



Heavy Ions Interactions

FLUKA Beginner's Course

Overview

The models

DPMJET
RQMD
BME

Input options

Beam definition
Transport thresholds

Heavy ion interaction models in FLUKA - 1

$E > 5 \text{ GeV/n}$

Dual Parton Model (DPM)

DPMJET-III (original code by R.Engel, J.Ranft and S.Roesler,
FLUKA-implementation by T.Empl *et al.*)

$\sim 0.1 \text{ GeV/n} < E < 5 \text{ GeV/n}$

Relativistic Quantum Molecular Dynamics Model (RQMD)

RQMD-2.4 (original code by H.Sorge *et al.*,
FLUKA-implementation by A.Ferrari *et al.*)

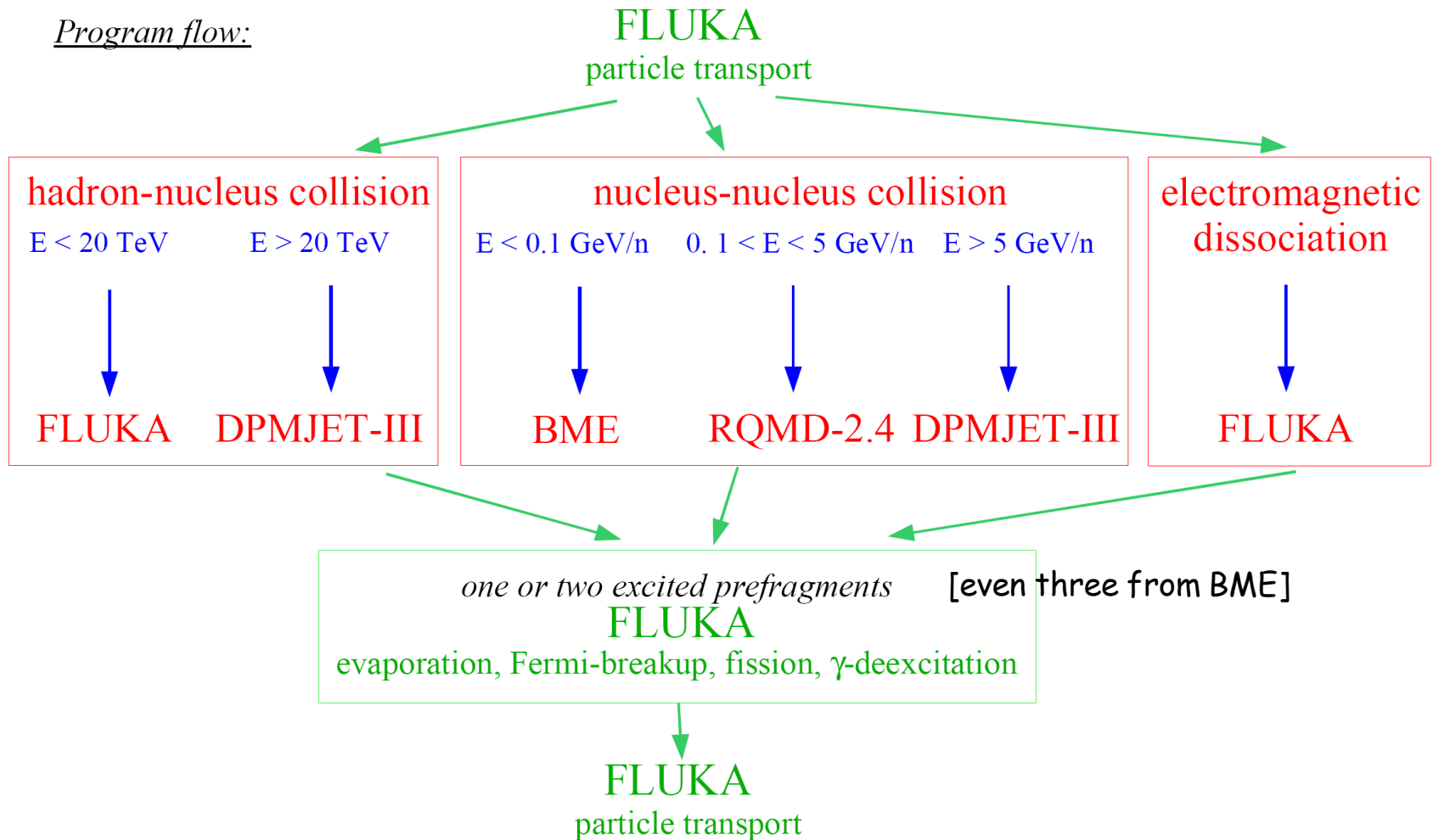
$E < \sim 0.1 \text{ GeV/n}$

Boltzmann Master Equation (BME) theory

BME (original code by E.Gadioli *et al.*,
FLUKA-implementation by F.Cerutti *et al.*)

Heavy ion interaction models in FLUKA - 2

Program flow:



DPMJET

$E > 5 \text{ GeV/n}$

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DPMJET - Overview

DPMJET = Dual Parton Model and JETs

Monte Carlo **event-generator** for the simulation of high-energy hadronic interactions

- hadron-hadron collisions,
hadron-nucleus collisions,
nucleus-nucleus collisions,
photoproduction off nuclei (only Version III)
- energy range: 5 GeV/nucleon – 10^{11} GeV/nucleon
- programming language: Fortran77
- size of the code (Version III): about 90.000 lines
- authors: J. Ranft (Version II),
R.Engel, J. Ranft, S. Roesler (Version III)

DPMJET - Main steps of a high energy interaction

1. Interaction of high-energy nuclei

- individual nucleon-nucleon scatterings
- formation of »strings« between valence and sea partons (quarks, gluons)



2. Hadronization process

- creation of hadrons / resonances



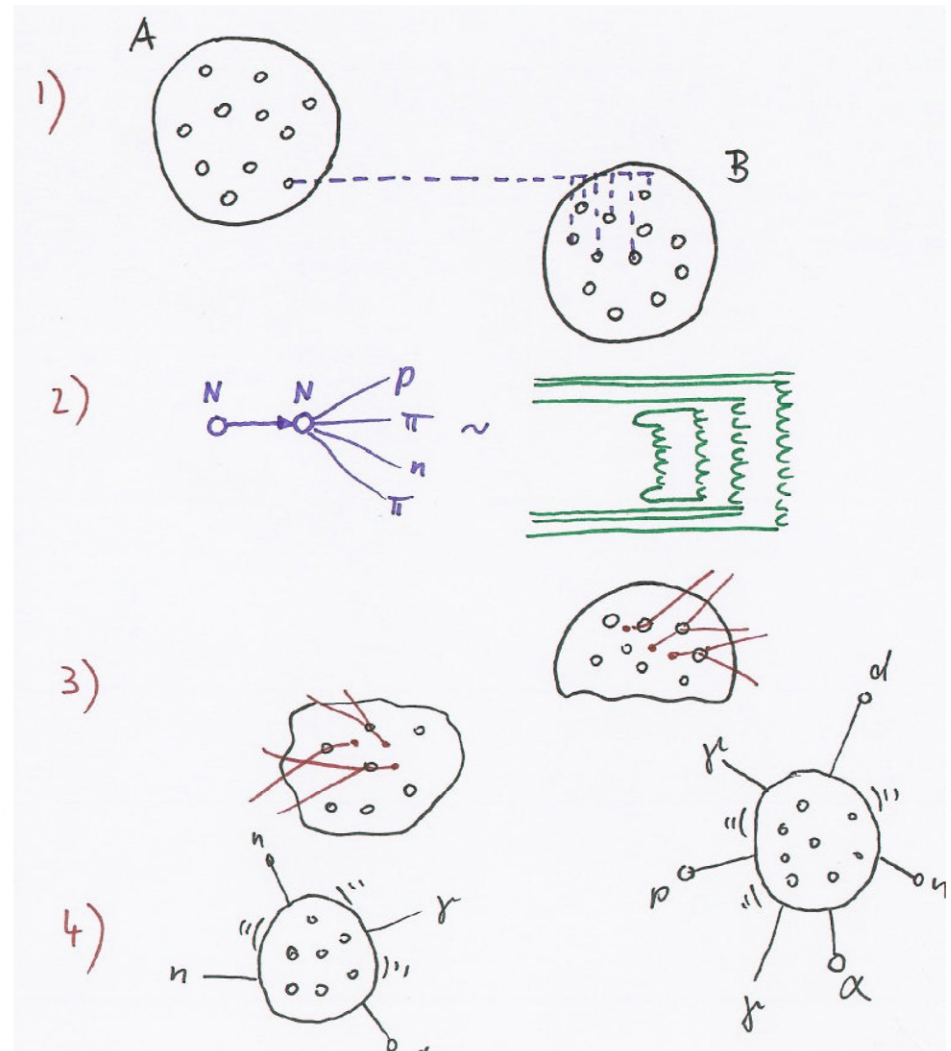
3. Intranuclear cascade

- low-energy interactions of hadrons in spectator nuclei



4. Fragmentation of excited spectator nuclei

- evaporation of light fragments (e.g., p, n, d, ^3H , ^3He , ^4He ,...),
- fragmentation, fission
- production of residual nuclei



DPMJET - *The Gribov-Glauber formalism*

Fundamental idea: nucleus-nucleus collision expressed in terms of individual nucleon-nucleon interactions

- nucleus-nucleus

- total cross section

$$\sigma_{AB}^{tot}(s) = 4 \int d^2 \vec{B} \mathfrak{I} [A_{AB}(s, \vec{B})]$$

- elastic cross section

$$\sigma_{AB}^{el}(s) = 4 \int d^2 \vec{B} \left| A_{AB}(s, \vec{B}) \right|^2$$

- scattering amplitude

$$A_{AB} = \frac{i}{2} \left[1 - \exp(\chi_{AB}) \right]$$

eikonal function

$$\chi_{AB} = \sum_{k,l} \chi_{N_k N_l}$$

- nucleon-nucleon

- scattering amplitude

$$a_{N_k N_l} = \frac{i}{2} \left[1 - \exp(\chi_{N_k N_l}) \right]$$

DPMJET - *Intranuclear cascade and fragmentation*

- nuclear model :
 - Fermi-gas of nucleons in potential well
 - nuclear densities: shell model ($A \leq 18$)
Wood-Saxon ($A > 18$)
- hadrons are followed in space and time on straight trajectories
- hadrons may re-interact after certain formation-time
(assume local nuclear density and vacuum cross sections)
- calculation of excitation energies (in AA interactions for both spectators)

