



# EM interactions

FLUKA Beginner's 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

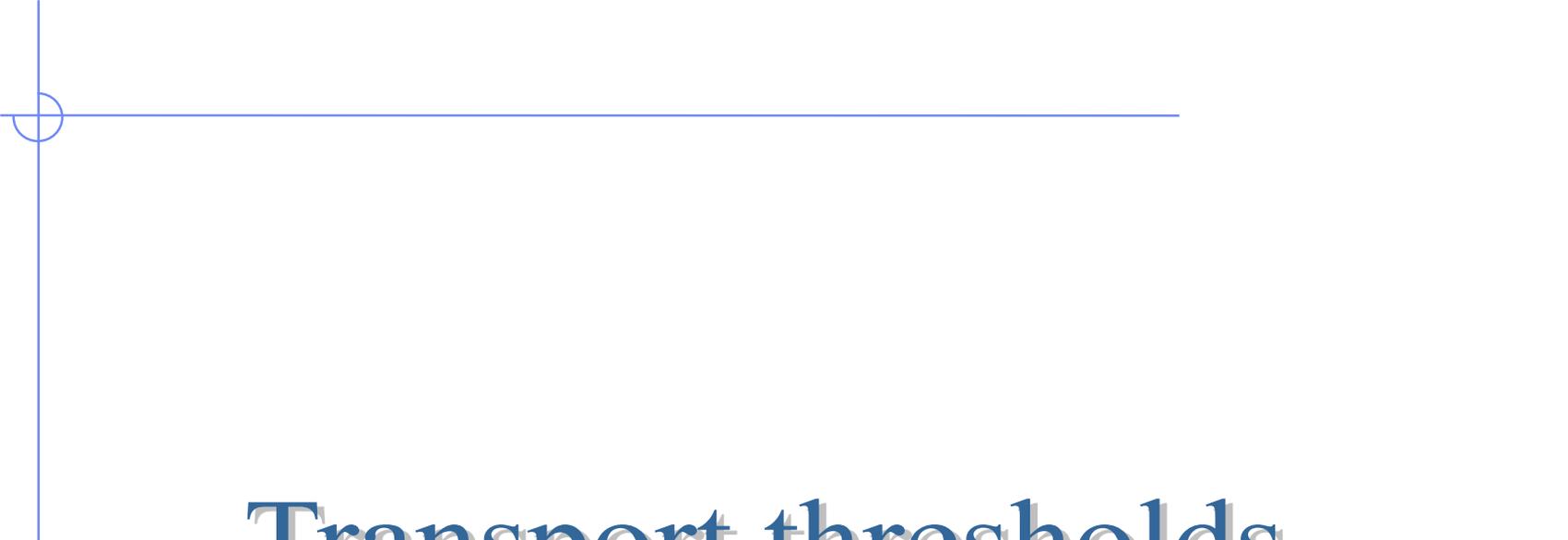
OFF ▼

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

# 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<sup>-</sup>, e<sup>+</sup>, gammas

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

<b>EMFCUT</b>	<b>e<sup>±</sup>Thresh</b>	<b>γThresh</b>	<b>0.0</b>	<b>Reg1</b>	<b>Reg2</b>	<b>Step</b>
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<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 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<sup>-</sup>/e<sup>+</sup>/gammas are CPU eaters*

# Transport thresholds for other particles

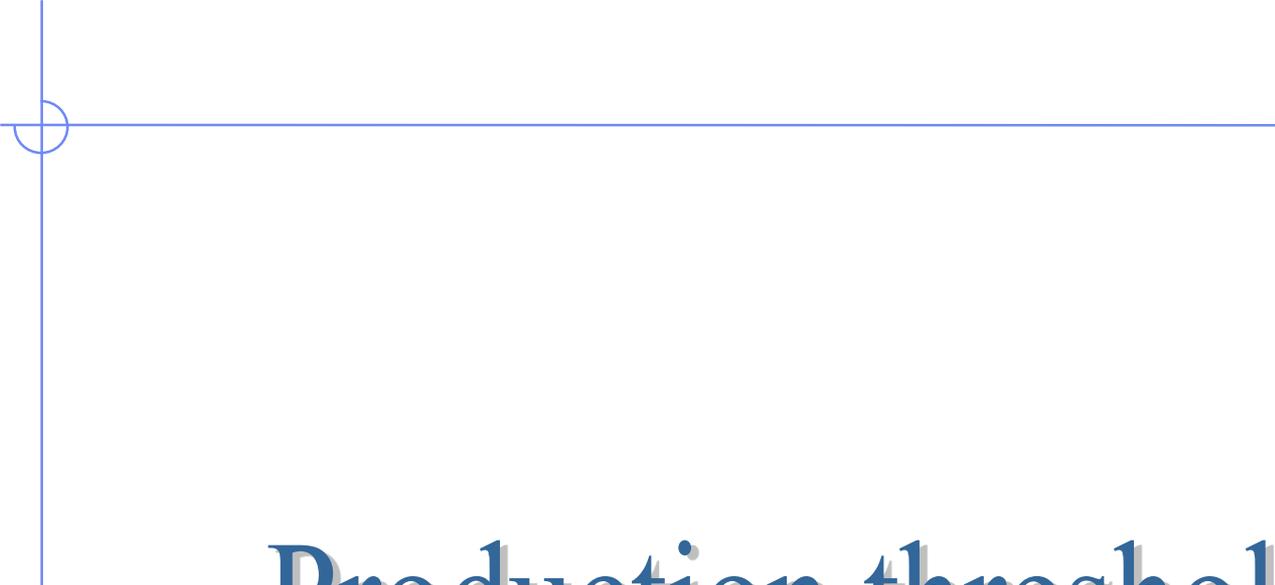
**PART-THR** card: allows to set transport threshold for hadrons, ions, muons and neutrinos globally for the entire geometry setup

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
```

```
PART-THR      Type: Momentum ▼      p:
              Part: ▼              to Part: ▼      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+/ $\gamma$ interactions

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

EMFCUT	e <sup>±</sup> Thresh	$\gamma$ Thresh	Fudgem	Mat1	Mat2	Step	PROD-CUT
--------	-----------------------	-----------------	--------	------	------	------	----------

EMFCUT	Type: PROD-CUT ▼	e-e+:	$\gamma$ :
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:** 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
```

