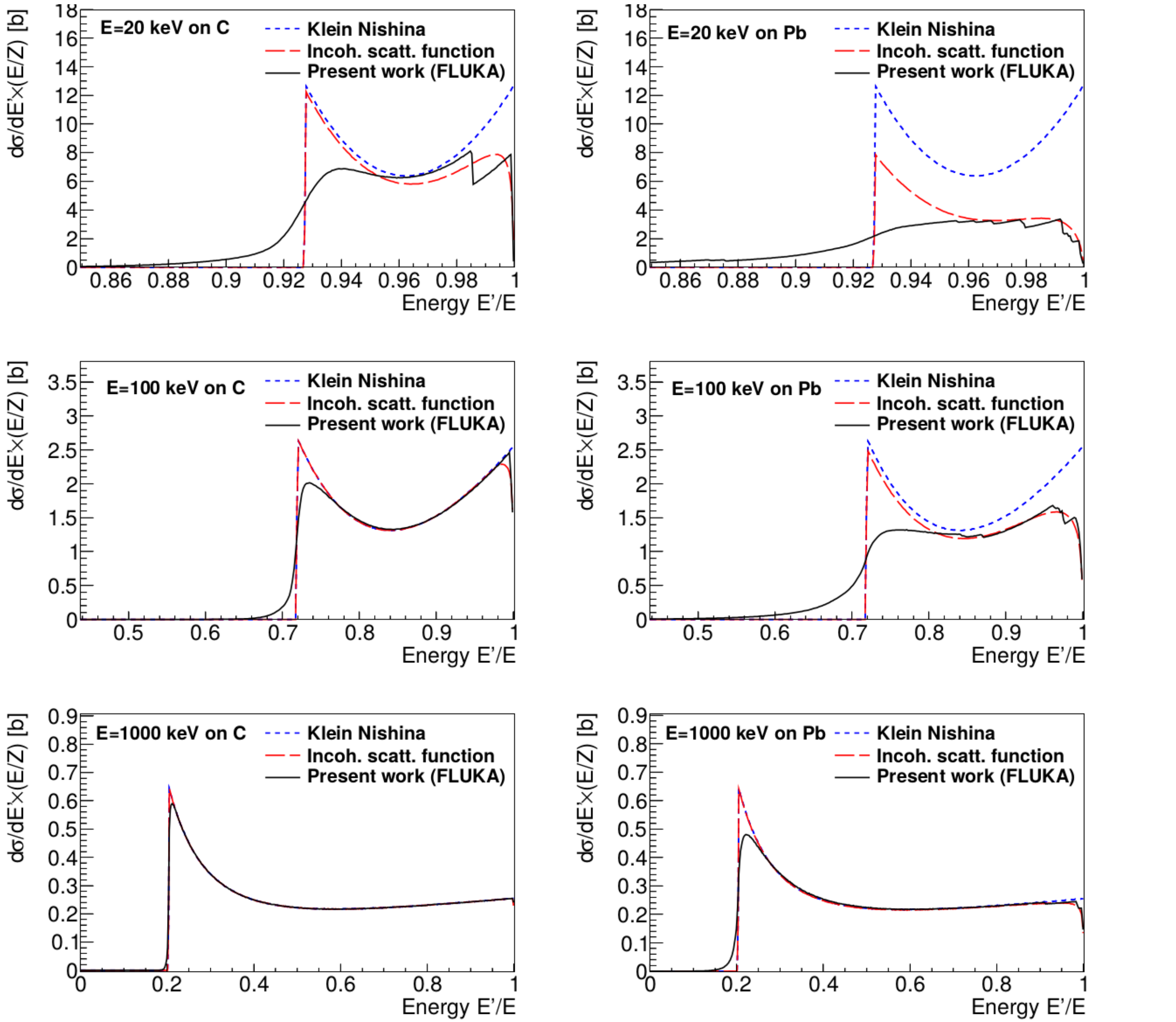
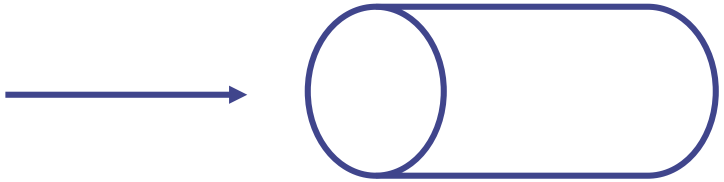


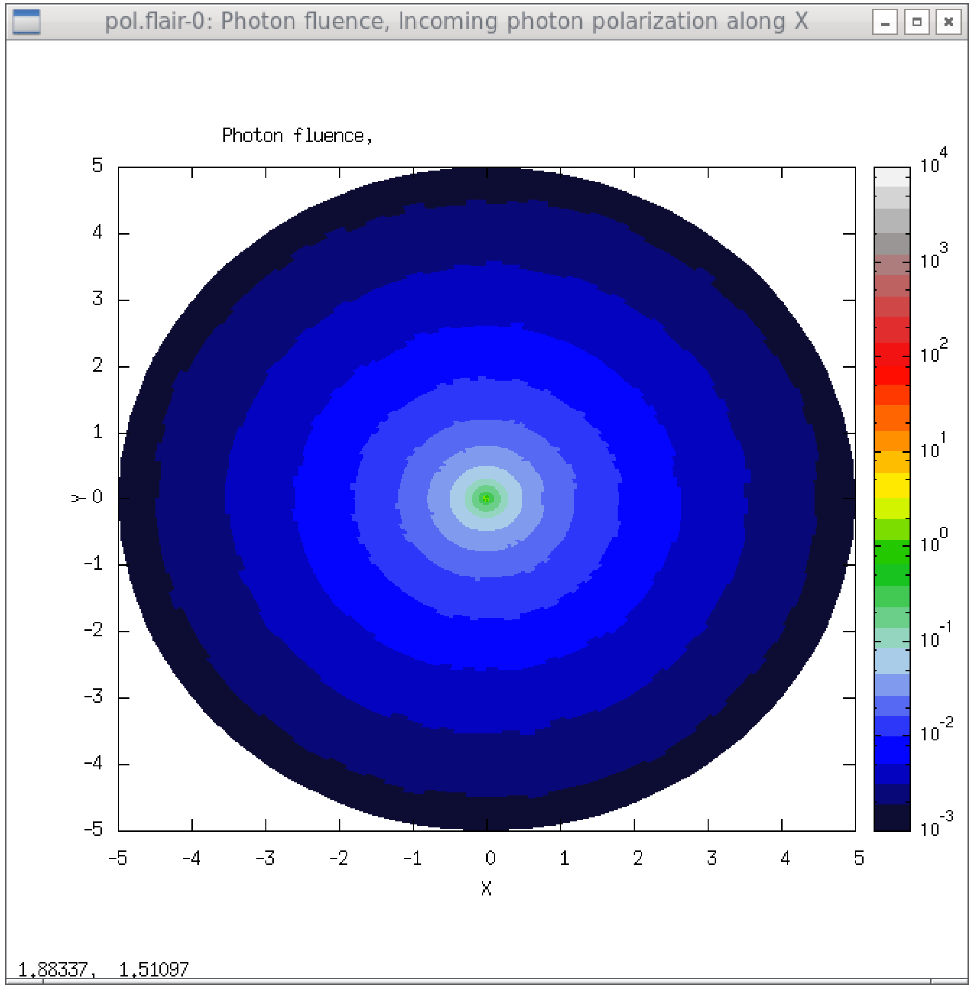
Figure 4. Compton scattering cross sections differential in the energy of the scattered photon E' at selected initial photon energies ($E = 20, 100, 1000$ keV) for carbon and lead. The cross sections are computed with the present Compton scattering model, using a fit to tabulations of the incoherent scattering function $S(q,Z)$ from EPDL97 [18], and using the KN cross section.

Effect of polarization on Compton scattering



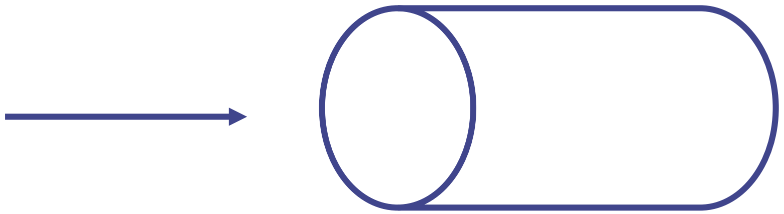
50-keV photons impinging along Z on water cylinder

Unpolarized



Effect of polarization on Compton scattering

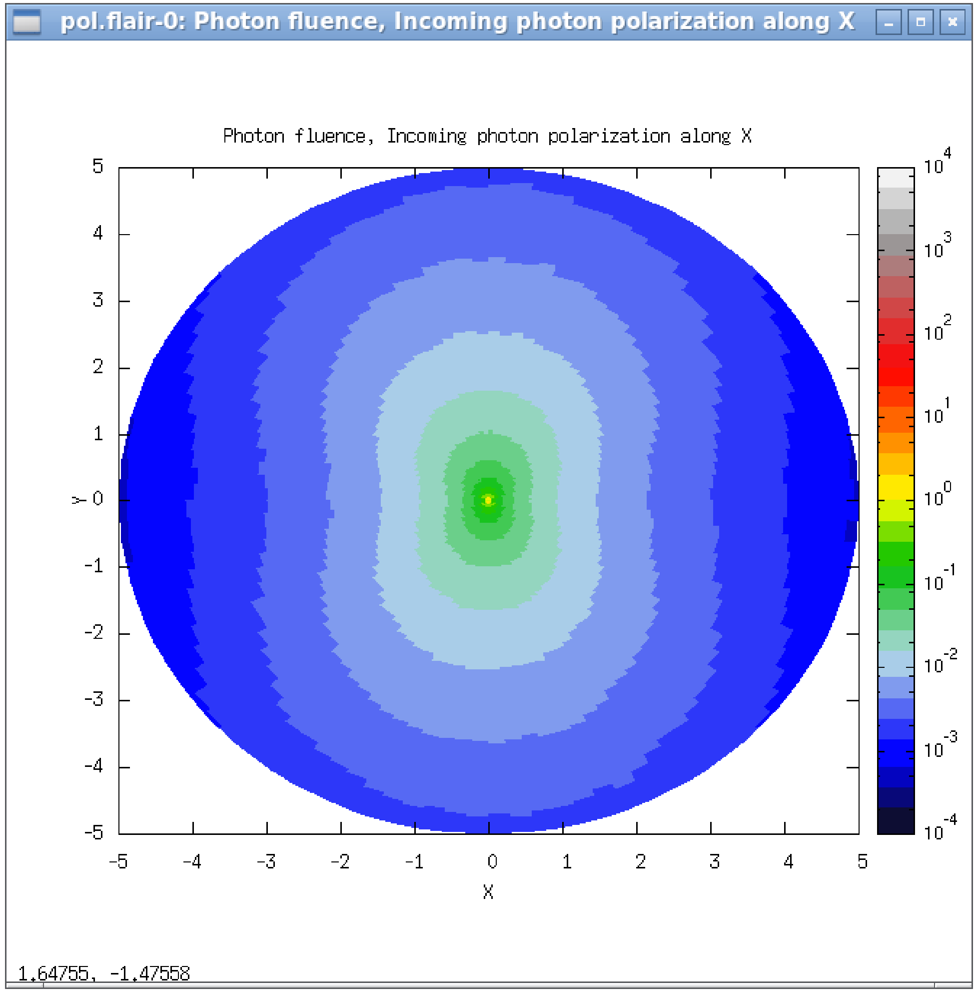
Azimuthal angle of outgoing photon preferentially along direction perpendicular to polarization.



50-keV photons impinging along Z on water cylinder

Incoming photon polarized along X

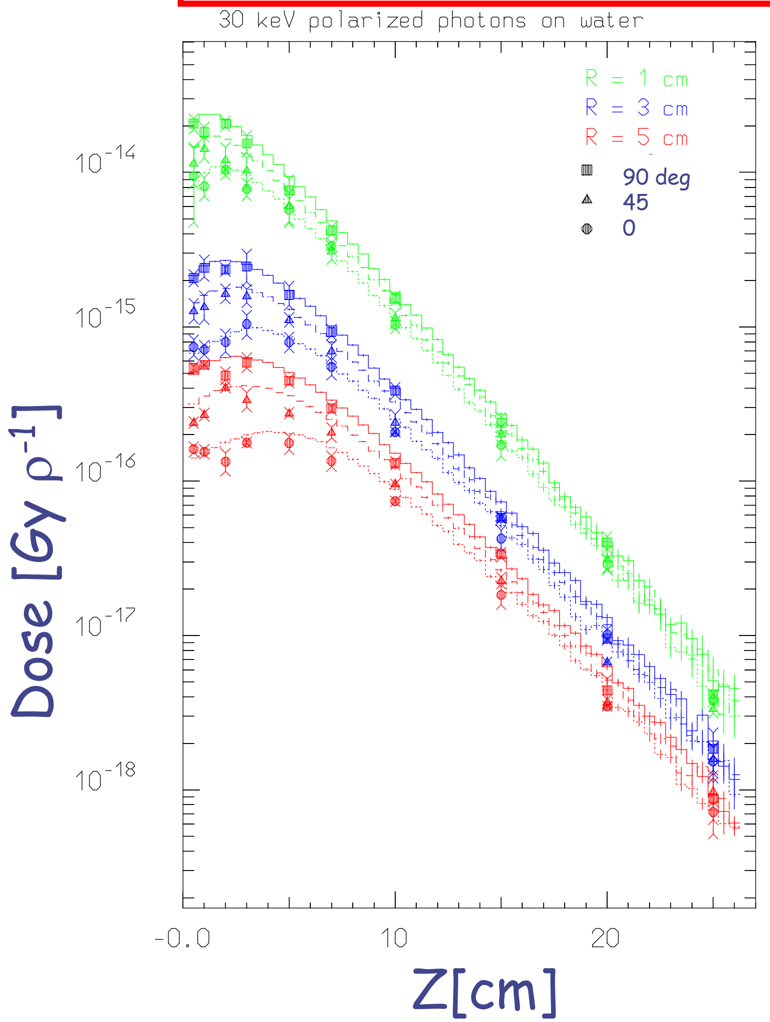
Compton photons preferentially emitted along Y (!)



