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Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

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Models in FLUKA

Alfredo Ferrari

CERN
Geneva
Switzerland

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Nuclear interaction models in the FLUKA code: details and applications

Alfredo.Ferrari@cern.ch
CERN, Geneva, Switzerland
for the FLUKA collaboration

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Outline:

- What is FLUKA *(short)*
  - History
  - Collaboration
  - Site/Download/info: **http://www.fluka.org**
- Hadronic Physics in FLUKA *(long)*
  - Hadron-Nucleon *(a little)*
  - Hadron-Nucleus
  - Nucleus-Nucleus *(if there is enough time)*
  - Real and Virtual Photonuclear interactions *(unlikely)*
  - Neutrino interactions *(nothing today)*
- Some examples of applications
  - Inventory evolution and residual dose rates
- Future Improvements *(sparse)*

Part I: FLUKA

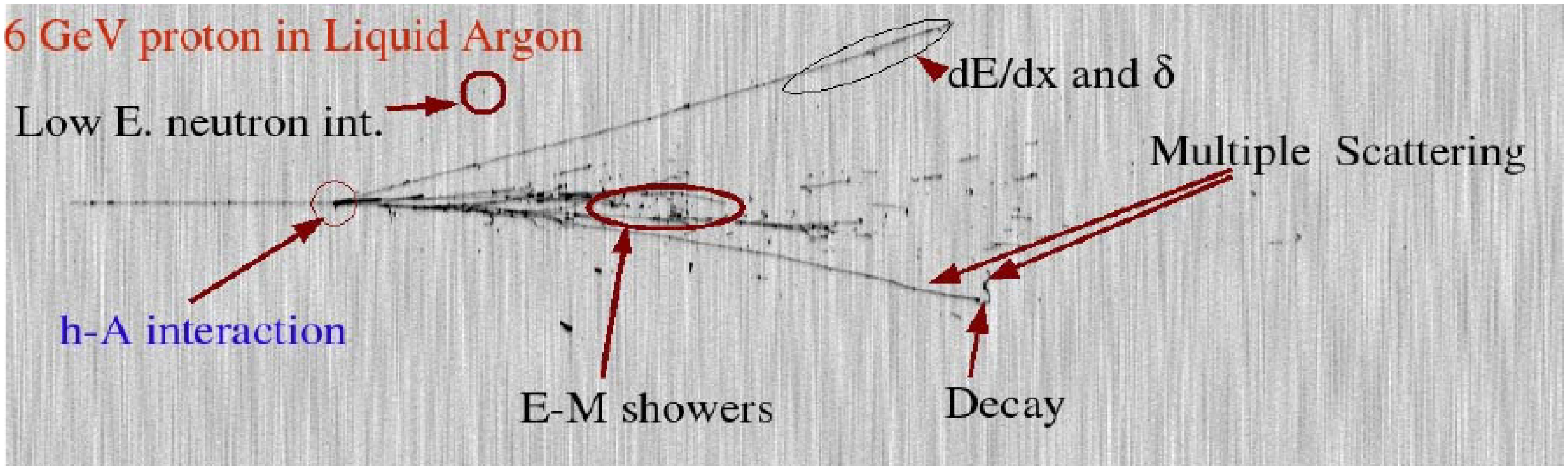
Authors: A. Fasso`[1], A. Ferrari[2], J. Ranft[3], P.R. Sala[4]

[1] SLAC Stanford, [2] CERN, [3] Siegen University, [4] INFN Milan

Contributing authors: G. Battistoni[4], F.Cerutti[2], T.Empl[7], M.Lantz[5], V.Patera[6], S.Roesler[2], V.Vlachoudis[2]

[5] Chalmers University, [6] University of Rome, [7]University of Houston

Interaction and Transport Monte Carlo code



Web site: http://www.fluka.org

The FLUKA collaboration

M.Brugger, F. Cerutti, A. Ferrari, M. Mauri, G. Lukasik, S. Roesler, L. Sarchiapone, G. Smirnov, F. Sommerer ,C. Theis, S. Trovati, H. Vinke, V.Vlachoudis
CERN

A. Fassò
SLAC, USA

J. Ranft
Univ. of Siegen, Germany

G. Battistoni, F. Broggi, M. Campanella, P. Colleoni, E. Gadioli, S. Muraro, P.R. Sala
INFN & Univ. Milano, Italy

M. Carboni, C. D'Ambrosio, A. Ferrari, A. Mostacci, V. Patera, M. Pelliccioni, R. Villari
INFN Frascati

M.C. Morone
Univ. Roma II, Italy

A. Margiotta, M. Sioli
INFN & Univ. Bologna, Italy

A. Mairani, K. Parodi
DKFZ & HIT, Heidelberg, Germany

A. Empl, L. Pinsky
Univ. of Houston, USA

K.T. Lee, T. Wilson, N. Zapp
NASA-Houston, USA

S. Rollet
ARC Seibersdorf Research, Austria

M. Lantz
Chalmers Univ. of Technology, Sweden

Fluka History:

The early days

The beginning:

1962: Johannes Ranft (Leipzig) and Hans Geibel (CERN): Monte Carlo for high-energy proton beams

The name:

1970: study of event-by-event fluctuations in a NaI calorimeter (FLUktuierende KAskade)

Early 70's to ≈1987: J. Ranft and coworkers (Leipzig University) with contributions from Helsinki University of Technology (J. Routti, P. Aarnio) and CERN (G.R. Stevenson, A. Fassò)

Link with EGS4 in 1986, later abandoned

The modern code: some dates

Since 1989: mostly INFN Milan and later CERN (A. Ferrari, P.R. Sala): little or no remnants of older versions. Link with the past: J. Ranft and A. Fassò

1990: LAHET / MCNPX: high-energy hadronic FLUKA generator *No further update*

1993: G-FLUKA (the FLUKA hadronic package in GEANT3). *No further update*

1998: FLUGG, interface to GEANT4 geometry

2000: grant from NASA to develop heavy ion interactions and transport

2001: the INFN FLUKA Project

2003: official CERN-INFN collaboration to develop, maintain and distribute FLUKA

2005: release of the source code and definition of the FLUKA license

Present version: Fluka2006.3b.10

FLUKA Description

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications: from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc.
- ≈70 different particles + Heavy Ions
  - ⇨ Hadron-hadron and hadron-nucleus interaction "0"-10000 TeV
  - Electromagnetic and μ interactions 1 keV – 10000 TeV
  - ⇨ Nucleus-nucleus interaction up to 10000 TeV/n
  - Charged particle transport and energy loss
  - Neutron multi-group transport and interactions 0-20 MeV
  - ν interactions
  - Transport in magnetic field
  - ⇨ Combinatorial (boolean) and Voxel geometries
  - Double capability to run either fully analogue and/or biased calculations
  - ⇨ On-line evolution of induced radioactivity and dose
  - User-friendly GUI interface thanks to the Flair interface

Full mixed field capability

- Maintained and developed under CERN-INFN agreement and copyright 1989-2008
- More than ***2000*** users all over the world

http://www.fluka.org

Fluka Applications (CERN, INFN, SLAC, NASA, PSI, GSI, HIT, …)

- Cosmic ray physics
- Neutrino physics
- Accelerator design (→ n_ToF, CNGS, LHC systems)
- Particle physics: calorimetry, tracking and detector simulation etc. (→ ALICE, ICARUS, ...)
- Shielding design
- Dosimetry and radioprotection
- Space radiation
- Hadrontherapy
- Neutronics
- ADS systems, waste transmutation, (→"Energy amplifier", FEAT, TARC,…)

FLUKA is NOT a toolkit or a collection of models! Its physical models are fully integrated

The user is presented with what is felt the best approach by the developers

The FLUKA hadronic Models

Hadron-nucleus: PEANUT

Elastic,exchange
Phase shifts
data, eikonal

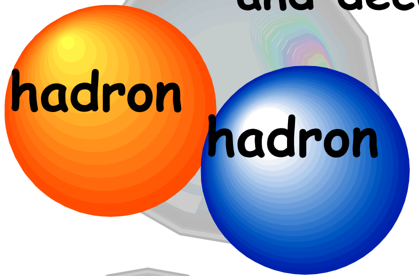
P<3-5GeV/c
Resonance prod
and decay

Sophisticated
G-Intranuclear
Cascade

Gradual onset of
Glauber-Gribov multiple
interactions

Preequilibrium

Coalescence

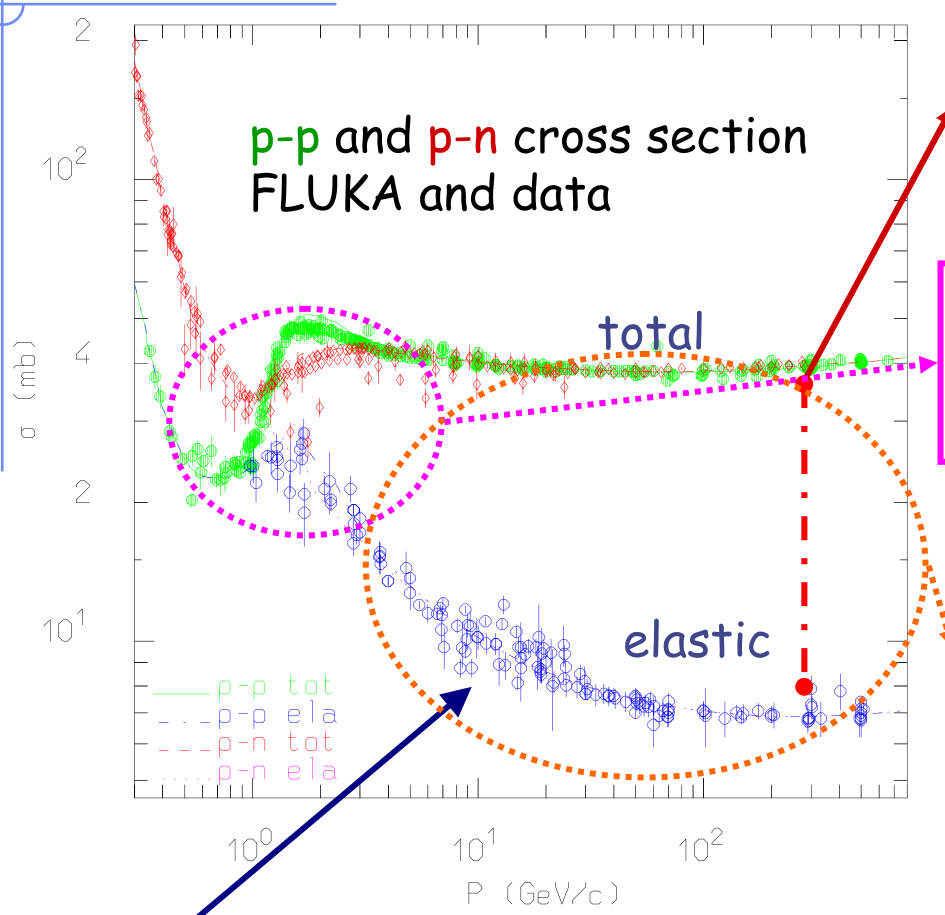


low E
π,K
Special

High Energy
DPM
hadronization

Evaporation/Fission/Fermi break-up
γ deexcitation

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/c

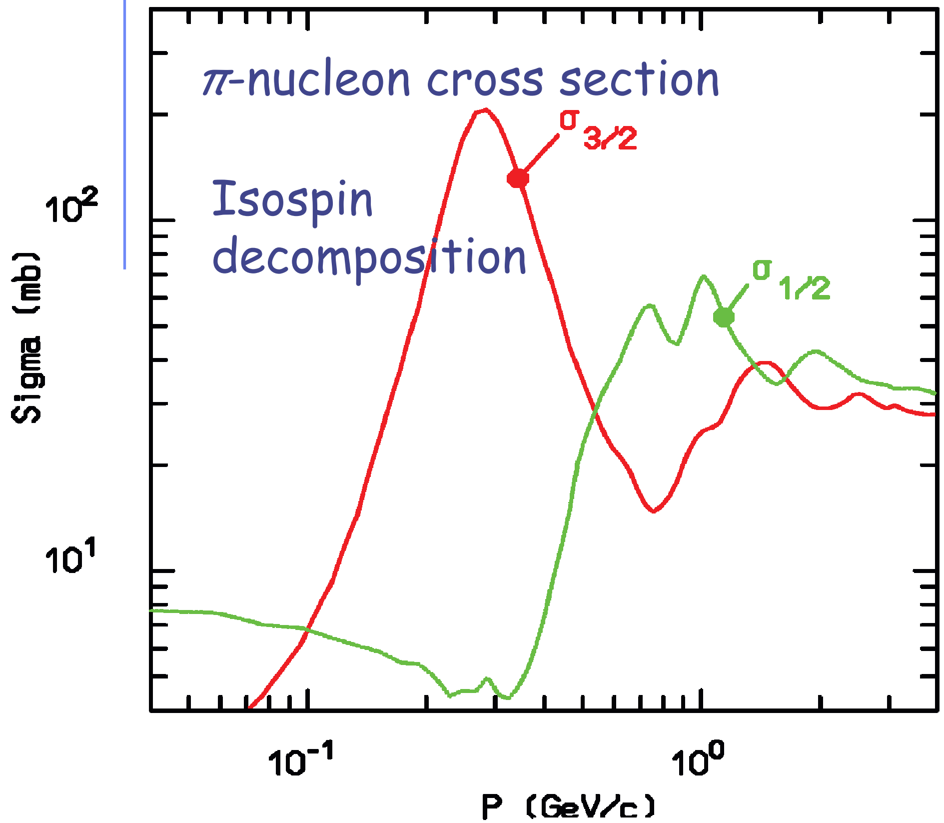
Those based on quark/parton string models, which provide reliable results up to several tens of TeV

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

Nonelastic hN interactions at intermediate energies

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

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

$$N_1 + N_2 \rightarrow N''_1 + \Delta(1232) \rightarrow N'_1 + N'_2 + \pi$$
$$\pi + N \rightarrow \Delta(1600) \rightarrow \pi' + \Delta(1232) \rightarrow \pi' + \pi'' + N'$$
$$N_1 + N_2 \rightarrow \Delta_1(1232) + \Delta_2(1232) \rightarrow N'_1 + \pi_1 + N'_2 + \pi_2$$

Hadron-Nucleon resonance production

Summarizing, all reactions are thought to proceed through channels like:

$$h + N \rightarrow X \rightarrow x_1 + \dots + x_n \rightarrow \dots$$

$$h + N \rightarrow X + Y \rightarrow x_1 + \dots x_n + y_1 + \dots y_m \rightarrow \dots$$

where X and Y can be real resonances or stable particles (π, n, p, K) directly

Resonances can be treated as real particles: they can be transported and then transformed into secondaries according to their lifetime and decay branching ratios

Reactions of 1st kind: s-channel reactions direct resonance production → ***bumps*** in the isospin cross section around a centre-of-mass energy $\sqrt{s} = M_X$

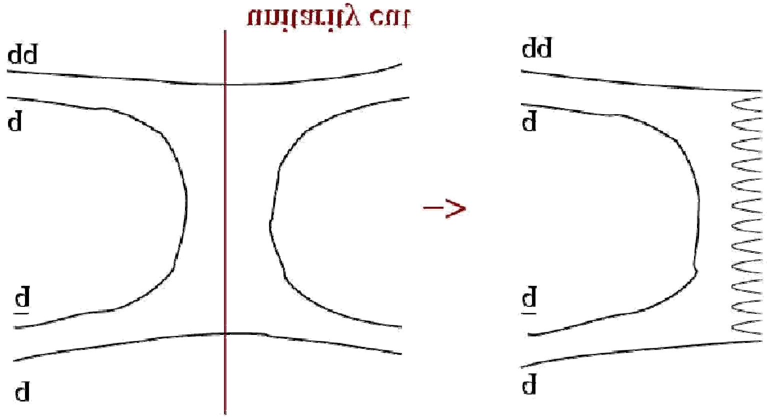
2nd kind: the extra degree of freedom associated to the X, Y relative motion → ***NO resonant behaviour,*** rather a relatively fast increase from $\sqrt{s} \approx M_X + M_Y$ followed by a smooth behaviour

N N reactions are all of type 2, while π N reactions can be of both types

FLUKA: ≈ 60 resonances, and ≈ 100 channels in describing p,n,π,pbar,nbar and K induced reactions up to 3-5 GeV/c

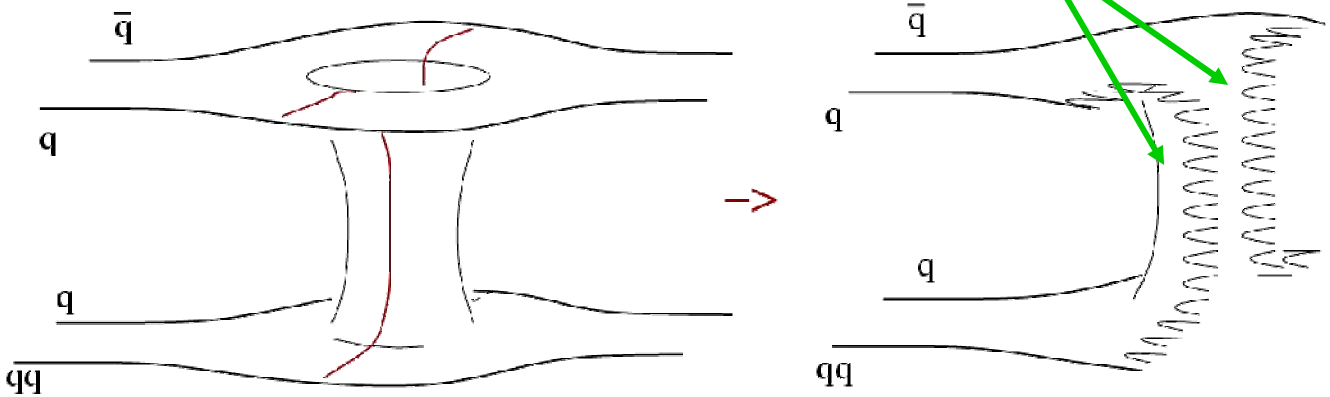
Inelastic hN at high energies (DPM):

Parton and color concepts, Topological expansion of QCD, Duality



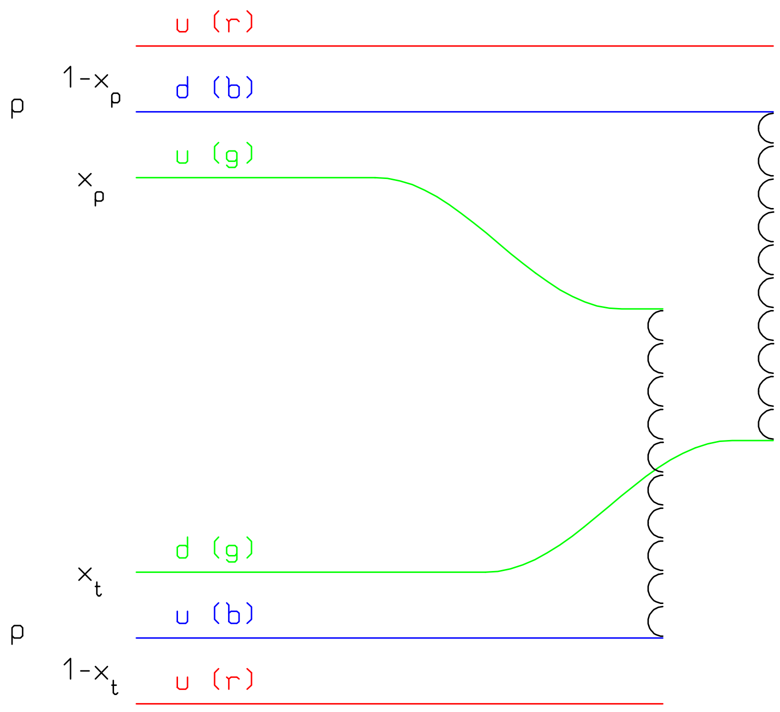
Reggeon exchange

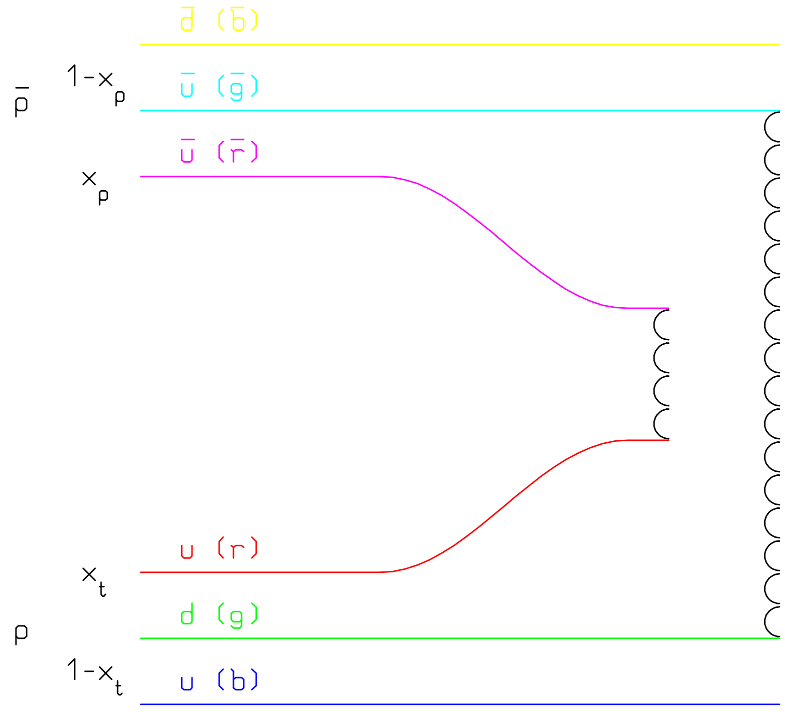
color strings to be "hadronized"



Pomeron exchange

Hadron-hadron collisions: chain examples

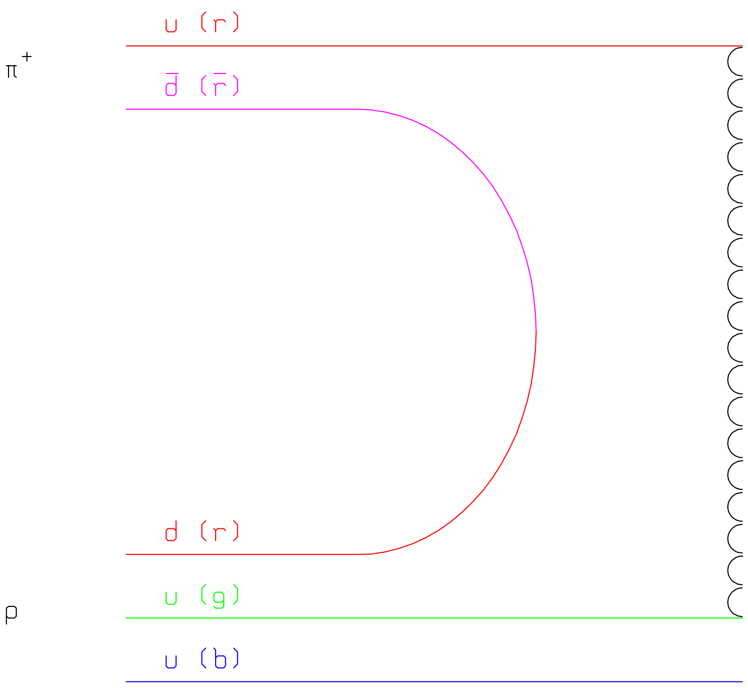


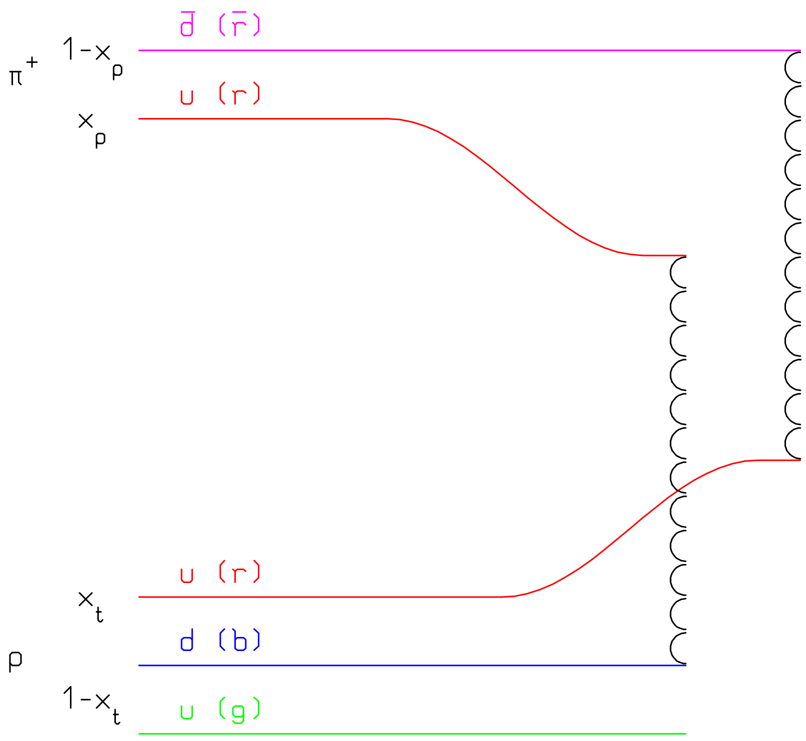


Leading two-chain diagram in DPM for p-p scattering. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities

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

Hadron-hadron collisions: chain examples



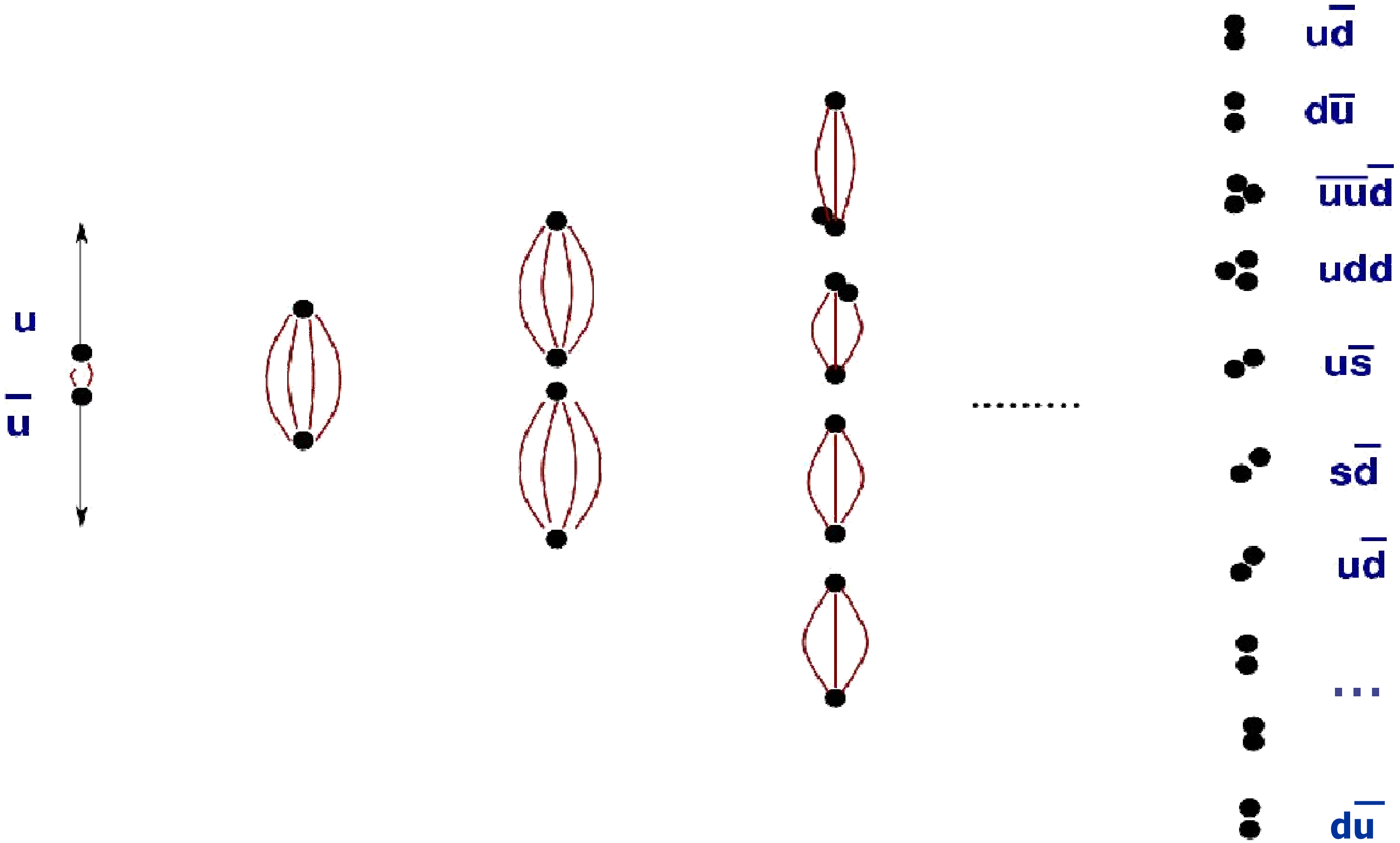


Single chain (s-channel) diagram
Leading two-chain diagram in DPM for π^+-p scattering. The color (red, antired, blue, and green) and quark combination shown
in the figure is just one of the allowed possibilities

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

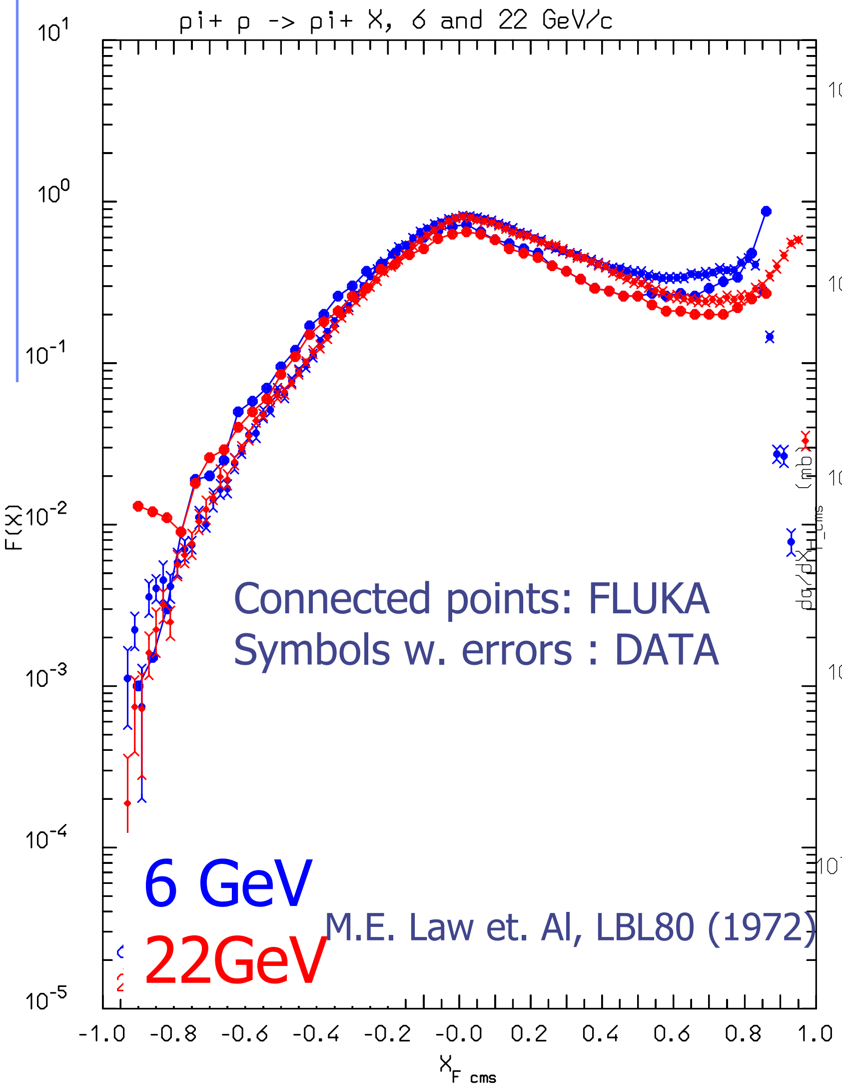
The "hadronization" of color strings

An example:

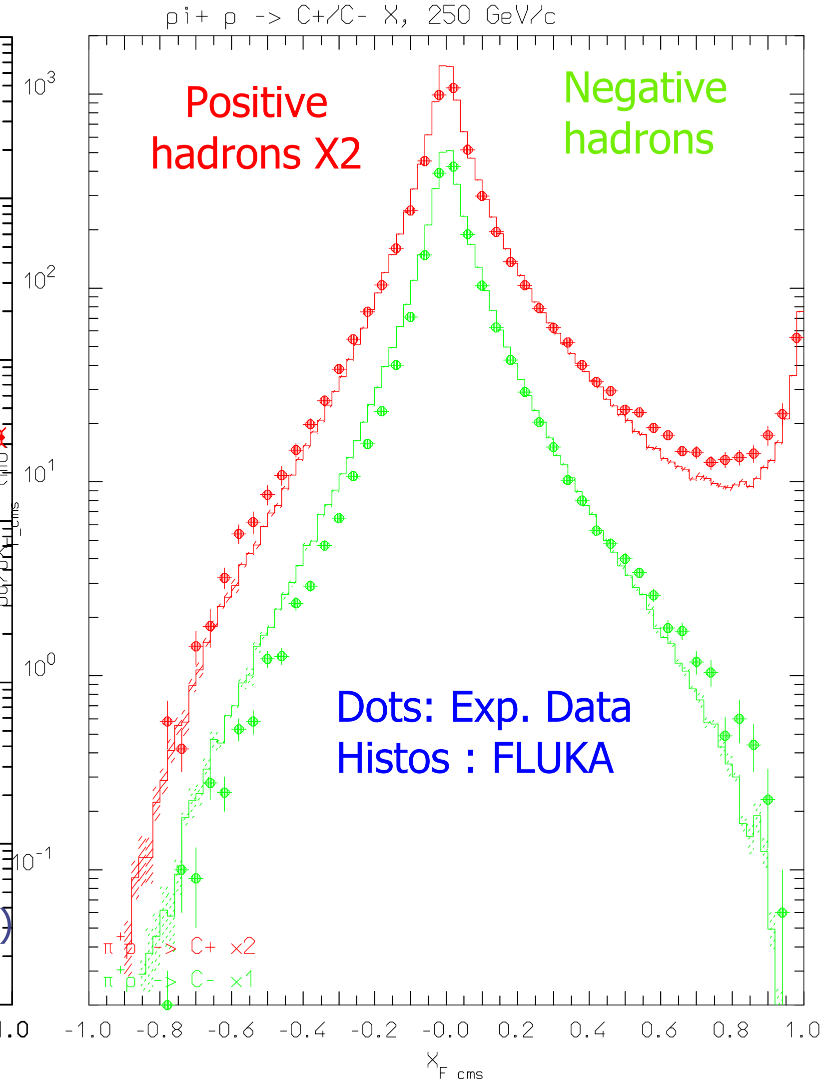


Inelastic hN interactions: examples

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



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



MC modeling of nuclear interactions:

Target nucleus description (density, Fermi motion, etc)

⇩

Glauber-Gribov cascade with formation zone

⇩

(Generalized) IntraNuclear cascade

⇩

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

⇩

Evaporation/Fragmentation/Fission model

⇩

γ deexcitation

t (s)

10^{-23}

10^{-22}

10^{-20}

10^{-16}

PEANUT:

PreEquilibrium Approach to NUclear Thermalization

- PEANUT handles hadron-nucleus interactions from threshold (or 20 MeV neutrons) up to several tens of TeV
- Sophisticated (?) Generalized IntraNuclear Cascade → GINC

⇓

Smooth transition (all non-nucleons emitted/decayed + all secondaries below 30-50 MeV)

⇓

Prequilibrium stage

⇓

Standard Assumption on exciton number or excitation energy

⇓

Common FLUKA Evaporation/Fission models

Nucleon Fermi Motion

Fermi gas model: Nucleons = Non-interacting Constrained Fermions

Momentum distribution: $\propto \frac{dN}{dk} = \frac{|k|^2}{2\pi^2}$

for *k* up to a (local) Fermi momentum $k_F(r)$ given by

$$k_F(r) = \left[3\pi^2 \rho_N(r)\right]^{\frac{1}{3}}$$

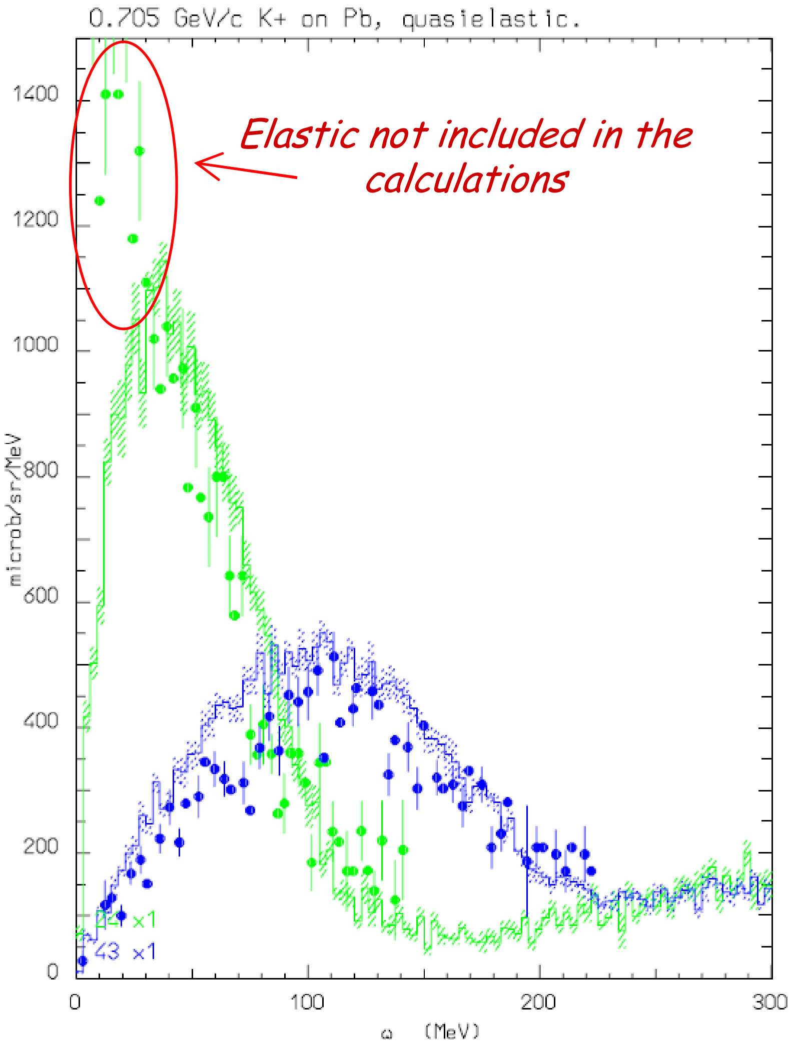
The Fermi energy ($k_F \approx 1.36$ fm, $P_F \approx 260$ MeV/c, $E_F \approx 35$ MeV, at nuclear max. density) is customarily used in building a self-consistent Nuclear Potential

⇓

Depth of the potential well (at the Fermi level) ≡ Fermi Energy (different p/n) + Nuclear Binding Energy (+ Coulomb)

In PEANUT velocity dependence and uncertainty related large momentum tails are added on top of this description

Positive kaons as a probe of Fermi motion



$K^+ \quad K^0$

No low mass S=1 baryons $\longrightarrow$ weak K^+N interaction

only elastic and ch. exch. up to ≈ 800 MeV/c

$(K^+, K^{+\prime})$ on Pb vs residual excitation, 705 MeV/c, at 24° and 43°. Histo: FLUKA, dots: data (Phys Rev. C51, 669 (1995))

On free nucleon: recoil energy : 43 MeV at 24° , 117 MeV at 43°.

(Generalized) IntraNuclear Cascade

- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear well according to the Fermi gas model (with possible extensions)
- Interaction probability
  $\sigma_{free}(\sqrt{s})$ + 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
- Interactions are incoherent and uncorrelated (apart Glauber,π,.)
- Interactions in projectile-target nucleon CMS $\rightarrow$ Lorentz boosts
- Multibody absorption for π, μ^-, K^-
- Quantum effects (Pauli, formation zone, correlations…)
- Exact conservation of energy, momenta and all addititive quantum numbers, including nuclear recoil

Advantages and Limitations of (G)INC

Advantages

- One of few models available for energies above the pion threshold production (others relativistic QMD, BUU models)
- One of few models for projectiles other than nucleons
- Easily available for on-line integration into transport codes
- Every target-projectile combination without any extra information
- Particle-to-particle correlations preserved
- Valid on light and on heavy nuclei
- Capability of computing cross sections, even when they are unknown

Limitations

- Low projectile energies E<200MeV are badly described *(partially solved in GINC+preequilibrium)*
- Quasi electric peaks above 100MeV are usually too sharp *(Glauber ???)*
- Coherent effect as well as direct transitions to discrete states are not included
- Nuclear medium effects, which can alter interaction properties are not taken into account *(partially solved in GINC)*
- Multibody processes (i.e. interaction on nucleon clusters) are not included *(solved in GINC)*
- Composite particle emissions (d,t,^{3}He,α) cannot be easily accommodated into INC, but for the evaporation stage *(solved in GINC through coalescence)*
- Backward angle emission poorly described *(solved in GINC)*

Generalized IntraNuclear Cascade: the PEANUT model

Some assets of the full GINC as implemented in FLUKA (PEANUT):

- Nucleus divided into 16 radial zones of different density, plus 6 outside the nucleus to account for nuclear potential, plus 10 for charged particles
- Different nuclear densities (and Fermi energies) for neutrons and protons (shell model ones for $A \leq 16$)
- Nuclear (complex) optical potential $\rightarrow$ curved trajectories in the mean nuclear+Coulomb field (reflection, refraction)
- Updating binding energy (from mass tables) after each particle emission
- Multibody absorption for $\pi^{+/0/-}$ $K^{-/0}$, μ^-
- Exact energy-momentum conservation including the recoil of the residual nucleus and experimental binding energies
- Nucleon Fermi motion including wave packet-like uncertainty smearing, (approximate) nucleon-nucleon, and $r \leftrightarrow E_f(r)$ correlations
- Quantum effects (mostly suppressive): Pauli blocking, Formation zone, Nucleon antisymmetrization, Nucleon-nucleon hard-core correlations, Coherence length

Nuclear depletion

Extension of PEANUT

- Peanut has proven to be a precise and reliable tool for intermediate energy hadron-nucleus reactions
- Its “nuclear environment” is also used in the modelization of (real and virtual) **photonuclear** reactions, **neutrino** interactions, **nucleon decays**, **muon captures**..

In 2005 it has been extended it to cover all the energy range, and substitute the (old) high energy h-A generator with the following advantages:

- Sophisticated (G)INC ⇒ better nuclear physics, particularly for residual production
- Smooth transition from intermediate to high energies
- Preequilibrium stage
- Explicit formation zone
- Possibility to account explicitly for QuasiElastic

The two main ingredients added:

1. The treatment of Glauber multiple scattering
2. A continuous and self consistent approach to the Quasi-Elastic reaction component

The Transition

High energy: the Glauber regime (E>≈10 GeV)

- The first interaction involves **many** target nucleons coherently
- Quasi-Elastic* cross section separated from non-elastic σ (experimentally is added to elastic)
- QE is suppressed since h-N inelastic is "integrated" over the projectile path in the nucleus
- Mass effects, energy losses, are small

Low energy: the "single collision" regime (E<≈5GeV)

- The first interaction involves **one** target nucleon (exc. pions)
- Quasi-Elastic is considered as a contribution to non-elastic
- QE fraction comes from single nucleon cross section ratio
- Mass effects and energy losses are essential

* Q.E=elastic interaction at the hadron-nucleon level

Problems:

Physics issues:

- Transition from ordinary to Glauber cascade
- Consistent approach for Quasi-elastic interactions in the Glauber regime
- Self-Consistent approach for inelastic screening in the Glauber calculus
- Onset of the formation zone (independent of Glauber, but somewhat related)

Practical issue:

✓ Experimental non-elastic cross sections at intermediate and high energies: what do they really measure?

Glauber Cascade *(essential at high energy)*

Quantum mechanical method to compute all relevant hadron-nucleus cross sections from hadron-nucleon scattering:

$$S_{hN}(\vec{b},s) = e^{i\chi_{hN}(\vec{b},s)} = \eta_{hN}(\vec{b},s)e^{2i\delta_{hN}(\vec{b},s)}$$

and nuclear ground state wave function Ψ_i

Total

$$\sigma_{hA\,T}(s) = 2\int d^2\vec{b}\int d^3\vec{u}\left|\Psi_i\left(\vec{u}\right)\right|^2\left[1-\prod_{j=1}^{A}\mathrm{Re}\,S_{hN}\left(\vec{b}-\vec{r}_{j\perp},s\right)\right]$$

Elastic

$$\sigma_{hA\,el}(s) = \int d^2\vec{b}\left|\int d^3\vec{u}\left|\Psi_i\left(\vec{u}\right)\right|^2\left[1-\prod_{j=1}^{A}S_{hN}\left(\vec{b}-\vec{r}_{j\perp},s\right)\right]\right|^2$$

Hint to INC limit??

Scattering

$$\sigma_{hA\,\Sigma f}(s) \equiv \sum_f \sigma_{hA\,fi}(s) = \int d^2\vec{b}\int d^3\vec{u}\left|\Psi_i\left(\vec{u}\right)\right|^2\left|\left[1-\prod_{j=1}^{A}S_{hN}\left(\vec{b}-\vec{r}_{j\perp},s\right)\right]\right|^2$$

Absorption (particle prod.)

Absorption probability over a given *b* and nucleon configuration

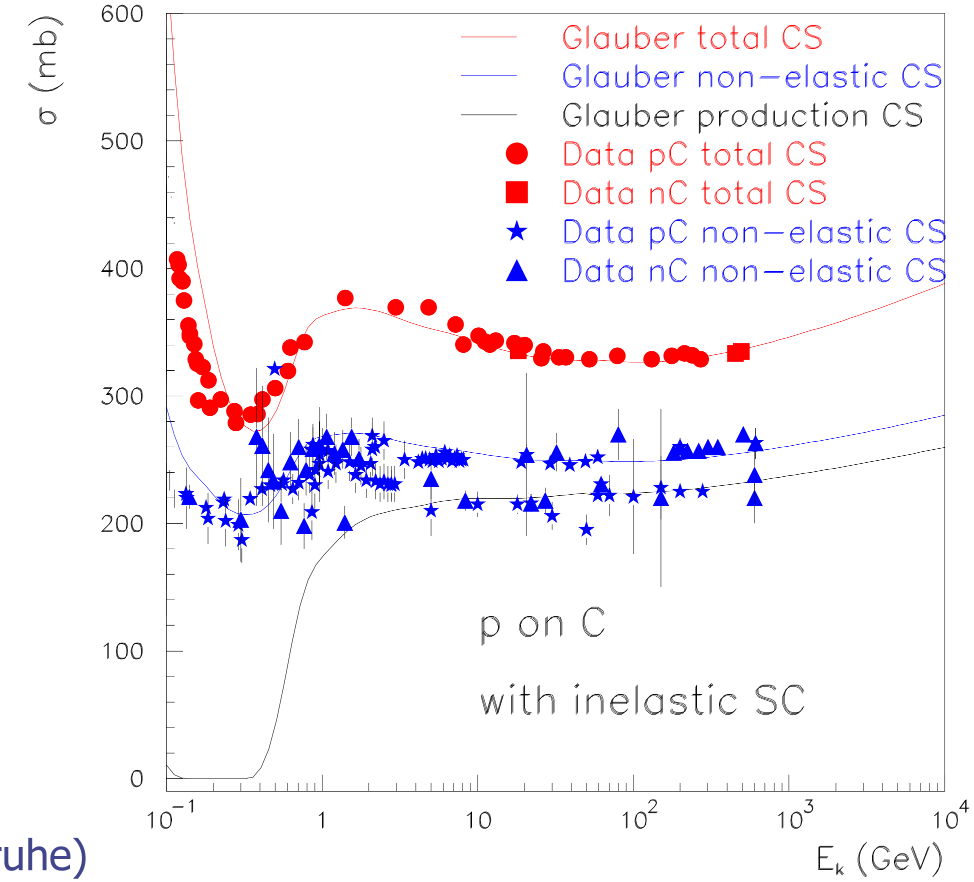
$$\sigma_{hA\,abs}(s) \equiv \sigma_{hA\,T}(s) - \sigma_{hA\,\Sigma f}(s)$$

$$= \int d^2\vec{b}\int d^3\vec{u}\left|\Psi_i\left(\vec{u}\right)\right|^2\left\{1-\left\{\prod_{j=1}^{A}1-\left[1-\left|S_{hN}\left(\vec{b}-\vec{r}_{j\perp},s\right)\right|^2\right]\right\}\right\}$$

Glauber cross section calculations

Self-consistent calculation* including "a priori" inelastic screening through the substitution where λ is the ratio of the single diffractive amplitude, 1 side only, over the elastic amplitude

$$\Gamma\left(s,\vec{b}\right) \rightarrow \hat{\Gamma}_{hN}\left(s,\vec{b}\right) = \begin{bmatrix} 1 & \lambda \\ \lambda & 1 \end{bmatrix} \Gamma_{hN}\left(s,\vec{b}\right)$$



* Ralph Engel, (Forschungszentrum Karlsruhe)

Proton Carbon cross sections with inelastic screening accounted for

Please note the ambiguity of the non-elastic exp. results, almost 2-population like

Glauber: continued

$\sigma_{hA\,abs}$ can be interpreted in terms of multiple collisions of the projectile:

From the impact parameter representation of the hadron-nucleon reaction cross section

$$\sigma_{hN\,r}(s) = \int d^2\vec{b}\left[1 - \left|S_{hN}\left(\vec{b}, s\right)\right|^2\right]$$

and with $P_{rj}(b) \equiv \sigma_{hNr} T_{rj}(b)$ = probability to have an inelastic reaction on the j-th target nucleon

$$\frac{d\sigma_{hA\,abs}}{d^2\vec{b}}(b) = \sum_{\nu=1}^{A}\binom{A}{\nu} P_r^{\nu}(b)\left[1 - P_r(b)\right]^{A-\nu} \equiv \sum_{\nu=1}^{A} P_{r\nu}(b)$$

$$P_{r\nu}(b) \equiv \binom{A}{\nu} P_r^{\nu}(b)\left[1 - P_r(b)\right]^{A-\nu}$$

Since $P_r(b)$ is the probability of getting one specific nucleon hit and there are A possible trials, $P_{r\nu}(b)$ is exactly the binomial distribution for getting ν successes out of A trials, with probability $P_r(b)$ each

$$\sigma_{hA\,abs}(s) \equiv \int d^2\vec{b}\; P_{r\nu}(b)$$

Gribov interpretation of Glauber multiple collisions

Therefore the absorption cross section is just the integral in the impact parameter plane of the probability of getting at least one non-elastic hadron-nucleon collision, and it is naturally written in a mutliple collision expansion

with the overall average number of collision is given by

$$\langle \nu \rangle = \frac{Z\sigma_{hp\,r} + N\sigma_{hn\,r}}{\sigma_{hA\,abs}}$$

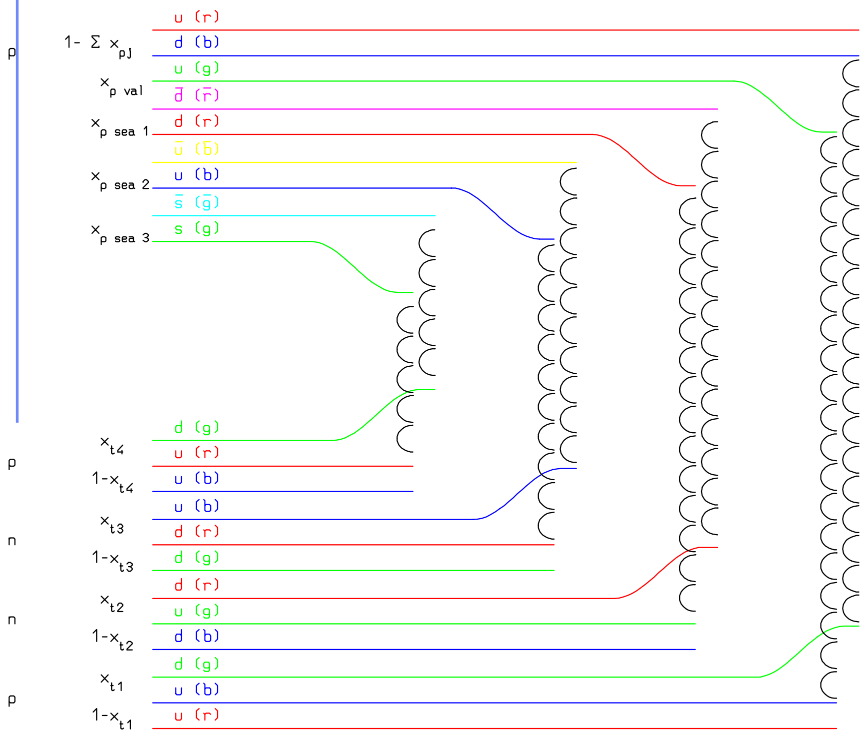
- Glauber-Gribov model = Field theory formulation of Glauber model
- Multiple collision terms ⇒Feynman graphs
- At high energies : exchange of one or more pomerons with one or more target nucleons

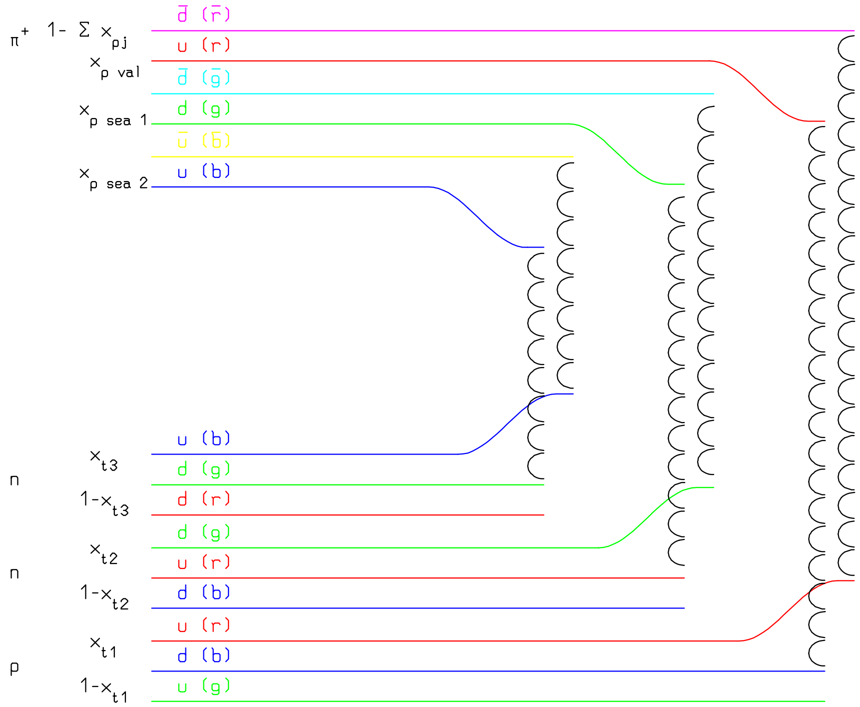
- In the Dual Parton Model language: (neglecting higher order diagrams):

Interaction with ***n*** target nucleons ⇒ ***2n*** chains

- Two chains from projectile valence quarks + valence quarks of one target nucleon ⇒valence-valence chains
- 2(n-1) chains from sea quarks of the projectile + valence quarks of target nucleons ⇒2(n-1) sea-valence chains

Glauber-Gribov: chain examples

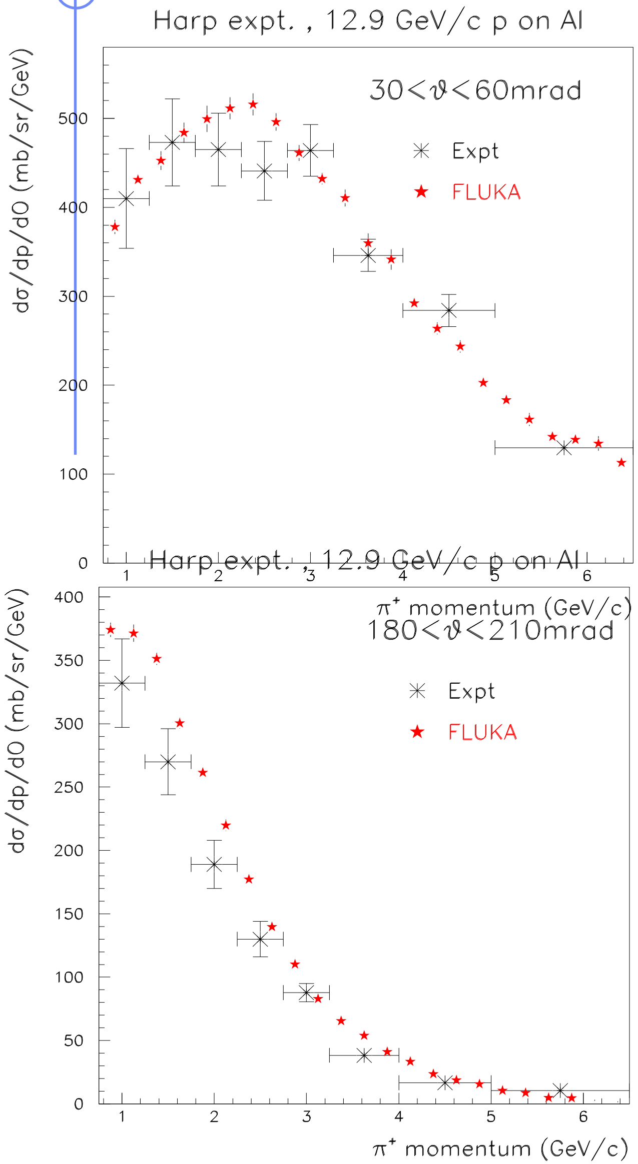




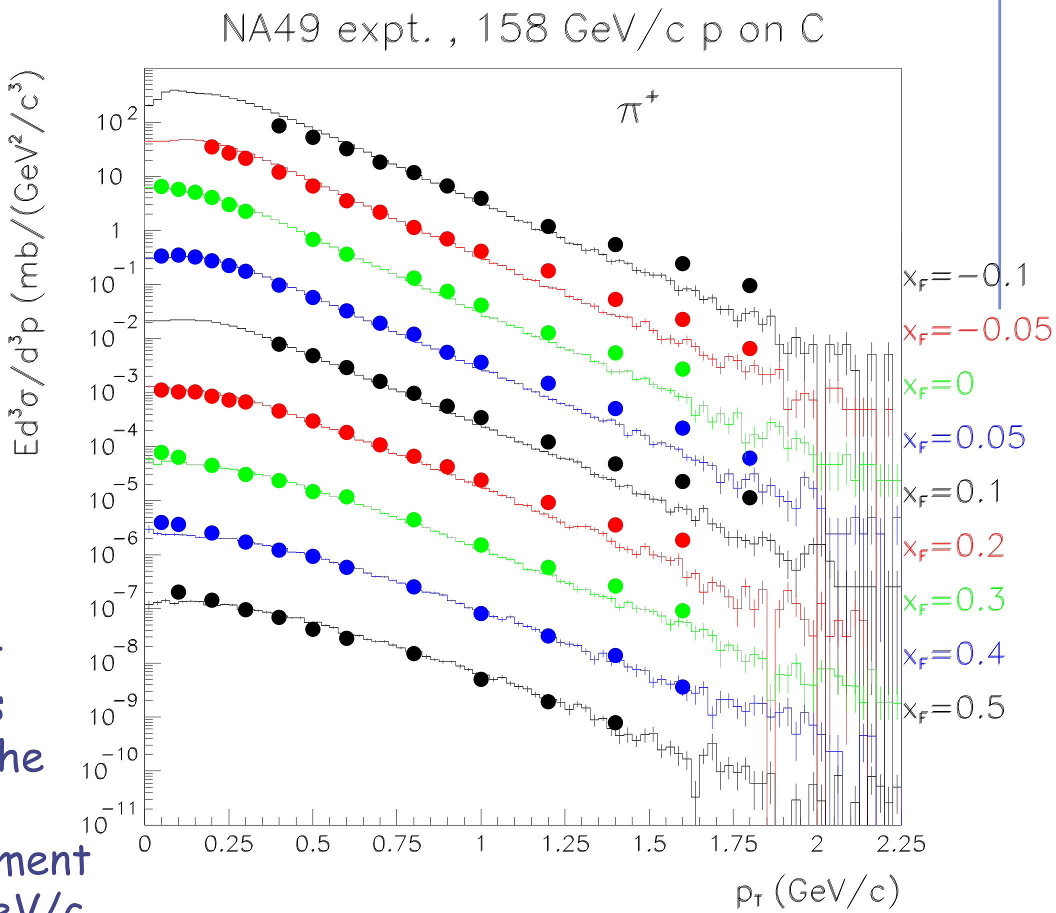
Leading two-chain diagrams in DPM for *p-A* Glauber scattering with 4 collisions. The color (red blue green) and quark combinations shown in the figure are just one of the allowed possibilities

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

Nonelastic hA interactions at high energies: examples



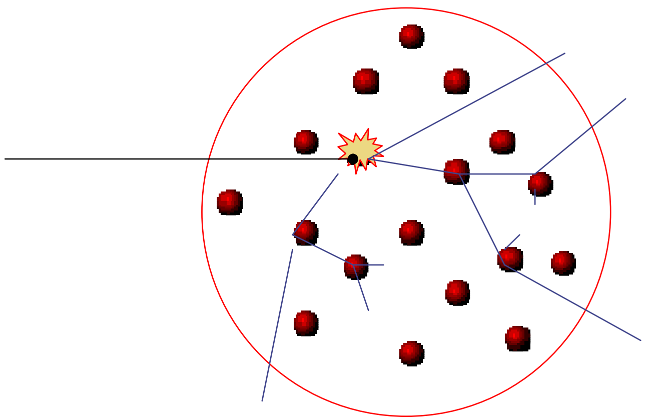
Recent results from the HARP experiment 12.9 GeV/c p on Al π^+ production at different angles

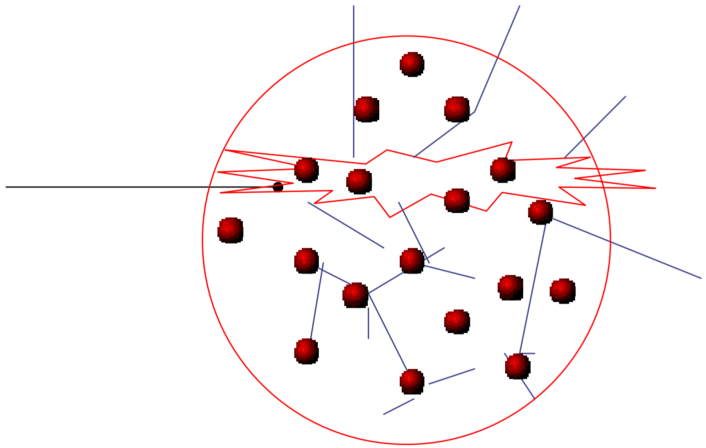


Double differential π+ production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)

From one to many:

While the Glauber analytical calculation of cross sections is accurate down to sub-GeV energy, the interpretation in terms of explicit (nonelastic) multiple collisions and its MonteCarlo implementation are less sound for projectile energies < 5-10 GeV





Glauber length

The Glauber expansions are based on the hadron-nucleon scattering amplitude: from the shape of the hadron-nucleon elastic scattering we can derive a typical four-momentum transfer:

$$f(t) \div e^{\frac{B_{slope}}{2} t} \quad \text{where} \quad t = -q^2$$

Therefore the average momentum transfer is $q^2 = 1/B_{slope}$
the energy transfer seen in the projectile frame is given by

$$\Delta E_{proj} = \nu_{proj} = \frac{q^2}{2\, m_{proj}} \equiv \frac{1}{2\, B_{slope} m_{proj}}$$

From the uncertainty principle this ΔE corresponds to an indetermination in proper time given by

$$\Delta\tau \cdot \Delta E_{proj} \approx \hbar$$

that boosted to the nucleus frame gives a Glauber length

$$\Delta x_{Glau} \approx \frac{p_{lab}}{m_{proj}} \cdot \Delta\tau \approx \frac{p_{lab}\hbar}{m_{proj}\nu_{proj}} = 2\, k_{Glau} B_{slope}\, p_{lab}\hbar$$

Formation zone* *(→ classical INC will never work)*

Naively: "materialization" time (J.Ranft, L.Stodolski).
Qualitative estimate:

In the frame where $p_{//}=0$

$$\bar{t} = \Delta t \approx \frac{\hbar}{E_T} = \frac{\hbar}{\sqrt{p_T^2 + M^2}}$$

