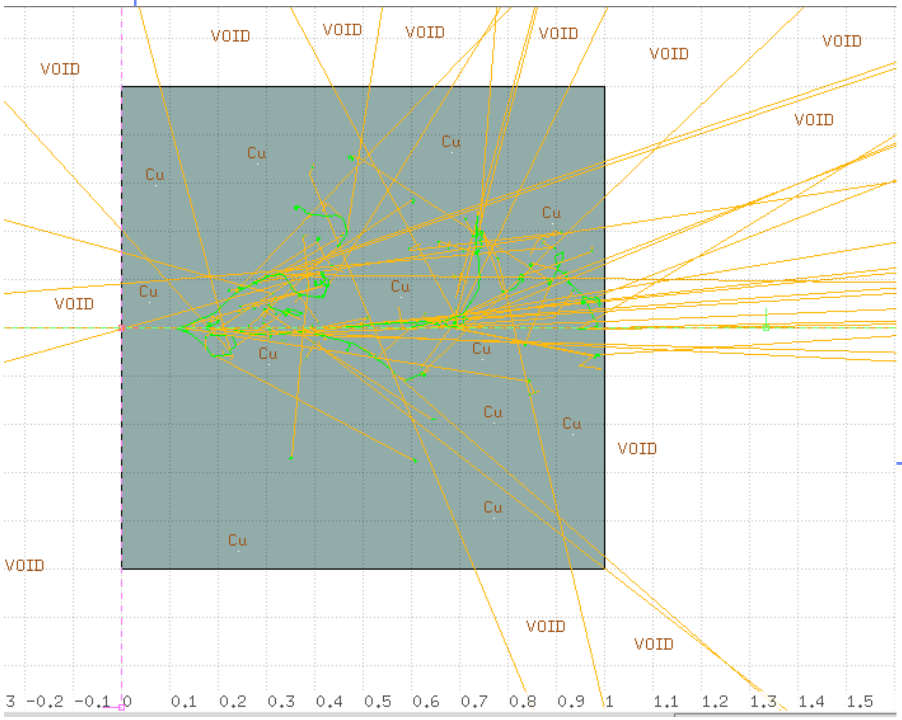
EM interactions



20th FLUKA Beginners' Course
Stellenbosch University
(South Africa)
May 28 – June 1, 2018

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:

