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Title: CEM03.02 and LAQGSM03.02 Overview

Author(s): Stepan G. Mashnik

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CEM03.02 and LAQGSM03.02 Overview

Stepan G. Mashnik

Los Alamos National Laboratory, Los Alamos, NM, USA

Current Developers

Many people participated in development of the Cascade-Exciton Model (CEM) and Los Alamos version of the Quark-Gluon String Model (LAQGSM) over their almost 40-year history.

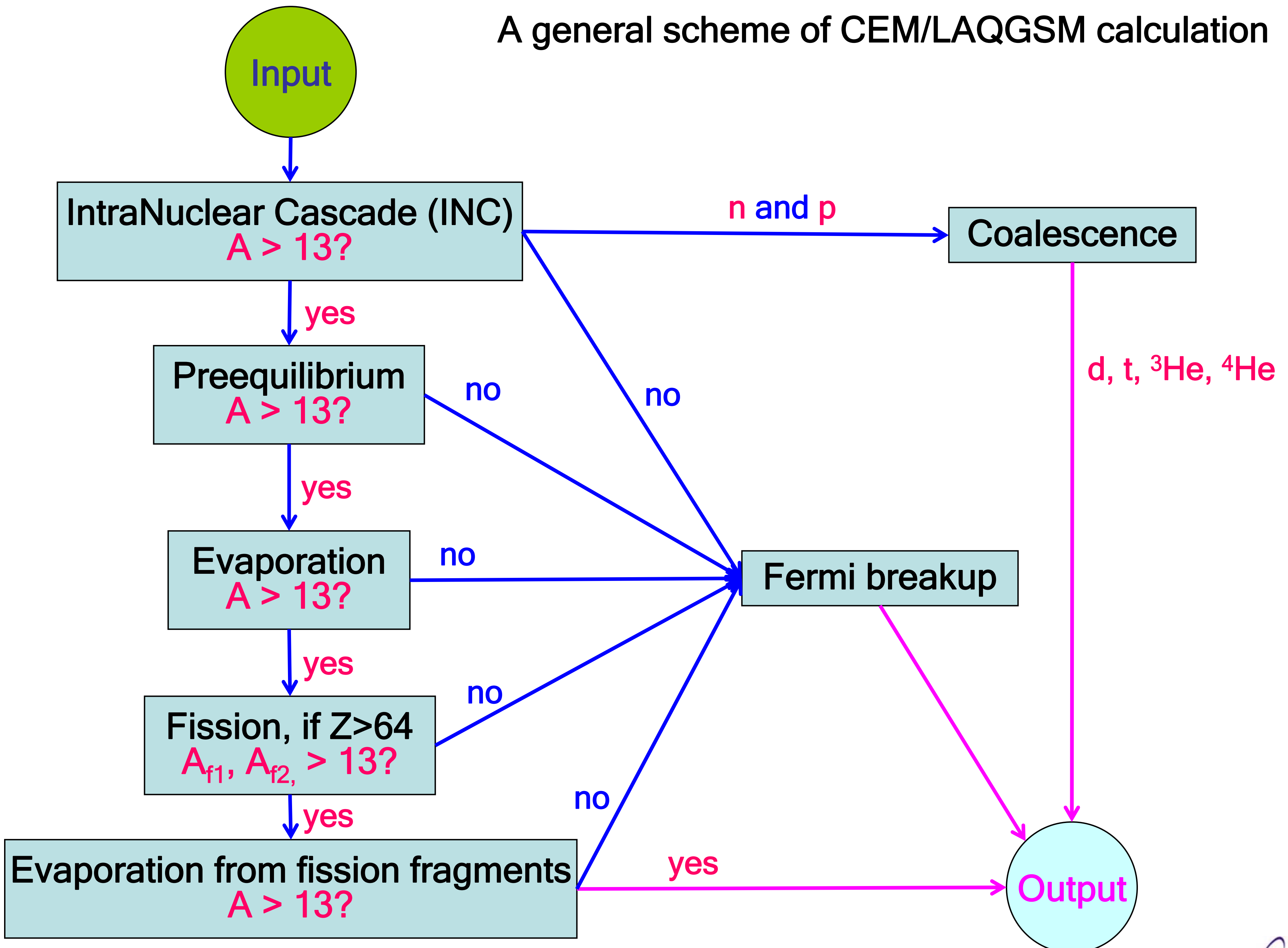
Current contributors are:

S. G. Mashnik, K. K. Gudima, A. J. Sierk, M. I. Baznat, R. E. Prael, N. V. Mokhov

Plus invaluable feedback from many of about 300 MARS and 2500 MCNPX/6 users worldwide, using our event generators in their calculations and from very many experimentalists collaborating with us

- Introduction
- INC of CEM03.02 and LAQGSM03.02
- The coalescence model
- Preequilibrium [the Modified Exciton Model (MEM)]
- Evaporation
- Fission
- Fermi break-up of light nuclei (A<13)
- Fission-like binary-decay by GEMINI and multifragmentation by the Statistical Multifragmentation Model (SMM) in the "G" and "S" versions of CEM03.01 and LAQGSM03.01
- Summary

A general scheme of CEM/LAQGSM calculation



The INC of CEM03.02 is based on the "standard" (non-time-dependent) version of the Dubna cascade model [1,2], improved and developed further at LANL during recent years [3-6]:

1) V. S. Barashenkov, K. K. Gudima, and V. D. Toneev, JINR Communications P2-4065 and P2-4066, Dubna (1968); P2-4661, Dubna (1969); Acta Physica Polinica 36 (1969) 415.

2) V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei*, Atomizdat, Moscow (1972); V. S. Barashenkov, *et al.,* Sov. Phys. Usp. 16 (1973) 31.

3) S. G. Mashnik and A. J. Sierk, Proc. SARE-4, Knoxville, TN, Sep. 13-16, 1998, pp. 29-51 (nucl-th/9812069).

4) S. G. Mashnik and A. J. Sierk, Proc. AccApp00, Washington, DC, USA, Nov. 12-16, 2000, pp. 328-341 (nucl-th/0011064).

5) S. G. Mashnik, K. K. Gudima, A. J. Sierk, R. E. Prael, Proc. ND2004, Sep. 26 — Oct. 1, 2004, Santa Fe, NM, AIP Conf. Proc. 769, pp. 1188-1192 (nucl-th/0502019)

6) S. G. Mashnik, M. I. Baznat, K. K. Gudima, A. J. Sierk, R. E. Prael, J. Nucl. and Radiochem. Sci. 6, (2005) pp. A1-A19 (nucl-th/0503061).

The nuclear matter density $\rho(r)$ is described by a Fermi distribution

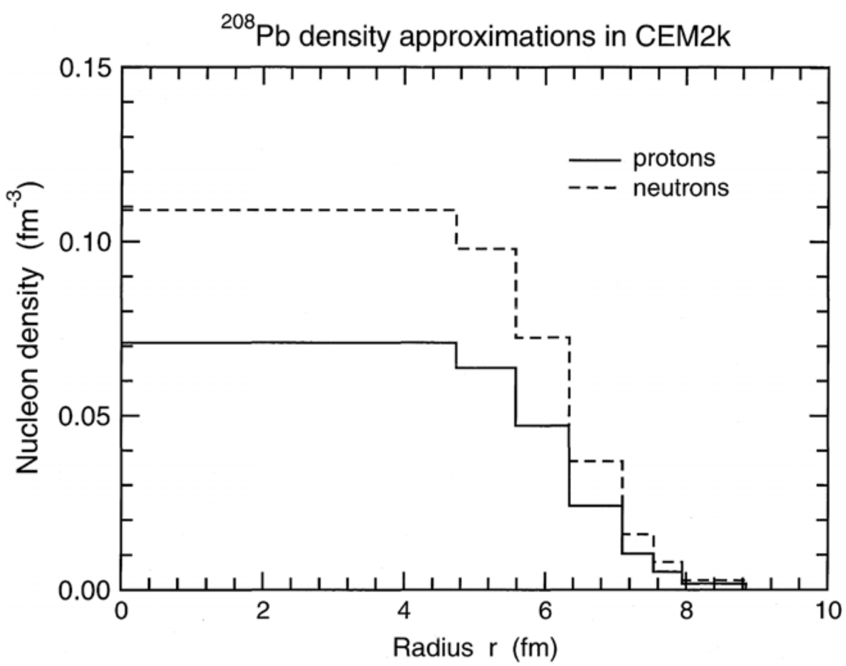
$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0\{1 + exp[(r - c)/a]\}$$

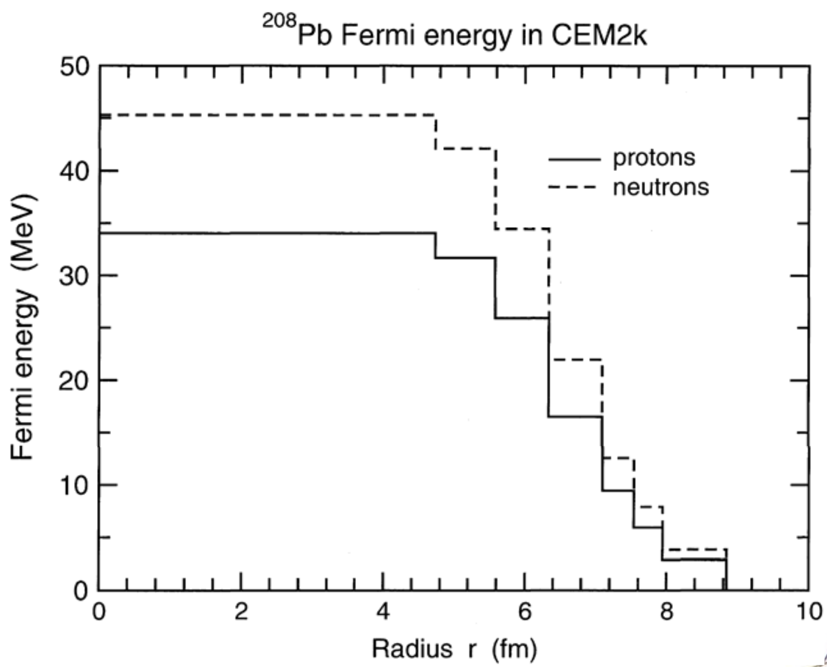
where $c = 1.07A^{1/3}$ fm and $a = 0.545$ fm

the target nucleus is divided by concentric spheres into seven zones

The energy spectrum of the target nucleons is estimated

with the local Fermi energy $T_F(r) = \hbar^2[3\pi^2\rho(r)]^{2/3}/(2m_N)$





$$NN \to NN, \qquad NN \to \pi NN, \qquad NN \to \pi_1, \cdots, \pi_i NN$$
$$\pi N \to \pi N, \qquad \pi N \to \pi_1, \cdots, \pi_i N \qquad (i \geq 2)$$

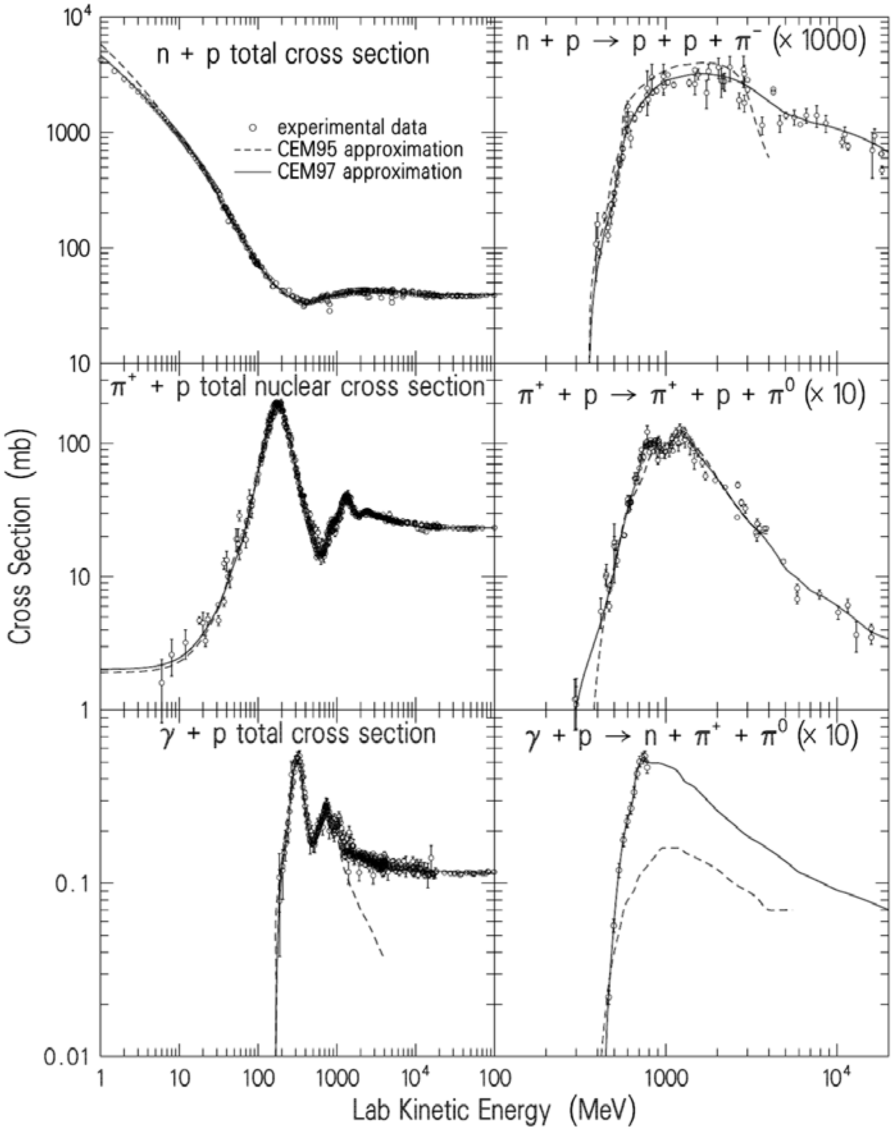
$$\pi NN \to NN$$

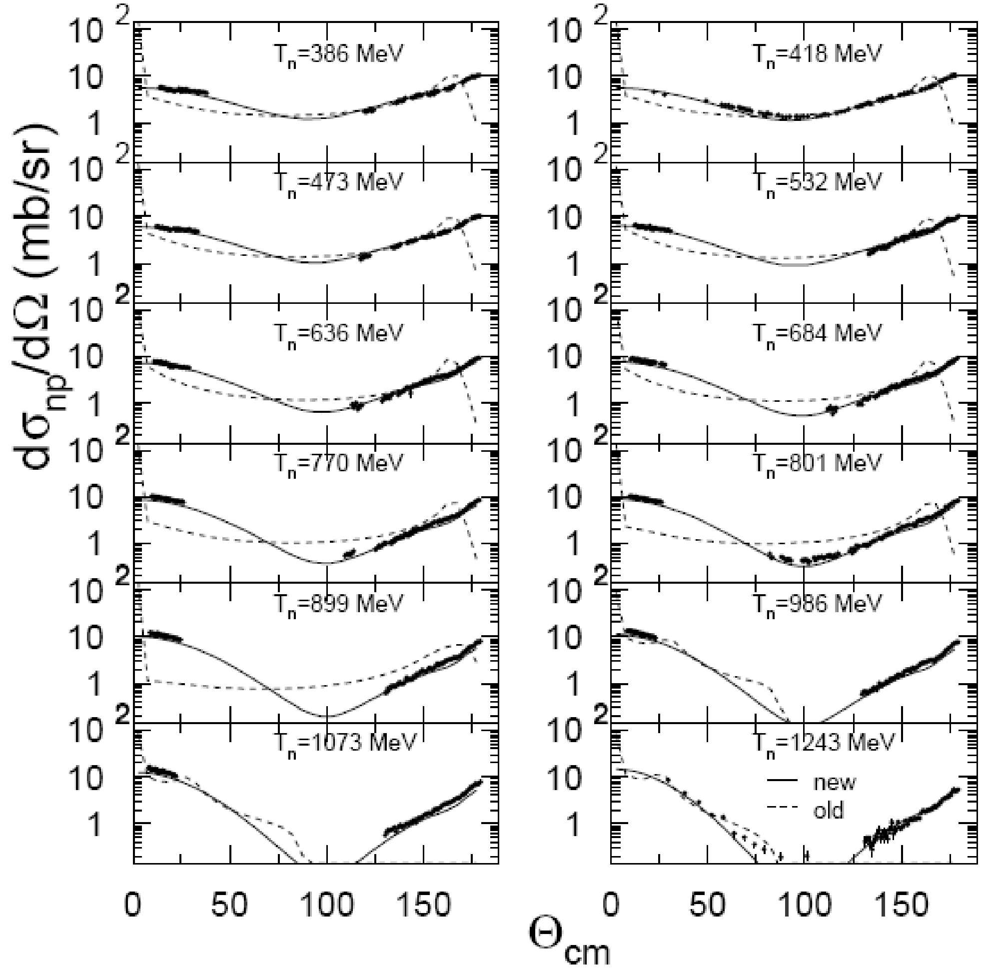
$$\sigma_{\gamma A} = L \frac{Z(A-Z)}{A} \sigma_{\gamma d}$$

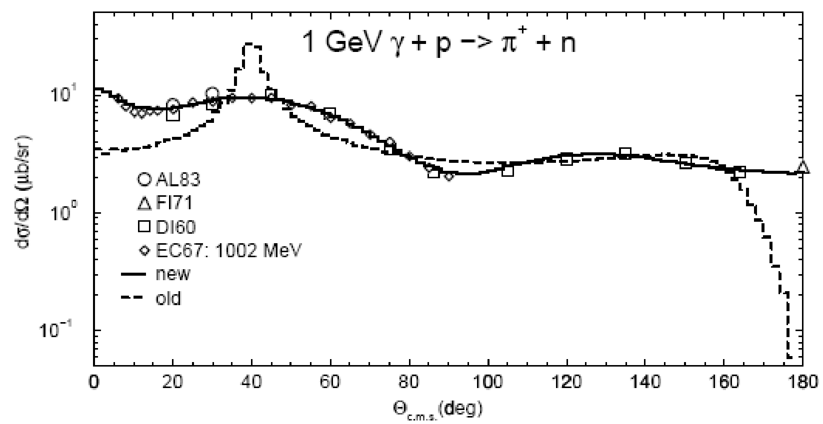
$$\begin{aligned} \gamma + p &\to p + \pi^0 , \\ &\to n + \pi^+ , \\ &\to p + \pi^+ + \pi^- , \\ &\to p + \pi^0 + \pi^0 , \\ &\to n + \pi^+ + \pi^0 . \end{aligned}$$

$$V \equiv V_N(r) = T_F(r) + \epsilon, \qquad V_\pi \simeq 25 \text{ MeV},$$

Pauli principle forbids a number of intranuclear collisions


n + p total cross section
experimental data
CEM95 approximation
CEM97 approximation
n + p → p + p + π⁻ (× 1000)
π⁺ + p total nuclear cross section
π⁺ + p → π⁺ + p + π⁰ (× 10)
γ + p total cross section
γ + p → n + π⁺ + π⁰ (× 10)
Cross Section (mb)
Lab Kinetic Energy (MeV)


dσnp/dΩ (mb/sr)
Tn=386 MeV
Tn=418 MeV
Tn=473 MeV
Tn=532 MeV
Tn=636 MeV
Tn=684 MeV
Tn=770 MeV
Tn=801 MeV
Tn=899 MeV
Tn=986 MeV
Tn=1073 MeV
Tn=1243 MeV
new
old
Θcm


