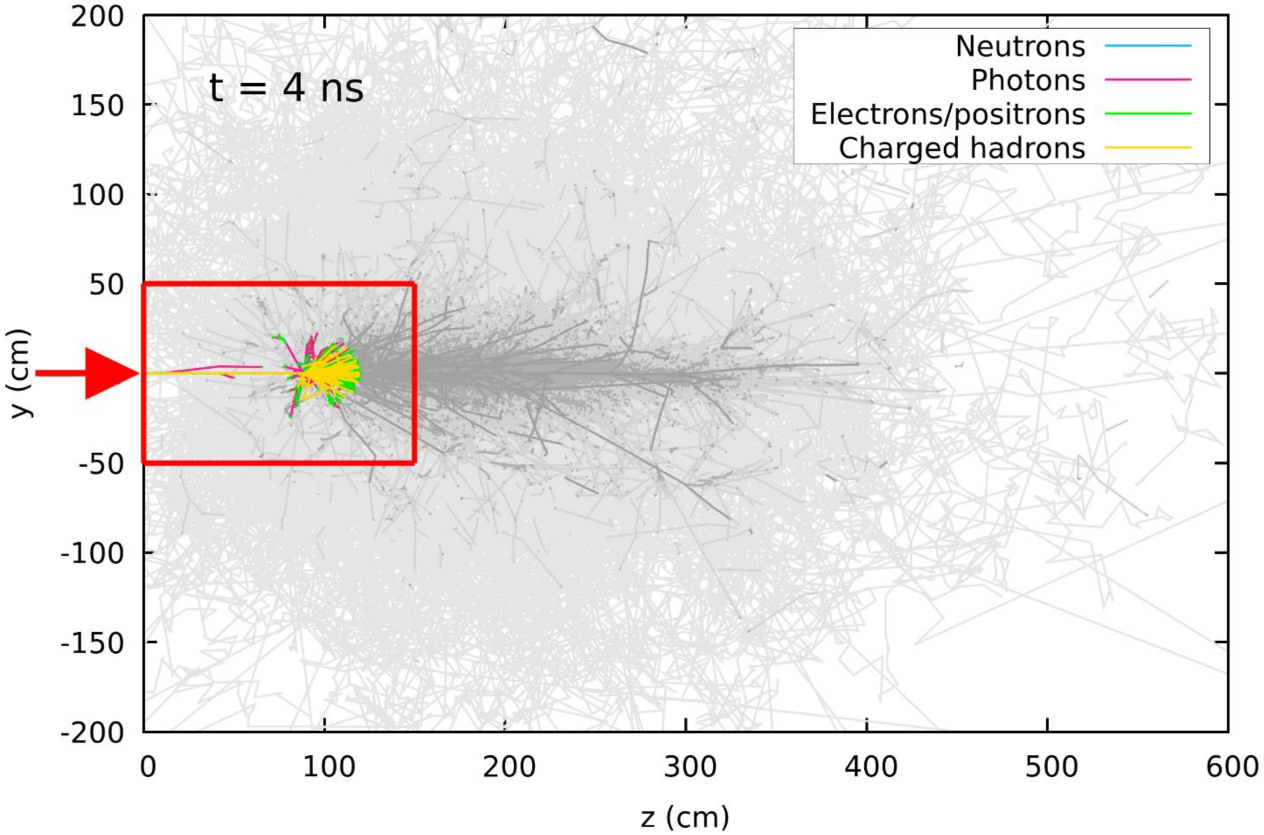
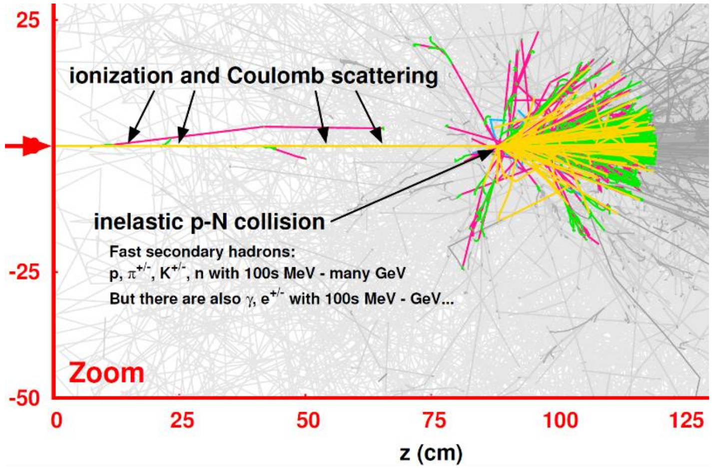
Hadronic interactions [I]

Hadron-nucleus reactions

The microscopic view [I]

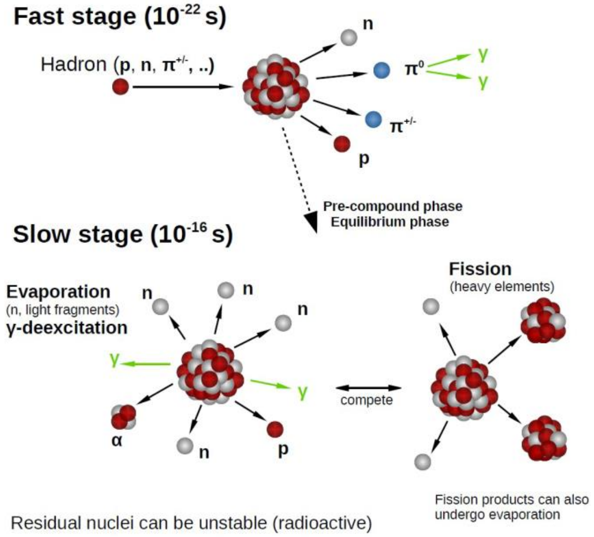
one 450 GeV proton on aluminum





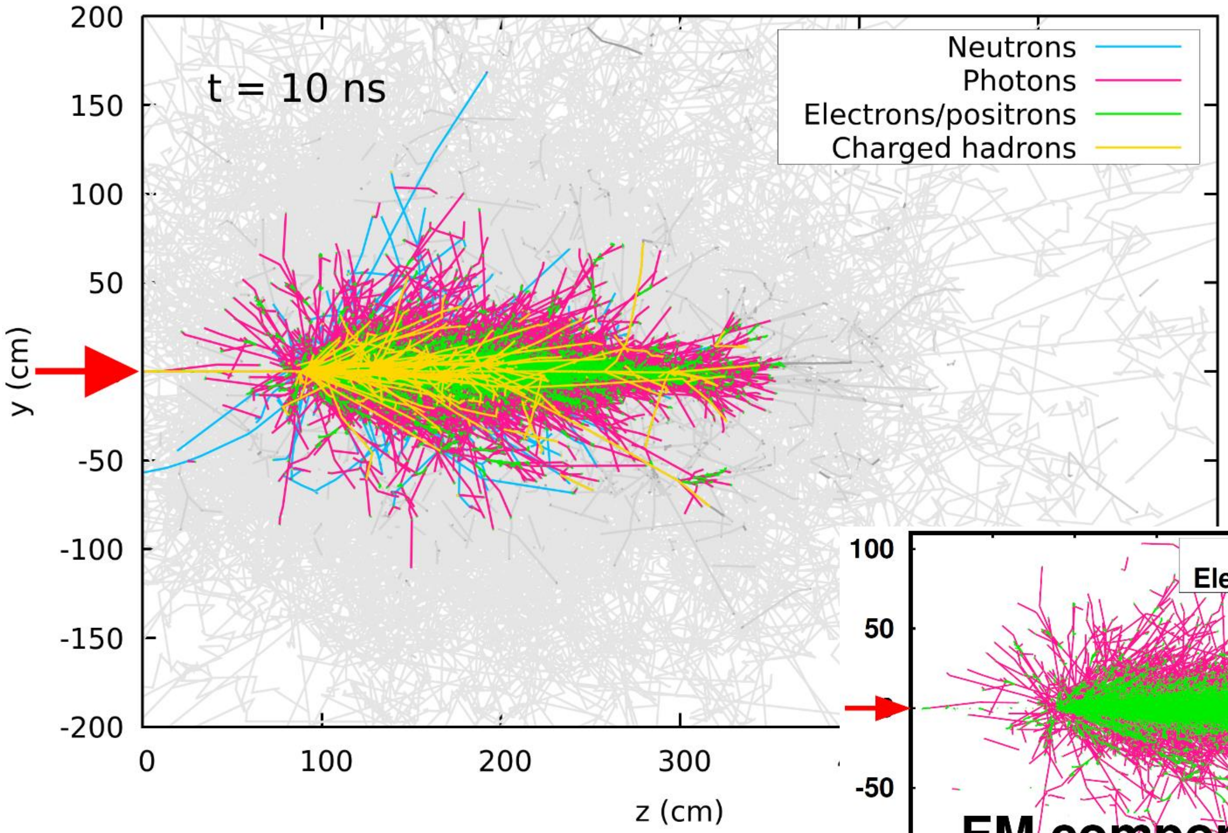
high energy nuclear reaction

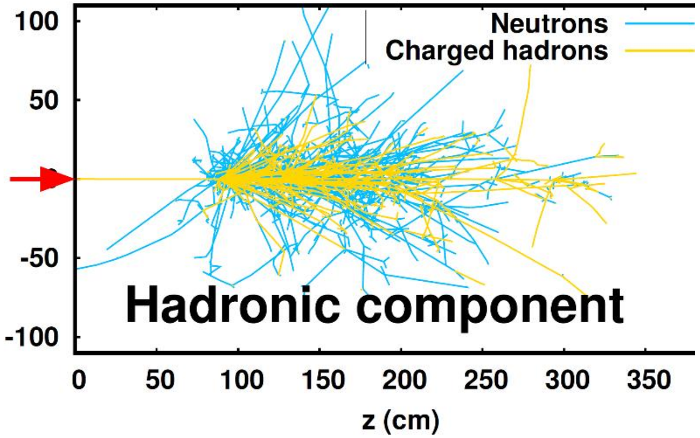
$$\lambda\rho = \frac{A}{\sigma_R N_A} \qquad \sigma_R \simeq \pi r_0^2 A^{2/3}$$



