EM interactions

Beginners' FLUKA Course

Topics

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

- 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....and with most **DEFAULTS** options, except: EET-TRAN, NEUTRONS, SHIELDING

To de-activate EMF:

EMF	OFF ▼

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

Transport thresholds

Transport thresholds

- Particles are transported until their energy falls below a preset threshold
- The thresholds have default settings, depending on the SDUM selected on the DEFAULTS card
- ***DO NOT RELY*** on them, choose those which are best suited for your problem
- Depending on the particle type they can be modified with different cards
  - EMFCUT for electrons, positrons and gammas (EMF particles)
  - PART-THR for hadrons, ions, muons and neutrinos
- The cards are briefly introduced in the following, but transport is discussed in more detail in the next lecture

Transport thresholds for e-,e+, gammas

EMFCUT card (without SDUM): energy transport threshold for electrons/positrons/gammas can be set REGION BY REGION.

```
EMFCUT    e±Thresh    γThresh    0.0    Reg1  Reg2    Step
```

HOW to choose the thresholds?

It depends on the "granularity" of the geometry and/or of the scoring mesh and on the "interest" in a given region. Energy/range tables are very useful (see for instance http://physics.nist.gov)

Warning 1: to reproduce correctly electronic equilibrium, neighboring regions should have the same electron energy (NOT range) threshold. To be kept in mind for sampling calorimeters

Warning 2 : Photon thresholds should be lower than electron thresholds (photons travel more)

Warning 3: ***low thresholds for e-/e+/gammas are CPU eaters***

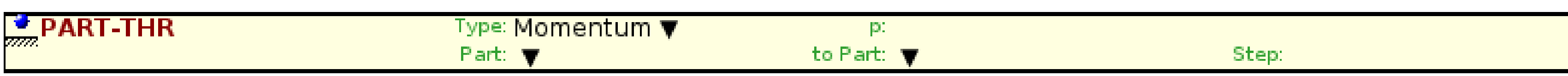
Transport thresholds for other particles

PART-THR card: allows to set transport threshold for hadrons, ions, muons and neutrinos globally for the entire geometry setup

Can be individually set for different particle types, or for all particles (neutrons are special -> see neutron lecture)

Heavy ion transport thresholds are derived from that of a He4 ion

```
*  ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
PART-THR      Thresh     Part1     Part2      Step
```



Production thresholds

Continuous vs discrete energy loss of charged particles

Let's introduce a concept that is treated again in the discussion of ionization energy losses - the separation between CONTINUOUS and DISCRETE energy transfer (loss):

The simulation of all atomic interaction processes is not possible in all-purposes MCs, because

- the modeling of very low energy transfer would need detailed atomic/molecular physics
- the CPU time would diverge

→ 1) ONLY interactions resulting in a "substantial" energy transfer are simulated explicitly

→ 2) All other interactions are "condensed" in a continuous energy loss along the particle step

Production thresholds

- The transition from CONTINUOUS to DISCRETE energy transfers is controlled by production thresholds
- Secondary production thresholds can be set for different processes and particle types using different cards:
  - EMFCUT: secondary production for processes of EMF particles processes (e.g. delta-ray and bremsstrahlung production by e-/e+) incl. also secondary production in photon interactions which are evidently all discrete interactions
  - DELTARAY: delta-ray production by muons and charged hadrons
  - PAIRBREM: bremsstrahlung and pair-production by muons and charged hadrons
- Like for transport thresholds, default production thresholds depend on the DEFAULTS card setting

Production thresholds for secondaries produced in e-/e+/γ interactions

- EMFCUT with SDUM=PROD-CUT allows to control the threshold for secondary production in any e-/e+/γ interactions

```
EMFCUT      e±Thresh γThresh Fudgem Mat1   Mat2    Step    PROD-CUT
```

EMFCUT	Type: PROD-CUT ▼	e-e+:	γ:
Fudgem:	Mat: ▼	to Mat: ▼	Step:

Fudgem is related to multiple scattering. = 0 below ≈ 10 keV , = 1 above
MUST be set, if the field is empty ➔ 0

Warning 1: if prod-cut < transport cut, CPU is wasted in producing/dumping particles on spot. Sometimes it could be convenient to define several "equal" materials with different production thresholds (and different names)

Warning 2: if prod-cut > transport cut , the program automatically increases the transport threshold , because it cannot transport a particle that it is not supposed to handle.

Delta-ray production by charged hadrons, ions and muons

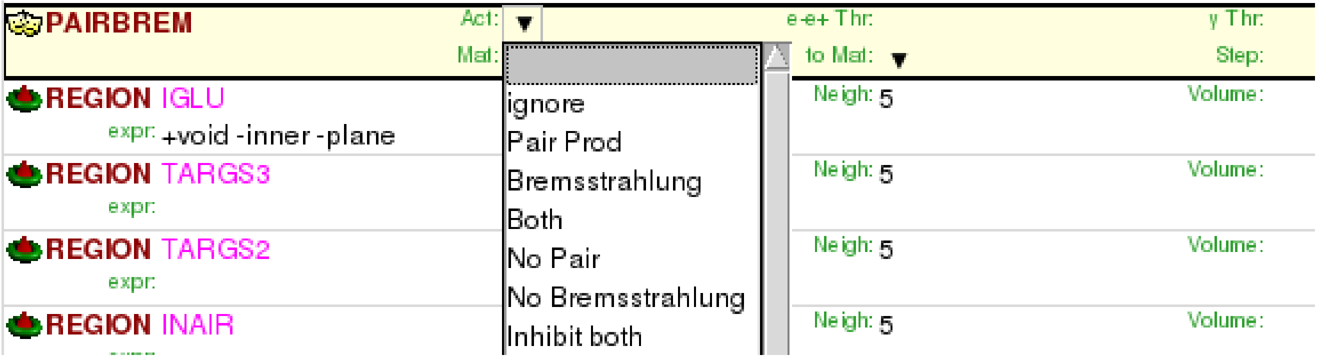
- DELTARAY card allows to control the delta-ray production by charged hadrons, ions and muons
- Settings depend on DEFAULTS card
- Should be higher than the energy transport cut requested by the EMF-CUT card

```
*  ..+....1....+....2....+....3....+....4....+....5....+....6....+....7..
DELTARAY     δThresh     Ntab      Wtab      Mat1      Mat2      Step PRINT
```

Bremsstrahlung and pair production by muons and charged hadrons (1/2)

- PAIRBREM card allows to control the production threshold for bremsstrahlung and pair production by muons, light ions (up to alphas) and charged hadrons
- Depending on the DEFAULTS, the processes might be active without explicit production of secondaries (only continuous energy loss treated – see manual)

```
PAIRBREM Flag  e±Thresh γThresh Mat1  Mat2    Step
```

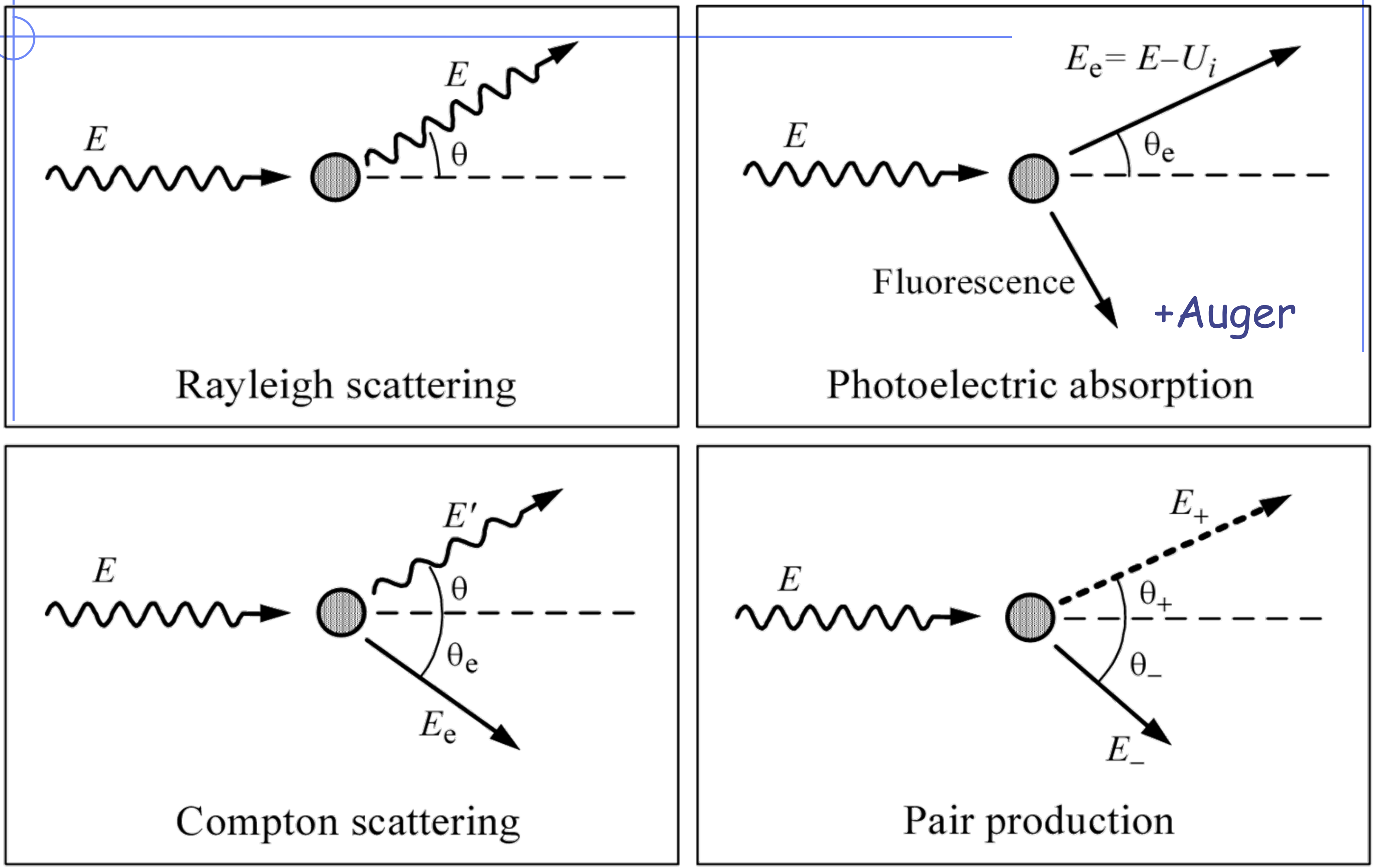


Bremsstrahlung and pair production by muons and charged hadrons (2/2)

