



# 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  $e^+$ ,  $e^-$ ,  $\gamma$ : 1 keV (100 eV for  $\gamma$ )- 1000 TeV

**Full coupling** in both directions with hadrons and low-energy neutrons

**Energy conservation** within computer precision

**Up-to-date**  $\gamma$  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

EM particles are transported until their energy falls below a preset threshold. In FLUKA, this energy threshold can be set **REGION BY REGION**.

EMFCUT	e <sup>±</sup> Thresh	γThresh	0.0	Reg1	Reg2	Step
<b>EMFCUT</b>	Type: ▼	e-e+:	γ:			
Old brems.: 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 (photons travel more)

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

# 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 particles ("delta rays") :

$$SDUM = PROD-CUT$$

The production threshold is also used as lowest energy limit to prepare cross section tabulations at initialization stage.

# Production Thresholds -II

For electromagnetic interactions: **BY MATERIAL !**

EMFCUT	e <sup>±</sup> Thresh	γThresh	Fudgem	Mat1	Mat2	Step	PROD-CUT
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EMFCUT	Type: PROD-CUT ▼	e-e+:	γ:
Fudgem:	Mat: ▼	to Mat: ▼	Step:

Fudgem is related to multiple scattering. = 0 below  $\approx 10$  keV , = 1 above  
**MUST** be set, if the field is empty  $\rightarrow 0$

**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 (and different names)

**Warning 3:** 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.



# 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
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Flag > 0: Activate

Flag < 0: De-activate

EMFFLUO

Fluorescence: ▼

Mat: ▼

to Mat: ▼

Step:

**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**

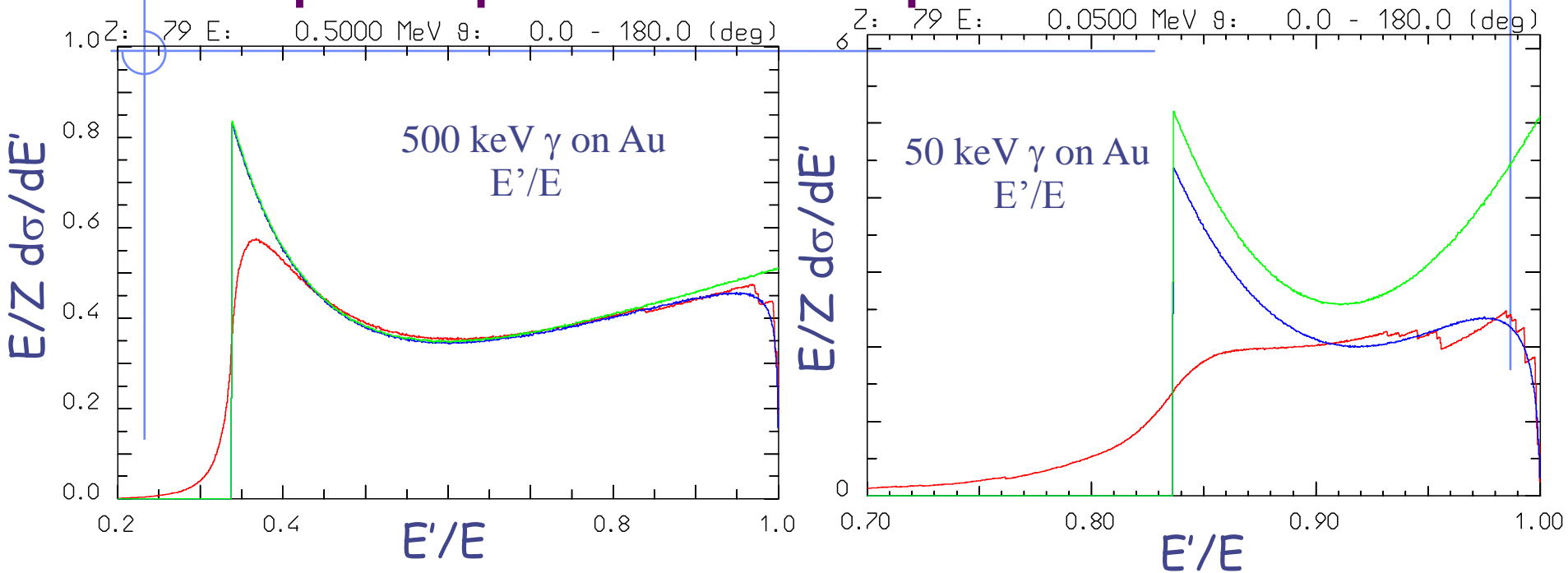
Inelastic Form Factors, Compton profile and Rayleigh scattering are activated only with a subset of DEFAULTS .

To activate/deactivate:

EMFRAY	Flag	Reg1	Reg2	Step
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*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

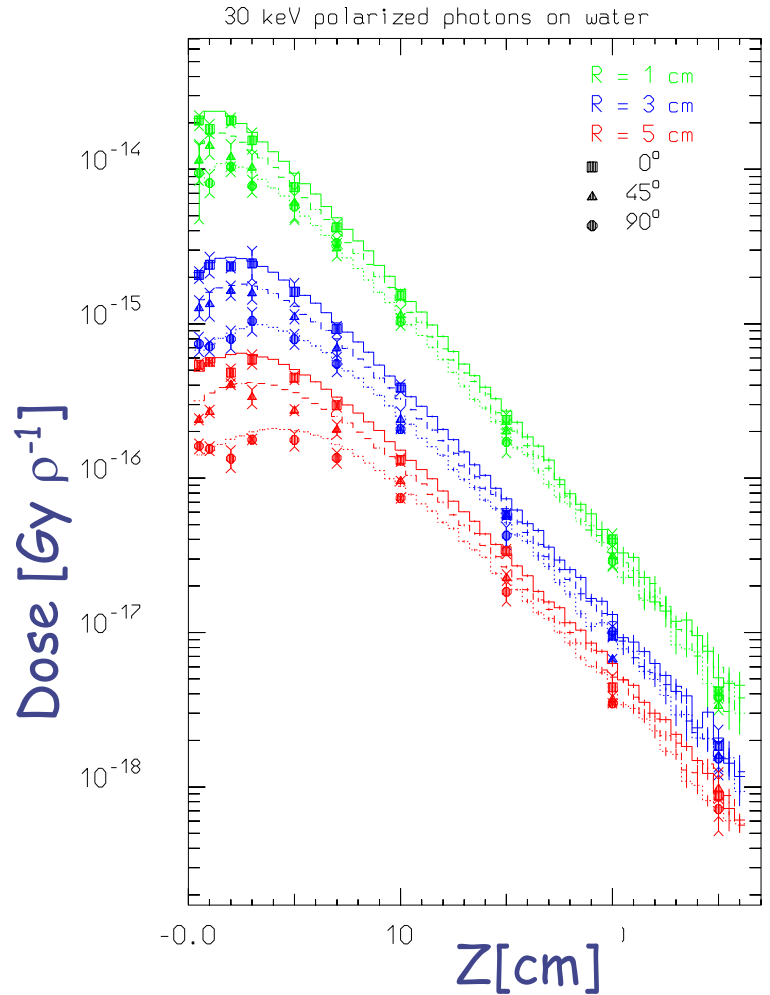
Larger effect at very low energies, where, however, the dominant process is photoelectric.

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  $\geq 1 \rightarrow$  Pol. direction orthogonal to direction of motion,  
Fraction + flag2  $\rightarrow$  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 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
- 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 ( $\gamma \equiv \rho, \Phi$  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)  $\rightarrow$  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
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**Flag** controls activation of interactions, with the possibility to select a subset of the photonuclear mechanisms

<b>PHOTONUC</b>	Type: ▼	All E: off ▼
E>0.7GeV On ▼	$\Delta$ resonance On ▼	Quasi D On ▼
	Mat: ▼	to Mat: ▼
		Giant Dipole off ▼
		Step:

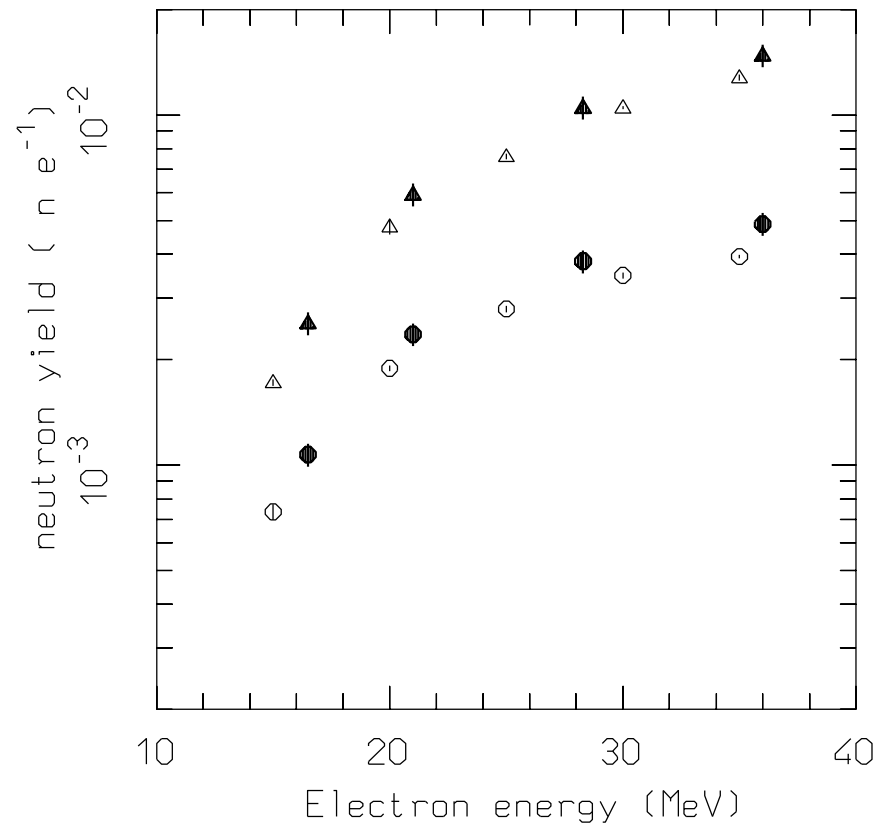
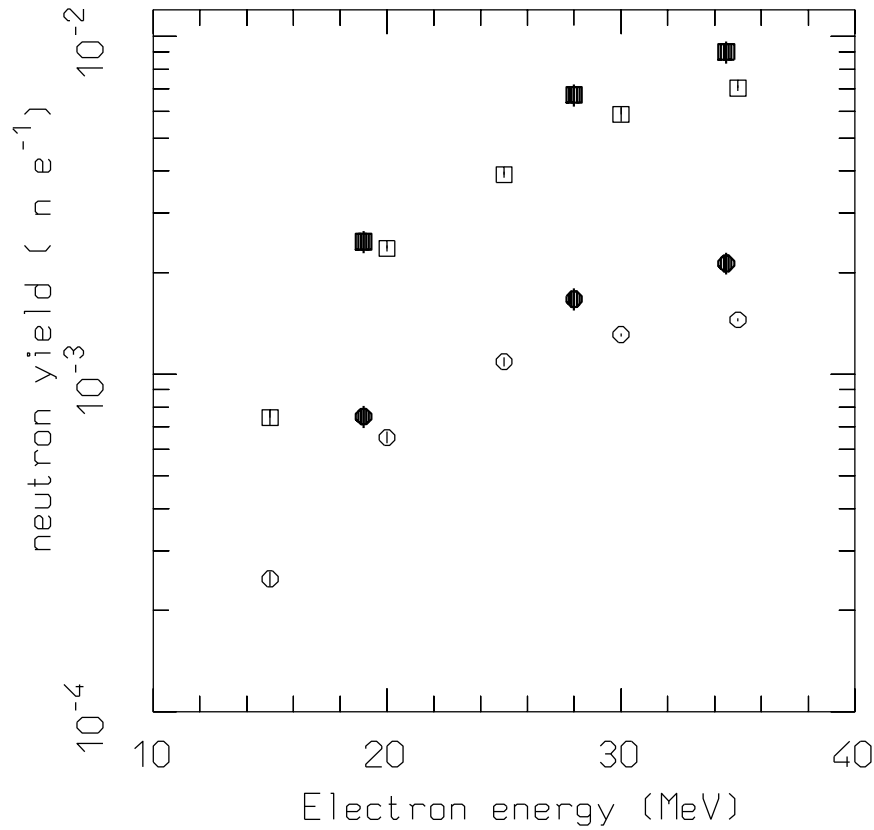
Since the photonuclear cross section is very small, **PHOTONUC** should be always accompanied by **LAM-BIAS** with SDUM = blank (see lecture on biasing)

LAM-BIAS	0.0	Factor	Mat	PHOTON
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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<sup>-</sup> energy.  
Open symbols: FLUKA, closed symbols: experimental data (Barber and George, Phys. Rev. 116, 1551-1559 (1959))

Left: Pb, 1.01 X<sub>0</sub> (lower points) and 5.93 X<sub>0</sub> (upper)

Right: U, 1.14 and 3.46 X<sub>0</sub>

# Photonuclear int.: example

Reaction:

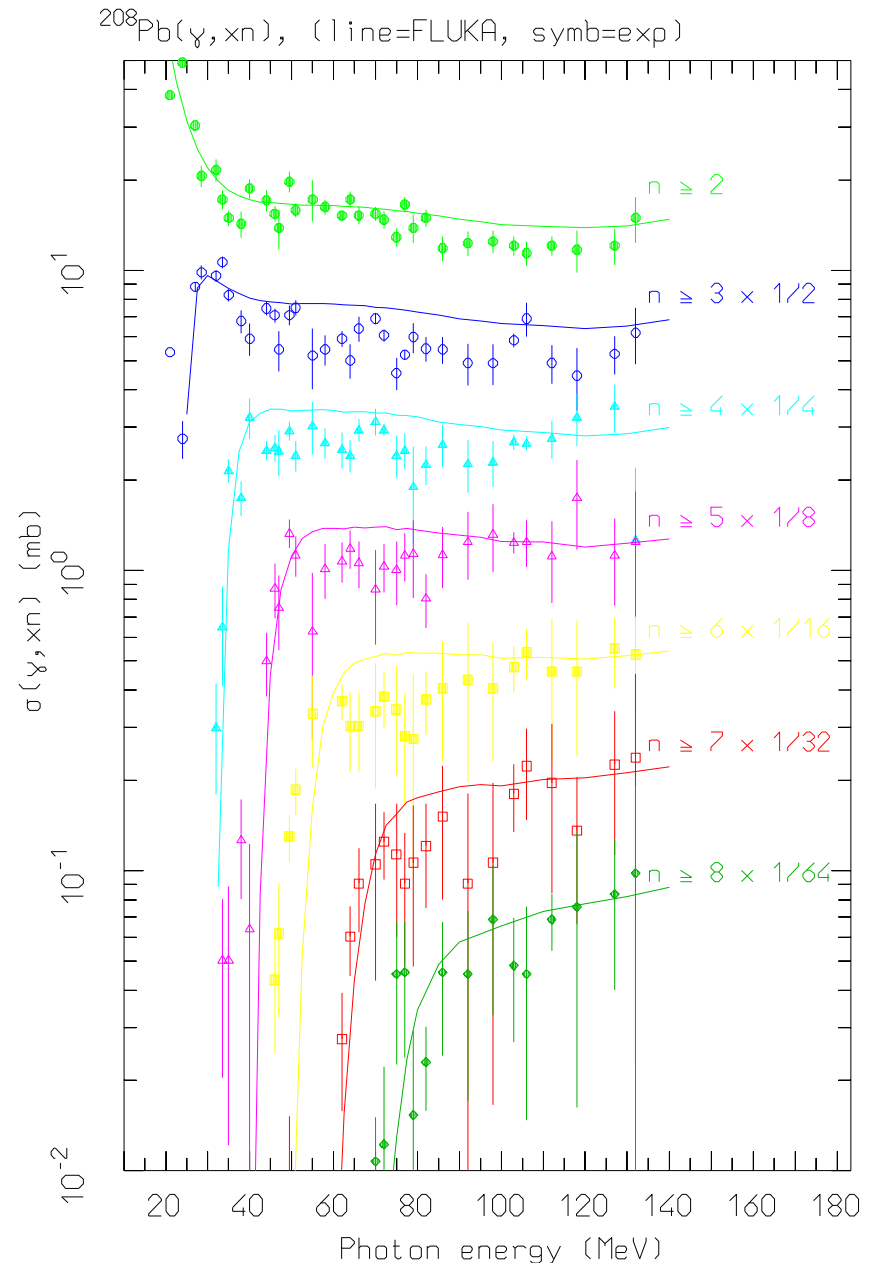


$$20 \leq E_\gamma \leq 140 \text{ MeV}$$

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





# 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
```

```
PHOTONUC Type: MUMUPAIR ▼  
Coherent: On ▼ InC. quasielastic: On ▼ Inc. Inelastic: On ▼ Deep Inelastic: off ▼  
Bias inter-λ: Mat: ▼ to Mat: ▼ Step:
```

**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)

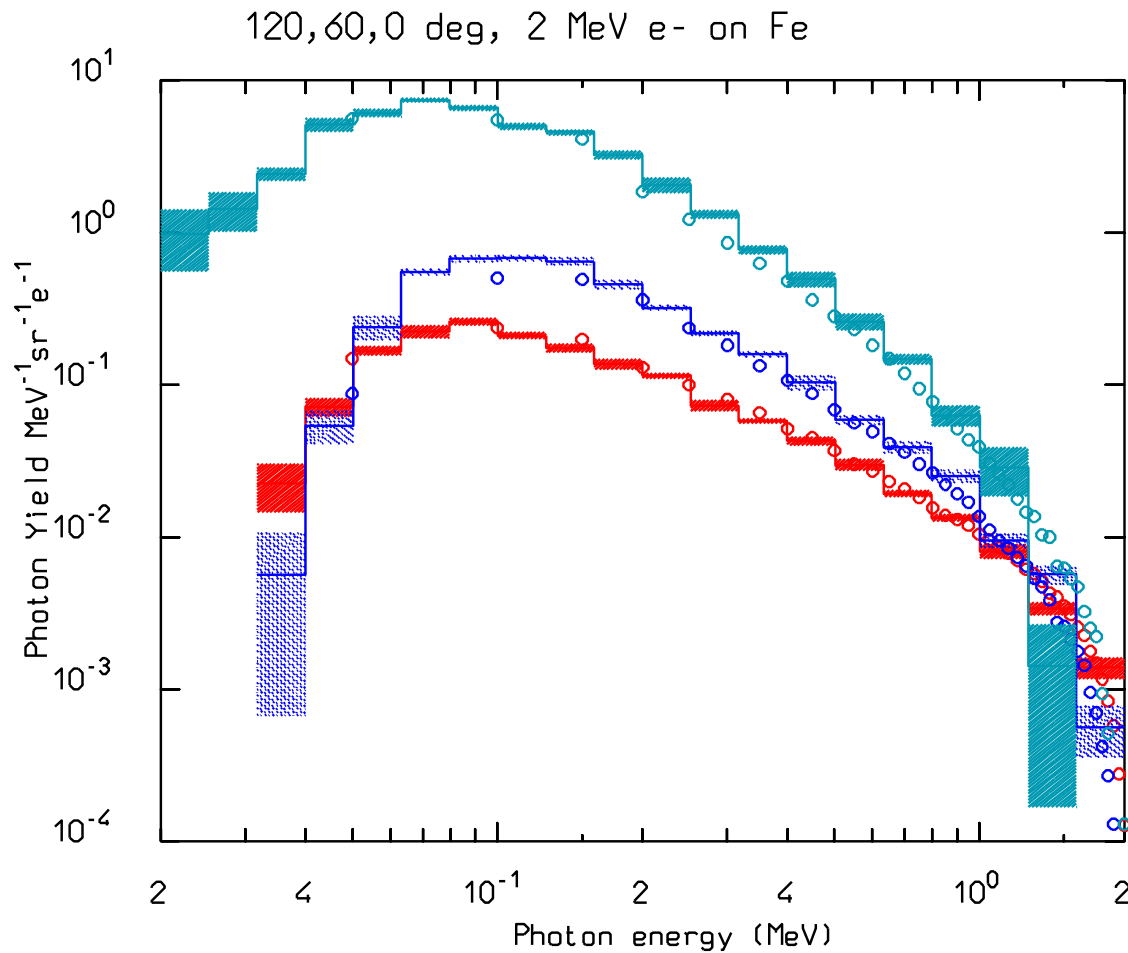


# Electron/Positron interactions

# Bremsstrahlung

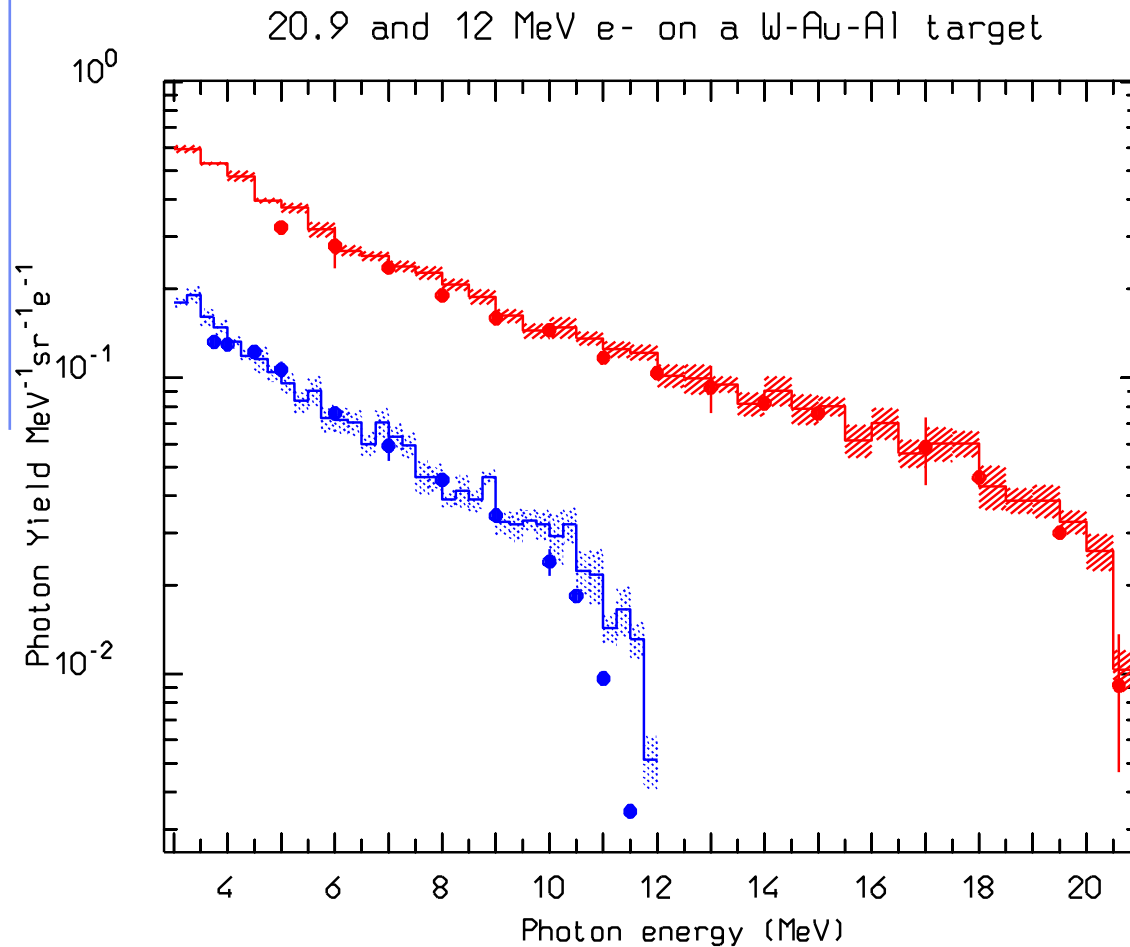
- Energy-differential cross sections based on the **Seltzer** and **Berger** database, interpolated and extended to a finer energy mesh, tip, and larger energies
- Finite value at **tip** energy (tip == max energy of photon)
- Extended to 1000 TeV taking into account the **LPM** (Landau-Pomeranchuk-Migdal) 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