Particle proper time

$$\tau = \frac{M}{E_T}\bar{t} = \frac{\hbar M}{p_T^2 + M^2}$$

Going to the nucleus system

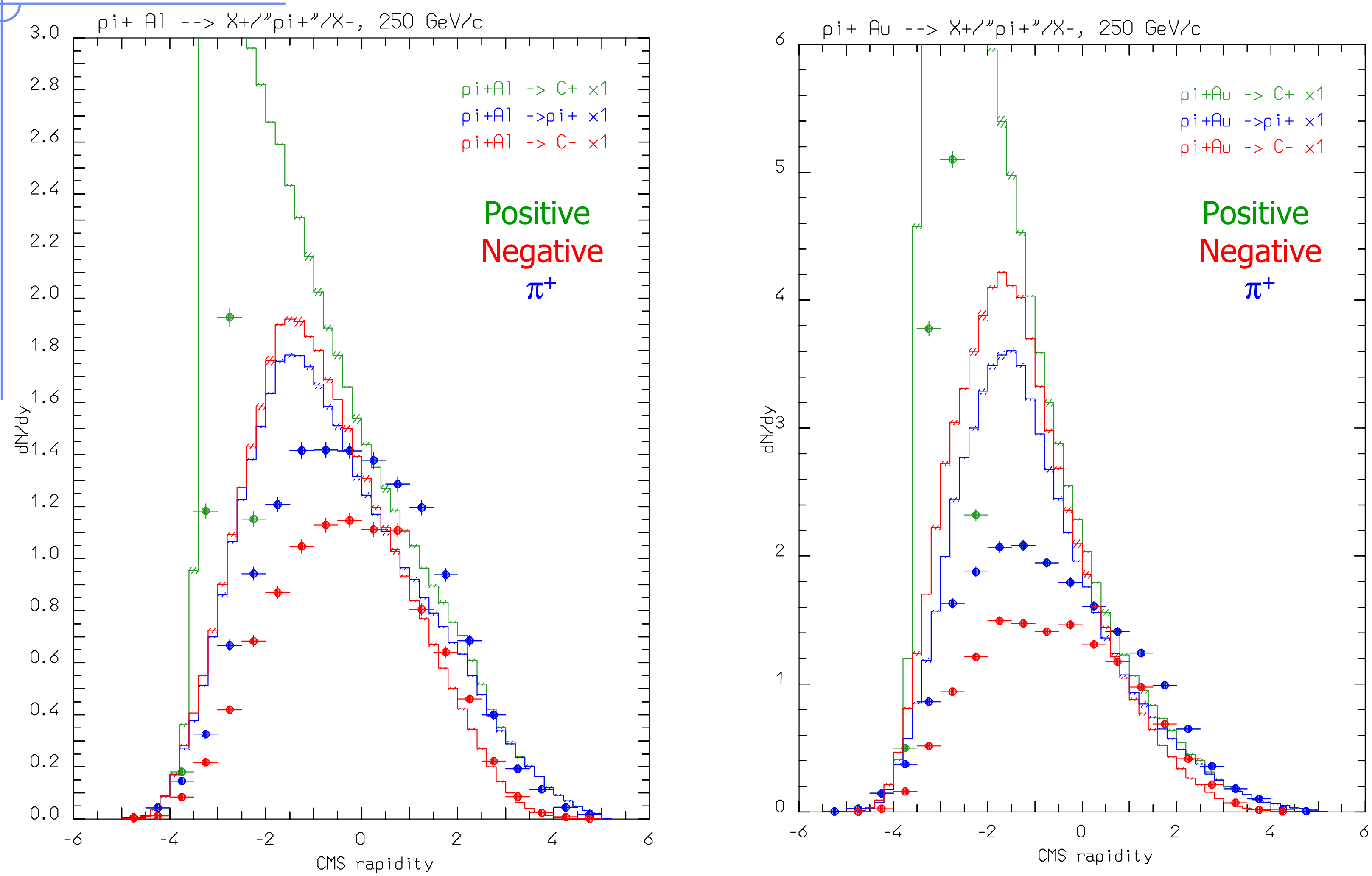
$$\Delta x_{for} \equiv \beta\, c \cdot t_{lab} \approx \frac{p_{lab}}{E_T}\bar{t} \approx \frac{p_{lab}}{M}\tau = k_{for}\frac{\hbar p_{lab}}{p_T^2 + M^2}$$

Condition for possible reinteraction inside a nucleus:

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

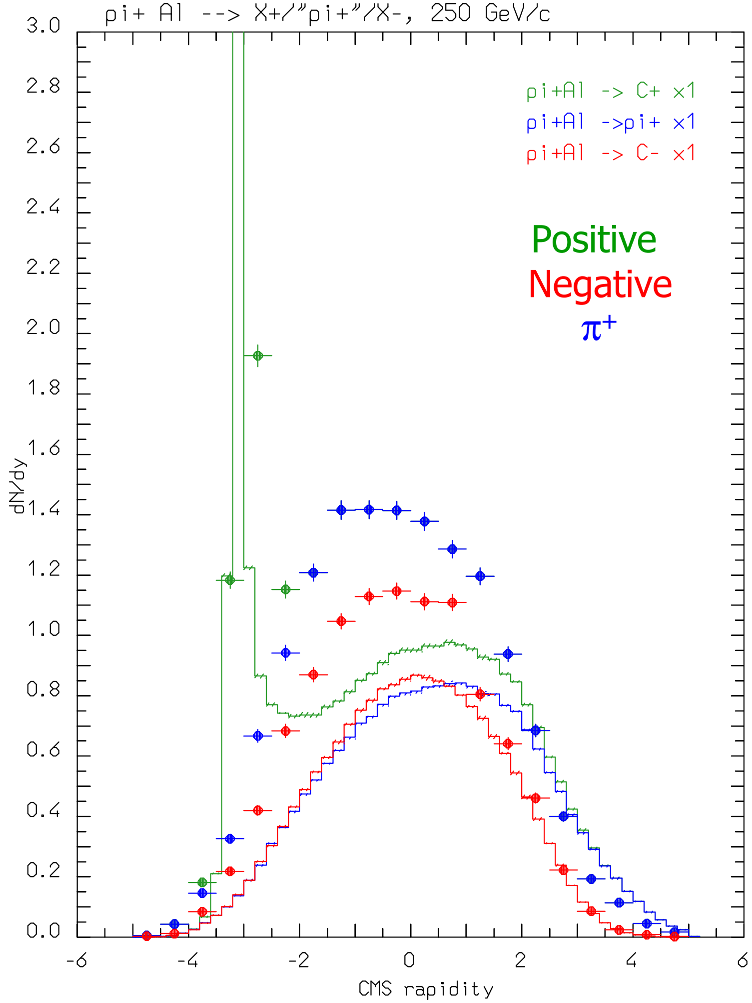
* J.Ranft applied the concept, originally proposed by Stodolski, to hA and AA nuclear interactions

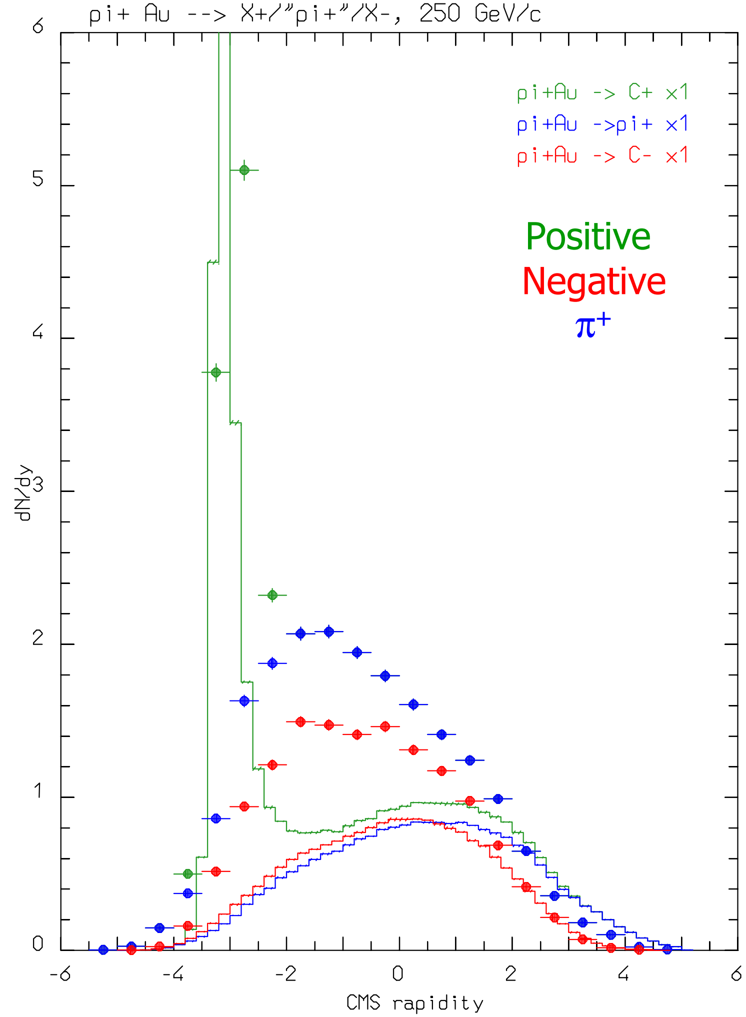
Setting the formation zone: no Glauber, no formation zone



Rapidity 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)).

Setting the formation zone: no Glauber, yes formation zone





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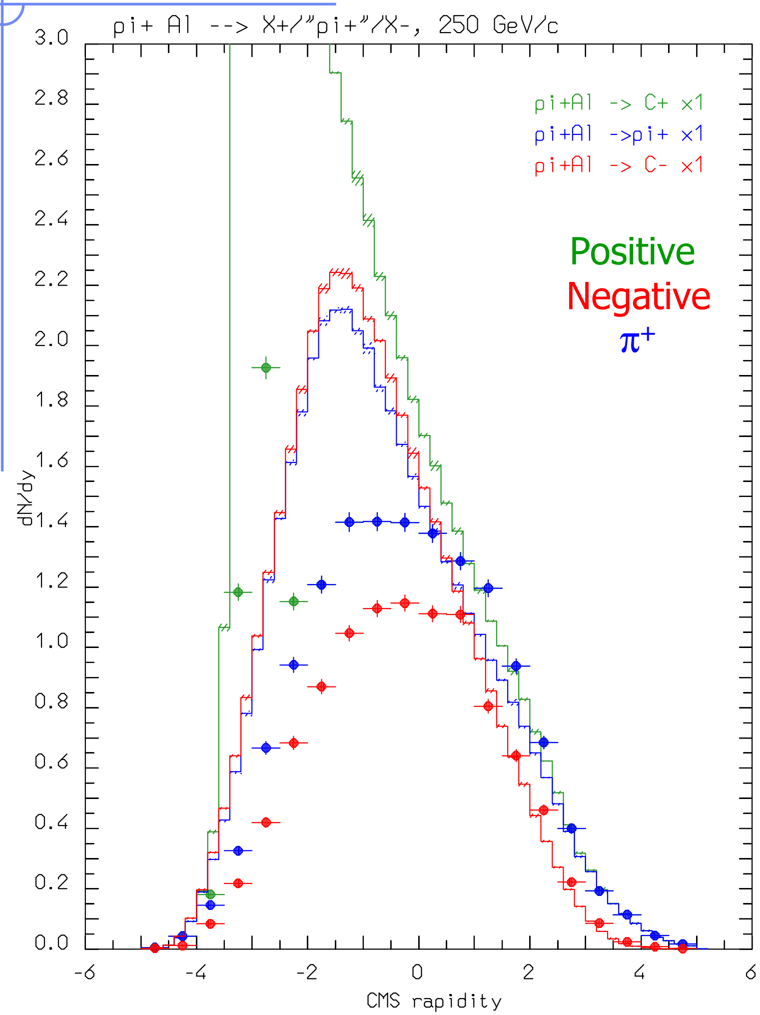

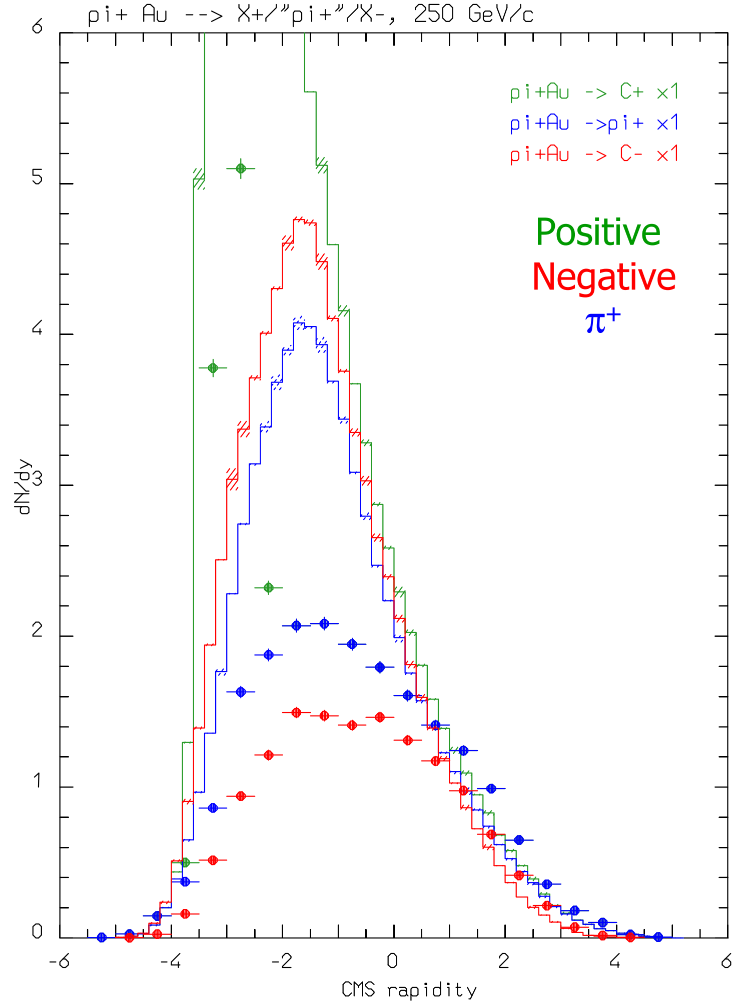

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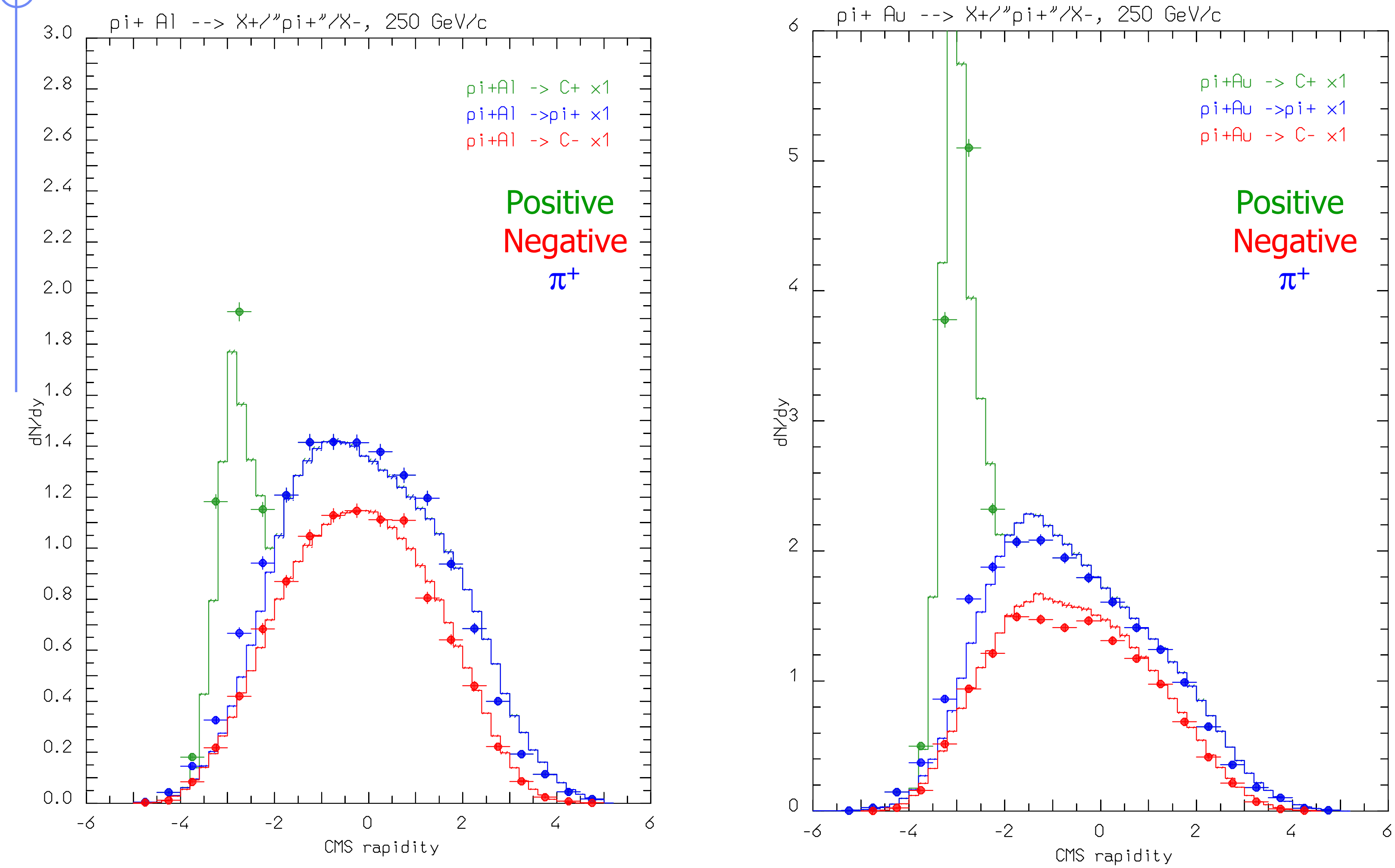


Rapidity distribution of charged particles produced in 250 GeV π^+ collisions on Aluminum (left) and Gold (right)
Points: exp. data (Agababyan et al., ZPC50, 361 (1991)).

Coherence length *(a reason why INC should never work)*

Coherence length ≈ formation time for elastic, charge exchange, or quasielastic interactions.

Given a two body interaction with four-momentum transfer

$$q = p_{1i} - p_{1f}$$

the energy transfer seen in a frame where the particle 2 is at rest is given by

$$\Delta E_2 = \nu_2 = \frac{q^2}{2m_2} = \frac{q \cdot p_{2i}}{m_2}$$

From the uncertainty principle this ΔE corresponds to an indetermination in proper time given by

$$\Delta\tau \cdot \Delta E_2 \approx \hbar$$

that boosted to the nucleus frame gives a coherence length

$$\Delta x_{coh} \approx \frac{p_{2lab}}{m_2} \cdot \Delta\tau = k_{coh} \frac{p_{2lab}\hbar}{m_2 \nu_2}$$

Nucleon-Nucleon: in medium treatment

The free NN scattering amplitudes and cross sections are modified by medium effects (Pauli blocking, coherence effects etc). The resulting in-medium cross sections are density dependent and smaller than σ_{NNfree}

Three approaches are implemented in FLUKA
(but not used! See comment below):

- *G.Q.Li et al., PRC48, 1702 (1993), PRC49, 566 (1994) (theoretical, ρ, E and θ dependent)*
- *C.Xiangshou et al., PRC58, 572 (1998) (phenomenological, ρ and E dependent)*
- *R.K.Tripathi et al., NIMB152, 425 (1999), NIMB173, 391 (2001) (phenomenological, only E dependent)*

One of the open questions in microscopic models is the (proper) implementation of medium corrected nucleon cross sections. Double counting with explicit Pauli blocking (which is required to get physical events) as well with other effects (correlations, antisymmetrization, coherence length) is an issue, as well as proper correlation with the angular distribution

Nuclear potential for pions

For pions, a complex ***resonant*** nuclear potential can be defined out of the π-nucleon scattering amplitude to be used in conjunction with the Klein-Gordon equation

$$\left[(\omega - V_c)^2 - 2\omega U_{opt} - K^2\right]\Psi = m_\pi^2 \Psi$$

In coordinate space (the upper/lower signs refer to $\pi^+/\ \pi^-$):

$$2\omega U_{opt}(\omega, r) = -\beta(\omega, r) + \frac{\omega}{2M}\nabla^2\alpha(\omega, r) - \nabla\frac{\alpha}{1+g\alpha(\omega, r)}\nabla$$

$$\beta = 4\pi\left[\left(1+\frac{\omega}{M}\right)\left(b_0(\omega) \mp b_1(\omega)\frac{N-Z}{A}\right)\rho(r) + \left(1+\frac{\omega}{2M}\right)B_0(\omega)\rho^2(r)\right]$$

$$\alpha = 4\pi\left[\frac{1}{\left(1+\frac{\omega}{M}\right)}\left(c_0(\omega) \mp c_1(\omega)\frac{N-Z}{A}\right)\rho(r) + \frac{1}{\left(1+\frac{\omega}{M}\right)}C_0(\omega)\rho^2(r)\right]$$

Using standard methods to get rid of the non-locality, in momentum space

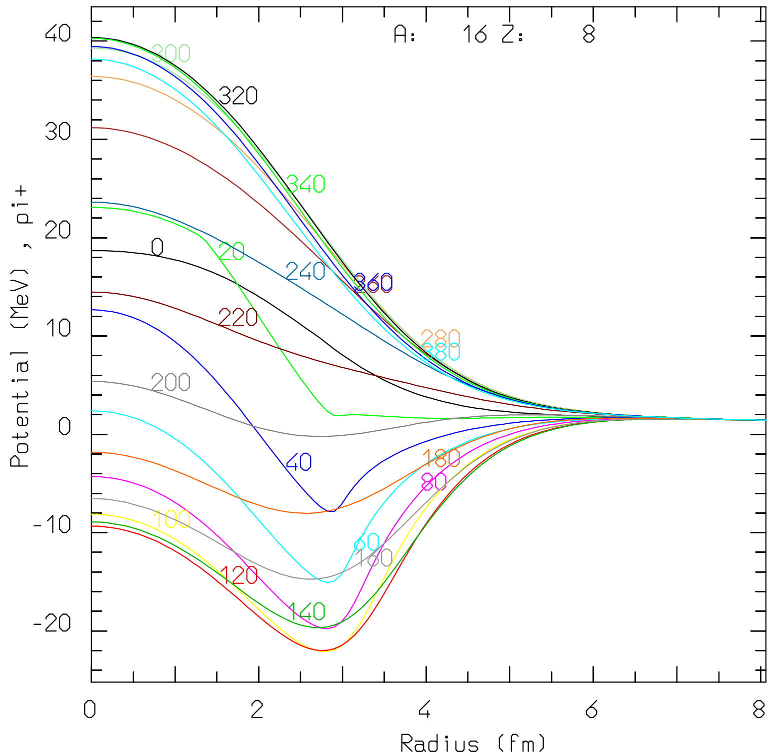
$$2\omega U_{opt}(\omega, r) = -\beta - K^2\frac{\alpha}{1+g\alpha} + \frac{\omega}{2M}\nabla^2\alpha$$

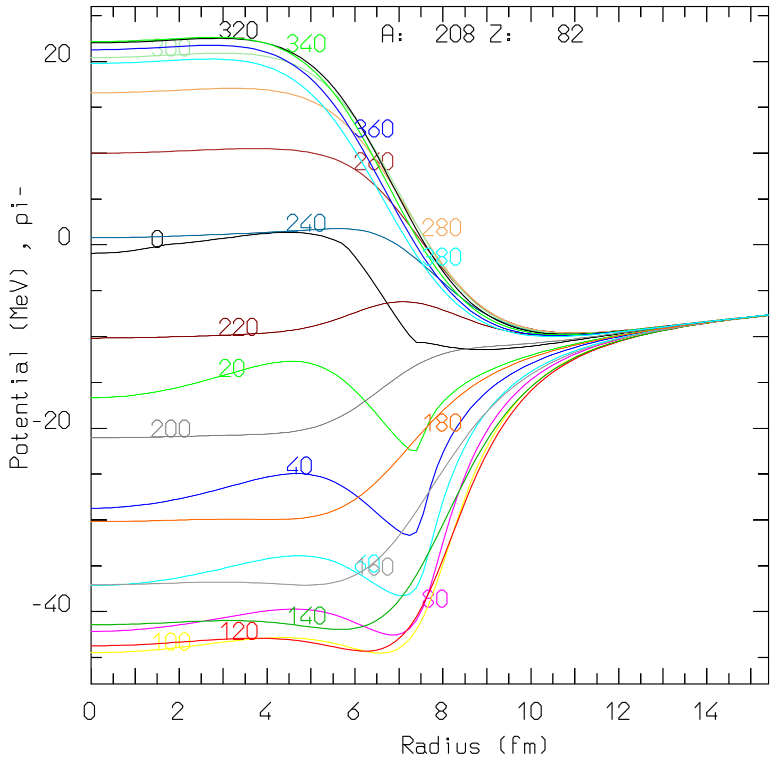
$$K^2 = k_0^2 + V_c^2 - 2\omega V_c^2 - 2\omega U_{opt}(\omega, r) = \frac{k_0^2 + V_c^2 - 2\omega V_c^2 + \beta - \frac{\omega}{2M}\nabla^2\alpha}{1-\overline{\alpha}}$$

$$\overline{\alpha} = \frac{\alpha}{1+g\alpha}$$

Nuclear potential for pions: examples

The real part of the pion optical potential for π^- on ^{16}O (left) and π^+ on ^{208}Pb (right) as a function of radius for various pion energies (MeV)





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

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

(Oset et al., NPA 468, 631)

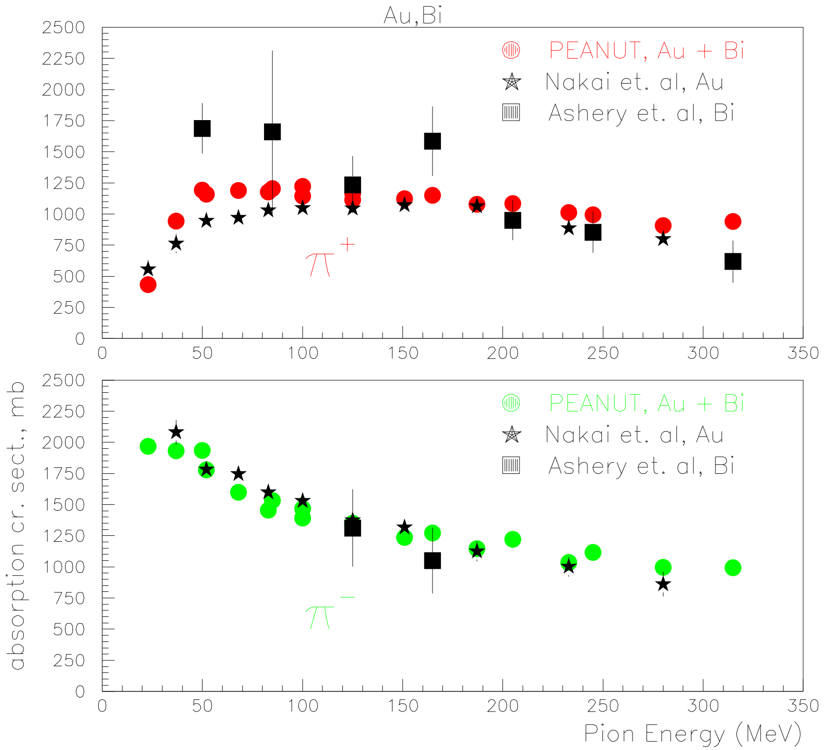
quasielastic scattering, ***two*** and ***three*** body absorption

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

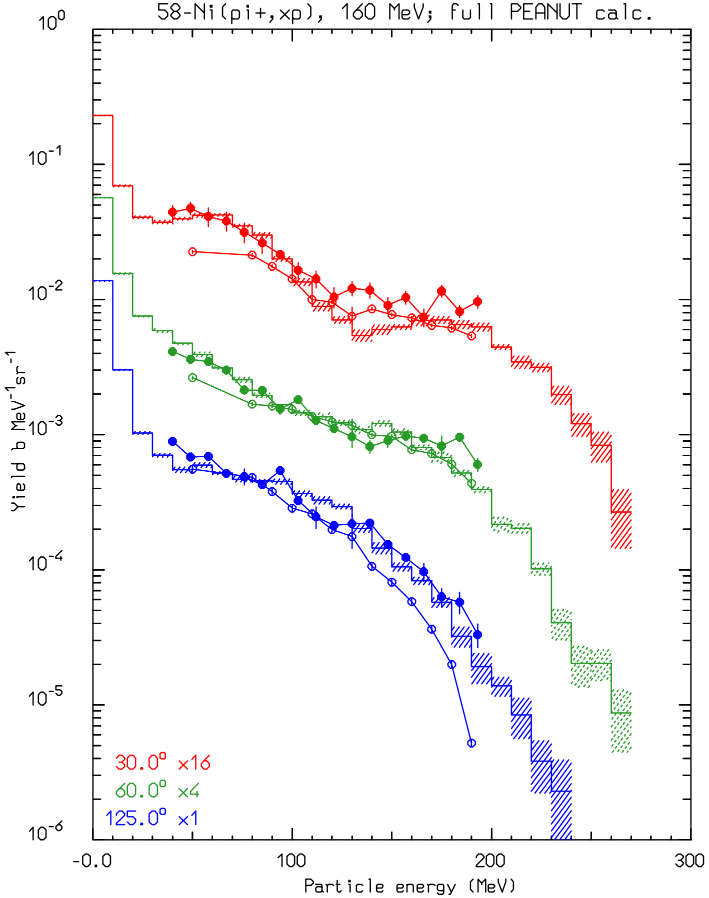
$$\sigma_t^A = \sigma_{res}^A + \sigma_t^{Free} - \sigma_{res}^{Free} + \sigma_s^A \qquad \sigma_s^A(\omega) = \frac{4\pi}{p}\left(1 + \frac{\omega}{2m}\right)\mathrm{Im}\,B_0(\omega)\rho$$

Pion absorption

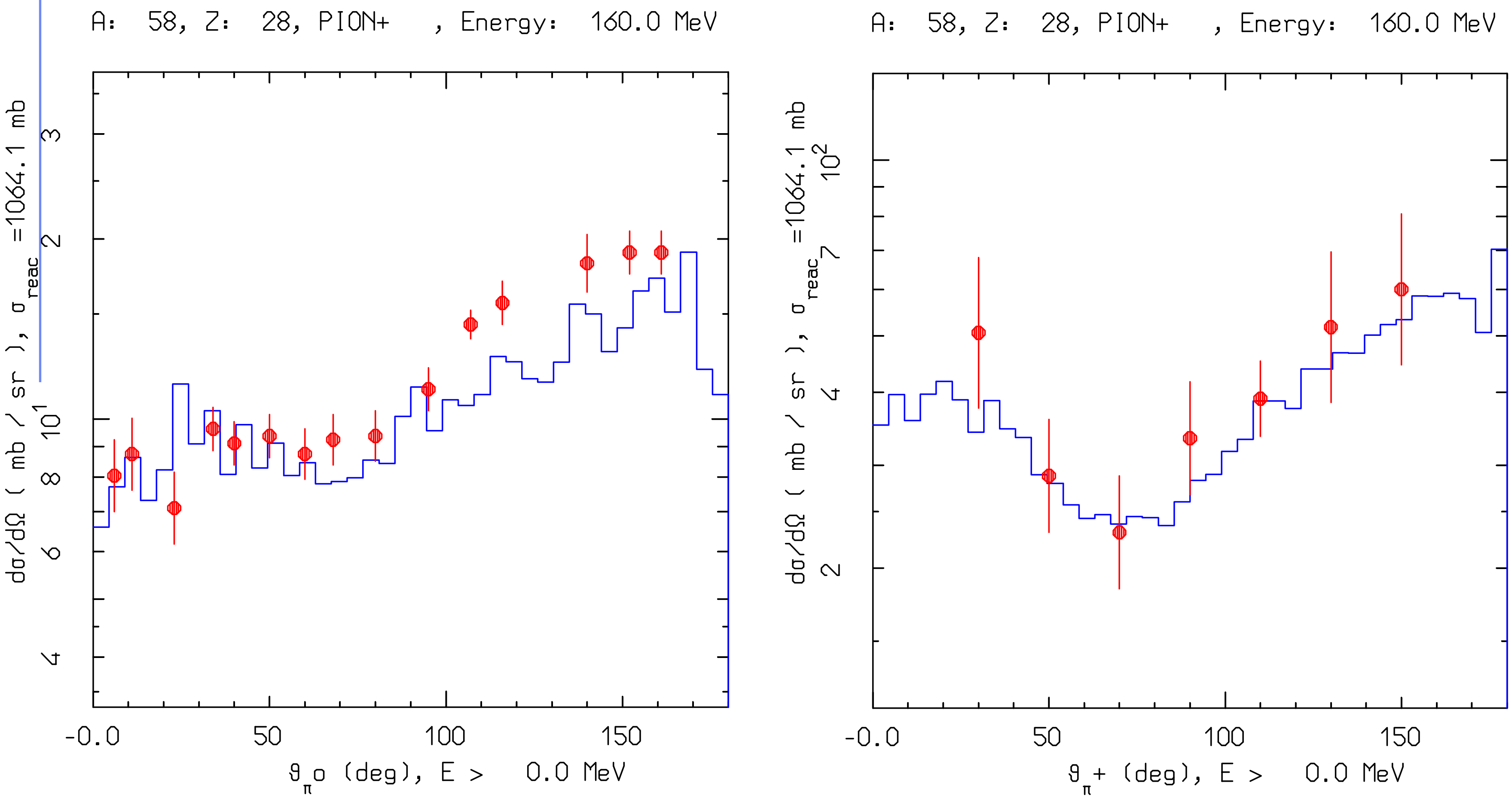
Pion absorption cross section on Gold and Bismuth in the Δ resonance region (multibody absorption in PEANUT)



