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- 1000 TeV
Full coupling in both directions with hadrons and low-energy neutrons
Energy conservation within computer precision
Up-to-date 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 (Cerenkov, scintillation) is implemented. Since it needs user coding, it is not treated in this beginners course

Transport thresholds

E.M particles are transported until their energy falls below a pre-set threshold. In FLUKA, this energy threshold can be set REGION BY REGION.

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

EMFCUT		Type: ▼		e-e+:		γ:	
Old bremss.:	off ▼	Bremsstrahlung:	off ▼	Pair Prod.:	off ▼	e+ ann @rest:	off ▼
Compton:	off ▼	Bhabha&Moller:	off ▼	Photo-electric:	off ▼	e+ ann @flight:	off ▼
		Reg:	▼	to Reg:	▼	Step:	

HOW to choose?

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 (they travel more)

Warning 3: ***low thresholds are CPU eaters***

- The EMFCUT card has more options: see later

Production Thresholds

Let's introduce a concept that is treated again in the discussion of ionization energy losses: the separation between CONTINUOUS and DISCRETE energy deposition:

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

Condition 1) is implemented by setting a threshold for the energy of the produced secondary particle

Production Thresholds -II

For electromagnetic interactions: ***BY MATERIAL !***

EMFCUT $e^{\pm}$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

Warning 1: production and transport thresholds are set by default, depending on the DEFAULTS card. ***DO NOT RELY*** on them, choose those best suited for your problem

Warning 2: 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

Photon interactions

Photoelectric effect

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

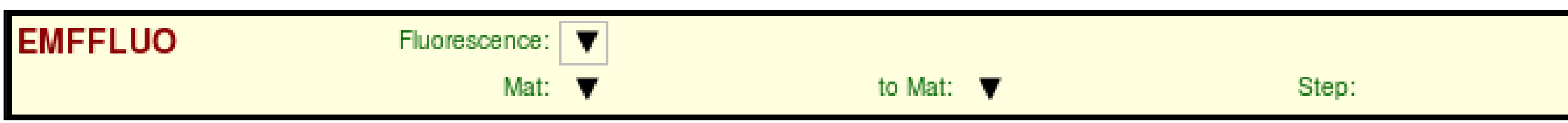
Fluorescence after photoelectric is activated only with a subset of DEFAULTS

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

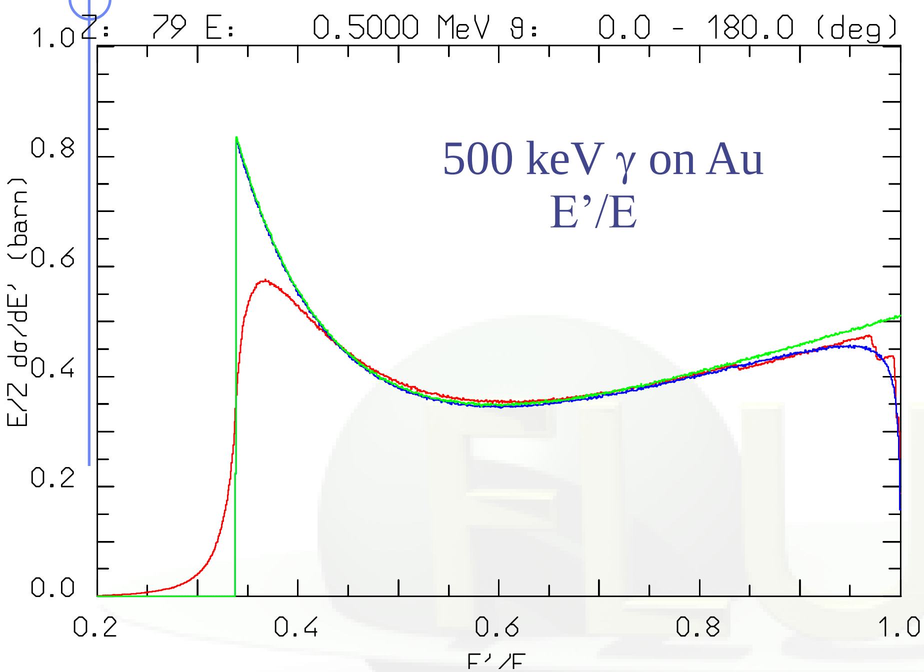
- Account for atomic bonds using inelastic Hartree-Fock form factors (very important at low E in high Z materials)
- NEW : Compton with atomic bonds and orbital motion (as better alternative to form factors)
  - Atomic shells from databases
  - Orbital motion from database + fit
  - Followed by fluorescence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

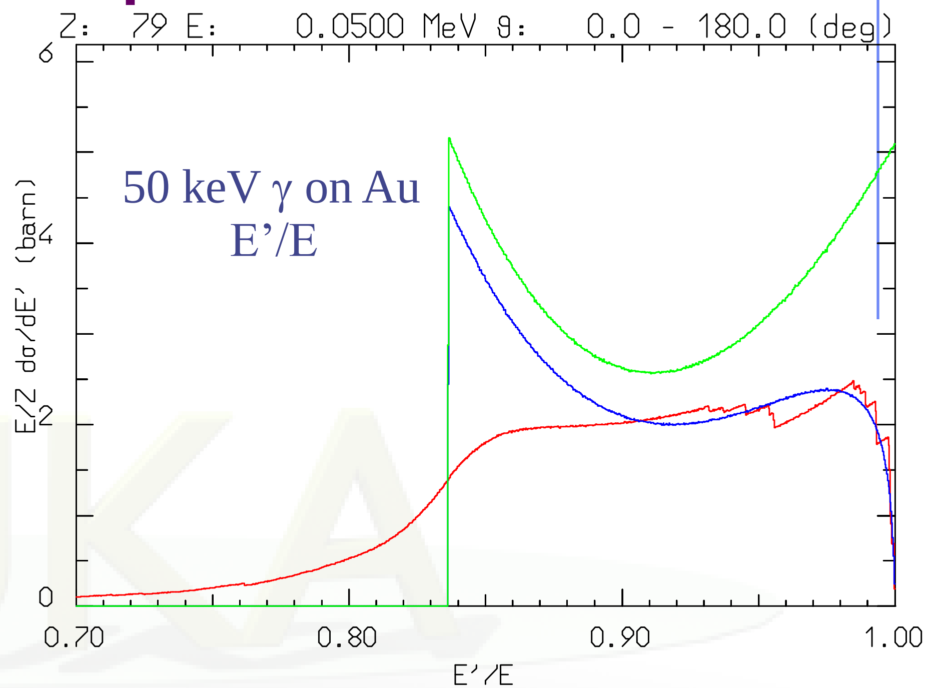
Inelastic Form Factors, Compton profile and Rayleigh scattering are activated only with a subset of DEFAULTS .
To activate/deactivate:

```
EMFRAY  Flag    Reg1    Reg2    Step
```