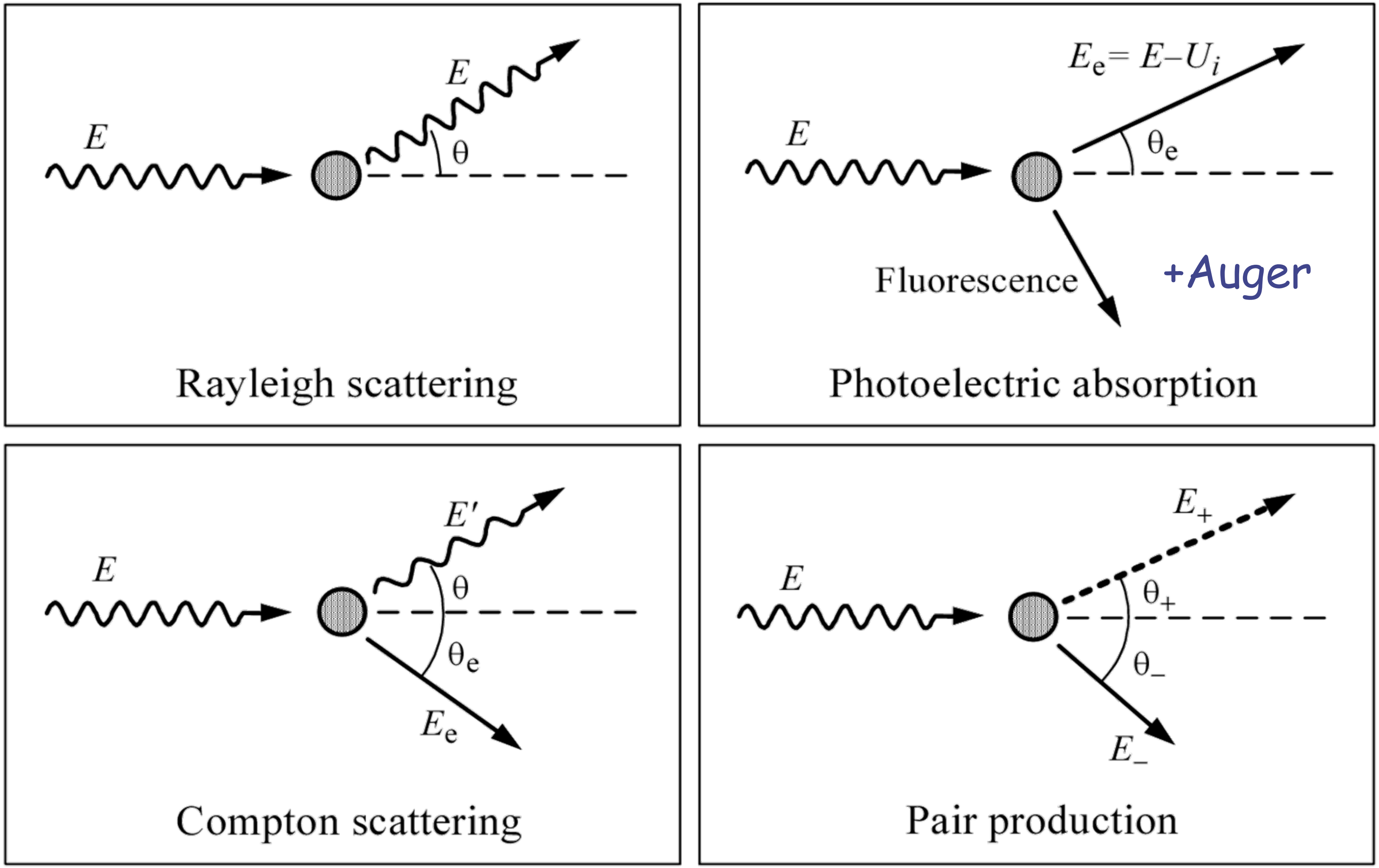
EMF	**EMF-OFF**

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 in this beginners course

Photon interactions

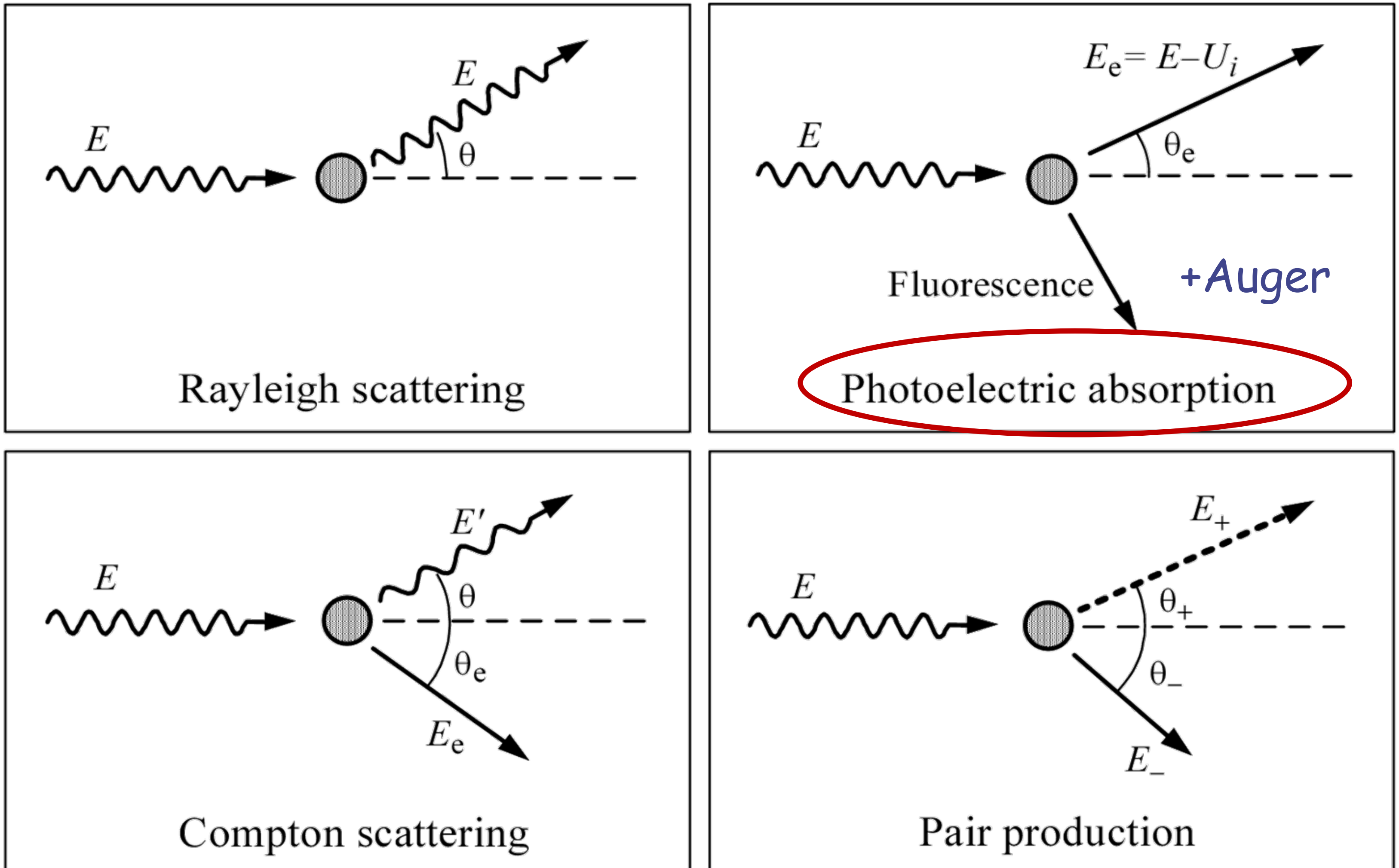
Photon interactions modeled in FLUKA



+photo-nuclear processes

+photo-muon production

Photon interactions modeled in FLUKA



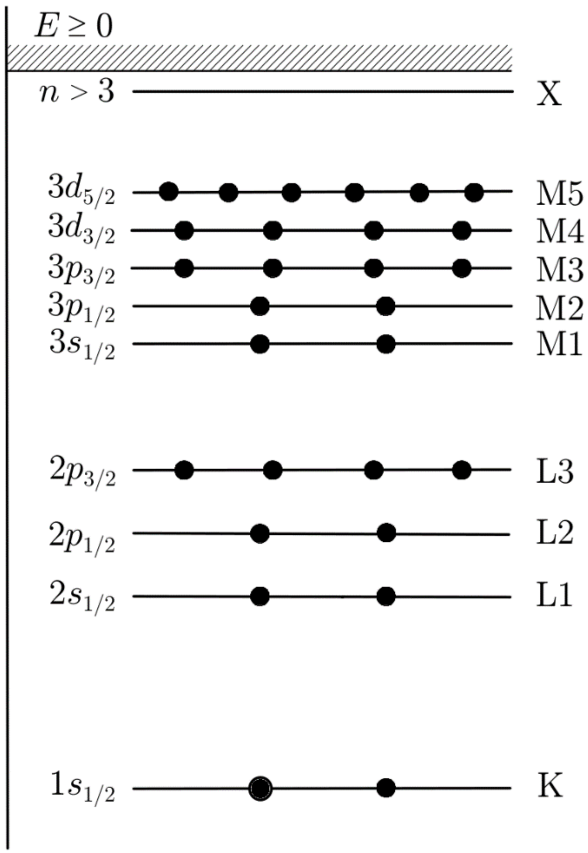
+photo-nuclear processes

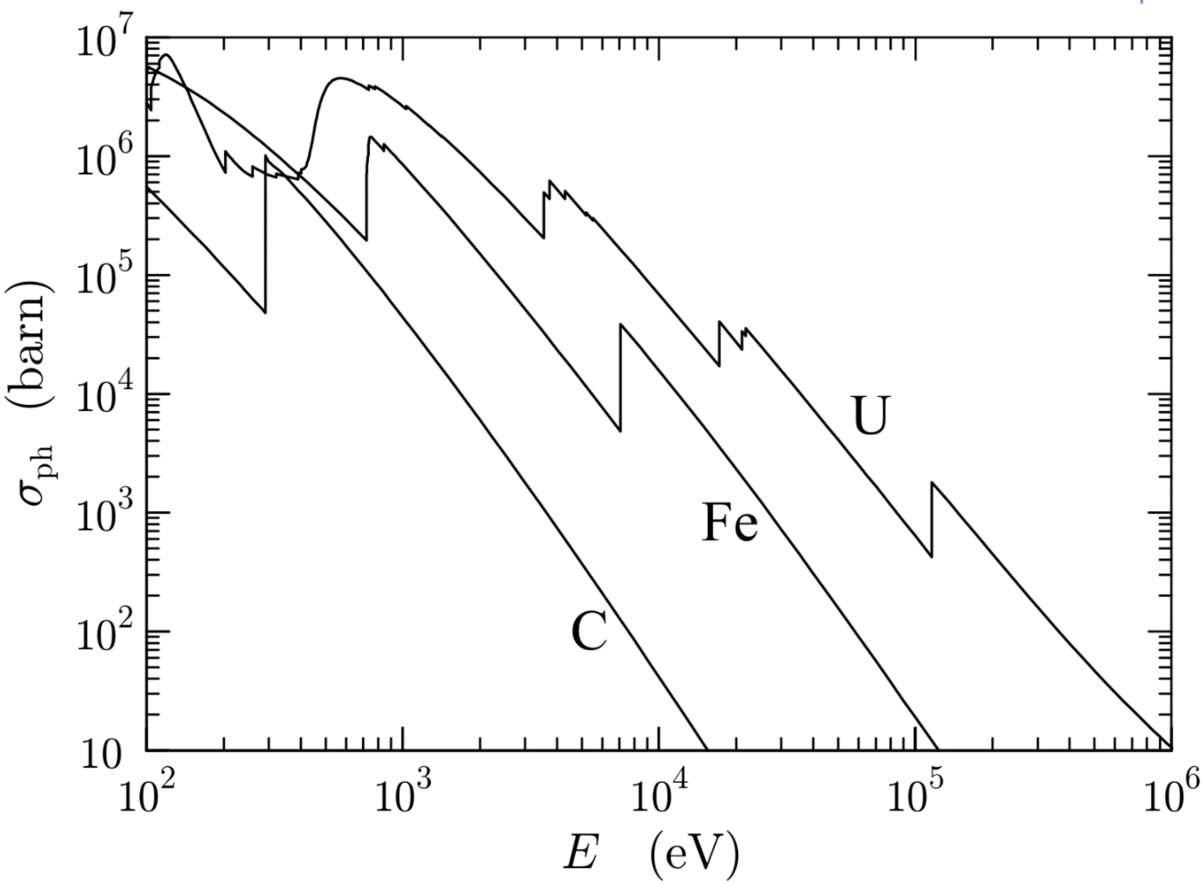
+photo-muon production

Photoelectric effect

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

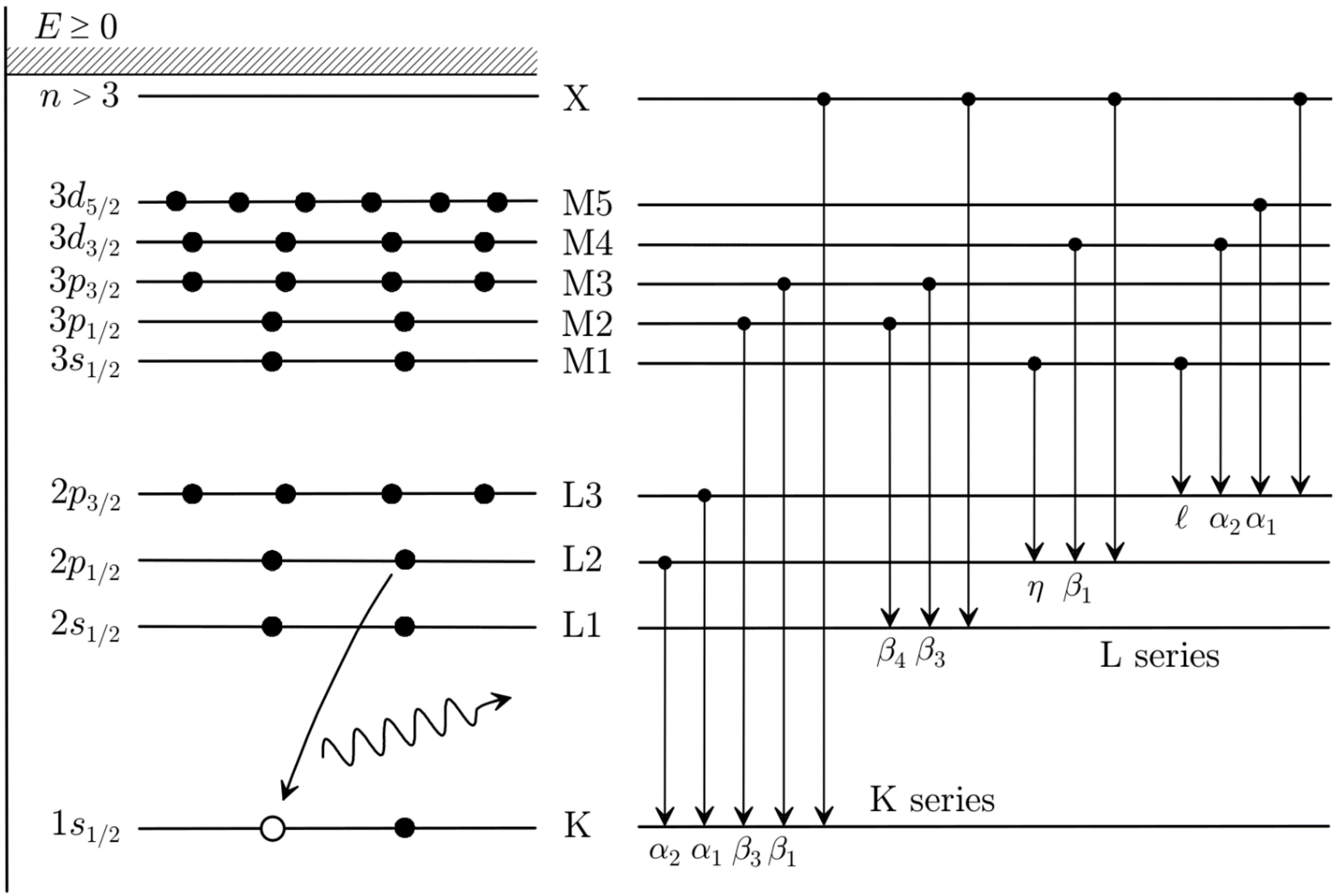
Source: Evaluated Photon Data Library (Cullen et al., EPDL97).