The microscopic view [II]

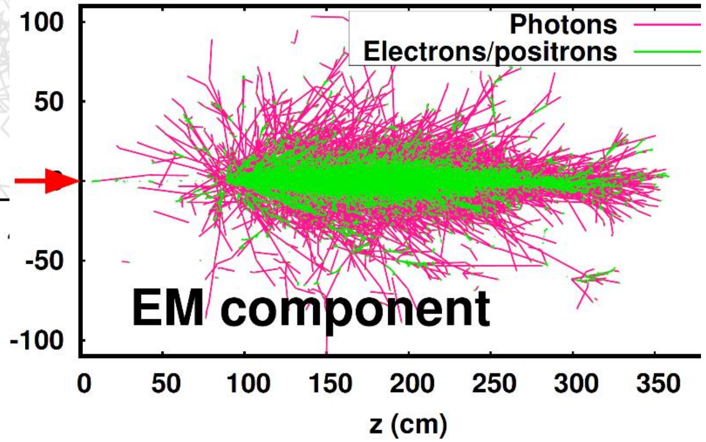
one 450 GeV proton on aluminum





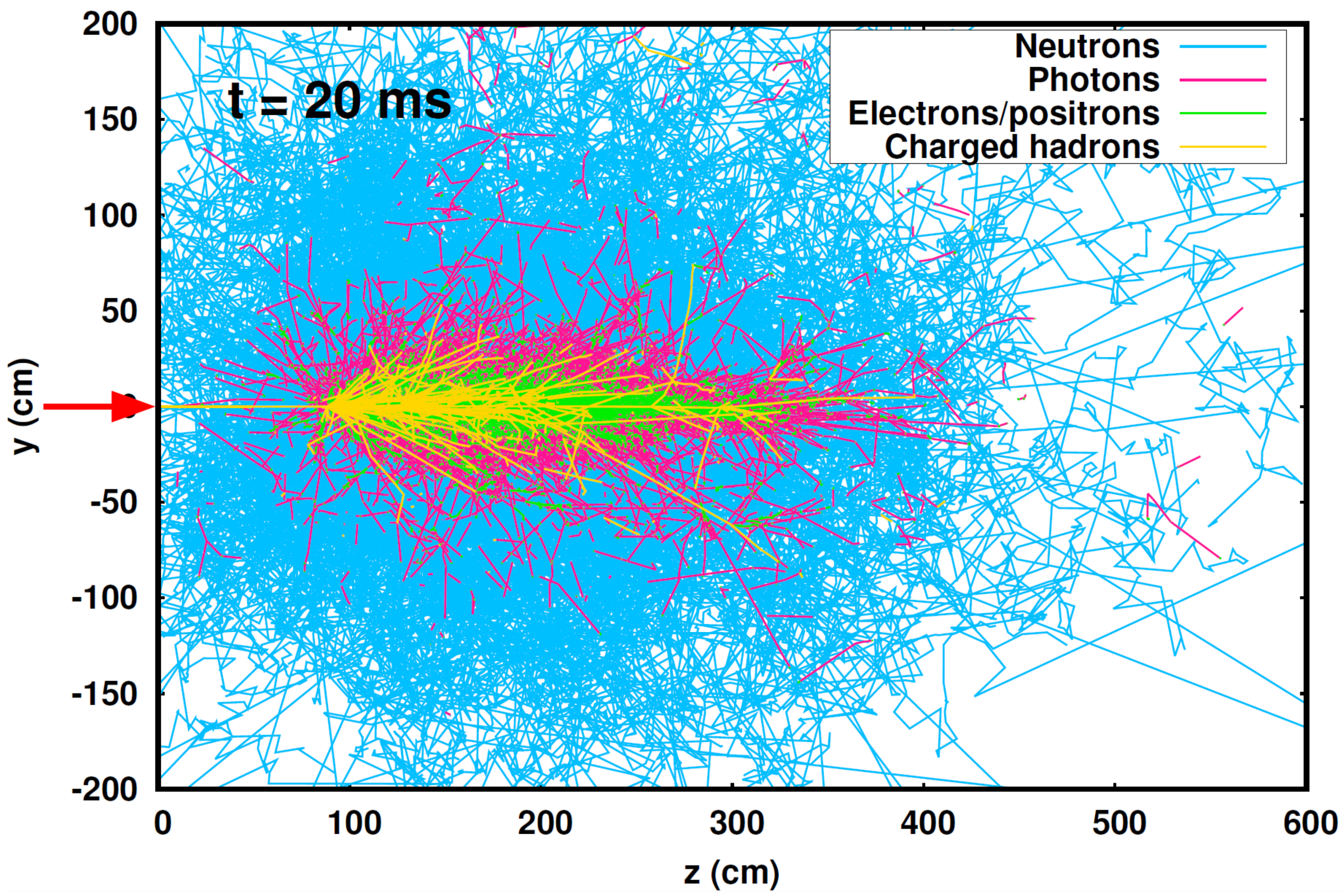
hadronic shower continues until particle energy falls below pion production threshold

non-negligible fraction of initial energy goes to mass by nuclear binding breaking



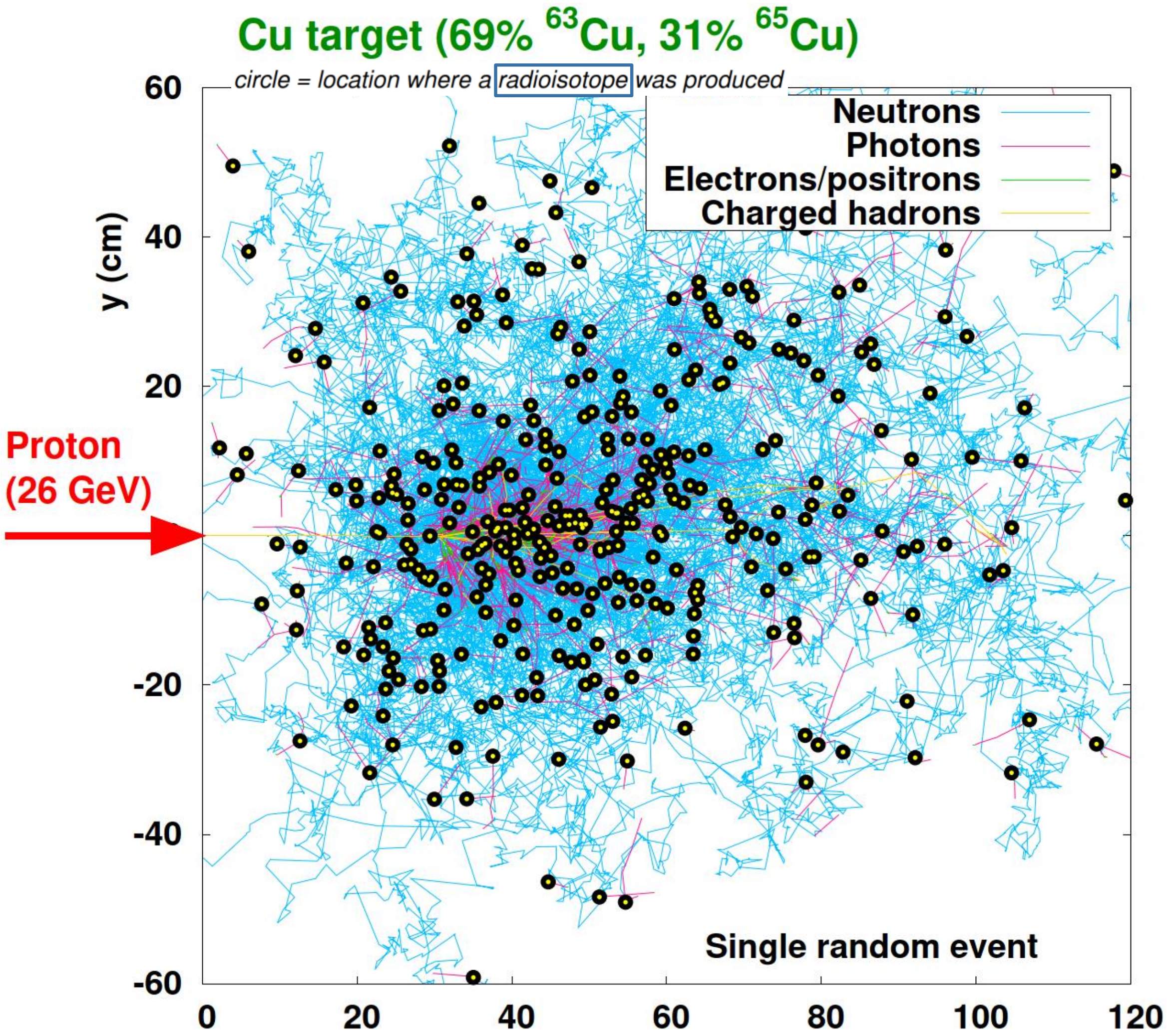
The microscopic view [III]