```
⚙ DELTARAY      E thres:      # Log dp/dx:      Log width dp/dx:
Print NOPRINT ▼      Mat: ▼      to Mat: ▼      Step:
```

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

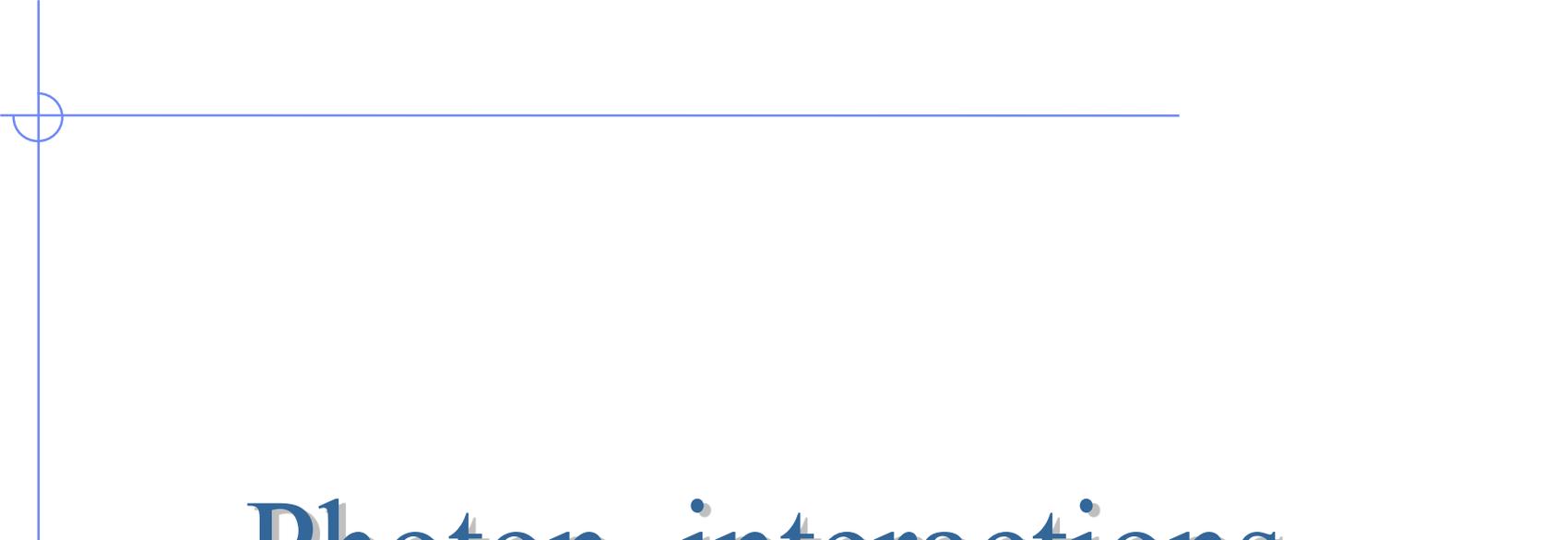
- **PAIRBREM** card allows to control the production threshold for bremsstrahlung and pair production by muons, light ions (up to alphas) and charged hadrons
- Depending on the **DEFAULTS**, the processes might be active without explicit production of secondaries (only continuous energy loss treated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

PAIRBREM	Flag	e±Thresh	γThresh	Mat1	Mat2	Step
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PAIRBREM	Act:	e-e+ Thr:	γ Thr:
	Mat:	to Mat:	Step:
REGION IGLU expr: +void -inner -plane	ignore	Neigh: 5	Volume:
REGION TARGS3 expr:	Pair Prod	Neigh: 5	Volume:
REGION TARGS2 expr:	Bremsstrahlung	Neigh: 5	Volume:
REGION INAIR	Both	Neigh: 5	Volume:
	No Pair	Neigh: 5	Volume:
	No Bremsstrahlung	Neigh: 5	Volume:
	Inhibit both	Neigh: 5	Volume:

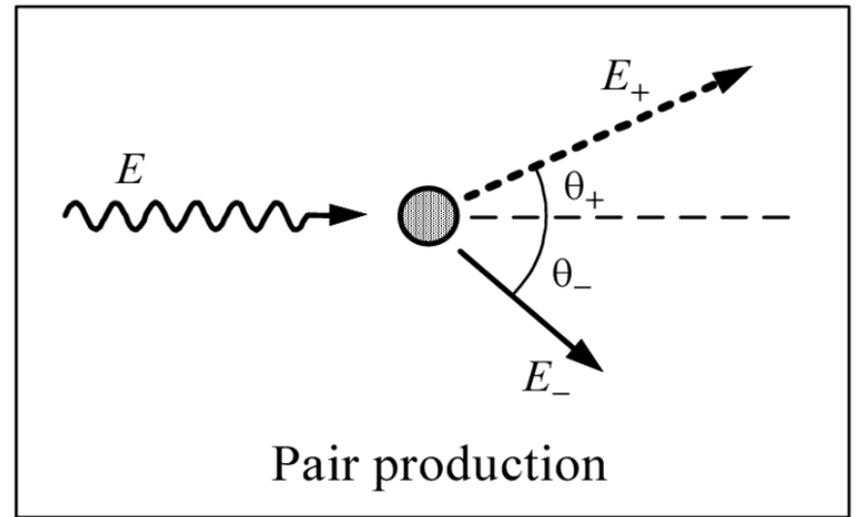
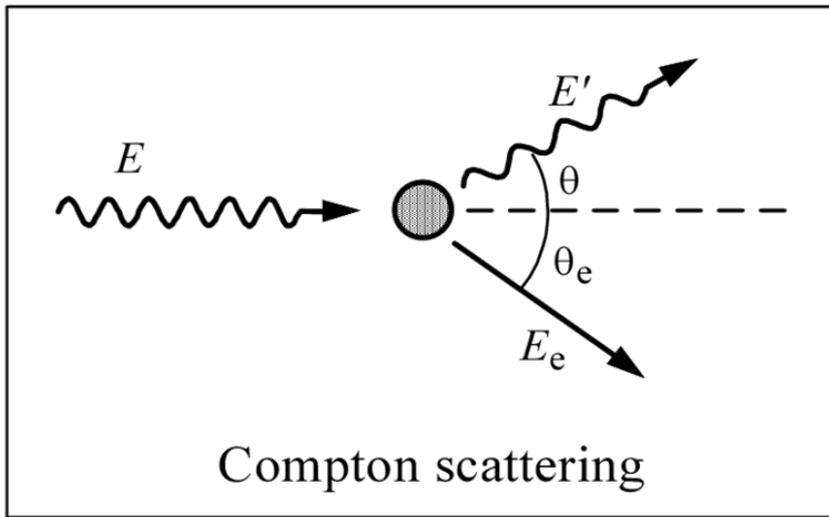
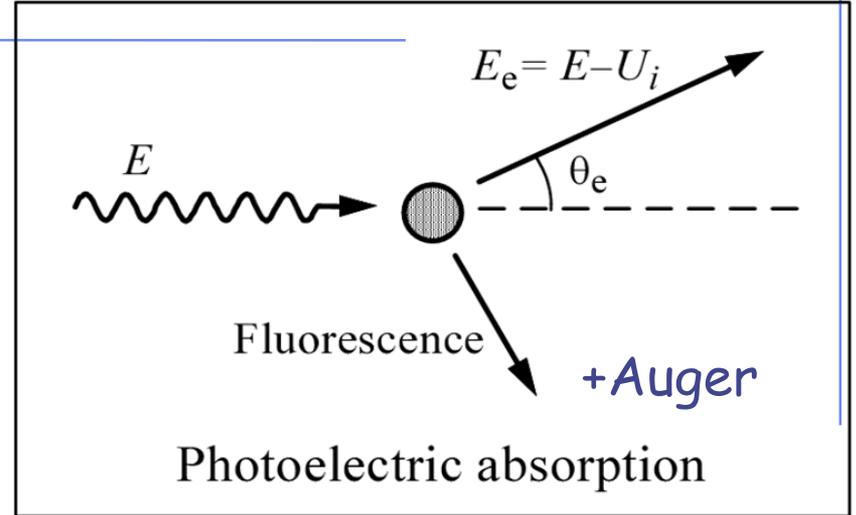
