# The physics of the FLUKA code: hadronic models

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HSS06

# FLUKA

**Interaction and Transport Monte Carlo code**

Main Authors


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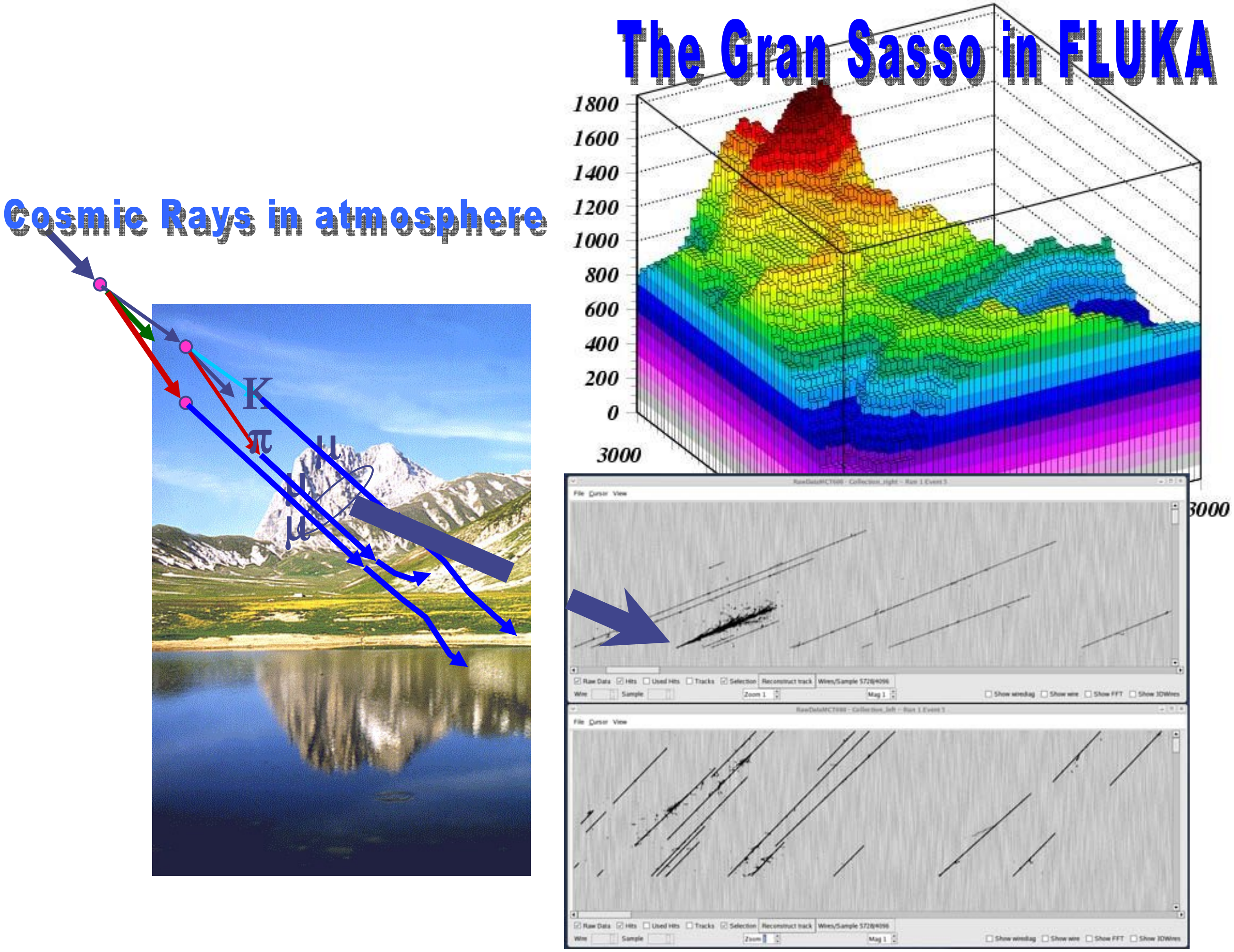

# Fluka History:

**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 (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, used by G-Calor***

**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**

# FLUKA collaboration

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# Fluka applications:

FLUKA is a well established tool in HEP for:

- Particle physics: calorimetry, tracking and detector simulation (→ ALICE, ICARUS, ... )
- Accelerator design (→ LHC systems)
- Radioprotection (standard tool at CERN and SLAC)
- Dosimetry
- Cosmic ray physics

FLUKA is also used for:

- ➢ Neutronics simulations
- ➢ ADS (Accelerator DrivenSystems)

FLUKA applications to Medicine/radiobiology are growing, thanks to

- ✓ Mixed field capability, including ion transport and interactions
- ✓ Accuracy
- ✓ Reliability

Download, papers and documentation : www.fluka.org

# FLUKA Description

- FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, detector design, Accelerator Driven Systems, cosmic rays, neutrino physics, radiotherapy etc.
- 60 different particles + Heavy Ions
  - Hadron-hadron and hadron-nucleus interactions 0-10000 TeV
  - Electromagnetic and μ interactions 1 keV – 10000 TeV
  - Nucleus-nucleus interactions 0-10000 TeV/n
  - Charged particle transport – ionization energy loss
  - Neutron multi-group transport and interactions 0-20 MeV
  - ν interactions
  - Transport in magnetic field
  - Combinatorial (boolean) and Voxel geometry
  - Double capability to run either fully analogue and/or biased calculations

- Maintained and developed under INFN-CERN agreement and copyright 1989-2006
- More than 1000 users all over the world

**http://www.fluka.org**

# The FLUKA hadronic Models

## Hadron-Hadron

| Elastic,exchange<br>Phase shifts<br>data, eikonal | P<3-5GeV/c<br>Resonance prod<br>and decay | low E π,K<br>Special | High Energy<br>DPM<br>hadronization |
|---|---|---|---|

## Hadron-Nucleus

PEANUT
Sophisticated GINC
Gradual onset of Glauber-Gribov multiple interactions
Preequilibrium
Coalescence

## Nucleus-Nucleus

| E< 0.1GeV/u | 0.1< E< 5 GeV/u | E> 5 GeV/u |
|---|---|---|
| BME<br>Complete fusion+<br>peripheral | rQMD-2.4<br>modified<br>new QMD | DPMJET<br>DPM+<br>Glauber+<br>GINC |

Evaporation/Fission/Fermi break-up
$\gamma$ deexcitation

# Inelastic hN interactions

**Intermediate Energies**

- $N_1 + N_2 \rightarrow N_1' + N_2' + \pi$ threshold around 290 MeV
  important above 700 MeV
- $\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV

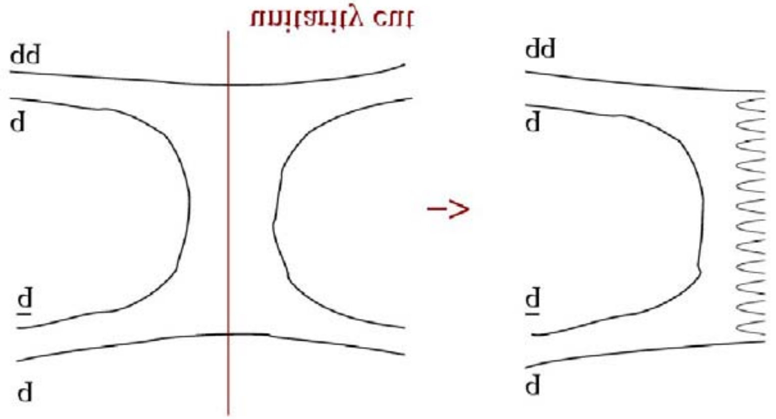
- Dominance of the $\Delta(1232)$ resonance and of the N* resonances $\rightarrow$ reactions treated in the framework of the isobar model $\rightarrow$ all reactions proceed through an intermediate state containing at least one resonance
- Resonance energies, widths, cross sections, branching ratios from data and conservation laws, whenever possible

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

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

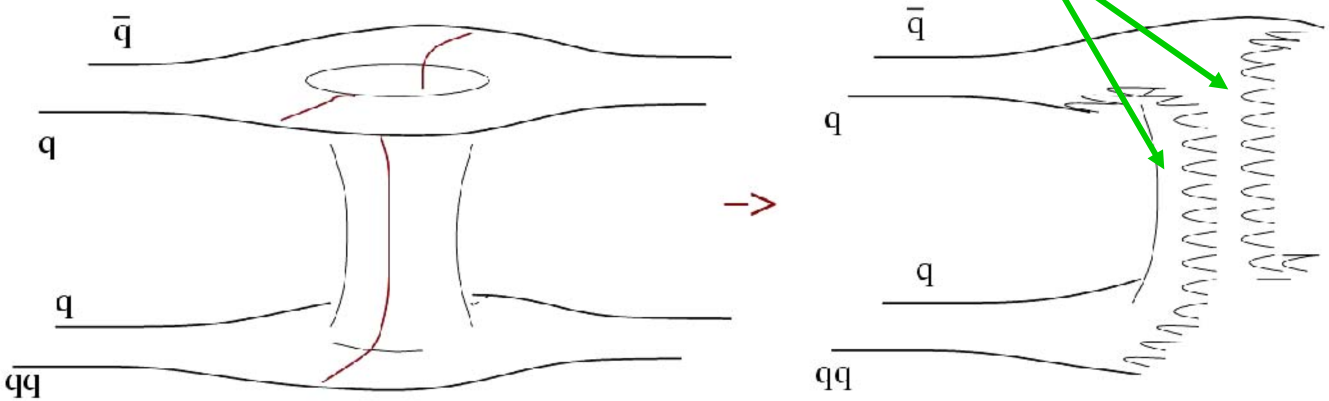
# Inelastic hN at high energies ( DPM )

