EM interactions

Beginners' FLUKA Course
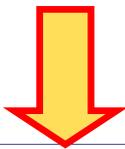
Topics

- 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

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±Thresh    γThresh    0.0    Reg1   Reg2    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±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: 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.
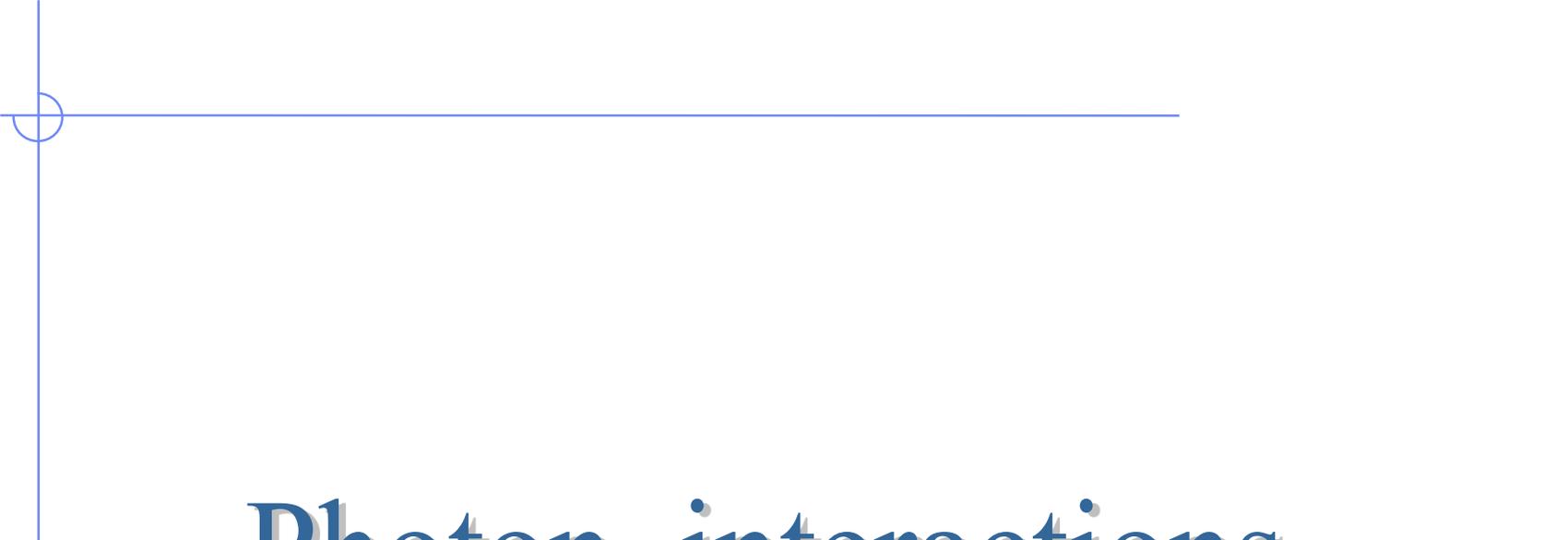
Photon interactions

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**

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
```

Look in the manual for further details

Compton profile examples

Z: 79 E: 0.5000 MeV θ: 0.0 - 180.0 (deg)

500 keV γ on Au
E'/E

Z: 79 E: 0.0500 MeV θ: 0.0 - 180.0 (deg)

50 keV γ on Au
E'/E
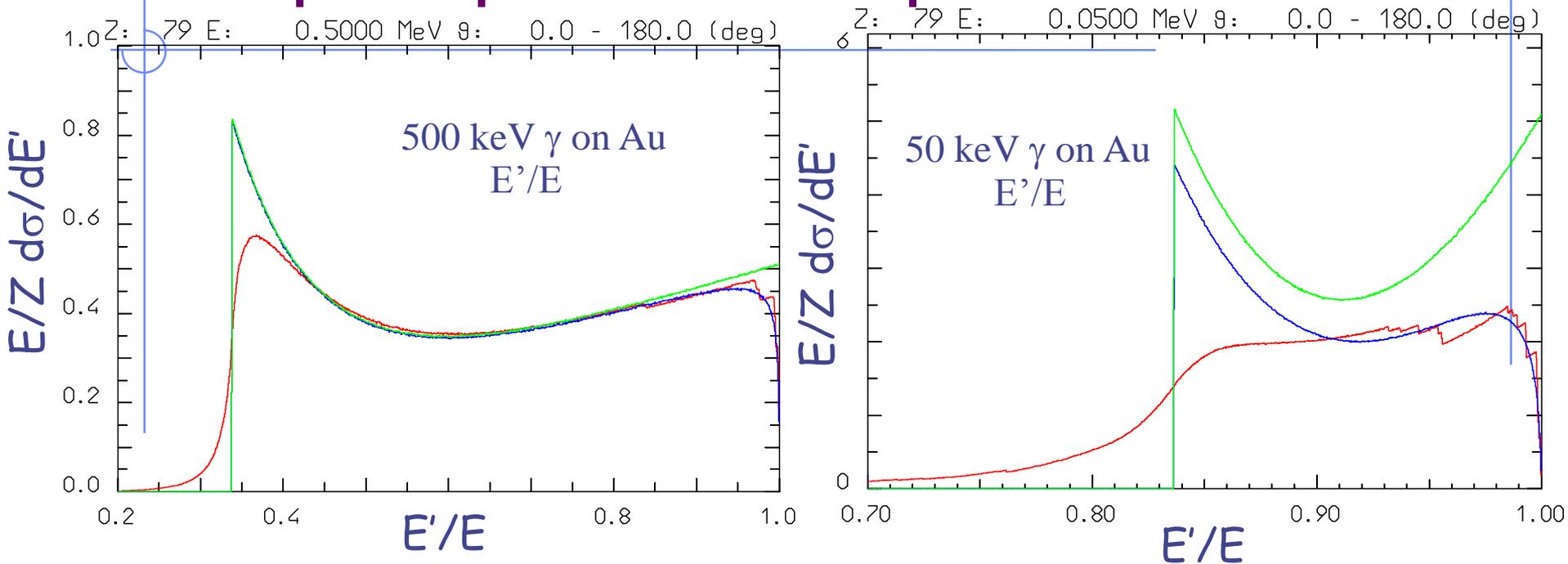
green = free electron
blue   = binding with form factors
red   = binding with shells and orbital motion

