Hadronic & photonuclear interactions

Hadron-nucleus, nucleus-nucleus and photon-nucleus reactions

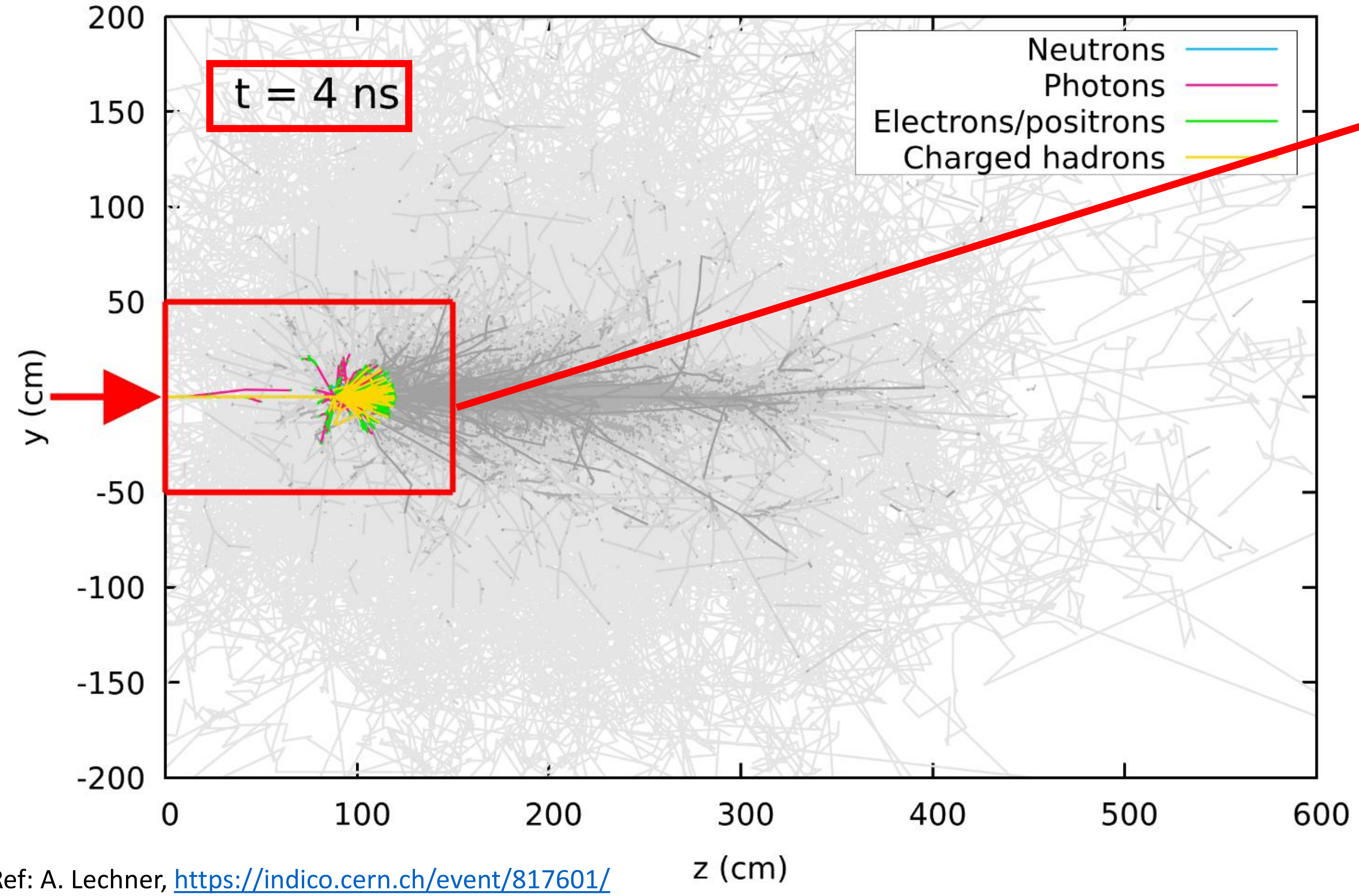
Relevant cards: **PHYSICS**, **PHOTONUC**

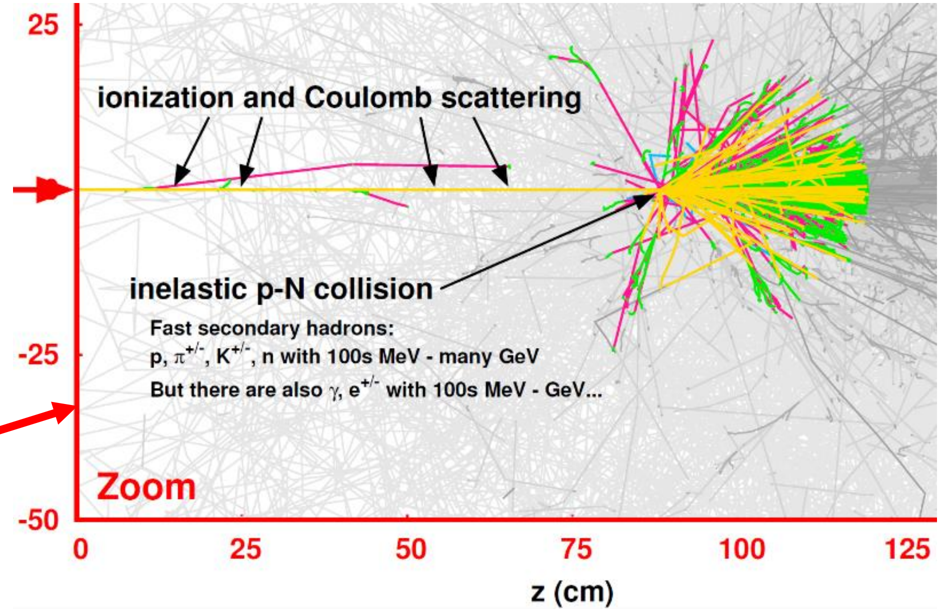
Hadronic interactions [I]

Hadron-nucleus reactions

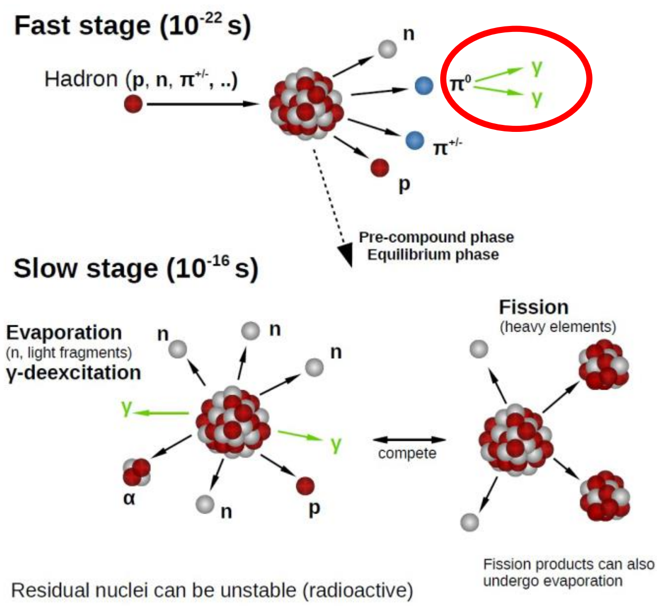
The microscopic view [I]

Simulated shower for a single 450 GeV proton in aluminum





Stages of a hadron-nucleus reaction:



Ref: A. Lechner, https://indico.cern.ch/event/817601/

How often do hadron-nucleus inelastic interactions occur?

- Mean free path to next (nuclear) inelastic interaction:

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

- This information is printed in the output file for the beam particle at the beam energy
- E.g. for 450 GeV p
- Typical mean free path to next nuclear reaction in dense media: O(10) cm

Material Number&Name	Atomic Number	Atomic Weight	Density g/cm**3	Inelastic Scattering Length for PROTON at Beam energy cm
1 BLCKHOLE	0.000	0.000	0.000	0.1000E+31
2 VACUUM	0.000	0.000	0.000	0.1000E+31
3 HYDROGEN	1.000	1.008	0.8370E-04	0.6059E+06
4 HELIUM	2.000	4.003	0.1660E-03	0.3590E+06
5 BERYLLIU	4.000	9.012	1.848	40.64
6 CARBON	6.000	12.01	2.000	40.77
7 NITROGEN	7.000	14.01	0.1170E-02	0.7278E+05
8 OXYGEN	8.000	16.00	0.1330E-02	0.6643E+05
9 MAGNESIU	12.00	24.30	1.740	57.10
10 ALUMINUM	13.00	26.98	2.699	37.90
11 IRON	26.00	55.84	7.874	15.97
12 COPPER	29.00	63.55	8.960	14.58
13 SILVER	47.00	107.9	10.50	14.46
14 SILICON	14.00	28.09	2.329	44.42
15 GOLD	79.00	197.0	19.32	9.328
16 MERCURY	80.00	200.6	13.55	13.37
17 LEAD	82.00	207.2	11.35	16.11
18 TANTALUM	73.00	180.9	16.65	10.56
19 SODIUM	11.00	22.99	0.9710	100.7
20 ARGON	18.00	39.95	0.1660E-02	0.6888E+05
21 CALCIUM	20.00	40.08	1.550	73.83
22 TIN	50.00	118.7	7.310	21.34
23 TUNGSTEN	74.00	183.8	19.30	9.156
24 TITANIUM	22.00	47.87	4.540	26.51
25 NICKEL	28.00	58.69	8.902	14.33

“GeV missing” at the end of the output file (don’t panic!)

- Hadron with kinetic energy T_a impinging on a nucleus b at rest, producing N secondaries: $a + b \to 1 + 2 + 3 + \ldots$

$$T_a + m_a + m_b = \sum_{j=1}^{N} T_j + \sum_{j=1}^{N} m_j.$$

- Total energy (kinetic energy plus rest mass) is conserved:

- Reaction Q value (typically in the order of MeV):

$$Q = \sum_{j=1}^{N} T_j - T_a = (m_a + m_b) - \sum_{j=1}^{N} m_j$$

- **$Q<0$** *(Endoenergetic)*: secondaries collectively have less kinetic energy than incoming hadron.
  Incoming kinetic energy partially spent in mass of secondaries*.
  Missing (kinetic) energy in the output file is **positive**.

- **$Q>0$** *(Exoenergetic)*: secondaries collectively have more kinetic energy than incoming hadron.
  Mass converted to kinetic energy.
  Missing (kinetic) energy in the output file is **negative**.

*overcoming nucleon separation energies, providing mass to generate new secondaries (pions, kaons, …), etc.