**Parton and color concepts, Topological expansion of QCD, Duality**



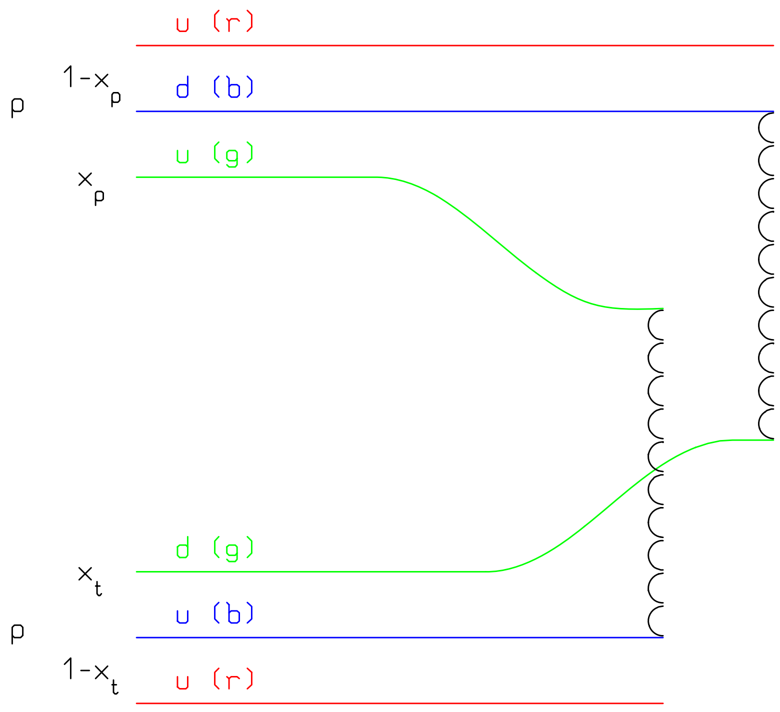
Reggeon exchange

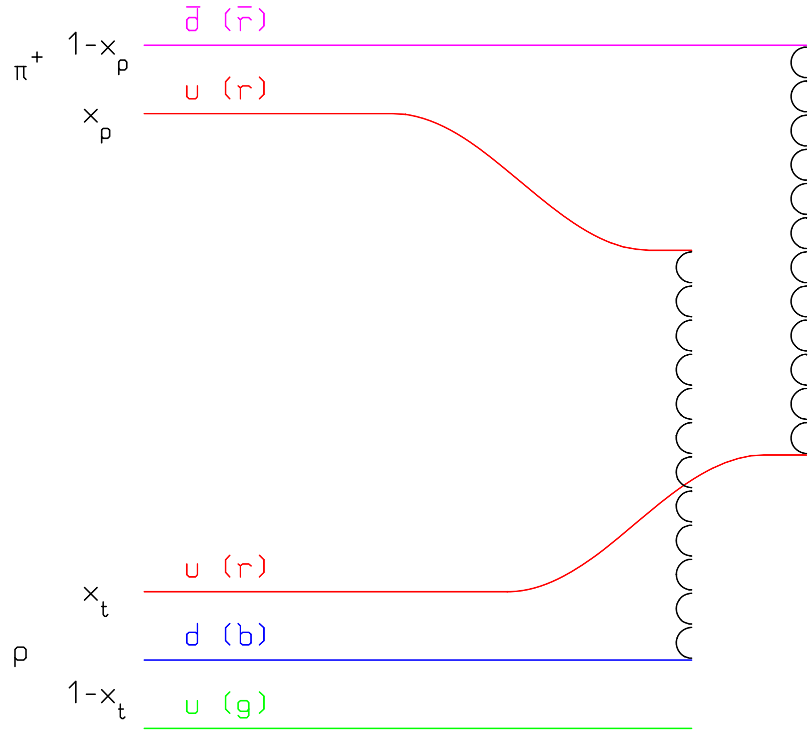
**color strings to be "hadronized"**



Pomeron exchange

# Hadron-hadron collisions: chain examples



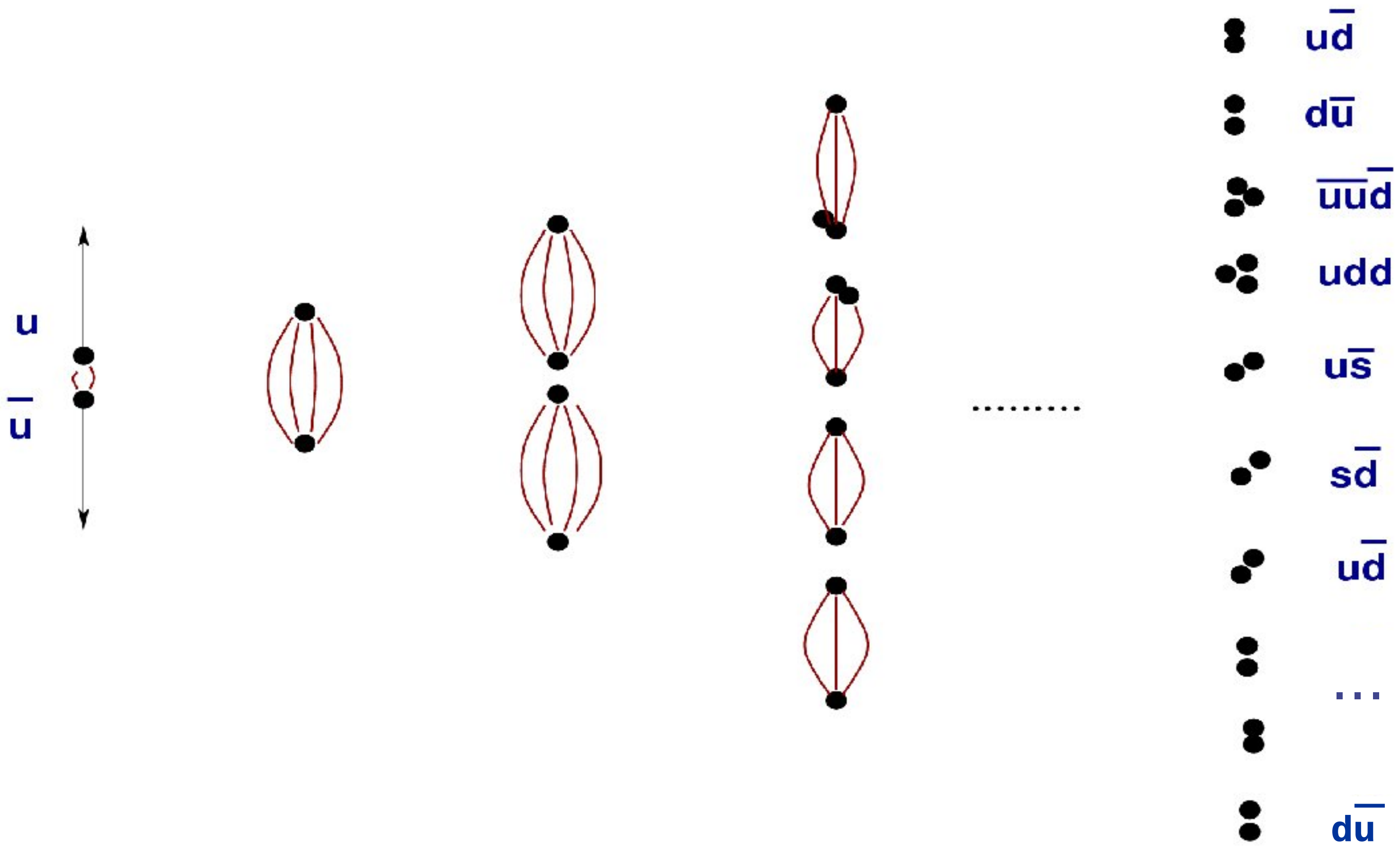




Leading two-chain diagram in DPM for p-p scattering. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities

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

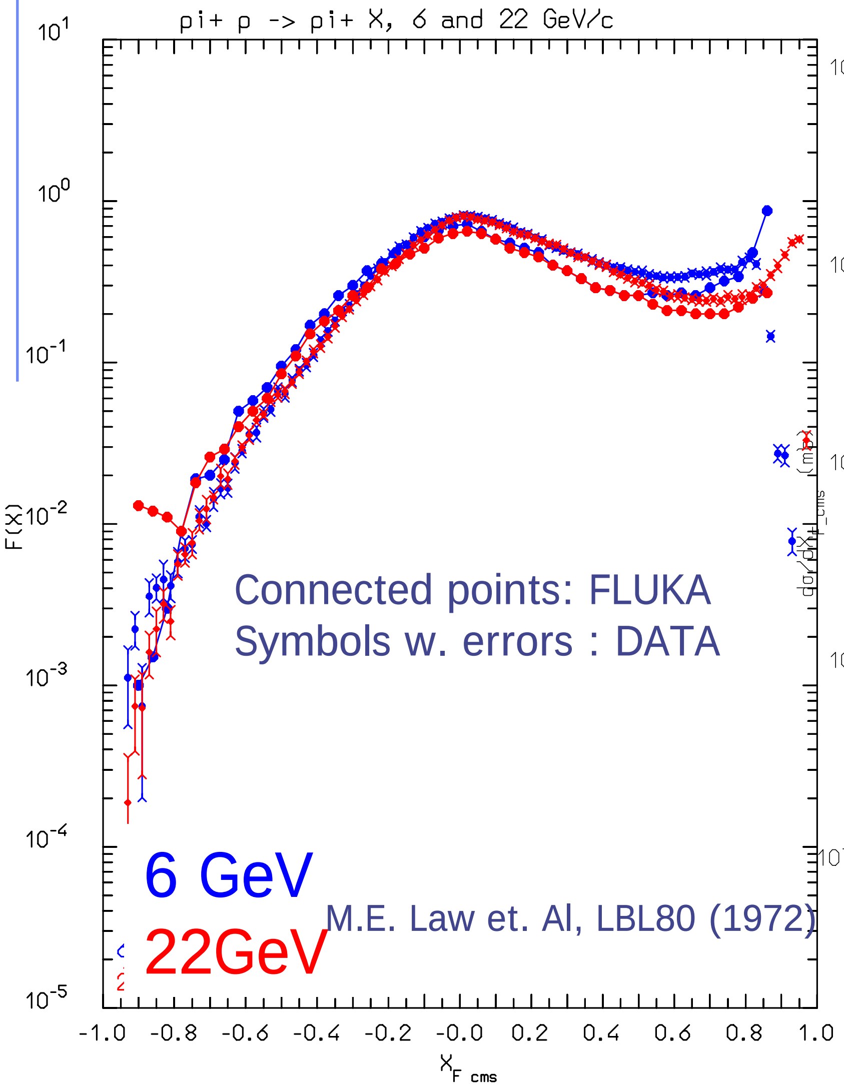
# The "hadronization" of color strings

An example:

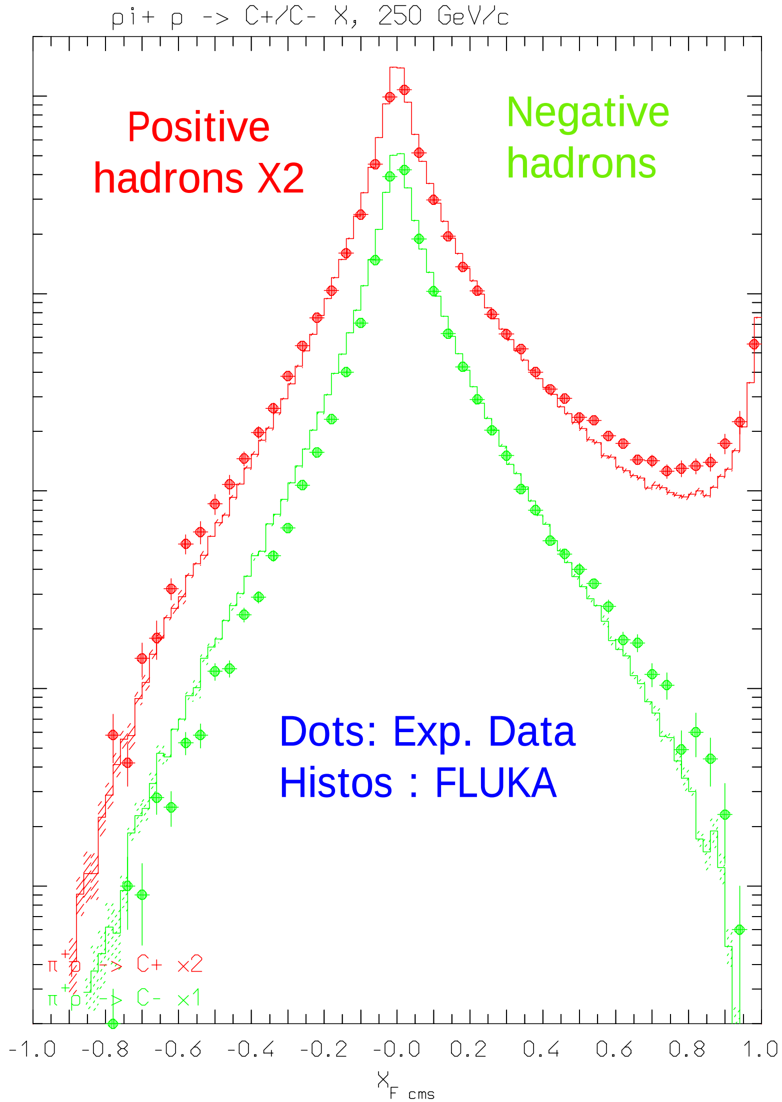


# Inelastic hN interactions: examples

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




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



# PEANUT

PreEquilibrium Approach to NUclear Thermalization

- PEANUT handles hadron-nucleus interactions from threshold (or 20 MeV neutrons) ~~to 5 GeV~~ up