Emitted proton spectra at different angles , 160 MeV π^+ on Ni
Phys. Rev. C41,2215 (1990)
Phys. Rev. C24,211 (1981)
Proton spectra extend up to 300 MeV



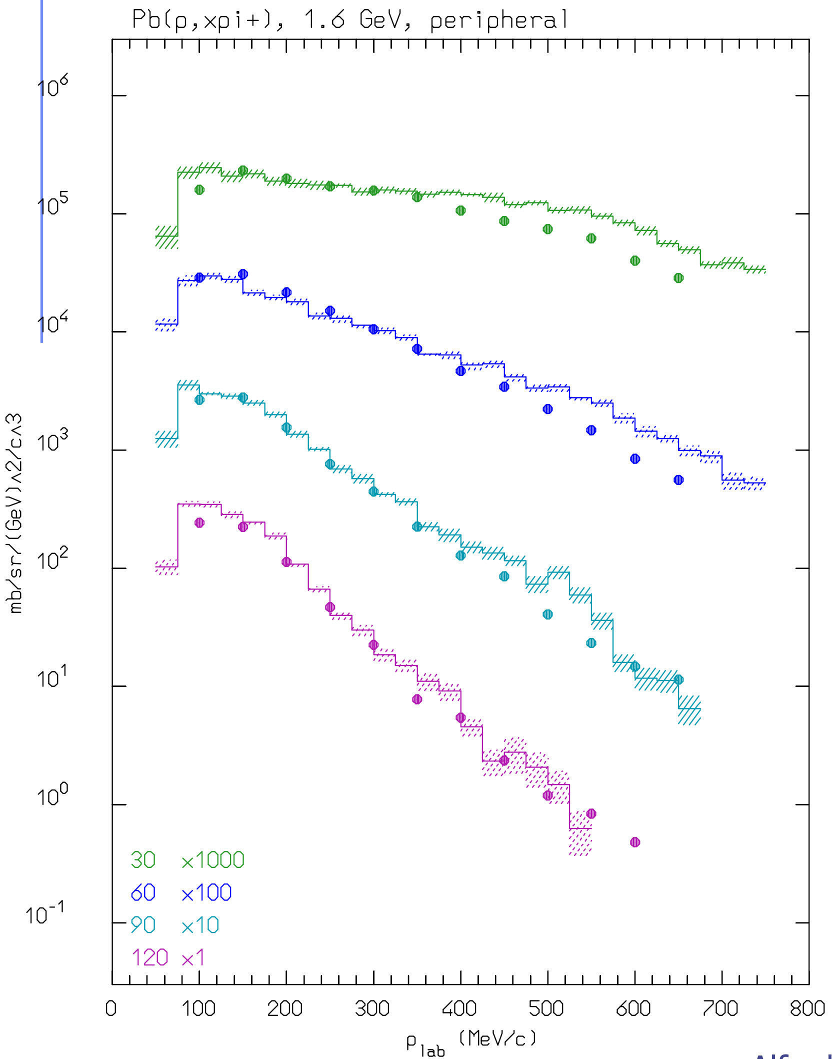
Pion-Nucleus scattering:



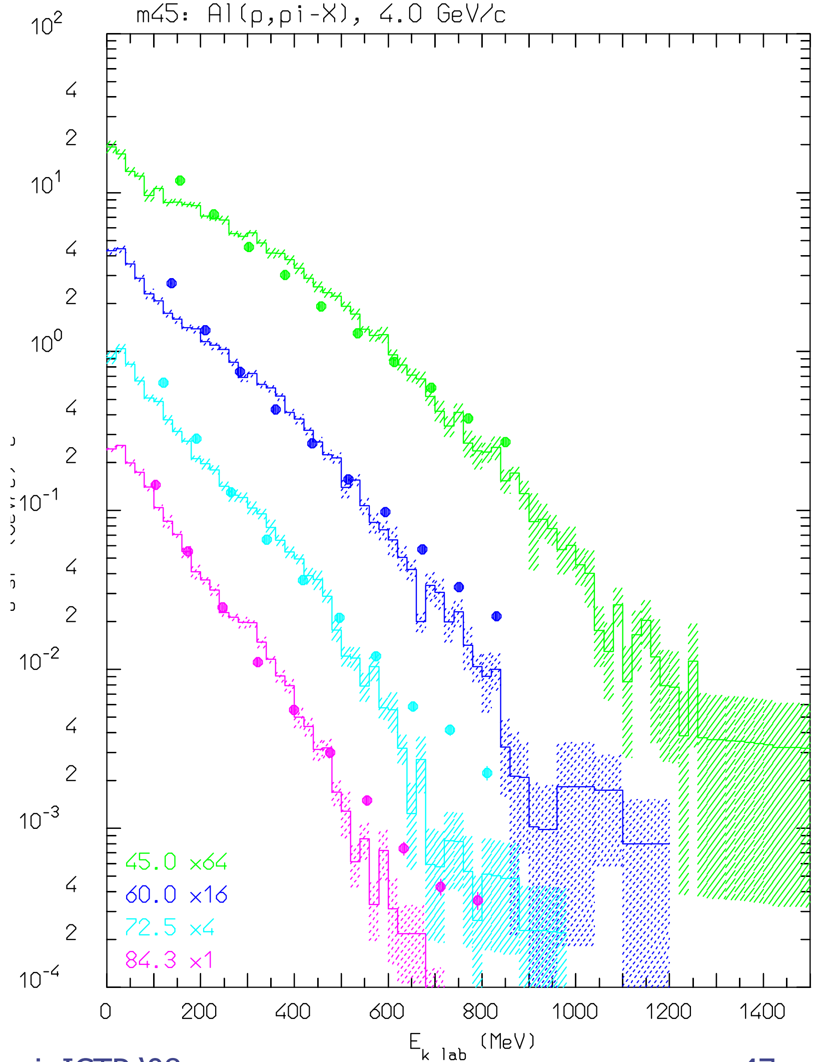
Angular distribution for ^{58}Ni(π^+,π^0X) (charge exchange, left) and ^{58}Ni(π^+,$\pi^{+'}$X) (inelastic scattering, right) at 160 MeV. ***Histos*** FLUKA, ***symbols*** exp. data

Pion production examples:

$p+Pb \rightarrow \pi^{+}+X$ (1.6 GeV)



$p+Al \rightarrow \pi^{-}+X$ (4 GeV/c)



Preequilibrium emission:
(based on M.Blann GDH cast in a Monte Carlo form)

For E > π production threshold $\rightarrow$ only (G)INC models
At lower energies a variety of preequilibrium models

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

Preequilibrium & GDH

Preequilibrium emission probability for particle type x at energy ε in *n*-th step; (n_{px}=number of particle-like excitons of type x)

$$P_{x,n}(\varepsilon)d\varepsilon = n_{p_x} \frac{\rho_n(U,\varepsilon) g d\varepsilon}{\rho_n(E)} \bullet \frac{r_c(\varepsilon)}{r_c(\varepsilon)+r_+(\varepsilon)}$$

where the density (MeV^{-1}) of exciton states is given by:

$$\rho_n(E) = \frac{g(gE)^{n-1}}{n!(n-1)!}$$

(g=single state density)

the emission rate in the continuum:

$$r_c = \sigma_{inv} \frac{\varepsilon}{g_x} \frac{(2s+1)8\pi m}{h^3}$$

and the reinteraction rate:

$$r_+(\varepsilon) = f_{Pauli}(\varepsilon, E_F)[\rho_p \sigma_{xp} + \rho_n \sigma_{xn}] \left[\frac{2(\varepsilon+V)}{m}\right]^{\frac{1}{2}}$$

(or from optical potential)

GDH : *ρ*, *r*, E_F "local" averages on the trajectory
constrained exciton state densities are used for small exciton numbers .

Modified GDH in PEANUT

- σ_{inv} from systematics
- Correlation/formation zone/hardcore effects on reinteractions

$$\frac{r_c(\varepsilon)}{r_c(\varepsilon)+r_+(\varepsilon)} \Rightarrow P_c^{h\tau} + P_c^{co} + P_c^{std}$$

$P_c^{h\tau}$ = escape probability in zone $h\tau$ L max(τ,hardcore)
P_c^{co} = escape/total prob. in zone (correlation - $h\tau$)
(reinteraction only on non-correlated nucleon specie)
P_c^{std} = standard escape/total in remaining zone

- Constrained exciton state densities configurations 1p-1h, 2p-1h, 1p-2h, 2p-2h, 3p-1h and 3p-2h
- Energy dependent form for *g*
- Angular distributions: fast particle approximation

Modified GDH in PEANUT II

- Position dependent parameters = point-like values:
  - First step: n_h holes generated in the INC step at positions x_i

$$\rho_{n_h}^{loc} = \frac{\sum_{i=1}^{n_h} \rho(\vec{x}_i)}{n_h} \qquad E_{F\,n_h}^{loc} = \frac{\sum_{i=1}^{n_h} E_F(\vec{x}_i)}{n_h}$$

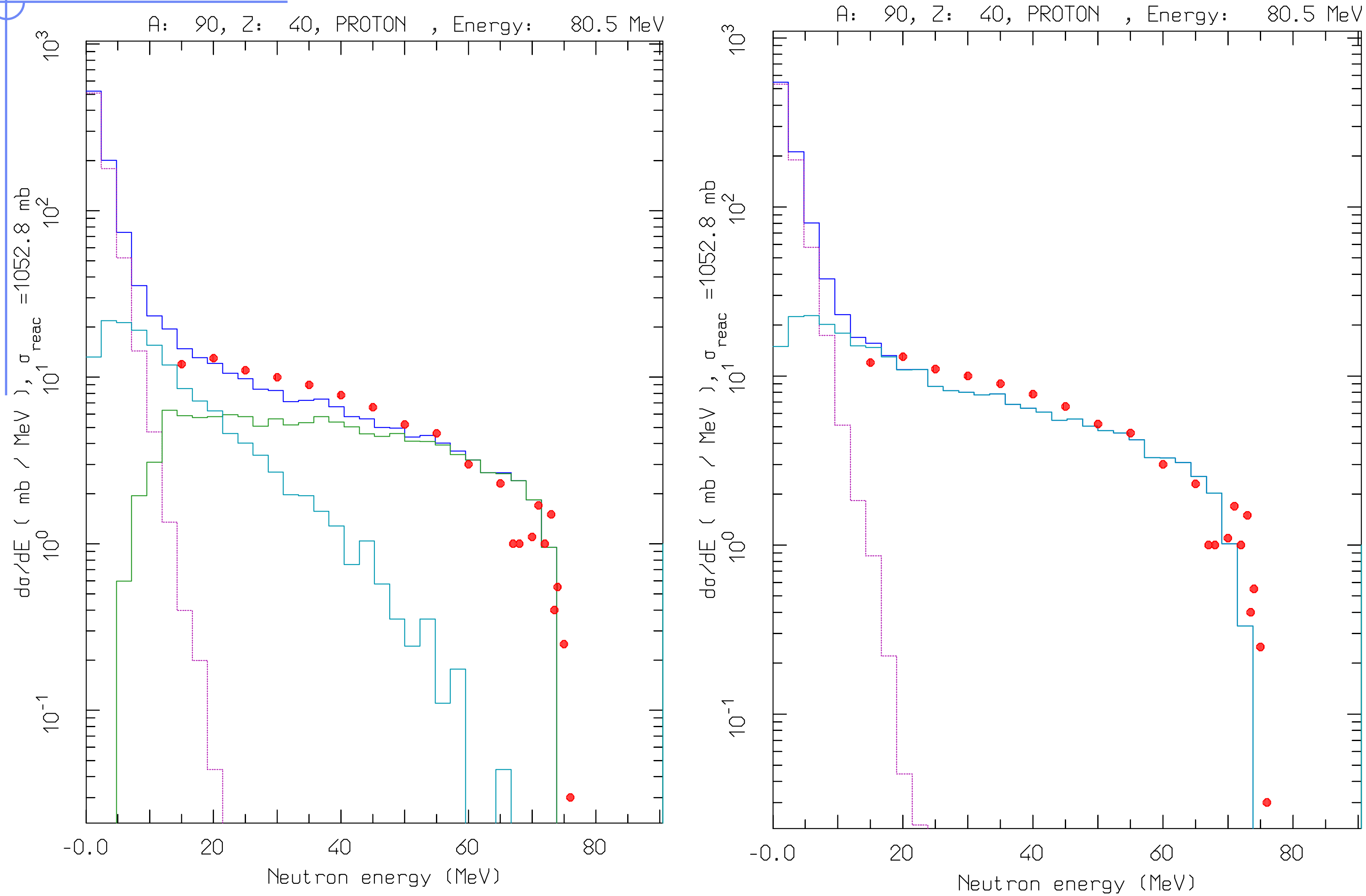
  - When looking at reinteractions: consider neighborhood:

$$\rho_{n_h}^{nei} = \frac{n_h \rho_{n_h}^{loc} + \rho^{ave}}{n_h + 1} \qquad E_{F\,n_h}^{nei} = \frac{n_h E_{F\,n_h}^{loc} + E_F^{ave}}{n_h + 1}$$

  - Subsequent steps: go towards *average* quantities

$$\rho_{n_h+1}^{loc} = \rho_{n_h}^{nei} \qquad E_{F\,n_h+1}^{loc} = E_{F\,n_h}^{nei}$$

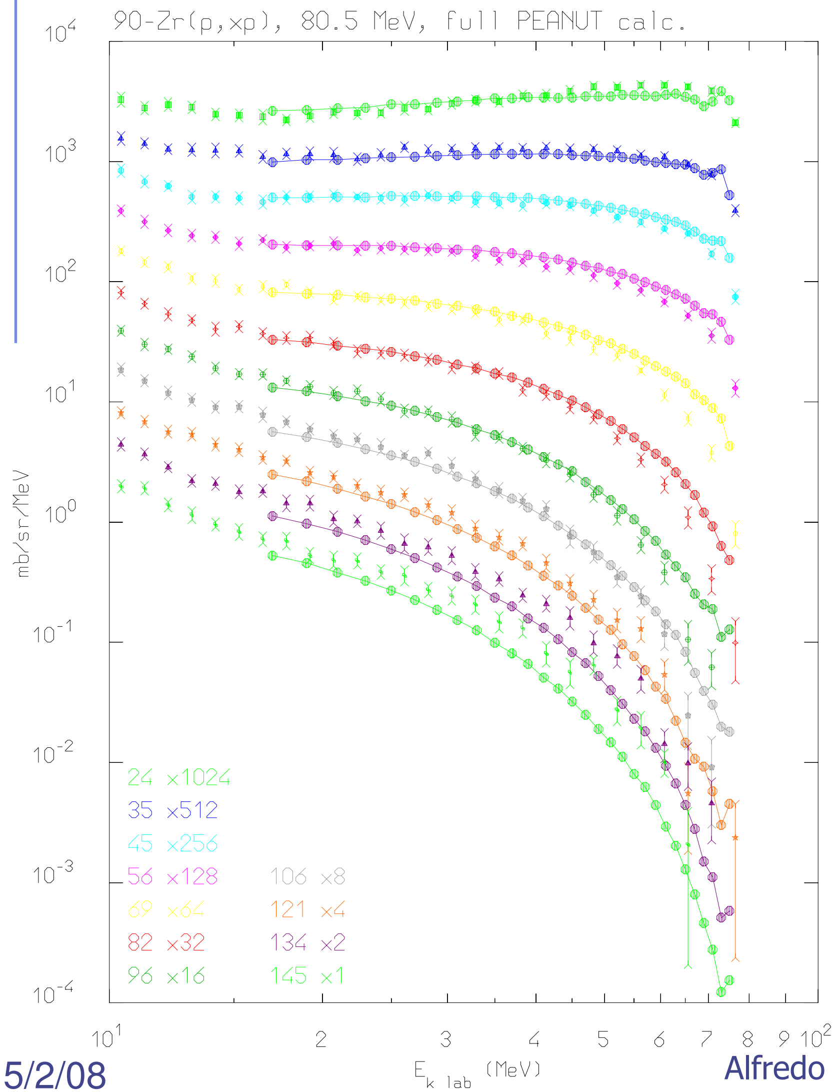
Cascade/preequilibrium transition:

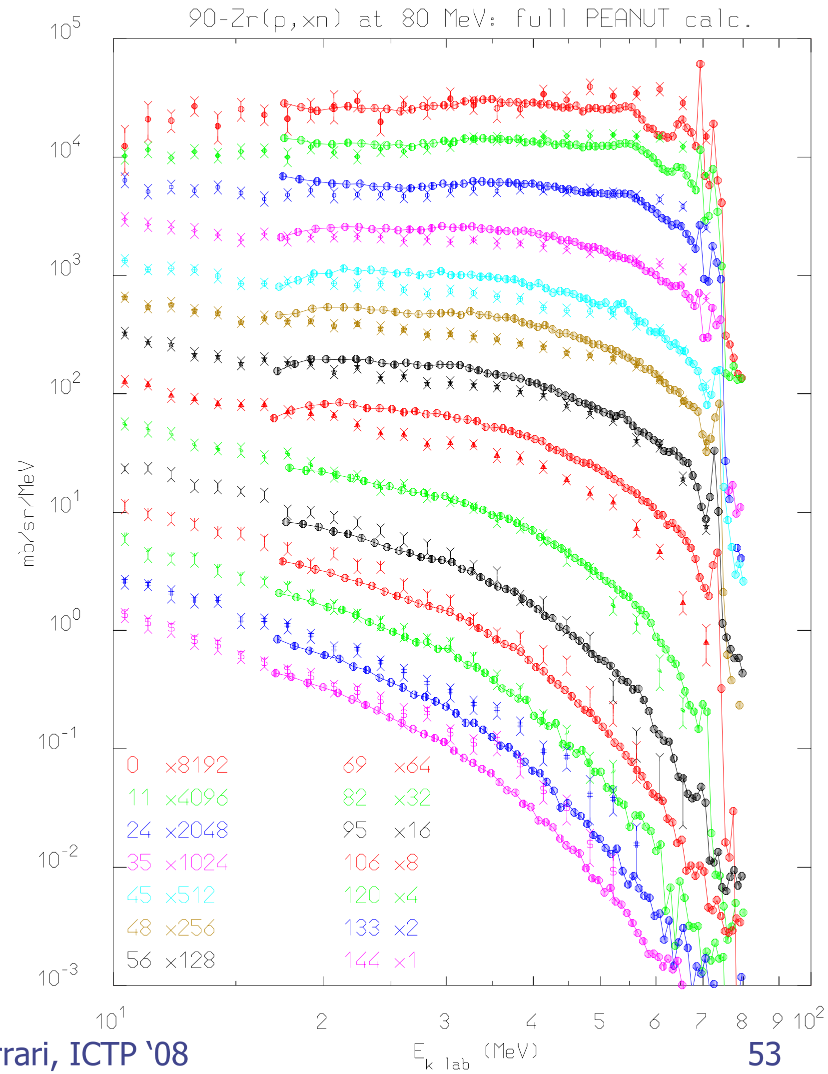


Angle-integrated ^{90}Zr(p,xn) at 80.5 MeV (INC+preeq left, preeq only right). The lines show the ***total***, *INC*, *preequilibrium*, and ***evaporation*** contributions. Exp. data: M. Trabandt et al., Phys. Rev. C39, 452 (1989).

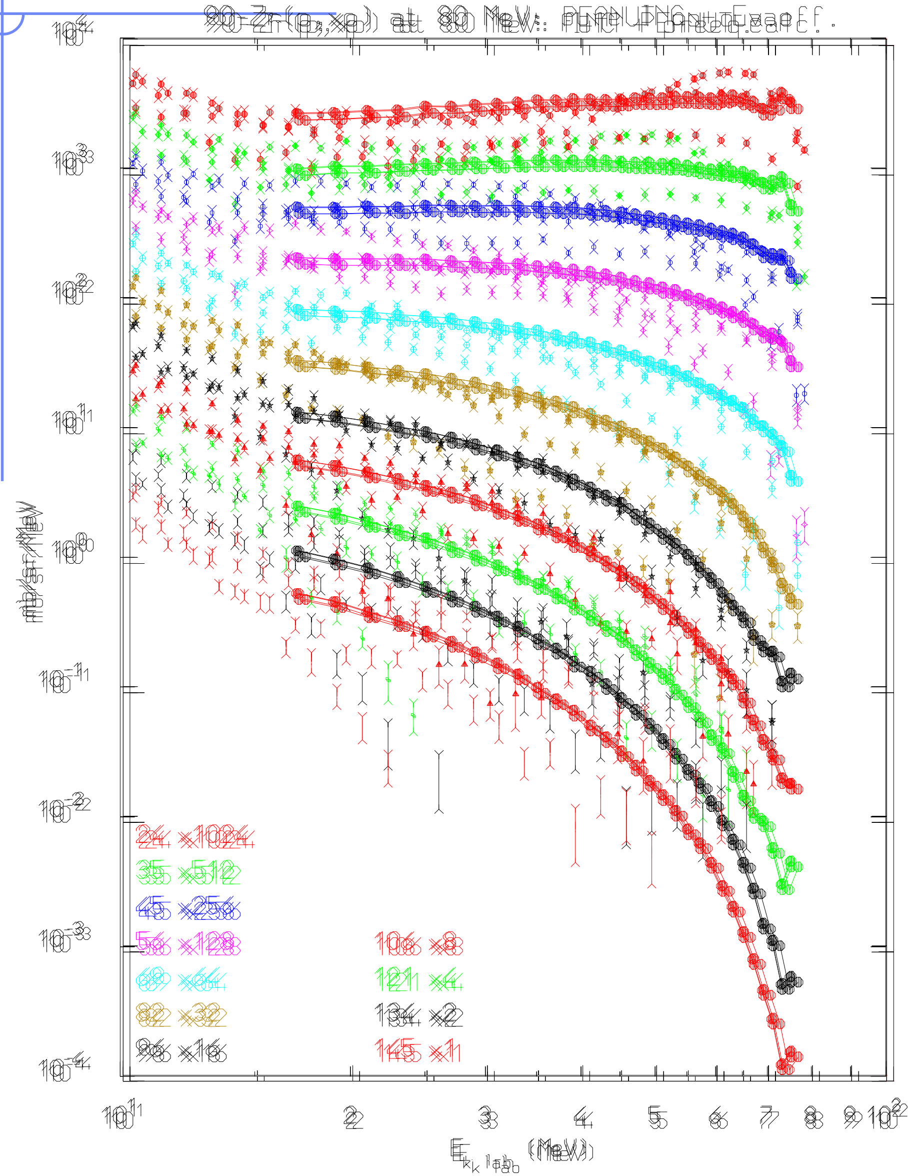
Thin target examples

$p + {}^{90}Zr \rightarrow p + X$ (80 MeV) $p + {}^{90}Zr \rightarrow n + X$ (80 MeV)





From INC to (G)INC: $^{90}Zr(p,xp)$ @ 80.5 MeV



Plain INC (a la Bertini)

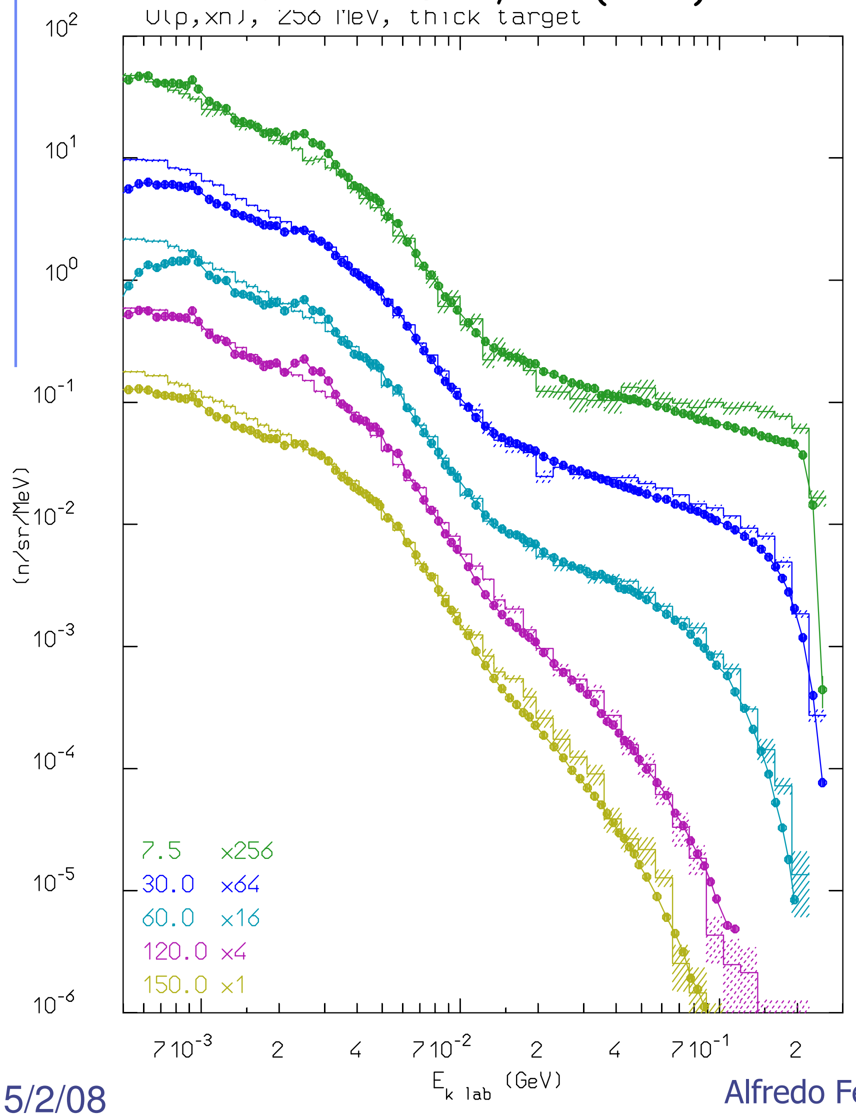
Plain INC plus preequilibrium

PEANUT calculation with no quantum effect, apart Pauli blocking

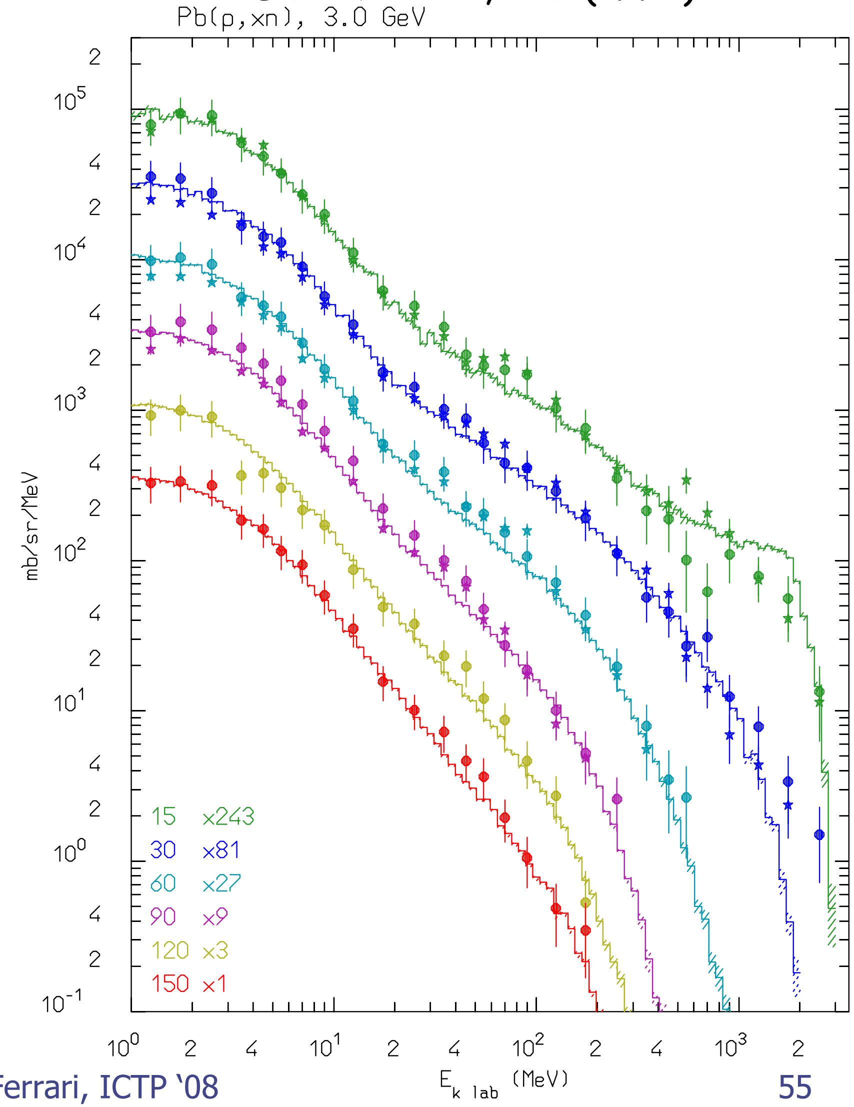
Full PEANUT calculation

Thick/Thin target examples: neutrons

U(p,xn) @ 256 GeV, stopping target
Data: NSE110, 299 (1992)

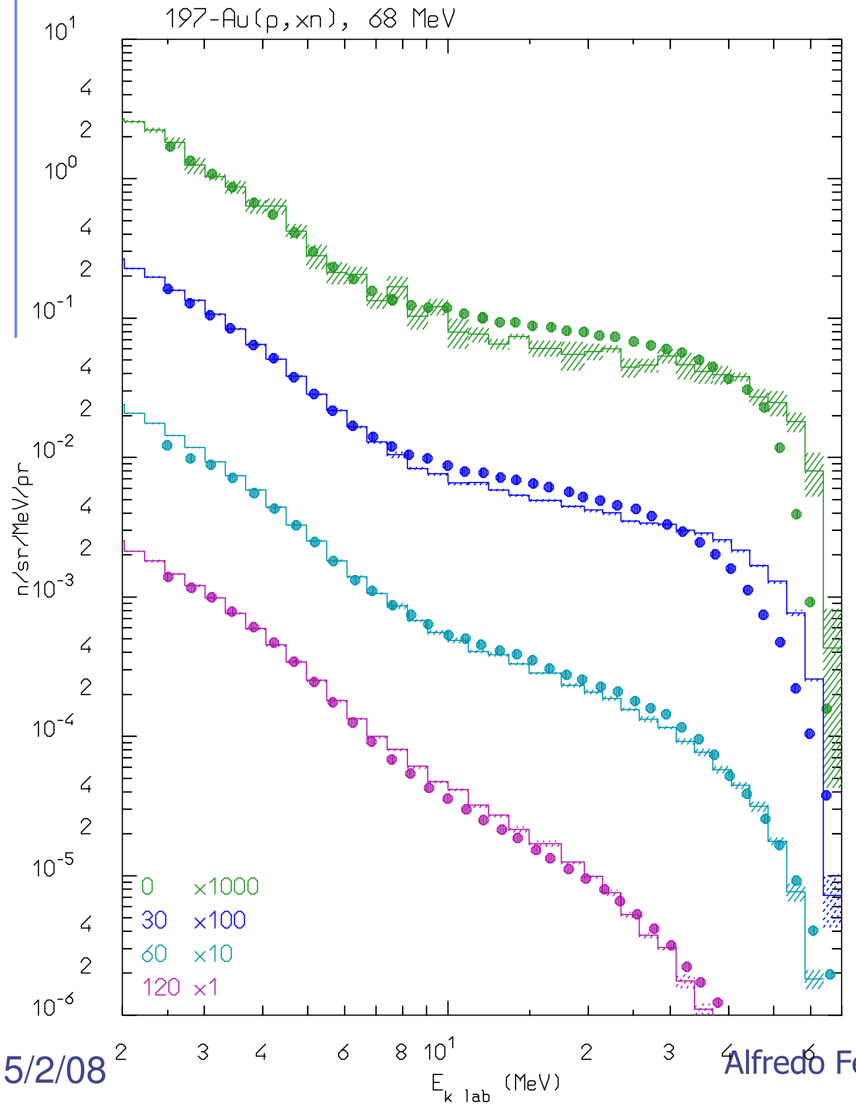


Pb(p,xn) @ 3 GeV, thin target
Data: NST32, 827 (1995)