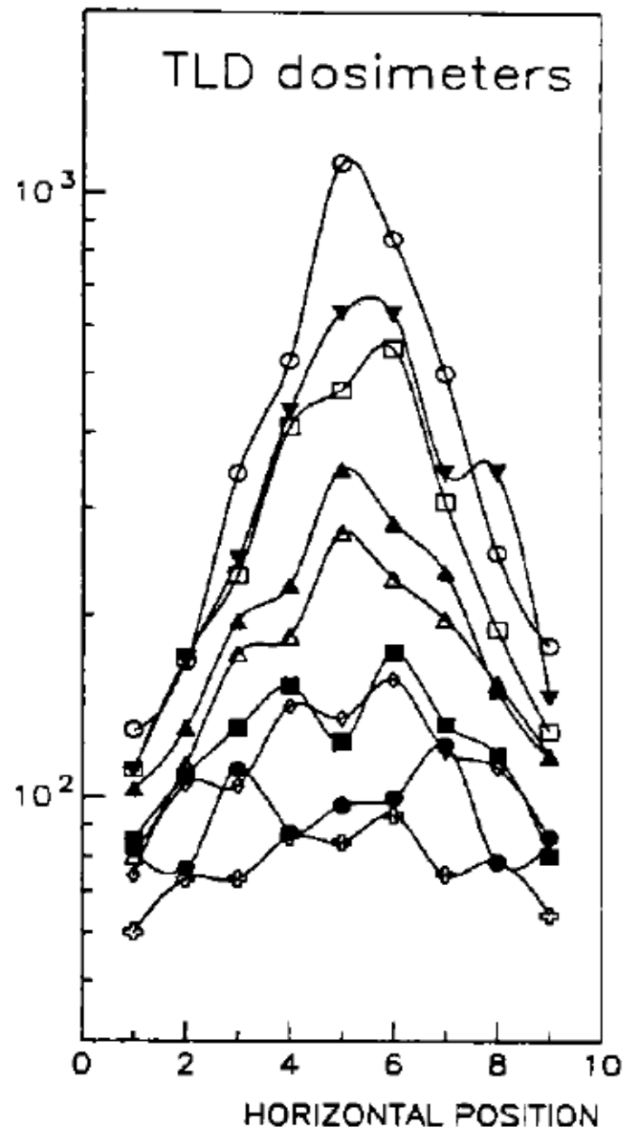
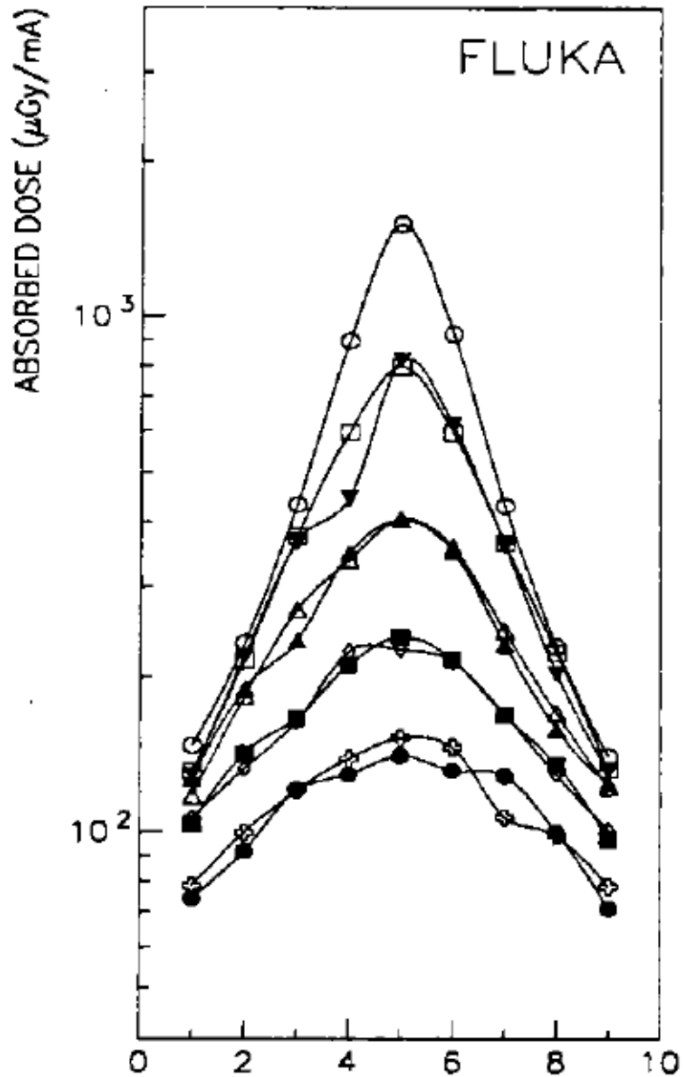
ADONE storage  
ring

1.5 GeV  $e^-$

Bremsstrahlung 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 ,  
 $d=218\text{cm}$



# Other $e^\pm$ interactions

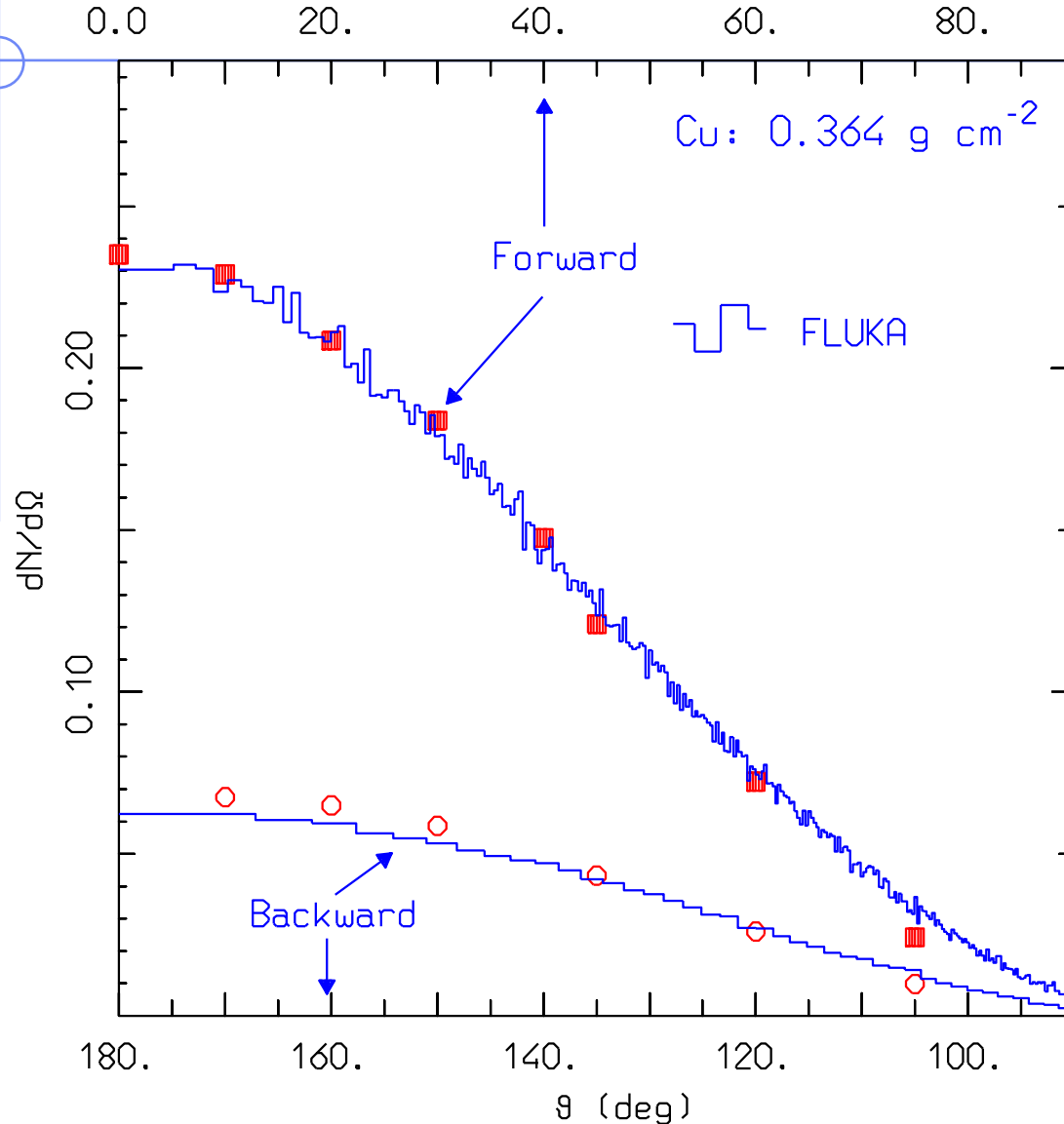
## Positron Annihilation

- *At rest* and *in flight* according to *Heitler*.
- In annihilation at rest, account for mutual *polarization* of the two photons
- *Acolinearity* of the photons at rest can be requested, with annihilation photon energies spread out

## Scattering

- $e^+$  : *Bhabha*
- $e^-$  : *Møller*

# Electron scattering:



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

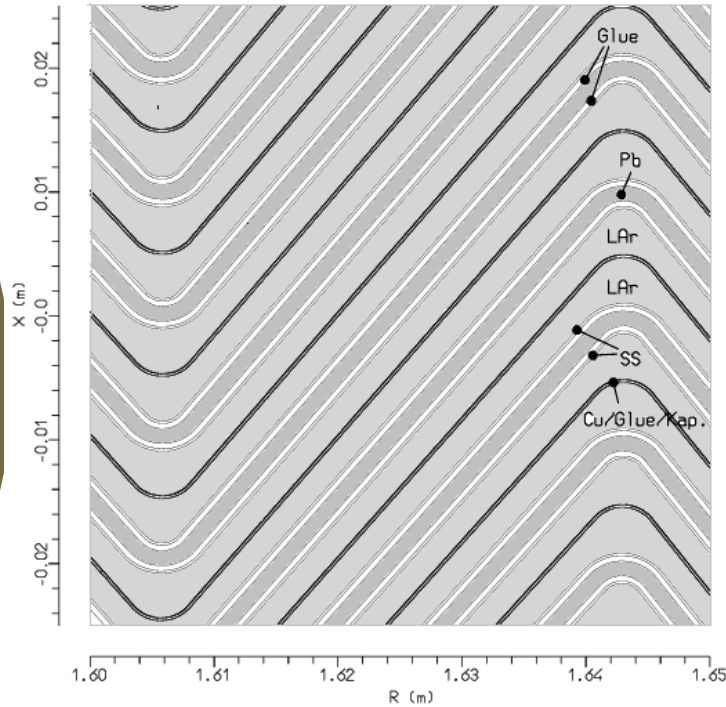


# The ATLAS EM "accordion" calo (standalone test beams)

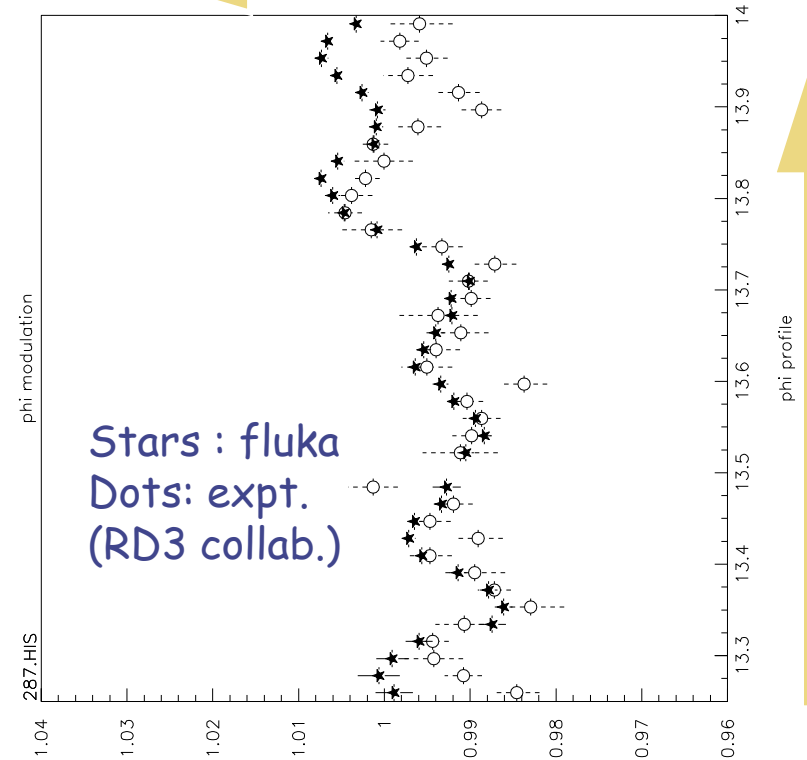
Detail of the FLUKA geometry and