In the output table, the average Q value per primary (histories may involve more than one nuclear inelastic interaction…)

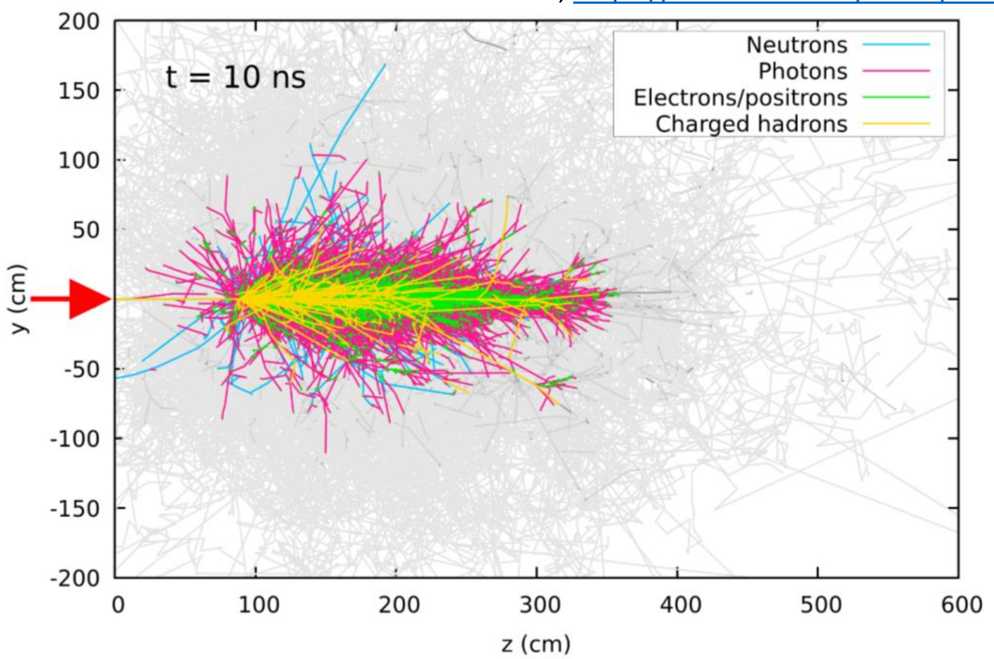
```
 4.5000E+02  (100.%) GeV available per beam particle divided into
Prompt radiation     Radioactive decays
 4.6364E+01  (10.3%)   7.0255E-03 ( 0.0%) GeV hadron and muon dE/dx
 2.1011E+02  (46.7%)   1.5204E-01 ( 0.0%) GeV electro-magnetic showers
 1.3057E+00  ( 0.3%)   1.8288E-05 ( 0.0%) GeV nuclear recoils and heavy fragments
 0.0000E+00  ( 0.0%)   0.0000E+00 ( 0.0%) GeV particles below threshold
 0.0000E+00  ( 0.0%)   0.0000E+00 ( 0.0%) GeV residual excitation energy
 0.0000E+00  ( 0.0%)   0.0000E+00 ( 0.0%) GeV low energy neutrons
 1.3611E+02  (30.2%)   5.0772E-02 ( 0.0%) GeV particles escaping the system
 4.3389E+01  ( 9.6%)   7.4494E-02 ( 0.0%) GeV particles discarded
 0.0000E+00  ( 0.0%)   0.0000E+00 ( 0.0%) GeV particles out of time limit
 1.2432E+01  ( 2.8%)                      GeV missing
```

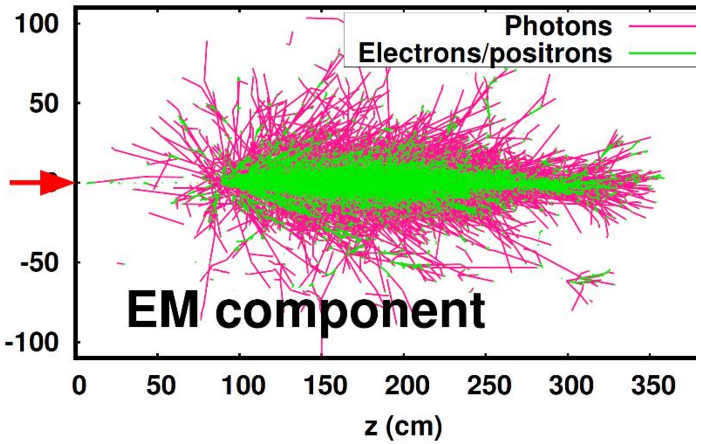
The microscopic view [II]

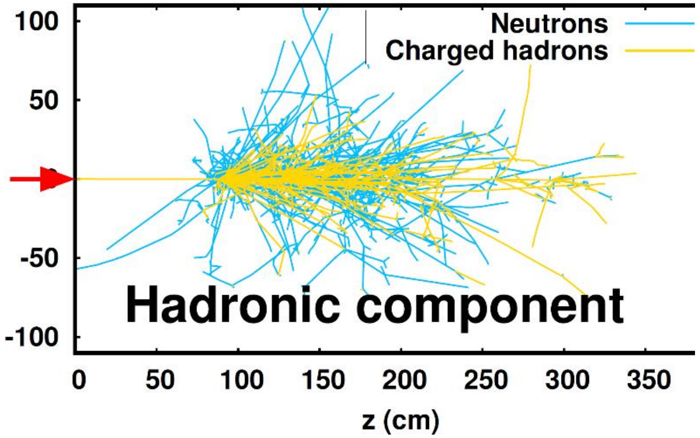
- Nuclear inelastic interactions generate plenty of secondaries
- Nearly geometrical increase in the number of particles in the shower
- Shower develops until hadron energy drops below pion production threshold
- Hadronic showers couple to EM showers ($\pi^0 \rightarrow 2\gamma$)
- EM showers couple to hadronic showers (photonuclear reactions), but at a much lower rate
- EM shower extent: radiation length (see below)

Simulated shower for a single 450 GeV proton in aluminum

Ref: A. Lechner, https://indico.cern.ch/event/817601/



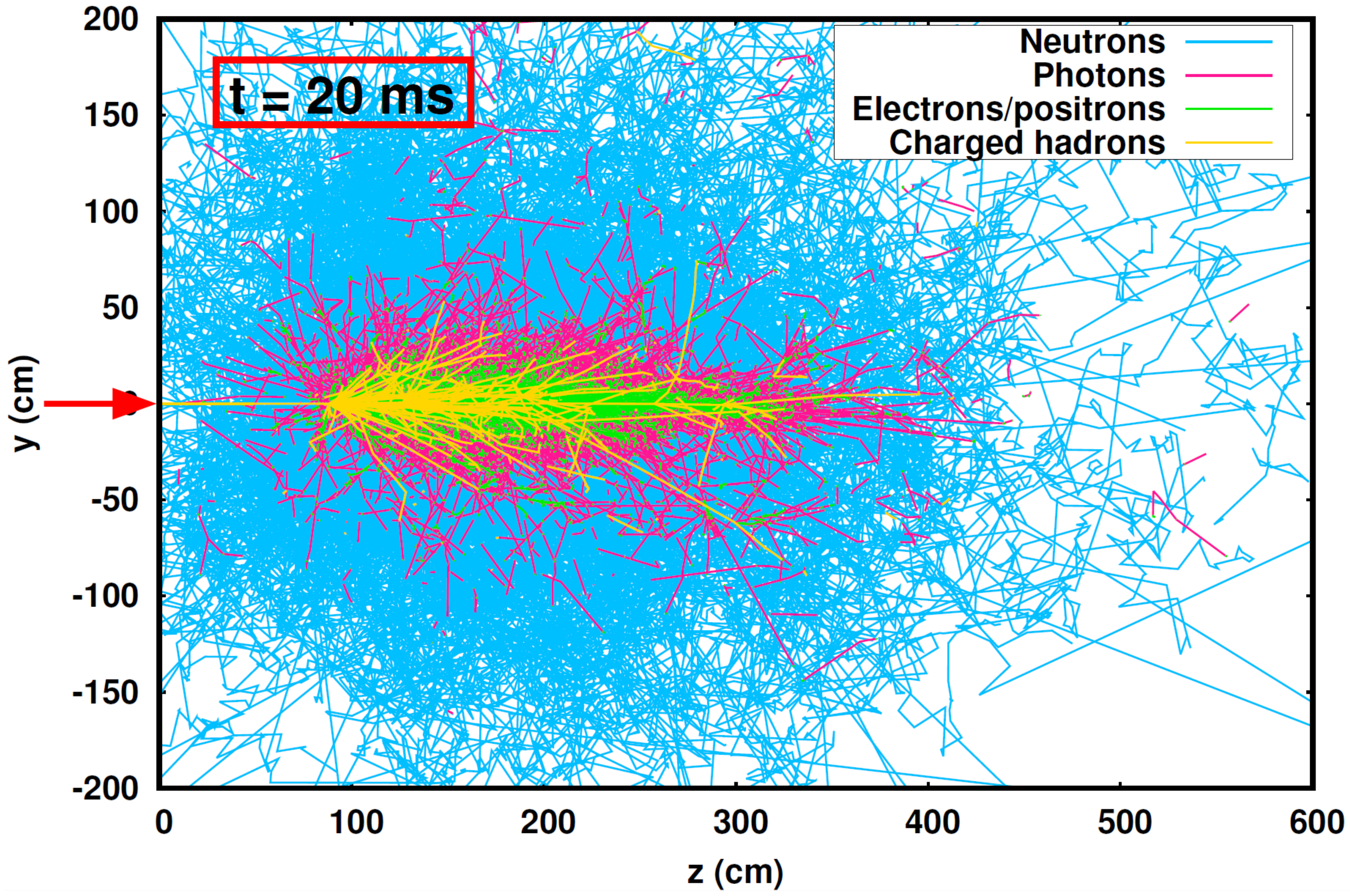




The microscopic view [III]

- After 20 ms, the picture is nearly filled by n
- As seen in the neutronics lecture, neutrons perform (n,el) until they are lost to (n,g), (n,f), or some inelastic channel
- They have to be followed down to thermal energies, as it is typically where (n,g) cross sections are largest – and for some isotopes there are inelastic channels as well, e.g. $^{10}B(n,a)$.