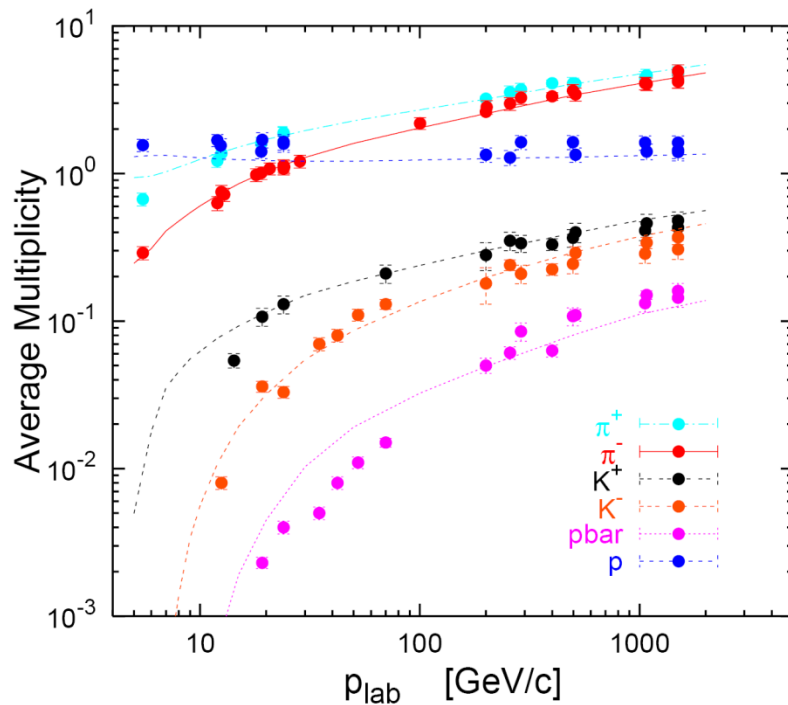
Note: DPMJET has its own implementation of intranuclear cascades. It is similar in its fundamental ideas to that one of FLUKA but is much more simplified.

- fragmentation by
 - nuclear evaporation
 - Fermi-breakup
 - high-energy fission
 - γ -deexcitation
- } FLUKA

DPMJET - Comparison to data (hadron-hadron)

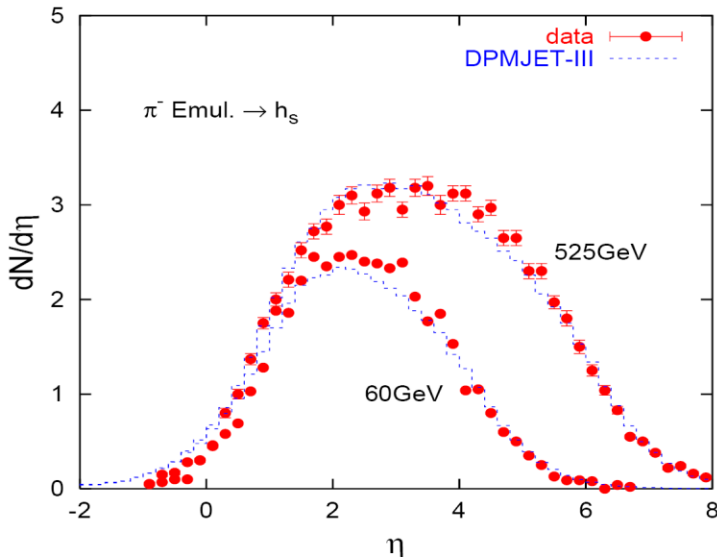
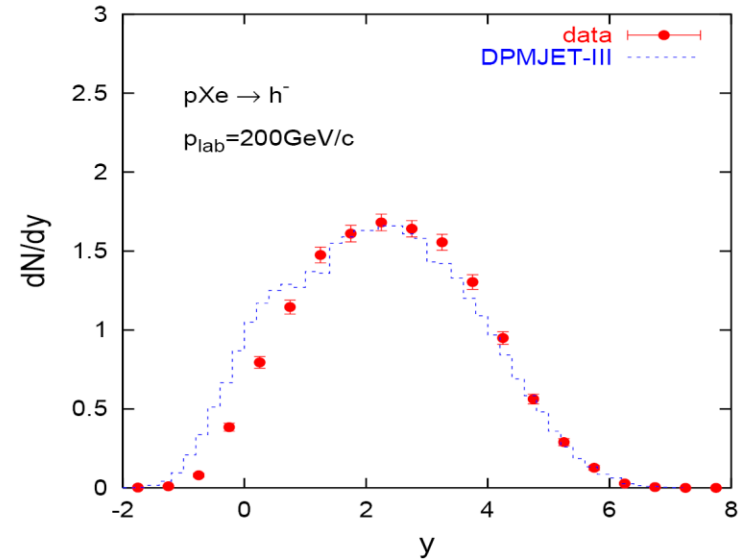
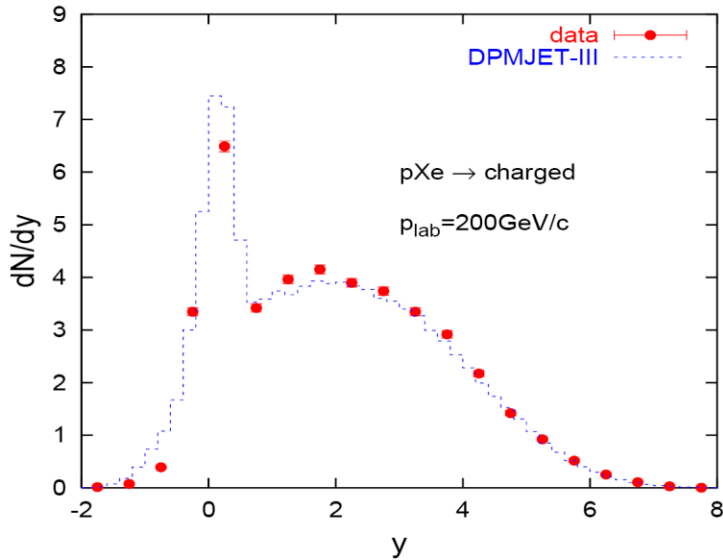
proton - proton

proton - proton, $E_{\text{lab}} = 200\text{GeV}$



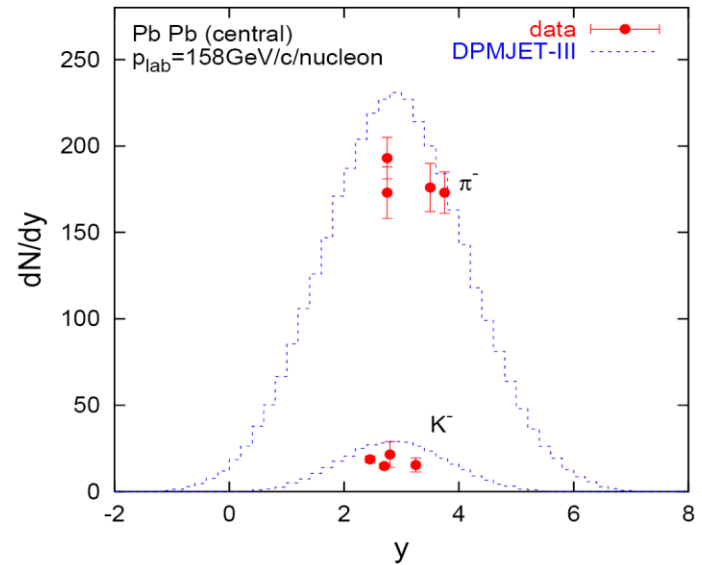
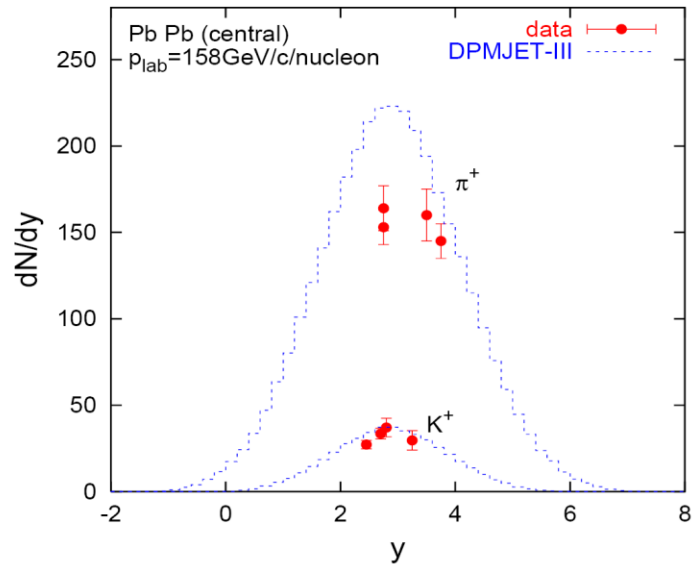
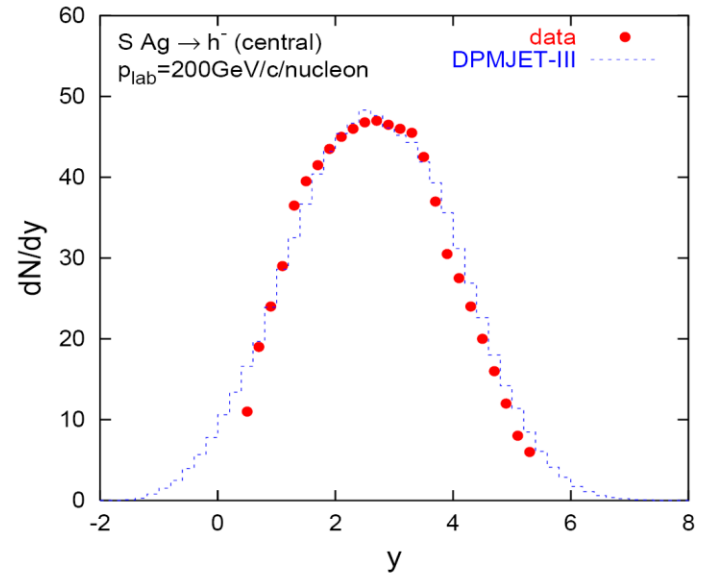
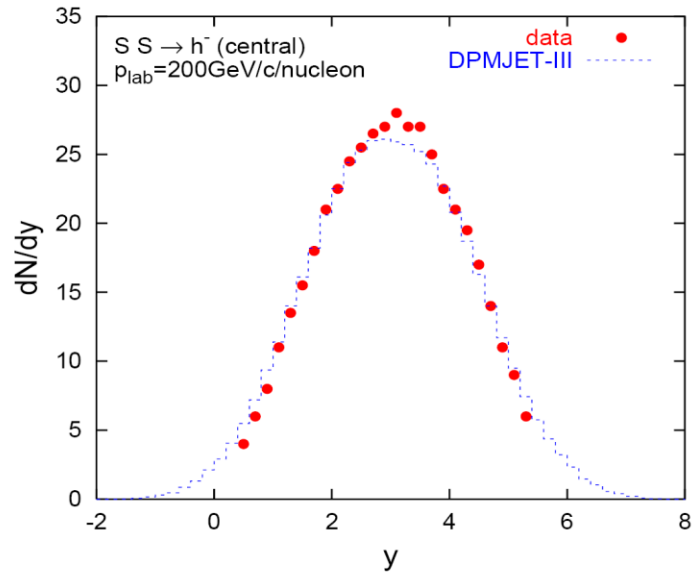
	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
K^-	0.18 ± 0.05	0.20
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105

