Hadron-Nucleus interactions

23rd FLUKA Beginner's Course
Lanzhou University
Lanzhou, China
June 2-7, 2024

Nuclear interactions: almost everywhere

- Naturally, high-energy physicists have a profound interest in the simulation of nuclear interactions,

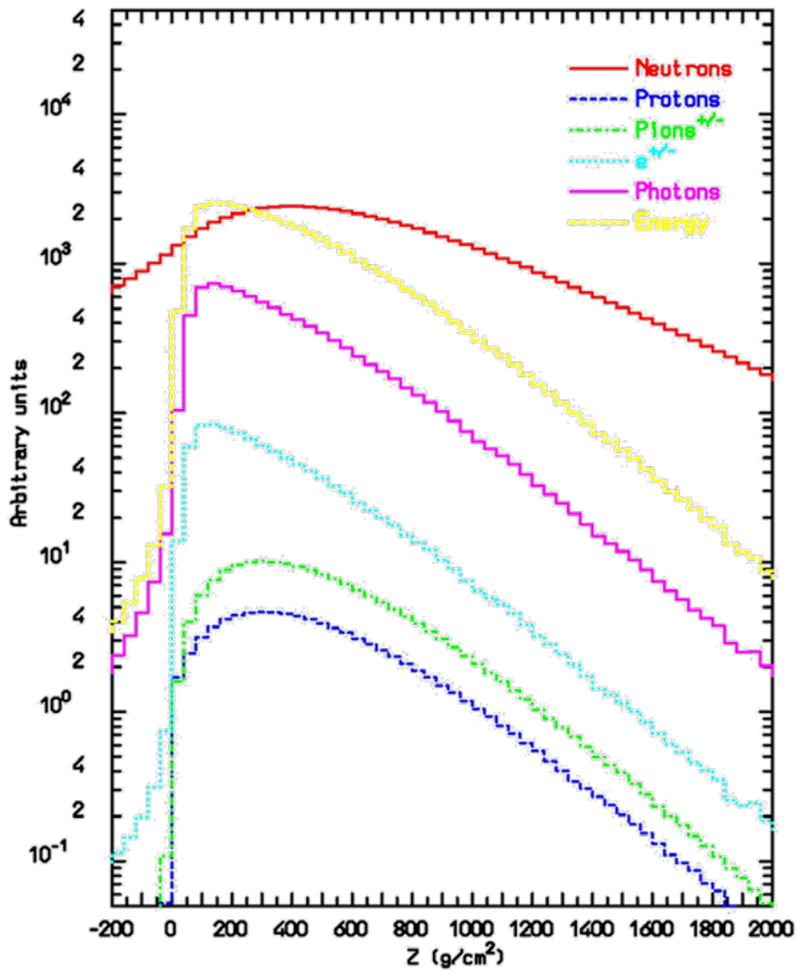
However, they are not alone:

- Few MeV photons or electrons (2.2 MeV γ on deuterium) can initiate electro/ photonuclear interactions, with further emission of nucleons and residual (often radioactive) nuclei
- Higher energy photons or electrons (few hundreds of MeV) can even produce pions and more
- Even "low energy Neutrons" (<20 MeV) , produce protons and light ions that can further interact with nuclei
- In therapeutic proton beams, nuclear interactions are responsible for dose before and after the Bragg peak

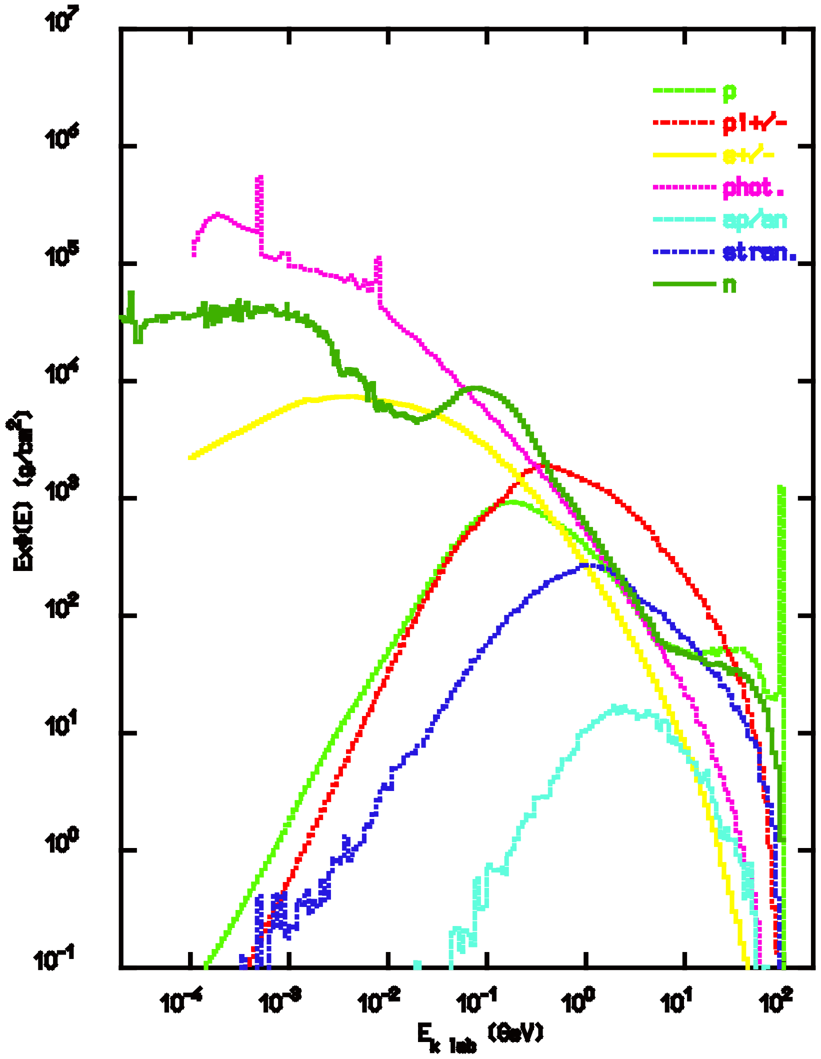
→ ***Almost every particle beam will produce nuclear interactions***

Hadronic showers: many particle species, wide energy range

100 GeV p on Pb
shower longitudinal development



100 GeV p in a Fe absorber:
space-averaged particle spectra



The FLUKA hadronic Models

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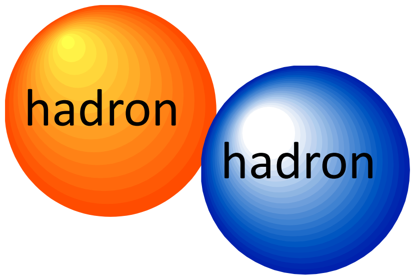
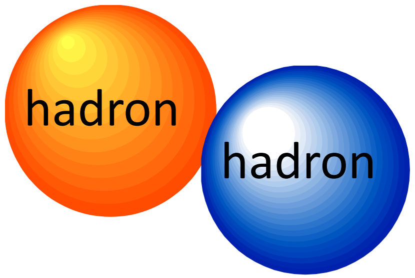


The FLUKA hadronic Models

Elastic, exchange
Phase shifts
data, eikonal



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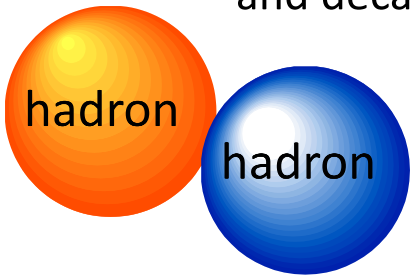
P<3-5GeV/c
Resonance prod
and decay



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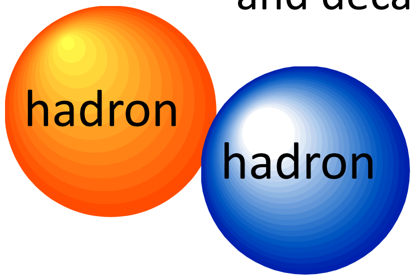

low E π,K
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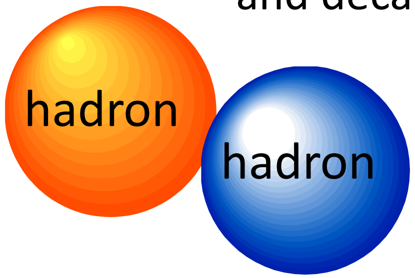

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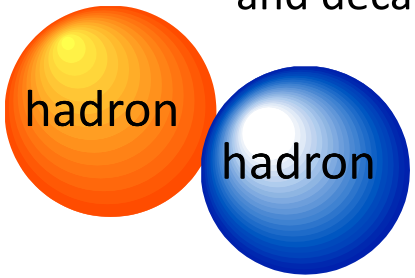

low E π,K
Special

High Energy
DPM
hadronization

The FLUKA hadronic M

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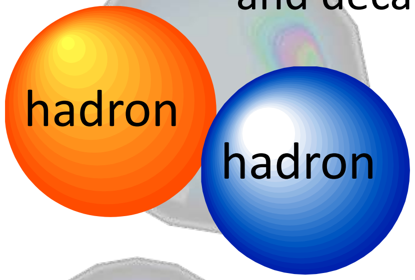

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The FLUKA hadronic M

Hadron-nucleus: PEANUT

Elastic, exchange
Phase shifts
data, eikonal

P<3-5GeV/c
Resonance prod
and decay

Sophisticated
G-Intranuclear Cascade

Gradual onset of Glauber-Gribov multiple interactions

Preequilibrium

Coalescence

hadron

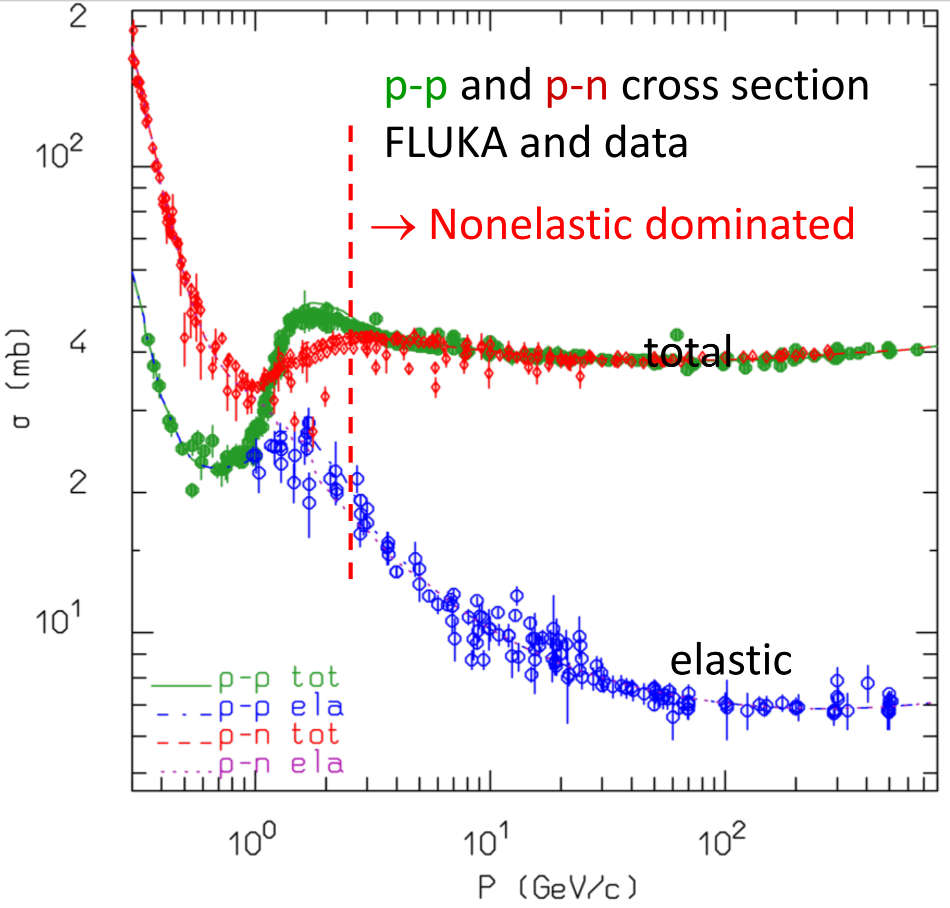
hadron

low E π,K
Special

High Energy
DPM
hadronization

Evaporation/Fission/Fermi break-up
γ deexcitation

Hadron-nucleon interaction models



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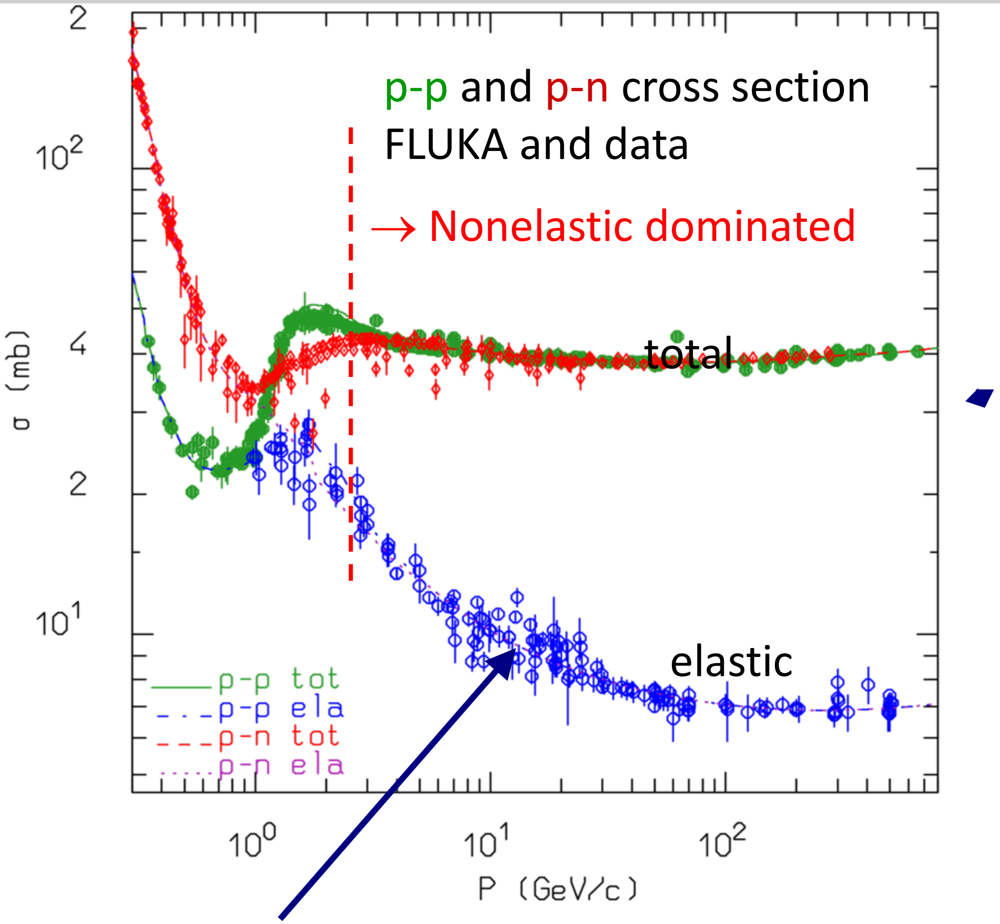
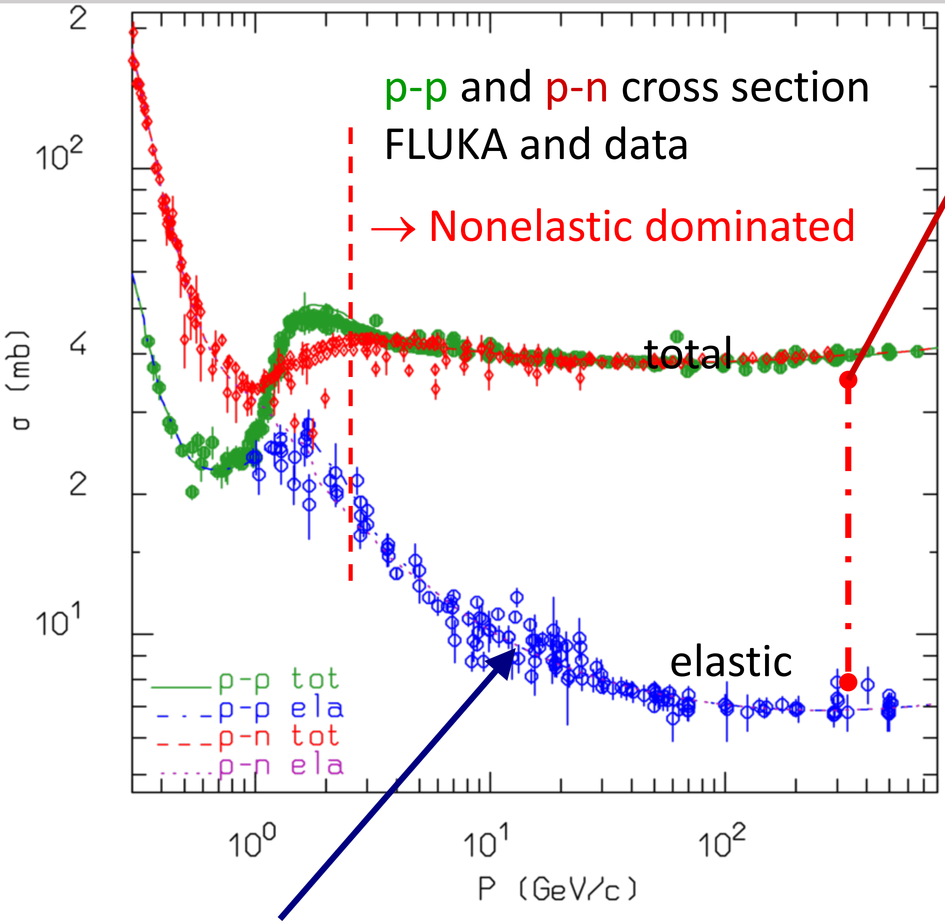


Elastic, charge exchange and strangeness exchange reactions:

- Available phase-shift analysis and/or fits of experimental differential data
- At high energies, standard eikonal approximations are used

Hadron-nucleon interaction models



Particle production interactions: two kinds of models

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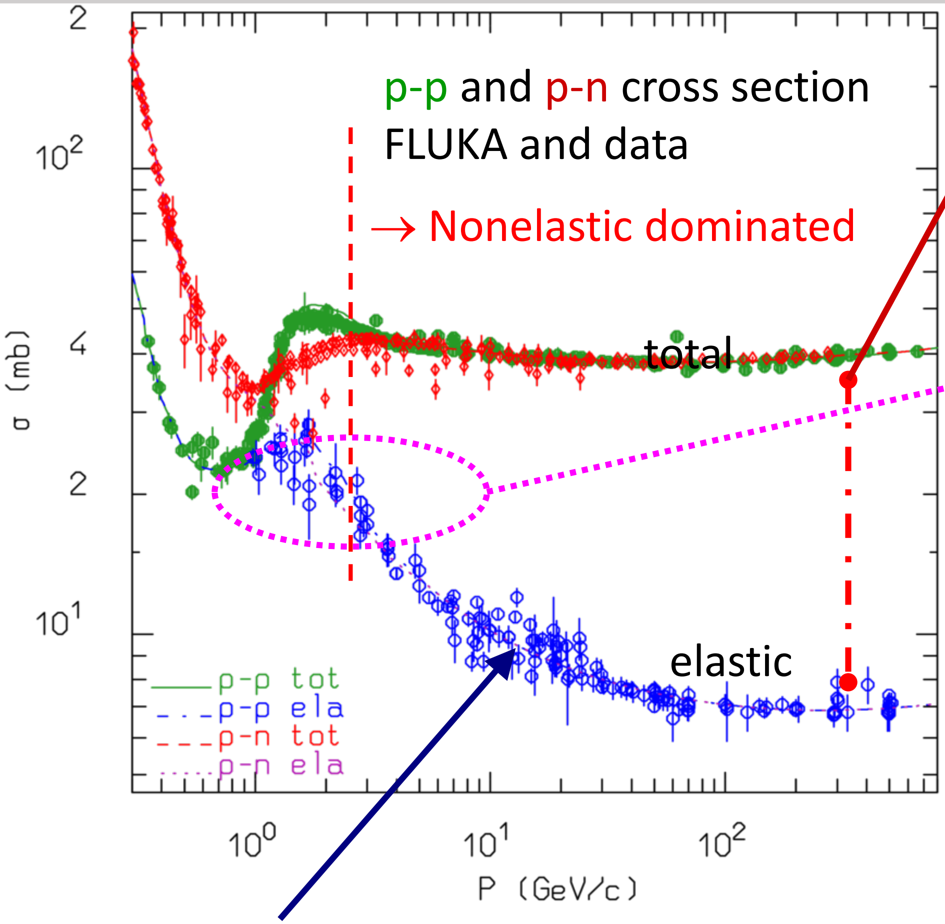

Particle production interactions: two kinds of models

Those based on “resonance” production and decays, cover the energy range up to 3–5 GeV

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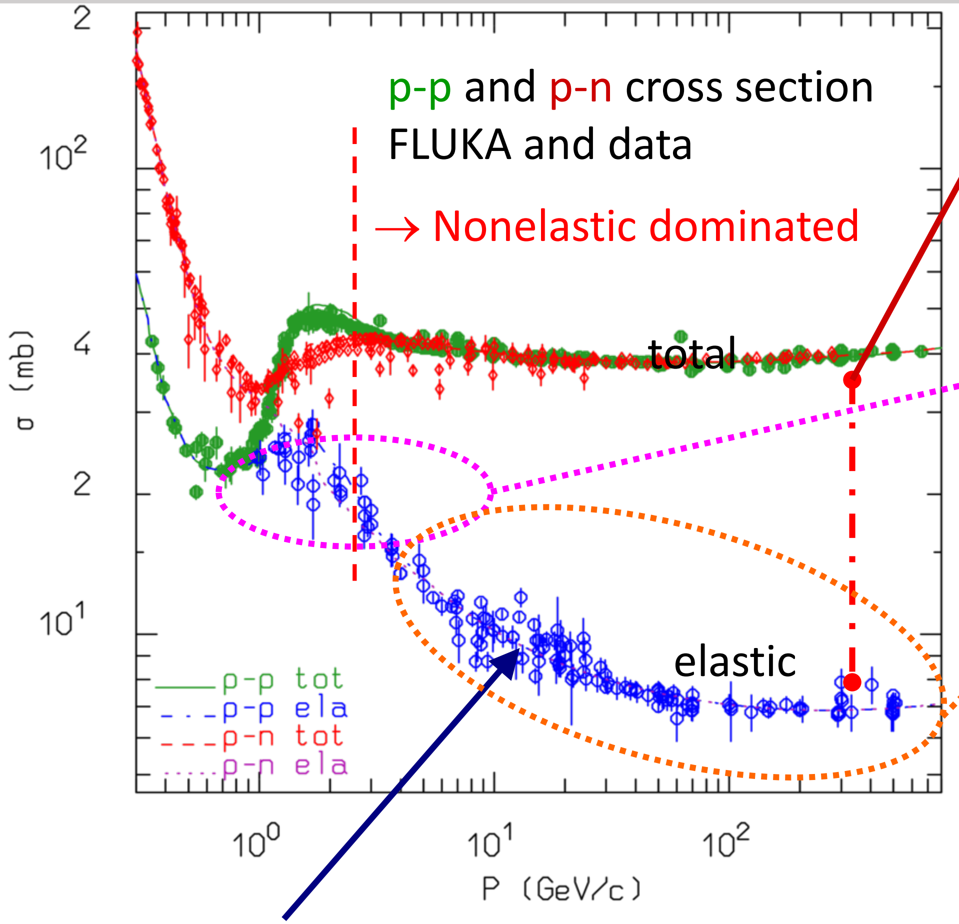
Hadron-nucleon interaction models



Particle production interactions: two kinds of models

Those based on "resonance" production and decays, cover the energy range up to 3–5 GeV

Those based on quark/parton string models, which provide reliable results up to several tens of TeV

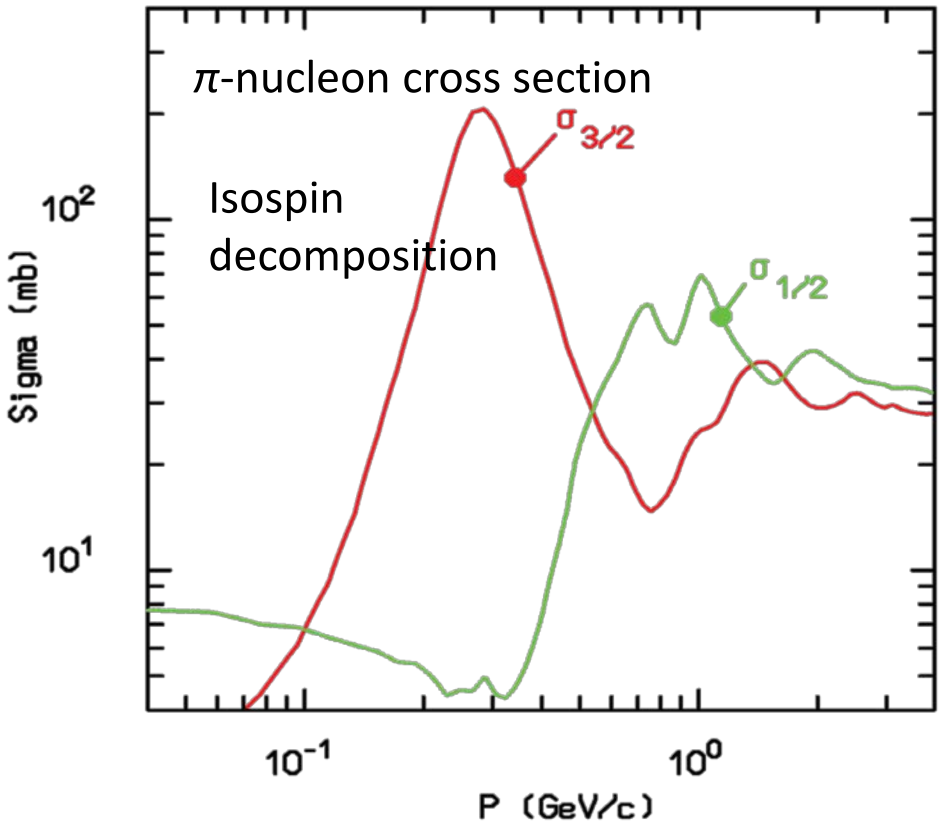
Elastic, charge exchange and strangeness exchange reactions:

- Available phase-shift analysis and/or fits of experimental differential data
- At high energies, standard eikonal approximations are used

Non-elastic hN interactions at intermediate energies

- $N_1 + N_2 \to N''_1 + N''_2 + \pi$ threshold at 290 MeV, important above 700 MeV,
- $\pi + N \to \pi' + \pi'' + N'$ opens at 170 MeV.

