Heavy Ion Interactions

Beginners' FLUKA Course

Overview

The models

- DPMJET
- RQMD
- BME

Input options

- Beam definition
- Transport thresholds

Heavy ion interaction models in FLUKA - 1

E > 5 GeV/n

Dual Parton Model (DPM)
DPMJET-III (original code by R.Engel, J.Ranft and S.Roesler,
FLUKA-implemenation by T.Empl *et al.*)

0.1 GeV/n < E < 5 GeV/n

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E < 0.1 GeV/n

Boltzmann Master Equation (BME) theory
BME (original code by E.Gadioli *et al.*,
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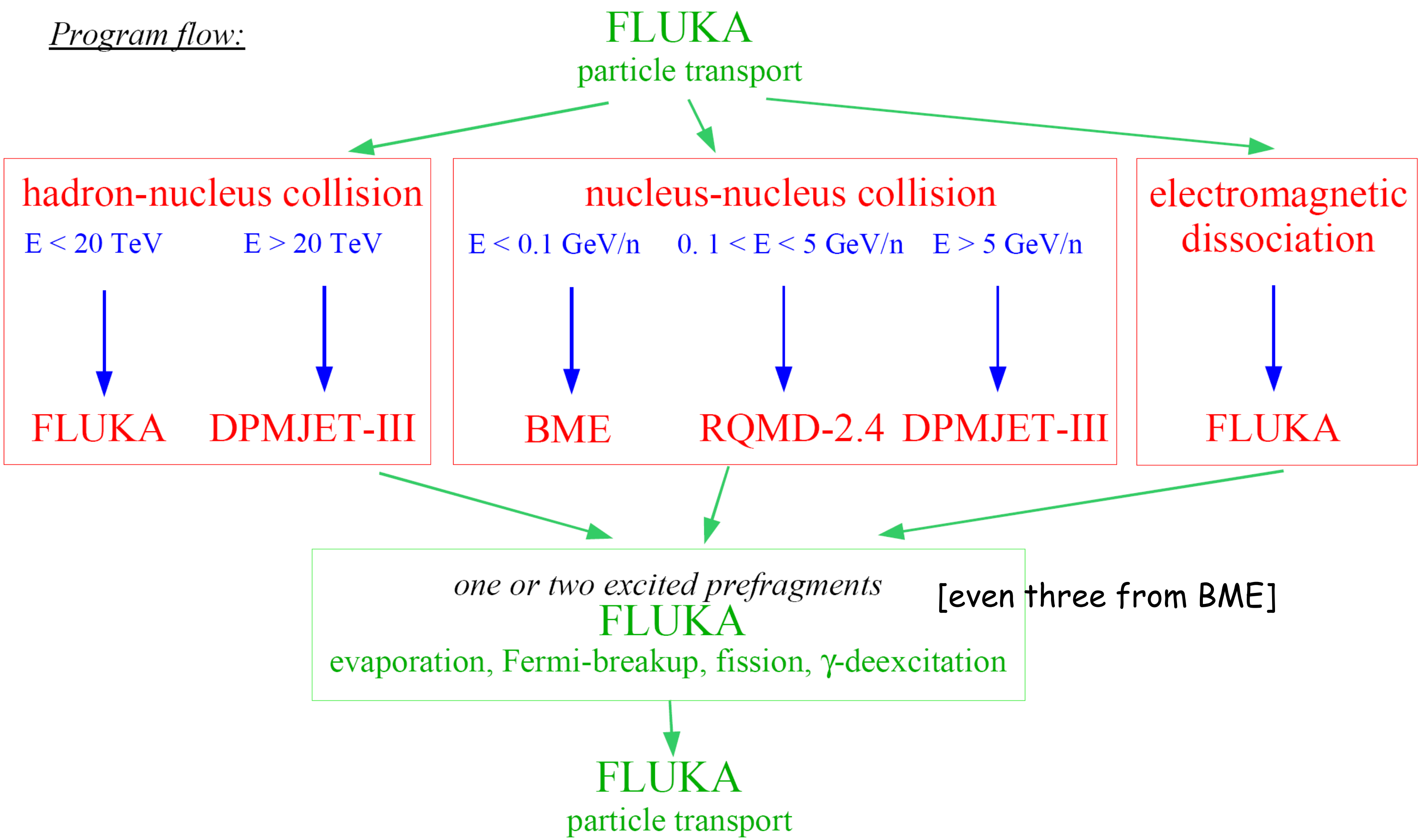
Heavy ion interaction models in FLUKA - 2

Program flow:



DPMJET

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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

↓

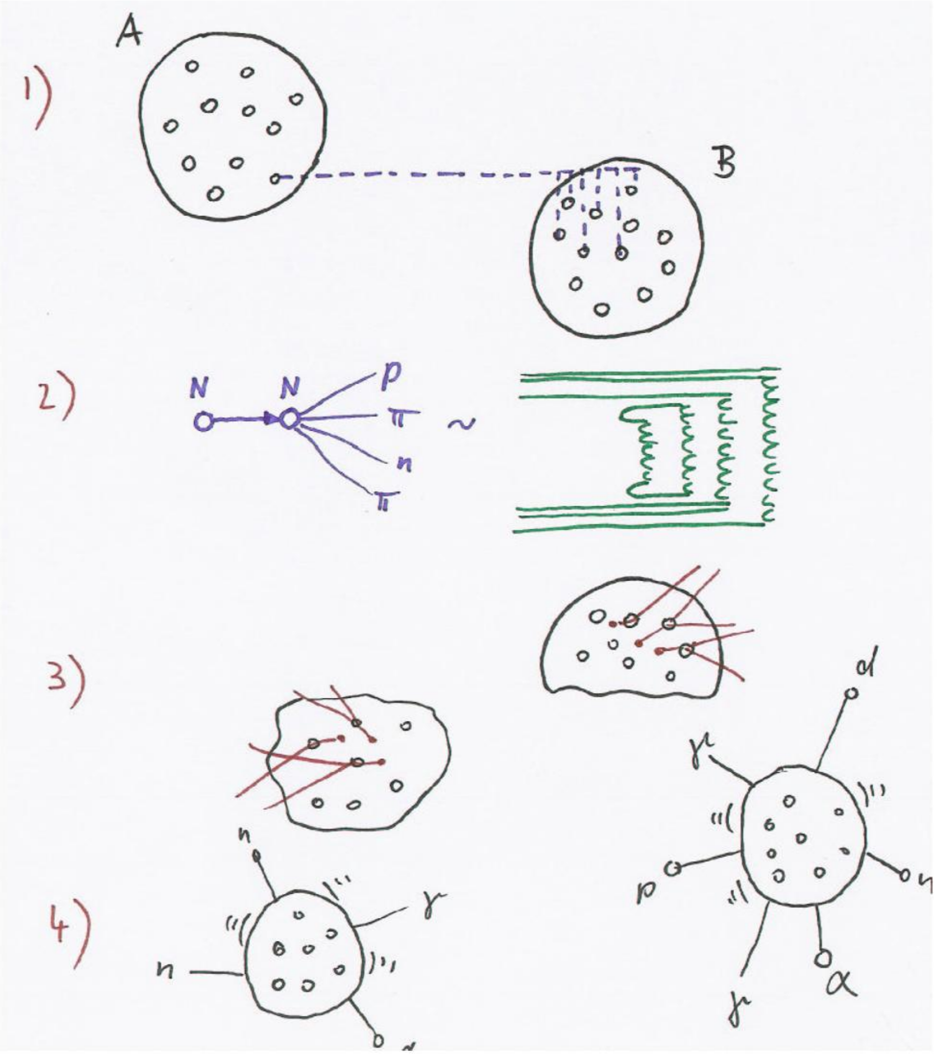
3. Intranuclear cascade

- low-energy interactions of hadrons in spectator nuclei

↓

4. Fragmentation of excited spectator nuclei

- evaporation of light fragments (e.g., p, n, d, ^{3}H, ^{3}He, ^{4}He,..),
- 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*

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

  - *elastic cross section*

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

  - *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)

