# Electronuclear Interactions in FLUKA

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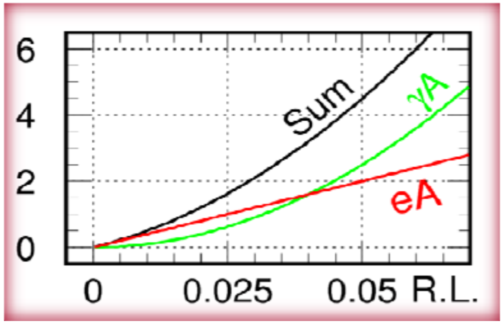
- What are the inelastic direct electronuclear (eA) reactions
- Why eA reactions important/critical for JLab's needs
- What is our approach to evaluating and handling eA reactions
- Neutron and pion production source terms in eA interactions
- Possible electronuclear processes' implementation in FLUKA

# Standard E-M Processes

- FLUKA implements electron and gamma interaction processes needed in most of simulation projects at electron accelerators at high energies.
- Complete set of "pure" electromagnetic interactions:
  - Multiple scattering, energy loss, delta-ray production, bremsstrahlung, etc., for charged particles.
  - Photoelectric, Compton, Rayleigh scattering for gammas.
- The photonuclear interactions in the full range of target nuclei and photon energies.
- Sufficient for detailed shielding and radiation background calculations involving thick targets and absorbers.
- For the fixed-target experiments involving thin (few percent of radiation length) targets at Jlab, there is a need in the simulations of the direct electronuclear interactions.