Look in the manual for further details

Compton profile examples

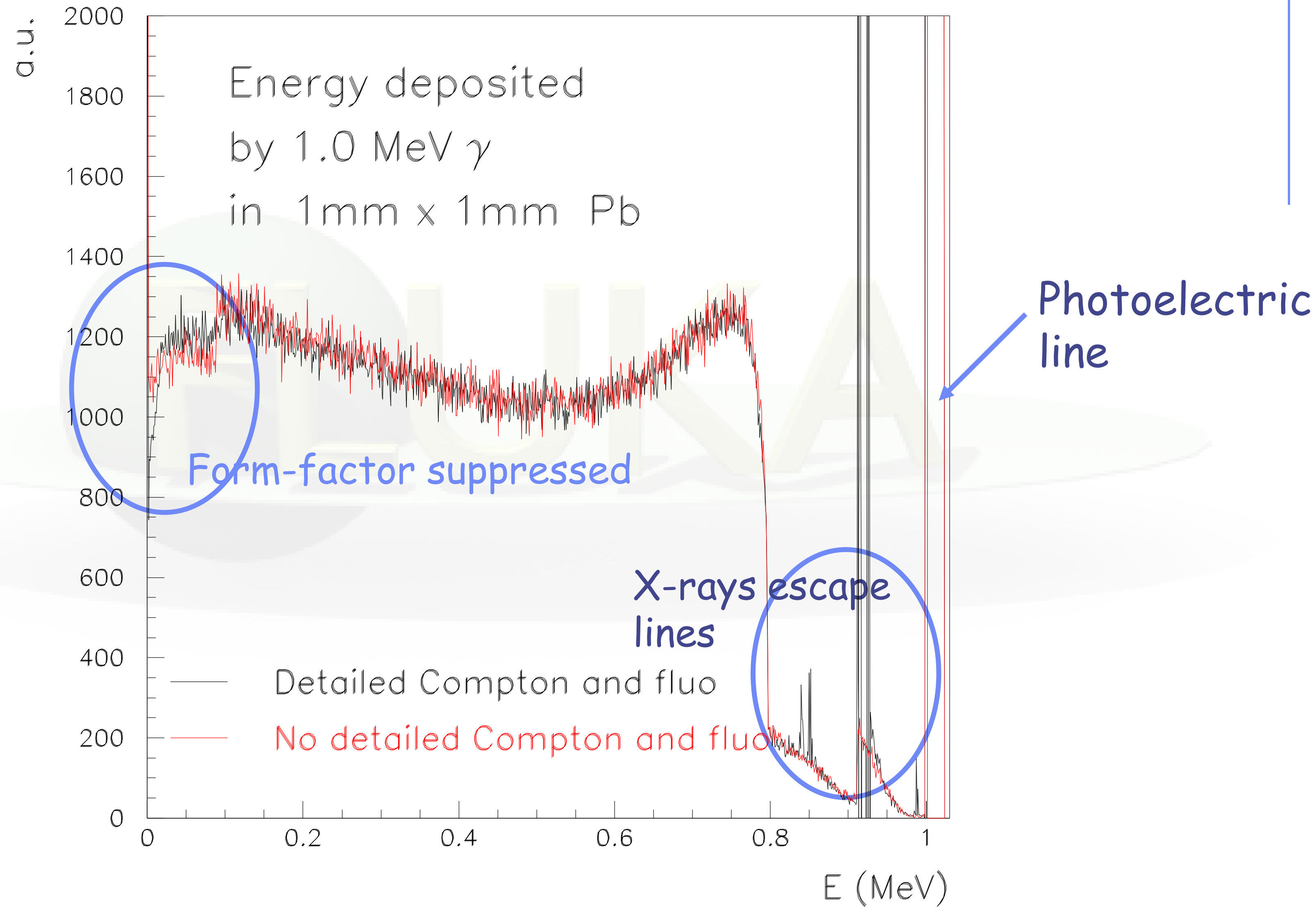




green = free electron
blue = binding with form factors
red =binding with shells and orbital motion

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'

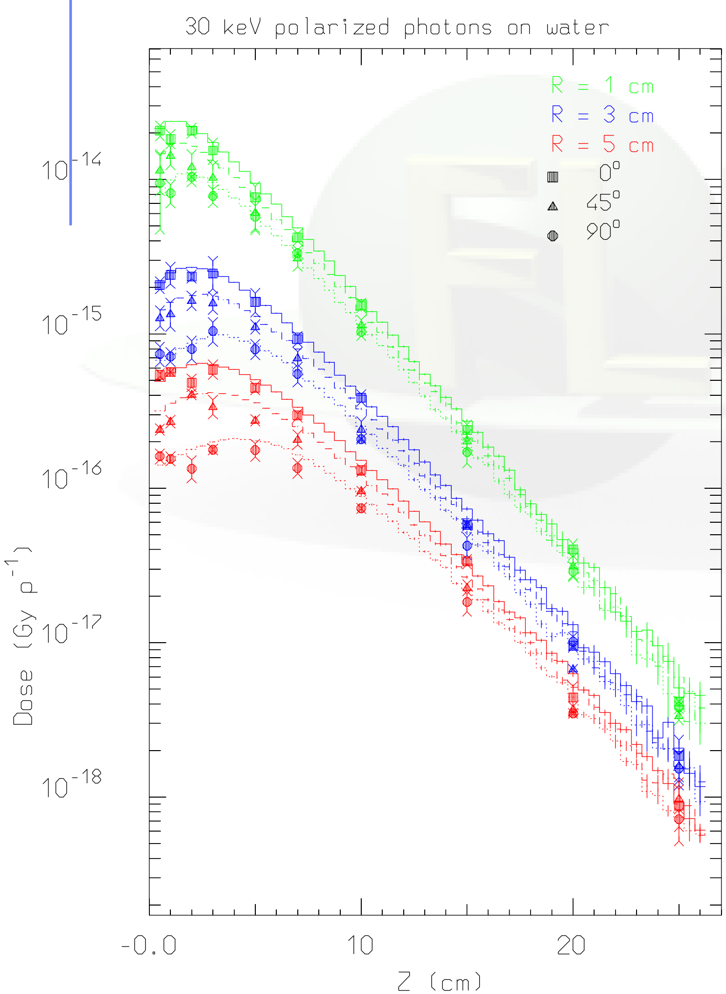
Effect of EMFFLUO and EMFRAY



Polarization

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

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



Flag1 ➔ Pol. direction wrt 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 on Water
at 3 distances from beam axis
as a function of penetration depth for 3 orientations wrt the polarization direction

Pair Production

- Angular and energy distribution of e^+,e^- described correctly (no “fixed angle” or similar approximation)
- No approximations near threshold
- 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 ($\gamma \equiv \rho, \Phi$ 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