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

30 keV polarized photons on water

R = 1 cm
R = 3 cm
R = 5 cm

0°
45°
90°
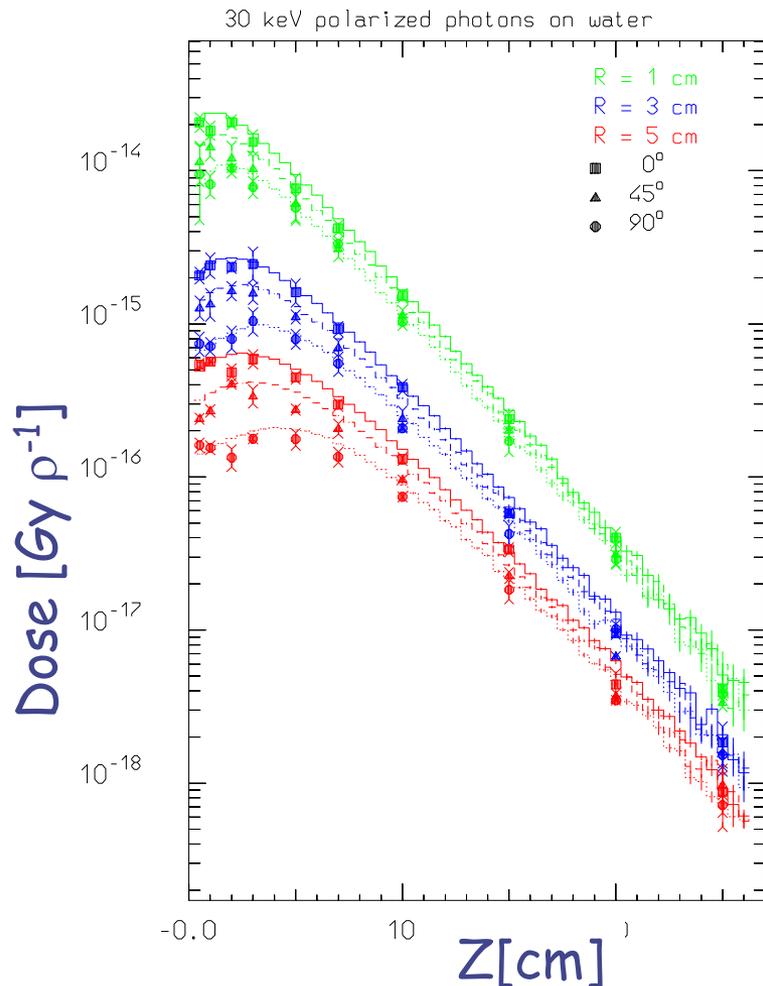
Flag1 >= 1 ➔ Pol. direction orthogonal to direction of motion,
Fraction + flag2 ➔ fraction of polarized/unpolarized or polarized/orthogonally polarized photons *(see the manual for further details)*

Effect of photon polarization
Deposited dose
by 30 keV photons 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

- 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) ➜ 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
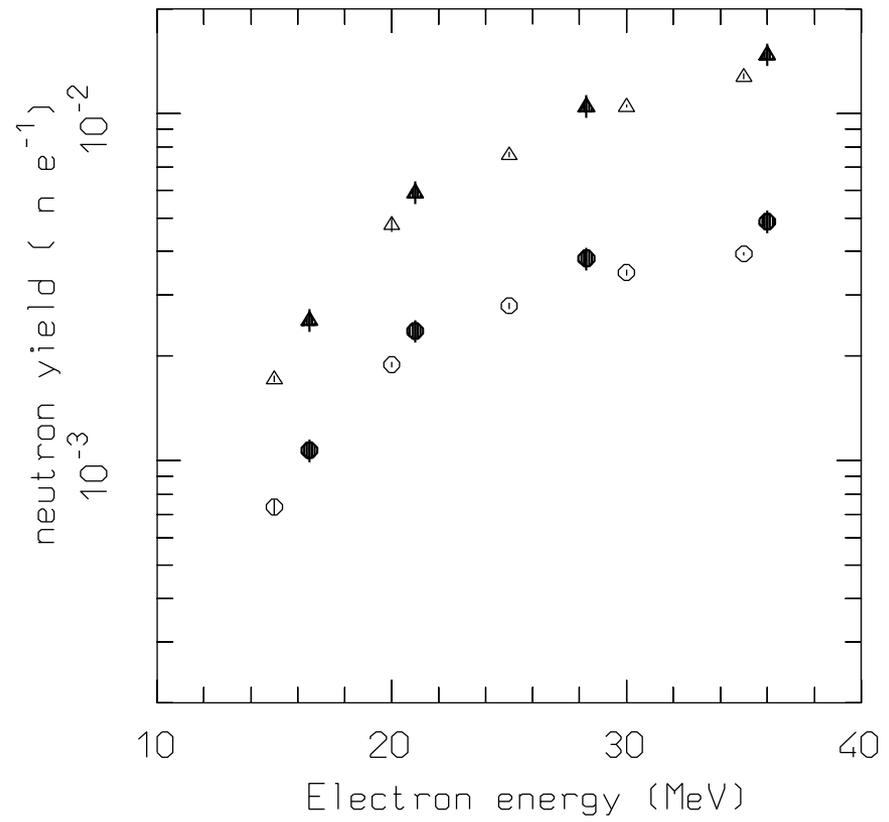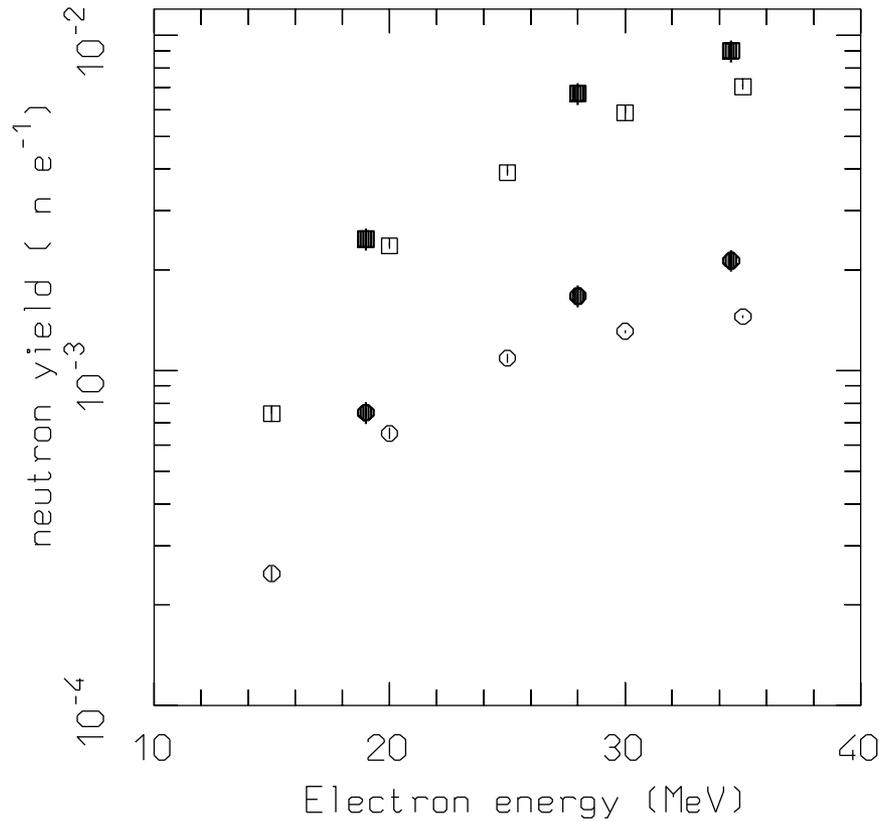
Yield of neutrons per incident electron as a function of initial e⁻ energy.
Open symbols: FLUKA, closed symbols: experimental data (Barber and George, Phys. Rev. 116, 1551-1559 (1959))