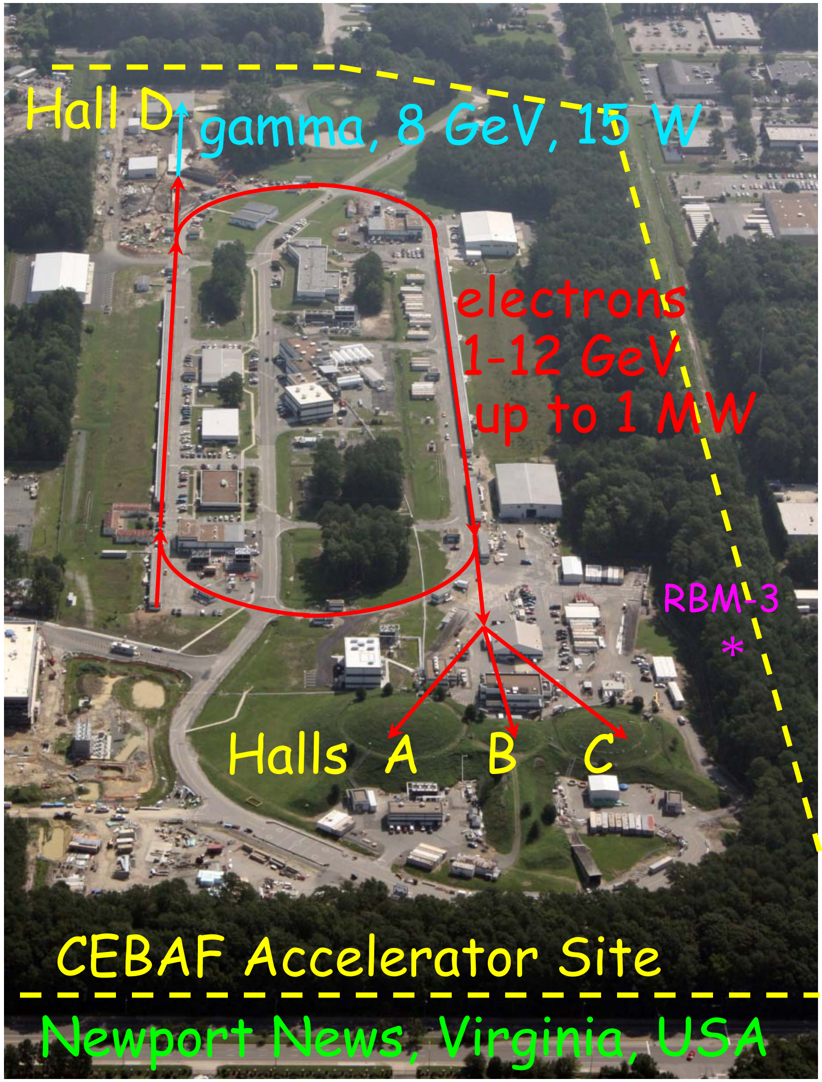
# Electronuclear Processes

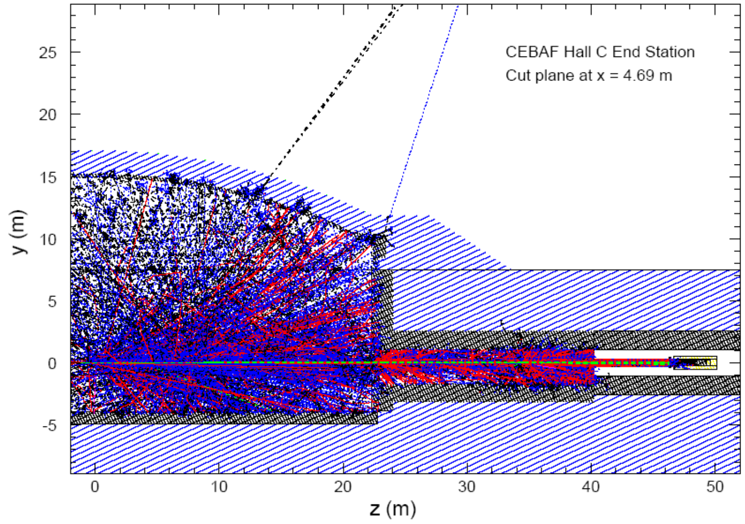
- At sufficiently high energy and momentum transfers electrons can scatter off the parts of the target nucleus
  - Nucleons: Quasielastic Scattering
  - Quarks: Deep Inelastic Scattering
- Electrons can break up the nucleus directly, without the need to produce first a real bremsstrahlung photon that would invoke subsequent photonuclear reaction.
- The electronuclear reactions are therefore the direct one-stage reactions with their rates linearly dependent on the target thickness. As opposed to the two-stage photo-nuclear reactions, dependent on the target thickness quadratically.

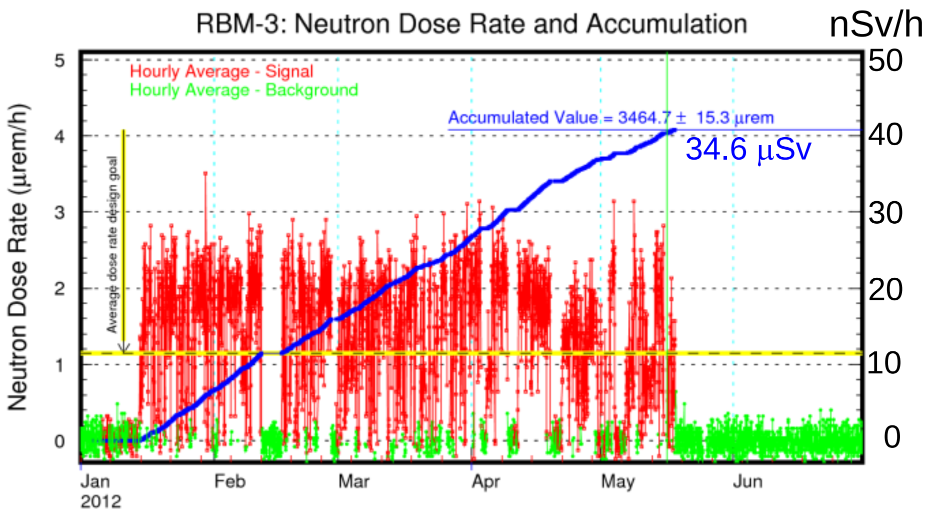



- For sufficiently thin targets the electronuclear reactions will therefore constitute a dominating term in hadron production.
- Neutron production source terms at Jlab are the example.

# Radiation Environment at JLab




Thin targets, relatively thin roofs, closeness of boundaries

Electronuclear Processes critical

# Electronuclear Processes at JLab

- The relative importance of electronuclear and photonuclear (bremss.) contributions to the GDR neutron yield was evaluated as $Y_{total}/Y_{bremss} = (1 + 0.04/T)$*

  (T is the target thickness in Radiation Lengths)
- Experiments at JLab generally use 1-5% R.L. thick targets. Quite popular are 10-20 cm liquid $H_2$ or $D_2$; other nuclei are also used. The targets are the major contributors to the production of higher energy secondary neutrons (>~ 50 MeV) which penetrate roofs and scatter / generate cascades in the atmosphere. Such neutron skyshine is the main source of radiation produced by our machine at the site boundary.
- The ability to evaluate and predict dose rates in the environment, as well as the neutron backgrounds inside the experimental halls has become critical at Jlab. Hence the need in the ability to evaluate electronuclear processes.

*X. Mao, K. R. Kase, and W. R. Nelson (SLAC-PUB-6628, January 1996)

# Simulation Tools

- Before 1995 there were no Monte Carlo simulation tools to evaluate both photo- and electronuclear processes at JLab.
- The solution was to implement our DINREG Nuclear Fragmentation MC event generator within the framework of the GEANT3 code available at that time, to simulate $\gamma$A reactions, as the first step.
- The second step was inventing the algorithm, compatible with GEANT3 and relatively effective, for the electronuclear part of the problem.
- The tasks were completed in 1995.* Since that time the simulation tool is being successfully used at JLab.
- The electronuclear processes were implemented in Geant4 (in 2000-2001), and in MARS (around 2003)

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**P. Degtyarenko and Geoff Stapleton (SARE-2, CERN, 9-11 October 1995)*

# FLUKA at JLab

- FLUKA wasn't popular at JLab until present, mostly because JLab physics wasn't fully represented in the code.
- However, several developments changed the situation:
  - Urgent need in activation calculation ability
  - New requirements to evaluate radiation damage to electronics during experiments
  - Flair interface promise (and delivery) of the "ease of use"
  - Alberto Fassò in our group!
- Several successful FLUKA solutions have been developed during the last two years, associated with the gamma beams in the Hall D setup, and also with background and activation calculations for experiments on relatively thick targets.
- If electronuclear processes were included, then I believe FLUKA would become the simulation tool of choice for JLab.