1 GeV γ + p -> π⁺ + n
dσ/dΩ (µb/sr)
AL83
FI71
DI60
EC67: 1002 MeV
new
old
Θc.m.s.(deg)

In comparison with the initial version [1,2] of INC, in CEM03.02 we have:

1) developed better approximations for the total elementary cross sections

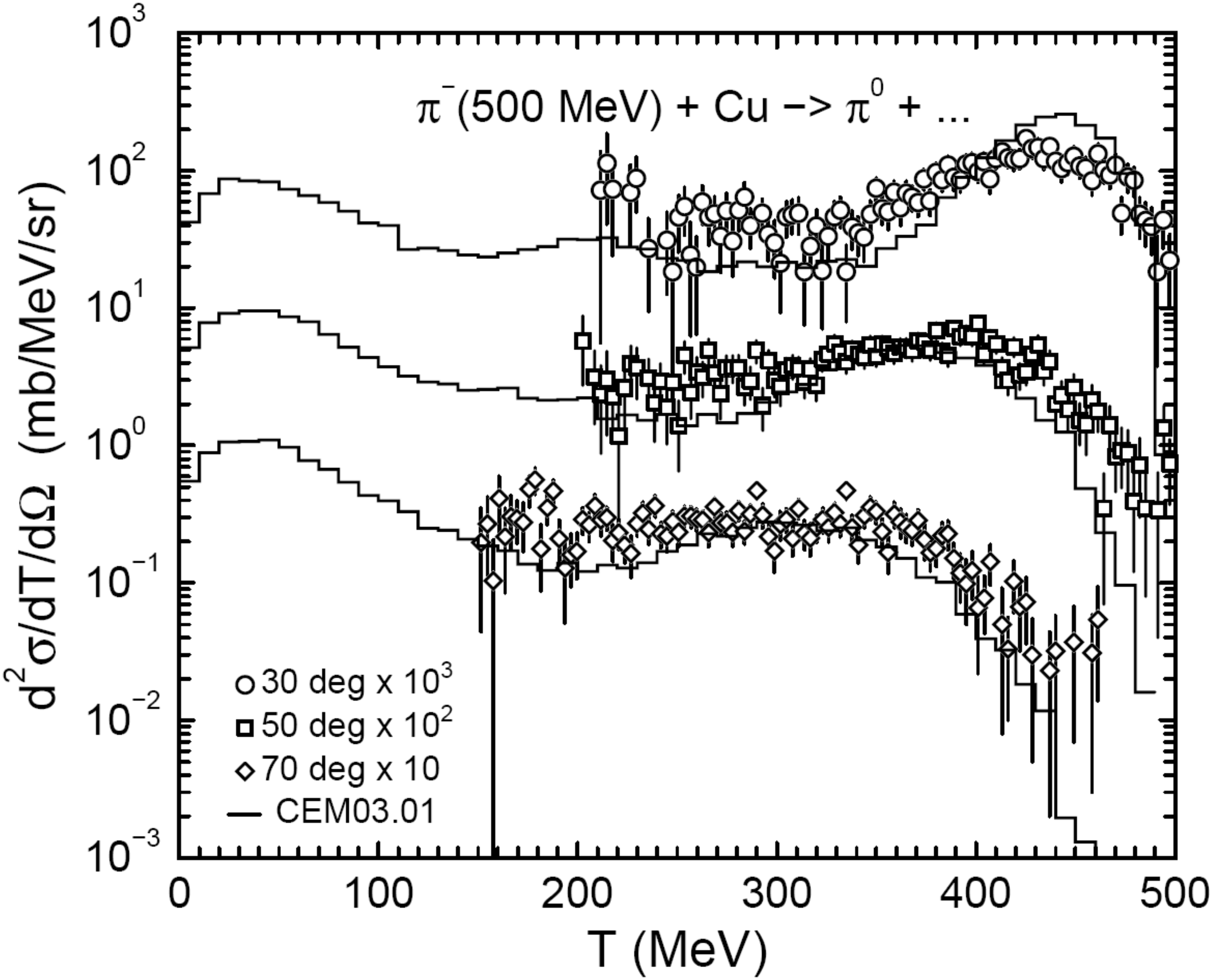
2) developed new approximations to describe more accurately experimental elementary energy and angular distributions of secondary particles from hadron-hadron and photon-hadron interactions

3) normalized photonuclear reactions to detailed systematics developed by M. Kosov and nucleon-induced reactions to NASA systematics

4) the condition for transition from the INC stage of a reaction to preequilibrium was changed; on the whole, the INC stage in CEM03.01 is longer while the preequilibrium stage is shorter in comparison with previous versions

5) the algorithms of many INC routines were changed and almost all INC routines were rewritten, which speeded up the code significantly

6) some preexisting bugs in the INC were fixed



Exp. data (symbols): J. Ouyang, PhD thesis U. of Colorado, 1992; S. G. Mashnik, R. J. Peterson, A. J. Sierk, M. R. Braunstein, Phys. Rev. C61 (2000) 034601

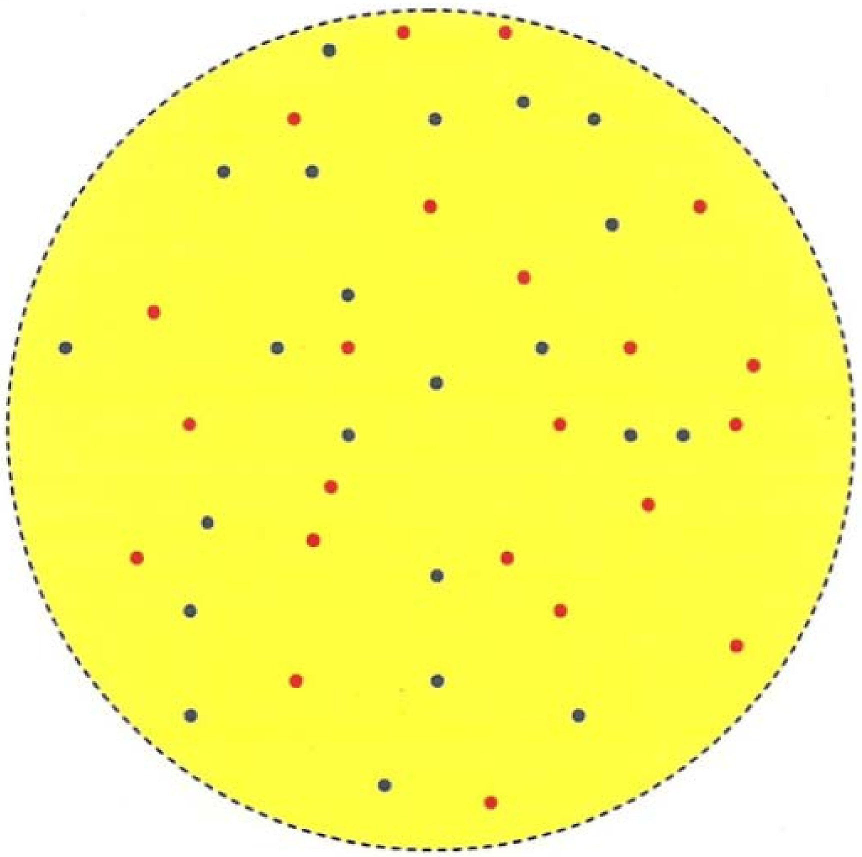
The INC stage of reactions is described by LAQGSM03.02 with a recently improved version [1] of the time-depending intranuclear cascade model developed initially in Dubna, often referred in the literature simply as the Dubna intranuclear Cascade Model, DCM [2], using the Quark-Gluon String Model (QGSM) [3] to describe elementary interactions at energies above 4.5 GeV.

[1] S.G. Mashnik, K.K. Gudima, M.I. Baznat, A.J. Sierk, R.A. Prael, N.V. Mokhov, LANL Report, LA-UR-06-1764, Los-Alamos (2006).
[2] V.D. Toneev, K.K. Gudima, Nucl. Phys. A400 (1983) 173c.
[3] N.S. Amelin, K.K. Gudima, V.D. Toneev, Sov. J. Nucl. Phys. 51 (1990) 327; ibid. 51 (1990) 1730; ibid. 52 (1990) 172;
N. S. Amelin, CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland (1999).

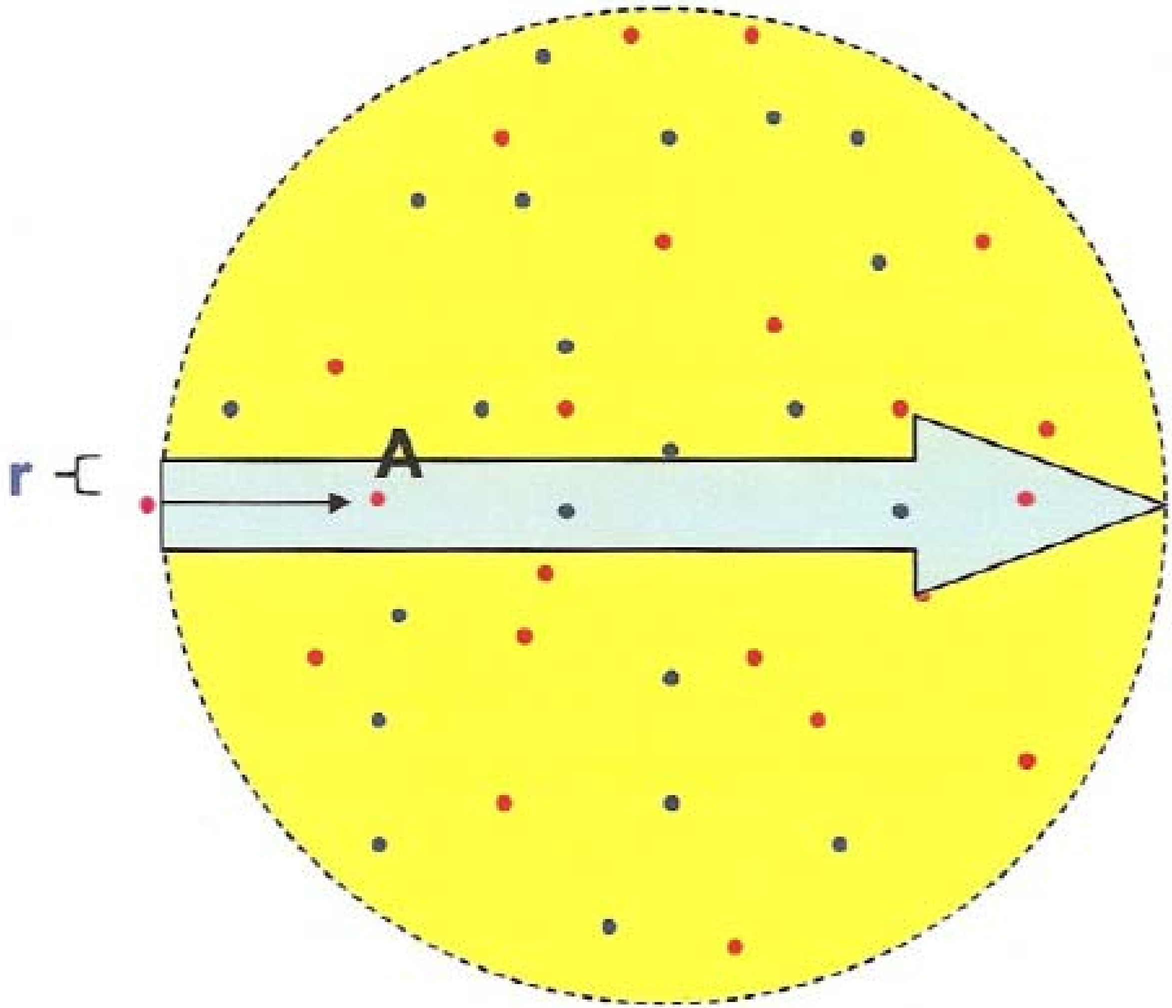
LAQGSM uses a continuous nuclear distribution (no "zones")

$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0\{1 + exp[(r - c)/a]\}$$

$$\text{where } c = 1.07A^{1/3} \text{ fm}, \quad \text{and } a = 0.545 \text{ fm}$$

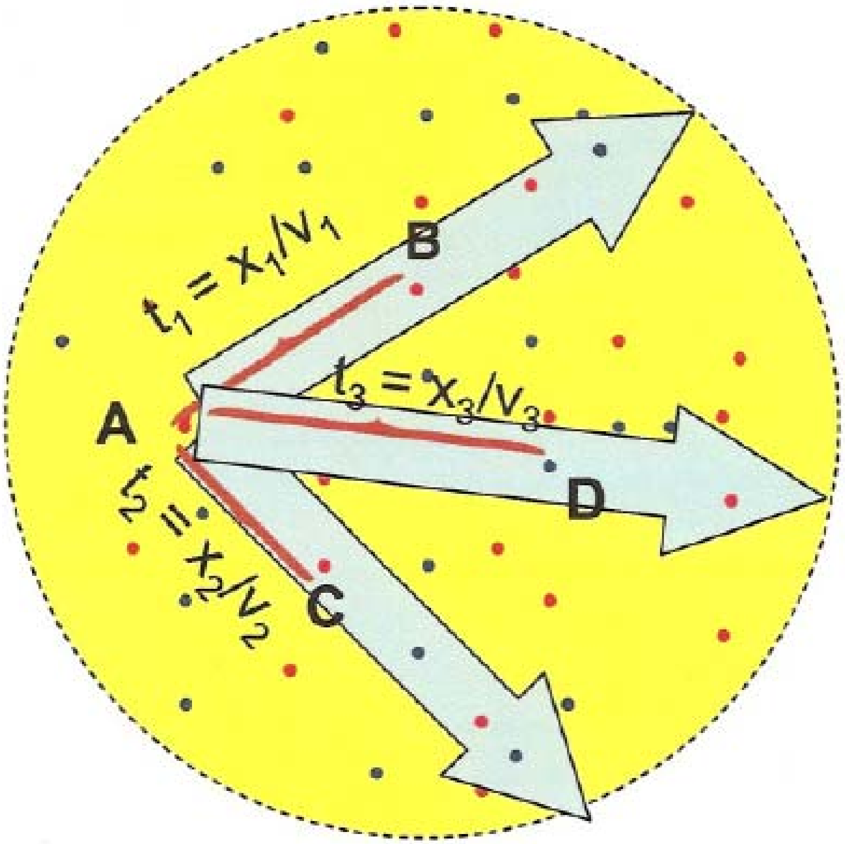


Before starting to simulate an INC event, position of all IntraNuclear nucleons are simulated and "frozen"



The projectile interacts (in point **A**) with the nearest target nucleon met inside the cylinder with the radius r

$r = r_{int} + \lambda/2\pi$, where $r_{int} = 1.3$ fm; $\lambda/2\pi$ is the de Broglie wavelength



$t^f_{1(2,3,\ldots)}$ is the formation time of the cascade particle #1(2,3,…)

If $t_2 < t_1$, $t_2 < t_3, \ldots$, and $t_2 > t^f_2$, particle #2 interacts first in point **C**

IntraNuclear nucleons involved in interactions become "cascade" particles and are removed from the status of "frozen" target nucleons (trailing effect)

The formation time: $t^f = (E/m)t_f^0$; $t_f^0 = C_t\, \hbar/m_\pi$;