Simulated shower for a single 450 GeV proton in aluminum

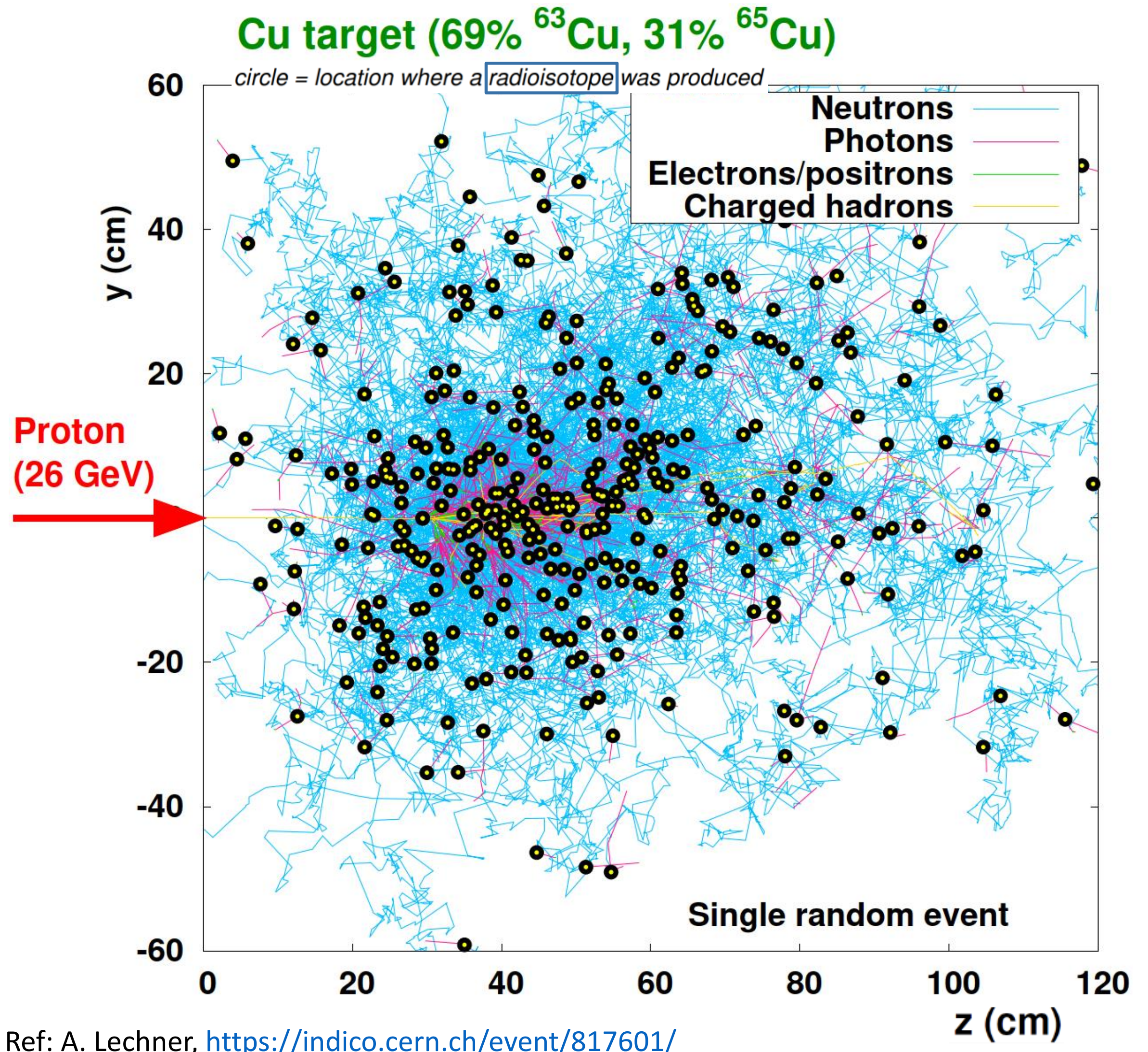


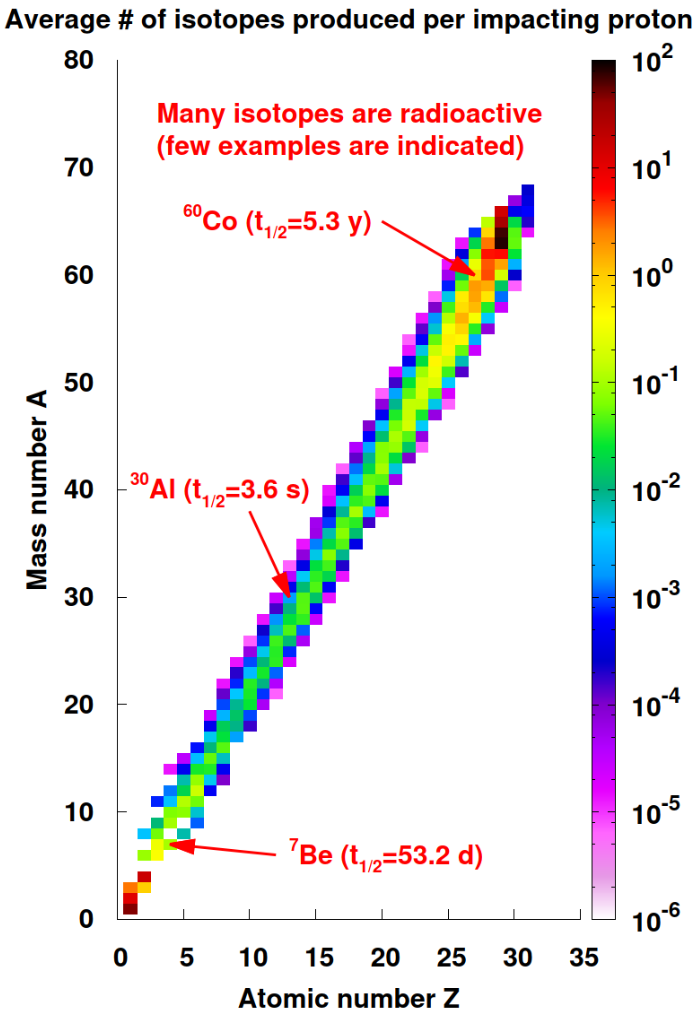
Ref: A. Lechner, https://indico.cern.ch/event/817601/

The microscopic view [IV]

THE MACROSCOPIC VIEW: ACTIVATION

Residual nuclei produced by a single 26 GeV proton on ^{nat}Cu





Averaged over a large number of primary p

Ref: A. Lechner, https://indico.cern.ch/event/817601/

Prompt run: stops with the generation of the residual nuclei
Decay run (much longer time scales): see the activation lecture+exercise on Fri!

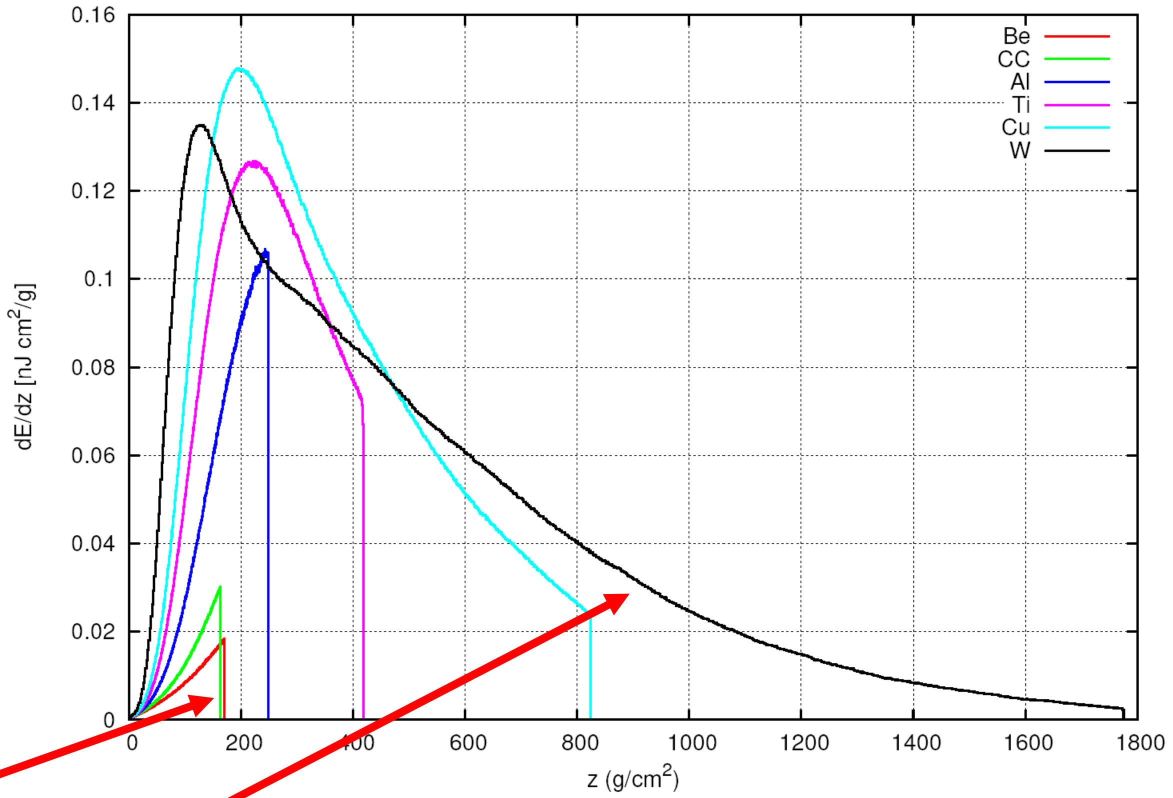
Radiation shower development in different materials

energy deposition transversally integrated

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

	ρ [g/cm3]	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

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



- For light materials (X_0 and λ are large): just the onset of the shower
- For dense materials: shower fully develops and peak is reached early on

- W would appear to be a great material for a collimator, but the material cannot sustain such a load.

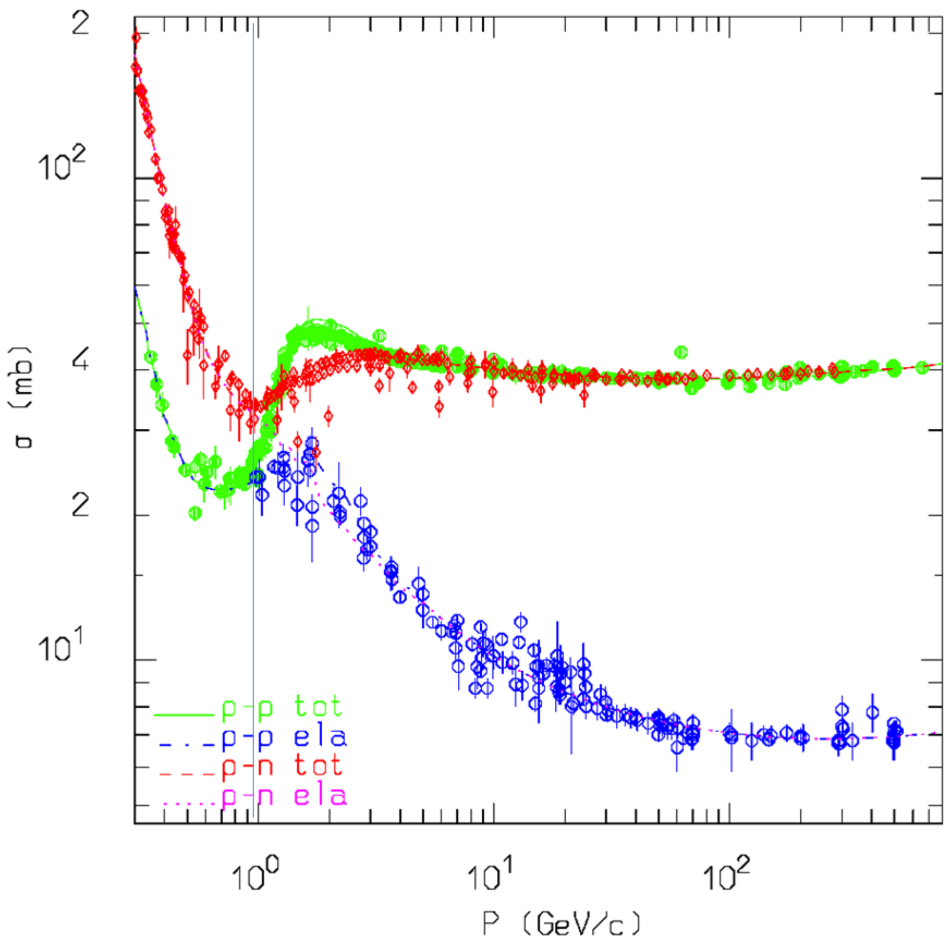
Two kinds of nuclear interactions

- **Elastic**:
  - Neither the target nor the projectile are excited
  - No new particles are produced
  - Projectile and target exchange kinetic energy
  - Their directions change accordingly to conserve 4-momentum
  - There is no threshold kinetic energy for this interaction mechanism.
  - NB: available in FLUKA for $\pi, K,$ ..., n, p - but not for d and heavier ions (possibly less relevant)
  - See https://arxiv.org/abs/2312.12300 for nuclear elastic scattering of protons below 250 MeV