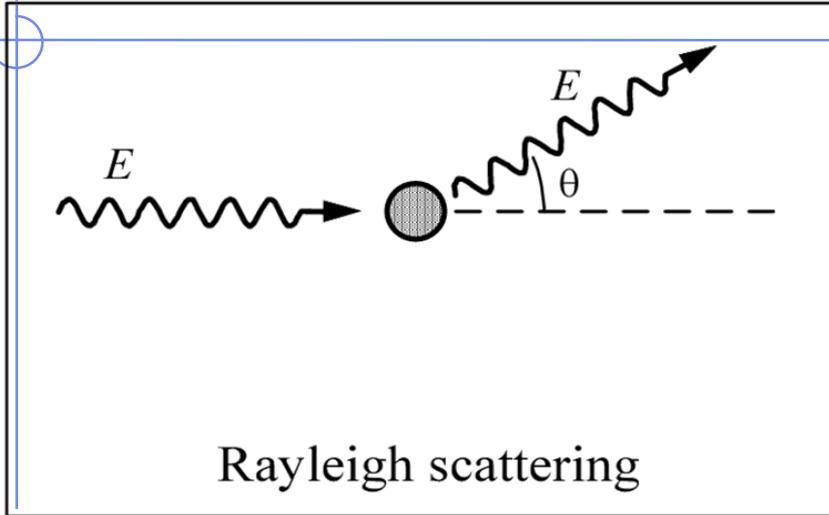
# Bremsstrahlung and pair production by muons and charged hadrons (2/2)

- 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
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Flag > 0: Activate

Flag < 0: De-activate

EMFFLUO	Fluorescence: ▼	Mat: ▼	to Mat: ▼	Step:
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**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**

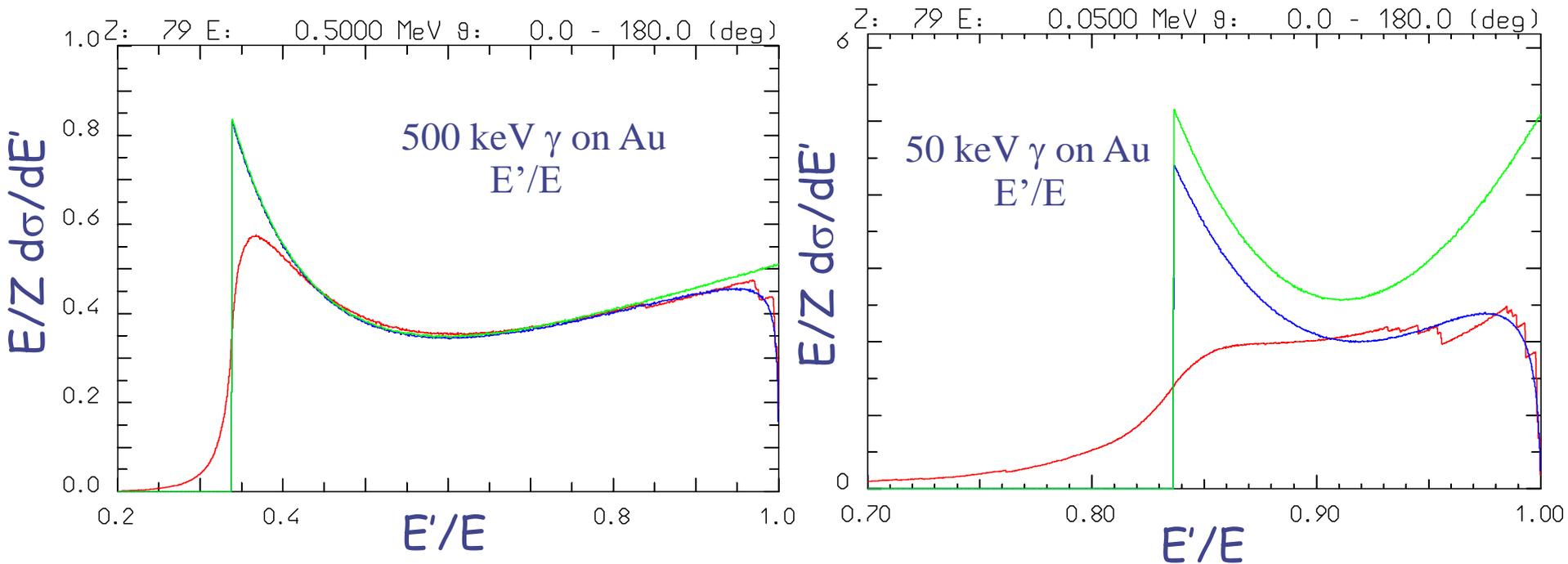
Inelastic Form Factors, Compton profile and Rayleigh scattering are activated only with a subset of DEFAULTS .

To activate/deactivate:

EMFRAY	Flag	Reg1	Reg2	Step
EMFRAY				
	Activate:			
	Reg:			
			to Reg: TARGS3	Step: 1
			W Disso: Proj&Target EM-Disso	
			Neigh: 5	Volume:
			Neigh: 5	Volume:
			Compton (bind+prof)	
			Nothing	

*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

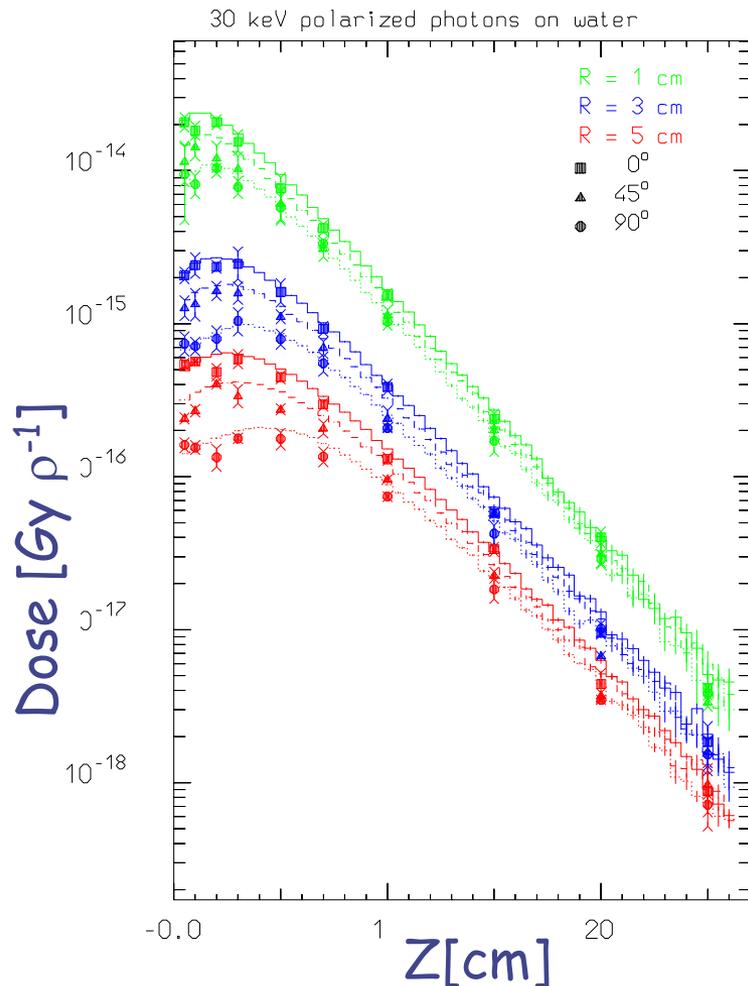
Larger effect at very low energies, where, however, the dominant process is photoelectric.

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