Anti-nucleon -nucleon open at rest !



Dominance of the Δ resonance and of the N^* resonances

→ isobar model

→ all reactions proceed through an intermediate state containing at least one resonance.

FLUKA: ≈ 60 resonances, and ≈ 100 channels

Resonance energies, widths, cross sections, branching ratios from data and conservation laws, whenever possible. Inferred from inclusive cross sections when needed

$N_1 + N_2 \to N''_1 + \Delta(1232) \quad \to N_1' + N_2' + \pi$

$\pi + N \to \Delta(1600) \to \pi' + \Delta(1232) \to \pi' + \pi'' + N'$

$N_{1,}\, N_2 \to \Delta_1(1232) + \Delta_2(1232) \quad \to N_1' + \pi_1 + N'_2 + \pi_2$

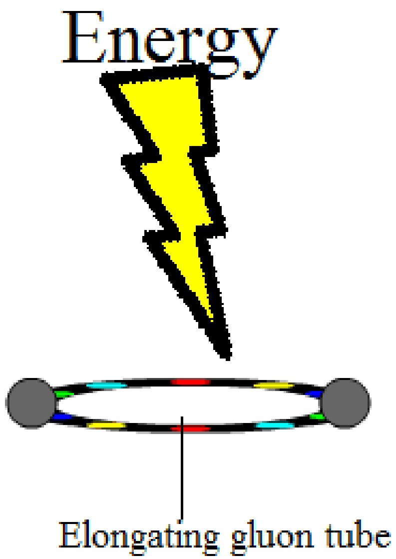
Non-elastic hN at high energies: (DPM, QGSM, ...)

- Problem: “soft” interactions → QCD perturbation theory cannot be applied.

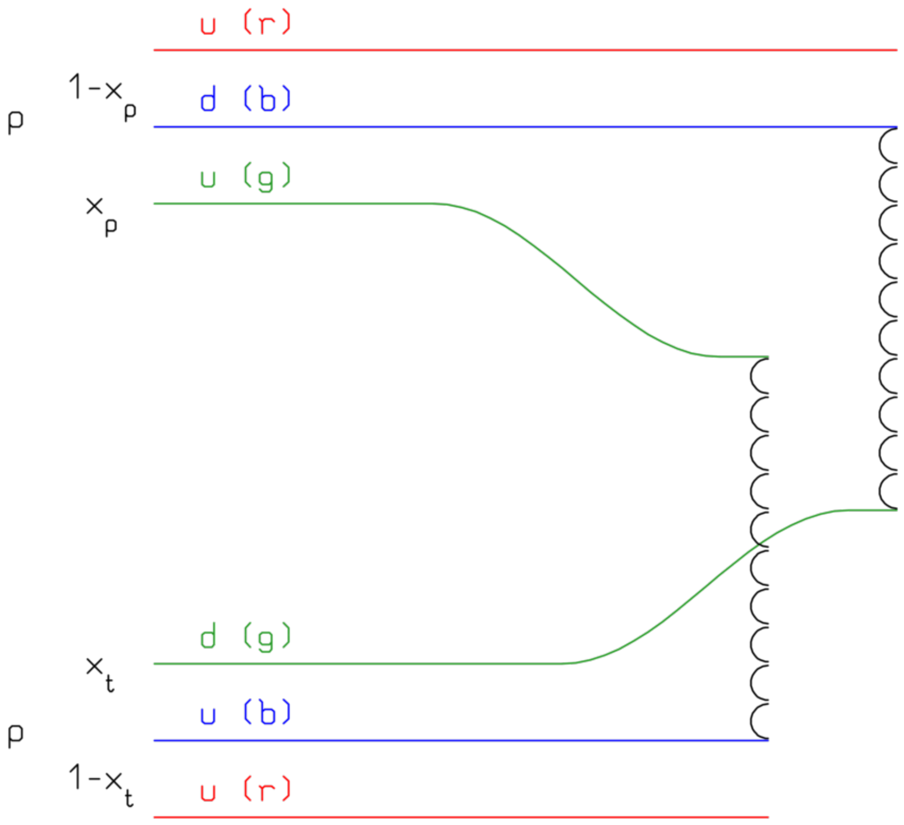
Solution!!

- Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
- Interactions treated in the Reggeon-Pomeron framework
- each of the two hadrons splits into 2 colored partons → combination into 2 colourless chains → 2 back-to-back jets
- each jet is then hadronized into physical hadrons

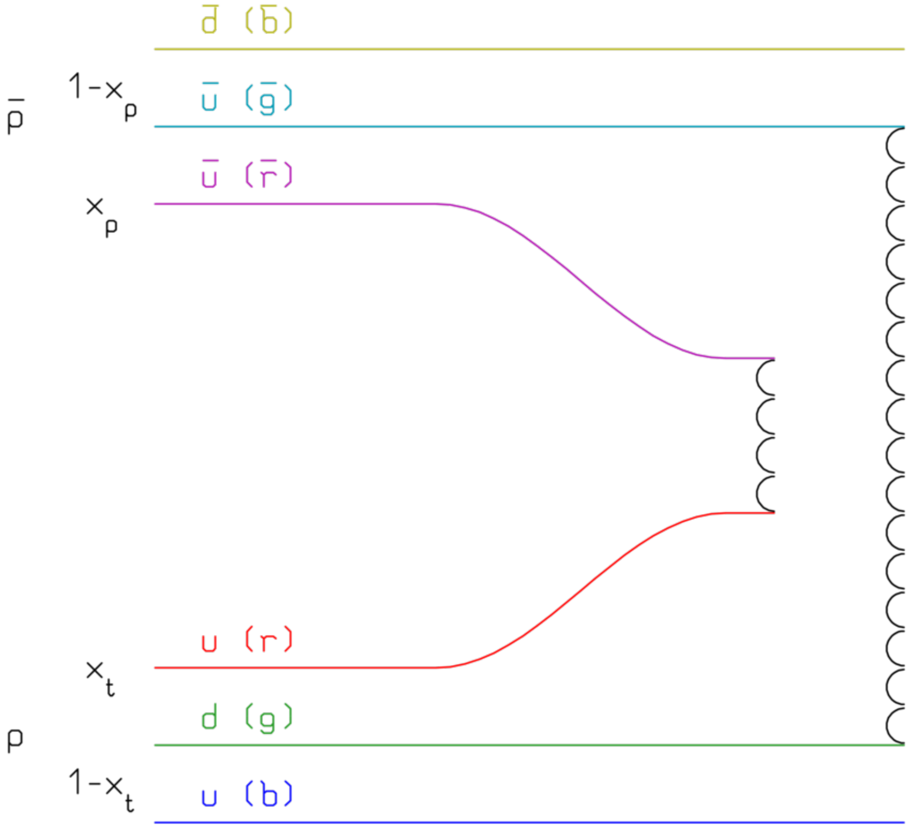
Picture
From Wikipedia



Hadron-hadron collisions: chain examples



Leading two-chain diagram in DPM for p-p scattering. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities

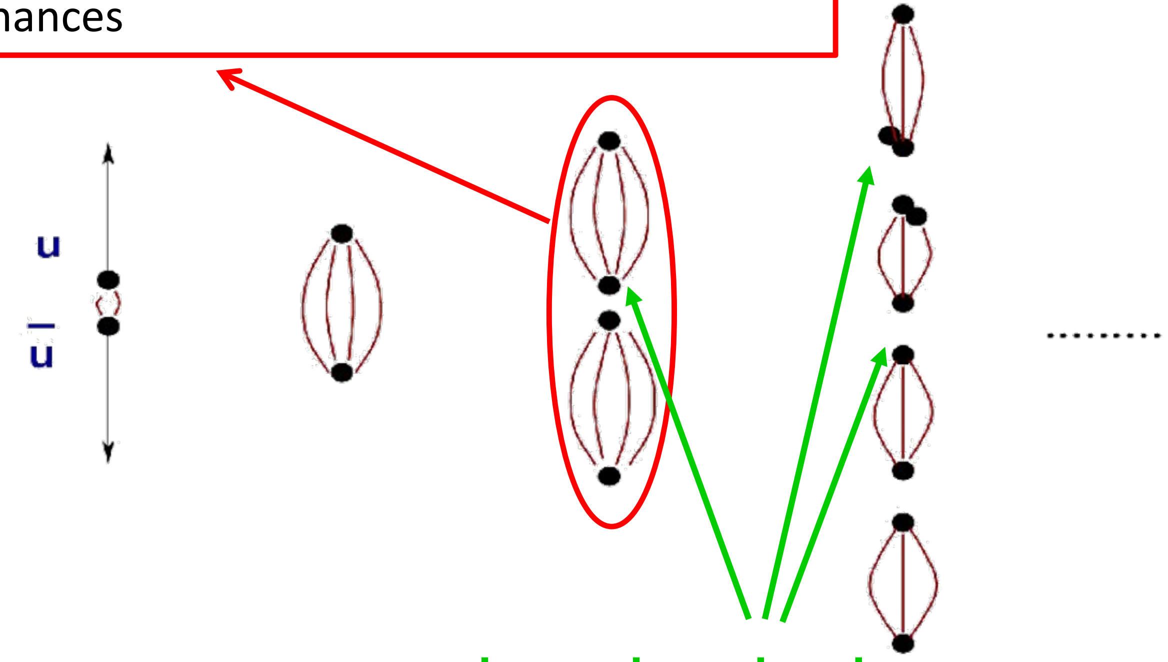


Leading two-chain diagram in DPM for pbar-p scattering. The color (red, antired, blue, antiblue, green, and antigreen) and quark combination shown in the figure is just one of the allowed possibilities

The “hadronization” of color strings

An example:

Low mass chain: just 2-3 meson/(anti)baryon resonances



q-qbar and qq-qbarqbar pairs generation

$u\bar{d}$	π^+, ρ^+, ...
$d\bar{u}$	π^-, ρ^-, ...
$\bar{u}\bar{u}\bar{d}$	$\bar{p}$, $\bar{\Delta}^-$, ...
udd	n, Δ^0, ...
$u\bar{s}$	K^+, K^{*+}, ...
$s\bar{d}$	$\bar{K}^0$, $\bar{K}^{*0}$, ...
$u\bar{d}$	π^+, ρ^+, ...
⋮	
$d\bar{u}$	π^-, ρ^-, ...

Dual Parton Model# and hadronization

From DPM:

- Number of chains
- Chain composition
- Chain energies and momenta
- Diffractive events

Almost No Freedom

Chain hadronization

- Assumes chain universality
- Fragmentation functions from hard processes and $e^{+}e^{-}$ scattering
- Transverse momentum from uncertainty considerations
- Mass effects at low energies

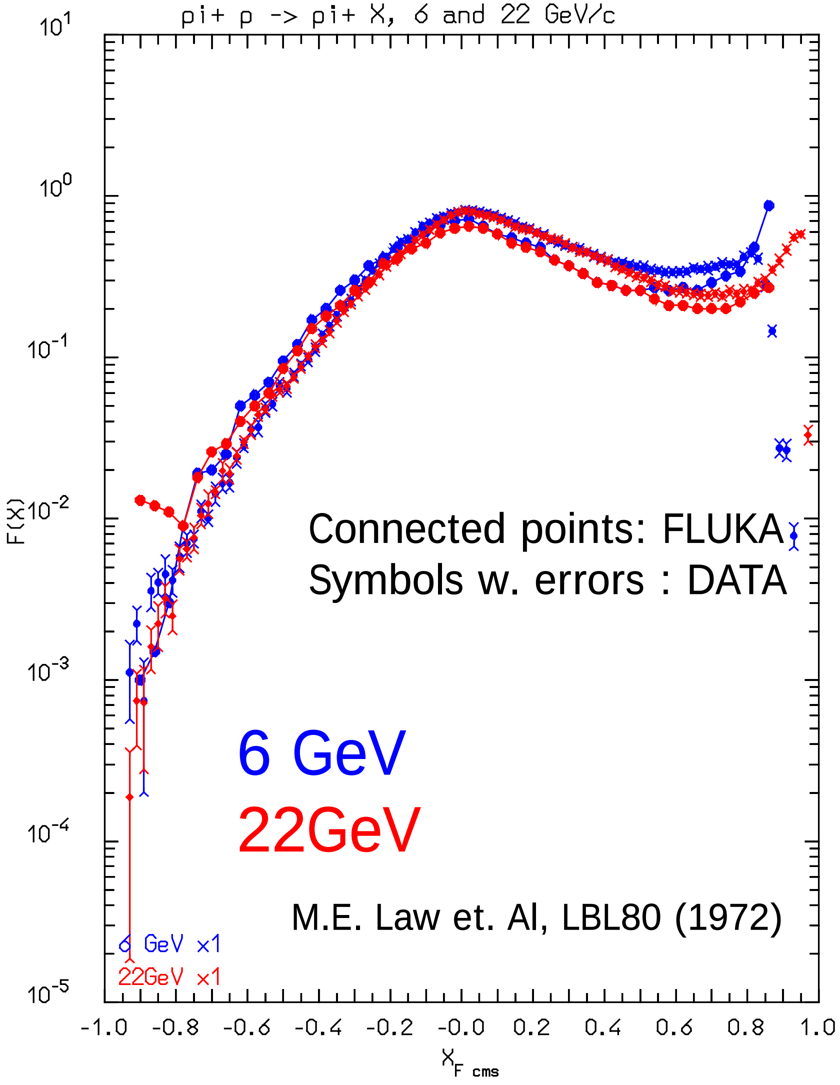
**Chain formation and "decay" (hadronization) processes are assumed to be decoupled*

The same functions and (few) parameters for all reactions and energies

#For a review: Physics Report 236

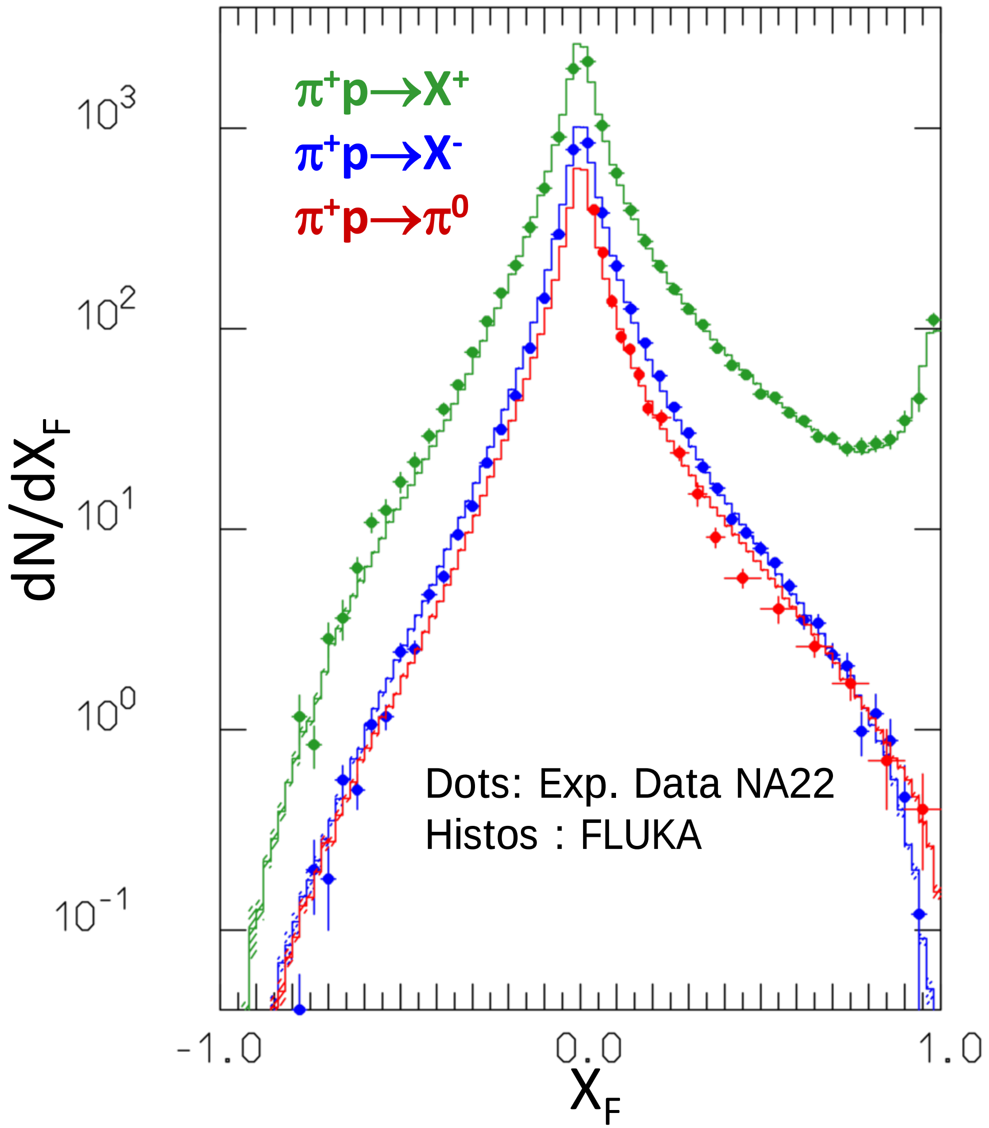
Non-elastic hN interactions: examples

$\pi^+ + p \rightarrow \pi^+ + X$ (6 & 22 GeV/c)

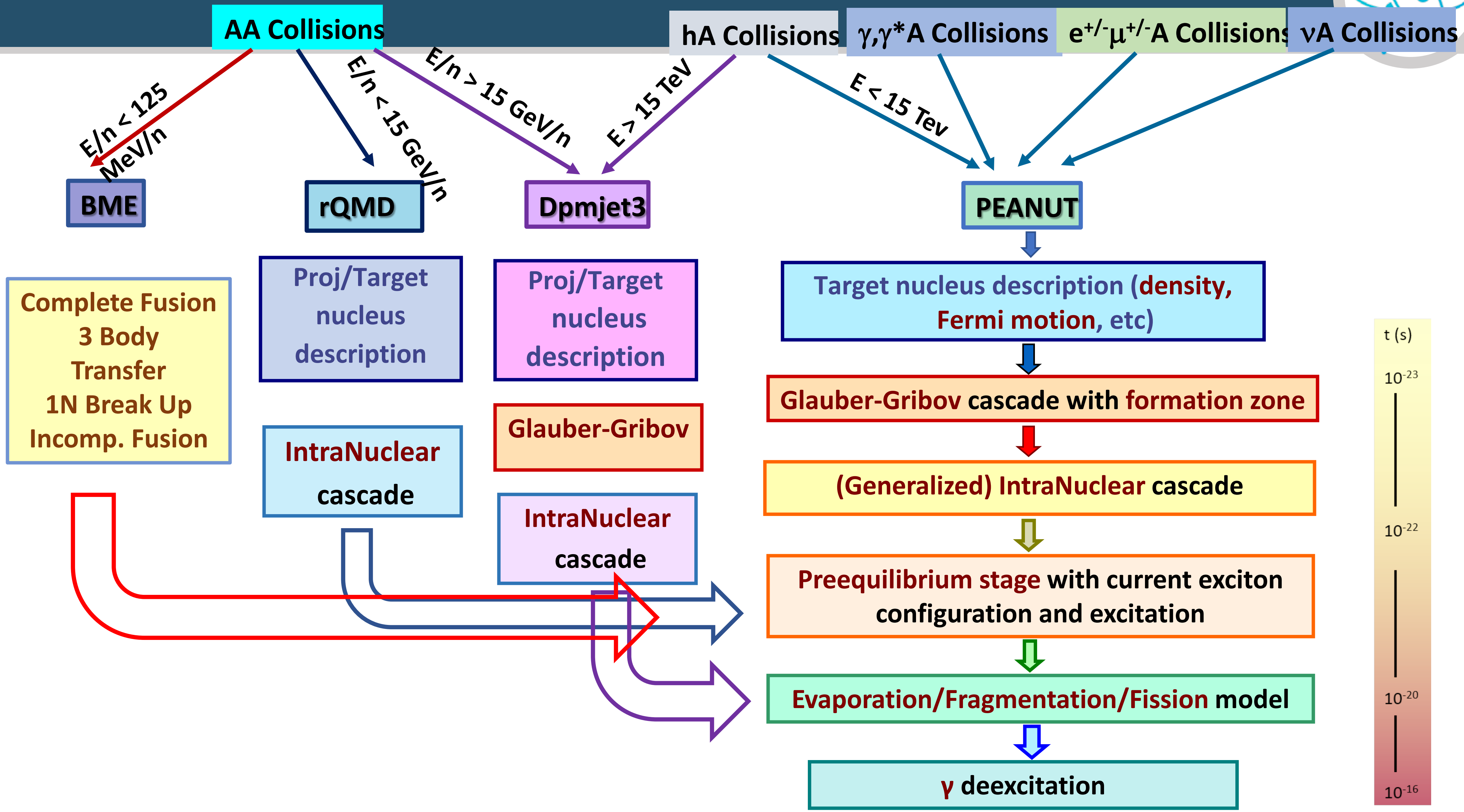


$$x_F = \frac{p_L}{p_{L\max}} = \frac{2p_L}{\sqrt{s}}$$

$\pi^+ + p \rightarrow X$ (250 GeV/c)



FLUKA nuclear interaction models:



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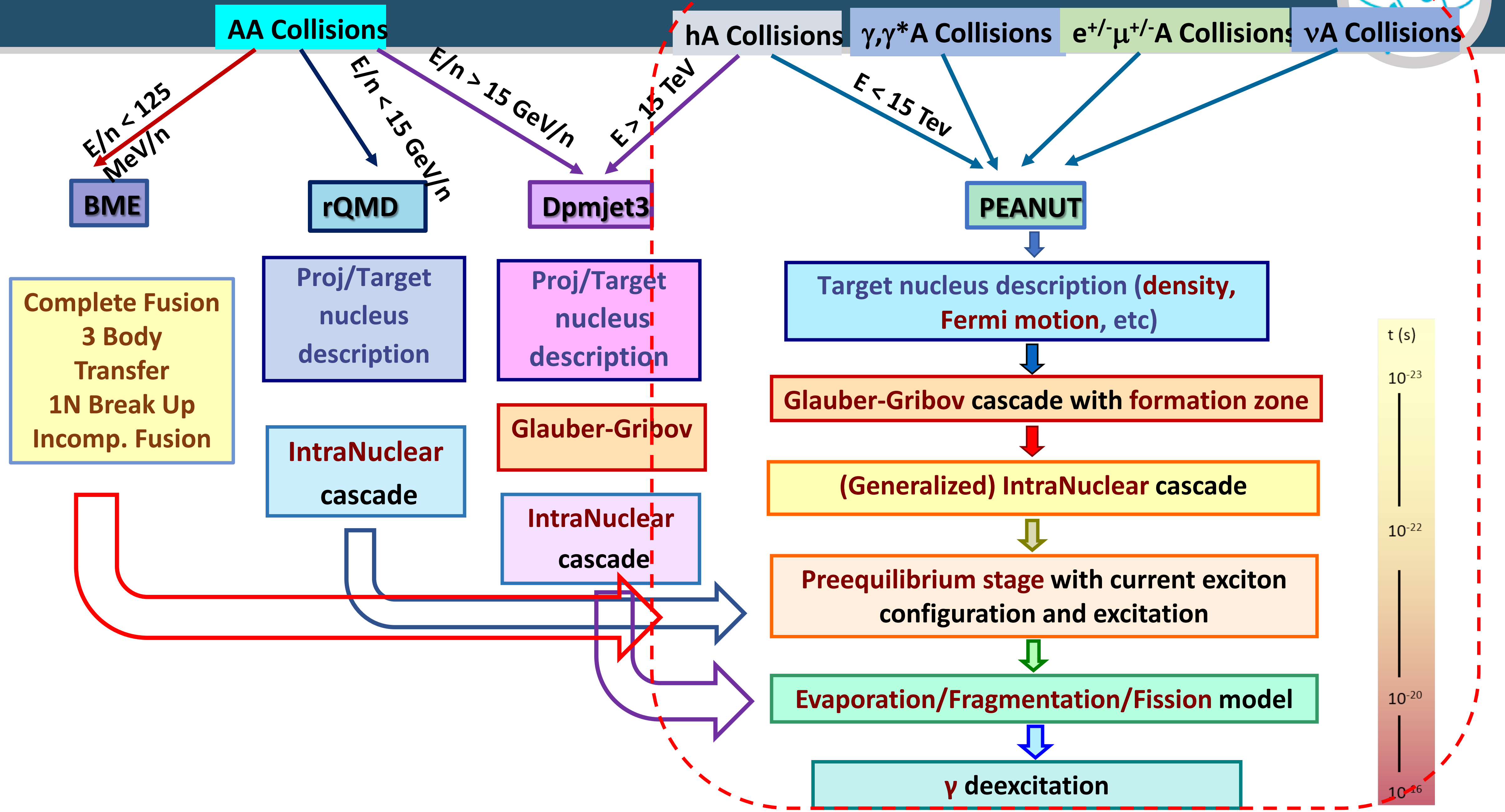

… INC, a bit like snooker…

The projectile is hitting a “**bag**” of **protons** and **neutrons** representing the nucleus. The products of this interaction can in turn hit other neutrons and protons and so on. The most energetic particles, p,n, π’s (and a few light fragments) are emitted in this phase

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…it is in this phase that if energy is enough extra “balls” (new particles) are produced (contrary to snooker). The target “balls” are anyway protons and neutrons, so further collisions will mostly knock out p’s and n’s

"Classical" IntraNuclearCascade (INC) model:

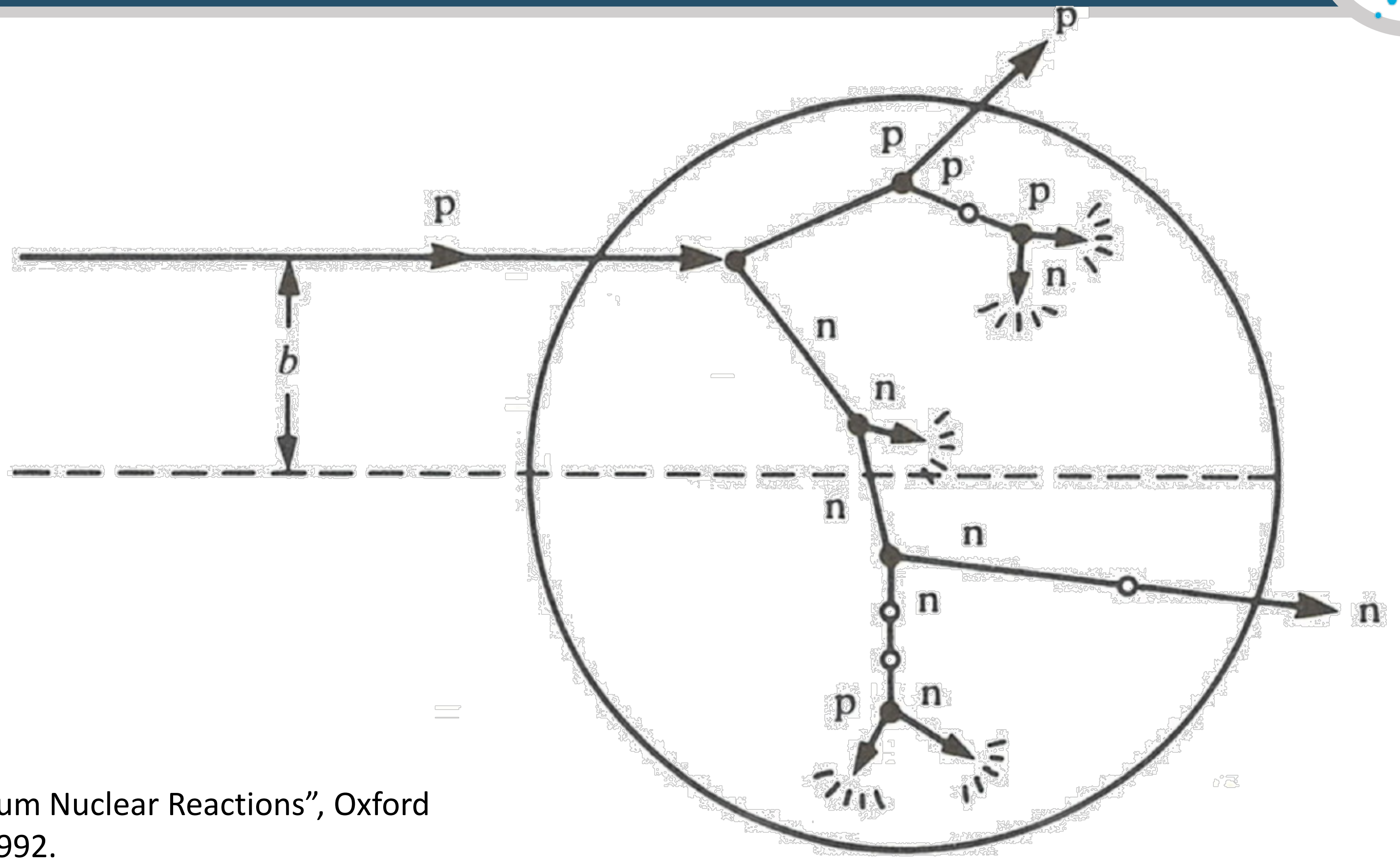
50 MeV nucleon: **$\lambda\!\!\!^{-}=\hbar/p$ = 0.64 fm**, **MFP ~ 1.2 fm** at **ρ~0.08**
200 MeV nucleon: **$\lambda\!\!\!^{-}=\hbar/p$ = 0.31 fm**, **MFP ~ 4 fm** at **ρ~0.08**
Both Mean Free Path's without accounting for Pauli blocking which would increase them by a significant factor (~2 at 50 MeV)

Hence at intermediate energies, nucleon-nuclear reactions can be described as the passage of the incoming nucleon through the nucleus, undergoing individual nucleon-nucleon collisions (IntraNuclear Cascade).

Main assumptions:

- Target nucleons occupy states of a **cold Fermi gas**;
- Incoming nucleon follows a **classical (straight) trajectory**;
- Given a nucleon-nucleon interaction **cross section** and **N, Z and density profile** of the target nucleus, one can evaluate the **mean free path** (MFP) of the incoming nucleon
- The nucleon trajectory can be simulated as **subsequent nucleon-nucleon collisions** between straight-line trajectory segments, governed by the calculated MFP
- Collision products must **be above the Fermi level ("Pauli blocking")** and can either escape or get "captured" if their energy is insufficient versus the binding or Coulomb barrier
- "Captured" nucleon energies above E_F and the holes in the Fermi gas both contribute to a **residual excitation** to be spent through the **statistical model**

Sketch* of IntraNuclearCascade (INC):



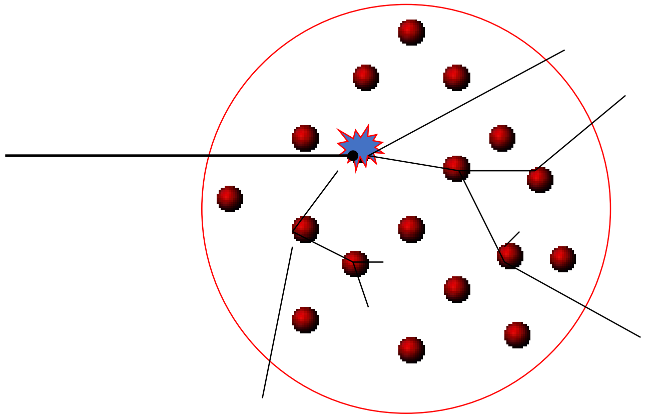
* E. Gadioli et al., “Pre-Equilibrium Nuclear Reactions”, Oxford Studies in Nuclear Physics 15, 1992.

hA at high energies: Glauber-Gribov cascade with formation zone

- **Glauber cascade**
  - Quantum mechanical method to compute Elastic, Quasi-elastic and Absorption hA cross sections from Free hadron-nucleon scattering + nuclear ground state
  - Multiple Collision expansion of the scattering amplitude
- **Glauber-Gribov**
  - Field theory formulation of Glauber model
  - Multiple collisions $\leftrightarrow$ Feynman diagrams
  - High energies: exchange of one or more Pomerons with one or more target nucleons (a closed string exchange)
- **Formation zone (=materialization time)**

From one to many: Glauber cascade

At energies below a few GeV hA interactions can be described by a single primary collision hN (elastic or non-elastic), followed by reinteraction of the secondary particles (INC).



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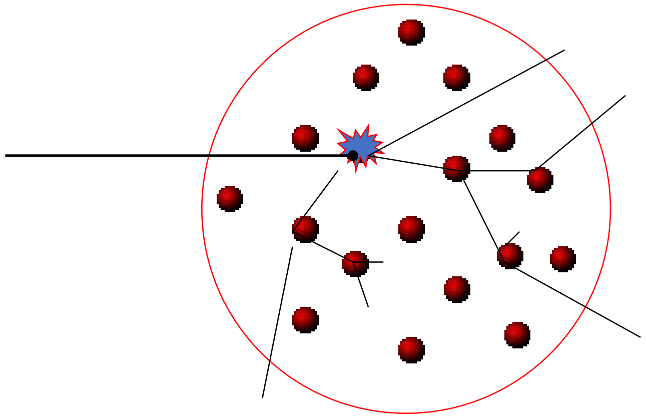
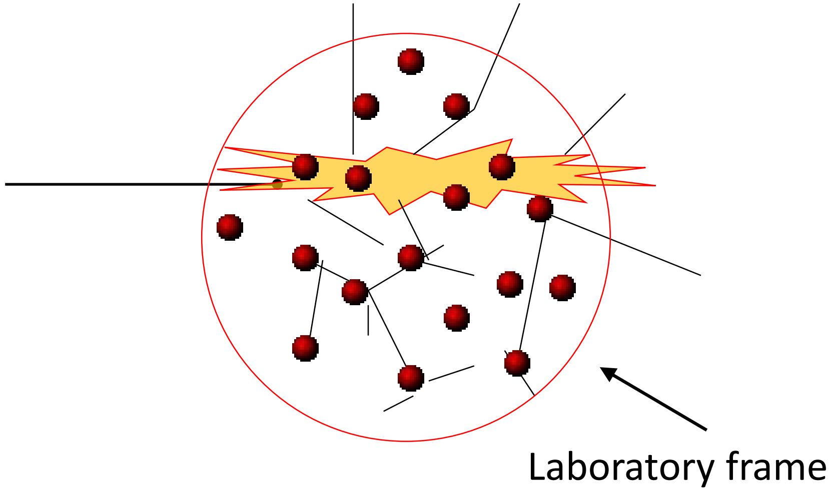
At higher energies, the **Glauber** calculus predicts explicit multiple primary collisions





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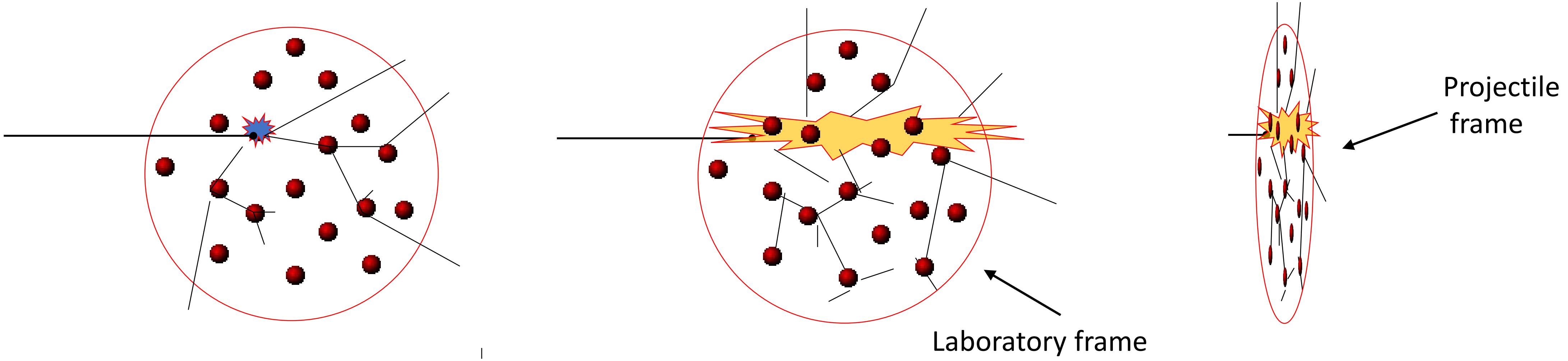
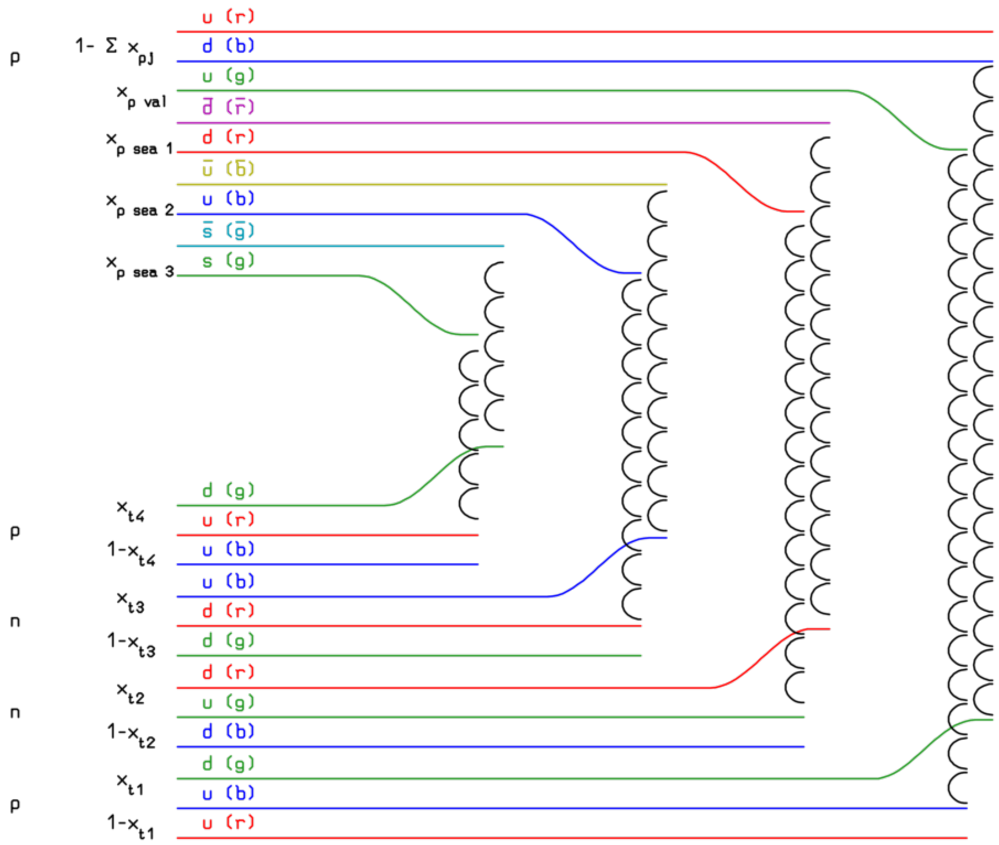
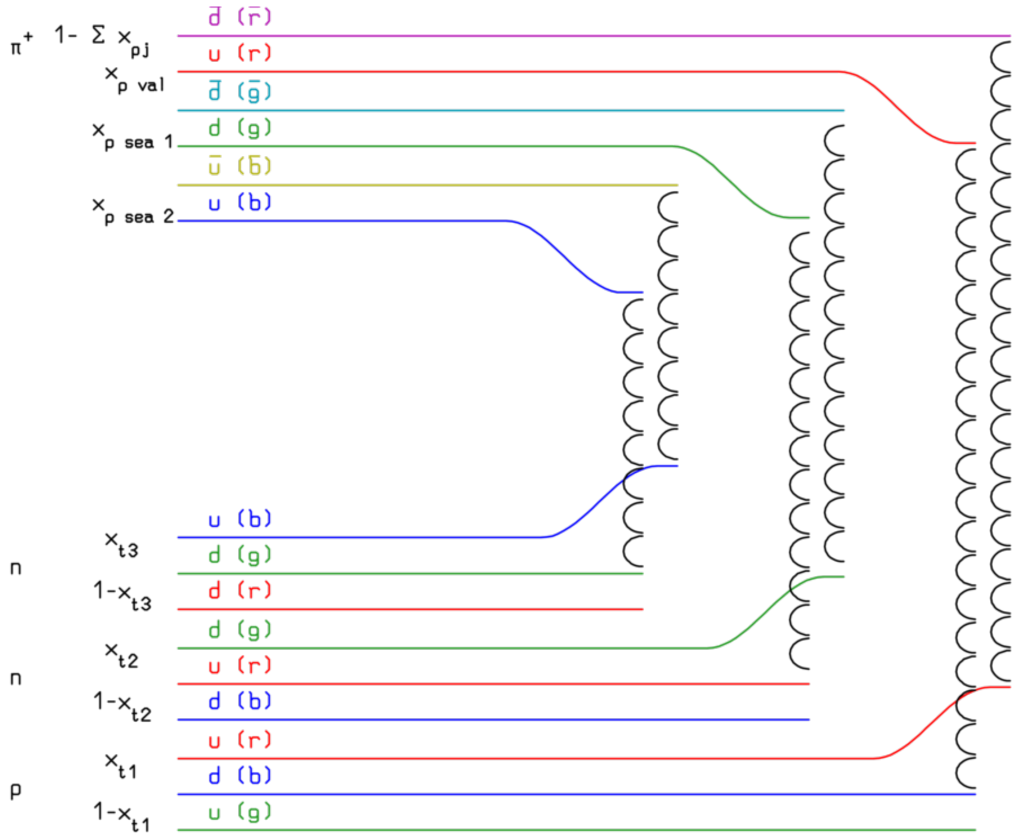


Due to the relativistic length contraction and the uncertainty principle, at high energy most of the newly produced particles escape the nucleus without further re-interaction

Glauber-Gribov: chain examples

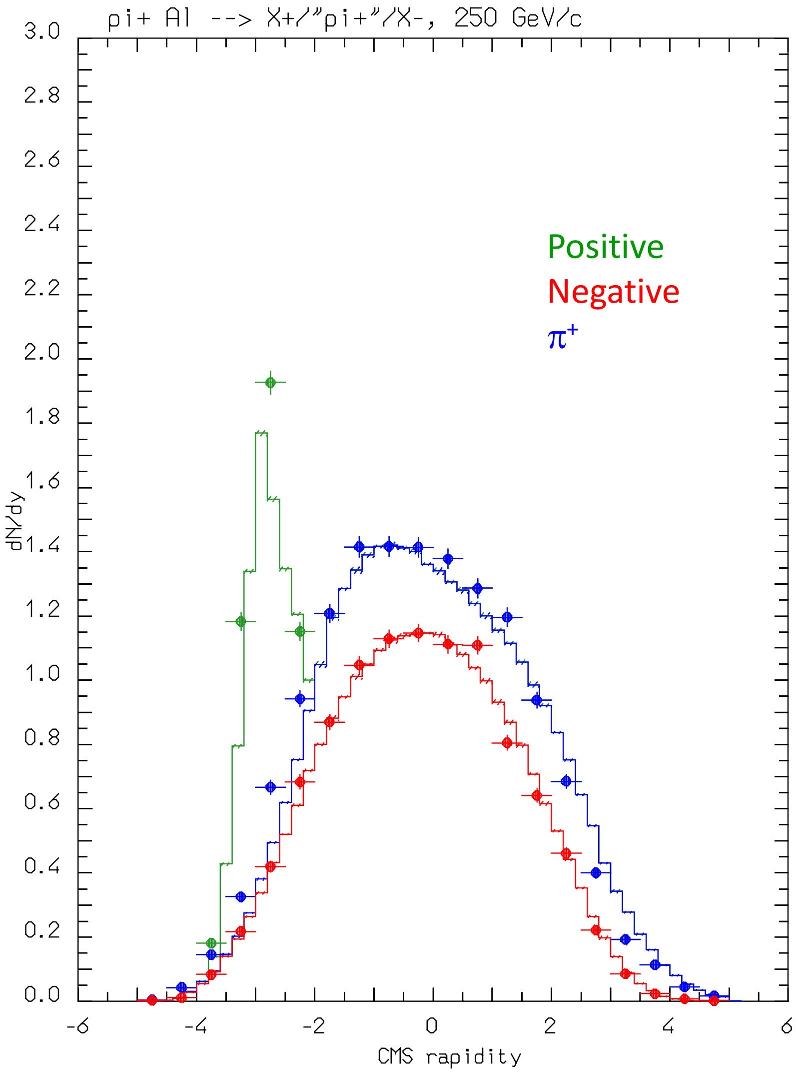


Leading two-chain diagrams in DPM for *p-A* Glauber scattering with 4 collisions. The color (red blue green) and quark combinations shown in the figure are just one of the allowed possibilities



Leading two-chain diagrams in DPM for π^{+-}A Glauber scattering with 3 collisions.

Example: yes Glauber, yes formation zone + (G)INC

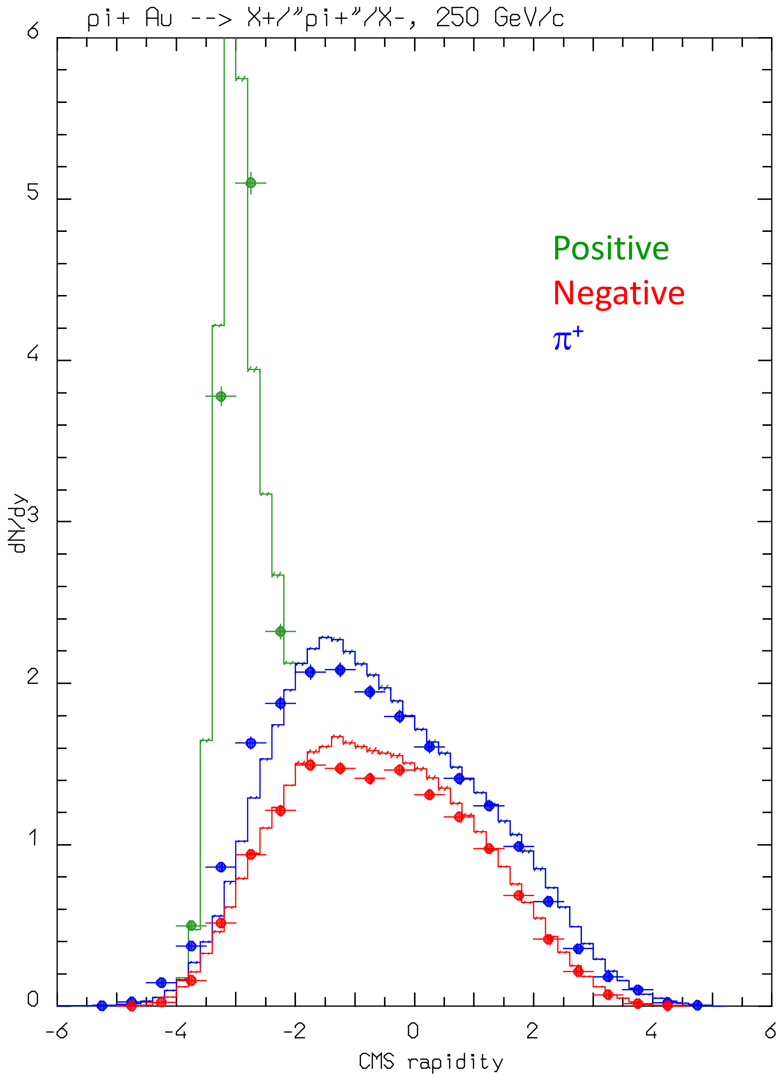


(Pseudo)rapidity y (η) distribution of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)

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

$$y = \cosh^{-1}\left(\frac{E}{m_T}\right) = \tanh^{-1}\left(\frac{p_\parallel}{E}\right) = \frac{1}{2}\ln\left(\frac{E+p_\parallel}{E-p_\parallel}\right)$$

$$\eta = -\ln\left(\tan\frac{\vartheta}{2}\right) = \frac{1}{2}\ln\left(\frac{p+p_\parallel}{p-p_\parallel}\right)$$



Evaporation:

After many collisions and possibly particle emissions, the residual nucleus is left in a highly excited “equilibrated” state. De-excitation can be described by **statistical models** which resemble the **evaporation** of “droplets”, actually **low energy particles (p, n, d, t, 3He, alphas…)** from a “boiling”soup characterized by a “nuclear temperature”

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The process is terminated when all available energy is spent $\rightarrow$ the leftover nucleus, possibly radioactive, is now “cold”, with **typical recoil energies ~ MeV**. For heavy nuclei the excitation energy can be large enough to allow breaking into two major chunks (**fission**). Since only neutrons have no barrier to overcome, **neutron emission is strongly favoured**.