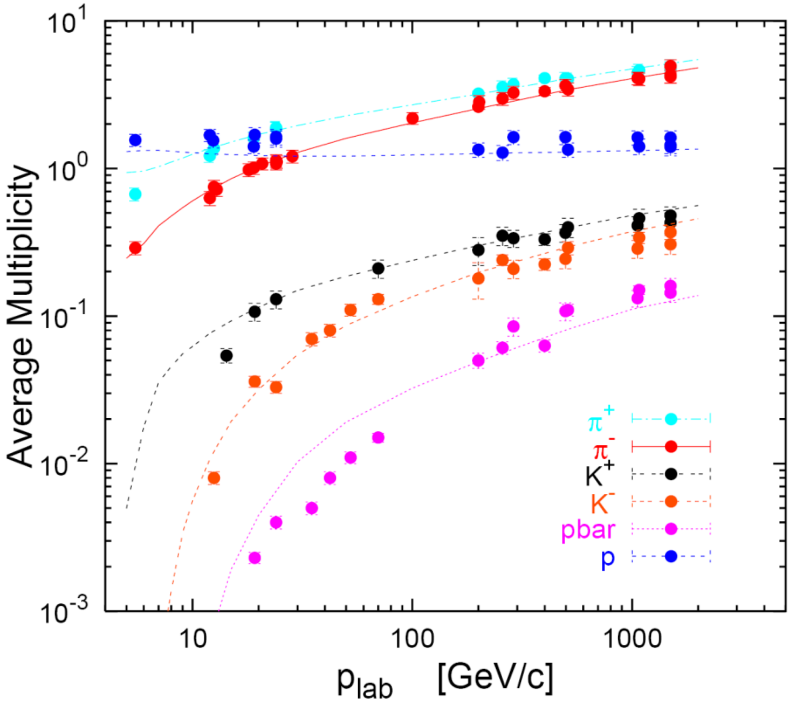
Note: *DPMJET has its own implementation of intranuclear cascades. It is similar in its fundamental ideas to that one of FLUKA but is much more simplified.*

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

  } FLUKA

DPMJET – *Comparison to data (hadron-hadron)*

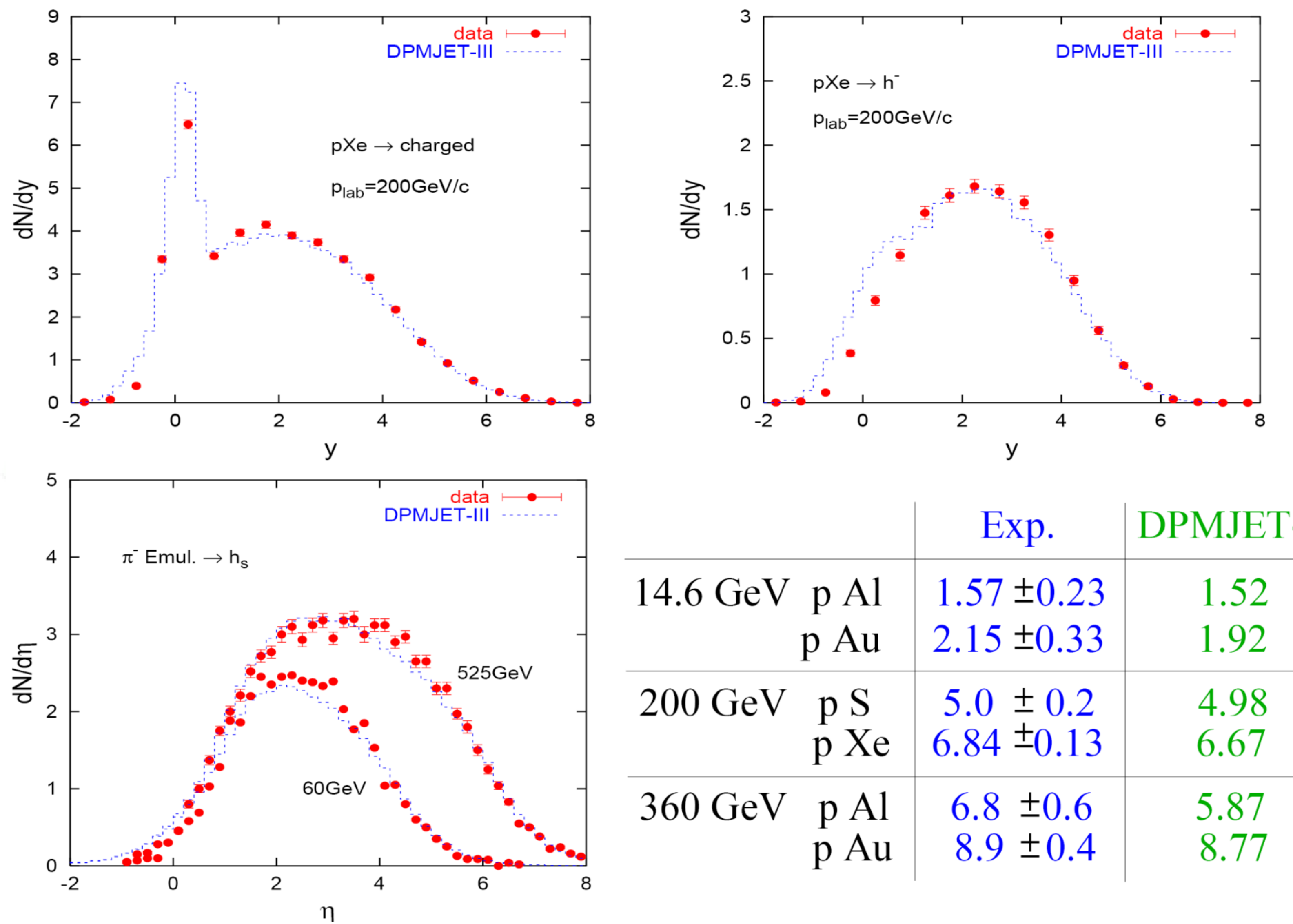
proton - proton



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

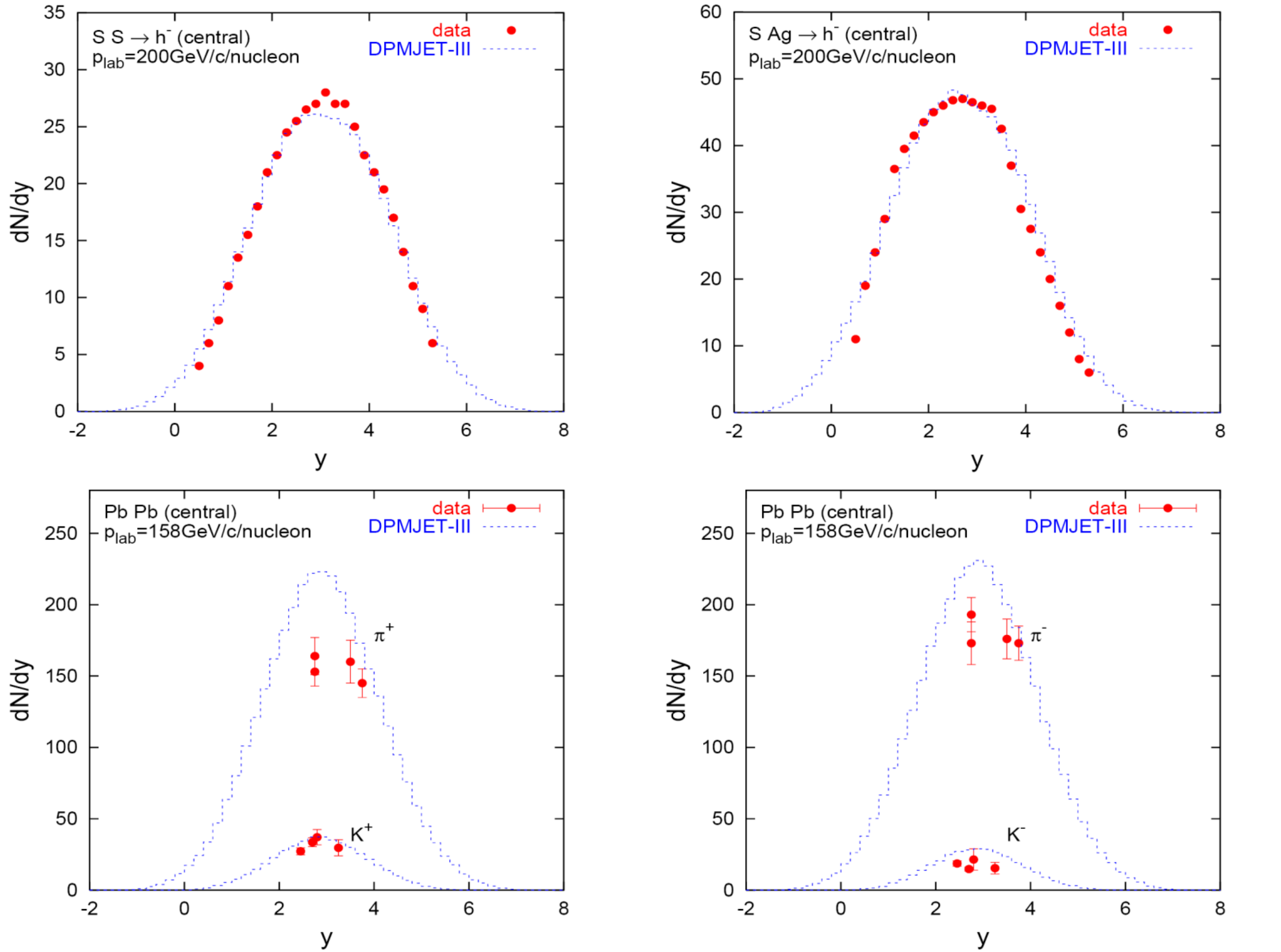
	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
K^-	0.18 ± 0.05	0.20
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105