Sophisticated Generalized IntraNuclear Cascade

⇓

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

⇓

Prequilibrium stage

⇓

Standard Assumption on exciton number or excitation energy

⇓

Common FLUKA Evaporation model

# 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**..

The goal was to extend it to cover all the energy range, and substitute the high energy h-A generator with the following advantages:

- Sophisticated (G)INC $\Rightarrow$ 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

Only two ingredients were missing:

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

For details see conference on nuclear reaction mechanisms, Varenna June 2006

# (Generalized) IntraNuclear Cascade

- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear well according to the Fermi gas model
- Interaction probability

  $\sigma_{free}$ + Fermi motion × $\rho(r)$ + exceptions (ex. $\pi$)
- Glauber cascade at higher energies
- Classical trajectories (+) nuclear mean potential (resonant for $\pi$)
- Curvature from nuclear potential $\rightarrow$ refraction and reflection
- Interactions are incoherent and uncorrelated
- Interactions in projectile-target nucleon CMS $\rightarrow$ Lorentz boosts
- Multibody absorption for $\pi$, $\mu^-$, $K^-$
- Quantum effects (Pauli, formation zone, correlations…)
- Exact conservation of energy, momenta and all addititive quantum numbers, including nuclear recoil

# hA at high energies: Glauber-Gribov cascade

- **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 ↔ Feynman diagrams
  - High energies: exchange of one or more Pomerons with one or more target nucleons (a closed string exchange)

# Glauber Cascade

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 $\Psi_i$

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

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

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

**Absorption (particle prod.)**

Absorption probability over a given *b* and nucleon configuration

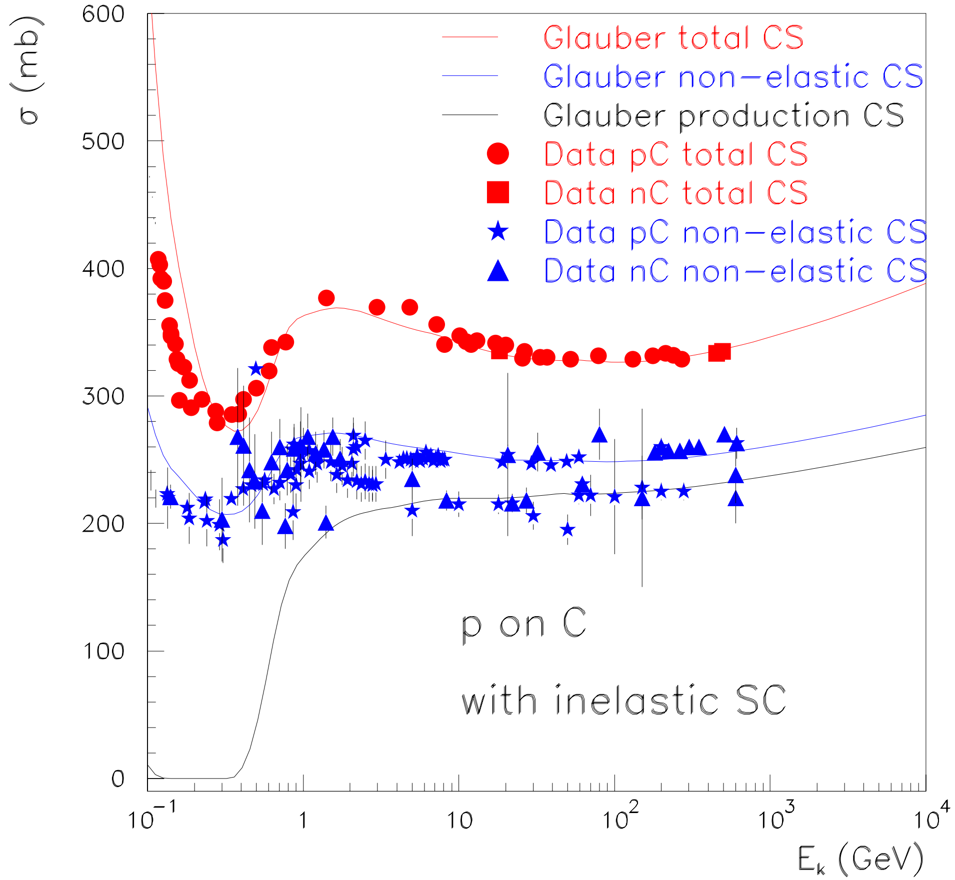
$$\sigma_{hA\,abs}(s) \equiv \sigma_{hA\,T}(s) - \sigma_{hA\,\Sigma f}(s)$$

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

# 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

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




Proton Carbon cross sections with inelastic screening accounted for

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

# 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 the overall average number of collision is given by

$$\langle \nu \rangle = \frac{Z\sigma_{hpr} + N\sigma_{hnr}}{\sigma_{hAabs}}$$

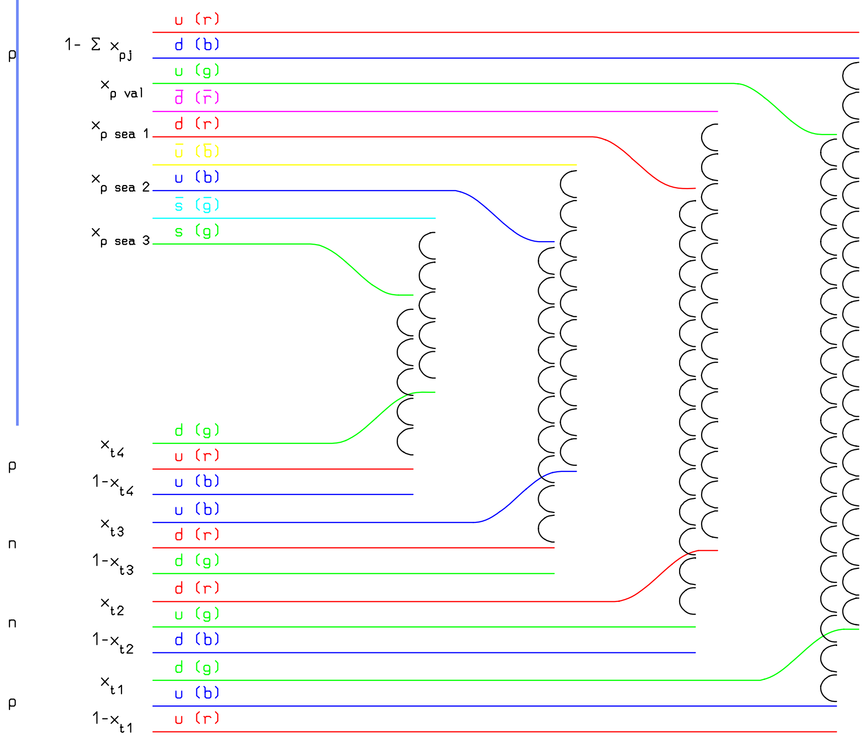
- Glauber-Gribov model = Field theory formulation of Glauber model
- Multiple collision terms ⇒Feynman graphs
- At high energies : exchange of one or more pomerons with one or more target nucleons

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

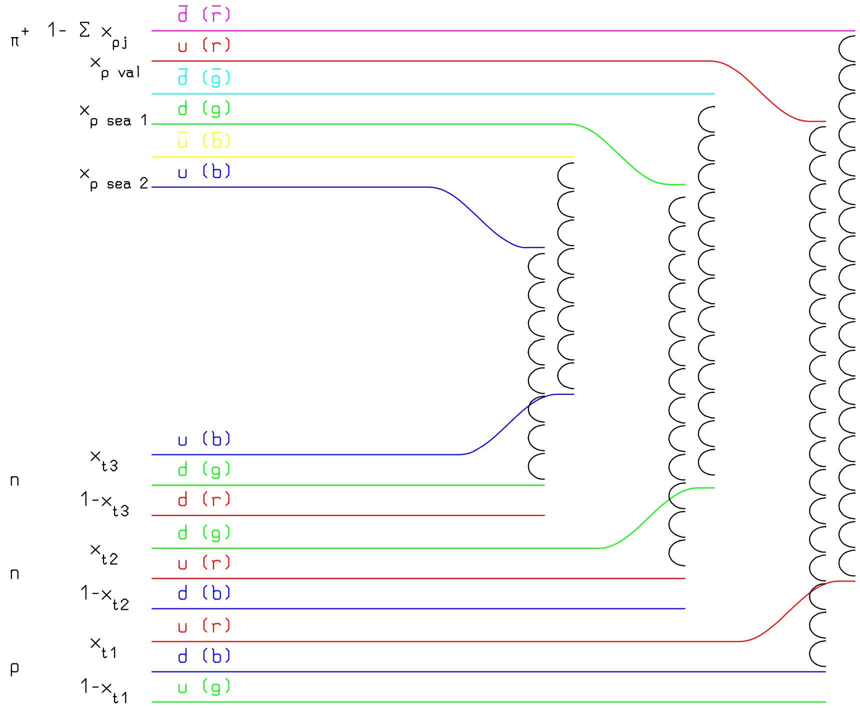
Interaction with ***n*** target nucleons ⇒ ***2n*** chains

- 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 $\pi^{+-}$A Glauber scattering with 3 collisions.

# Formation zone

Naively: "materialization" time (originally proposed by 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