Polarization

By default, source photons are NOT polarized. Polarization can be set by

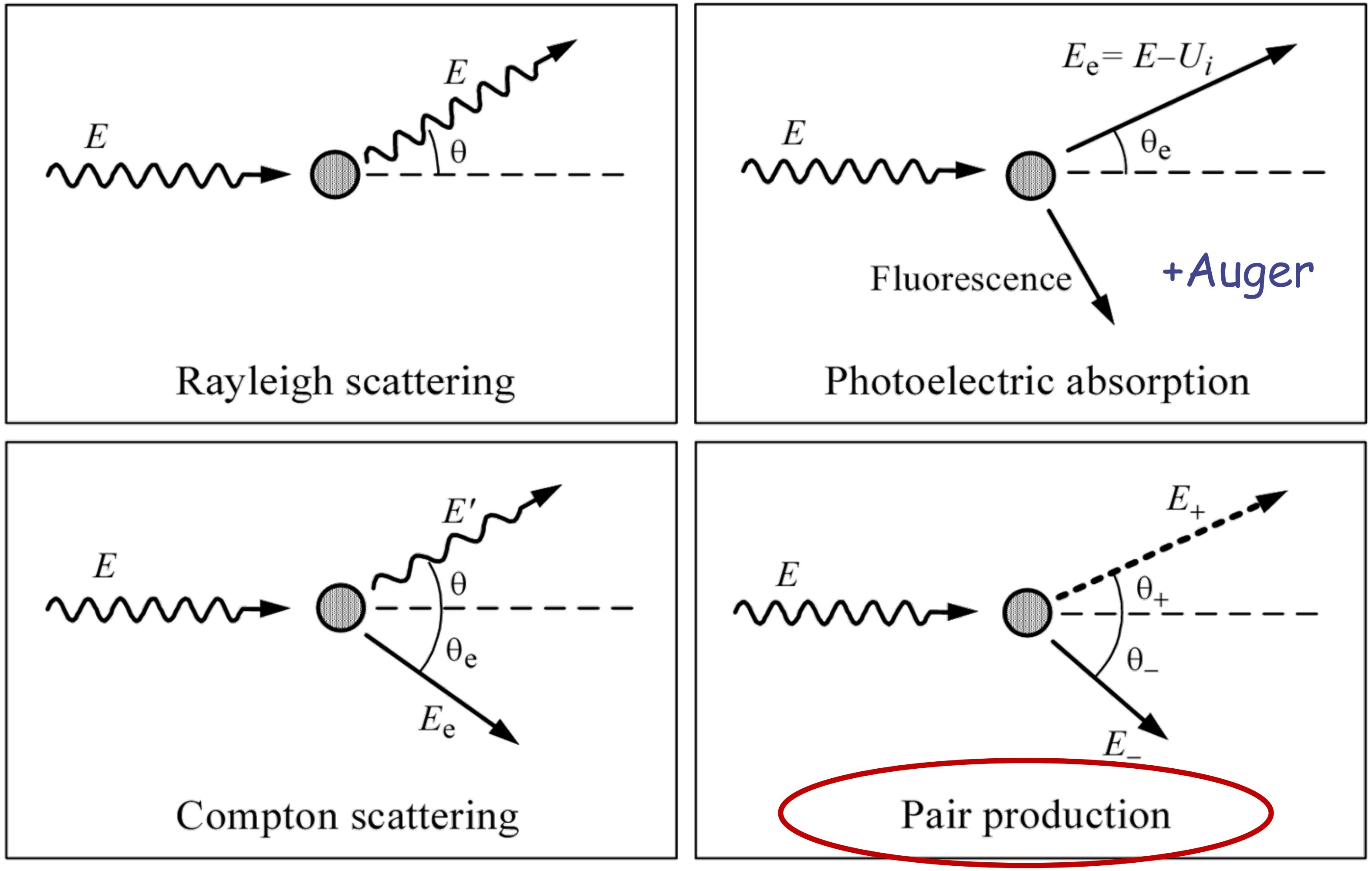
```
POLARIZA  Pcosx  Pcosy  Pcosz      Flag1      Fraction     Flag2
```



Flag1 >= 1 ➔ Pol. direction orthogonal to direction of motion,
Fraction + flag2 ➔ fraction of polarized/unpolarized or polarized/orthogonally polarized photons ***(see the manual for further details)***

Effect of photon polarization
Deposited dose by 30 keV photons in Water at 3 distances from beam axis as a function of penetration depth for 3 orientations wrt the polarization direction

e^-e^+ Pair Production



+photo-nuclear processes +photo-muon production

e^-e^+ Pair Production

- Kinematics: requires presence of target mass, threshold at ~2*511 keV.
- Dominant photon interaction mechanism at energies above ~100 MeV
- Angular and energy distribution of e^+,e^- described correctly (no "fixed angle" theta=m/k or similar approximation)
- No approximations near threshold. Differences between emitted e^+ and e^- at threshold accounted for
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect

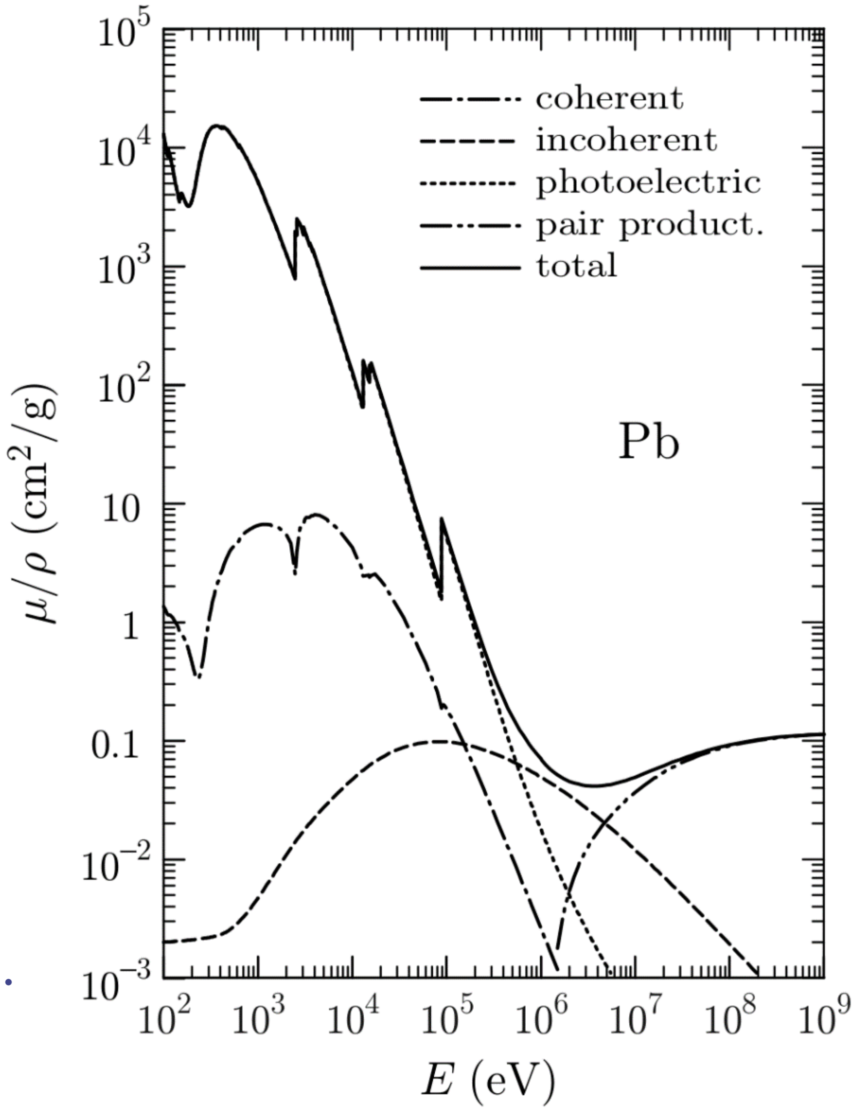
Relative importance of processes (sub GeV)

Mass attenuation coefficient μ

μ =N sigma : inverse mean free path

Rho: density

μ/rho is therefore a way to quote the integrated cross section in such a way that it is independent of aggregation state.



Coherent = Rayleigh
Incoherent = Compton
Pair product. = e-e+ pair prod.

Photomuon production

Muon mass ~ 105 MeV/c^2. For photon energies above ~2*105 MeV/c^2 we can expect muon-+ pair production near target mass.

Relative importance wrt e-e+ pair prod.: $(m_e/m_\mu)^2$ → ~1/40000

Muon pair production by photons **is NOT activated** by any DEFAULT

To activate it use PHOTONUC with SDUM=MUMUPAIR:

```
PHOTONUC Flag  Lambias   0.0   Mat1    Mat2    Step    MUMUPAIR
```

Flag controls activation of interactions, with the possibility to select a subset of the photomuon mechanisms (coherent, incoherent, inelastic...)
Biasing of photomuon production can be done directly with this card, setting WHAT(2)

Ref: Y.S. Tsai, *Rev. Mod. Phys.* **46 4** 815-851 (1974)
+ ERRATUM

Photonuclear interactions

Photon-nucleus interactions in FLUKA are simulated over the whole energy range, through different mechanisms:

- Giant Resonance interaction (~10-20 MeV)
- Quasi-Deuteron effect (~50-150 MeV)
- Delta Resonance production (~150-400 MeV)
- Vector Meson Dominance ($\gamma \equiv \rho$, Φ mesons) at high energies

Nuclear effects on the ***initial state*** (i.e. Fermi motion) and on the ***final state*** (reinteraction / emission of reaction products) are treated by the FLUKA hadronic interaction model (PEANUT) ➔ INC + pre-equilibrium + evaporation/fission/breakup *(Tuesday lecture)*

The (small) photonuclear interaction probability can be enhanced through biasing (see command LAM-BIAS)

Photonuclear interactions: options

Photonuclear interactions are NOT activated with any default

To activate them:

```
PHOTONUC Flag                    Mat1    Mat2    Step
```

Flag controls activation of interactions, with the possibility to select a subset of the photonuclear mechanisms

Since the photonuclear cross section is very small, PHOTONUC should be always accompanied by LAM-BIAS with SDUM = blank (see lecture on biasing)

```
LAM-BIAS   0.0   Factor    Mat   PHOTON
```

Applications:

electron accelerator shielding and activation

neutron background by underground muons (together with muon photonuclear interactions (option MUPHOTON))

Photonuclear int.: example

Reaction:

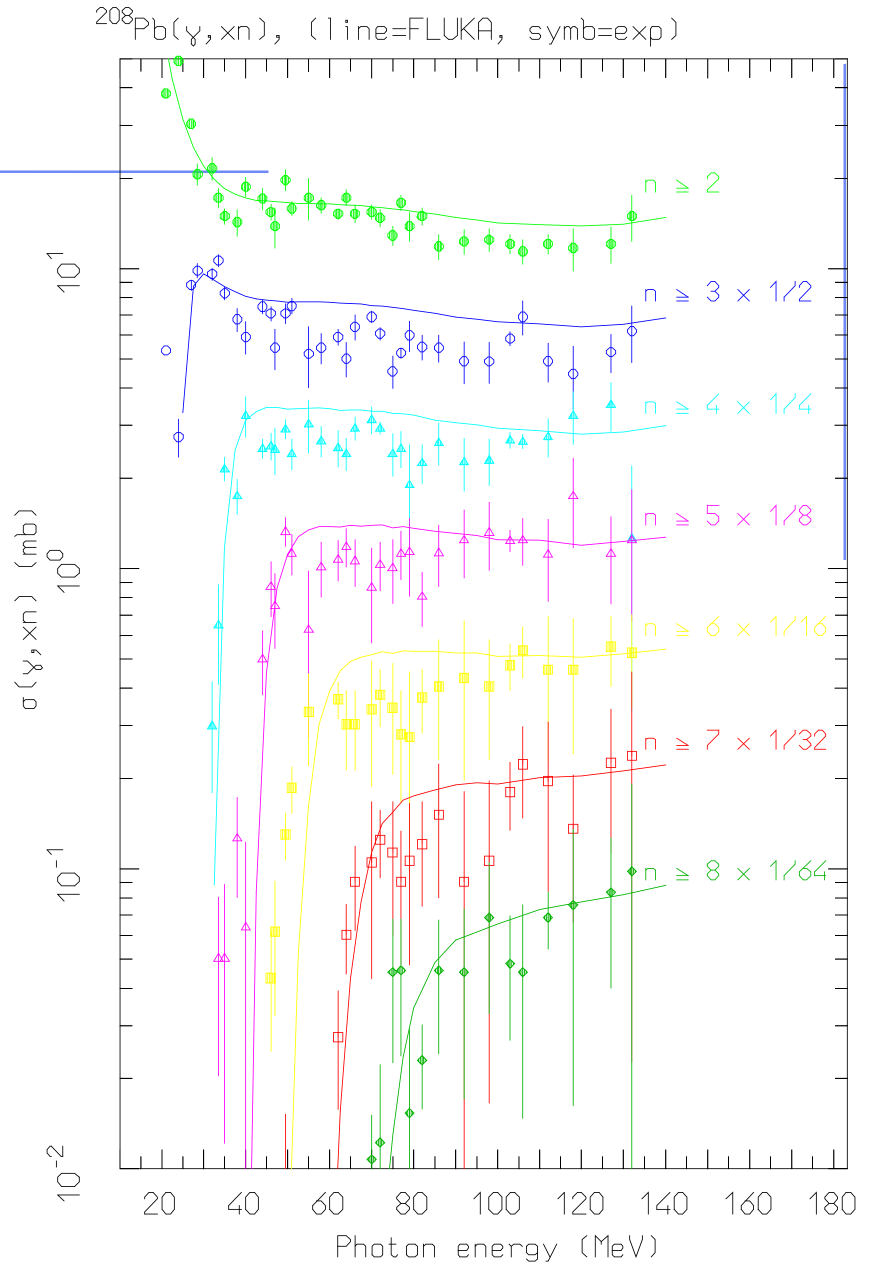
$^{208}Pb(\gamma, x\ n)$

$20 \leq E_\gamma \leq 140$ MeV

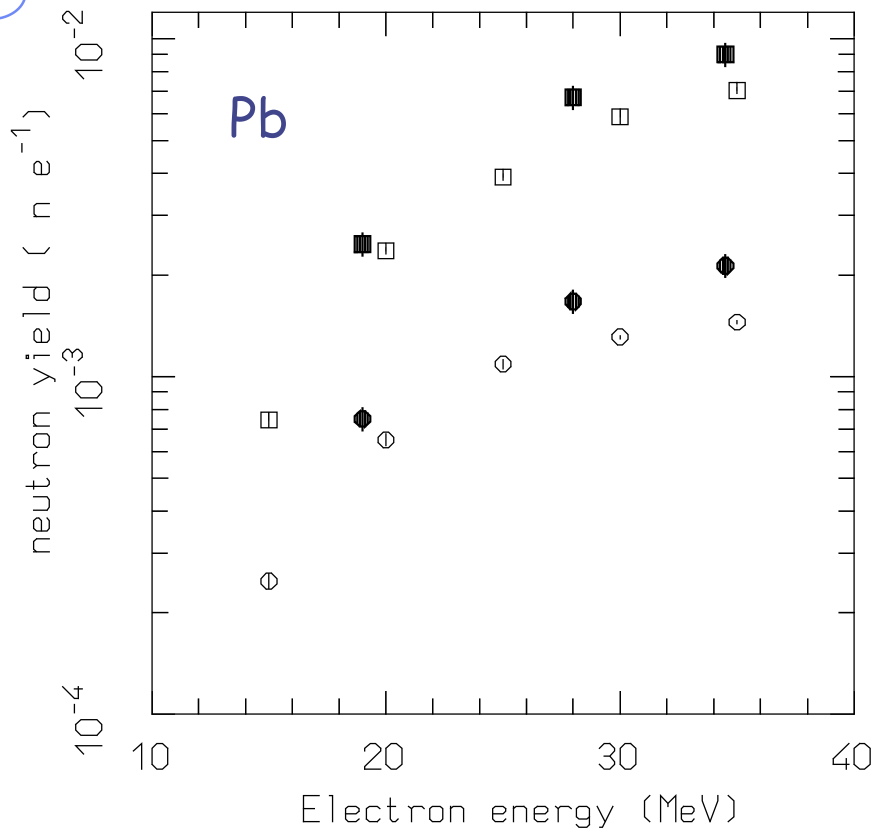
Cross section for multiple neutron emission as a function of photon energy, **Different colors refer to neutron multiplicity $\geq n$, with $2 \leq n \leq 8$**