one 450 GeV proton on aluminum

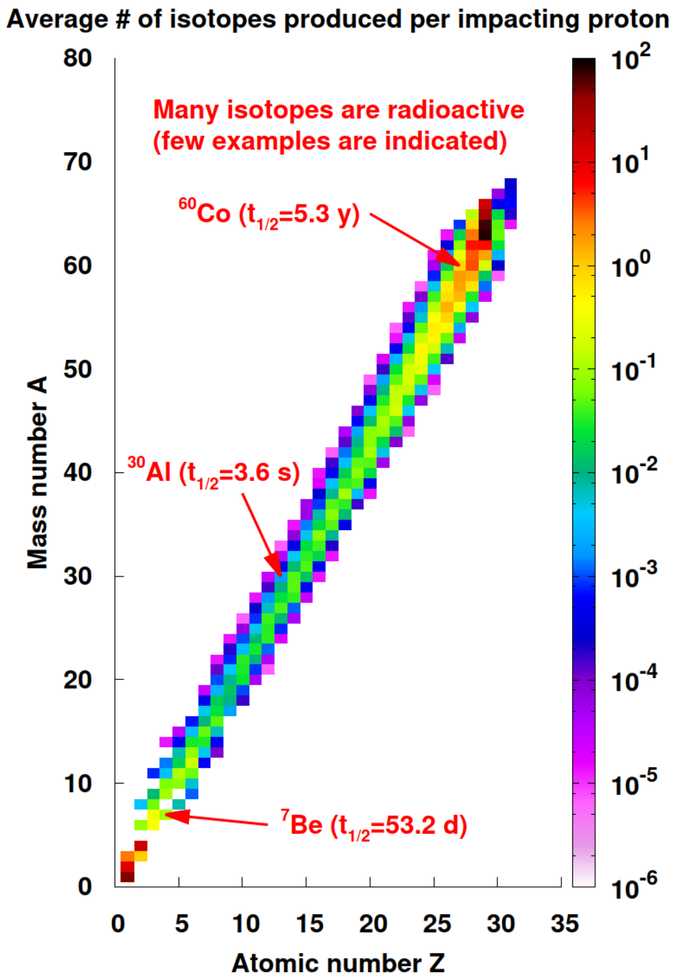


The microscopic view [IV]

one 26 GeV proton on copper



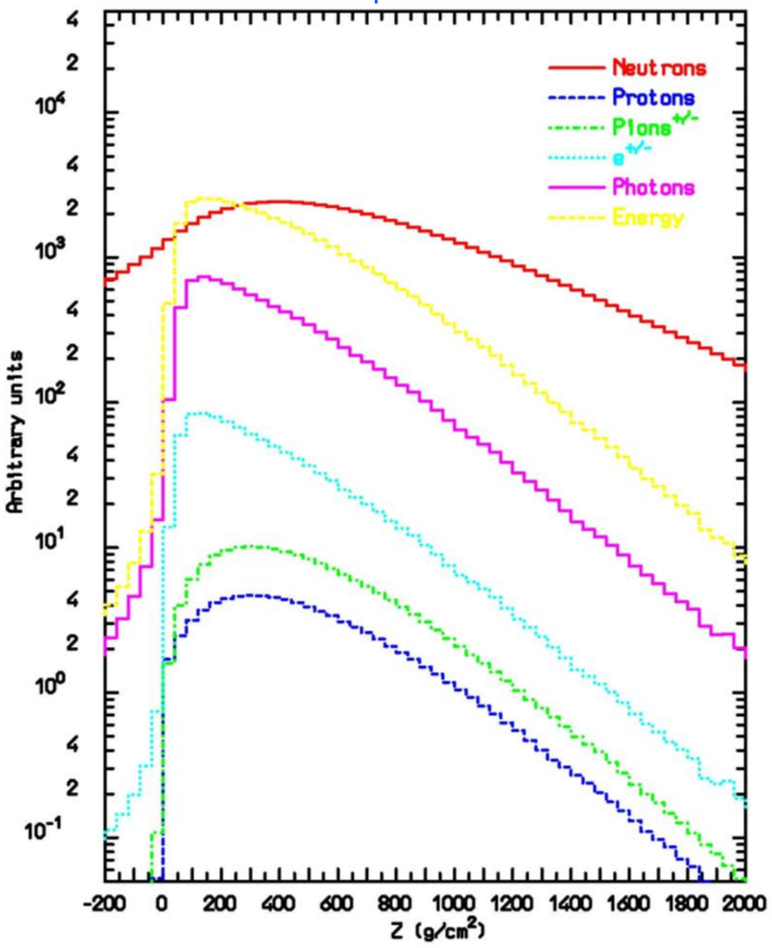
THE MACROSCOPIC VIEW: ACTIVATION



The macroscopic view of high energy showers

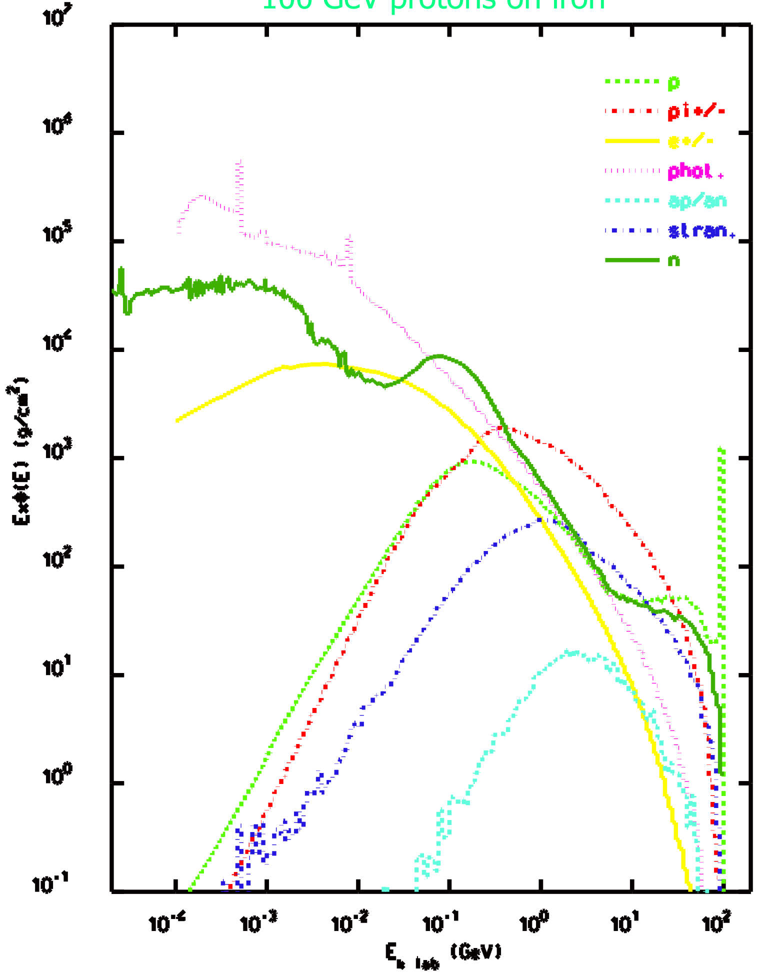
particle fluence and energy deposition profile