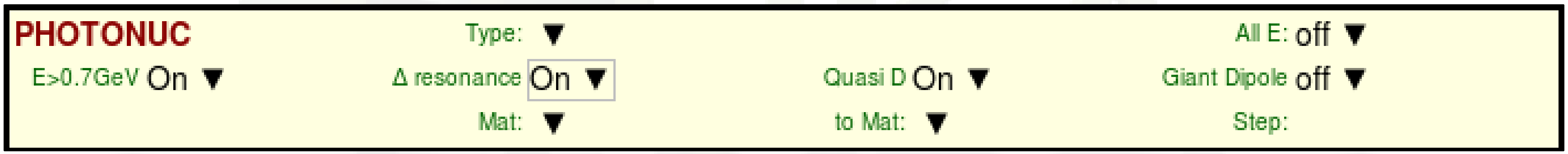
Photonuclear interactions: options

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



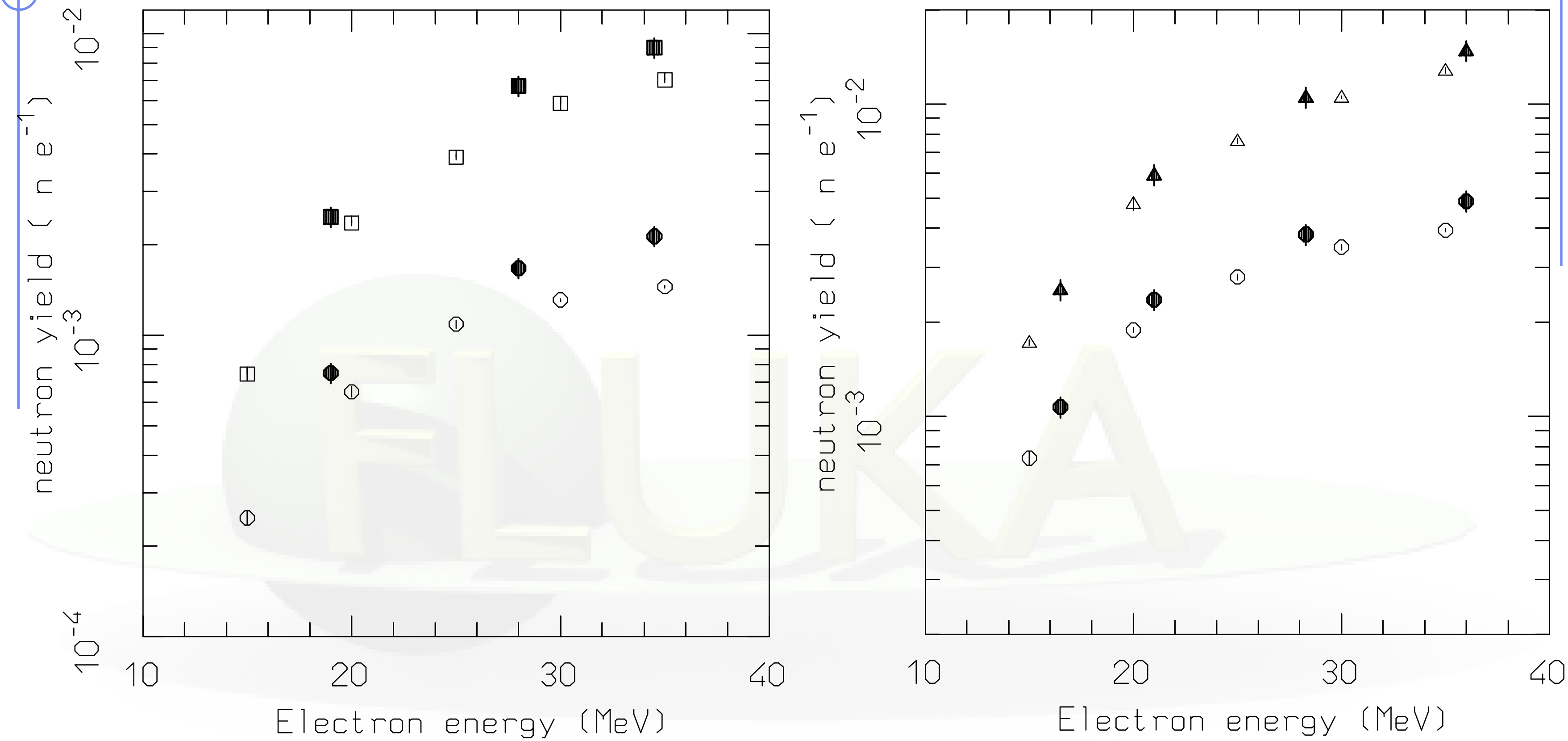
Since the photonuclear cross section is very small, PHOTONUC should be always accompanied by LAM-BIAS (see lecture on biasing)

```
LAM-BIAS       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:

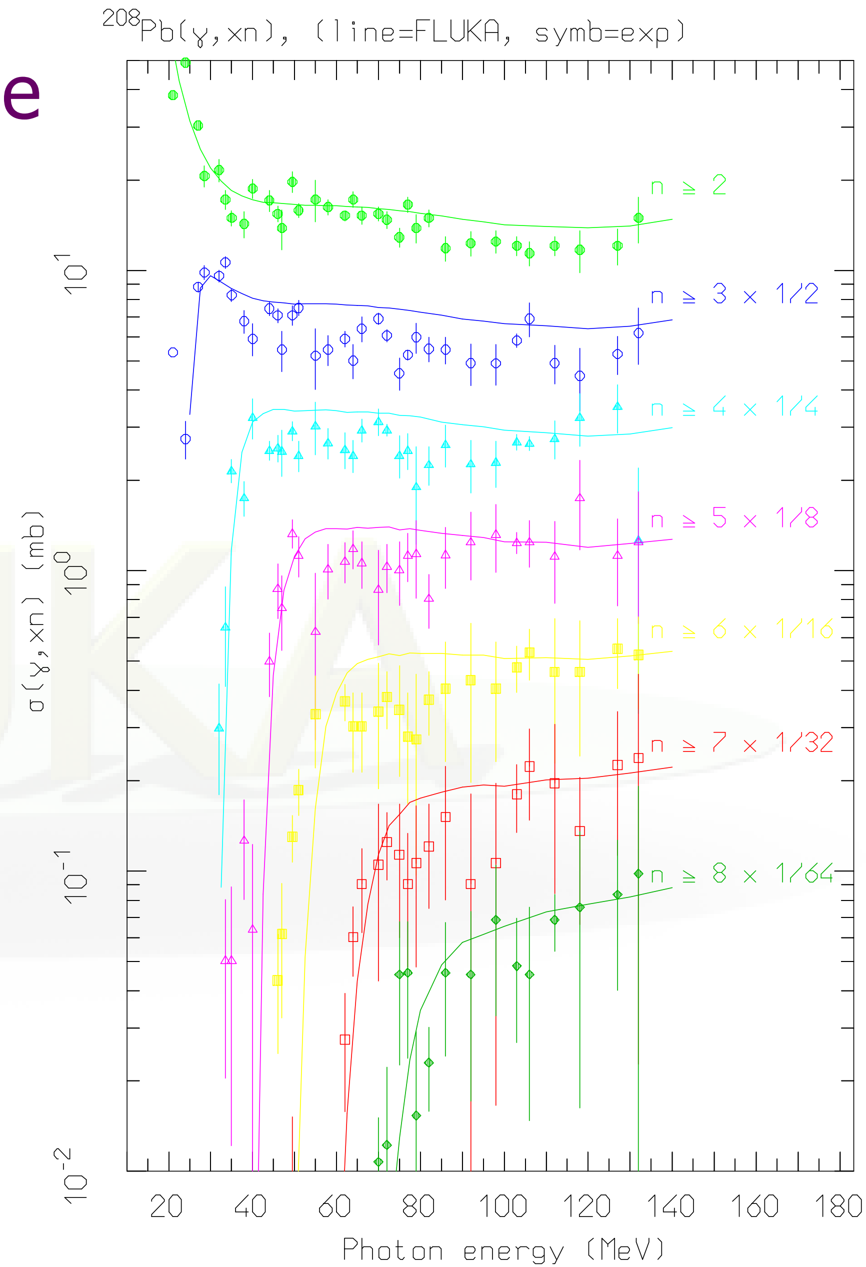
$^{208}Pb(\gamma,x\,n)$

$20 \leq E\gamma \leq 140$ 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        Mat1     Mat2     Step     MUMUPAIR
```

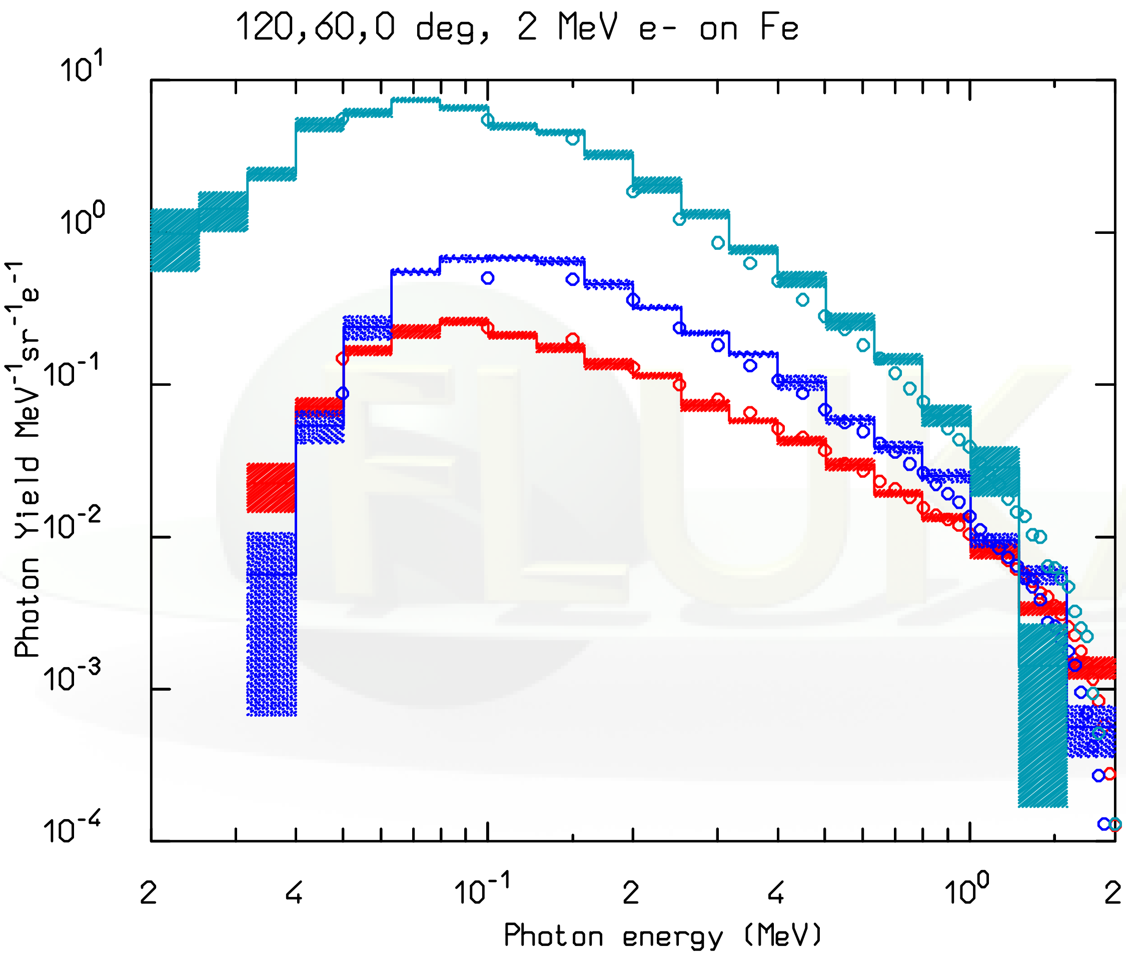
Flag controls activation of interactions, with the possibility to select a subset of the photonuclear mechanisms
Biasing of photomuon production can be done directly with this card, setting what(2)