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

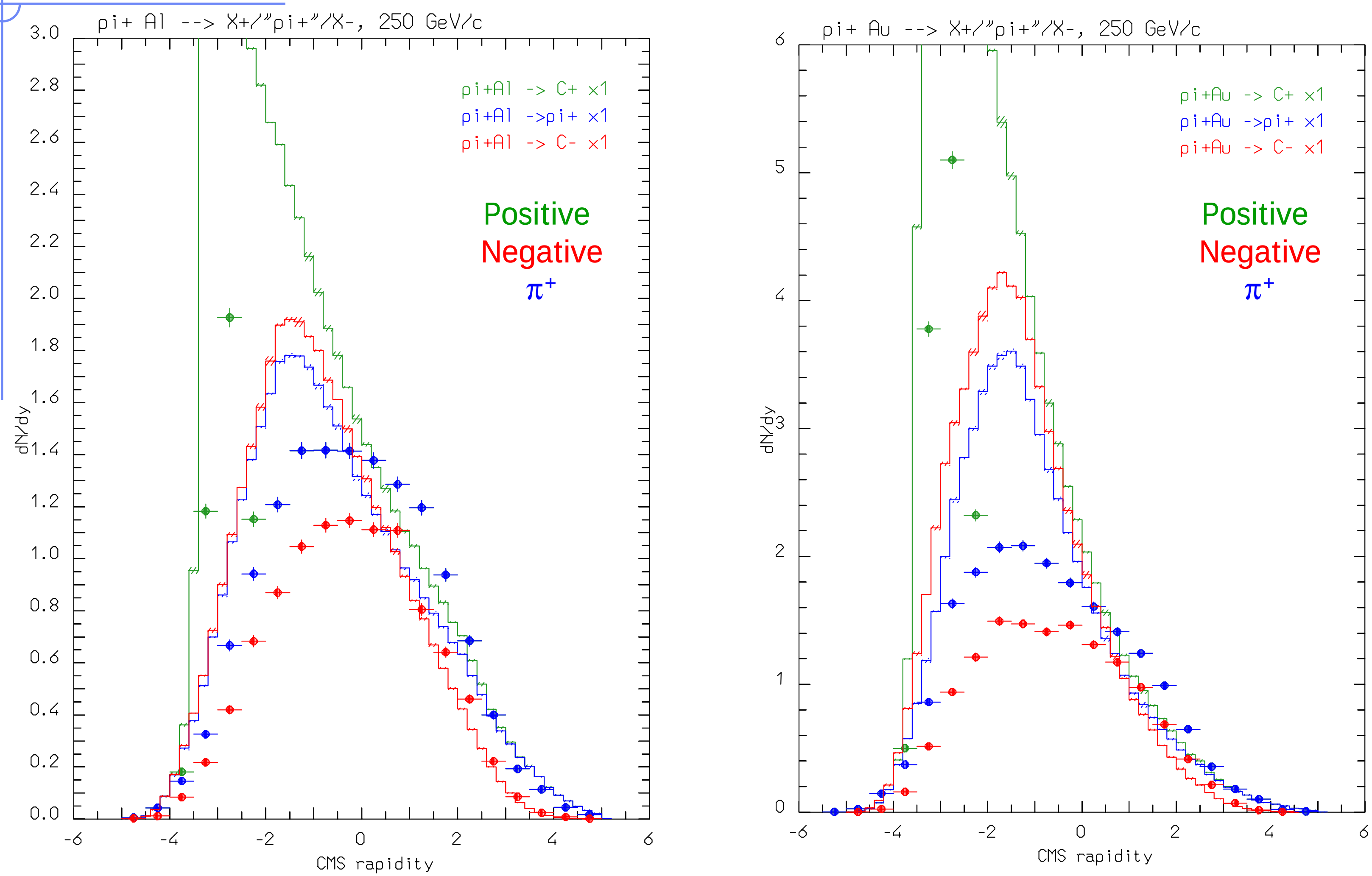
Going to the nucleus system

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

Condition for possible reinteraction inside a nucleus:

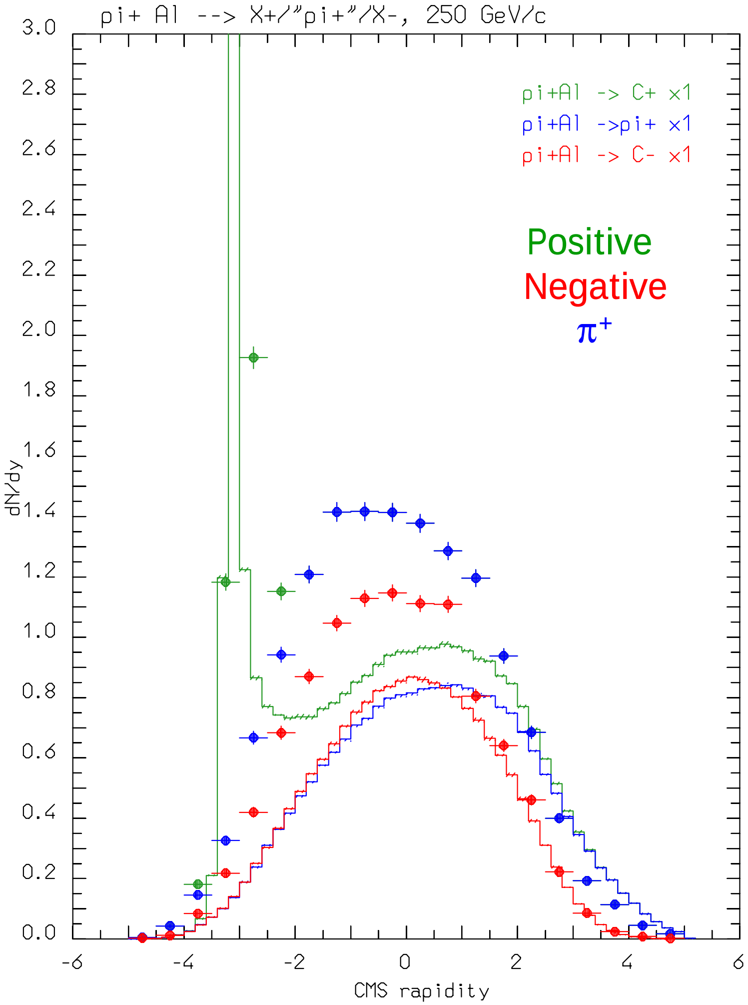
$$\Delta x_{for} \leq R_A \approx r_0 A^{\frac{1}{3}}$$

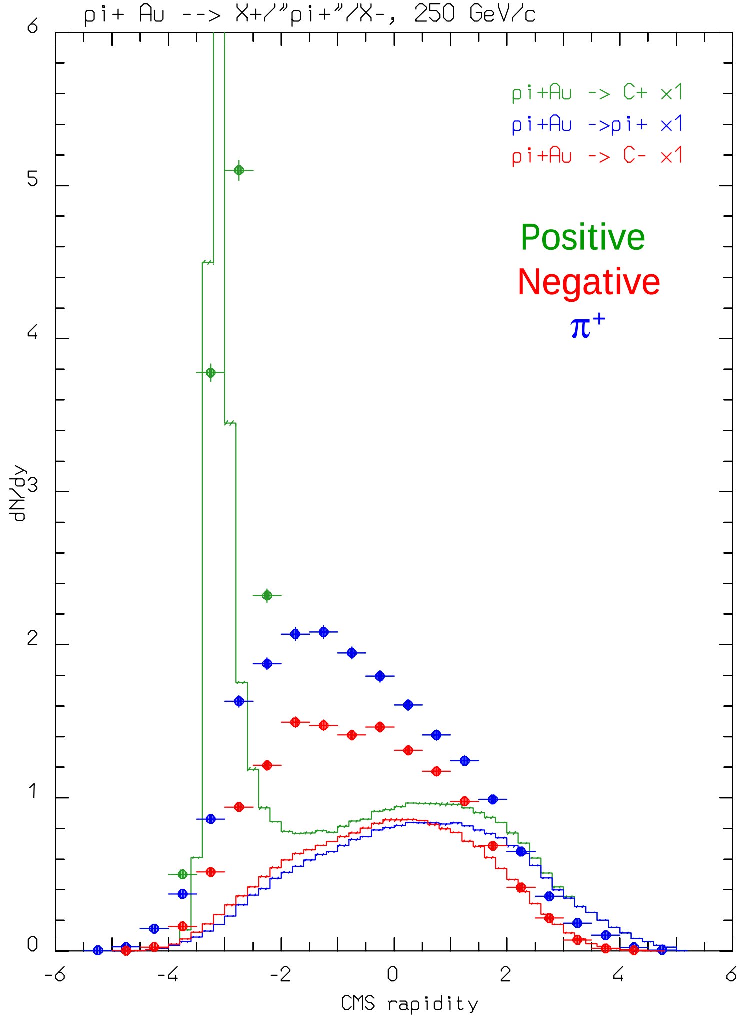
# Setting the formation zone: **no** Glauber, **no** formation zone




Rapidity distribution of charged particles produced in 250 GeV $\pi^+$ 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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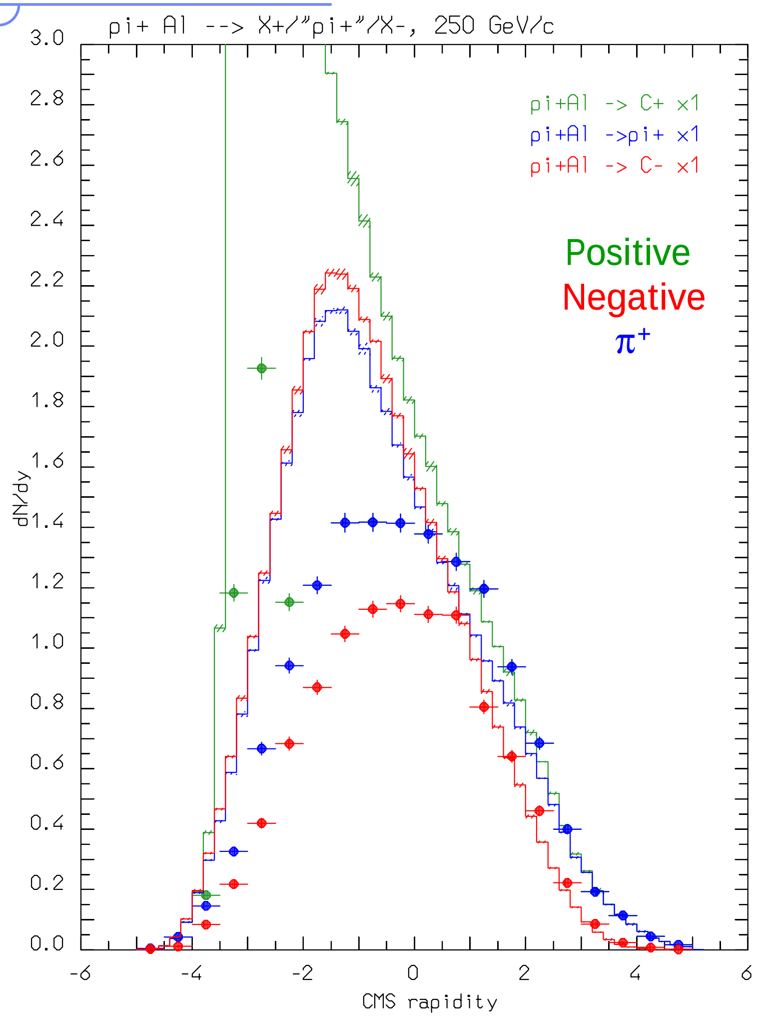