- Evidently, the photon transport threshold requested by the EMF-CUT card should be lower than the Bremsstrahlung production threshold set via PAIRBREM
- On the other hand, it is generally recommended to set the e-/e+ pair production threshold to 0 (there is anyway a natural threshold for pair production)
- With high thresholds energy loss straggling and energy deposition is not correctly reproduced (but allows to correctly reproduce the average range of muons)

Photon interactions

Photon interactions modeled in FLUKA



+photo-nuclear processes

+photo-muon production

Photoelectric effect

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

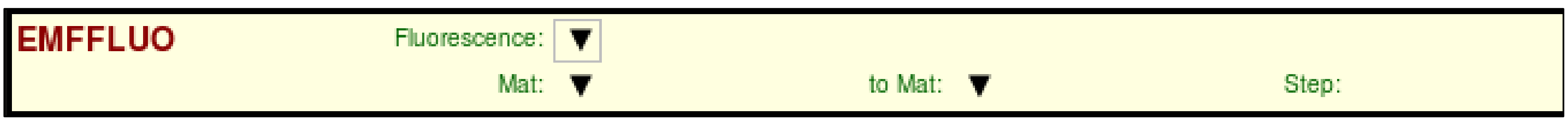
Fluorescence after photoelectric is activated only with a subset of DEFAULTS: CALORIMEtry, EM-CASCA, ICARUS, PRECISIOn

CPU time vs. precision in small granularity

To activate/deactivate it:

```
EMFFLUO          Flag      Mat1      Mat2      Step
```

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



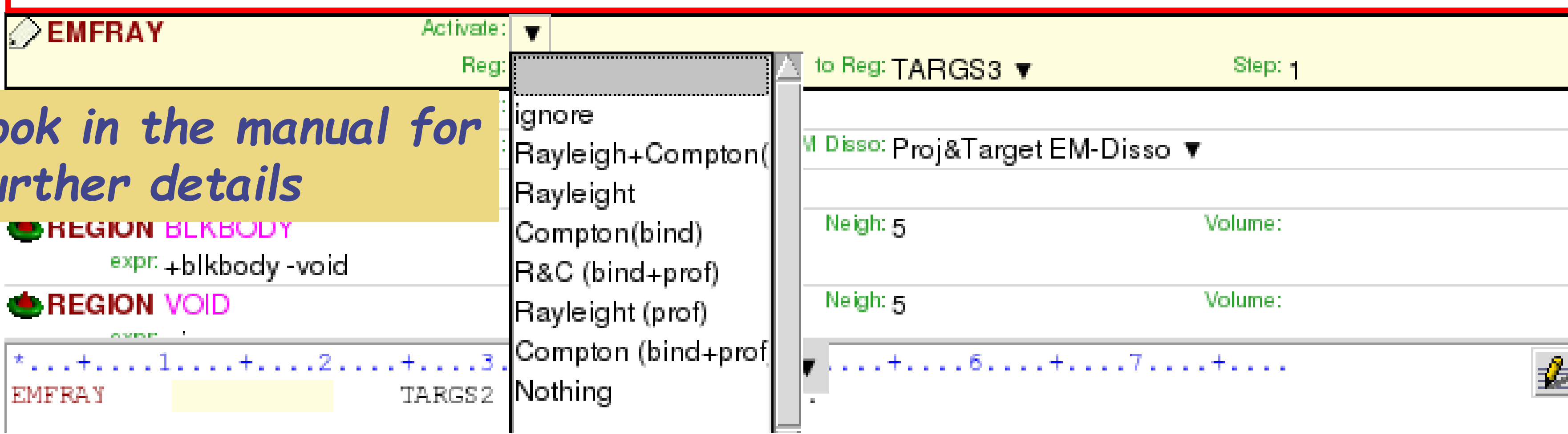
Warning: check consistency with production/transport thresholds

Compton and Rayleigh scattering

- 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 photon polarization

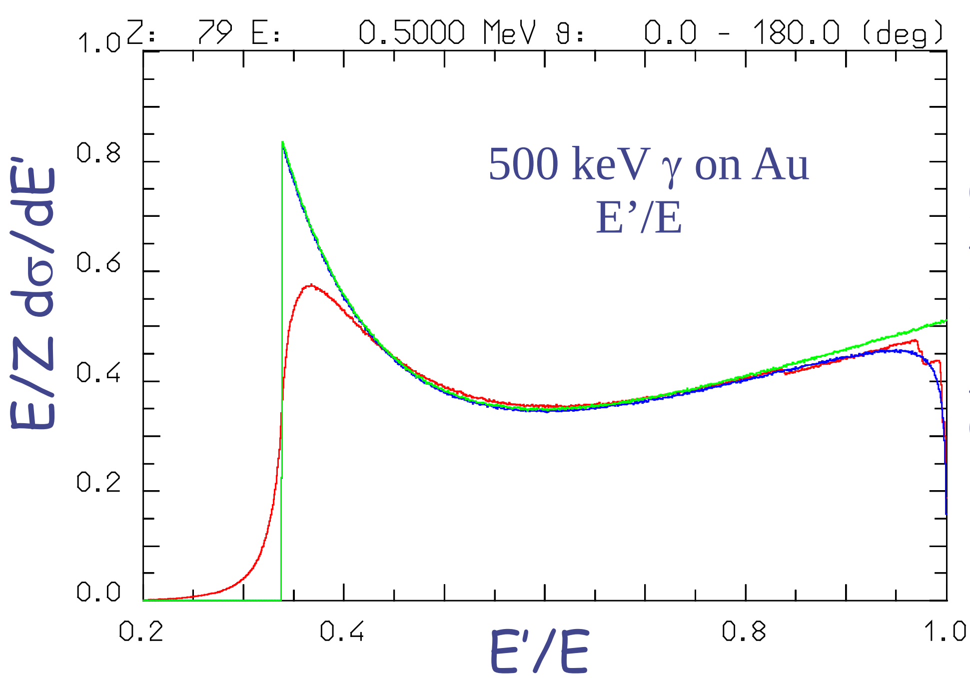
Inelastic Form Factors, Compton profile and Rayleigh scattering are activated only with a subset of DEFAULTS .
To activate/deactivate:

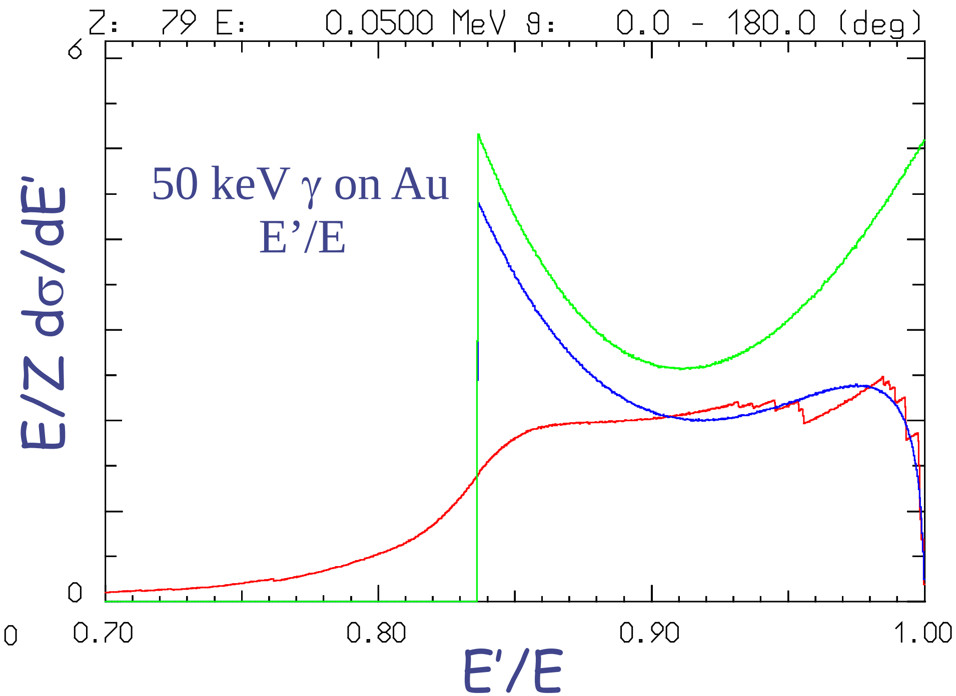
```
EMFRAY  Flag    Reg1    Reg2    Step
```



Look in the manual for further details

Compton profile examples





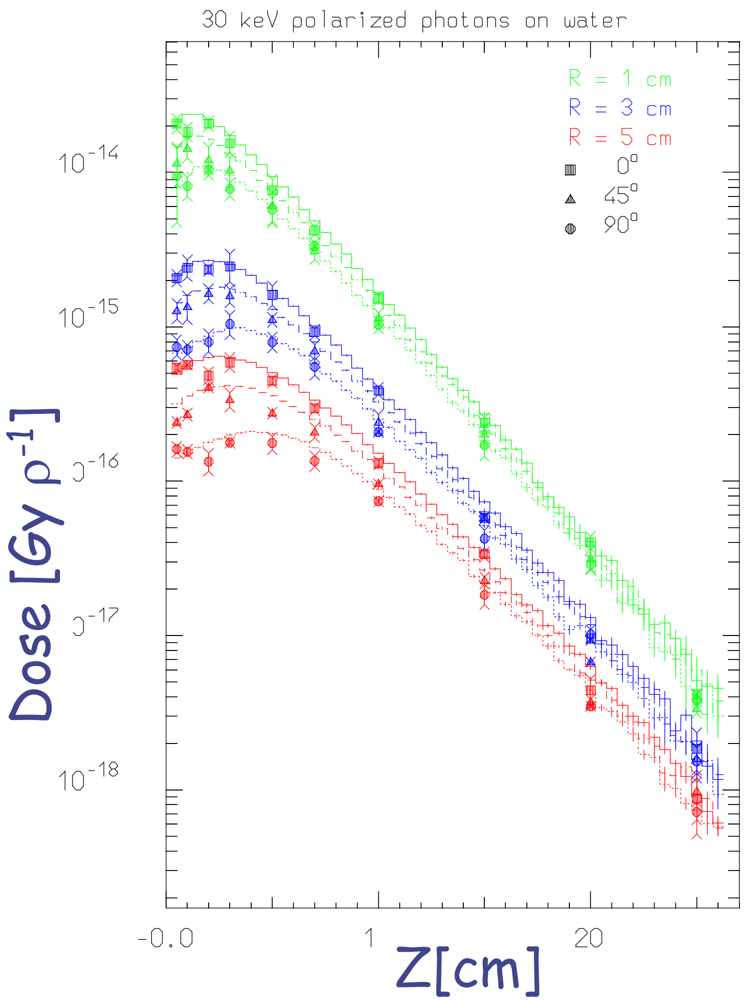
green = free electron
blue = binding with form factors
red = binding with shells and orbital motion