DPMJET - *Comparison to data (hadron-nucleus)*

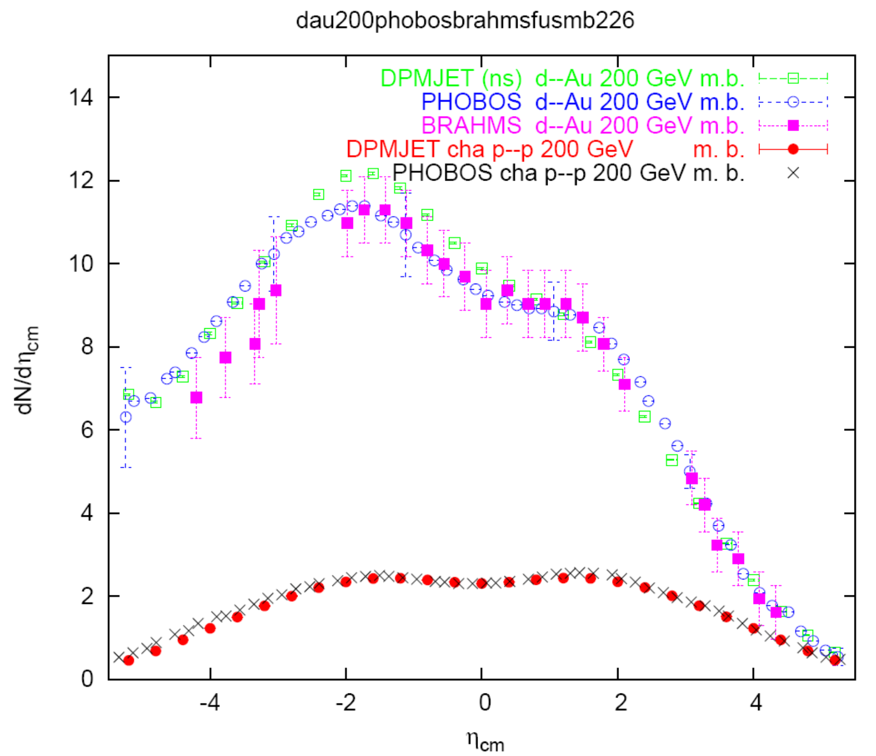


		Exp.	DPMJET-III
14.6 GeV	p Al	1.57 ±0.23	1.52
	p Au	2.15 ±0.33	1.92
200 GeV	p S	5.0 ± 0.2	4.98
	p Xe	6.84 ±0.13	6.67
360 GeV	p Al	6.8 ±0.6	5.87
	p Au	8.9 ±0.4	8.77

DPMJET - *Comparison to data (nucleus-nucleus)*



DPMJET – *Comparison to data (nucleus-nucleus)*

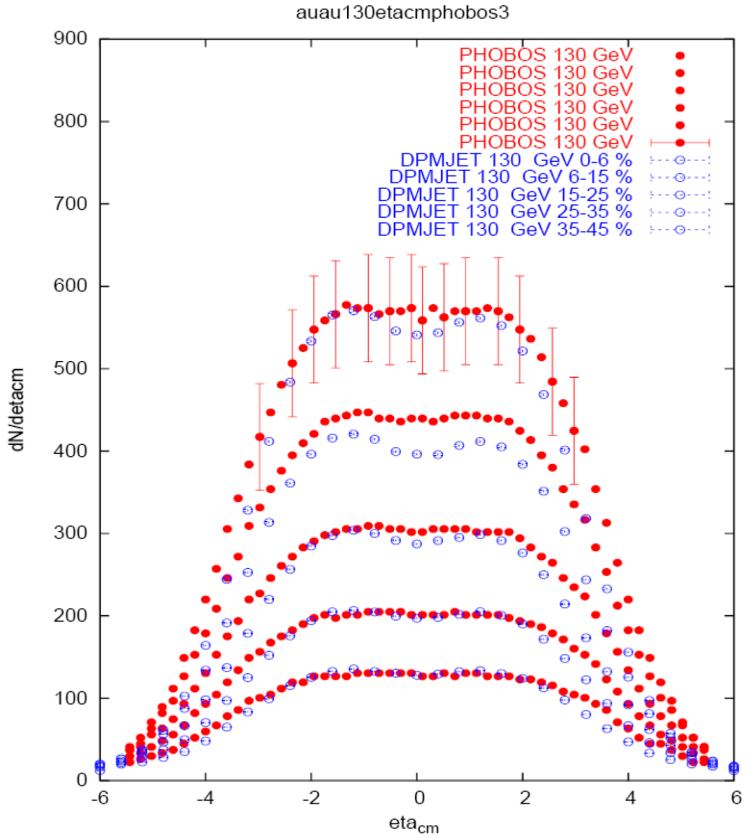


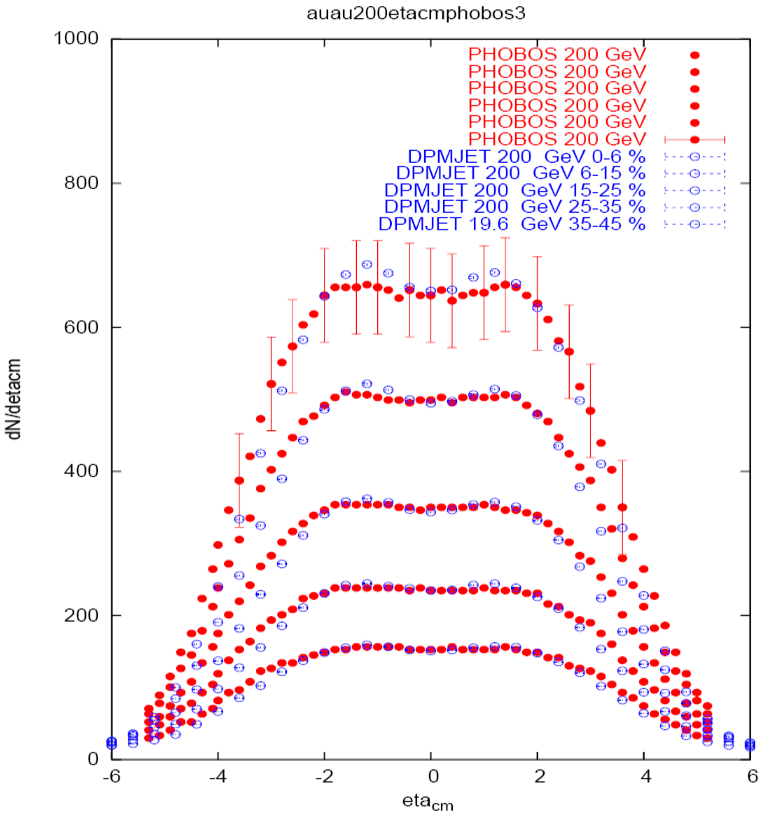
Pseudorapidity distribution of charged hadrons produced in minimum bias d-Au and p-p collisions at a c.m. energy of 200GeV/A.