# Equivalent Photon Approximation

- The electromagnetic interaction of fast charged particles with nuclei can be reduced to the effective interaction of equivalent flux of photons distributed with some density $n(\omega)$ on a frequency (energy) spectrum.*
- The EPA (Weizsäcker-Williams' method) was derived in details by V.M. Budnev et al.** in the form applicable for the MC applications to simulate electronuclear processes.

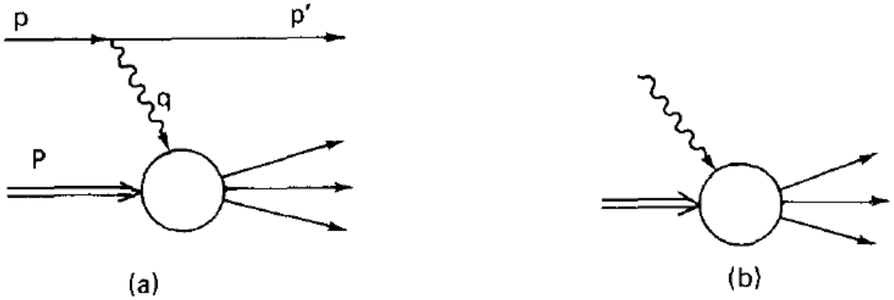


Fig. 35. Electroproduction and photo-absorption.

$$d\sigma_{ep} = \sigma_\gamma(\omega)\,dn$$

$$(E - \omega \gg m_e)$$

$\omega/E$ may be not small(!)

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* *E. Fermi, Z. Physik 29 (1924) 315*

*K.F. von Weizsäcker, Z. Physik 88 (1934) 612*

*E.J. Williams, Kgl. Danske Vidensk. Selskab. Mat.-Fiz. Medd. 13 (1935) N4*

** *V.M. Budnev, I.F. Ginzburg, G.V. Meledin and V.G. Serbo, Physics Reports 15, no.4 (1975) 181-282*

# EPA: the ω-distribution

$$d\sigma = \sigma_\gamma(\omega)\, dn(\omega); \qquad (6.17a)$$

$$dn(\omega) = \int_{q^2_{min}}^{q^2_{max}} dn(\omega, q^2) = N(\omega)\, d\omega/\omega;$$

$$N(\omega) = \frac{\alpha}{\pi}\left[\left(1 - \frac{\omega}{E} + \frac{\omega^2}{2E^2}\right)\ln\frac{q^2_{max}}{q^2_{min}} - \left(1 - \frac{\omega}{2E}\right)^2 \ln\frac{\omega^2 + q^2_{max}}{\omega^2 + q^2_{min}} - \frac{m_e^2\omega^2}{E^2 q^2_{min}}\left(1 - \frac{q^2_{min}}{q^2_{max}}\right)\right]. \qquad (6.17b)$$

$$q^2_{min} = \frac{m_e^2\omega^2}{E(E-\omega)}\left[1 + O\left(\frac{m_e^2}{(E-\omega)^2}\right)\right] \leqslant -q^2 \leqslant 4E(E-\omega). \qquad (6.11)$$

V.M. Budnev et al. evaluate accuracy of this approximation in the whole range of ω:

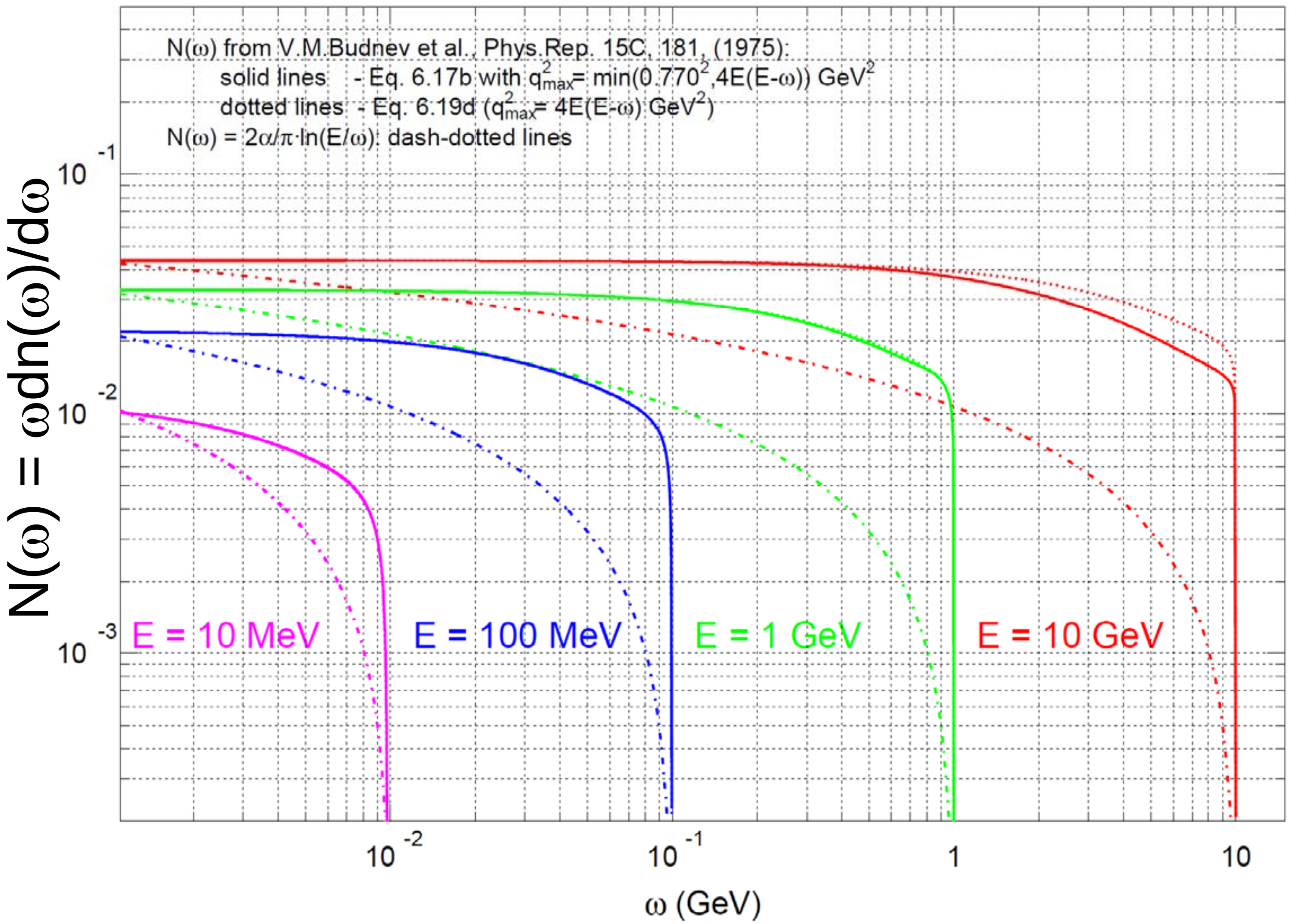
Let us note, that the spectrum (6.17b) with $q^2_{max} = \Lambda^2_\gamma$ may be used for the description of the whole ω-distribution with an accuracy not worse than logarithmic.

$$\eta \sim \frac{\omega^2}{\Lambda^2_\gamma}\frac{\ln(\Lambda^2_\gamma/\omega^2)}{\ln(\omega^2/q^2_{min})} \approx \frac{\omega^2}{\Lambda^2_\gamma}\frac{\ln(\Lambda^2_\gamma/\omega^2)}{\ln(E^2/m_e^2)}; \qquad (\omega < \Lambda_\gamma;\ q^2_{max} = \Lambda^2_\gamma)$$

$$\eta \sim [\ln(\Lambda^2_\gamma/q^2_{min})]^{-1}; \qquad (\omega \gtrsim \Lambda_\gamma;\ q^2_{max} = \Lambda^2_\gamma)$$

$\Lambda_\gamma \sim m_\rho$ for the electroproduction off proton

# EPA: functions N(ω), different E




Eq. 6.17b from V.M.Budnev et al. differs dramatically from the "classical" Weizsäcker-Williams EPA equation

# EPA Algorithm in GEANT3

- At each step of the cascade, the electron is represented as carrying a collinear flux of equivalent photons distributed according to dn(ω) (Eq. 6.17b) in the range of ω from the threshold energy $E_{thr}$ up to the electron energy $E_e$.
- One "virtual" equivalent photon is generated with energy $\omega_v$ in accordance with the spectrum dn(ω) (function GEFLUX).
- The distance to the next nuclear interaction point of this photon (considered as real) is generated according to its photonuclear cross section, multiplied by the flux factor (the total flux is obtained by integrating dn(ω) from $E_{thr}$ to $E_e$ in the function EFLUXI).
- If this generated point happens to be the closest among all of the electron interaction candidates at the step, then the photon interaction is generated, producing secondaries, and the electron is continuing in the cascade with decreased energy. If other electron interaction process is the winner at the step, then the virtual equivalent photon is discarded.