Electron/Positron interactions

Bremsstrahlung

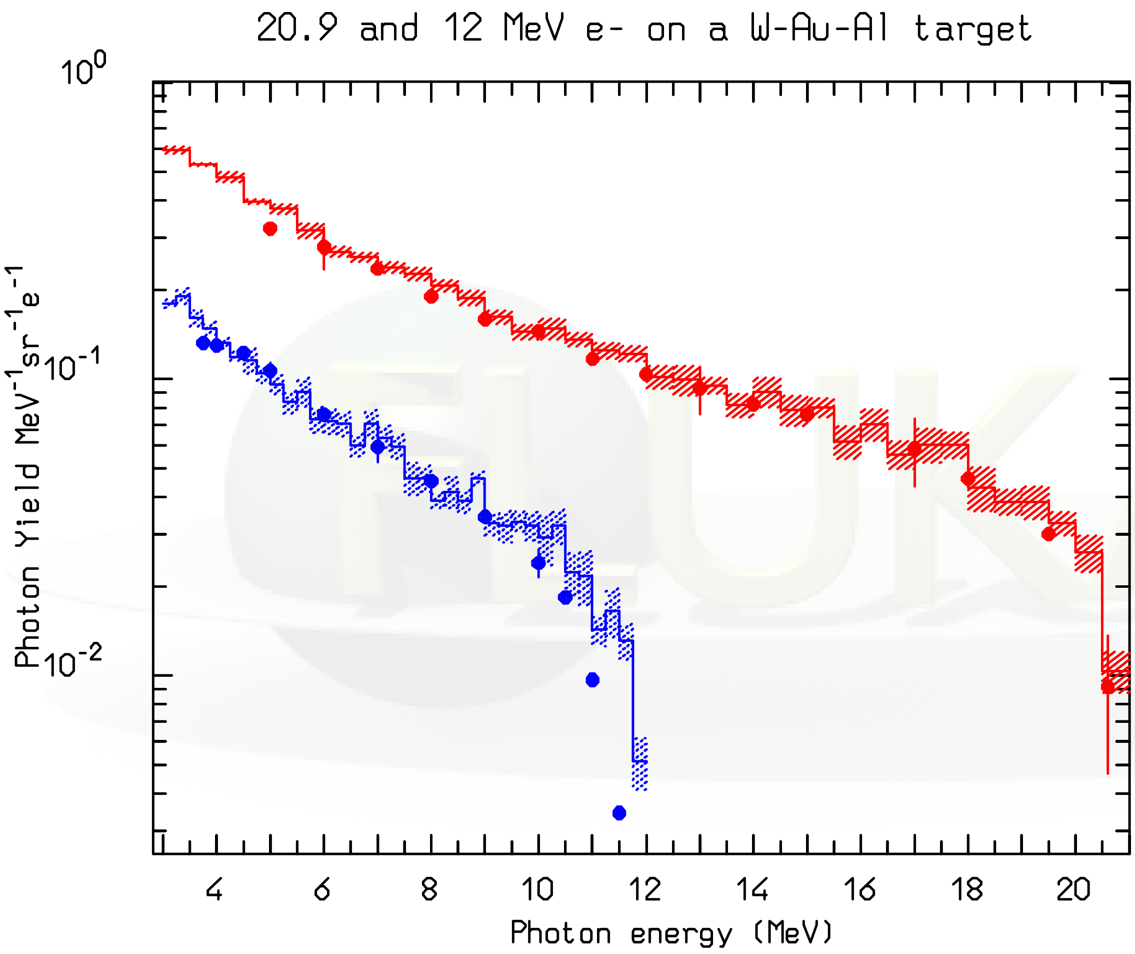
- Energy-differential cross sections based on the Seltzer and Berger database, interpolated and extended to a finer energy mesh, tip, and larger energies
- Finite value at tip energy
- Extended to 1000 TeV taking into account the LPM (Landau-Pomeranchuk-Migdal) effect
- Soft photon suppression (Ter-Mikaelyan) polarization effect
- Special treatment of positron bremsstrahlung with ad hoc spectra at low energies
- Detailed photon angular distribution fully correlated to energy