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 130GeV/A (left) and 200GeV/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*

FLUKA

Initialization of DPMJET:

pre-computed cross sections and impact parameter distributions read in from data files

(complete matrix of projectile-target combinations up to A=246 and entire energy range)

Request: Single nucleus-nucleus interaction (A+A)

↓

Interface

↓

DPMJET

A+A $\longrightarrow$ p, n, π^+, π^-, ..., excited prefragments

↓

Interface

↓

FLUKA

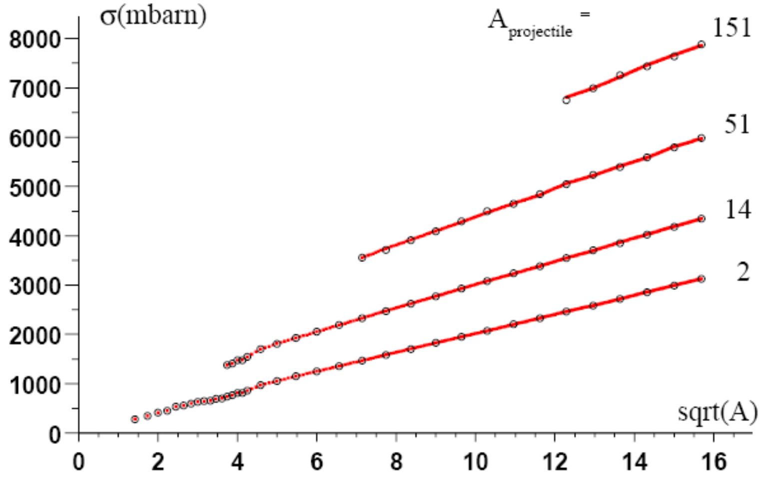
Evaporation, fragmentation, de-excitation of prefragments

Transport of produced hadrons

DPMJET - *Interface to FLUKA*

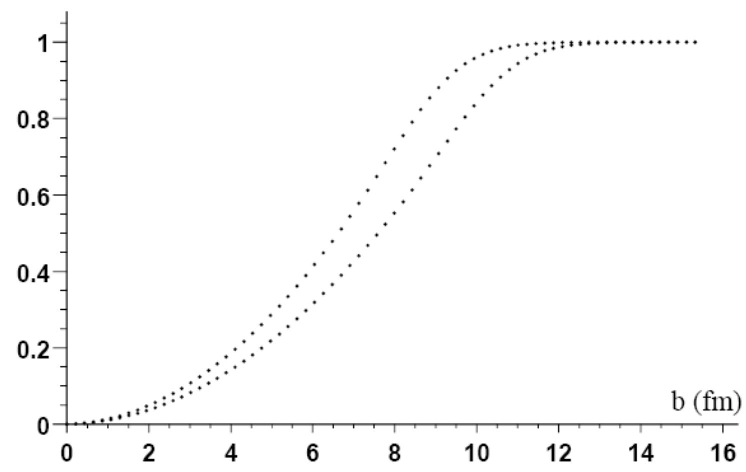
Examples for pre-initialised data:

Inelastic cross sections



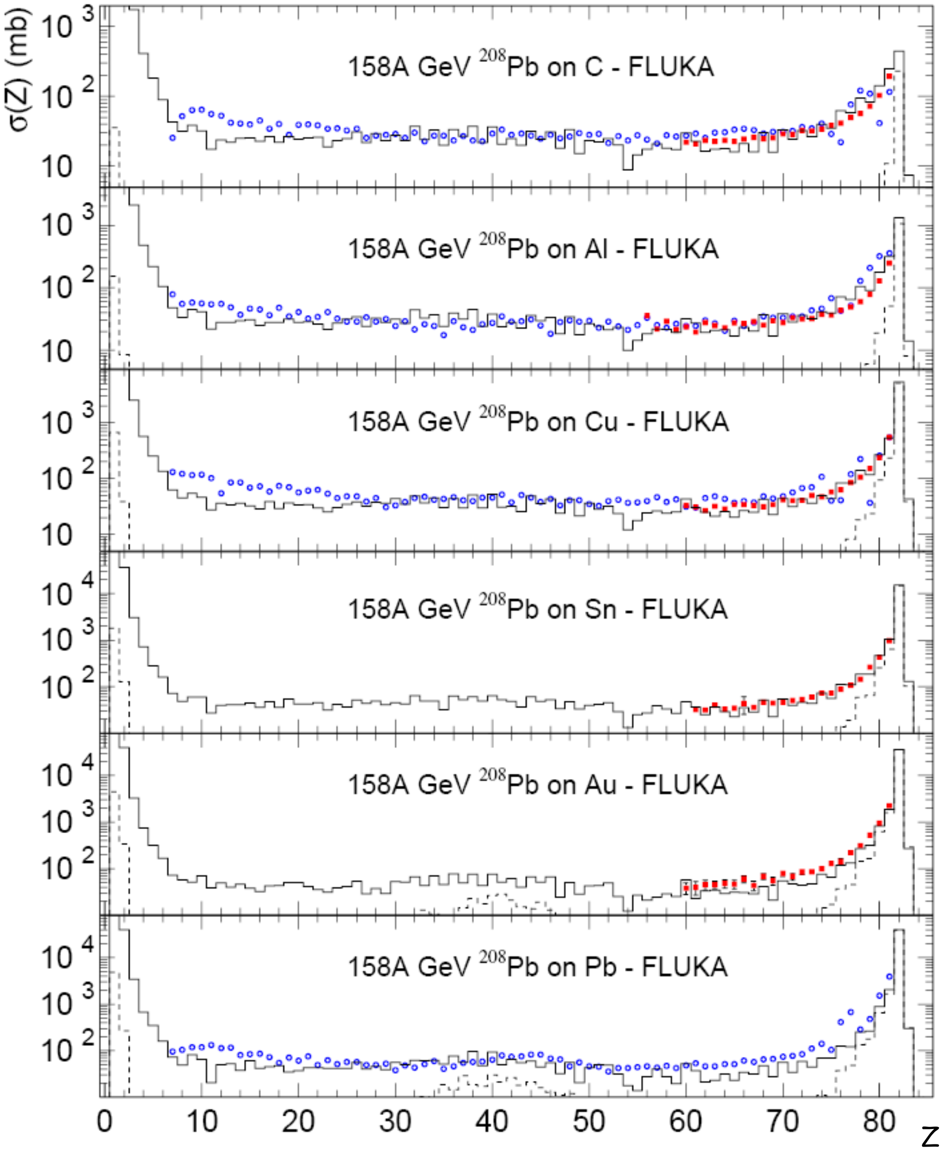
$E_{Lab} = 6.3 \times 10^9$ GeV/nucleon

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 GeV/n

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BME (original code by E.Gadioli et al.,
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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 $p_{F0} = \hbar \left(3\pi^2 \frac{A}{2V}\right)^{1/3}$ $V = (4/3)\,\pi\,\left(r_0 A^{1/3}\right)^3$ $r_0 = 1.12\,fm \Rightarrow \rho = 0.17\,\frac{nucl.}{fm^3}$

nucleon momentum $\boxed{p = p_{F0}\left(\frac{\rho(r)}{\rho_0}\right)^{\frac{1}{3}} \epsilon^{1/3}}$ $\epsilon \in [0, 1]$ random