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
```

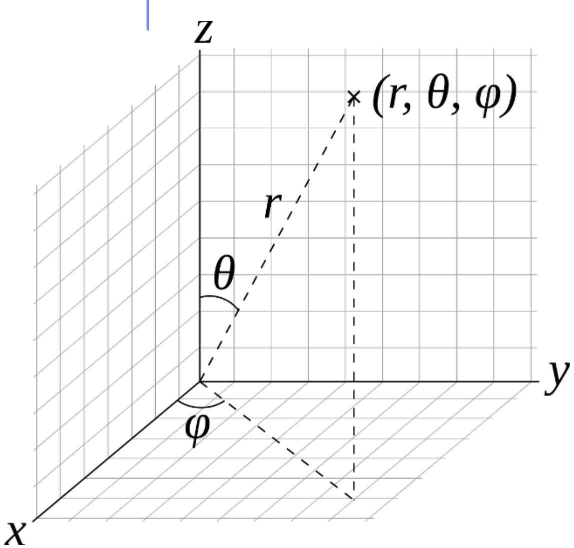
Flag > 0: Activate Flag < 0: De-activate

Warning: check consistency with production/transport thresholds

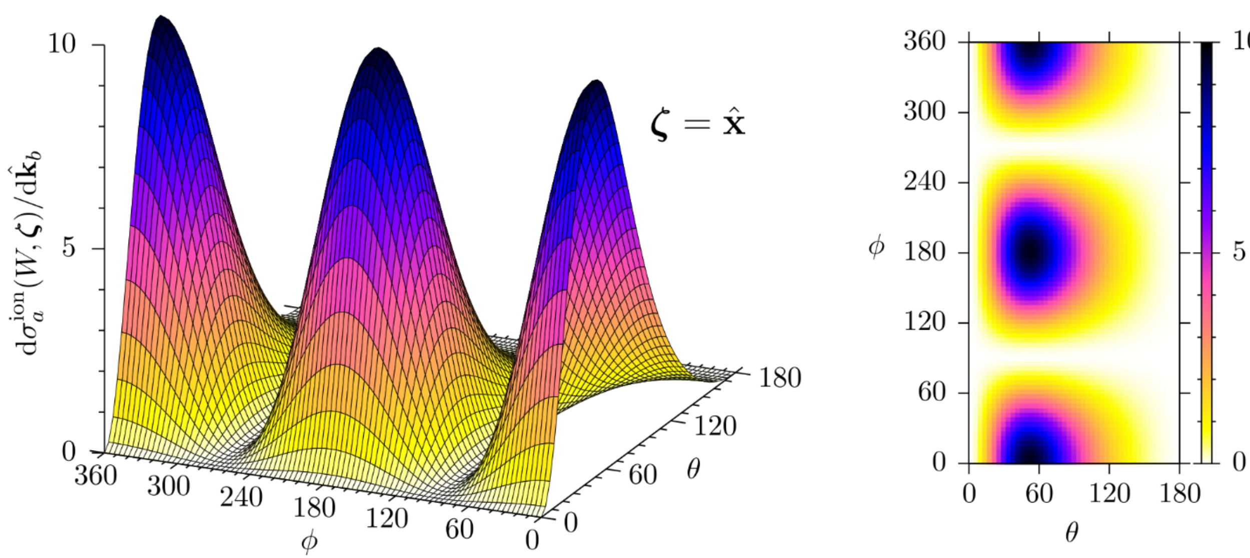
Effect of polarization

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

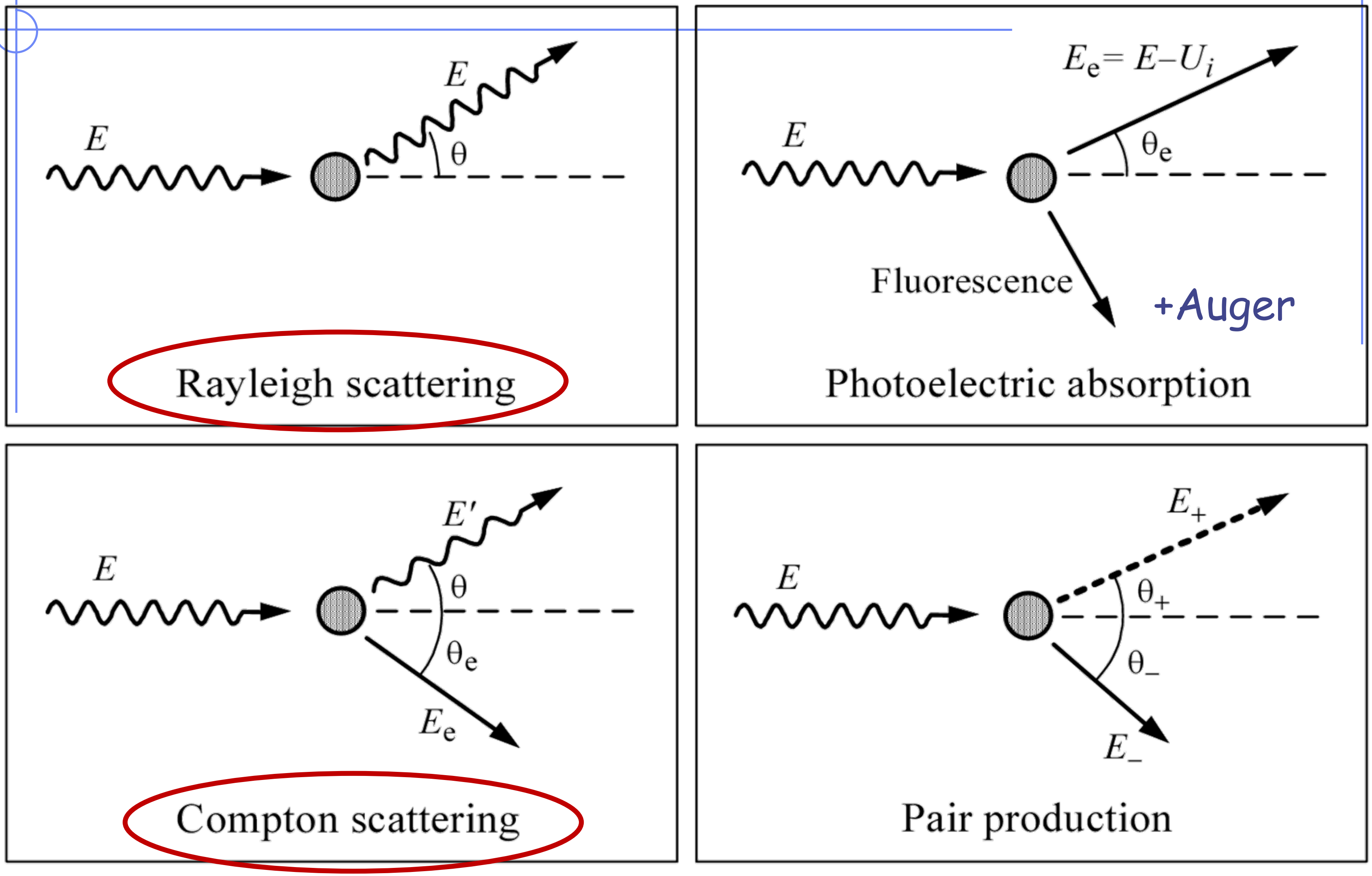


L. Sabbatucci, F. Salvat / Radiation Physics and Chemistry 121 (2016) 122–140



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)

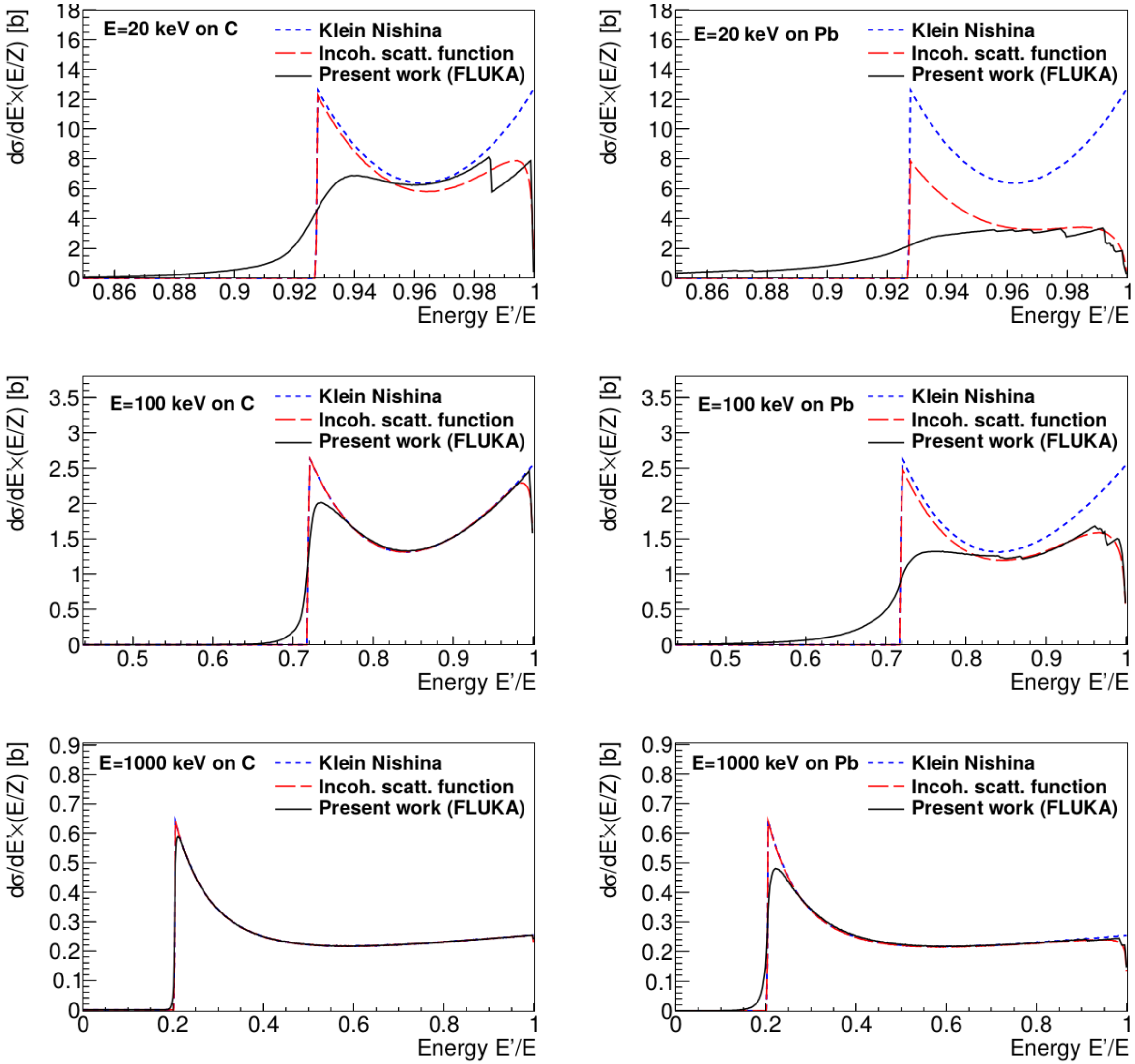
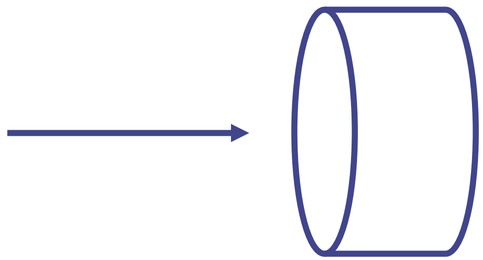


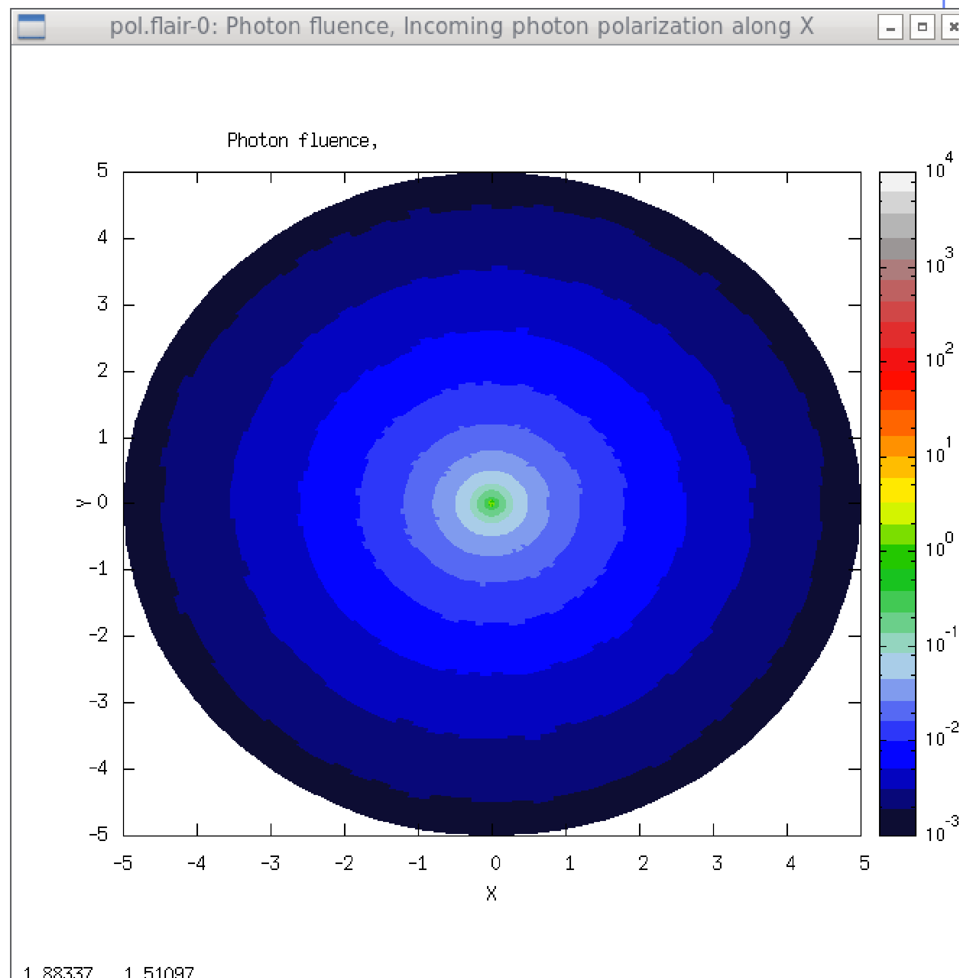
Figure 4. Compton scattering cross sections differential in the energy of the scattered photon E' at selected initial photon energies ($E = 20, 100, 1000\,\mathrm{keV}$) for carbon and lead. The cross sections are computed with the present Compton scattering model, using a fit to tabulations of the incoherent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

Effect of polarization on Compton scattering