response vs. electron impact position

287 GeV  
electron  
beam



deposited energy



Energy resolution 10-100 GeV:

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

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



# 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

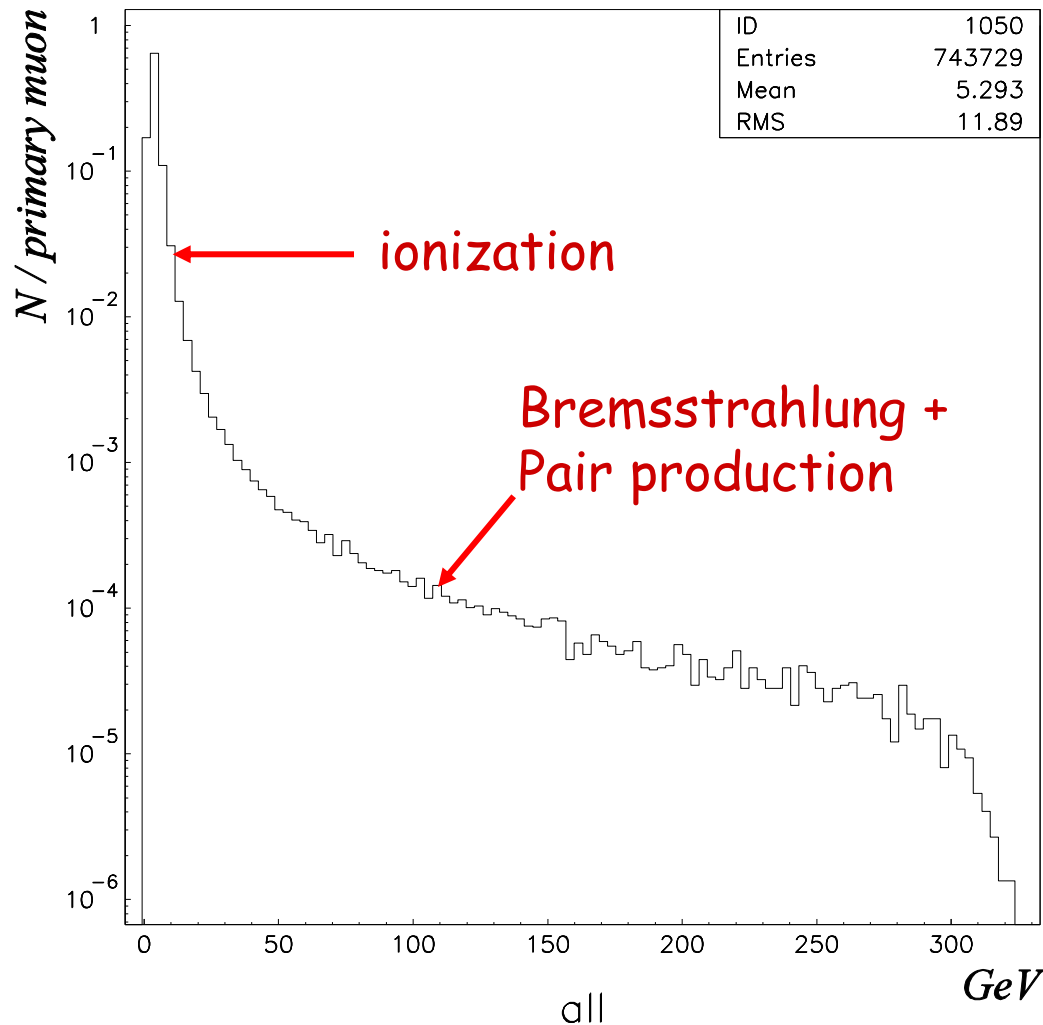
Activation of these processes and thresholds of **EXPLICIT**  $\gamma$  and  $e^\pm$  production depend on the DEFAULTS chosen. They are controlled by the card

<code>PAIRBREM</code>	<code>Flag</code>	<code>e±Thresh</code>	<code>γThresh</code>	<code>Mat1</code>	<code>Mat2</code>	<code>Step</code>
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Below threshold, energy loss is accounted for in a continuous approximation

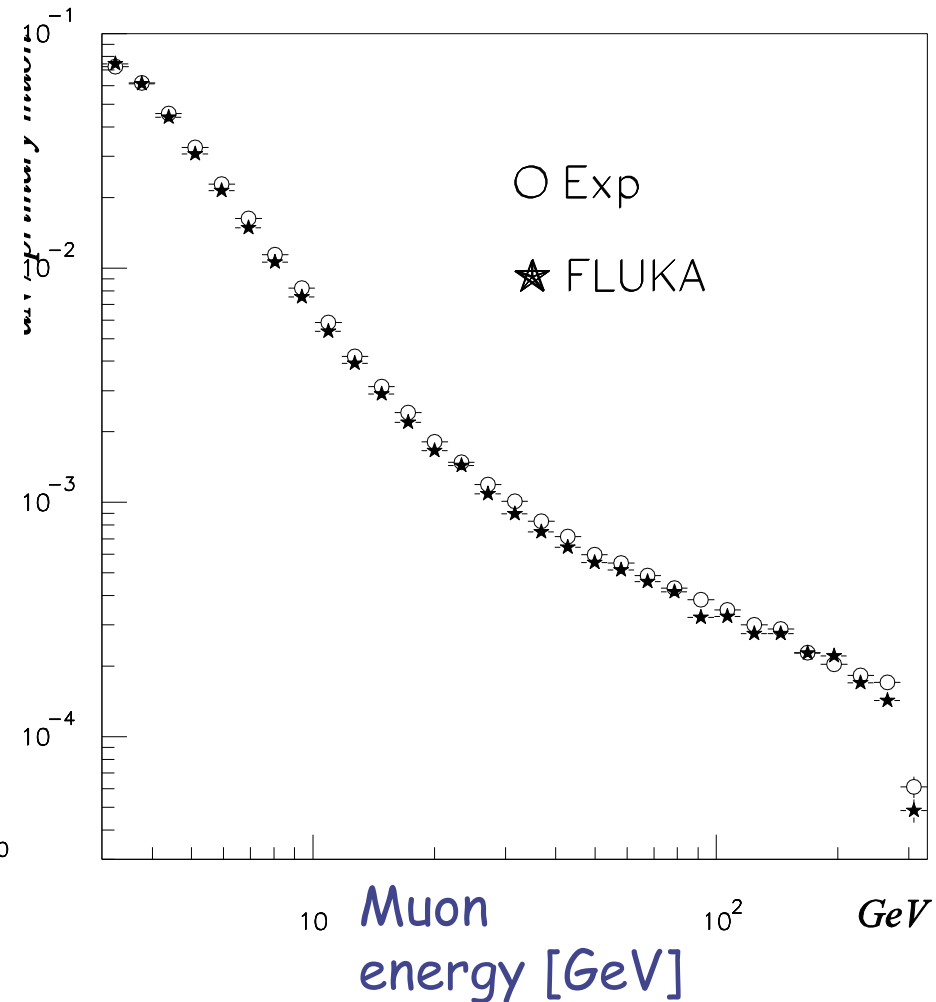
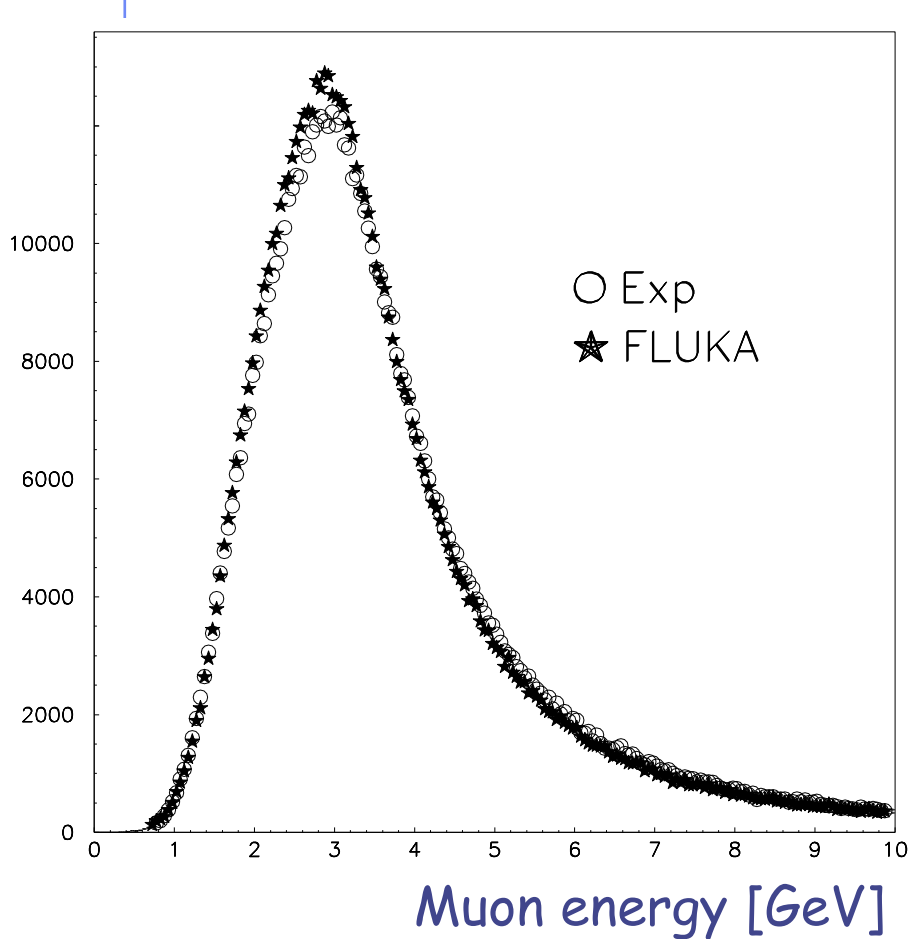
# Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