$\phi = 2\pi\epsilon$ $\cos\theta = 1 - 2\epsilon$

$$
\begin{aligned}
p_x &= p \sin\theta \cos\phi \quad - \left(\sum p_x\right)/A \\
p_y &= p \sin\theta \sin\phi \quad - \left(\sum p_y\right)/A \\
p_z &= p \cos\theta \quad - \left(\sum p_z\right)/A
\end{aligned}
$$

so $\sum p_x = \sum p_y = \sum p_z = 0$

FINAL STATE

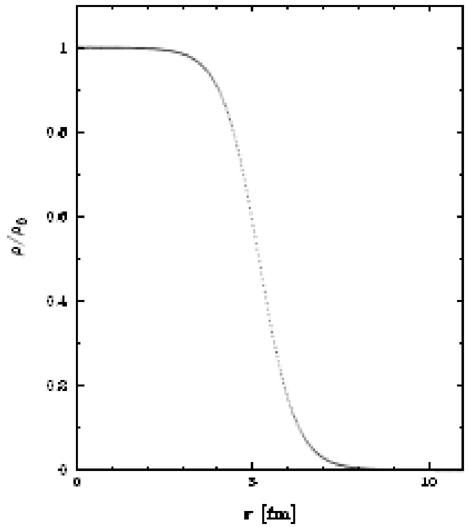
- $\left(p^0, p_x, p_y, p_z\right)$ for nucleons (and produced particles) in the LAB frame
- the spectators are marked
- no residue and fragment identification
- energy non-conservation issues, particularly when run in full QMD mode