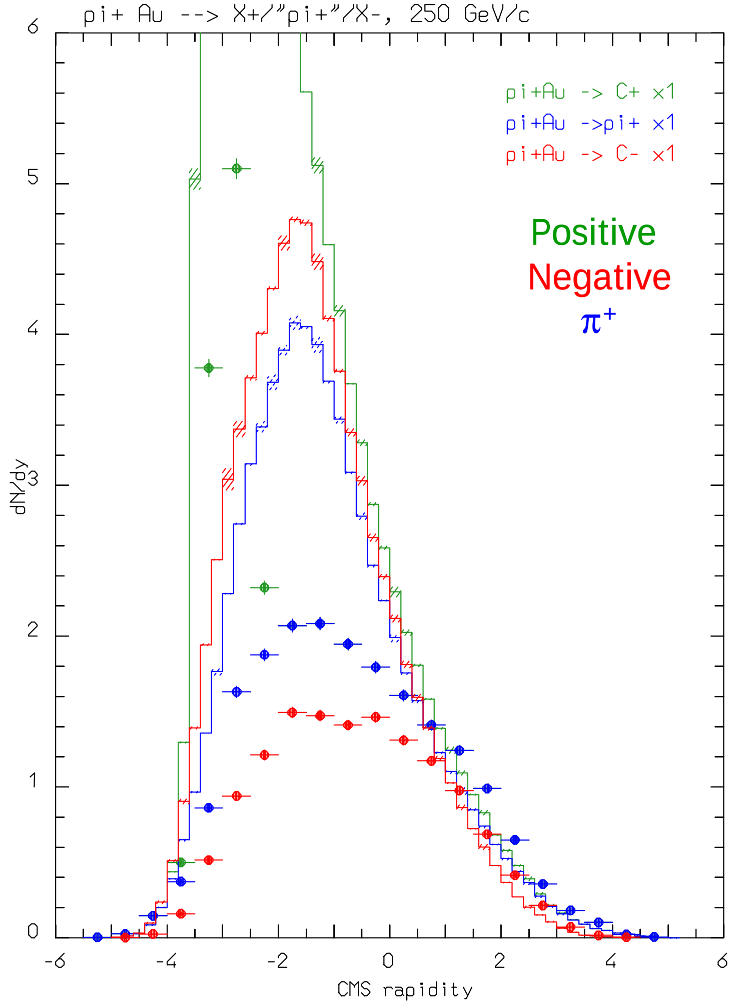


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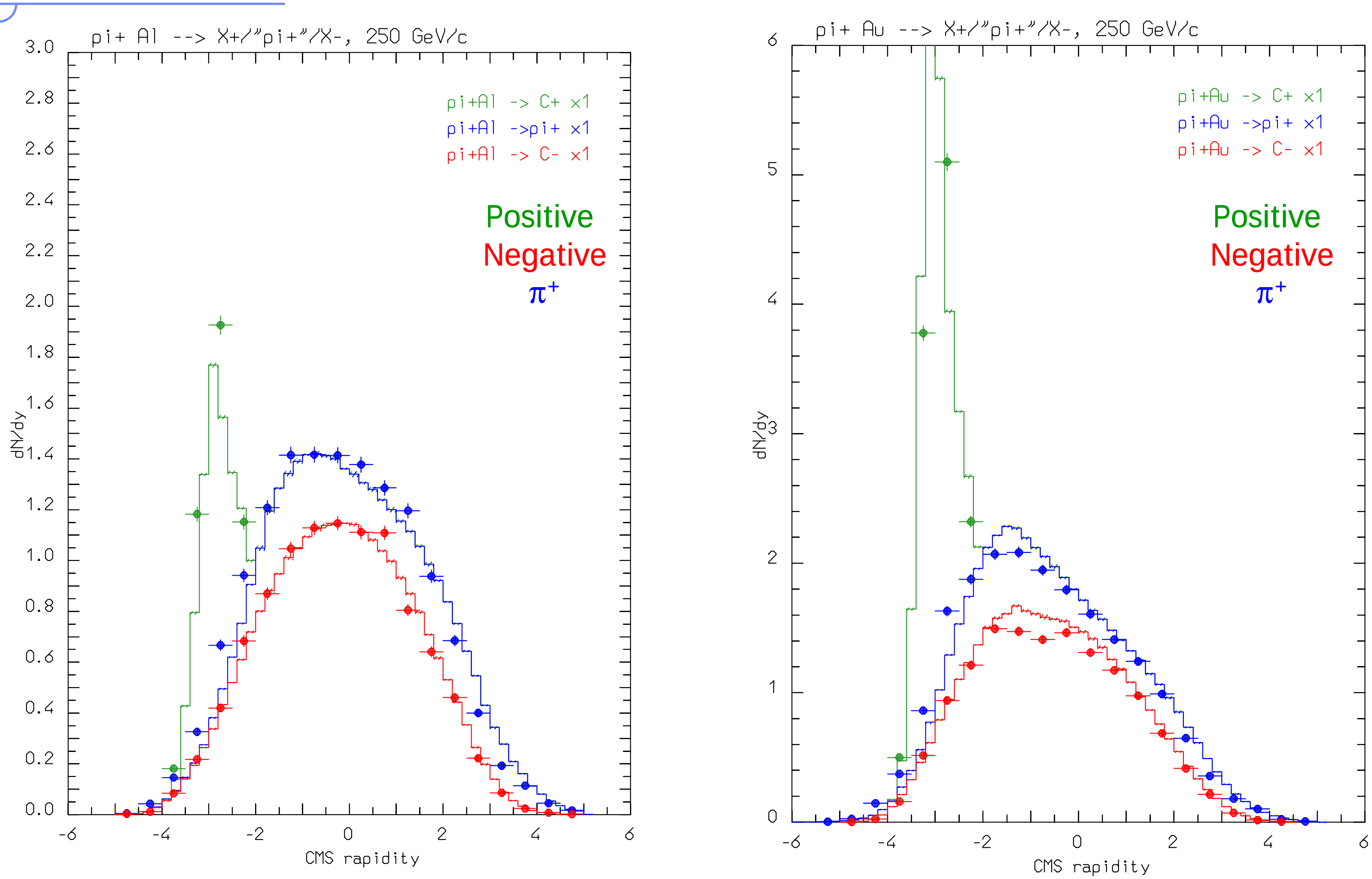


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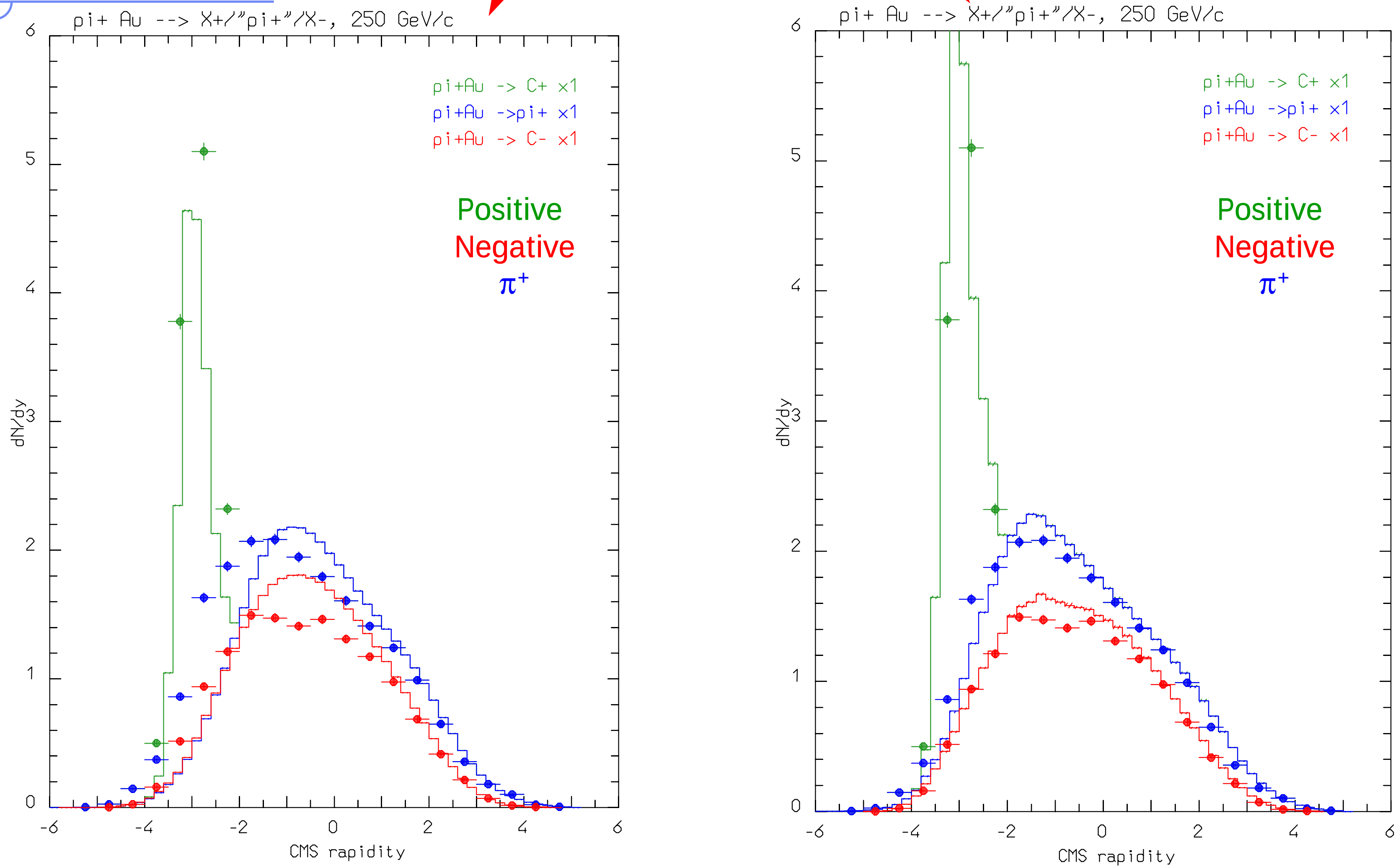
Points: exp. data ( Agababyan et al., ZPC50, 361 (1991)).

# Old HE model (left) vs new (PEANUT extended)



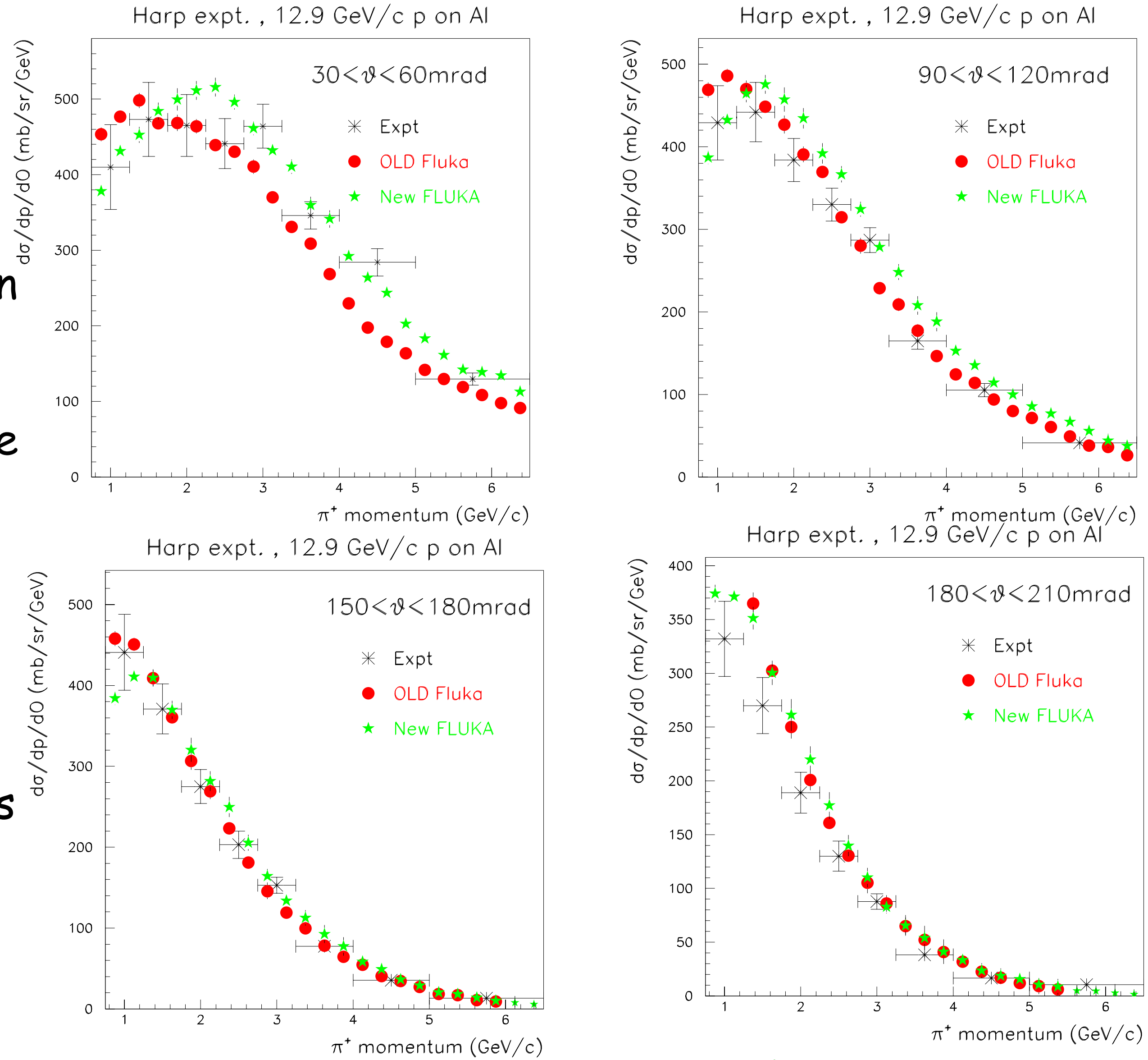

Rapidity distribution of charged particles produced in 250 GeV $\pi^+$ collisions on Gold
Points: exp. data ( Agababyan et al., ZPC50, 361 (1991)).