C_t = 1.0 for mesons and ~0.0 for baryons

#	γp-interactions	γn-interactions
1	$\gamma p \to \pi^+ n$	$\gamma n \to \pi^- p$
2	$\gamma p \to \pi^0 n$	$\gamma n \to \pi^0 n$
3	$\gamma p \to \Delta^{++}\pi^-$	$\gamma n \to \Delta^+\pi^-$
4	$\gamma p \to \Delta^+\pi^0$	$\gamma n \to \Delta^0\pi^0$
5	$\gamma p \to \Delta^0\pi^+$	$\gamma n \to \Delta^-\pi^+$
6	$\gamma p \to \rho^0 p$	$\gamma n \to \rho^0 n$
7	$\gamma p \to \rho^+ n$	$\gamma n \to \rho^- p$
8	$\gamma p \to \eta p$	$\gamma n \to \eta n$
9	$\gamma p \to \omega p$	$\gamma n \to \omega n$
10	$\gamma p \to \Lambda K^+$	$\gamma n \to \Lambda K^0$
11	$\gamma p \to \Sigma^0 K^+$	$\gamma n \to \Sigma^0 K^0$
12	$\gamma p \to \Sigma^+ K^0$	$\gamma n \to \Sigma^- K^+$
13	$\gamma p \to \eta' p$	$\gamma n \to \eta' n$
14	$\gamma p \to \phi p$	$\gamma n \to \phi n$
15	$\gamma p \to \pi^+\pi^- p$	$\gamma n \to \pi^+\pi^- n$
16	$\gamma p \to \pi^0\pi^+ n$	$\gamma n \to \pi^0\pi^- p$
17	$\gamma p \to \pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0 n$
18	$\gamma p \to \pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0\pi^0 n$
19	$\gamma p \to \pi^+\pi^-\pi^0 p$	$\gamma n \to \pi^+\pi^-\pi^0 n$
20	$\gamma p \to \pi^+\pi^0\pi^0 n$	$\gamma n \to \pi^-\pi^0\pi^0 p$
21	$\gamma p \to \pi^+\pi^+\pi^- n$	$\gamma n \to \pi^+\pi^-\pi^- p$
22	$\gamma p \to \pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0\pi^0\pi^0 n$
23	$\gamma p \to \pi^+\pi^-\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^-\pi^0\pi^0 n$
24	$\gamma p \to \pi^+\pi^+\pi^-\pi^- p$	$\gamma n \to \pi^+\pi^+\pi^-\pi^- n$
25	$\gamma p \to \pi^+\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^-\pi^0\pi^0\pi^0 p$
26	$\gamma p \to \pi^+\pi^+\pi^-\pi^0 n$	$\gamma n \to \pi^+\pi^-\pi^-\pi^0 p$
27	$\gamma p \to \pi^0\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0\pi^0\pi^0\pi^0 n$
28	$\gamma p \to \pi^+\pi^-\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^-\pi^0\pi^0\pi^0 n$
29	$\gamma p \to \pi^+\pi^+\pi^-\pi^-\pi^0 p$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^0 n$
30	$\gamma p \to \pi^+\pi^0\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^-\pi^0\pi^0\pi^0\pi^0 p$
31	$\gamma p \to \pi^+\pi^+\pi^-\pi^0\pi^0 n$	$\gamma n \to \pi^+\pi^-\pi^-\pi^0\pi^0 p$
32	$\gamma p \to \pi^+\pi^+\pi^+\pi^-\pi^- n$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^- p$
33	$\gamma p \to \pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 n$
34	$\gamma p \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0 n$
35	$\gamma p \to \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0 n$
36	$\gamma p \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^- p$	$\gamma n \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^- n$
37	$\gamma p \to \pi^+\pi^0\pi^0\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^-\pi^0\pi^0\pi^0\pi^0\pi^0 p$
38	$\gamma p \to \pi^+\pi^+\pi^-\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^+\pi^-\pi^-\pi^0\pi^0\pi^0 p$
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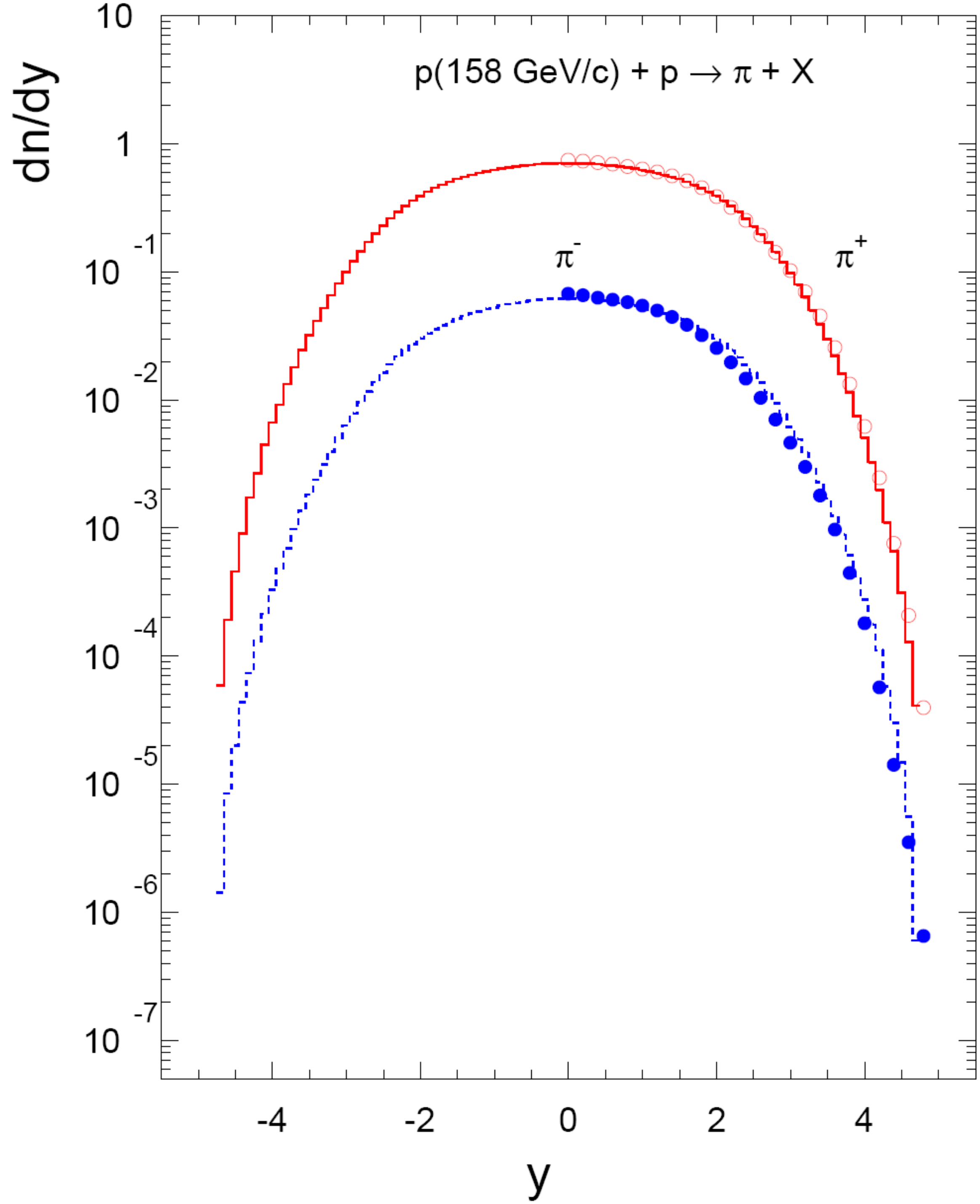
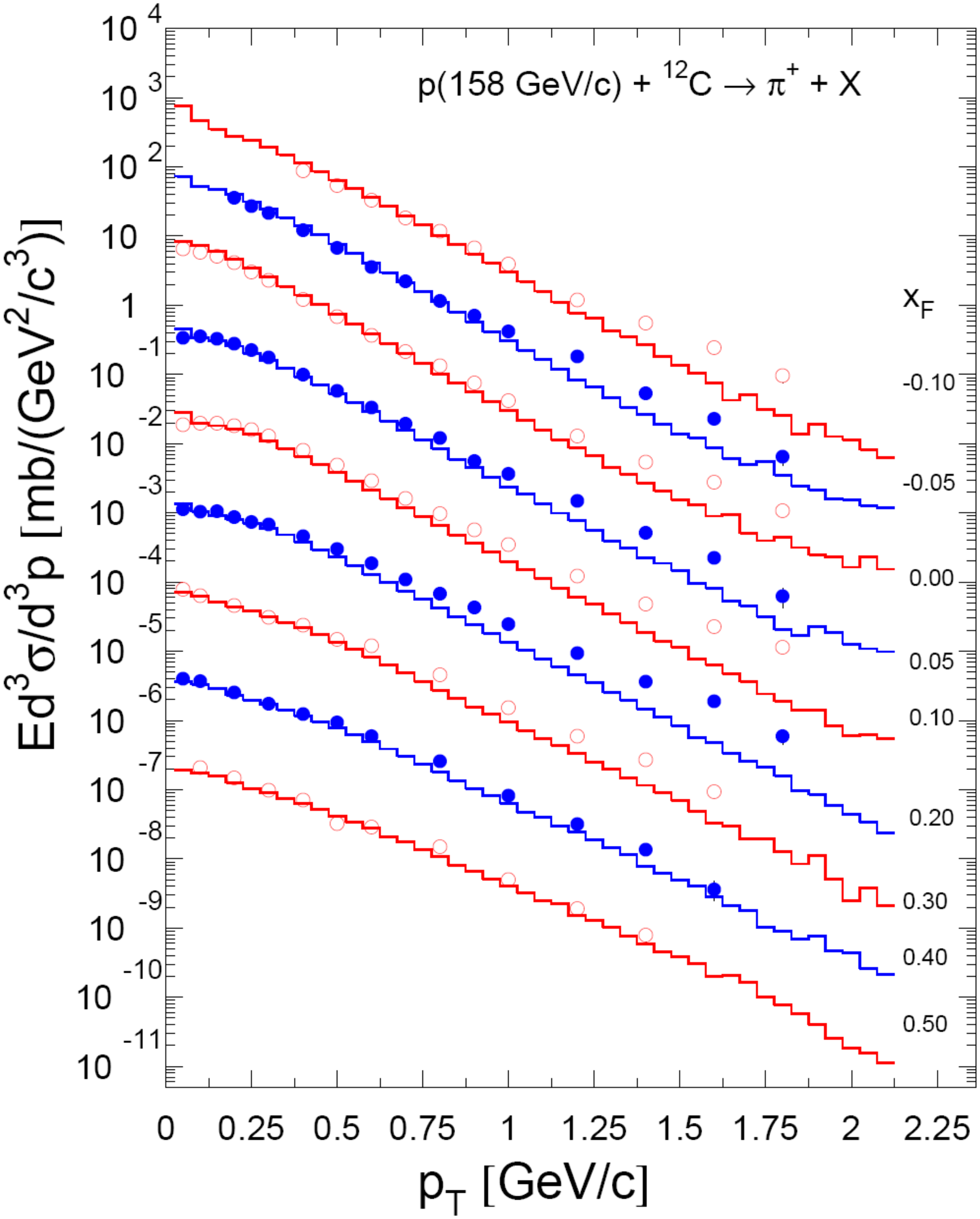
40	$\gamma p \to \pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 n$
41	$\gamma p \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0 n$
42	$\gamma p \to \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0 n$
43	$\gamma p \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0 p$	$\gamma n \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0 n$
44	$\gamma p \to \pi^+\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^-\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 p$
45	$\gamma p \to \pi^+\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^+\pi^-\pi^-\pi^0\pi^0\pi^0\pi^0 p$
46	$\gamma p \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0 n$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^-\pi^0\pi^0 p$
47	$\gamma p \to \pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^- n$	$\gamma n \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^- p$
48	$\gamma p \to \pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 n$
49	$\gamma p \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 n$
50	$\gamma p \to \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0\pi^0 n$
51	$\gamma p \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0\pi^0 p$	$\gamma n \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0\pi^0 n$
52	$\gamma p \to \pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^- p$	$\gamma n \to \pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^- n$
53	$\gamma p \to \pi^+\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^-\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0 p$
54	$\gamma p \to \pi^+\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^+\pi^-\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0 p$
55	$\gamma p \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0 n$	$\gamma n \to \pi^+\pi^+\pi^-\pi^-\pi^-\pi^0\pi^0\pi^0 p$
56	$\gamma p \to \pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0 n$	$\gamma n \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^0 p$



NA49 data (symbols):
C. Alt et al.,
Eur. Phys. J.
C45 (2006) 343-381;

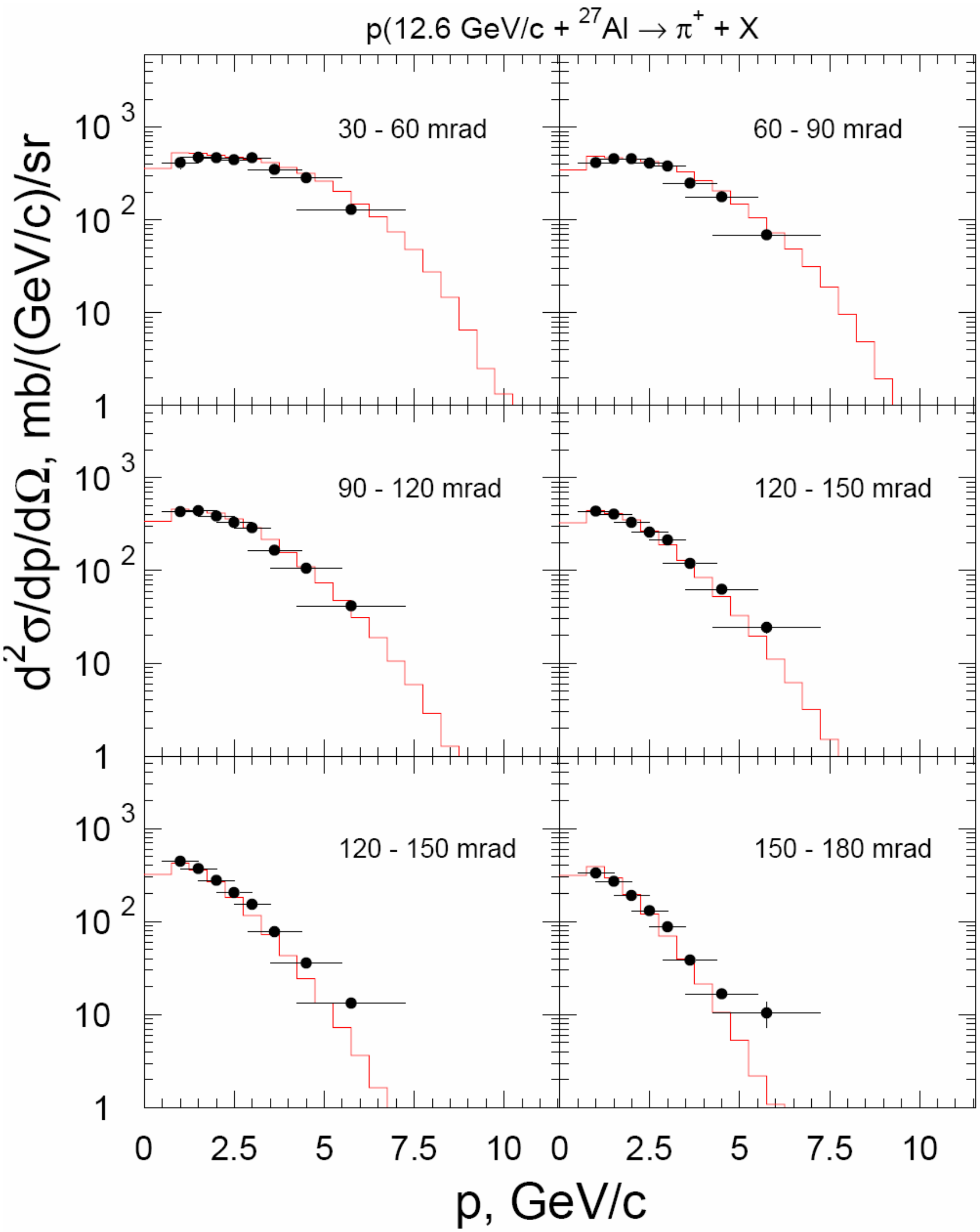
LAQGSM03.02 results:
histograms

(π^- xsec is multiplied by 0.1)



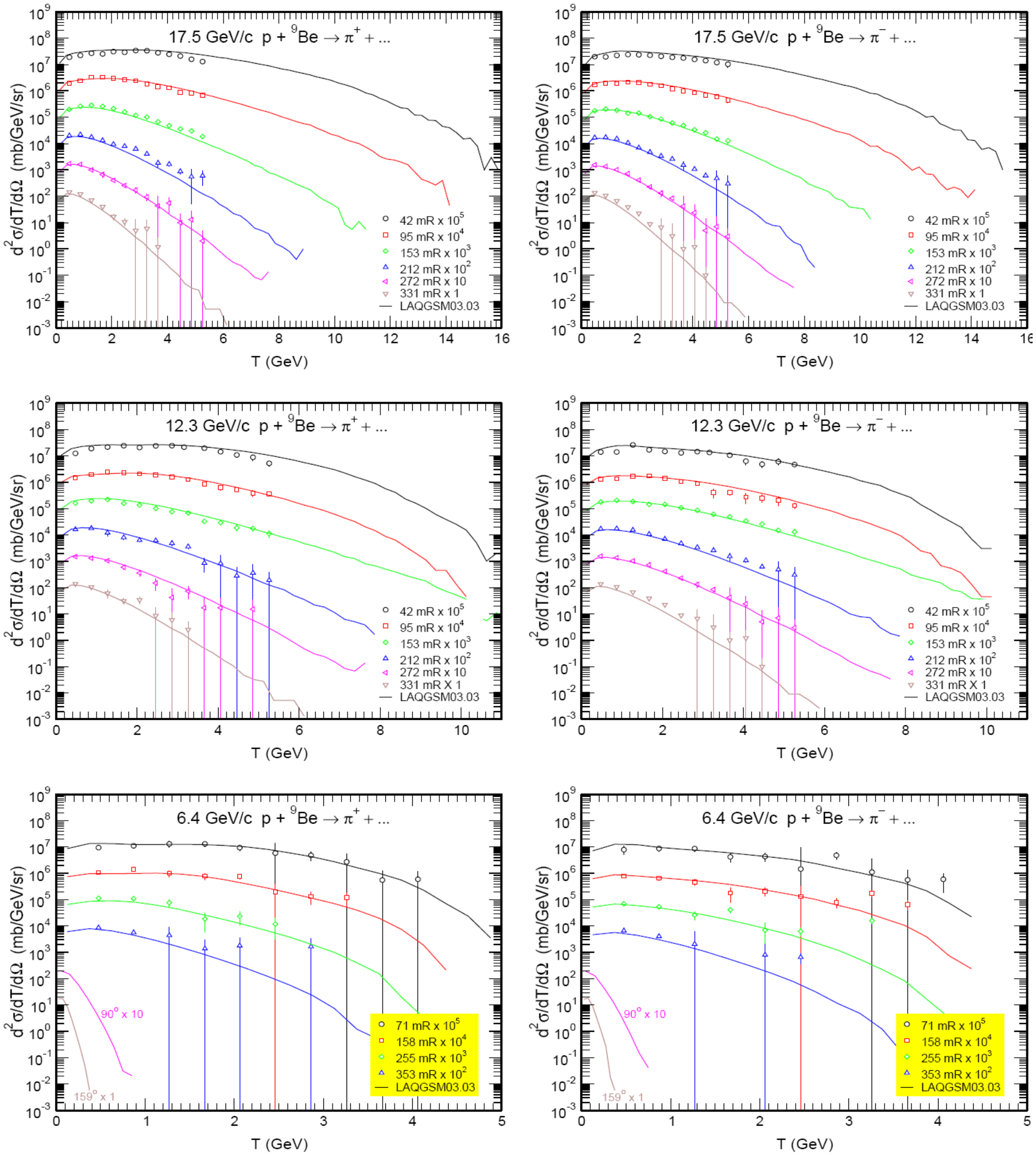
NA49 data (symbols):
C. Alt et al.,
E-print: hep-ex/0606028,
submitted to
Eur. Phys. J. ;