- **Non-elastic / inelastic / reactions:**
  - Target and/or projectile may be excited
  - New particles may be produced
  - There is a threshold kinetic energy (except for neutron capture)

Non-elastic hadron-nucleon reactions [I]

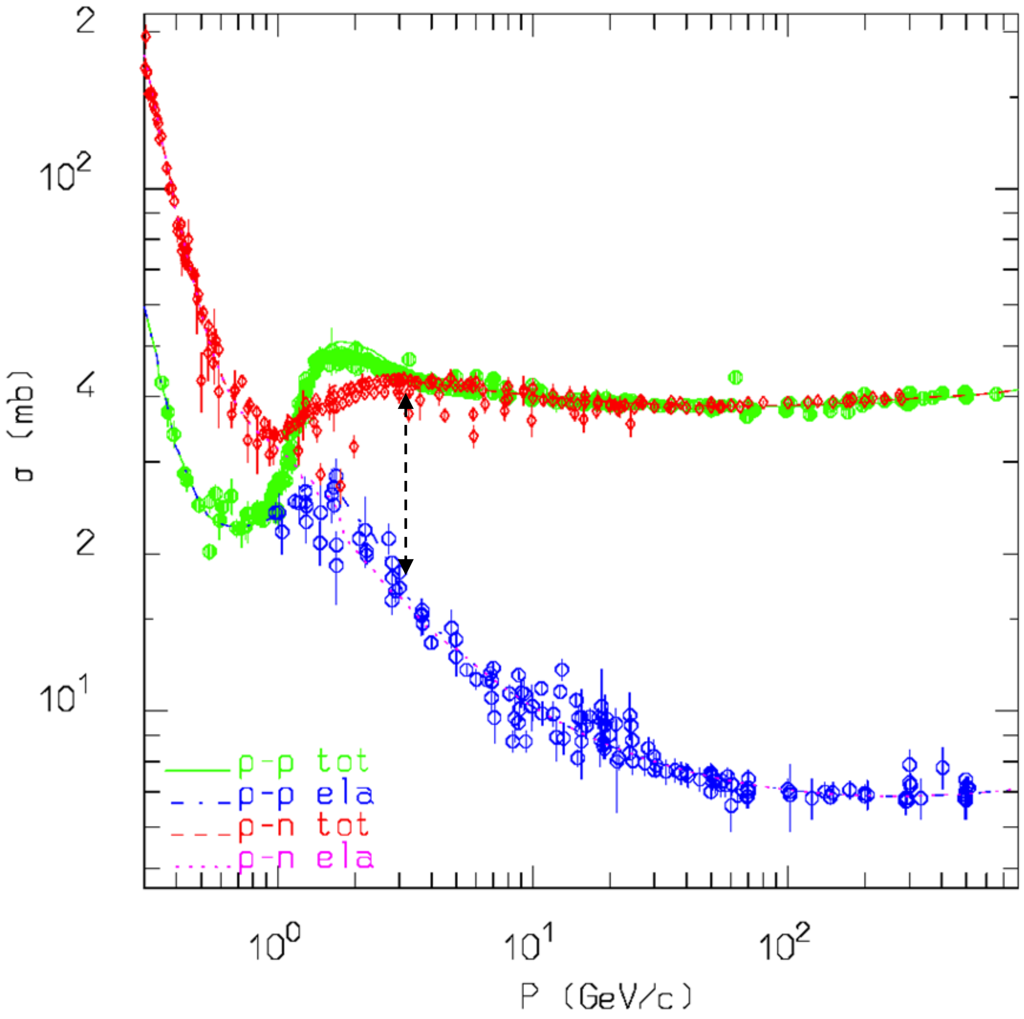
- To understand hadron-Nucleus (hA) nuclear reactions, one must understand first hadron-Nucleon (hN) reactions, since nuclei are made up by protons and neutrons.
- Cross sections for the scattering of n and p projectiles on target nucleons:
- Above ~ GeV/c, most of the hN cross section goes into inelastic processes
- Below particle production threshold:
  - **Cascade of elastic hN collisions inside the nucleus**
  - Knock-on nucleons may be emitted individually or as light fragments (d, t, 3He, 4He, etc)
  - Since particles in the final state are different than those in the original state, the process (nuclear reaction) is indeed inelastic



Ref: Mokhov N.V. and Cerutti F., CERN-2016-002 83-110 and references therein

Non-elastic hadron-nucleon reactions [II]

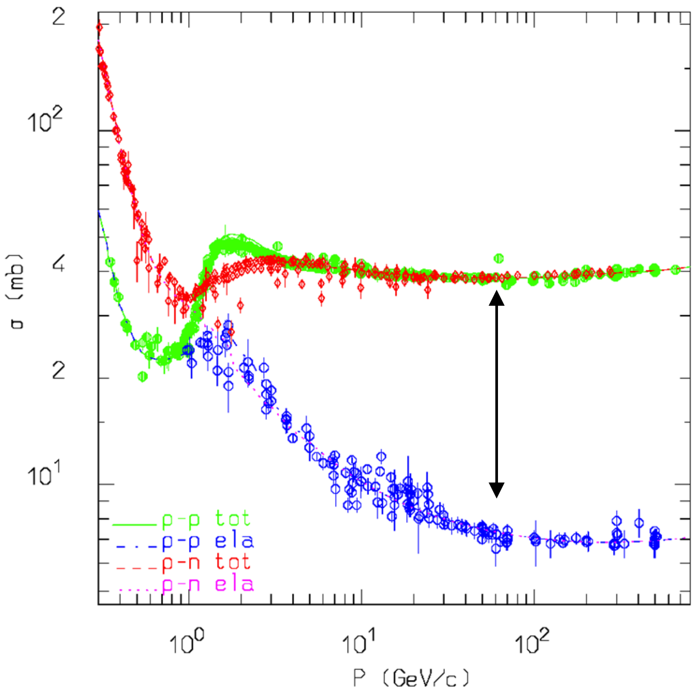
- At *Intermediate Energies*, all reactions proceed through an intermediate state containing at least one resonance (dominance of the Δ(1232) resonance and of the N* resonances) which decays into other particles.
- N1 + N2 → N1' + N2' + π
  (threshold around 290 MeV, important above 700 MeV)
- π + N → π' + π" + N'
  (opens at 170 MeV)



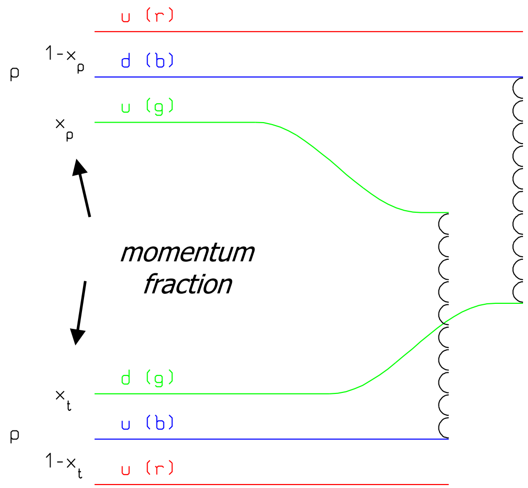
Ref: *Mokhov N.V. and Cerutti F., CERN-2016-002 83-110 and references therein*

Non-elastic hadron-nucleon reactions [III]

- Resonance model breaks down at high energies.
- Dual Parton Model based descriptions are applicable: colliding hadron+nucleon described in terms of quarks
- Quarks held together by the gluon-gluon interaction into the form of a string.
- Strings eventually lead to physical hadrons (see next slides)



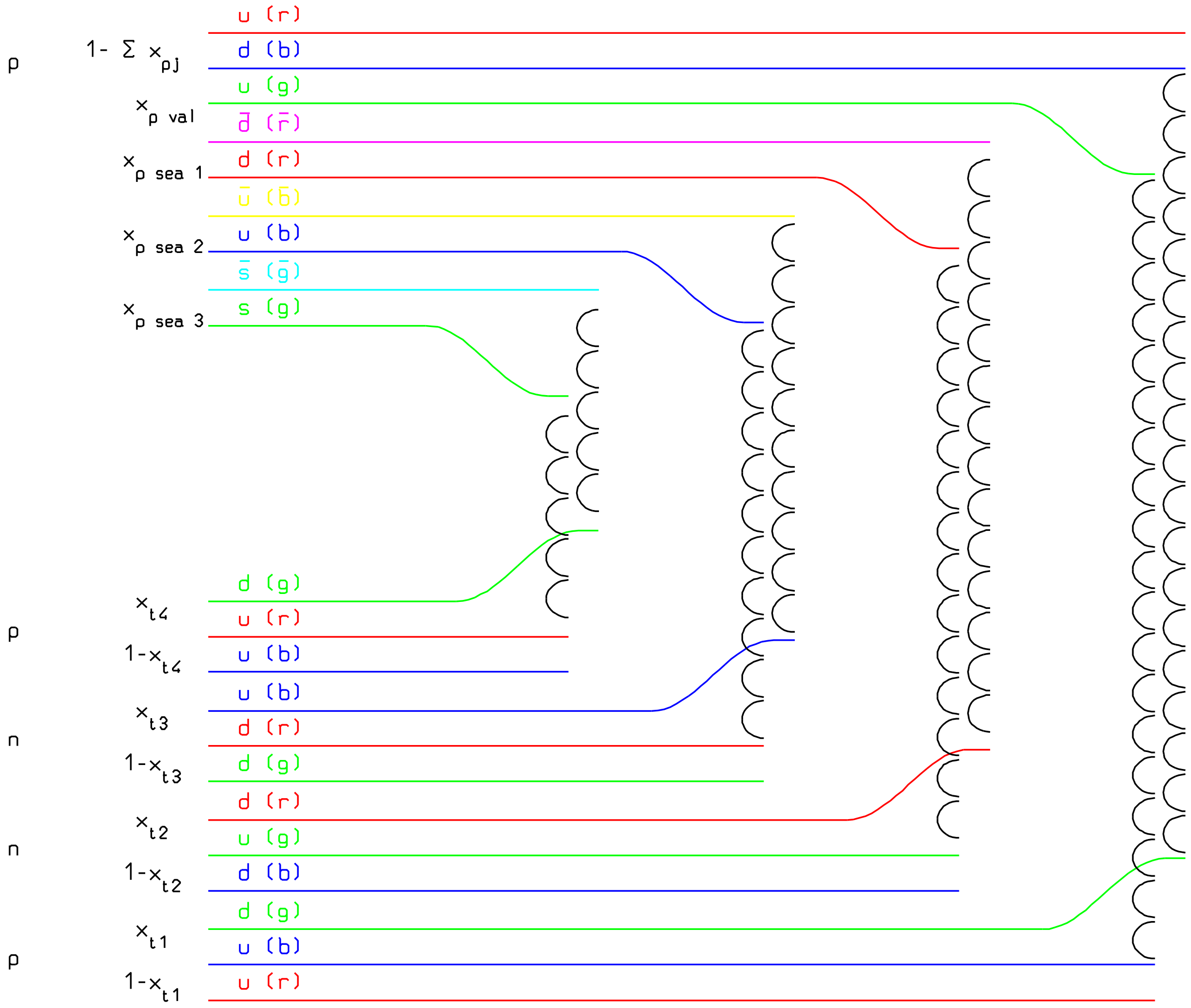
Ref: Mokhov N.V. and Cerutti F., CERN-2016-002 83-110 and references therein