DPMJET - Comparison to data (hadron-nucleus)

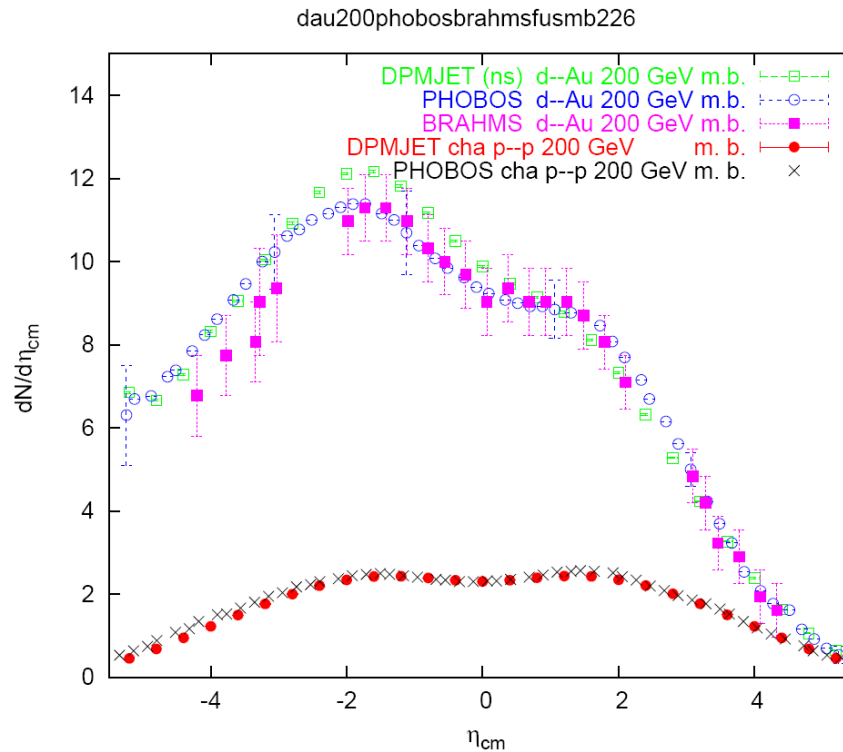


	Exp.	DPMJET-III
14.6 GeV p Al	1.57 ± 0.23	1.52
p Au	2.15 ± 0.33	1.92
200 GeV p S	5.0 ± 0.2	4.98
p Xe	6.84 ± 0.13	6.67
360 GeV p Al	6.8 ± 0.6	5.87
p Au	8.9 ± 0.4	8.77

DPMJET - Comparison to data (nucleus-nucleus)



DPMJET - Comparison to data (nucleus-nucleus)

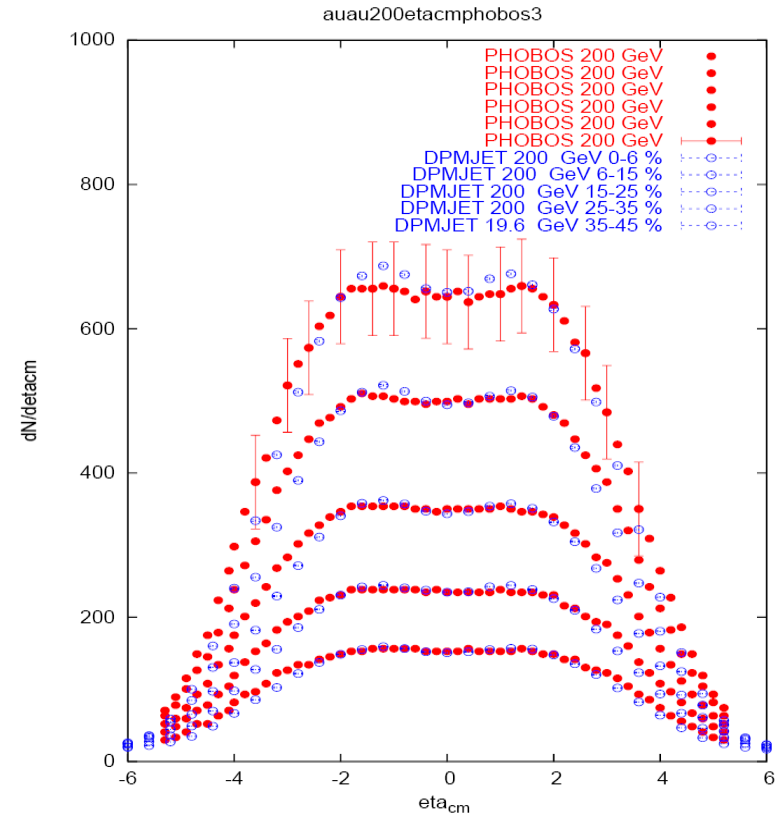
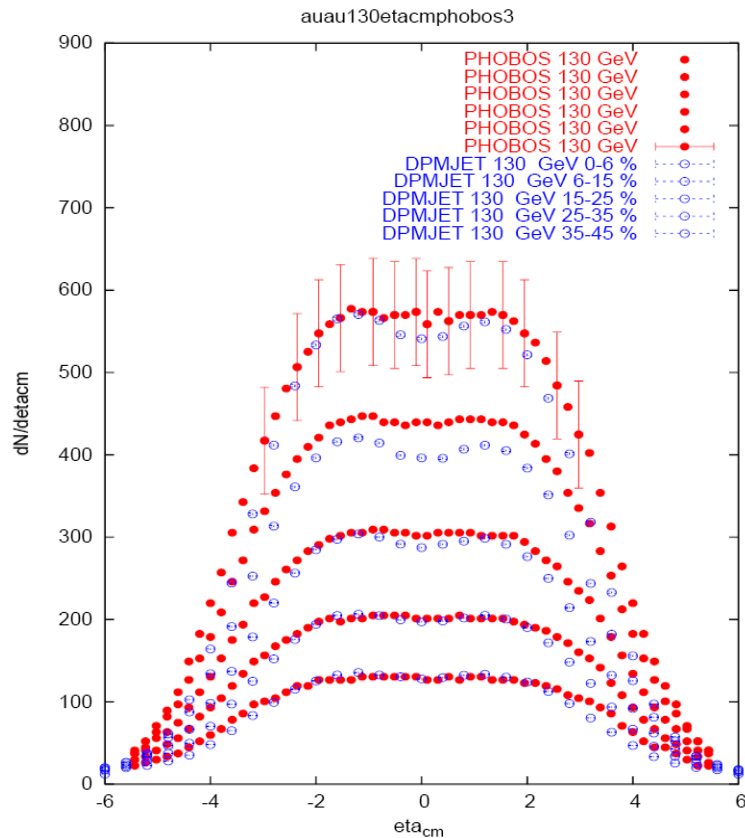


Pseudorapidity distribution of charged hadrons produced in minimum bias d-Au and p-p collisions at a c.m. energy of 200 GeV/A.