100 GeV protons on lead



volume-averaged particle spectra

100 GeV protons on iron



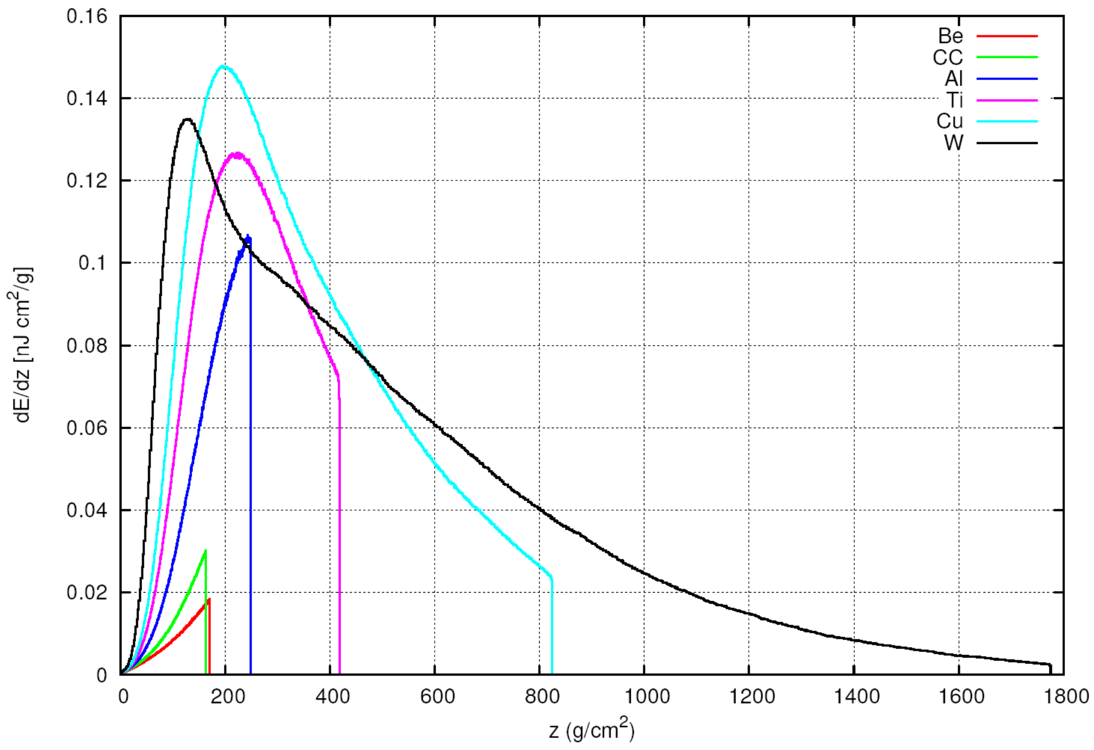
Material dependence

	ρ [g/cm^3]	Z	X_0 [cm]	λ [cm] for 7 TeV p
Be	1.85	4	35.28	37.06
CC	1.77	6	24.12	42.09
Al	2.70	13	8.90	35.35
Ti	4.54	22	3.56	25.04
Fe	7.9	26	1.76	15.1
Cu	8.96	29	1.44	13.86
W	19.3	74	0.35	8.90

energy deposition transversally integrated

[different from *peak density* profile, which depends on beam size]

for a 7 TeV proton impacting on a 92 cm long jaw



Nuclear reactions

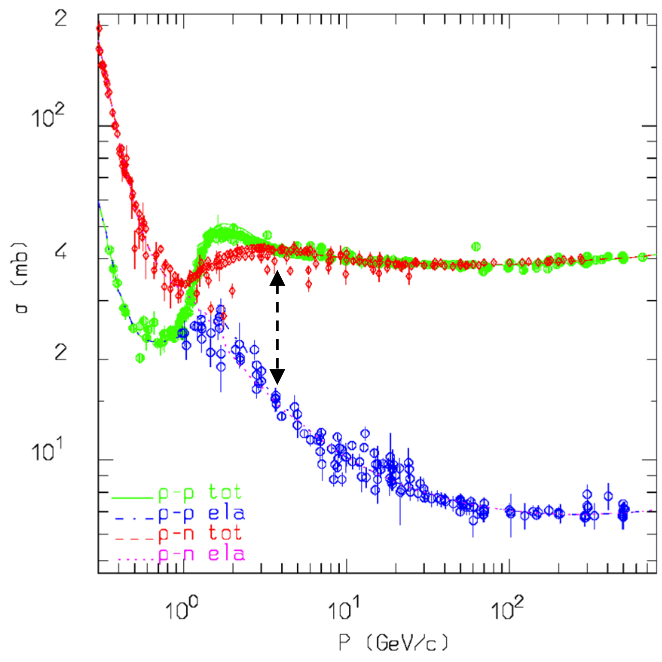
In general there are two kinds of nuclear reactions:

- **Elastic** interactions are those that **do not change the internal structure** of the projectile/target and **do not produce new particles**. Their effect is to transfer part of the projectile energy to the target (lab system), or equivalently to deflect in opposite directions target and projectile in the Centre-of-Mass system with no change in their energy.
  There is no threshold for elastic interactions.

- **Non-elastic** reactions are those where **new particles are produced** and/or the **internal structure** of the projectile/target **is changed** (e.g. the nucleus is excited).
  A specific non-elastic reaction has usually an energy threshold below which it cannot occur (the exception being neutron capture).

Non-elastic hadron-nucleon reactions [I]

In order to understand Hadron-Nucleus (hA) nuclear reactions, one has to understand first Hadron-Nucleon (hN) reactions, since nuclei are made up by protons and neutrons.



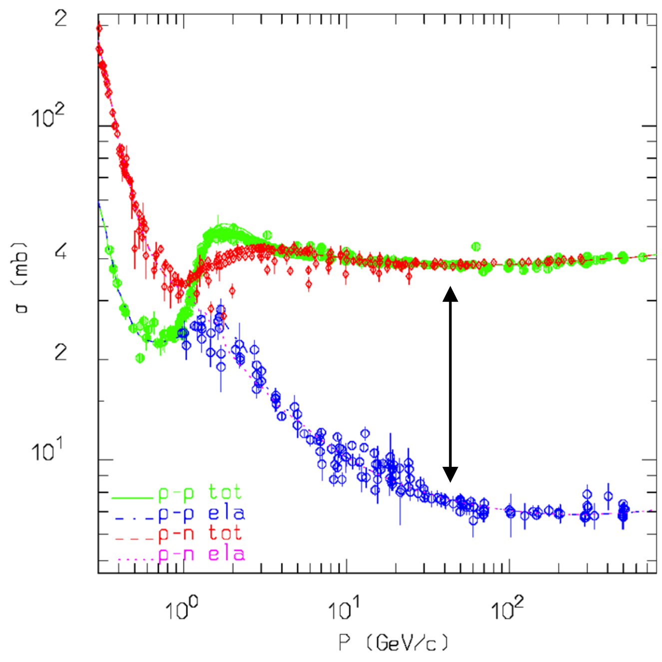
Intermediate Energies

All reactions proceed through an intermediate state containing at least one resonance (dominance of the $\Delta(1232)$ resonance and of the N* resonances)

$N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold around 290 MeV, important above 700 MeV

$\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV

Non-elastic hadron-nucleon reactions [II]

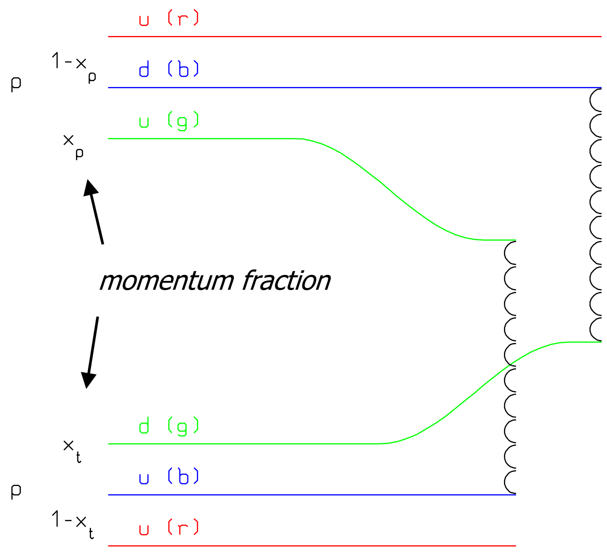


High Energies: Dual Parton Model/Quark Gluon String Model etc

Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string). Each of the two hadrons splits into 2 colored partons $\rightarrow$ combination into 2 colorless chains $\rightarrow$ 2 back-to-back jets.

Each jet is then hadronized

into physical hadrons.



Non-elastic hadron-nucleus reactions

FLUKA PEANUT

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

Generalized IntraNuclear cascade

↓

Preequilibrium stage
with current excitation energy and exciton configuration
(non-nucleons are emitted/decayed)

↓

Evaporation/Fragmentation/Fission

γ de-excitation

t (s)