Left: Pb, 1.01 X_0 (lower points) and 5.93 X_0 (upper)
Right: U, 1.14 and 3.46 X_0

Photonuclear int.: example

Reaction:
^{208}Pb(γ,x n)
$20 \leq E_\gamma \leq 140$ MeV

Cross section for multiple neutron emission as a function of photon energy, Different colors refer to neutron multiplicity $\geq n$, with $2 \leq n \leq 8$

Symbols: exp. data (NPA367, 237 (1981) ; NPA390, 221 (1982))

Lines: FLUKA

^{208}Pb(γ,xn), (line=FLUKA, symb=exp)
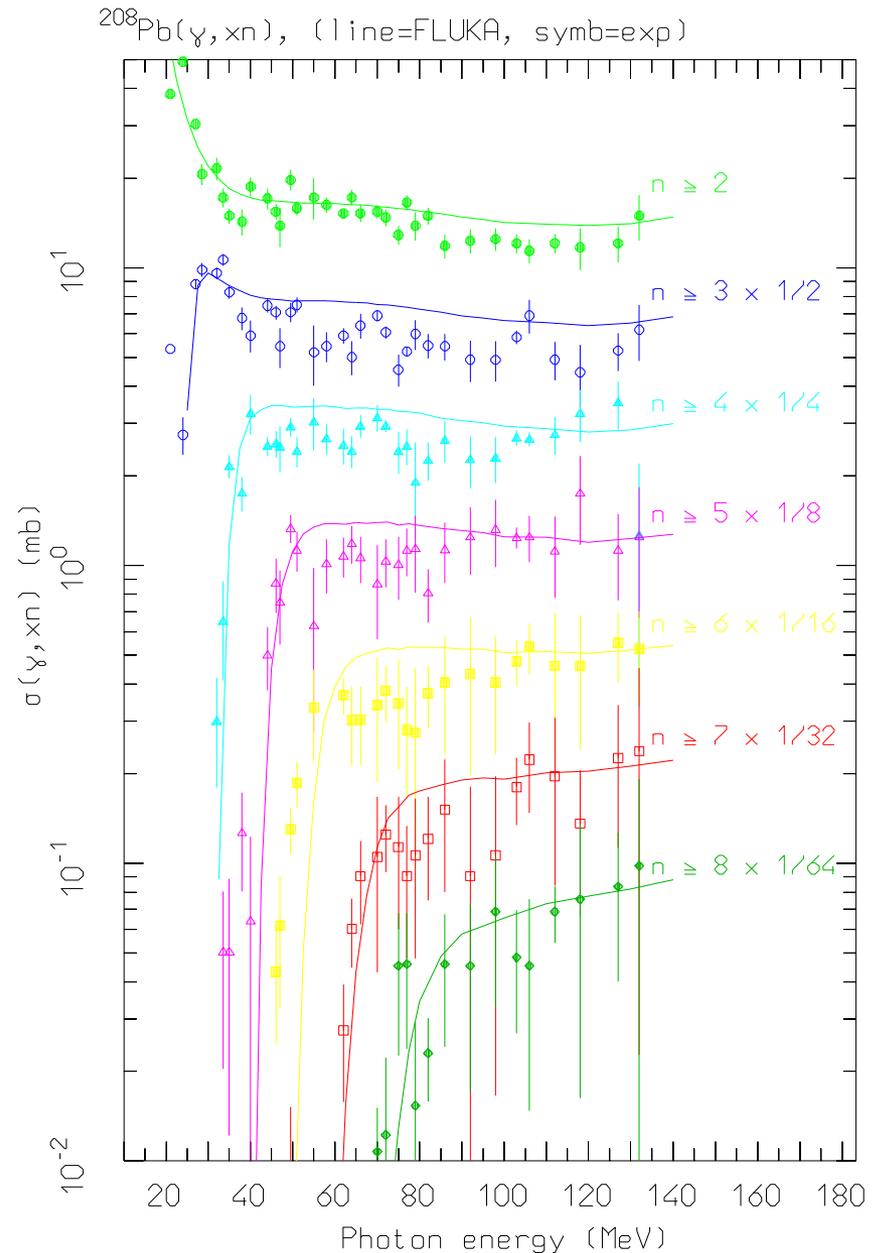
Photomuon production

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)
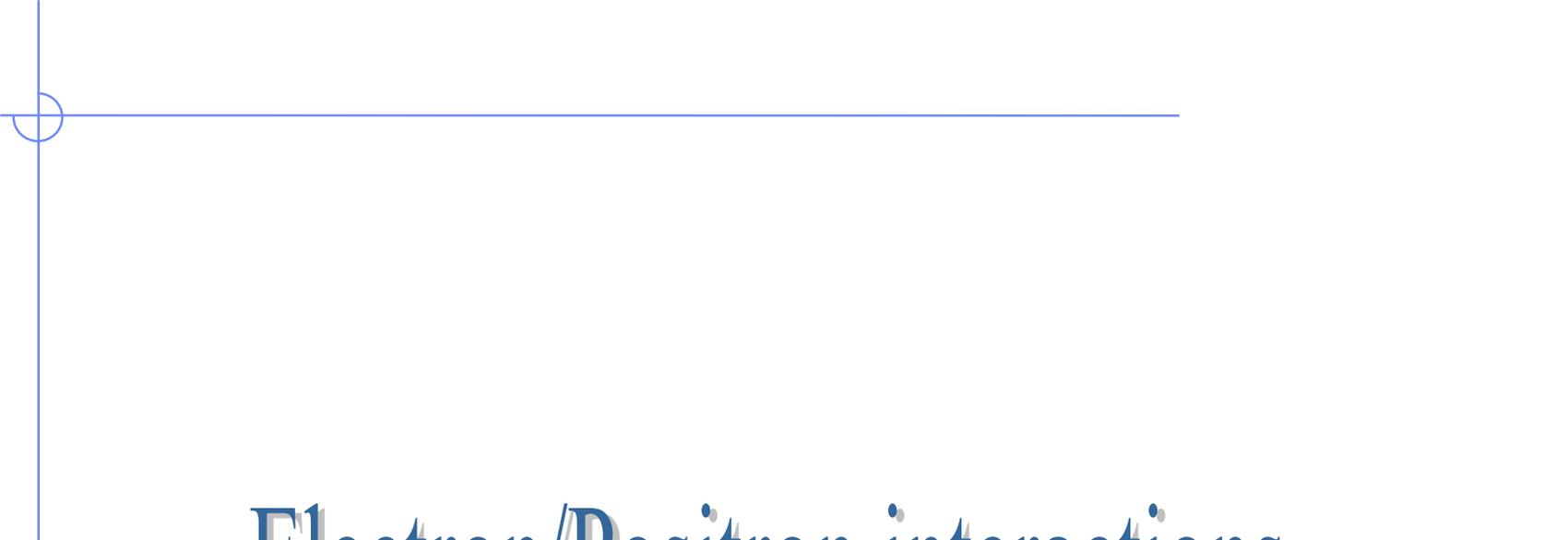
Electron/Positron interactions

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

120,60,0 deg, 2 MeV e- on Fe
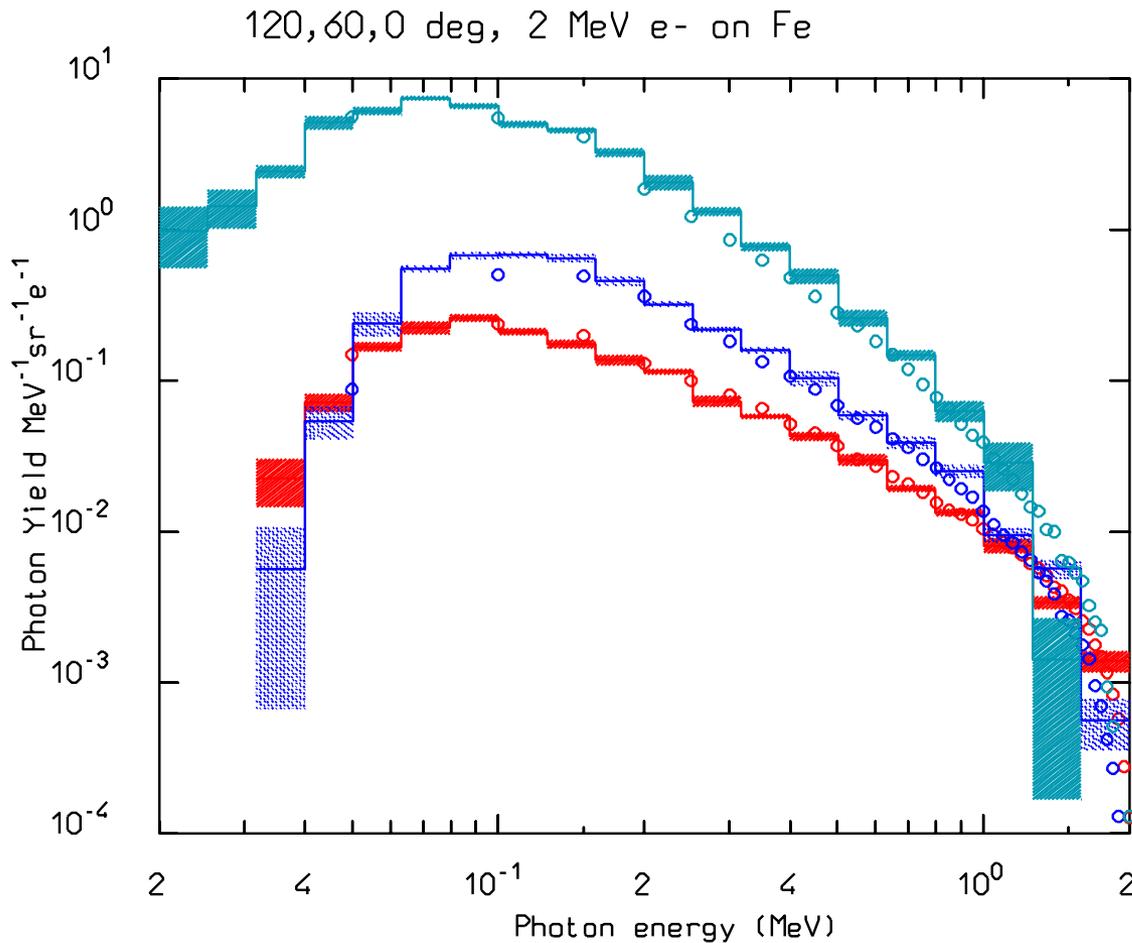
2 MeV electrons on Iron,
Bremsstrahlung photon spectra measured (dots)
 and
simulated (histos) at three different angles

Bremsstrahlung: benchmark II