Exp. data: BRAHMS- and PHOBOS-Collaborations

J.Ranft, in Proceedings of the Hadronic Shower Simulation Workshop, CP896, Batavia, Illinois (USA), 6-8 September 2006

DPMJET - Comparison to data (nucleus-nucleus)

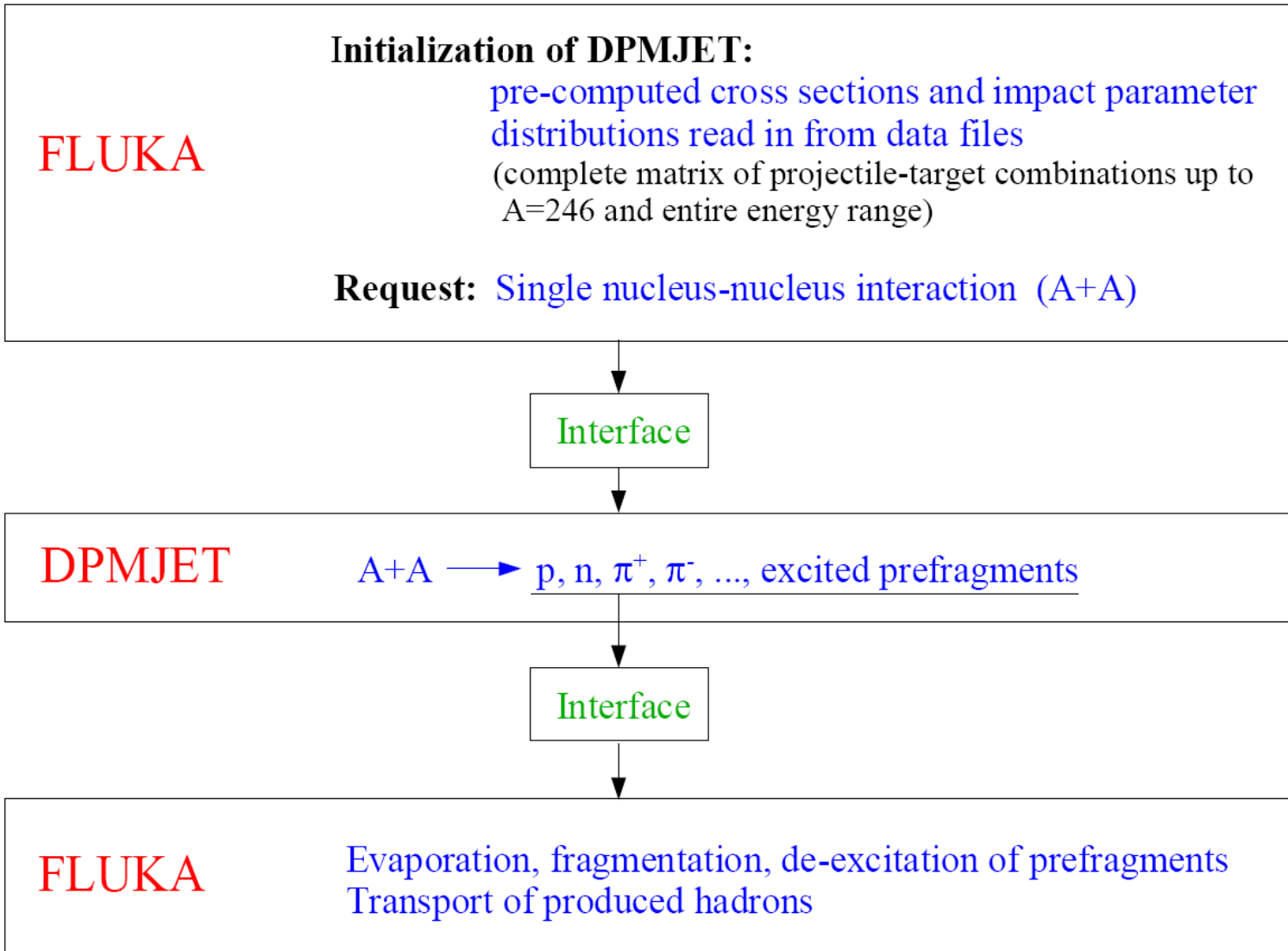


Pseudorapidity distribution of charged hadrons produced in Au-Au collisions at a c.m. energy of 130 GeV/A (left) and 200 GeV/A (right) for different ranges of centralities.

Exp. data: PHOBOS-Collaboration

J.Ranft, in Proceedings of the Hadronic Shower Simulation Workshop, CP896, Batavia, Illinois (USA), 6-8 September 2006

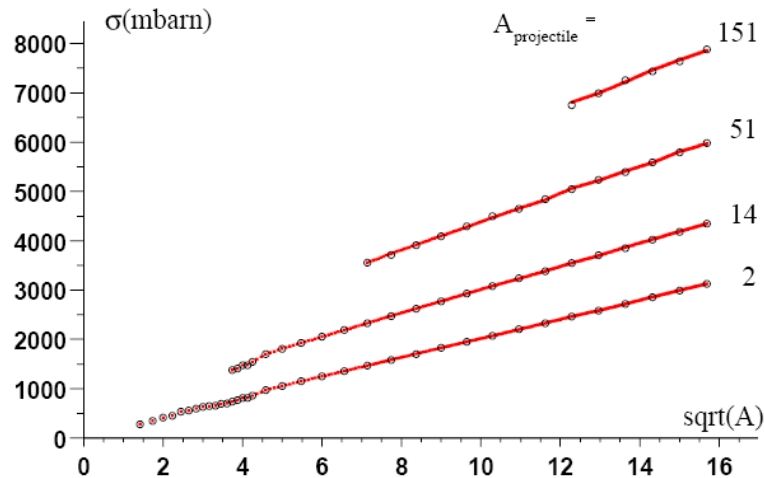
DPMJET - Interface to FLUKA



DPMJET - Interface to FLUKA

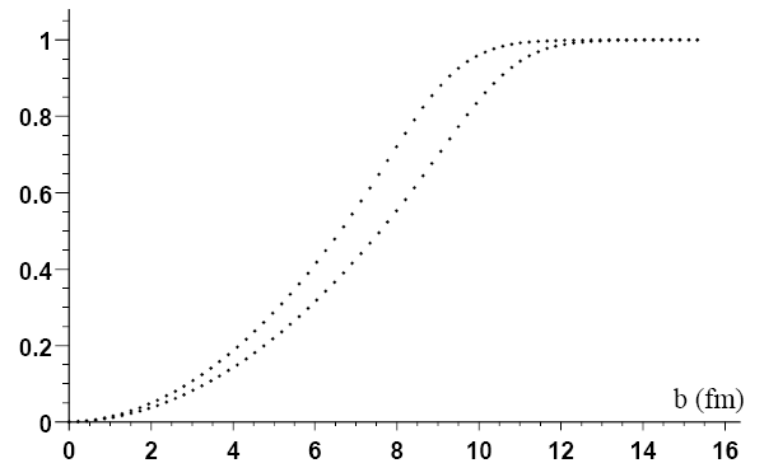
Examples for pre-initialised data:

Inelastic cross sections



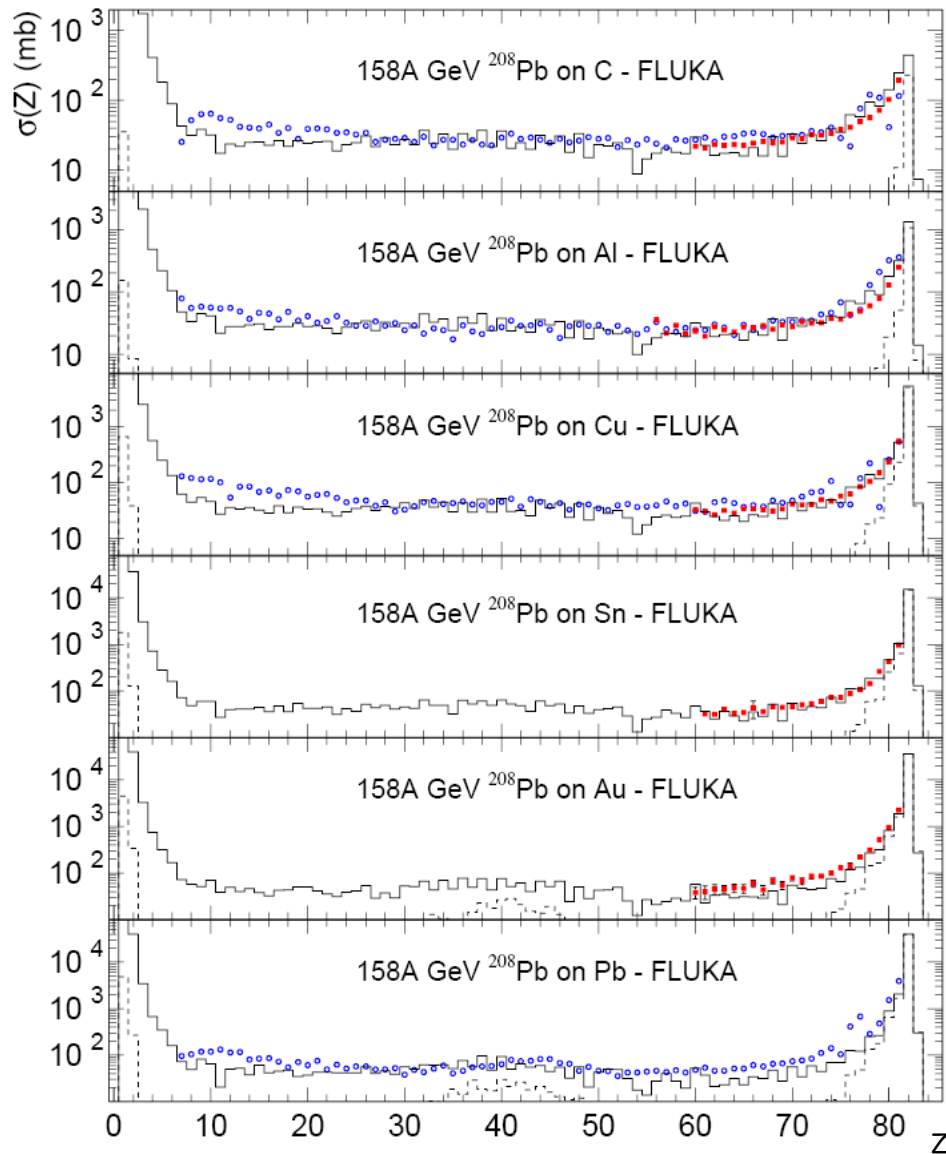
$$E_{\text{Lab}} = 6.3 \times 10^9 \text{ GeV/nucleon}$$

Impact parameter distribution



e.g., for highest and lowest energy at one fixed projectile-target configuration

DPMJET - FLUKA benchmarks



Fragment charge cross sections for
158GeV/n Pb ions on various targets.

FLUKA: solid histogram (total)

dashed histogram (em diss.)