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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 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 ( $\gamma \equiv \rho, \Phi$  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 ▼	Δ resonance On ▼	Quasi D On ▼
	Mat: ▼	to Mat: ▼
		Giant Dipole off ▼
		Step:

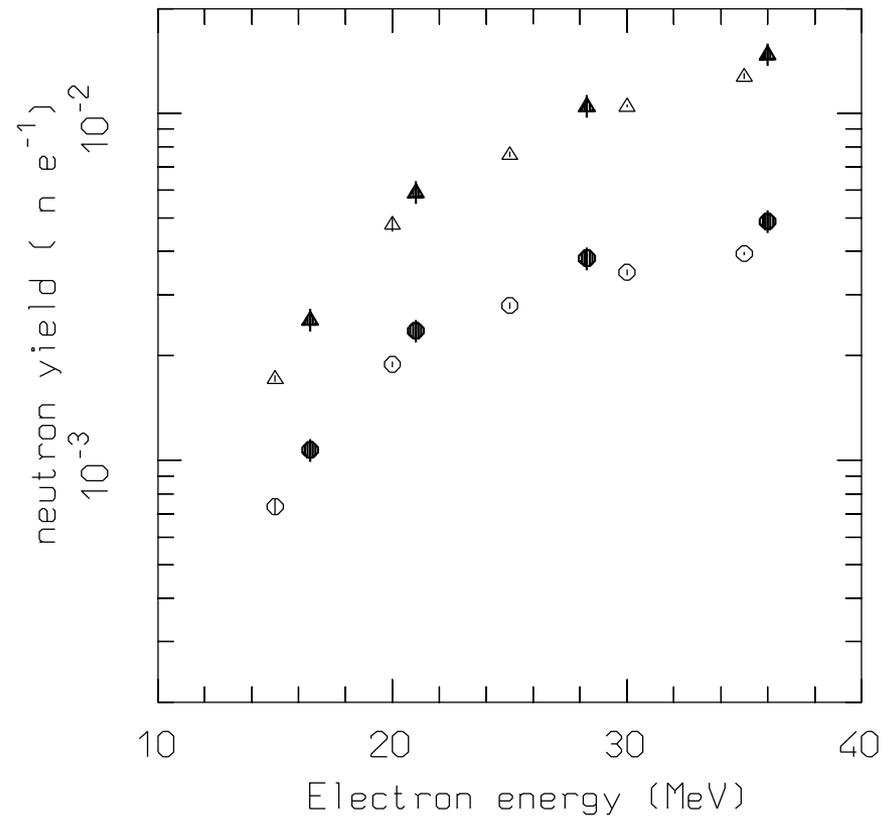
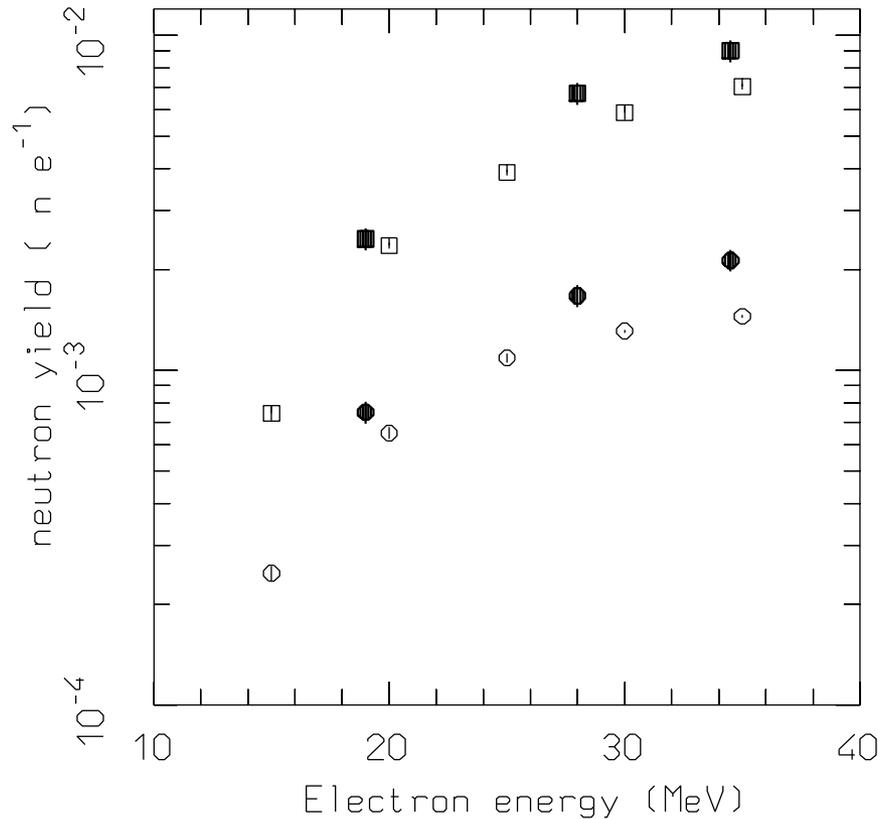
Since the photonuclear cross section is very small, **PHOTONUC** should be always accompanied by **LAM-BIAS** with SDUM = blank (see lecture on biasing)

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:

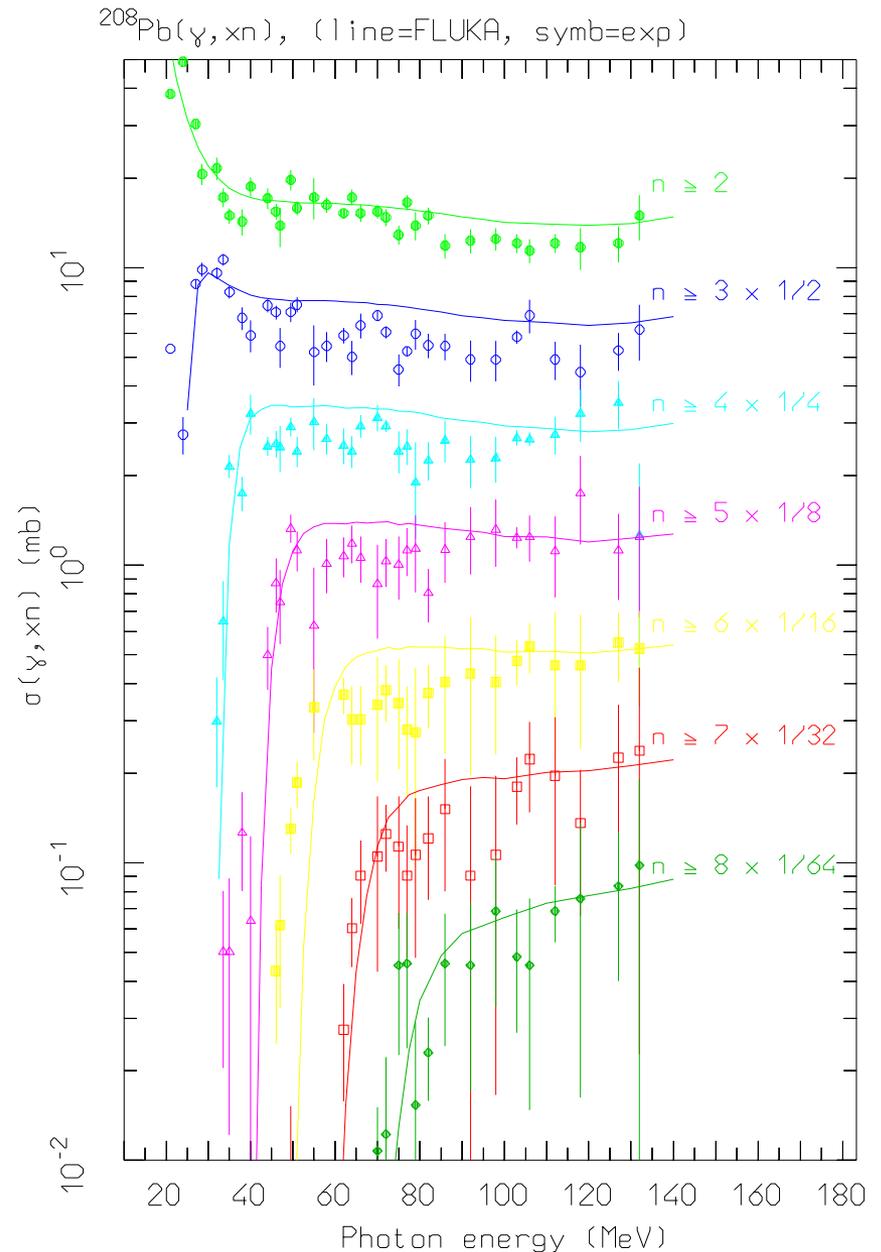


$$20 \leq E_\gamma \leq 140 \text{ MeV}$$

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

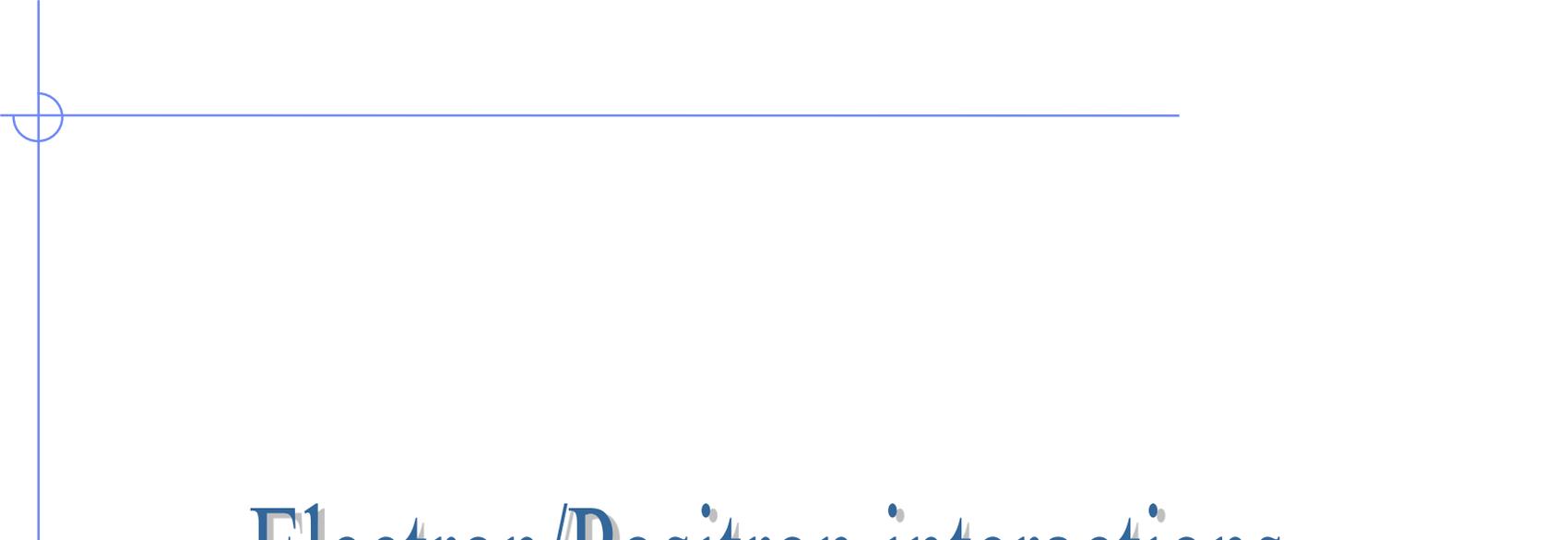
Muon pair production by photons is **NOT activated** with any default

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)

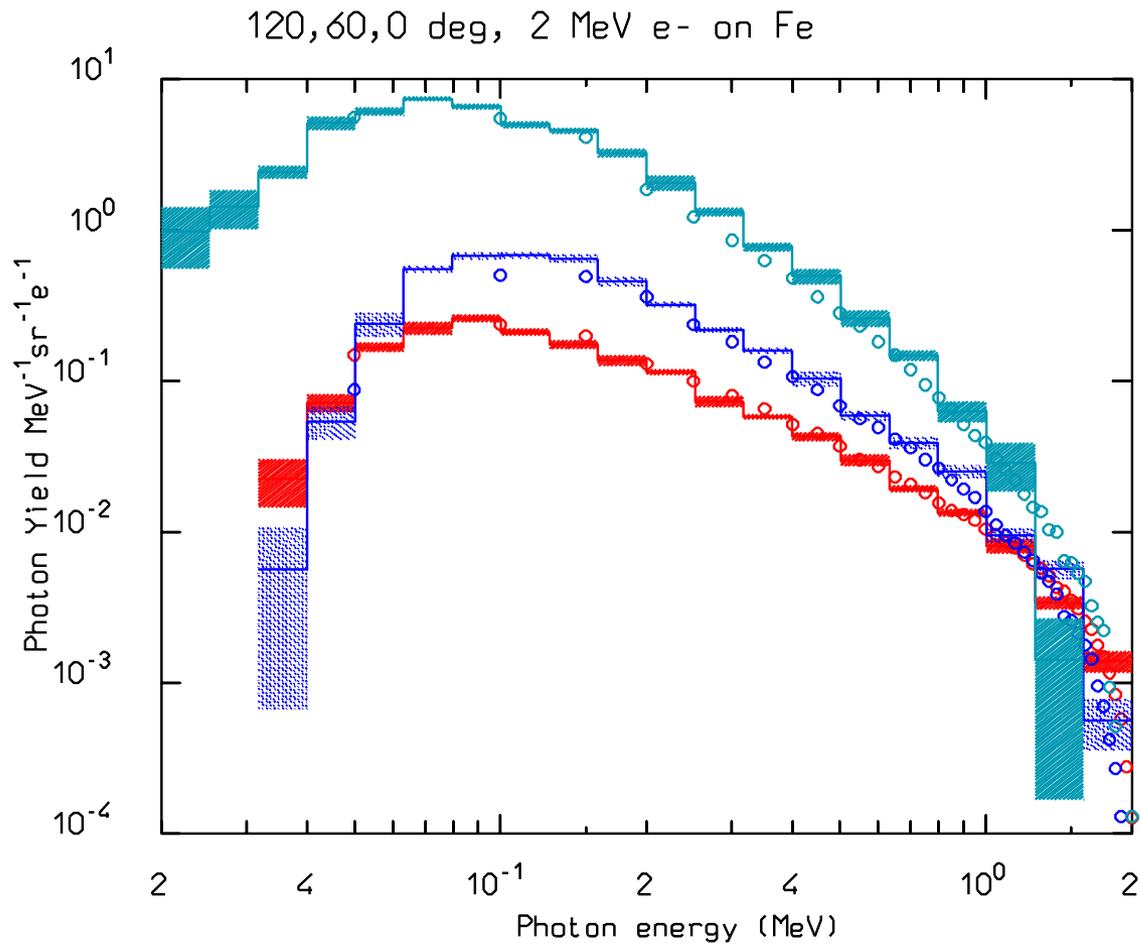


# Electron/Positron interactions

# e<sup>+</sup>/e<sup>-</sup> interactions modelled in FLUKA

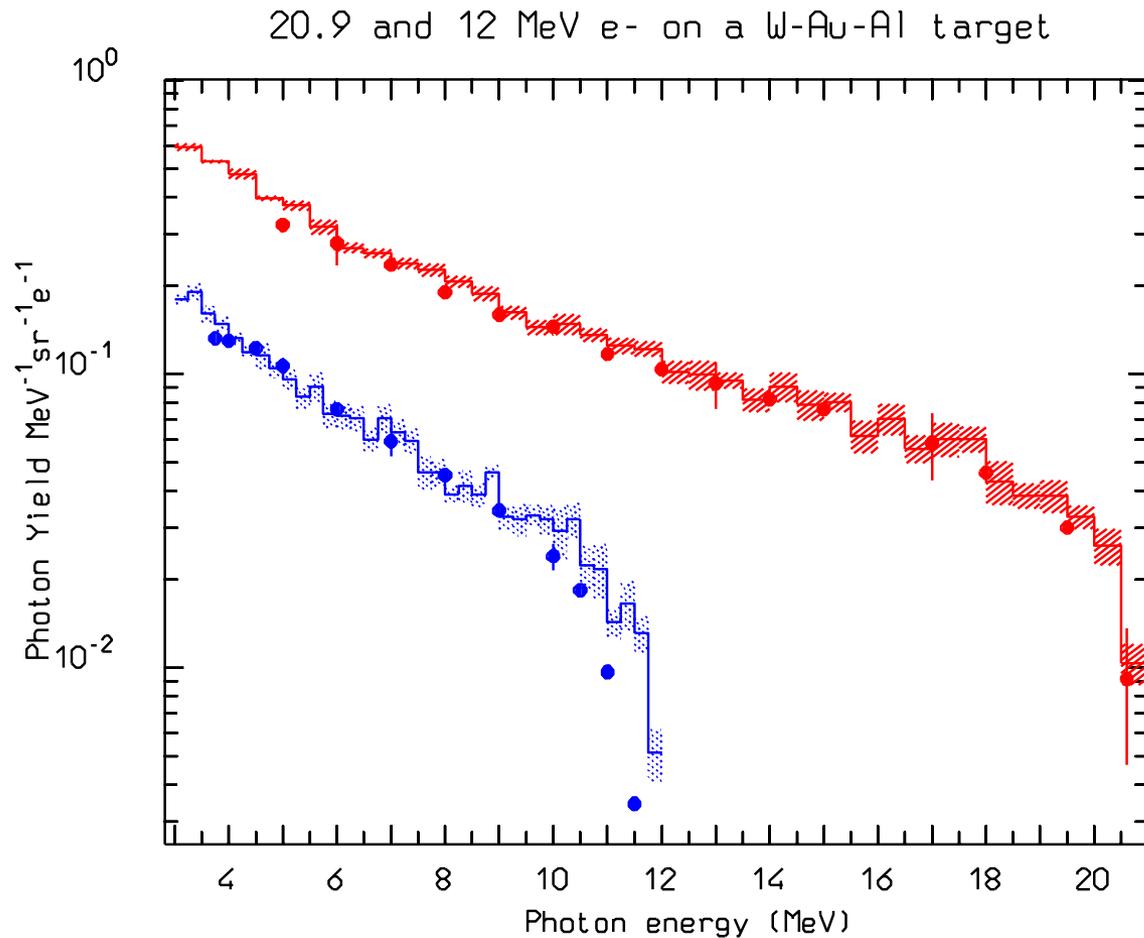
- Delta-ray production (-> EMFCUT)
  - Delta-ray production via **Bhabha** and **Moeller** scattering