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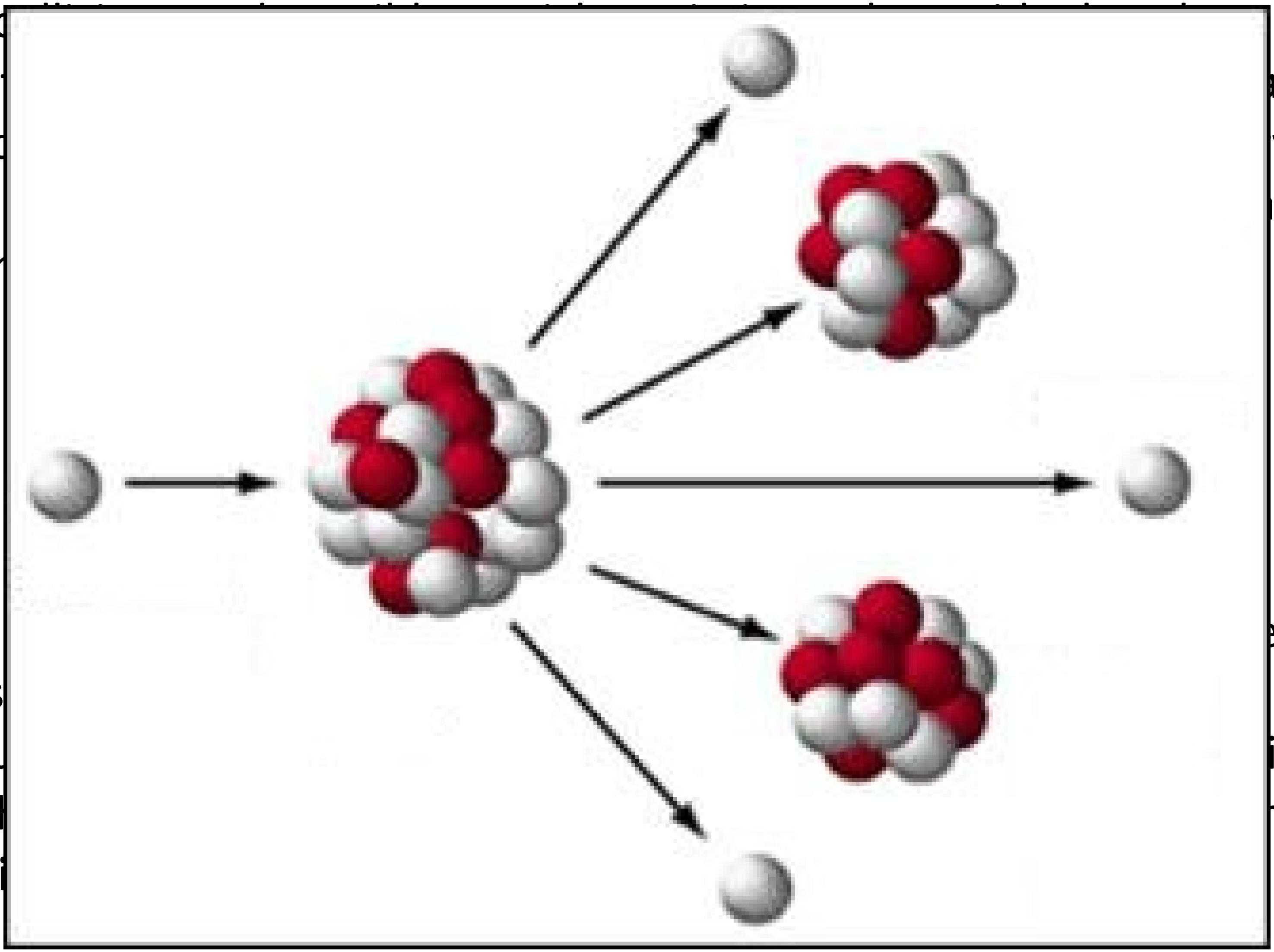


The process er nucleus, pos **MeV**. For heavy nu ing into two major ch me, **neutron emi**

Fermi gas model: Nucleons = Non-interacting Constrained Fermions

The observed central/saturation density of nuclei, $\rho \approx 0.17\ \mathrm{fm}^{-3}$ ($1.7\mathrm{x}10^{38}$ nucleons/cm^3), implies:

$$K_F = 1.36\,\mathrm{fm}^{-1} \qquad E_F = 38\,\mathrm{MeV}$$

These are called the **Fermi momentum** *and* **Fermi Energy**

The probability distribution for the momentum/energy of a nucleon are therefore given by:

$$P(K)\mathrm{d}K = \frac{K^2}{3K_F^3}\mathrm{d}K \qquad P(E_k)\mathrm{d}E_k = \frac{2\sqrt{E_k}}{3E_F^3}\mathrm{d}E_k$$

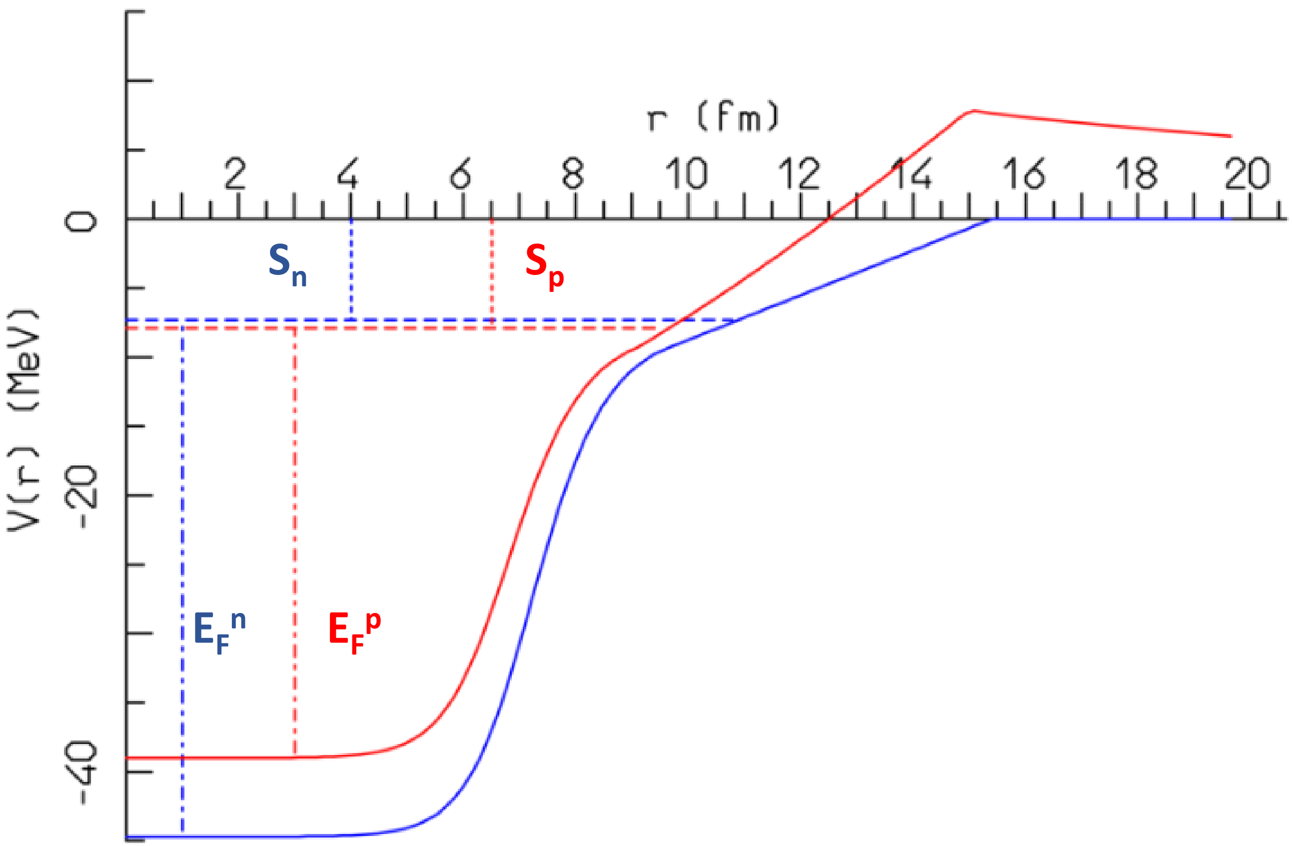
In nuclei with $N \neq Z$, two different values of the Fermi energy can be defined:

$$\rho_p(r) = \frac{Z}{A}\rho = \frac{1}{3\pi^2}\left(K_F^p\right)^3 \qquad \rho_n(r) = \frac{N}{A}\rho = \frac{1}{3\pi^2}\left(K_F^n\right)^3$$

The so defined Fermi energies are kinetic energies, counted from the bottom of a potential well that in this model must be input from outside. This gives an average potential depth of about **38+8=46 MeV**. The Fermi energy can be made radius-dependent in a straightforward way, through the so called ***local density approximation:***

$$\rho(r) = \frac{2}{3\pi^2}K_F^3(r)$$

Nuclear potential for n/p: schematic drawing



^{208}Pb:

- Blue: neutron
- Red: proton

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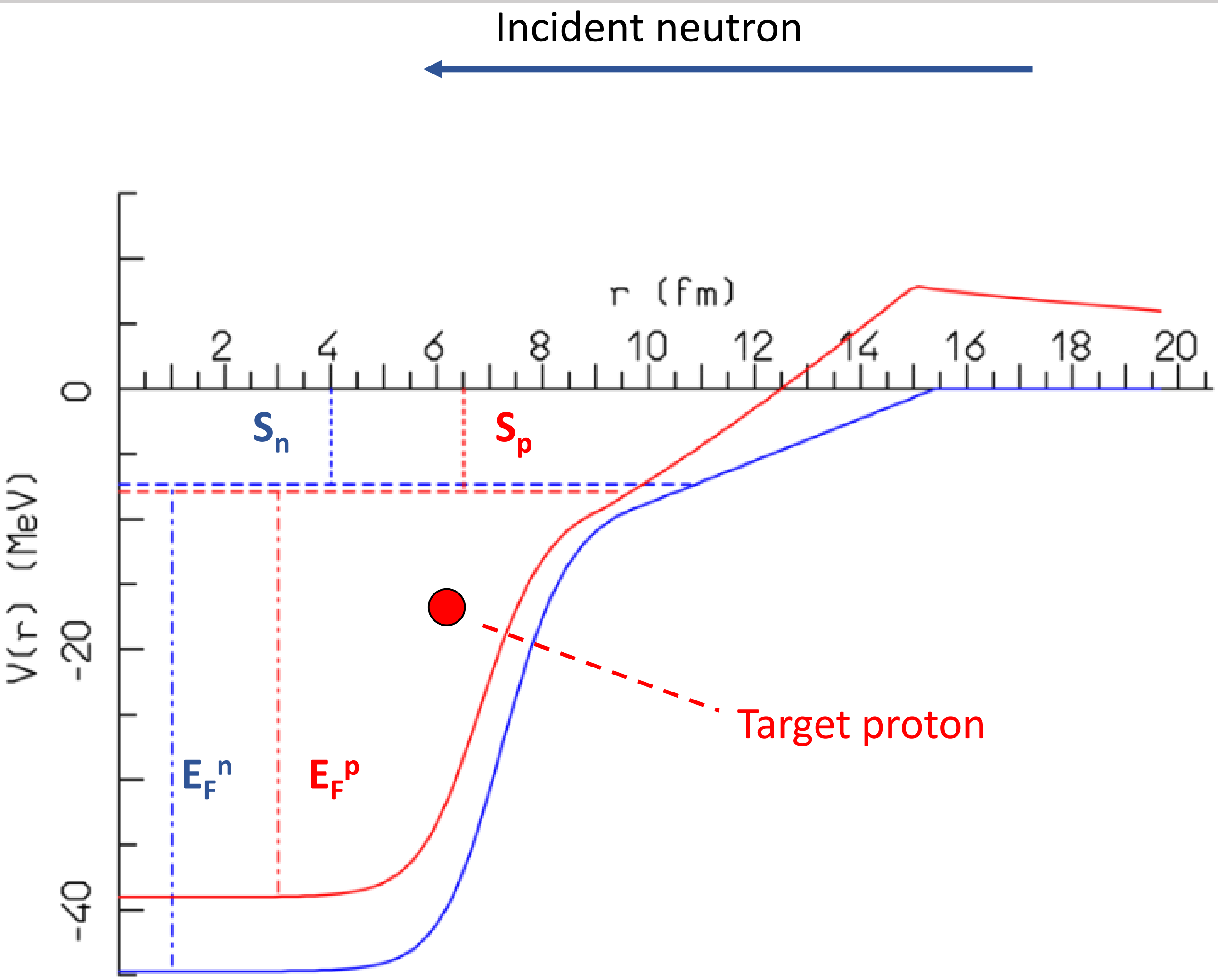

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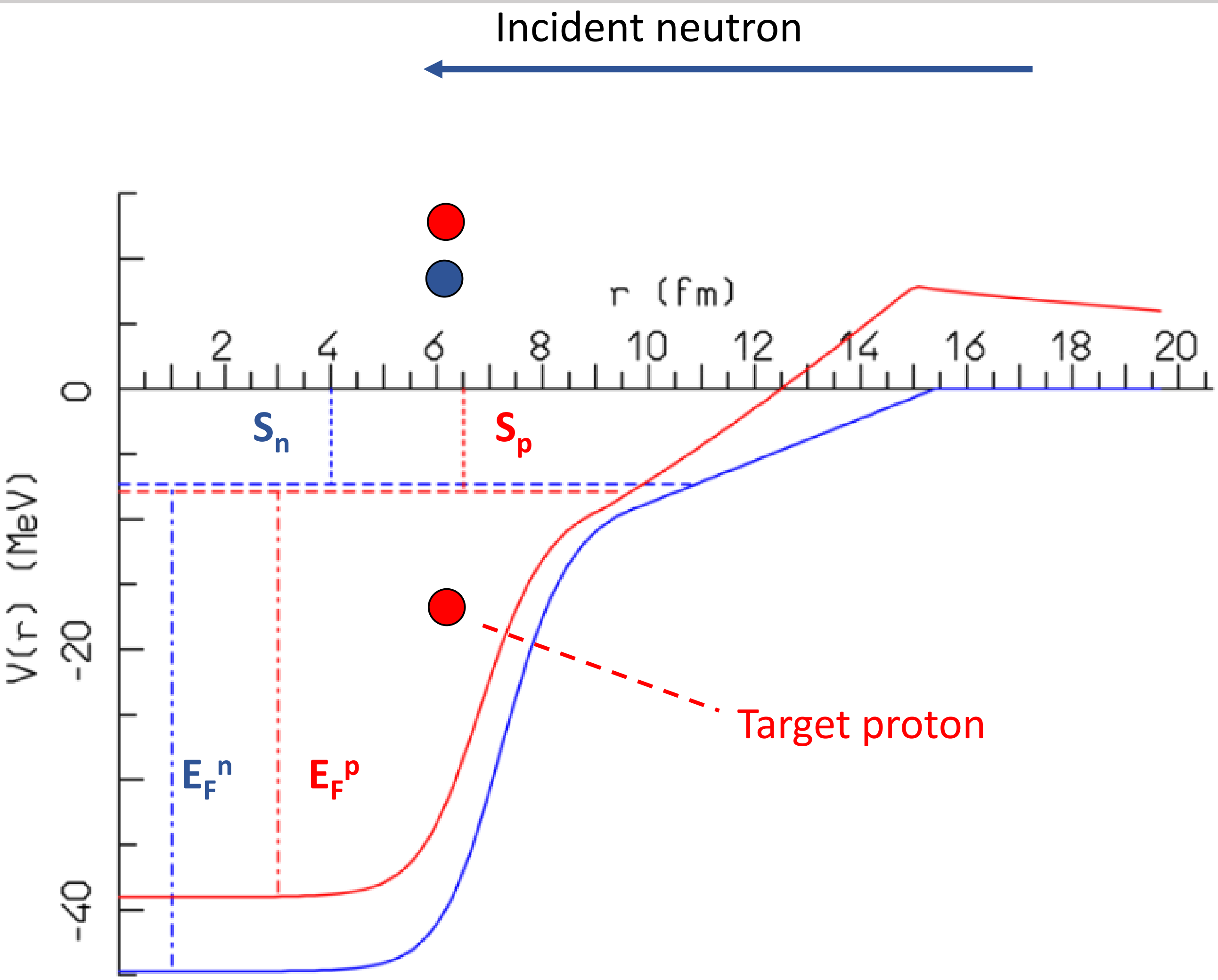

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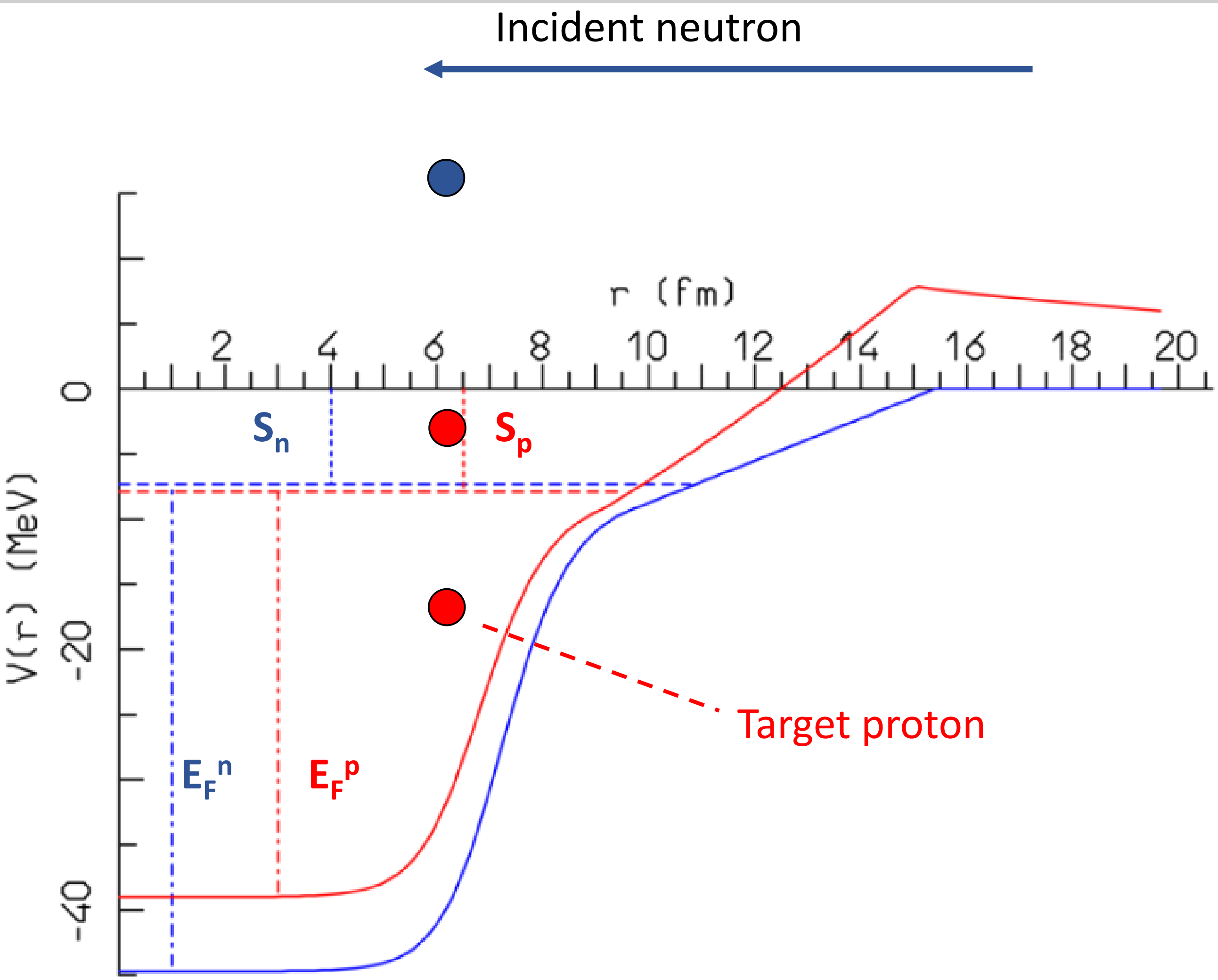
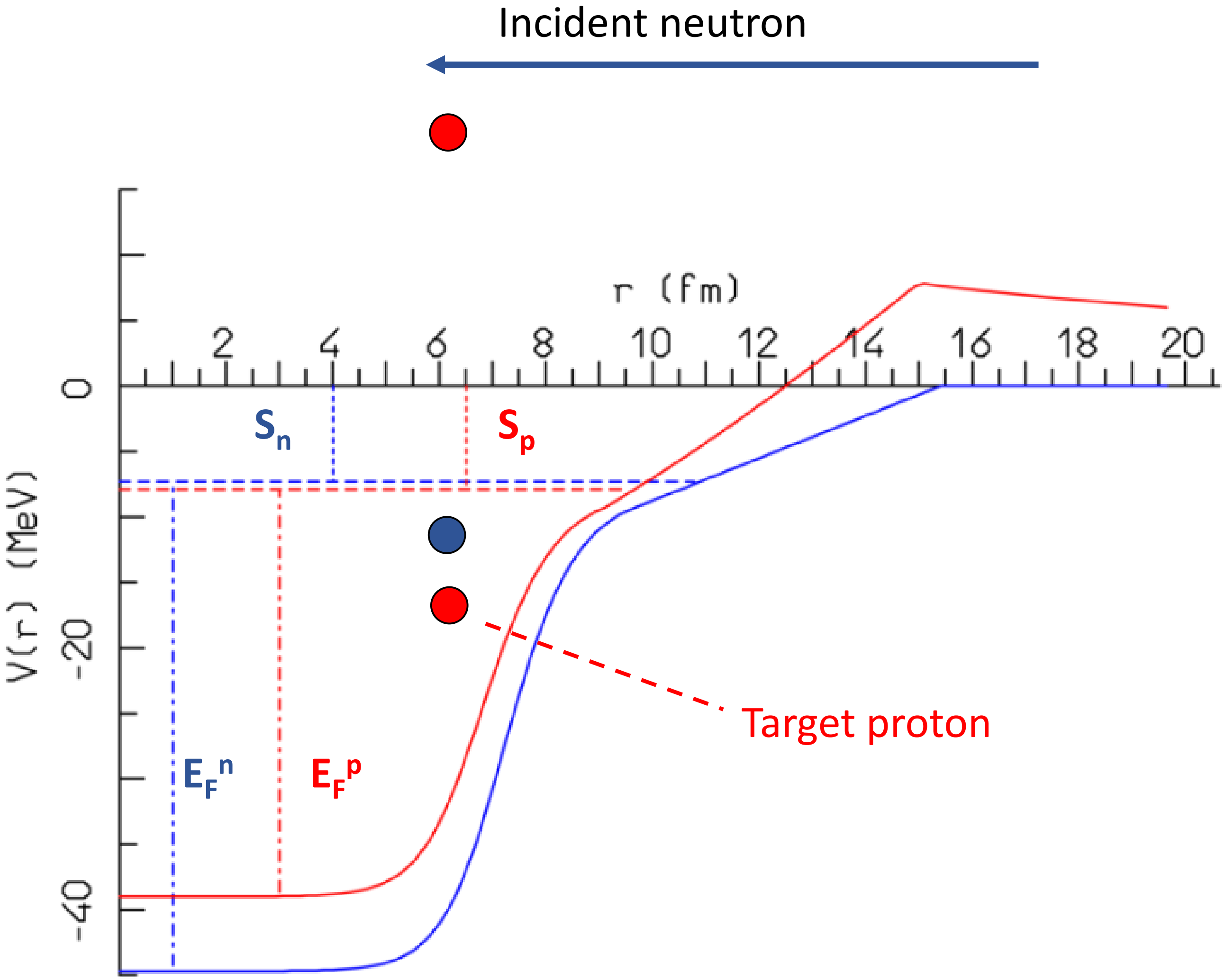
Nuclear potential for n/p: schematic drawing