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'

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

Electron Positron Pair Production

- Angular and energy distribution of e^+,e^- described correctly (no "fixed angle" or similar approximation)
- No approximations near threshold
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect
- Differences between emitted e^+ and e^- at threshold accounted for

Photonuclear interactions

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

- Giant Resonance interaction
- Quasi-Deuteron effect
- Delta Resonance production
- 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

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

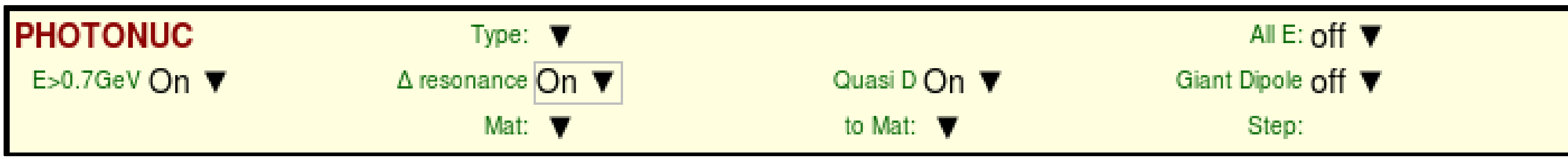
Photonuclear interactions: options

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)

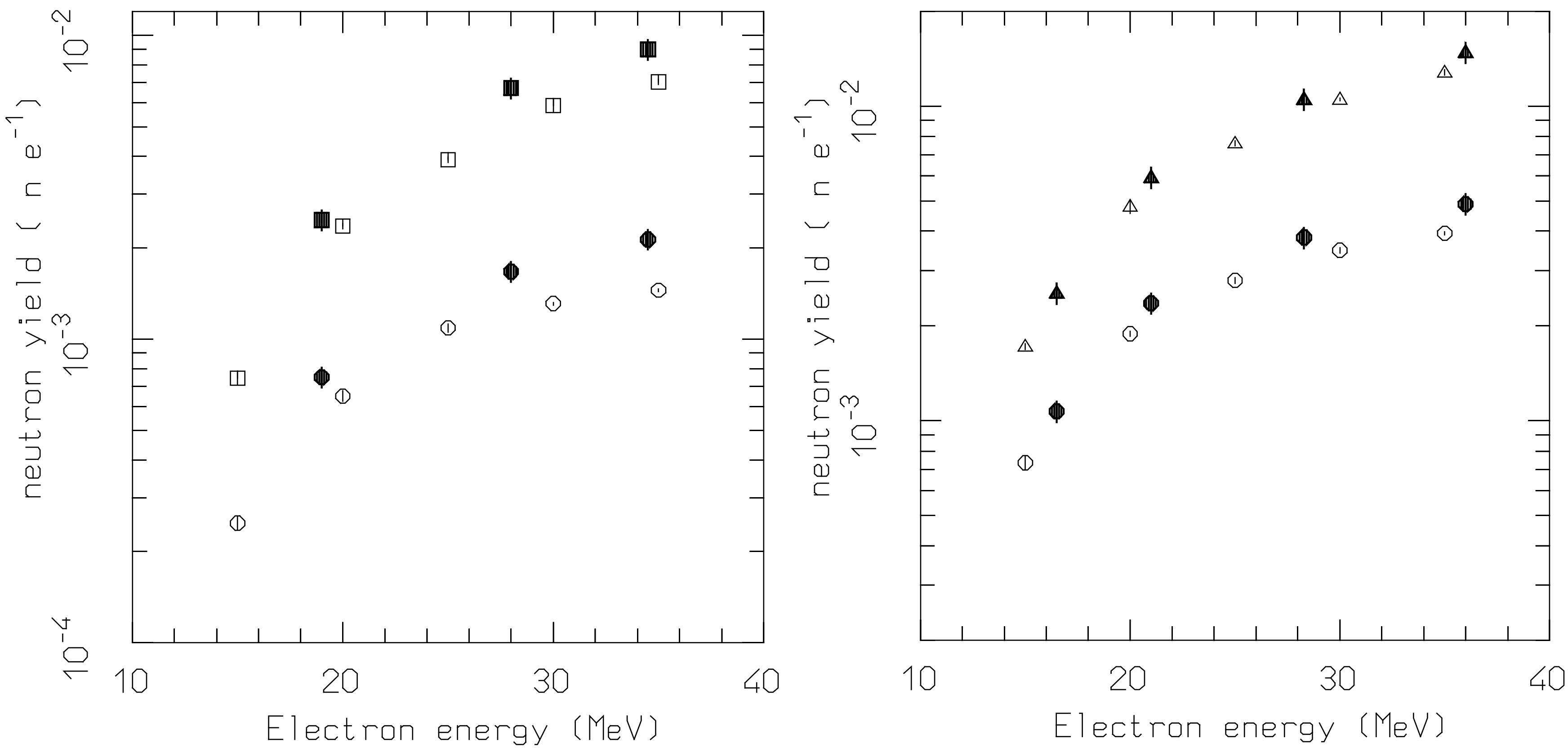
```
LAM-BIAS  0.0  Factor   Mat   PHOTON
```

Applications:

electron accelerator shielding and activation

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

Photonuclear 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

Photonuclear int.: example

Reaction:

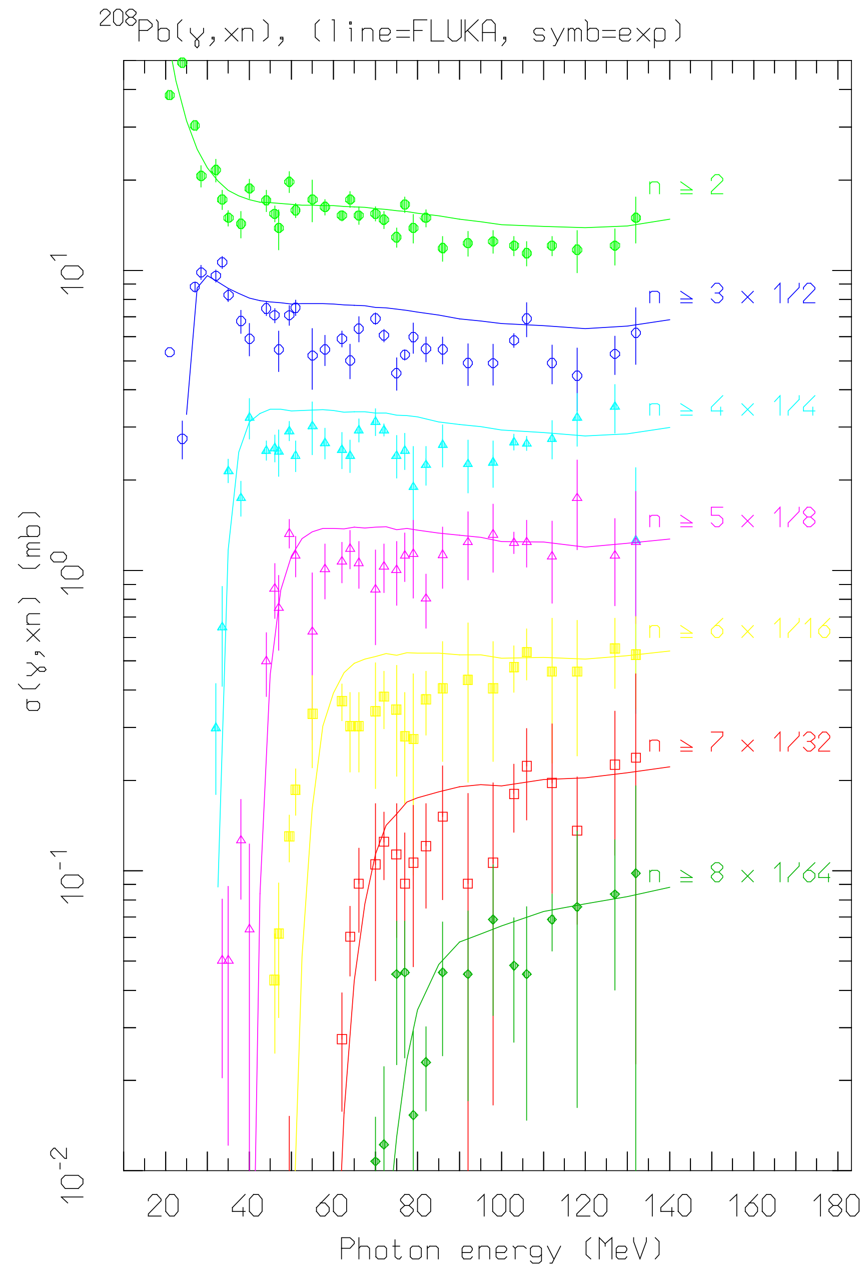
$^{208}Pb(\gamma,x\ n)$

$20 \leq E_\gamma \leq 140$ 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



Photomuon production

Muon pair production by photons is NOT activated with any default

To activate it:

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

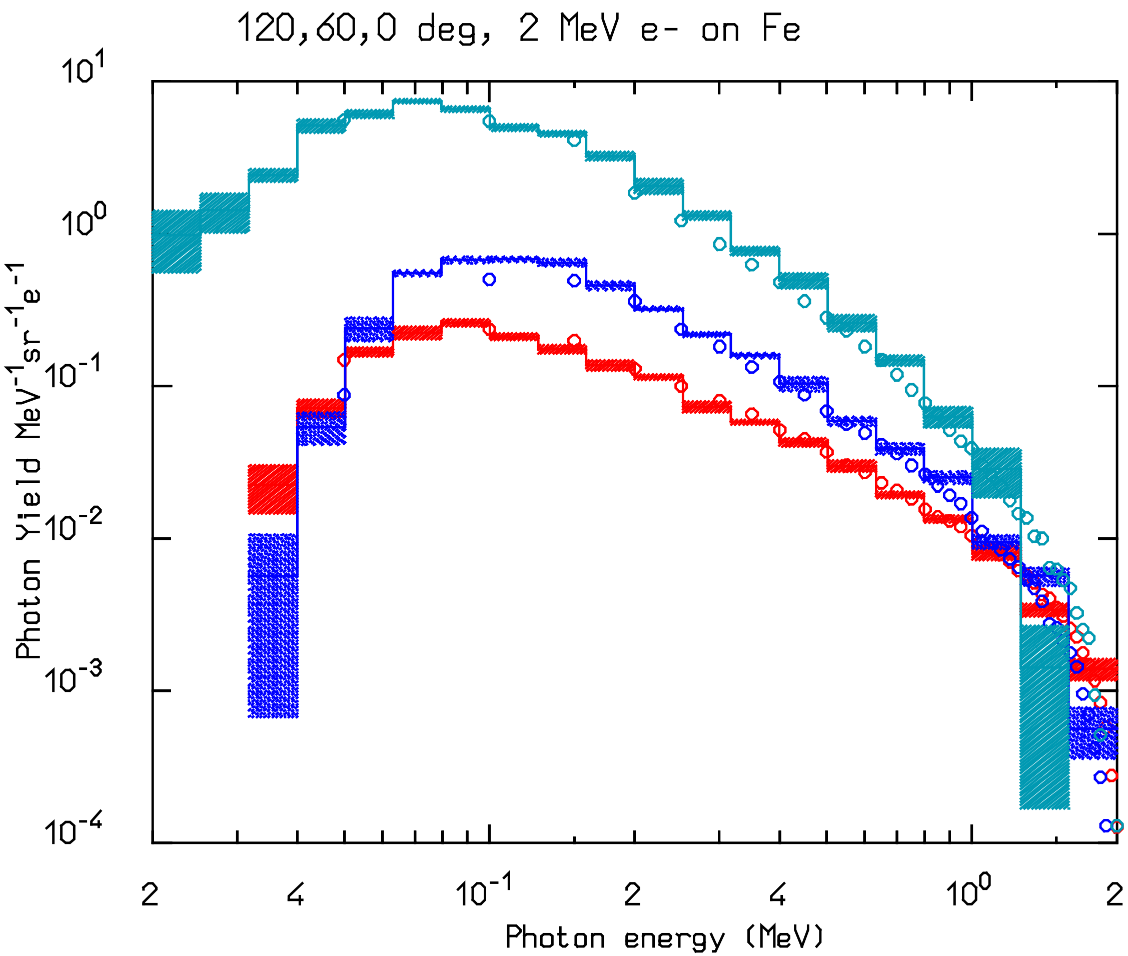
Flag controls activation of interactions, with the possibility to select a subset of the photomuon mechanisms (coherent, incoherent, inelastic...)
Biasing of photomuon production can be done directly with this card, setting WHAT(2)

Electron/Positron interactions

e+/e- interactions modelled in FLUKA

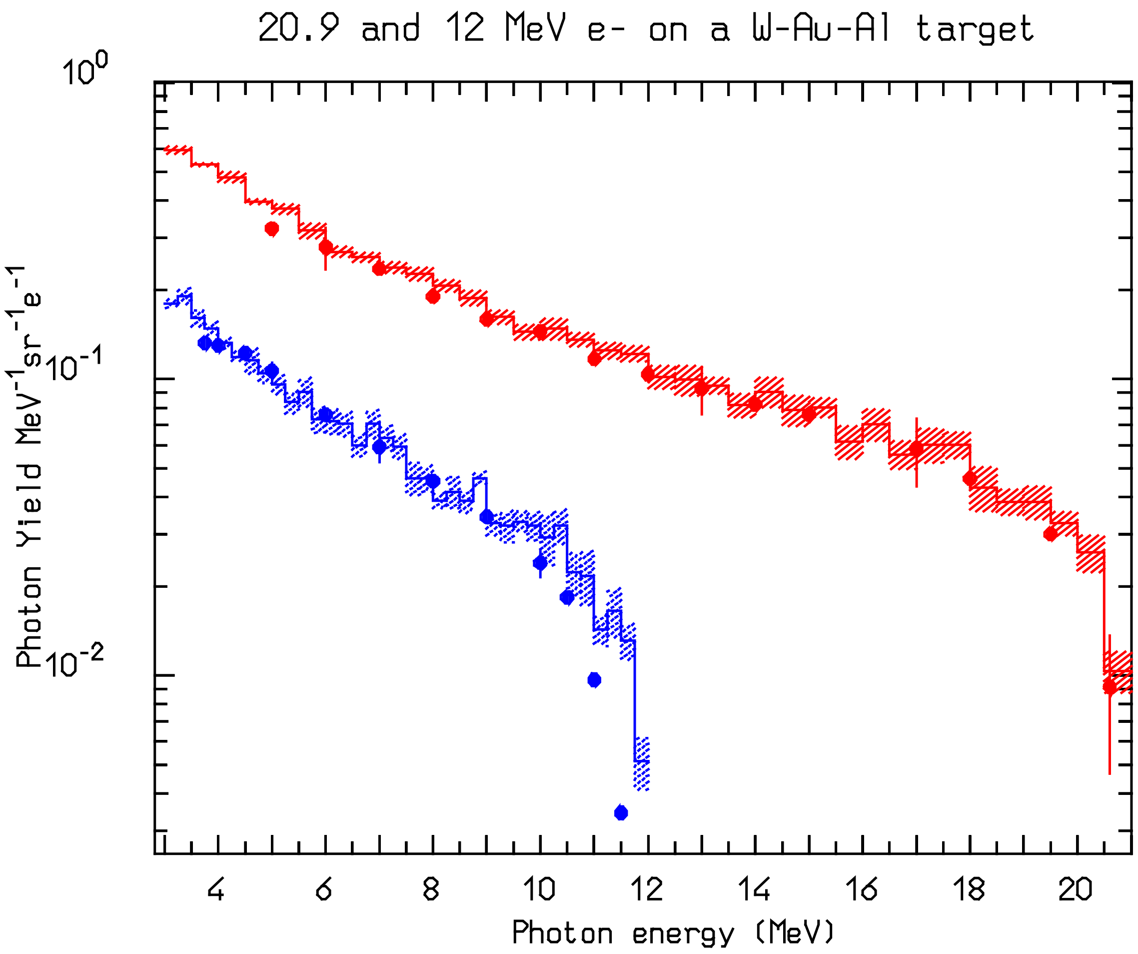
- Delta-ray production (-> EMFCUT)
  - Delta-ray production via Bhabha and Moeller scattering
- Bremsstrahlung production (-> EMFCUT)
  - Energy-differential cross sections based on the Seltzer and Berger database
  - Considers the LPM effect and the soft photon suppression (Ter-Mikaelyan) polarization 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: benchmark



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

Bremsstrahlung: benchmark II



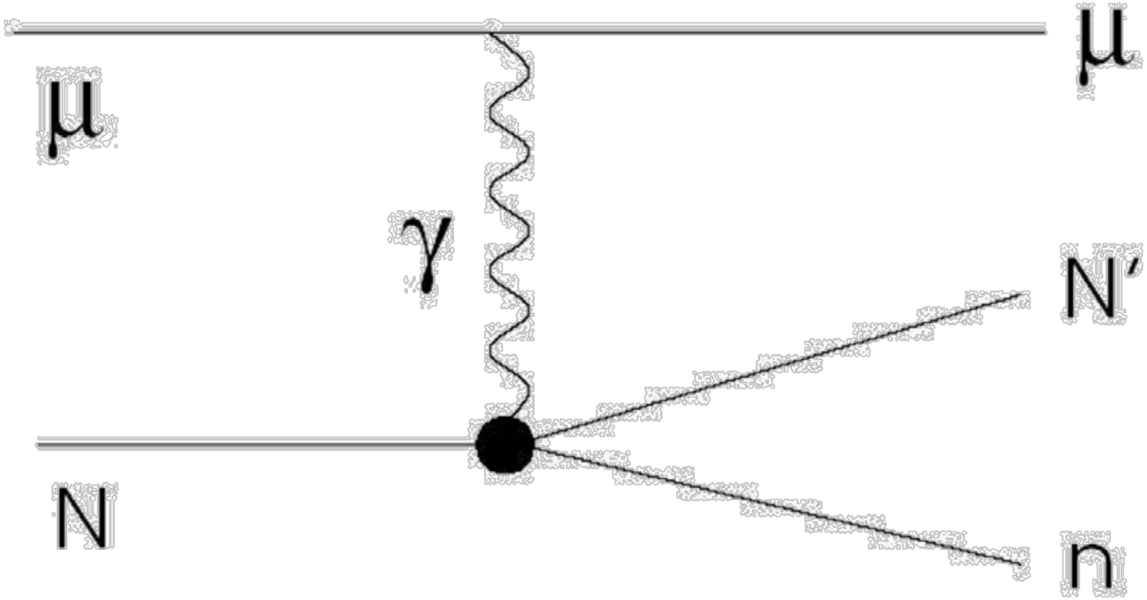
12 and 20.9 MeV electrons on a W-Au-Al target, bremsstrahlung photon spectra in the forward direction measured (dots) and simulated (histos)

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

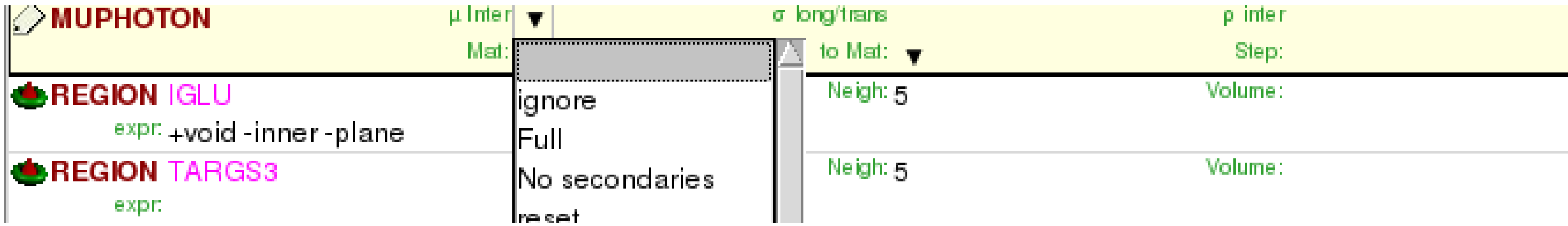
- The cross section can be factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction
- Nuclear screening is taken into account
- Only Virtual Meson Interactions are modeled, following the FLUKA meson-nucleon interaction models
- Nuclear effects are the same as for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

An exotic source of neutron background *(See background at nTOF)*

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

μ^- at rest + atom $\rightarrow$ excited muonic atom $\rightarrow$ x-rays+g.s muonic atom

Competition between μ decay and μ capture by the nucleus.