- Bremsstrahlung production (-> EMFCUT)
  - Energy-differential cross sections based on the **Seltzer** and **Berger** database
  - Considers the **LPM** effect and the soft photon suppression (Ter-Mikaelyan)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

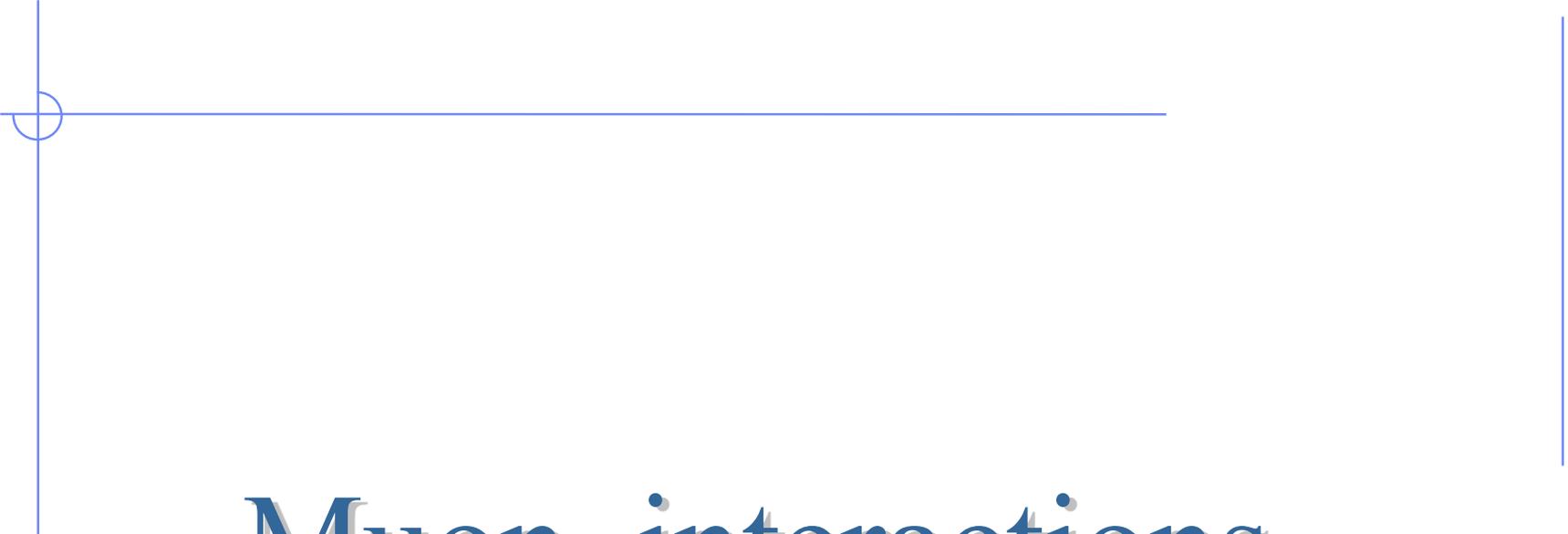


2 MeV electrons on Iron,  
Bremsstrahlung photon spectra  
measured (dots)  
and  
simulated (histos)  
at three different  
angles

# 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)

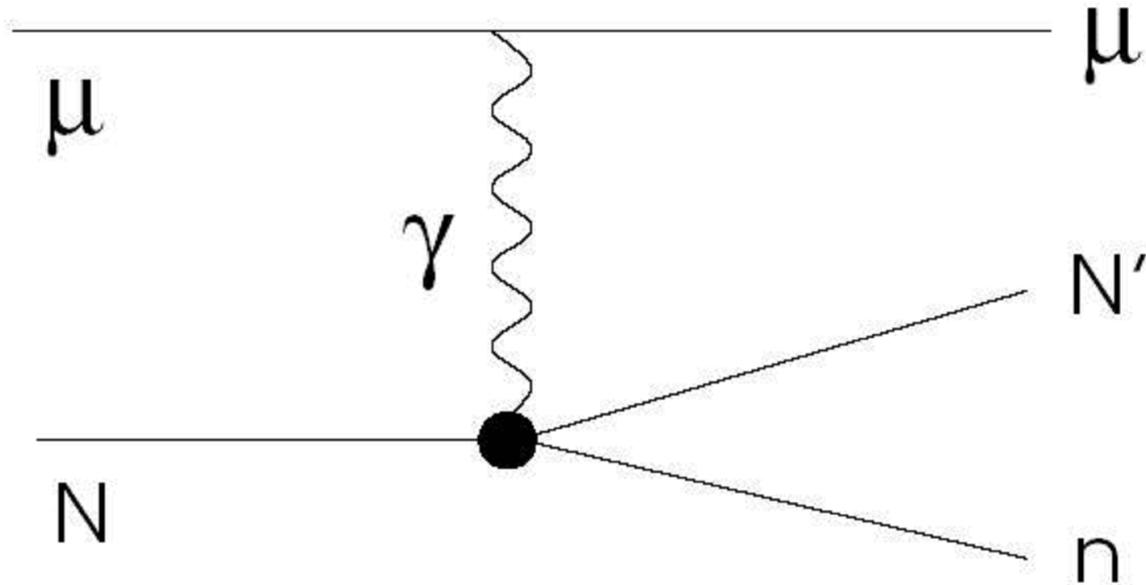


# Muon interactions

# 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  $\mu$  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 reactions: options

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

To activate them:

MUPHOTON	Flag	0.0	0.0	Mat1	Mat2	Step
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MUPHOTON configuration window showing options for  $\mu$  Inter,  $\sigma$  long/trans, and  $\rho$  inter. The 'Mat:' dropdown menu is open, showing options: ignore, Full, No secondaries, and reset. The 'to Mat:' dropdown is set to 5. The 'Step:' and 'Volume:' fields are also visible.