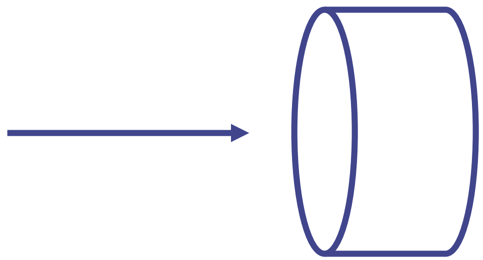
50-keV photons impinging along Z on water cylinder

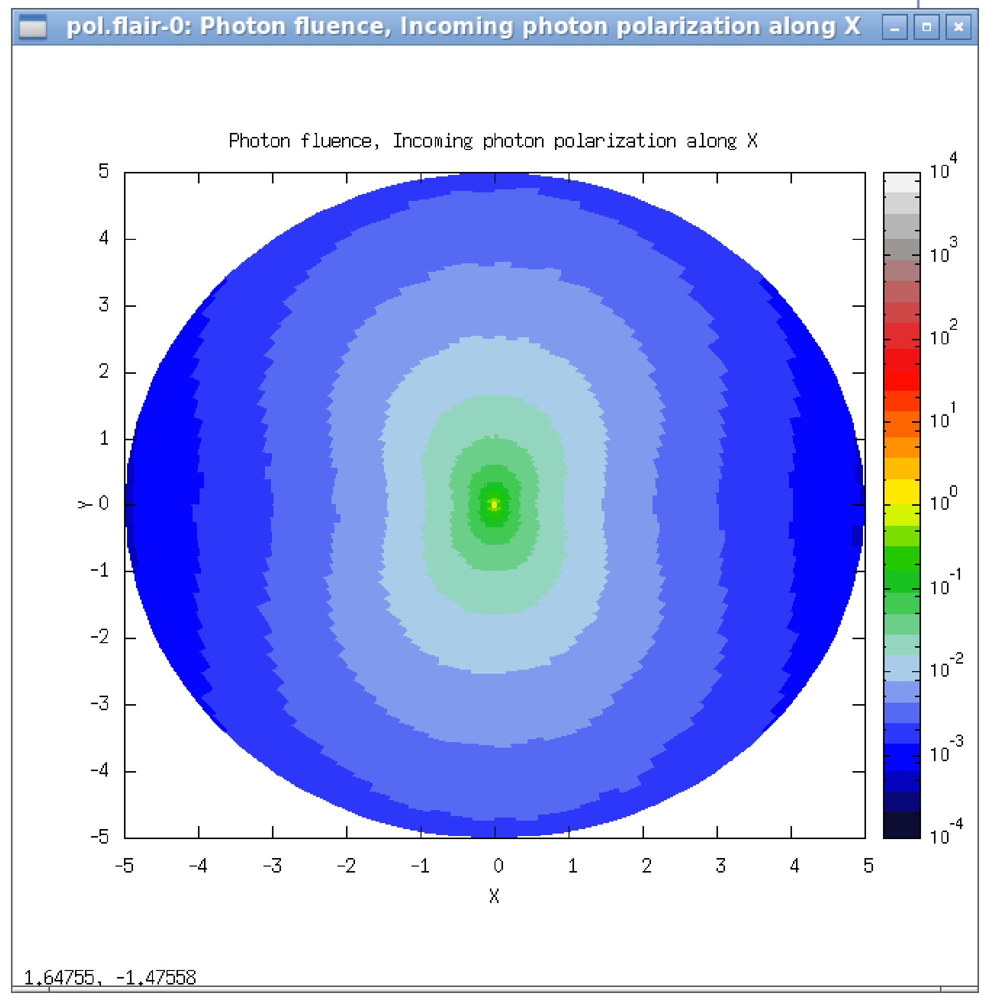
Unpolarized



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

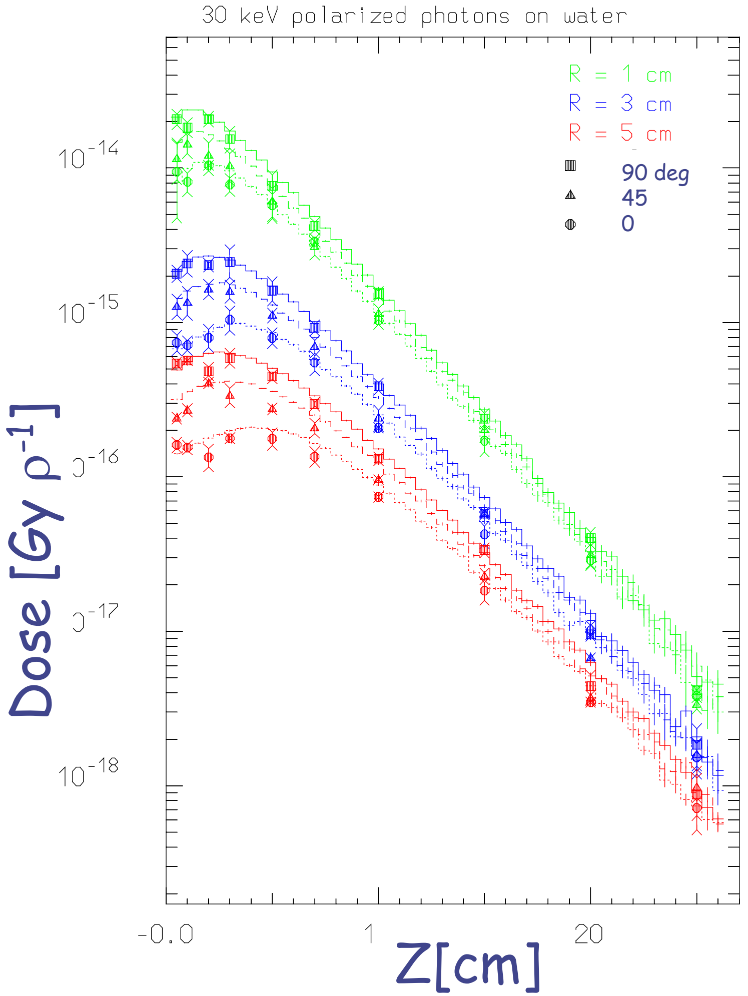
Incoming photon polarized along X

Compton photons preferentially emitted along Y (!)

Polarization

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

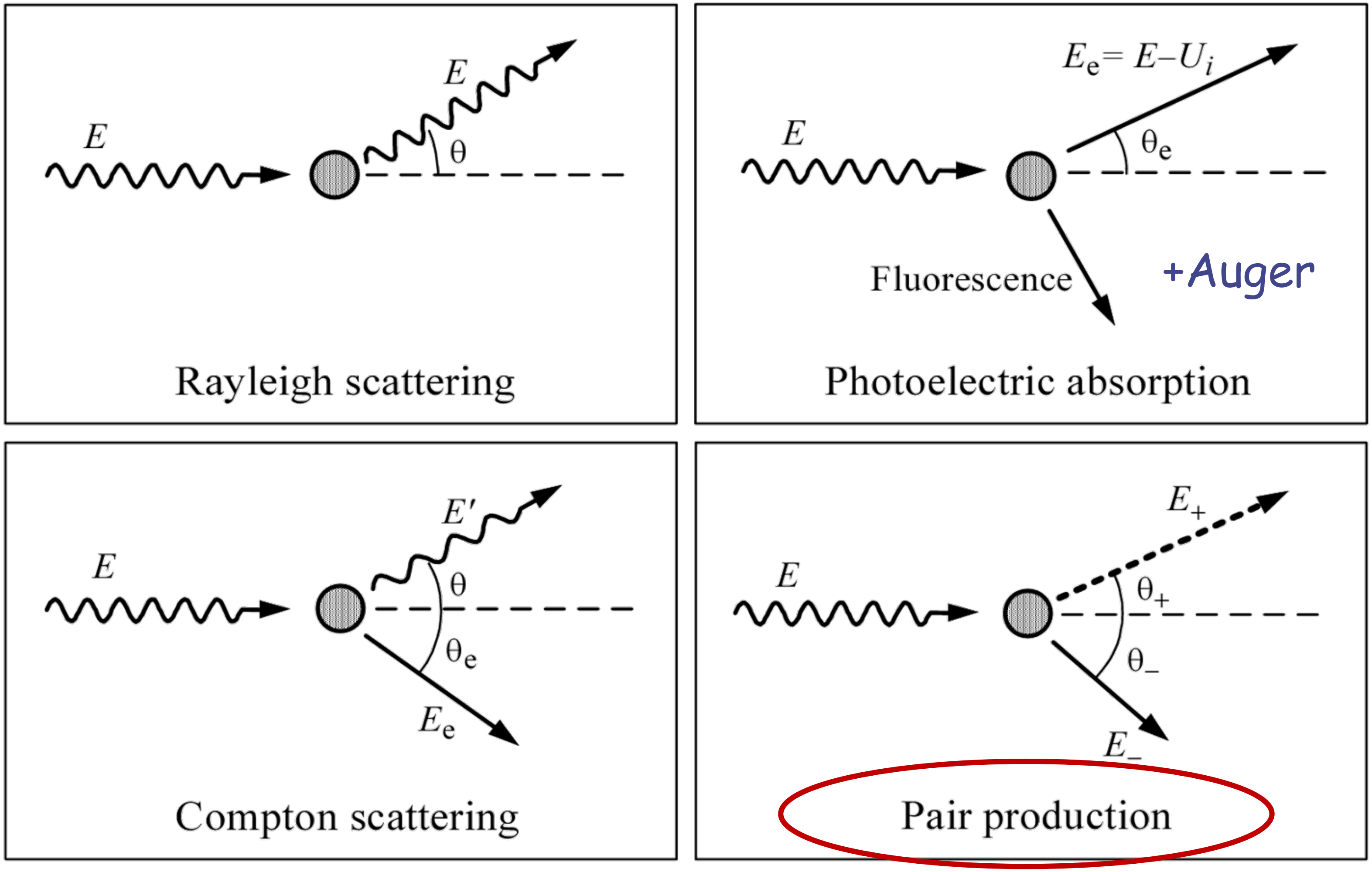
```
POLARIZA Pcosx Pcosy Pcosz     Flag1     Fraction     Flag2
```



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, $\mu^-\mu^+$ pair production



+photo-nuclear processes

+photo-muon production

e^-e^+ Pair Production

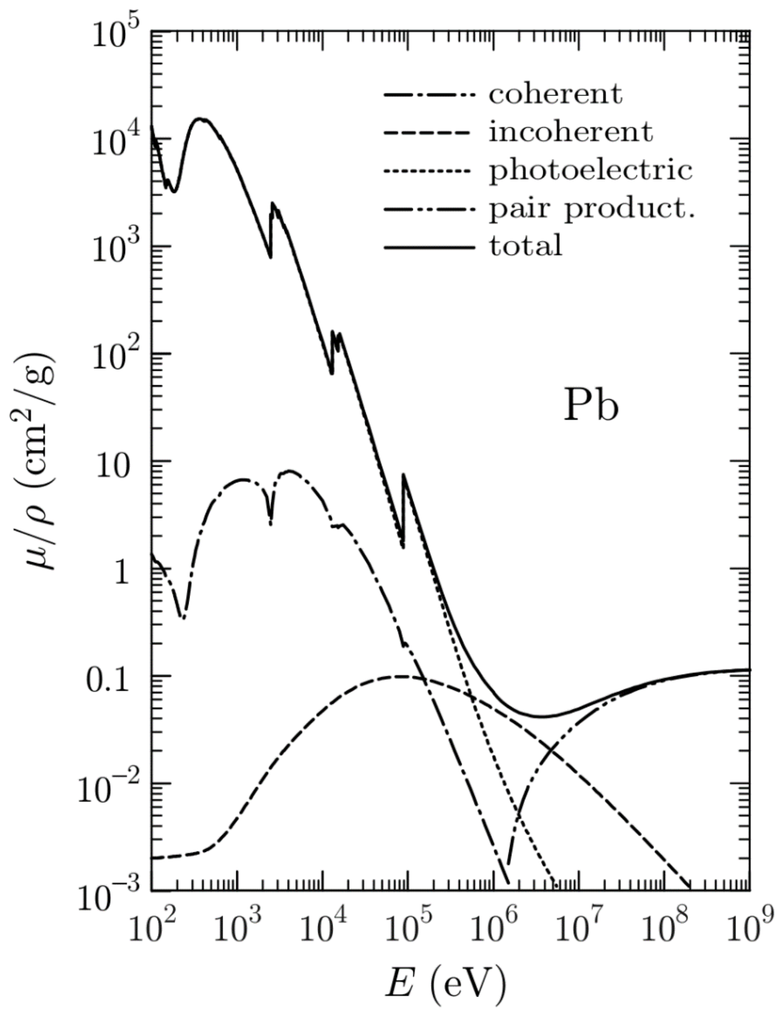
- Kinematics: requires presence of target mass, threshold at ~2*511 keV.
- Dominant photon interaction mechanism at energies above ~100 MeV
- Angular and energy distribution of e^+,e^- described correctly (no "fixed angle" theta=m/k or similar approximation)
- No approximations near threshold. Differences 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))