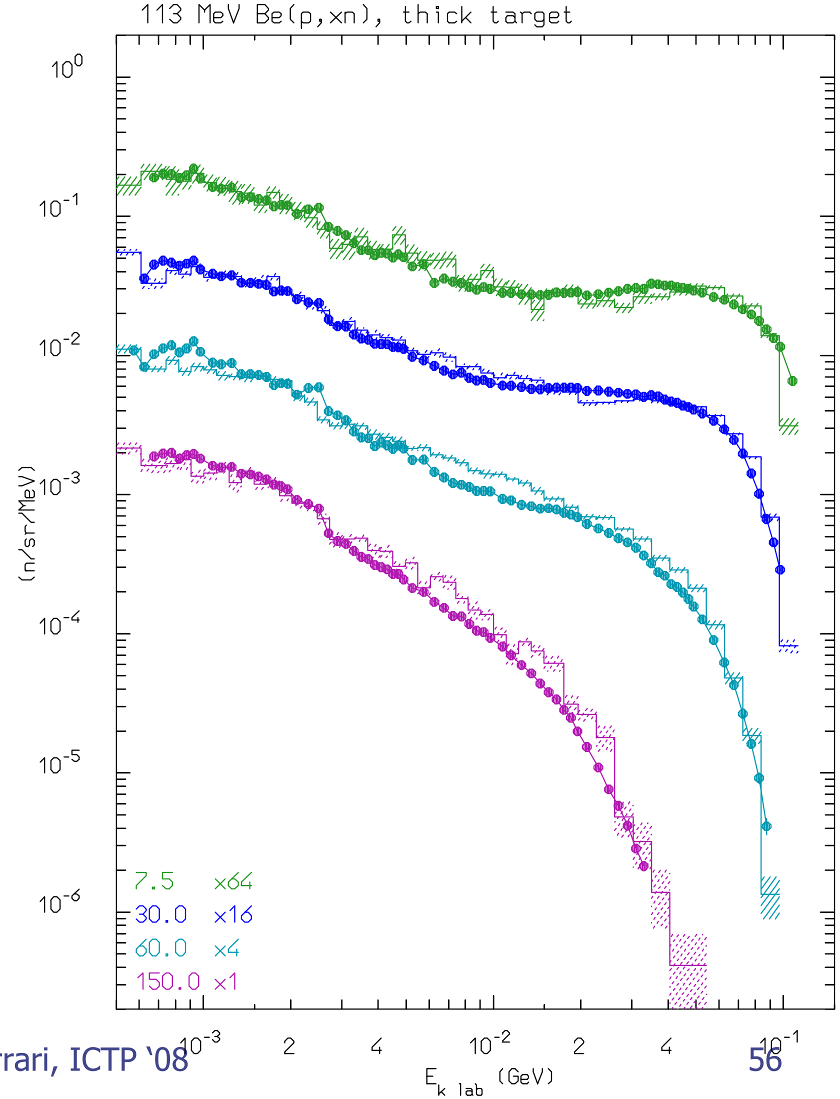


Thick target examples: neutrons

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



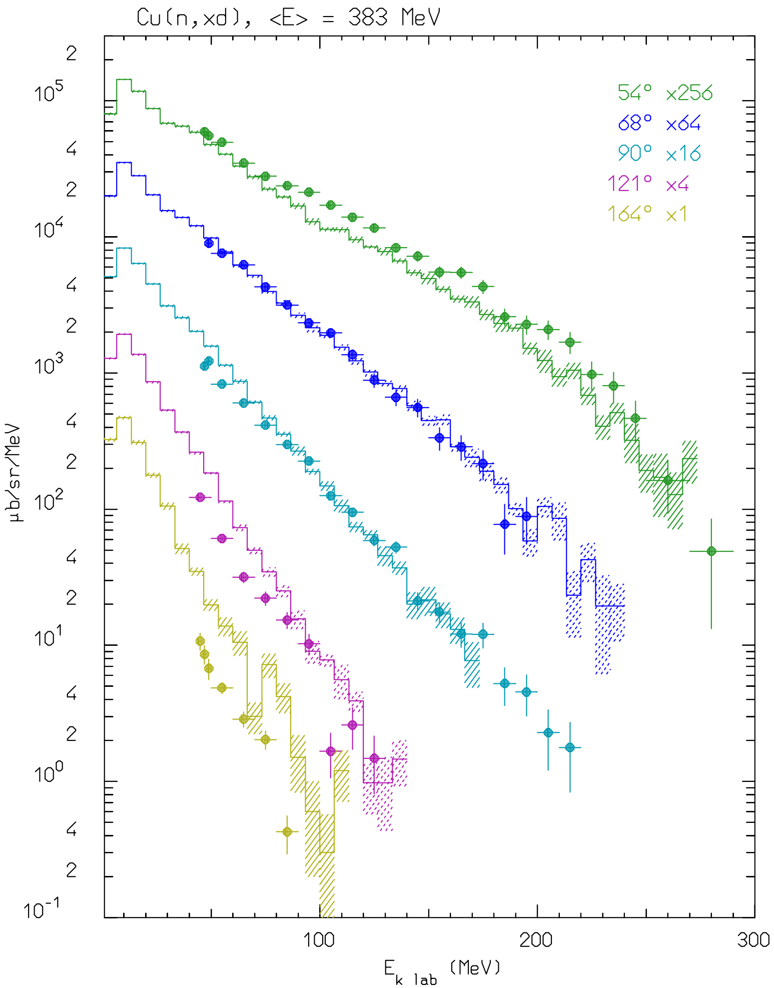
^{9}Be(p,xn) @ 113 MeV, stopping target
Data: NSE110, 299 (1992)



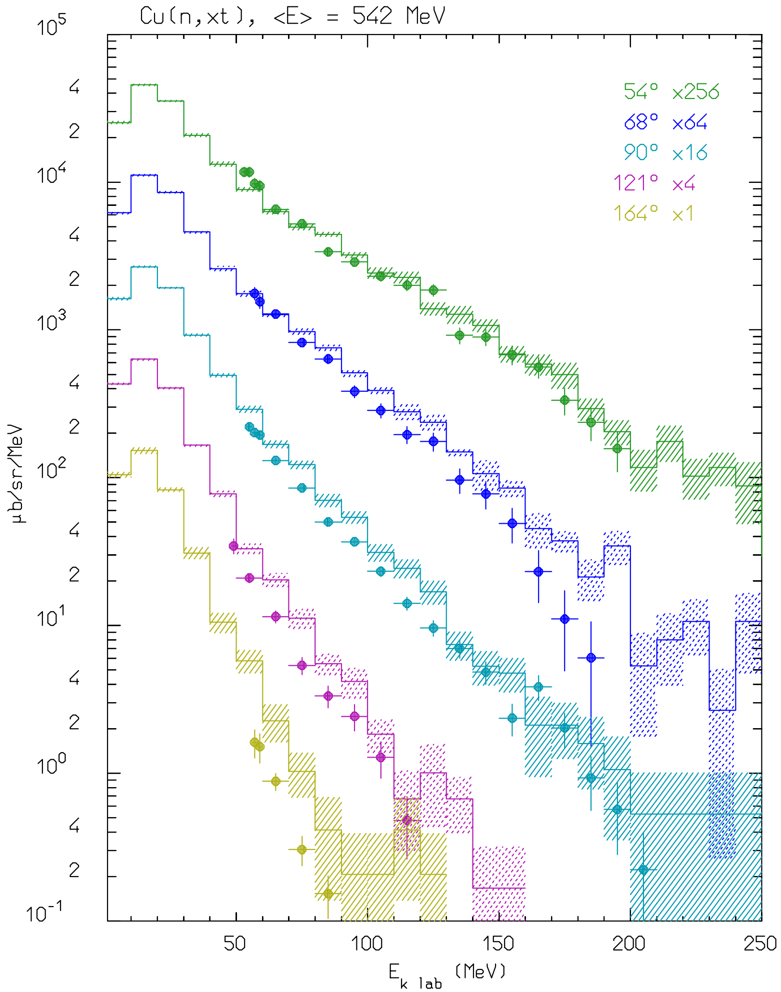
Coalescence:

- d, t, ^{3}He, and alpha's generated during the (G)INC and preequilibrium stage
- All possible combinations of (unbound) nucleons and/or light fragments checked at each stage of system evolution
- FOM evaluation based on phase space "closeness" used to decide whether a light fragment is formed rather than not
  - FOM evaluated in the CMS of the candidate fragment at the time of minimum distance
  - Naively a momentum or position FOM should be used, but not both due to quantum non commutation
  - … however the best results are obtained with a Wigner transform FOM (assuming gaussian wave packets) which should be the correct way of considering together positions and momenta
- Binding energy redistributed between the emitted fragment and residual excitation (exact conservation of 4-momenta)

Coalescence: examples

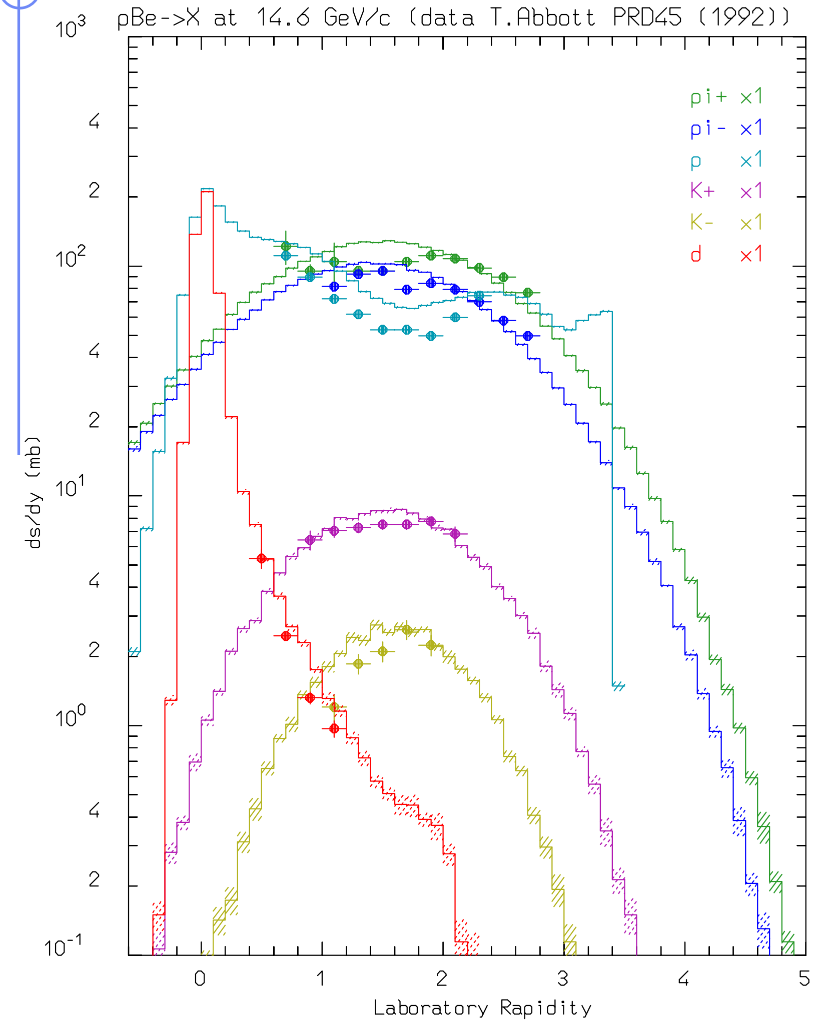


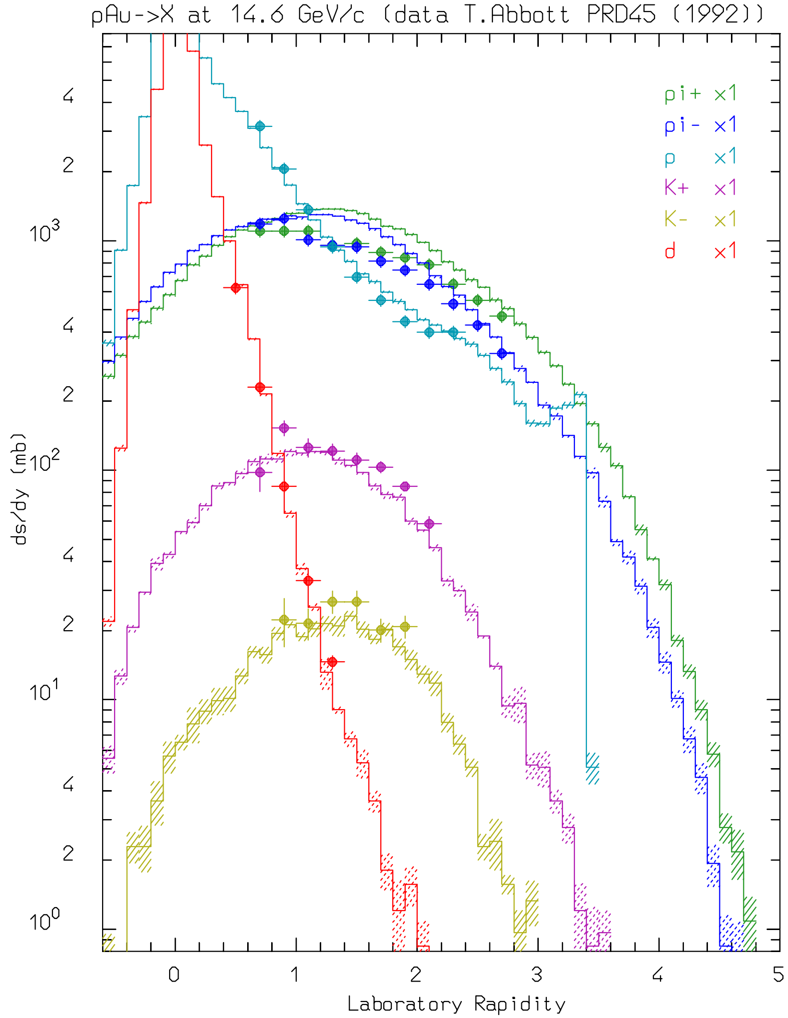
Double differential d production from 383 MeV neutrons on Copper Nucl. Phys. A510, 774 (1990)



Double differential t production from 542 MeV neutrons on Copper

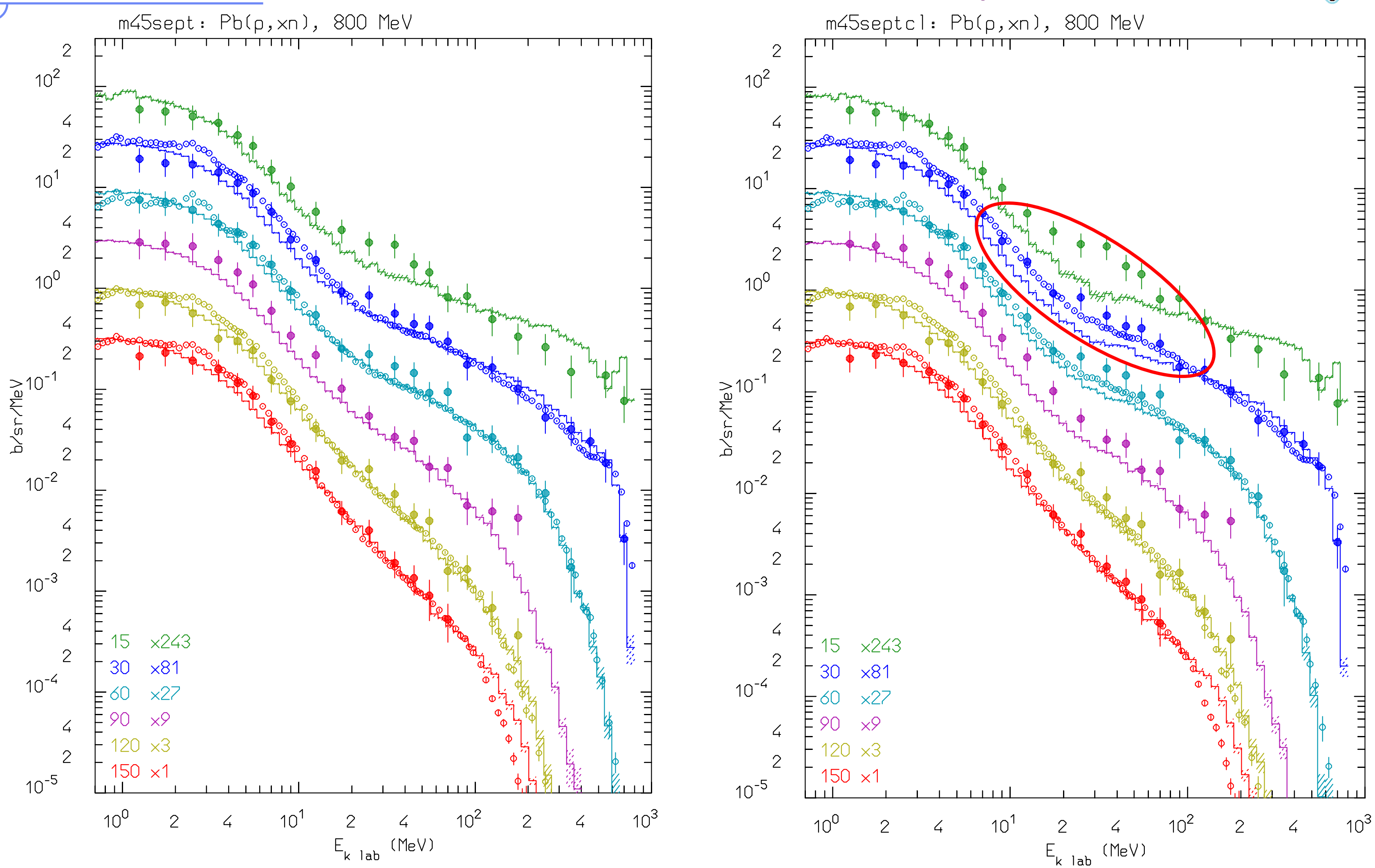
Going to lower energies: yes Glauber, yes formation zone as set @250





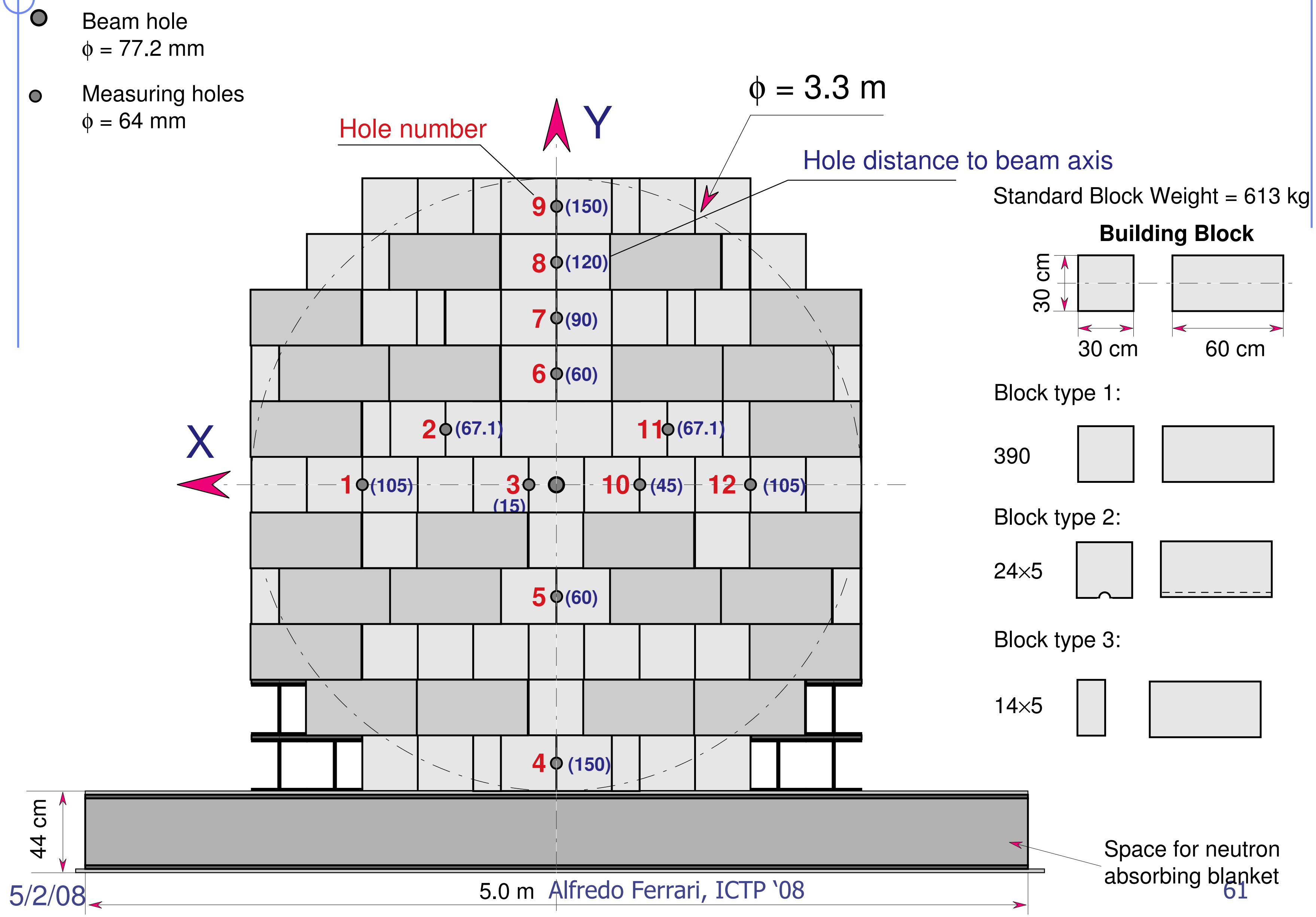
Rapidity distribution of protons, deuterons, positive pions, negative pions, positive kaons and negative kaons produced in 14.6 GeV/c p collisions on Beryllium (left) and Gold (right)
Points: exp. data (Abbott et al., PRD45, 3906 (1992)).

Coalescence: issue with N-spectra?



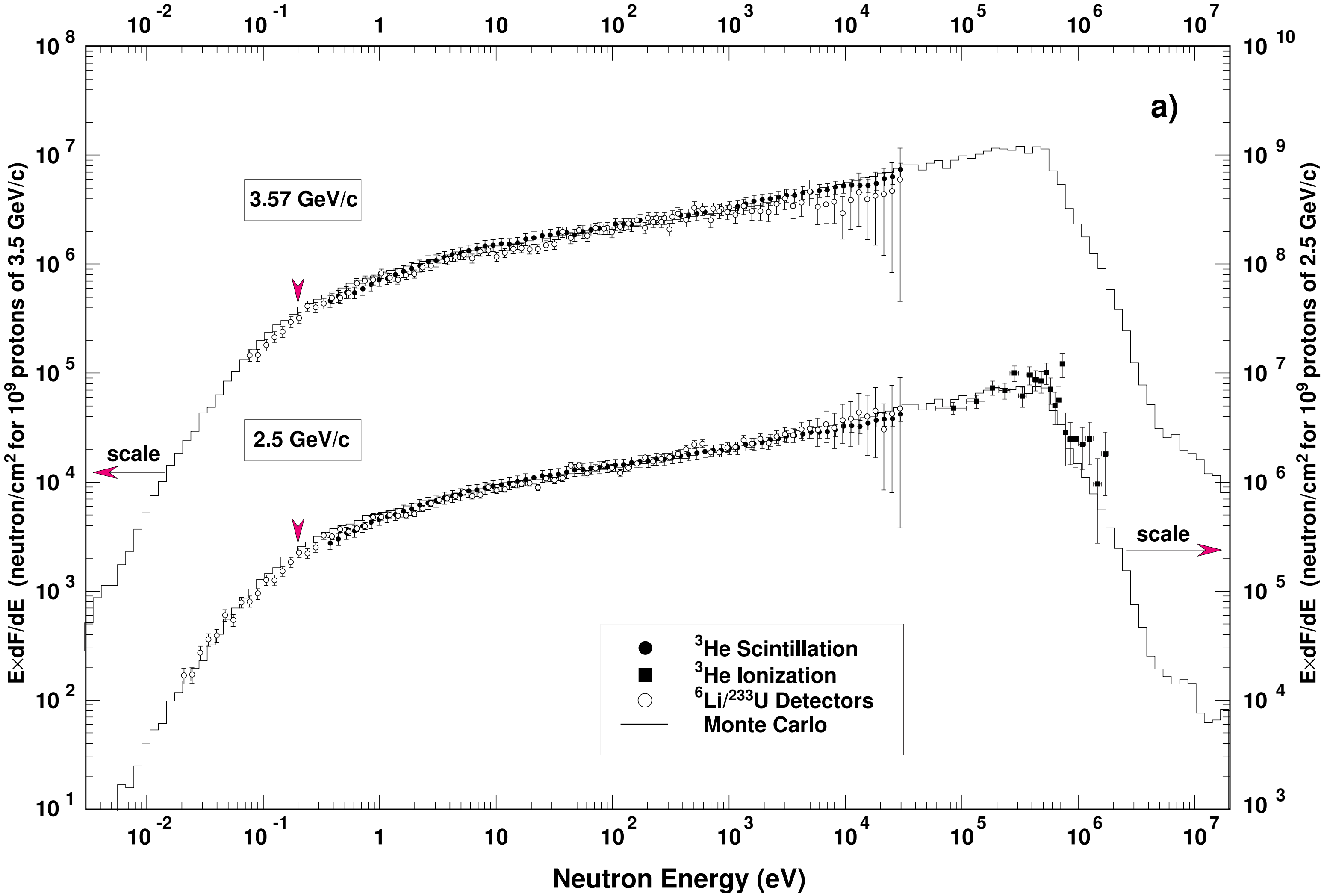
Pb(p,xn) at 800 MeV (histo FLUKA, full dots NST32, 827 (1995), open circles NSE112, 78 (1992)): left ***without*** coalescence, right ***with*** coalescence

The TARC experiment at CERN:

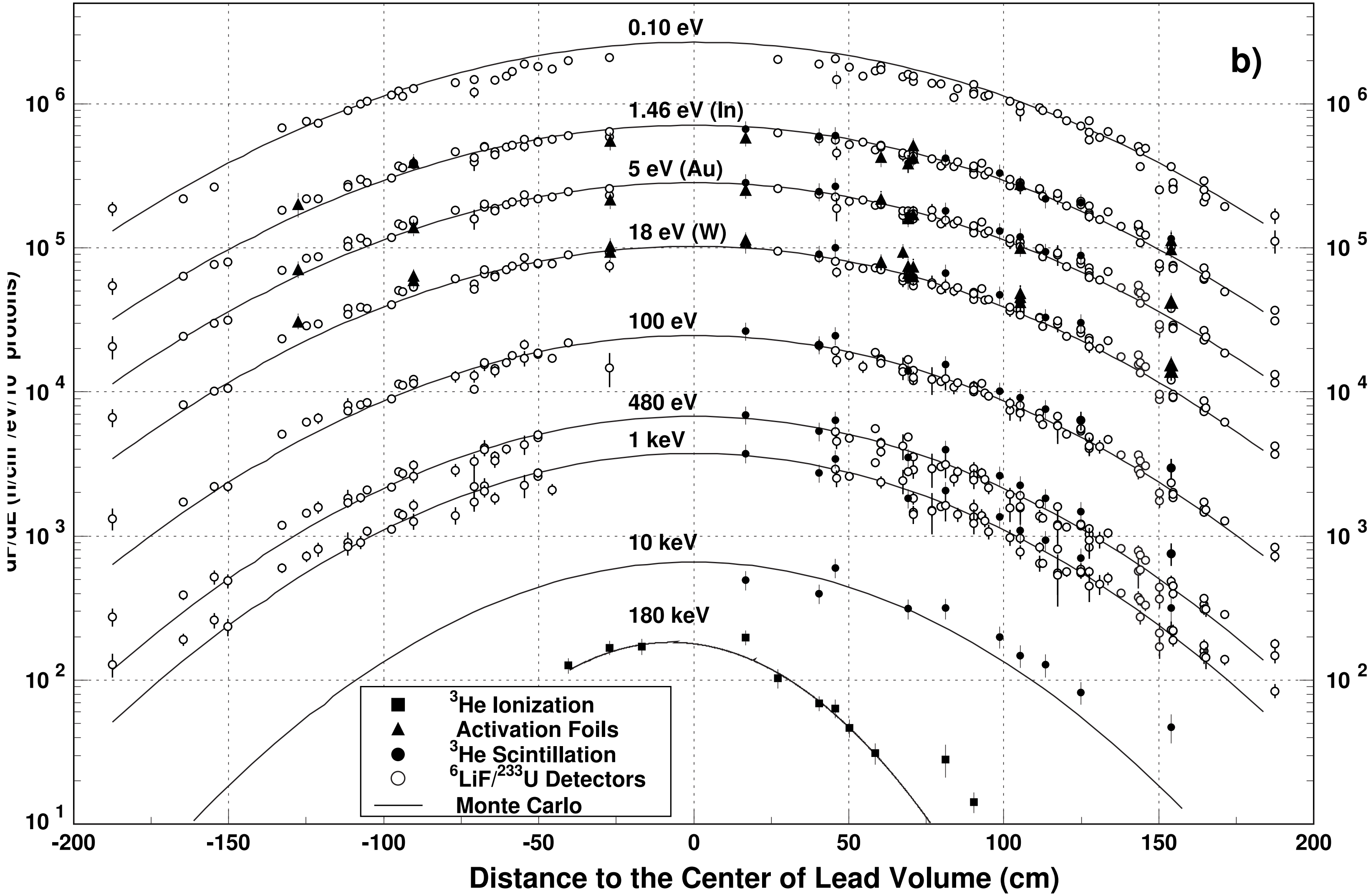


The TARC experiment: neutron spectra

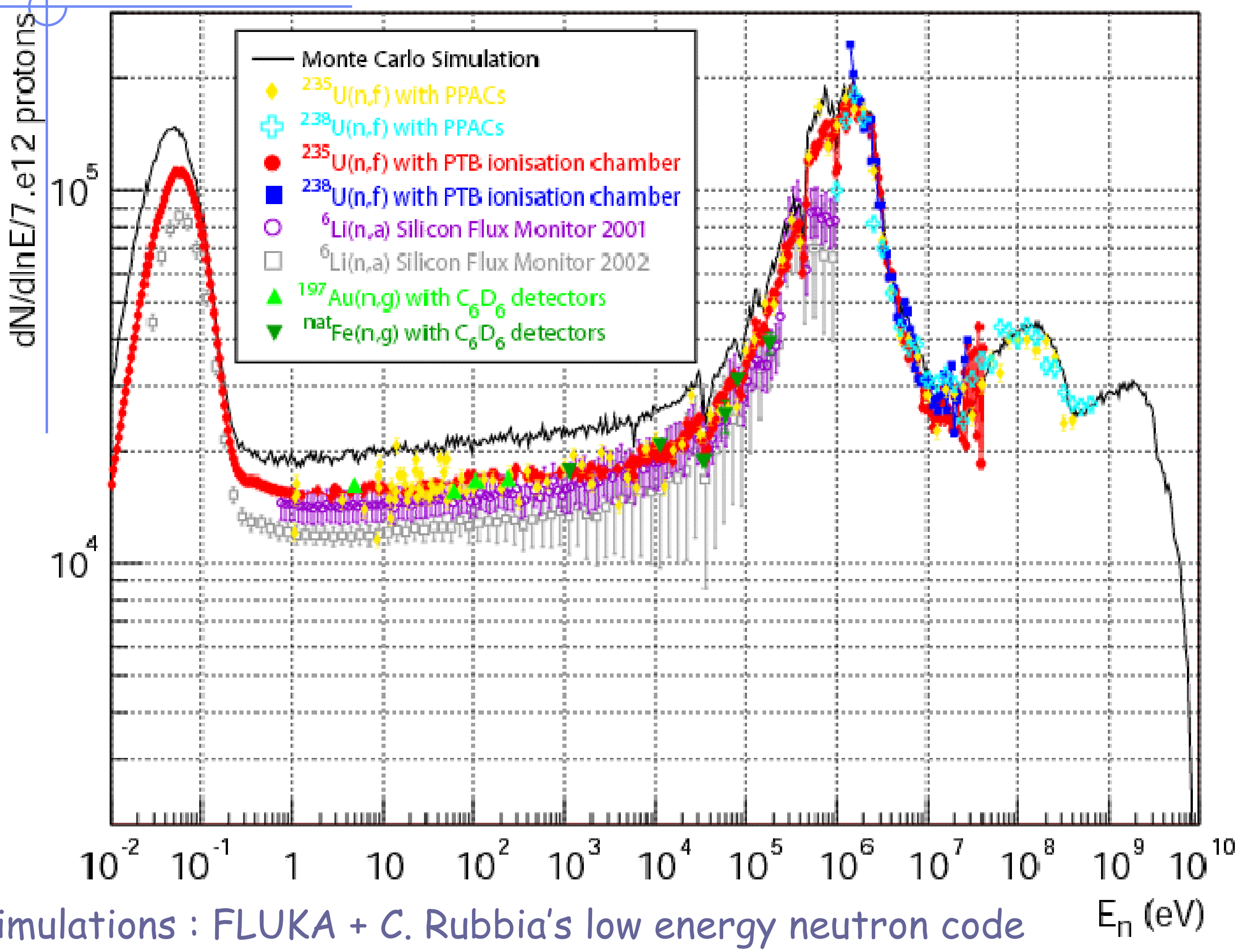
FLUKA + EA-MC (C.Rubbia et al.)