^{208}Pb:

- Blue: neutron
- Red: proton

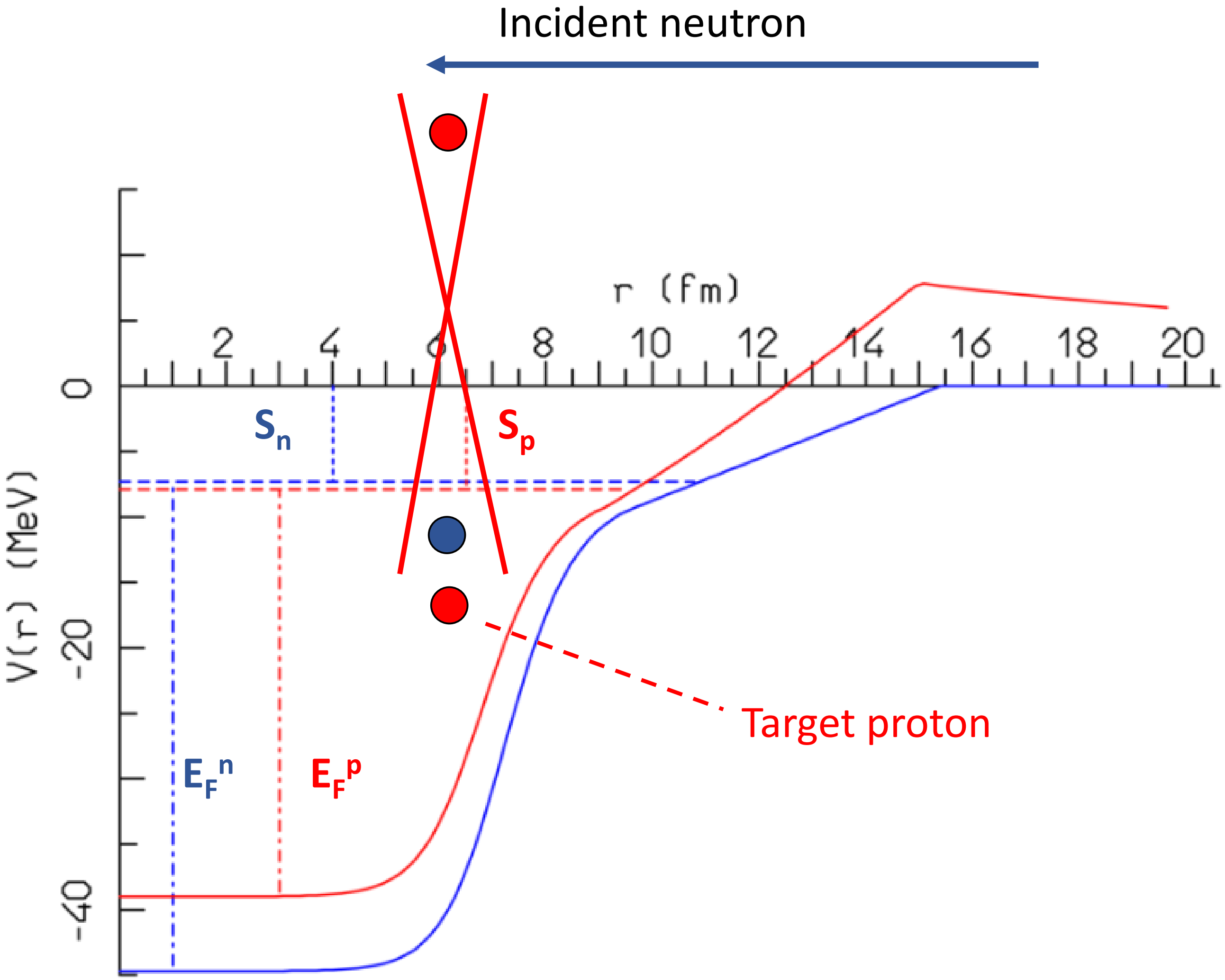
Nuclear potential for n/p: schematic drawing



^{208}Pb:

- Blue: neutron
- Red: proton

Nuclear potential for n/p: schematic drawing



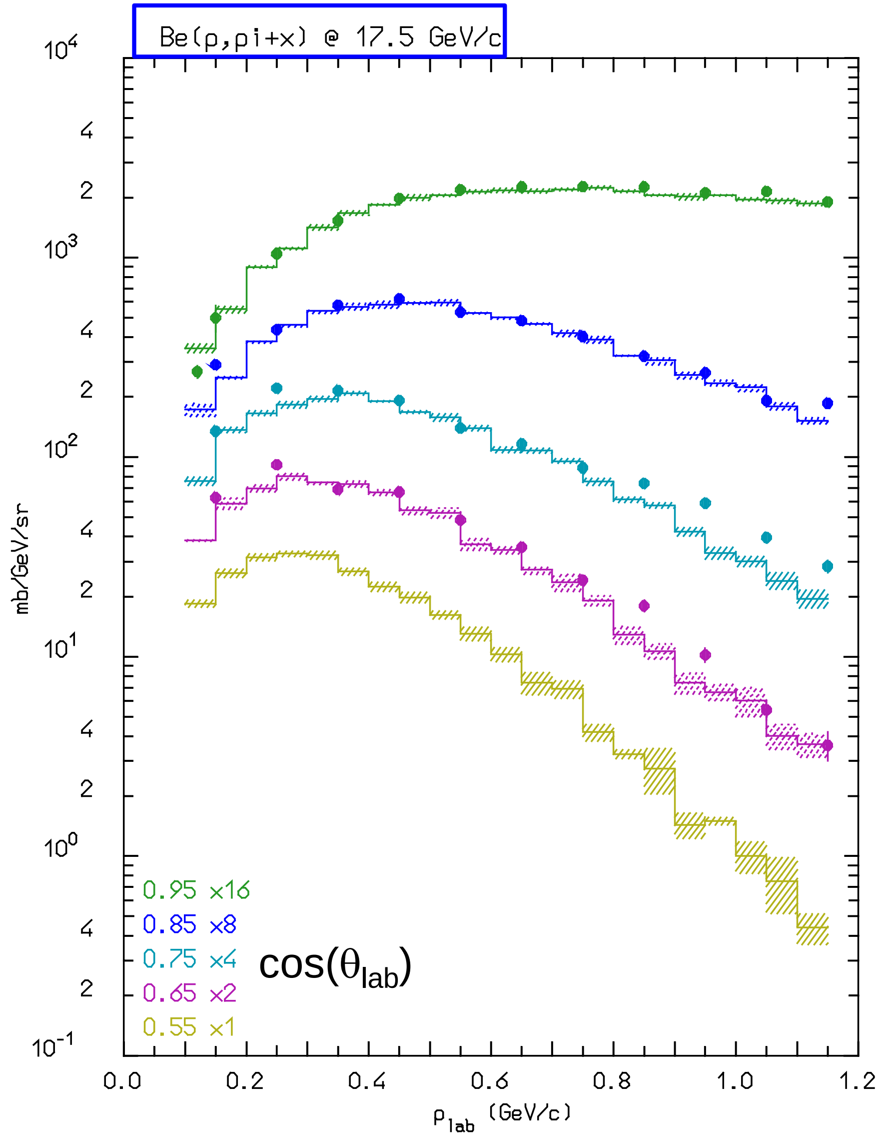
^{208}Pb:

- Blue: neutron
- Red: proton

(Generalized) IntraNuclear Cascade in PEANUT

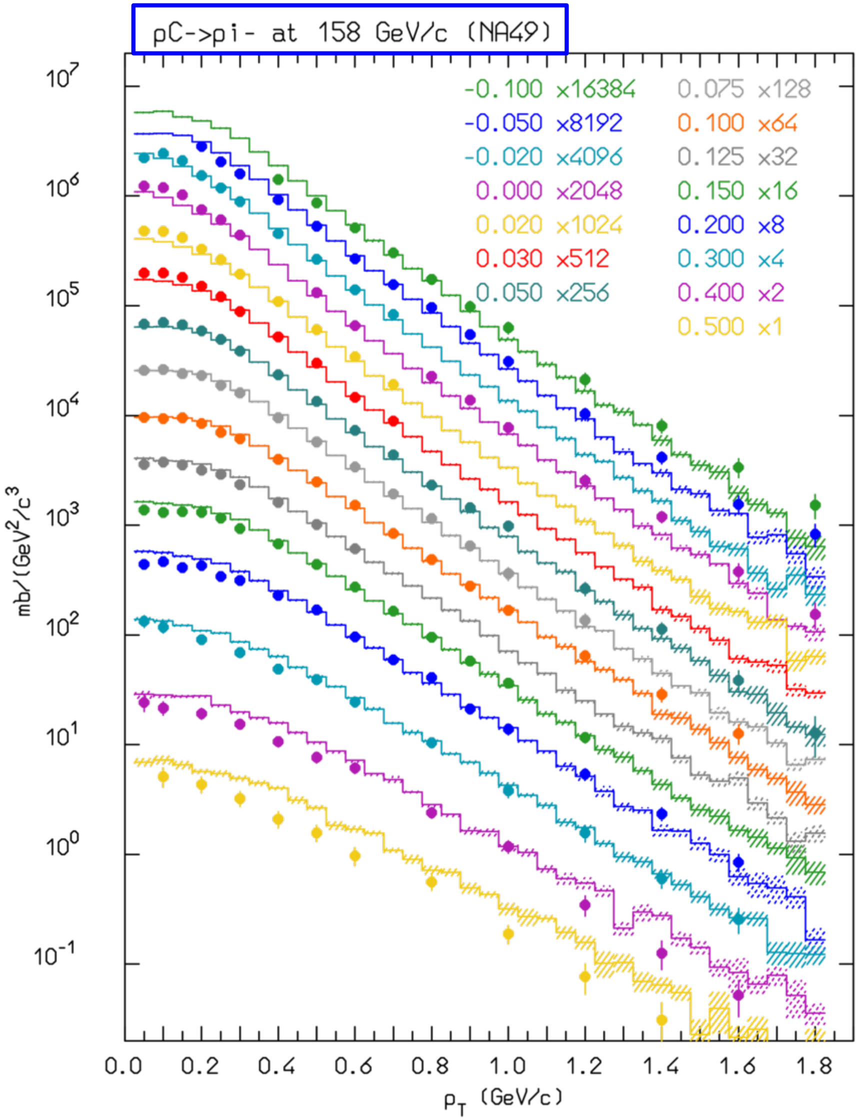
- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear well according to the Fermi gas model
- Interaction probability
  σ_{free} + Fermi motion × $\rho(r)$ + exceptions (ex. π)
- Glauber cascade at higher energies
- Classical trajectories (+) nuclear mean potential (resonant for π)
- Curvature from nuclear potential $\rightarrow$ refraction and reflection throughout the nucleus
- Interactions are incoherent and uncorrelated
- Interactions in projectile-target nucleon CMS $\rightarrow$ Lorentz boosts
- Multibody absorption for π, μ^-, K^-
- Quantum effects (Pauli, formation zone, coherence length, correlations…)
- Preequilibrium step
- Exact conservation of energy, momenta and all additive quantum numbers, including nuclear recoil

Nonelastic hA at high energies: examples



Double differential π+ production for pBe interactions at 17.5 GeV/c, as measured by BNL910 (symbols) ← and predicted by FLUKA (histograms). The data are plotted as a function of pion momentum for a few cos(θ) values

Double differential π- production for pC interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA → (histograms). The data are plotted as a function of transverse momentum for various x_F intervals



Pions: nuclear medium effects

Free π N interactions ⇒ ⇒ Non resonant channel

⇒ P-wave resonant Δ production

Δ in nuclear medium ⇒ decay ⇒ elastic scattering, charge exchange

⇒ reinteraction ⇒ Multibody pion absorption

Assuming for the free resonant σ a Breit-Wigner form with width Γ_F

$$\sigma_{res}^{Free} = \frac{8\pi}{p_{cms}^2} \frac{M_\Delta^2 \Gamma_F^2(p_{cms})}{\left(s - M_\Delta^2\right)^2 + M_\Delta^2 \Gamma_F^2(p_{cms})}$$

An ``in medium'' resonant σ (σ^A_{res}) can be obtained adding to Γ_F the imaginary part of the (extra) width arising from nuclear medium

$$\tfrac{1}{2}\Gamma_T = \tfrac{1}{2}\Gamma_F - \mathrm{Im}\Sigma_\Delta \qquad \Sigma_\Delta = \Sigma_{qe} + \Sigma_2 + \Sigma_3$$

(Oset et al., NPA 468, 631)

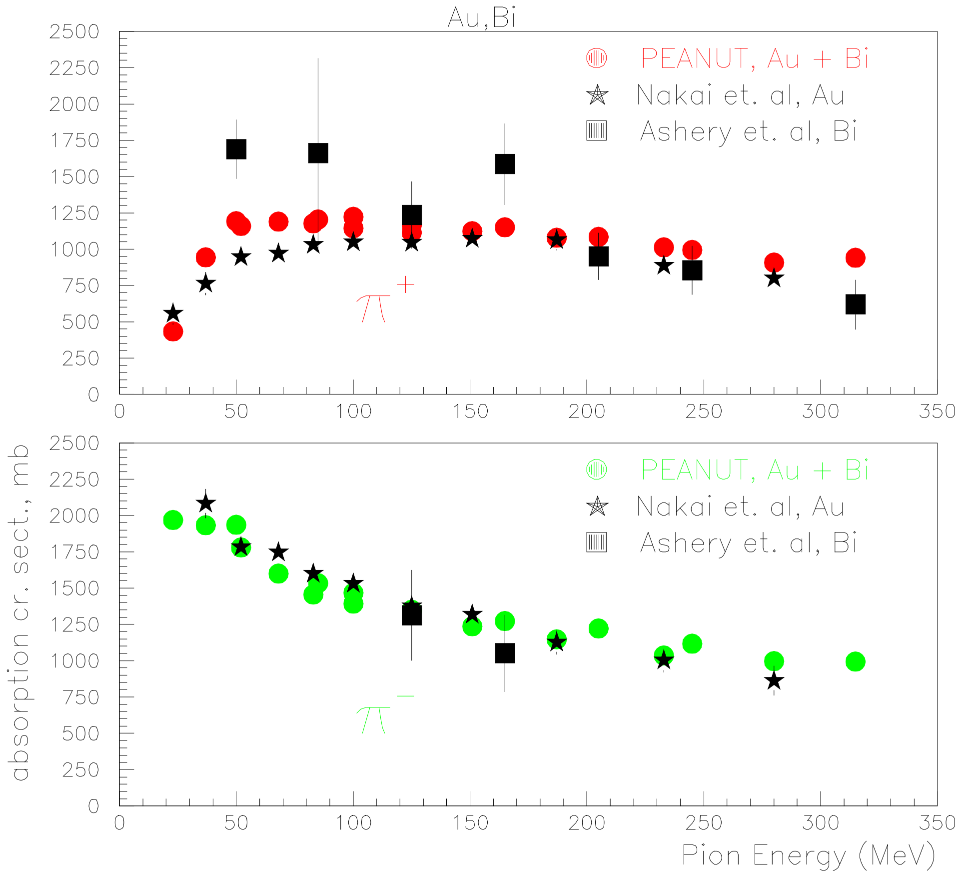
quasielastic scattering, two and three body absorption

The in-nucleus σ_t^A takes also into account a two-body s-wave absorption σ_s^A derived from the optical model

$$\sigma_t^A = \sigma_{res}^A + \sigma_t^{Free} - \sigma_{res}^{Free} + \sigma_s^A \qquad \sigma_s^A(\omega) = \tfrac{4\pi}{p}\left(1 + \tfrac{\omega}{2m}\right)\mathrm{Im}\,B_0(\omega)\rho$$

Pion absorption

Pion absorption cross section on Gold and Bismuth in the Δ resonance region (multibody absorption in PEANUT)

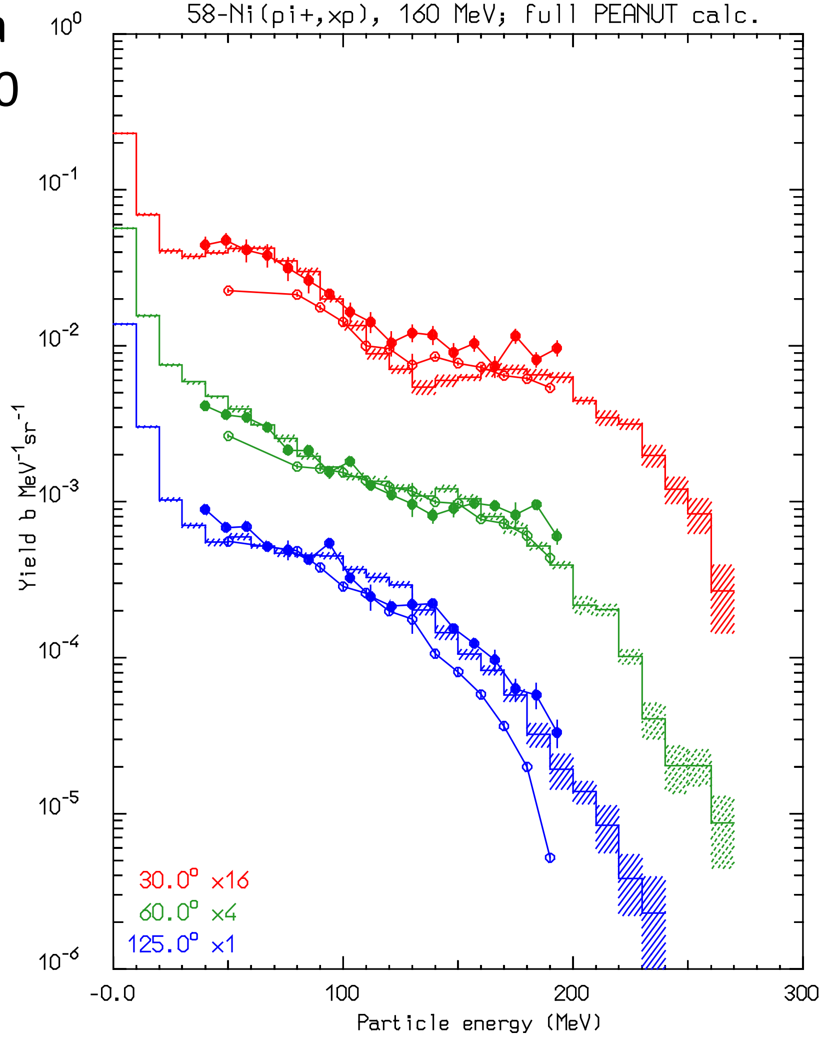


Emitted proton spectra at different angles , 160 MeV π^+ on ^{58}Ni

Phys. Rev. C41,2215

Phys. Rev. C24,211

Proton spectra extend up to 300 MeV



Preequilibrium emission

For E > π production threshold $\rightarrow$ only (G)INC models

At lower energies a variety of preequilibrium models == share the excitation energy among many nucleons/holes

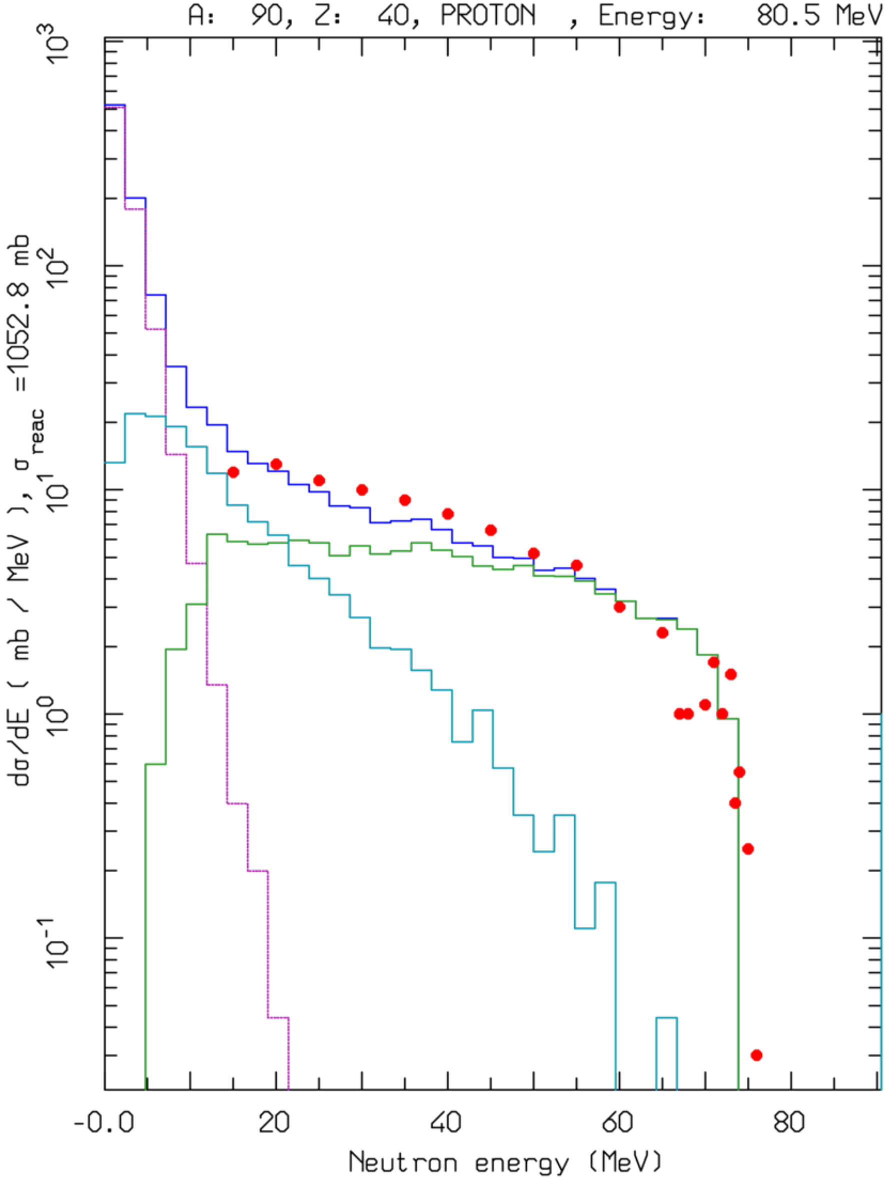
Two leading approaches

The quantum-mechanical multistep model:
Very good theoretical background
Complex, difficulties for multiple emissions

The semiclassical exciton model
Statistical assumptions
Simple and fast
Suitable for MC

Statistical assumption:
any partition of the excitation energy E^* among N, $N = N_h + N_p$, excitons has the same probability to occur
Step: nucleon-nucleon collision with $N_{n+1}=N_n+2$ ("never come back approximation)
Chain end = equilibrium = N_n sufficiently high or excitation energy below threshold
N_1 depends on the reaction type and cascade history