In FLUKA: Goulard-Primakoff formula

$\Lambda_c \propto Z^4_{eff}$, calculated Z_{eff}, Pauli blocking from fit to data.

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

Nuclear environment (Fermi motion, reinteractions, deexcitation..) from the FLUKA intermediate-energy module PEANUT

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

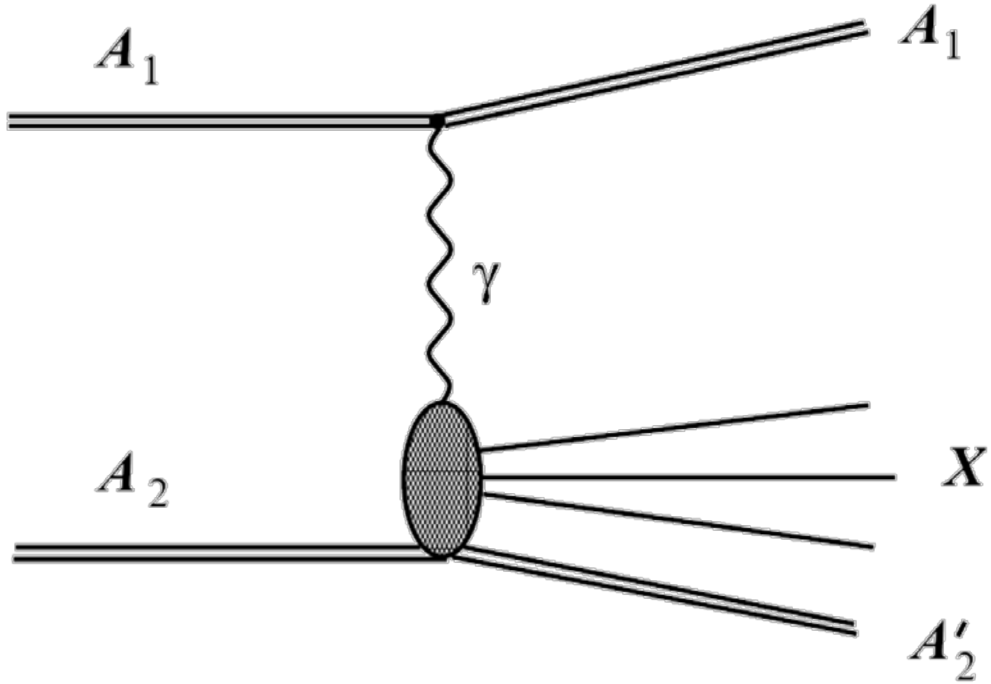
Experimentally: high energy tails in n-spectra