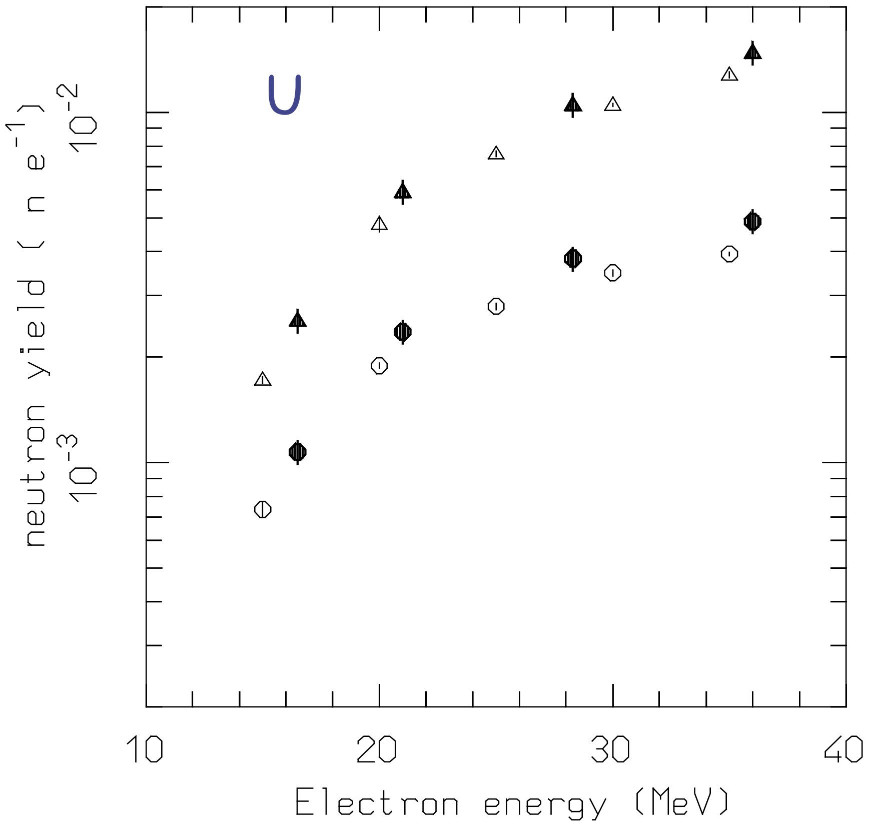
Symbols: exp. data (NPA367, 237 (1981) ; NPA390, 221 (1982))

Lines: FLUKA



Photonuclear Interactions: benchmark





Yield of neutrons per incident electron as a function of initial e^- energy. Open symbols: FLUKA, closed symbols: experimental data (Barber and George, Phys. Rev. 116, 1551-1559 (1959))

Left: Pb, 1.01 X_0 (lower points) and 5.93 X_0 (upper)

Right: U, 1.14 and 3.46 X_0

Electron/Positron interactions

e+/e- interactions modelled in FLUKA

- Delta-ray production (-> EMFCUT)
  - Delta-ray production via Bhabha and Moeller scattering
- Bremsstrahlung production (-> EMFCUT)
  - Energy-differential cross sections based on the Seltzer and Berger database
  - Considers the LPM effect and the soft photon suppression (Ter-Mikaelyan) polarization effect
  - Detailed photon angular distribution fully correlated to energy
- Positron annihilation
  - *At rest* and *in flight* according to Heitler.
  - In annihilation at rest, account for mutual polarization of the two photons
- Muon capture

Bremsstrahlung

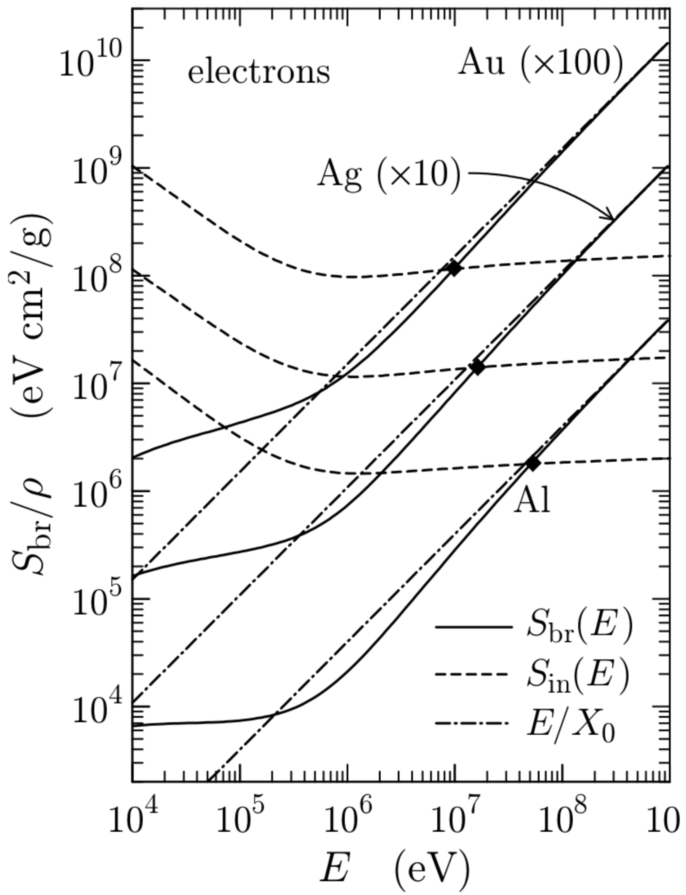
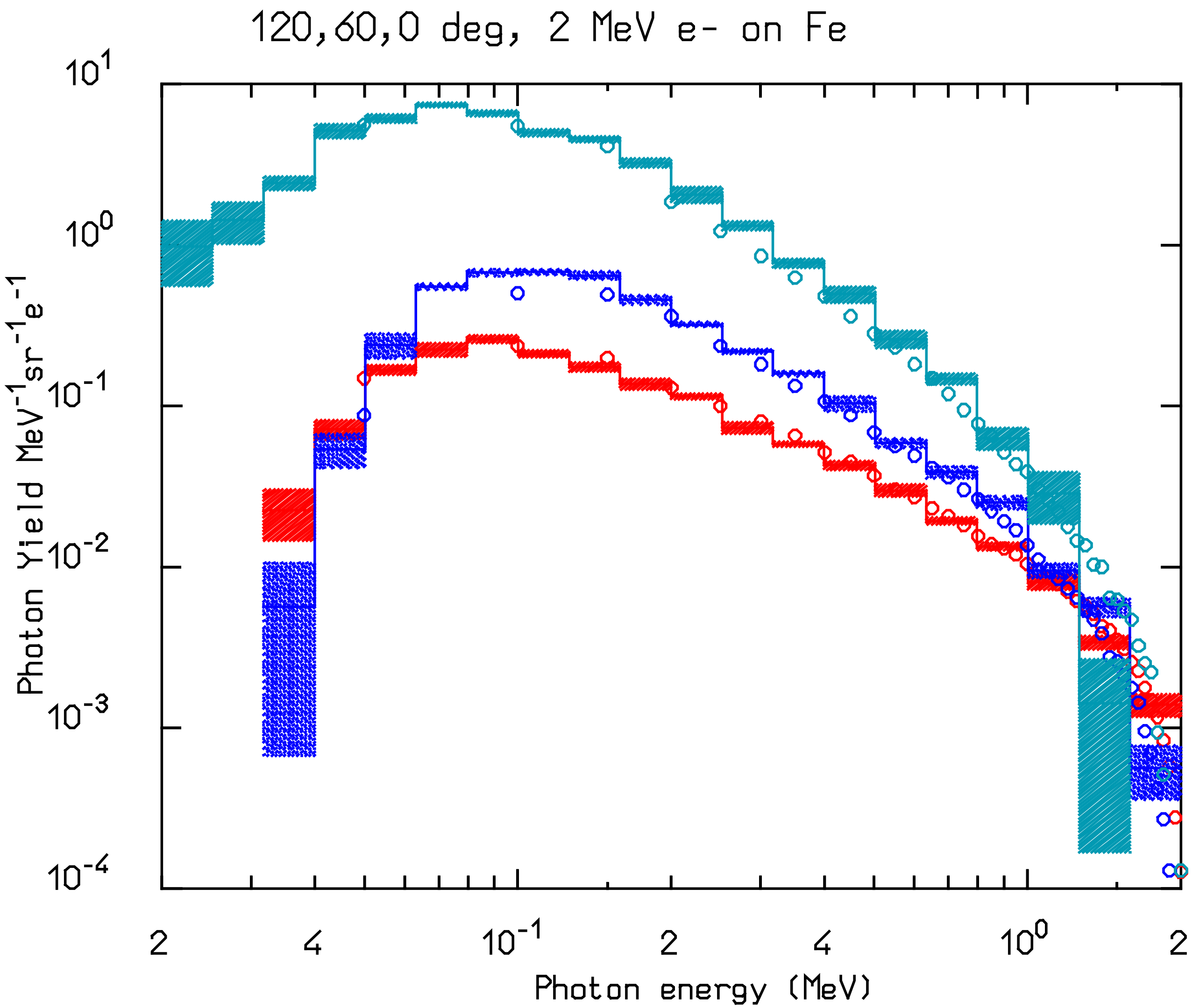


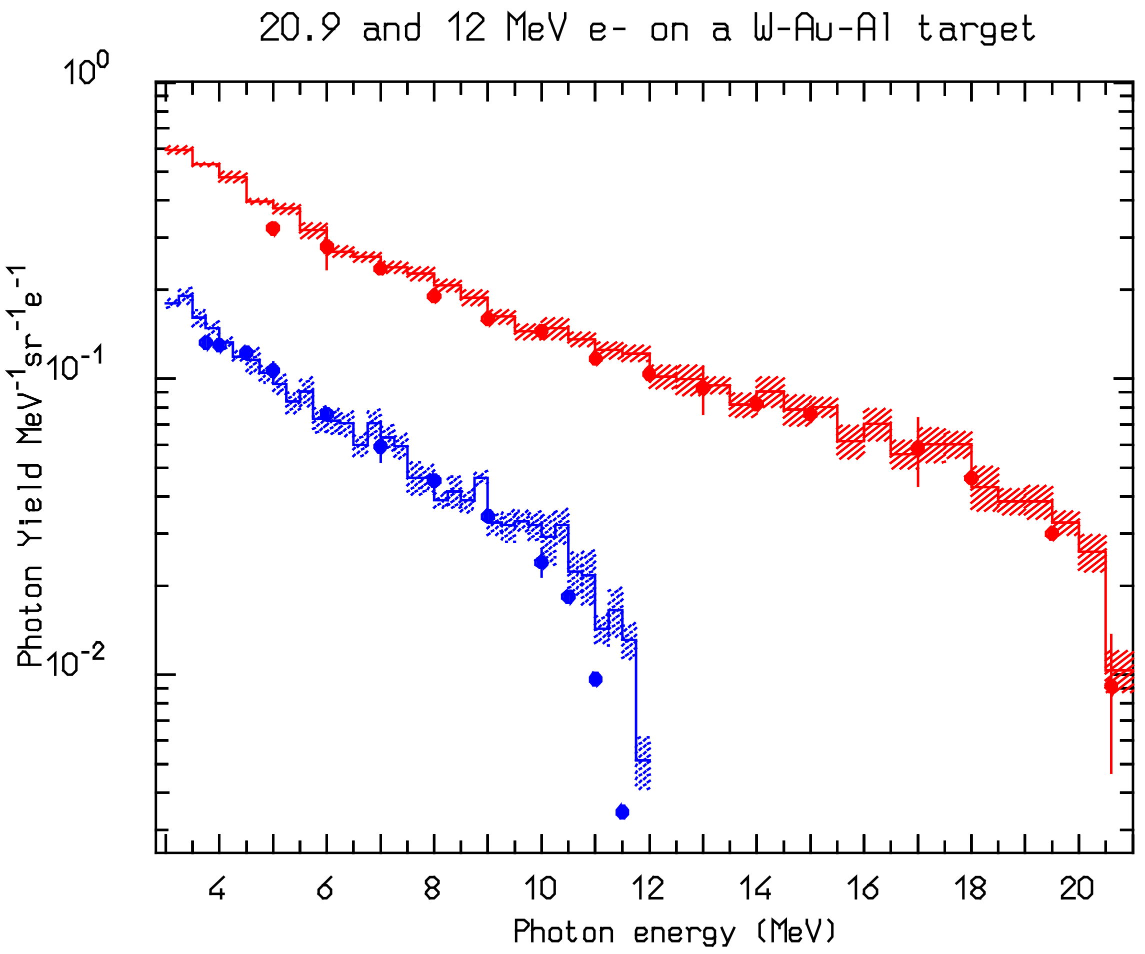
Figure 3.15: Radiative and collision stopping powers for electrons in aluminium, silver (×10) and gold (×100) as functions of the kinetic energy (solid and dashed curves, respectively). Dot-dashed lines represent the high-energy approximation given by Eq. (3.160). Diamonds indicate the critical energy E_{crit} at which the radiative stopping power starts dominating for each material.