Exp. data: symbols

NPA662, 207 (2000),

NPA707, 513 (2002),

C.Scheidenberger *et al.* PRC

RQMD

$E > 5 \text{ GeV/n}$

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$E < 0.1 \text{ GeV/n}$

Boltzmann Master Equation (BME) theory
BME (original code by E.Gadioli *et al.*,
FLUKA-implementation by F.Cerutti *et al.*)

RQMD - *References*

interface to a suitably modified **RQMD model**

RQMD-2.4 (H. Sorge, 1998) was successfully applied
to relativistic A-A particle production over a wide energy range

[H. Sorge, Phys. Rev. **C 52**, 3291 (1995);

H. Sorge, H. Stöcker, and W. Greiner, Ann. Phys. **192**, 266 (1989)

and Nucl. Phys. **A 498**, 567c (1989)]

RQMD - *The original code*

The RQMD-2.4 code

INITIAL CONDITION two Fermi gases (projectile and target)

Fermi momentum $p_{F0} = \hbar \left(3\pi^2 \frac{A}{2V} \right)^{1/3}$ $V = (4/3) \pi (r_0 A^{1/3})^3$ $r_0 = 1.12 \text{ fm} \Rightarrow \rho = 0.17 \frac{\text{nucl.}}{\text{fm}^3}$

$$\text{nucleon momentum } \boxed{p = p_{F0} \left(\frac{\rho(r)}{\rho_0} \right)^{1/3} \epsilon^{1/3}} \quad \epsilon \in [0, 1] \text{ random}$$
$$\phi = 2\pi\epsilon \qquad \cos \theta = 1 - 2\epsilon$$

$$p_x = p \sin \theta \cos \phi \quad - (\sum p_x) / A$$

$$p_y = p \sin \theta \sin \phi \quad - (\sum p_y) / A$$

$$p_z = p \cos \theta \quad - (\sum p_z) / A$$

$$\text{so } \sum p_x = \sum p_y = \sum p_z = 0$$

FINAL STATE

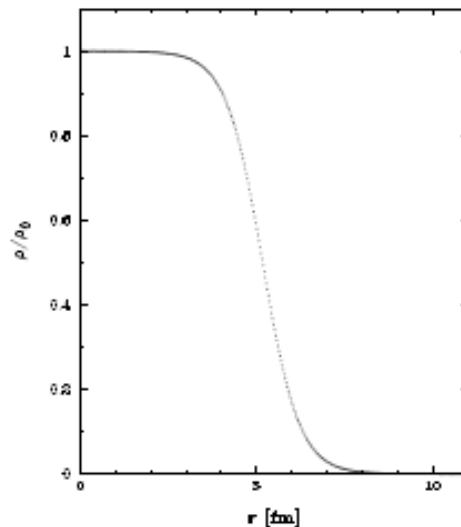
- (p^0, p_x, p_y, p_z) for nucleons (and produced particles) in the LAB frame
- the spectators are marked
- no residue and fragment identification
- energy non-conservation issues, particularly when run in full QMD mode

RQMD - The interfaced code

Implemented developments

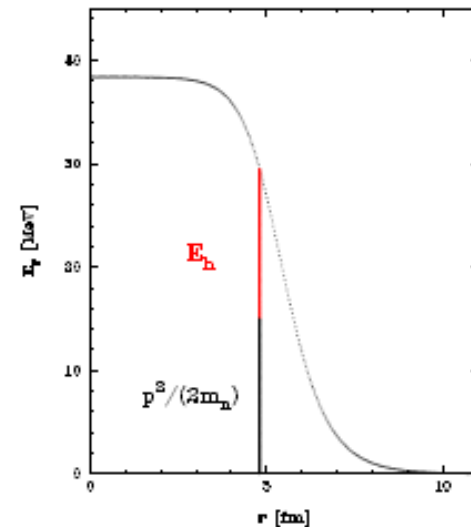
- construct the **projectile- and target-like** nuclei by gathering *spectator* nucleons,

$$\text{assuming } E_{PL}^* = \sum_{pa.} p E_h \quad (TL)$$



$$\rho(r) \propto \left(1 + \exp\left(\frac{r-R}{a}\right)\right)^{-1}$$

$$R = 1.19 A^{1/3} - 1.61 A^{-1/3} \text{ fm} \quad a = 0.52 \text{ fm}$$

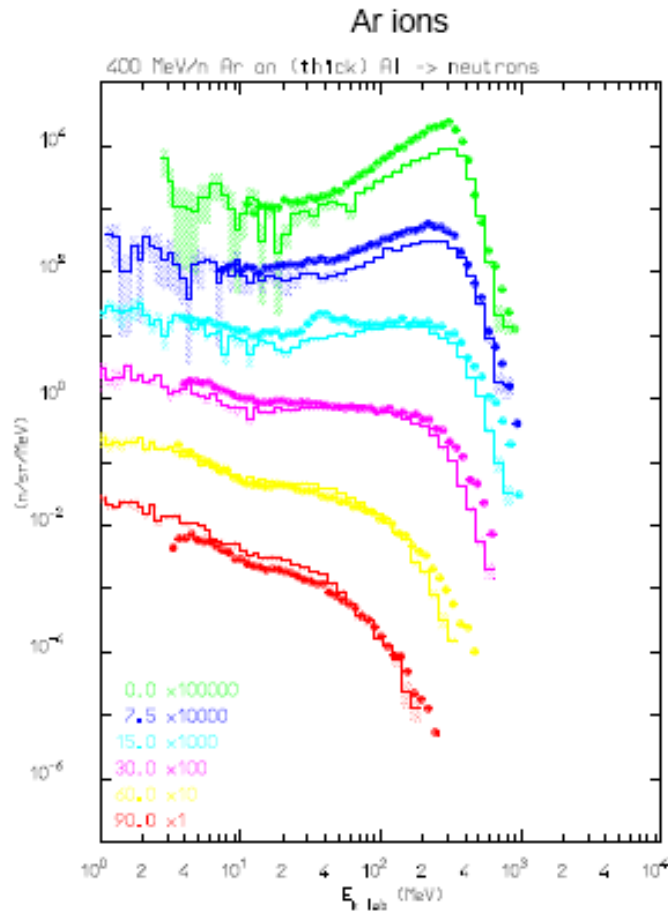


$$E_h = \frac{1}{2m_n} \left\{ \left[p_{F0} (\rho(r)/\rho_0)^{1/3} \right]^2 - p^2 \right\}_{r, p(t=0)}$$

- fix the remaining energy-momentum conservation issues taking into account **experimental binding energies**
- use the FLUKA evaporation/fission/fragmentation module

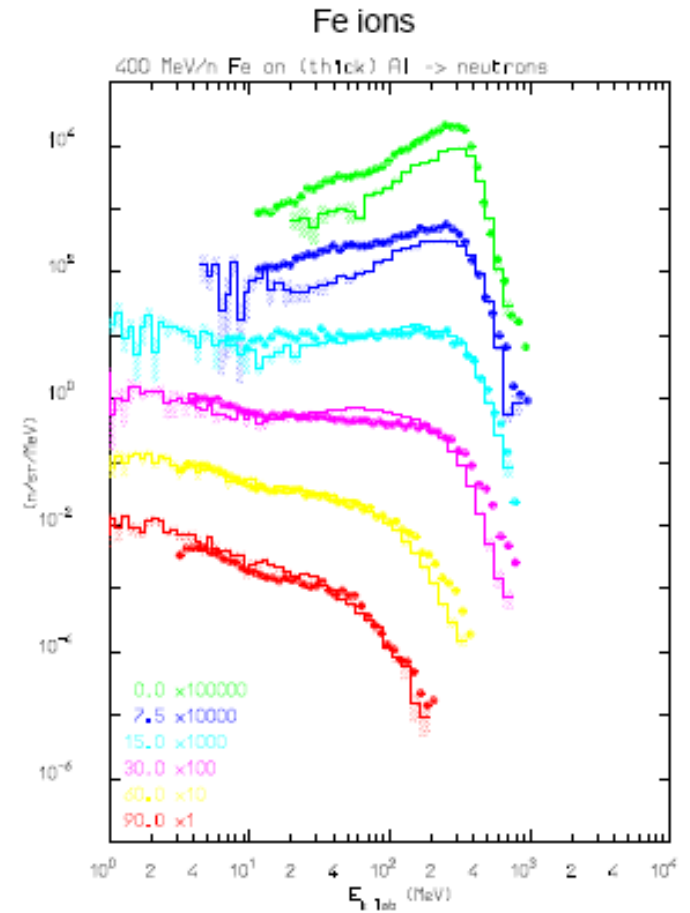
RQMD - FLUKA benchmarks

Double differential neutron yield



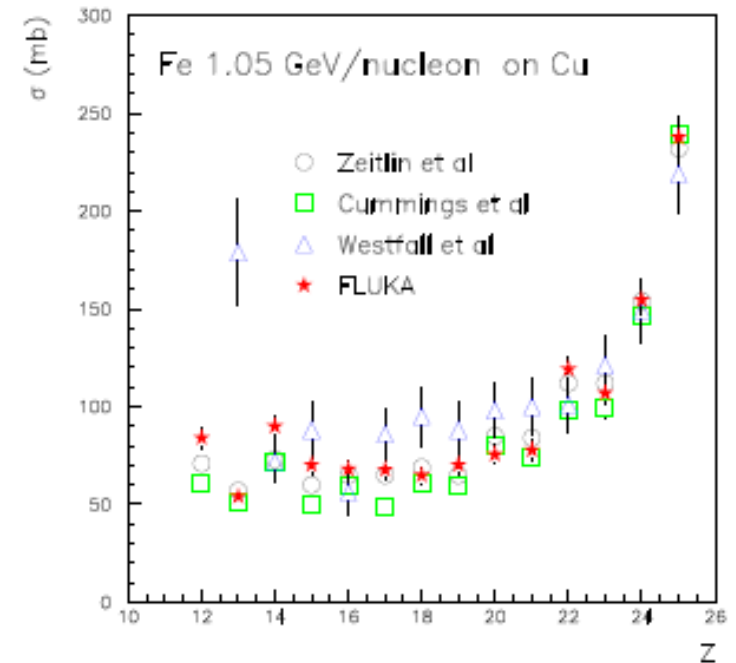
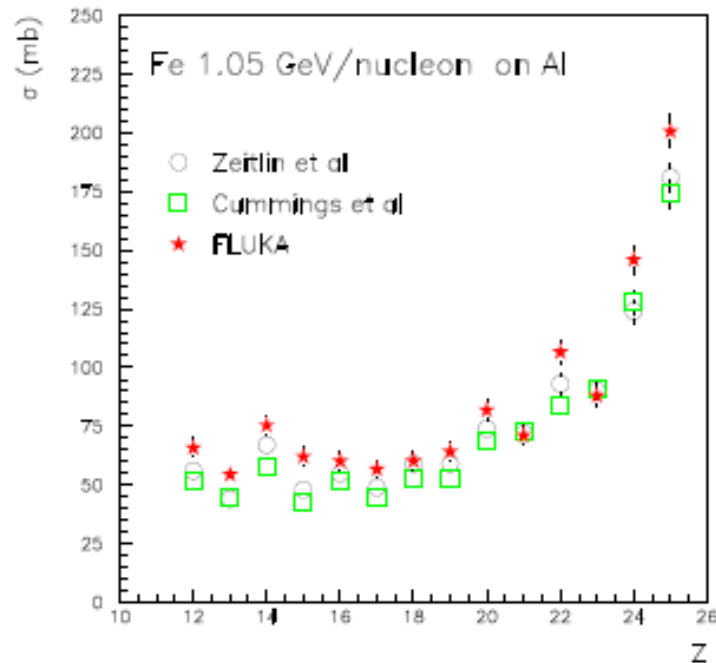
400 MeV/n

on *thick*
Al targets



exp. data from T. Kurosawa *et al.*, Phys. Rev. C **62**, 044615 (2000)

