EM Interactions

23rd FLUKA Beginner's Course
Lanzhou University
Lanzhou, China
June 2–7, 2024

Topics:

- General settings
- Interactions of leptons/photons
  - Photon interactions
    - Photoelectric
    - Compton
    - Coherent (Rayleigh)
    - Pair production
    - Photonuclear
    - Photomuon production
  - Electron/positron interactions
    - Bremsstrahlung
    - Annihilation
    - Electro- and positron- nuclear
  - 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

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- Electromagnetic dissociation

- ~~Ionization energy losses~~
  - ~~Continuous~~
  - ~~Delta-ray production~~
- ~~Transport~~

These topics will be discussed in another lecture

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

Electro-Magnetic FLUKA (EMF) at a glance

Energy range for e^+, e^-, γ : 1 keV (100 eV for γ)- 100 EeV (10^{20} eV)
Full coupling in both directions with hadrons and low-energy neutrons
Energy conservation within computer precision
Up-to-date γ cross section tabulations from EPICS2017 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

- γ and secondary e+/- production thresholds can be set by:

EMFCUT	e_{thr}	γ_{thr}	**1**	mat_1	mat_2	Δ_{mat}	**PROD-CUT**

- γ and e+/- transport thresholds can be set by:

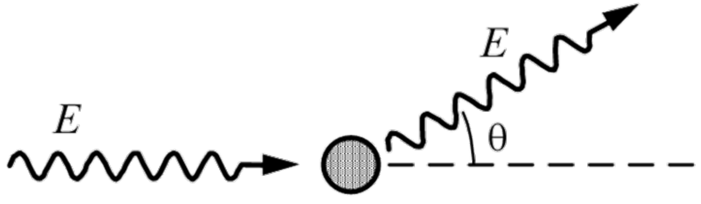
EMFCUT	e_{thr}	γ_{thr}	**0**	reg_1	reg_2	Δ_{reg}	

Optical photons:

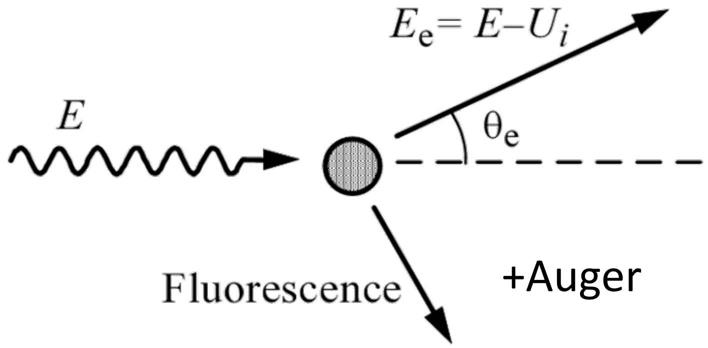
- Production and transport of **optical photons** (Cherenkov, scintillation) is also possible.
- Since it needs user input about the material (s) optical properties, it is not treated further in this beginners' course.
- ***See the manual for details/examples***

Photon Interactions

Photon interactions modeled in FLUKA



Rayleigh scattering



Photoelectric absorption

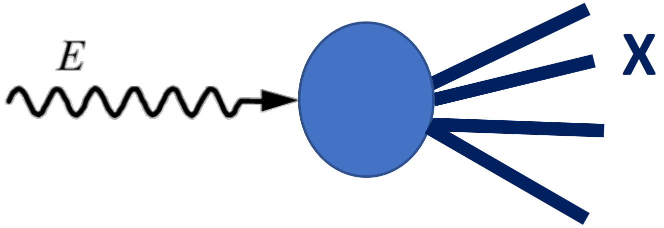
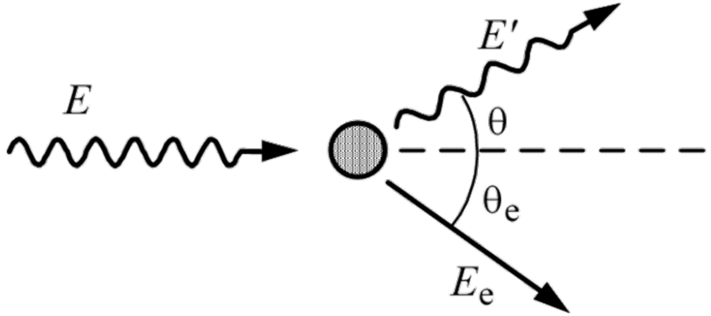
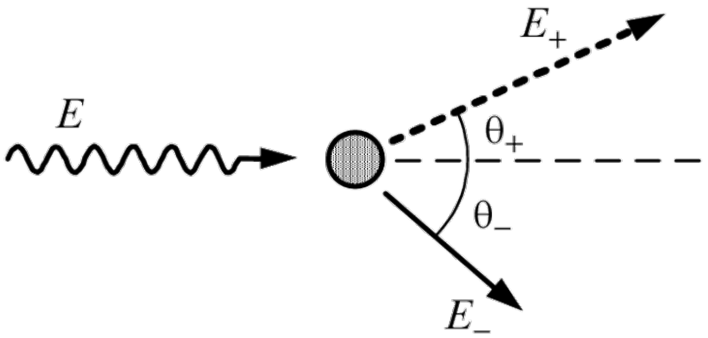


photo-nuclear processes



Compton scattering



Pair production

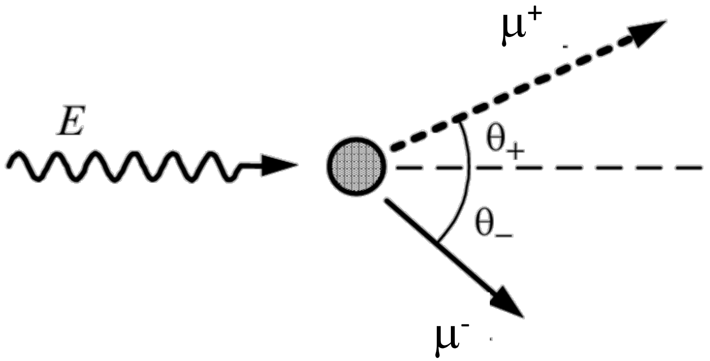
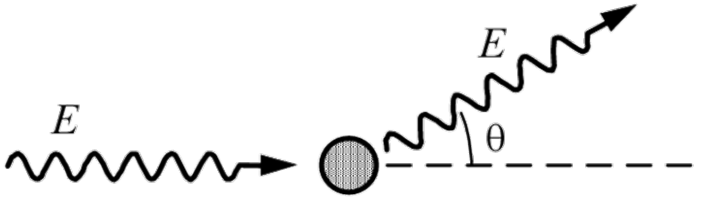


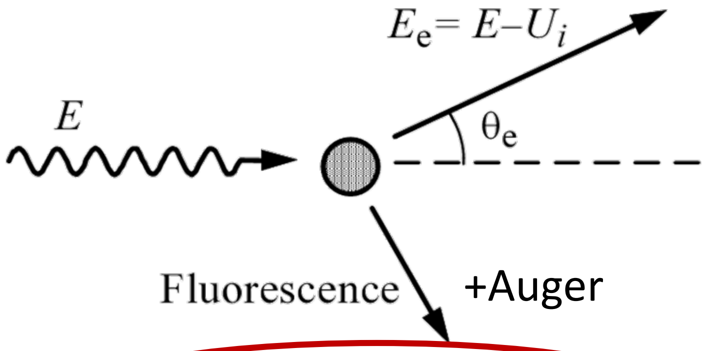
photo-muon production

+

Photon interactions modeled in FLUKA



Rayleigh scattering



Photoelectric absorption

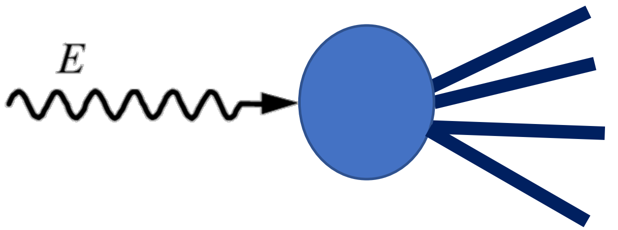
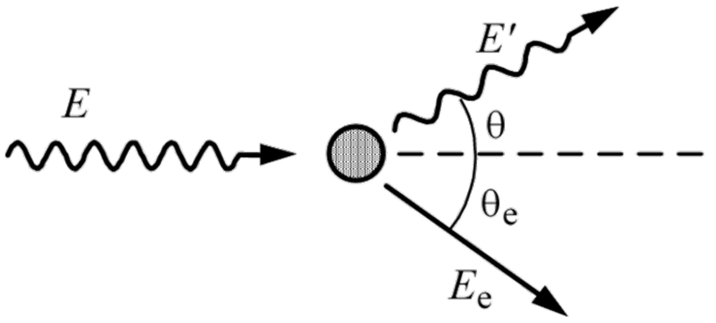
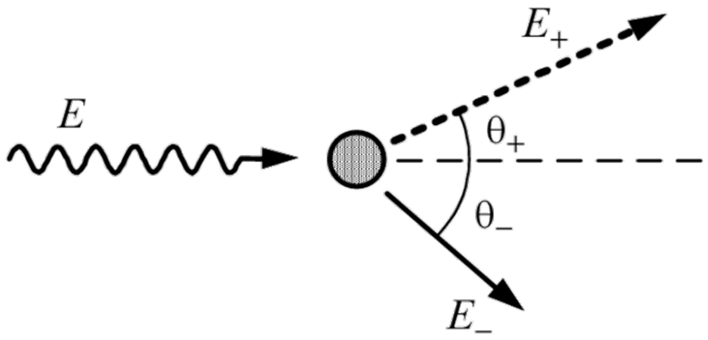


photo-nuclear processes



Compton scattering



Pair production

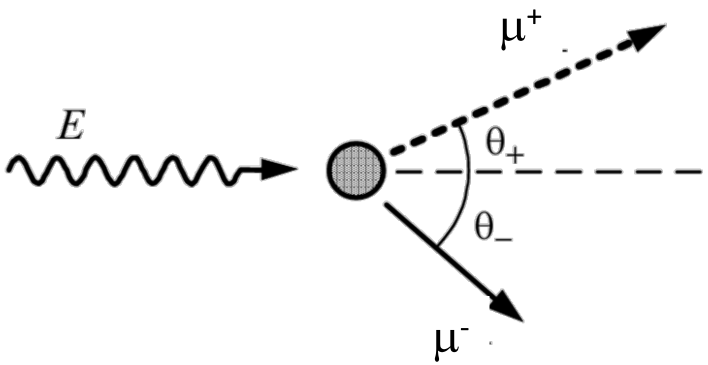
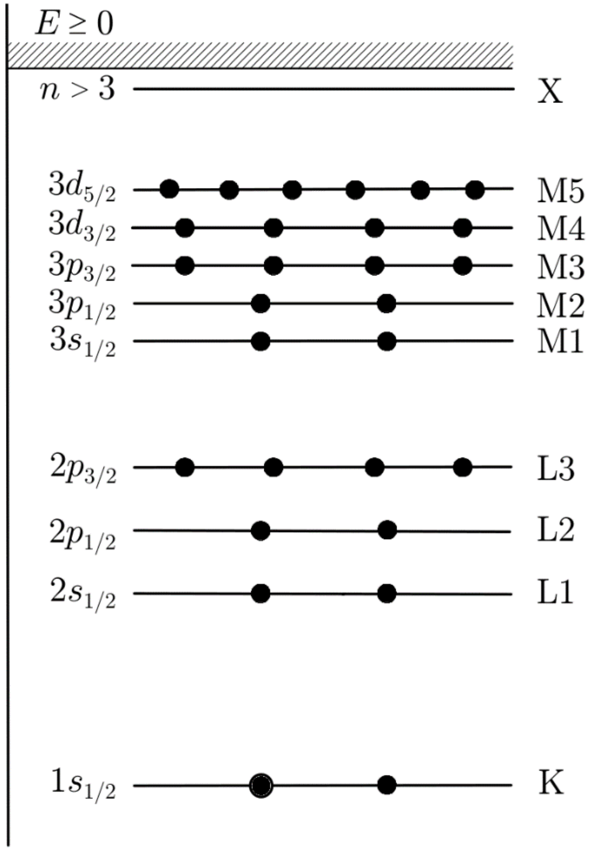


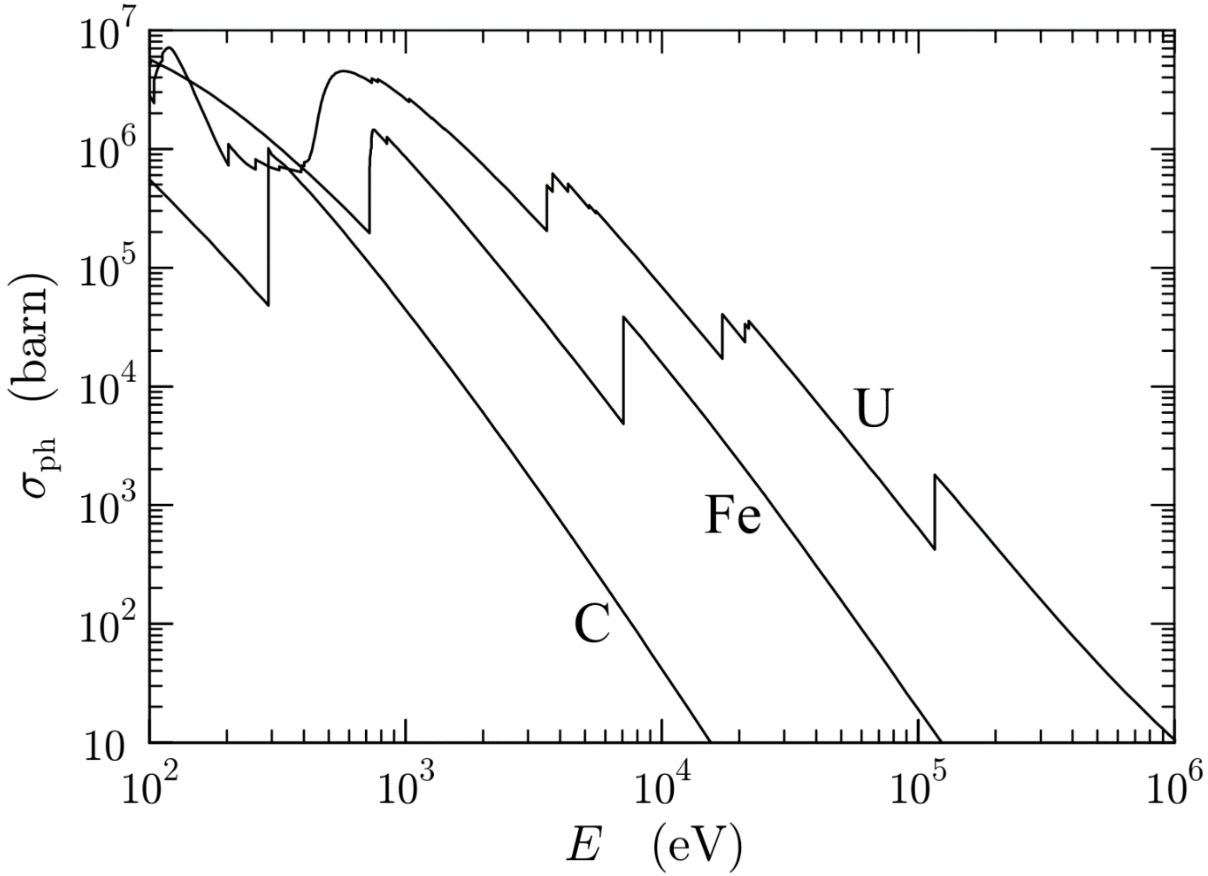
photo-muon production

Photoelectric effect

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

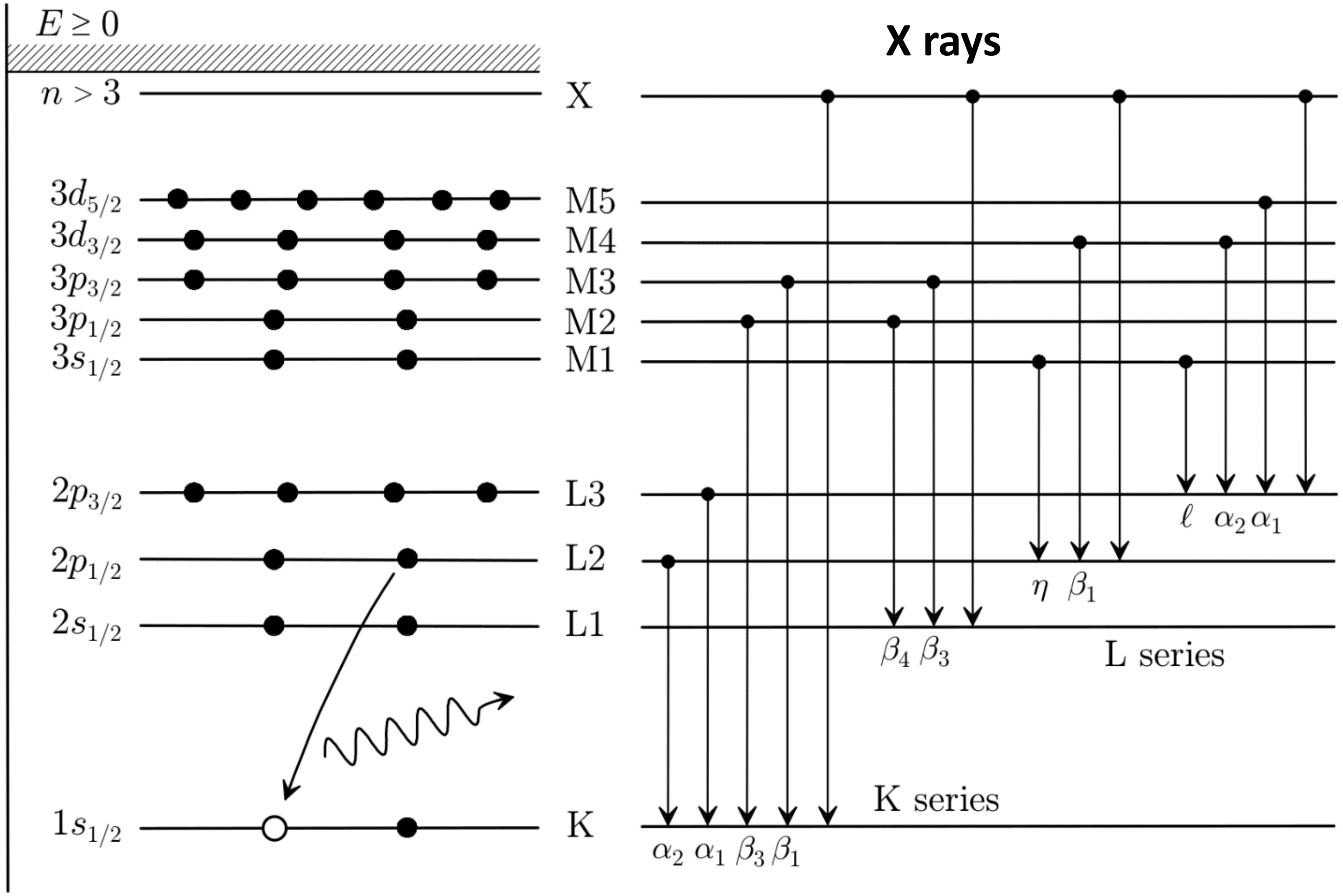
FLUKA cross sections: **E**lectron **P**hoton **I**nteraction **C**ross **S**ections 2017 (Cullen et al., EPICS2023 σ's sections are the same).