Hadron nucleus reaction

- At high energies, incoming hadron interacts with all nucleons at the same time (multiple primary collision picture of Glauber – field theory expansion by Gribov)
- Quark interaction generates chains
- Valence as well as sea quarks participate (!)

i. Two-chain diagram for p,α reaction

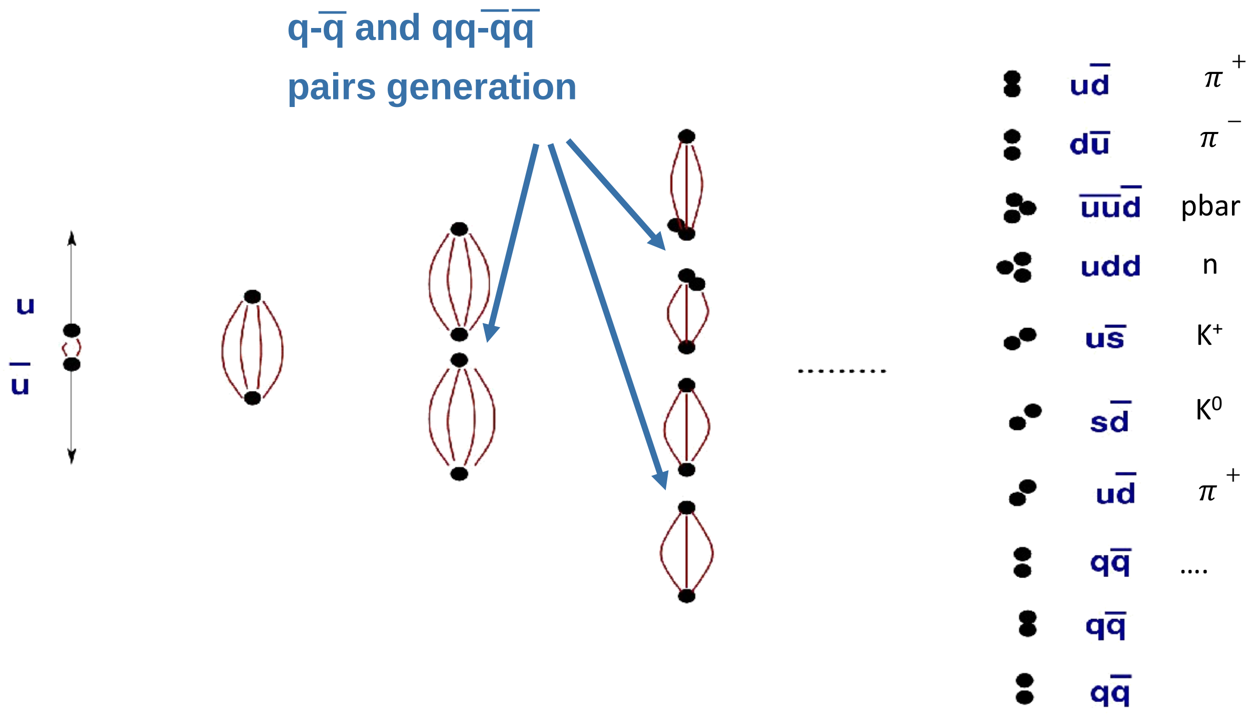


Ref: Mokhov N.V. and Cerutti F., CERN-2016-002 83-110 and refs therein

Hadron nucleus reaction

- Strings generate quark/antiquark combinations
- Hadronization into physical baryons and mesons
- It takes some time for the hadron to materialize. Heisenberg uncertainty principle implies there is a formation zone (length) for hadrons to materialize (before they can reinteract).
- In absence of a formation zone, secondary particle yield would be overestimated

ii. Hadronization



iii. formation zone

Condition for possible re-interaction inside a nucleus:

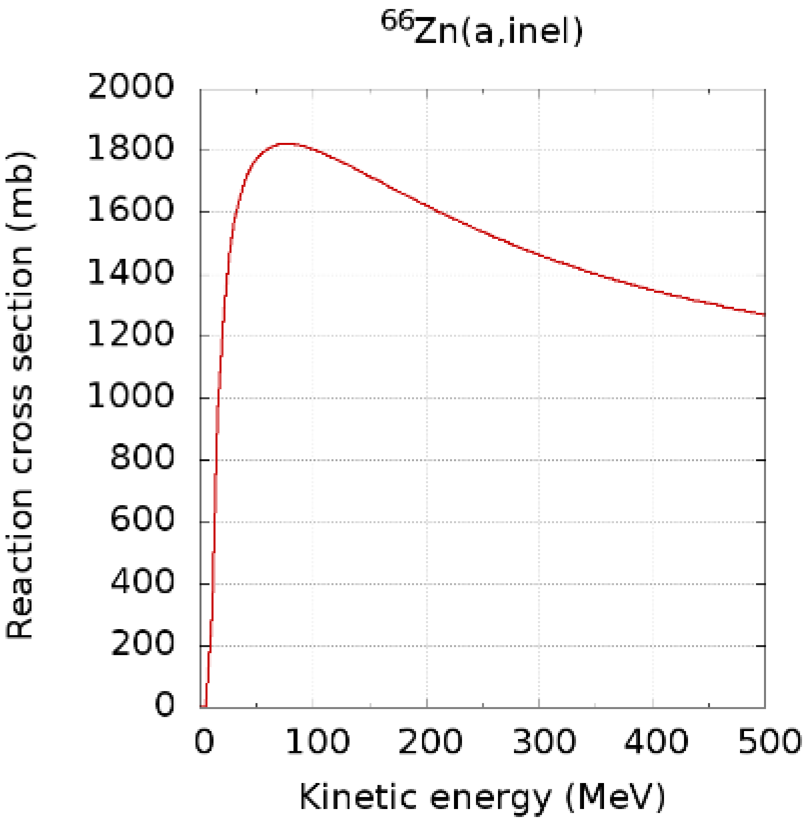
$$\Delta x_{for} \leq R_A \approx r_0 A^{\frac{1}{3}}$$

reflecting the materialization time

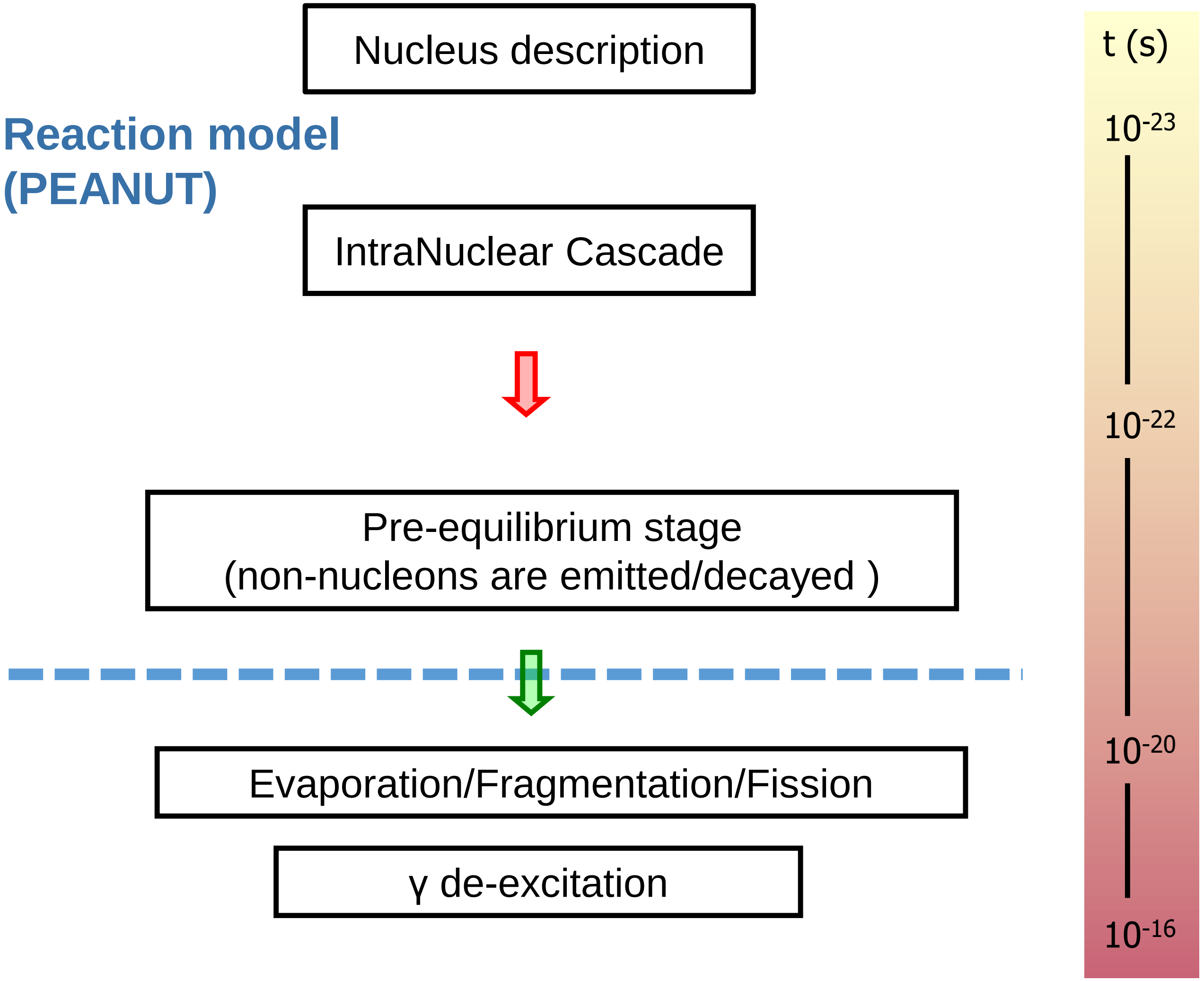
Nuclear reactions in FLUKA

i. To decide the process occurrence

Reaction cross section (typically parametrized)