Example of (G)INC + Preeq + evaporation



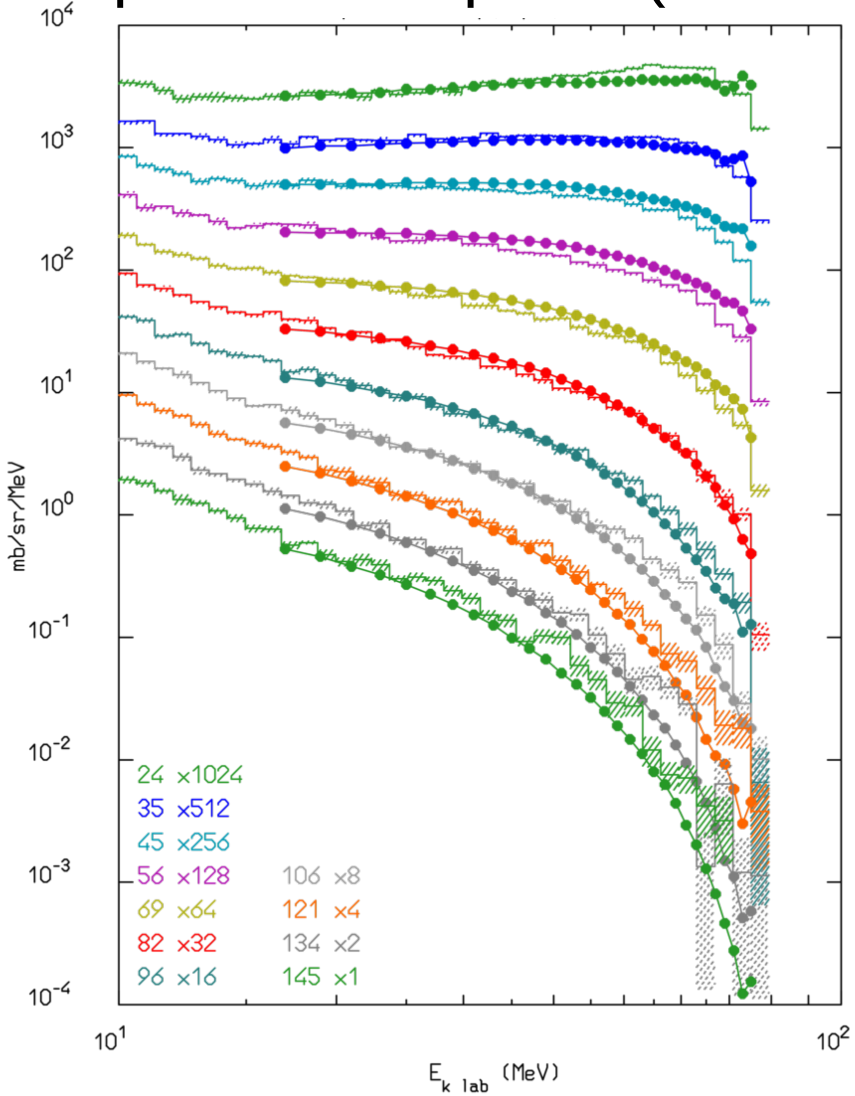
Angle-integrated $^{90}Zr(p,xn)$ at 80.5 MeV

The various lines show the ***total, INC, preequilibrium*** and ***evaporation*** contributions

Experimental data ● from
M. Trabandt et al., Phys. Rev. C39, 452 (1989)

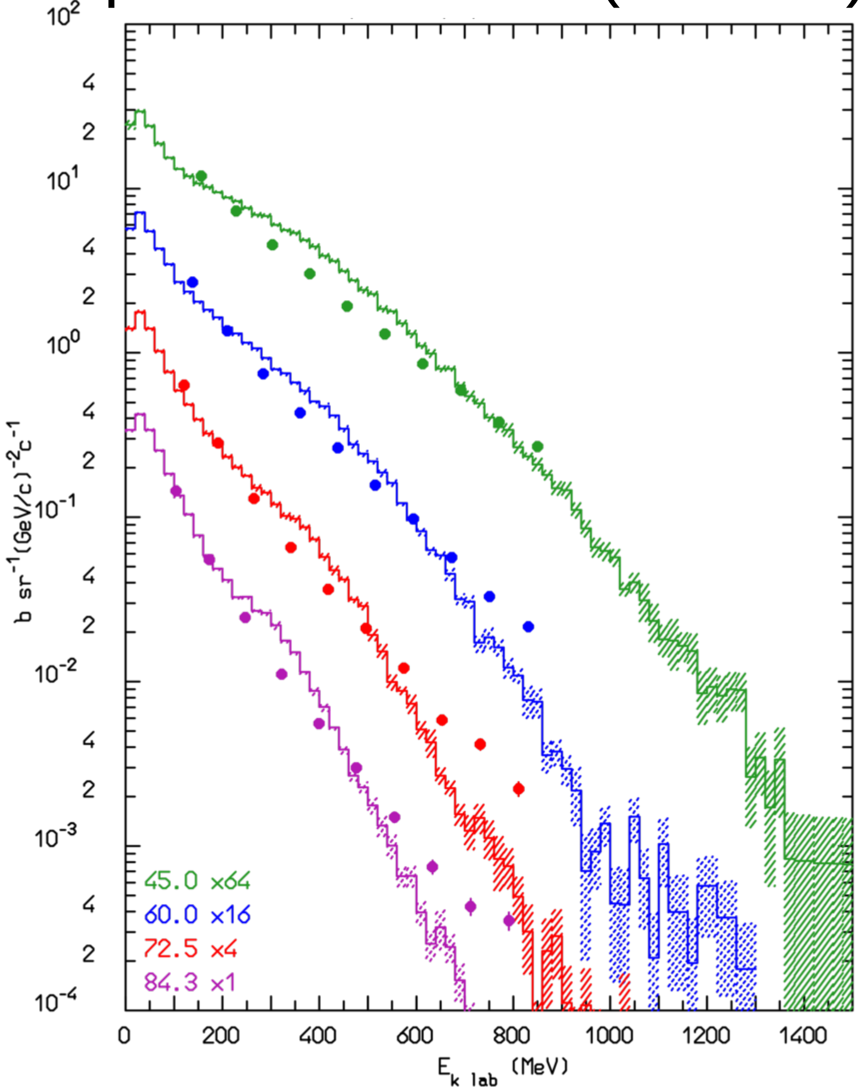
Thin target examples

p + ^{90}Zr → p + X (80 MeV)

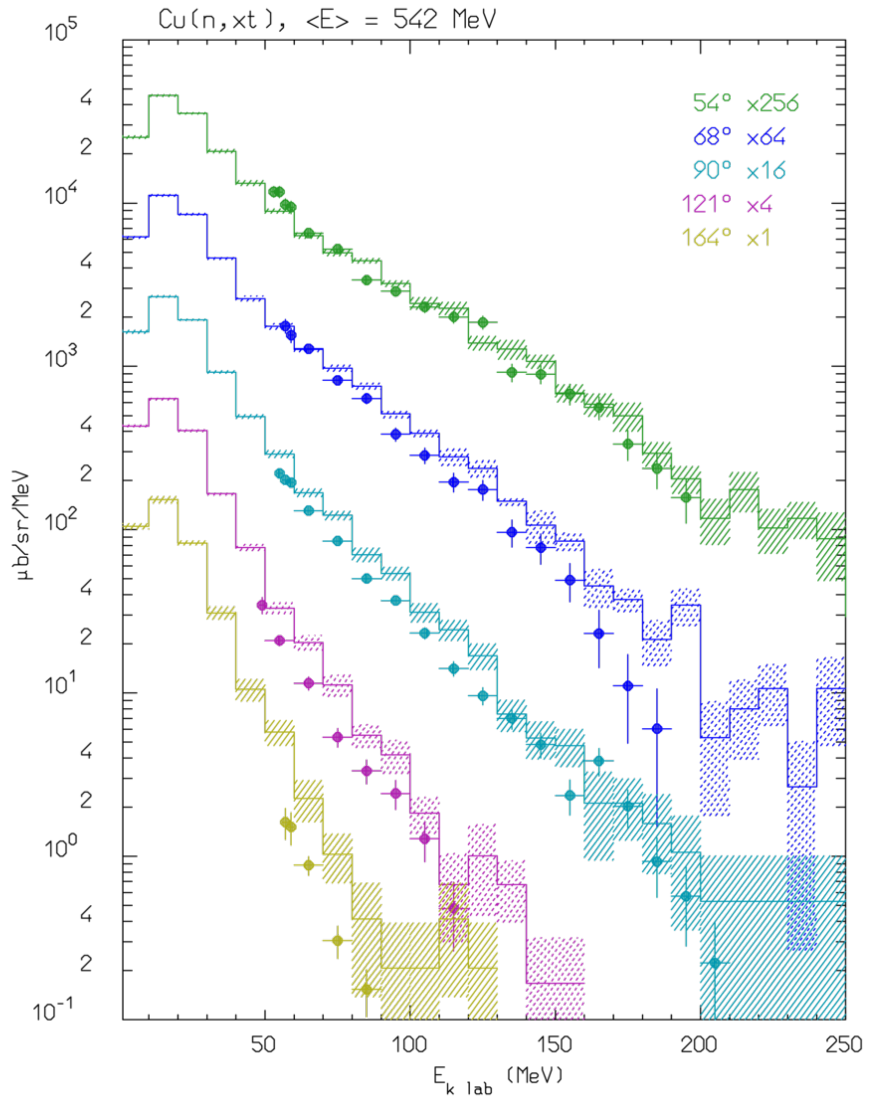


Double differential, $d^2\sigma/dEd\Omega$ emission spectra for various angles
Histos: FLUKA
Symbols: exp. data

p + Al → π^- + X (4 GeV/c)



Coalescence



High energy light fragments are emitted through the coalescence mechanism: "put together" emitted nucleons that are near in phase space.

Example : double differential t (^{3}H) production from 542 MeV neutrons on Copper

Warning: coalescence is ***OFF*** by default
Can be important, expecially for residual nuclei.
To activate it (recommended):

```
PHYSICS 1.                                              COALESCE
```

If coalescence is on, switch on Heavy ion transport and interactions (see later)

Equilibrium particle emission in Fluka

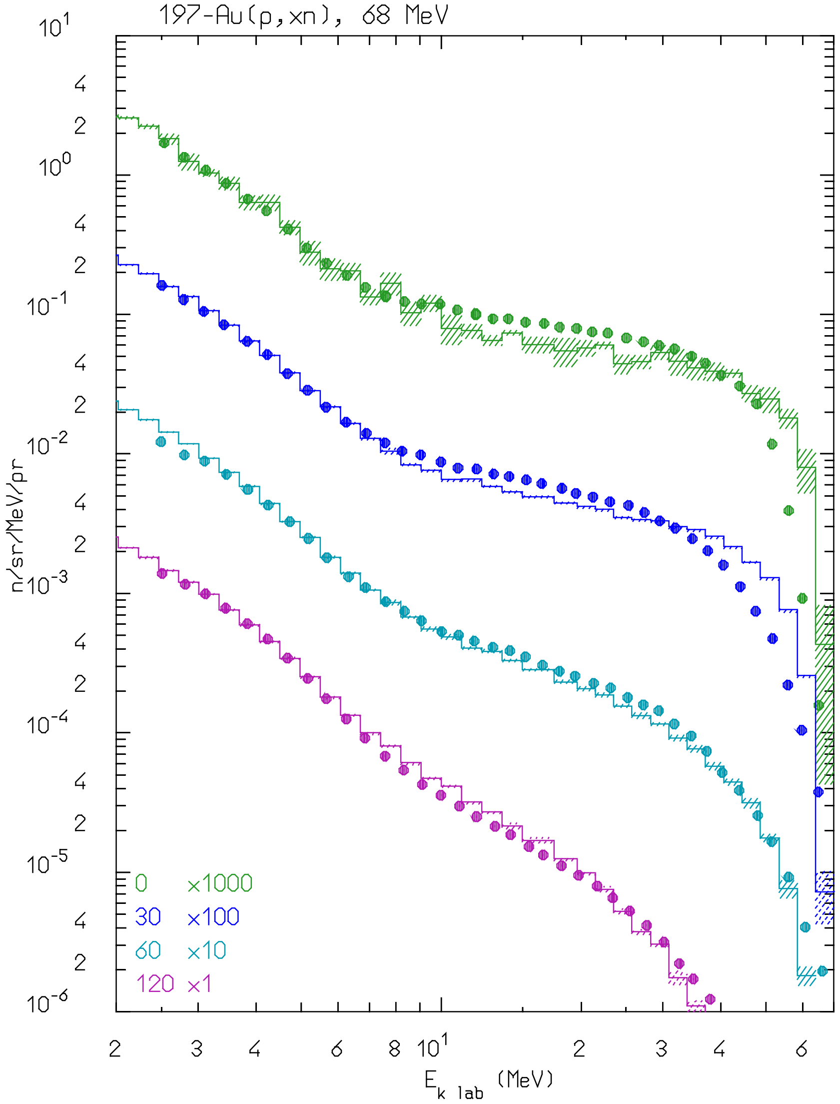
- Evaporation: Weisskopf-Ewing approach
  - ~600 possible emitted particles/states (A<25) with an extended (heavy) evaporation/fragmentation formalism
  - Full level density formula with level density parameter A,Z and excitation dependent
  - Inverse cross section with proper sub-barrier
  - Analytic solution for the emission widths (neglecting the level density dependence on U, taken into account by rejection
  - Emission energies from the width expression with no. approx.
- Fission:
  - Γ_{fis} based of first principles, full competition with evaporation
  - Improved mass and charge widths
  - Myers and Swiatecki fission barriers, with exc. en. dependent level density enhancement at saddle point

```
PHYSICS 3.                                EVAPORAT
```

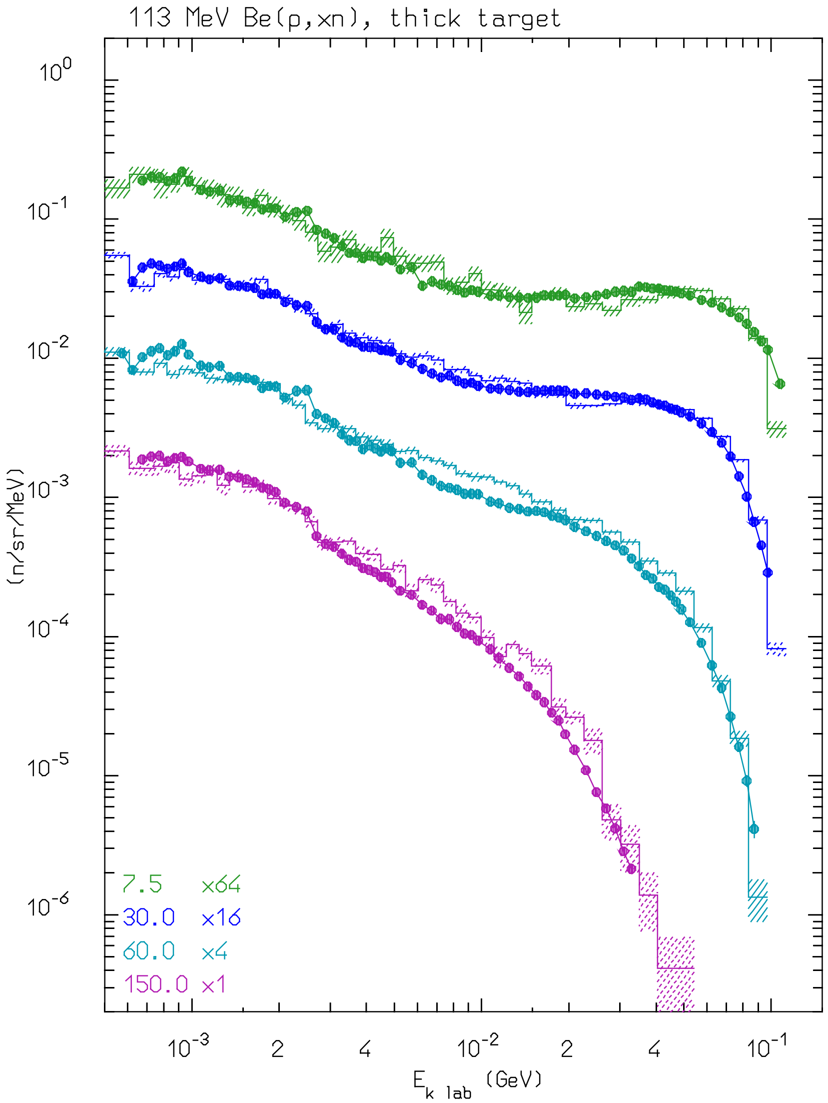
- Fermi Break-up for A<18 nuclei
  - ~ 50000 combinations included with up to 6 ejectiles
- γ de-excitation: statistical + rotational + tabulated levels

Thick target examples: neutrons

$^{197}Au(p,xn)$ @ 68 MeV, stopping target
Data: JAERI-C-96-008, 217 (1996)



$^{9}Be(p,xn)$ @ 113 MeV, stopping target
Data: NSE110, 299 (1992)



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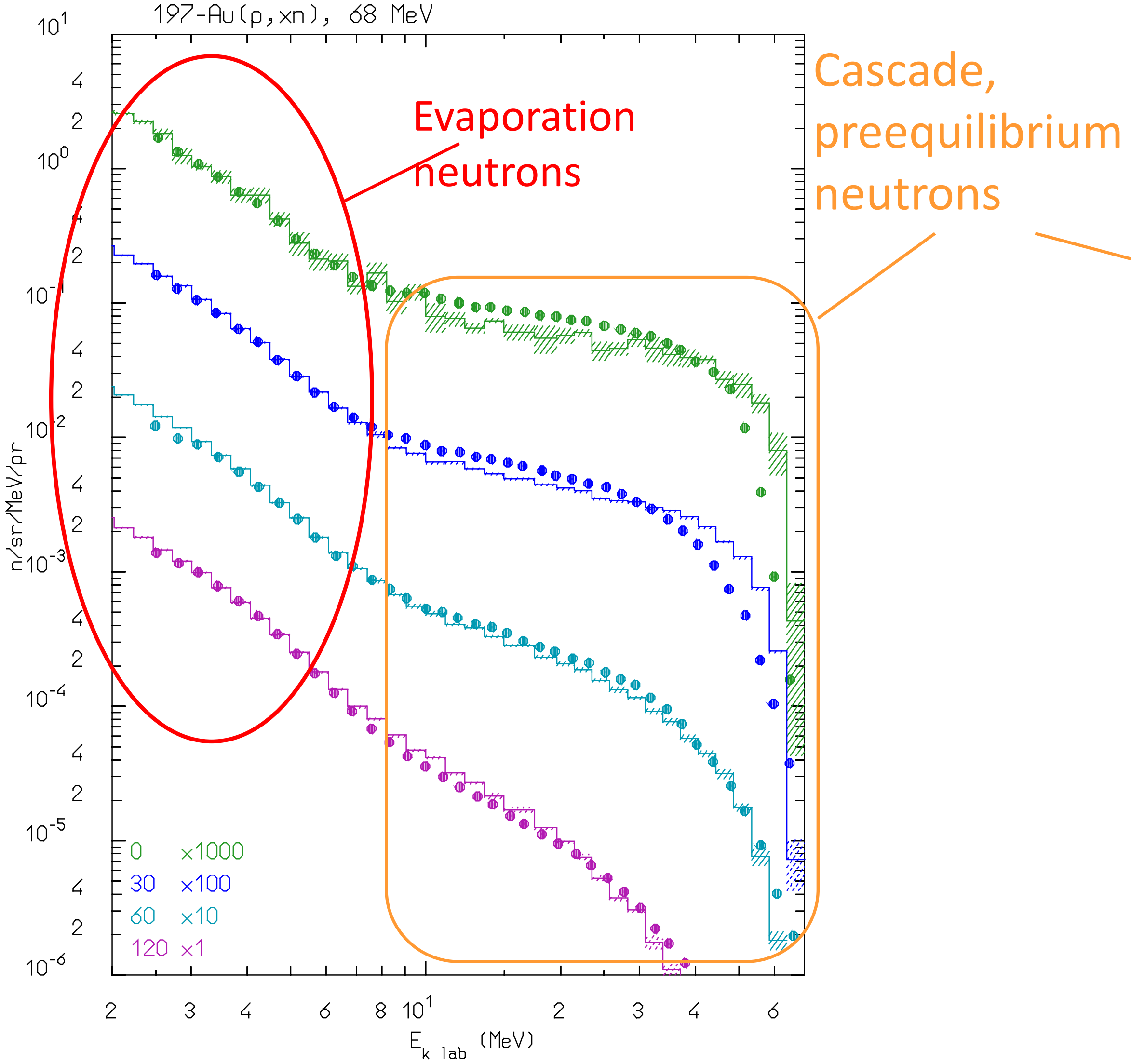

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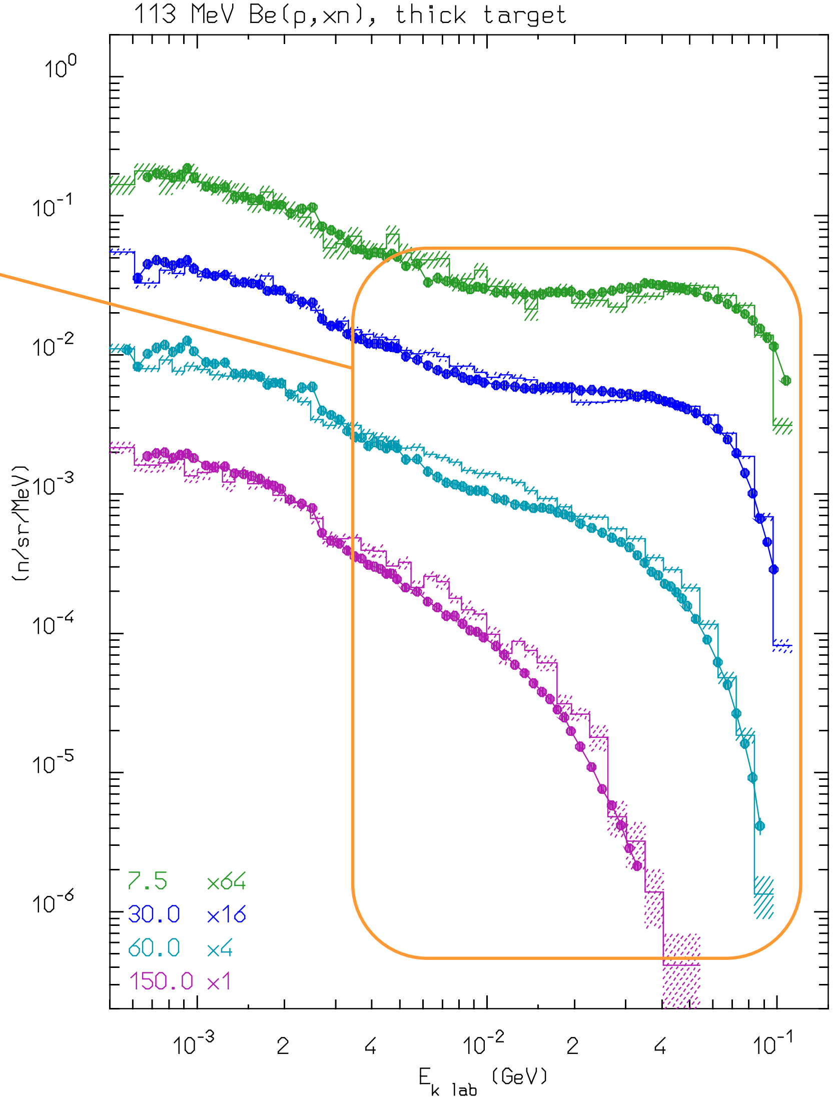
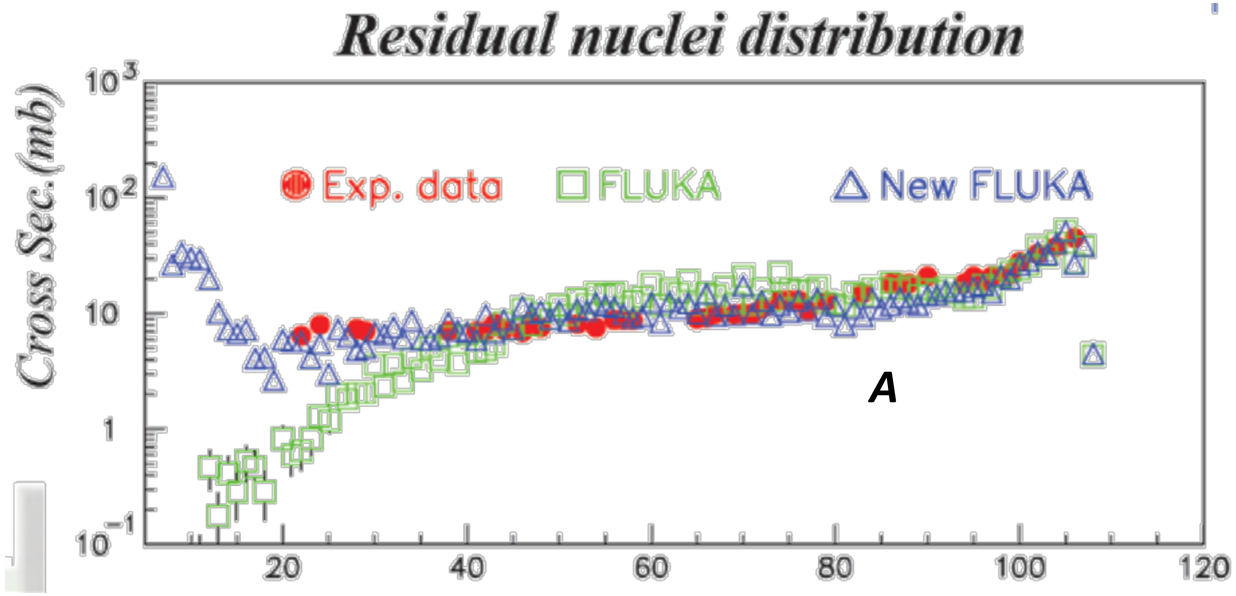