# Comparison with the HARP experiment

Data from the HARP experiment at CERN

particle production with p beams in the 1.5-15 GeV/c range on several targets

First published results : 12.9 GeV/c protons on Aluminum, $\pi^+$ production cross section as a function of emission energy and angle



# Preequilibrium emission

For E > $\pi$ production threshold → 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

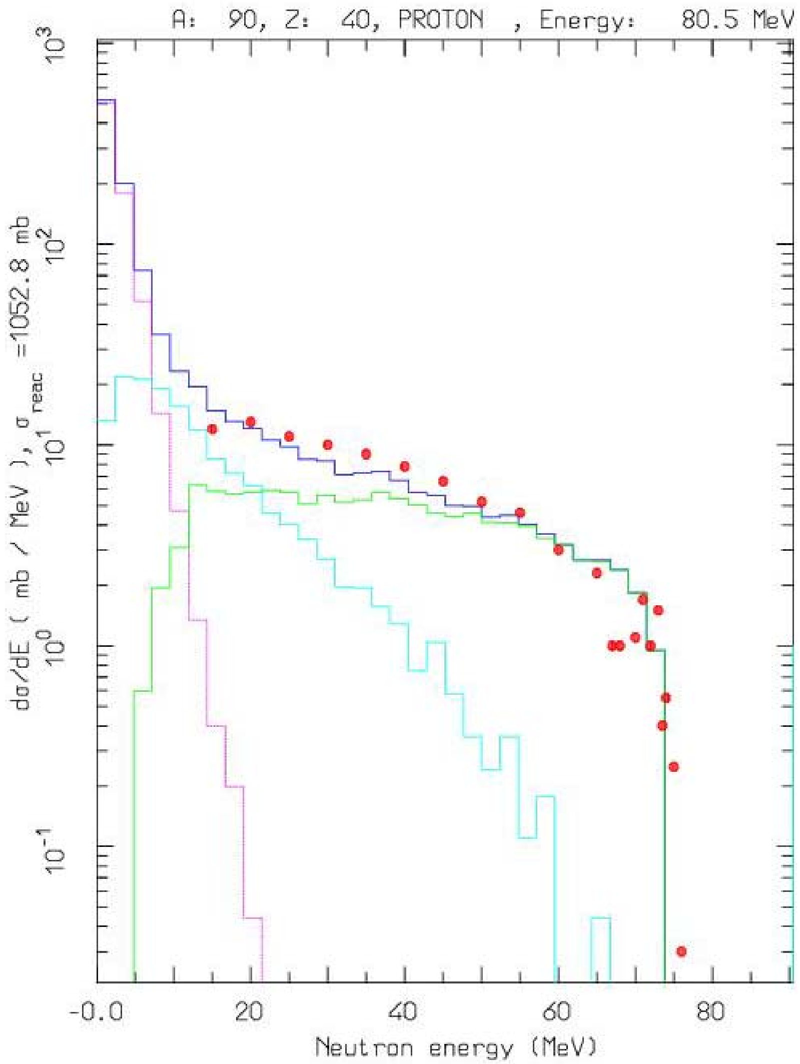
**Statistical assumption:**
any partition of the excitation energy $E^*$ among N, $N = N_h + N_p$, excitons has the same probability to occur
Step: nucleon-nucleon collision with $N_{n+1}=N_n+2$ ("never come back approximation)
Chain end = equilibrium = $N_n$ sufficiently high or excitation energy below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

***$N_1$ depends on the reaction type and cascade history***

# Preequilibrium in FLUKA

- FLUKA preequilibrium is based on GDH (M. Blann et al.) cast in a MonteCarlo form
- GDH: Exciton model, r, $E_f$ are "local" averages on the trajectory and constrained state densities are used for the lowest lying configurations.
- Modification of GDH in FLUKA:
  - cross section $\sigma_{inv}$ from systematics
  - Correlation /coherence length/ hardcore effect on reinteractions
  - Constrained exciton state densities configurations 1p-ih, 2p-ih, 1p-2h, 2p-2h, 3p-1h and 3p-2h
  - True local r, $E_f$ for the initial configuration, evolving into average
  - Non-isotropic angular distribution (fast particle approximation)

# Thin target example



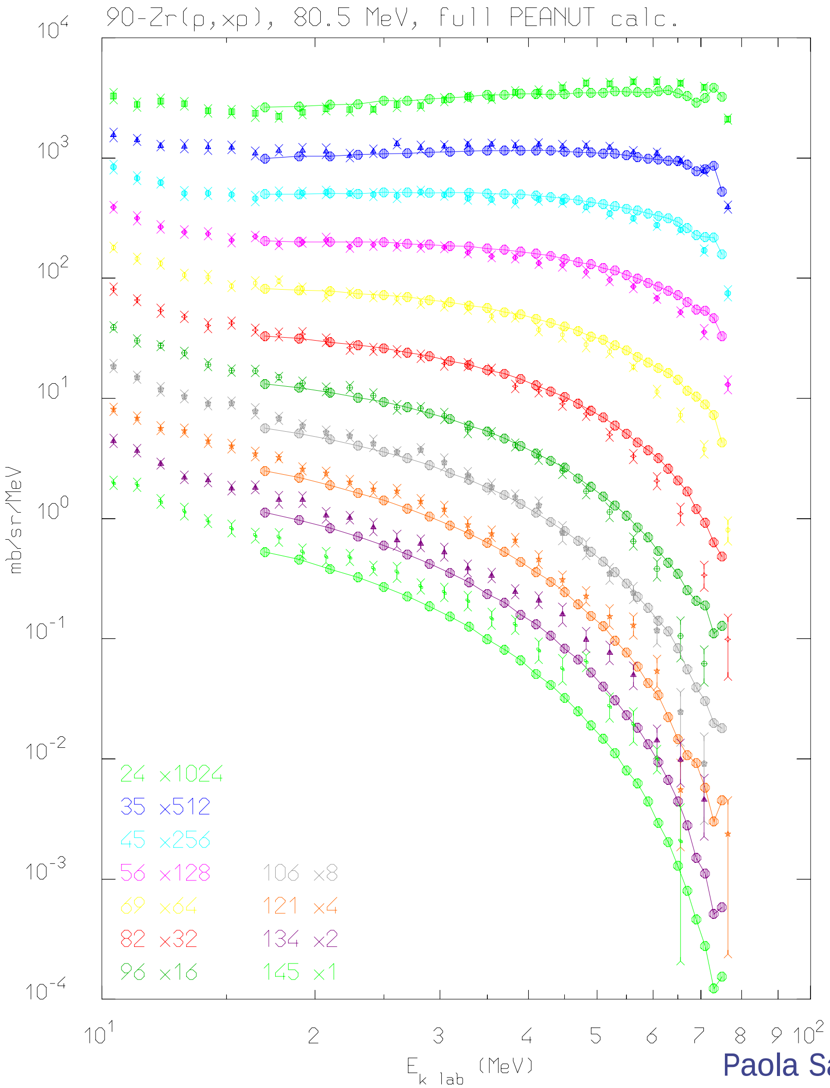

Angle-integrated $^{90}Zr(p,xn)$ at 80.5 MeV

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

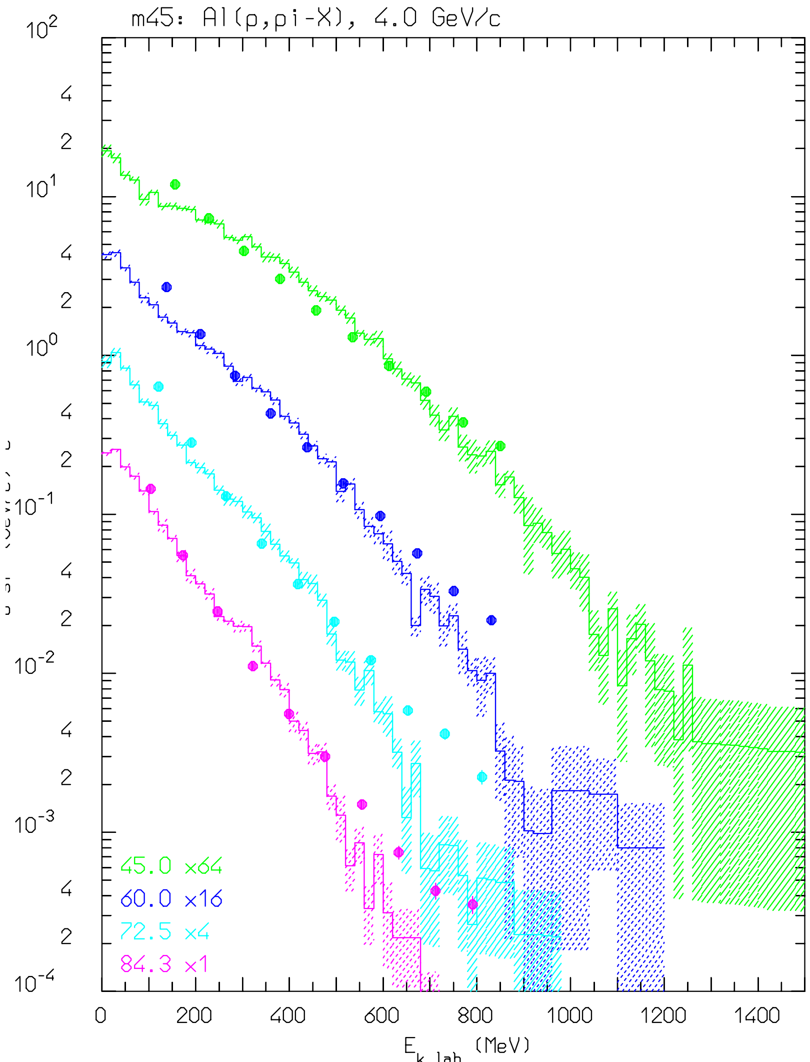
Experimental data from M. Trabandt et al., Phys. Rev. C39, 452 (1989)