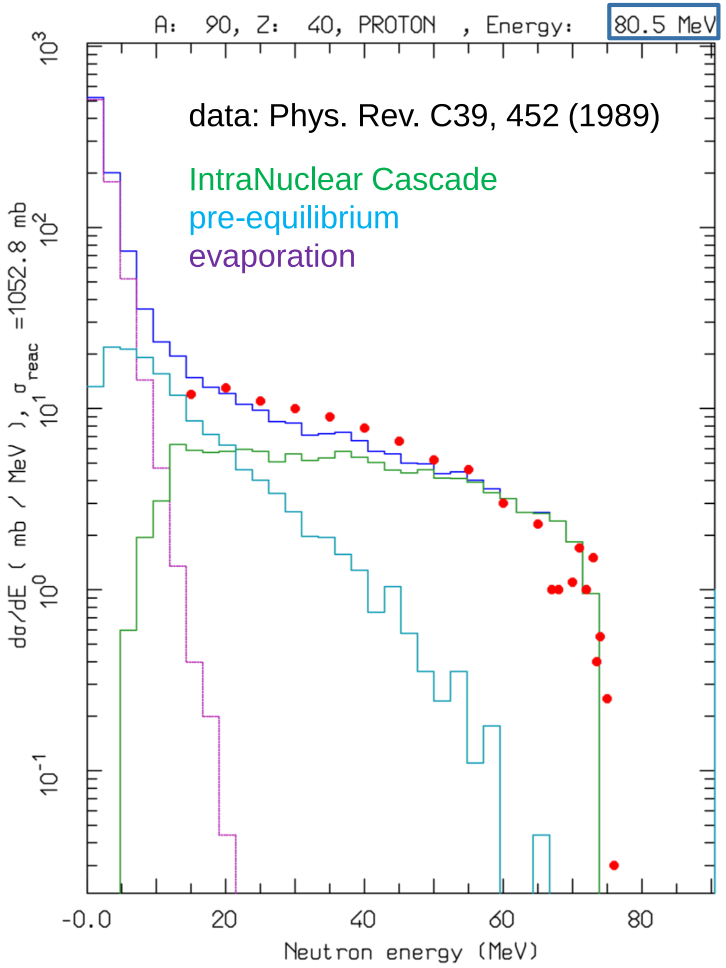
ii. To decide the reaction final state



Pre-equilibrium and evaporation

- After the cascade stage, the nucleus remains excited.
- Excitation energy not equally shared among nucleons. Semiclassical exciton model:
  - Excitation energy sharing among nucleons and holes
- Last reaction stages: evaporation (Weisskopf-Ewing model) or fission (Myers and Swiatecki model), or fragmentation (Fermi break-up for A<18), and γ de-excitation.