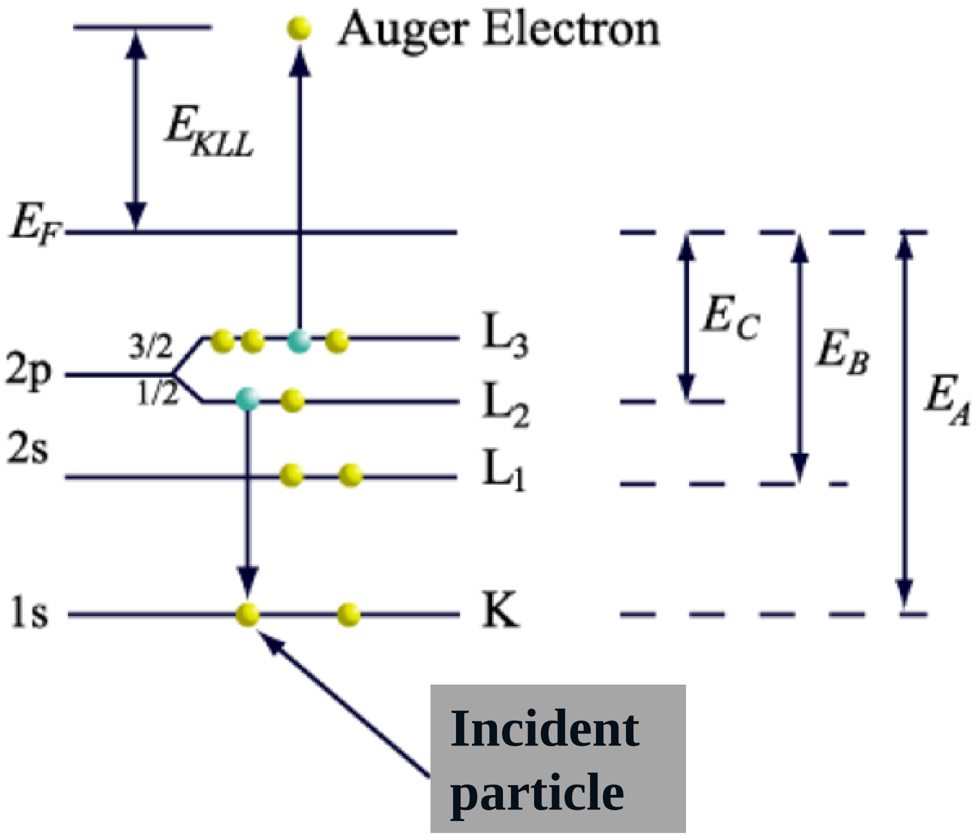




Atomic de-excitation

Fluorescence vs Auger emission





Photoelectric effect

Fluorescence (and Auger) after photoelectric is activated with most DEFAULTS:
CALORIMEtry, EM-CASCA, ICARUS, HADROTHErapy, PRECISIOn, DAMAGE

Detailed treatment of	X-ray Fluorescence
Photoelectron	Angular distribution
Approximate	Auger electrons
Effect of photon	Polarization

To activate/deactivate fluorescence:
suggestion keep it active all the time (X-rays will not be emitted otherwise)

```
EMFFLUO          Flag     Mat1     Mat2     Step
```

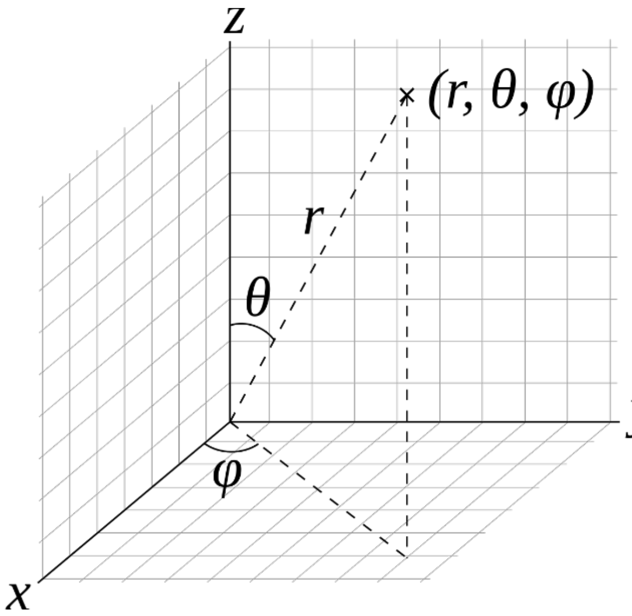
Flag **>** 0: Activate   Flag **<** 0: De-activate

Warning: check consistency with γ and e^- production/transport thresholds

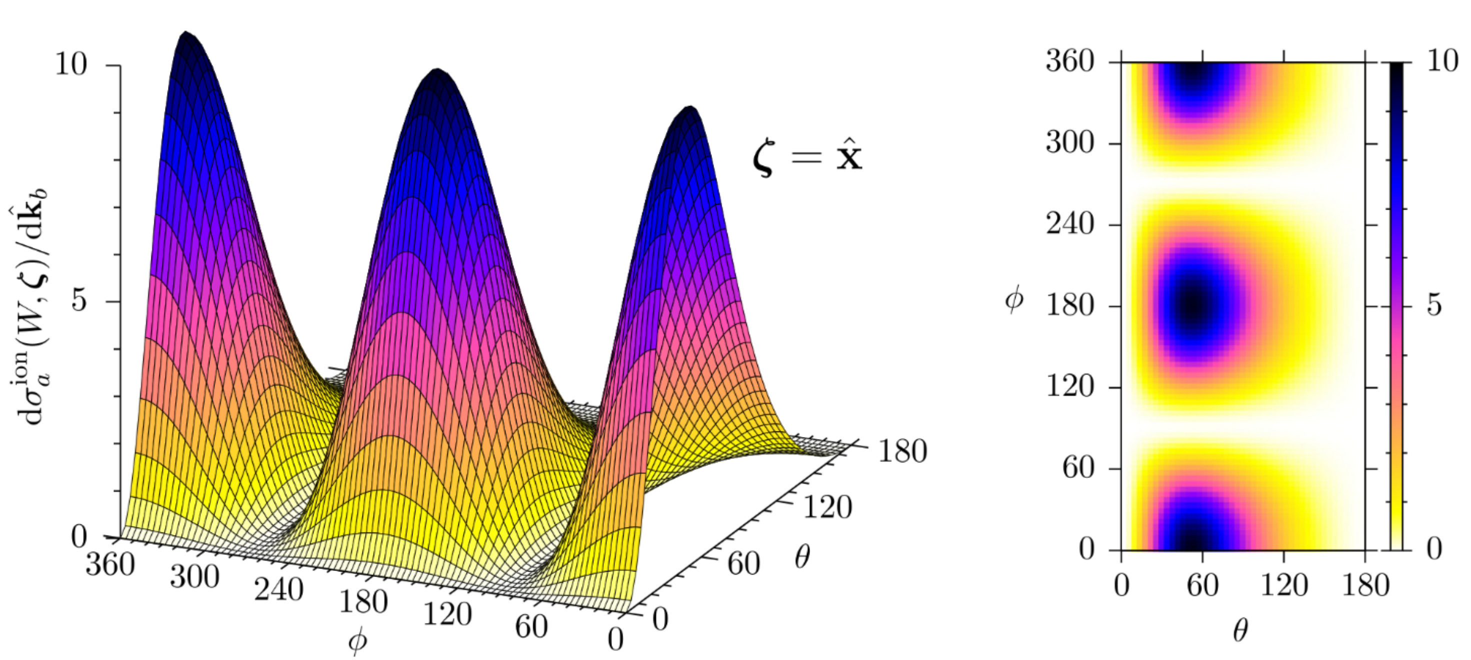
Effect of polarization

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=90º, phi=0º or 180º) we have

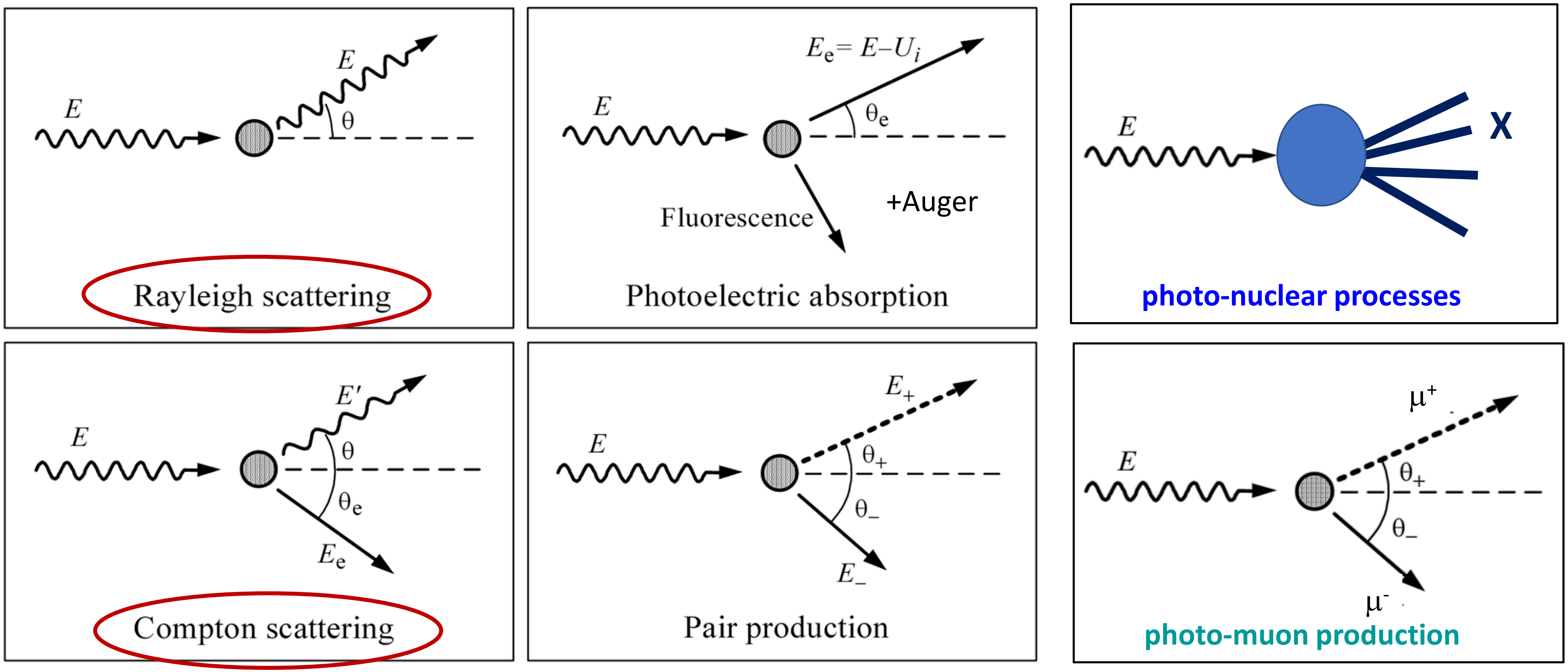


L. Sabbatucci, F. Salvat / Radiation Physics and Chemistry 121 (2016) 122–140



Card **POLARIZA** discussed later

Compton and Coherent (Rayleigh) scattering



Compton and Coherent (Rayleigh) scattering

Compton, 3 alternative treatments implemented:

- Klein-Nishina cross section: free target electron at rest
- Account for atomic bonds using inelastic Hartree-Fock ***form factors***
- Compton with atomic bonds and orbital motion (by far the best and most accurate approach)
  - Atomic shells from databases
  - Orbital motion from database + fit
  - Followed by fluorescence/Auger
- Coherent: angular distribution according to the Atomic elastic form factor, accounting also for the anomalous real and imaginary form factors (***new!***)
- Account for effect of incoming photon polarization for both Compton and coherent

Compton and coherent: cont.

Inelastic Form Factors, Compton profile and Coherent scattering are activated only with a subset of DEFAULTS.

To activate/deactivate/control the various possibilities for:

- Compton
- Coherent
- Positron annihilation acolinearity
- Ortho- para- positronium competition

One can use the EMFRAY option:

```
EMFRAY Flag    Reg1    Reg2    Step
```

Suggestion: use always **Flag=1104** (most accurate options activated for everything, default for CALORIMEtry, HADROTHErapy, ICARUS, PRECISIOn)

Look in the manual for further details

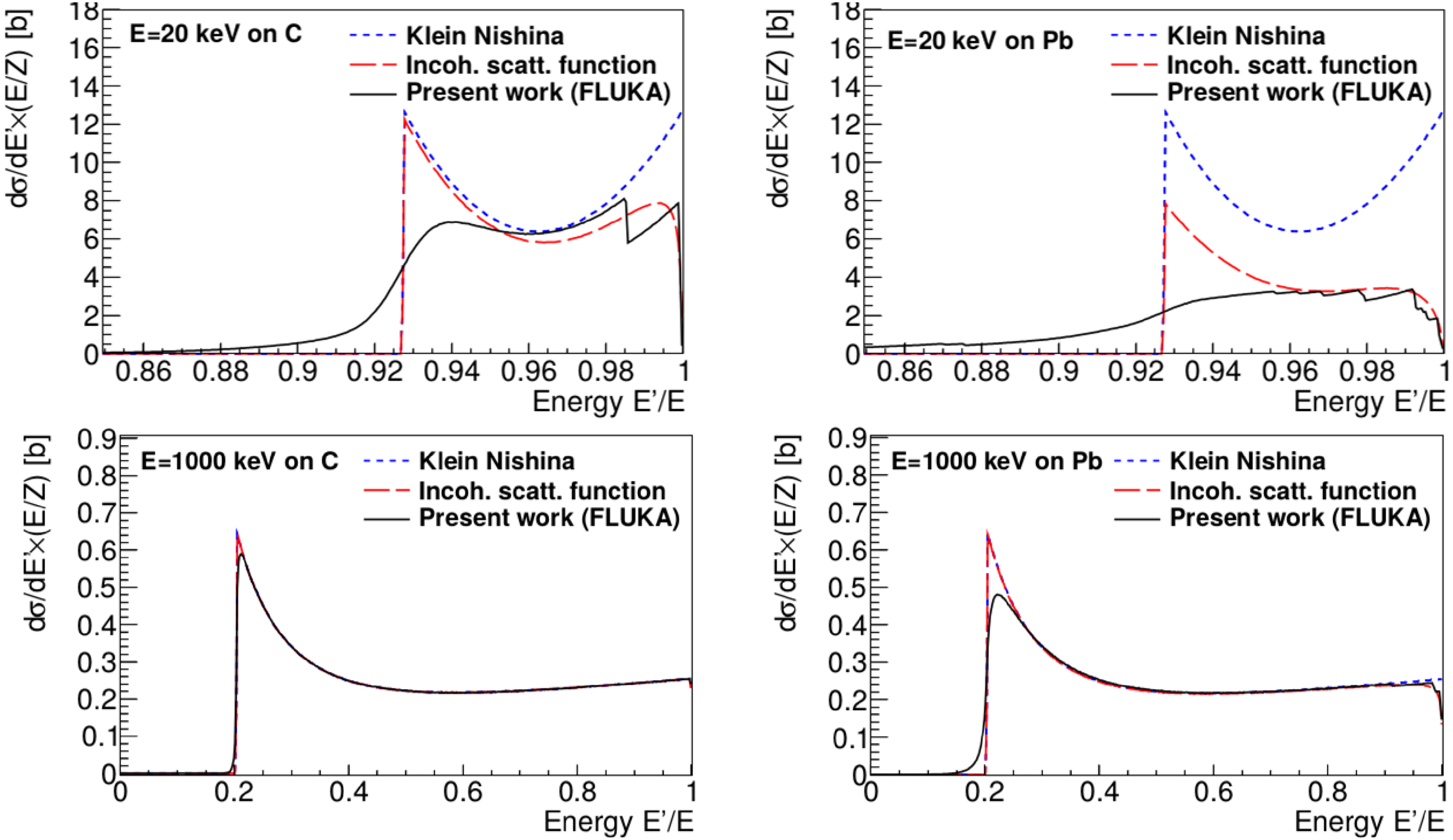
Compton scattering

FLUKA: accounting for atomic shell binding energies and e⁻ orbital motion. Also for positron annihilation