Bremsstrahlung: benchmark



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

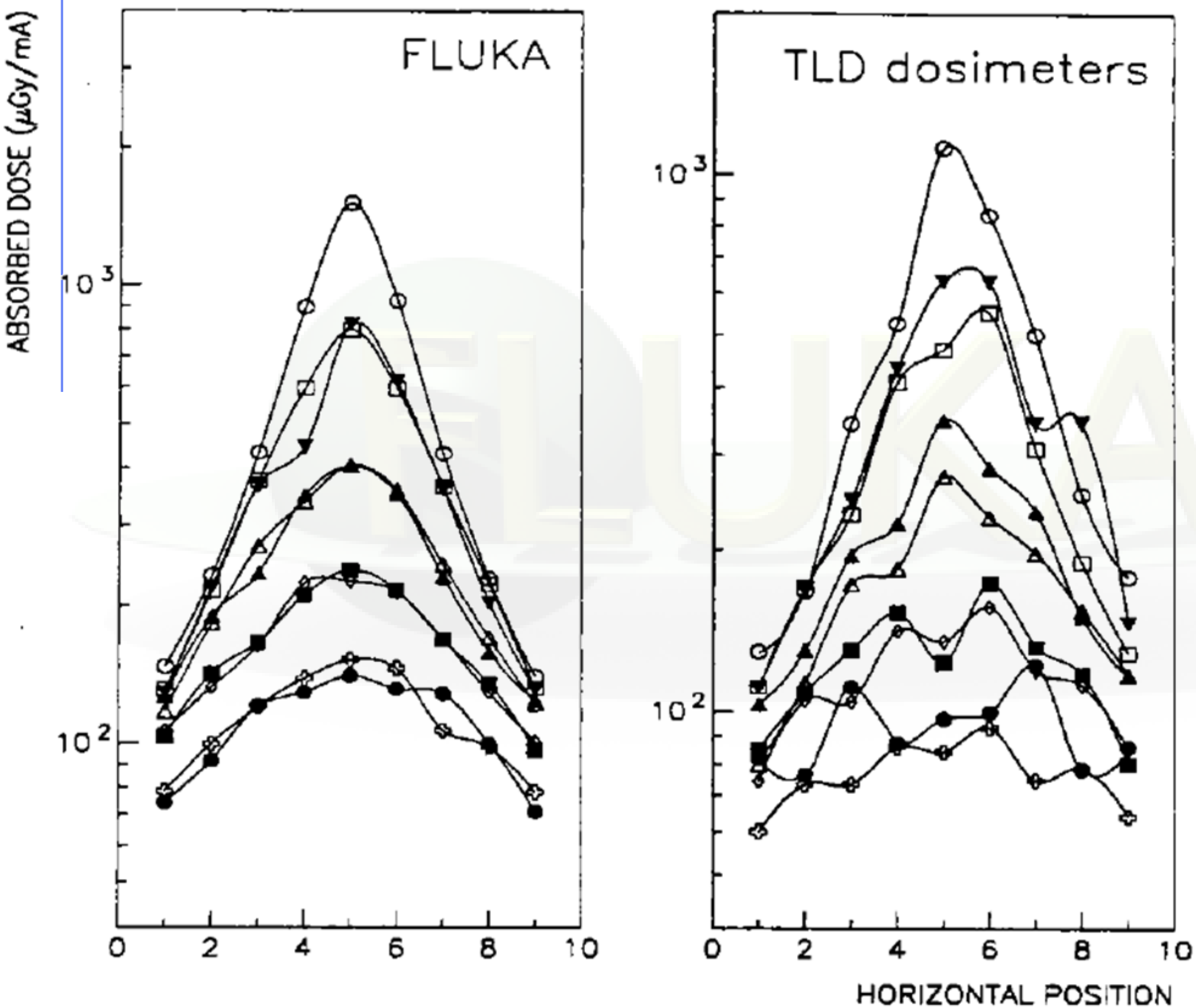
Bremsstrahlung: benchmark II



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

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

Other $e^{\pm}$ interactions

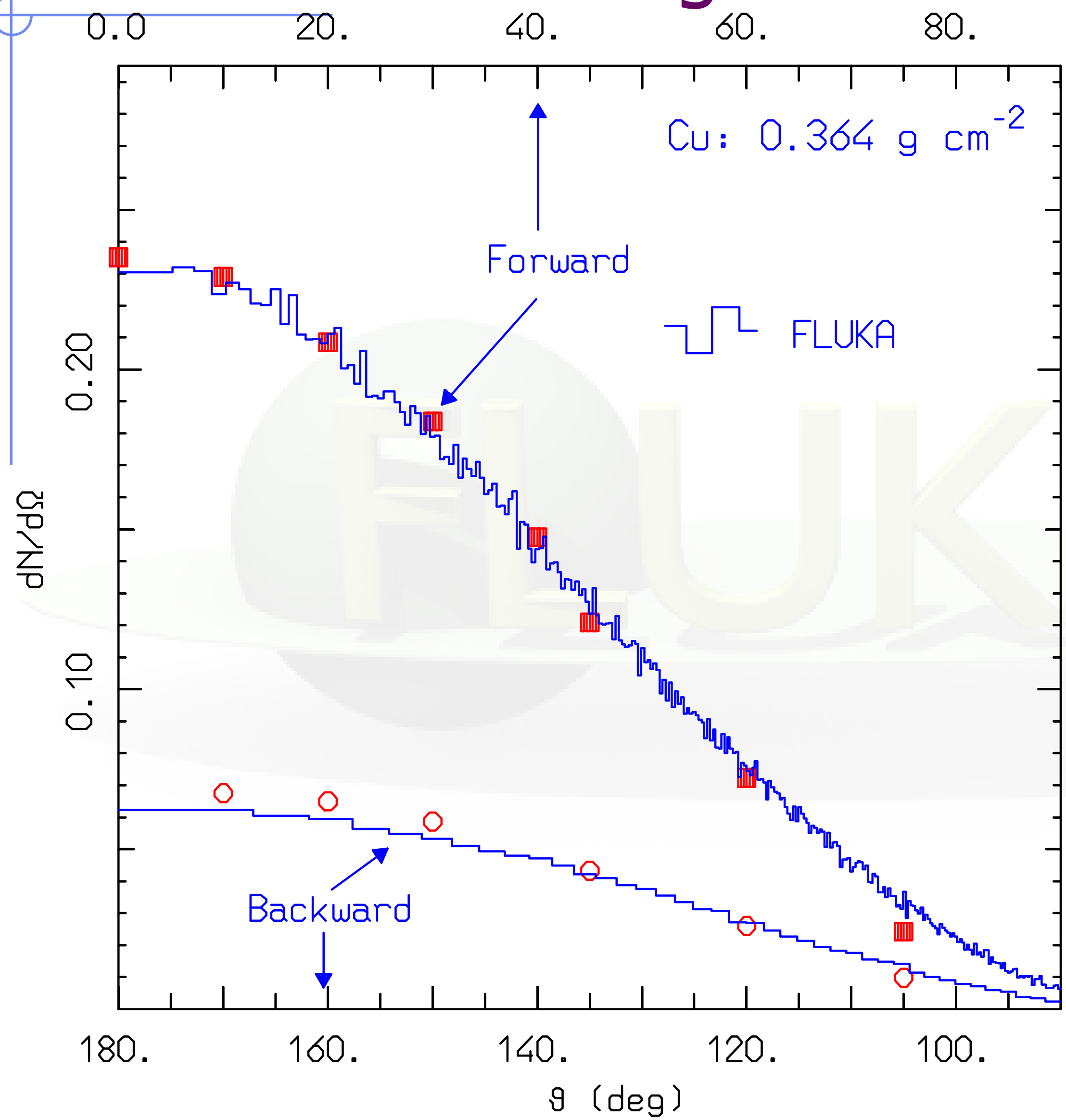
Positron Annihilation

- At rest and in flight according to Heitler.
- In annihilation at rest, account for mutual polarization of the two photons

Scattering

- e^{+} : Bhabha
- e^{-} : Møller

Electron scattering:

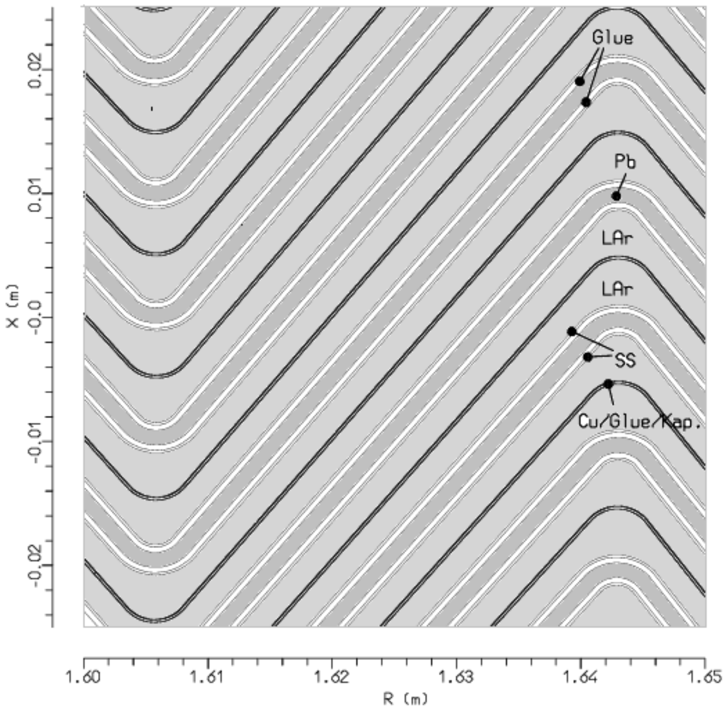


Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm^2 thick Copper foil
Measured (dots) and simulated (histos) data

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

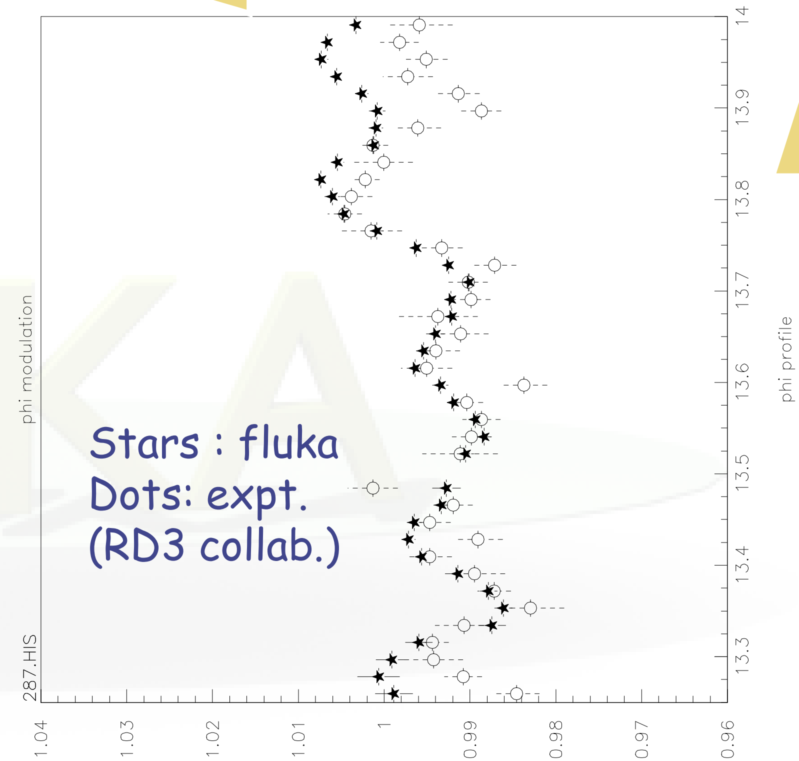
Detail of the FLUKA geometry and response vs. electron impact position

287 GeV electron beam



deposited energy

impact position



Energy resolution 10-100 GeV:

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

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

Longitudinal Development

E	E1/E		r.m.s.	
GeV	Data	Fluka	Data	Fluka
100	0.68	0.69		
287	0.61	0.58	.091	.094

Muon interactions

Bremsstrahlung and pair production

- At high energies, bremsstrahlung and pair production are important also for muons and charged hadrons. For instance, in Lead the muon energy loss is dominated by these processes above 300 GeV.

For muons and all charged hadrons:

- Bremsstrahlung :implemented in FLUKA including the effect of nuclear form factors
- Pair Production :implemented

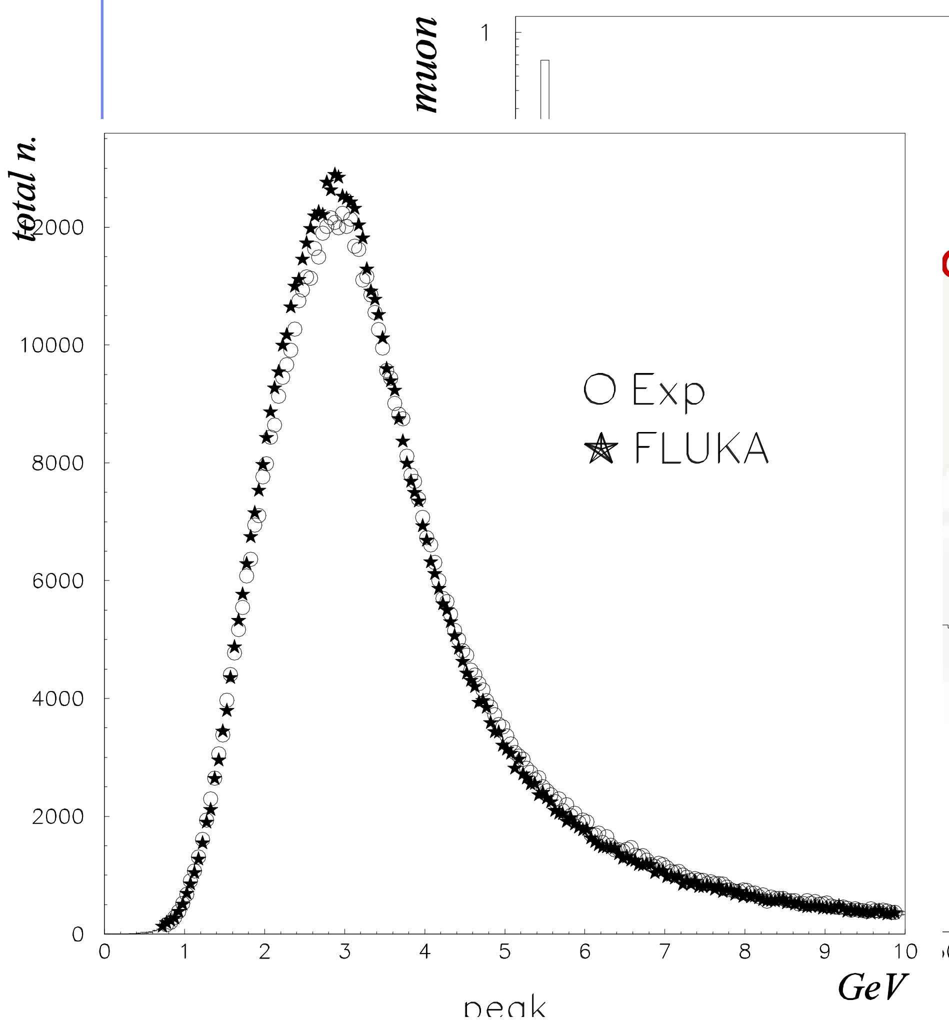
Activation of these processes and thresholds of EXPLICIT γ and $e^{\pm}$ production depend on the DEFAULTS chosen. They are controlled by the card