The TARC experiment: spatial distribut.



n_ToF (FLUKA + EA-MC)

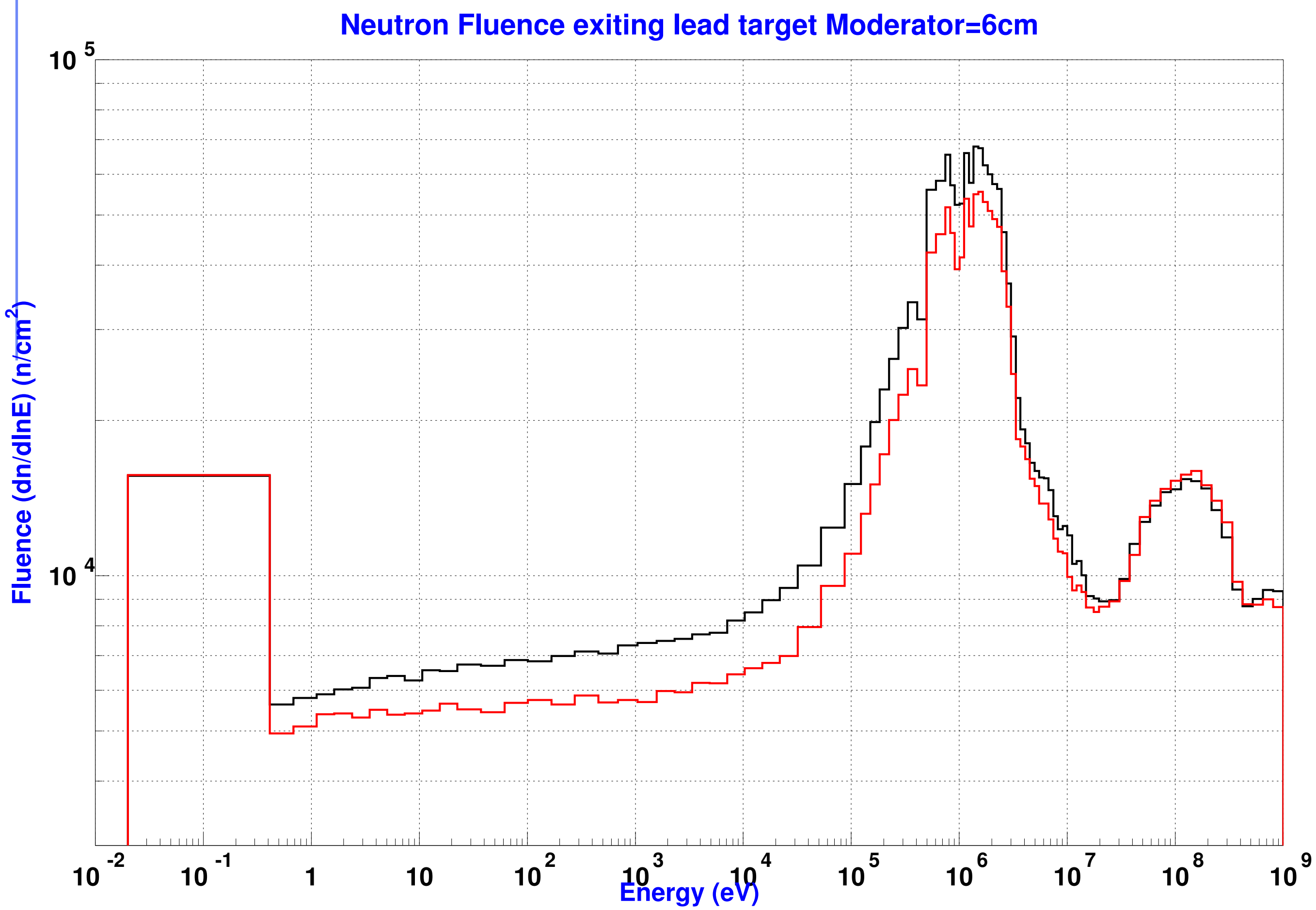


The n_ToF facility at CERN: neutron beam with excellent energy resolution for cross section studies

Beam from PS : 20 GeV/c protons + massive Lead target
Water moderator neutron beam line

Simulations : FLUKA + C. Rubbia's low energy neutron code
Assumption : 5 cm water moderator as in the design of the facility. Comparison with measured neutron spectrum shows up to 20% difference in the range 1-10^5 eV (published data)

n-TOF: … surprise … surprise



Preparing for Lead target removal: discovery that the water layer is 6 cm thick instead of 5

FLUKA simulations with 6 cm water (red) compared with 5 cm (black)

PRELIMINARY, thanks to V. Vlachoudis-CERN

Equilibrium particle emission

- **Evaporation**: Weisskopf-Ewing approach
  - 600 possible emitted particles/states (A<25) with an extended 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
  - Emission energies from the width expression with no. approx.
  - Mass table extended to A=330
  - Pairing energies and shell corrections consistent with level densities and with the extended mass table
- **Fission**:
  - Fission/evaporation competition done on first principles
  - Improved mass and charge widths
  - Detailed fission barrier and level density calculations
  - Fission level density enhancement at saddle point washing out with excitation energy
- **Fermi Break-up** for A<18 nuclei
  - ~ 50000 combinations included with up to 6 ejectiles
- **γ de-excitation**: statistical + rotational + tabulated levels

Equilibrium particle emission (evaporation, fission, and nuclear break-up)

From statistical considerations and the detailed balance principle, the probabilities for emitting a particle of mass m_j, spin $S_j \hbar$ and energy E, or of fissioning are given by:
(i, f for initial/final state, Fiss for fission saddle point)

Probability per unit time of emitting a particle j with energy E

$$P_J = \frac{(2S_j+1)m_j c}{\pi^2 \hbar^3} \int_{V_j}^{U_i - Q_j - \Delta_f} \frac{\rho_f(U_f)}{\rho_i(U_i)} \sigma_{inv}(E) E dE$$

Probability per unit time of fissioning

$$P_{Fiss} = \frac{1}{2\pi\hbar} \int_0^{U_i - B_{Fiss}} \frac{\rho_{Fiss}(U_i - B_{Fiss} - E)}{\rho_i(U_i)} dE$$

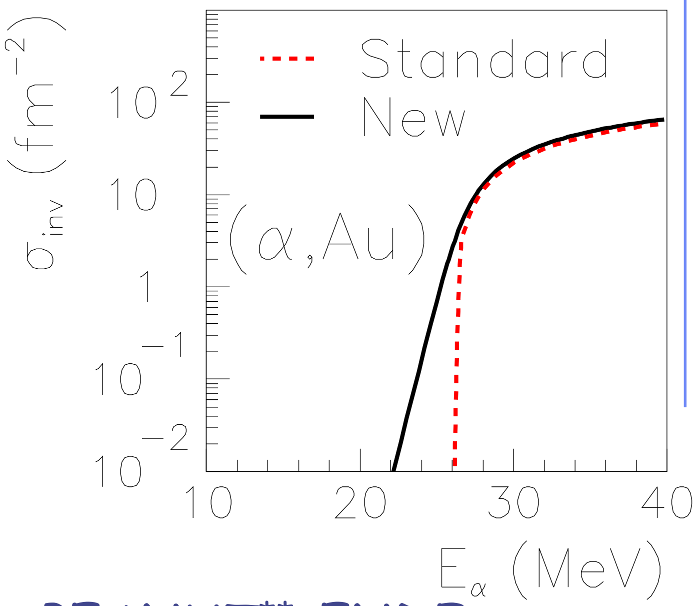
- ρ's: nuclear level densities
- U's: excitation energies
- V_j's: possible Coulomb barrier for emitting a particle type j
- B_{Fiss}: fission barrier

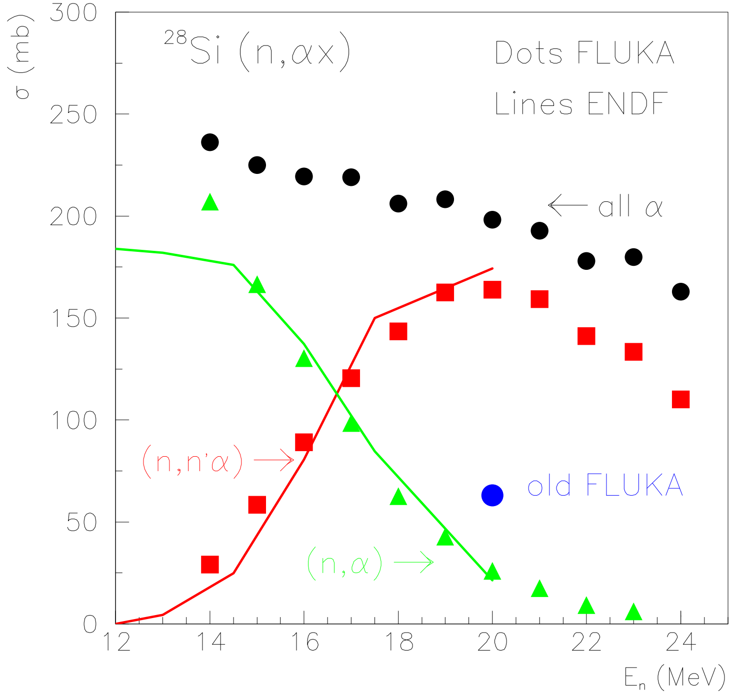
- Q_j's: reaction Q for emitting a particle type j
- σ_{inv}: cross section for the inverse process
- Δ's: pairing energies

Neutron emission is strongly favoured because of the lack of any barrier
Heavy nuclei generally reach higher excitations because of more intense cascading

Sub-barrier emission:

$$\sigma_{inv}^{x} = \left(R + \bar{\lambda}\right)^2 \frac{\hbar\omega_x}{2E} \ln\left[1 + e^{\frac{2\pi(E-V_c)}{\hbar\omega_x}}\right]$$





Comparison PEANUT**-ENDF
Excitation function for α particle production by neutrons on Si.
Symbols: PEANUT
Lines: ENDF
The blue point is total α emission calculated without sub-barrier

**in standard FLUKA simulations PEANUT is NOT used for neutrons below 20 MeV, where the multigroup treatment is at work

Evaporation/(pseudo)fragmentation: ingredients

- Nuclear masses up to A=330, from experimental databases supplemented by calculated masses following the RIPL-2 IAEA report (2005). The use of masses calculated offline with high reliability models allows:
  - to extend to A larger than those experimentally accessible,
  - to minimize resorting to empirical mass formulae online which often generate artifacts
- Shell corrections (Moller and NiX) coherent with the masses
- Full energy dependence of level densities
- Energy dependent (a la Ignyatuk), self-consistent level densities parameters according to the IAEA RIPL-2 working group recommendations
- Pairing energies consistent with the above point
- Up to 600 different ejectiles (fragmentation always binary-like)
- Dependence of barrier, radii etc on excitation/temperature
- Fermi break-up for A<18 nuclei (~ 50000 combinations included with up to 6 ejectiles)

Evaporation: integration of widths

- Exact integration of Γ_i (E) and Γ_f (E) accounting for the full U dependence of the level density formula (neglecting only the level density parameter, a, dependence on U, taken into account by rejection later) and the inverse cross section with sub-barrier expression
- Exact sampling of the evaporated fragment energy by numerical inversion of the Γ_i (E) integral
- Possibility of γ emission competition
- (Rough) account for discrete states below pairing
- Initial account for some spin/parity effect for low-lying states
- Plans to do something specific for isomers

Fission Model: details

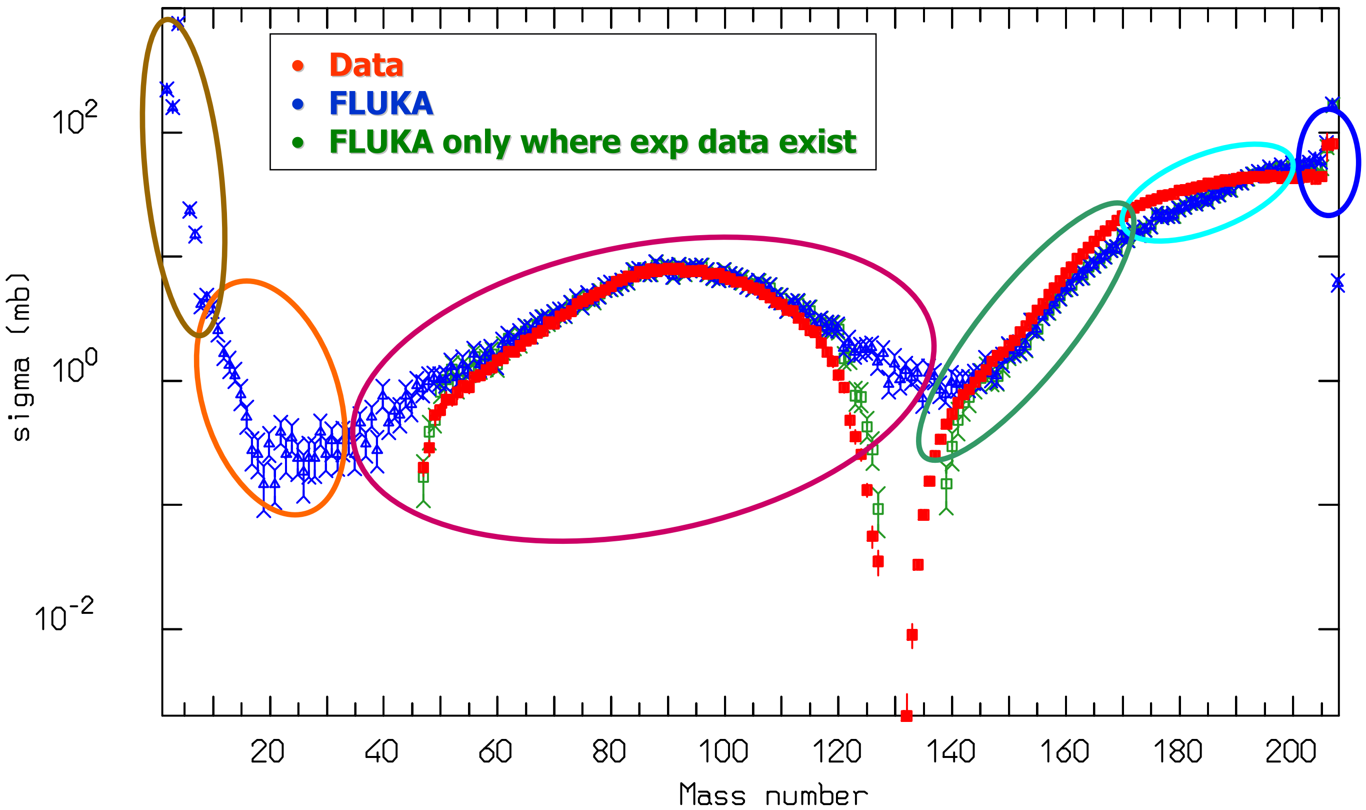
- Fission probability from explicit Γ_{fiss} expression for all isotopes including Actinides
- Fission barrier systematics following Myers & Swiatecki (Phys. ReV. C60, 014606 (1999))
- Double humped barrier for Actinides
- Fission level density enhancement at saddle point washing out with excitation energy in agreement with IAEA RIPL-2
- Fission product widths and asymmetric versus symmetric probabilities accurately parameterized according to recent data/approaches
- Work on using angular momenta from the "fast" stage in progress

Evaporation/fission models are unavoidably cross-linked (and should be adapted accordingly) with the "fast" stage description, and in particular on the extent of the (G)INC stage, the presence and time extent of a preequilibrium stage (and coalescence, availability of angular momenta infos, etc …).
The expectation that "fast" and "equilibrium" stages can be assembled like independent bricks is naïve

Example of fission/evaporation

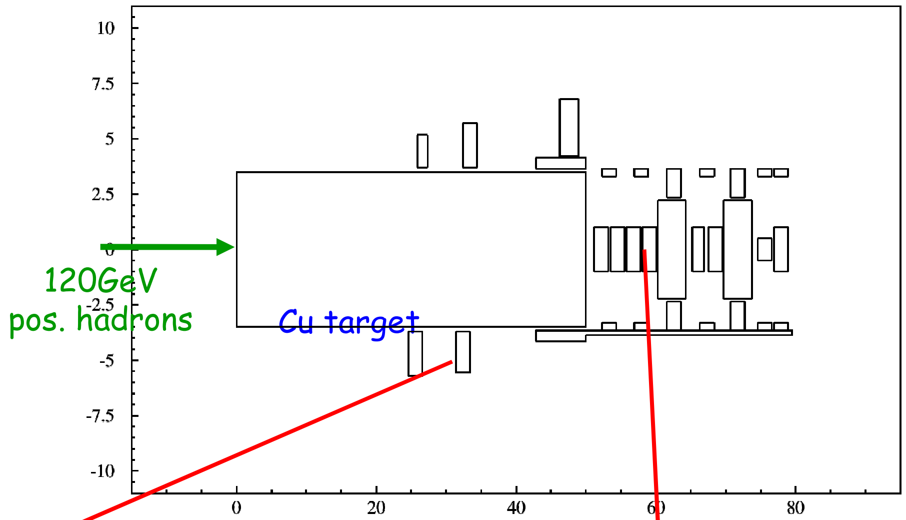
- Quasi-elastic products
- Spallation products
- Deep spallation products
- Fission products
- Fragmentation products
- Evaporation products

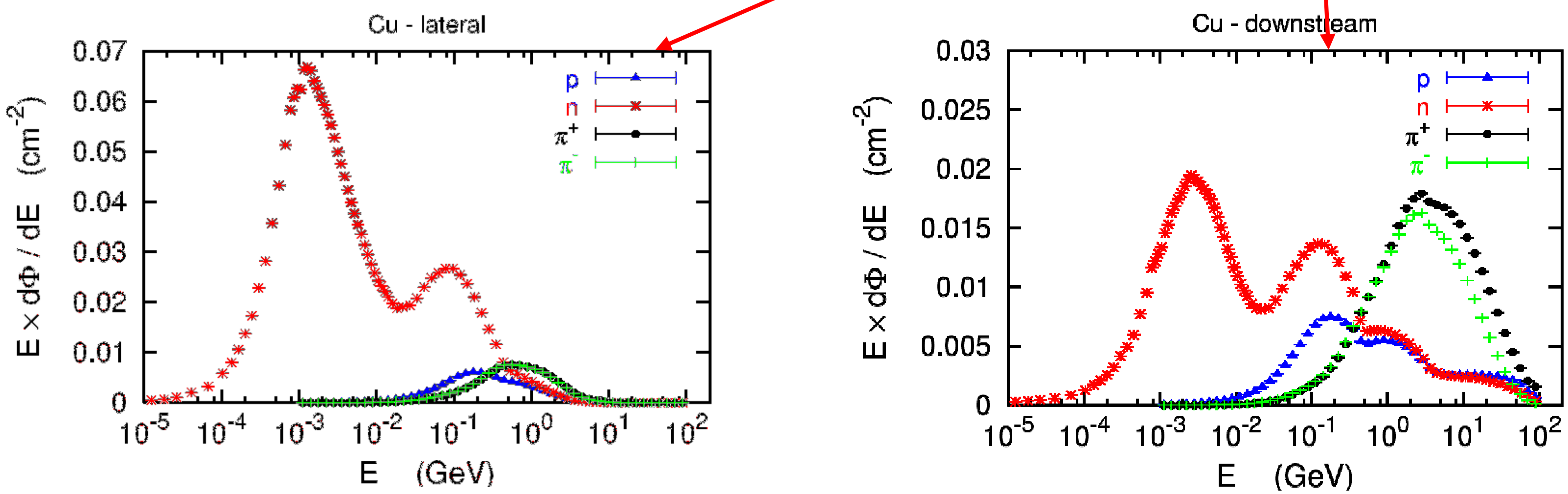
1 A GeV ^{208}Pb + p reactions Nucl. Phys. A 686 (2001) 481-524



Activation Benchmark Experiments at CERN:

Irradiation of samples of different materials to the stray radiation field created by the interaction of a 120 GeV positively charged hadron beam in a copper target





Isotope		Copper		Iron		Titanium		Stainless Steel			Aluminum			Concrete		
^{7}Be	53.29d	1.47 ± 0.19	M	1.65 ± 0.22		1.50 ± 0.19		0.98 ± 0.24	M	C,N	0.71 ± 0.09		Al	1.17 ± 0.14		O, C
		0.84 ± 0.25		0.90 ± 0.15												
^{22}Na	2.60y	0.72 ± 0.11		0.70 ± 0.13	M	0.85 ± 0.11		———			0.76 ± 0.07		Al	0.86 ± 0.09		Ca,(Si,Mg)
^{24}Na	14.96h	0.42 ± 0.03		0.48 ± 0.02		0.63 ± 0.02		0.37 ± 0.02		Fe,(Cr,Si)	0.81 ± 0.03		Al,Mg	0.62 ± 0.02		Ca,(Si,Al)
^{27}Mg	9.46m					0.79 ± 0.14	M				1.52 ± 0.25		Al,Mg			
^{28}Mg	20.91h	0.25 ± 0.04	-	0.23 ± 0.03	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.02	-	Ca,(Si)
^{28}Al	2.24m	0.25 ± 0.03	-	0.21 ± 0.02	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.03	-	Ca,(Si)
^{29}Al	6.56m			———		0.93 ± 0.25	M									
^{38}S	2.84h	———		———		0.60 ± 0.12	-	———								
^{m34}Cl	32.00m			0.91 ± 0.19	M	1.19 ± 0.16		0.77 ± 0.15		Fe,Cr,(Mn)				1.25 ± 0.07		Ca
^{38}Cl	37.24m	———		0.61 ± 0.08		0.60 ± 0.01		0.58 ± 0.07		Fe,Cr,(Mn)						
^{39}Cl	55.60m			0.64 ± 0.11	M	0.73 ± 0.08		0.66 ± 0.12		Fe,Cr,(Mn)						
^{41}Ar	1.82h	0.39 ± 0.06		0.46 ± 0.05		0.47 ± 0.04	-	0.38 ± 0.05		Fe,Cr,(Mn)				0.98 ± 0.14		Ca
^{38}K	7.64m	———		———				———						1.76 ± 0.20	-	Ca
^{42}K	12.36h	0.66 ± 0.10		0.83 ± 0.06		0.95 ± 0.05		0.76 ± 0.09		Fe,Cr,(Mn)				1.21 ± 0.08		Ca
^{43}K	22.30h	0.81 ± 0.10	-	0.77 ± 0.05		0.85 ± 0.03		0.74 ± 0.04		Fe,Cr,(Mn)	———			1.16 ± 0.05		Ca
^{44}K	22.13m					———										
^{45}K	17.30m					———										
^{47}Ca	4.54d	0.59 ± 0.16		0.56 ± 0.17	M	0.73 ± 0.12		0.51 ± 0.15	M	Fe,Cr,(Mn)				0.79 ± 0.12		Ca
^{43}Sc	3.89h	0.40 ± 0.07	-	1.01 ± 0.14		1.28 ± 0.28	-	0.93 ± 0.15		Fe,Cr,(Mn)						
^{44}Sc	3.93h	0.89 ± 0.07		1.06 ± 0.06		0.88 ± 0.05		0.96 ± 0.08		Fe,Cr,(Mn)	———			0.83 ± 0.06		Fe,(Ti)
^{m44}Sc	58.60h	0.95 ± 0.12		1.20 ± 0.09		2.13 ± 0.12		1.24 ± 0.09		Fe,Cr,(Mn)	1.08 ± 0.17		Fe,Mn	1.67 ± 0.22		Fe,(Ti)
^{46}Sc	83.79d	0.81 ± 0.07		0.86 ± 0.07		0.93 ± 0.08		0.89 ± 0.08		Fe,Cr,(Mn)	0.79 ± 0.18		Mn,(Ti,Fe)	0.88 ± 0.10		Fe,(Ti)
^{47}Sc	80.28h	1.09 ± 0.14		1.17 ± 0.10	-	0.87 ± 0.07		1.06 ± 0.09		Fe,Cr,(Mn)	1.04 ± 0.15		Mn,(Ti,Fe)	1.00 ± 0.09		Fe,Ti,(Ca)
^{48}Sc	43.67h	1.39 ± 0.16		1.47 ± 0.10		1.10 ± 0.04		1.42 ± 0.08		Fe,Cr,(Mn)				1.36 ± 0.25		Fe,Ti,(Ca)
^{48}V	15.97d	1.16 ± 0.08		1.45 ± 0.06		1.11 ± 0.07		1.44 ± 0.11		Fe,Cr,(Mn)	1.07 ± 0.13		Fe,Mn	1.63 ± 0.16		Fe
^{48}Cr	21.56h	0.92 ± 0.14		0.97 ± 0.07				1.02 ± 0.08		Fe,(Cr)				1.06 ± 0.23	M	Fe
^{49}Cr	42.30m	1.00 ± 0.22	M	1.24 ± 0.12	-			1.06 ± 0.12		Fe,(Cr)						
^{51}Cr	27.70d	1.06 ± 0.13		1.15 ± 0.12		0.64 ± 0.24	M	1.24 ± 0.16		Fe,Cr	0.86 ± 0.16		Fe,Mn	1.33 ± 0.22		Fe
^{52}Mn	5.59d	0.68 ± 0.05		1.15 ± 0.04				1.09 ± 0.03		Fe,(Mn)	0.88 ± 0.07		Fe,Mn	1.39 ± 0.07		Fe
^{m52}Mn	21.10m	1.68 ± 0.35		1.24 ± 0.09				1.12 ± 0.10		Fe,(Mn)				1.75 ± 0.79	M	Fe
^{54}Mn	312.12d	1.13 ± 0.12		1.01 ± 0.10				1.08 ± 0.11		Fe,(Mn)	0.96 ± 0.12		Mn,Fe	1.06 ± 0.13		Fe
^{56}Mn	2.58h	0.81 ± 0.06		0.99 ± 0.05				1.33 ± 0.10		Fe	1.53 ± 0.25		Mn	1.03 ± 0.25		Mn,Fe
^{52}Fe	8.28h	———		1.09 ± 0.13				0.99 ± 0.19	M	Fe,(Mn)						
^{53}Fe	8.51m			———												
^{59}Fe	44.50d	0.82 ± 0.09														
^{55}Co	17.53h	0.66 ± 0.09		0.76 ± 0.04				1.03 ± 0.05		Fe,Ni				———		
				1.13 ± 0.10												
^{56}Co	77.27d	1.04 ± 0.08		1.15 ± 0.10				1.37 ± 0.11		Fe,Ni	———			0.80 ± 0.20	M	Fe
				1.79 ± 0.15												
^{57}Co	271.79d	0.85 ± 0.09		0.38 ± 0.09	M			1.16 ± 0.13		Ni	0.66 ± 0.24	M	Cu,Zn,Ni			
^{58}Co	70.82d	0.91 ± 0.09		0.31 ± 0.08	M			0.98 ± 0.10		Ni	0.82 ± 0.19		Cu,Zn,Ni	———		
^{60}Co	5.27y	0.90 ± 0.08														
^{61}Co	99.00m	0.68 ± 0.08														
^{62}Co	90.00s	———														
^{57}Ni	35.60h	0.76 ± 0.11		———				1.44 ± 0.07		Ni				———		
^{65}Ni	2.52h	1.46 ± 0.29														
^{60}Cu	23.70m	0.78 ± 0.08														
^{61}Cu	3.33h	0.87 ± 0.25														
^{64}Cu	12.70h	0.63 ± 0.10														
^{62}Zn	9.19h	1.05 ± 0.23														
^{63}Zn	38.47m	———														
^{65}Zn	244.26d	0.62 ± 0.08														
		0.97 ± 0.20														

R = Ratio FLUKA/Exp

$0.8 < R < 1.2$

$0.8 < R \pm Error < 1.2$

Exp/MDA < 1

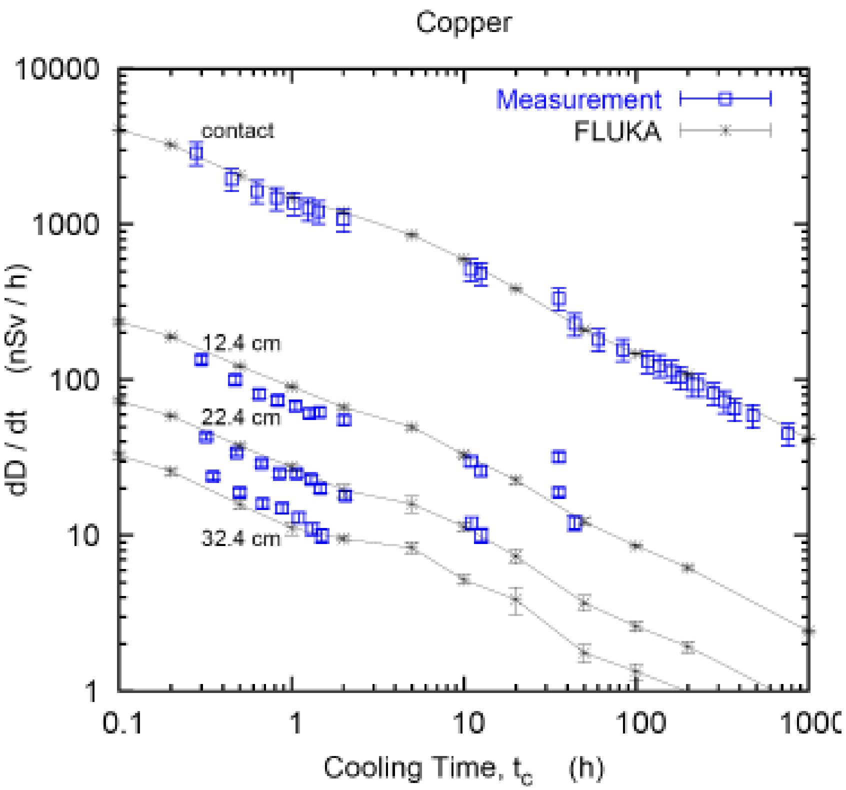
$R + Error < 0.8$ or
$R - Error > 1.2$

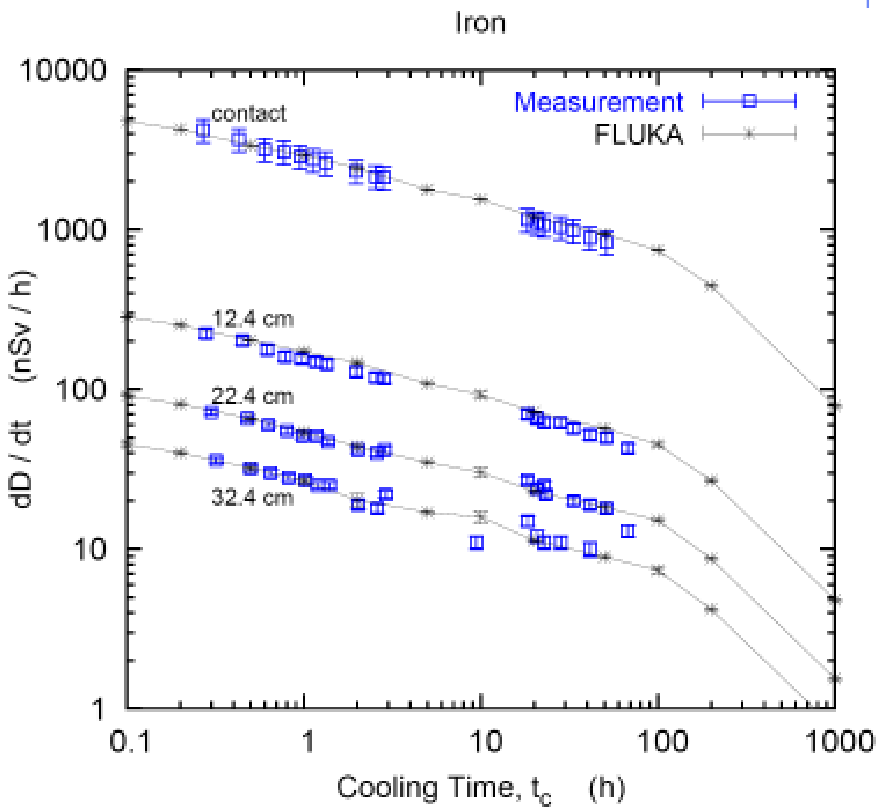
Reference:
M. Brugger, *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

Benchmark Experiment - *Residual Dose Rates*

Reference: M. Brugger *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Dose rate as function of cooling time
for different distances between sample and detector