Bremsstrahlung: benchmark



2-MeV electrons on Iron, Bremsstrahlung photon spectra measured (dots) and simulated (histos) at three different angles

Bremsstrahlung: benchmark II



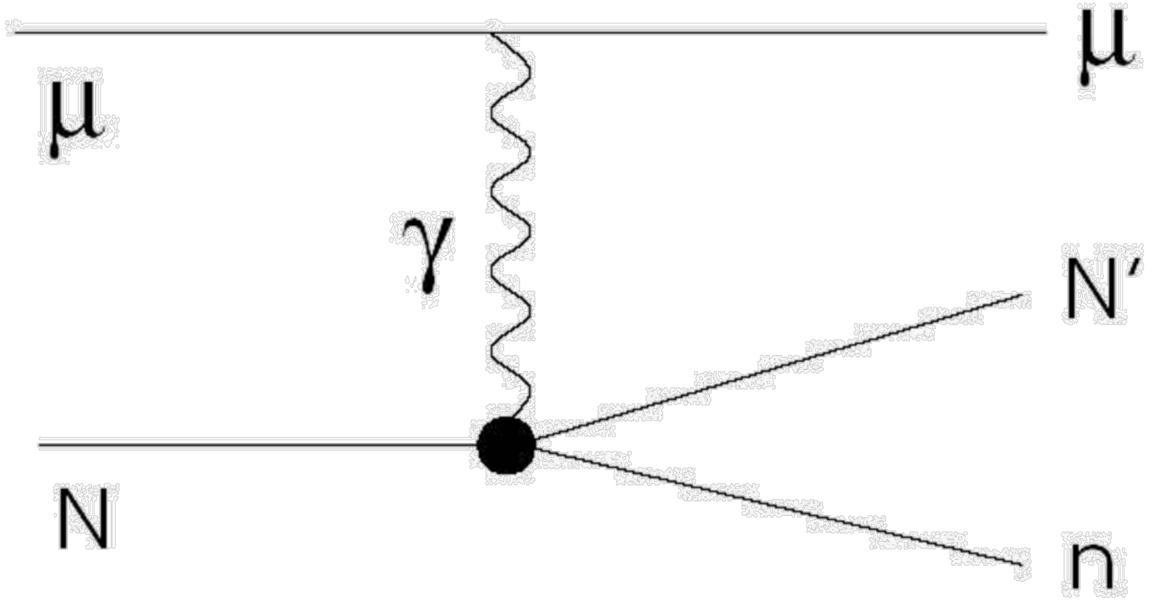
12 and 20.9 MeV electrons on a W-Au-Al target, bremsstrahlung photon spectra in the forward direction measured (dots) and simulated (histos)

Muon interactions

Muon interactions modelled in FLUKA

- Delta-ray production (-> DELTARAY card)
- Bremsstrahlung (-> PAIRBREM card)
  - Consideration of LPM effect
  - Detailed photon angular distribution fully correlated to energy
- Pair production (-> PAIRBREM card)
  - Consideration of LPM effect
  - Correlated angular and energy distribution
- Muon photo-nuclear reactions
  - See next slides
- Muon capture
  - See next slides

Muon Photonuclear Reactions



Schematic view of a μ hadronic interaction.

The interaction is mediated by a virtual photon.

The final state can be more complex

- The cross section can be factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction
- Nuclear screening is taken into account
- Only Vector Meson Interactions are modeled, following the FLUKA meson-nucleon interaction models
- Nuclear effects are the same as for hadron-nucleus interactions

Muon photonuclear reactions: options

- µ photonuclear interactions are NOT activated with any default

To activate them:

```
MUPHOTON Flag     0.0      0.0       Mat1     Mat2     Step
```

Flag controls activation of interactions, with the possibility to simulate the interaction without explicit production and transport of secondaries (this gives the correct muon energy loss/ straggling)

Since the µ photonuclear cross section is very small, MUPHOTON should be always accompanied by LAM-BIAS (see lecture on biasing)

```
LAM-BIAS    0.0    Factor     Mat    MUON+    MUON-
```

Muon interactions

- Muon photonuc. is less likely than other proc.
- Bremsstrahlung dominates large losses
- Pair production and ionization dominate small energy losses

Ref: Groom D.E. *et al*, LBNL 44742 (2001).

D. E. GROOM, N. V. MOKHOV, and S. STRIGANOV   Muon Stopping Power and Range

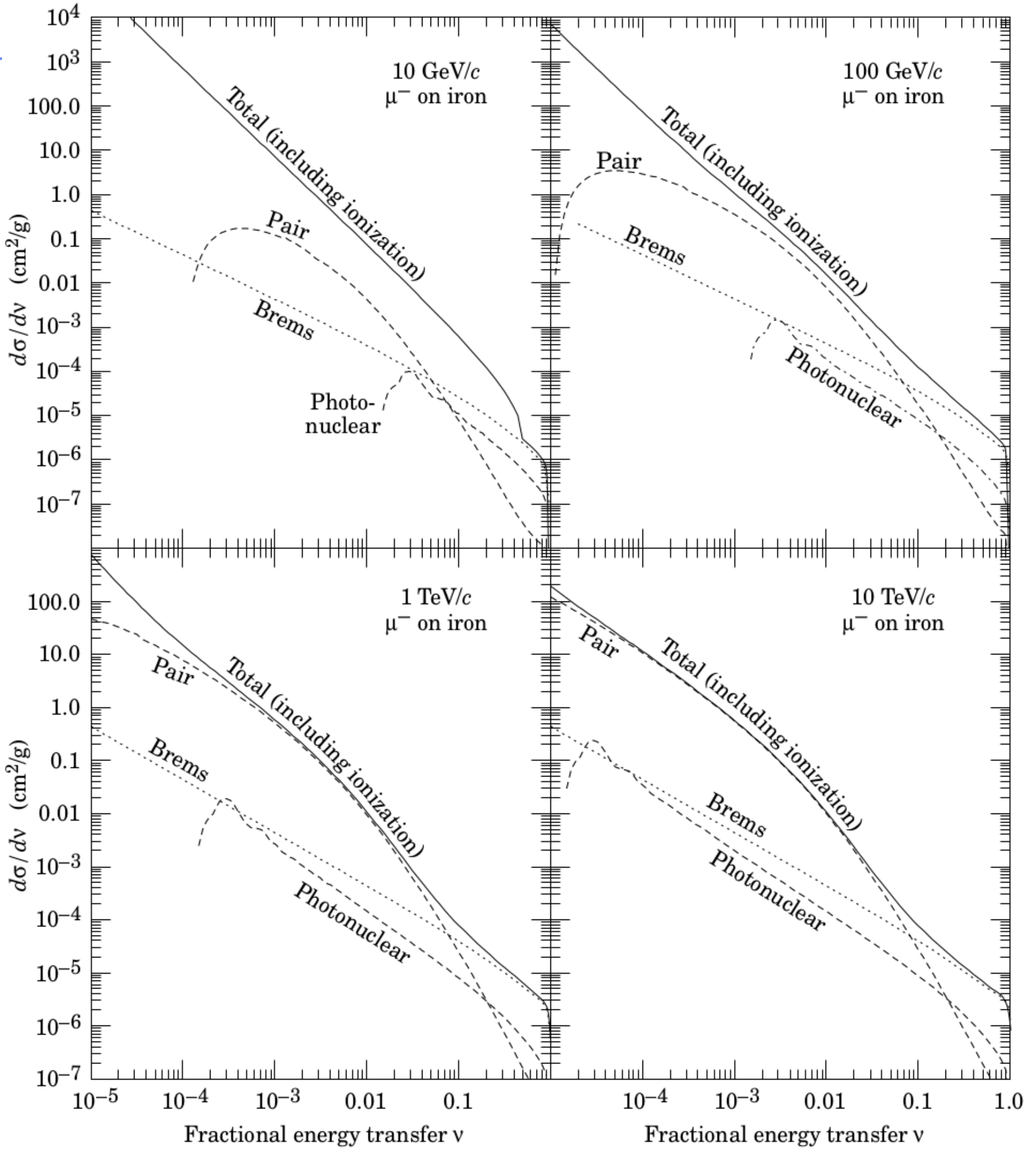


Figure 4: Differential cross section for total and radiative processes as a function of the fractional energy transfer for muons on iron.

Muon capture

An exotic source of neutron background

Basic weak process: $\mu^- + p \rightarrow \nu_\mu + n$

Competes with:

μ^- at rest + atom = excited muonic atom ->x rays +g.s. muonic atom

Competition between μ^- decay Λ_d and capture by nucleus Λ_c

In FLUKA: Goulard-Primakoff formula

$\Lambda_c \div Z^4_{eff}$ Calculated Z_{eff} , Pauli blocking from data

$$\frac{\Lambda_c}{\Lambda d} = 9.2\ 10^{-4} \text{ for H, } 3.1 \text{ for Ar, } 25.7 \text{ for Pb}$$

Nuclear environment from PEANUT

Slow projectile, low energy transfer (neutron E=5 MeV on free p)

Experimentally: high energy tails in n-spectra

Synchrotron radiation

Synchrotron radiation

A charged particle in a curved trajectory in a magnetic field may emit synchrotron radiation (SR), even in vacuum.

FLUKA can model the emission of SR by any charged particle traversing **up to 2 circular arcs** or helical paths, accounting for the emitted photon polarization, and sampling:

- SR photon energy
- SR photon angle

The emitting charged particle is NOT transported: SR photons are sampled directly.

Readily usable for bending magnets and wigglers (two steps so far).

Synchrotron radiation: cards

```
SPECSOUR      ELECTRON       3.0      -2.0 0.0000001     1.000       0.0SYNC-RAS
SPECSOUR         150.0       0.0      -0.5    -1000.       0.0    -0.100&
```

```
WHAT(1) = particle emitting the radiation
          Default: 3.0 (ELECTRON)
WHAT(2) > 0.0: emitting particle momentum (GeV/c)
        < 0.0: kinetic energy of the emitting particle (GeV)
WHAT(3) > 0.0: curvature radius of the emitting particle trajectory (cm)
        < 0.0: absolute value of the bending magnetic field (T)
WHAT(4) = lower limit of the photon energy spectrum (GeV)
          Default: 1.E-7 GeV
WHAT(5) = x-component of the magnetic field versor
WHAT(6) = y-component of the magnetic field versor

SDUM    = SYNC-RAD if the z-component of the magnetic field versor is > 0.0

          SYNC-RDN if the z-component is < 0.0

          SYNC-RAS if the z-component of the magnetic field versor is > 0.0
          and the magnetic field of the second arc (if present) has opposed
          sign to that of the first arc.

          SYNC-RDS if the z-component is < 0.0 and the magnetic field of
          the second arc (if present) has opposed sign to that of the first
          arc.
```

Synchrotron radiation: cards (continuation card)

```
SPECSOUR    ELECTRON       3.0      -2.0 0.0000001     1.000       0.0SYNC-RAS
SPECSOUR       150.0       0.0      -0.5    -1000.       0.0    -0.100&
```

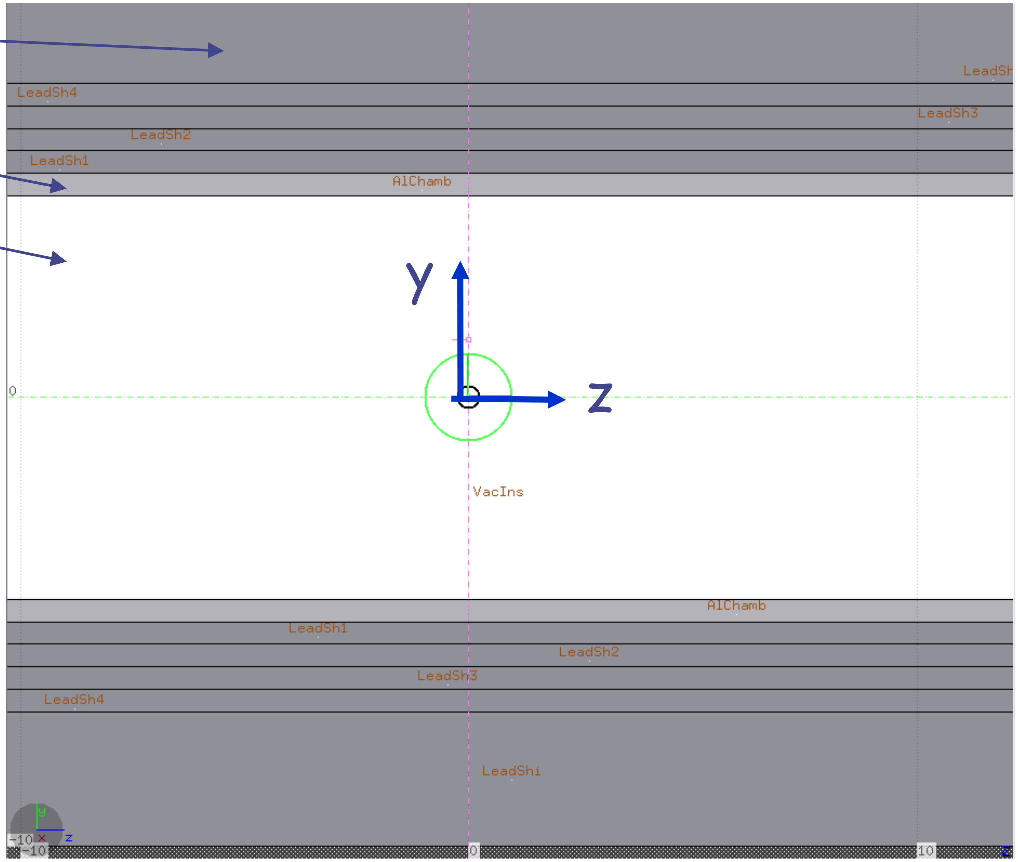
```
Continuation card:

WHAT(1) = length of the emission arc or helical path (cm)
          Default = 100.0 cm
WHAT(2) = x-coordinate of the starting point of a possible second path of
          same length (see Note 1)
WHAT(3) = y-coordinate of the starting point of the second path (see Note 1)
WHAT(4) = z-coordinate of the starting point of the second path (see Note 1)
WHAT(5) = x-component of the emitting particle direction versor at the
          beginning of the second path (see Notes 1 and 2)
WHAT(6) = y-component of the emitting particle direction versor at the
          beginning of the second path (see Notes 1 and 2)
SDUM    = "&" in any position in columns 71-78 (or in last field if free
          format is used)
```