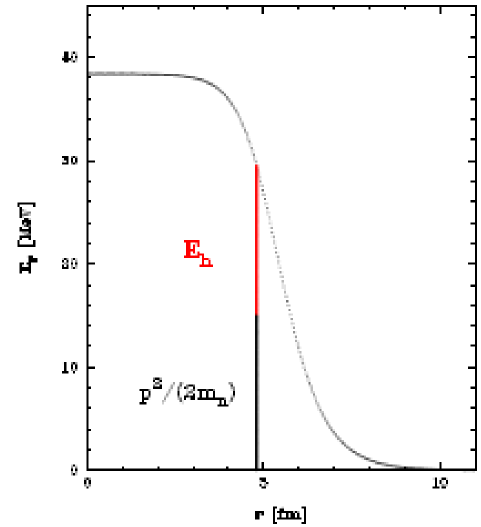
RQMD – *The interfaced code*

Implemented developments

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

assuming $E^*_{PL} = \sum_{pa.\ P} E_h \qquad (TL)$





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

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

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

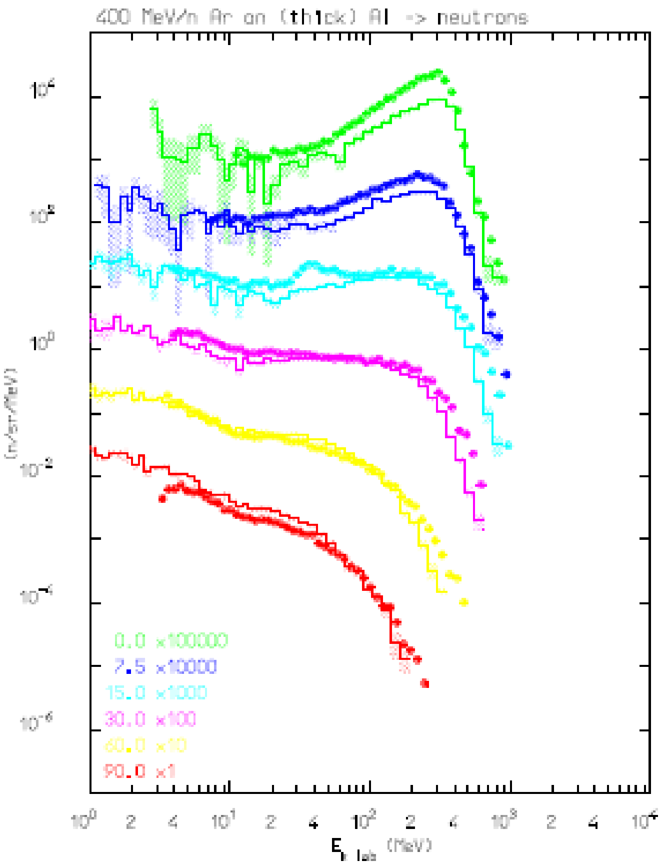
$$r, p\,(t=0)$$

- 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

Ar ions

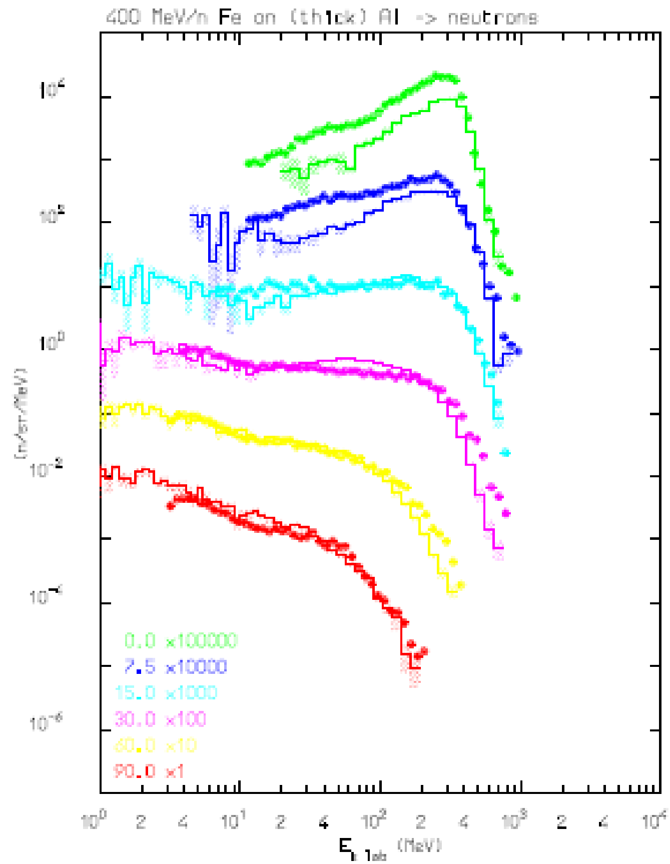


400 MeV/n

on *thick*

Al targets

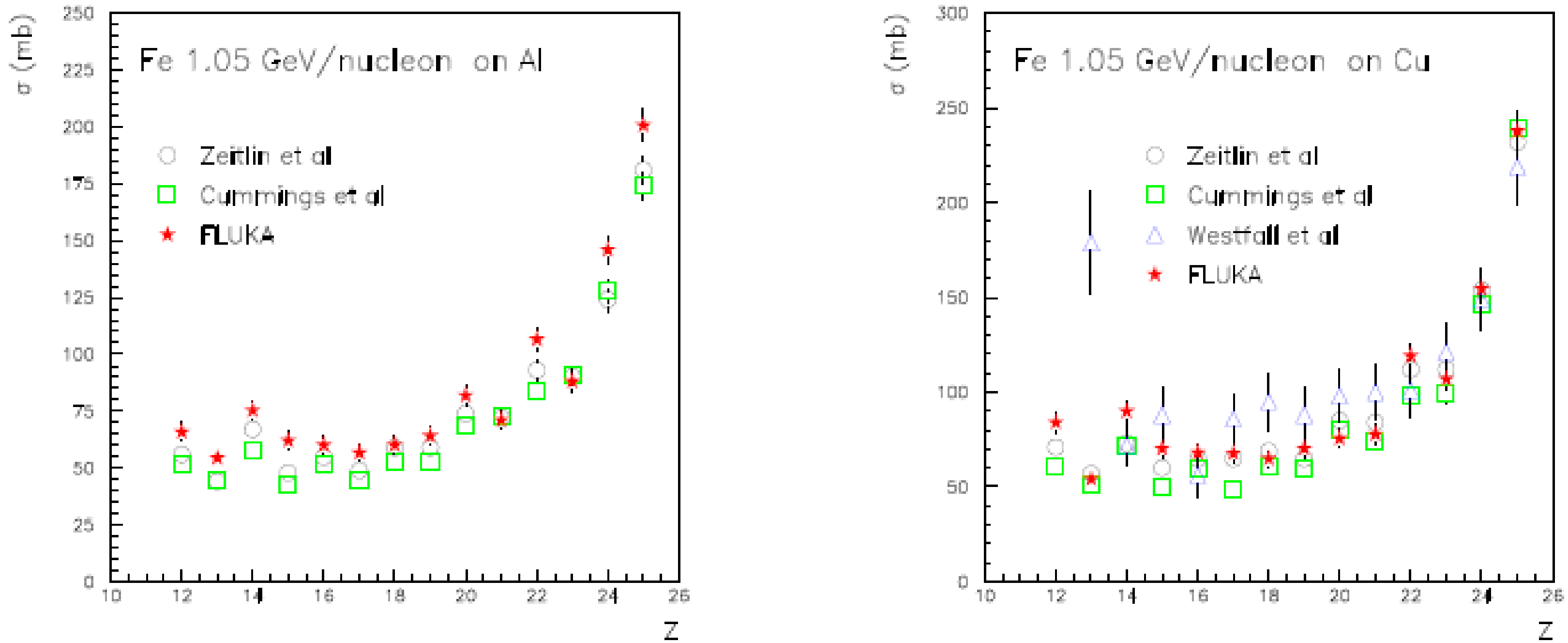
Fe ions



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

RQMD - *FLUKA benchmarks*

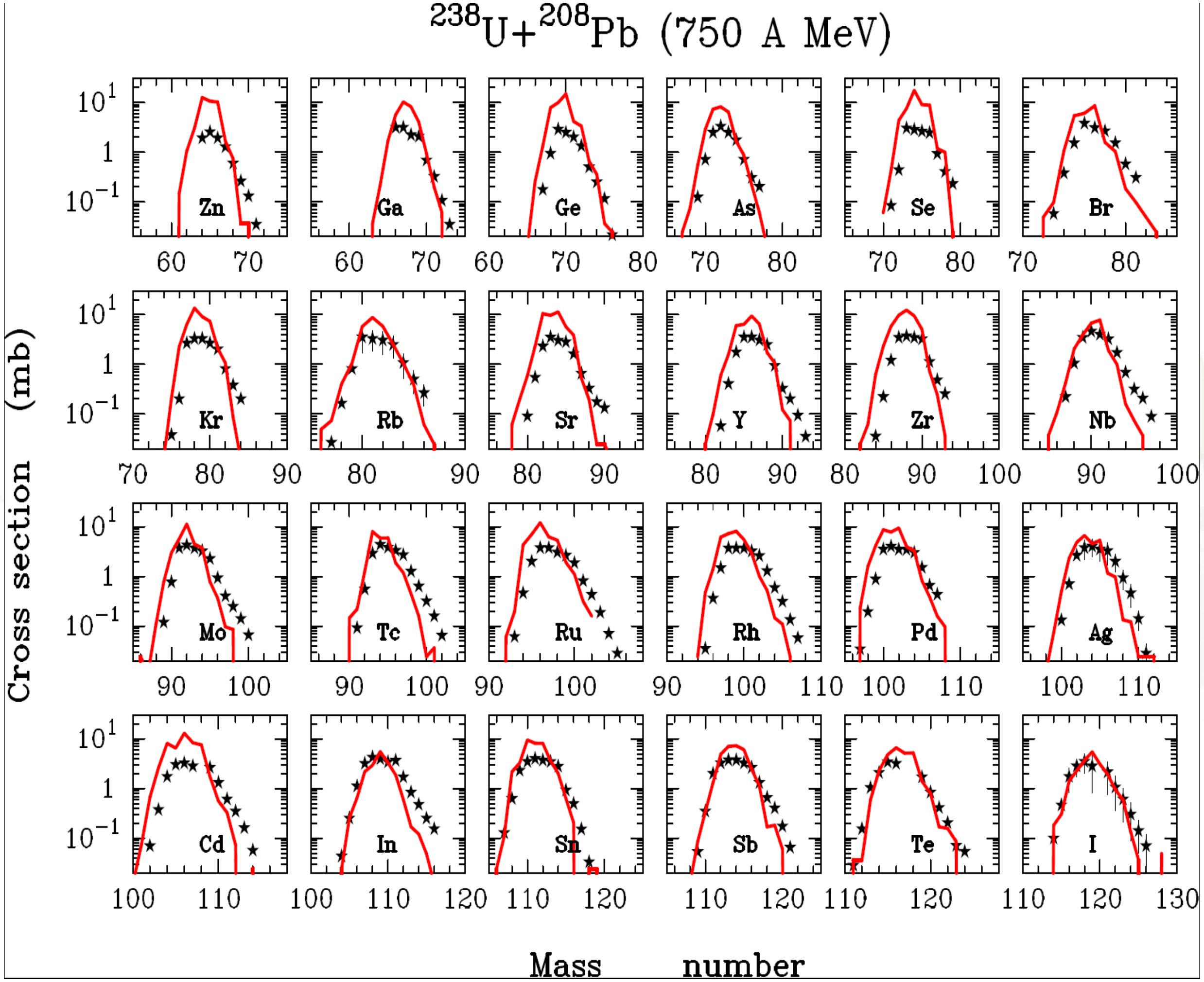
Fragment charge cross sections



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



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 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*

work in progress

two different reaction paths have been adopted:

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

FLUKA evaporation

1. 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.

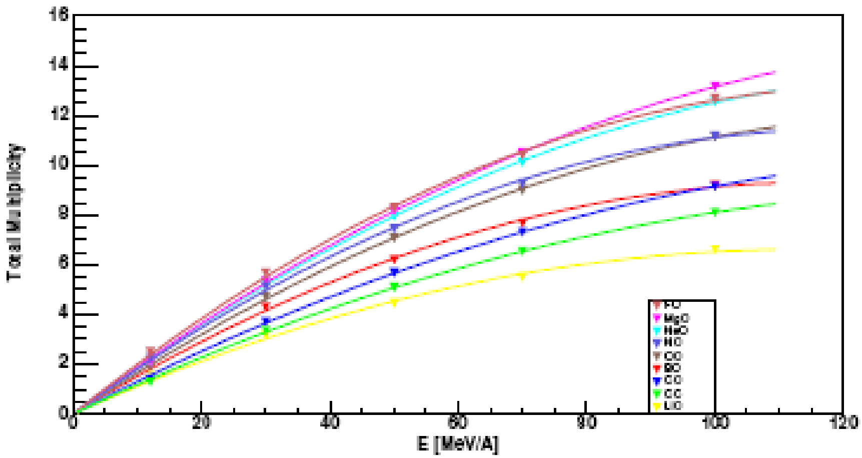
2. The complete fusion cross section decreases with increasing bombarding energy. We integrate the nuclear densities of the projectile and the target over their overlapping region, as a function of the impact parameter, and obtain a preferentially excited "middle source" and two fragments (projectile-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

BME – *The database for the pre-equilibrium emissions*

^{16}O + ^{6}Li, ^{8}Li, ^{8}B, ^{10}B, ^{12}C, ^{14}N, ^{16}O, ^{19}F, ^{20}Ne, ^{24}Mg, ^{27}Al, ^{56}Fe, ^{197}Au

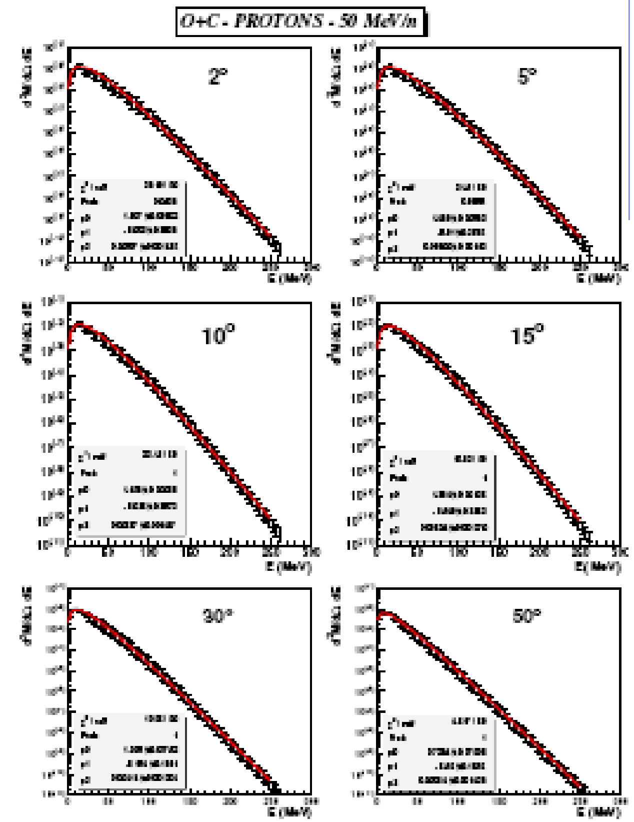
^{12}C + ^{8}Li, ^{8}B, ^{12}C, ^{27}Al, ^{40}Ca