Beyond the simple one-body absorption

Good results from addition of two-nucleon absorption

EM Dissociation

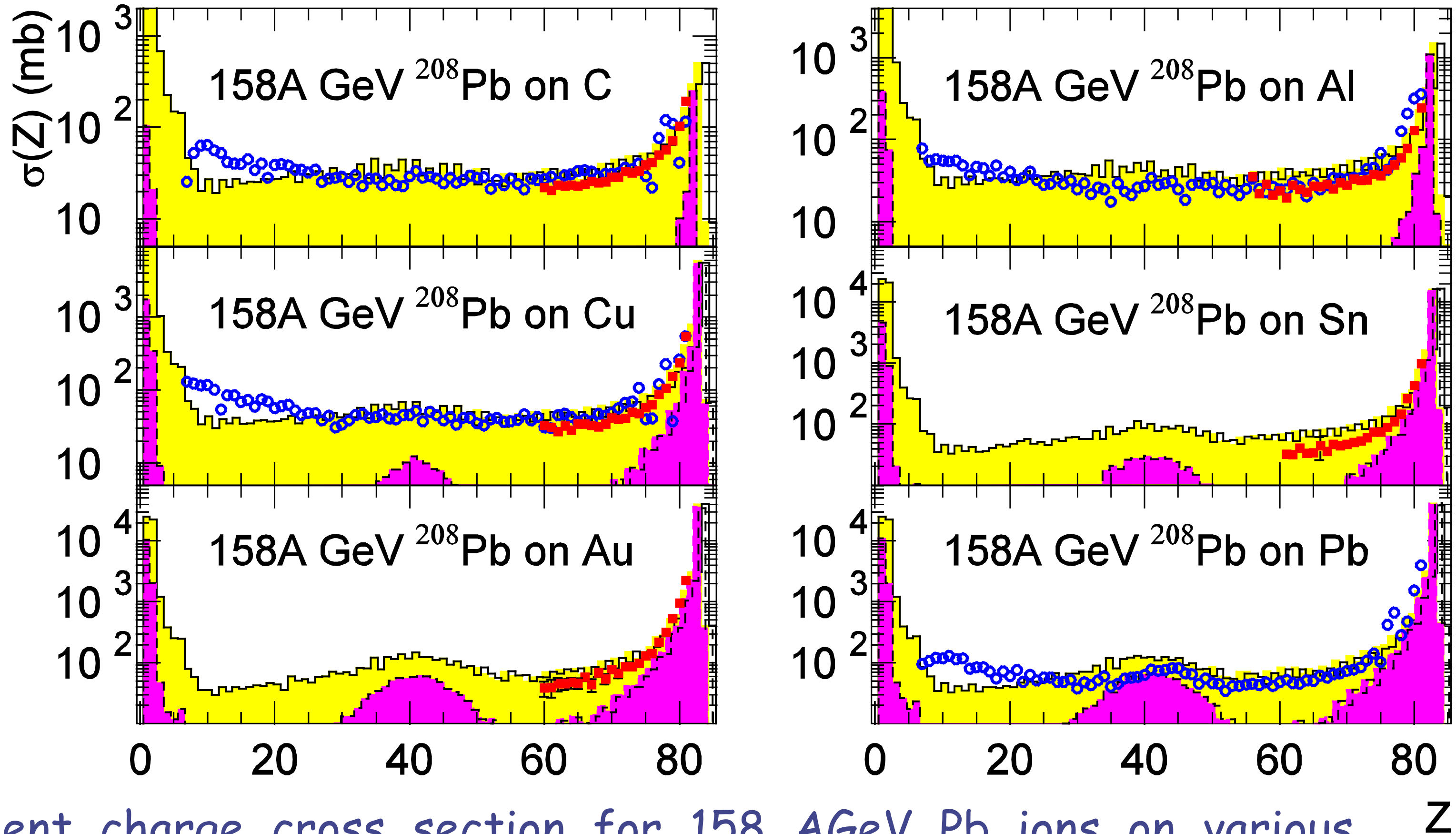
Electromagnetic dissociation



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

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

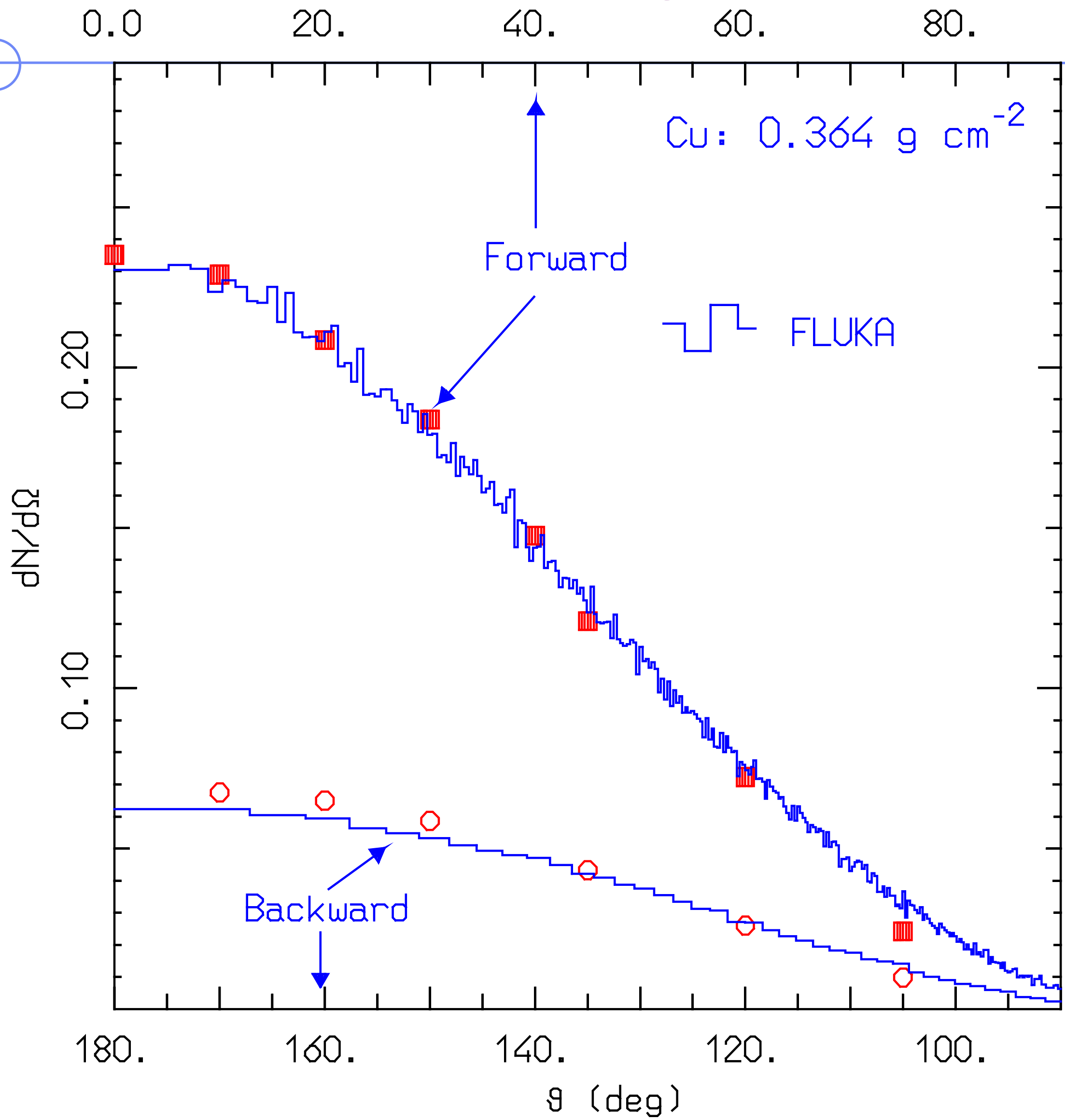
158 GeV/n Pb ion fragmentation



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

Spare slides

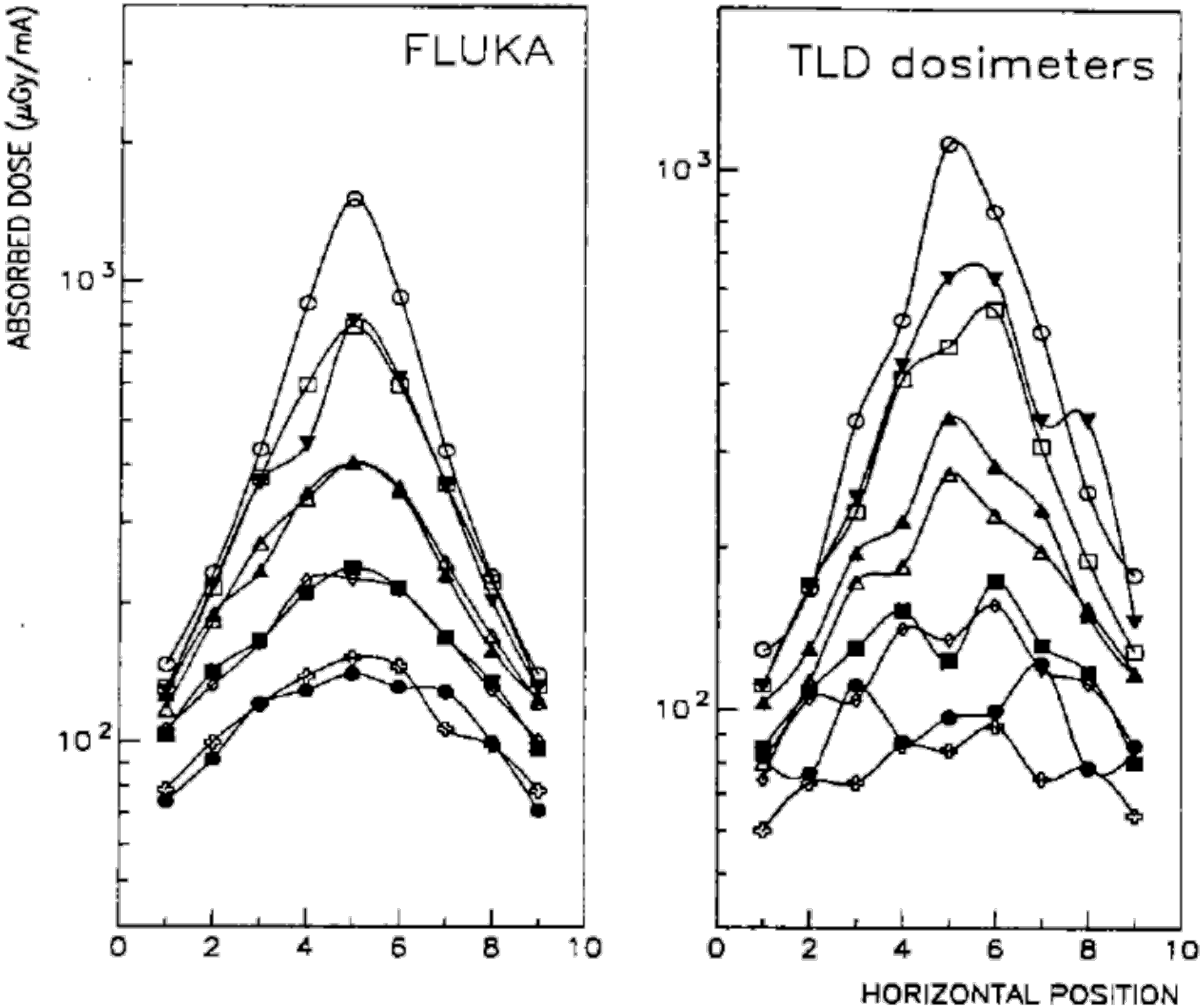
Electron scattering:



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

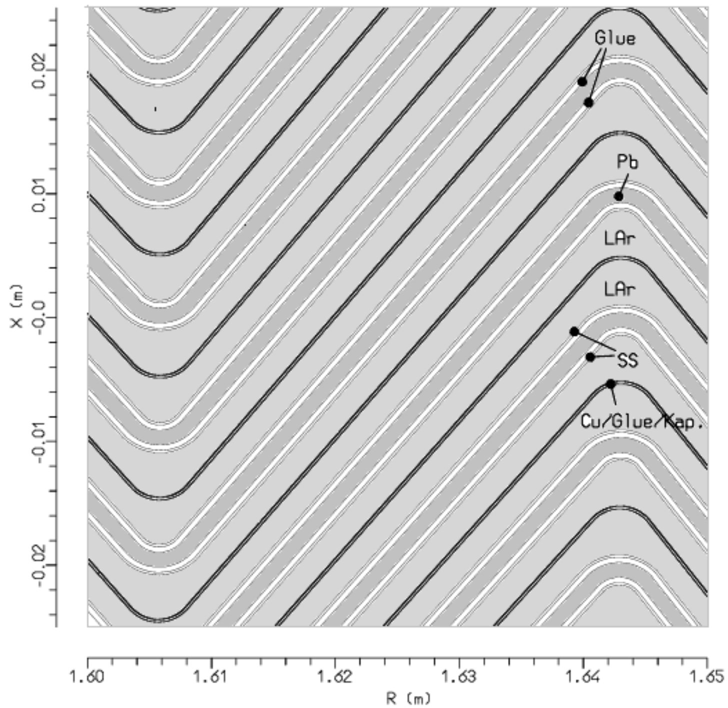
Measured with TLD's matrices at different distances from the straight Section

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

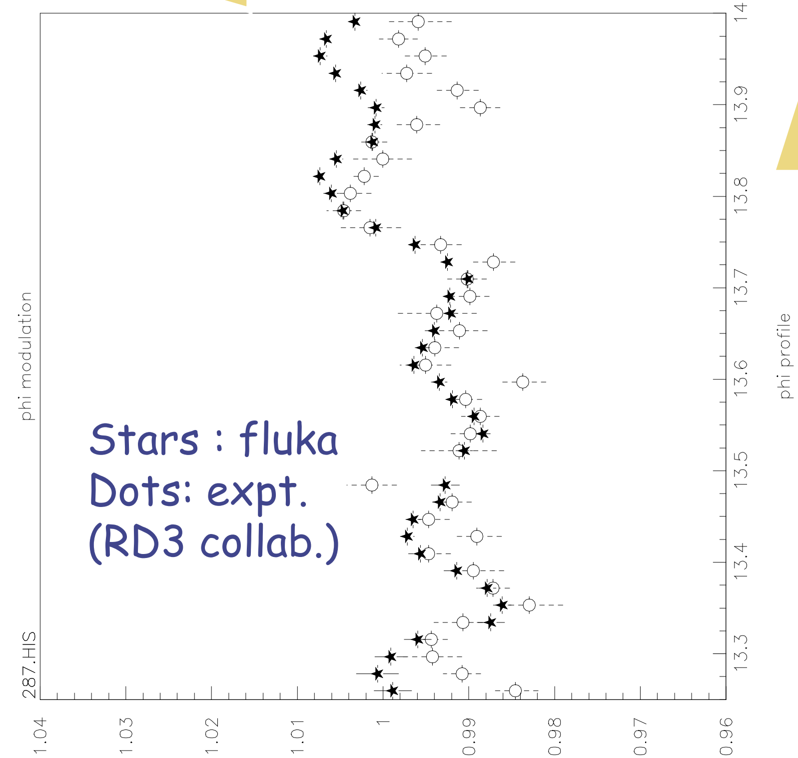
The ATLAS EM “accordion” calo (standalone test beams)

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

287 GeV electron beam



deposited energy



Stars : fluka
Dots: expt.
(RD3 collab.)

impact position

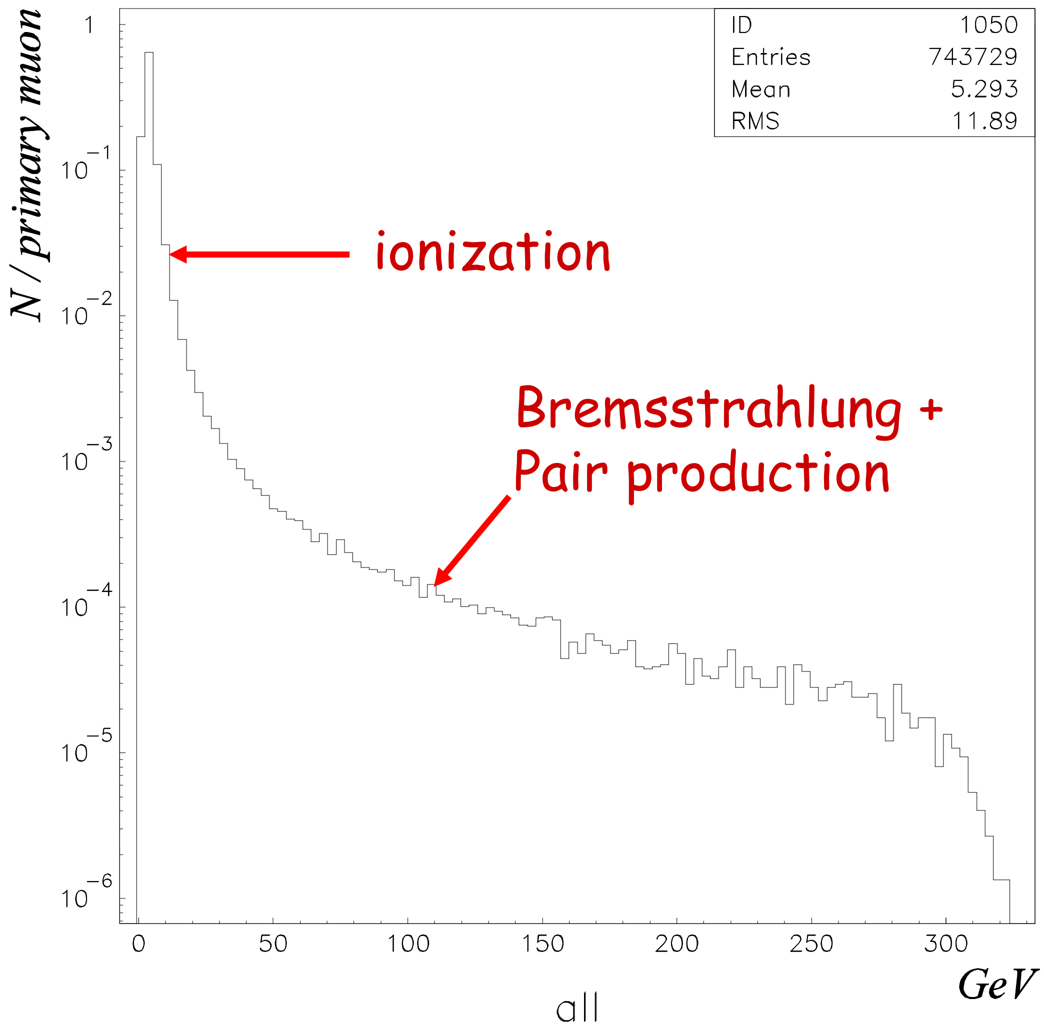
Energy resolution 10-100 GeV:

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

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

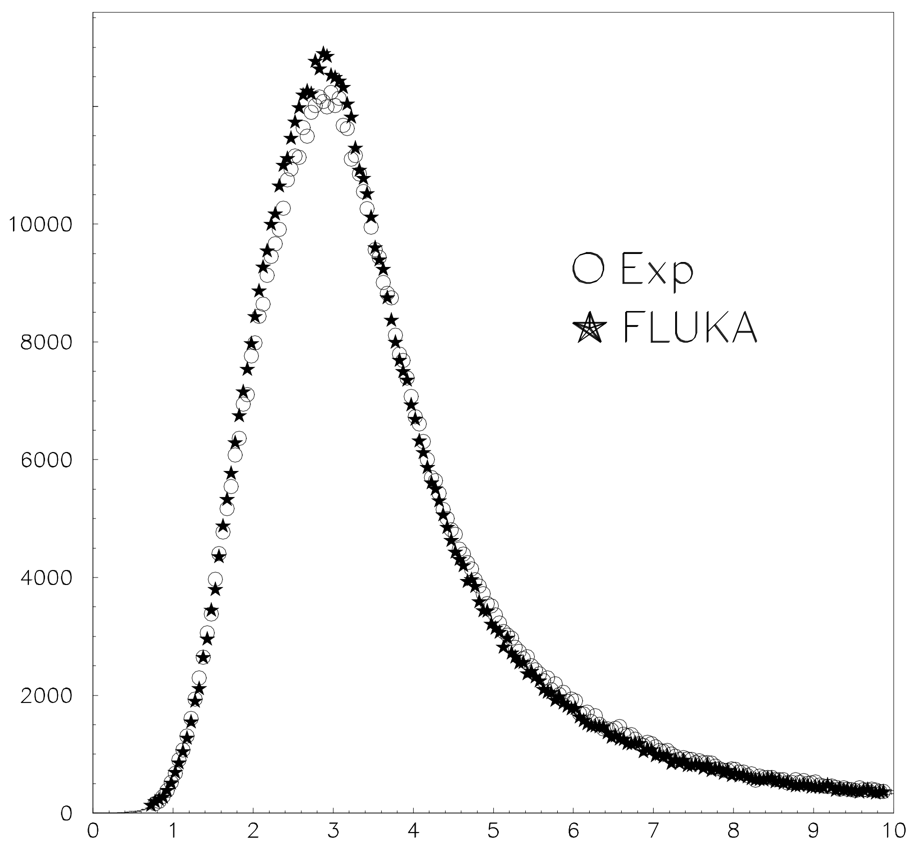
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

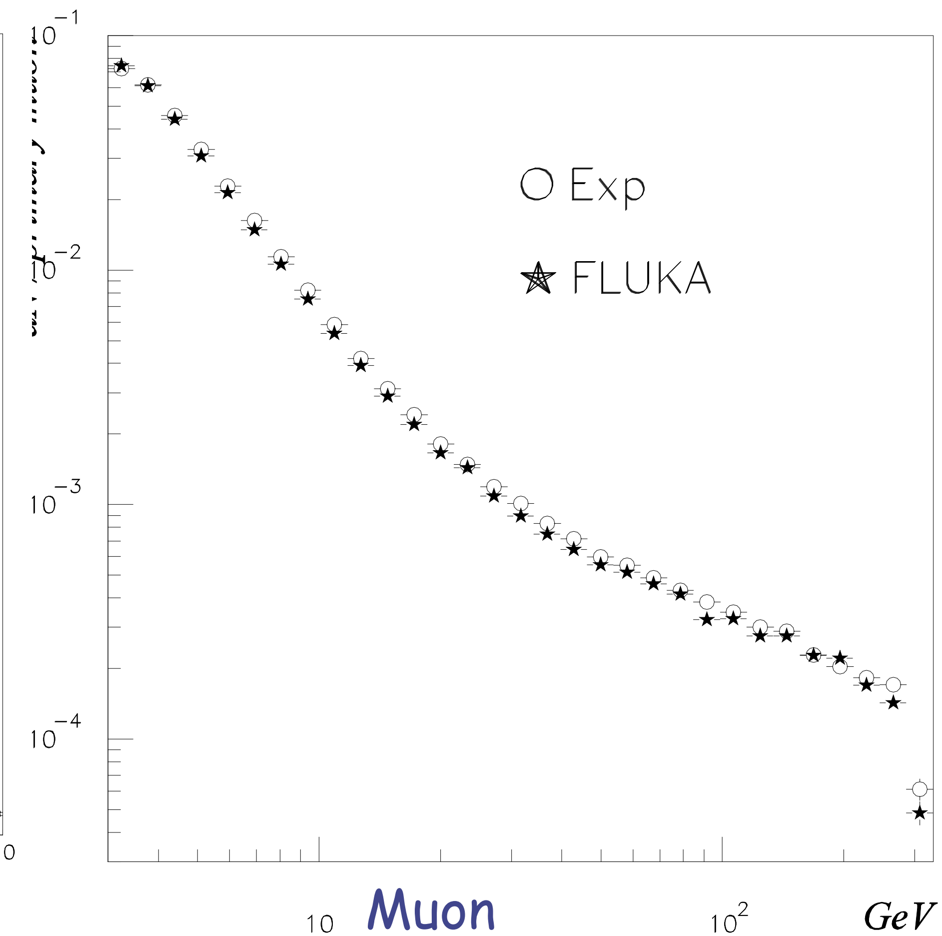


Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure



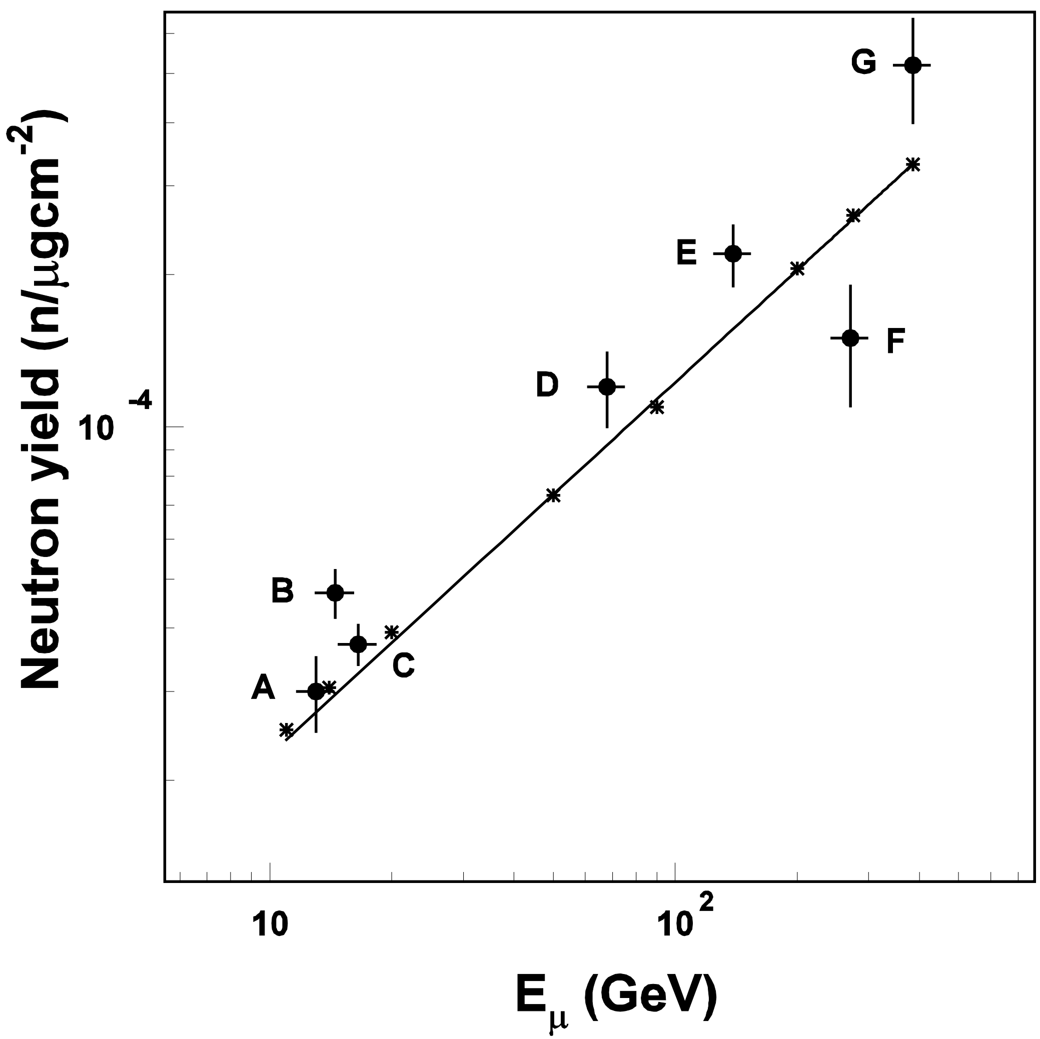
Muon energy [GeV]