Synchrotron radiation: example

Lead shielding

Al layer

Vacuum

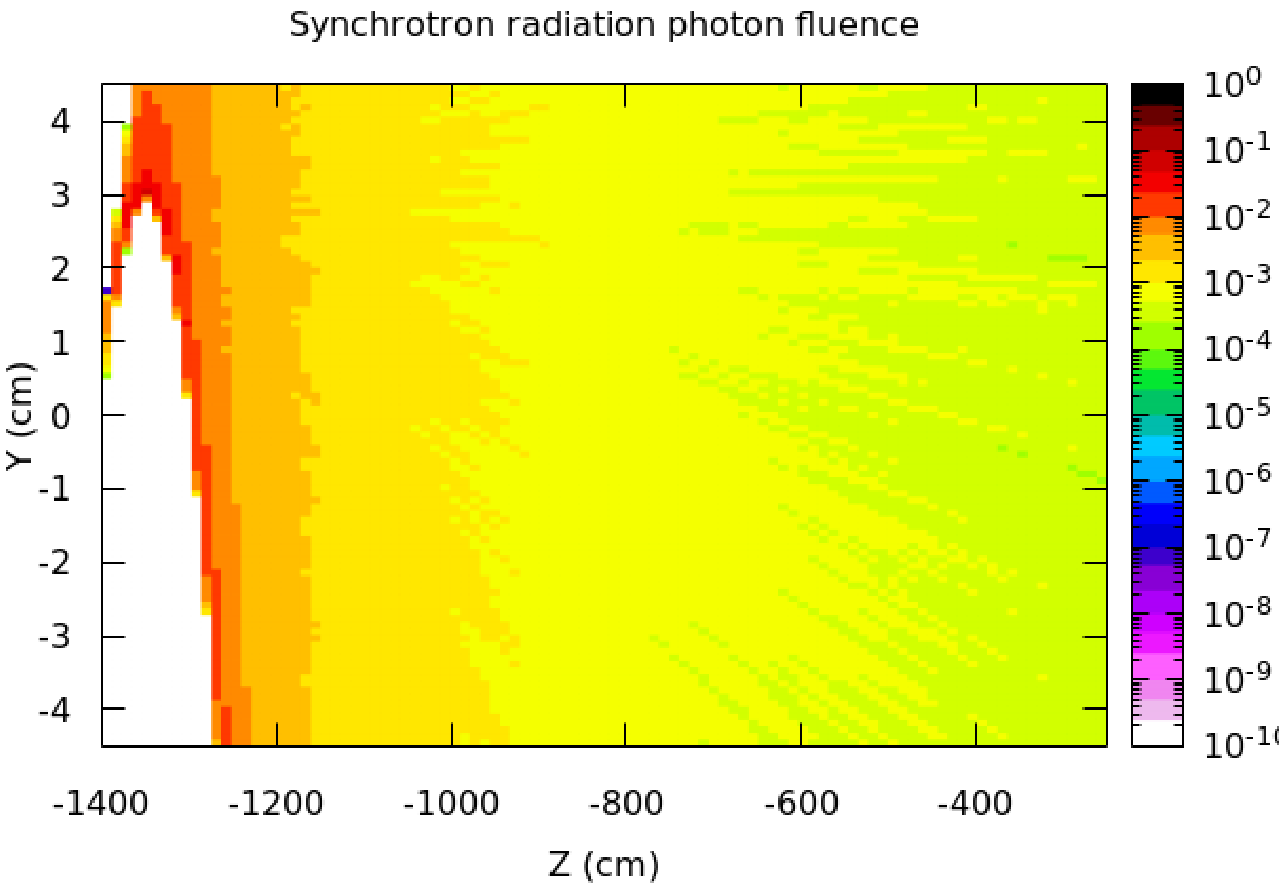


Start of first arc

Synchrotron radiation photons from 3-GeV electrons on a 150 cm arc in B=2 T along X (into the screen)

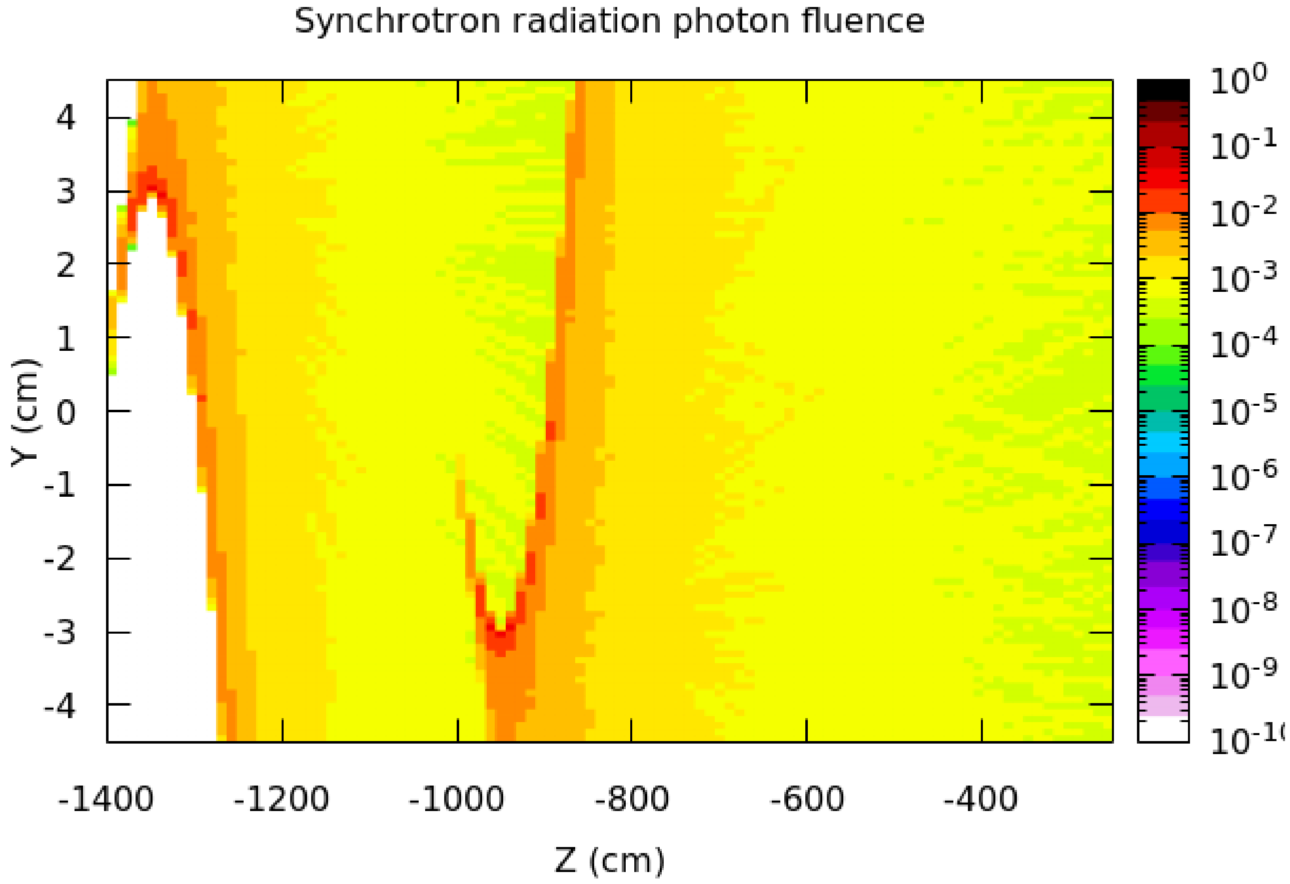
```
BEAMPOS                   0.5   -1400.0              0.100
SPECSOUR   ELECTRON       3.0       -2.0 0.0000001   1.000       0.0SYNC-RAS
SPECSOUR      150.0                                                 &
```

Synchrotron radiation: 1-arc example




```
BEAMPOS                      0.5   -1400.0              0.100
SPECSOUR    ELECTRON         3.0     -2.0 0.0000001     1.000          0.0SYNC-RAS
SPECSOUR       150.0                                                      &
```

Synchrotron radiation: 2-arc example




```
BEAMPOS                      0.5   -1400.0              0.100
SPECSOUR    ELECTRON         3.0      -2.0 0.0000001    1.000         0.0SYNC-RAS
SPECSOUR       150.0         0.0      -0.5    -1000.      0.0     -0.100&
```

A comment about the units

All simulation results for the synchrotron radiation SPECSOUR are quoted **per simulated synchrotron radiation photon**.

From the output file:

```
<<< Synchrotron radiation source n.   1 >>>

Emitting particle: ELECTRON P:      3.00000 GeV/c
  Initial position :    0.0000000       0.50000000       -1400.0000      cm
  Initial direction:    0.0000000       0.10000000       0.99498744

Magnetic field:    2.0000000       0.0000000       0.0000000     T
Nominal curvature radius:    500.34614     cm
Nominal arc:    150.00000     cm
Arc angle:   0.29979246     rad
Actual  curvature radius:    500.34614     cm
Actual arc:    150.00000      cm
Transverse p_T:       3.00000 GeV/c  and gamma:       5870.85237

Critical energy:    0.0000119705 GeV

Photon emission threshold        :   1.00000000E-07 GeV
Photons >1 eV/nominal unit length:   0.11693748     cm^-1
Photons/unit length 1 eV   thres.:   2.38764527E-02 cm^-1
Photons/unit length above  thres.:   9.30610323E-02 cm^-1

Total energy/nominal unit length:   4.55537630E-07 GeV/cm
Energy/unit length below thresh.:   7.54228751E-10 GeV/cm
Energy/unit length above thresh.:   4.54783401E-07 GeV cm
```

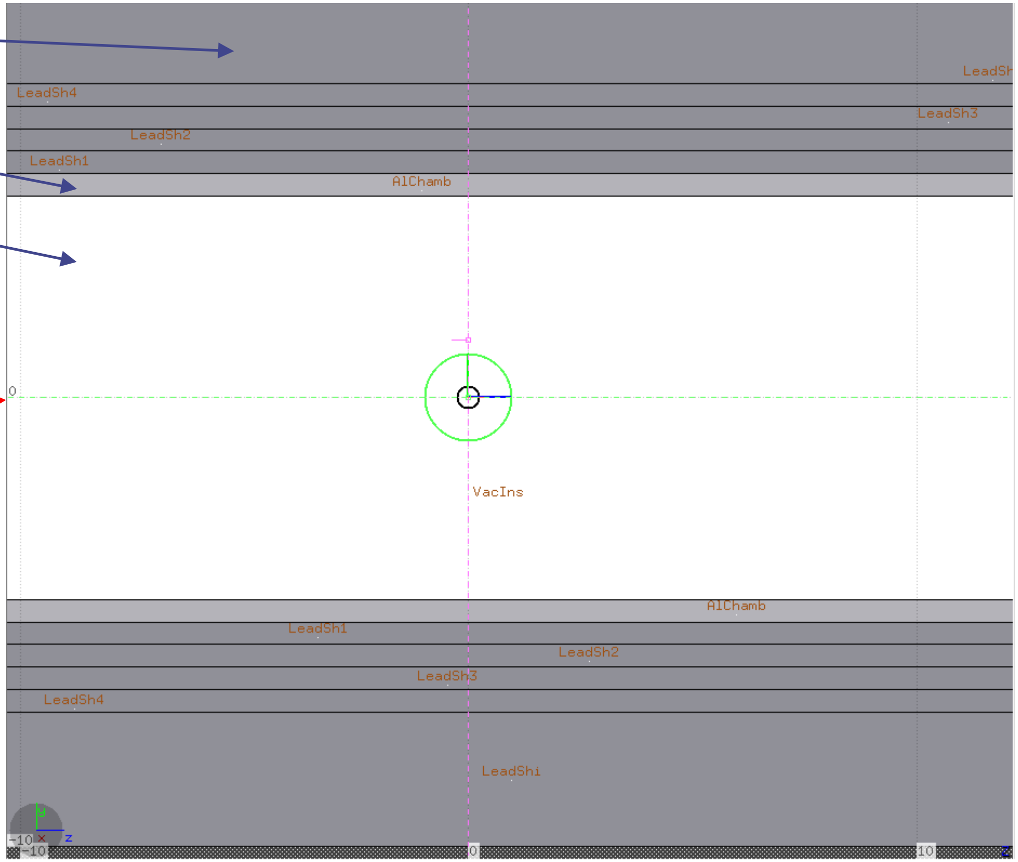
We would have to scale results by 150*.093061 so as to obtain results **per primary emitting particle.**