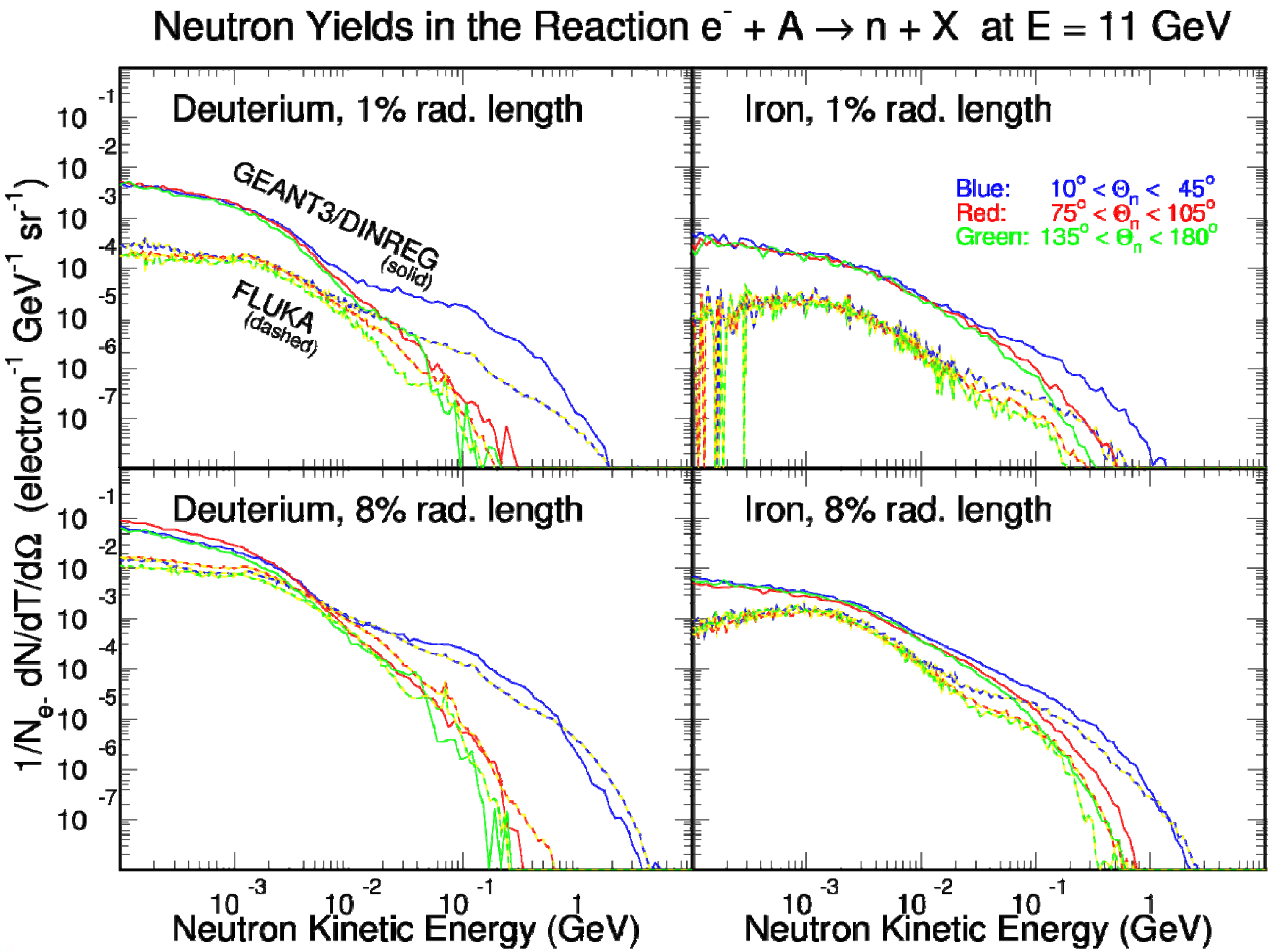
# EPA implementation in a MC code

- Provided that the photonuclear reactions are already available in the code, addition of the electronuclear processes is relatively straightforward.
- Modifications in the electron tracking routines
  - Introducing the new electron interaction process
- Minimal performance overhead:
  - Quick generation of the equivalent photons using a simple approximate $\omega_V$ generator function, and the "Roulette" type fine correction to the exact distribution.
  - Quick evaluation of the flux integral by using pre-calculated look-up tables.
- Biasing is possible by varying the number of generated virtual equivalent photons per electron step, and also by modifying photonuclear cross sections (together with biasing of the photonuclear processes).