PROTON – Zr

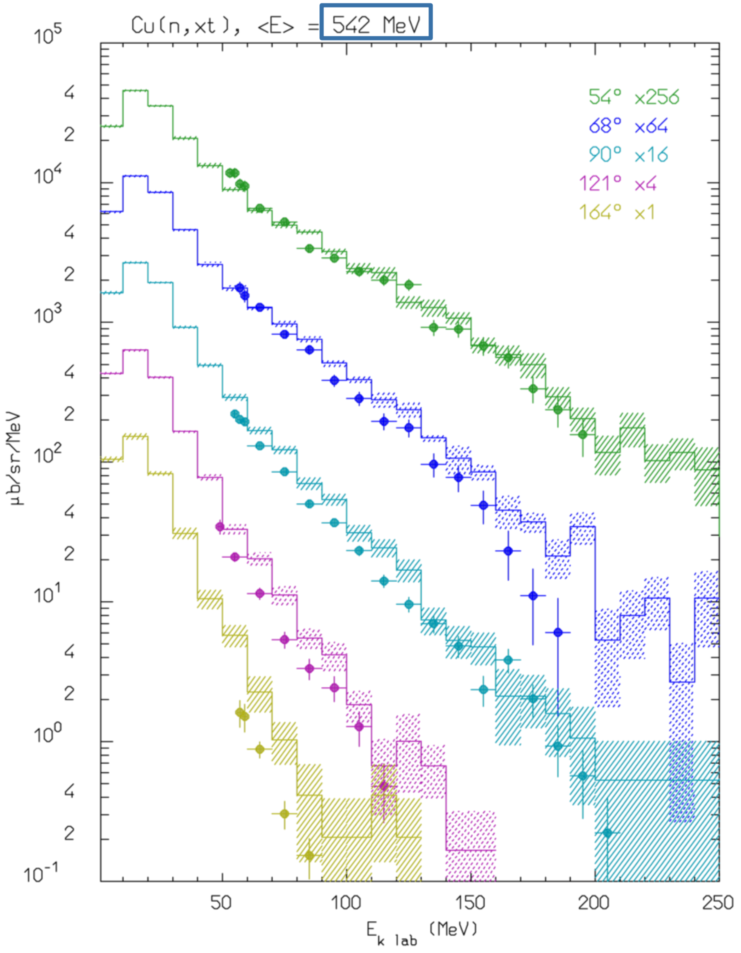


angle-integrated neutron spectrum

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
```

N.B. Remove the card previously required to invoke low energy *deuteron splitting at interaction:*

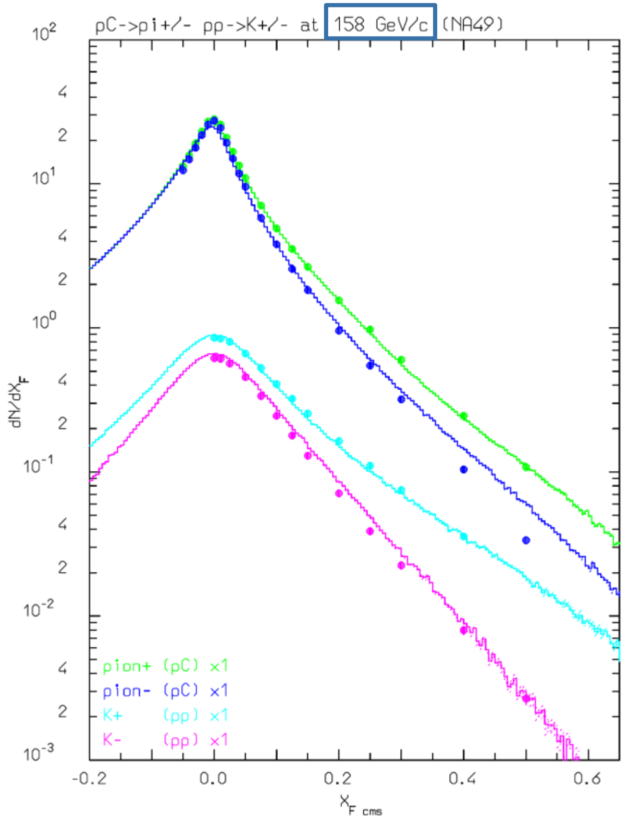
~~PHYSICS Type: IONSPLIT ▾ Ion Split: On ▾ Splitting: Nonelastic ▾~~
~~Emin: 0.005 Emax: 0.15 Amin: 2 Amax: 2~~

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

A dedicated **deuteron interaction** model is now available since FLUKA-4.2.0 and invoked by default (unless splitting is requested) !

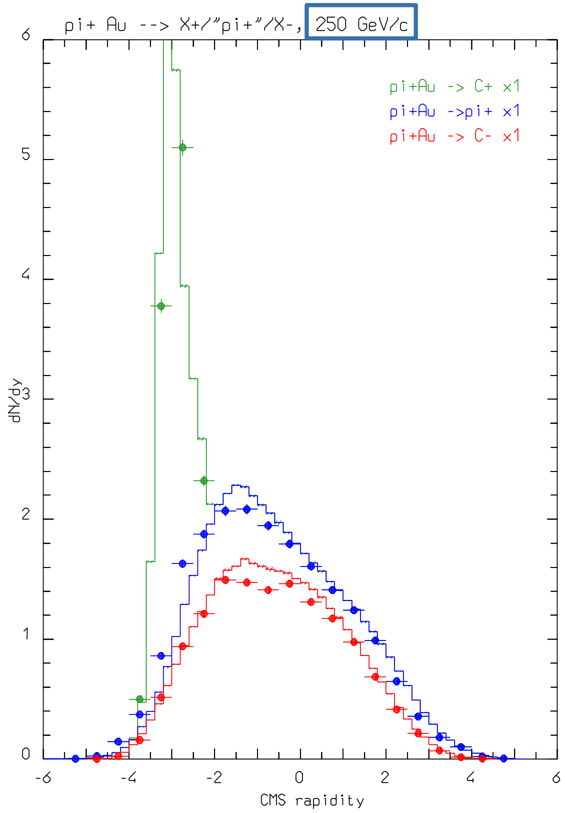
A benchmark glimpse

PROTON – C, PROTON



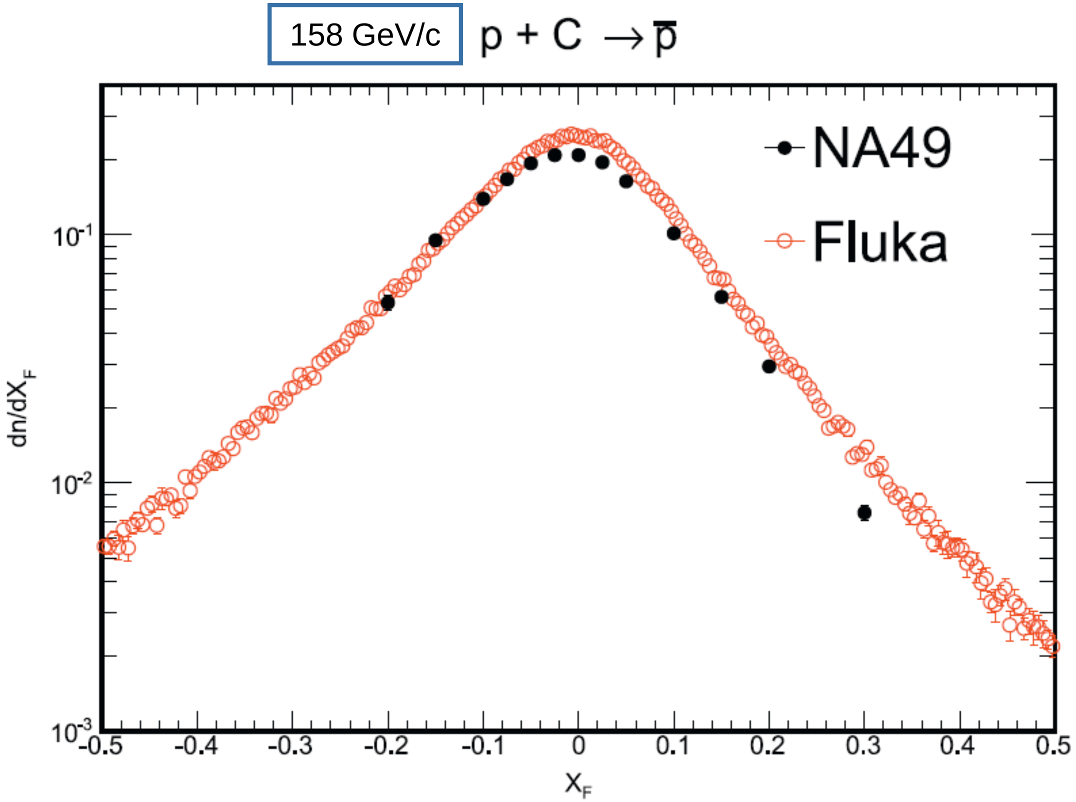
Differential **pion and kaon** production
Points: exp. data (C. Alt et al., EPJC49 (2007) 897 and T. Anticic et al. (NA49) EPJC68 (2010) 1)
Histogram: FLUKA

PROTON – Au



Differential **charged particle** production
Points: exp. data (Agababyan et al., ZPC50 (1991) 361)
Histogram: FLUKA

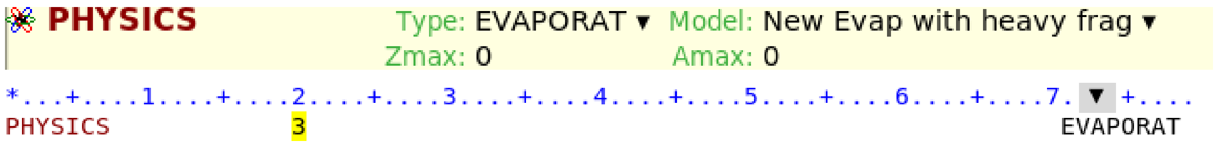
PROTON – C

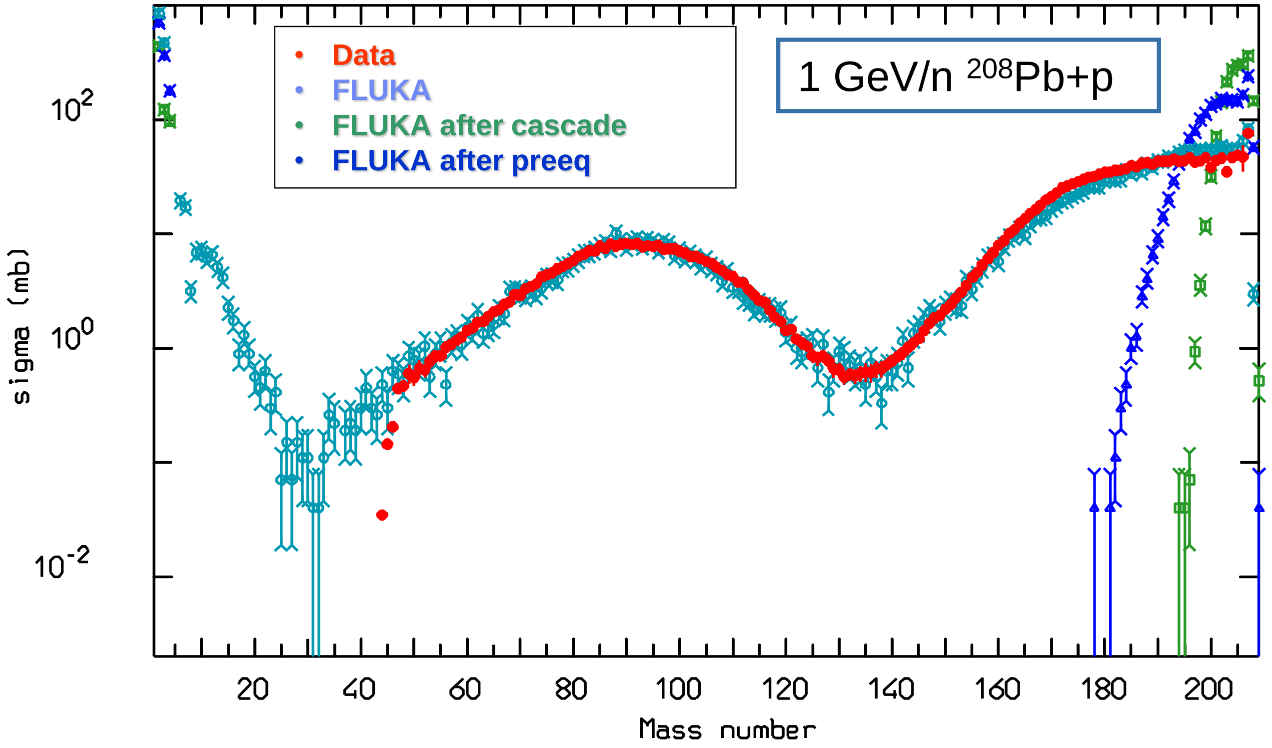


Differential **antiproton** production

Production of residual nuclei

- Besides the emission of secondary particles (nucleons and other hadrons), a nuclear reaction generally leads to the production of a residual nucleus
- Lecture on Fri: we see what happens when the residual nucleus is unstable
- Whenever residual nuclei inventories are of interest (e.g., activation calculations), one should pass a **`PHYSICS`** card with the evaporation of heavy fragments (up to A=24)





Inclusive fragment production

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

Simulation: Mokhov N.V. and Cerutti F., CERN-2016-002 83-110 and references therein

Hadronic interactions [II]

Nucleus-nucleus (A-A) reactions

Different energy ranges and event generators

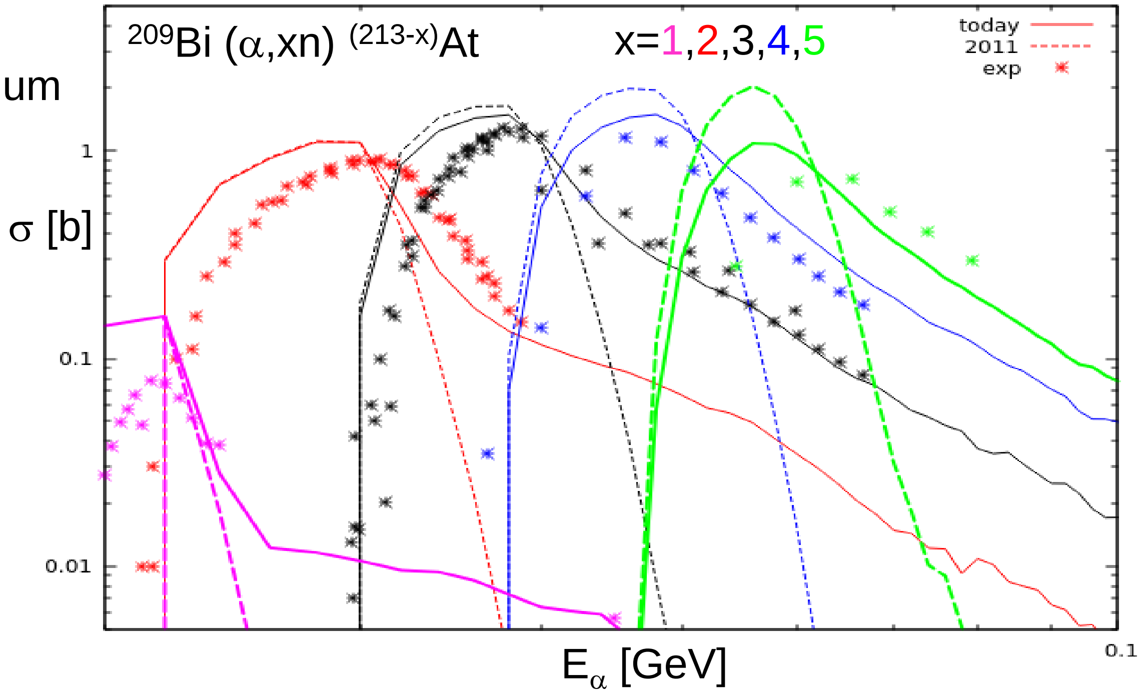
A-A nuclear reaction treatment in FLUKA:

- above 5 GeV/n: DPMJET-III
  - 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 125ǂ MeV/n and 5ǂ GeV/n: RQMD-2.4
  - original code by H. Sorge et al., interfaced with FLUKA by A. Ferrari et al., no longer actively developed
  - **to be linked by *ldpmqmd***
  - ǂ 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, but treated independently (dedicated interaction model as of FLUKA v4-2.0)**

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 18)
- 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 residuals produced by low energy alphas



Photonuclear interactions

Photon-nucleus reactions

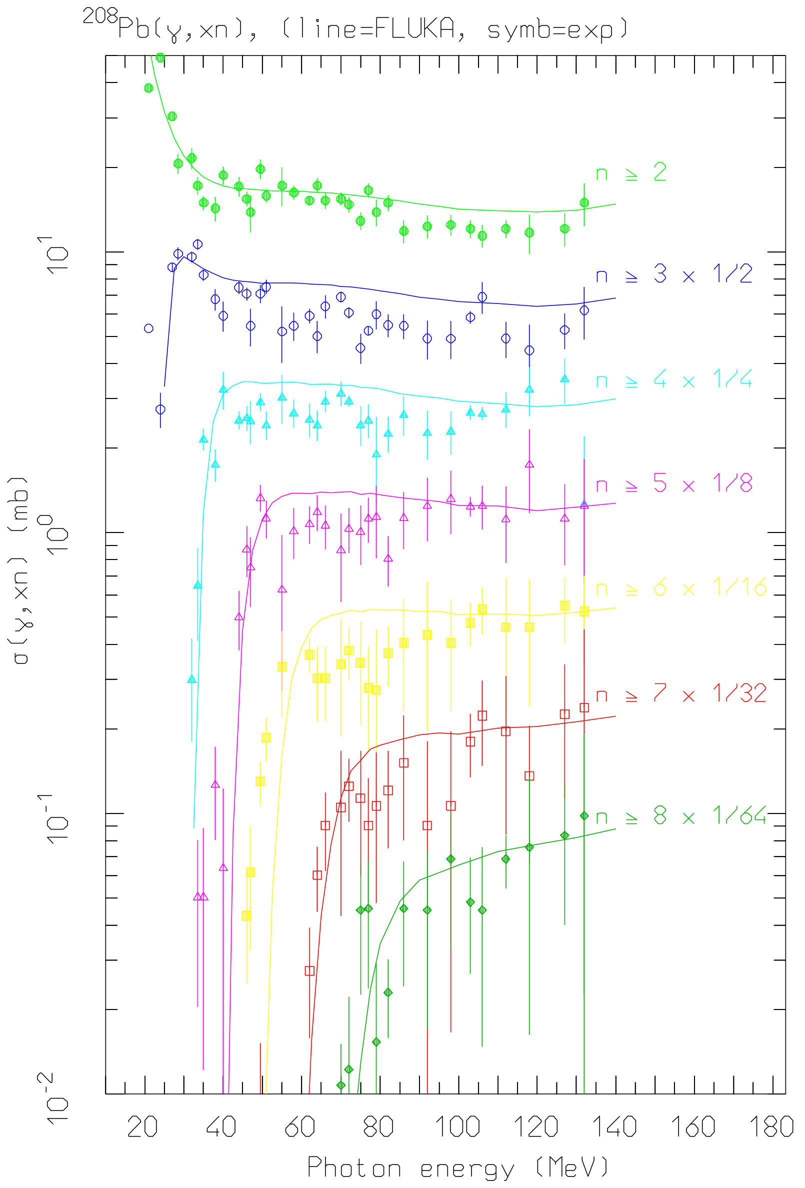
Photonuclear reactions

γ – Pb

- Photons above a few MeV can be absorbed and initiate a nuclear reaction. Relevant e.g. for activation in e-/e+ machines: Bremsstrahlung can produce energetic photons!
- To activate it:

```
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 slides)