10^{-23}

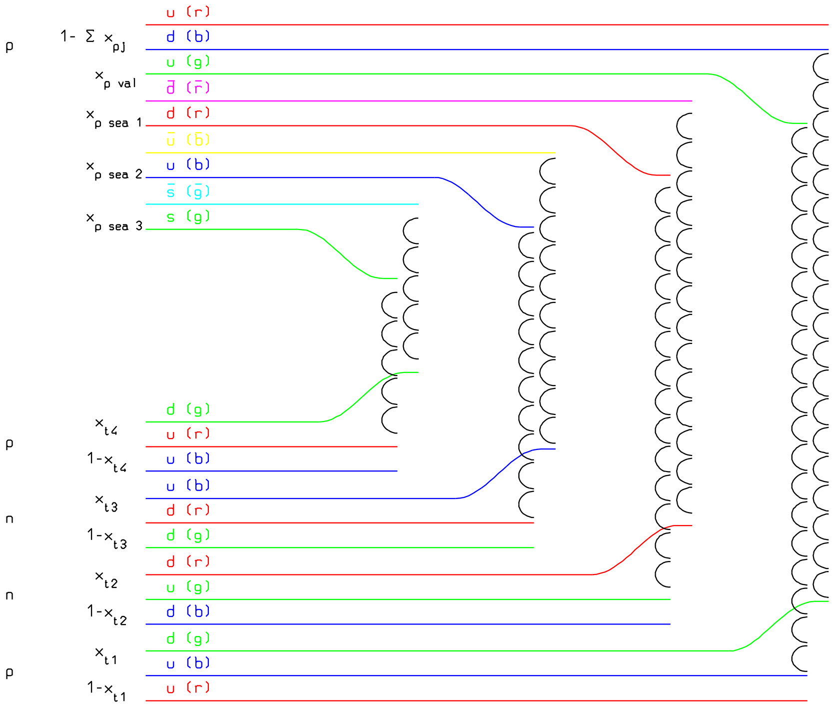
10^{-22}

10^{-20}

10^{-16}

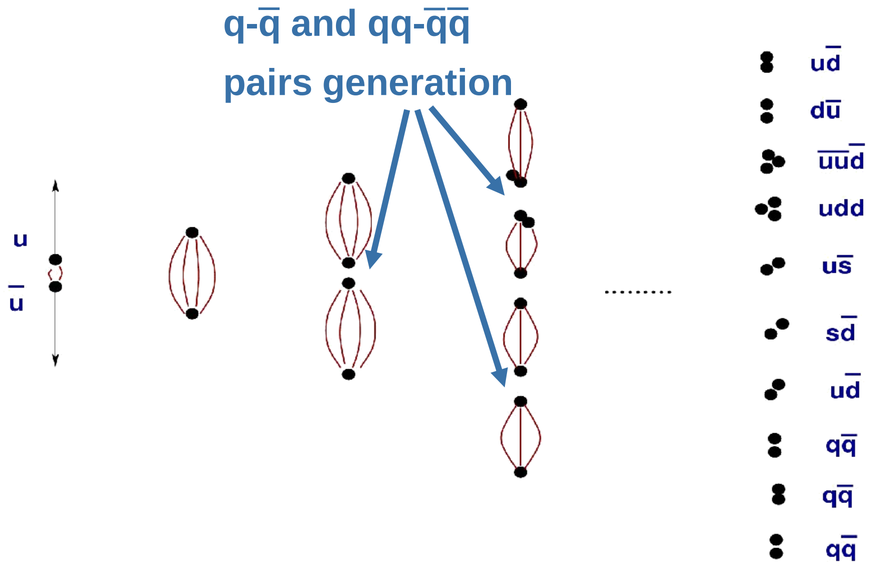
Cascade

i. two-chain diagram



The Glauber calculus predicts explicit *multiple primary* collisions

ii. hadronization



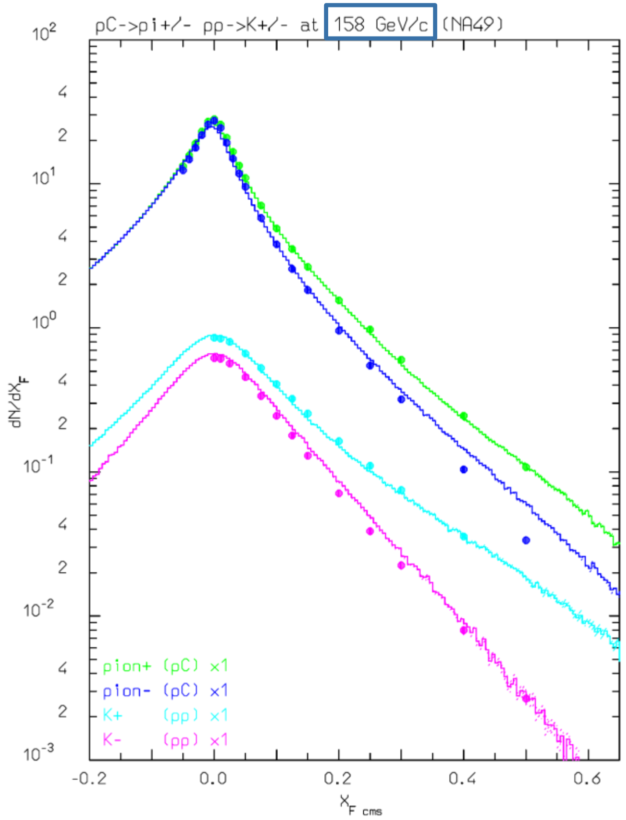
iii. formation zone

Condition for possible re-interaction inside a nucleus: $\Delta x_{for} \leq R_A \approx r_0 A^{\frac{1}{3}}$

reflecting the materialization time

A benchmark glimpse

PROTON – C, PROTON

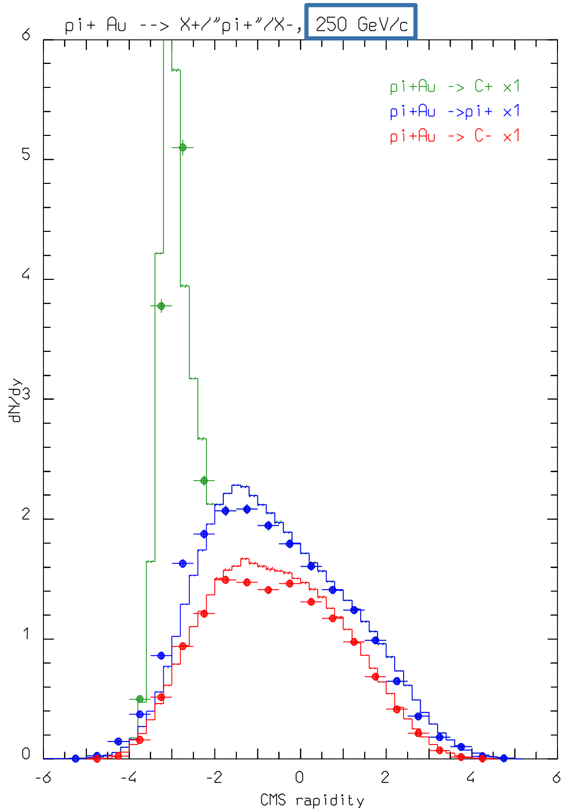


Differential pion and kaon production

Points: exp. data (C. Alt et al., EPJC49 (2007) 897 and T. Anticic et al. (NA49) EPJC68 (2010) 1)

Histogram: FLUKA

PROTON – Au

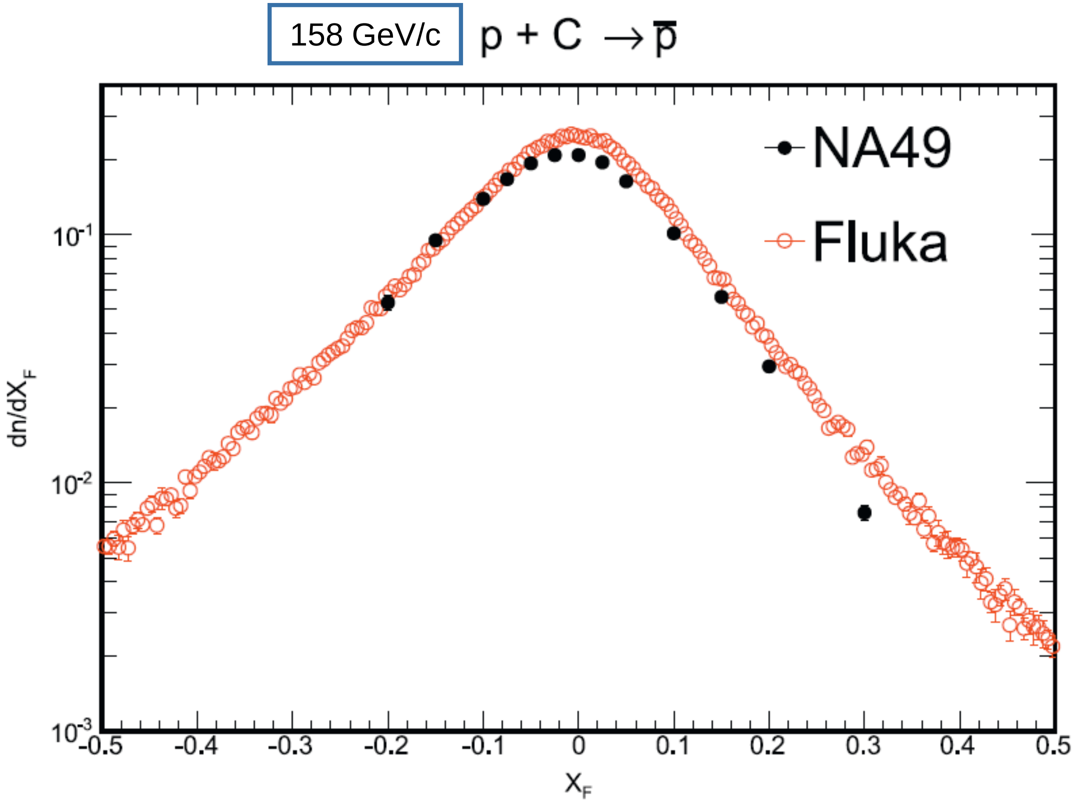


Differential charged particle production

Points: exp. data (Agababyan et al., ZPC50 (1991) 361)