LAQGSM03.02 results:
histograms



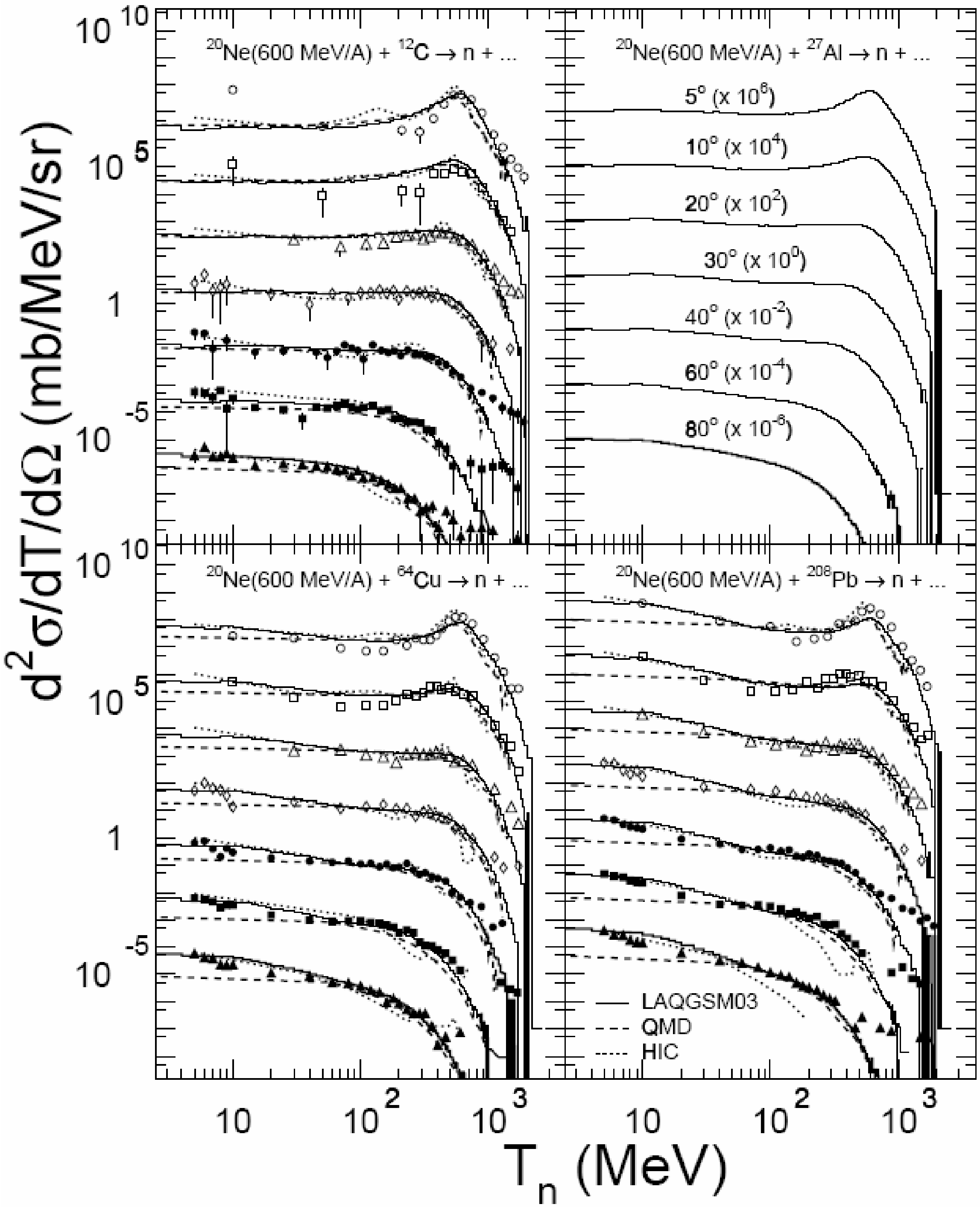
HARP data (symbols):
M. G. Catanesi et al.,
Nucl. Phys. B 732
(2006) 1-45;

LAQGSM03.02 results:
histograms

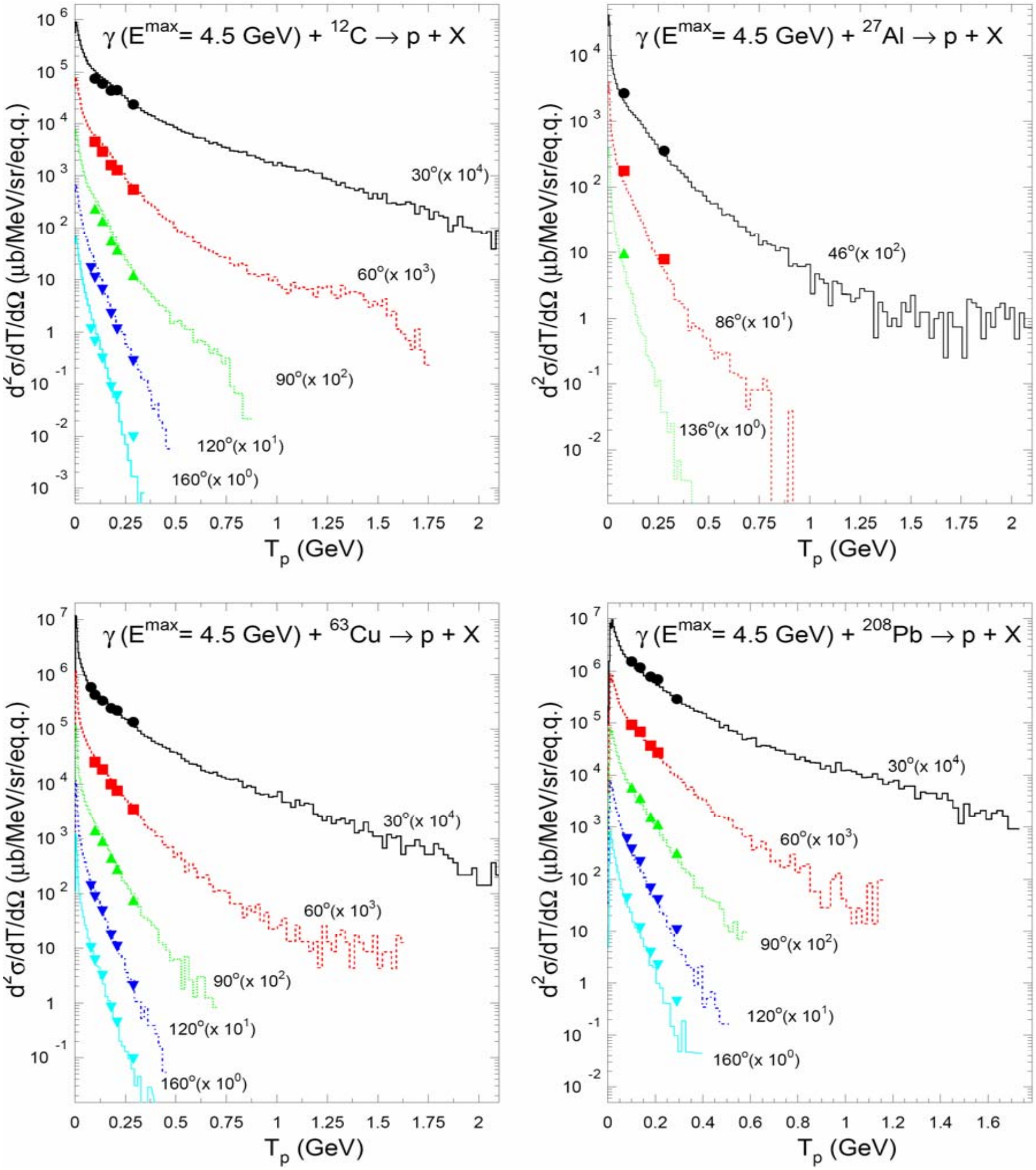


E910 data (symbols):

I. Chemakin et al., arXiv:0707.2375v1 [nucl-ex] 16 Jul 2007



Proc. ND2004:
Hiroshi Iwase,
Yoshiyuki Iwata,
Takashi Nakamura,
Konstantin Gudima,
Stepan Mashnik,
Arnold Sierk,
Richard Prael,
AIP Conf. Proc.
769 (2005) 1066-1069
(nucl-th/0501066)



Experimental data:

K. V. Alanakyan *et al.*,

Sov. J. Nucl. Phys.

25 (1977) 292; **34** (1981) 828;

Nucl. Phys. **A367** (1981) 429

LAQGSM03.02 results:

histograms

The coalescence model implemented in LAQGSM/CEM is described in [1]; We have changed the coalescence momentum radii p_0 for the various light composite particles up to ^{4}He by fitting them to measured data on various reactions and have fixed several bugs observed in the original version [1].

[1] V. D. Toneev and K. K. Gudima, Nucl. Phys. **A400** (1983) 173c.

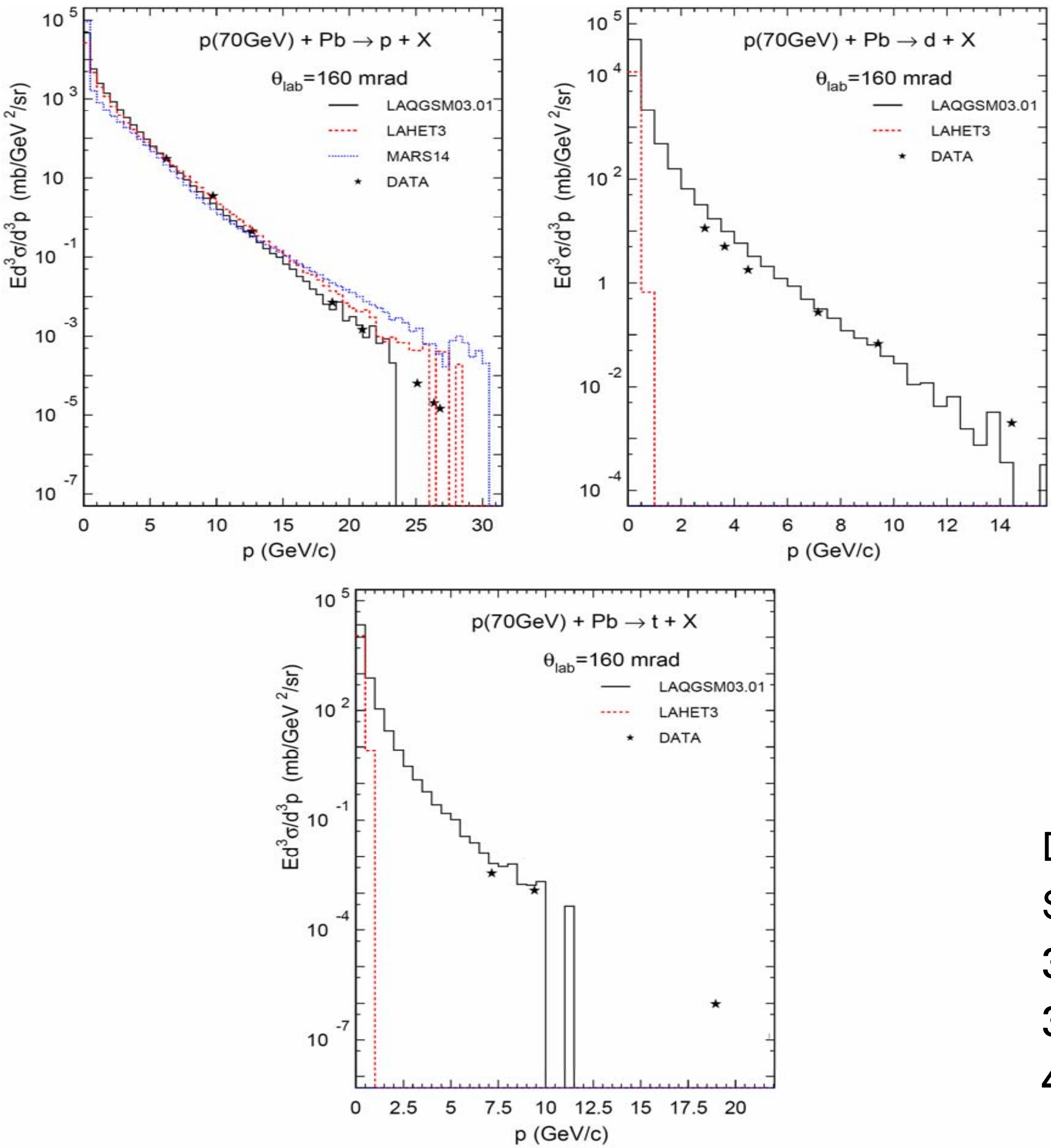
$$W_d(\vec{p}, b) = \int\int d\vec{p}_p d\vec{p}_n \rho^C(\vec{p}_p, b)\rho^C(\vec{p}_n, b)\delta(\vec{p}_p + \vec{p}_n - \vec{p})\Theta(p_c - |\vec{p}_p - \vec{p}_n|)$$

LAQGSM:

$p_c(d)$ = 90 MeV/c; $P_c(t) = p_c(^3\text{He})$ = 108 MeV/c; $p_c(^4\text{He})$ = 115 MeV/c

CEM:

$p_c(d)$ = 150 MeV/c; $p_c(t) = P_c(^3\text{He})$ = 175 MeV/c; $p_c(^4\text{He})$ = 175 MeV/c



Data: L. M. Barkov *et al.,*
Sov. J. Nucl. Phys.
35 (1982) 694;
37 (1983) 732;
41 (1985) 227

The preequilibrium part of reactions is described with the latest version [1] of the Modified Exciton Model (MEM) from the improved Cascade-Exciton Model (CEM) [2] released in the Code CEM03.01 [1]:

[1] S.G. Mashnik, K.K. Gudima, A.J. Sierk, M.I. Baznat, N.V. Mokhov, "CEM03.01 User Manual," LANL Report LA-UR-05-7321, Los Alamos (2005); RSICC Code Package PSR-532, http://www-rsicc.ornl.gov/codes/psr/psr5/psr-532.html (2006).

[2] K.K. Gudima, S.G. Mashnik, V.D. Toneev, Nucl. Phys. **A401** (1983) 329.

$$\Gamma_j(p,h,E) = \int_{V_j^c}^{E-B_j} \lambda_c^j(p,h,E,T)dT \ ,$$

$$\lambda_c^j(p,h,E,T) = \frac{2s_j+1}{\pi^2\hbar^3}\mu_j \Re_j(p,h)\frac{\omega(p-1,h,E-B_j-T)}{\omega(p,h,E)}T\sigma_{inv}(T)$$

$$\gamma_j \simeq p_j^3(V_j/V)^{p_j-1} = p_j^3(p_j/A)^{p_j-1}$$

$$<\sigma> \rightarrow <\sigma> F(\Omega) \ ,$$

$$F(\Omega) = \frac{d\sigma^{free}/d\Omega}{\int d\Omega' d\sigma^{free}/d\Omega'}$$

1) γ_j was fitted for proton-induced reactions

2) Kalbach systematics for angular distribution of preequilibrium particles was incorporated at energies below 210 MeV to replace the CEM approach

In comparison with the initial version [2] of CEM, the preequilibrium (PREC) part of CEM03.01 have been changed:

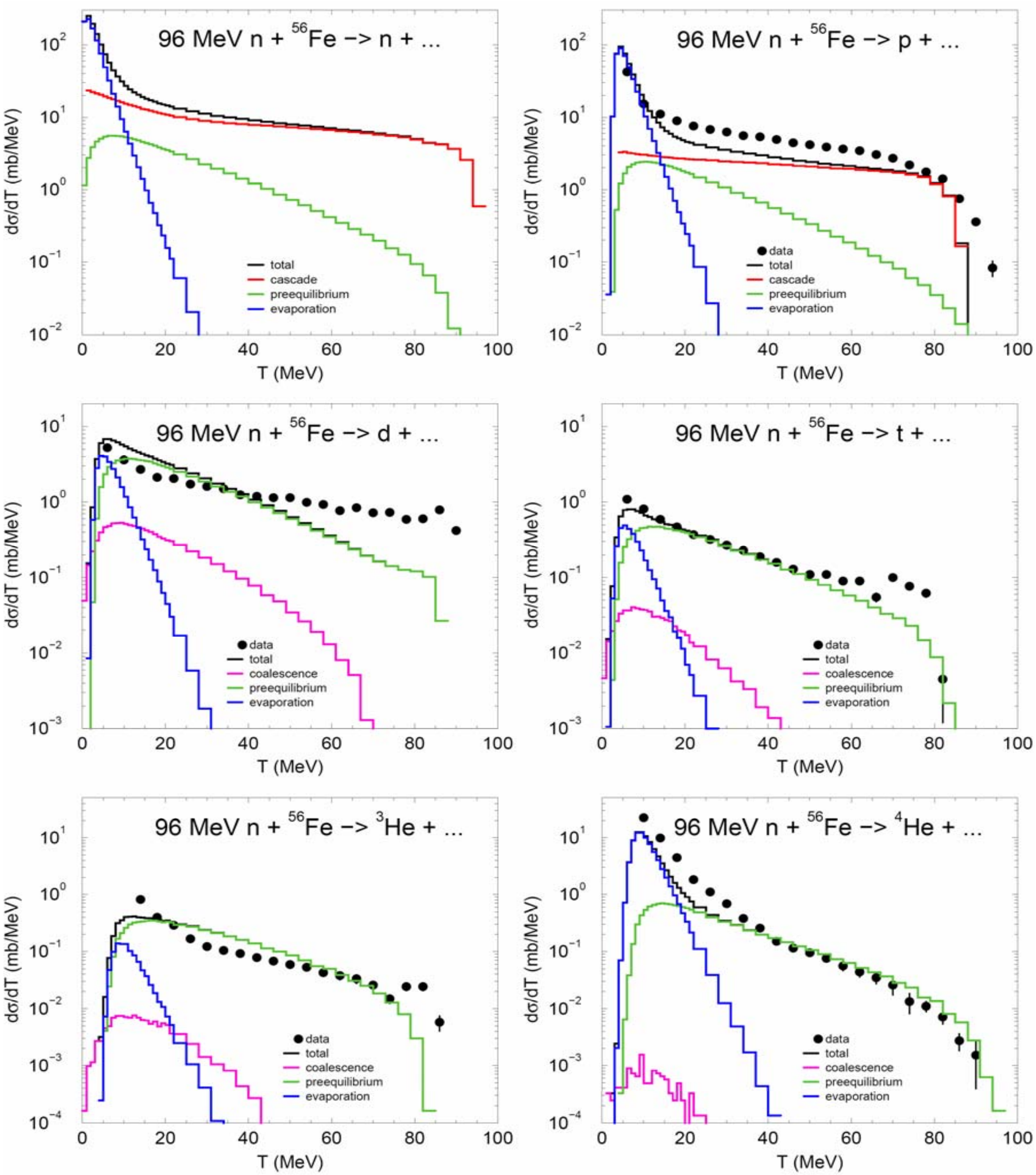
1) the condition for transition from the preequilibrium stage of a reaction to evaporation/fission was changed; on the whole, the preequilibrium stage in CEM03.01 is shorter while the evaporation stage is longer in comparison with previous versions