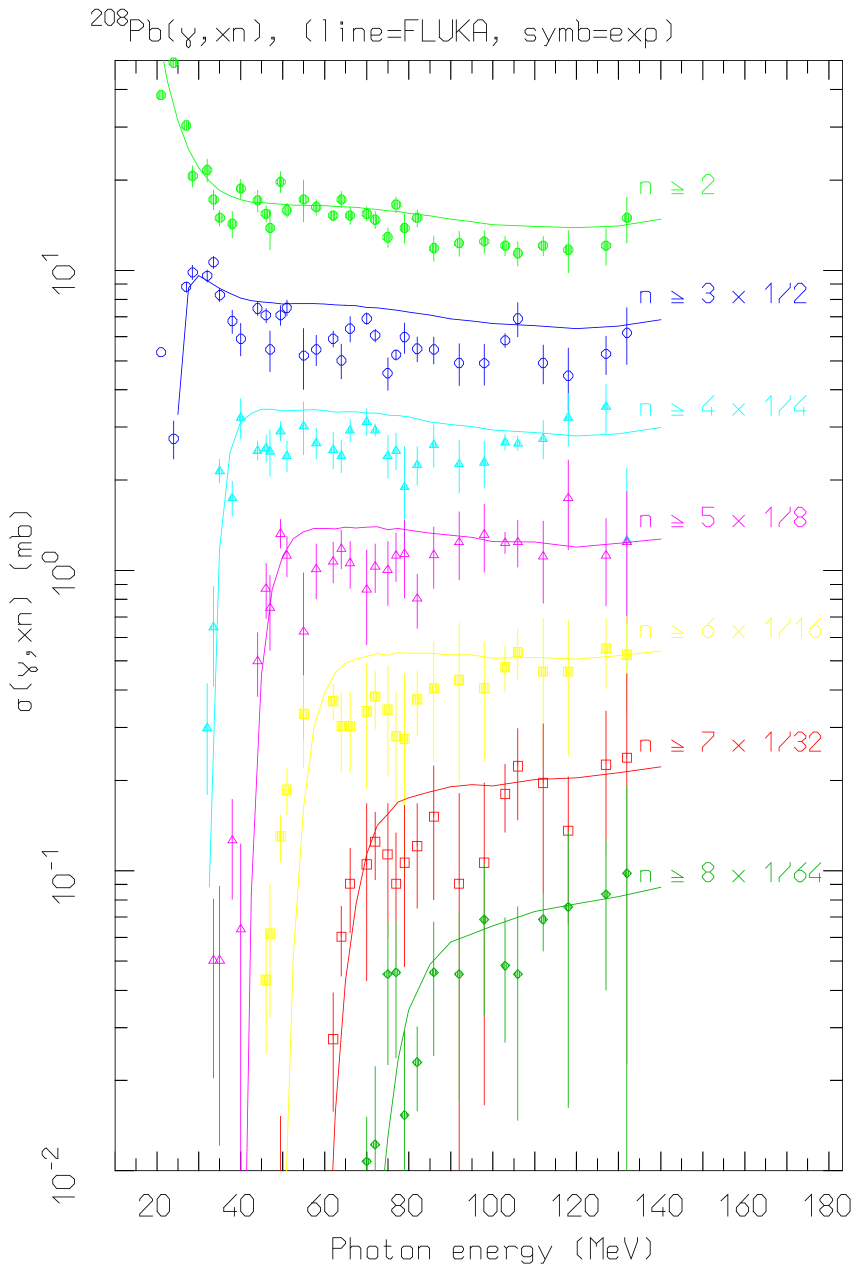
Photonuclear int.: example

Reaction:
$^{208}Pb(\gamma,x\ n)$
$20 \leq E_\gamma \leq 140$ MeV

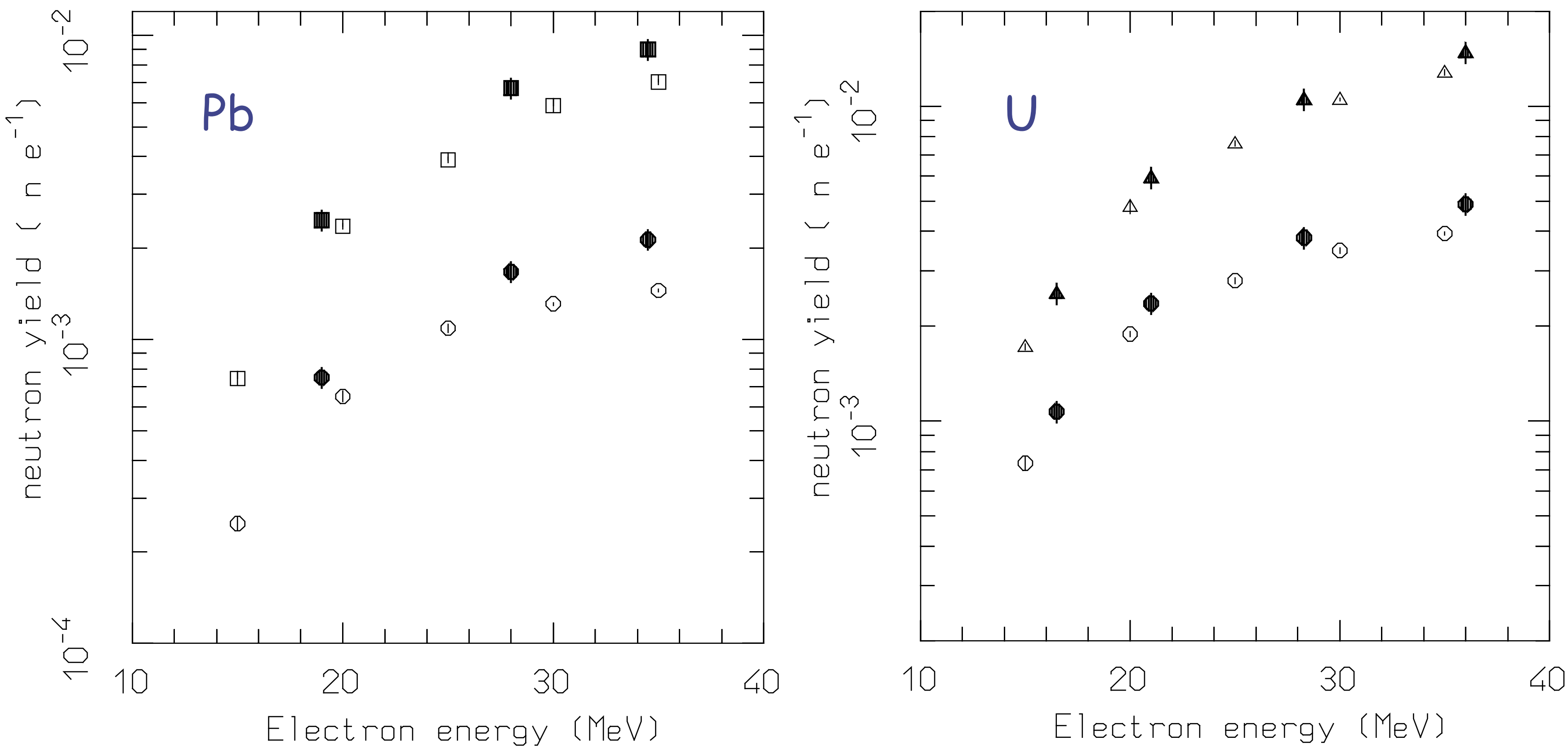
Cross section for multiple neutron emission as a function of photon energy, **Different colors refer to neutron multiplicity ≥ *n* , with 2 ≤ *n* ≤ 8**

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

Bremsstrahlung

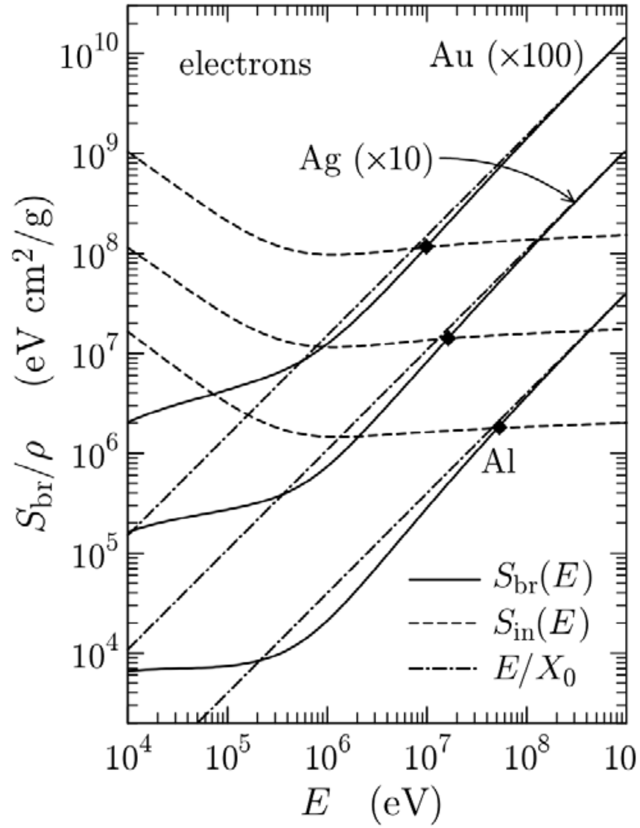
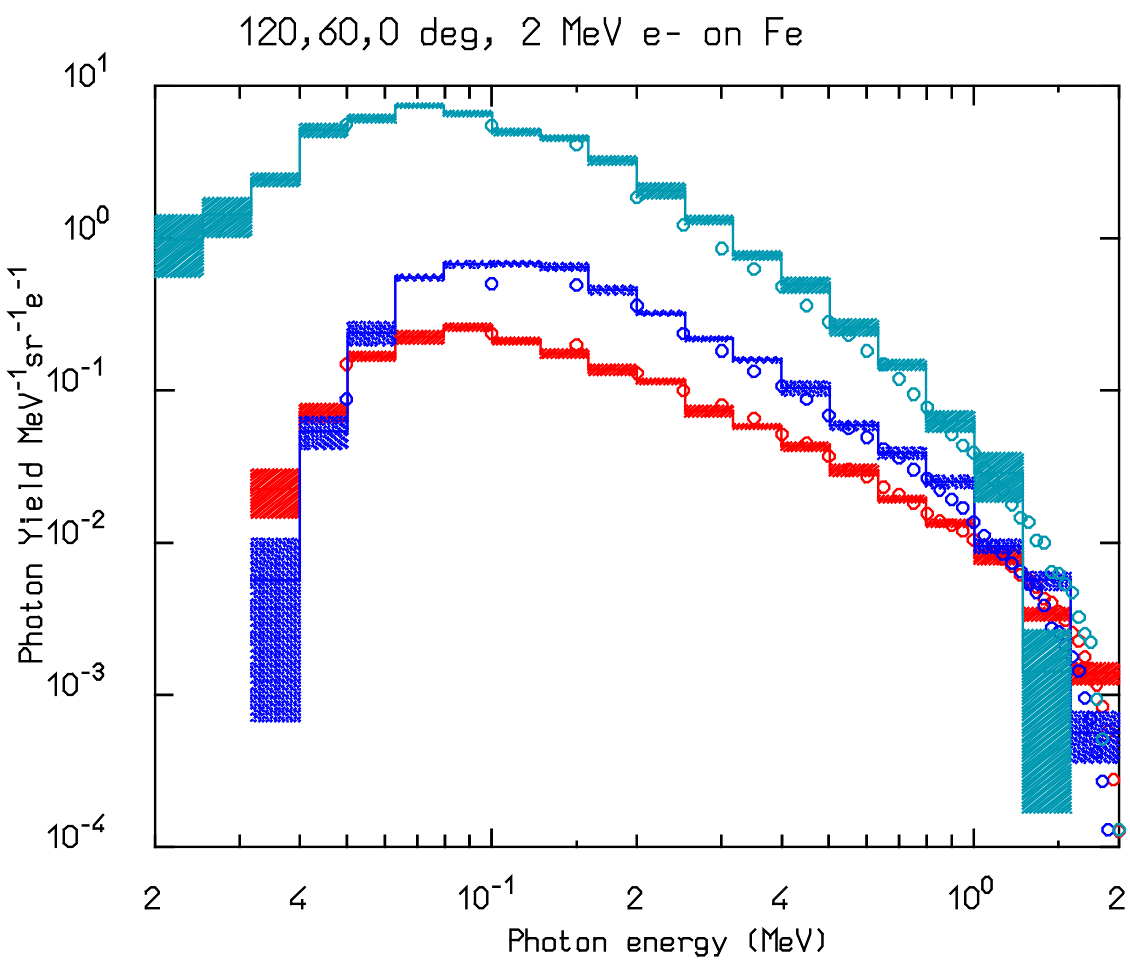


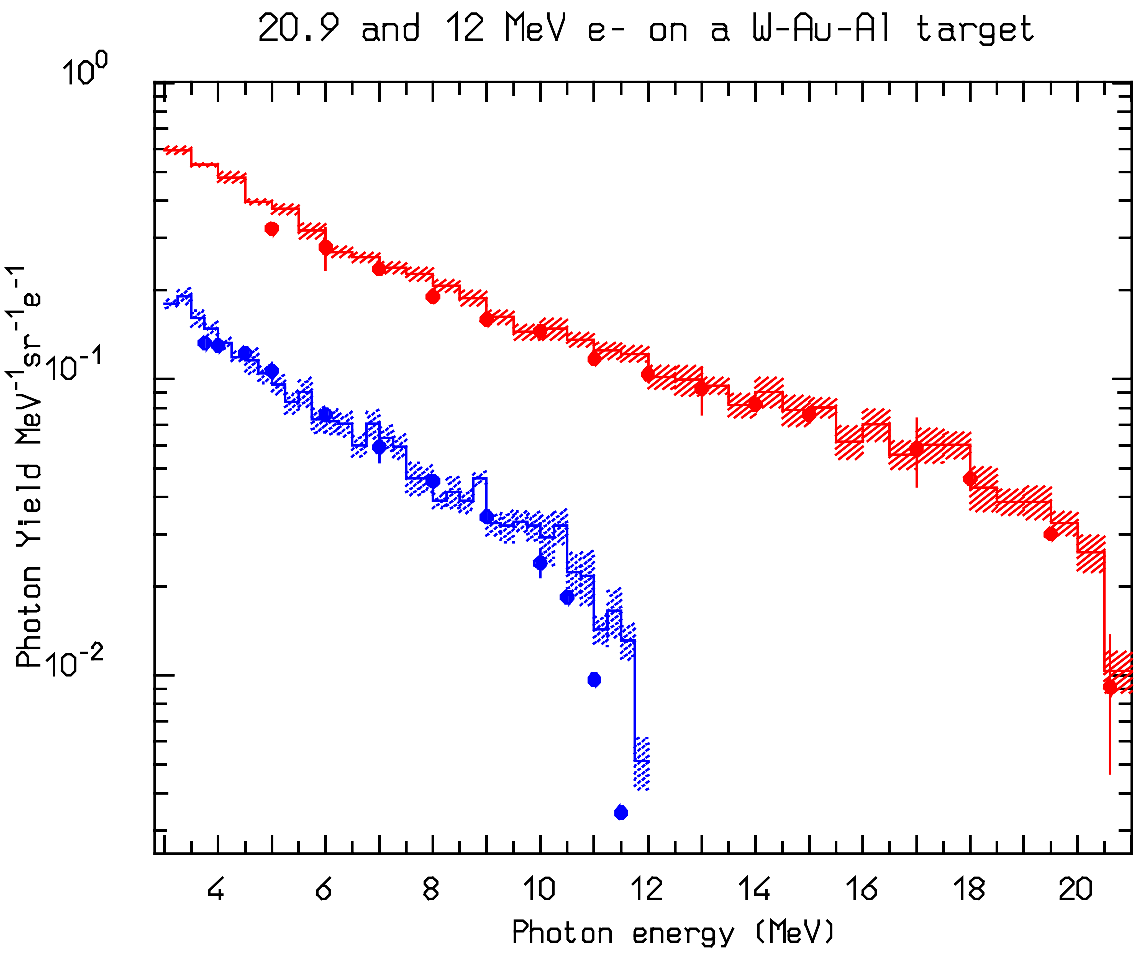
Figure 3.15: Radiative and collision stopping powers for electrons in aluminium, silver (×10) and gold (×100) as functions of the kinetic energy (solid and dashed curves, respectively). Dot-dashed lines represent the high-energy approximation given by Eq. (3.160). Diamonds indicate the critical energy 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



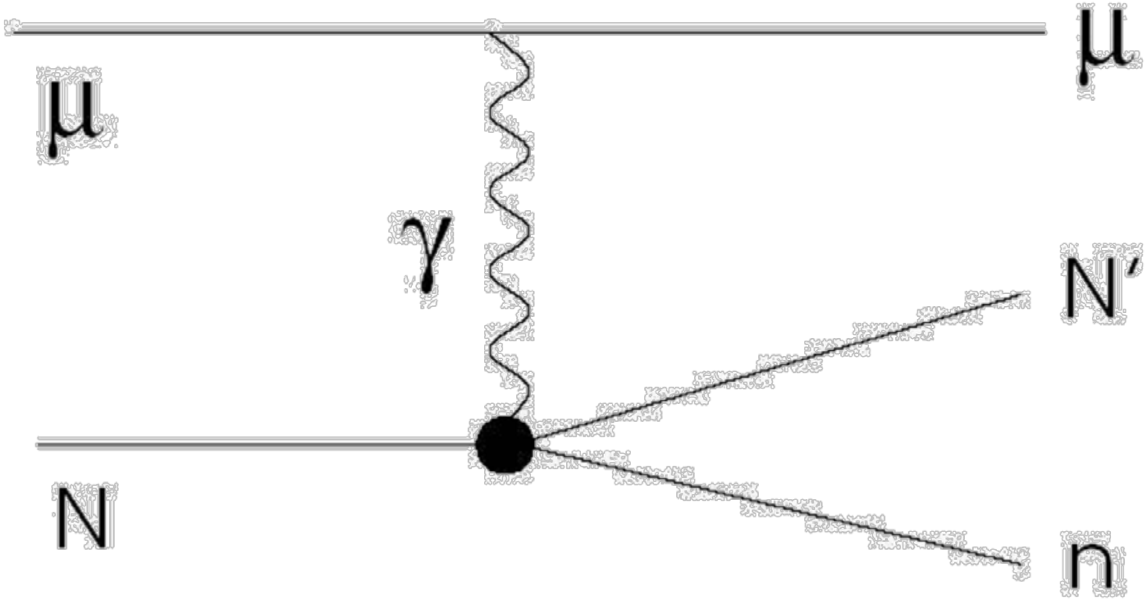
12 and 20.9 MeV electrons on a W-Au-Al target, bremsstrahlung photon spectra in the forward direction measured (dots) and simulated (histos)