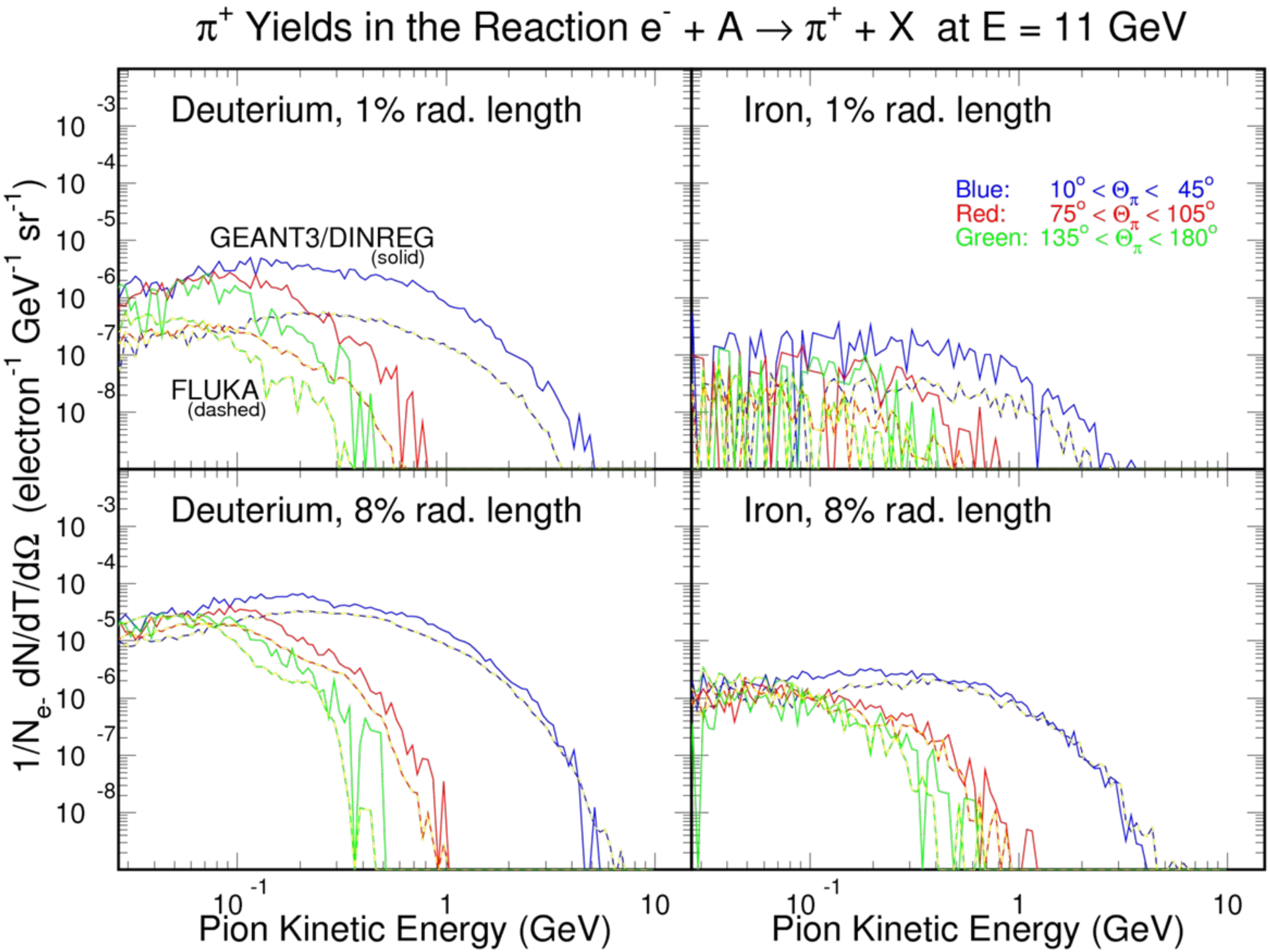
# Photo/Electronuclear source terms

- An exercise in FLUKA and an illustration to the relative importance of the electronuclear process contributions:
  - calculations of the source terms (particle yields) from several targets.
- Targets: 5 cm diameter cylinders of
  Liquid Deuterium, Carbon, Iron, Lead
- Thicknesses: 1%, 2%, 4%, 8%, 16% radiation lengths
- Beam: electrons at 11 GeV ("12 GeV" CEBAF conditions)
- Score yields: gamma, e+/e-, pion+/pion-, proton and neutron
- Compare FLUKA and GEANT3/DINREG
- Plan to include Geant4 in the list
- Hope the source term calculation tool will be useful for comparisons with other models and experimental data, benchmarking, and evaluating the systematic errors in the simulations.