Residual nuclei

Experimental and computed residual nuclei mass distribution for Ag(p,x)X at 300 GeV

Data from Phys. Rev. C19 2388 (1979)

The heavy evaporation/fragmentation model ("New FLUKA") has much improved the FLUKA predictions



Also for A-A interactions

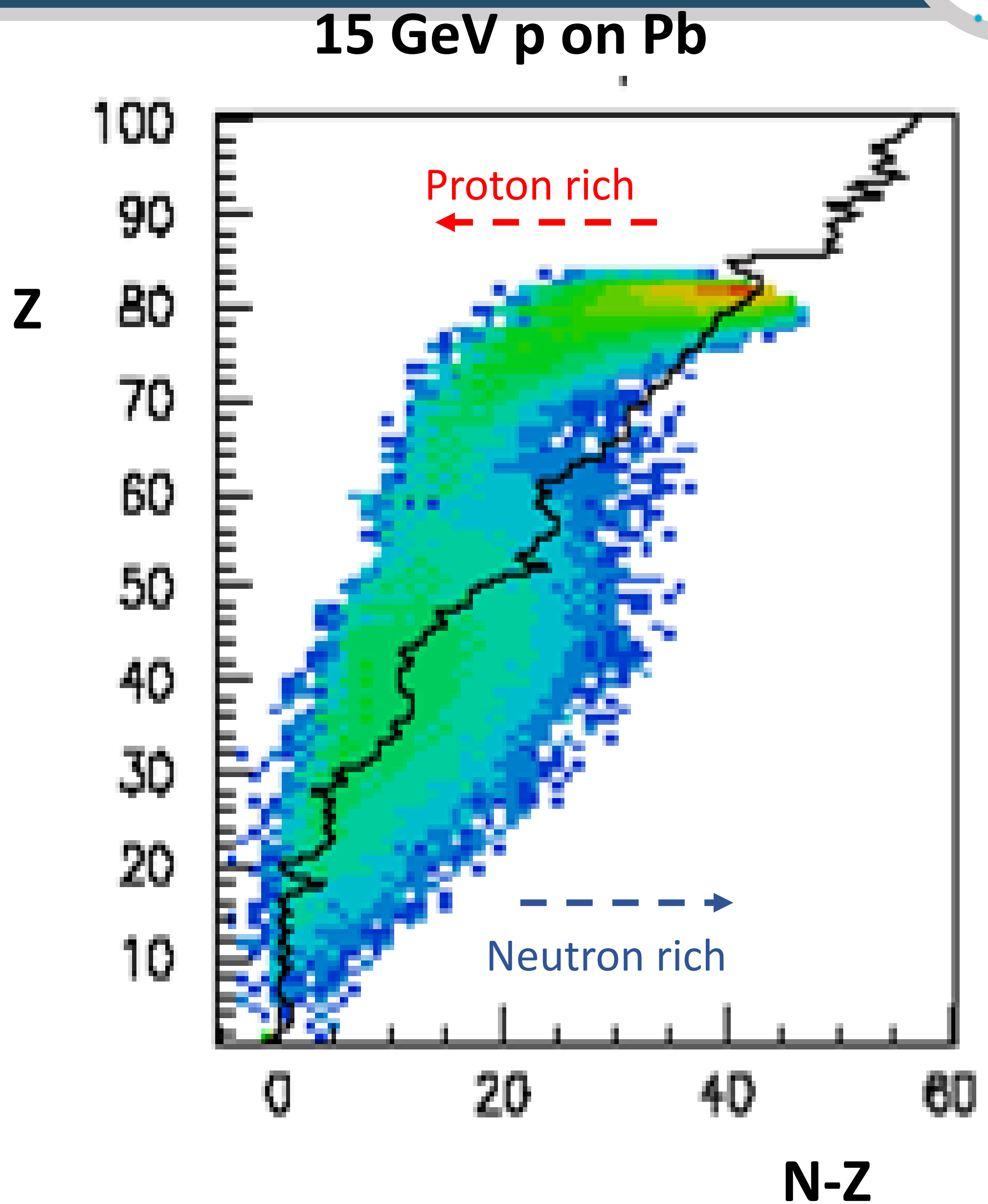
Warning: heavy evaporation/fragmentation is ***only partially ON*** by default, and only for a few defaults, because it is a cpu-eater. It is NECESSARY to activate it ***fully*** for activation studies:

```
PHYSICS 3.                                                    EVAPORAT
```

If fragmentation is on, switch on Heavy ion transport and interactions (see later)

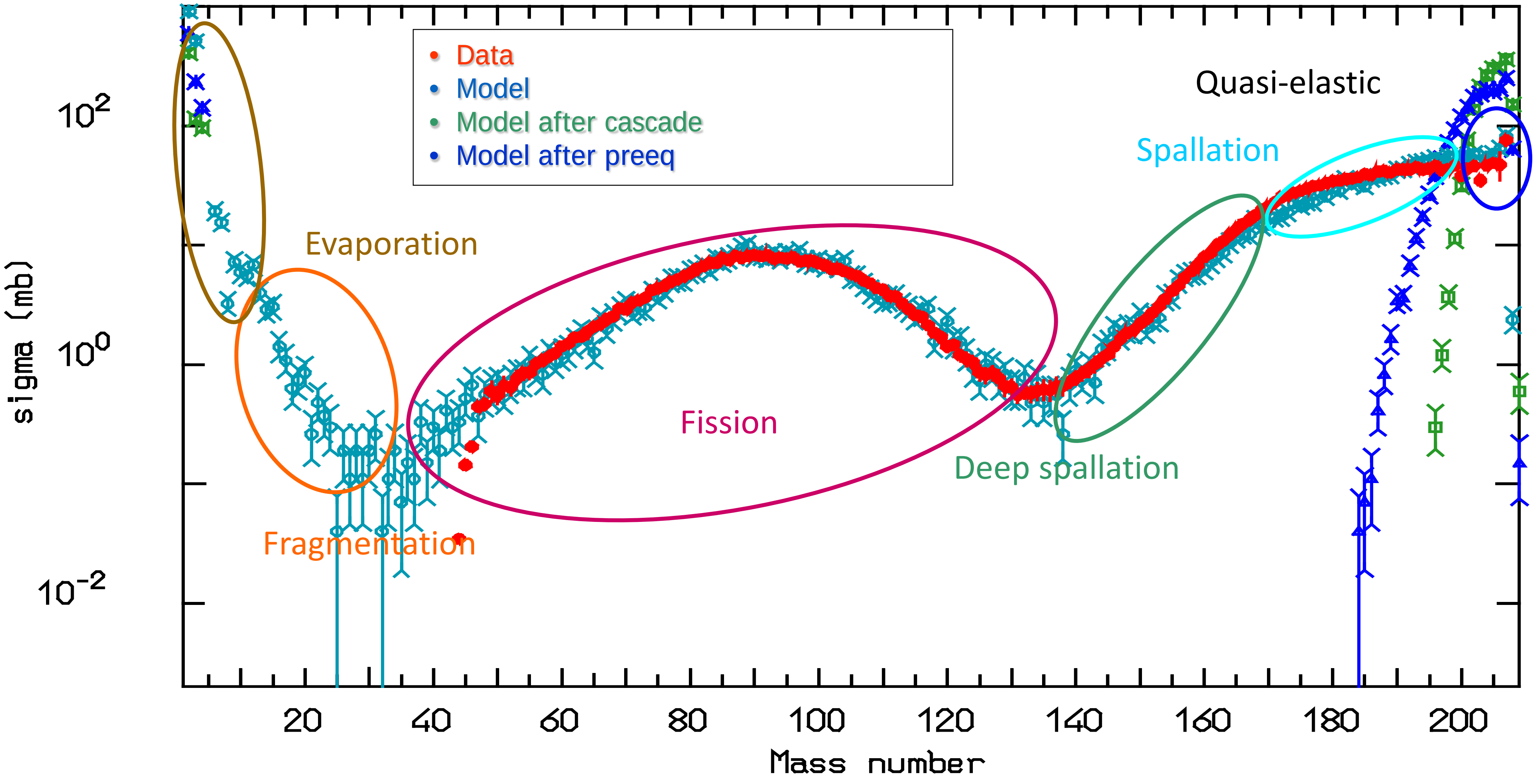
Residual Nuclei

- The production of residuals is the result of the last step of the nuclear reaction, thus it is influenced by all the previous stages
- Residual mass distributions can be very well reproduced
- Individual residuals near to the compound mass are usually well reproduced
- The production of specific isotopes may be influenced by additional problems which have little or no impact on the emitted particle spectra (Sensitive to details of evaporation, Nuclear structure effects, Lack of spin-parity dependent calculations in most MC models)



Example of fission/evaporation

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524

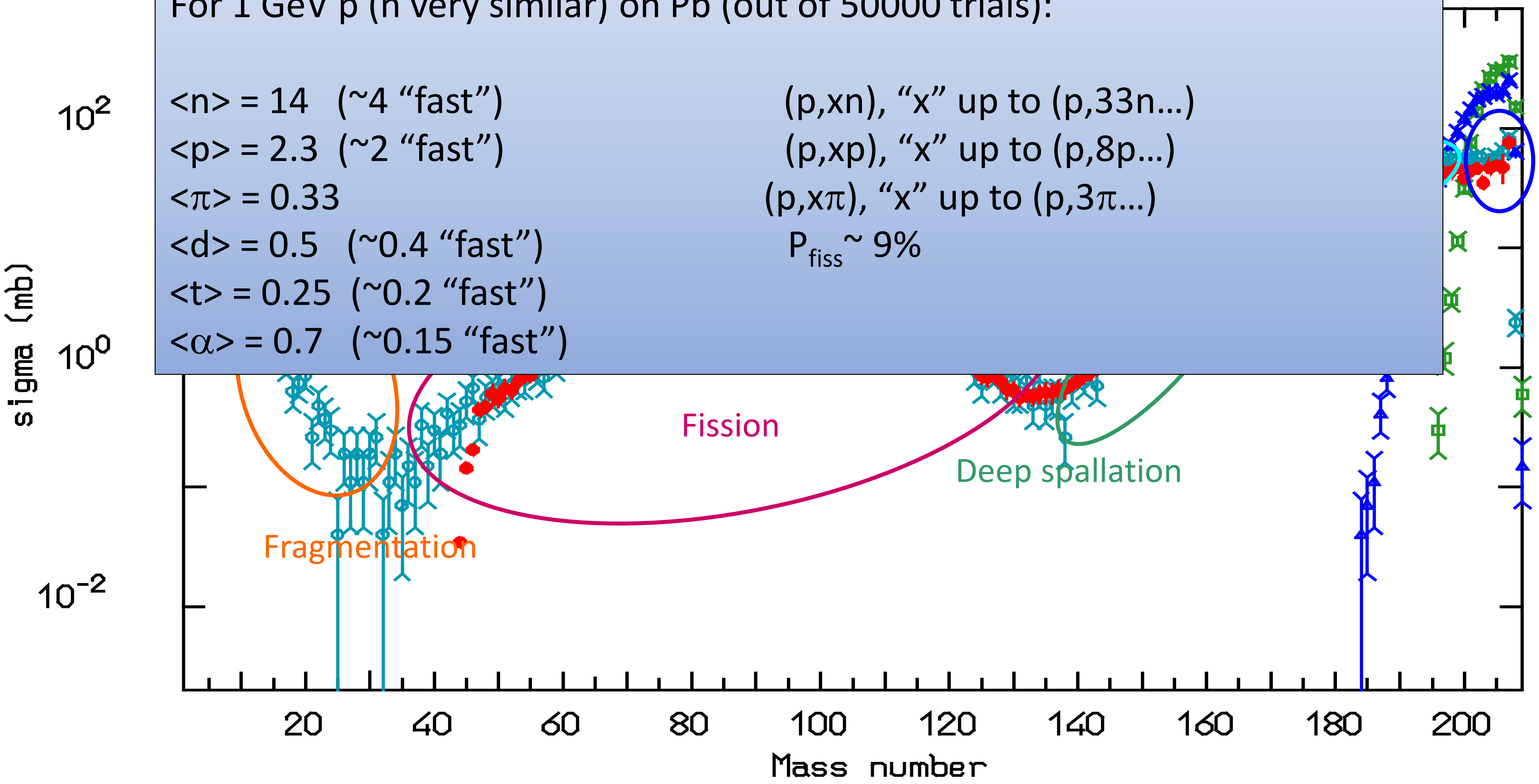


Example of fission/evaporation

1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524

For 1 GeV p (n very similar) on Pb (out of 50000 trials):

$\langle n \rangle = 14$ (~4 "fast")	(p,xn), "x" up to (p,33n…)
$\langle p \rangle = 2.3$ (~2 "fast")	(p,xp), "x" up to (p,8p…)
$\langle \pi \rangle = 0.33$	(p,xπ), "x" up to (p,3π…)
$\langle d \rangle = 0.5$ (~0.4 "fast")	P_{fiss} ~ 9%
$\langle t \rangle = 0.25$ (~0.2 "fast")	
$\langle \alpha \rangle = 0.7$ (~0.15 "fast")	



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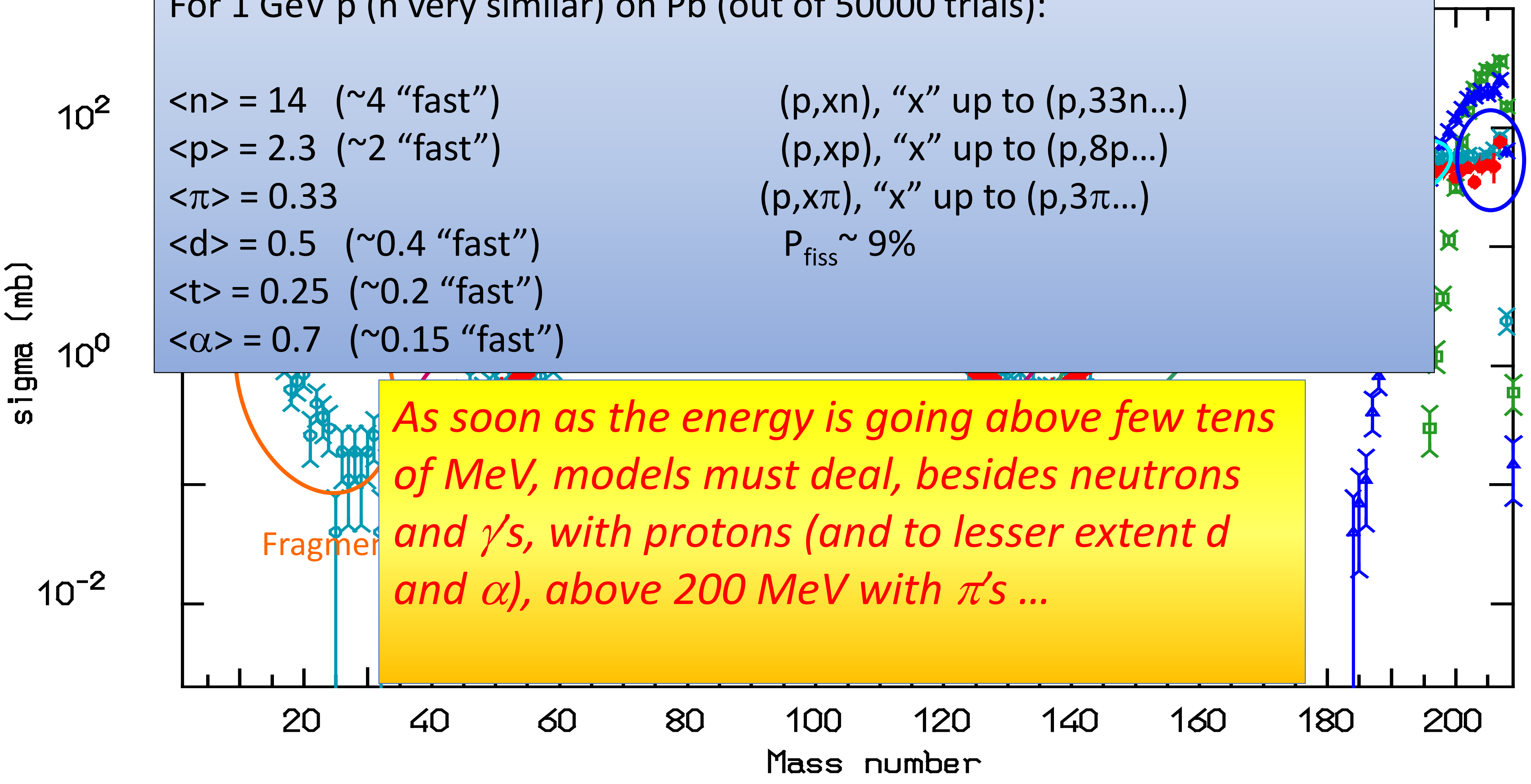
<p> = 2.3 (~2 “fast”) (p,xp), “x” up to (p,8p…)
<π> = 0.33 (p,xπ), “x” up to (p,3π…)
<d> = 0.5 (~0.4 “fast”) P_{fiss} ~ 9%
<t> = 0.25 (~0.2 “fast”)
<α> = 0.7 (~0.15 “fast”)

As soon as the energy is going above few tens of MeV, models must deal, besides neutrons and γ's, with protons (and to lesser extent d and α), above 200 MeV with π's …



Gamma De-excitation in Fluka

- At the end of evaporation : cascade of γ transitions
- At high excitation: assume continuous level density and statistical emission:

$$P(E_\gamma)dE_\gamma = \frac{\rho_f(U_f)}{\rho_i(U_i)} \sum_L f(E_\gamma, L)$$

L= multipole order
ρ=level density at excitation energy. U

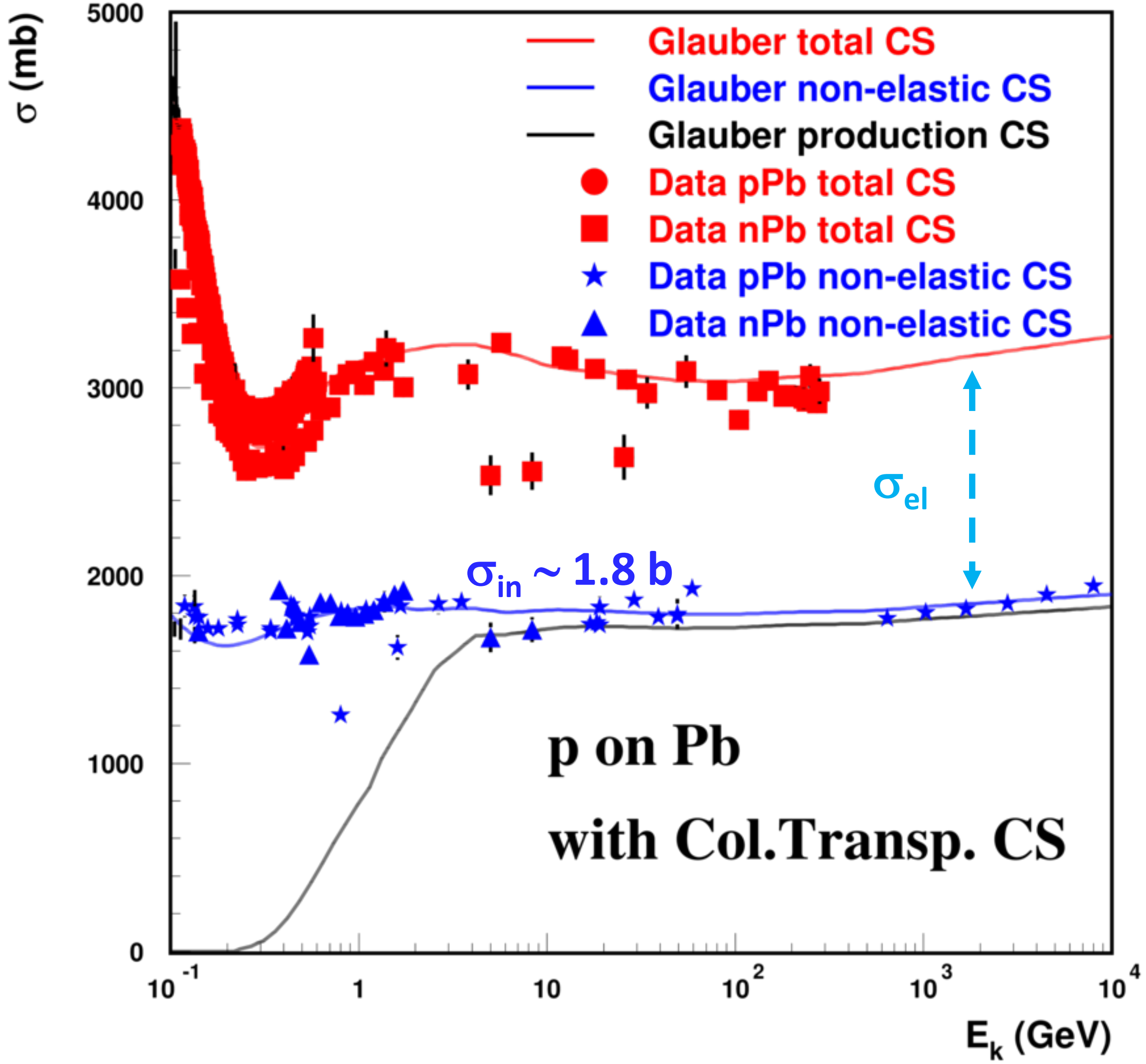
f = strength from single particle estimate (c)+ hindrance (F)

$$f(E_\gamma, L) = c_L F_L(A) E_\gamma^{(2L+1)}$$

- At low excitation: through discrete levels
  - database of known levels and transitions taken from RIPL-3 (IAEA)
- Rotational approximation outside tabulations

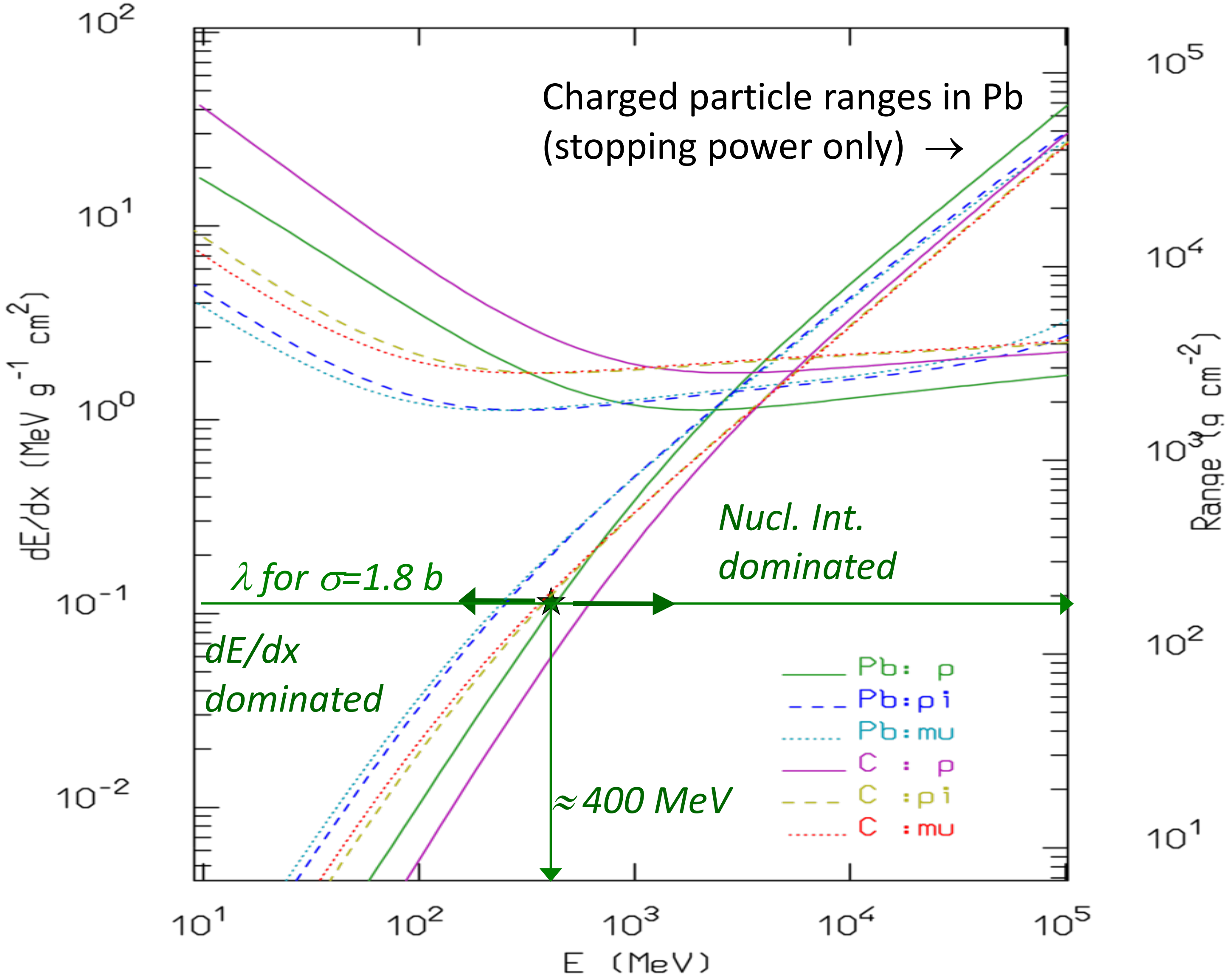
Examples of prompt photon predictions for therapy monitoring in the medical lectures, last day