KN: free e⁻ at rest

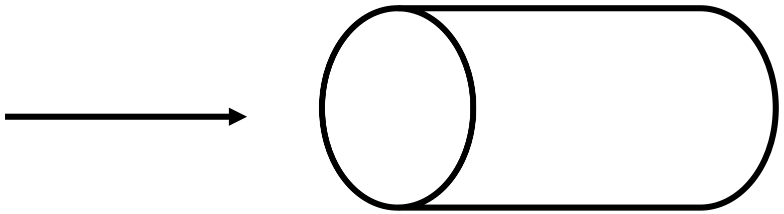
Incoh. scatt. function: binding via form factor

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



Effect of polarization on Compton scattering

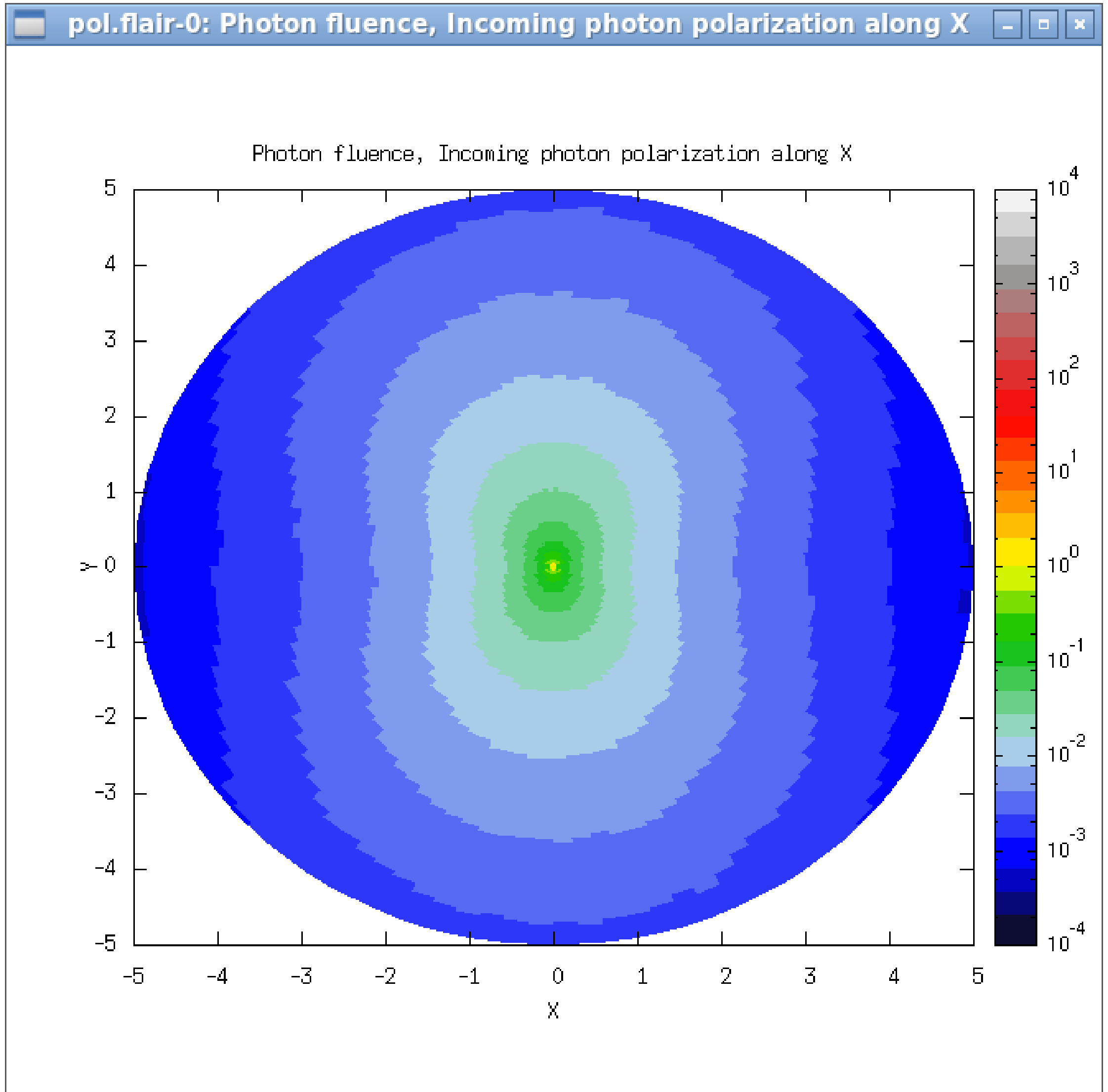
Azimuthal angle of outgoing photon preferentially along direction perpendicular to polarization.



50-keV photons impinging along Z on water cylinder

Incoming photon polarized ***along X***

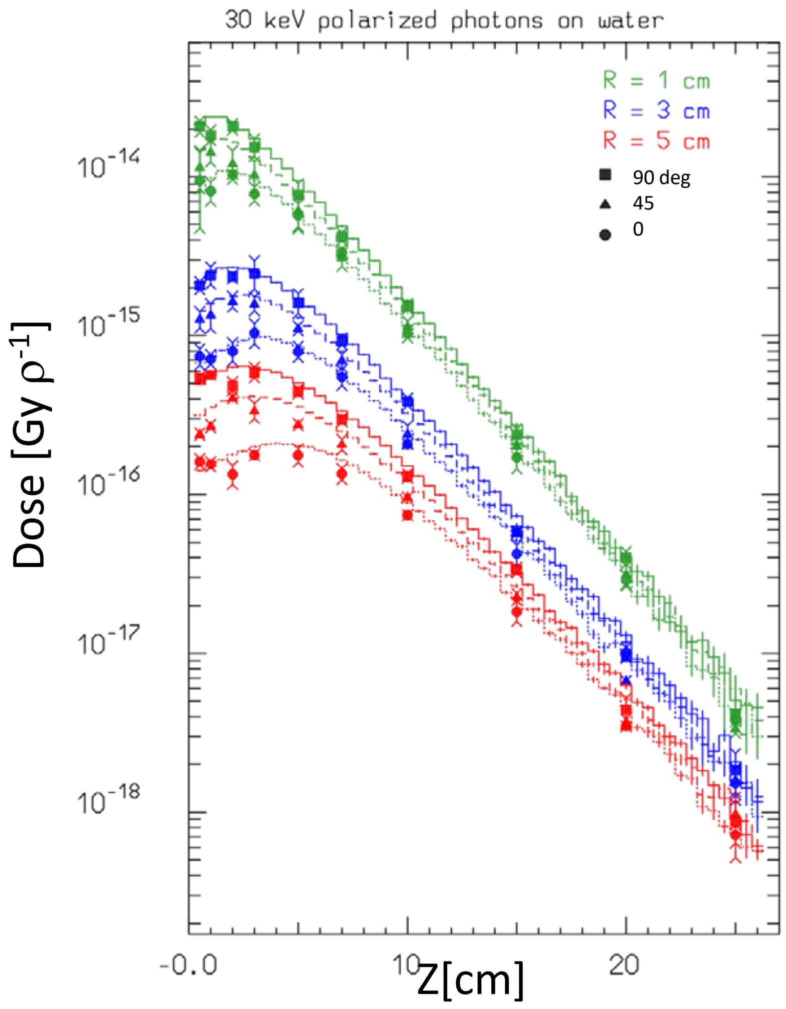
Compton photons preferentially emitted ***along Y***



Polarization

By default, **source** photons are NOT polarized. **Source** polarization can be set by*

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



Pcosx/y/z = polarization vector direction (must be ⊥ to the photon direction)

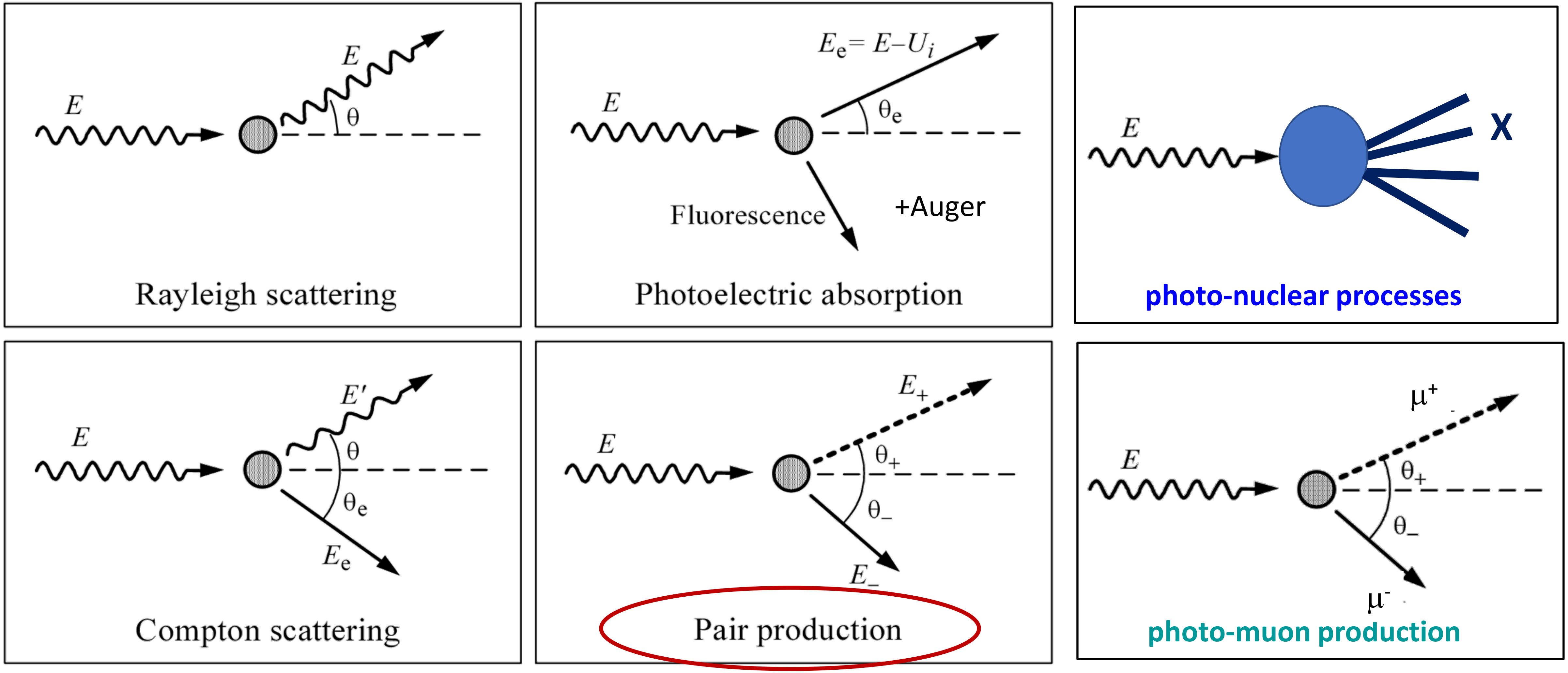
Flag1 must be = 1 for photons, Flag2, Fraction ***(see the manual for further details)***

← 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

** even if there is no initial polarized beam, some processes (eg Compton, annihilation, X-ray reflection) can result in partially polarized secondary photons, whose polarization is then always accounted for*

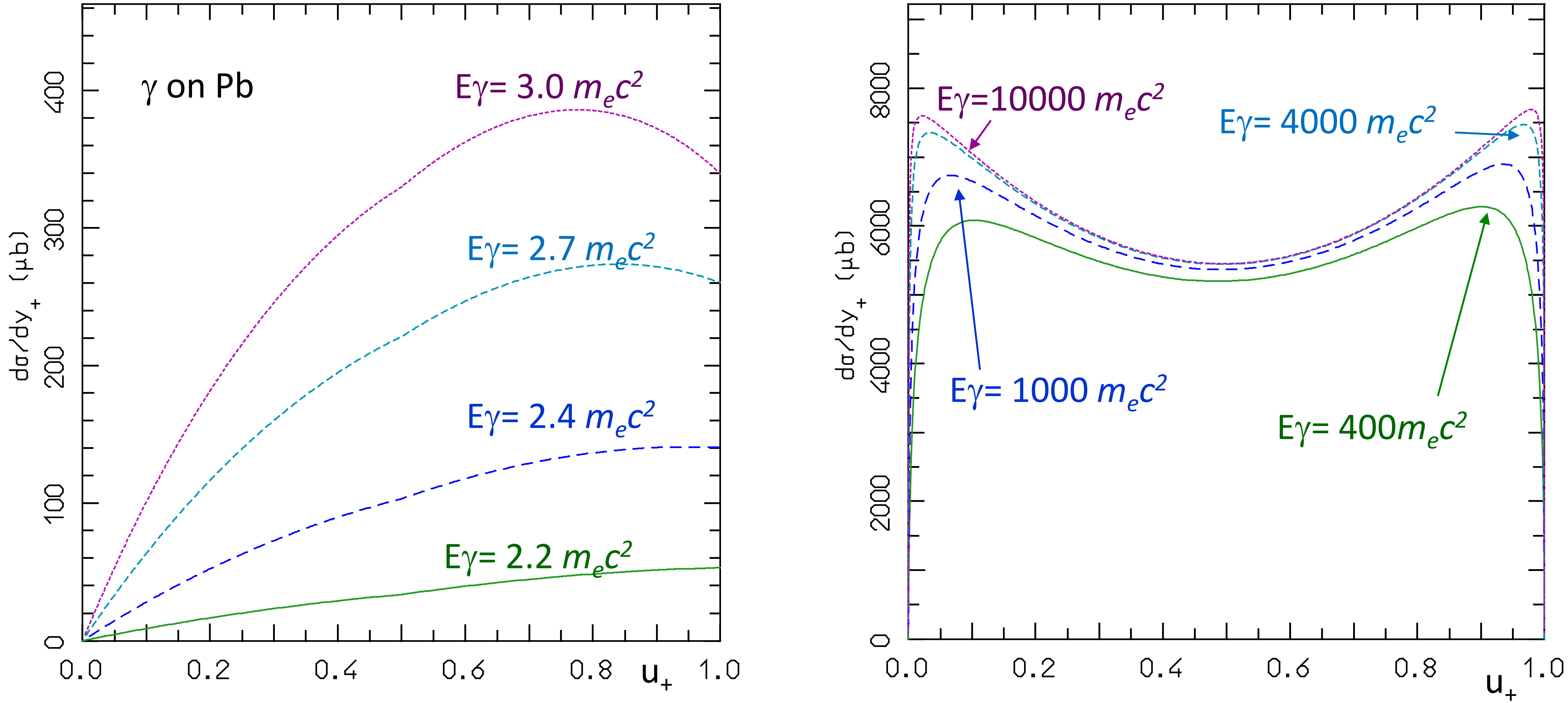
e^-e^+ Pair Production



e^-e^+ Pair Production

- Kinematics: it can occur in the nuclear or atomic electron Coulomb field
- Threshold at ~2*511 keV.
- Dominant photon interaction mechanism at energies above ~10-100 MeV (depending on Z)
- FLUKA:
  - 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 100 EeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect

Pair production: examples and asymmetry



$\boldsymbol{1/Z^2 d\sigma_{pair}/du_+}$ ($u_+ = E(e+)/E\gamma$) for different incoming photon energies (in units of $\boldsymbol{m_ec^2}$)

Relative importance of processes (sub GeV)