**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)

LAM-BIAS	0.0	Factor	Mat	MUON+	MUON-
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# Muon capture

An exotic source of neutron background

Basic weak process:  $\mu + p \rightarrow \nu_{\mu} + n$

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

Competition between  $\mu$  decay  $\Lambda_d$  and absorption by nucleus  $\Lambda_c$

In FLUKA: Goulard-Primakoff formula

$\Lambda_c \div Z_{eff}^4$  Calculated  $Z_{eff}$ , Pauli blocking from data

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

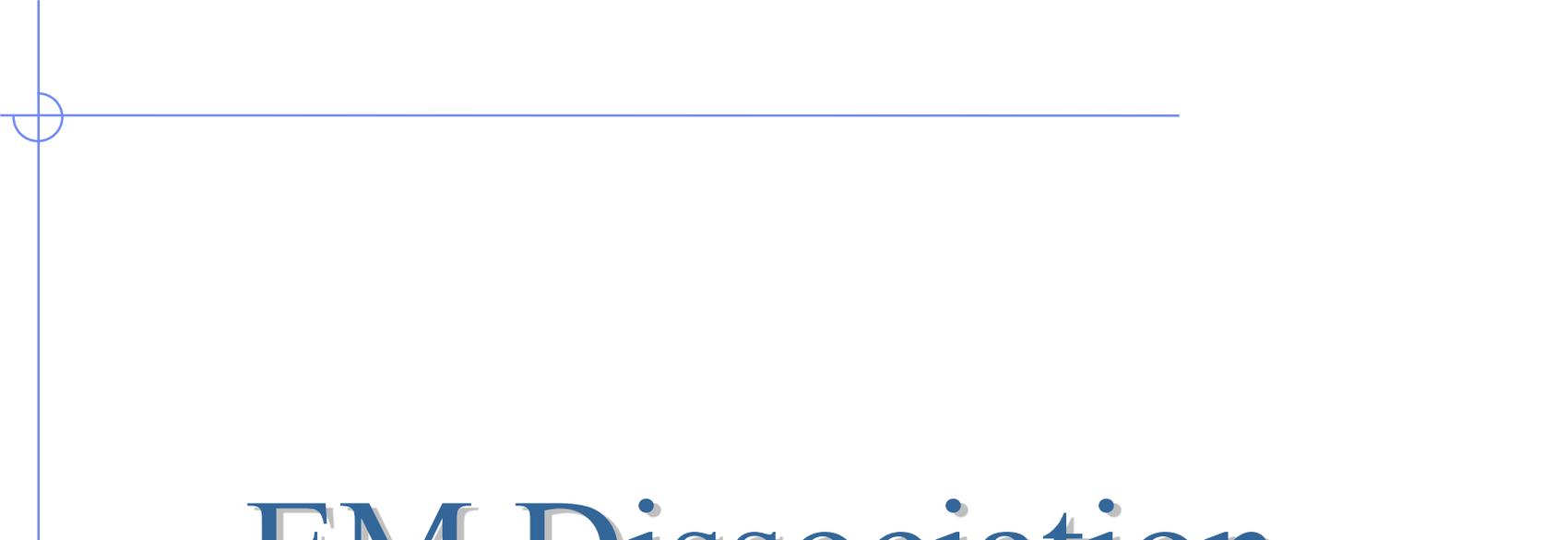
Nuclear environment from PEANUT

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

Experimentally: high energy tails in n-spectra

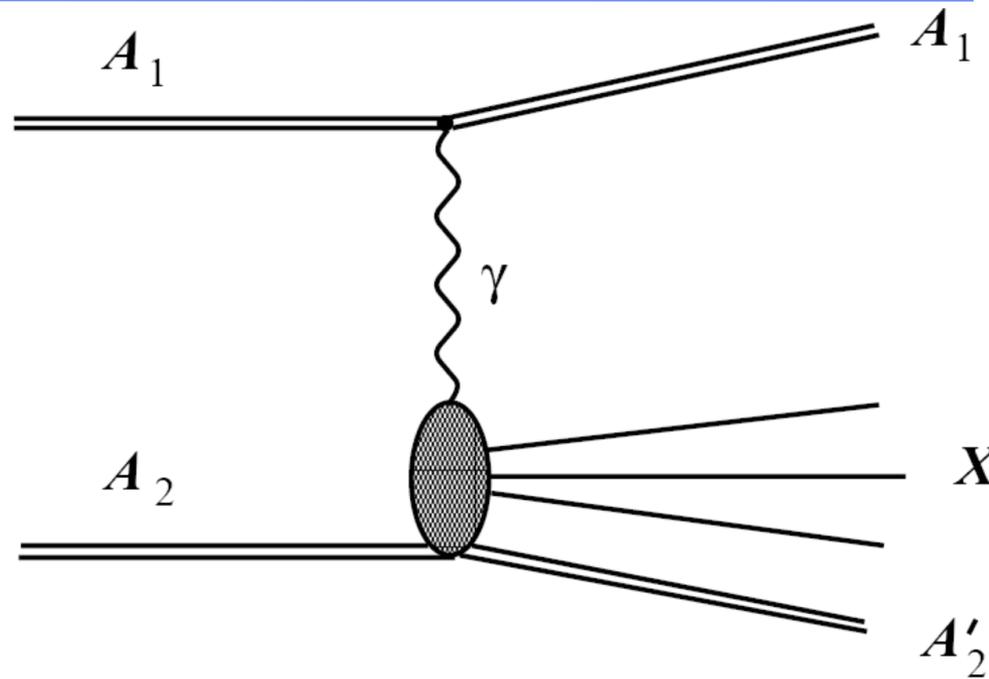
Beyond the simple one-nucleon absorption

Good results from addition of two-nucleon absorption



# EM Dissociation

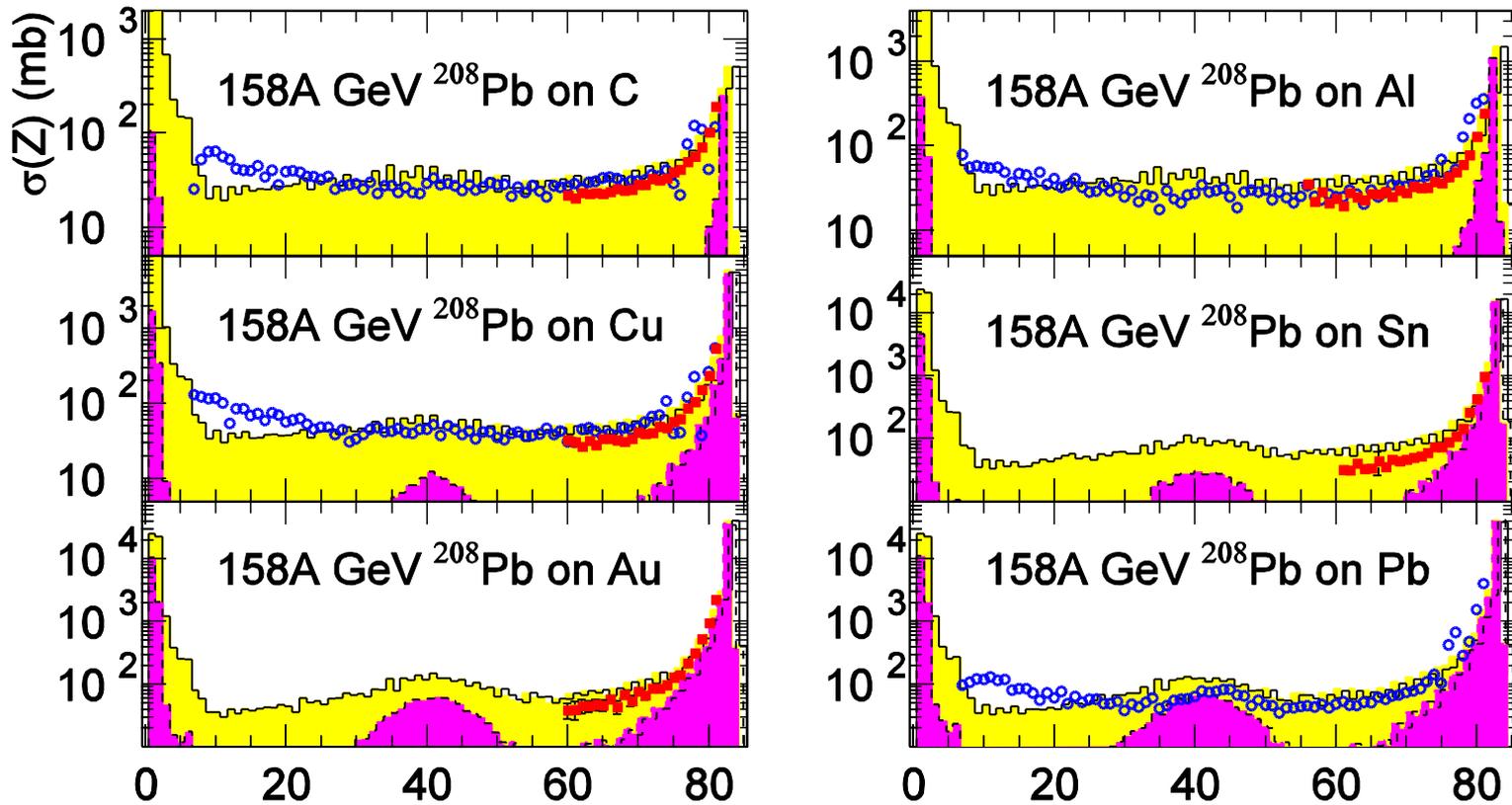
# Electromagnetic dissociation



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

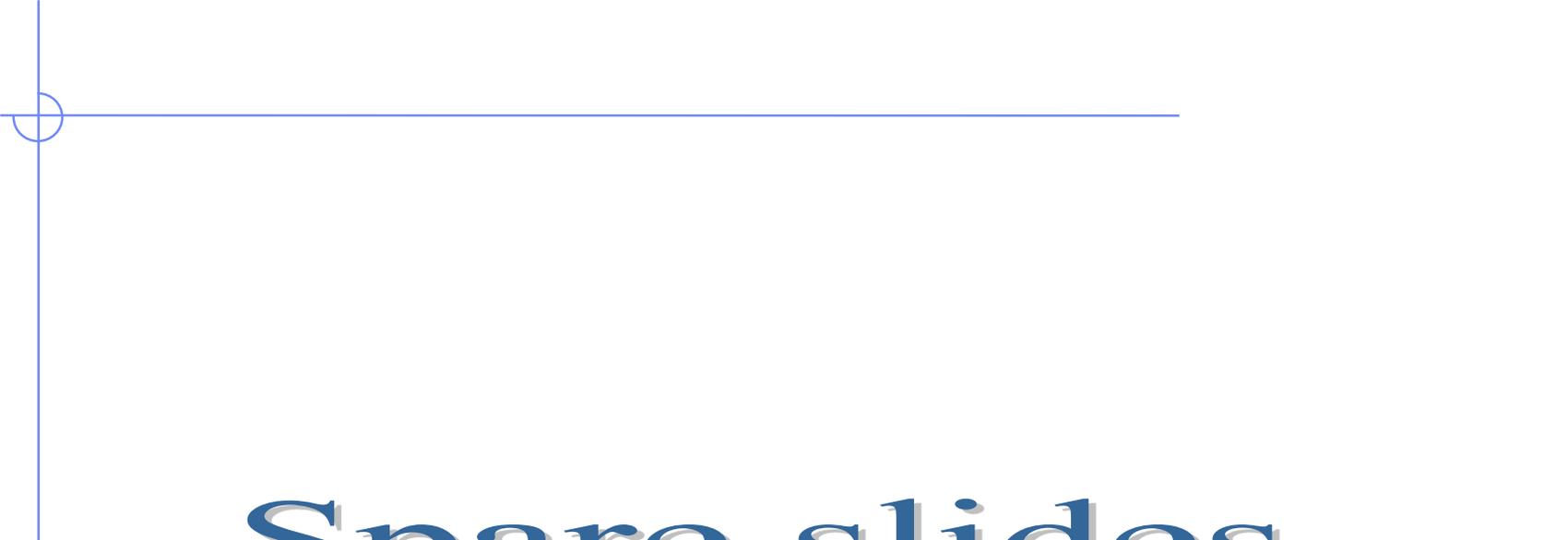