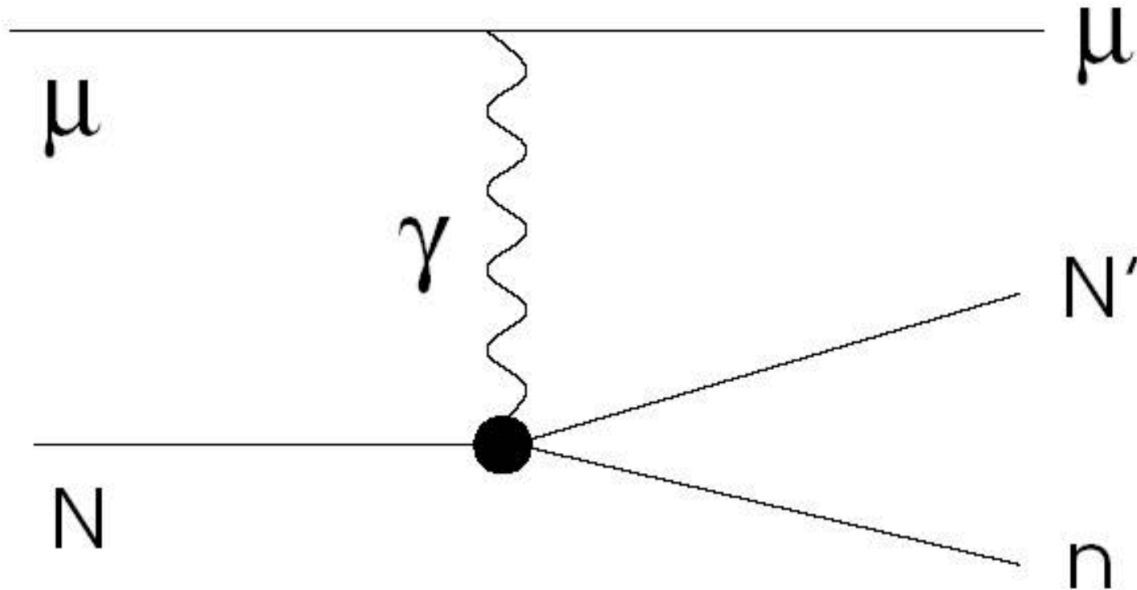


# Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure



# Muon Photonuclear Reactions



Schematic view of a  $\mu$  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

$\mu$  photonuclear interactions are **NOT activated** with any default

To activate them:

<b>MUPHOTON</b>	<b>Flag</b>	<b>0.0</b>	<b>0.0</b>	<b>Mat1</b>	<b>Mat2</b>	<b>Step</b>
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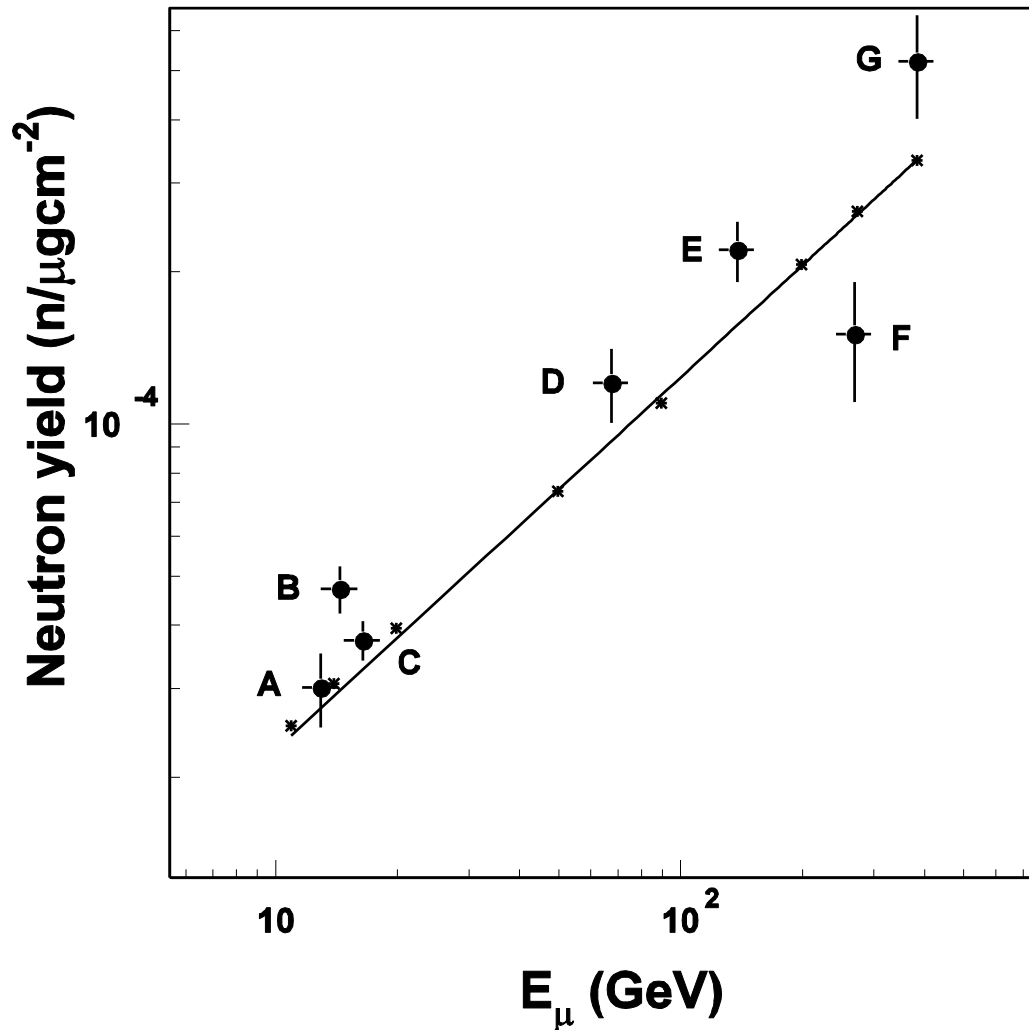
**Flag** controls activation of interactions, with the possibility to simulate the interaction without explicit production and transport of secondaries (this gives the correct muon energy loss/ straggling)

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

<b>LAM-BIAS</b>	<b>0.0</b>	<b>Factor</b>	<b>Mat</b>	<b>MUON+</b>	<b>MUON-</b>