Benchmark Experiment - *Residual Dose Rates*

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Dose rate as function of cooling time
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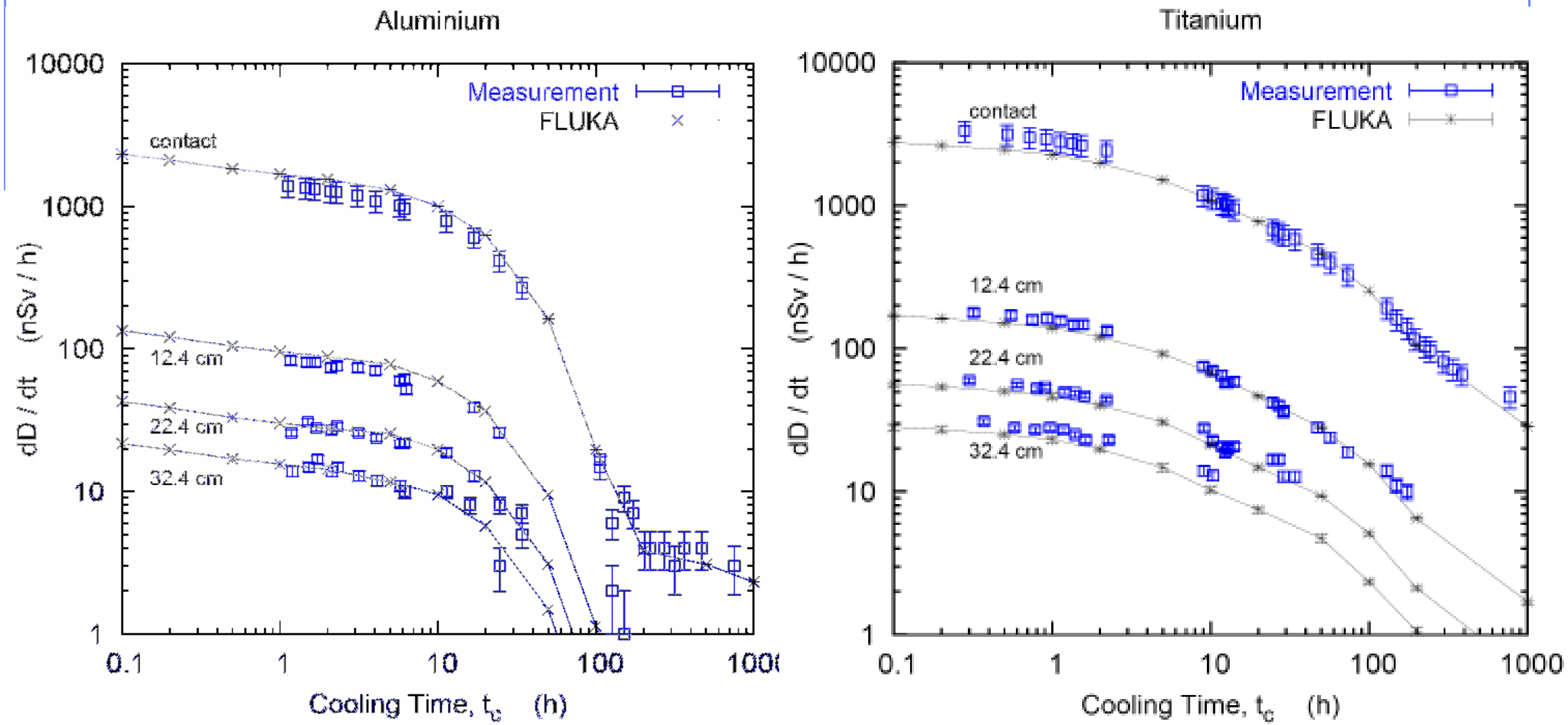

Benchmark Experiment - *Residual Dose Rates*

<u>Reference:</u> M. Brugger *et al.*, Radiat. Prot. Dosim. 116 (2005) 12-15

Dose rate as function of cooling time
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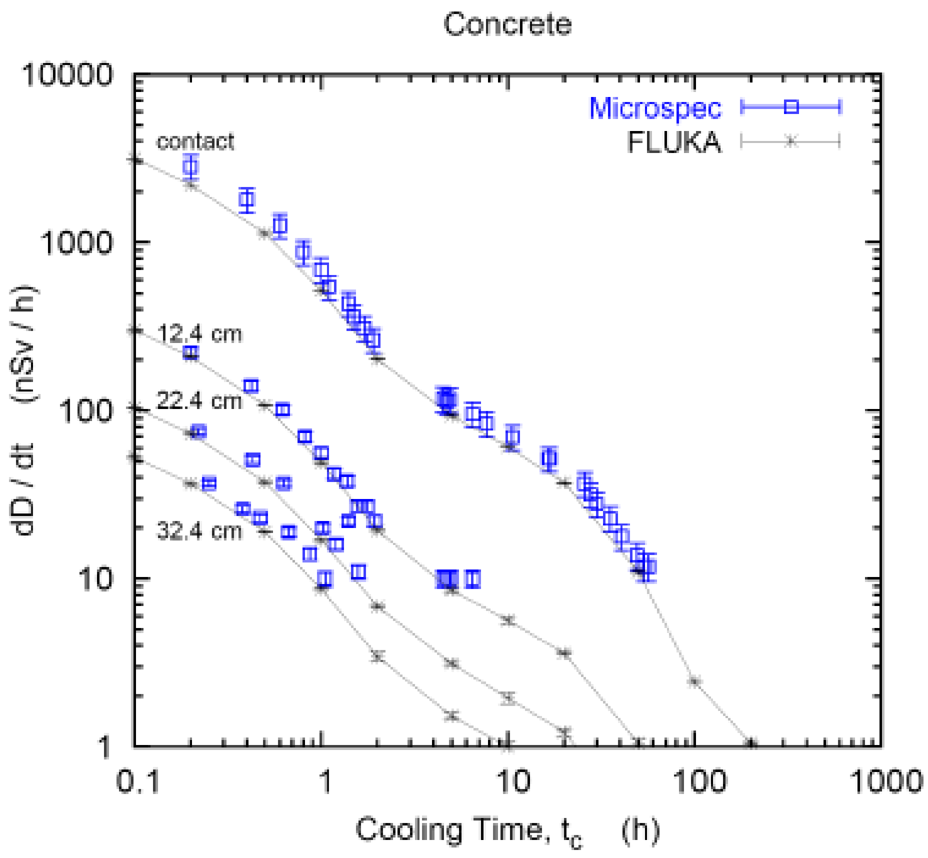


Heavy ion interaction models in FLUKA

E (GeV/A): 10^{10} — 5 — 0.1

Electromagnetic dissociation

DPMJET-III

DPMJET (R. Engel, J. Ranft , S. Roesler[1]): Nucleus-Nucleus interaction model. Used in many Cosmic Ray shower codes. Based on the Dual Parton Model and formation zone Glauber cascade, like the high-energy FLUKA h-A event generator

Modified version of rQMD-2.4

rQMD-2.4 (H. Sorge et al.[2]) Cascade-Relativistic QMD model
Successfully applied to relativistic A-A particle production

BME (BoltzmannMasterEquation)

FLUKA implementation of BME from E.Gadioli et al (Milan)
Now ready for initial release

FLUKA Evaporation-fission-fragmentation module handles fragment deexcitation **Tested and benchmarked** in h-A reactions

(Projectile-like evaporation is responsible for the most energetic fragments)

[1] proc. MC2000 , p 1033 (2001)
[2] NPA 498, 567c (1989), Ann.Phys. 192,266 (1989), PRC 52, 3291 (1995)

BME – *The interface for A-A reactions below 100 MeV/n*

A first version of the BME (*Boltzmann Master Equations* NPA **643**, 15 (1998); **679**, 753 (2001)) event generator considering two different reaction mechanisms is included in the most recent FLUKA versions

1. COMPLETE FUSION

$P_{CF} = \sigma_{CF}/\sigma_R$

pre-equilibrium
according to the BME theory

2. PERIPHERAL COLLISION

$P = 1 - P_{CF}$

three body mechanism
or "**inelastic scattering**" (for high *b*)
or "**transfer reactions**"
(for low *b* and very asymmetric systems)

FLUKA evaporation/fission/fragmentation

1. In order to get the multiplicities of the pre-equilibrium particles and their double differential spectra, the BME theory is applied to a few significant systems at different bombarding energies and the results are parametrized

2. The complete fusion cross section decreases with increasing bombarding energy. We integrate the nuclear densities of projectile and target over their overlapping region, as a function of the impact parameter, and obtain an excited "middle source" and two fragments (projectile- and target-like). The kinematics is suggested by break-up studies.

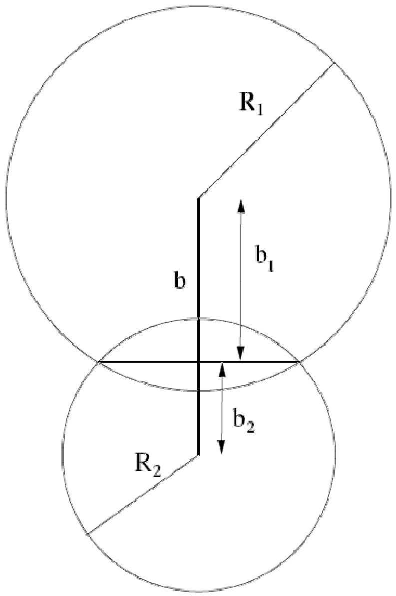
BME – *Peripheral collisions*

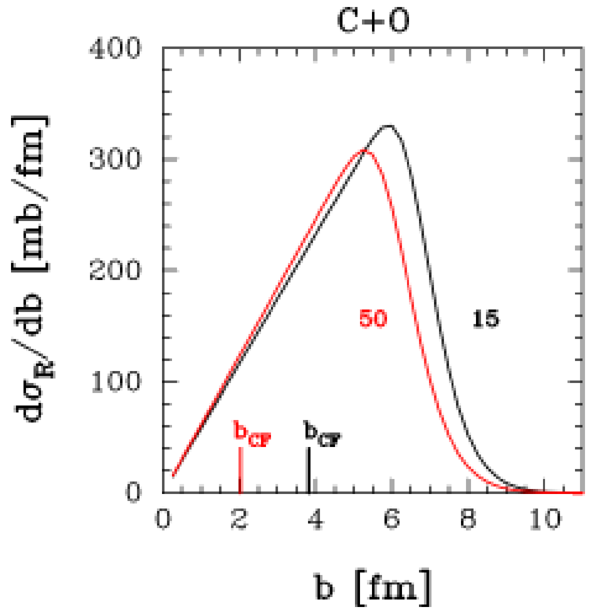
selection of the ***impact parameter***

PL

MS

TL





θ_{MS} momentum conservation ϕ_{PL} free

p_{MS} momentum conservation ϕ_{TL}, ϕ_{MS} same reaction plane

θ_{PL}, θ_{TL} sampled according to $[d\sigma/d\Omega]_{cm} \sim \exp(-k\theta_{cm})$ $k=k(A_{PL}/A_P)$

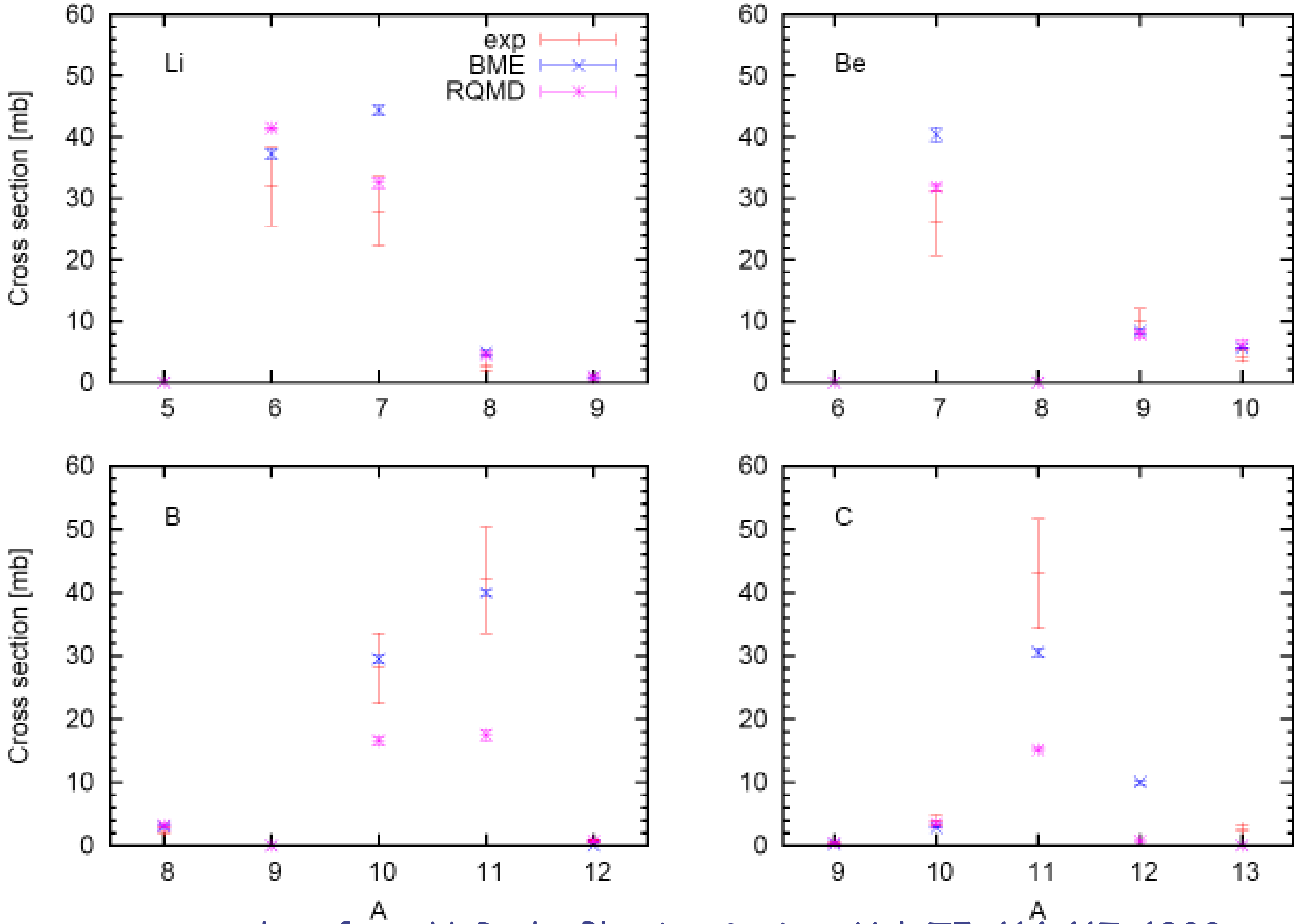
p_{PL}, p_{TL} sampled according to a uniform energy loss distribution over a given interval depending on E_{nucl}

$$E^\star_{MS} = (A_{MS}/A_{tot})E^\star_{tot}\sum_{n=0}^{k}(1 - A_{MS}/A_{tot})^n$$

$$E^\star_{PL} = f(A_{PL}, A_{TL})\left(E^\star_{tot} - E^\star_{MS}\right)$$

$$E^\star_{TL} = \left(E^\star_{tot} - E^\star_{MS} - E^\star_{PL}\right)$$

BME - *Benchmarking [I]* $^{12}C+^{12}C$ @ 86 MeV/n

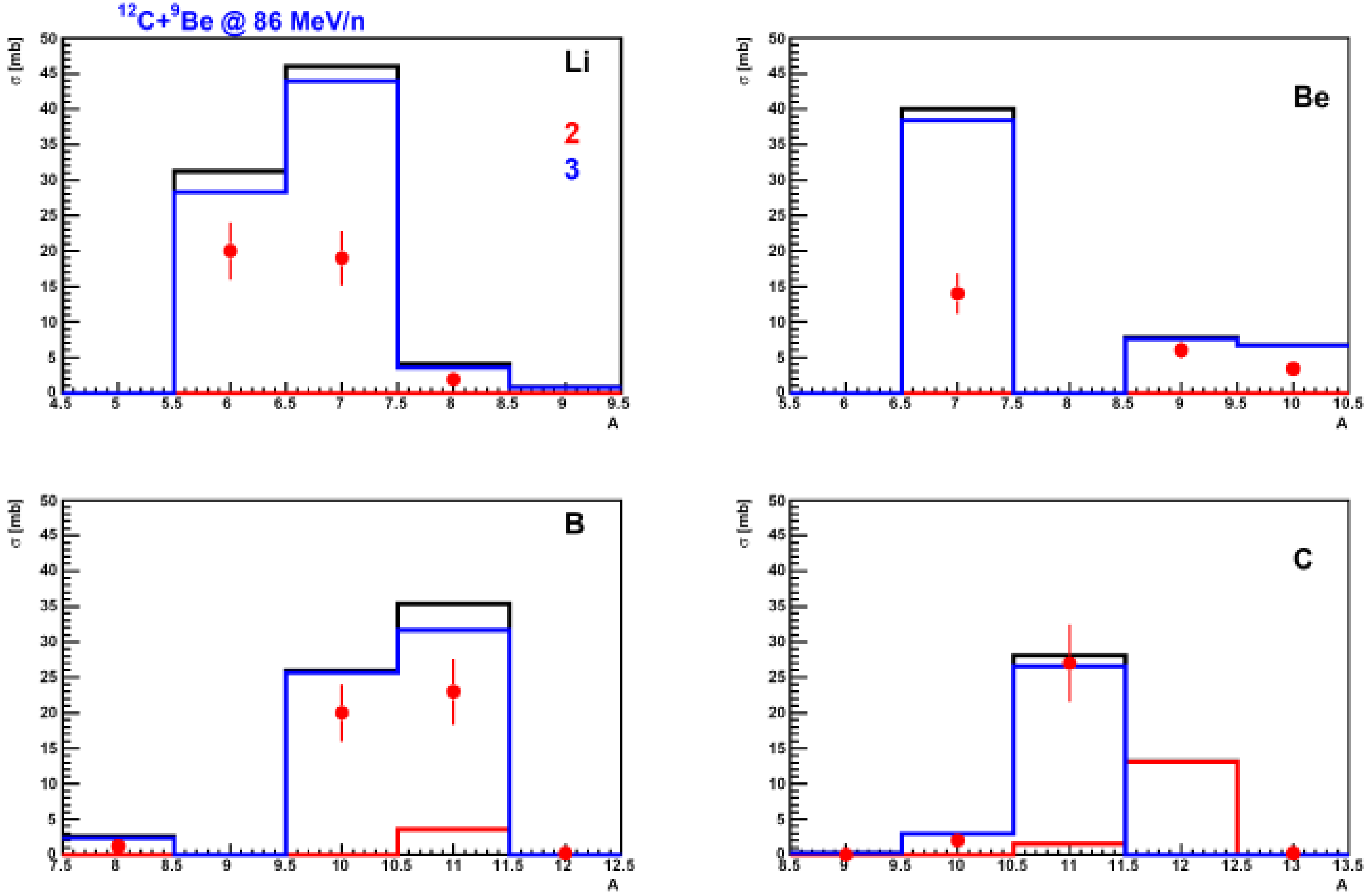


exp data from H. Ryde, Physica Scripta Vol. T5, 114-117, 1983

$2^o < \theta_{LAB} < 22^o$ $T_{LAB} > 10$ MeV/n

BME - *Benchmarking [II]*

$^{12}C+^{9}Be$ @ 86 MeV/n



exp data from H. Ryde, Physica Scripta Vol. T5, 114-117, 1983

$2^o < \theta_{LAB} < 22^o$ $T_{LAB} > 10$ MeV/n

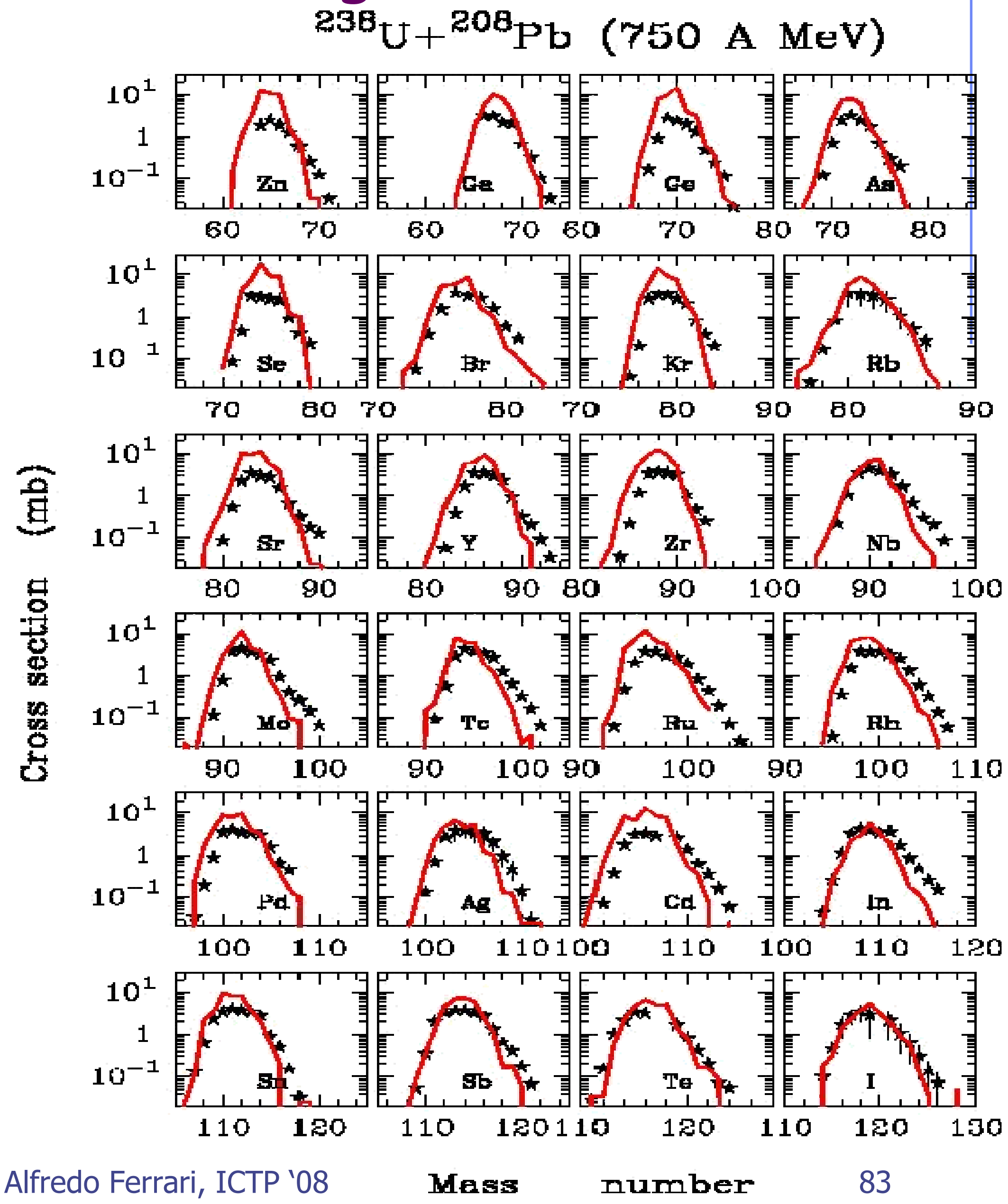
FLUKA+(modified) rQMD-2.4 fragmentation results

Fragment charge cross section for 750 MeV/n U ions on Pb.

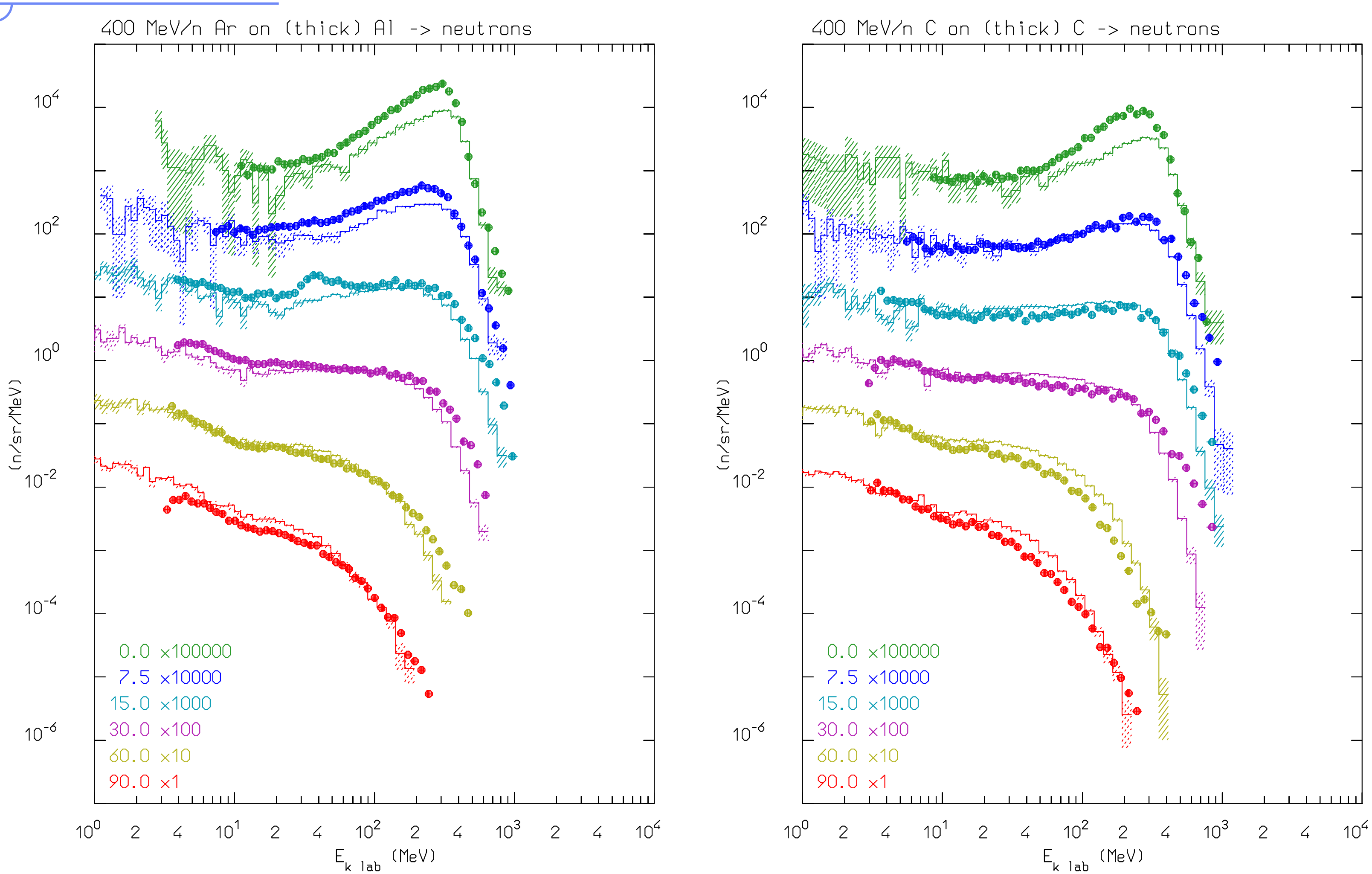
Data (stars) from

J. Benlliure, P. Ambruster et al., Eur. Phys. J. A2, 193-198 (1988).

Fission products have been excluded like in the experimental analysis

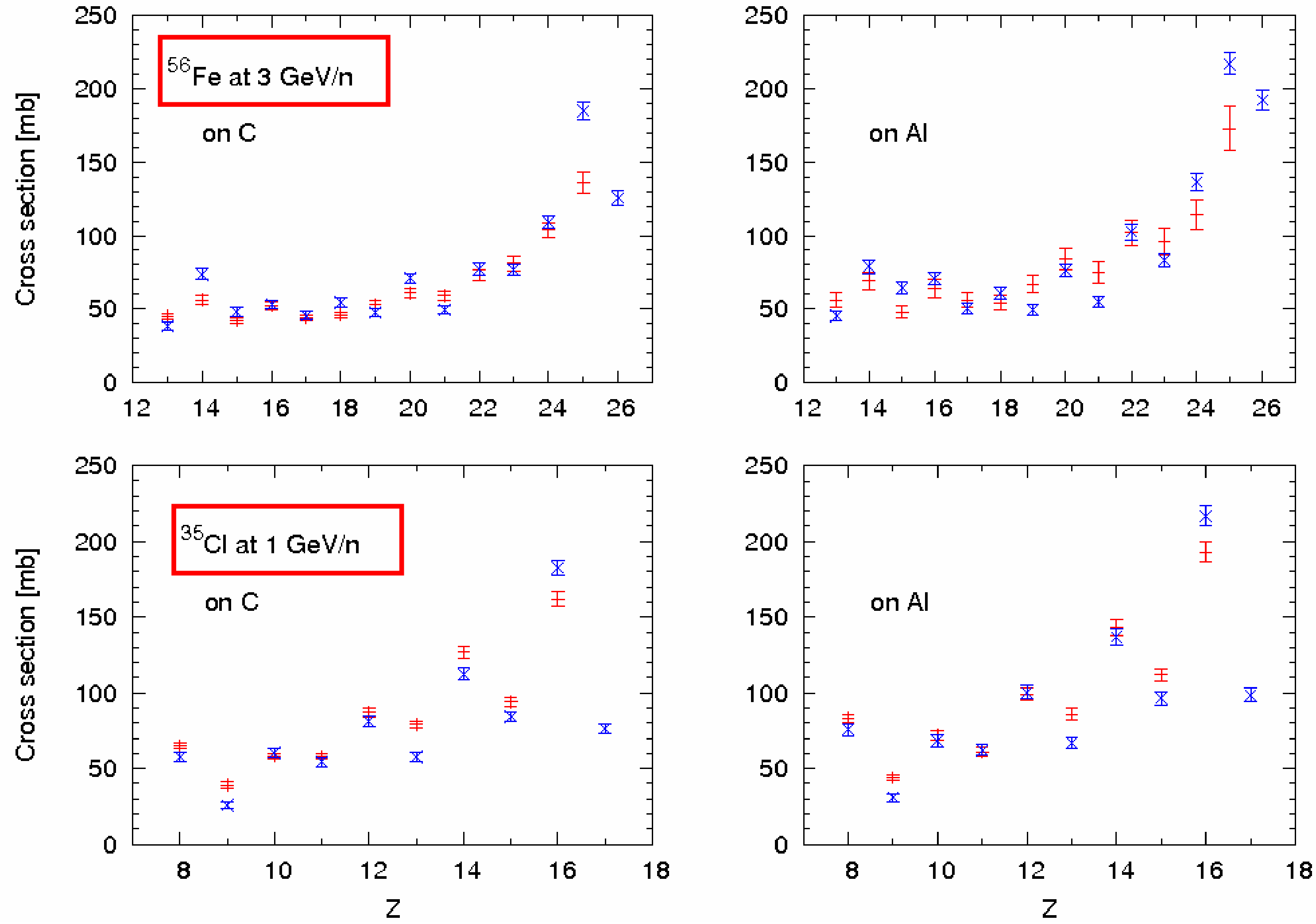


FLUKA with modified RQMD-2.4:



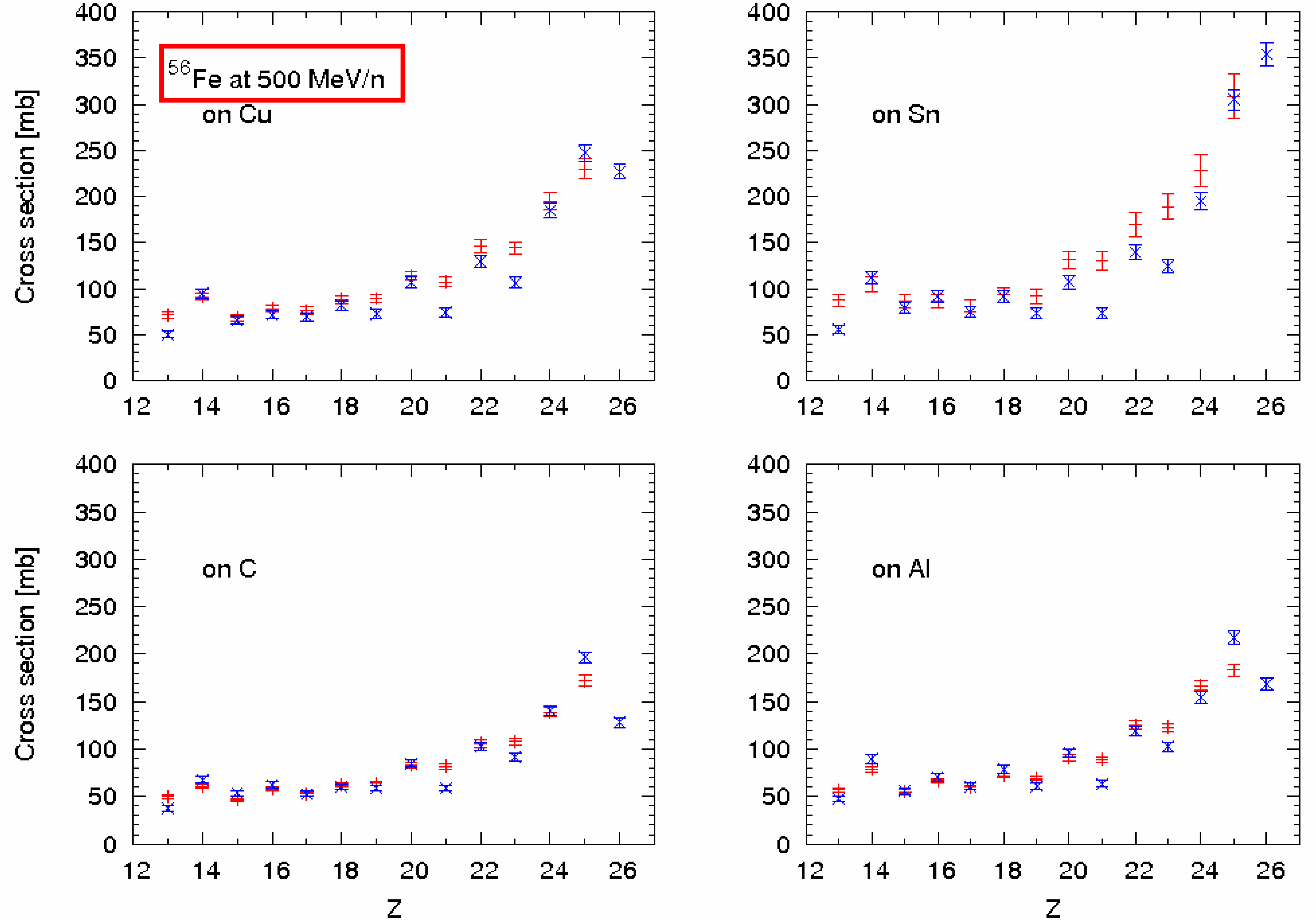
Double-differential neutron yield by 400 MeV/n Ar (left) and C (right) ions on thick Al and C targets. Histogram: FLUKA. Experimental data points: Phys. Rev. C62, 044615 (2000)