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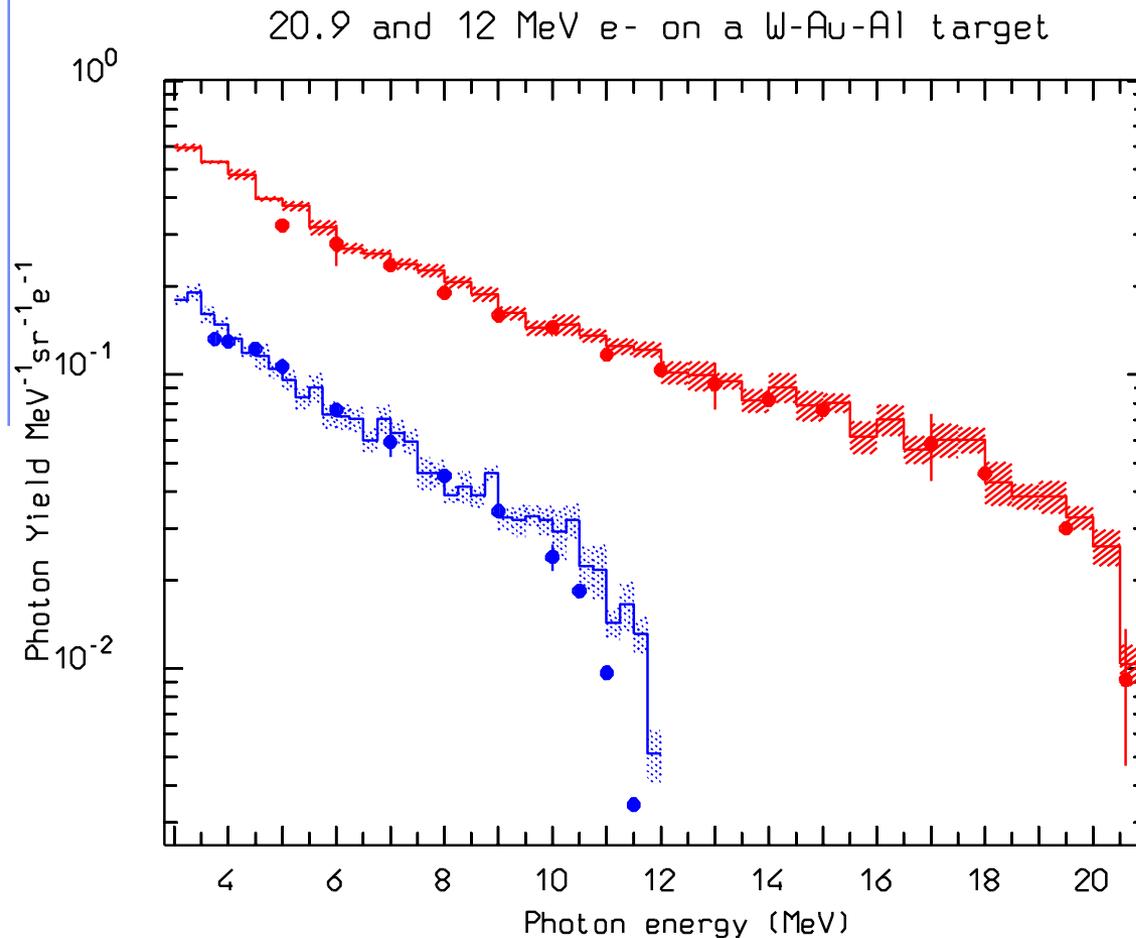
12 and 20.9 MeV electrons on a W-Au-Al target, bremsstrahlung photon spectra in the forward direction measured (dots) and simulated (histos)

# 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
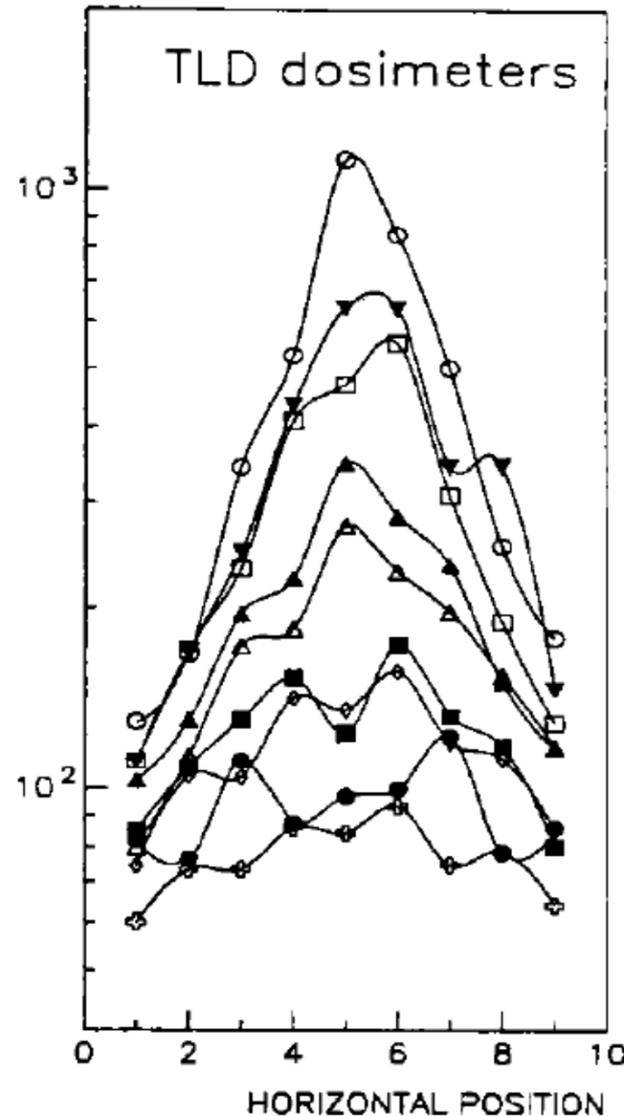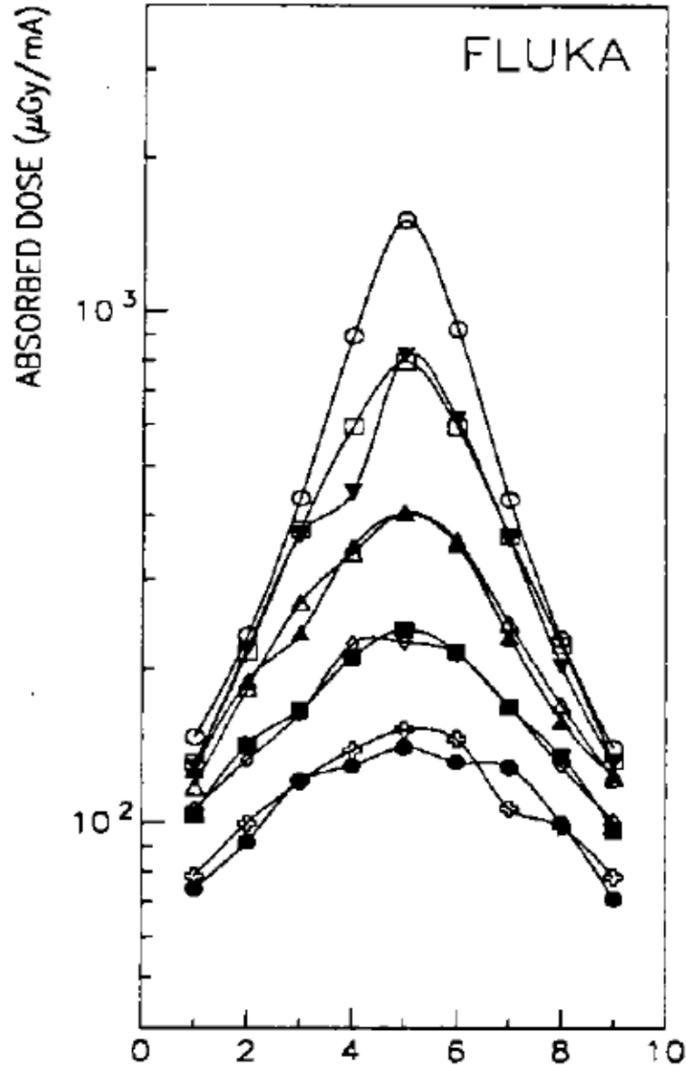
Other e± interactions

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:
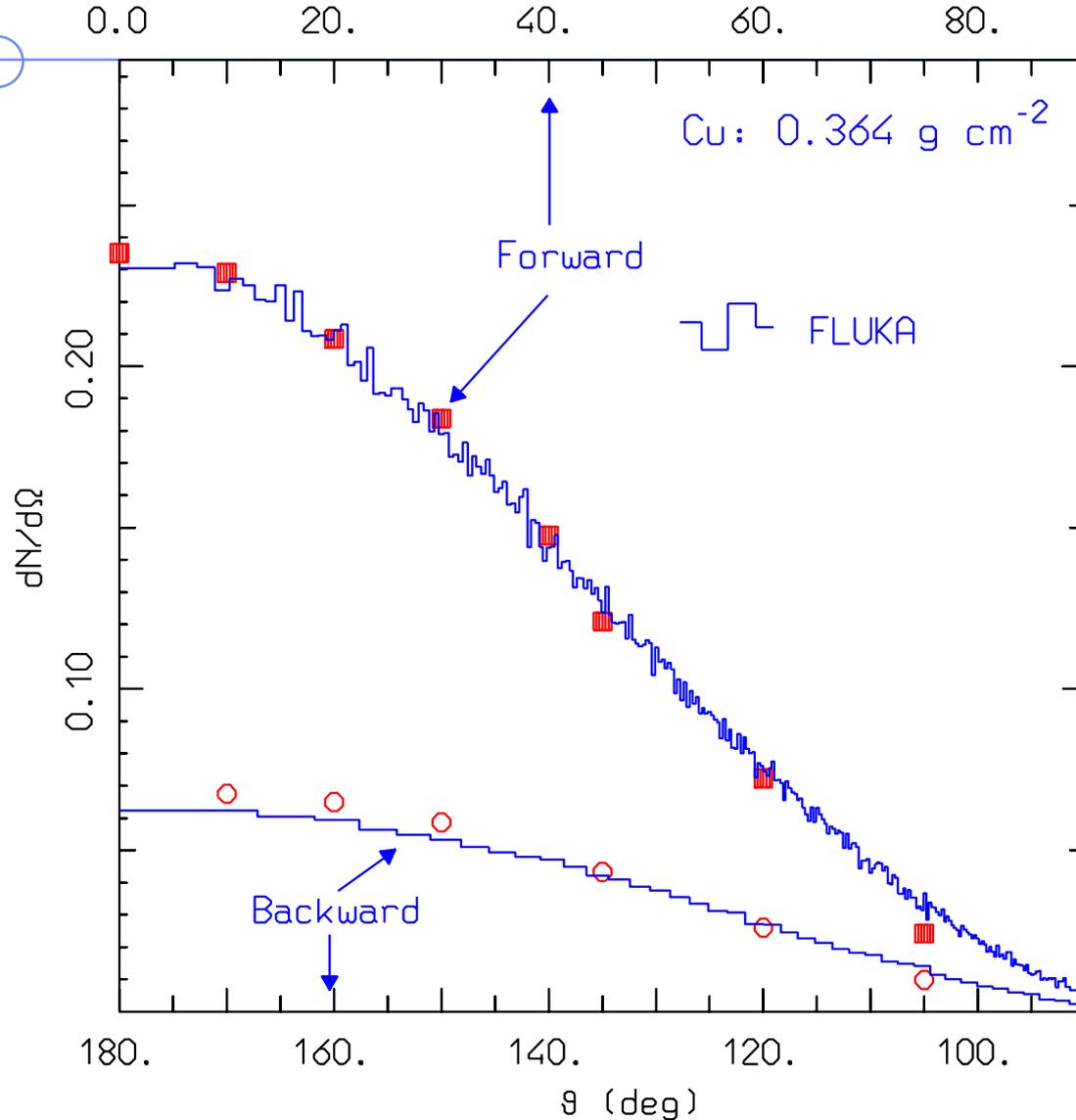
Transmitted (forward) and backscattered (backward) electron angular distributions for 1.75 MeV electrons on a 0.364 g/cm² thick Copper foil Measured (dots) and simulated (histos) data

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

Detail of the FLUKA geometry and

response vs. electron impact position

deposited energy

287 GeV electron beam

impact position

Glue

Pb

LAr

LAr

SS

Cu/Glue/Kap.