2) the widths for complex-particle emission were changed by fitting the probability of several excitons to "coalesce" into a complex particle that may be emitted during the preequilibrium stage to available experimental data on reactions induced by protons and neutrons

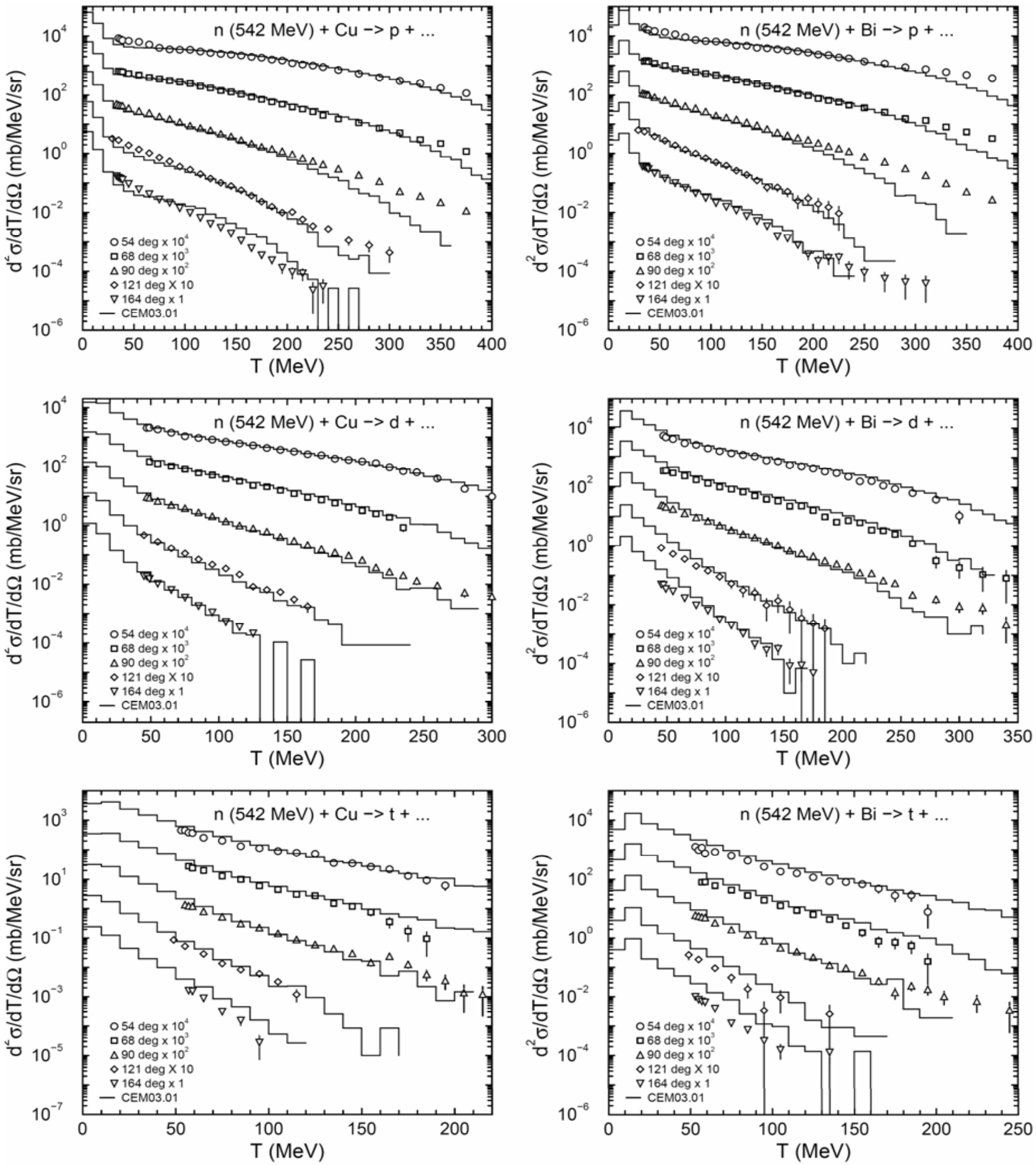
3) algorithms of many PREC routines were changed and almost all PREC routines were rewritten, which speeded up the code significantly

4) some bugs were discovered and fixed

5) Kalbach systematics for angular distribution of complex particles and nucleons with $T < 210$ MeV was incorporated into CEM/LAQGSM



Data: V. Blideanu *et al.*, Phys. Rev. C **70** (2004) 014607

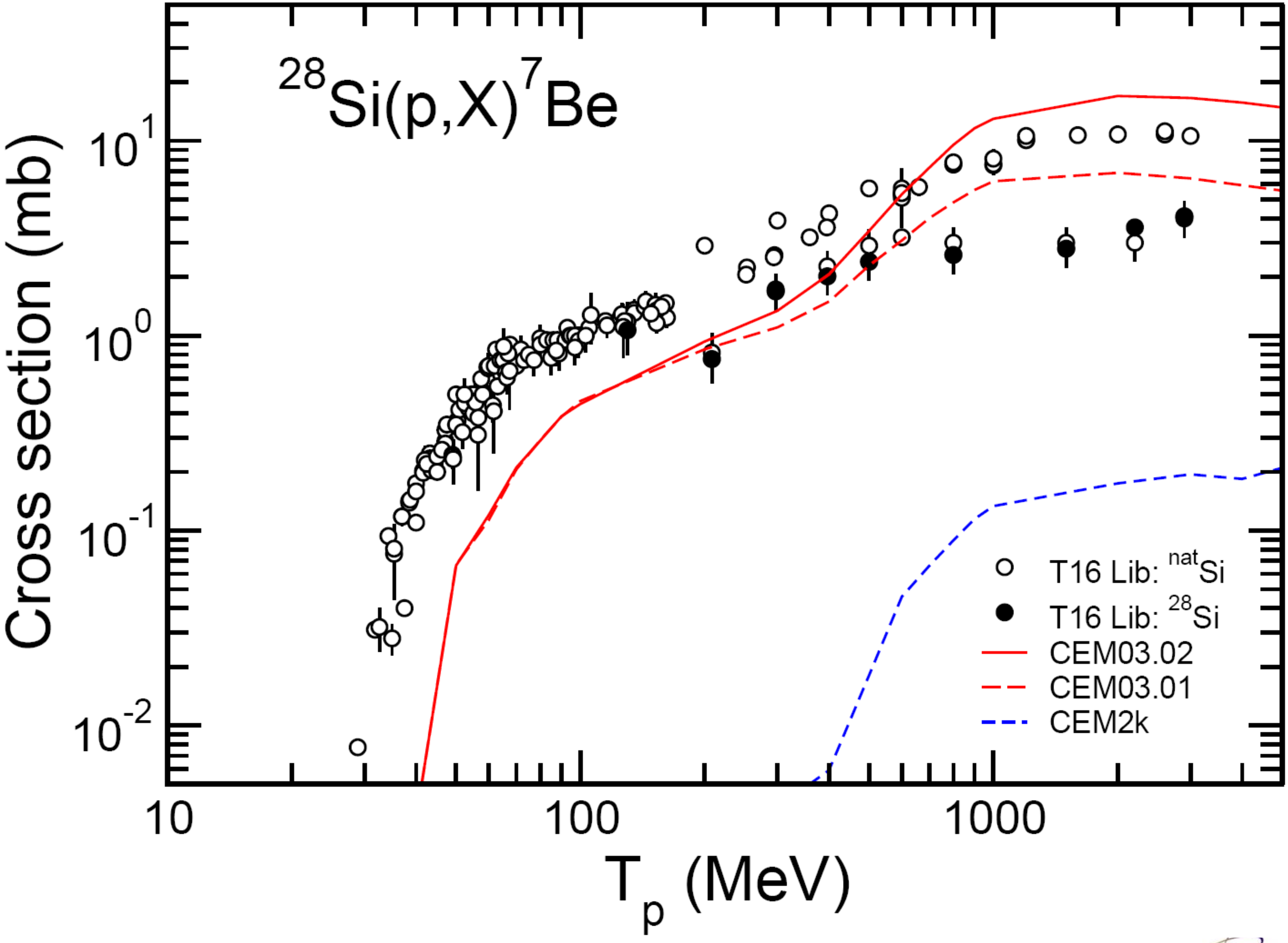


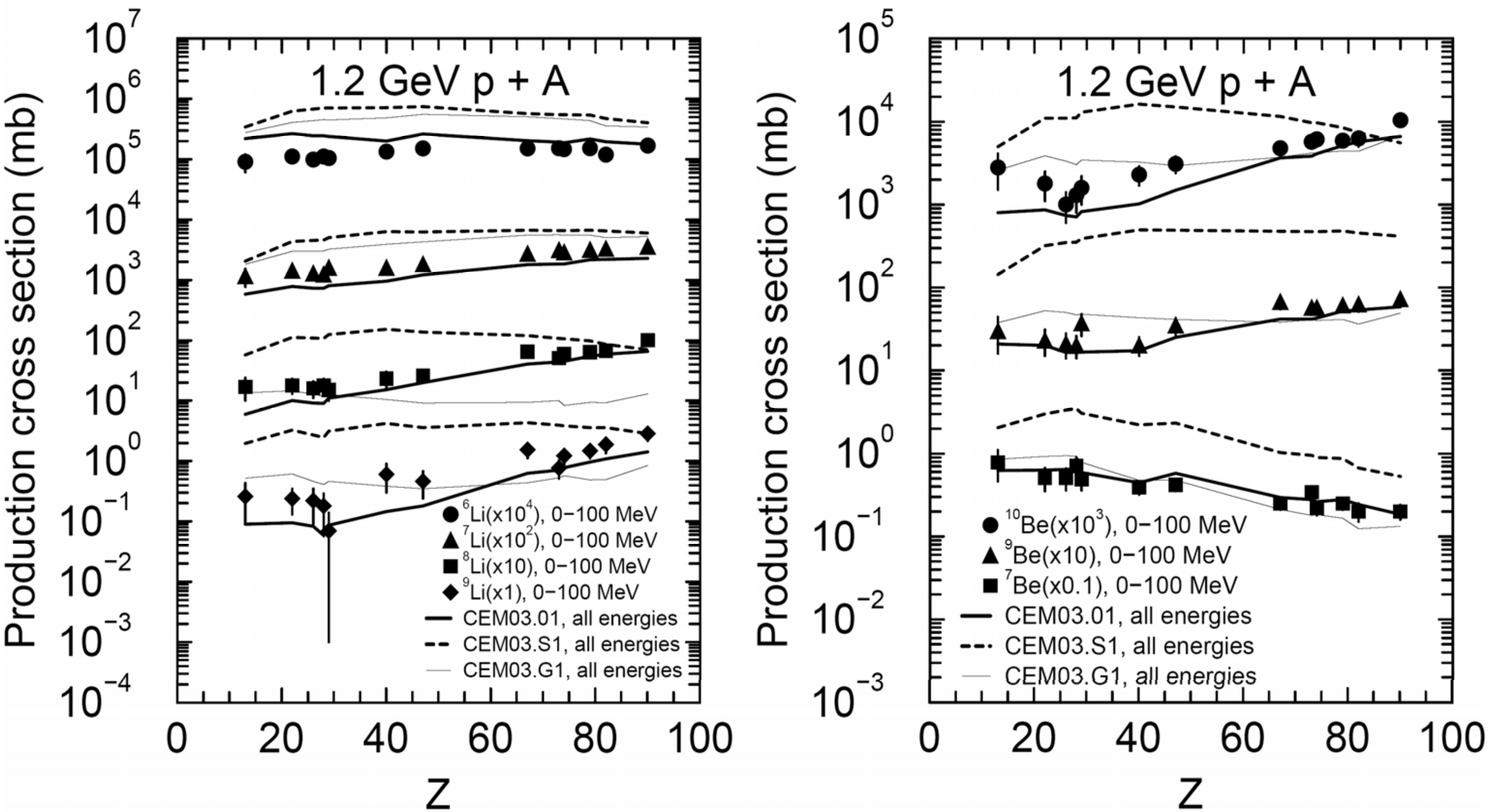
Data: J. Franz *et al.*,
Nucl. Phys. **A510** (1990) 774

The **evaporation** stages of reactions is calculated with an improved version of the Generalized Evaporation Model (GEM2) by Furihata (several routines by Furihata from GEM2 were slightly modified in CEM03.01/LAQGSM03.01; some bugs found in GEM2 were fixed).

$$P_j(\epsilon)d\epsilon = g_j \sigma_{inv}(\epsilon) \frac{\rho_d(E - Q - \epsilon)}{\rho_i(E)} \epsilon d\epsilon$$

Z_j	Ejectiles						
0	n						
1	p	d	t				
2	^{3}He	^{4}He	^{6}He	^{8}He			
3	^{6}Li	^{7}Li	^{8}Li	^{9}Li			
4	^{7}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be		
5	^{8}B	^{10}B	^{11}B	^{12}B	^{13}B		
6	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C
7	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	
8	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O
9	^{17}F	^{18}F	^{19}F	^{20}F	^{21}F		
10	^{18}Ne	^{19}Ne	^{20}Ne	^{21}Ne	^{22}Ne	^{23}Ne	^{24}Ne
11	^{21}Na	^{22}Na	^{23}Na	^{24}Na	^{25}Na		
12	^{22}Mg	^{23}Mg	^{24}Mg	^{25}Mg	^{26}Mg	^{27}Mg	^{28}Mg


28Si(p,X)7Be
Cross section (mb)
T p (MeV)
10
100
1000
10-2
10-1
100
101
T16 Lib: natSi
T16 Lib: 28Si
CEM03.02
CEM03.01
CEM2k



NESSI data: C.-M. Herbach *et al.*, Nucl. Phys. A765 (2006) 426-463

Fission is calculated with an improved version of GEM2 that is an extension by Furihata of the RAL fission model of Atchison.

We have changed the calculation of the fission cross sections; several routines by Furihata from GEM2 were slightly modified in CEM03.02/LAQGSM03.02; some bugs found in GEM2 were fixed.

Fission cross section calculation:

1) $70 \le Z_j \le 88$ the Weisskopf and Ewing statistical model

$$P_f = \frac{\Gamma_f}{\Gamma_f + \Gamma_n} = \frac{1}{1 + \Gamma_n/\Gamma_f}$$

$$\Gamma_n = 0.352\big(1.68J_0 + 1.93A_i^{1/3}J_1 + A_i^{2/3}(0.76J_1 - 0.05J_0)\big), \qquad J_0 = \frac{(s_n - 1)e^{s_n} + 1}{2a_n},$$

$$s_n (= 2\sqrt{a_n(E - Q_n - \delta)}) \quad a_n = (A_i - 1)/8 \qquad J_1 = \frac{(2s_n^2 - 6s_n + 6)e^{s_n} + s_n^2 - 6}{8a_n^2}$$

$$\Gamma_f = \frac{(s_f - 1)e^{s_f} + 1}{a_f}, \; a_f = a_n\left(1.08926 + 0.01098(\chi - 31.08551)^2\right), \text{ and } \chi = Z^2/A.$$

$$B_f = Q_n + 321.2 - 16.7\frac{Z_i^2}{A} + 0.218\left(\frac{Z_i^2}{A_i}\right)^2$$