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# 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  $\mu$  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 (1)

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

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

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

Competition between  $\mu$  decay and  $\mu$  capture by the nucleus.

In **FLUKA**: Goulard-Primakoff formula

$\Lambda_c \propto Z_{eff}^4$ , 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)

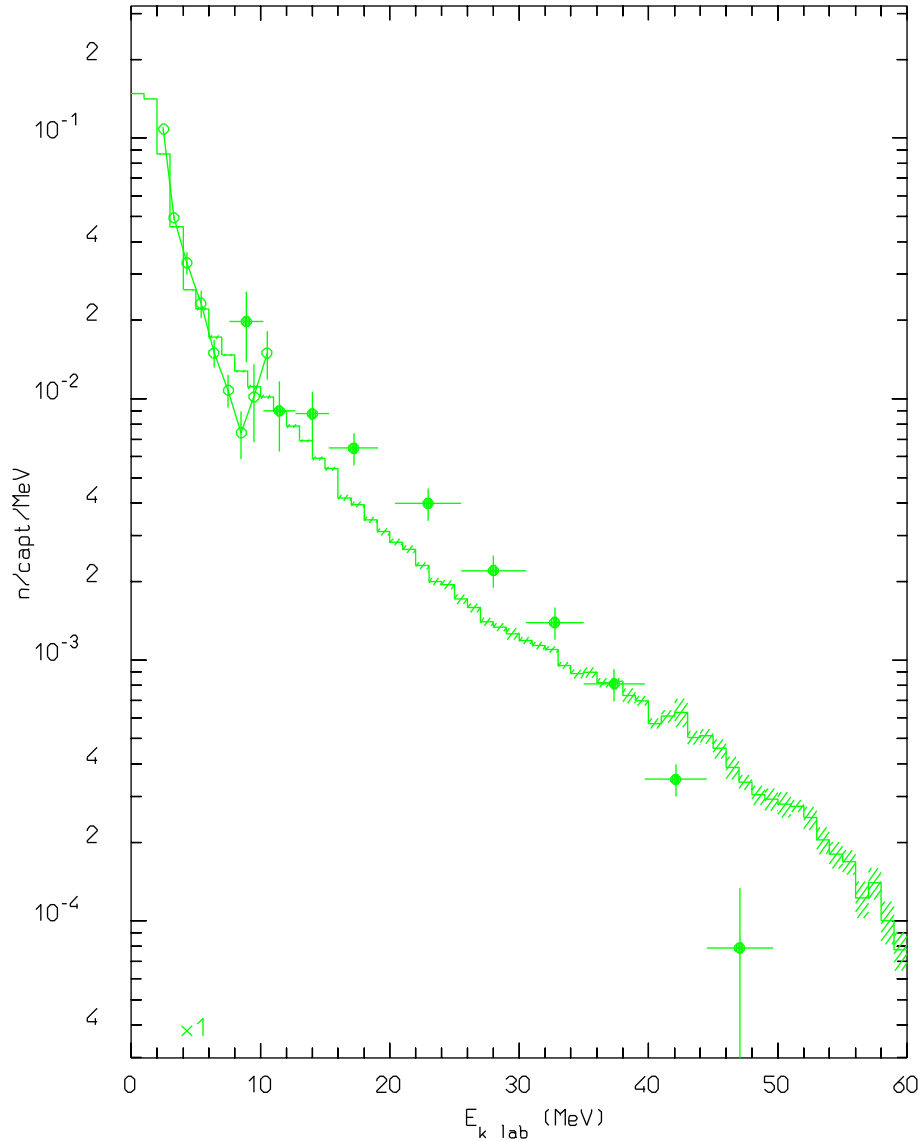
Experimentally: high energy tails in n-spectra

Beyond the simple one-body absorption

Good results from addition of two-nucleon absorption

# Muon Capture (2)

Muon capture on ca : neutron spectrum



capture on Calcium

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

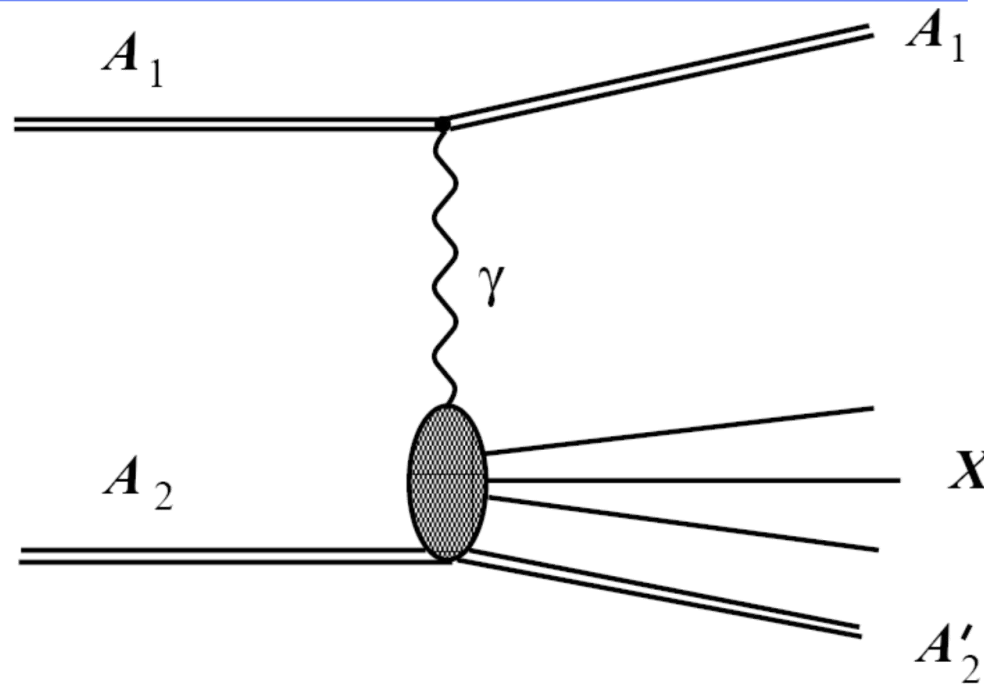
histograms: FLUKA calculations

Emitted:

0.62 neutrons/capture

0.27 protons/capture