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



total multiplicity

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



energy spectra

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

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

^{40}Ca + ^{120}Sn ^{56}Fe + ^{28}Si, ^{40}Ca, ^{48}Ca, ^{120}Sn

and consequently review the fitting functions
and the extrapolation recipes over a significantly larger mass range

BME – *Theoretical framework*

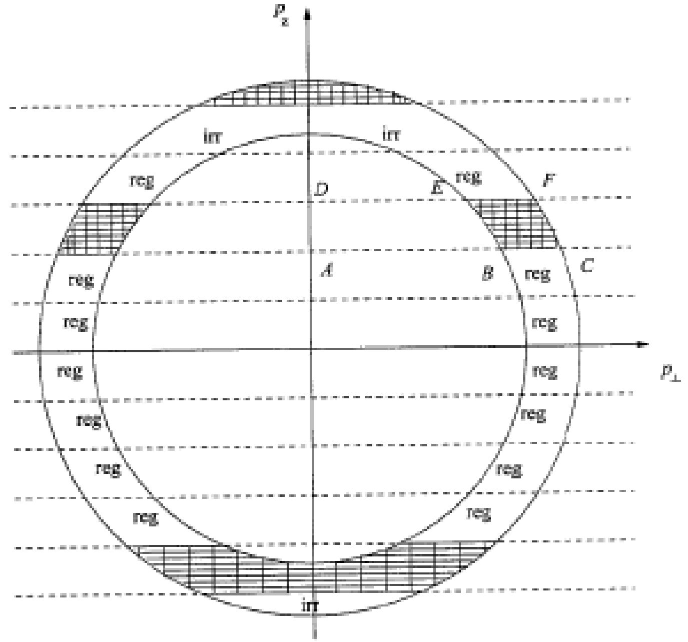
Calculation of preequilibrium for the composite nucleus

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

$$N_i = n_i \, g_i$$

- N_i: nucleon number
- n_i: occupation probability
- g_i: number of states in bin i

$$\frac{d(n_i^\pi g_i^\pi)}{dt} = \sum_{jlm} [\omega^{\pi\pi}_{lm\to ij} \, g_l^\pi \, n_l^\pi \, g_m^\pi \, n_m^\pi \, (1-n_i^\pi)(1-n_j^\pi)$$

$$-\omega^{\pi\pi}_{ij\to lm} \, g_i^\pi \, n_i^\pi \, g_j^\pi \, n_j^\pi \, (1-n_l^\pi)(1-n_m^\pi)]$$

$$+\sum_{jlm} [\omega^{\pi\nu}_{lm\to ij} \, g_l^\pi \, n_l^\pi \, g_m^\nu \, n_m^\nu \, (1-n_i^\pi)(1-n_j^\nu)$$

$$-\omega^{\pi\nu}_{ij\to lm} \, g_i^\pi \, n_i^\pi \, g_j^\nu \, n_j^\nu \, (1-n_l^\pi)(1-n_m^\nu)]$$

$$-n_i^\pi g_i^\pi \omega^\pi_{i\to i'} \, g_{i'}^\pi \, \delta(\varepsilon_i^\pi - \varepsilon_{i'}^\pi - \varepsilon_F^\pi - B^\pi) - \frac{dD_i^\pi}{dt}$$

BME – *Theoretical framework*

Multiplicity spectra

of emitted nucleons

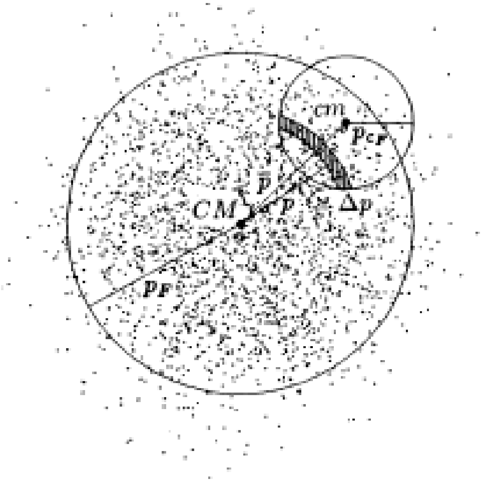
$$\frac{d^2M(\varepsilon',\theta)}{d\varepsilon'\,d\Omega} = \frac{1}{2\pi\sin\theta}\int_0^{t_{eq}} n(\varepsilon,\theta,t)\,\frac{\sigma_{inv}V}{V}\,\rho(\varepsilon',\theta)\,dt$$

of a cluster c

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

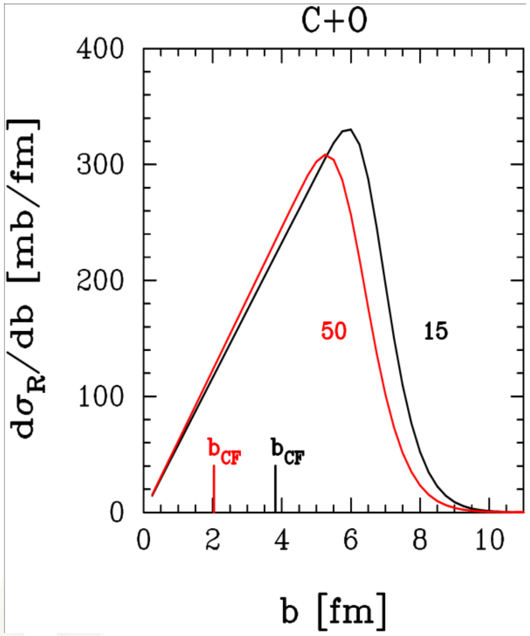
$$N_c(E_c,\theta_c,t) = \prod_i \left(n_i^{\pi}(\varepsilon,\theta,t)\right)^{P_i(E_c,\theta_c)Z_c} \cdot \prod_i \left(n_i^{\nu}(\varepsilon,\theta,t)\right)^{P_i(E_c,\theta_c)N_c}$$

joint probability



BME - *Peripheral collisions*

i. selection of the *impact parameter b*



ii. kinematics determination

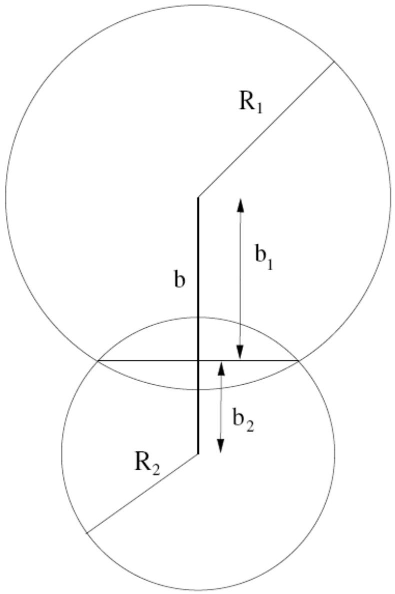
θ_{PL} , θ_{TL} chosen according to $[d\sigma/d\Omega]_{cm} \sim \exp(-k\theta_{cm})$
θ_{MS} momentum conservation
p_{PL} , p_{TL} chosen according to a given energy loss distribution
p_{MS} momentum conservation
ϕ_{PL} free
ϕ_{TL} , ϕ_{MS} same reaction plane