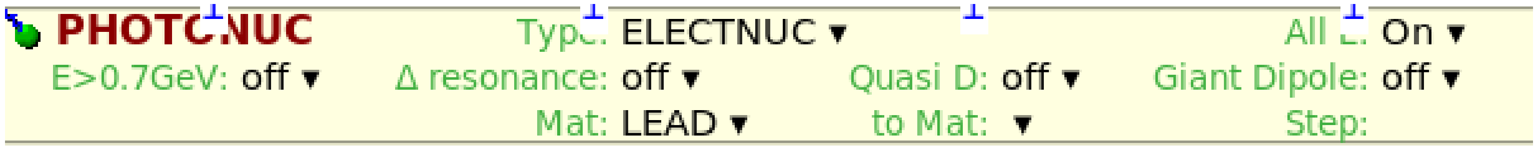


cross section for multiple neutron emission
data: NPA367, 237 (1981) and NPA390, 221 (1982)

μ-A, e^--A, e^+-A

Virtual-photon-mediated reactions are also implemented:

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




```
*...+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....
PHOTONUC                1                                   LEAD                     ELECTNUC
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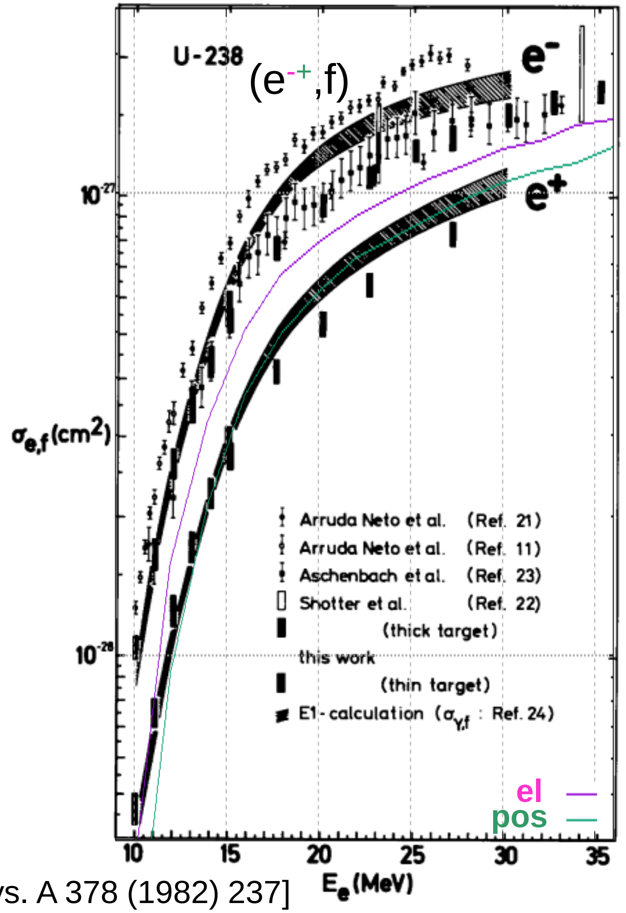
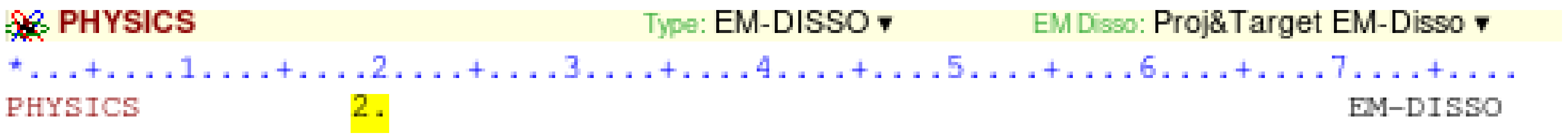


- For *electron/positron beams*, they play a role in case of thin target. Instead, for material thicknesses exceeding the radiation length, reactions by real bremsstrahlung photons dominate.
- The card above activates automatically real photon reactions too (*no need for an additional card* as in the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

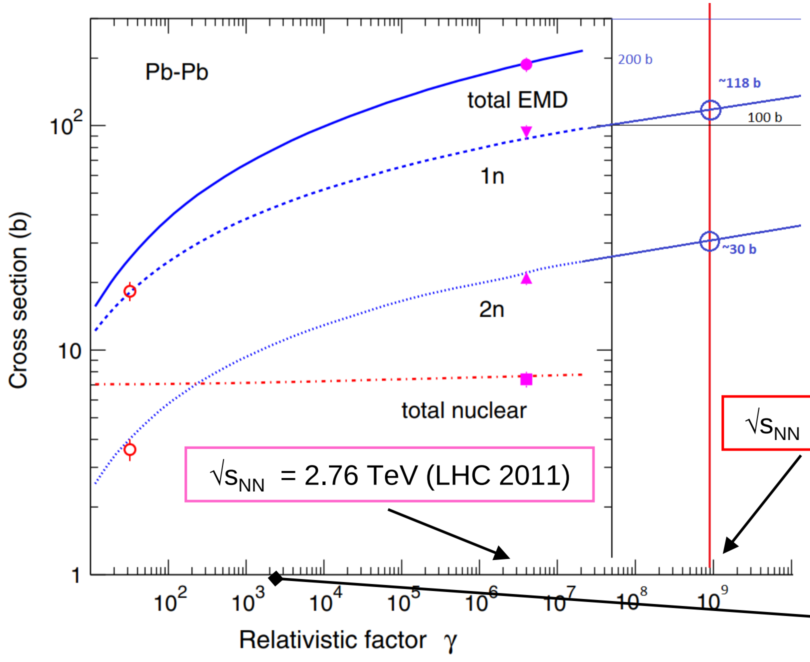
[H. Ströher et al, Nucl. Phys. A 378 (1982) 237]

Electromagnetic dissociation (EMD) of ions

- Relevant for high-energy ion beams, e.g. in Pb-Pb collisions at the LHC
- To activate it:

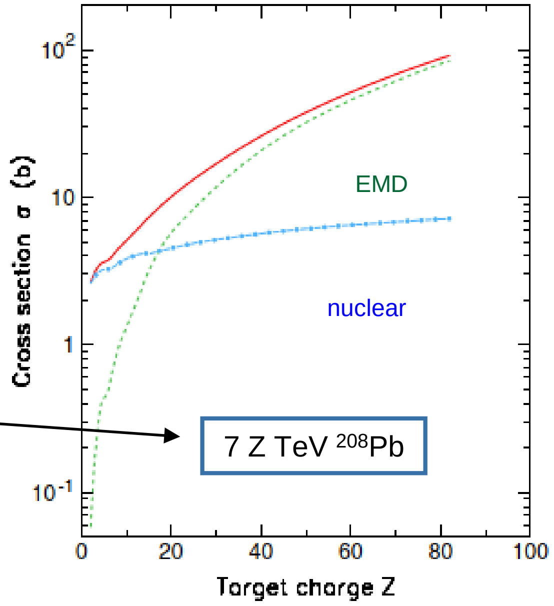


Pb – Pb



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

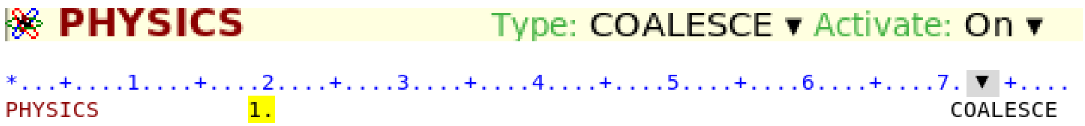
Pb – Z



- While nuclear inelastic cross section is reasonably flat in Z, the EMD cross section rises.
- EMD becomes dominant at high energies with high Z ions

Summary

- Generalities of hadronic showers in matter
- Hadron-nucleon cross section
- FLUKA's hadron nuclear inelastic interaction model from low to high energies:
    - (Generalized) Intranuclear cascade stage → pre-equilibrium → evaporation/fission/Fermi break-up → gamma de-excitation
    - Inelastic scattering length in the output file
- FLUKA's nucleus-nucleus inelastic interaction models (BME, rQMD, DPMJET)
- Whenever residual nuclei production is of interest:



- Photonuclear and electronuclear interactions (**PHOTONUC** card)
- Muon photonuclear interactions (on by default)
- Electromagnetic dissociation of ions (**PHYSICS** card)

FLUKA

Pion absorption

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

in nuclear medium

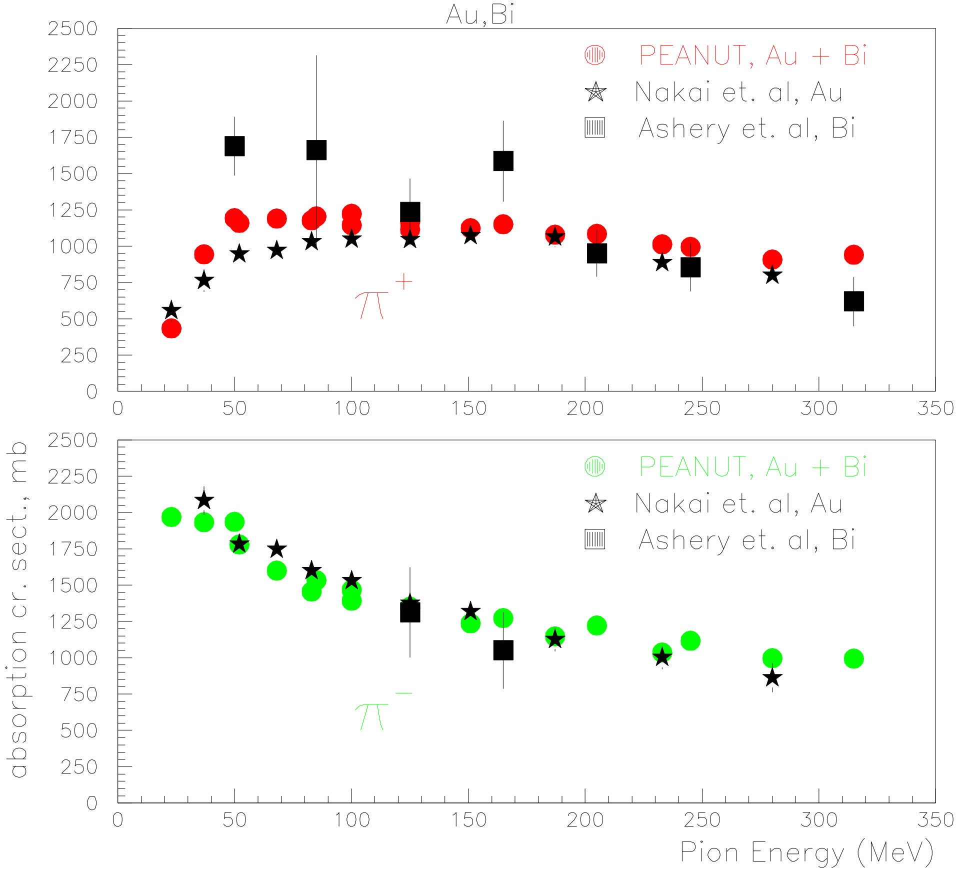
elastic scattering

quasi-elastic scattering

charge exchange

multibody absorption

PION – Au, Bi



in the Δ resonance region

PION – Ni

Emitted proton spectra at different angles