Synchrotron radiation: a higher-energy example

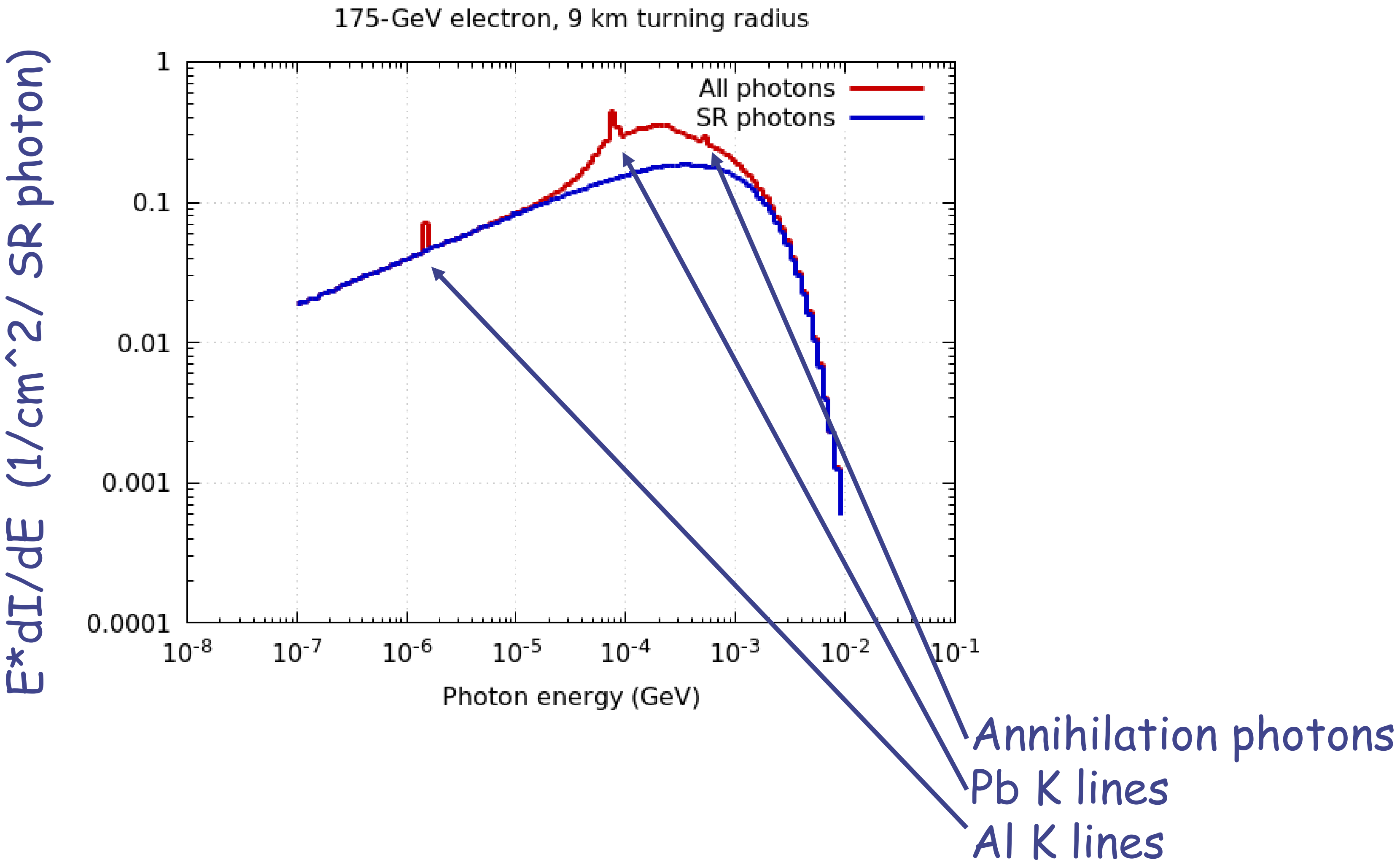
175-GeV electrons on a few cm in an arc with 9 km turning radius:

Lead shielding
Al layer
Vacuum

175-GeV e-
R=9000 km



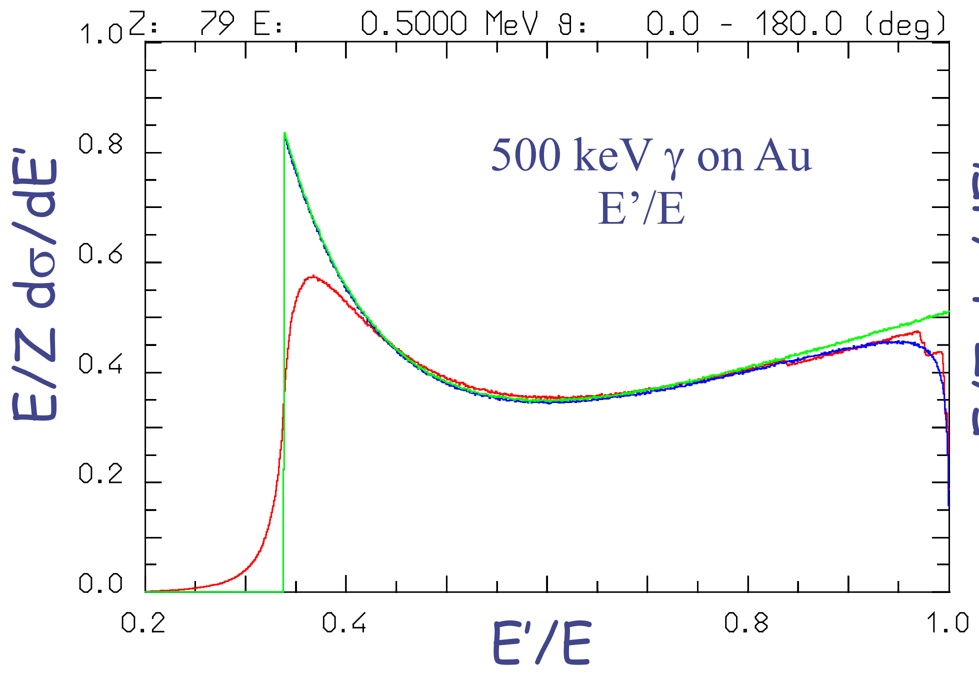
Synchrotron radiation: a higher-energy example

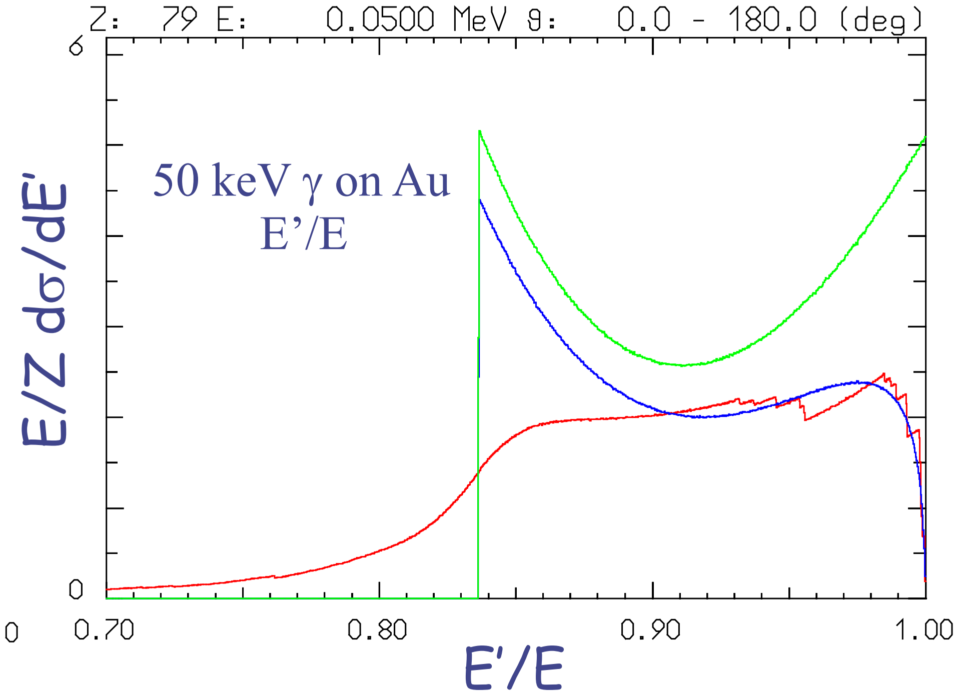


END

Spare slides

Compton profile examples



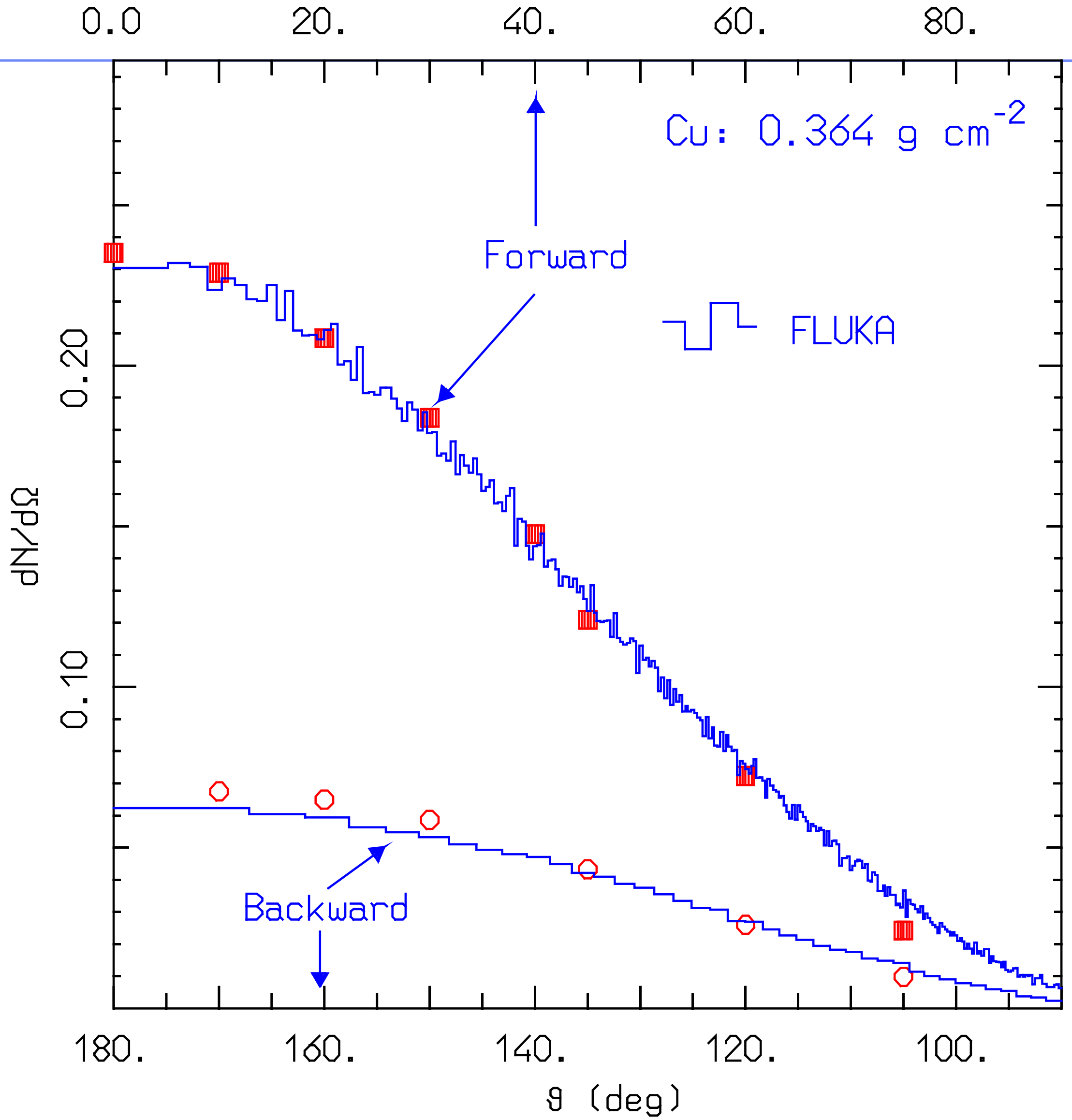


E: energy of incoming photon, E': energy of the emitted photon

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 absorption.
Visible: shell structure near E'=E, smearing from motion at low E'

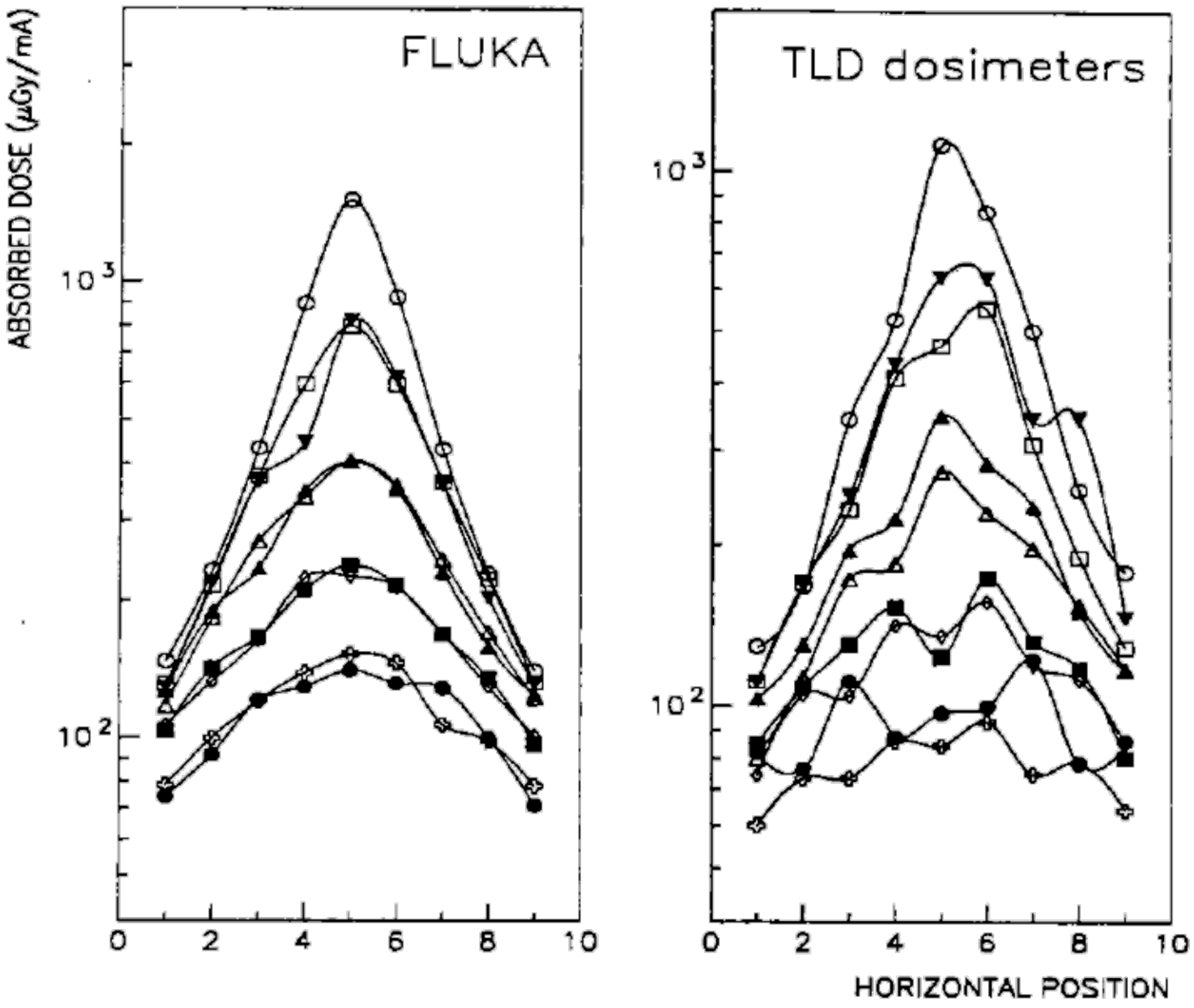
Electron scattering:



Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm^2 thick Copper foil
Measured (dots) and simulated (histos) data

Bremsstrahlung: benchmark III

Esposito et al., LNF 93-072



ADONE storage ring

1.5 GeV e^-

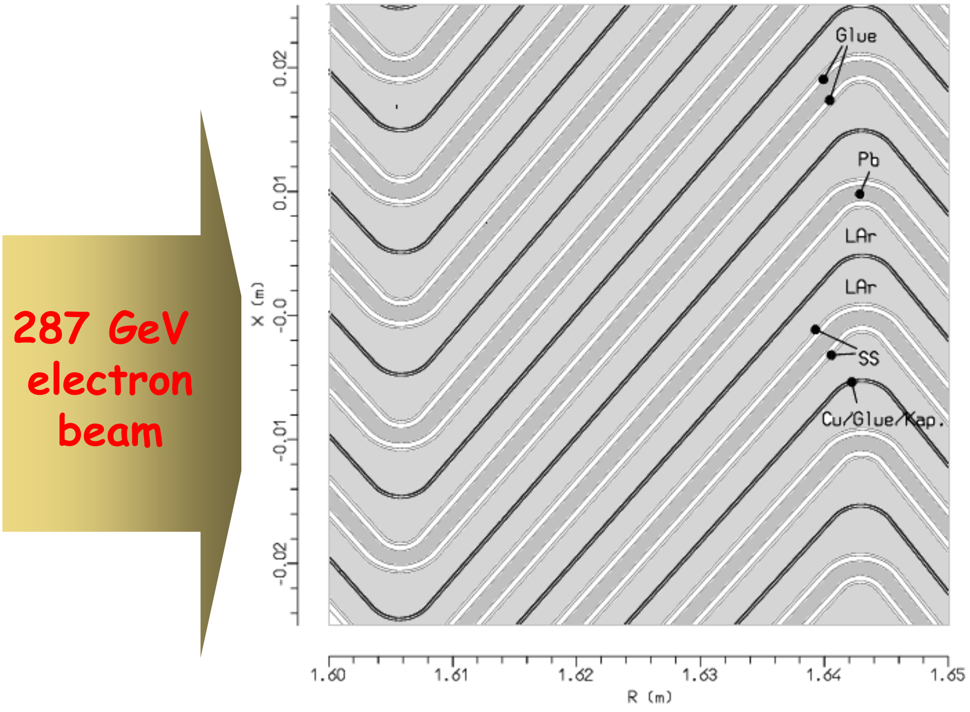
Bremss. on the residual gas in the straight sections

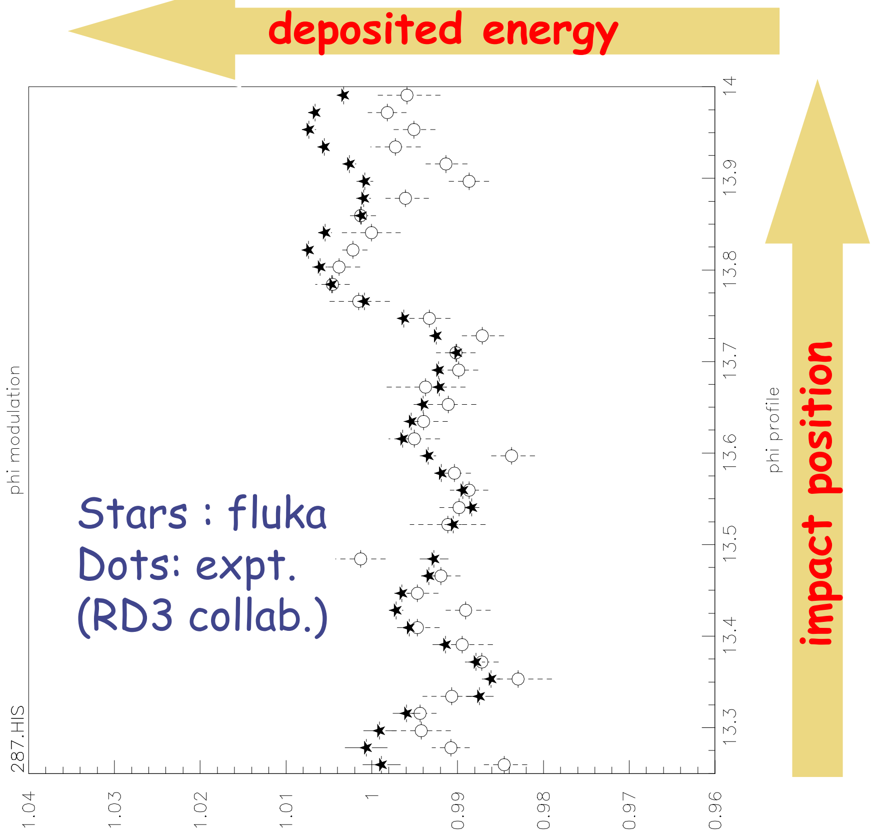
Measured with TLD's matrices at different distances from the straight Section

Here: dose vs. horizontal position at different vertical positions , d=218cm

The ATLAS EM "accordion" calo (standalone test beams)

Detail of the FLUKA geometry and response vs. electron impact position





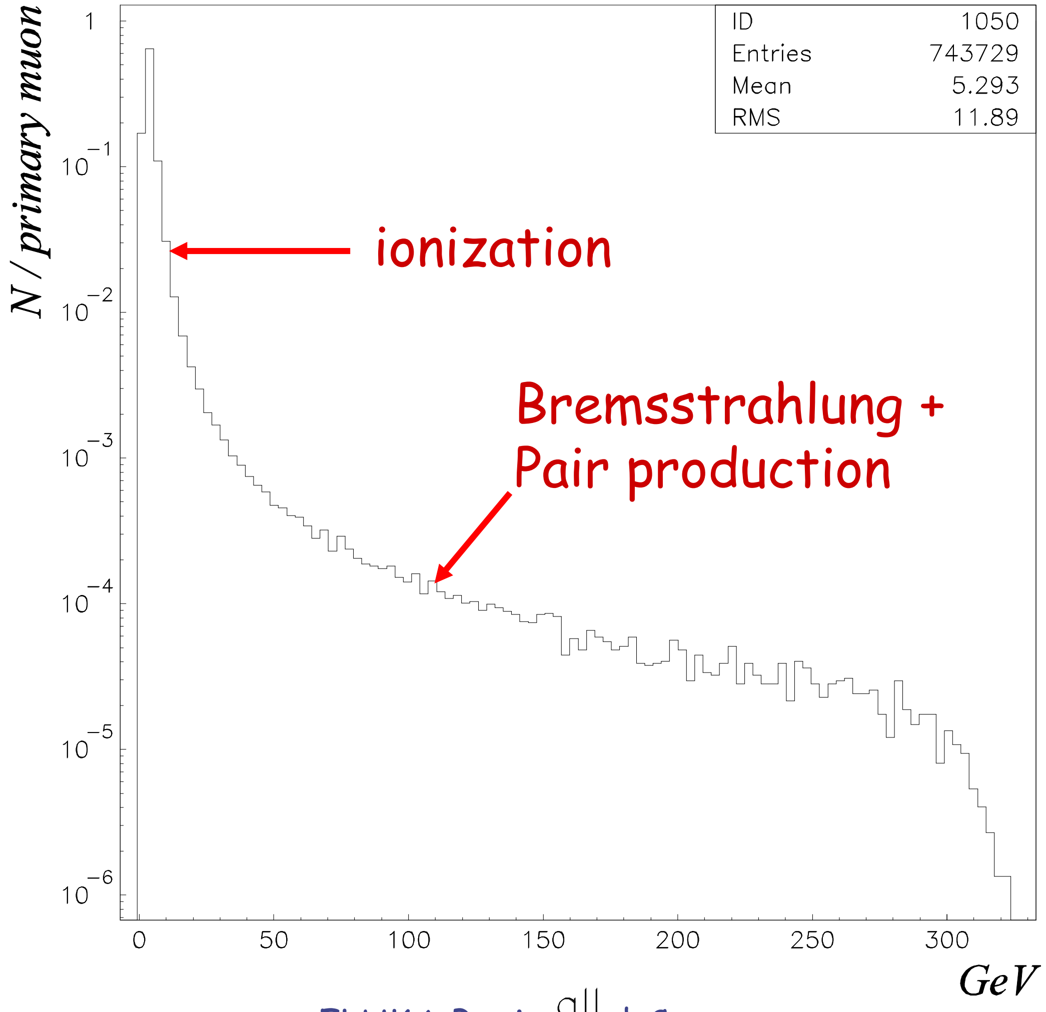
Energy resolution 10-100 GeV:

$$Exp: \frac{\sigma}{E} = \frac{9.8 \pm 0.4\%}{\sqrt{E}}$$

$$Fluka: \frac{\sigma}{E} = \frac{9.2 \pm 0.3\%}{\sqrt{E}}$$

Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure



Energy Deposition spectrum in the Atlas tile-calorimeter prototype

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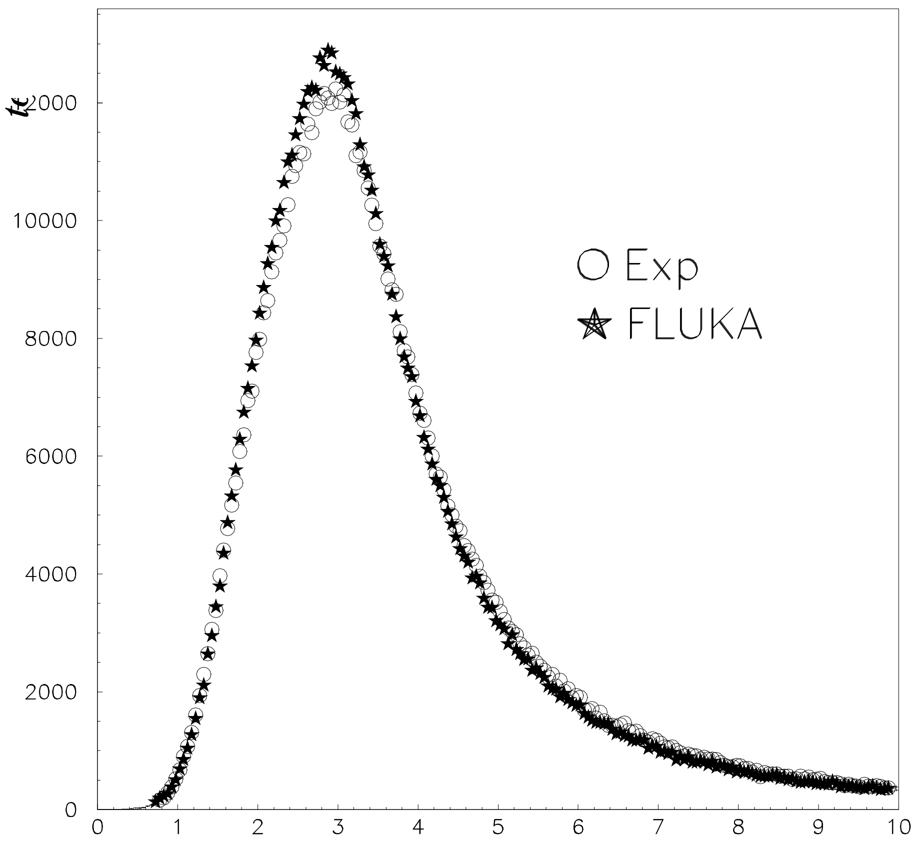
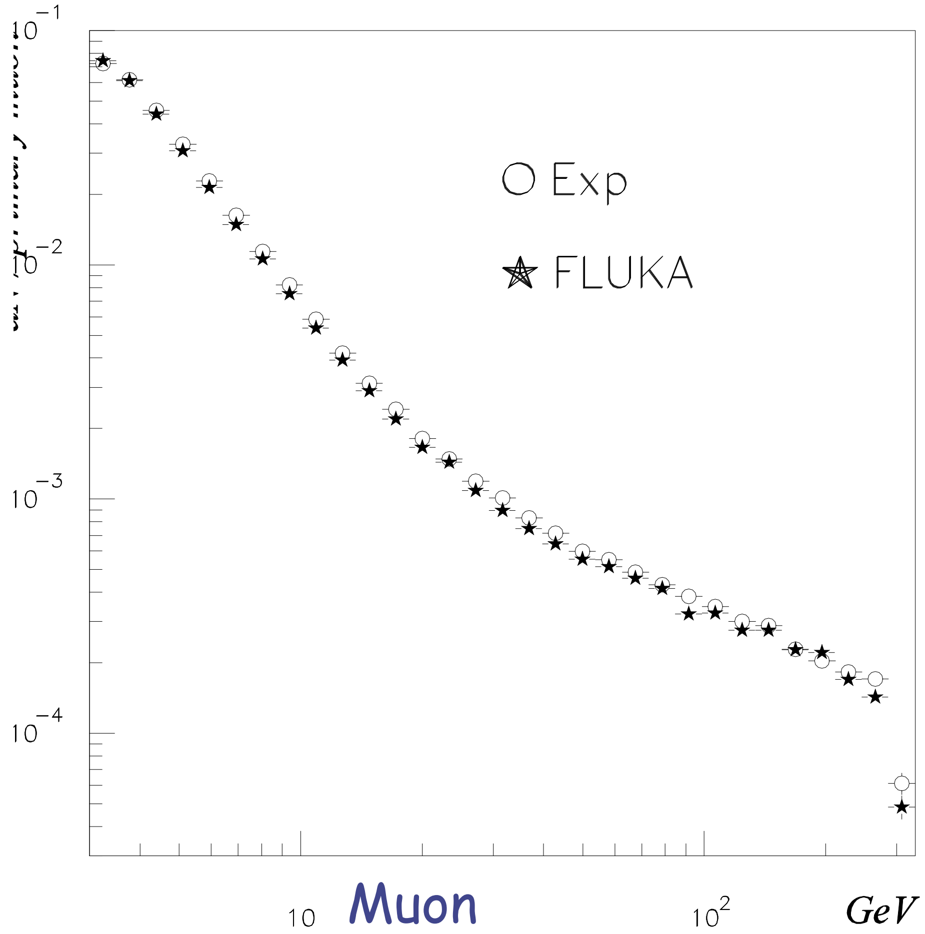