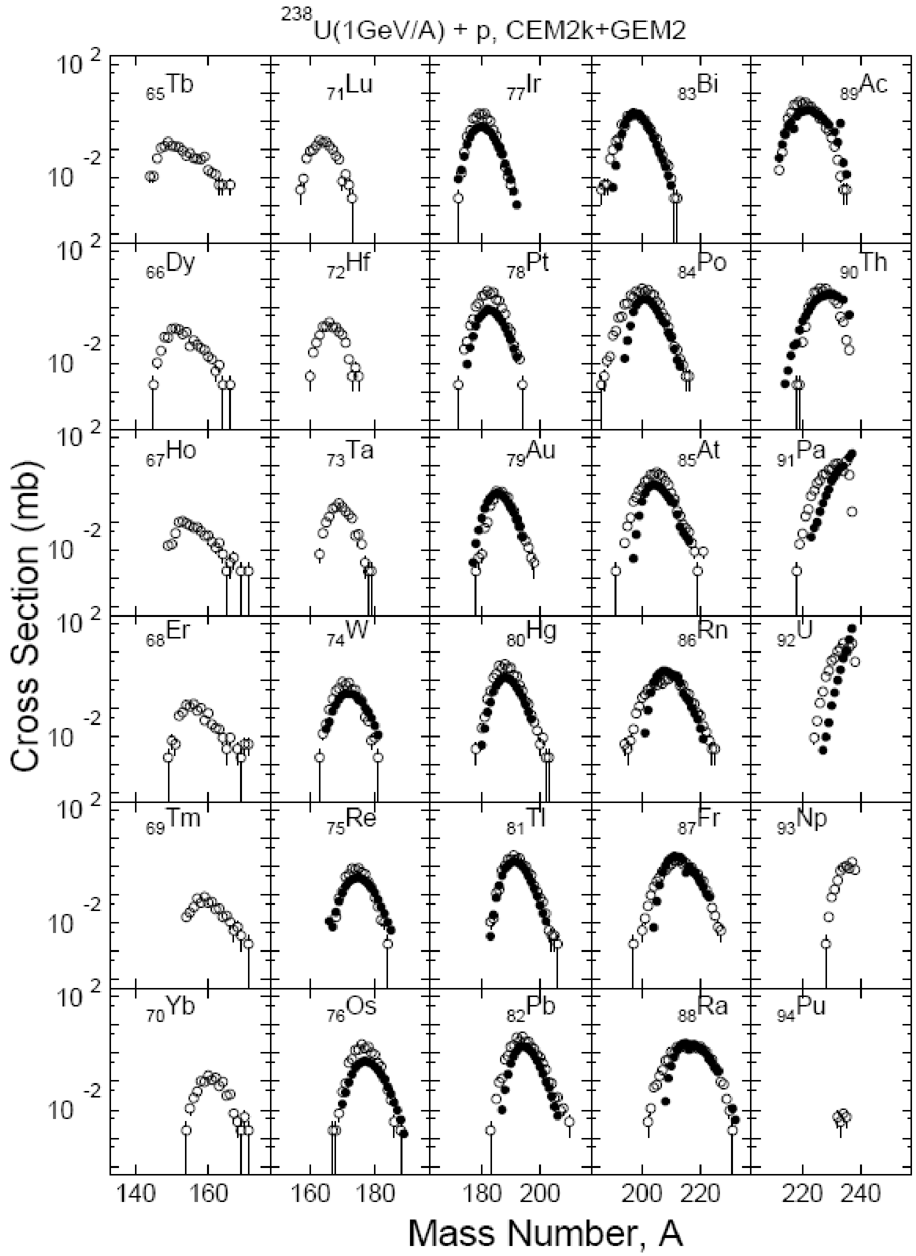
2) $Z_j \geq 89$

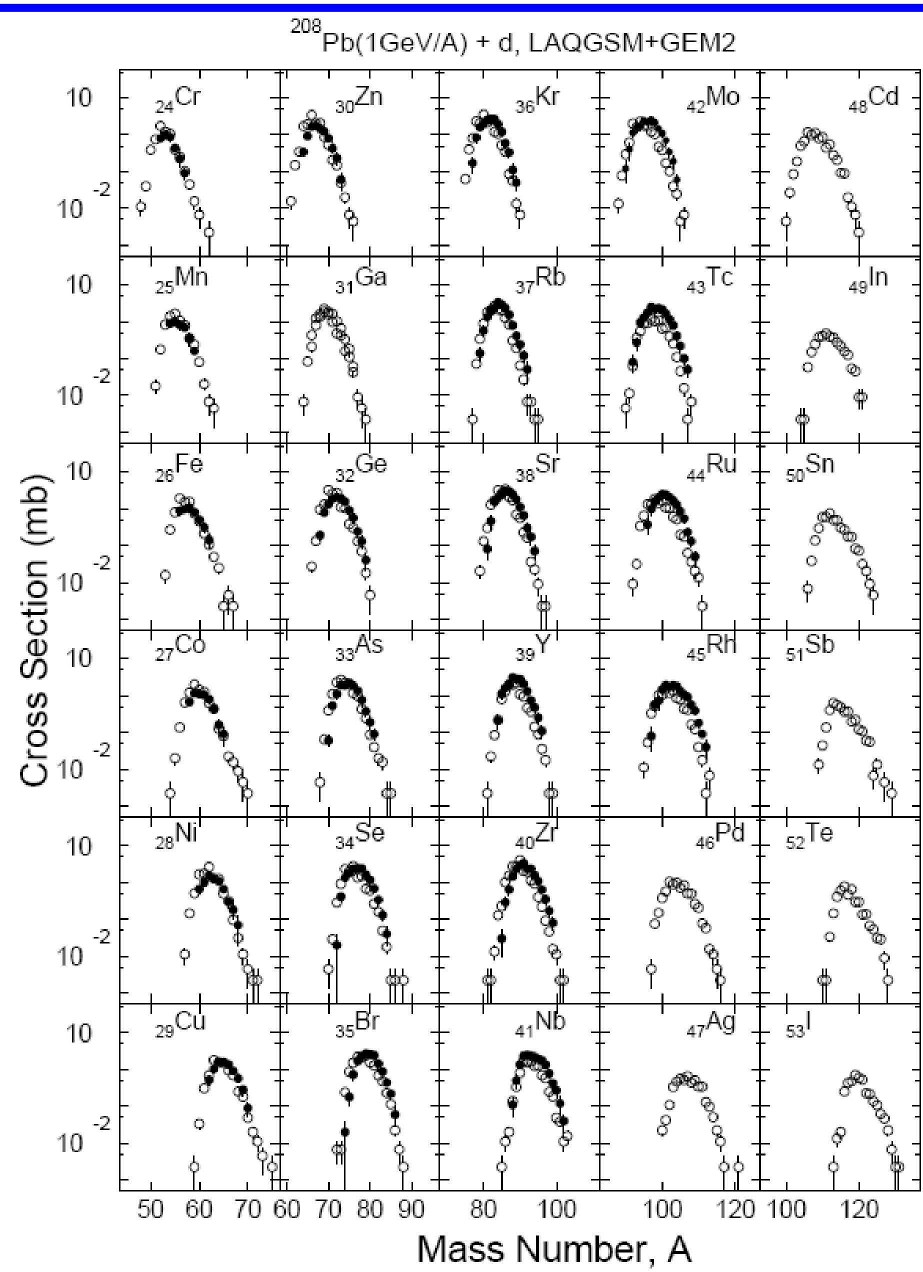
$$\log(\Gamma_n/\Gamma_f) = C(Z_i)(A_i - A_0(Z_i)),$$

$C(Z)$ and $A_0(Z)$ are constants

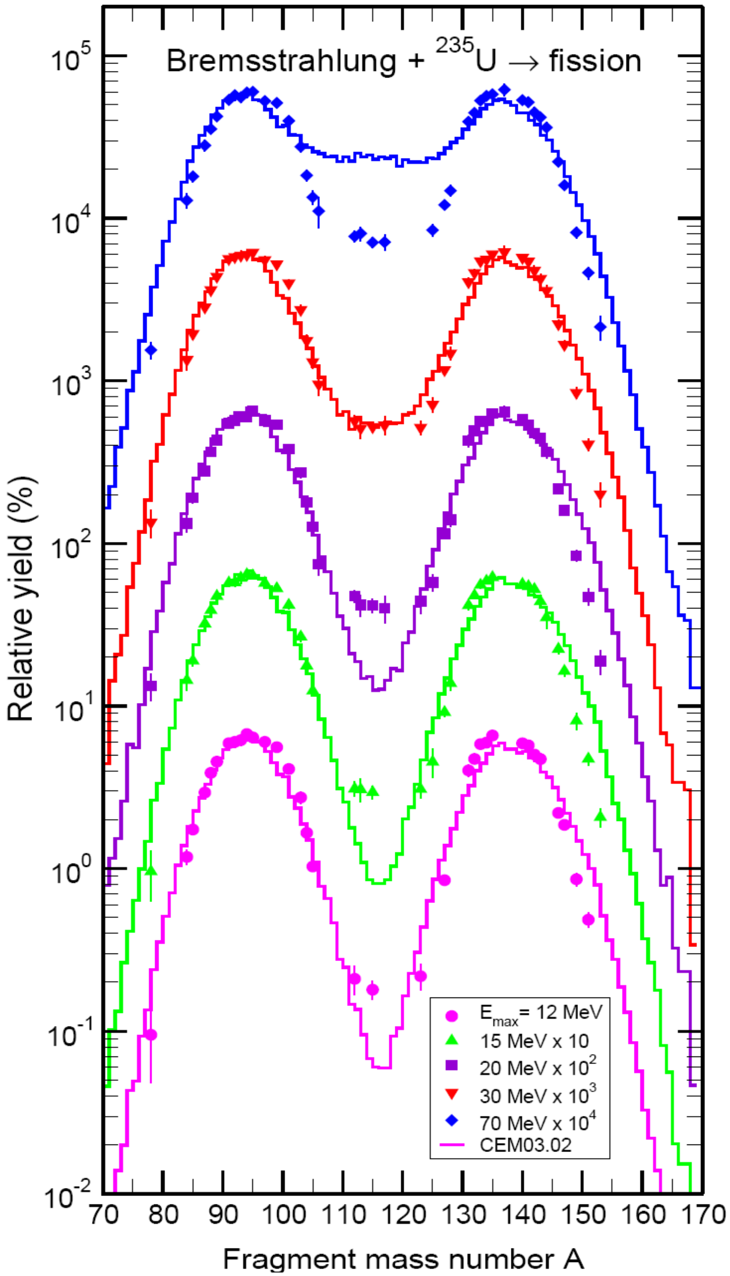
Z	$C(Z)$	$A_0(Z)$
89	0.23000	219.40
90	0.23300	226.90
91	0.12225	229.75
92	0.14727	234.04
93	0.13559	238.88
94	0.15735	241.34
95	0.16597	243.04
96	0.17589	245.52
97	0.18018	246.84
98	0.19568	250.18
99	0.16313	254.00
100	0.17123	257.80
101	0.17123	261.30
102	0.17123	264.80
103	0.17123	268.30
104	0.17123	271.80
105	0.17123	275.30
106	0.17123	278.80

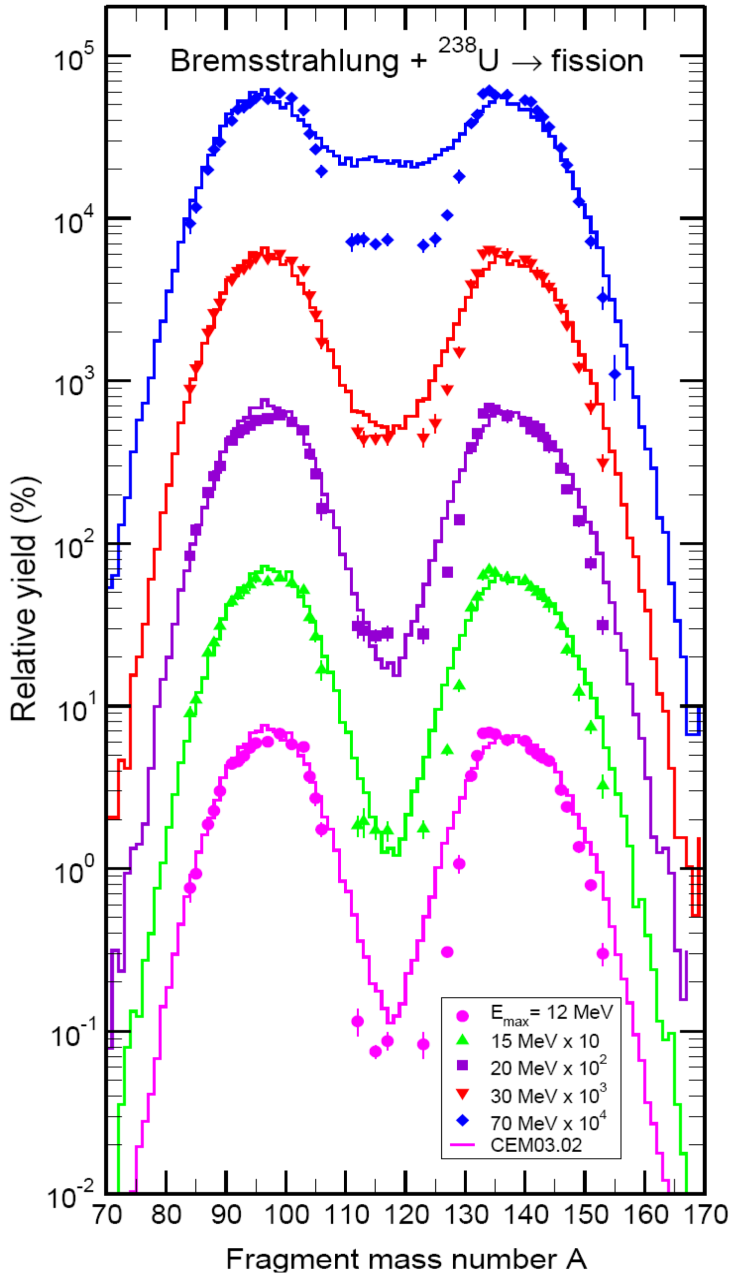
In CEM03.02 and LAQGSM03.02: $a_f \to C_a \times a_f \quad C(Z_i) \to C_c \times C(Z_i)$





GSI data (filled circles): M. Bernas *et al.*, Nucl. Phys. A725 (2003) 213; T. Enqvist *et al.*, Nucl. Phys. A703 (2003) 435; LAQGSM results: open circles





Data:

E. Jacobs et al., Phys. Rev. C: **19** (1979) 422; **21** (1980) 237

The Fermi breakup model code used in LAQGSM03.01 and in CEM03.01 was developed in the group of Prof. Barashenkov at JINR, Dubna and is described in details in [1].

[1] N. Amelin, "Physics and Algorithms of the Hadronic Monte-Carlo Event Generators. Notes for a Developer," CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland (1999); "GEANT4, Users' Documents, Physics Reference Manual," last update: 08/04/1999; http://wwwinfo.cern.ch/asd/geant4/G4UsersDocuments/UsersGuides/PhysicsReferenceManual/html/PhysicsReferenceManual.html/.

The total probability per unit time of a nucleus (A,Z) with excitation energy U to breakup into n components is:

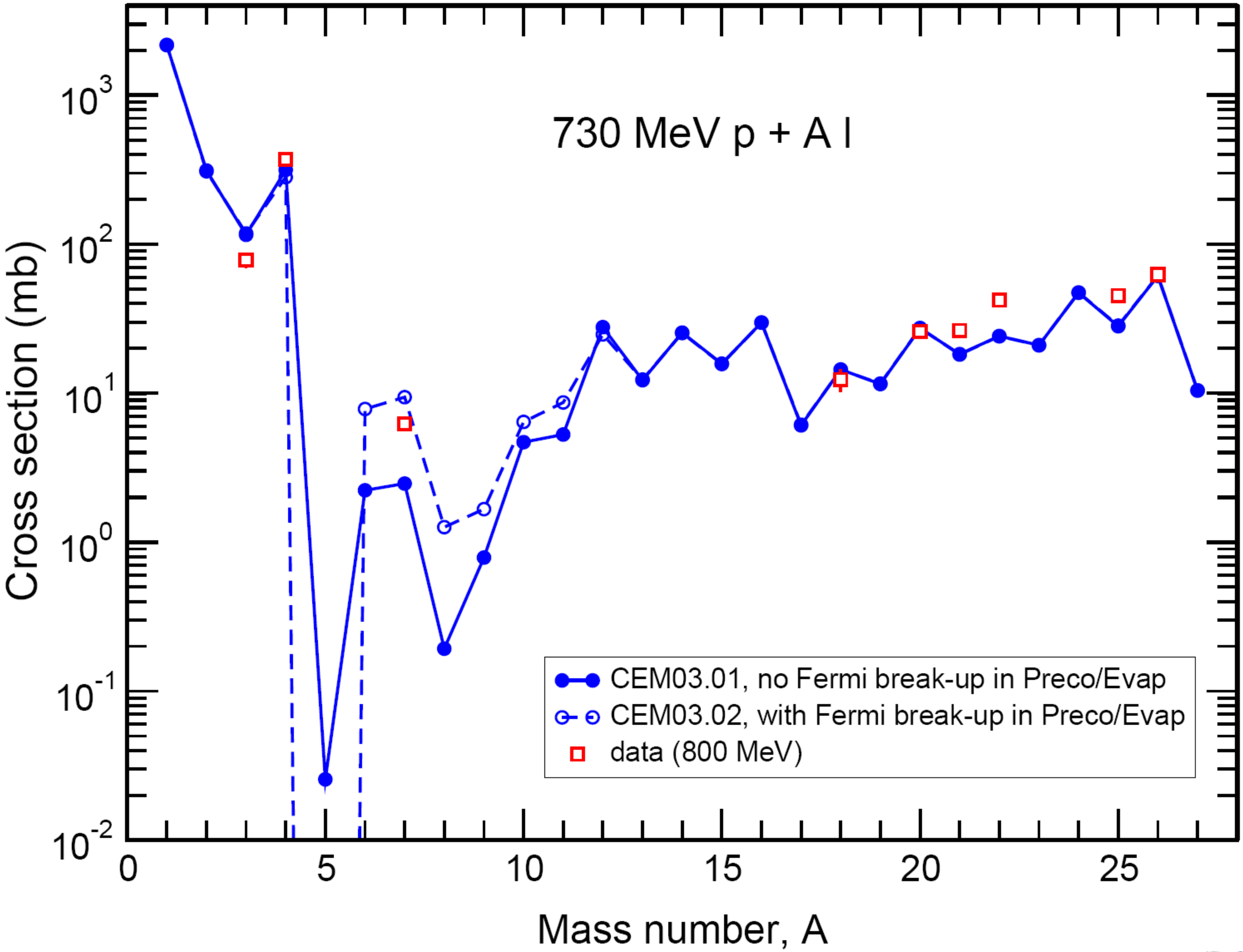
$$W(E,n) = (V/\Omega)^{n-1}\rho_n(E), \qquad E = U + M(A,Z), \qquad \Omega = (2\pi\hbar)^3$$

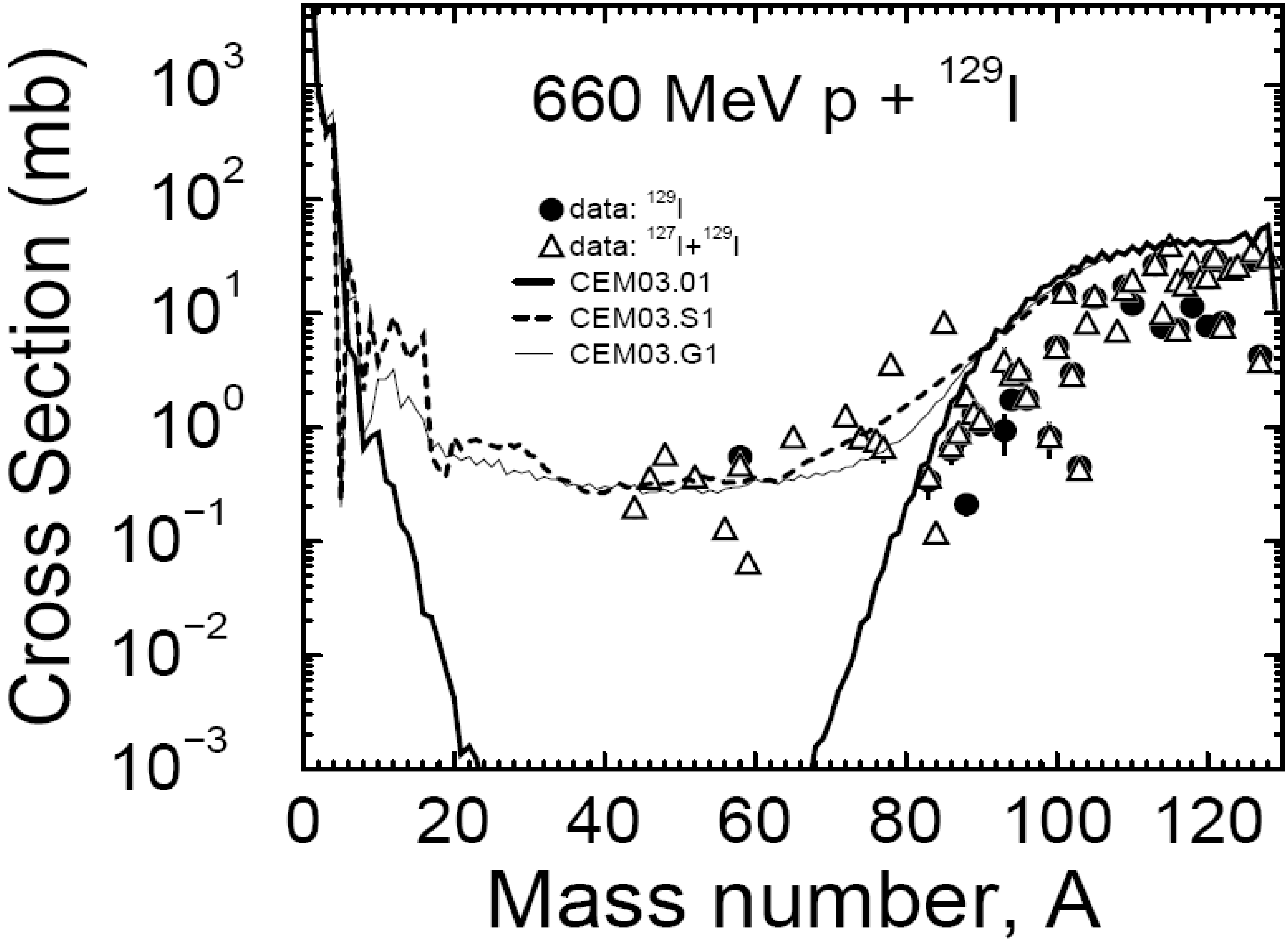
$$V = 4\pi R^3/3 = 4\pi r_0^3 A/3,$$

where r_0= 1.4 fm, is the only "free" parameter (fixed) of the model.