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

phi modulation

phi profile

287.HIS
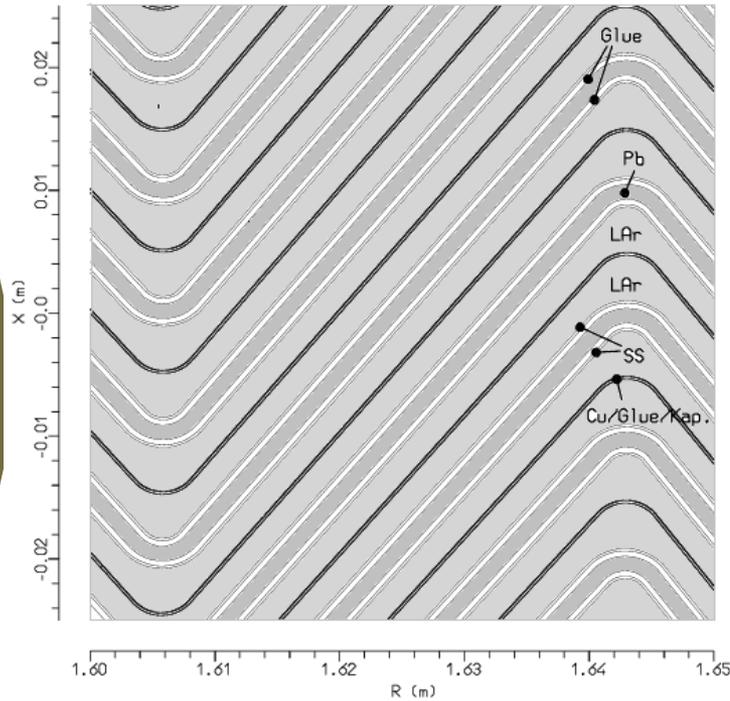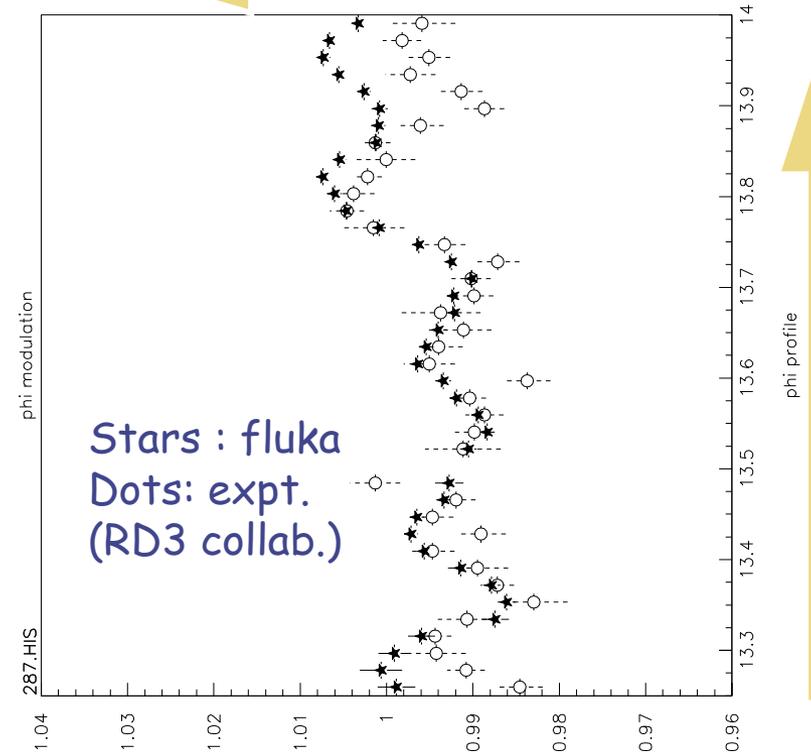
Energy resolution 10-100 GeV:

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

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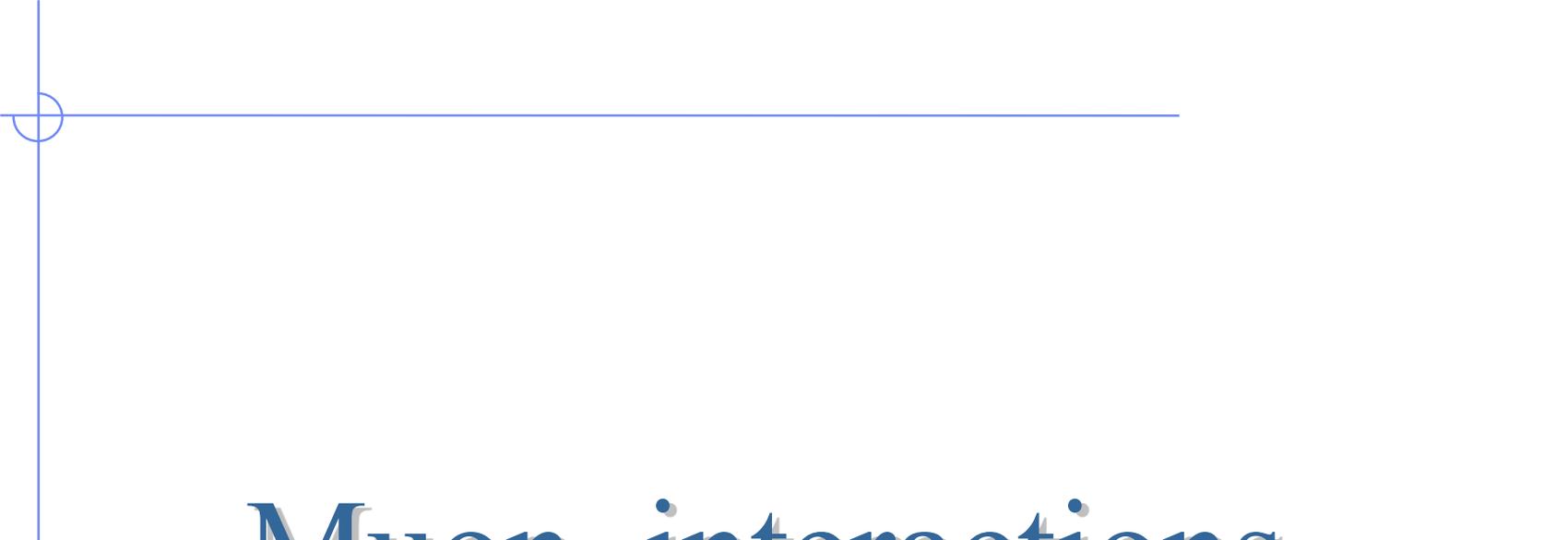
Muon interactions

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 γ and e± 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

Energy Deposition spectrum in the Atlas tile-calorimeter prototype

300 GeV muons on iron + scintillator structure

Muon energy [GeV]

Muon energy [GeV]
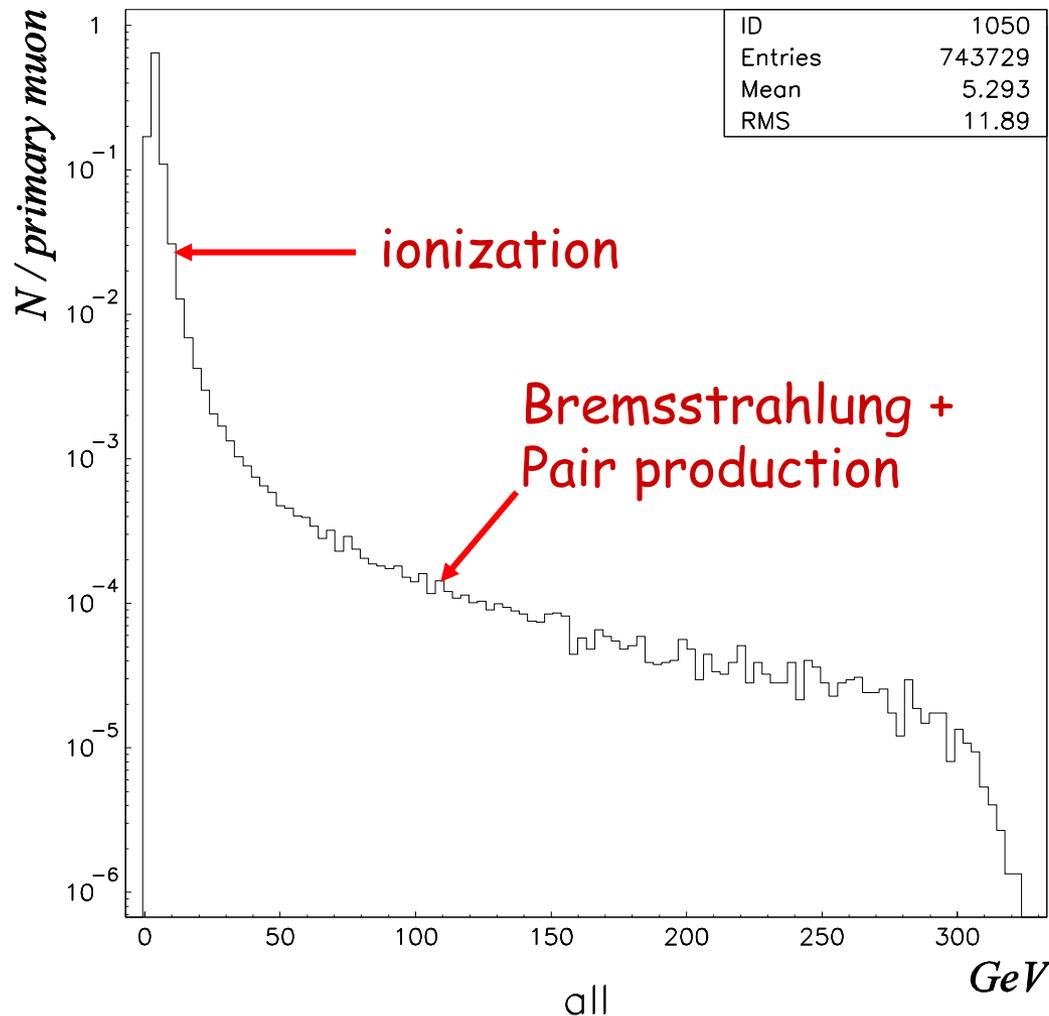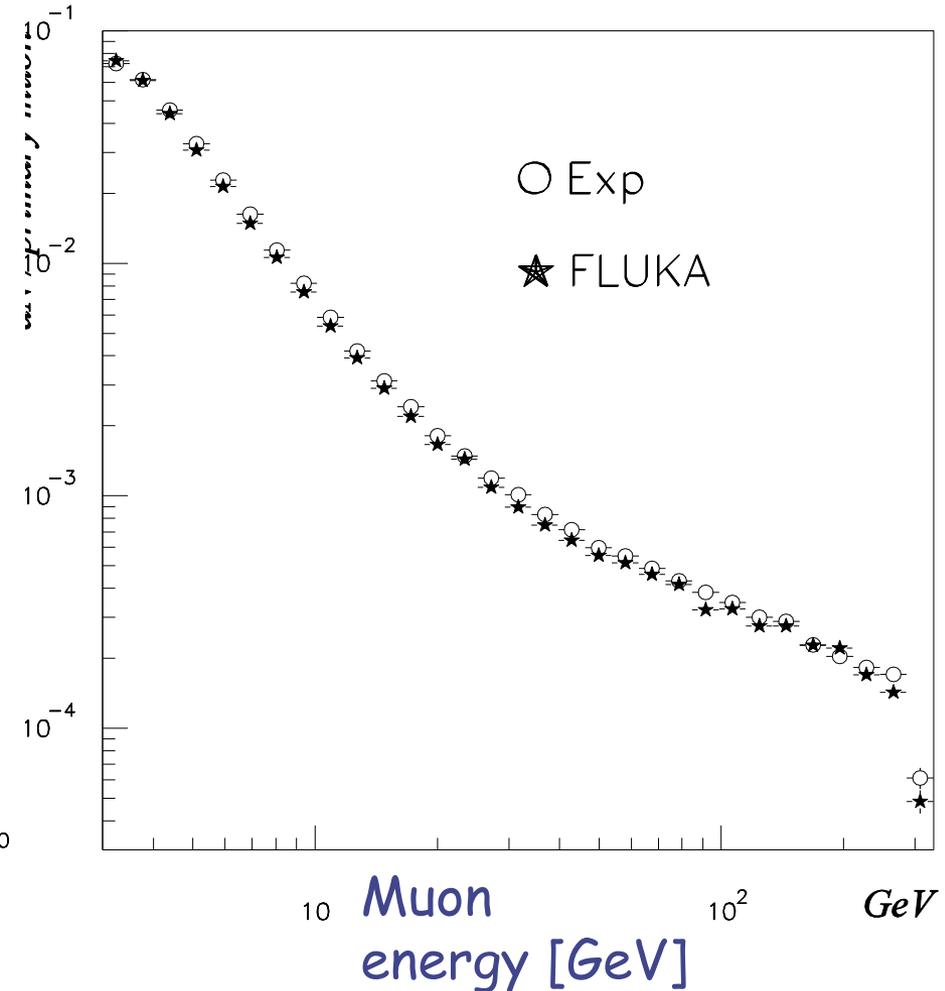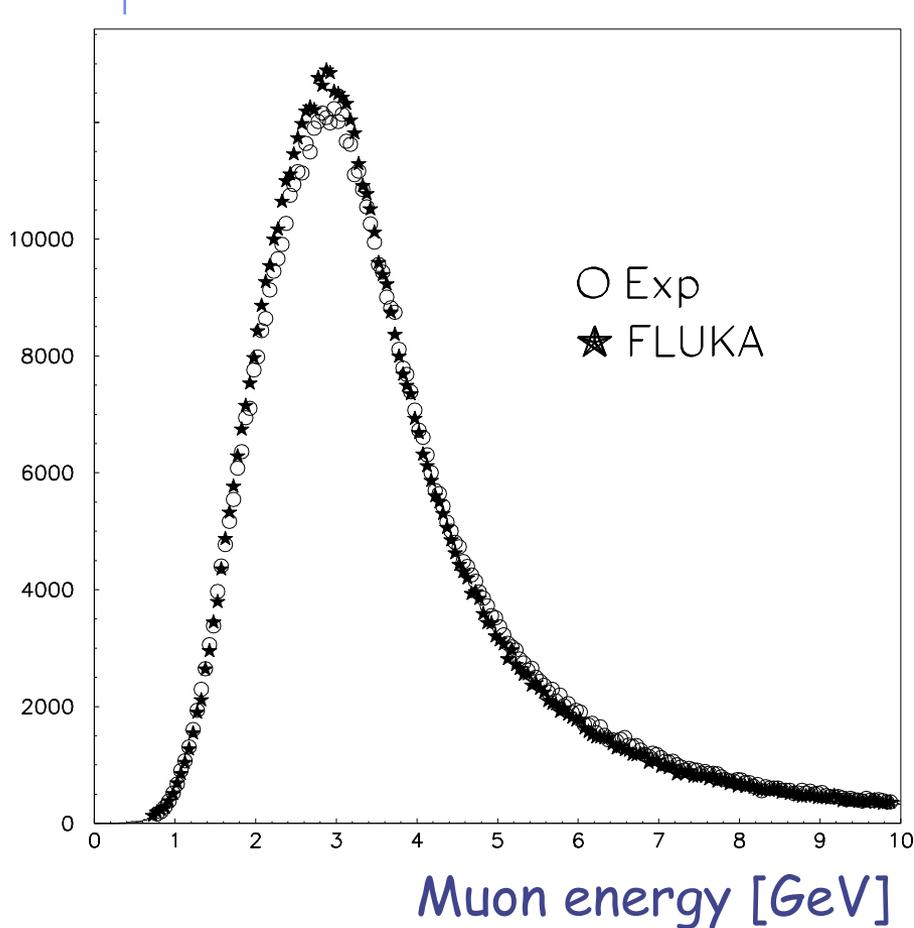
Muon Photonuclear Reactions