Note: Electromagnetic dissociation is already relevant for interactions of few GeV/n ions in heavy targets.

# 158 GeV/n Pb ion fragmentation



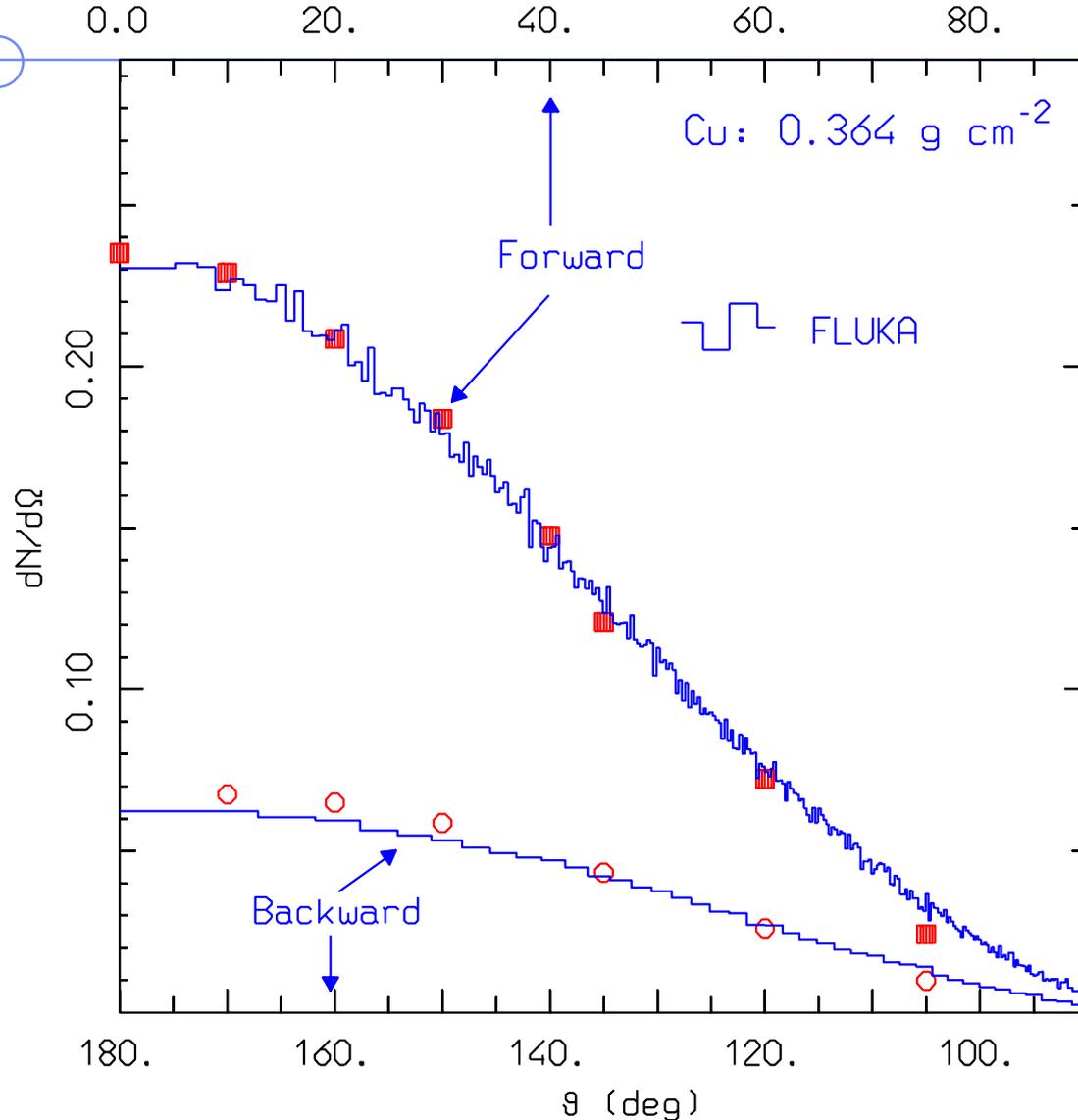
Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), yellow hists are FLUKA (with DPMJET-III) predictions: purple hists are the electromagnetic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

Z



**Spare slides**

# Electron scattering:



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

# Bremsstrahlung: benchmark III

Esposito et al., LNF 93-072

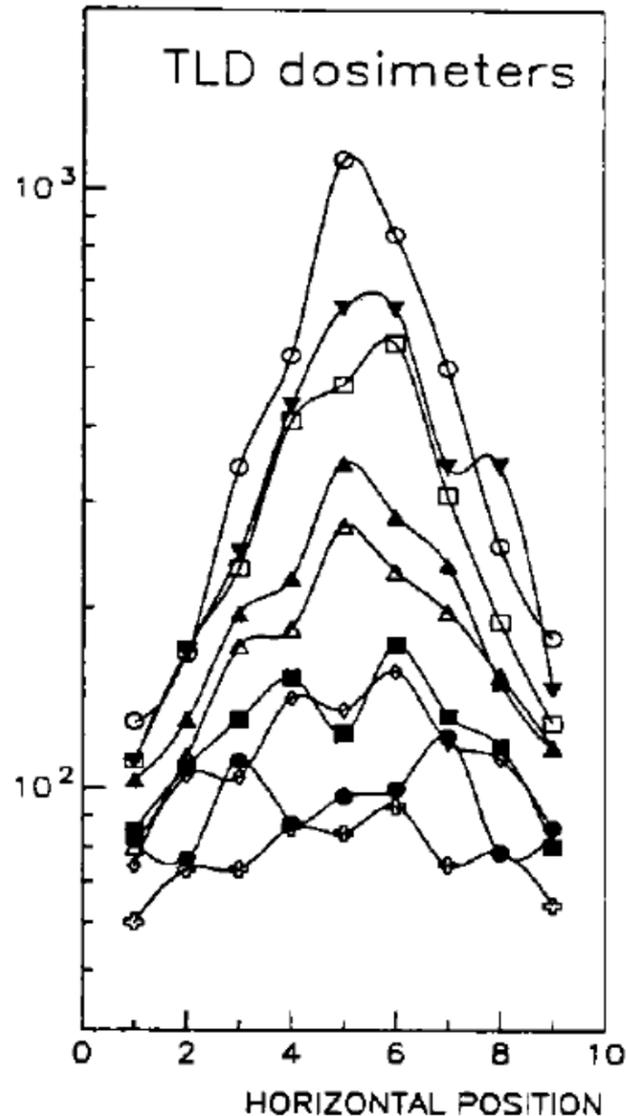
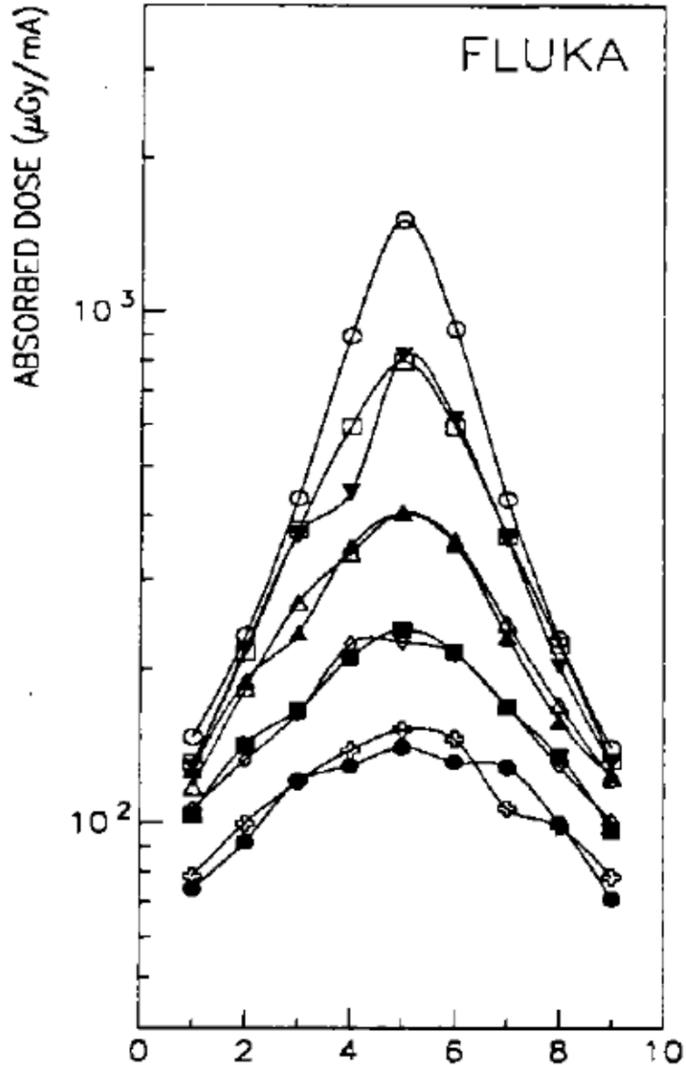
ADONE storage ring

1.5 GeV  $e^-$

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,  $d=218\text{cm}$

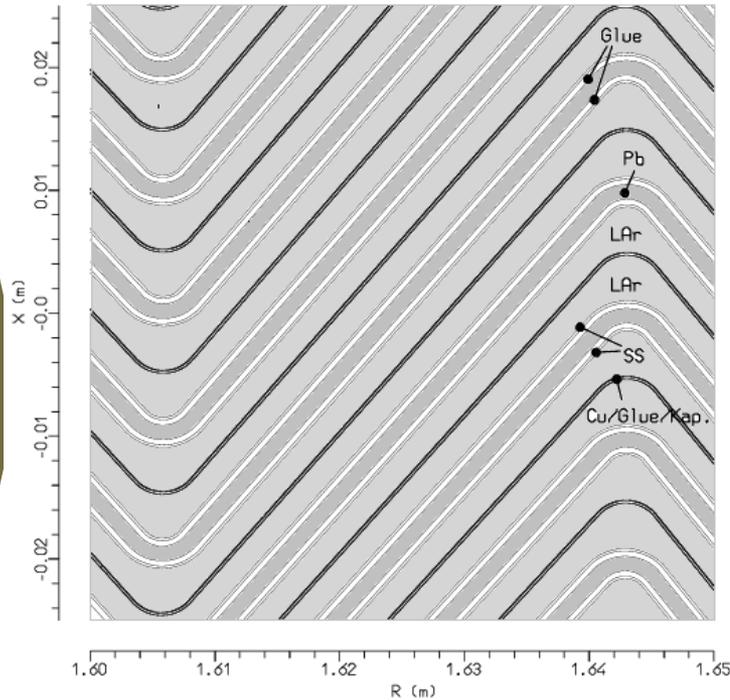


# The ATLAS EM "accordion" calo (standalone test beams)

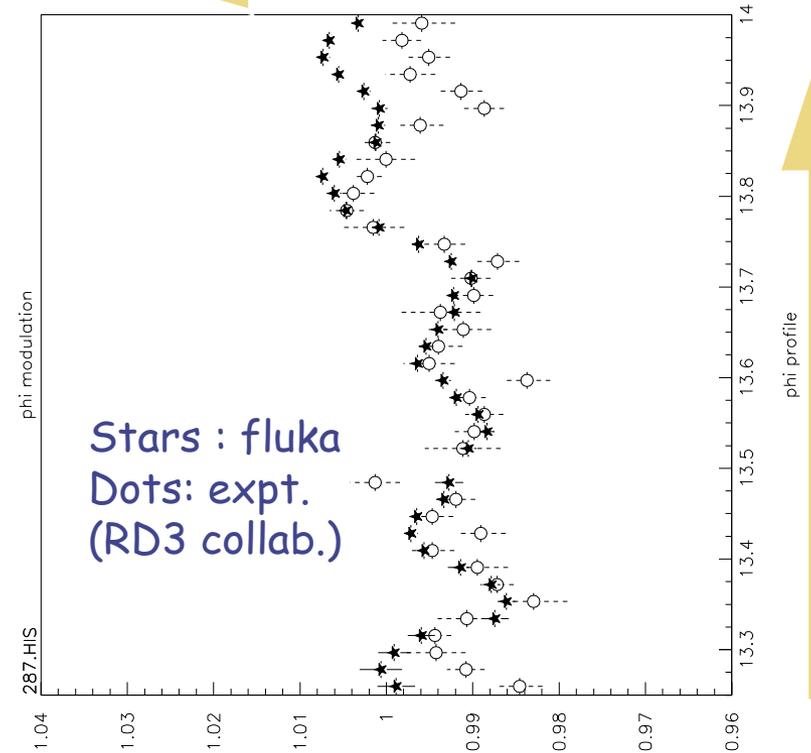
Detail of the FLUKA geometry and

response vs. electron impact position

287 GeV  
electron  
beam



deposited energy



impact position

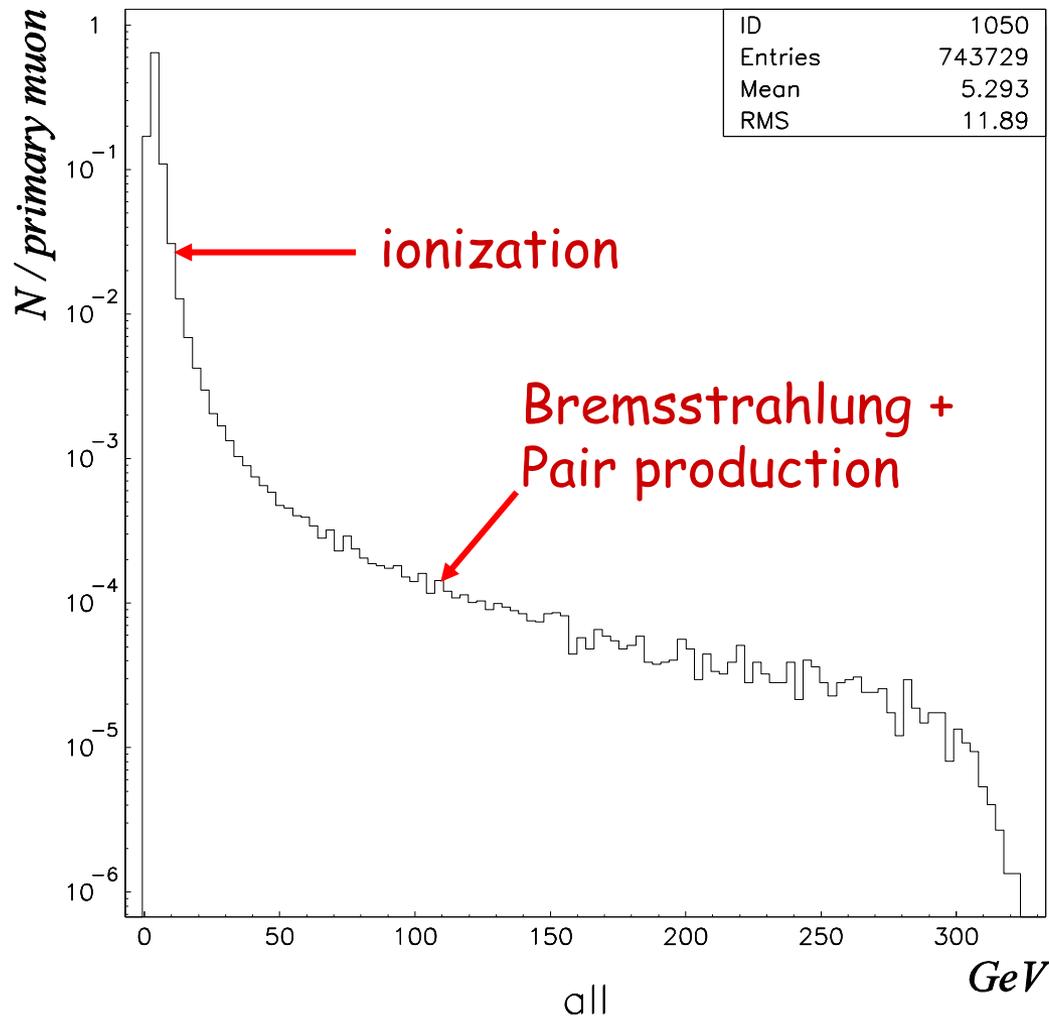
Energy resolution 10-100 GeV:

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