Fragment charge cross sections

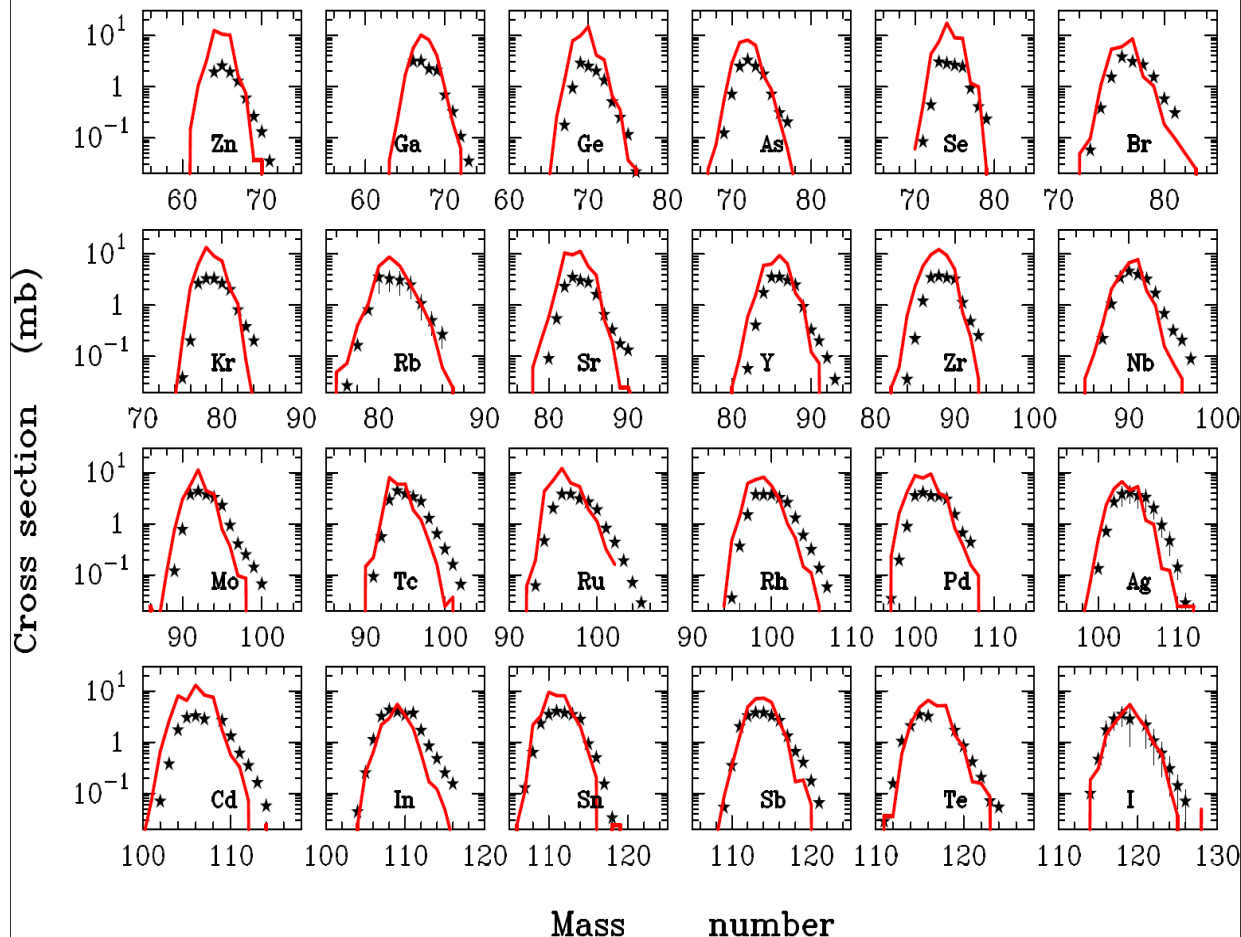


exp. data from C. Zeitlin *et al.*, Phys. Rev. **C 56**, 388 (1997),
J.R. Cummings *et al.*, Phys. Rev. **C 42**, 2508 (1990) (at 1.5 GeV/n),
G.D. Westfall *et al.*, Phys. Rev. **C 19**, 1309 (1979) (at 1.88 GeV/n)

RQMD - FLUKA benchmarks

Isotopic distributions of fragmentation products

$^{238}\text{U} + ^{208}\text{Pb}$ (750 A MeV)



fission products excluded
like in the experimental
analysis

exp. data (stars) from J. Benlliure, P. Armbruster *et al.*, Eur. Phys. J **A 2**, 193 (1998)

BME

$E > 5 \text{ GeV/n}$

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BME - References

interface to a Monte Carlo code
founded on the BME theory (E. Gadioli et al.)

[M. Cavinato *et al.*, Nucl. Phys. **A 679**, 753 (2001),
M. Cavinato *et al.*, Phys. Lett. **B 382**, 1 (1996)]

BME - *The interfaced code*

two different main reaction paths have been adopted:

1. COMPLETE FUSION

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

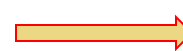
composite nucleus formation

2. PERIPHERAL COLLISION

$$P = 1 - P_{CF}$$

*three body mechanism with possible incomplete fusion
one nucleon break-up and possibly transfer (at high b)
pickup/stripping (for asymmetric systems at low b)*

pre-equilibrium de-excitation of the produced fragment(s)
according to the BME theory (where available)
or the PEANUT exciton model



*NB interface to PEANUT pre-eq
not yet distributed!*

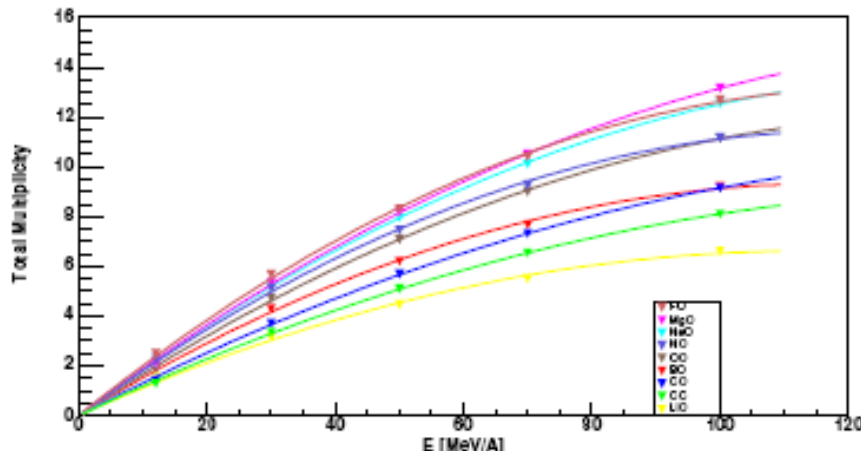
FLUKA evaporation/fission/fragmentation/gamma de-excitation

BME - The database for the pre-equilibrium emissions

In order to get the multiplicities of the pre-equilibrium particles and their double differential spectra, the BME theory is applied to several representative systems at different bombarding energies and the results are parameterized.



@ 12, 30, 50, 70, 100 MeV/n



total multiplicity

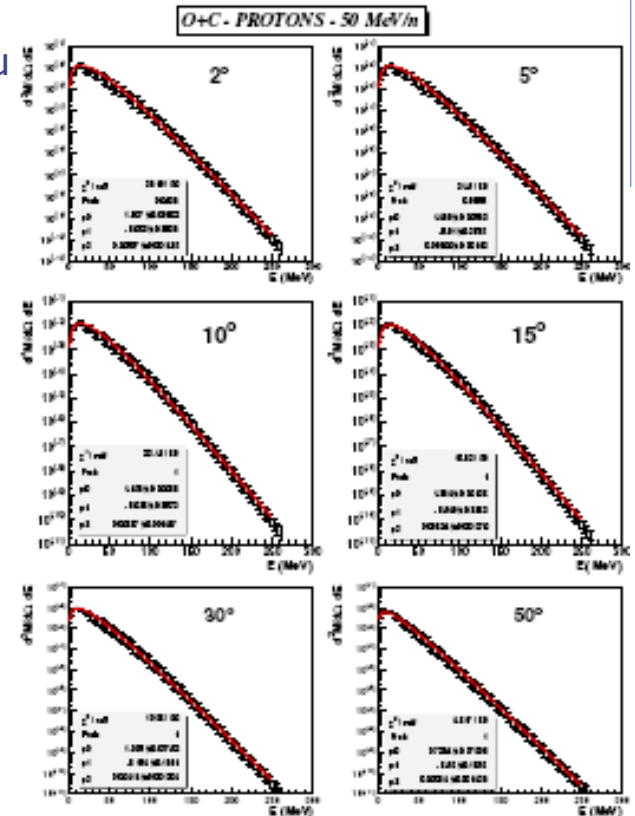
$$M = P_1 E_{nucl} - P_2 E_{nucl}^2$$

Work is ongoing to extend it to more massive systems, i.e.