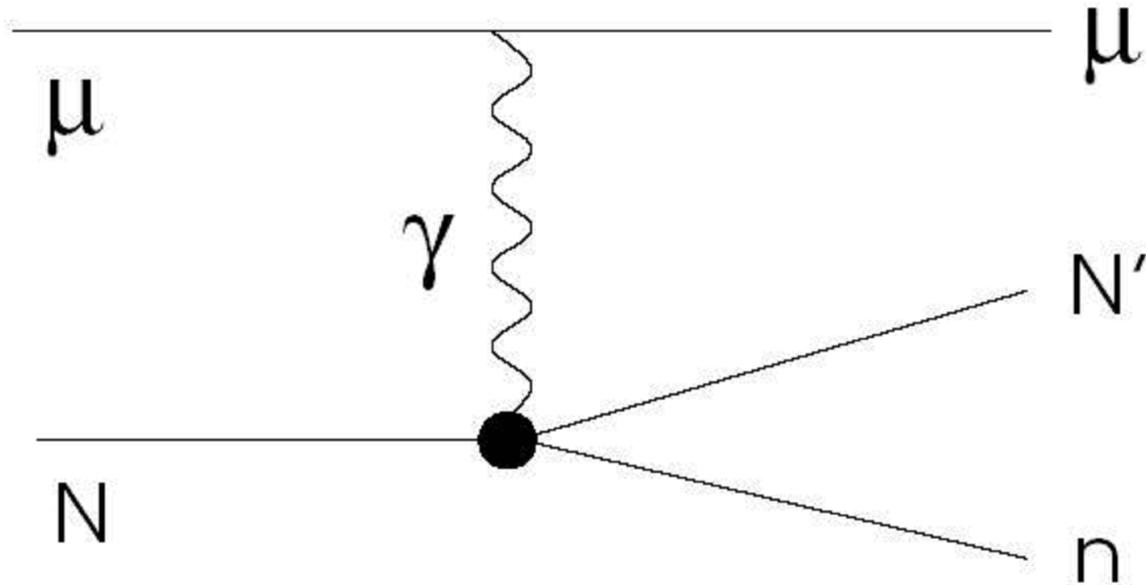
Schematic view of a μ hadronic interaction.
The interaction is mediated by a virtual photon.
The final state can be more complex

- 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      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-induced neutron background in underground labs

PRD64 (2001) 013012

Neutron yield (n/μgcm^{-2}) vs **E$_\mu$ (GeV)**
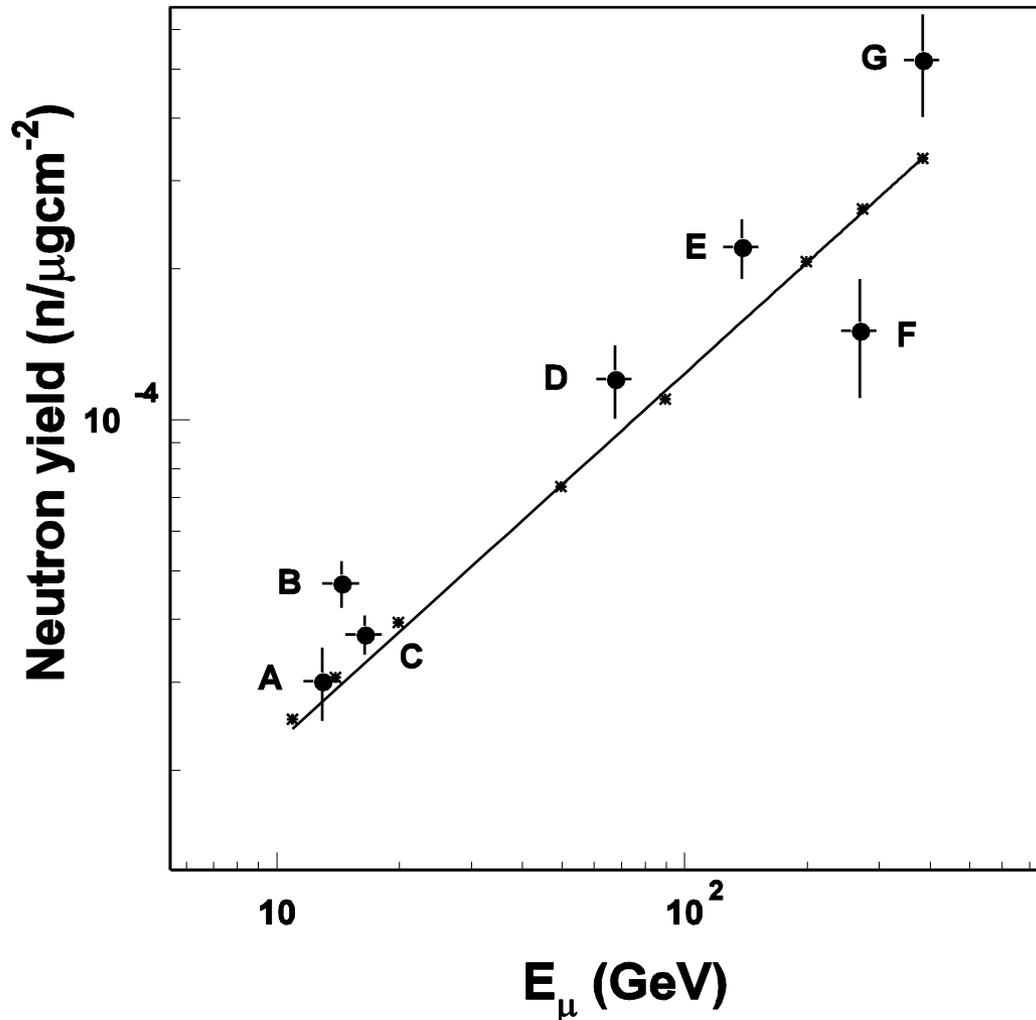
Neutron production rate as a function of muon energy

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 (1)

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

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

$\frac{\Lambda_c}{\Lambda_d} = 9.2 \cdot 10^{-4}$ for H, $\qquad$ 3.1 for Ar, $\qquad$ 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