Fragmentation: 3 GeV/n Fe, 1 GeV/n Cl ions



Exp. and **MC (FLUKA)** charge fragment cross sections for 3 GeV/n Fe and 1 GeV/n Cl ions (exp. data from http://fragserver.lbl.gov/main.html)

Fragmentation: 500 MeV/n Fe ions

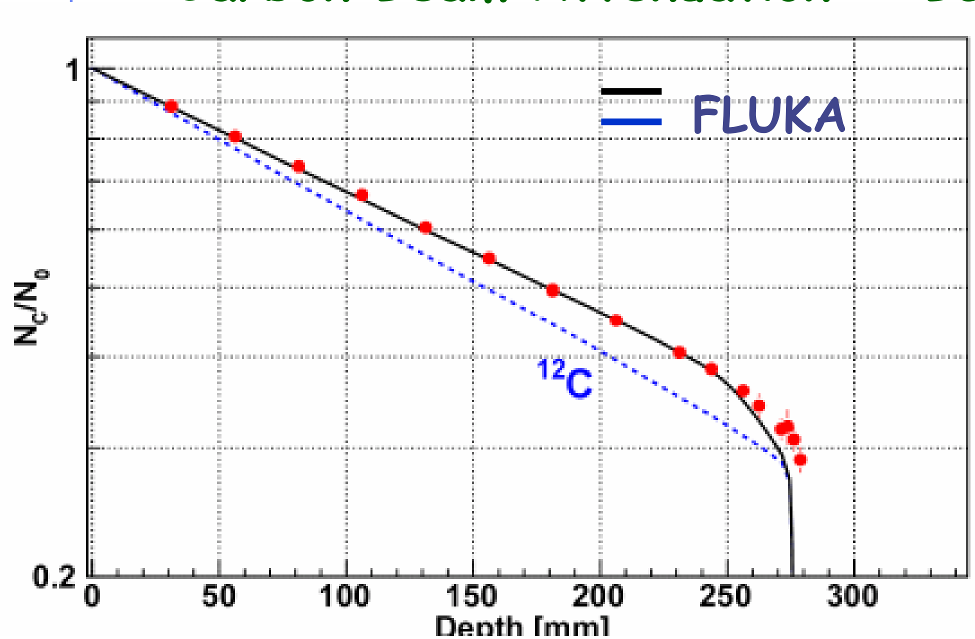


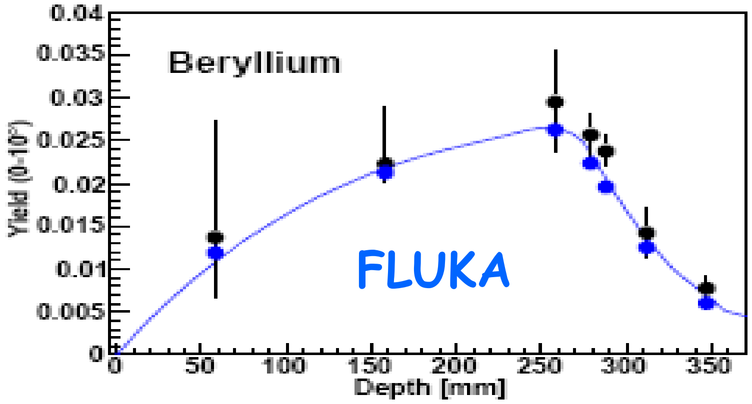
Exp. and **MC (FLUKA)** charge fragment cross sections for 500 MeV/n Fe ions (exp. data from http://fragserver.lbl.gov/main.html)

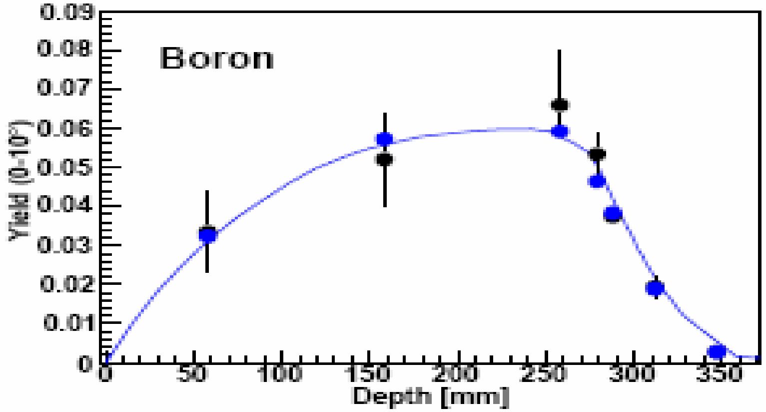
Carbon beam fragmentation:

^{12}C ions (400 MeV/u) on Water phantoms

Carbon Beam Attenuation **Build-up of secondary fragments**

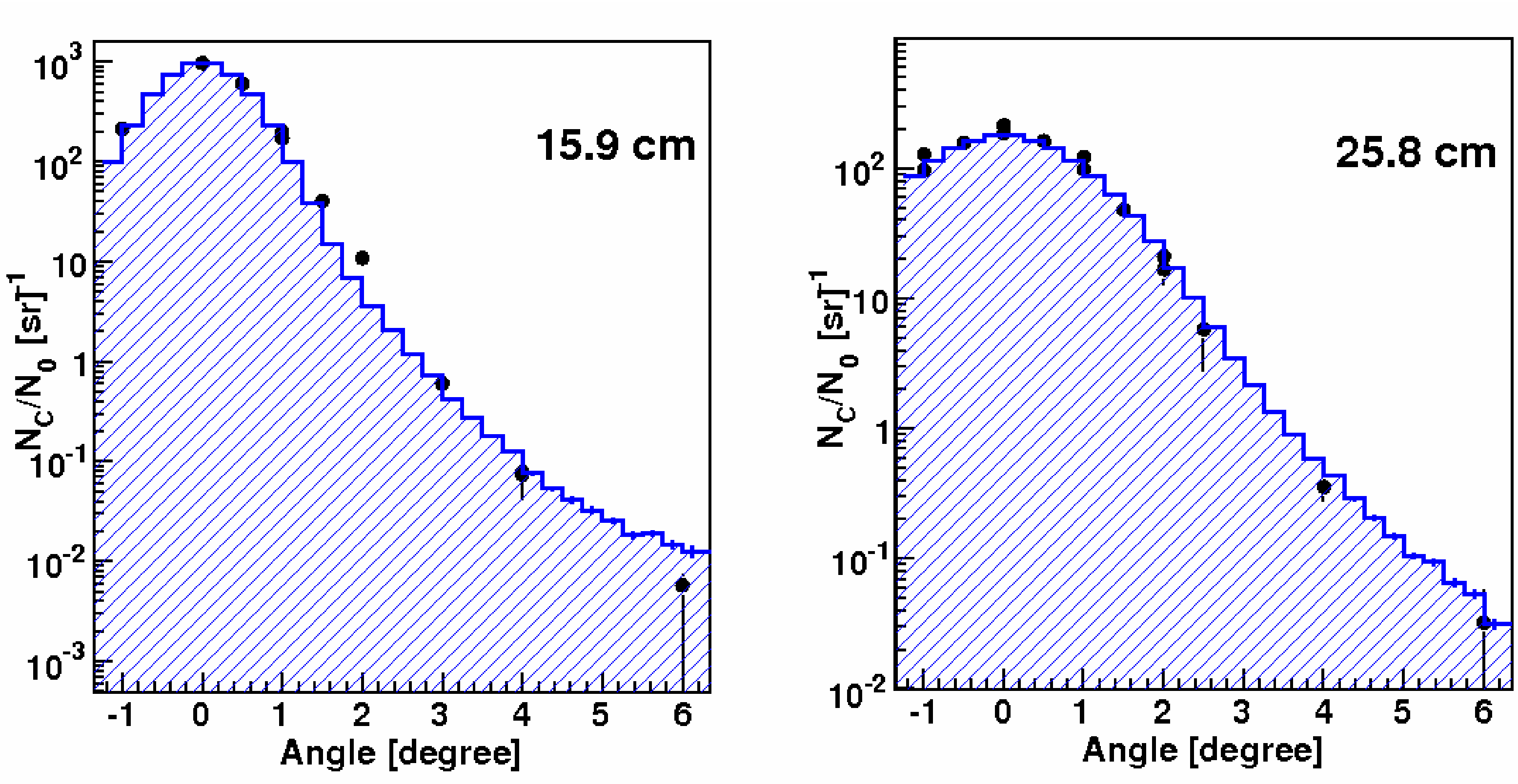






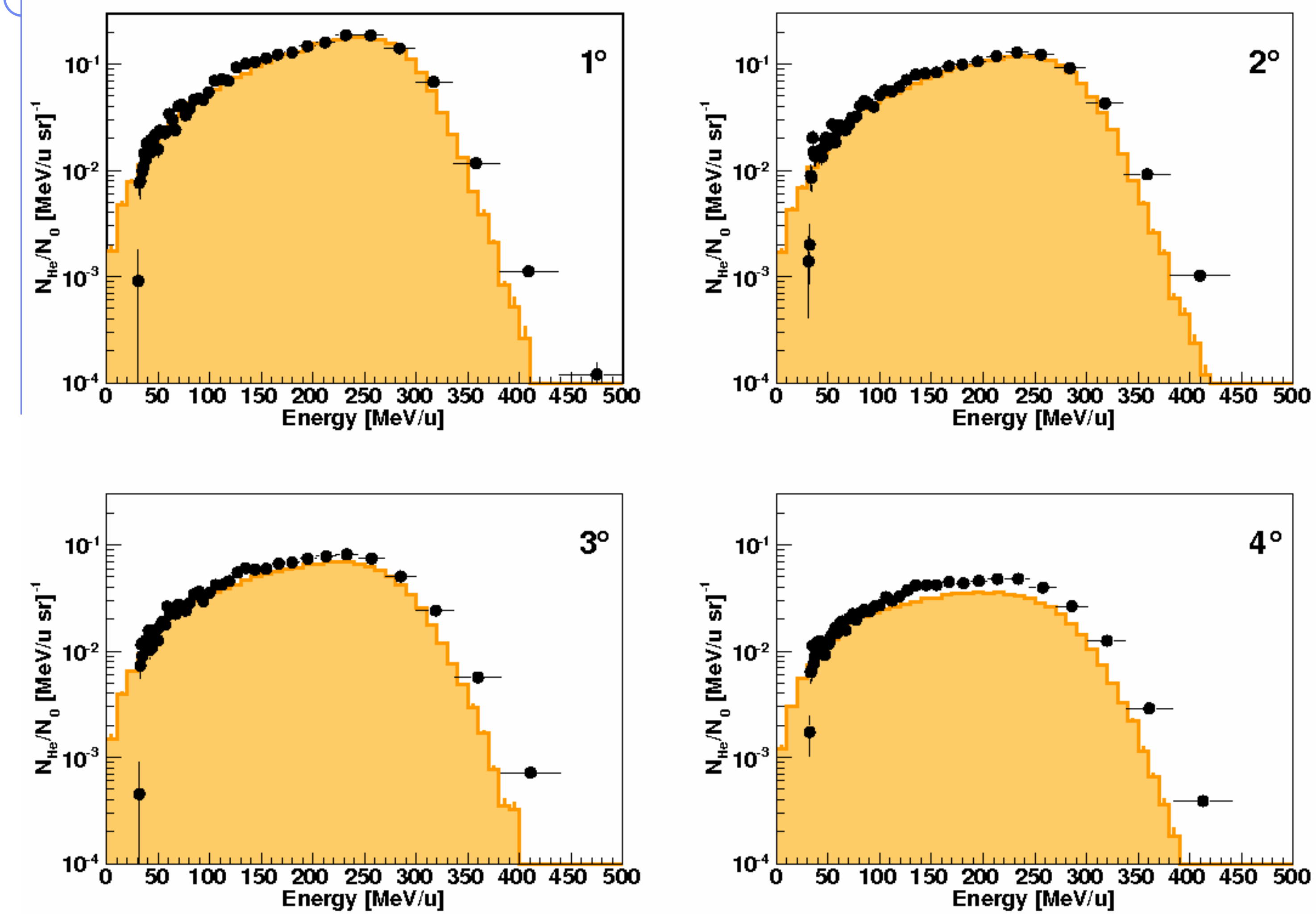
Exp. Data (points) from Haettner et al, Rad. Prot. Dos. 2006

^{12}C @ 400 MeV/n: C ions angular dist. at various depths



Preliminary exp. data courtesy of E.Haettner (Diploma thesis), D.Schardt, GSI, and S.Brons, K.Parodi, HIT. Simulations: A.Mairani PhD thesis

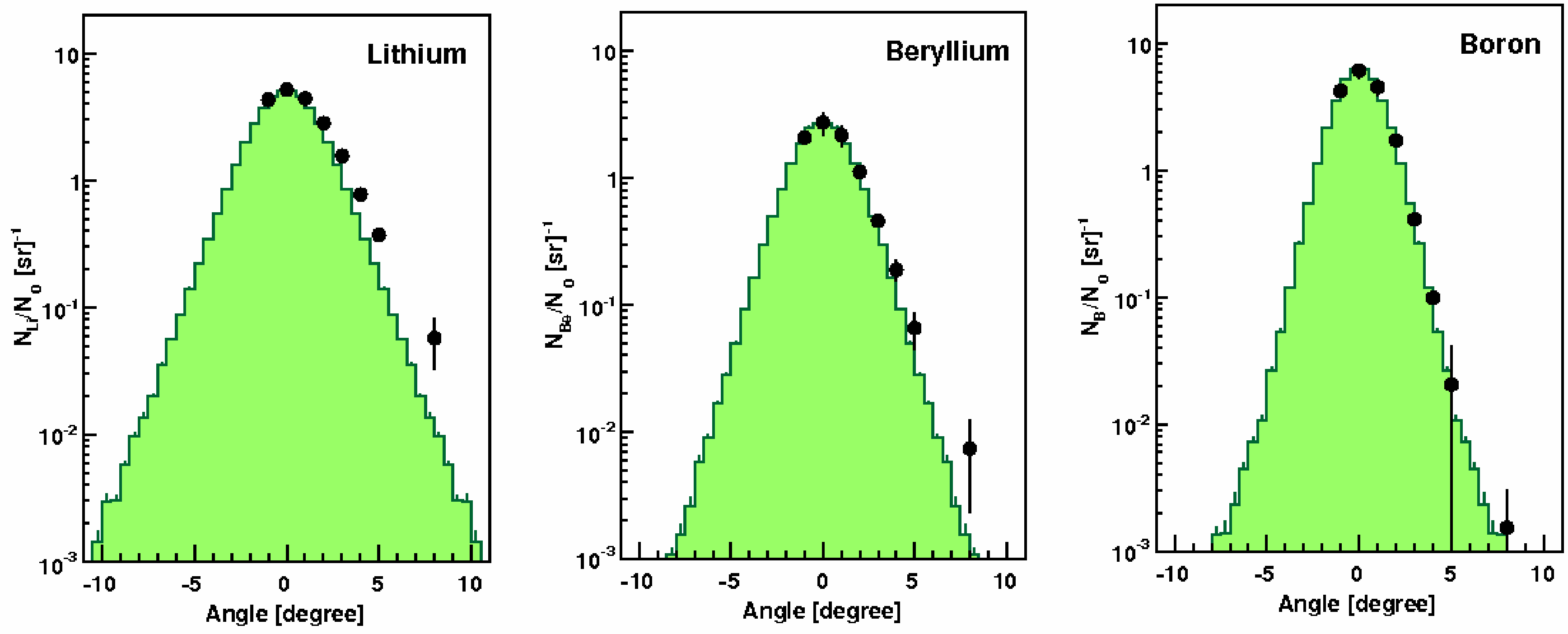
^{12}C 400 MeV/n: Alpha energy-angle spectra at 28.8 cm



Preliminary exp. data courtesy of E.Haettner (Diploma thesis), D.Schardt, GSI, and S.Brons, K.Parodi, HIT. Simulations: A.Mairani PhD thesis

The simulated data assume perfect energy resolution: accounting for the experimental ToF resolution will further improve the comparison

^{12}C, 400 MeV/n: Heavy Fragment ang. distr. at 31.2 cm



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Real and Virtual Photonuclear Interactions

Photonuclear reactions

- 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

Virtual photon reactions

- Muon photonuclear interactions
- Electromagnetic dissociation

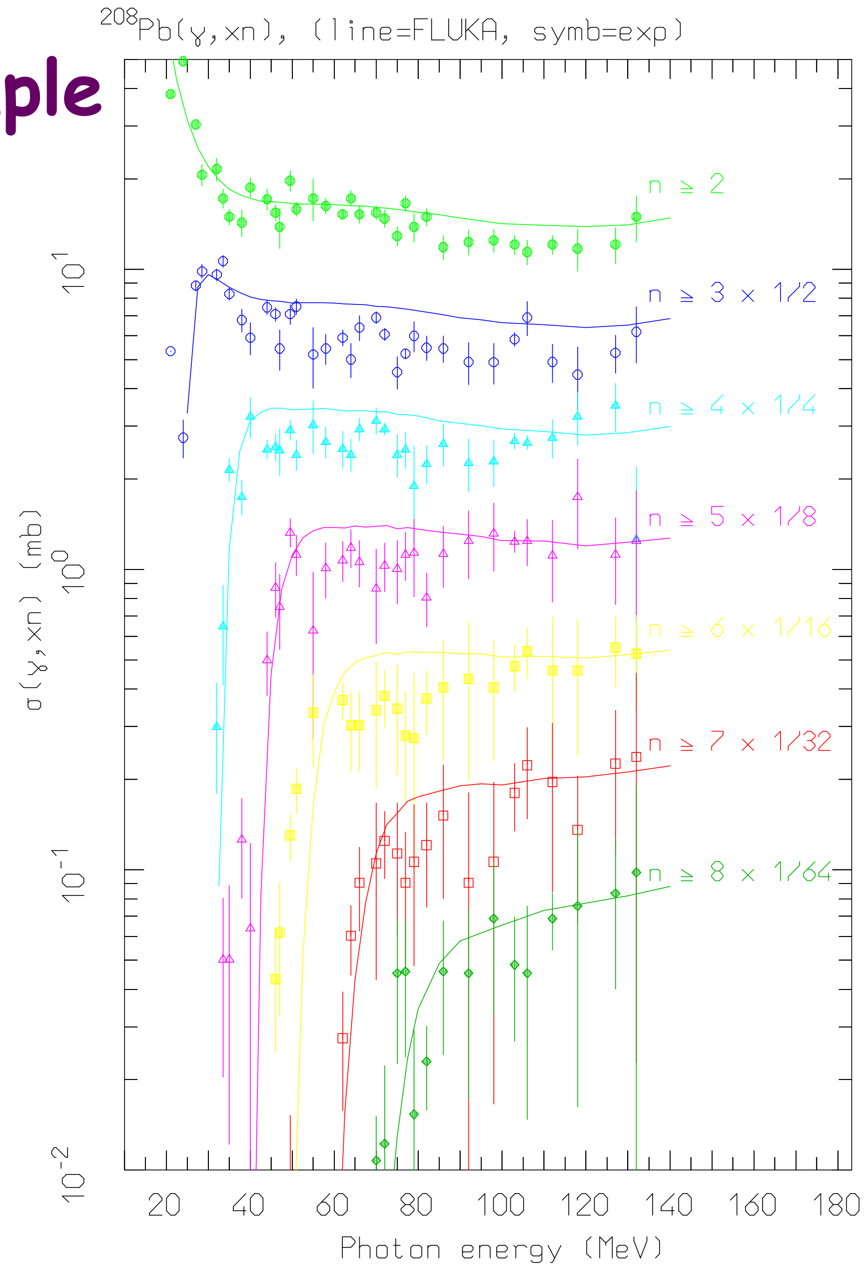
Photonuclear int.: example

Reaction:
^{208}Pb(γ,x n)
20≤Eγ ≤140 MeV

Cross section for multiple neutron emission as a function of photon energy,
Different colors refer to neutron multiplicity ≥ *n* , with 2≤*n*≤8

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

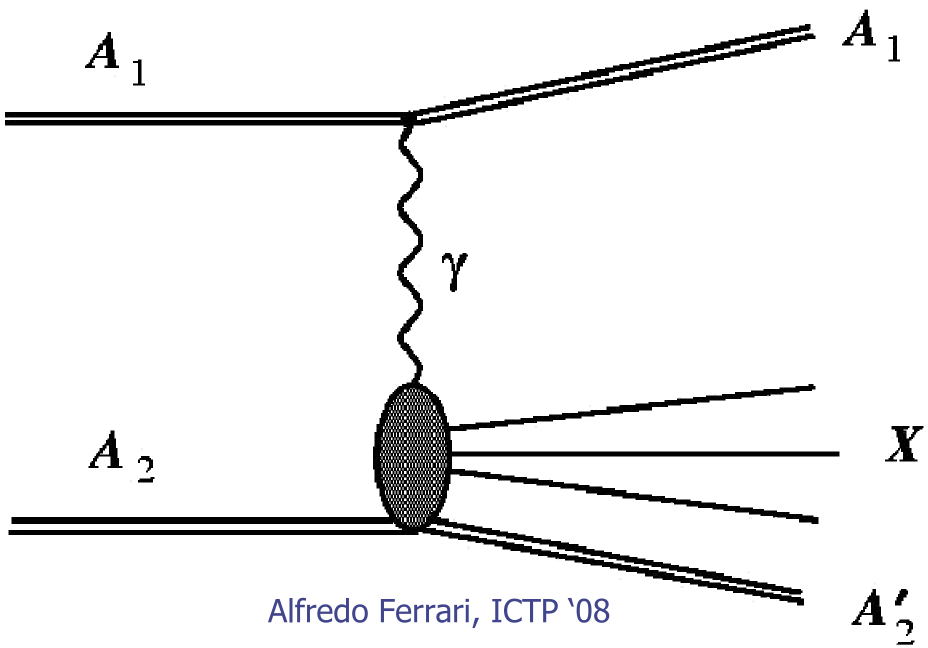
Lines: FLUKA



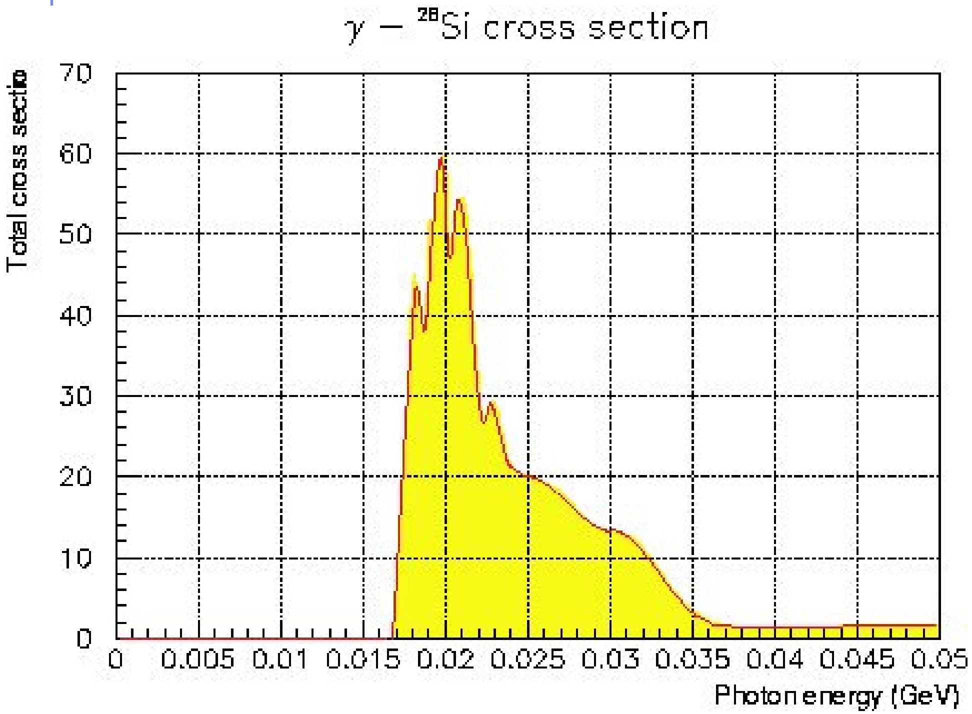
Electromagnetic dissociation:

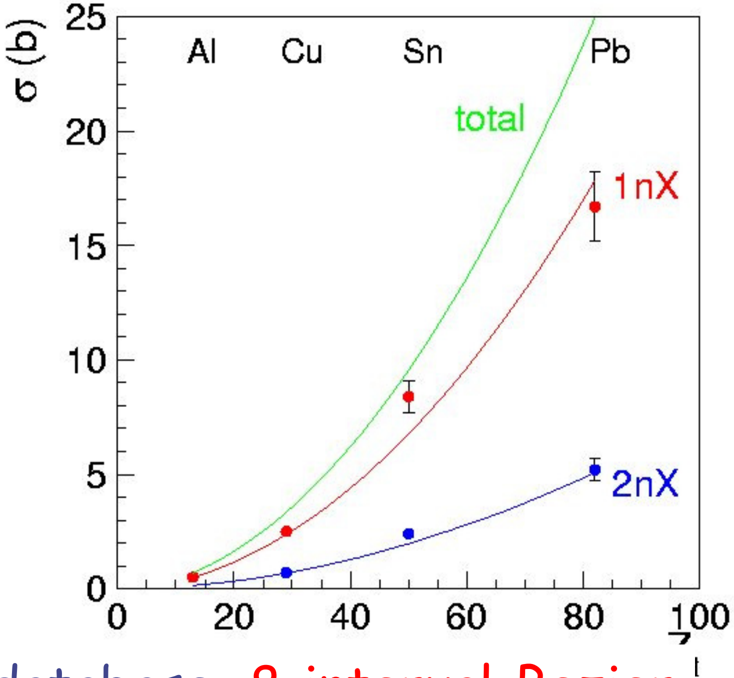
Electromagnetic dissociation: σ_{EM} increasingly large with (target) Z's and energy. Already relevant for few GeV/n ions on heavy targets (σ_{EM} ~ 1 b vs σ_{nucl} ~ 5 b for 1 GeV/n Fe on Pb)

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



Electromagnetic dissociation: example



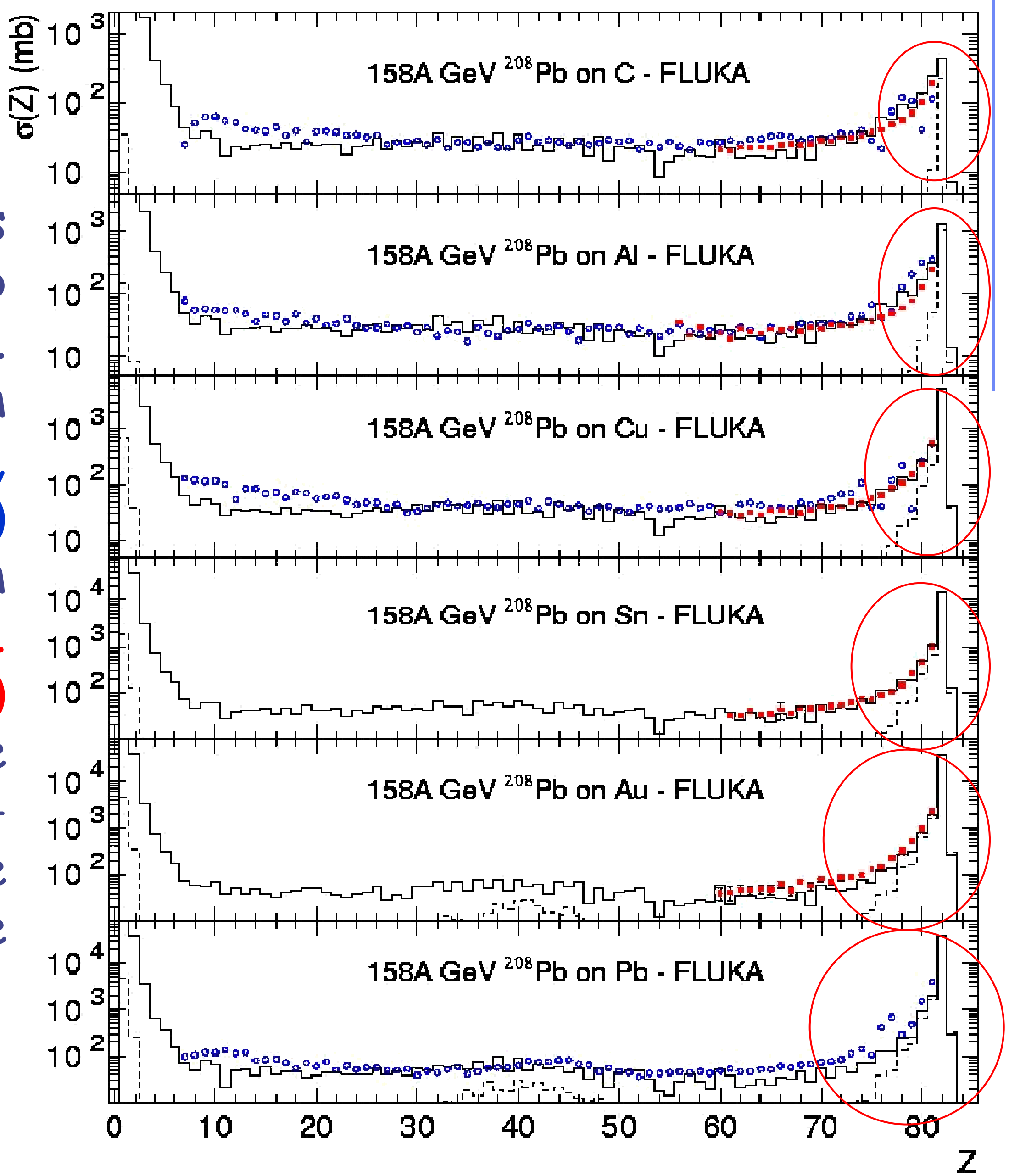


Left: ^{28}Si(g,tot) as recorded in FLUKA database, 8 interval Bezier fit as used for the Electromagnetic Dissociation event generator.

Right: calculated total, 1nX and 2nX electromagnetic dissociation cross sections for 30 A GeV Pb ions on Al, Cu, Sn and Pb targets. Points – measured cross sections of forward 1n and 2n emissions as a function of target charge (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 014802 (2004) (red squares), histos are FLUKA (with DPMJET-III) predictions: the dashed histo is the electromagnetic dissociation contribution



Code complexity:

- Inelastic h-N: ~***72000 lines***
- Cross sections (h-N and h-A), and elastic (h-N and h-A): ~***32000 lines***
- (G)INC and preequilibrium (PEANUT): ~***114000 lines***
- Evap./Fragm./Fission/Deexc.: ~***27000 lines***
- ν-N interactions: ~***35000 lines***
- A-A interactions:
  - ✓ FLUKA native (including BME): ~***8000 lines***
  - ✓ DPMJET-3: ~***130000 lines***
  - ✓ (modified) rQMD-2.4: ~***42000 lines***
- **FLUKA** in total (including transport, EM, geometry, scoring): ~***680000 lines***
- … + ~***20000 lines*** of ancillary off-line codes used for data pre-generation
- … and ~***30000 lines*** of post-processing codes

Thank you for your attention!!