Muon energy [GeV]

Muon-induced neutron background in underground labs

PRD64 (2001) 013012



Neutron production rate as a function of muon energy

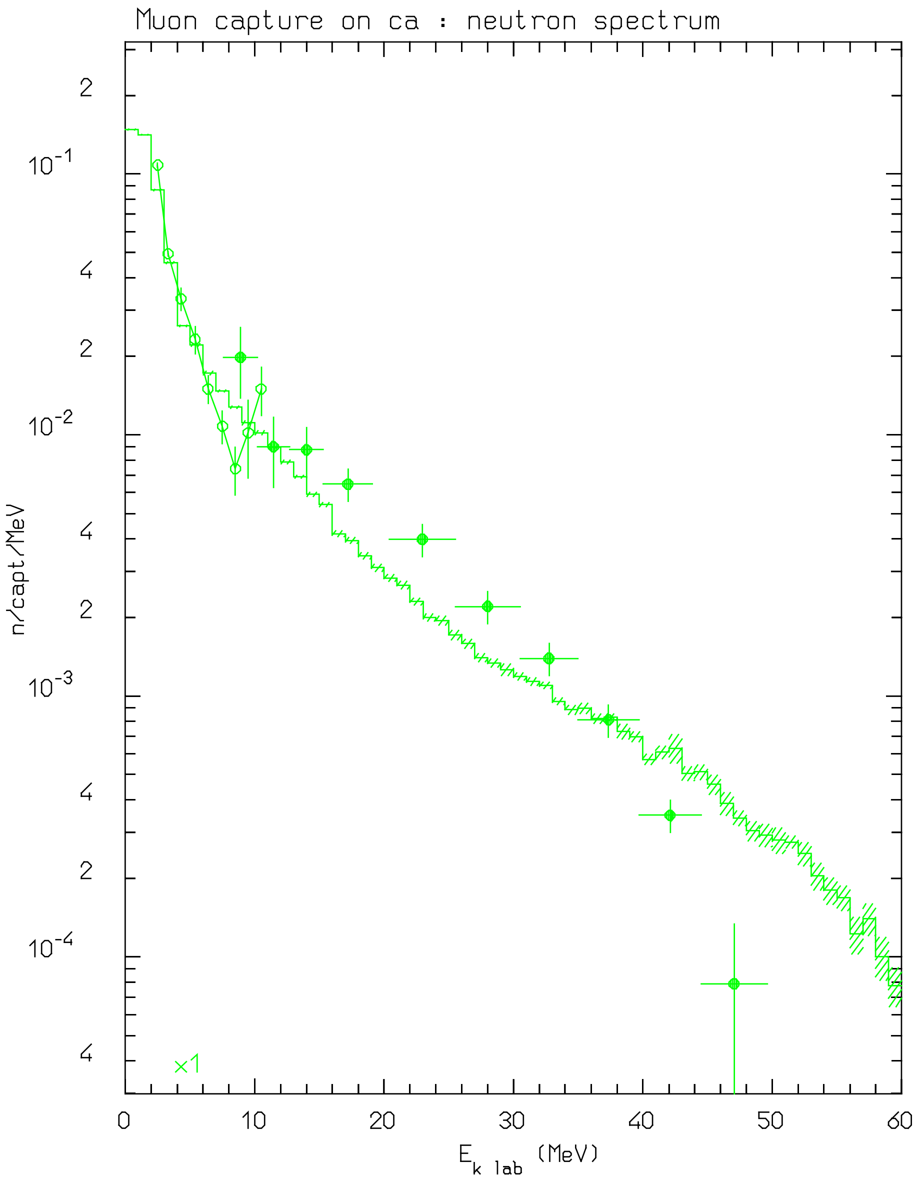
Stars+line : FLUKA simulation with a fit to a power law.

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))

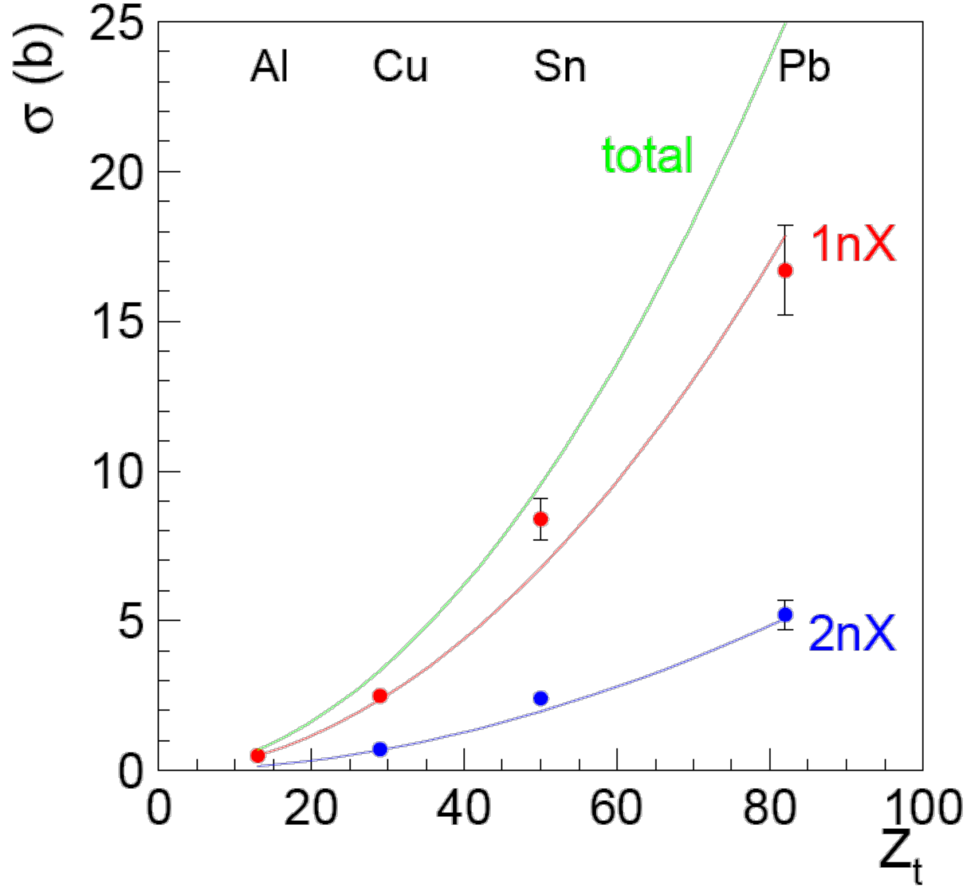
histograms: FLUKA calculations

Emitted:

0.62 neutrons/capture

0.27 protons/capture

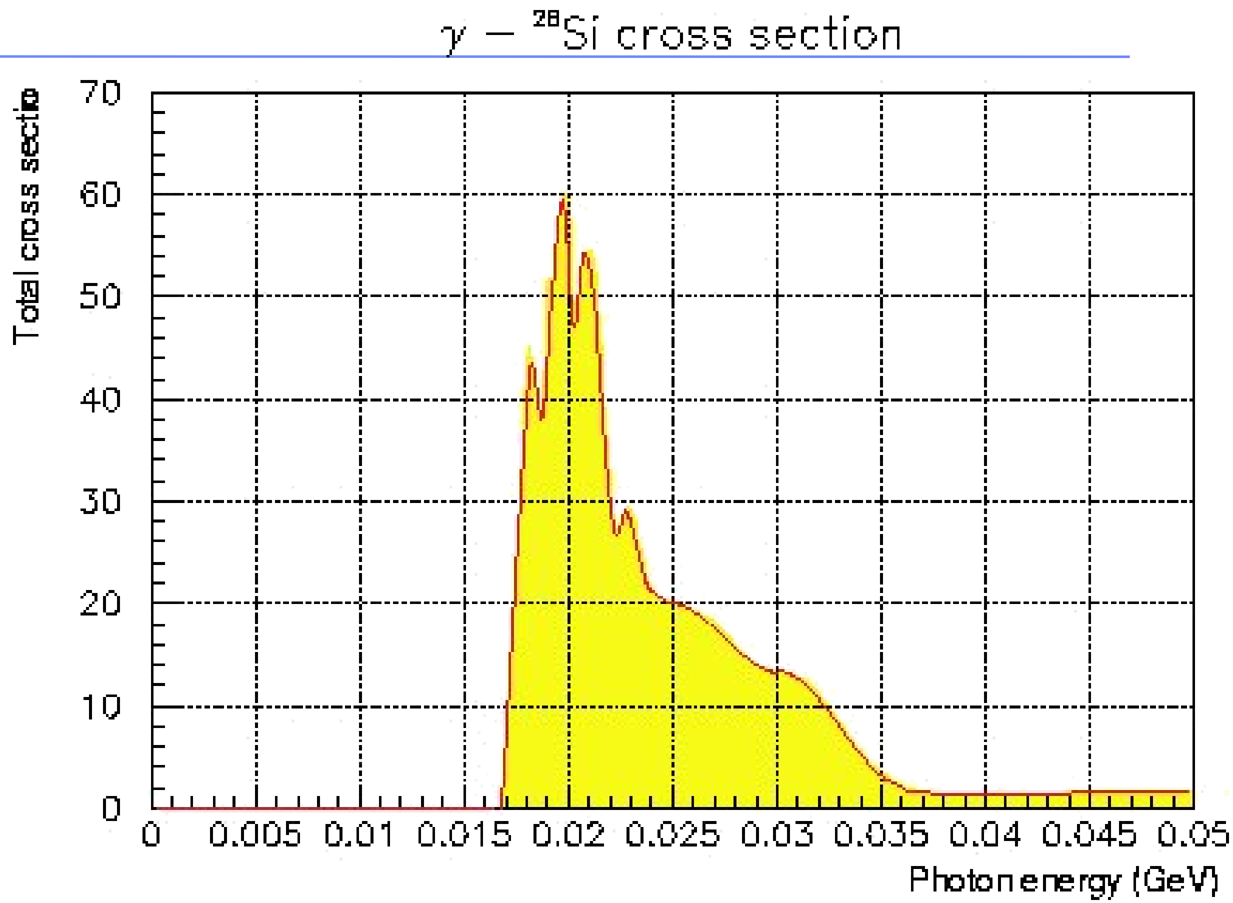
Electromagnetic dissociation - *Benchmarks*



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.