# Thin target examples

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




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

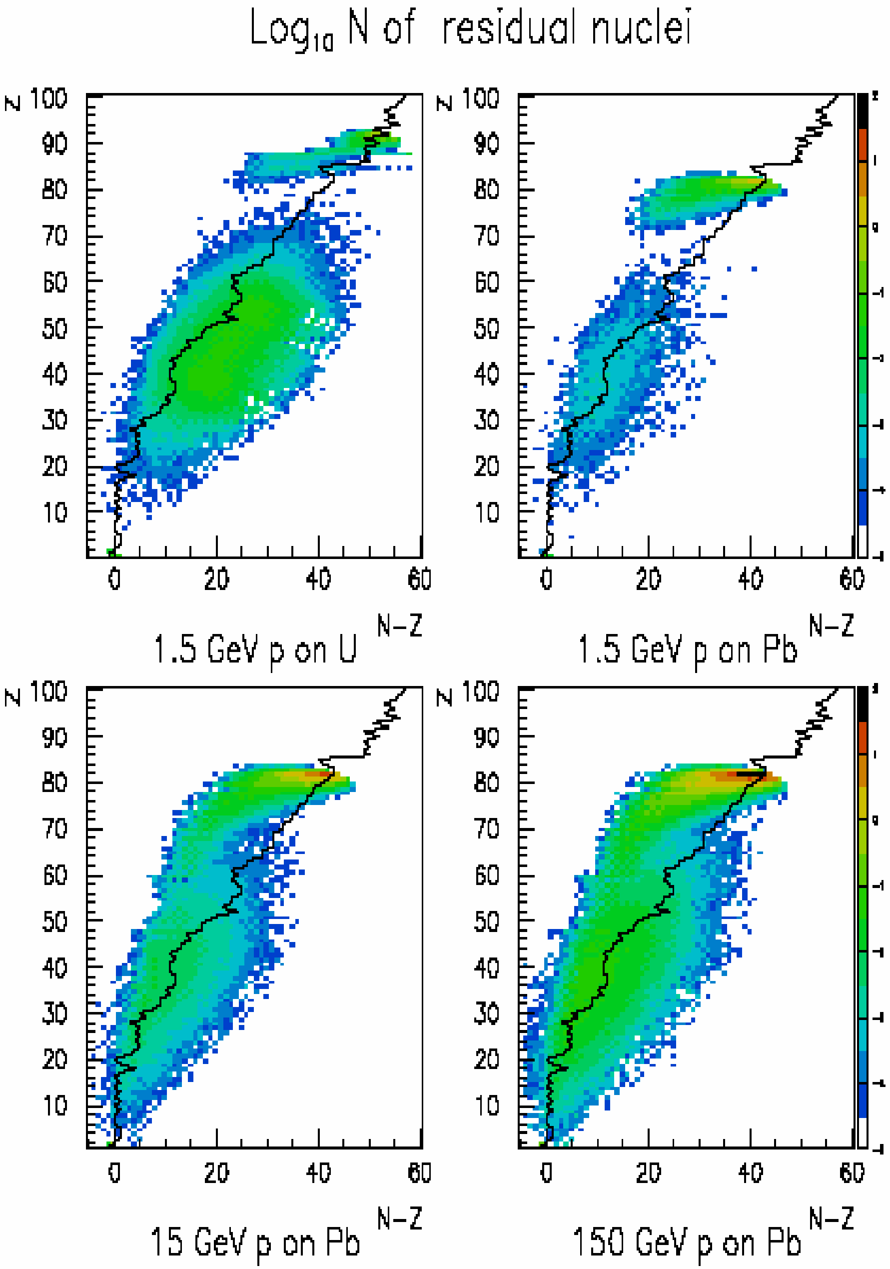


# Equilibrium particle emission

- **Evaporation**: Weisskopf-Ewing approach
  - 600 possible emitted particles/states (A<25) with an extended evaporation/fragmentation formalism
  - Full level density formula
  - Inverse cross section with proper sub-barrier
  - Analytic solution for the emission widths
  - Emission energies from the width expression with no. approx.
  - NEW! New energy dependent self-consistent evaporation level densities (RIPL-2/IAEA recommendations)
  - NEW! New pairing energies consistent with the above point
  - NEW! Extension of mass tables till A=330 using available offline calculations
  - NEW! New shell corrections coherent with the new masses
- **Fission**:
  - NEW! Actinide fission done on first principles
  - NEW! New fission barrier calculations ( following Myers & Swiatecki)
  - NEW! Fission level density enhancement at saddle point washing out with excitation energy (following IAEA recommendations)
  - NEW! Fission product widths and asymmetric versus symmetric probabilities better parameterized
- **Fermi Break-up** for A<18 nuclei
  - ~ 50000 combinations included with up to 6 ejectiles
- $\gamma$ **de-excitation**: statistical + rotational + tabulated levels

# Residual Nuclei

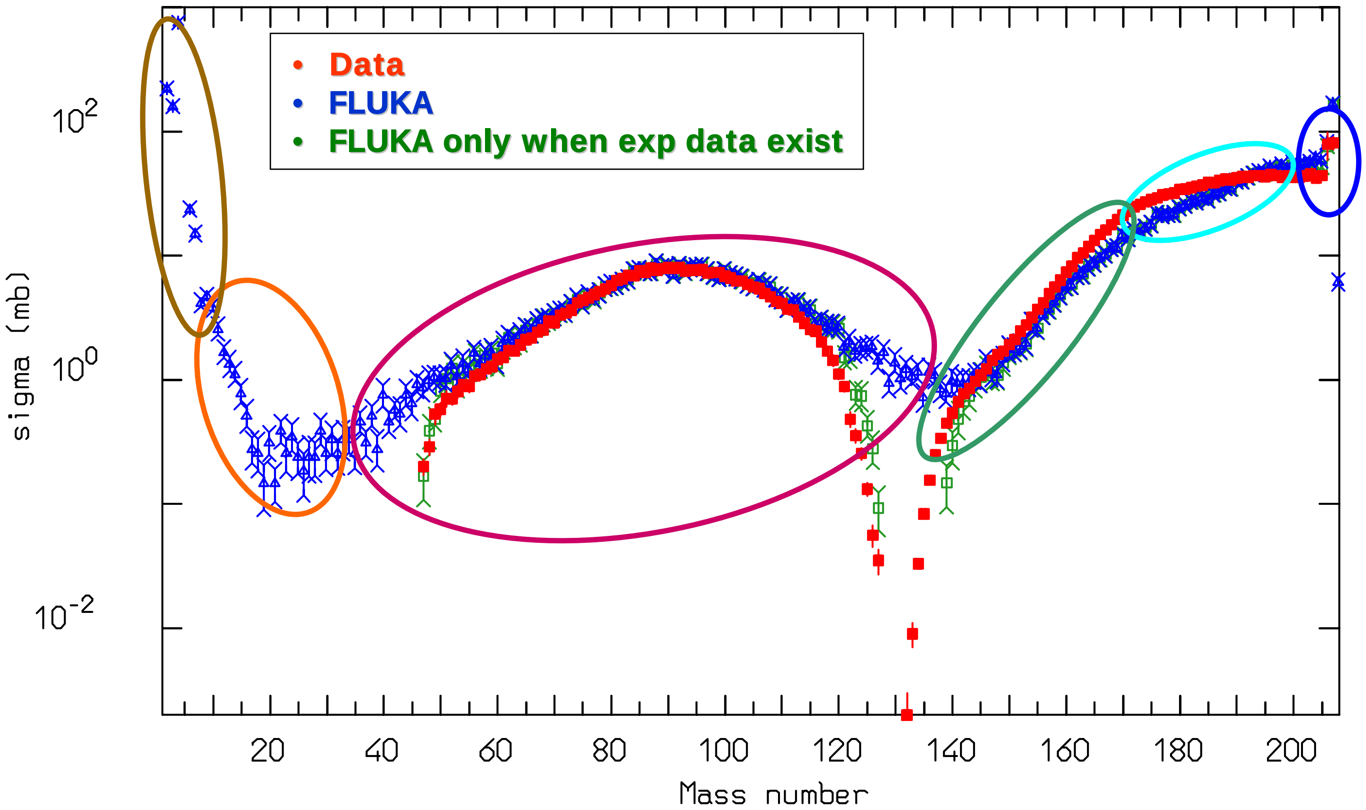
- The production of residuals is the result of the last step of the nuclear reaction, thus it is influenced by all the previous stages
- Residual mass distributions are very well reproduced
- Residuals near to the compound mass are usually well reproduced
- However, the production of specific isotopes 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

- 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



# Low-energy neutron transport in FLUKA

performed by a multigroup algorithm:

- Widely used in low-energy neutron transport codes (not only Monte Carlo, but also Discrete Ordinate codes)
- Energy range of interest is divided in a given number of discrete intervals "energy groups"
- Elastic and inelastic reactions simulated not as exclusive process, but by group-to-group transfer probabilities (down-scattering matrix)
- The scattering transfer probability between different groups represented by a Legendre polynomial expansion truncated at the (N+1)th term:

$$\sigma_s(g \to g', \mu) = \sum_{i=0}^{N} \frac{2i+1}{4\pi} P_i(\mu)\, \sigma_s^i(g \to g')$$

μ = scattering angle

N = chosen Legendre order of anisotropy

# FLUKA Implementation

- Both fully biased and semi-analog approaches available
- Energy range up to 19.6 MeV divided in 72 energy groups of approximately equal logarithmic width, and one thermal
- Prepared using a specialized code (NJOY) and ad-hoc programs
- Continuously enriched and updated on the basis of the most recent evaluations (ENDF/B, JEF, JENDL, etc.)
- The library contains 140 different materials/temperatures
- Cross sections of some materials are available at 2 or 3 different temperatures (0, 87 and 293° K) + Doppler broadening
- Hydrogen cross sections available for different types of molecular binding (free, $H_2O$, $CH_2$)
- Neutron energy deposition calculated by means of kerma factors
- However, H recoil protons, protons from $^{14}N(n,p)$ and $(\alpha, {}^3H)$ from neutron capture in $^6Li$ and $^{10}B$ can be produced and transported explicitly
- Pointwise cross sections available for reactions in H, $^6Li$ , Ar

**The new library**

- A new library is in preparation, based on 260 n and 40 γ groups including 30 thermal groups at different temperatures and different self-shielding

# Other features

### Gamma Generation

- In general, gamma generation by low energy neutrons (but not gamma transport) is treated also in the frame of a multigroup scheme
- A downscattering matrix provides the probability, for a neutron in a given energy group, to generate a photon in each of 22 gamma energy groups, covering the range from 10 keV to 20 MeV.
- The actual energy of the photon is sampled randomly in the energy interval corresponding to its gamma group. With the exception of a few important gamma lines, such as the 2.2 MeV transition of Deuterium and the 478 keV photon from $^{10}B(n,\gamma)$ reaction, all $^{40}Ar$ lines, and the capture lines for Cd and Xe
- The gamma generation matrix apart from capture gammas, includes also gammas produced by other inelastic reactions such as (n,n')

### Residual Nuclei

- For many materials (not for all), group-dependent information on the residual nuclei produced by low-energy neutron interactions is available in the FLUKA library
- This information can be used to score residual nuclei, but the user must check its availability before requesting scoring