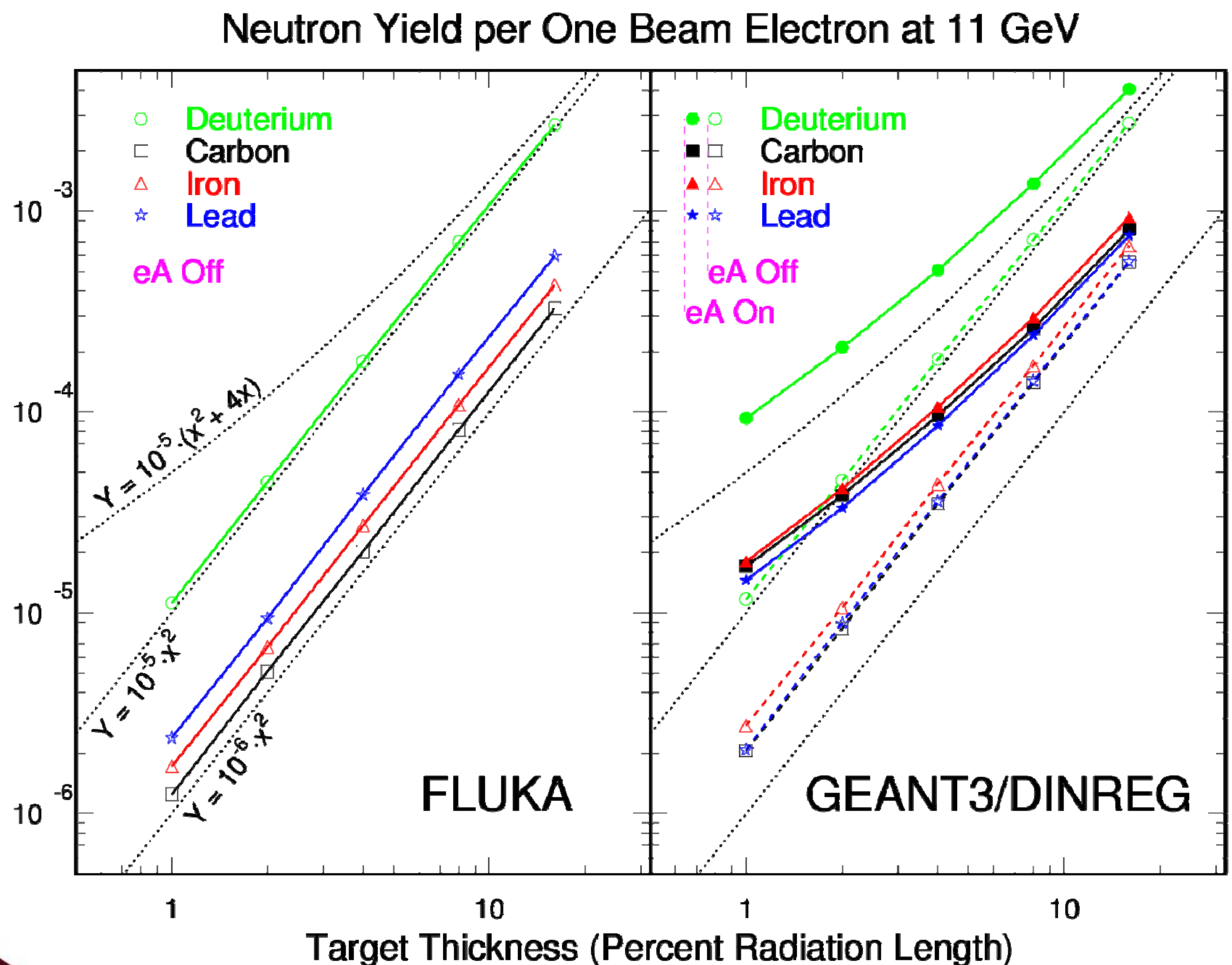
# Source term examples



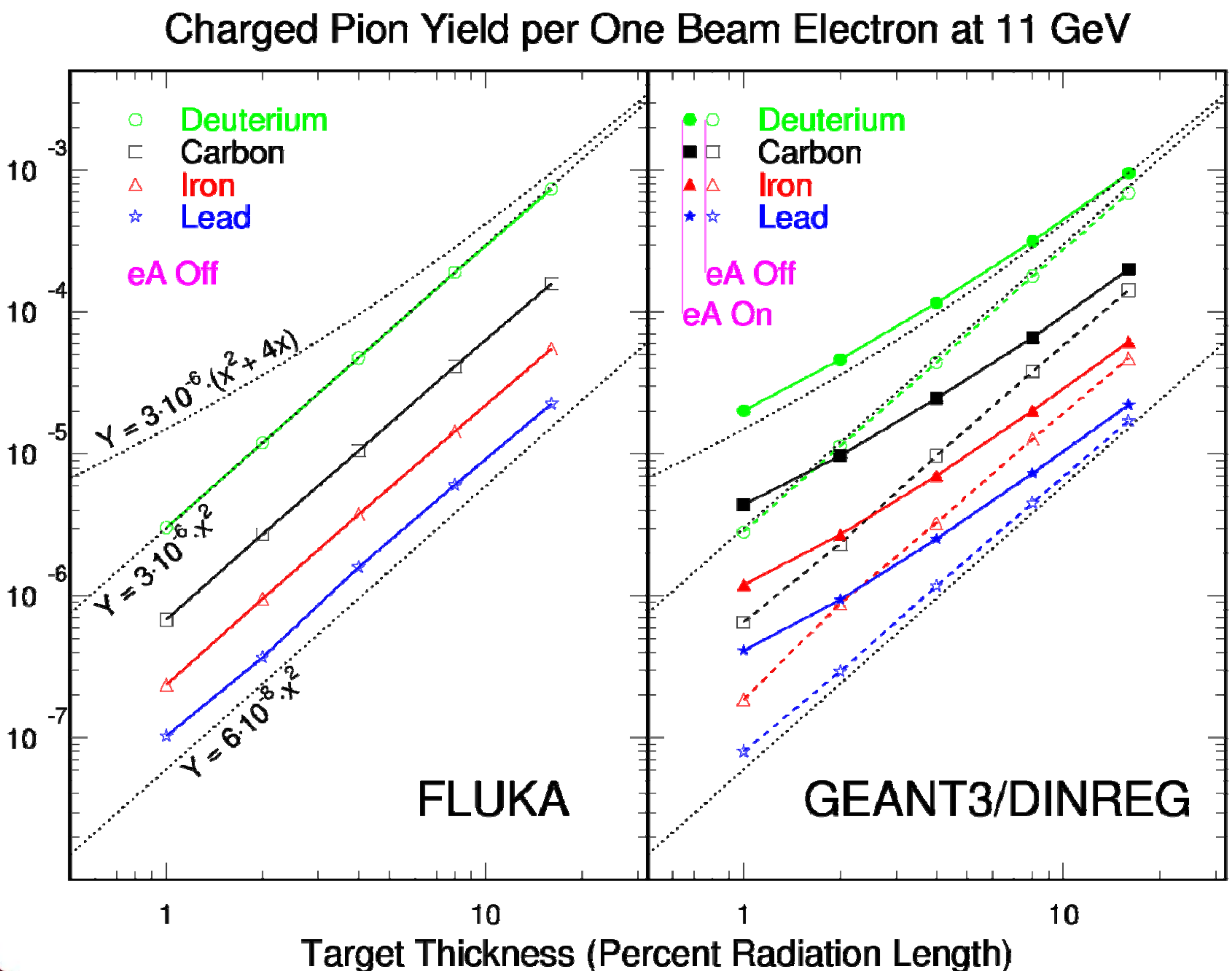
# Source term examples



# FLUKA vs. GEANT3/DINREG



# FLUKA vs. GEANT3/DINREG



# Conclusions

- JLab's need in good MC simulation tools is getting stronger:
  - 12 GeV upgrade of the machine - new era
  - New high current experiments in the pipeline
  - New requirements for evaluation of damage to electronics
  - New requirements for evaluation of material activation
- Present tools:
  - Outdated (GEANT3/DINREG)
  - Need further development and benchmarking (Geant4)