Competition nuclear int. vs dE/dx: examples for protons:



Cross sections for proton interactions on Lead

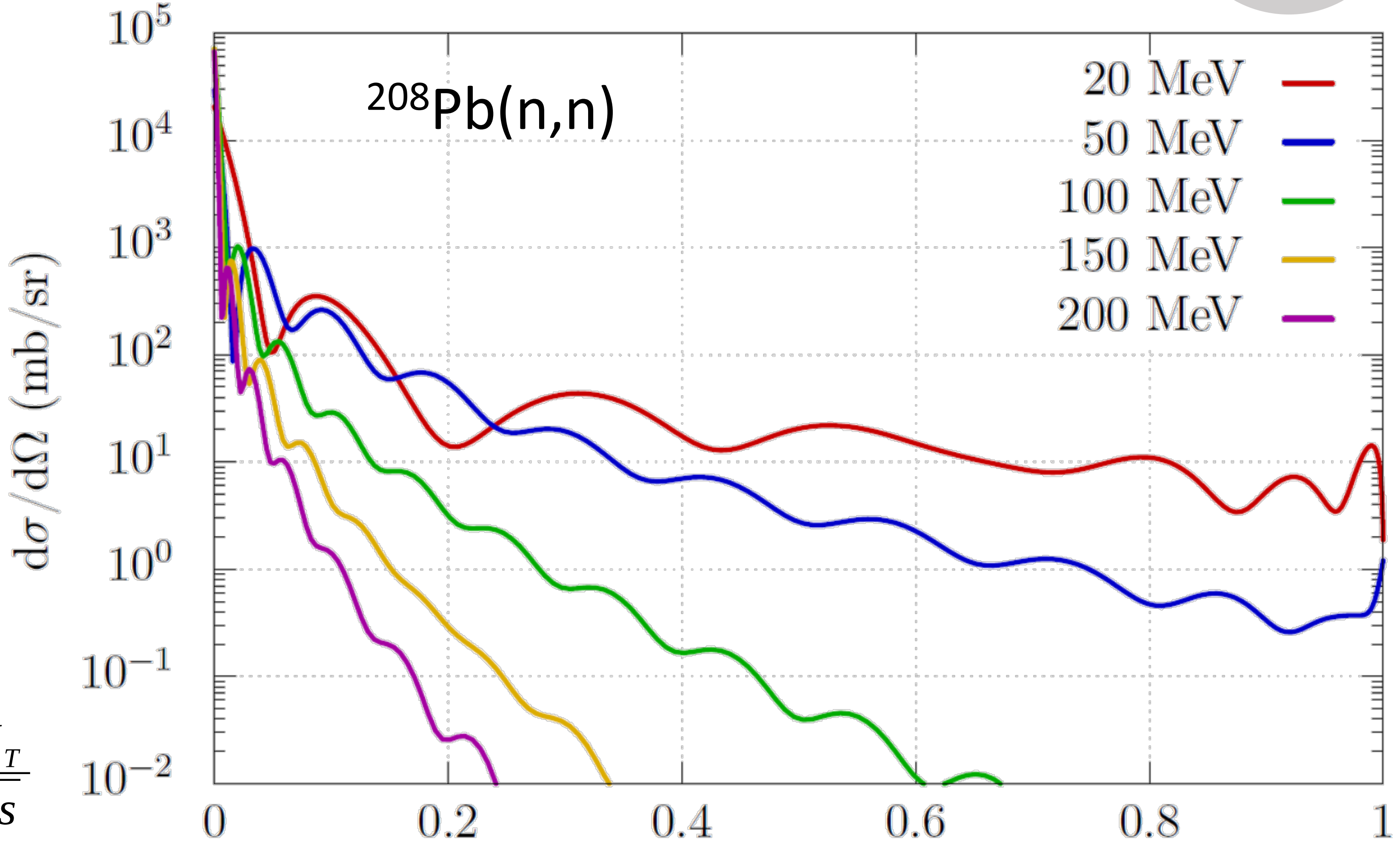
Competition nuclear int. vs dE/dx: examples for protons:



Around 400 MeV the proton mfp (λ) in Lead for nuclear inelastic interactions is becoming comparable to the range → at higher energies nuclear interactions dominate and protons behave very similar to neutrons of the same energy (apart the charge of course)

Elastic Nucleon-Nucleus:

Elastic scattering cross section for $n^{208}Pb$ at different incident kinetic energies, as a function of the cosine of the scattering angle in the centre of mass system



$$q^2 = -t = 2p^{*2}(1-\cos\vartheta^*)$$

$$s = (m_p + M_T)^2 + 2E_{k\,lab}M_T$$

$$p^* = p_{lab}\frac{M_T}{\sqrt{s}} = \sqrt{E_{k\,lab}(E_{k\,lab}+2m_p)}\frac{M_T}{\sqrt{s}}$$

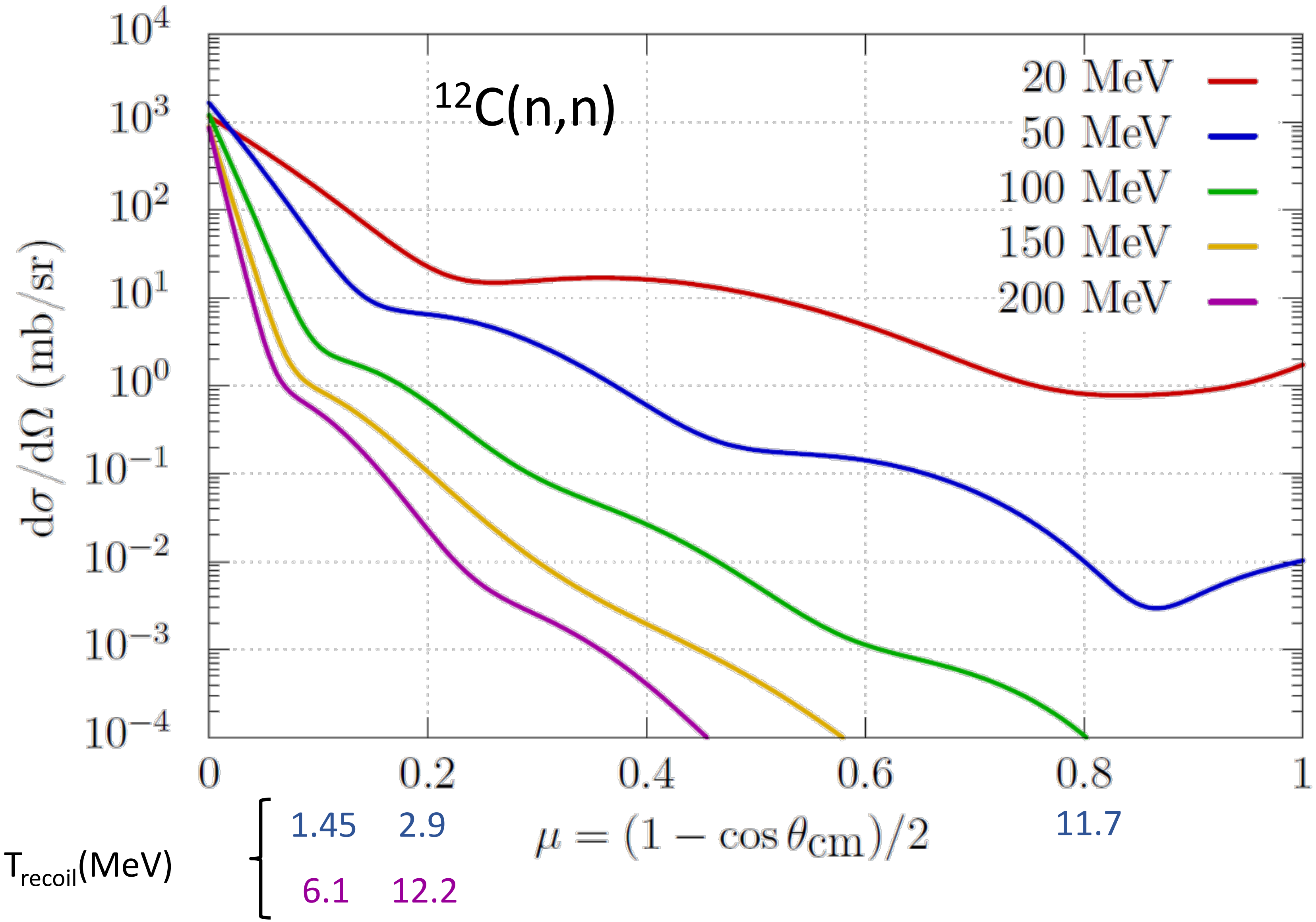
$$T_{recoil} = \frac{q^2}{2M_T} = \frac{2p^{*2}}{M_T}\frac{(1-\cos\vartheta^*)}{2}$$

T_{recoil}(keV) $\left\{ \begin{array}{l} 99 \qquad\qquad\qquad\qquad 789 \\ 424 \quad 828 \end{array} \right.$

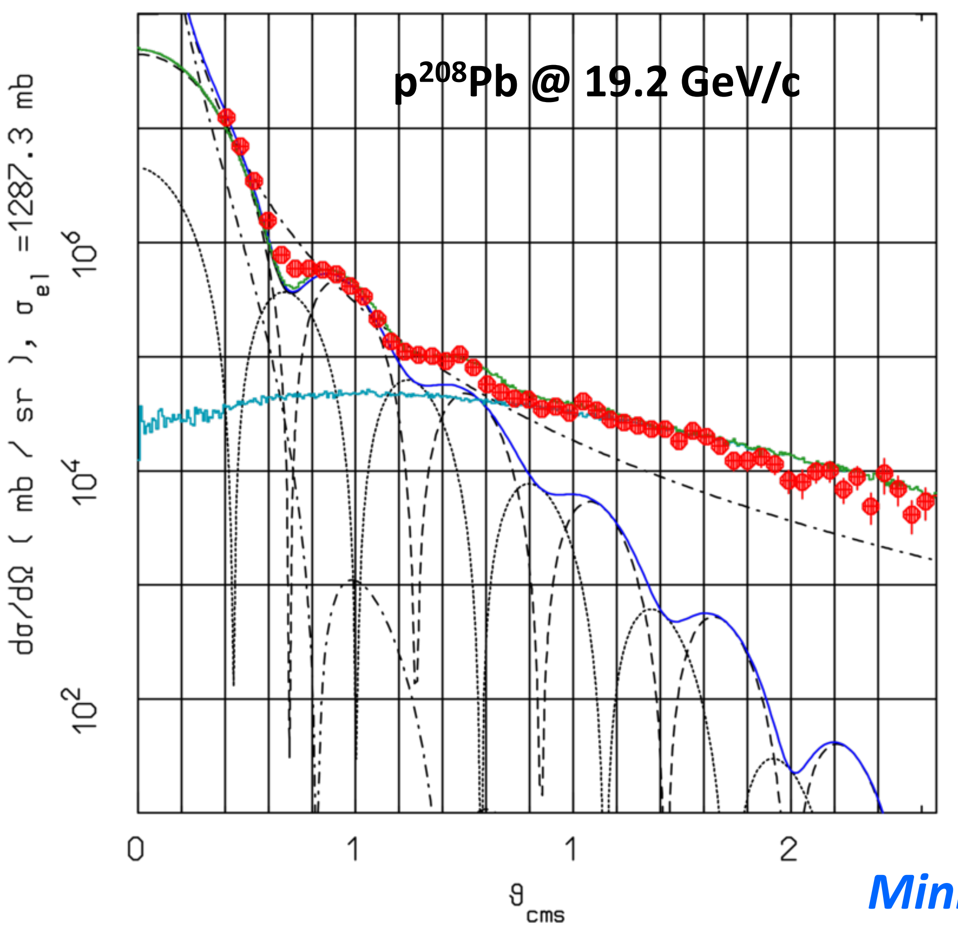
Elastic Nucleon-Nucleus:

Elastic scattering cross section for $n^{12}C$ at different incident kinetic energies, as a function of the cosine of the scattering angle in the centre of mass system

Elastic scattering is increasingly important when projectiles energies are lower than 100-200 MeV and for light material, particularly for neutrons!!



Hadron-nucleus elastic scattering: high energy

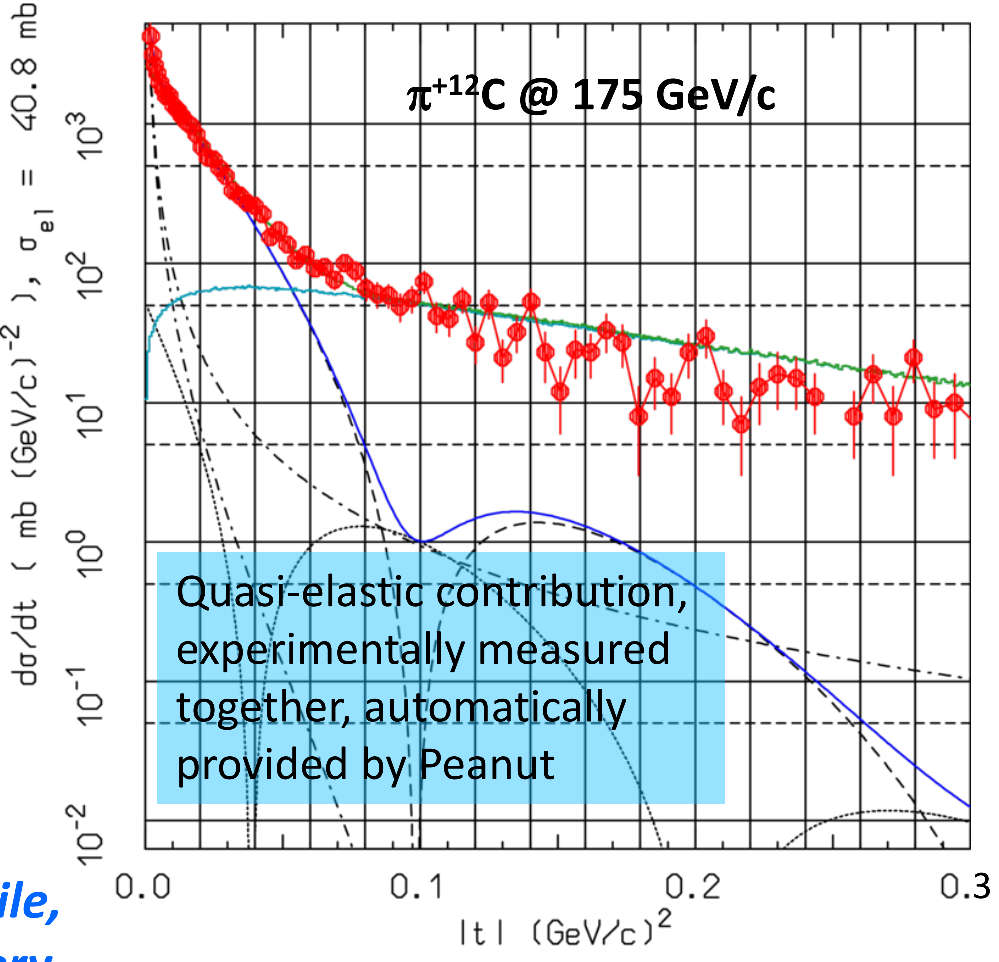


Green Fluka (w/o Coulomb)

Red: exp. Data (with Coulomb)

Light Blue Fluka qe

Blue Fluka Coh. Only (with Coulomb)



$|t| \sim p^2 \sin^2\theta$

Minimal effect on the projectile, small angle scattering and very small (fractional) energy loss

Real and Virtual Photonuclear Interactions

Photonuclear reactions *(**PHOTONUC** card, off by default)*

- ❑Giant Dipole Resonance interaction (special database)
- ❑Quasi-Deuteron effect
- ❑Delta Resonance energy region
- ❑Vector Meson Dominance in the high energy region
- ❑INC, preequilibrium and evaporation via the PEANUT model
- ❑Possibility to bias the photon nuclear inelastic interaction length to enhance interaction probability *(**LAM-BIAS** card, see manual)*

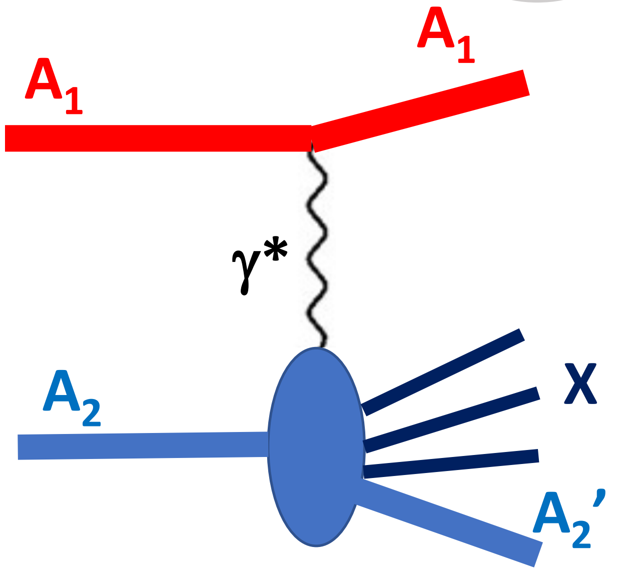
To be discussed in the EM lecture

Virtual photon reactions

- ❑Muon photonuclear interactions *(**MUPHOTON** card, on by default)*
- ❑Electro/positronuclear interactions *(**PHOTONUC** card with **SDUM=ELECTNUC**, off by default)*
- ❑Electromagnetic dissociation *(**PHYSICS** card with **SDUM=EM-DISSO**, off by default)* ← ***Only this topic today***

Electromagnetic dissociation

- Very peripheral collisions
- Break-up of one of the colliding nuclei in the electromagnetic field of the other nucleus




```
PHYSICS 2.                                                  EM-DISSO
```

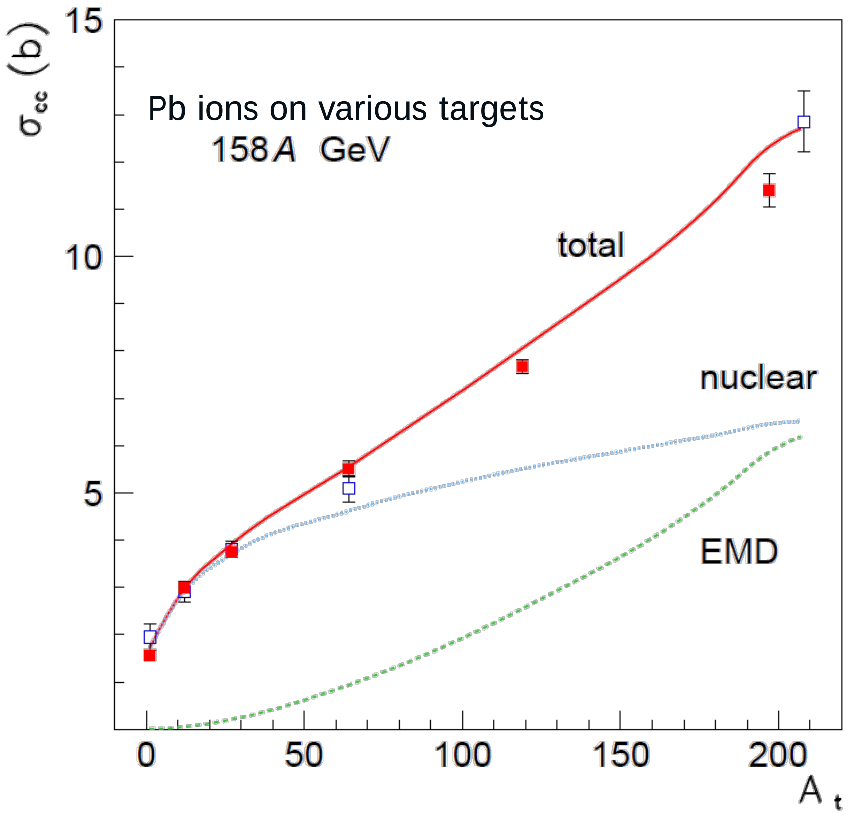
PHYSICS Type: EM-DISSO ▼ EM Disso: Proj&Target EM-Disso ▼

```
WHAT(1) : flag for activating ion electromagnetic-dissociation

        =< -1.0 : resets to default (no em-dissociation)
        =   0.0 : ignored
        =   1.0 : (default) no em-dissociation
        =   2.0 : projectile and target em-dissociation activated
        =   3.0 : projectile only em-dissociation activated
        =   4.0 : target only em-dissociation activated

WHAT(2)-WHAT(6): not used
```

… EMD examples:

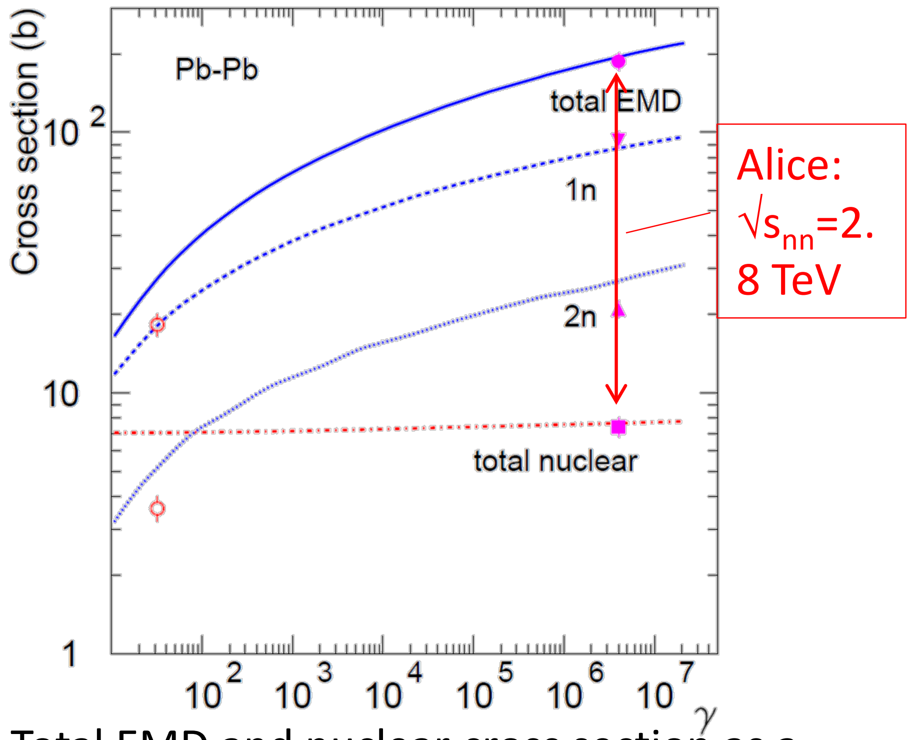
… **ElectroMagneticDissociation** produce a **variety** of (excited), possibly radioactive, **fragments**

Symbols: exp. Data
Lines: Fluka



Total charge changing cross section as a function of the target atomic mass

Pb-Pb collisions at LHC



Total EMD and nuclear cross section as a function of the effective γ factor

Summary of cards controlling hadron nuclear interactions

You cannot really control too much…

```
PHYSICS Flag                                    EVAPORAT
```

```
PHYSICS Flag                                    COALESCE
```

```
PHYSICS Flag                                    EM-DISSO
```

Thanks for your attention!