work in progress

PL

MS

TL



iii. excitation energy sharing

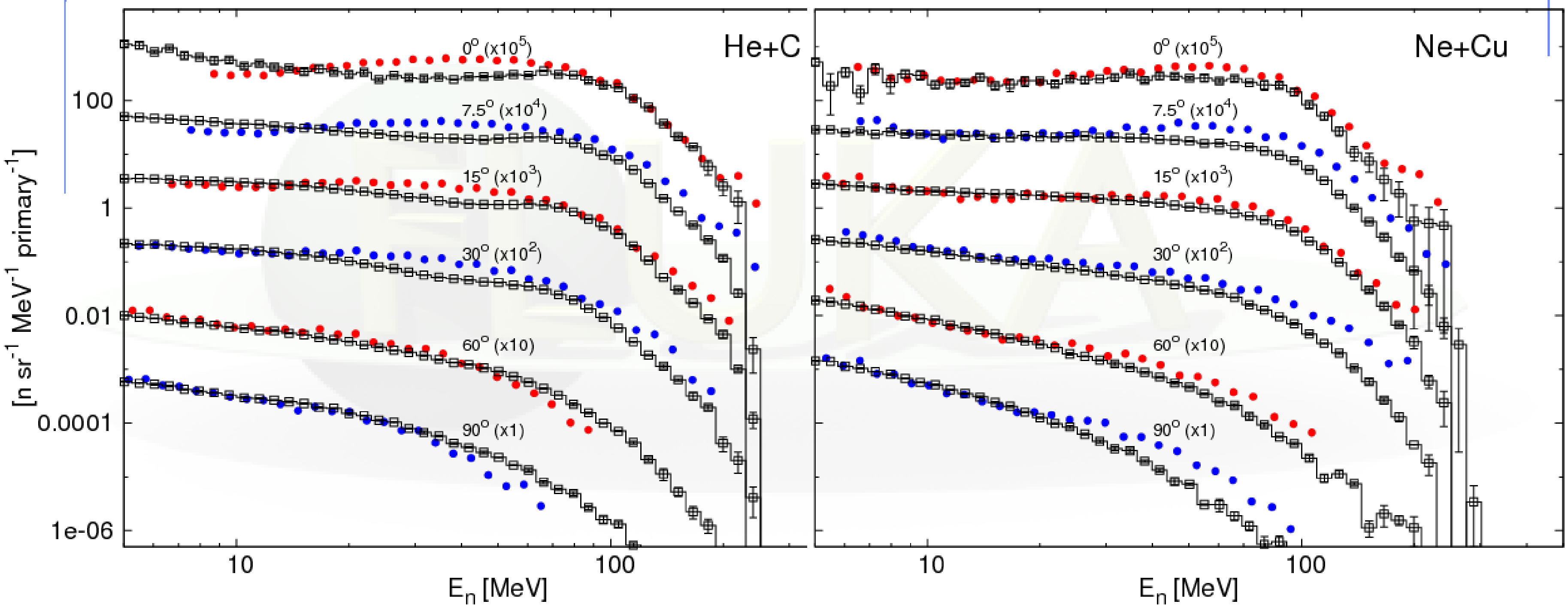
$$E^{\star}_{MS} = (A_{MS}/A_{tot})E^{\star}_{tot} \sum_{n=0}^{k} (1 - A_{MS}/A_{tot})^n$$

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

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

BME - *Benchmarking*

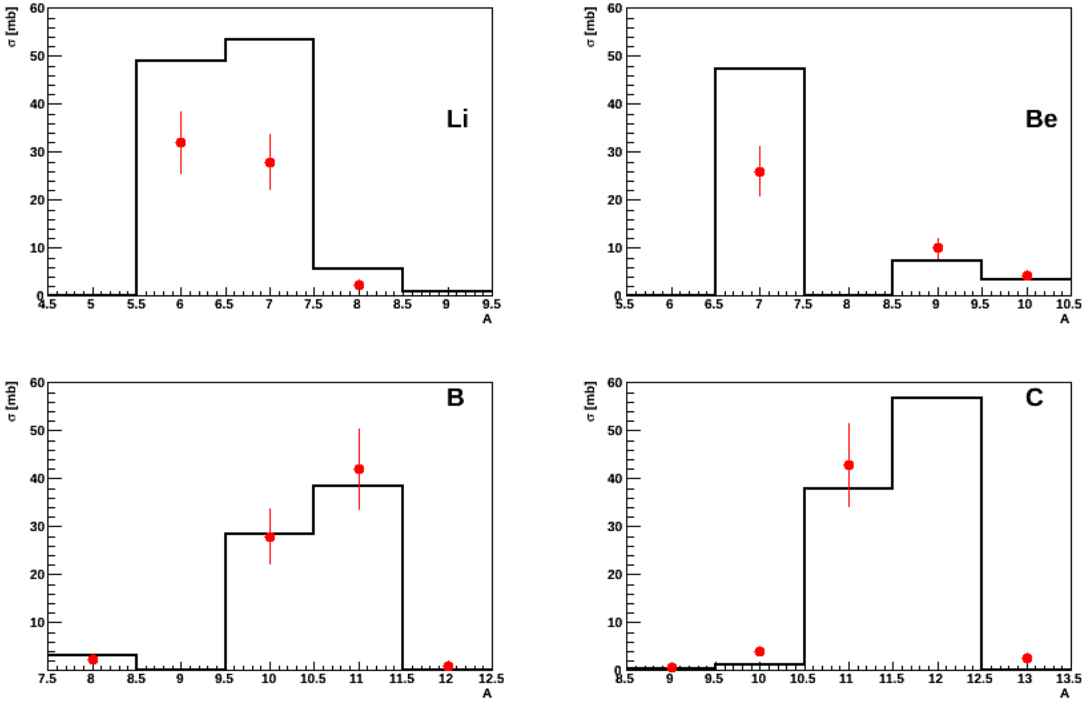
DOUBLE DIFFERENTIAL NEUTRON YIELDS FROM 100 MeV/n BEAMS ON THICK TARGETS



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



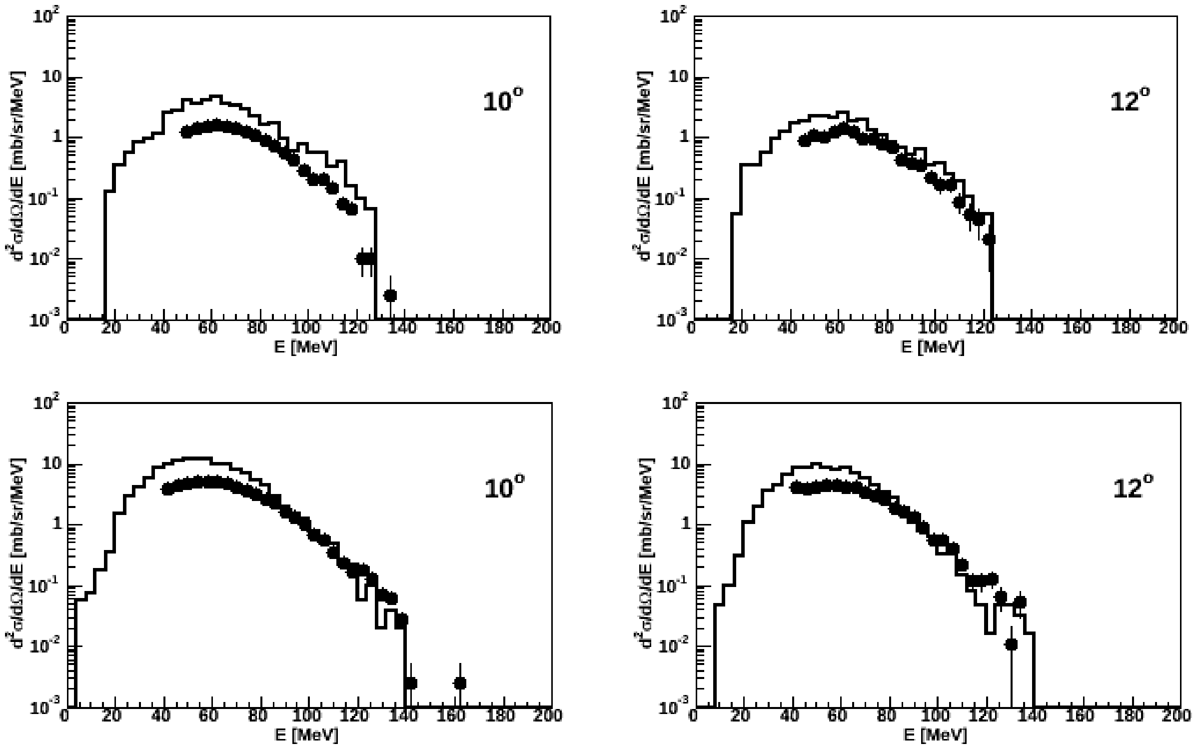
experimental data from H. Ryde, Physica Scripta T5, 114 (1983)

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
```

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
```

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
```

(pleonastic in case of ion beams)

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

```
PHYSICS          2.0       0.0       0.0       0.0       0.0       0.0EM-DISSO
```

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

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

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