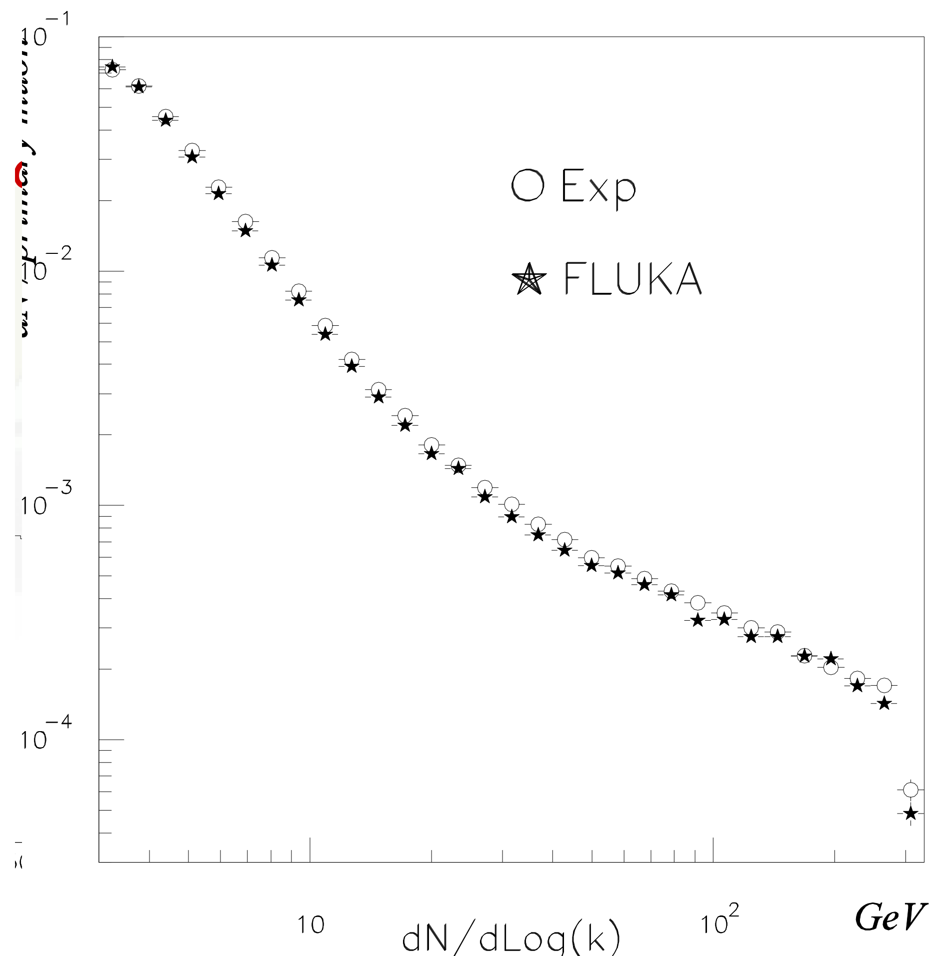
```
PAIRBREM Flag  e±Thresh γThresh Mat1  Mat2    Step
```

Below threshold, energy loss is accounted for in a continuous approximation

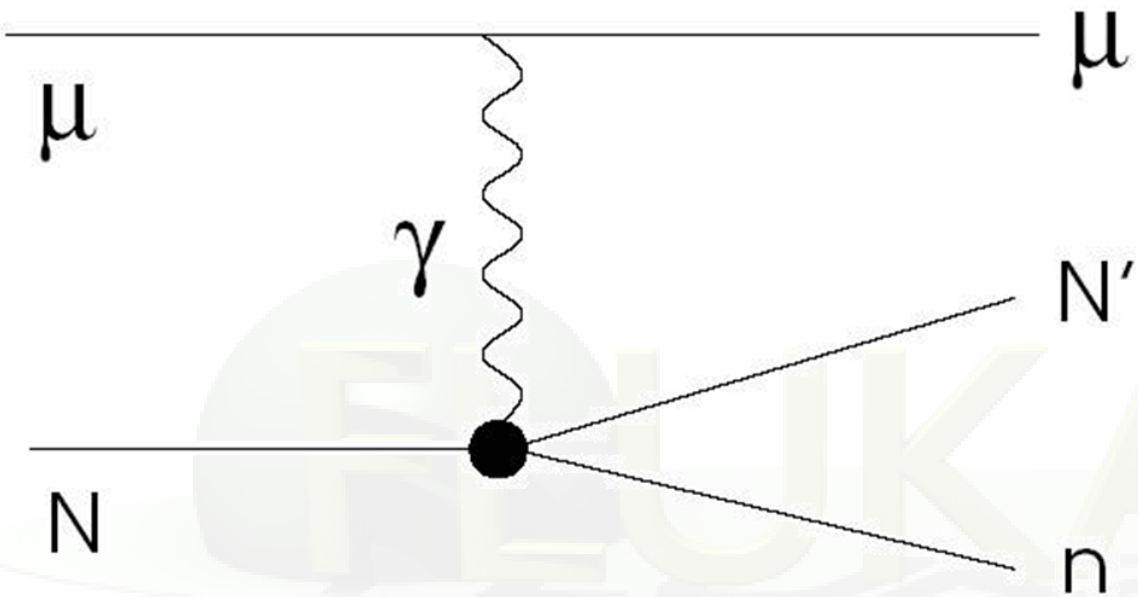
Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure





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: options

μ photonuclear interactions are NOT activated with any default

To activate them:

```
MUPHOTON Flag                          Mat1     Mat2     Step
```

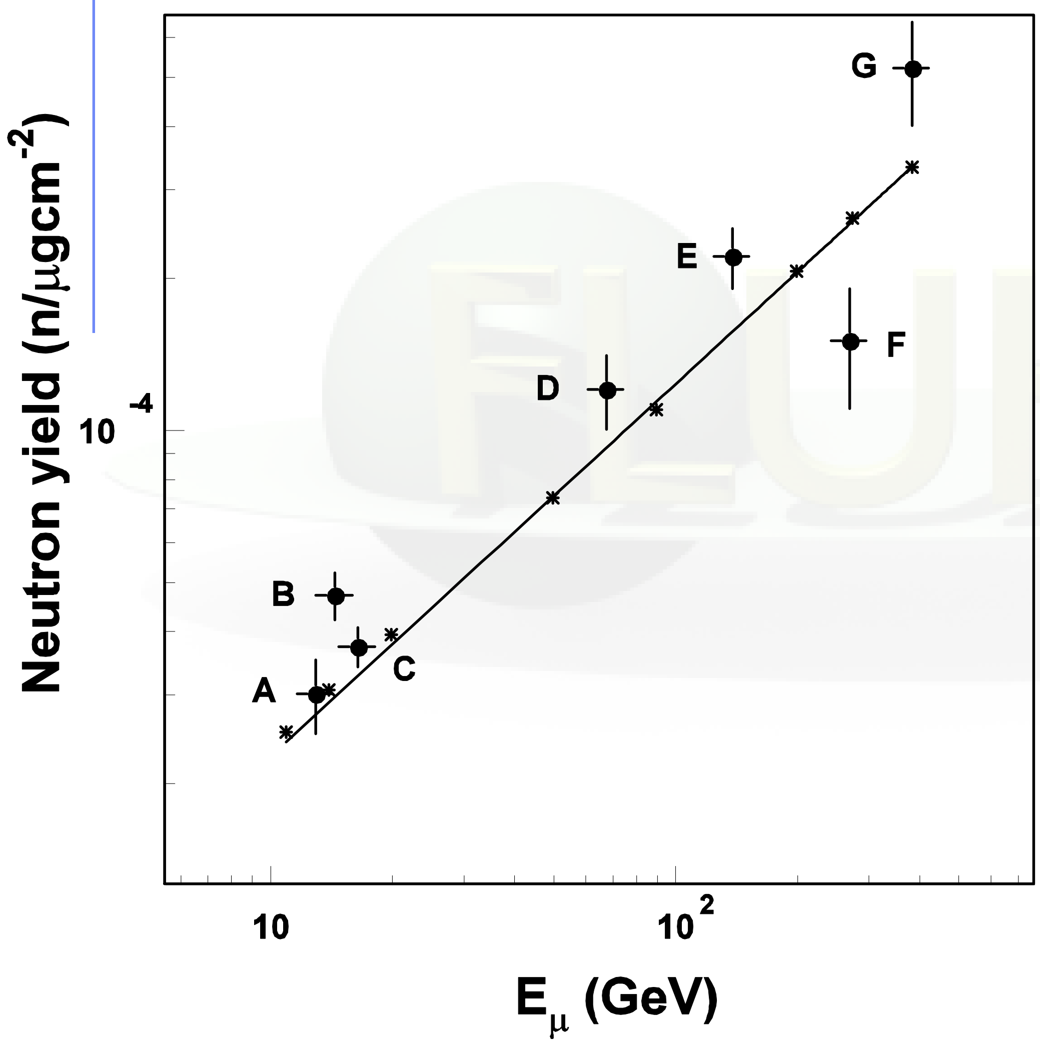
Flag controls activation of interactions, with the possibility to simulate the interaction without explicit production and transport of secondaries (this gives the correct muon energy loss/ straggling)