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).*

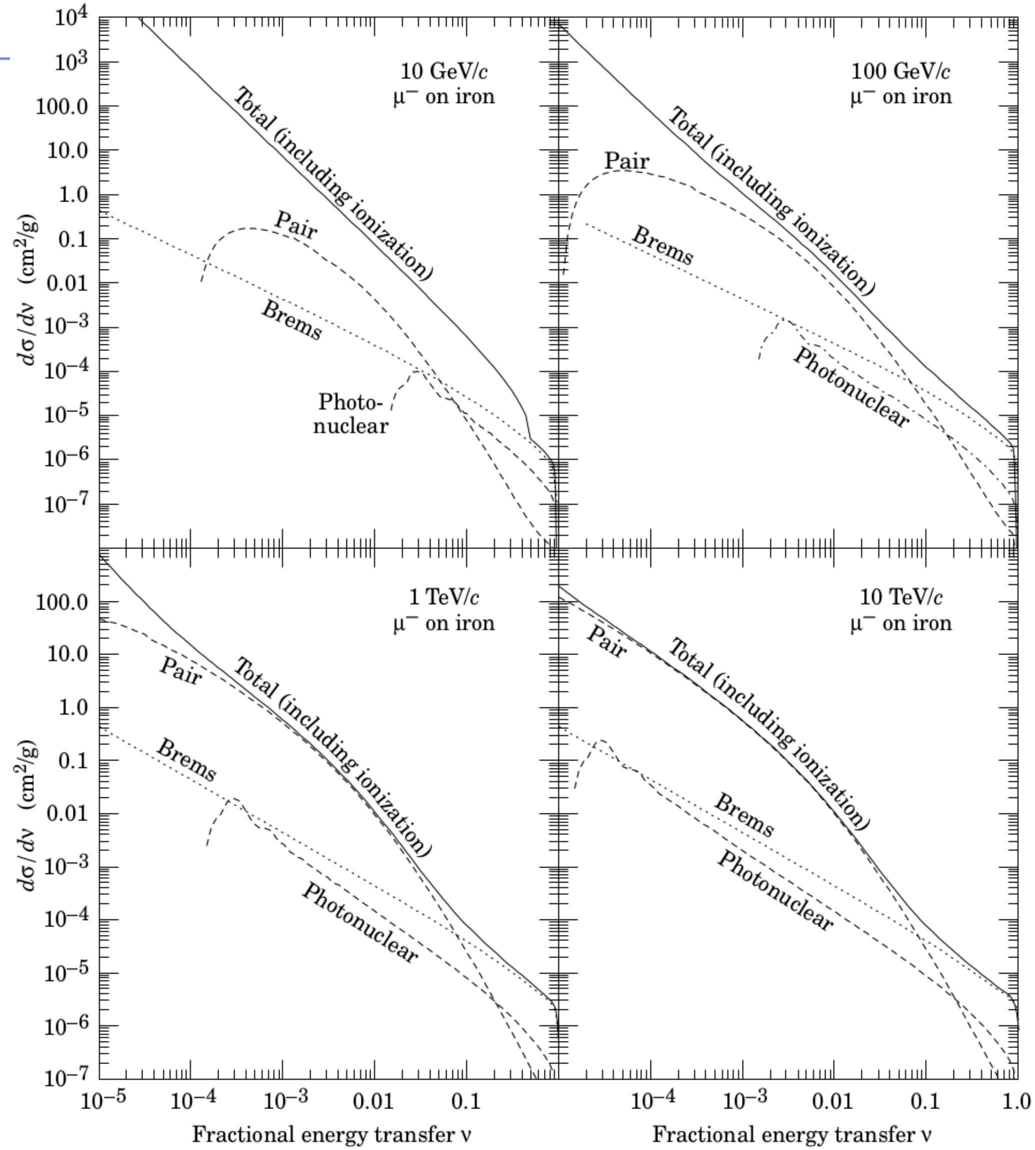


Figure 4: Differential cross section for total and radiative processes as a function of the fractional energy transfer for muons on iron.

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

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

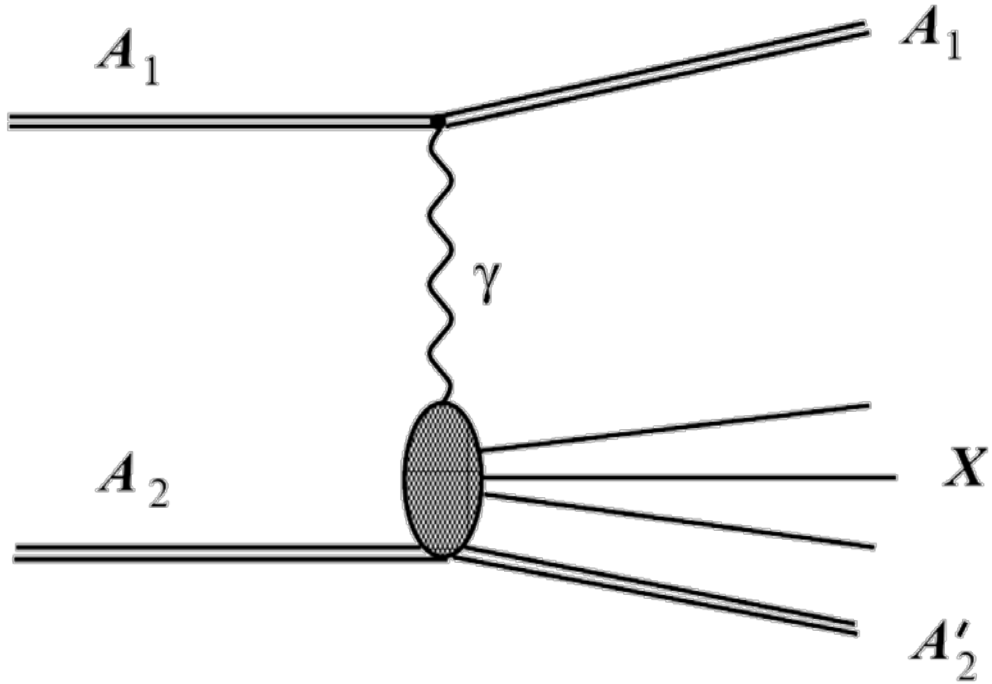
Nuclear environment from PEANUT

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

Experimentally: high energy tails in n-spectra

EM Dissociation

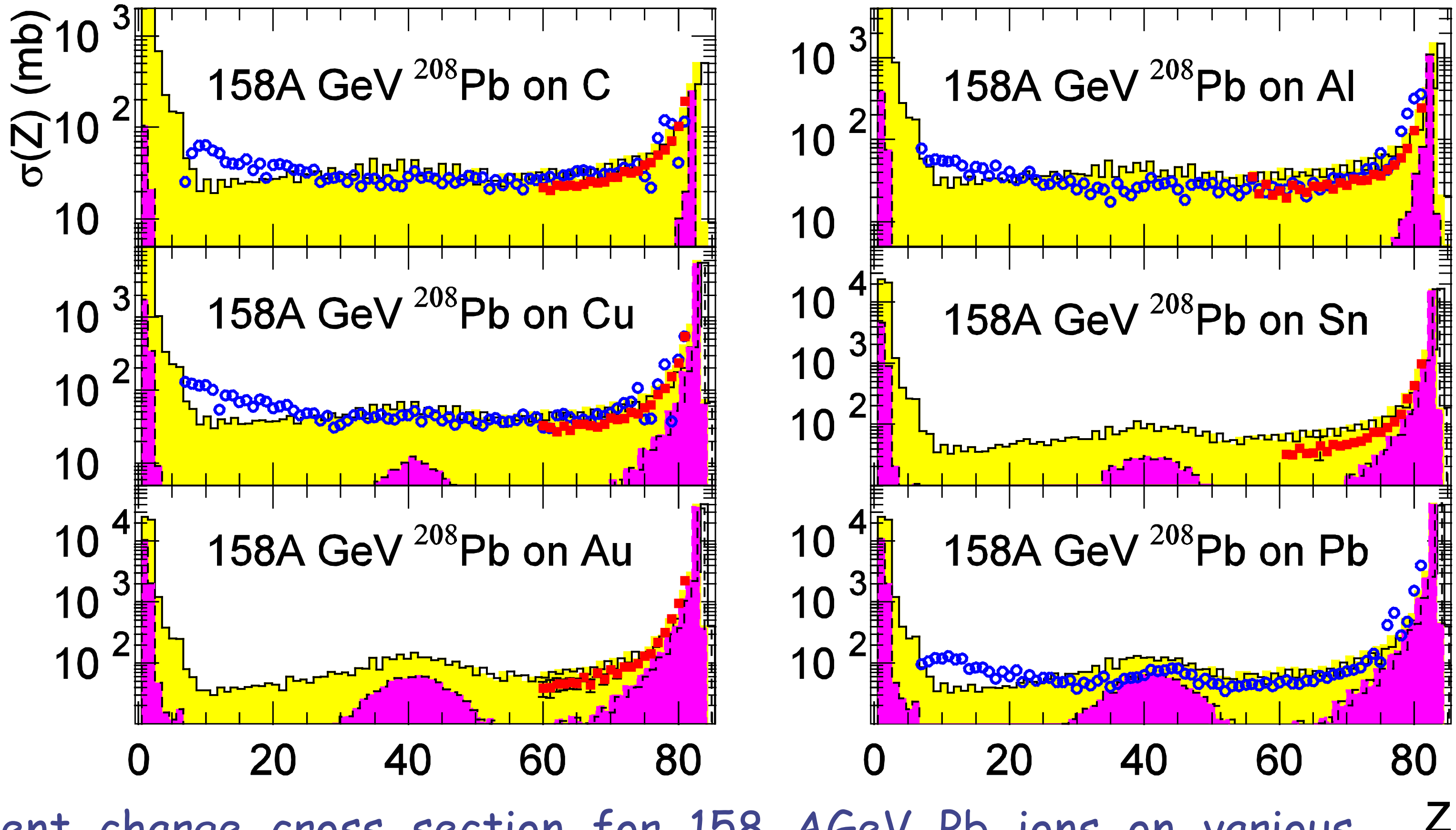
Electromagnetic dissociation



$$\sigma_{1\gamma} = \int \frac{d\omega}{\omega} n_{A_1}(\omega)\sigma_{\gamma A_2}(\omega), \quad n_{A_1}(\omega) \propto Z_1^2$$

Note: Electromagnetic dissociation is already relevant for interactions of few GeV/n ions in heavy targets.

158 GeV/n Pb ion fragmentation

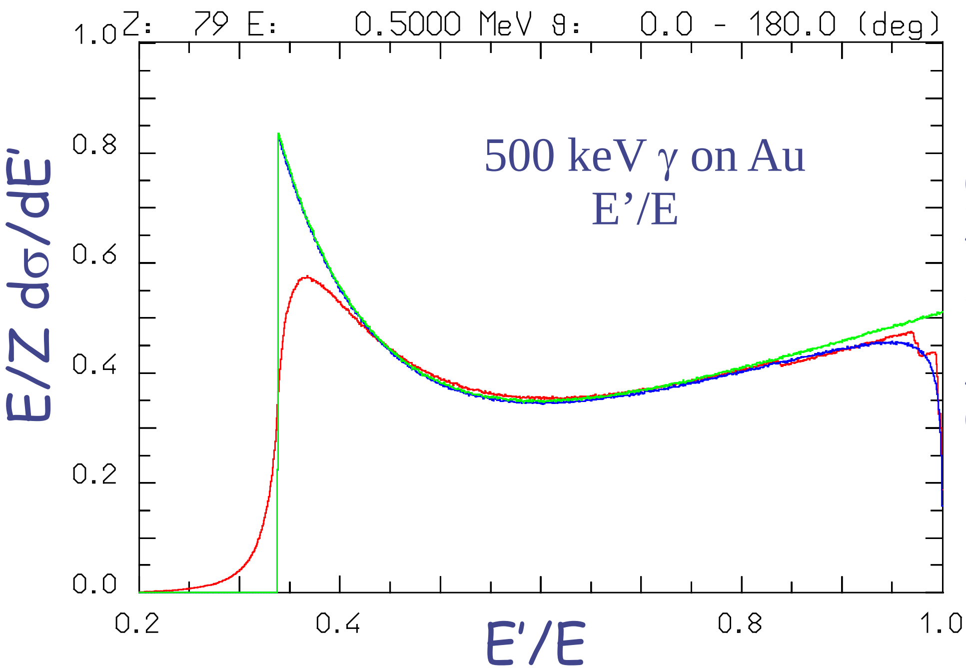


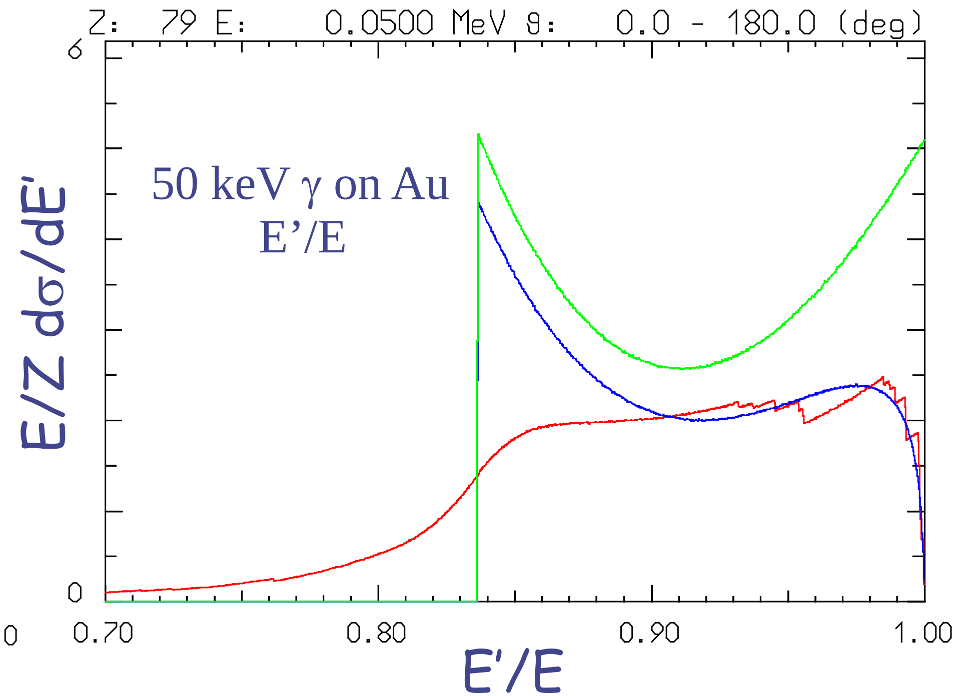
Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), *yellow* histos are FLUKA (with DPMJET-III) predictions: *purple* histos are the electromagnetic dissociation contribution

END

Spare slides

Compton profile examples





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

green = free electron

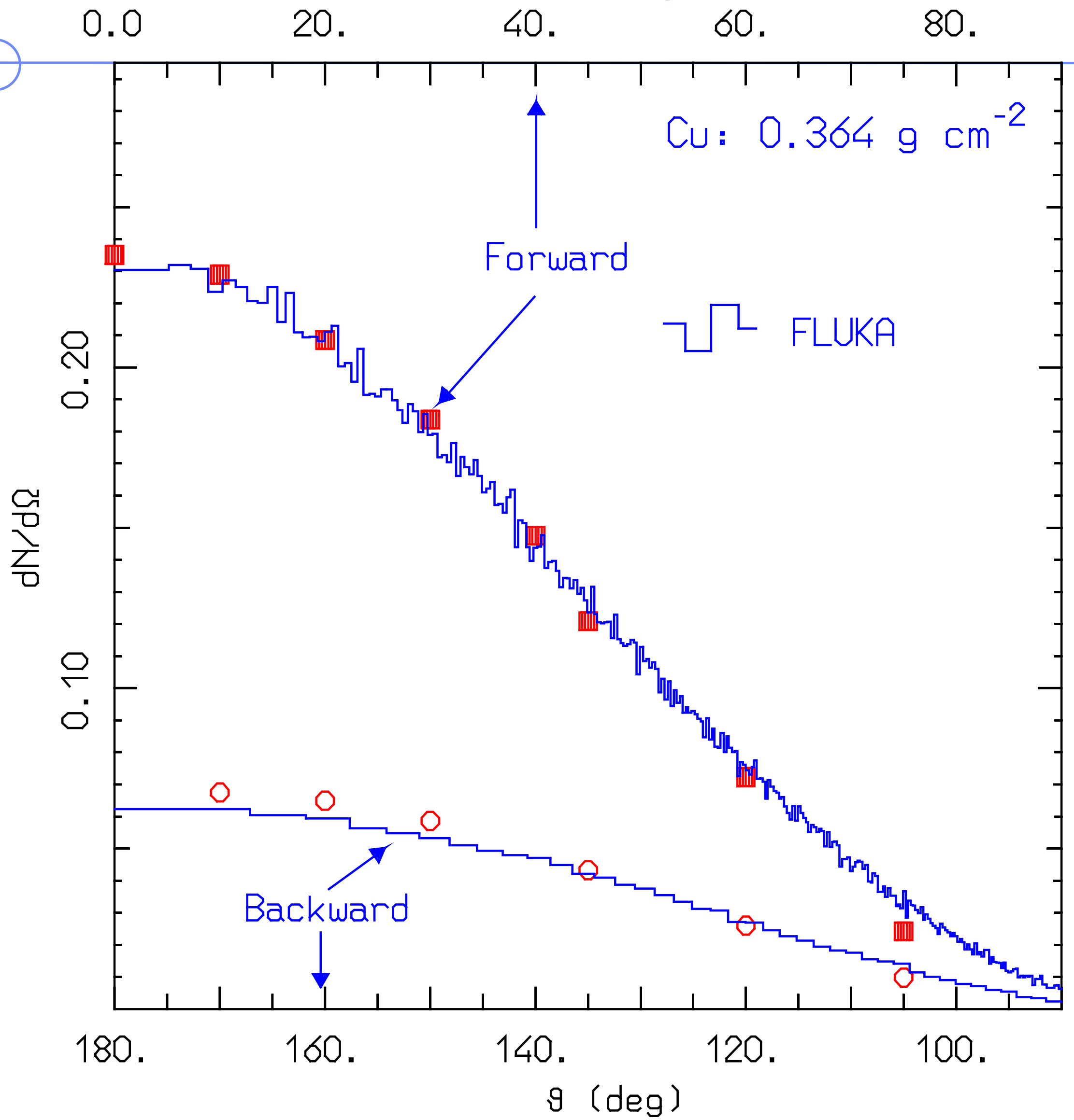
blue = binding with form factors

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'

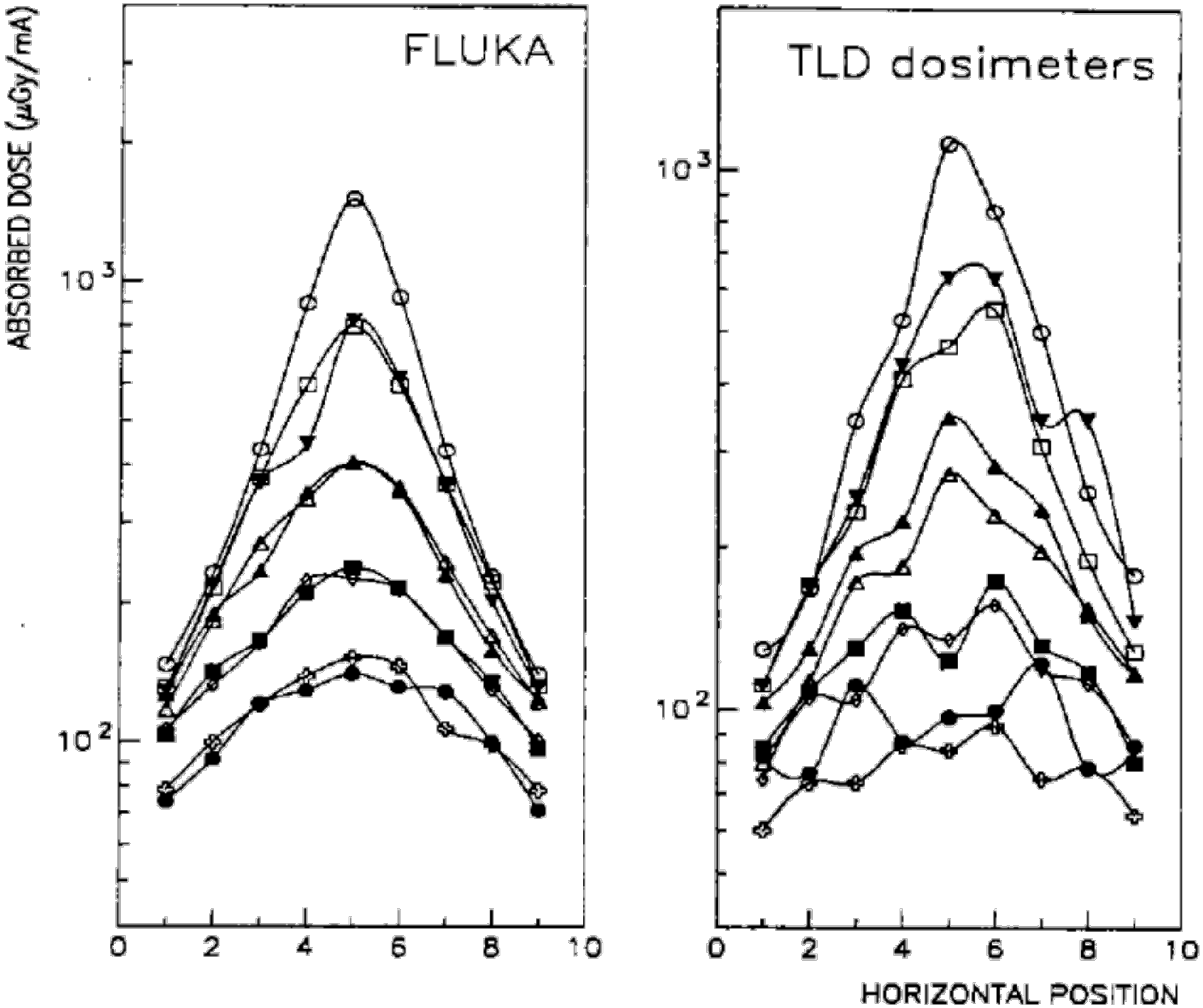
Electron scattering:



Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm² 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

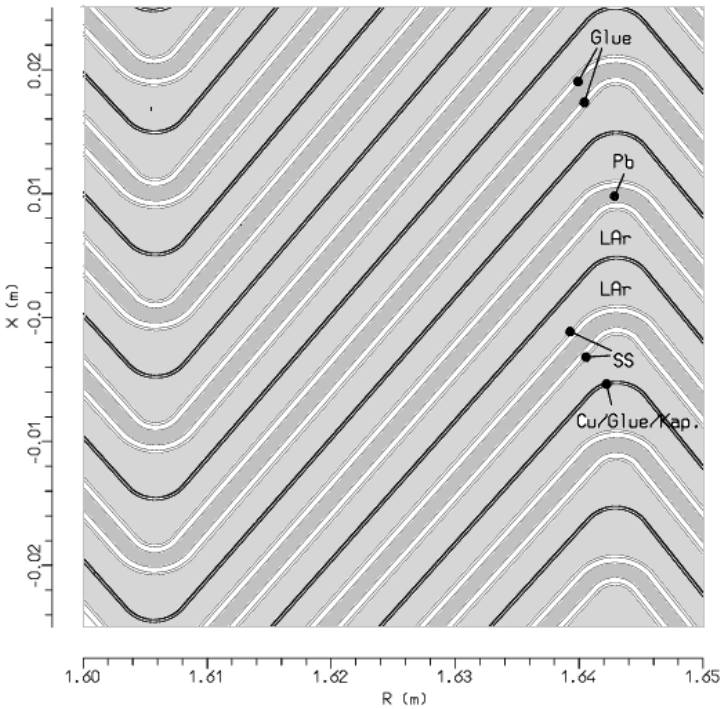
Measured with TLD's matrices at different distances from the straight Section

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

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

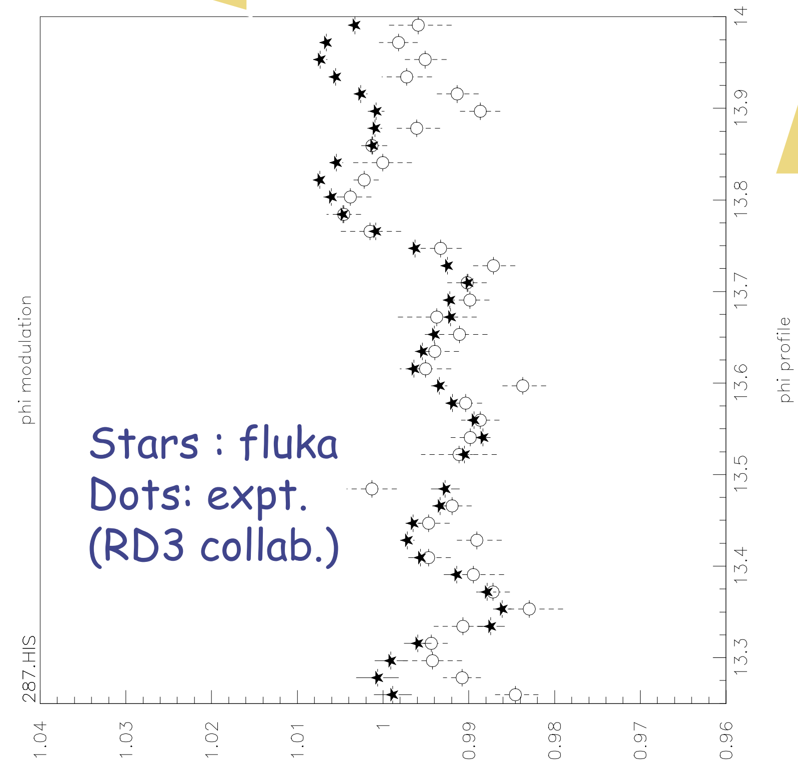
Detail of the FLUKA geometry and response vs. electron impact position

287 GeV electron beam



deposited energy

impact position



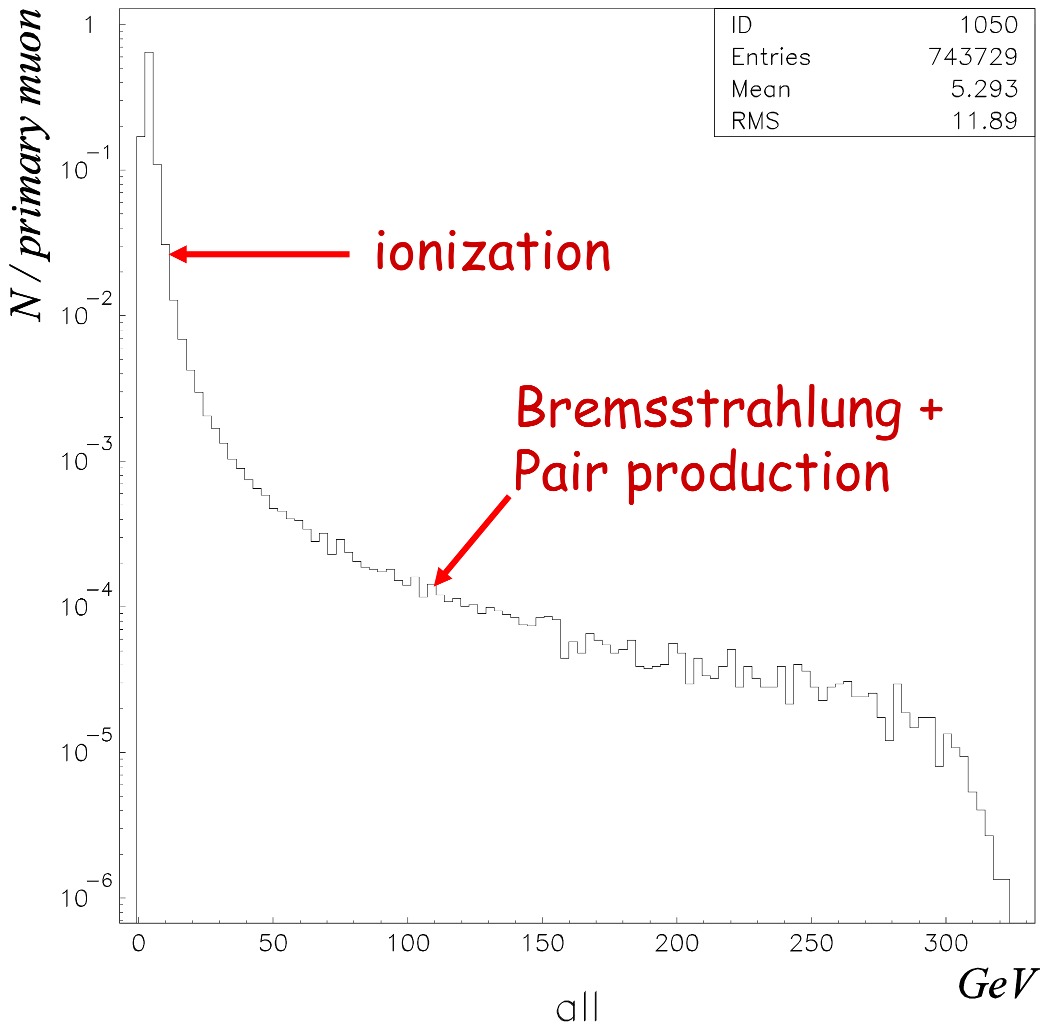
Energy resolution 10-100 GeV:

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

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

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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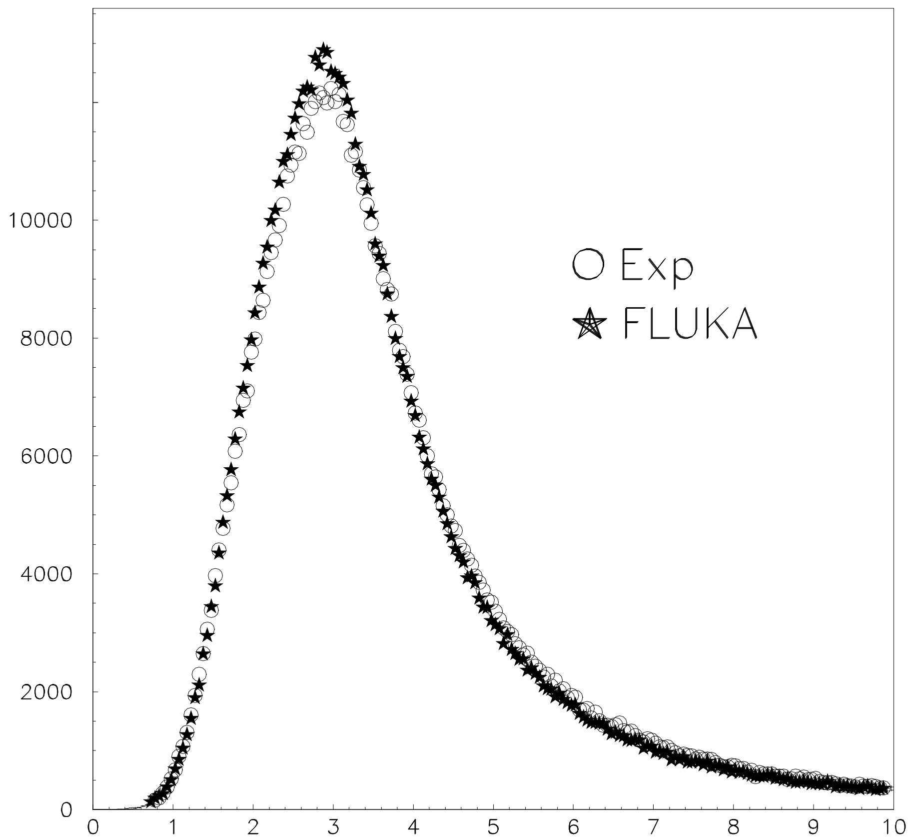
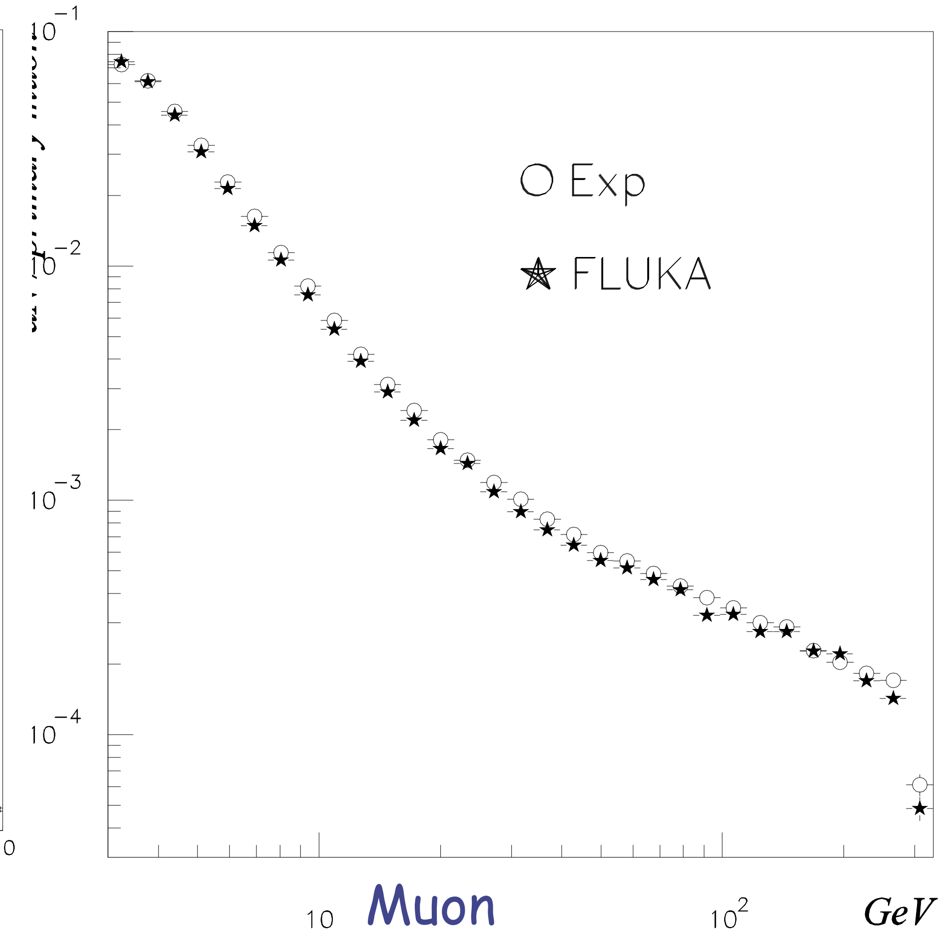


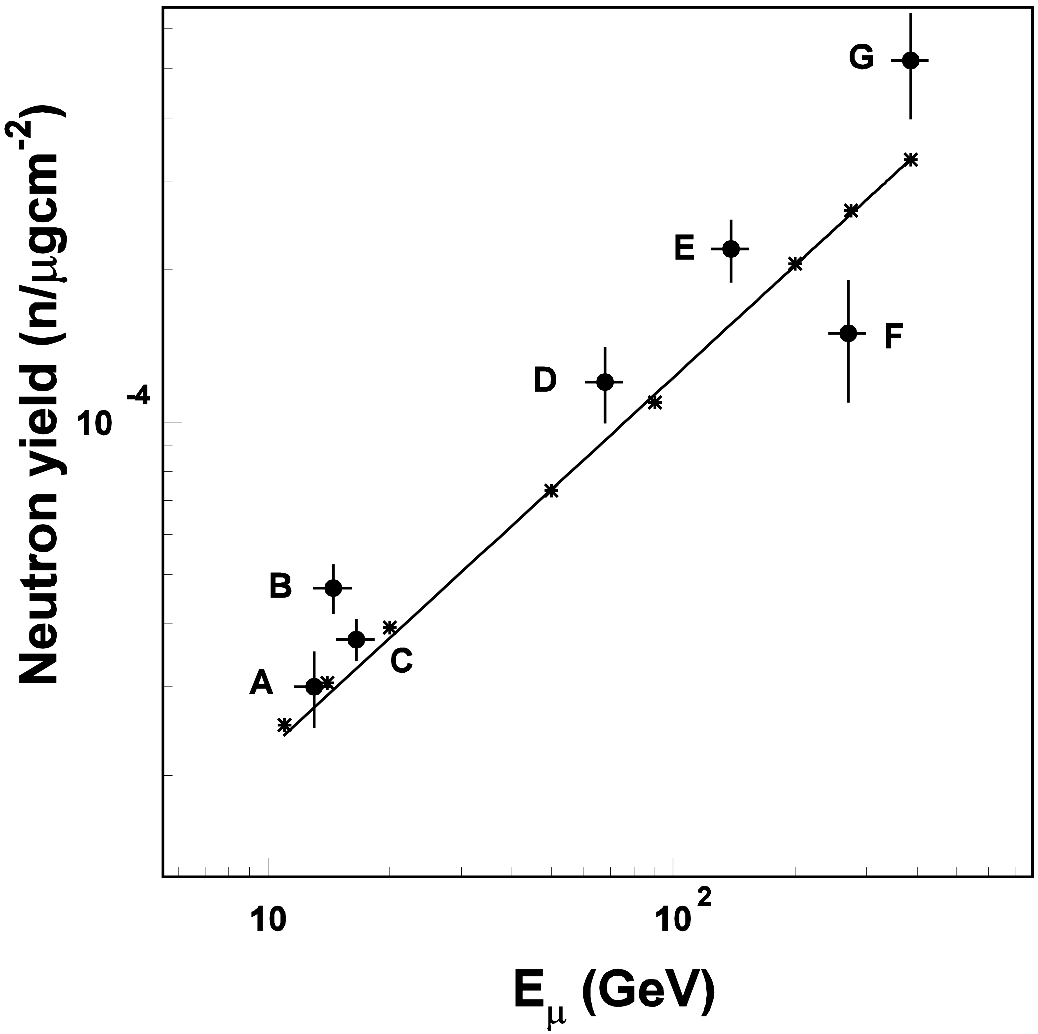
Muon energy [GeV]



Muon energy [GeV]

Muon-induced neutron background in underground labs

PRD64 (2001) 013012



Neutron production rate as a function of muon energy

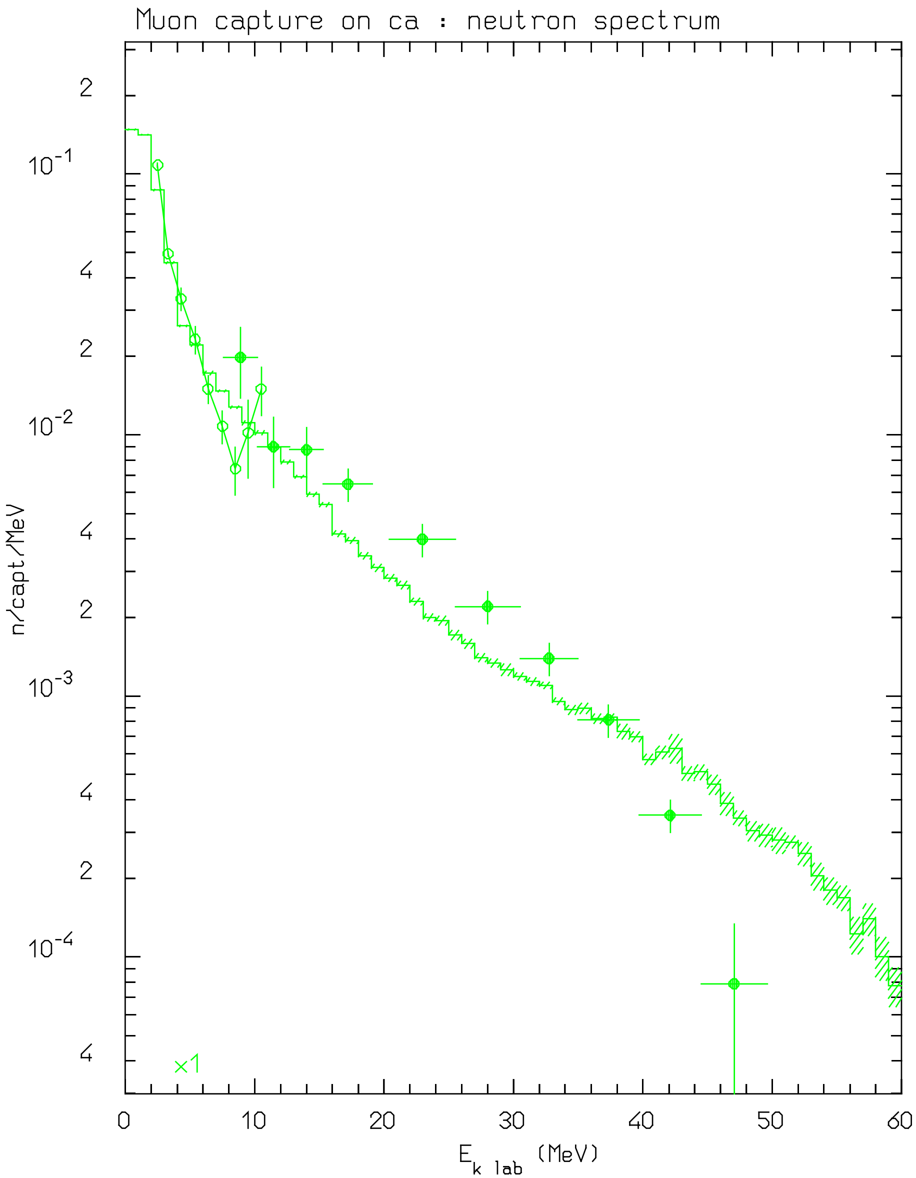
Stars+line : FLUKA simulation with a fit to a power law.

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))

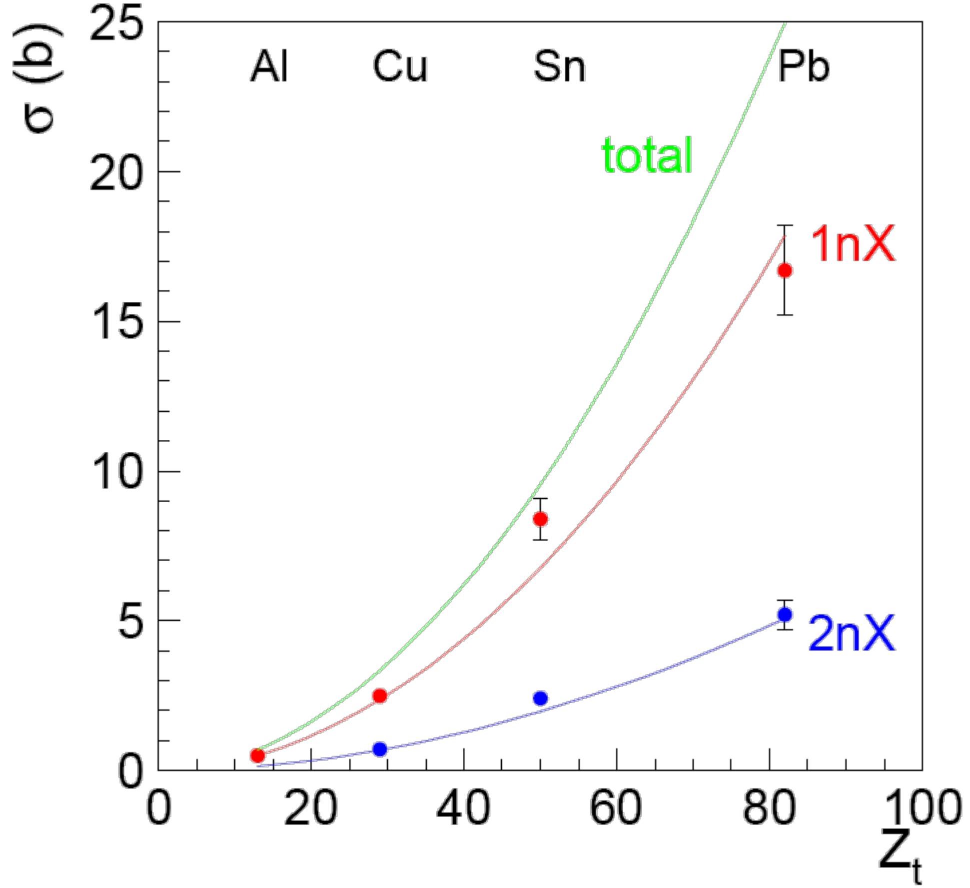
histograms: FLUKA calculations

Emitted:

0.62 neutrons/capture

0.27 protons/capture

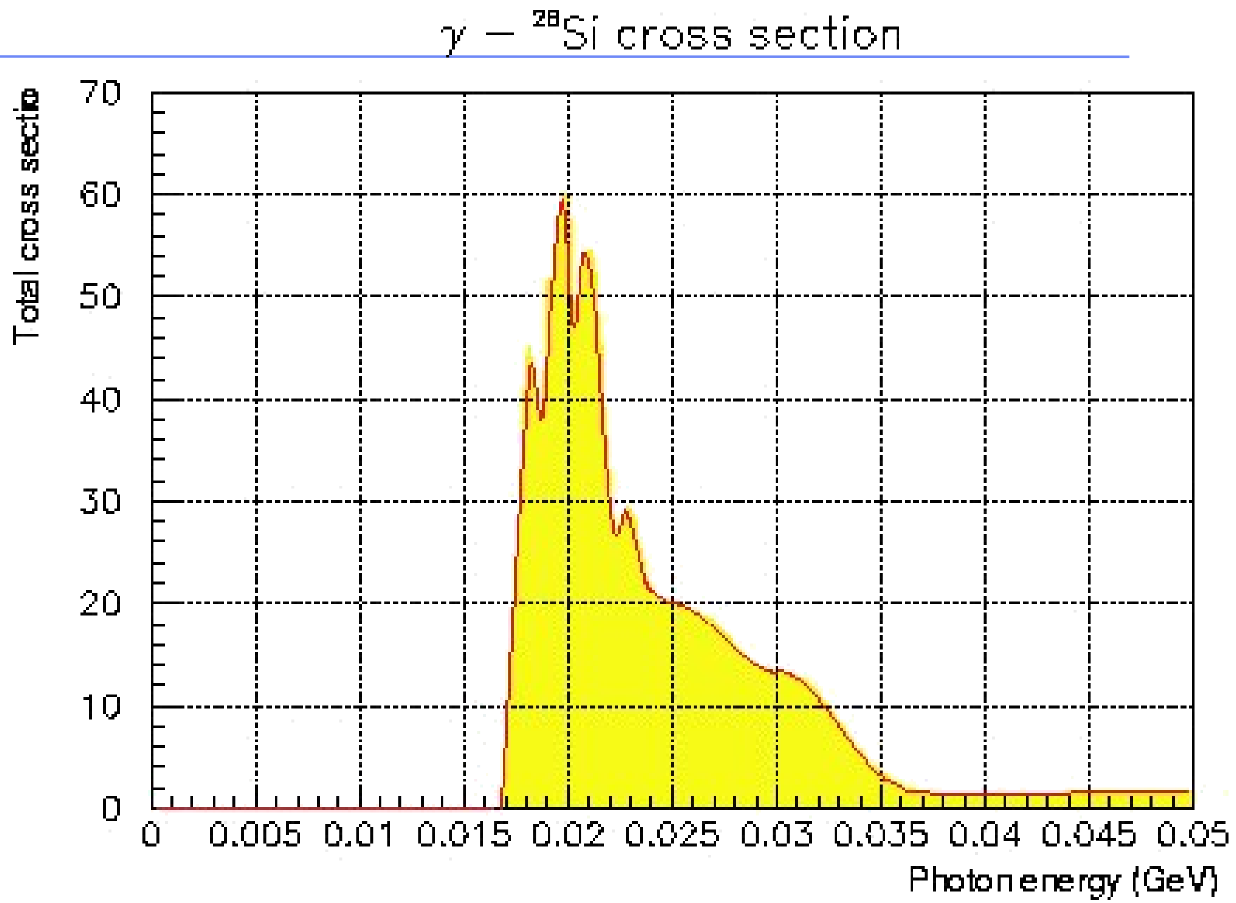
Electromagnetic dissociation - *Benchmarks*



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(γ,tot) as recorded in FLUKA database, 8 interval Bezier fit as used for the Electromagnetic Dissociation event generator.