and consequently review the fitting functions

and the extrapolation recipes over a significantly larger mass range



energy spectra

$$\frac{d^2M}{(dE d\Omega)} = E^{P_0(\theta)} \exp(-P_1(\theta) - P_2(\theta)E)$$

BME - Theoretical framework

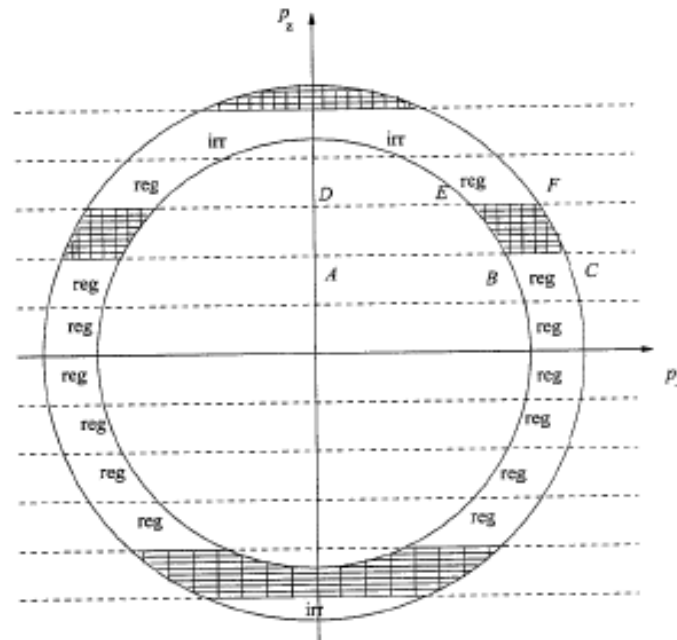
Calculation of preequilibrium for the composite nucleus

proton and neutron momentum spaces divided into **bins**

$$\left\{ (p_x, p_y, p_z) : p_z \in [p_{zi}, p_{zi} + \Delta p_z), \varepsilon = (2m)^{-1} (p_x^2 + p_y^2 + p_z^2) \in [\varepsilon_i, \varepsilon_i + \Delta\varepsilon) \right\}$$

(**Z** is the beam direction)

of volume $2\pi m \Delta\varepsilon \Delta p_z$



BME - Theoretical framework

The BME system

$$N_i = n_i g_i$$

nucleon number
occupation probability
number of states in bin i

$$\begin{aligned}
 \frac{d(n_i^\pi g_i^\pi)}{dt} = & \sum_{jlm} [\omega_{lm \rightarrow ij}^{\pi\pi} g_i^\pi n_i^\pi g_m^\pi n_m^\pi (1 - n_i^\pi)(1 - n_j^\pi) \\
 & - \omega_{ij \rightarrow lm}^{\pi\pi} g_i^\pi n_i^\pi g_j^\pi n_j^\pi (1 - n_i^\pi)(1 - n_m^\pi)] \\
 + & \sum_{jlm} [\omega_{lm \rightarrow ij}^{\pi\nu} g_i^\pi n_i^\pi g_m^\nu n_m^\nu (1 - n_i^\pi)(1 - n_j^\nu) \\
 & - \omega_{ij \rightarrow lm}^{\pi\nu} g_i^\pi n_i^\pi g_j^\nu n_j^\nu (1 - n_i^\pi)(1 - n_m^\nu)] \\
 - & n_i^\pi g_i^\pi \omega_{i \rightarrow i'}^\pi g_{i'}^\pi \delta(\epsilon_i^\pi - \epsilon_{i'}^\pi - \epsilon_F^\pi - B^\pi) - \frac{dD_i^\pi}{dt}
 \end{aligned}$$

BME - Theoretical framework

Multiplicity spectra

of emitted nucleons

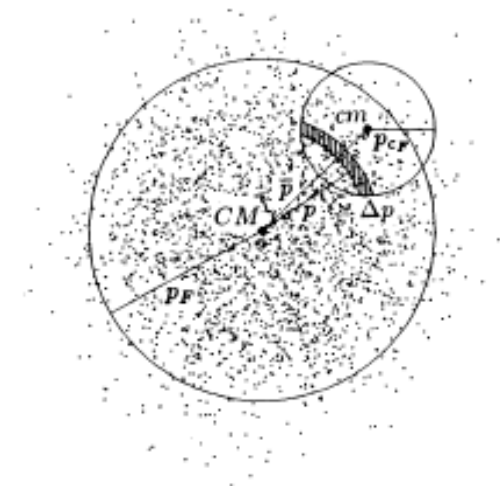
$$\frac{d^2 M(\varepsilon', \theta)}{d\varepsilon' d\Omega} = \frac{1}{2\pi \sin \theta} \int_0^{t_{eq}} n(\varepsilon, \theta, t) \frac{\sigma_{inv} V}{V} \rho(\varepsilon', \theta) dt$$

of a cluster c

$$\frac{d^2 M_c(E'_c, \theta_c)}{dE'_c d\Omega} = \frac{R_c}{2\pi \sin \theta} \int_0^{t_{eq}} N_c(E_c, \theta_c, t) \frac{\sigma_{inv,c} V_c}{V} \rho_c(E'_c, \theta_c) dt$$

$$N_c(E_c, \theta_c, t) = \prod_i (n_i^\pi(\varepsilon, \theta, t))^{P_i(E_c, \theta_c) Z_c} \cdot \prod_i (n_i^\nu(\varepsilon, \theta, t))^{P_i(E_c, \theta_c) N_c}$$

joint probability

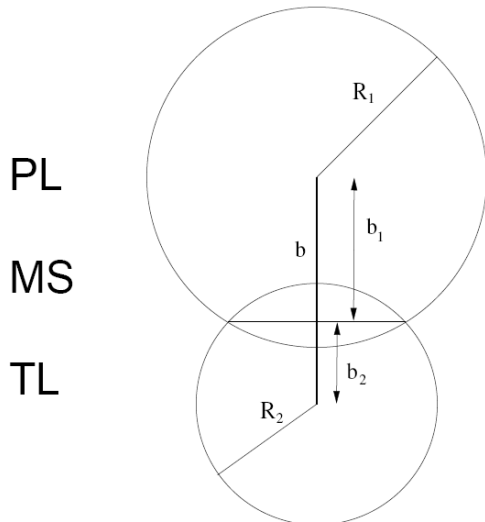


BME - Peripheral collisions

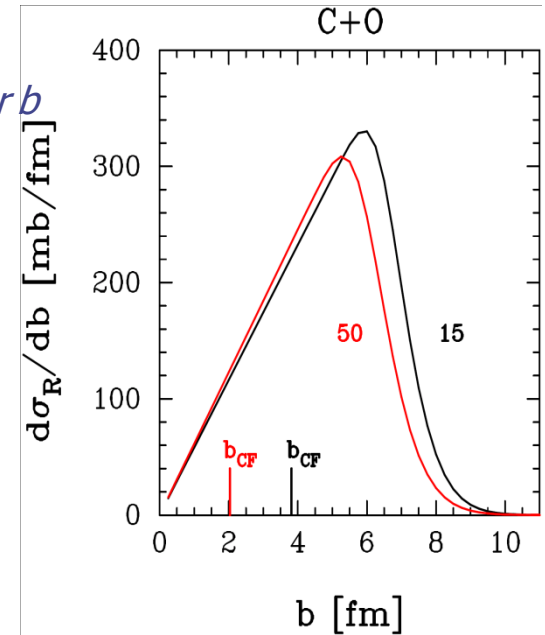
We integrate the nuclear densities of the projectile and the target over their overlapping region, as a function of the impact parameter, and obtain a preferentially excited "middle source" and two fragments (projectile- and target-like). The kinematics is suggested by break-up studies.

ii. kinematics determination

- θ_{PL}, θ_{TL} chosen according to $[d\sigma/d\Omega]_{cm} \sim \exp(-k\theta_{cm})$
- θ_{MS} momentum conservation
- p_{PL}, p_{TL} chosen according to a given energy loss distribution
- p_{MS} momentum conservation
- ϕ_{PL} free
- ϕ_{TL}, ϕ_{MS} same reaction plane



i. selection of the impact parameter b



iii. excitation energy sharing

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

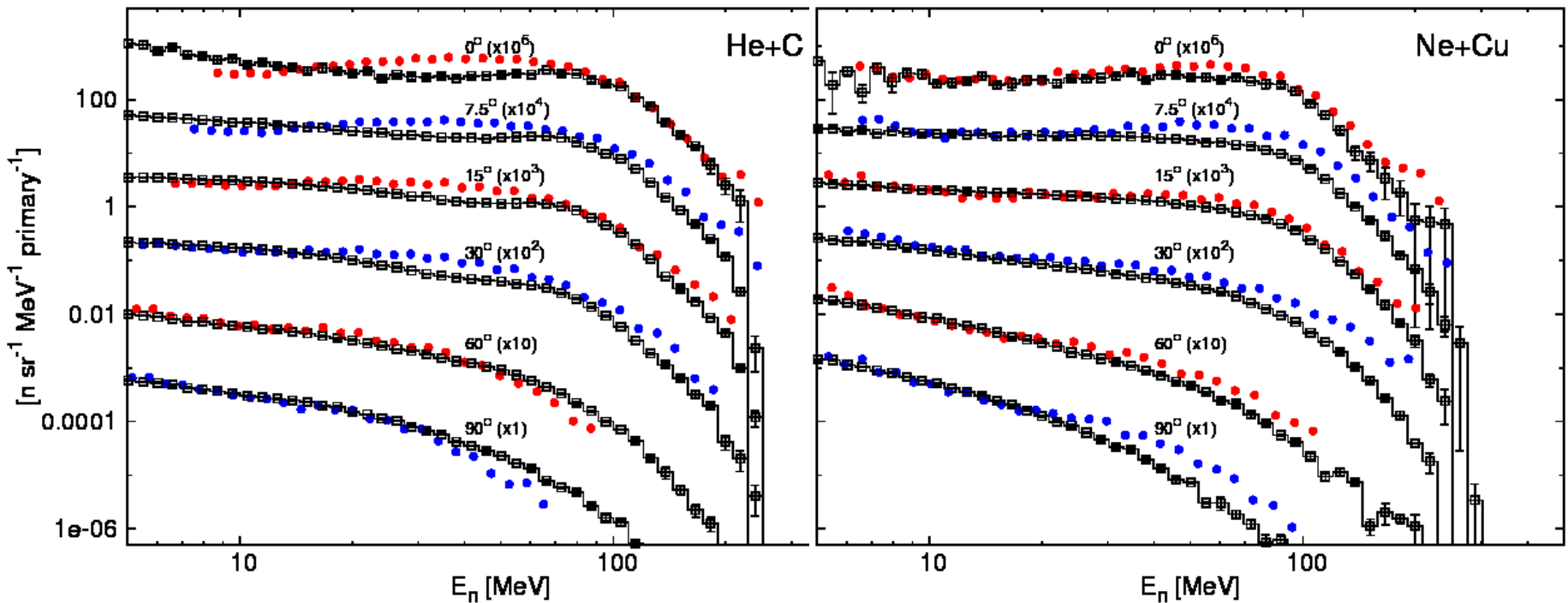
$$E_{PL}^* = f(A_{PL}, A_{TL}) (E_{tot}^* - E_{MS}^*)$$