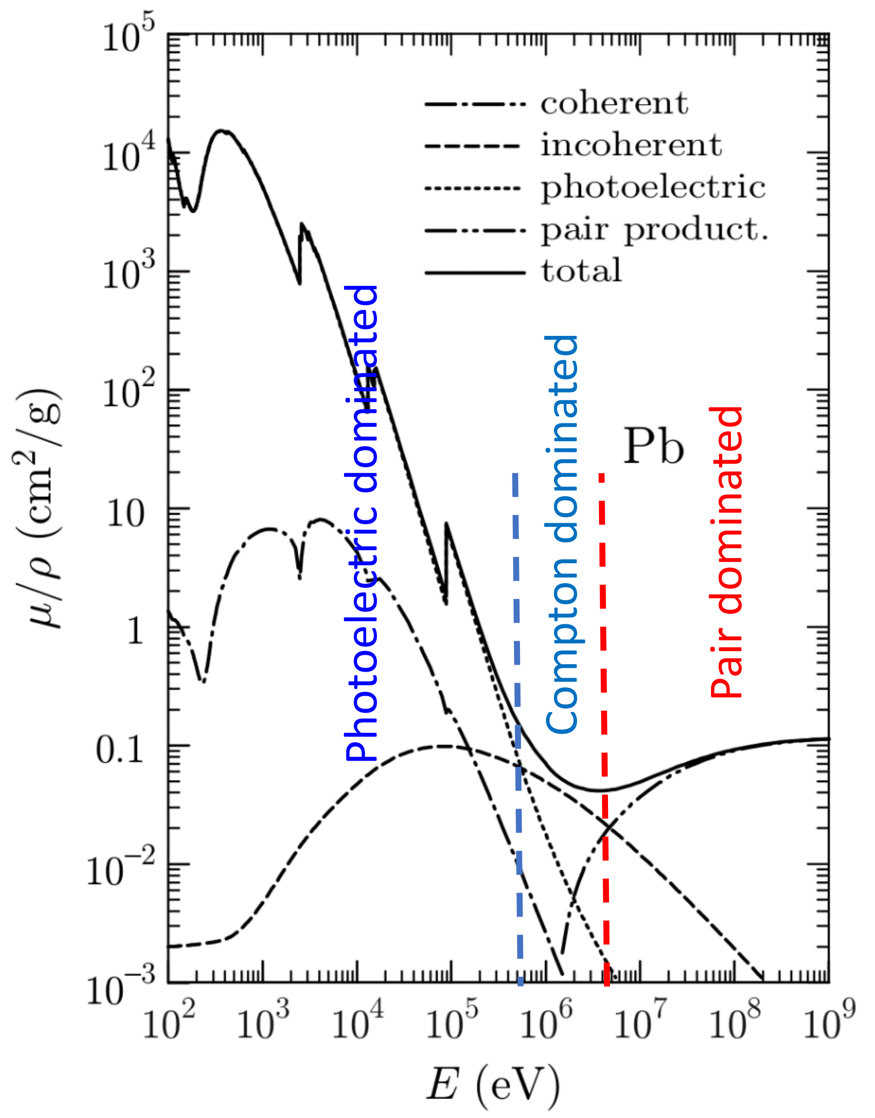
Mass attenuation coefficient μ

$\mu = dN_{Atom}/dV$ sigma : inverse mean free path

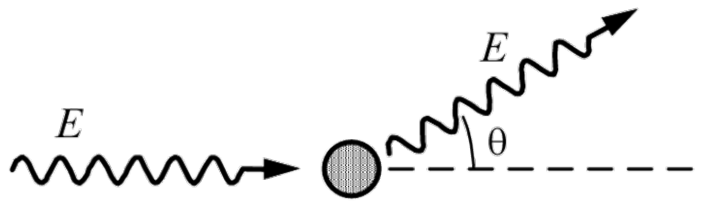
Rho: density

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

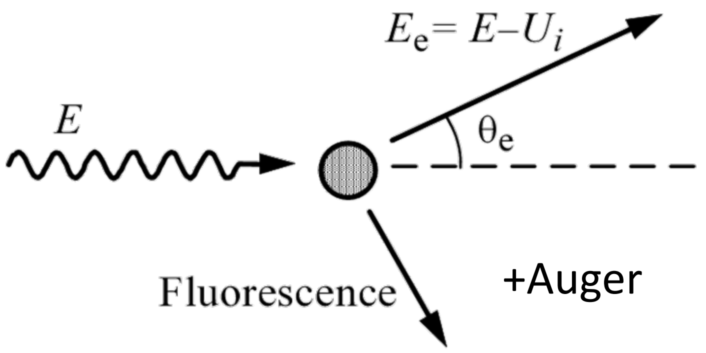
Photoelectric
Coherent = Rayleigh
Incoherent = Compton
Pair product. = e-e+ pair prod.



Photomuon Production



Rayleigh scattering



Photoelectric absorption

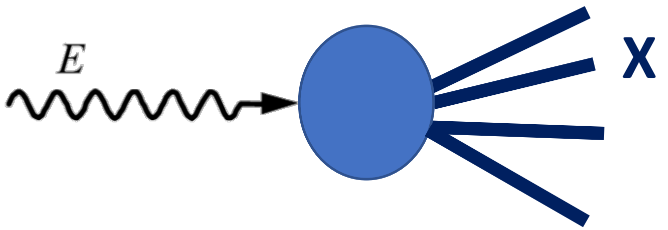
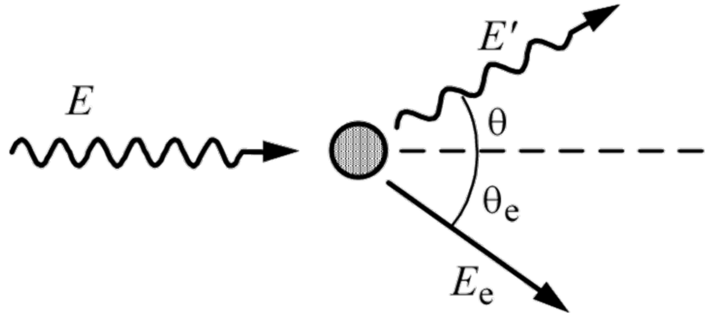
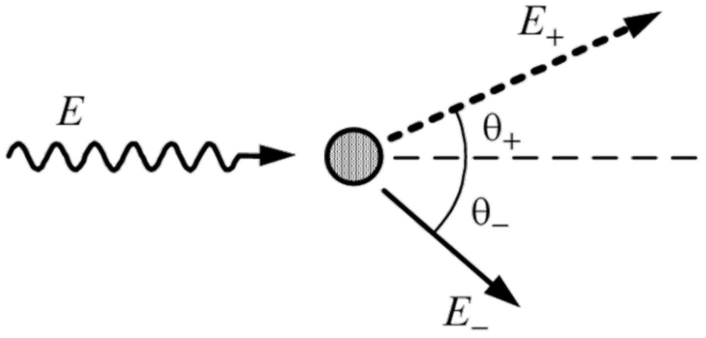


photo-nuclear processes



Compton scattering



Pair production

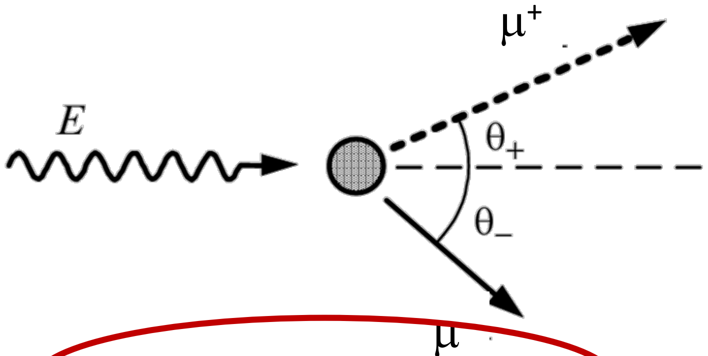


photo-muon production

Photomuon production

Muon mass ~ 105 MeV/c^2. For photon energies above ~2*105 MeV/c^2 we can expect muon^{-+} pair production to become possible.