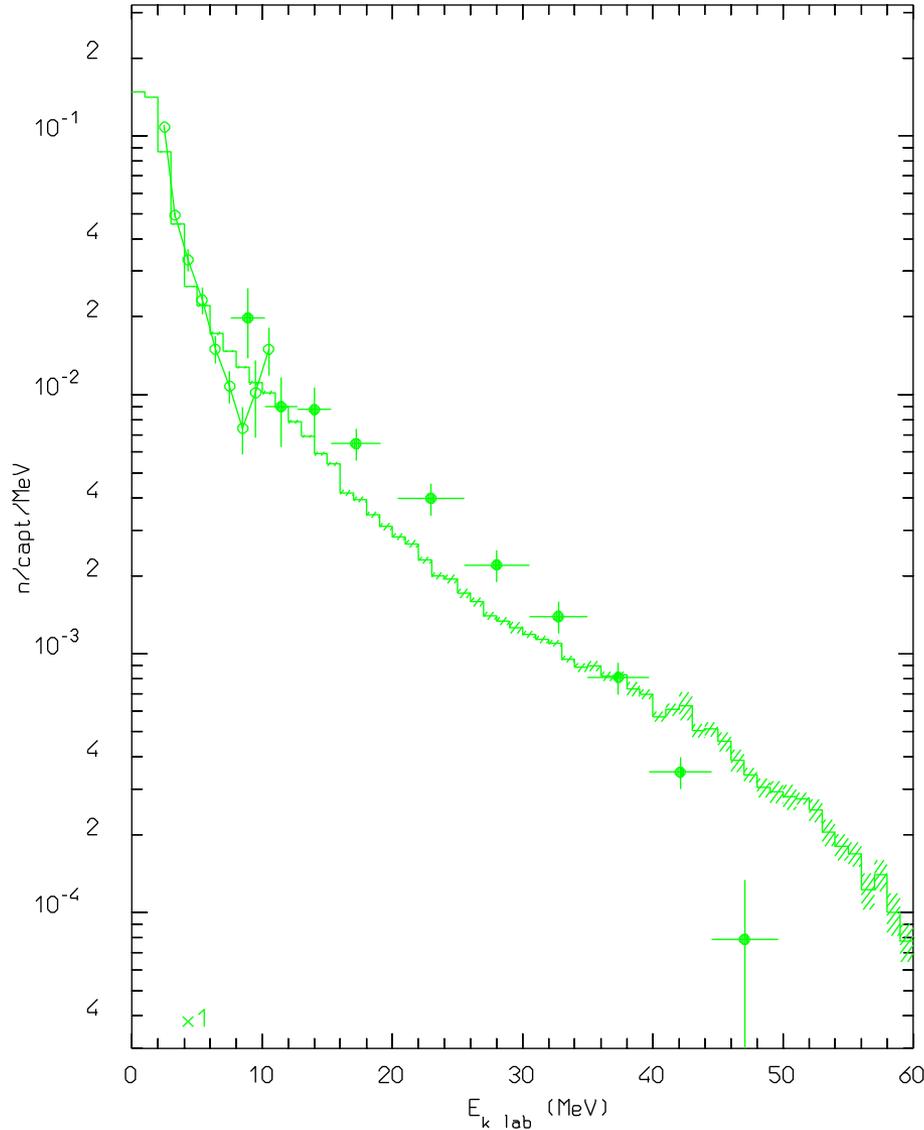
capture on Calcium
Dots: experimental data (Columbia
Univ. rep. NEVIS-172 (1969), Phys. ReV.
C7, 1037 (1973), Yad. Fiz. 14, 624 (1972))
histograms: FLUKA
calculations
Emitted:
0.62 neutrons/capture
0.27 protons/capture

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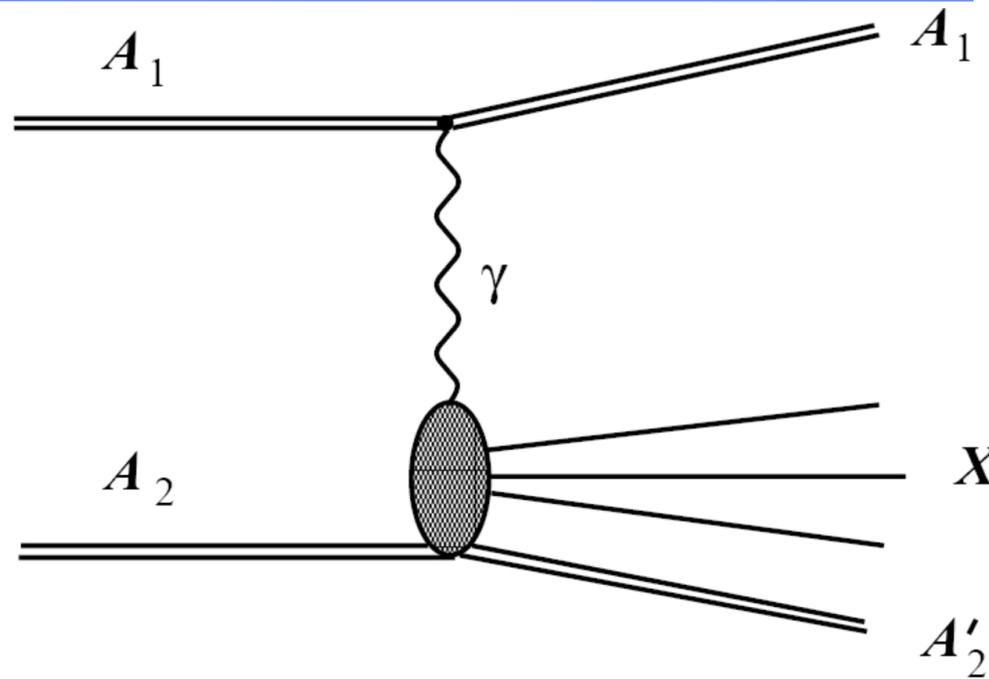
$$\sigma_{1\gamma} = \int \frac{d\omega}{\omega} n_{A_1}(\omega) \sigma_{\gamma A_2}(\omega), \qquad n_{A_1}(\omega) \propto Z_1^2$$

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

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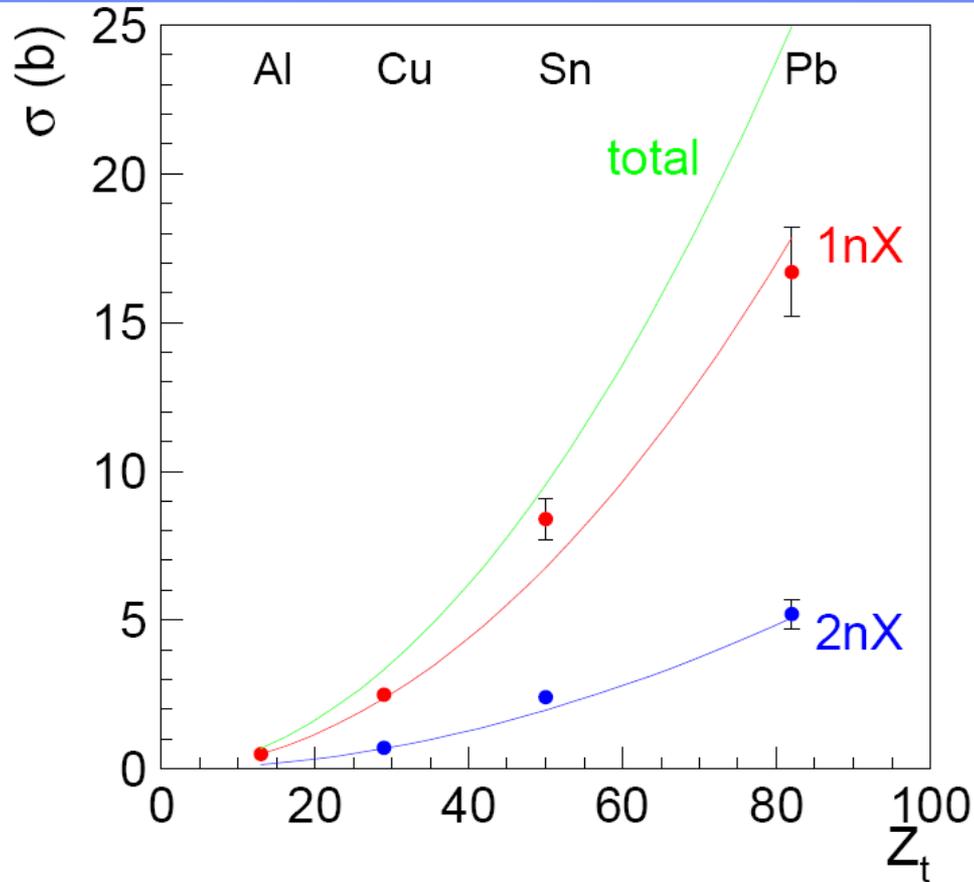
Electromagnetic dissociation cross sections (total, 1nX, 2nX) for 30GeV/n Pb ions on Al, Cu, Sn, and Pb targets.