  - (Almost) perfect FLUKA. But it also needs benchmarking for JLab physics, and – the eA processes included.
- More eA applications: activation and neutron production by the electron beams in thin windows and in the residual gas, interactions at the Electron-Ion colliders, processes at $Q^2>0$ …

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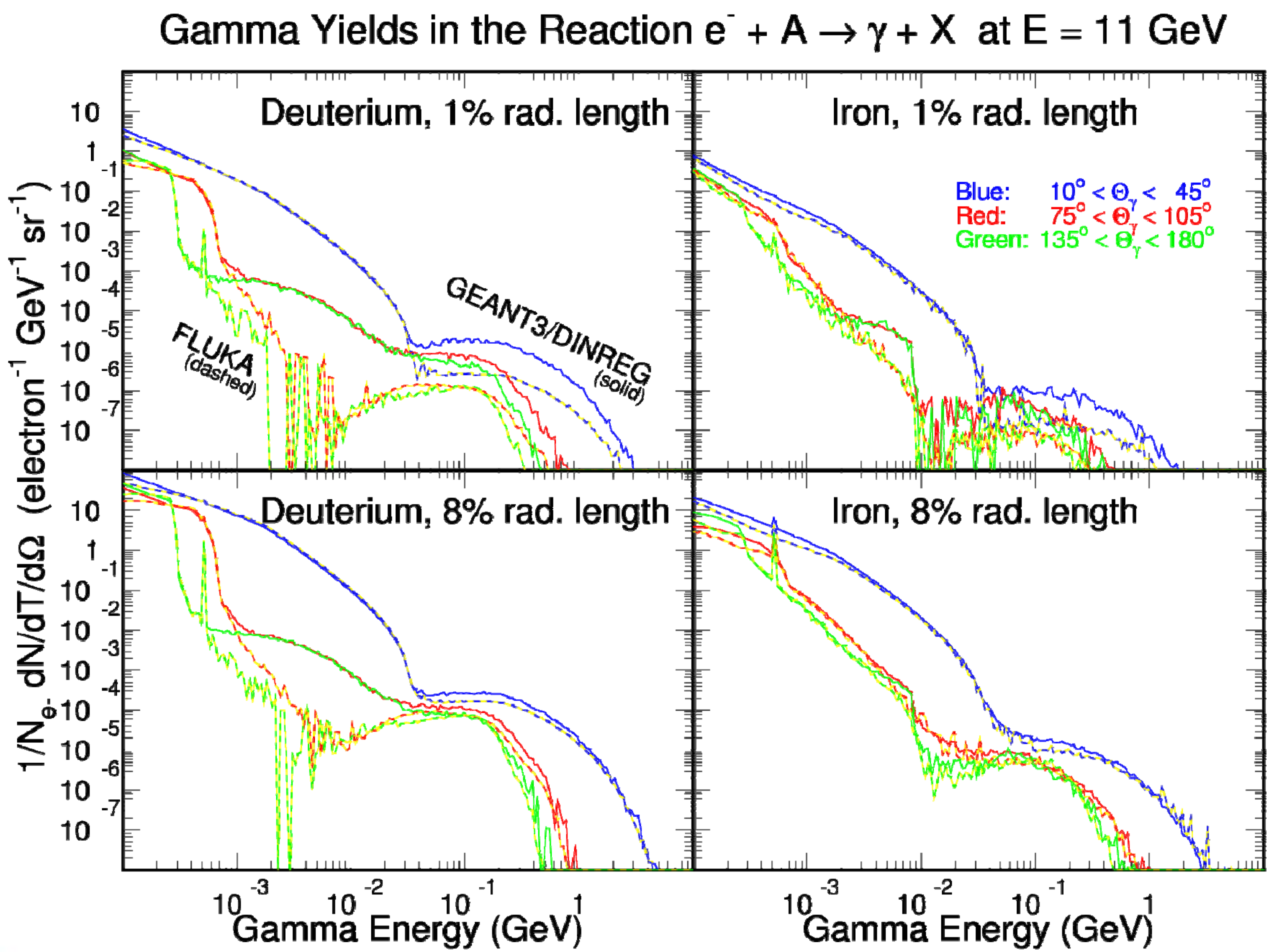
RadCon@JLab is interested in a possible mutually beneficial collaboration with the FLUKA team in implementing the electronuclear processes in the code.

# Source term examples



# Electronuclear Processes in FLUKA