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

Muon pair production by photons is NOT activated by any DEFAULT

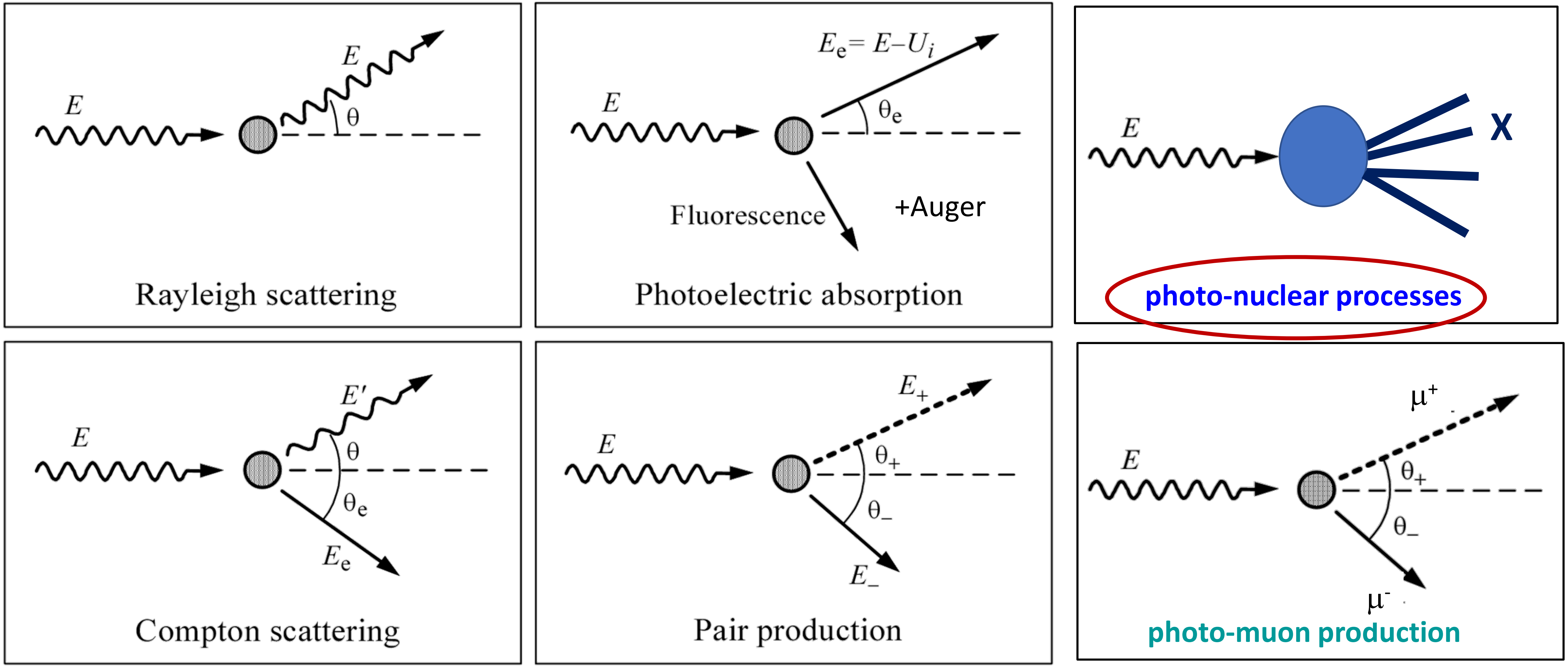
To **activate** it use PHOTONUC with SDUM=MUMUPAIR:

```
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 (currently only BH implemented)
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

Photomuon Production



Real and Virtual Photonuclear Interactions

Photonuclear reactions *(**PHOTONUC** card, off by default)*

- ❑Giant Dipole Resonance interaction (special database) (~ 10- 30 MeV)
- ❑Quasi-Deuteron effect (~ 50-150 MeV)
- ❑Delta Resonance energy region (~200-400 MeV)
- ❑Vector Meson Dominance in the high energy region (>> 1 GeV)
- ❑INC, preequilibrium and evaporation via the PEANUT model
- ❑Possibility to bias the photon nuclear inelastic interaction length to enhance interaction probability *(**LAM-BIAS** card, see manual)*

Virtual photon reactions

- ❑Muon photonuclear interactions *(**MUPHOTON** card, on by default)*
- ❑Electro/positronuclear interactions *(**PHOTONUC** card with **SDUM=ELECTNUC**, off by default)*
- ❑Electromagnetic dissociation *(**PHYSICS** card with **SDUM=EM-DISSO**, off by default)* ← ***this topic discussed already in the hadronic lecture***

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 reaction mechanisms (only for experts!). Set to 1 to activate photonuclear

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

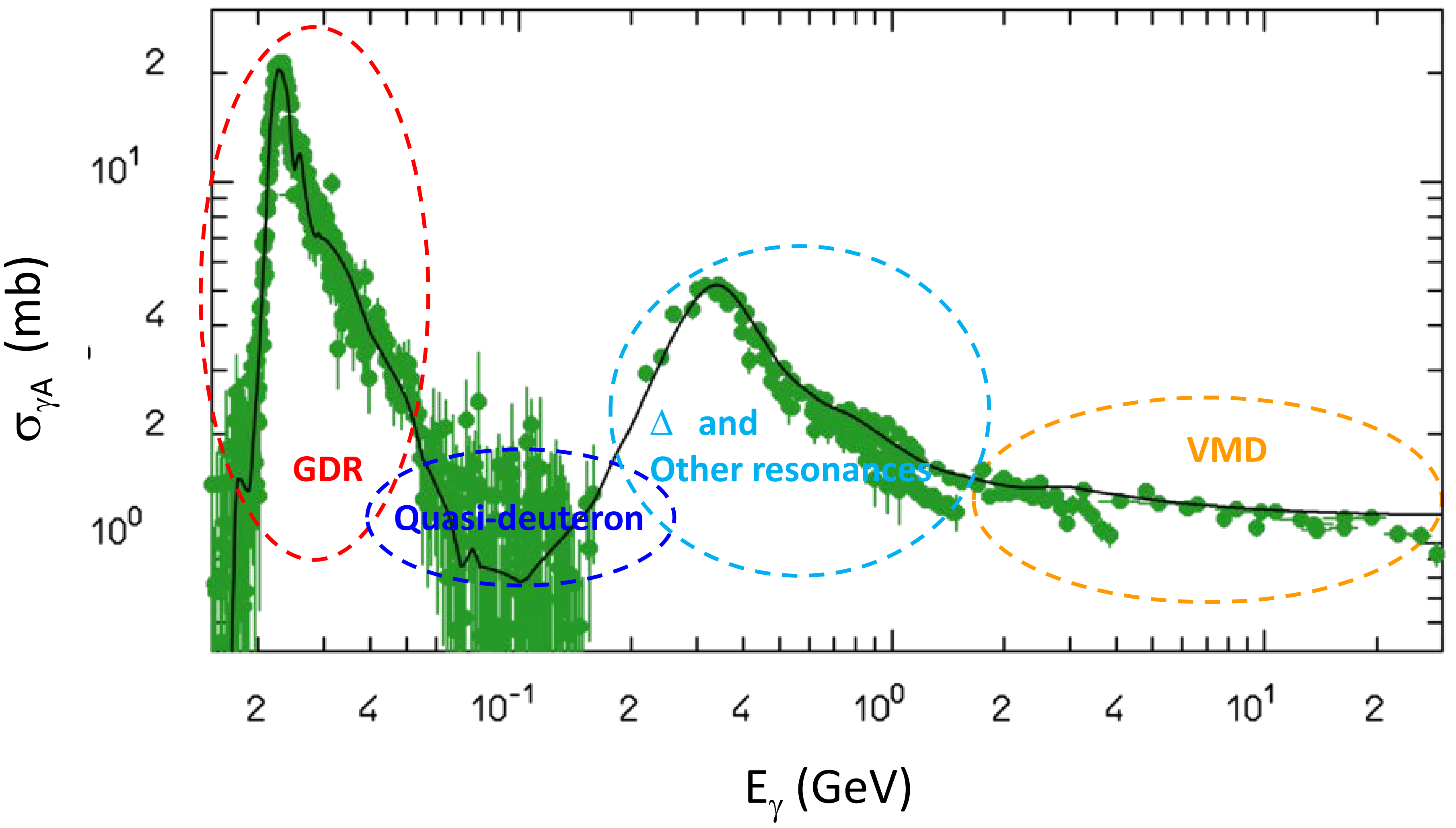
```
LAM-BIAS  0.0  Factor    Mat   PHOTON
```

Applications:

electron accelerator shielding and activation
neutron background by underground muons (together with muon photonuclear interactions, option **MUPHOTON**)

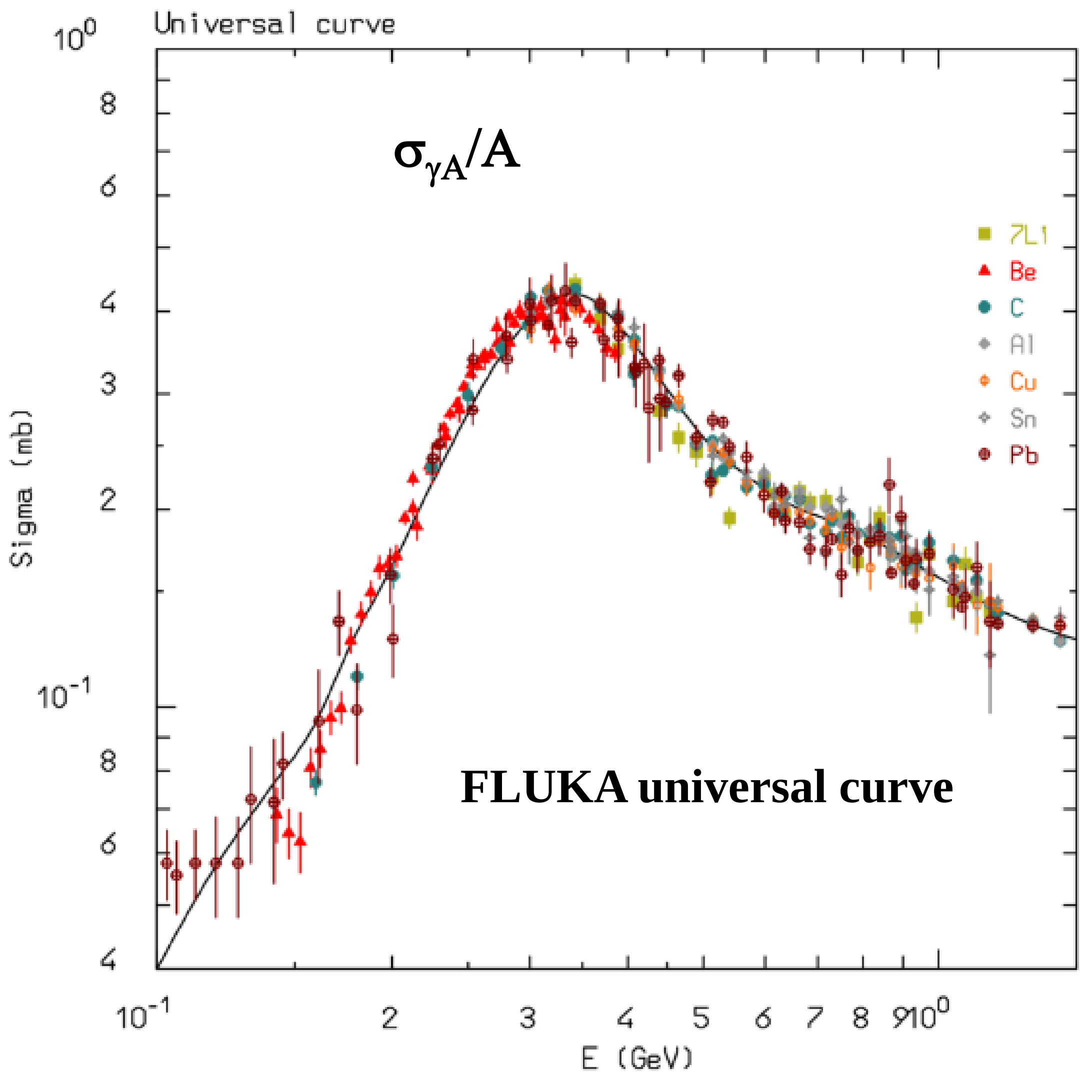
$^{12}C(\gamma, abs)$ cross section:

- ^{12}C photonuclear cross section from threshold up to ~30 GeV.
- FLUKA: black curve
- Exp. Data: green symbols (from Exfor database)



Fluka2023/4.x: γA, Δ region and just above

Above the pion threshold, and up to ~2 GeV for nuclei with A > 4, $\boldsymbol{\sigma_{\gamma A}}$ scales with A (see plot). The FLUKA "universal" curve for this energy range is shown in black.



Photonuclear int.: example

Reaction:

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

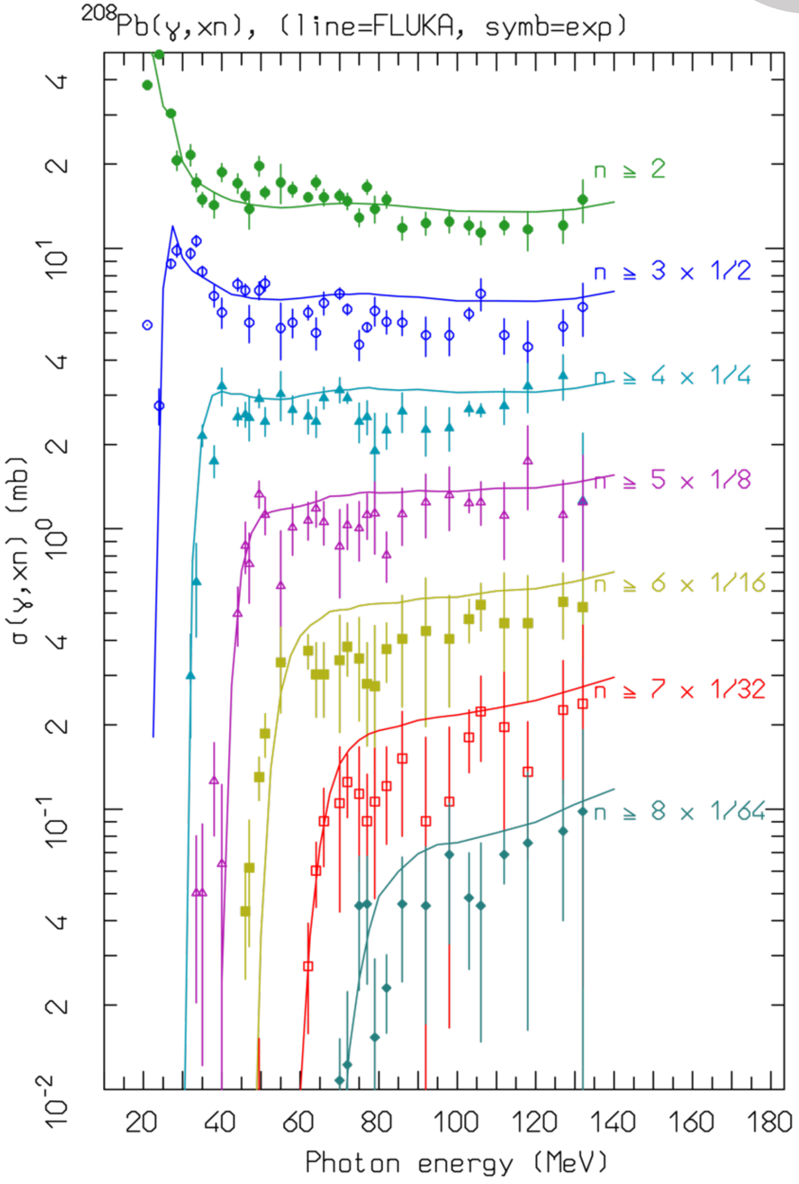
$20 \leq E_\gamma \leq 140$ MeV

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



Electron/Positron interactions

e+/e- interactions modelled in FLUKA

- Multiple and Single Coulomb scattering *(dealt with in another lecture)*
- Ionization energy losses *(dealt with in another lecture)*