forced on the experimental values in the discrete level region

$$E_{TL}^* = (E_{tot}^* - E_{MS}^* - E_{PL}^*)$$

BME - Benchmarking

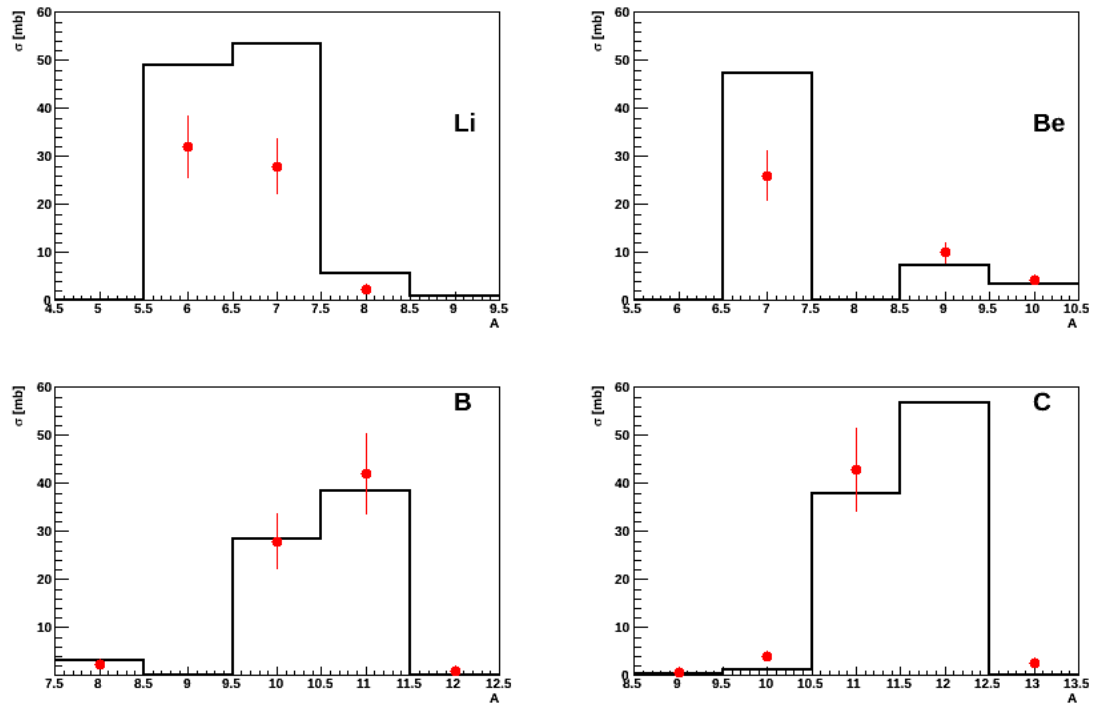
DOUBLE DIFFERENTIAL NEUTRON YIELDS FROM 100 MeV/n BEAMS ON THICK TARGETS



FLUKA vs experimental data from T. Kurosawa, N. Nakao, T. Nakamura et al., Nucl. Sci. Eng. 132, 30 (1999)

BME - Benchmarking

ISOTOPE YIELDS FROM C+C at 86 MeV/n

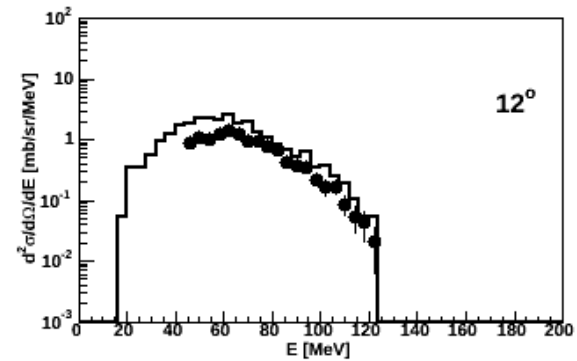
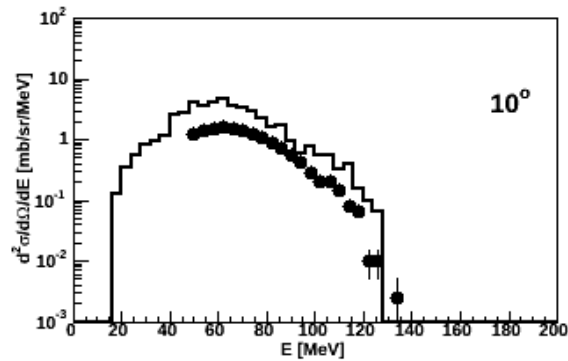


experimental data from H. Ryde, Physica Scripta T5, 114 (1983)

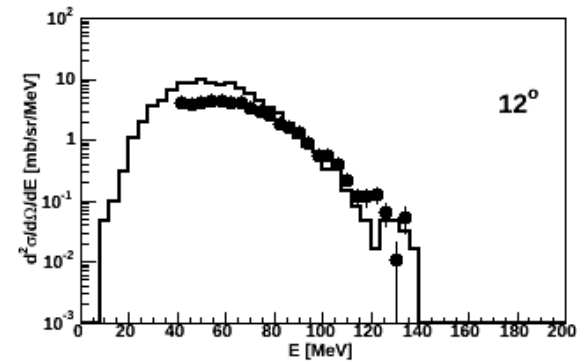
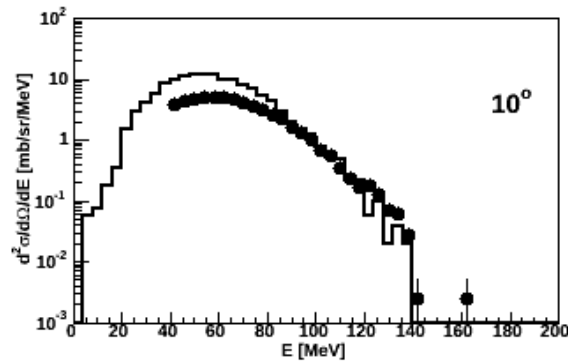
BME - Benchmarking

DOUBLE DIFFERENTIAL FRAGMENT SPECTRA FROM C+C at 13 MeV/n

Fluorine



Oxygen



experimental data by courtesy of S. Fortsch et al., iThemba Labs, South Africa

Input options - 1

a) define momentum / energy

BEAM	-10.0	0.0	0.0	0.0	0.0	0.0HEAVYION
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WHAT (1) > 0.0 : average beam momentum (GeV/c)
< 0.0 : average beam kinetic energy (GeV)

WHAT (2) beam momentum spread (GeV/c)

Note: for SDUM = HEAVYION units per nucleon (in fact per *nmu*)
for SDUM = 4-HELIUM, etc. per nucleus

WHAT (3) -WHAT (6) (as for any other particle)

SDUM = HEAVYION

also **4-HELIUM** alpha
 3-HELIUM 3-helium
 TRITON tritium
 DEUTERON deuterium

Input options - 2

b) define charge and mass (*required for* BEAM/SDUM=HEAVYION)

HI-PROPE	79.0	197.0	0.0	0.0	0.0	0.0
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WHAT (1) = Atomic number Z of the heavy ion, Default: 6.0

WHAT (2) = Mass number A of the heavy ion, Default: 12.0

WHAT (3) = if < 0 isomeric state of the heavy ion

c) switch on heavy ion transport and interactions

IONTRANS	-2.0	<i>(pleonastic in case of ion beams)</i>
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Note: Don't forget to link the DPMJET/RQMD event generators for enabling ion-ion interactions above 125MeV/n either using FLAIR or `$FLUPRO/flutil/ldpmqmd`

The BME event generator, covering the low energy range up to 150MeV/n (125MeV/n is the default threshold, that you can change through PHYSICS/SDUM=DPMTHRES), does not need to be linked since it's already embedded in the main FLUKA library

Input options - 3

Notes:

- The transport momentum threshold for ions ($p_{th,HI}$) is fixed to that of alphas ($p_{th,\alpha}$)

$$p_{th,HI} = p_{th,\alpha} \times m_{HI}/m_{\alpha} \quad (GeV/c)$$

- Unless the transport threshold for alphas is defined with a PART-THR card (*requiring GeV and not GeV per nucleon*) it is set equal to 10 MeV
if `DEFAULTS=NEW-DEFA.`
- When the energy of an ion becomes lower than the transport threshold, and if such threshold is lower than 100 MeV/n, the ion is not stopped, but it is ranged out to rest

Input options - 4

Electromagnetic dissociation

<code>PHYSICS</code>	<code>2.0</code>	<code>0.0</code>	<code>0.0</code>	<code>0.0</code>	<code>0.0</code>	<code>0.0EM-DISSO</code>
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WHAT(1) : flag for activating ion electromagnetic-dissociation

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

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