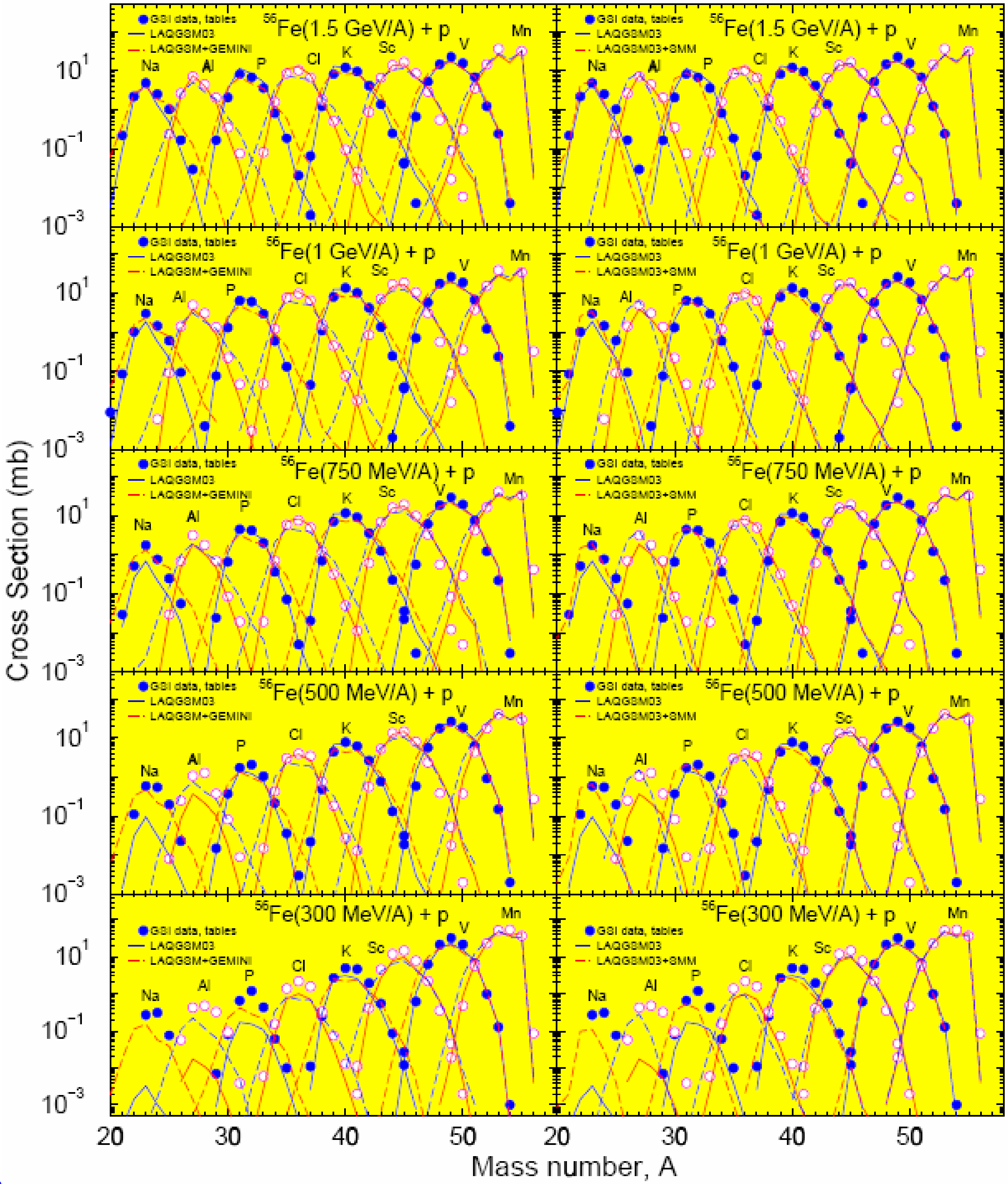
In comparison with its initial version [1] used in QGSM, in the initial version of LAQGSM, and in GEANT4 and SHIELD, we have modified the Fermi breakup model in the last ("03.02") versions of CEM and LAQGSM:

1) To decay some unstable light fragments like ^{5}He, ^{5}Li, ^{8}Be, ^{9}B, *etc.*, that were produced by the original Fermi breakup model;
2) Several bugs/uncertainties observed in the original version [1] were fixed; this solved the problem of the production of "nucleon stars" like "nuclides" xn and yp allowed by the original version;
3) We have incorporated the Fermi breakup model at the preequilibrium and evaporation stages of reactions (earlier, it was used only after the INC).


730 MeV p + Al
Cross section (mb)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
5
10
15
20
25
Mass number, A
CEM03.01, no Fermi break-up in Preco/Evap
CEM03.02, with Fermi break-up in Preco/Evap
data (800 MeV)



JINR data: J. Adam et al., Part. Nucl. Lett. **4** (2004) 53 (arXiv:nucl-ex/0403056)

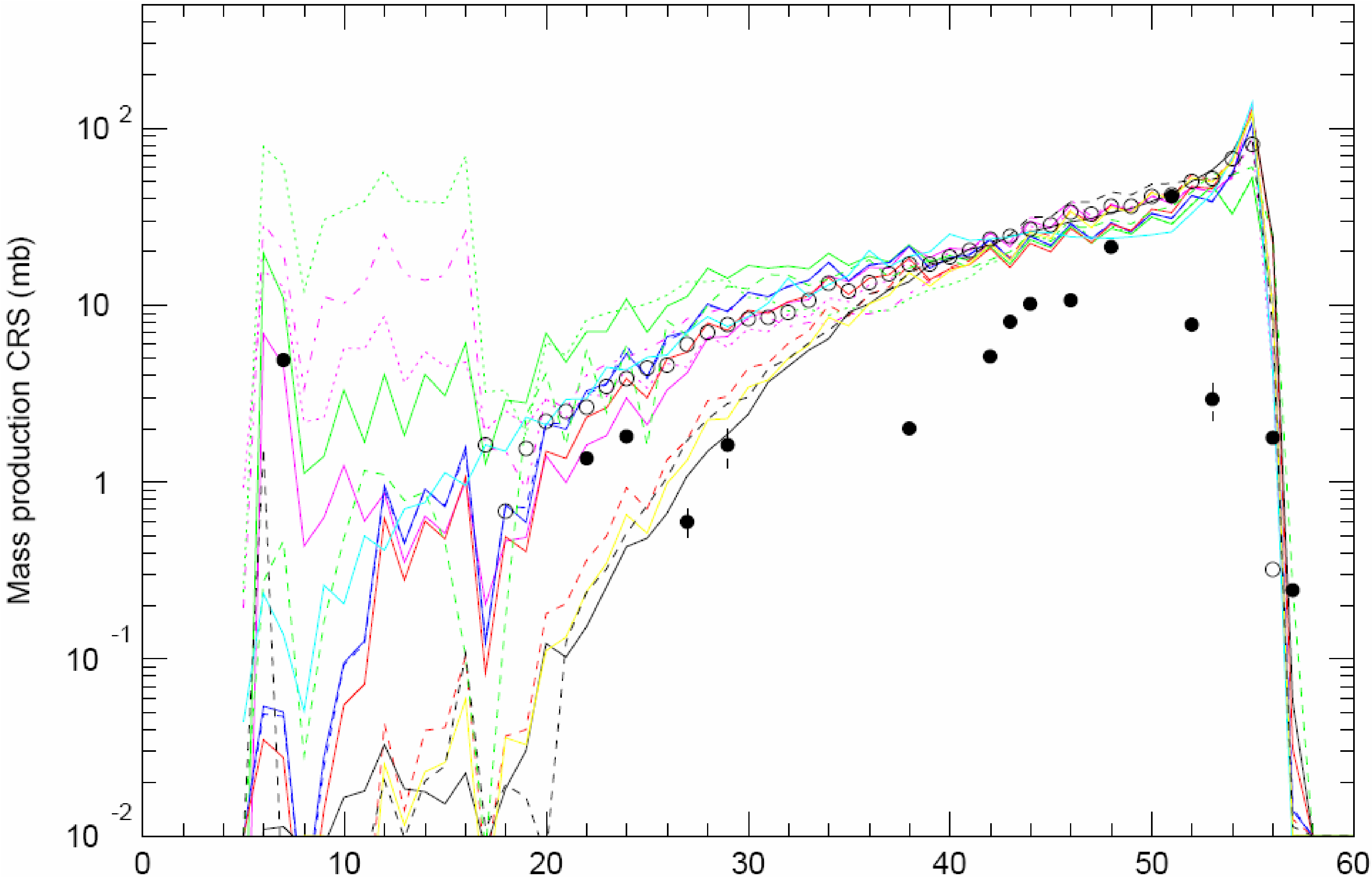


GIS data (circles) :
C. Villagrasa et al., Proc. ND2004, IIP Conf. Proc. 769 (2005) 842; PhD thesis, Universite de Paris XI, France, 2003.

To describe production of light fragments, we developed the G and S versions of our codes:

1) Using the fission-like binary-decay model GEMINI by R. Charity *et al.* ("G" stands for GEMINI);

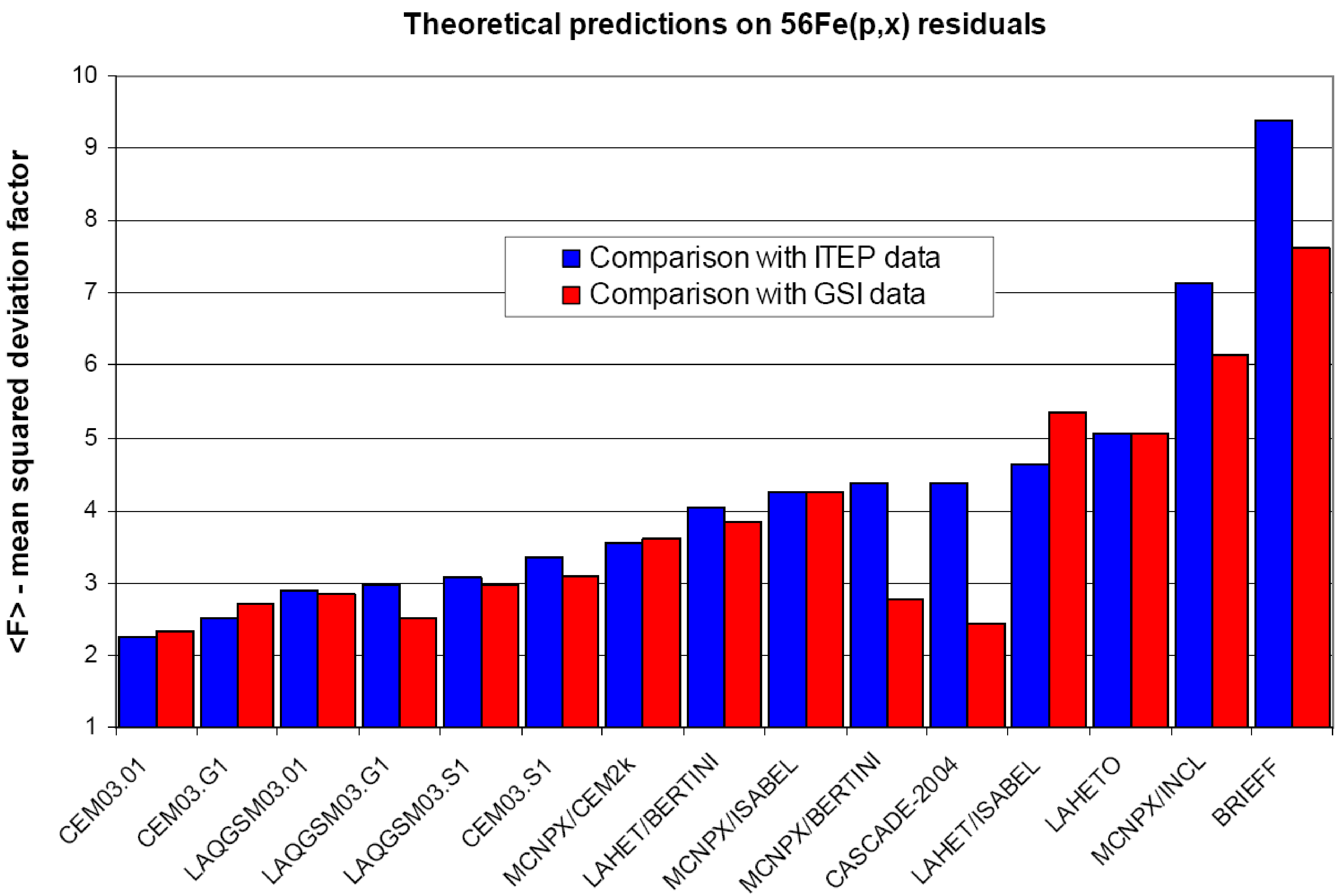
2) Using the Statistical Multifragmentation Model (SMM) by A. Botvina *et al.* ("S" stands for SMM)



1.5 GeV p + ^{56}Fe:

GIS data (open circles) : C. Villagrasa et al., Proc. ND2004, IIP Conf. Proc. 769 (2005) 842-845; PhD thesis, Universite de Paris XI, France, December 2003, http://www-w2k.gsi.de/charms/theses.htm

ITEP data (filled circles): ISTC Project # 3266, Yu. E. Titarenko et al., LA-UR-06-4098, presented at NN2006, Rio de Janeiro, Brazil, Aug 28 – Sep 1, 2006, and to be published and data to be included into the EXFOR data base


Theoretical predictions on 56Fe(p,x) residuals
<F> - mean squared deviation factor
10
9
8
7
6
5
4
3
2
1
Comparison with ITEP data
Comparison with GSI data
CEM03.01
CEM03.G1
LAQGSM03.01
LAQGSM03.G1
LAQGSM03.S1
CEM03.S1
MCNPX/CEM2k
LAHET/BERTINI
MCNPX/ISABEL
MCNPX/BERTINI
CASCADE-2004
LAHET/ISABEL
LAHETO
MCNPX/INCL
BRIEFF

PHYSICAL REVIEW C **76**, 014609 (2007)

Projectile fragmentation of ^{86}Kr at 64 MeV/nucleon

M. Mocko,[1,2,*] M. B. Tsang,[1,2] Z. Y. Sun,[3] N. Aoi,[4] J. M. Cook,[1,2] F. Delaunay,[1] M. A. Famiano,[1] H. Hui,[1] N. Imai,[4] H. Iwasaki,[5] W. G. Lynch,[1,2] T. Motobayashi,[4] M. Niikura,[6] T. Onishi,[5] A. M. Rogers,[1,2] H. Sakurai,[5] A. Stolz,[1] H. Suzuki,[5] E. Takeshita,[7] S. Takeuchi,[4] and M. S. Wallace[1,2]

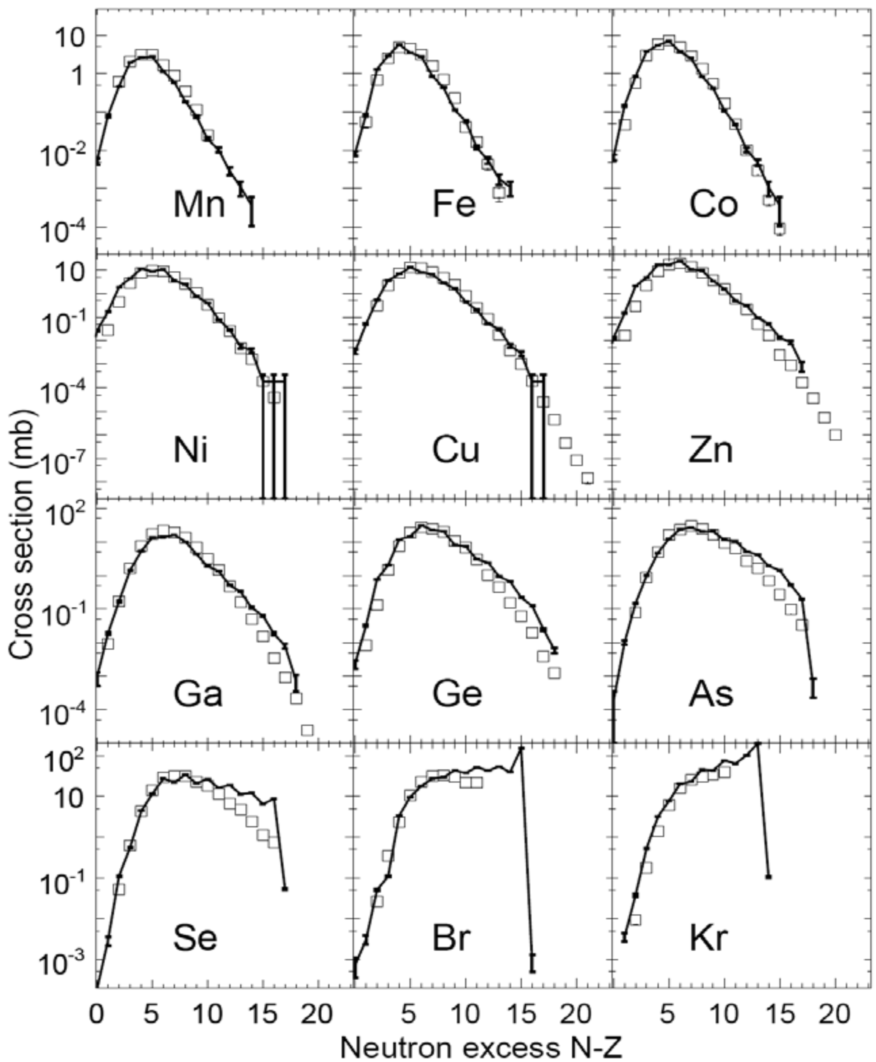


Figure 9: Experimental data for ^{86}Kr+^{9}Be reactions compared to LAQGSM model.