- Delta-ray (Møller and Bhabha) production (-> EMFCUT)
  - Delta-ray production via Bhabha and Møller scattering
- Bremsstrahlung production (-> EMFCUT)
  - Energy-differential cross sections based on the Seltzer and Berger database at low/intermediate energies, on DMBO theory at higher energies
  - 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 acolinearity, ortho- and para-positronium competition
  - In annihilation at rest, account for mutual polarization of the two photons

Bremsstrahlung

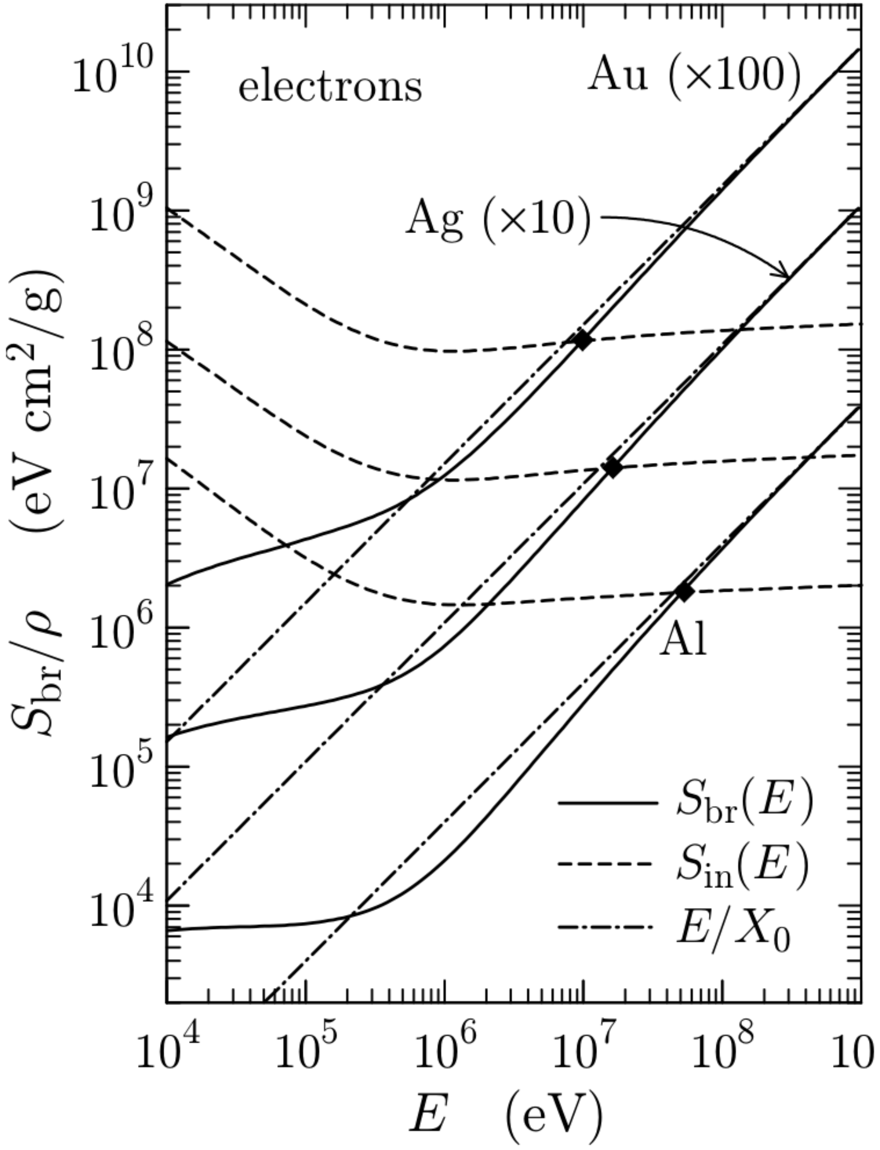
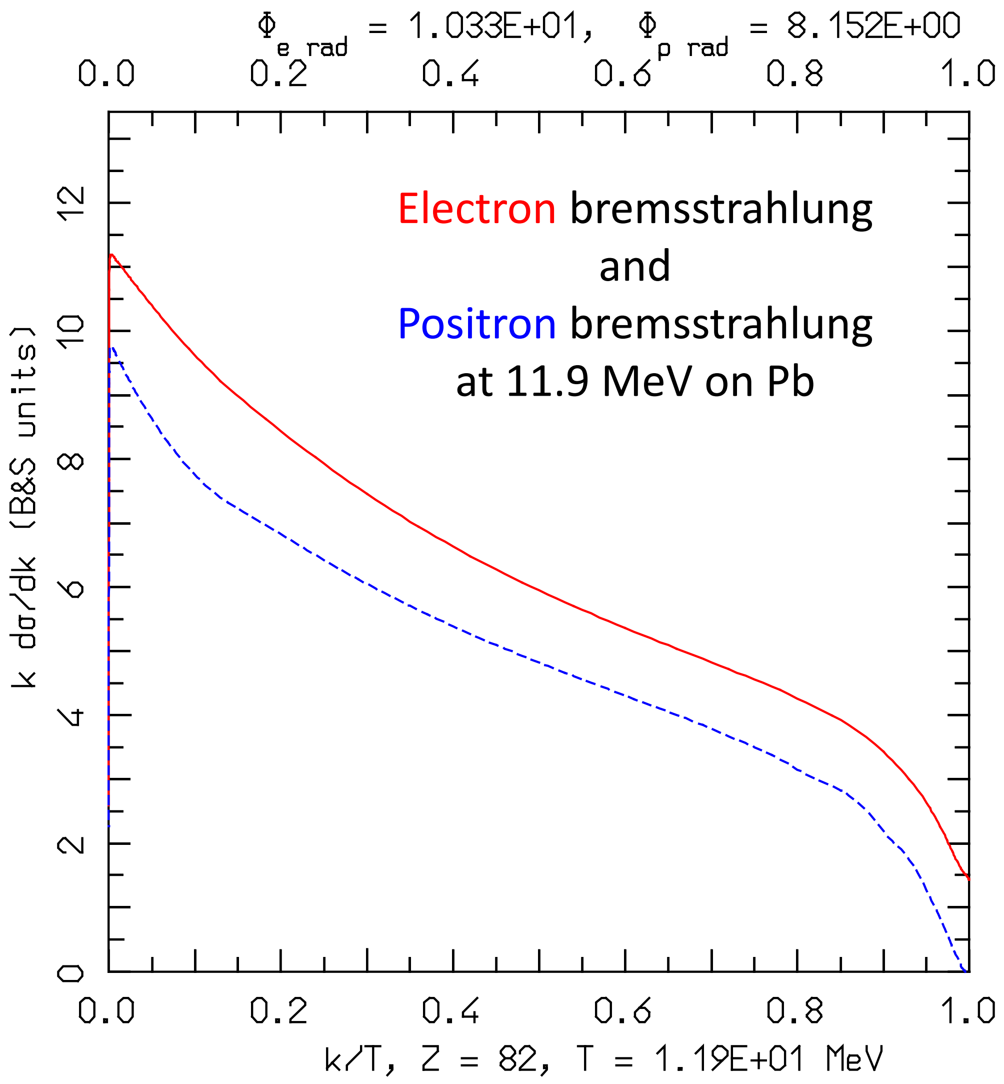
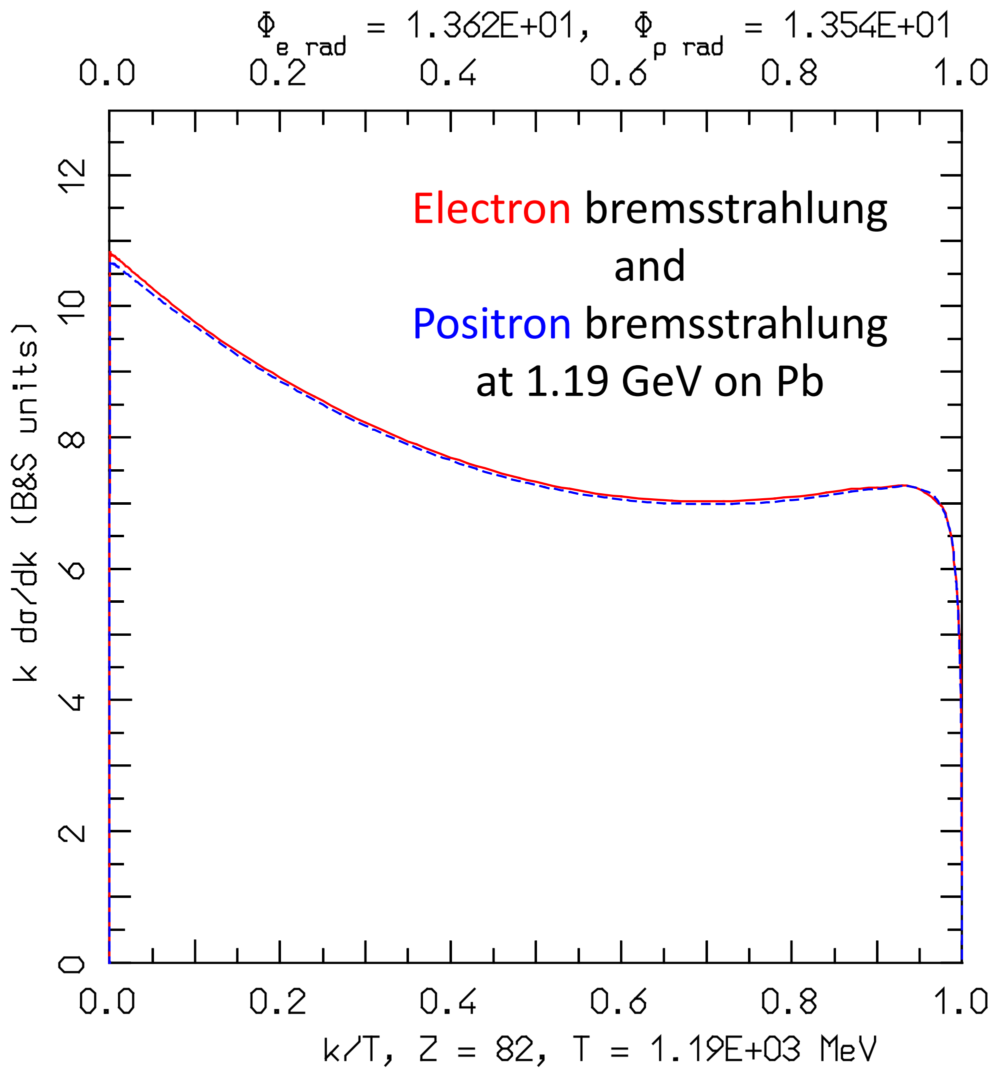


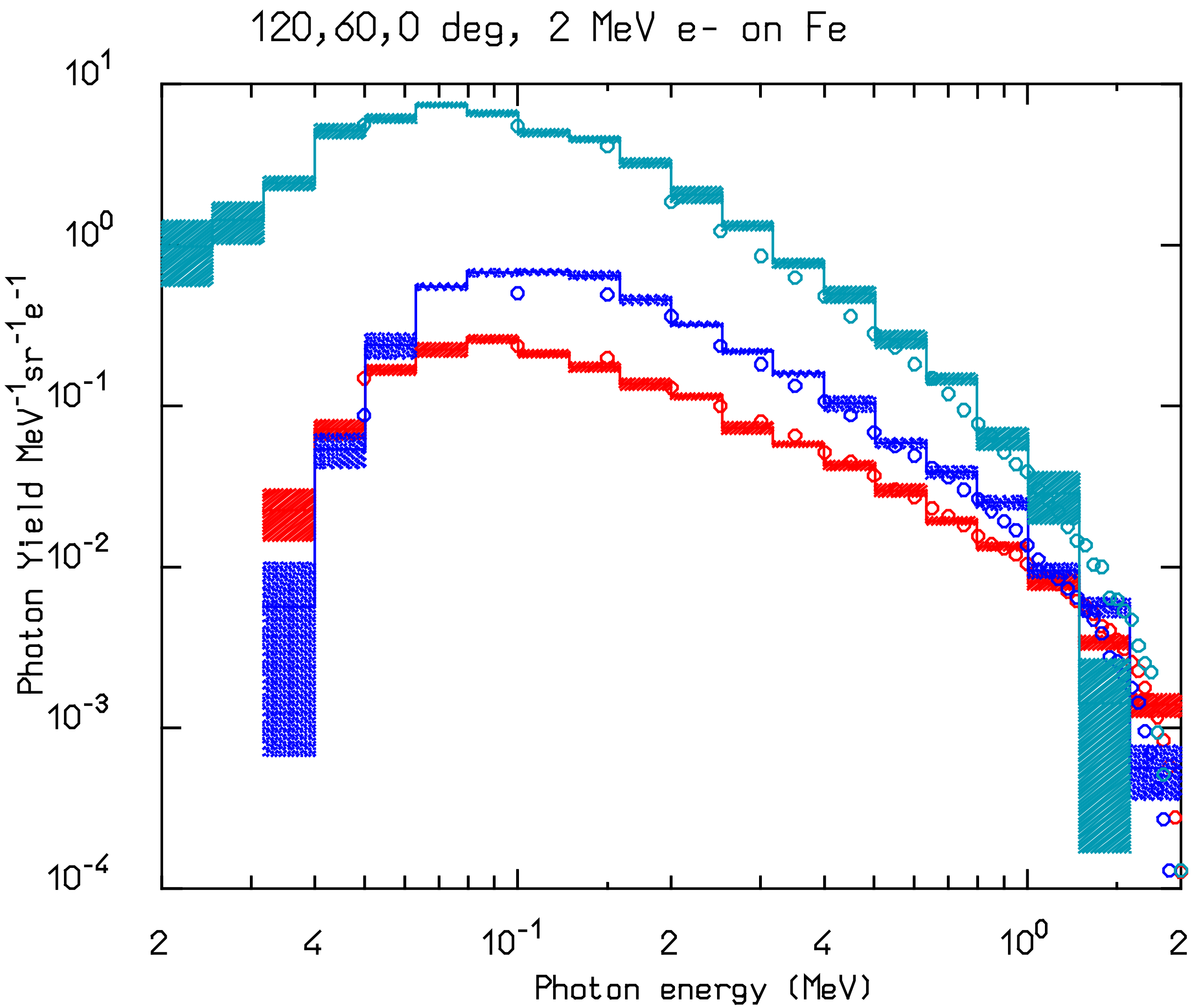
Figure 3.15: Radiative and collision stopping powers for electrons in aluminium, silver (×10) and gold (×100) as functions of the kinetic energy (solid and dashed curves, respectively). Dot-dashed lines represent the high-energy approximation given by Eq. (3.160). Diamonds indicate the critical energy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

Bremsstrahlung spectra: example



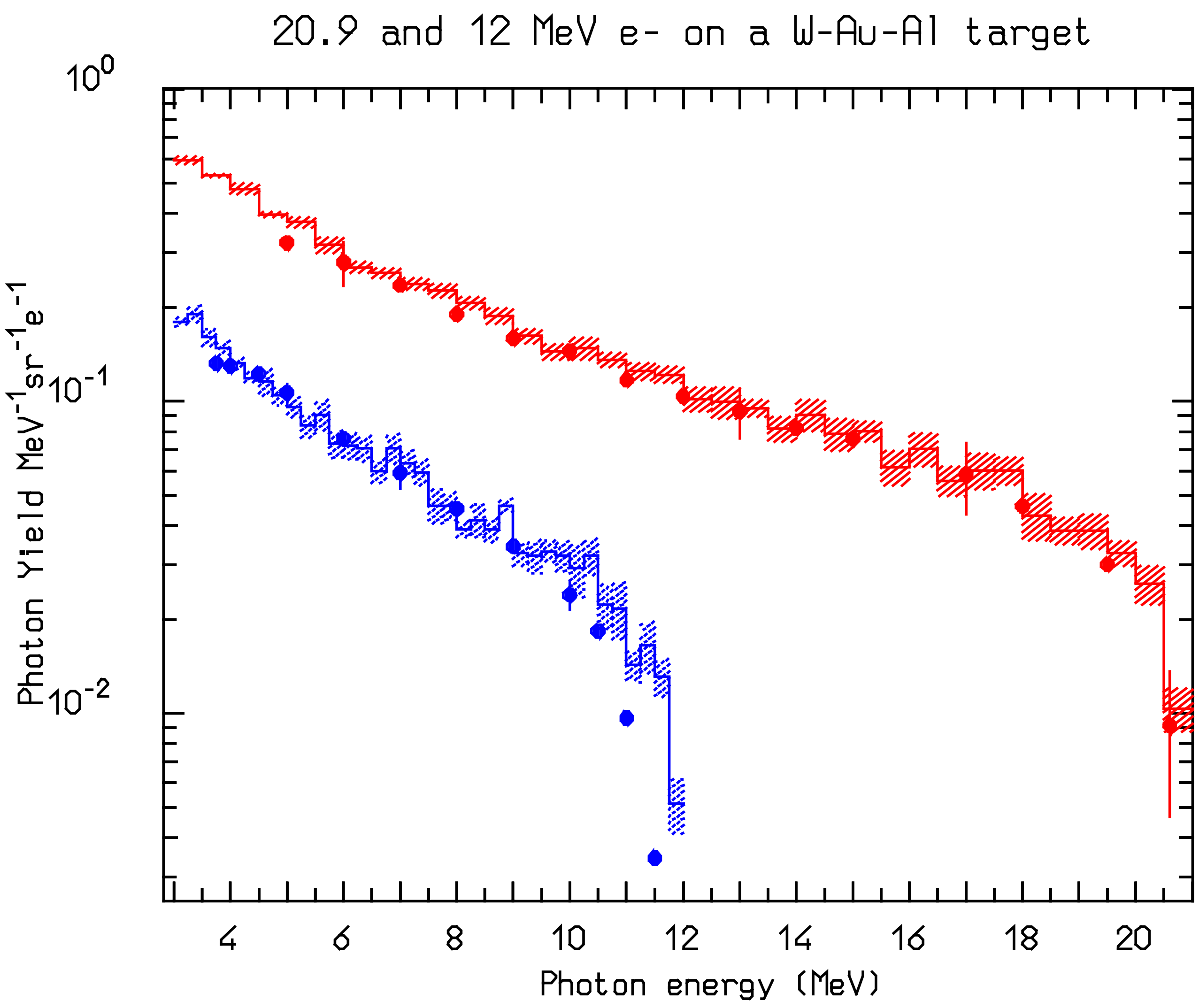


Bremsstrahlung: benchmark



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

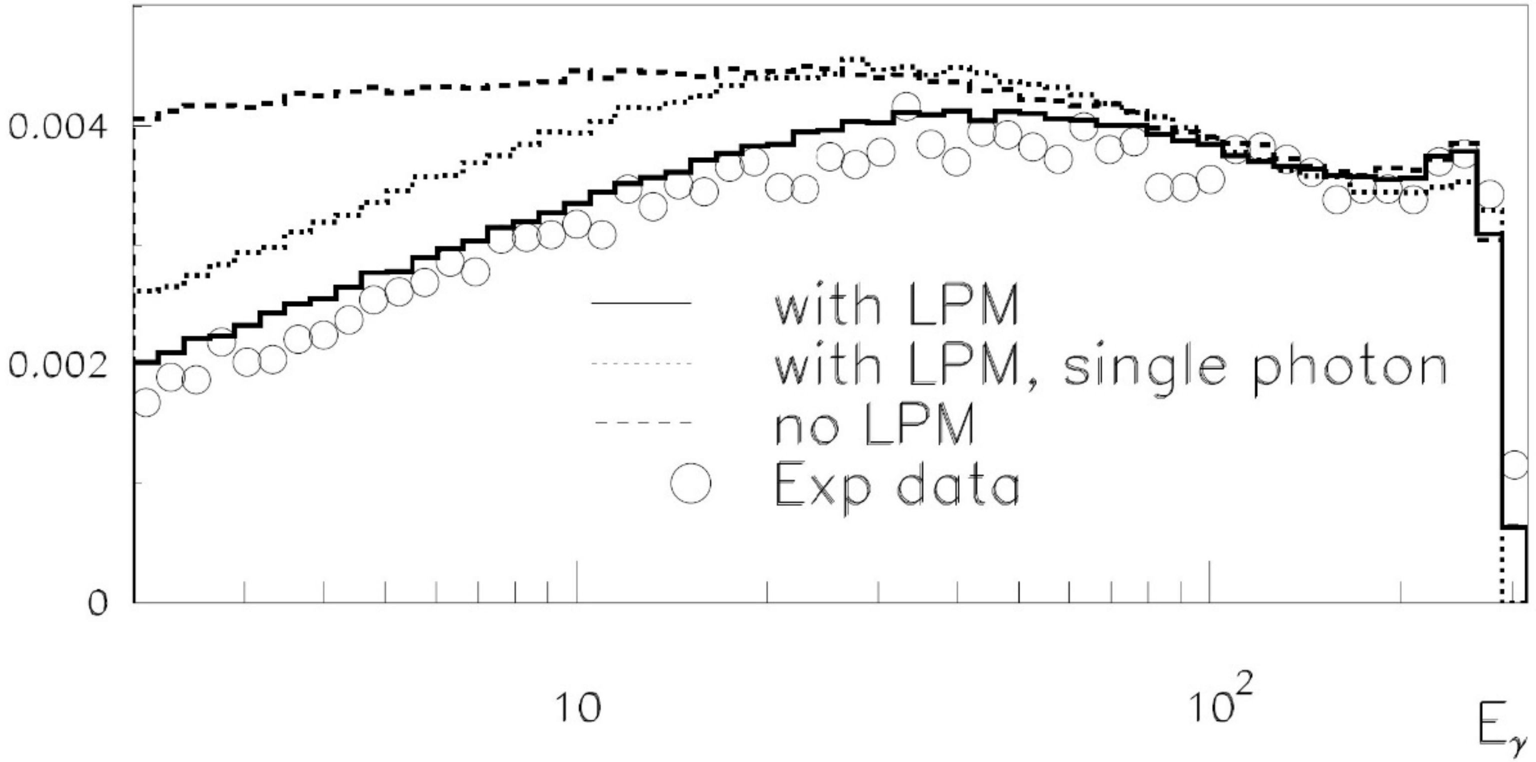
Bremsstrahlung: benchmark II



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

Landau-Pomeranchuk-Migdal benchmark

Bremsstrahlung spectrum, dNγ /dlog(Eγ), for 287 GeV electrons on 0.128 mm Ir (~4.36% X_0). The vertical scale is normalized to the number of incoming electrons.
Data from Phys.Rev. D 69,032001 (2004)



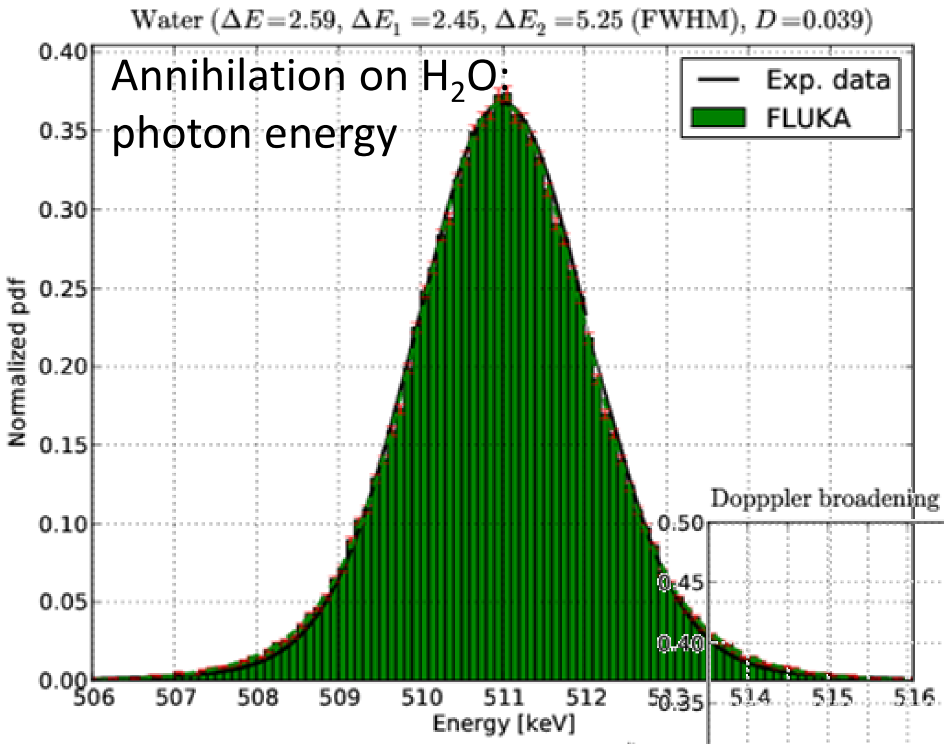
Simulations (lines) with FLUKA
The full and dashed lines include the effect of pile-up (multiple superimposed photon detection), with and without LPM.
The dotted line is the single photon spectrum (no pile-up) including LPM

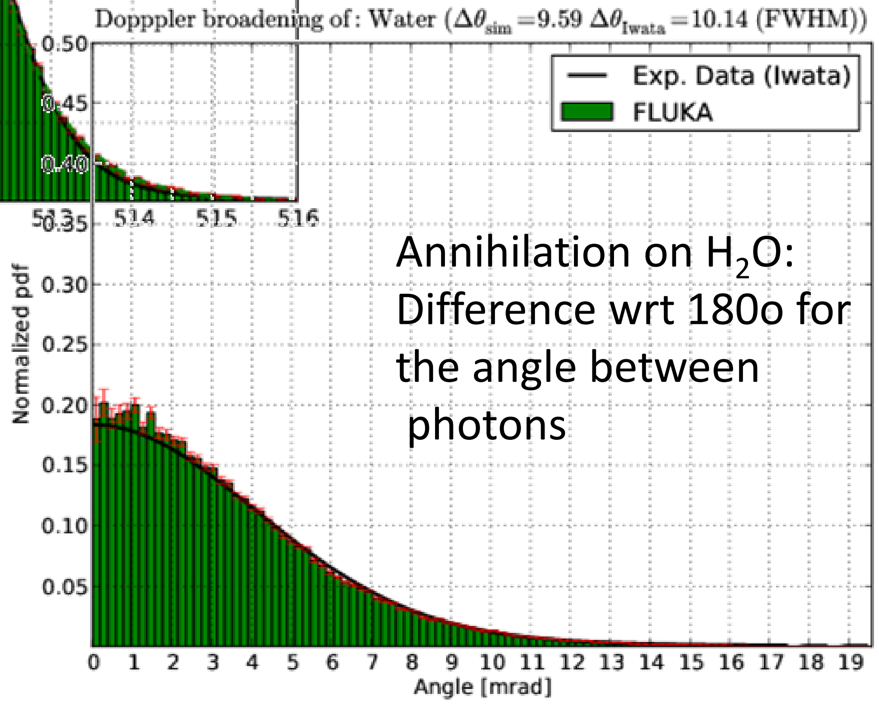
LPM: interference among scattering centres within the photon “formation zone”: **scales ~ E^2 / X_0**
- also for pair production. Important at high energies (>> 100 GeV) and for heavy and dense materials

Annihilation on bound electrons:

Positron annihilation at rest

- Account for atomic electron motion and binding …
- … resulting a-collinearity (see plot at bottom right) …
- … and energy spread wrt 511 keV (see plot at top right)
- account for mutual polarization of the two photons
- Para- (2 γ) and ortho- (3 γ) positronium competition (look at the **EMFRAY** option, SDUM's





Electro-/Positro-nuclear interactions

Electronuclear interactions: options

Electronuclear interactions are ***NOT activated*** with any default

To activate them:

```
PHOTONUC Flag                Mat1    Mat2    Step    ELECTNUC
```

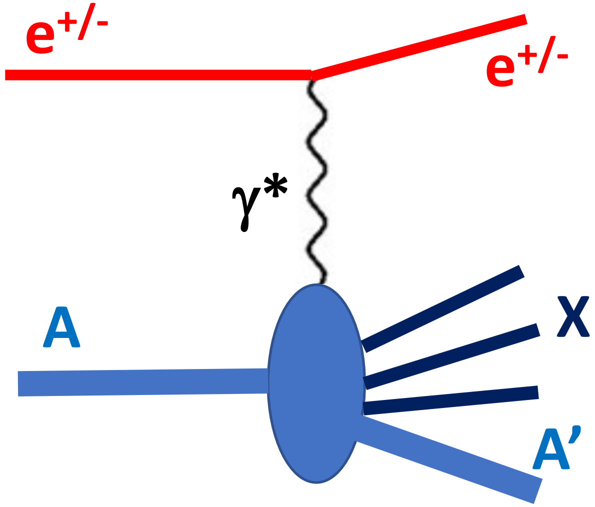
Flag controls activation of interactions, with the possibility to select a subset of the photonuclear reaction mechanisms *(only for experts!)*. Set to 1 to activate electronuclear

Since the electronuclear cross section is very small compared with atomic ones, **PHOTONUC** should be in many problems accompanied by **LAM-BIAS** with SDUM = blank (see lecture on biasing)

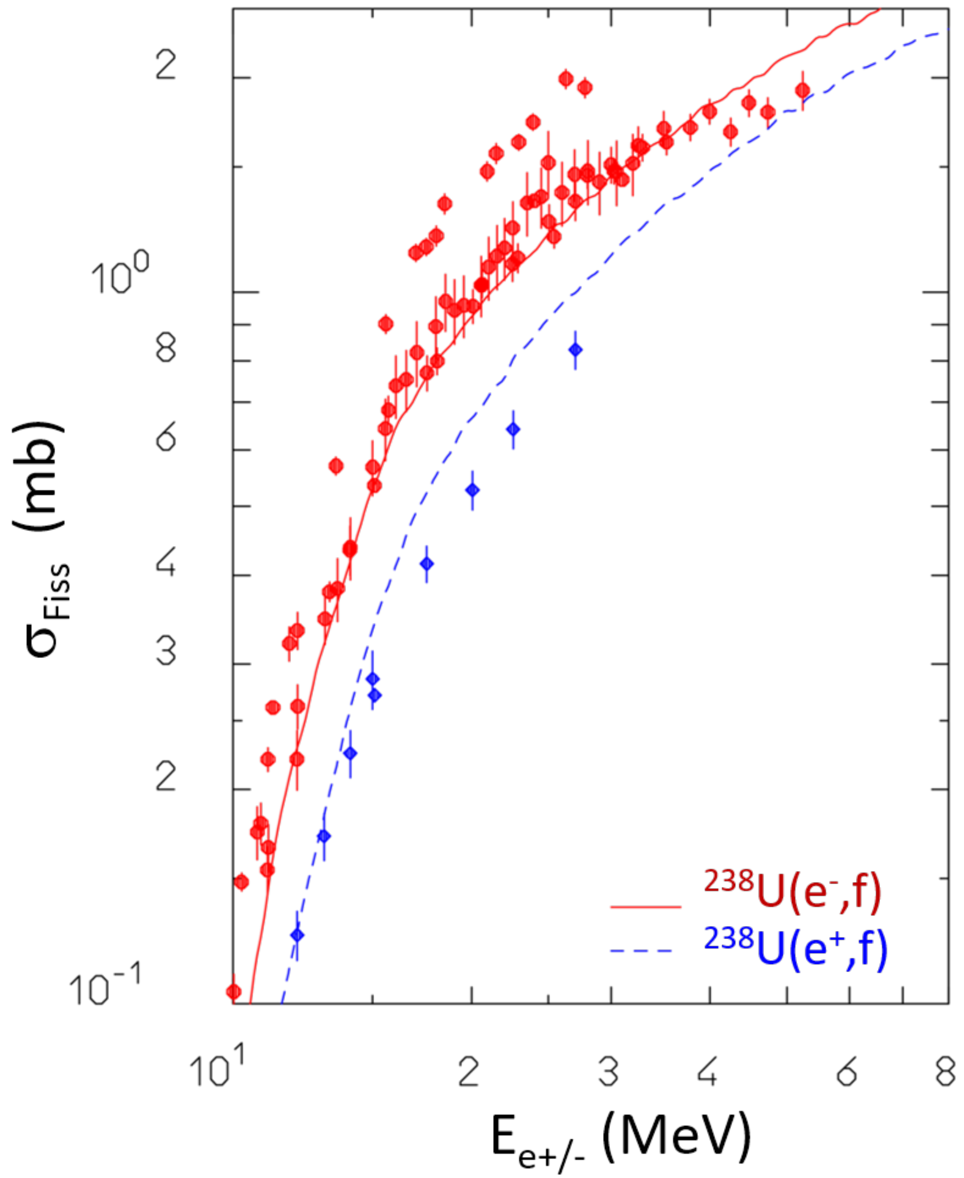
```
LAM-BIAS  0.0  Factor   Mat  ELECTRON  POSITRON
```

Applications: same as for photonuclear

Electro- and positro-nuclear interactions



Computed (lines) and experimental (symbols) **electron (red)** and **positron (blue)** induced fission cross sections as a function of energy



Muon interactions

Muon interactions modelled in FLUKA

- Delta-ray (secondary electron) production (-> **DELTARAY** card)
- Bremsstrahlung (-> **PAIRBREM** card, activated for most defaults)
  - Detailed photon angular distribution fully correlated to energy
- Pair production (-> **PAIRBREM** card, activated for most defaults)
  - Correlated angular and energy distribution

PAIRBREM	Flag	$e^{+/-}_{pair}$	γ_{brems}	Mat_1	Mat_2	Step

Flag=1/on,-1/off

- Muon photo-nuclear reactions
  - See next slides
- Negative Muon capture
  - See next slides

Muon interactions

- Muon photonuc. is less likely than other processes
- 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

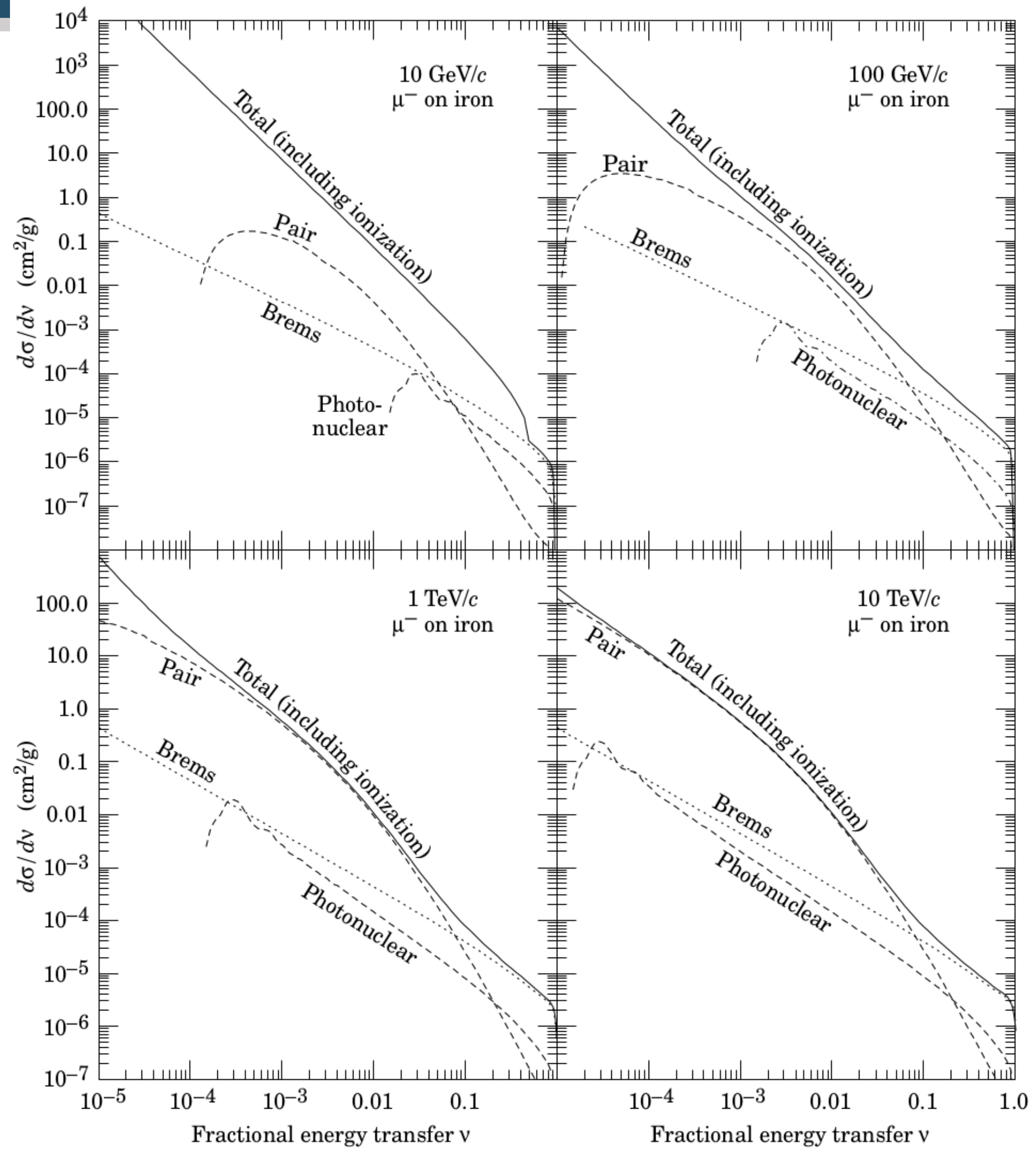
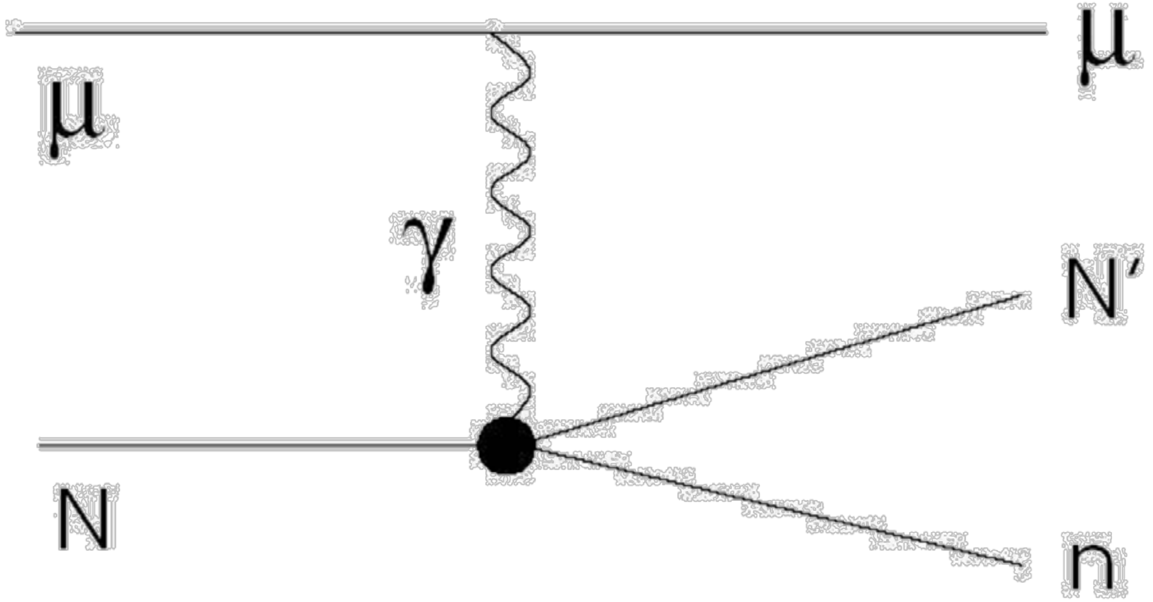


Figure 4: Differential cross section for total and radiative processes as a function of the fractional energy transfer for muons on iron.

Muon Photonuclear Reactions



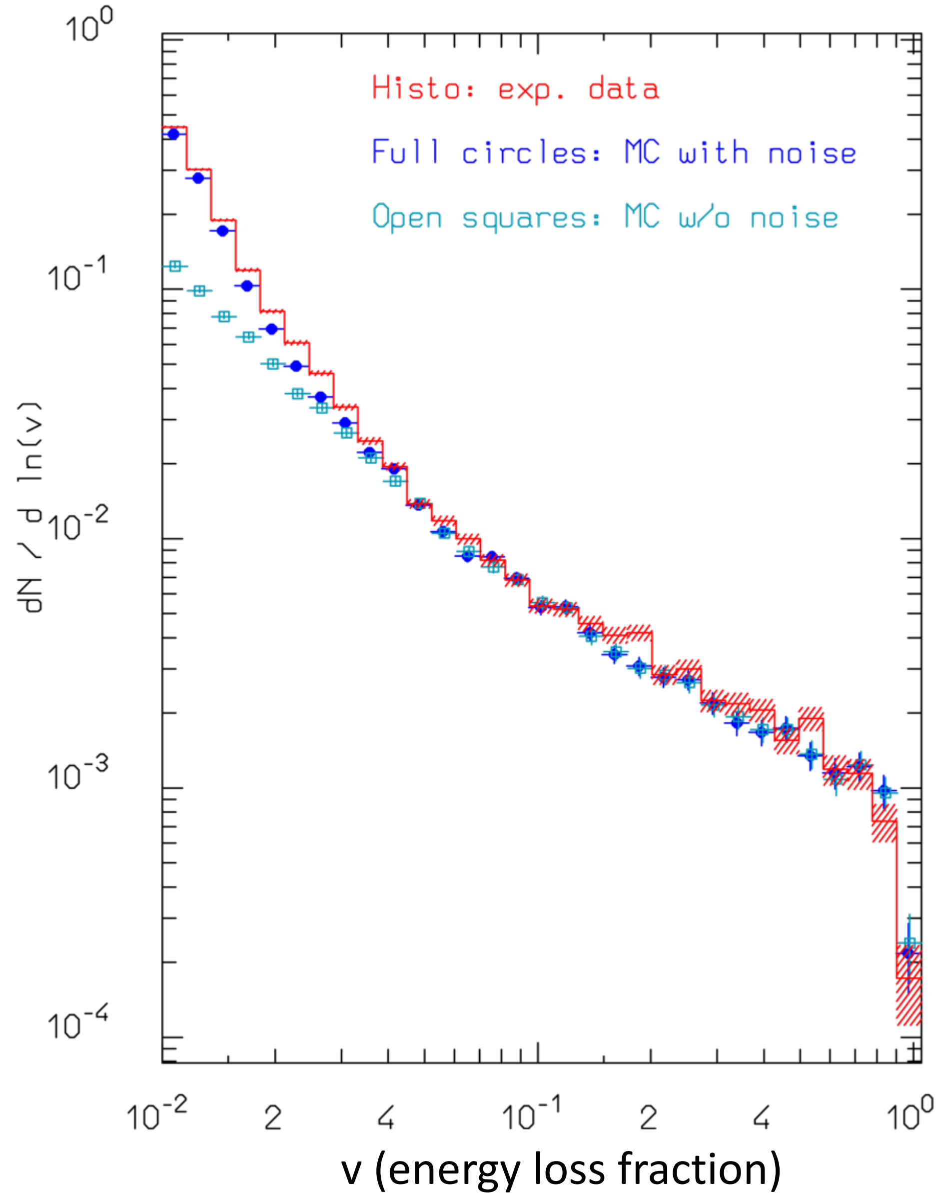
Schematic view of a μ hadronic interaction.

The interaction is mediated by a virtual photon.

The final state can be more complex

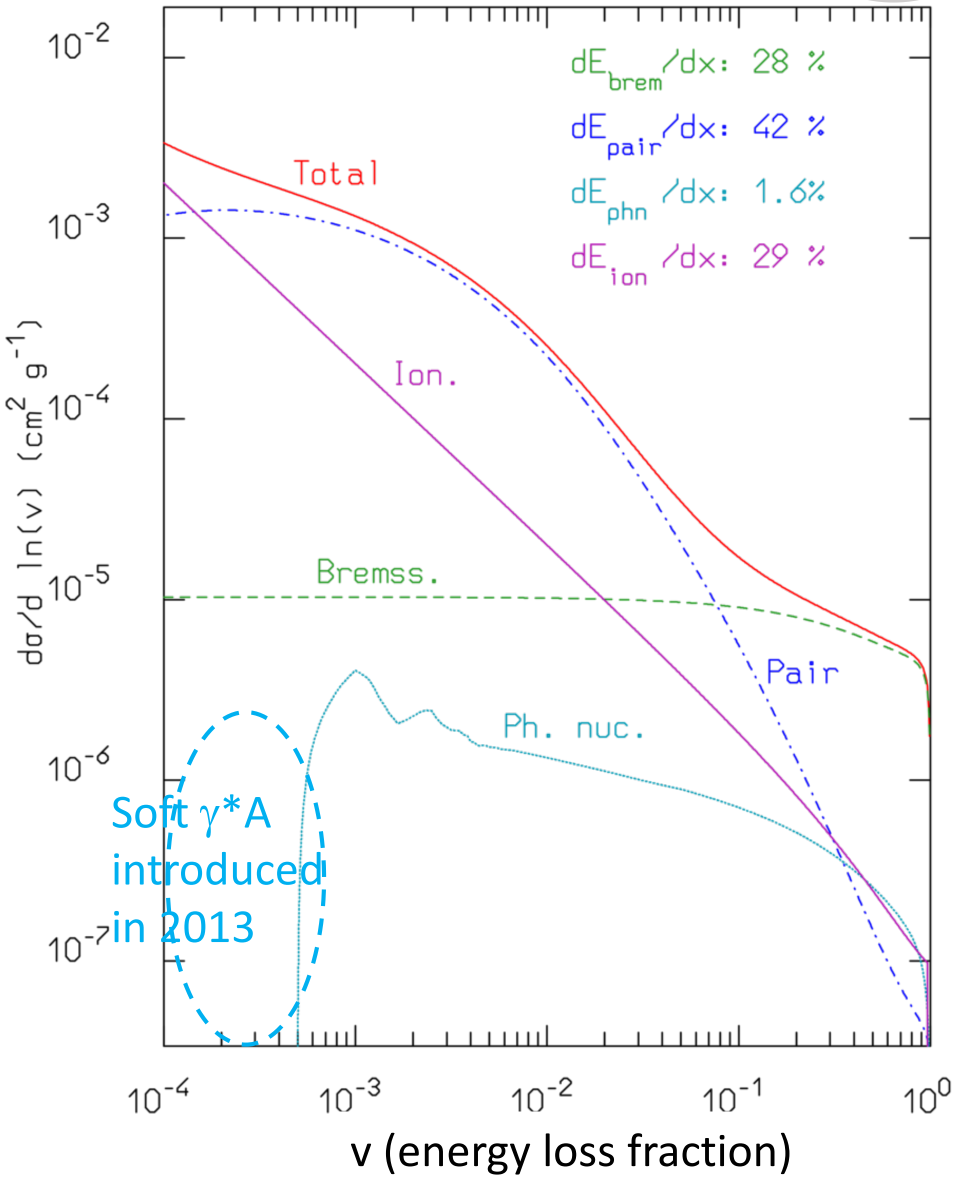
- The cross section can be factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction
- Nuclear shadowing is taken into account
- All interaction mechanisms supported by the FLUKA photo-nuclear algorithms, including GDR, quasi-deuteron, resonance, and Vector Meson Interactions are implemented
- Nuclear effects are the same as for photon-nucleus interactions

300 GeV muon losses in the ATLAS EM (Pb-LAr) calorimeter



Muon energy ← losses spectra (v·dN/dv) measured in the ATLAS LAr-Pb accordion prototype calorimeter

Expected muon energy losses for the ATLAS EM calo setup split into the various components →



Muon photonuclear reactions: options

μ photonuclear interactions are ***activated by default*** with most defaults

To (de)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 often accompanied by LAM-BIAS if this process is important for the studied problem (see lecture on biasing)

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

Negative Muon capture:

An exotic source of neutron background

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

Before the nuclear capture:

μ^- at rest + atom = excited muonic atom ->muonic 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**

Kinematically the neutrino gets most of the energy $\rightarrow$ low energy transfer (neutron E=5 MeV on free p)

Experimentally: high energy tails in n-spectra, reproduced in **PEANUT** with a 2-nucleon absorption component

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
- SR photon polarization

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

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

There is an example in the extra slides, also look into the manual!

Thanks for the attention

Extra Slides

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)
```