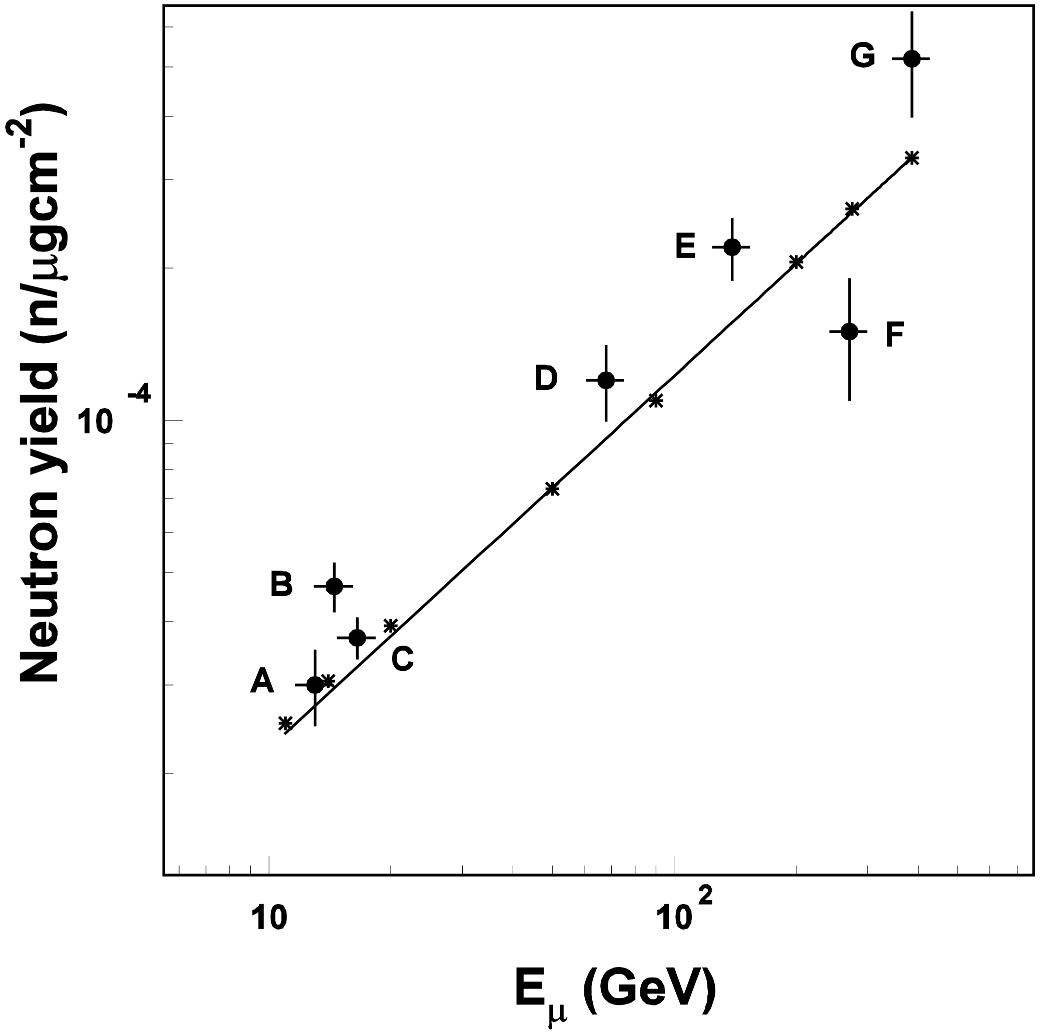
Muon energy [GeV]



Muon energy [GeV]

Muon-induced neutron background in underground labs

PRD64 (2001) 013012



Neutron production rate as a function of muon energy

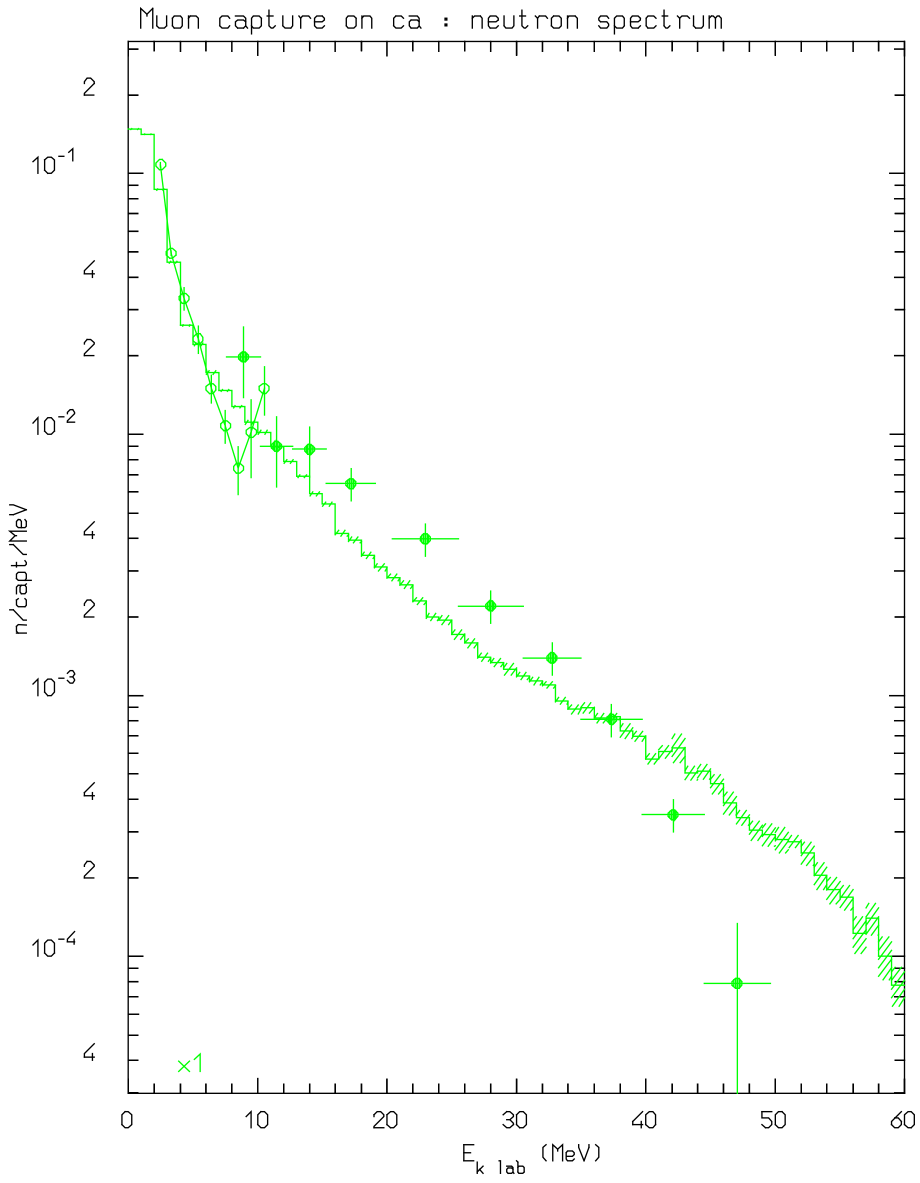
Stars+line : FLUKA simulation with a fit to a power law.

Exp. points:
abscissa →average μ energy at the experiment's depth:

A) 20 m.w.e.
B) 25 m.w.e.
C) 32 m.w.e. (Palo Verde)
D) 316 m.w.e.
E) 750 m.w.e.
F) 3650 m.w.e. (LVD)
G) 5200 m.w.e. (LSD)

m.w.e. = meter of water equivalent

Muon Capture (2)



capture on Calcium

Dots: experimental data (Columbia Univ. rep. NEVIS-172 (1969), Phys. ReV. C7, 1037 (1973), Yad. Fiz. 14, 624 (1972))

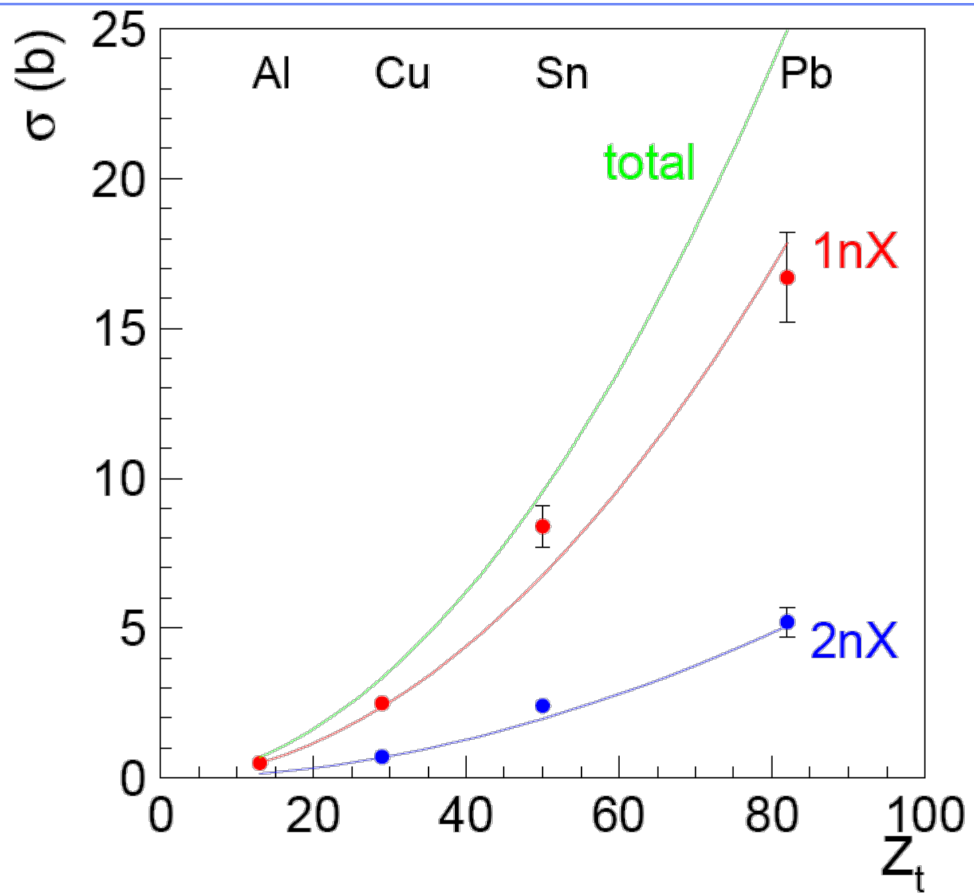
histograms: FLUKA calculations

Emitted:

0.62 neutrons/capture

0.27 protons/capture

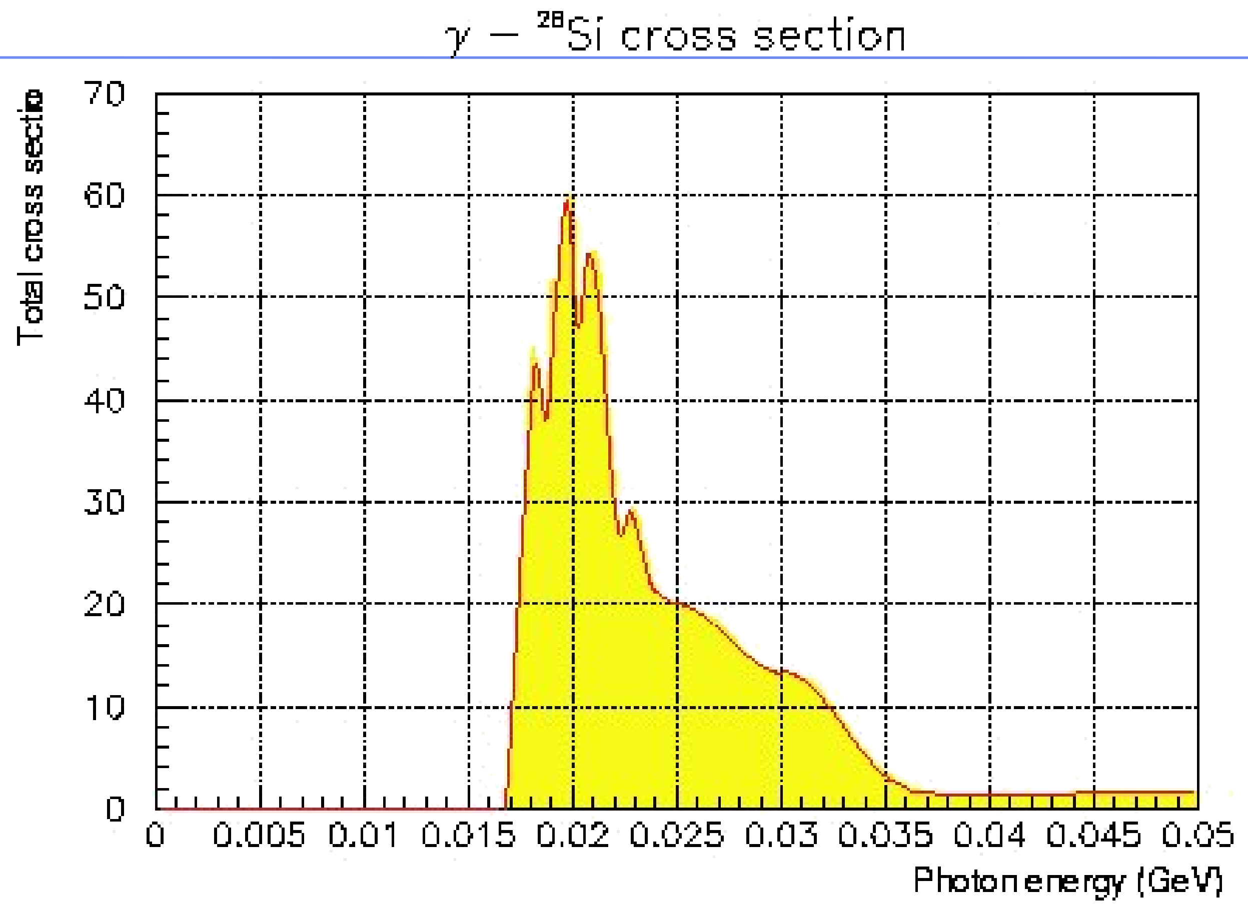
Electromagnetic dissociation - *Benchmarks*



Electromagnetic dissociation cross sections (total, 1nX, 2nX) for 30GeV/n Pb ions on Al, Cu, Sn, and Pb targets.

FLUKA: lines (calculated cross section as a function of target charge)
Exp. data: M.B.Golubeva *et al.*

Electromagnetic dissociation: example



$^{28}Si(\gamma,tot)$ as recorded in FLUKA database, 8 interval Bezier fit as used for the Electromagnetic Dissociation event generator.