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

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

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)

Muon Capture

An exotic source of neutron background

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

μ^- at rest + atom $\longrightarrow$ excited muonic atom $\longrightarrow$ 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

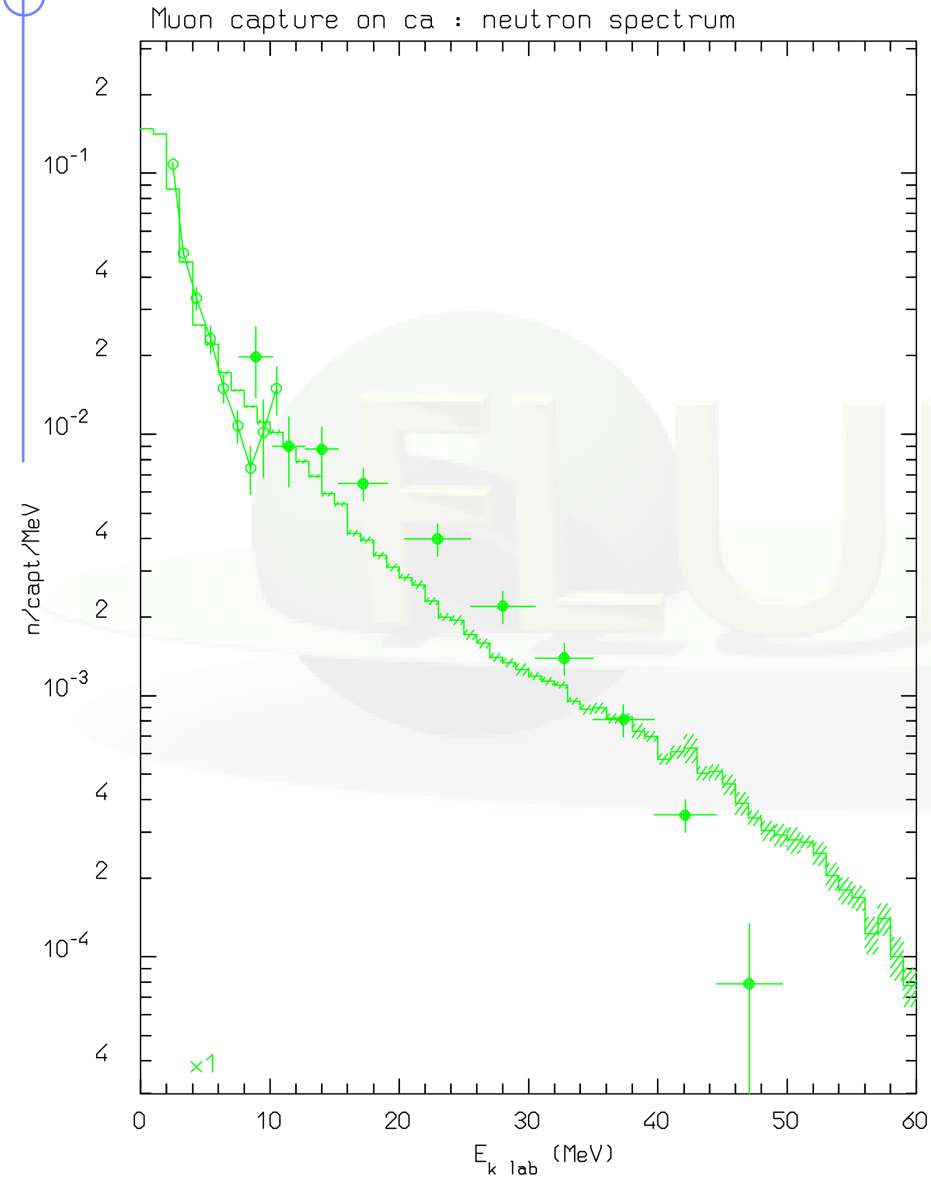
Slow projectile, low energy transfer (neutron E=5 MeV on free p)

Experimentally: high energy tails in n-spectra

Beyond the simple one-body absorption

Good results from addition of two-nucleon absorption

Muon Capture II



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

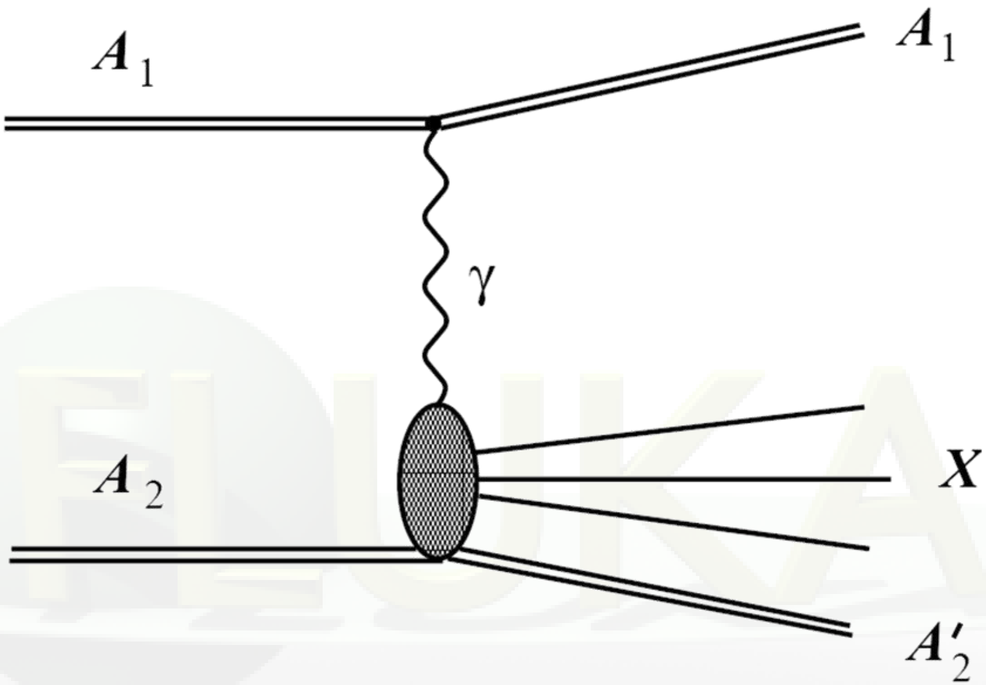
Emitted:

0.62 neutrons/capture

0.27 protons/capture

Electromagnetic dissociation

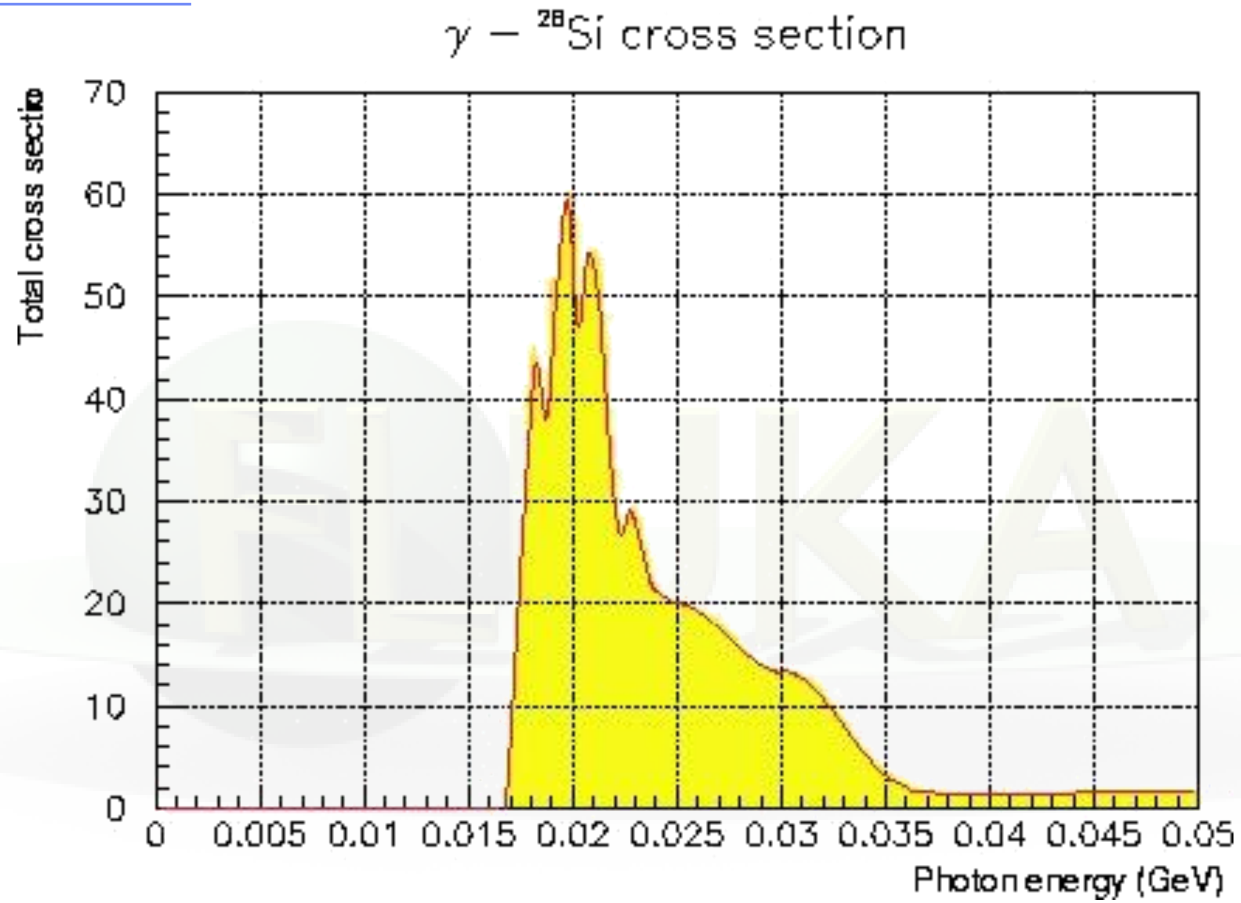
Electromagnetic dissociation



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

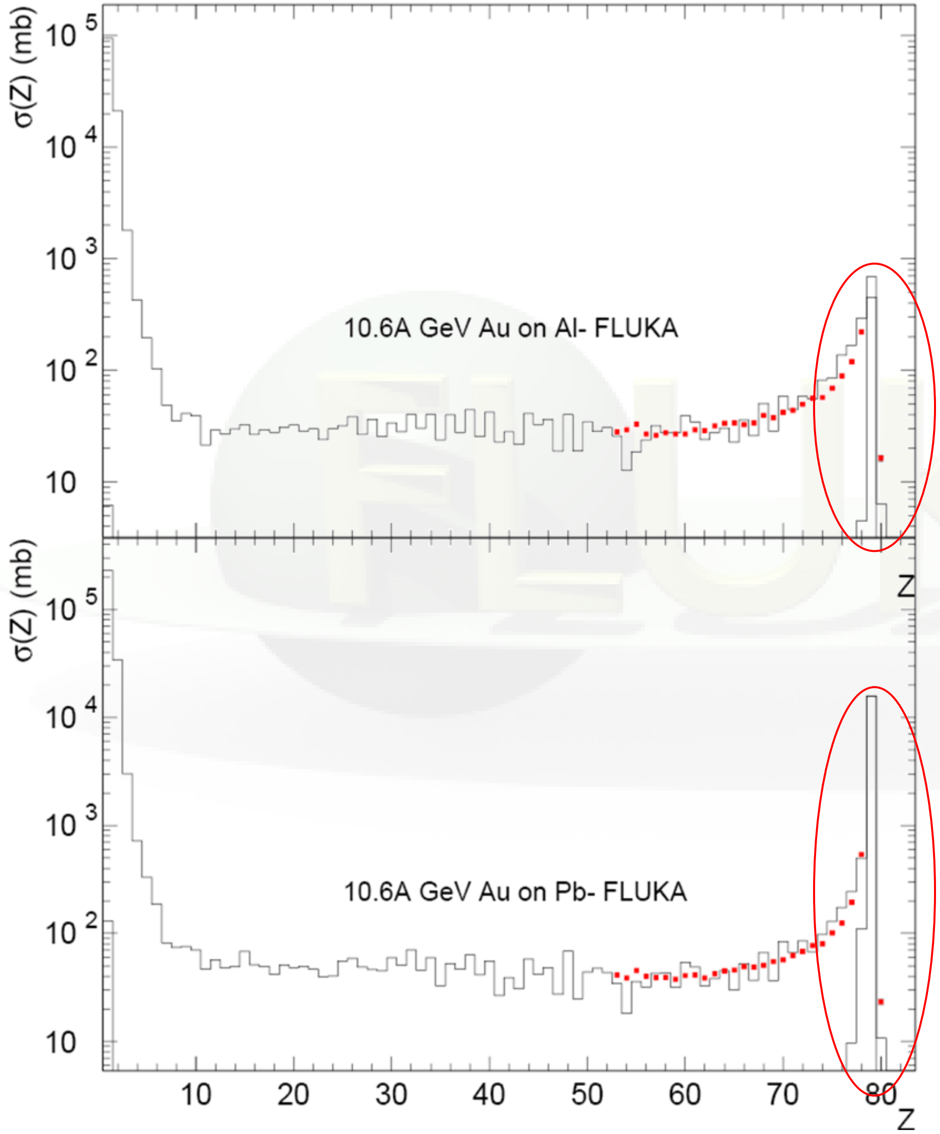
Note: Electromagnetic dissociation is already relevant for interactions of few GeV/n ions in heavy targets.

Electromagnetic dissociation: example



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

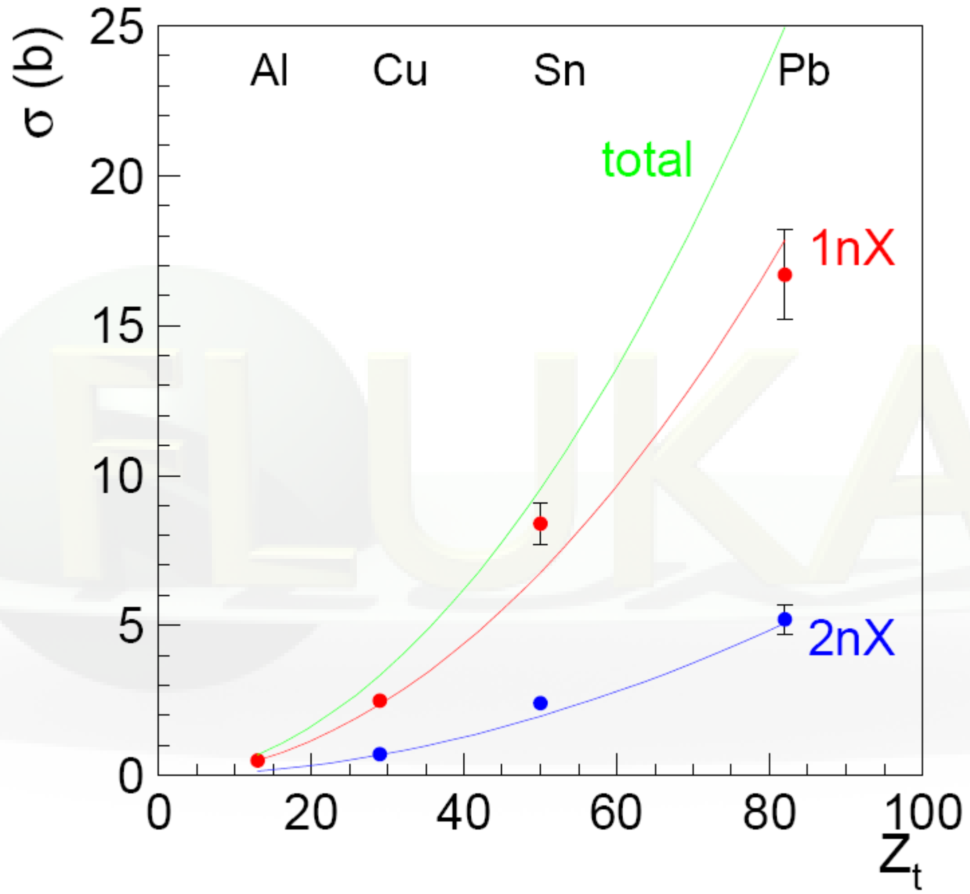
Electromagnetic dissociation - *Benchmarks*



Fragment charge cross sections for 10.6 GeV/n Au ions on Al and Pb.

FLUKA: solid histogram(total)
dashed histogram (em diss.)
Exp. data: symbols
PRC52, 334 (1995)

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.*,