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

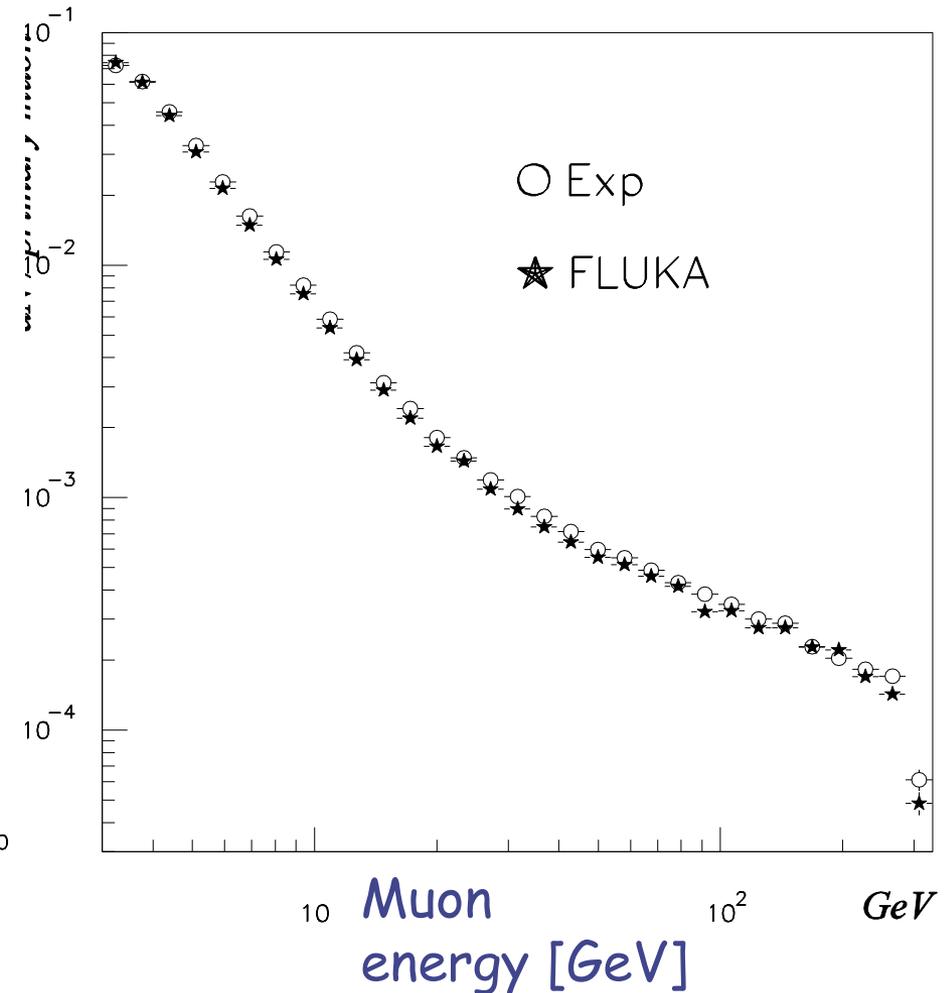
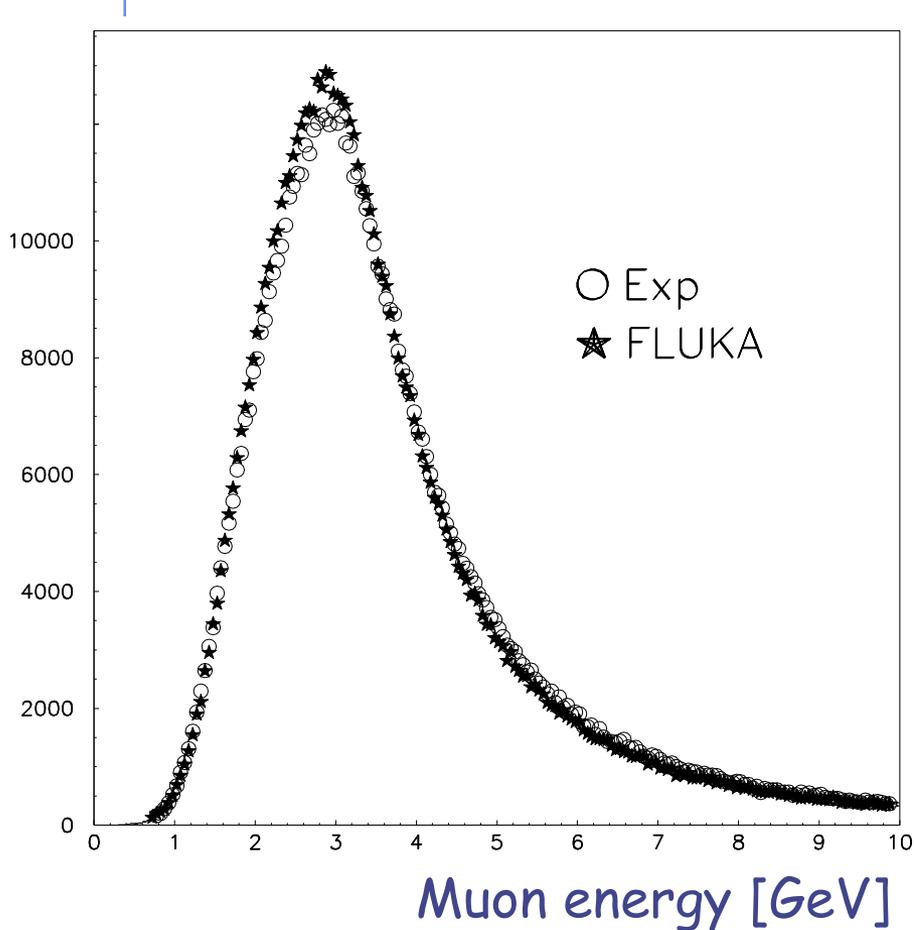
# Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure



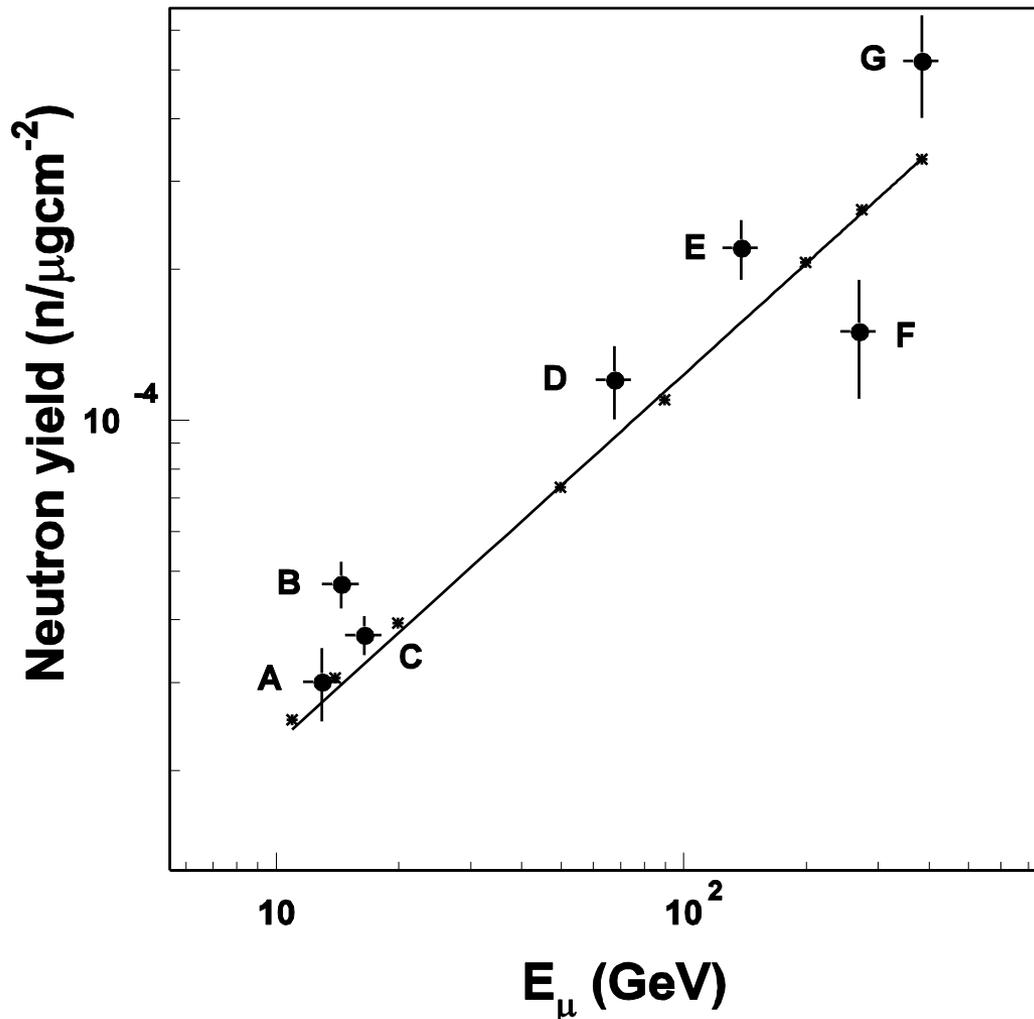
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# Muon-induced neutron background in underground labs

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.

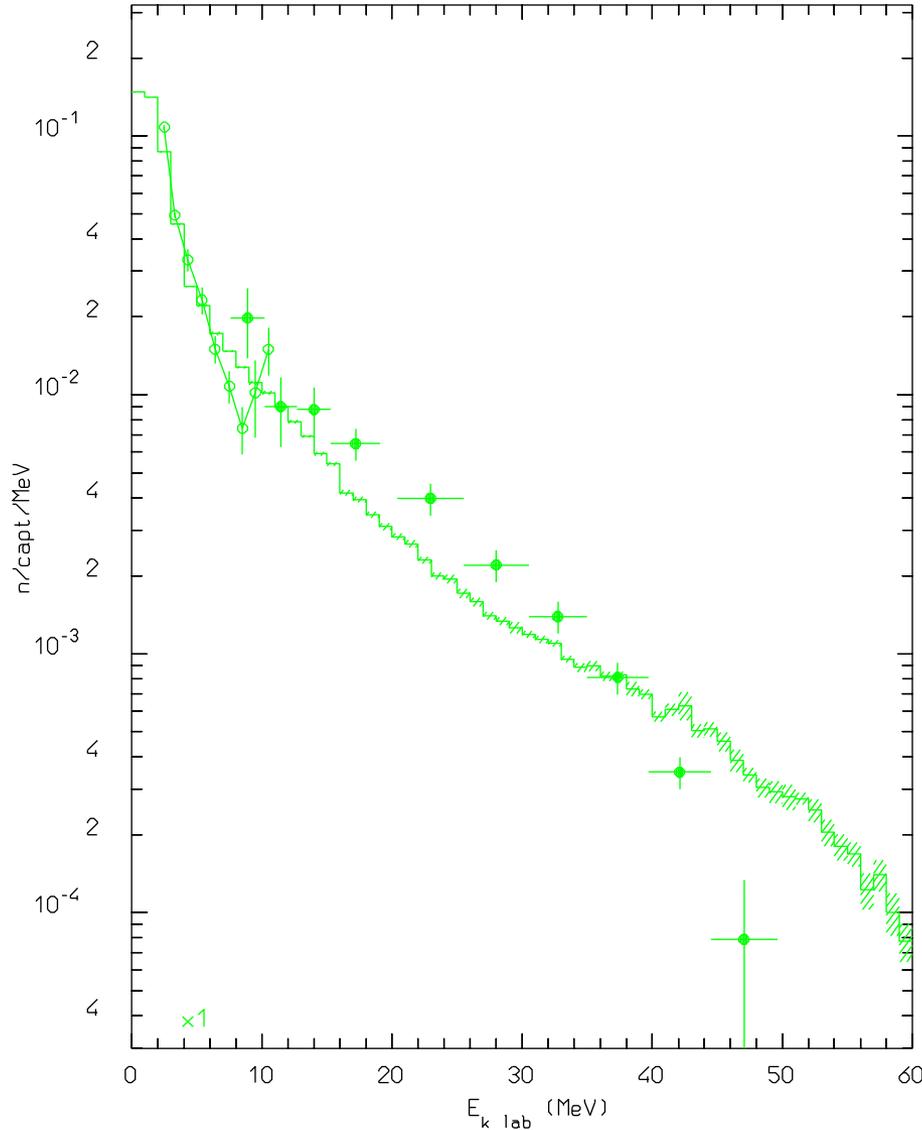
F) 3650 m.w.e. (LVD)

G) 5200 m.w.e. (LSD)

m.w.e. = meter of water equivalent

# Muon Capture (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) )

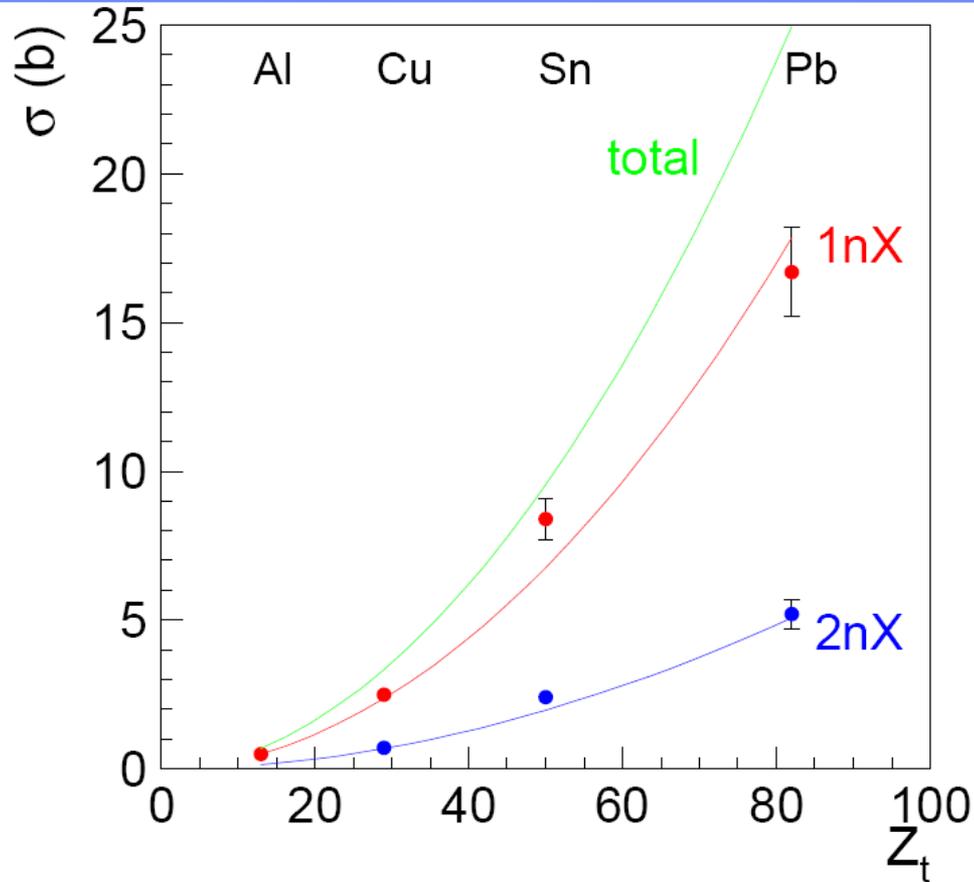
histograms: FLUKA calculations

Emitted:

0.62 neutrons/capture

0.27 protons/capture

# Electromagnetic dissociation - Benchmarks

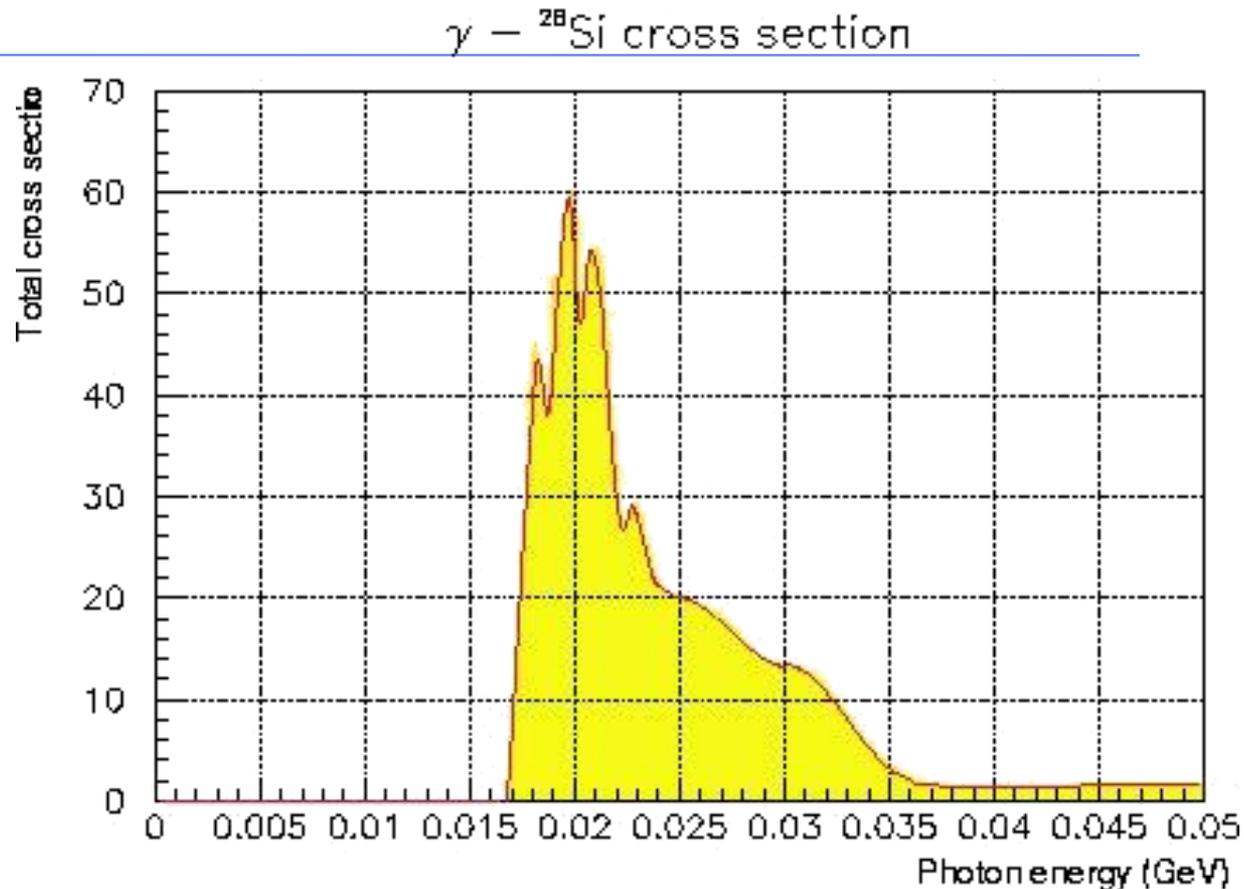


Electromagnetic dissociation cross sections (total, 1nX, 2nX) for 30GeV/n Pb ions on Al, Cu, Sn, and Pb targets.

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

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

# Electromagnetic dissociation: example



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