FLUKA: lines (calculated cross section as a function of target charge)
Exp. data: M.B.Golubeva *et al.*

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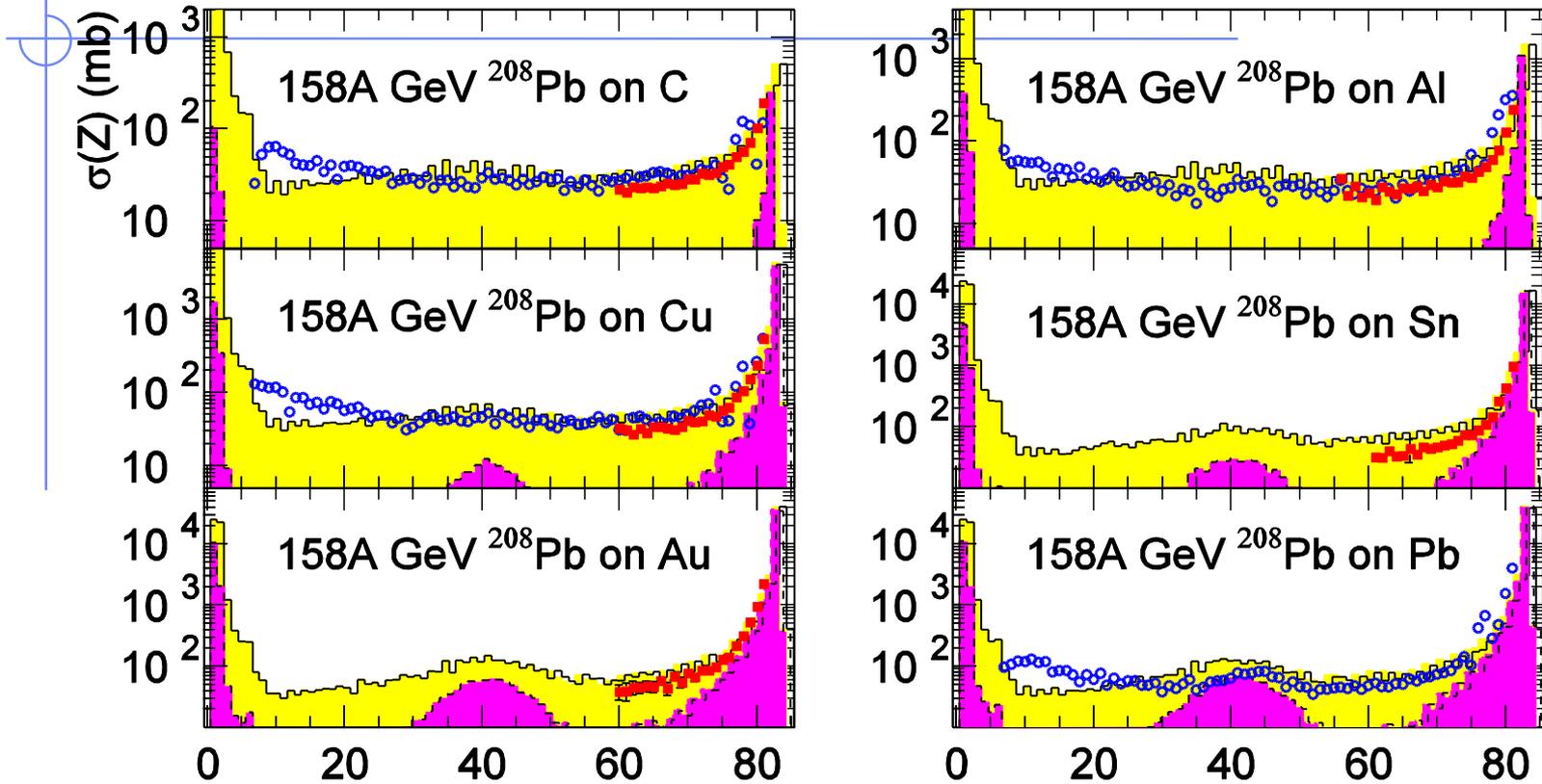
Fragment charge cross section for 158 AGeV Pb ions on various targets. Data (symbols) from NPA662, 207 (2000), NPA707, 513 (2002) (blue circles) and from C.Scheidenberger et al. PRC70, 014902 (2004), (red squares), *yellow* histos are FLUKA (with DPMJET-III) predictions: *purple* histos are the electromagnetic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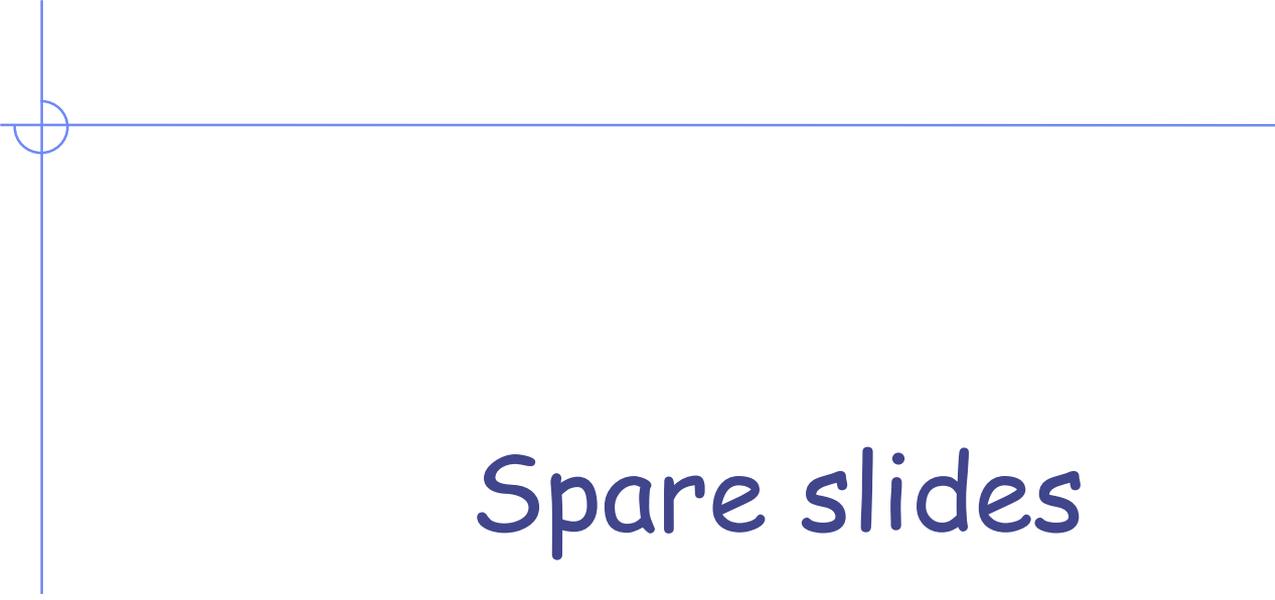
Spare slides

Electromagnetic dissociation: example

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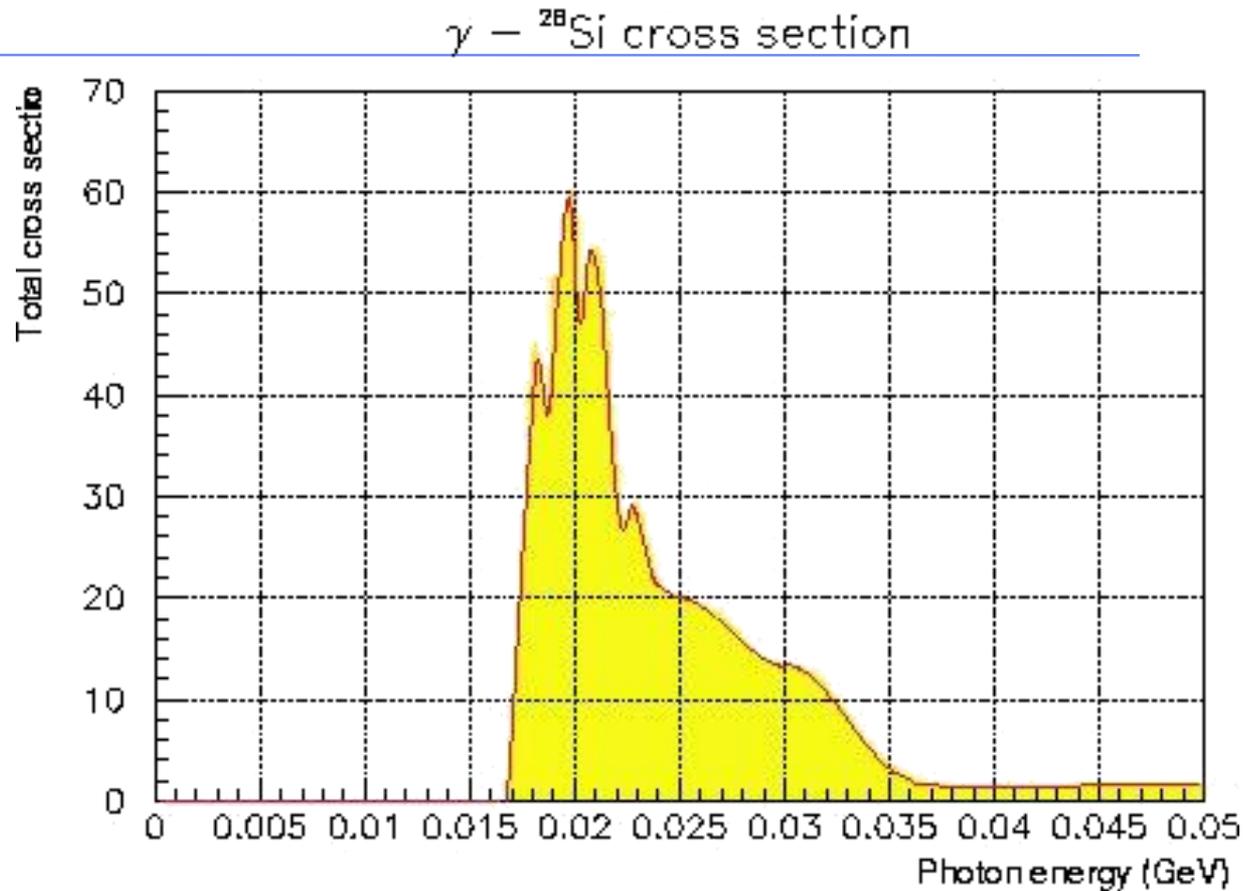
^{28}Si(γ,tot) as recorded in FLUKA database, 8 interval Bezier fit as used for the Electromagnetic Dissociation event generator.