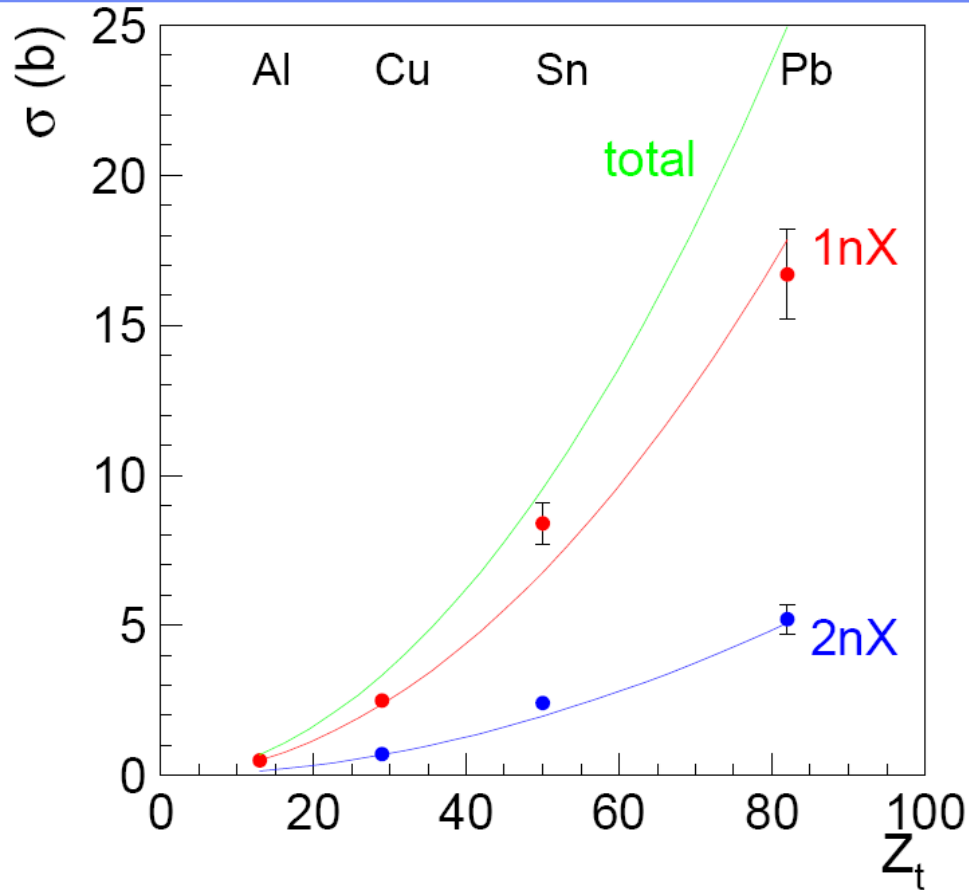
# Electromagnetic dissociation



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

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

# Electromagnetic dissociation - *Benchmarks*

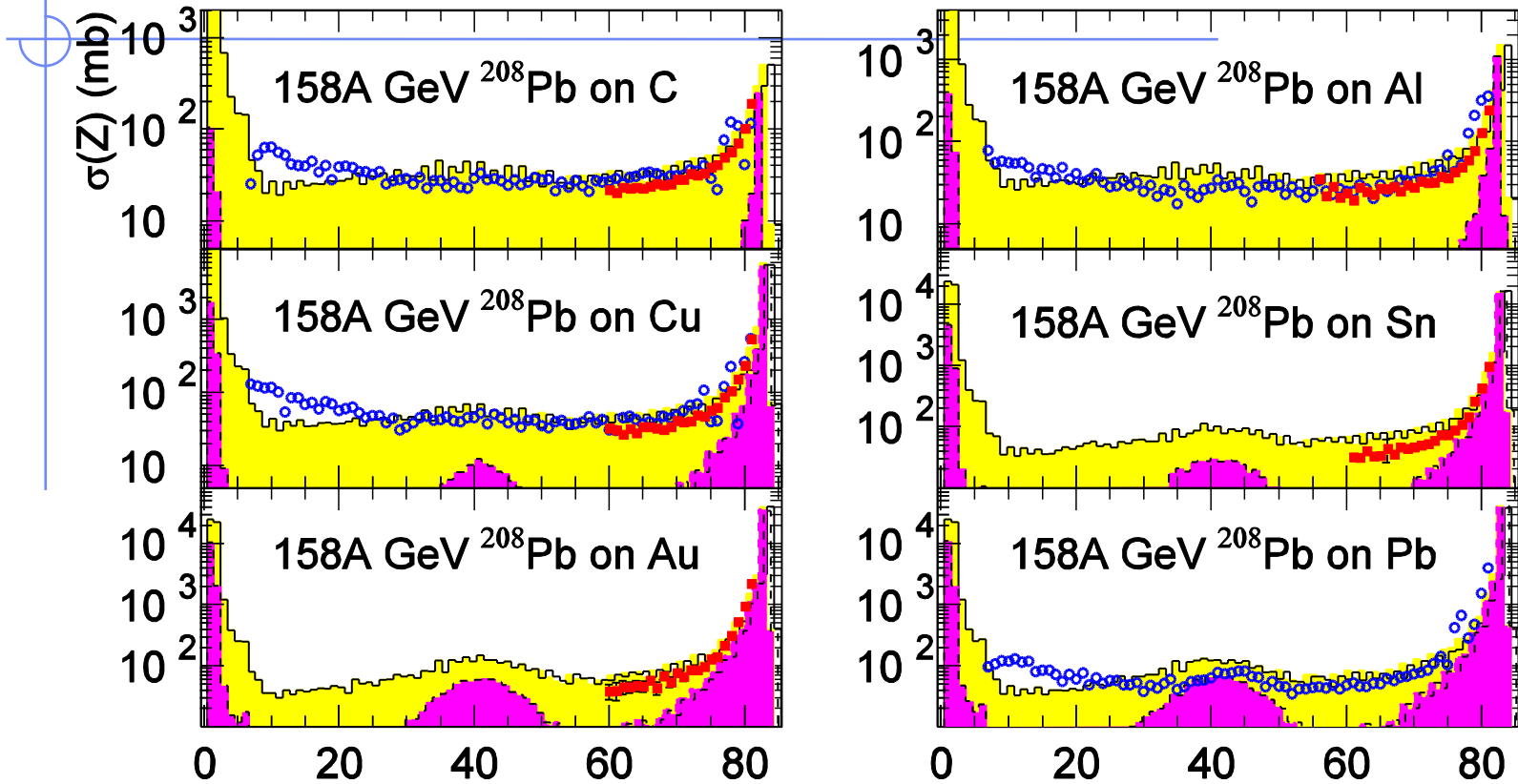


Electromagnetic dissociation cross sections (total, 1nX, 2nX) for 30GeV/n Pb ions on Al, Cu, Sn, and Pb targets.

FLUKA: lines (calculated cross section as a function of target charge)

Exp. data: M.B.Golubeva *et al.*

# 158 GeV/n Pb ion fragmentation



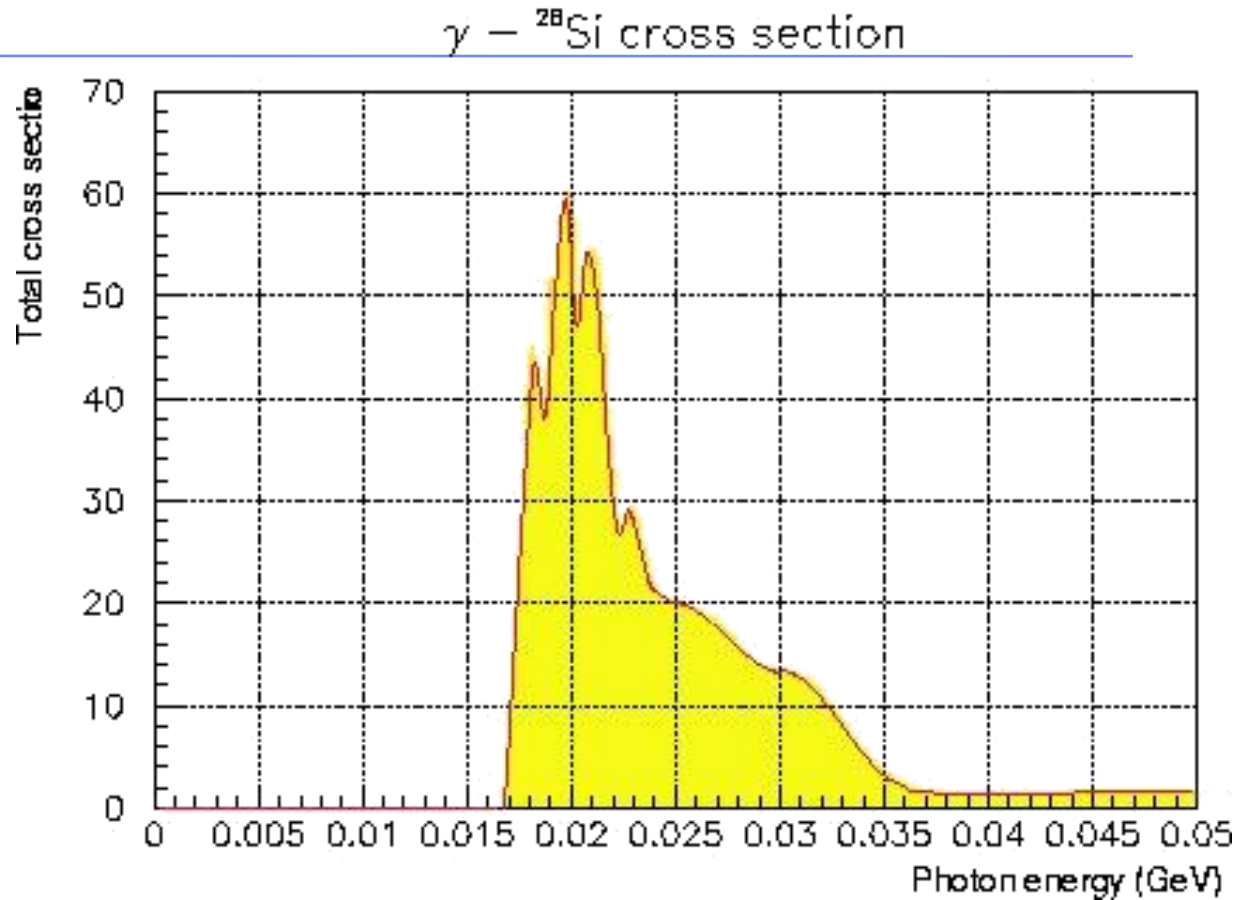
Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), yellow hists are FLUKA (with DPMJET-III) predictions: purple hists are the electromagnetic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

Z



*Spare slides*

# Electromagnetic dissociation: example



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