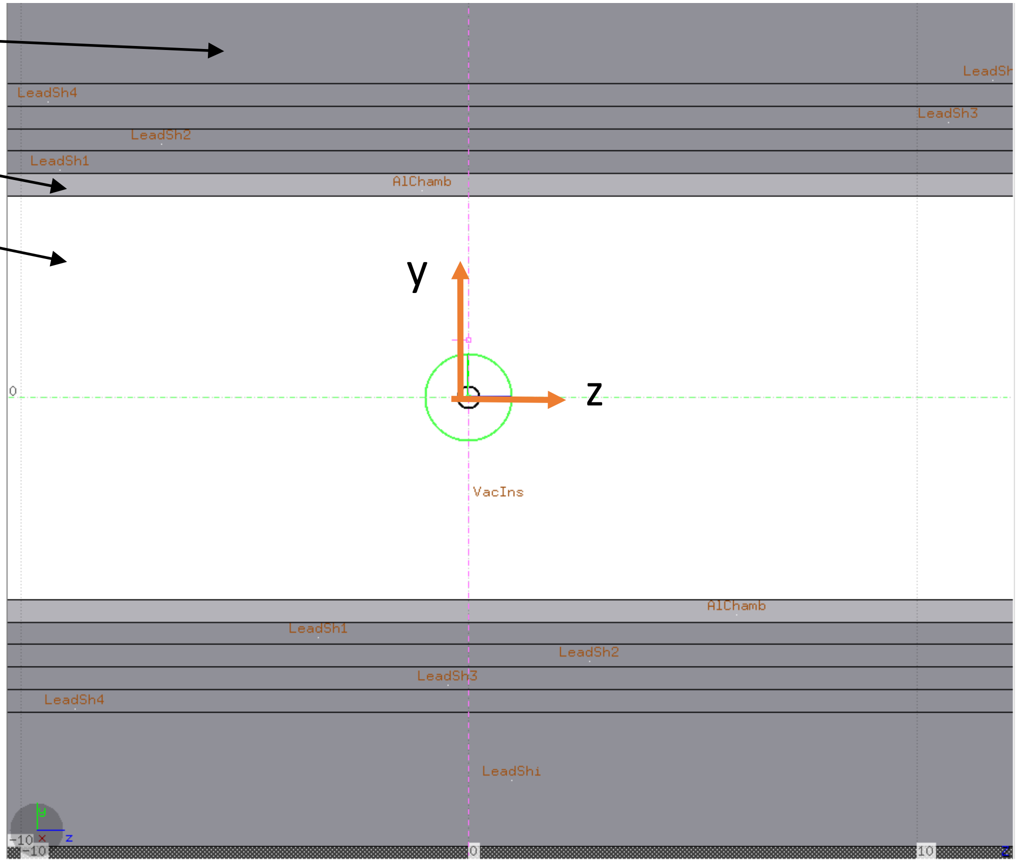
Synchrotron radiation: example

Lead shielding

Al layer

Vacuum

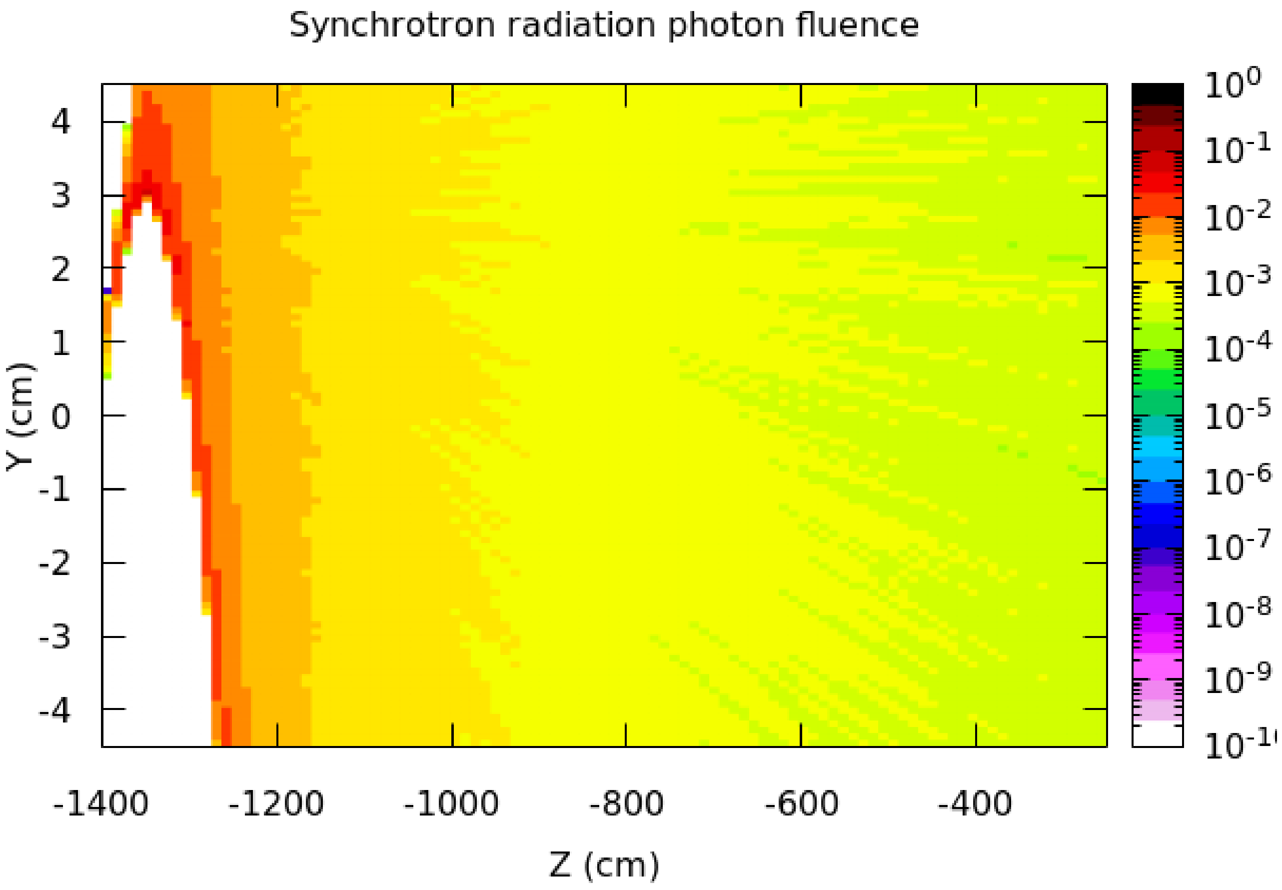
Start of first arc



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

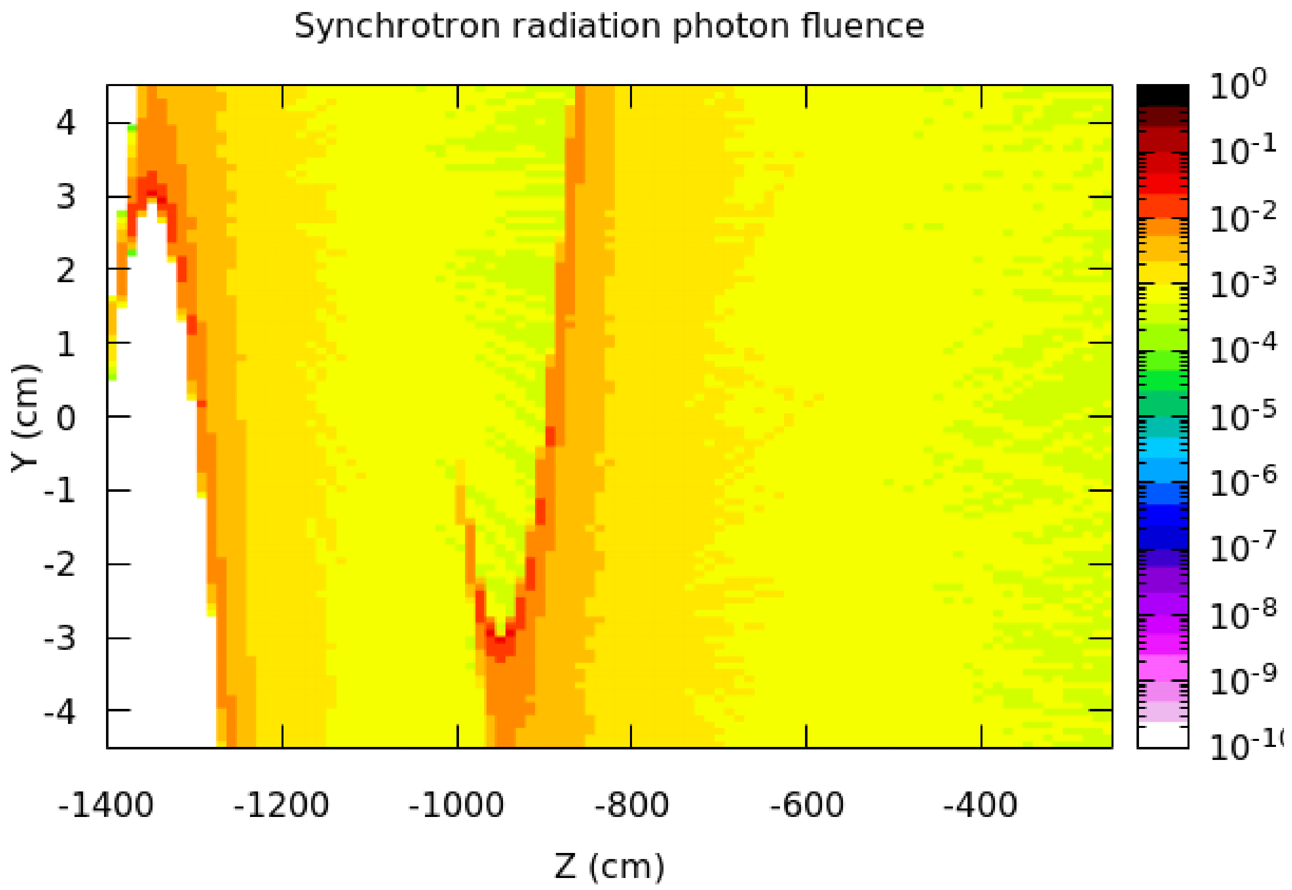
```
BEAMPOS                        0.5   -1400.0                 0.100
SPECSOUR     ELECTRON          3.0         -2.0  0.0000001   1.000            0.0SYNC-RAS
SPECSOUR        150.0                                                            &
```

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:

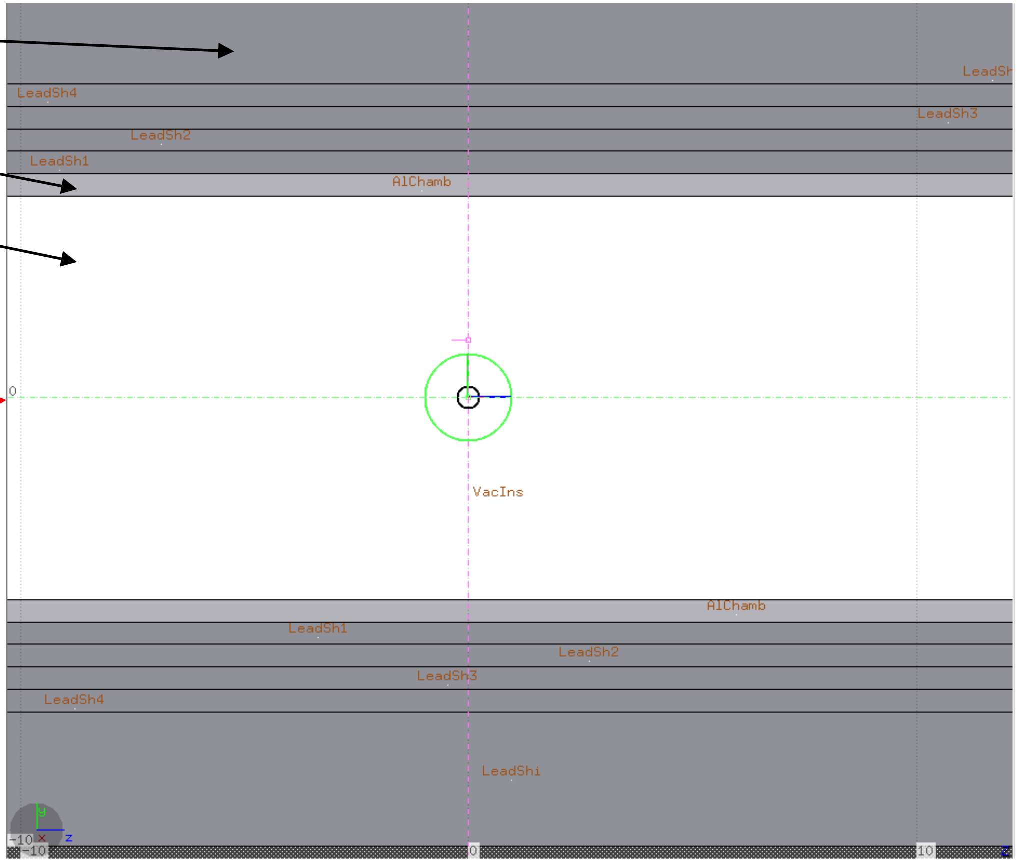
Lead shielding

Al layer

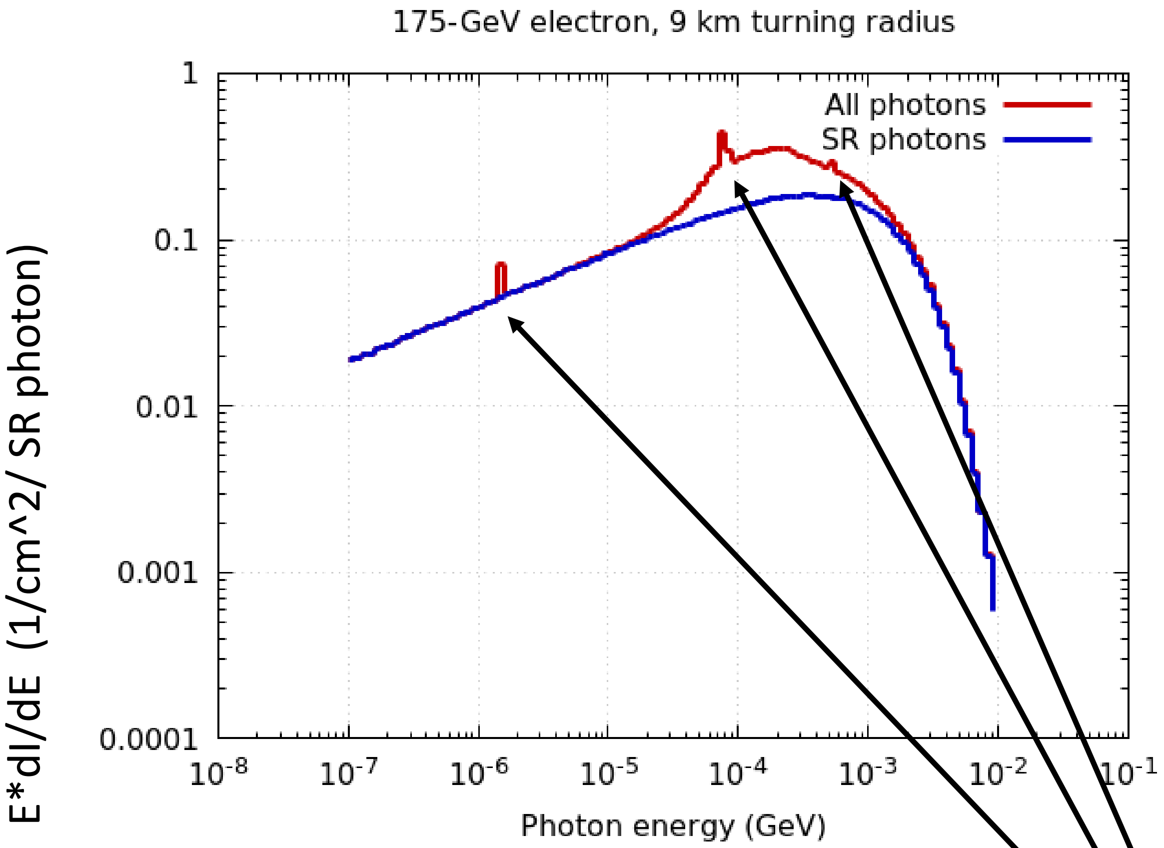
Vacuum

175-GeV e-

R=9000 km



Synchrotron radiation: a higher-energy example



Annihilation photons
Pb K lines
Al K lines