# Heavy ion interaction models

- DPMJET-III for energies ≥ 5 GeV/n
  - DPMJET (R. Engel, J. Ranft and S. Roesler) Nucleus-Nucleus interaction model
  - Energy range: from 5-10 GeV/n up to the highest Cosmic Ray energies ($10^{18}$-$10^{20}$ eV)
  - Used in many Cosmic Ray shower codes
  - Based on the Dual Parton Model and the Glauber model, like the high-energy FLUKA hadron-nucleus event generator
- Modified and improved version of rQMD-2.4 for 0.1 < E < 5 GeV/n
  - rQMD-2.4 (H. Sorge et al.) Cascade-Relativistic QMD model
  - Energy range: from 0.1 GeV/n up to several hundred GeV/n
  - Successfully applied to relativistic A-A particle production
- BME (Boltzmann Master Equation) for E < 0.1 GeV/n
  - FLUKA implementation of BME from E.Gadioli et al (Milan)
  - Now under test for light ions
- Developemnt of new QMD codes
  - Non relativistic in Milan : 0.1-≈0.7 GeV/n Poster TC3-0194
  - Relativistic in Houston : Poster TC3-0195
- Standard FLUKA evaporation/fission/fragmentation used in both Target/Projectile final de-excitation
- Electromagnetic dissociation

# 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
- (G)INC, preequilibrium and evaporation like for hadron-nucleus

## Virtual photon reactions

- Muon photonuclear interactions
- Electromagnetic dissociation

# Photonuclear int.: example

Reaction:

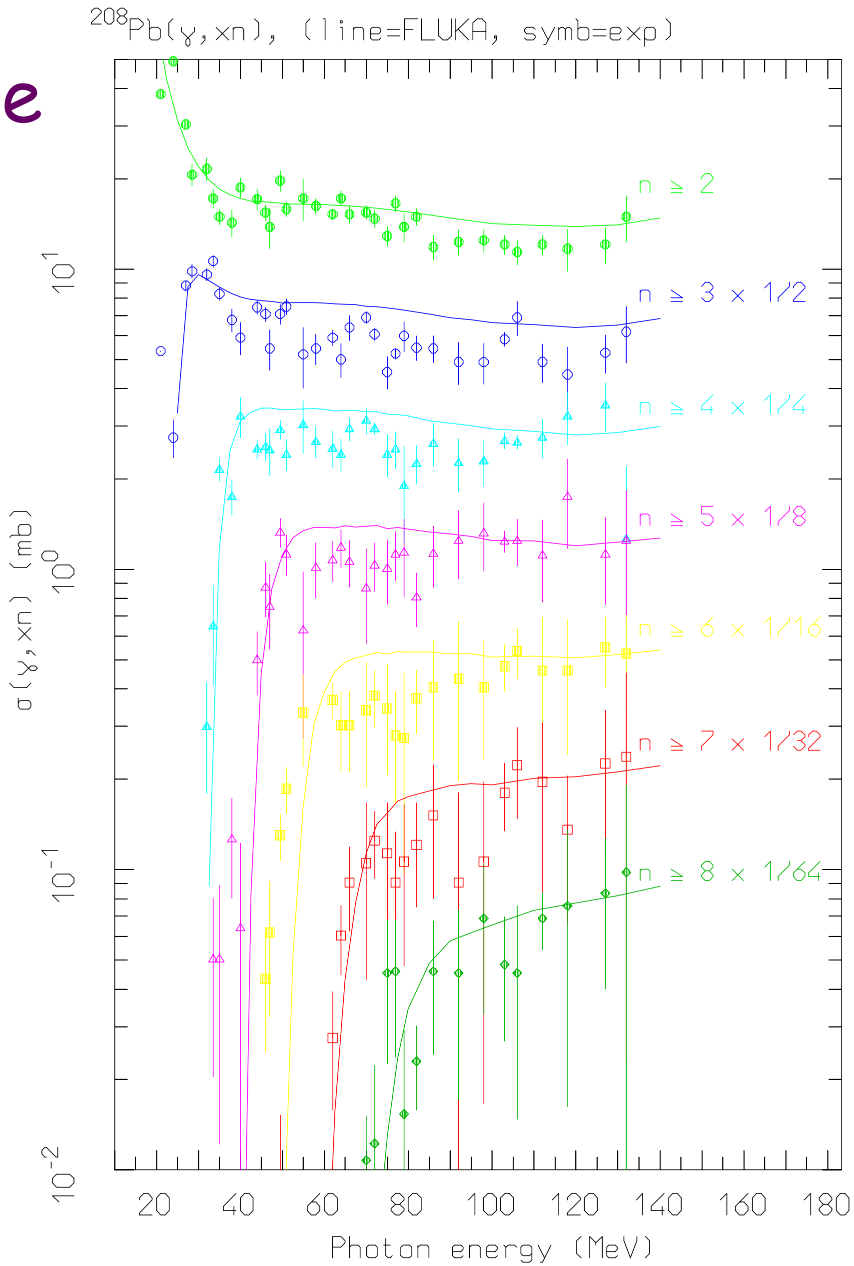
$^{208}Pb(\gamma,x\ n)$

$20 \leq E\gamma \leq 140$ 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) )

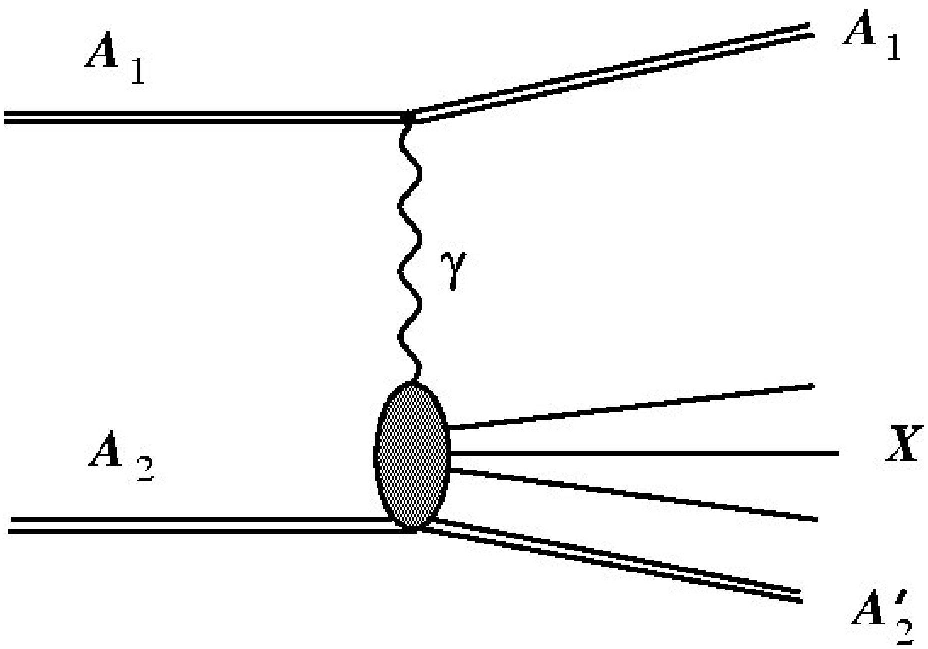
Lines: FLUKA



# Electromagnetic dissociation

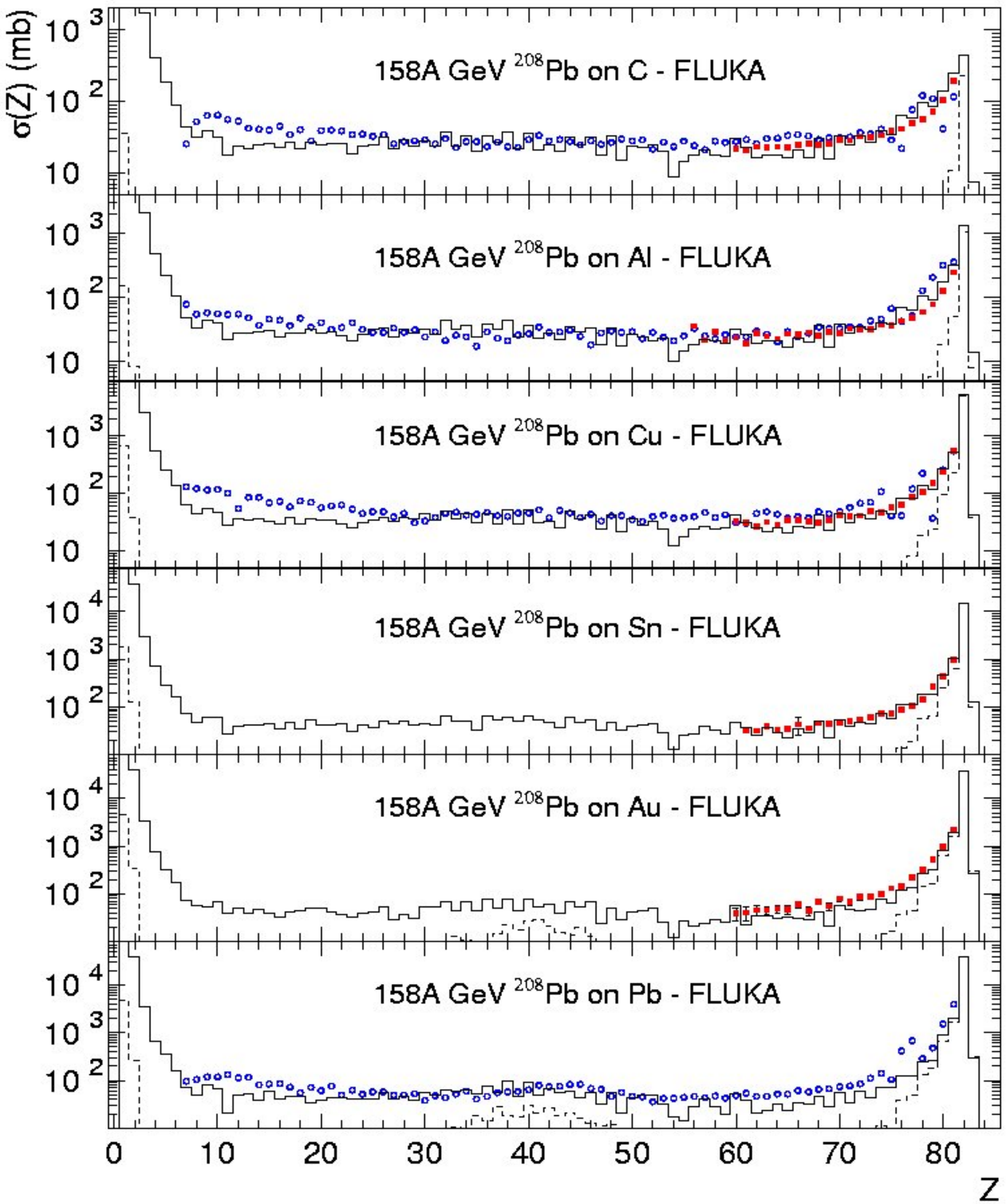
Electromagnetic dissociation: $\sigma_{EM}$ increasingly large with (target) Z's and energy. Already relevant for few GeV/n ions on heavy targets ($\sigma_{EM}$ ~ 1 b vs $\sigma_{nucl}$ ~ 5 b for 1 GeV/n Fe on Pb)

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



## 158 GeV/n 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. PRC, in press (red squares), histos are FLUKA (with DPMJET-III) predictions: the dashed histo is the electromagnetic dissociation contribution



# EMF ElectroMagneticFluka

- Photoelectric : fluorescence, angular distribution, Auger, polarization
- Compton and Rayleigh : atomic bonds, polarization
- Pair production correlated angular and energy distribution; also for μ
- Photonuclear interactions; also for μ
- Bremsstrahlung : LPM, angular distribution, ... also for μ
- Bhabha and Möller scattering
- Positron annihilation at rest and in flight
- μ capture at rest
- Optical photon (Cherenkov) production and transport

PHOTONS

- NEW! cross sections from EPDL97
- NEW! new coherent scattering
- NEW! updated photoelectric
- NEW! updated pair production
- NEW! Compton profile