Histogram: FLUKA

PROTON – C

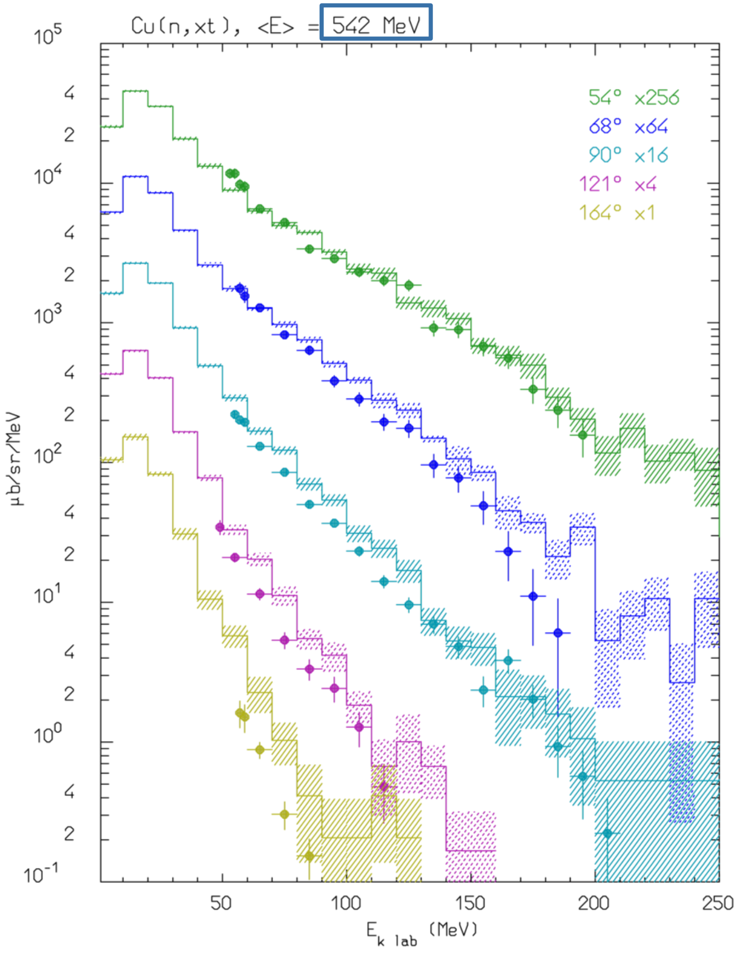


Differential antiproton production

Coalescence

High energy light fragments can be produced by a mechanism joining together nucleons that are near in the phase space.

NEUTRON – Cu



double-differential triton spectra

To be activated when light fragment spectra or residual nuclei are of interest:

PHYSICS Type: COALESCE ▾ Activate: On ▾

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7.▼+....
PHYSICS           1.                                                    COALESCE
```

… together with *deuteron splitting at* low energy *interaction:*

PHYSICS Type: IONSPLIT ▾ Ion Split: On ▾ Splitting: Nonelastic ▾
Emin: 0.005 Emax: 0.15 Amin: 2 Amax: 2

```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7.▼+....
PHYSICS                   1.      0.005      0.15        2.        2.   3.IONSPLIT
```

to compensate for the lack of a respective interaction model

Pion absorption

$$\sigma_t^{A} = \sigma_{res}^{A} + \sigma_t^{Free} - \sigma_{res}^{Free} + \sigma_s^{A}$$

in nuclear medium

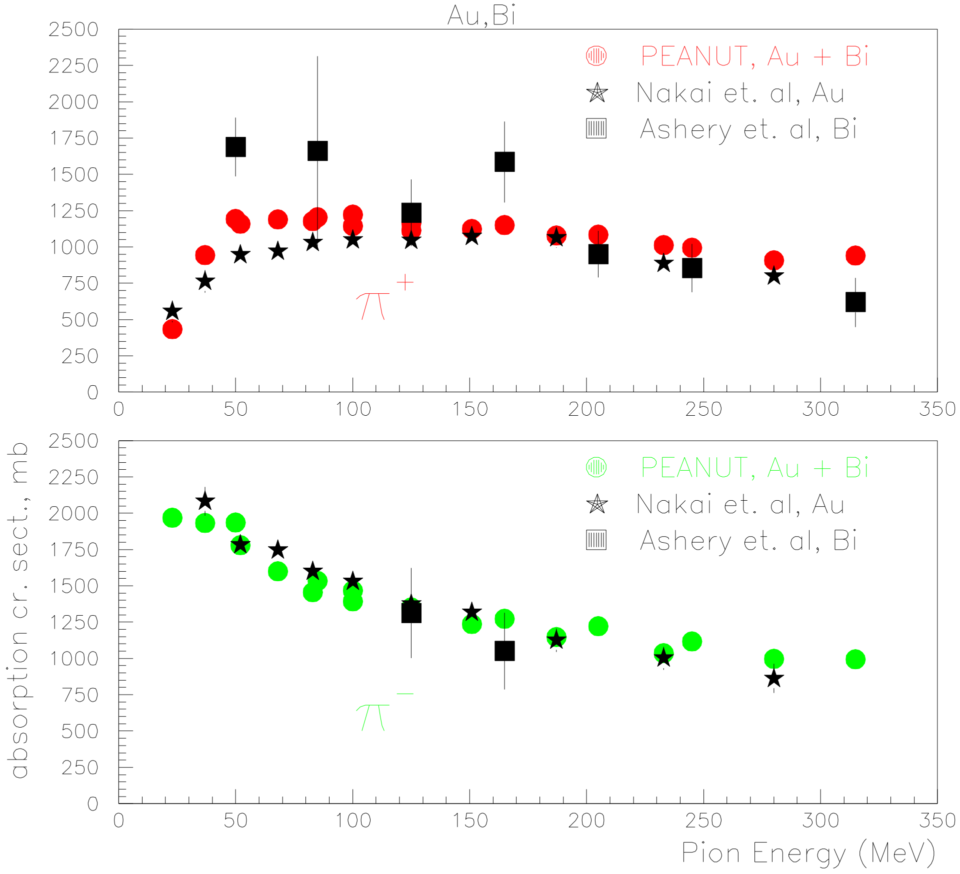
elastic scattering

quasi-elastic scattering

charge exchange

multibody absorption

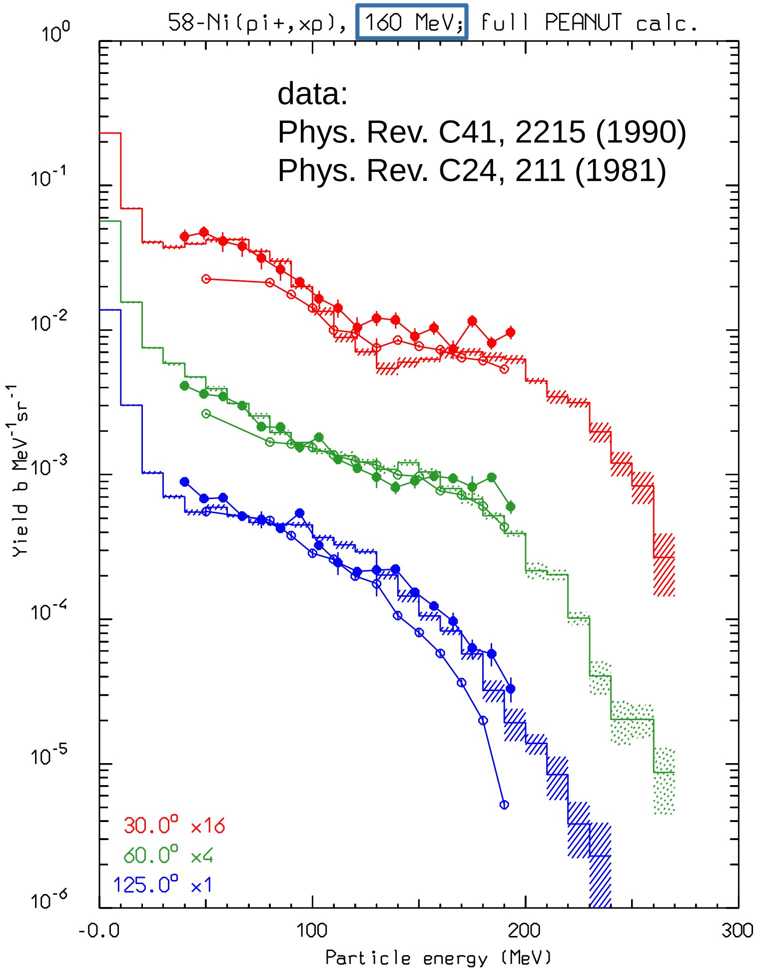
PION – Au, Bi



in the Δ resonance region

PION – Ni

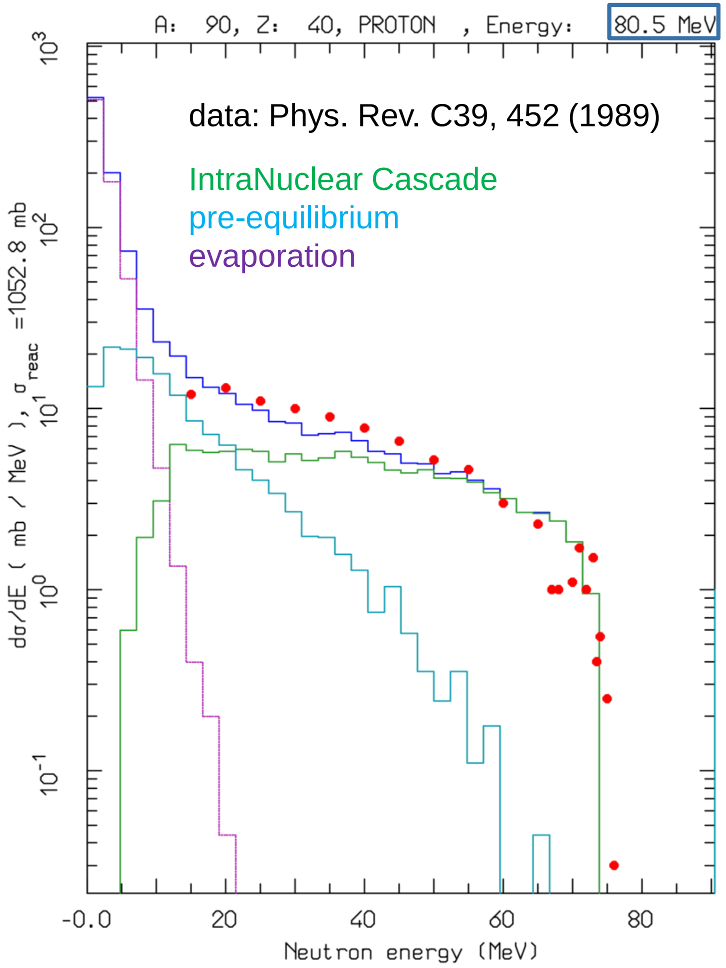
Emitted proton spectra at different angles



Pre-equilibrium

semiclassical exciton model:
excitation energy sharing among nucleons and holes

PROTON – Zr

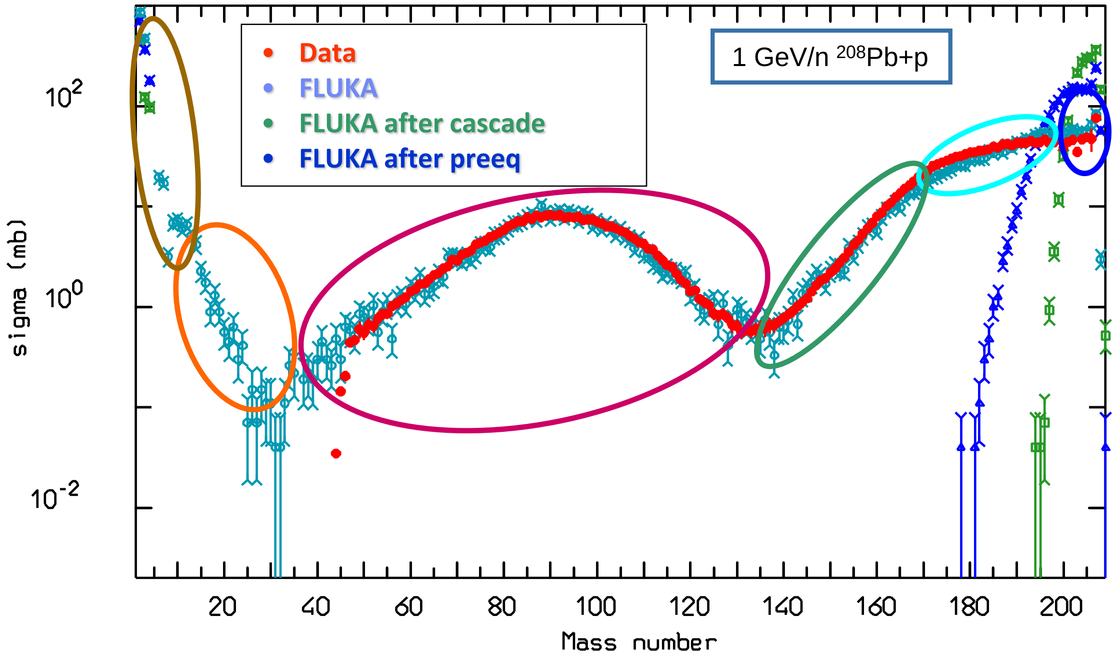


angle-integrated neutron spectrum

Evaporation

In the final stage of the nuclear reaction, a nucleus of given charge (Z), mass (A) and excitation energy undergoes evaporation (Weisskopf-Ewing) or fission (Myers and Swiatecki), or fragmentation (Fermi break-up for A<18), and γ de-excitation.

Pb – PROTON



Inclusive fragment production

Points: exp. data (T. Enqvist, Nucl. Phys. A 686 (2001) 481)

The evaporation of heavy fragments (up to A=24) has to be activated when residual nuclei are of interest:

```
PHYSICS          Type: EVAPORAT ▾   Model: New Evap with heavy frag ▾
                 Zmax: 0            Amax: 0
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7..+....
PHYSICS                 3                                                EVAPORAT
```

Hadronic interactions [II]

Nucleus-nucleus reactions

Different energy ranges and event generators

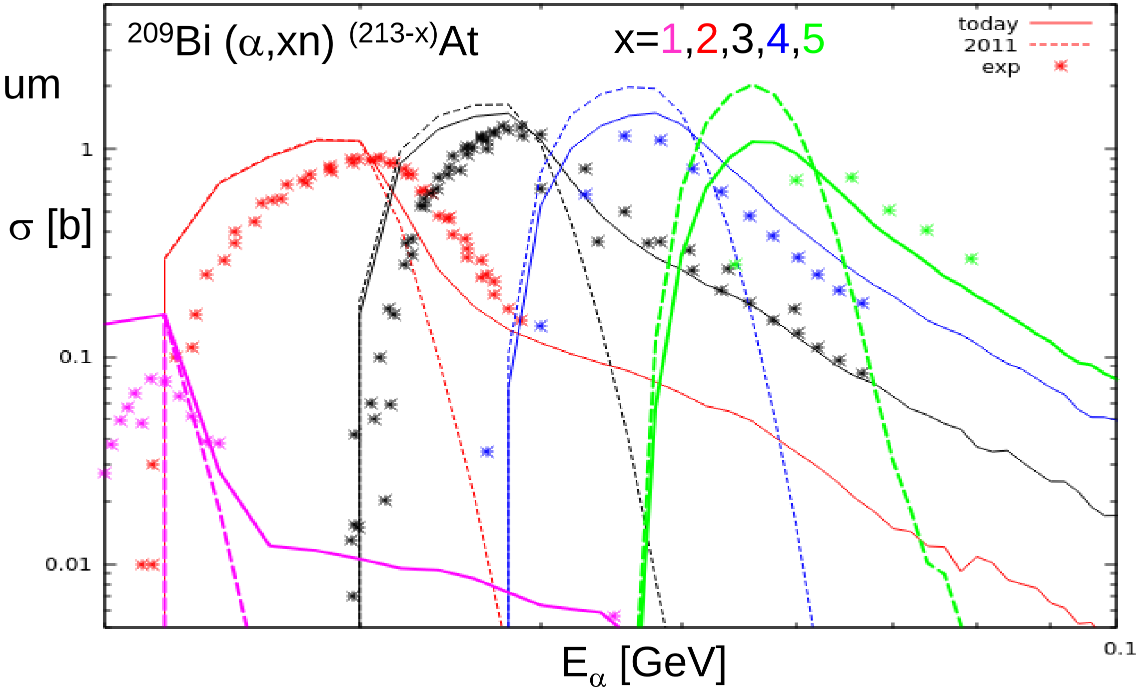
A-A nuclear reactions are treated:

- above 5* GeV/n by DPMJET-III:
  - it’s an independent code by R. Engel, J. Ranft and S. Roesler, interfaced with FLUKA by A. Empl et al., nowadays developed and distributed by A. Fedynitch
  - to be linked by *ldpmqmd*
  - * overlap with RQMD-2.4 from 4.5 to 5.5 GeV/n
  - **required also for h-h and h-A reactions above 20 TeV** (overlap with PEANUT from 10 to 30 TeV)
- between 125† MeV/n and 5† GeV/n by RQMD-2.4:
  - original code by H. Sorge et al., interfaced with FLUKA by A. Ferrari et al., no longer developed
  - to be linked by *ldpmqmd*
  - † overlap with BME from 0.1 to 0.15 GeV/n and with DPMJET-III from 4.5 to 5.5 GeV/n
- below 125§ MeV/n by BME:
  - original code by E. Gadioli et al., interfaced with FLUKA by F. Cerutti et al.
  - already linked as part of the FLUKA library
  - § overlap with RQMD-2.4 from 0.1 to 0.15 GeV/n
  - **deuterons are not covered**

Sharing the same FLUKA de-excitation modules

- The projectile- and target-like excited nuclei produced by DPMJET-III go through the final evaporation stage (see slide 17)
- The projectile- and target-like excited nuclei reconstructed from the RQMD-2.4 final state go first through the pre-equilibrium stage (see slide 16)
- The excited nuclei generated by BME, as their pre-equilibrium de-excitation cannot be directly performed by BME since they fall outside the BME database domain, also go through the PEANUT pre-equilibrium stage

The BME interface with the PEANUT pre-equilibrium yielded a particular improvement for the excitation functions of heavy residues produced by low energy alphas



Photonuclear interactions

Photon-nucleus reactions

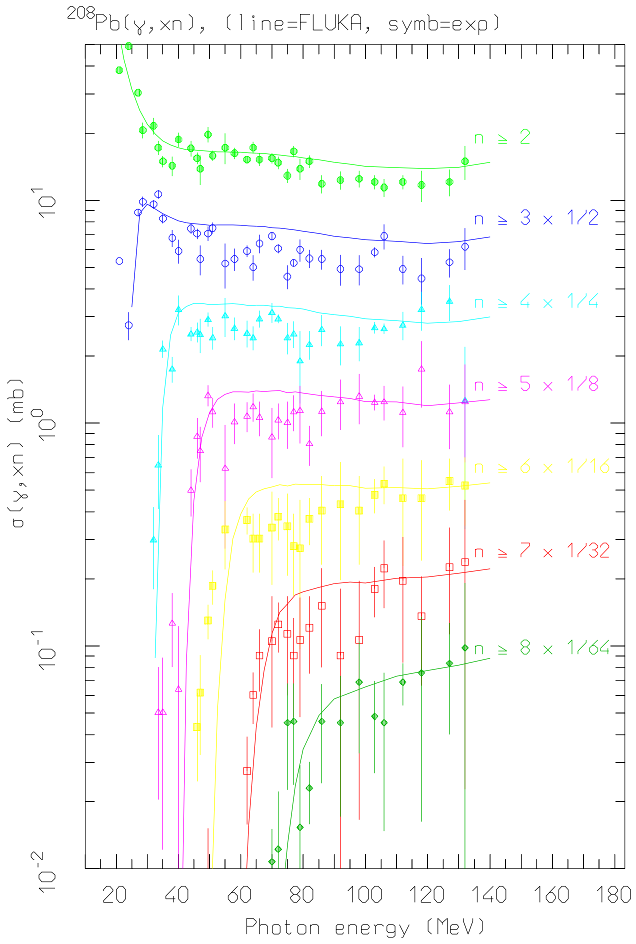
γ-A

To be activated when relevant:

```
PHOTONUC                Type: ▼                                   All E: On ▼
   E>0.7GeV: off ▼   Δ resonance: off ▼      Quasi D: off ▼   Giant Dipole: off ▼
                           Mat: COPPER ▼       to Mat:  ▼              Step:
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7.▼+....
PHOTONUC                 1                               COPPER
```

- The reaction cross section features four energy ranges:
  - Giant Dipole Resonance (6-60 MeV, stored in a special database)
  - Quasi-deuteron
  - Delta resonance
  - Vector Meson Dominance (high energy > 0.7 GeV)
- The reaction outcome is calculated through the IntraNuclear Cascade, pre-equilibrium and evaporation stages
- Photonuclear reactions need to be biased by the **LAM-BIAS** card (see the Biasing lecture)

γ – Pb

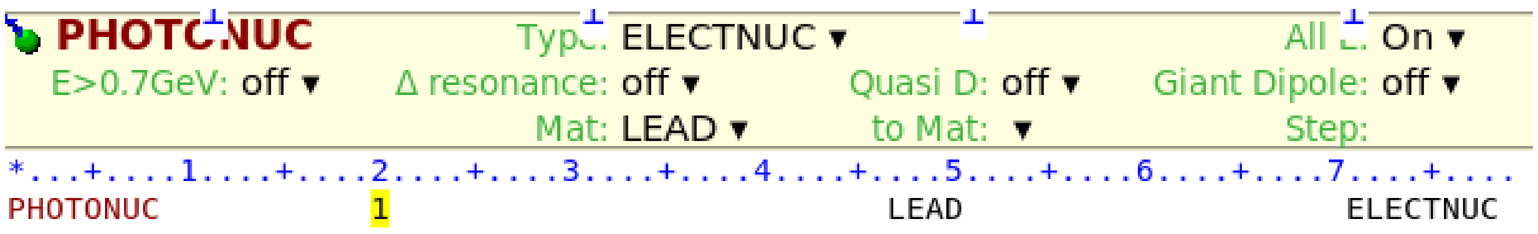


cross section for multiple neutron emission
data: NPA367, 237 (1981) and NPA390, 221 (1982)

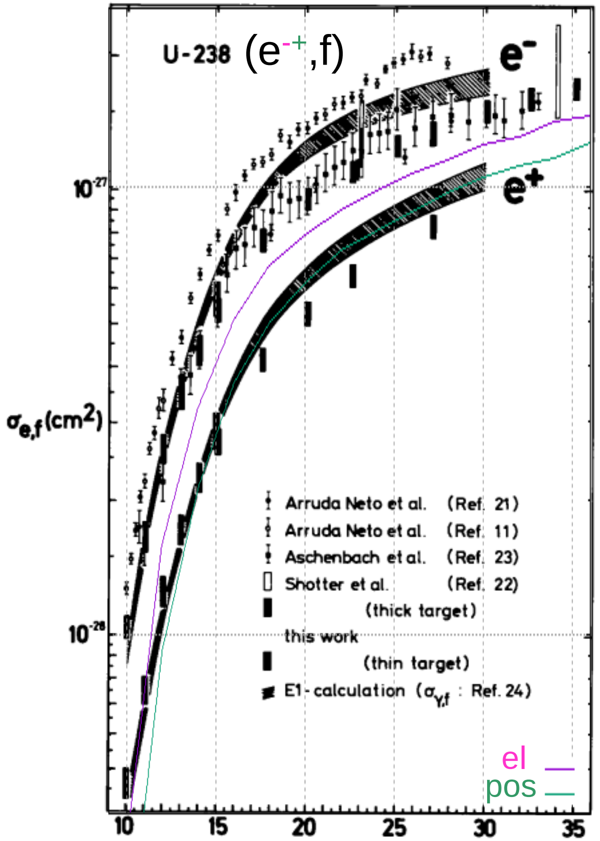
μ-A, e$^-$-A, e$^+$-A

Virtual photon reactions are also implemented:

- **muon photonuclear** interactions (normally on by default, no need for the **MUPHOTON** card)
- **electronuclear** interactions, to be activated:



- For *electron/positron beams*, they play a role in case of thin target. As the material thickness exceeds the respective radiation length, reactions by real bremsstrahlung photons dominate.
- The card above activates automatically real photon reactions too (*no need for an additional card* as in the previous slide)



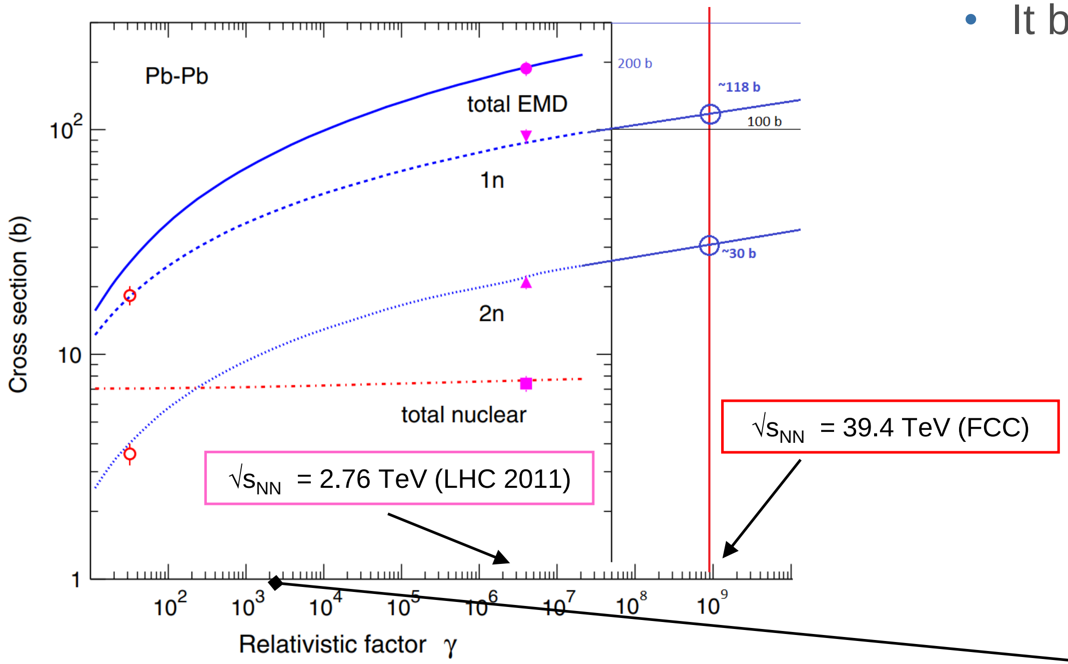
[H. Ströher et al, Nucl. Phys. A 378 (1982) 237]

A-A

- **electromagnetic dissociation** of ions, to be activated:

```
PHYSICS                    Type: EM-DISSO ▾            EM Disso: Proj&Target EM-Disso ▾
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....
PHYSICS              2.                                                  EM-DISSO
```

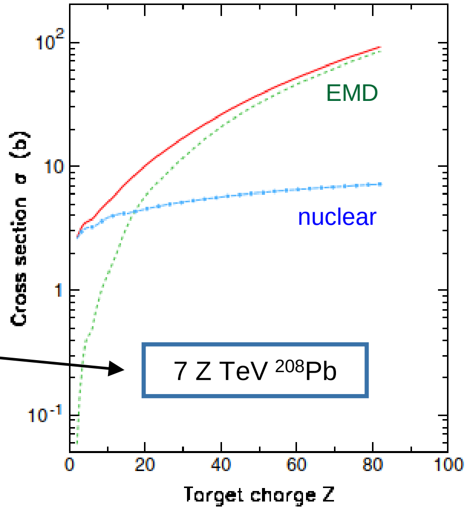
Pb – Pb



[H.H. Braun et al, Phys. Rev. ST AB 17 (2014) 021006]

- It becomes dominant at high energies with high Z ions

Pb – Z



FLUKA