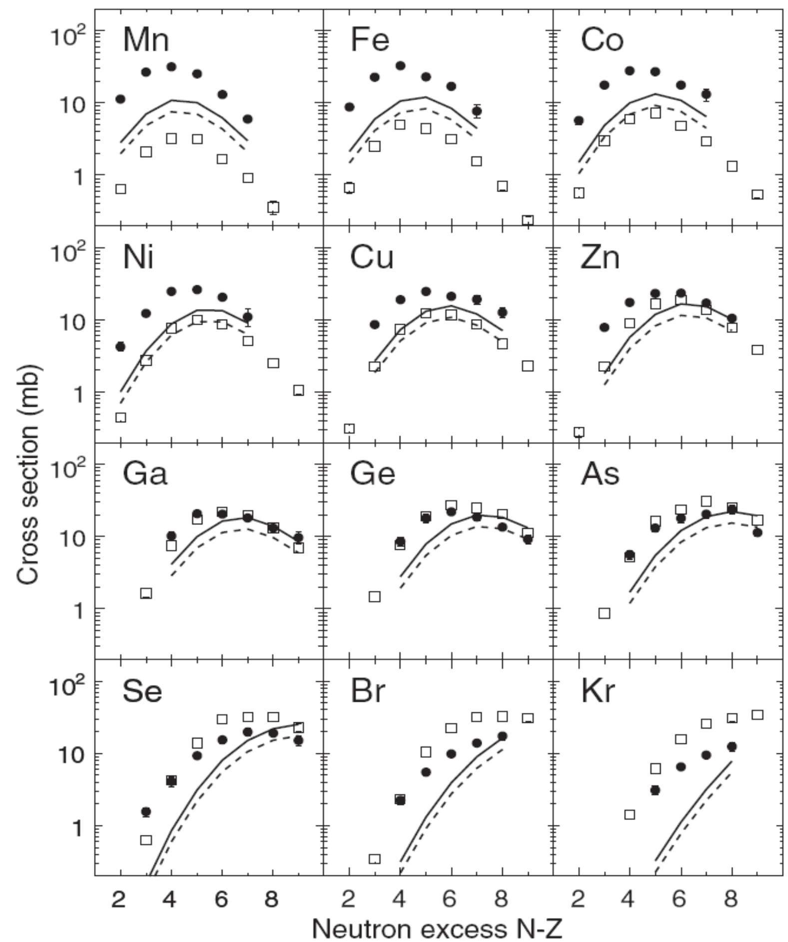
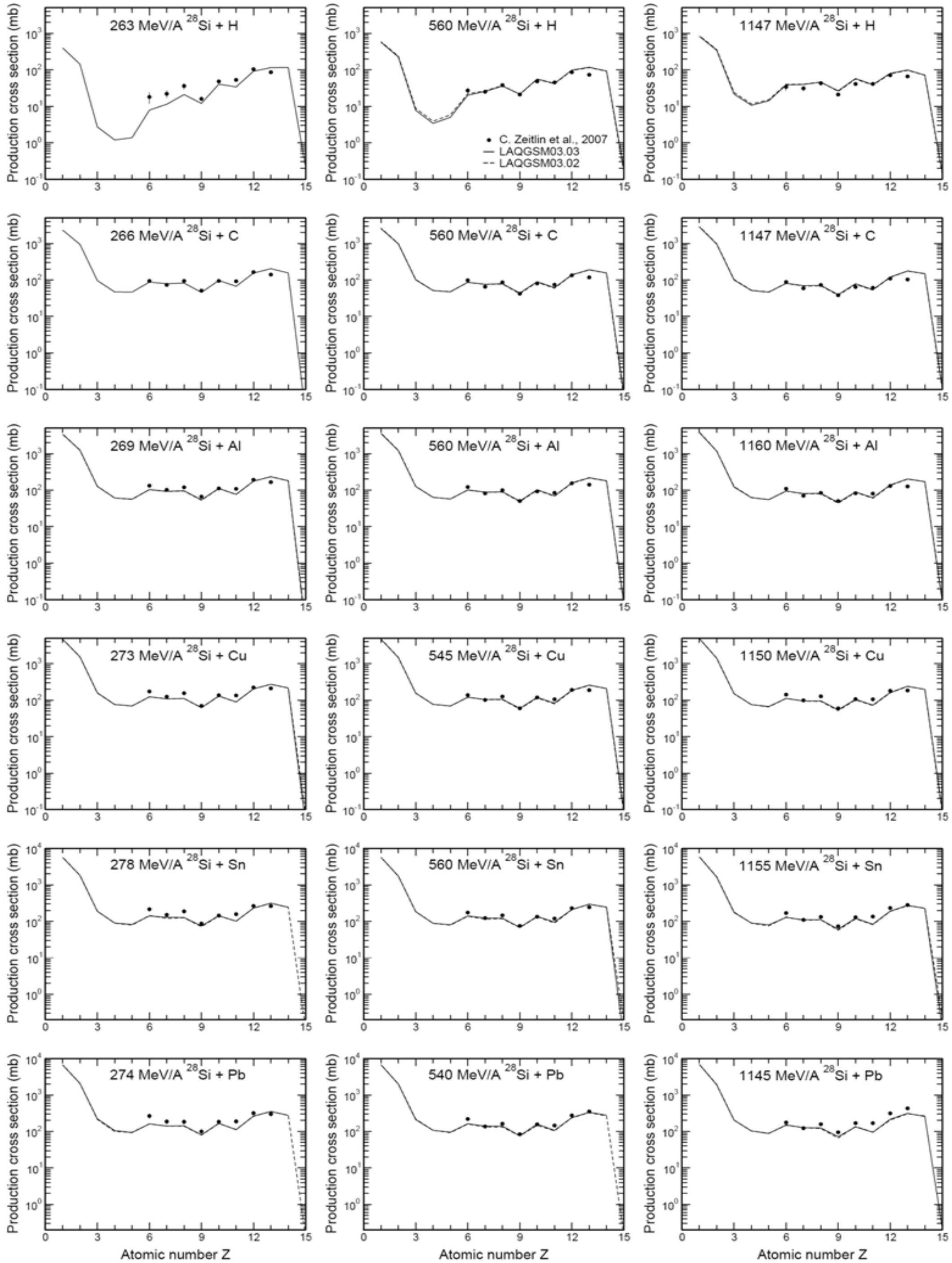
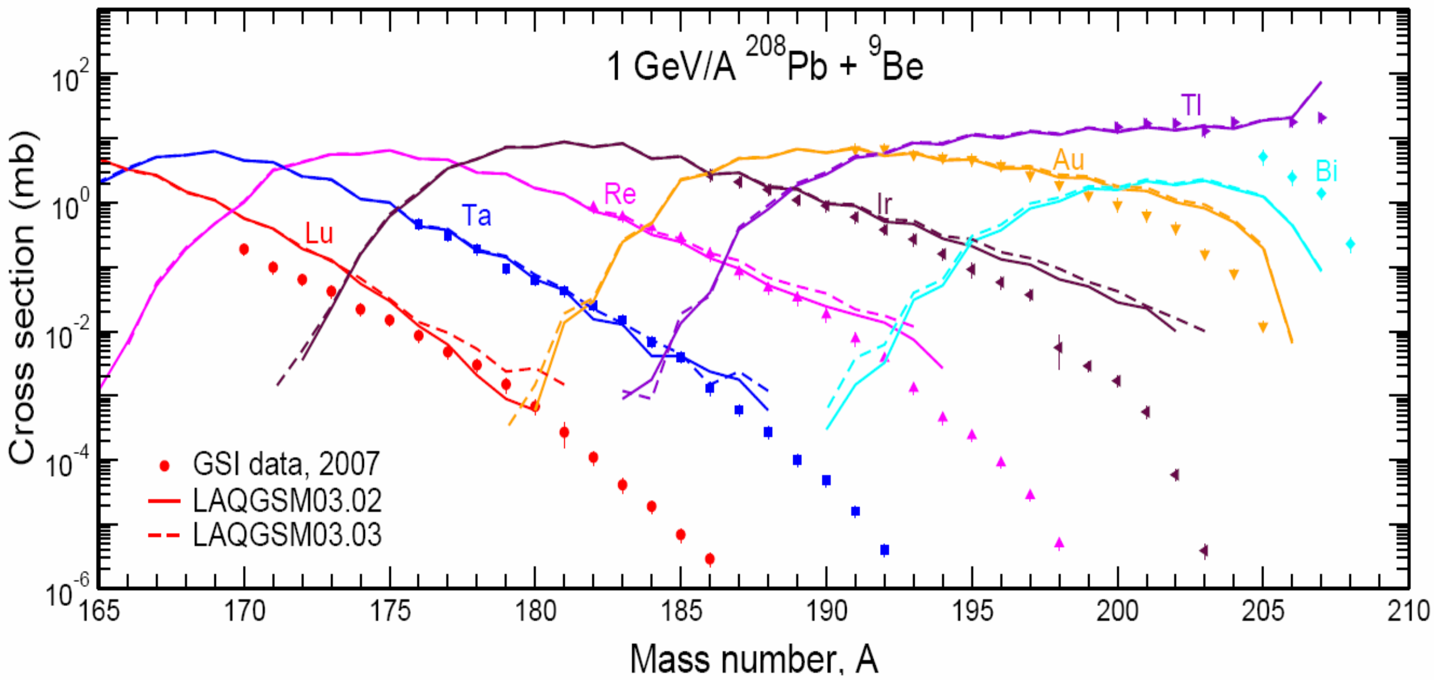


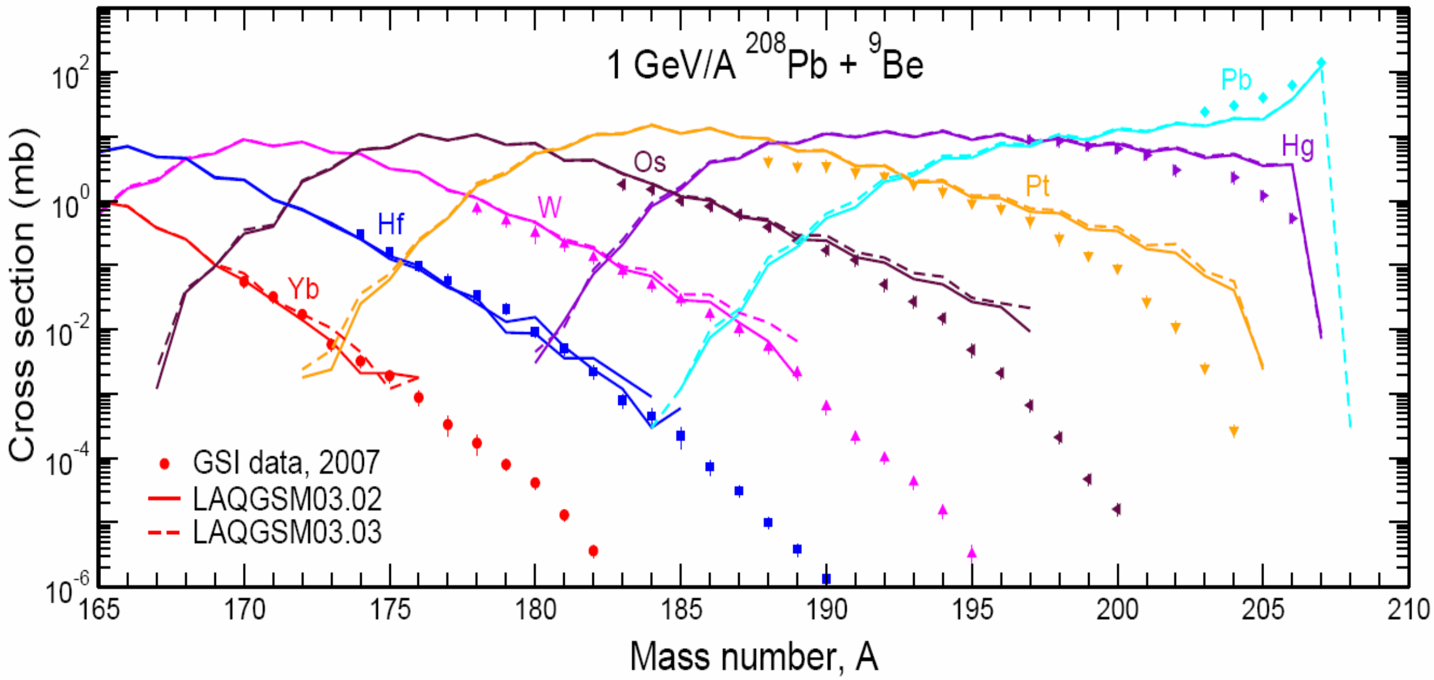
FIG. 8. Measured cross sections presented as isotope distributions for $25 \leqslant Z \leqslant 36$ elements detected in the ^{86}Kr+^{181}Ta reactions (filled circles) and in the ^{86}Kr+^{9}Be reactions (open squares) at 64 MeV/nucleon. EPAX calculations are shown as dashed (^{86}Kr+^{9}Be) and solid (^{86}Kr+^{181}Ta) curves.



Data (symbols):

C. Zeitlin *et al.*,
Nucl. Phys. A784 (2007) 341

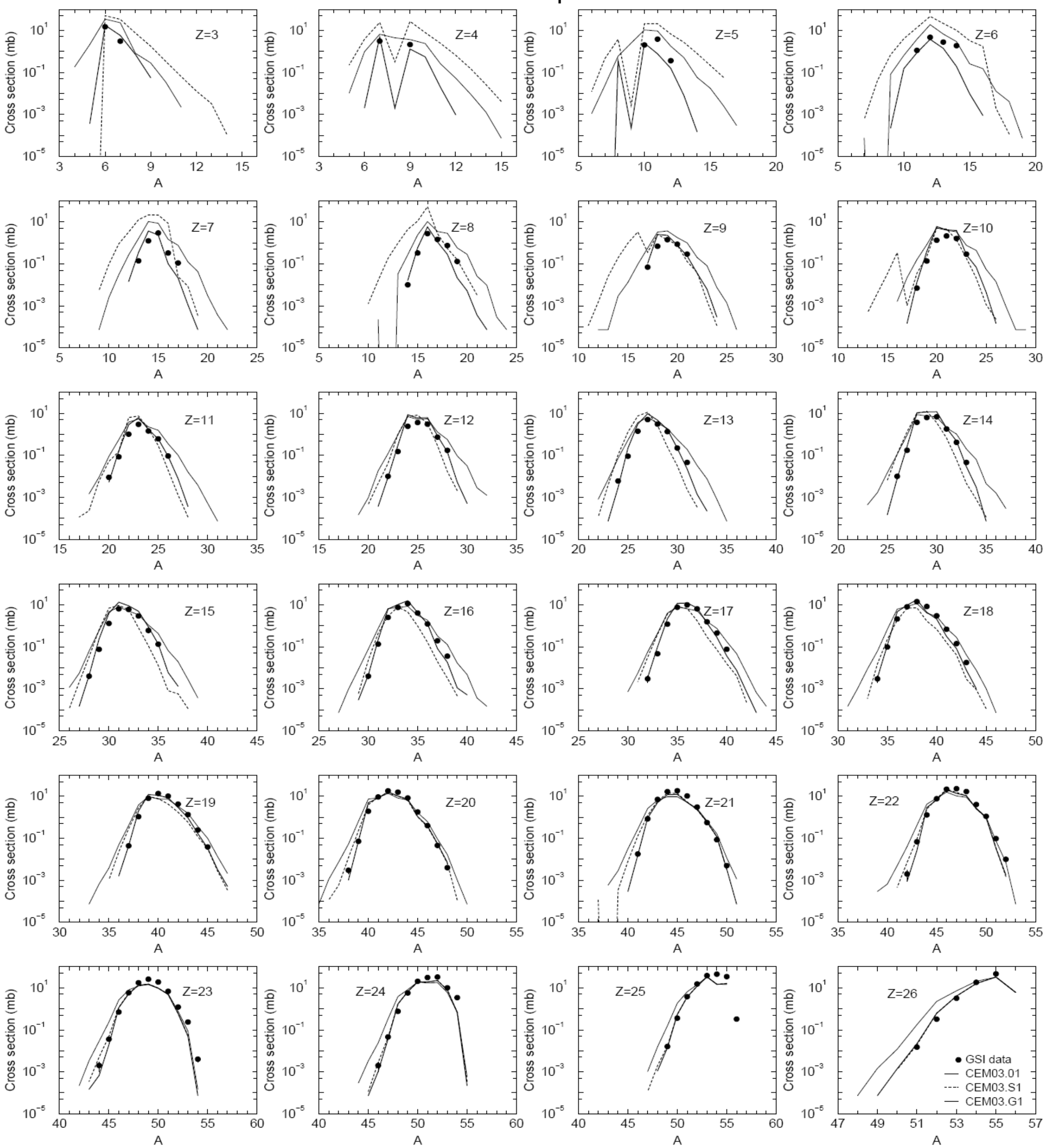




GSI data (symbols):

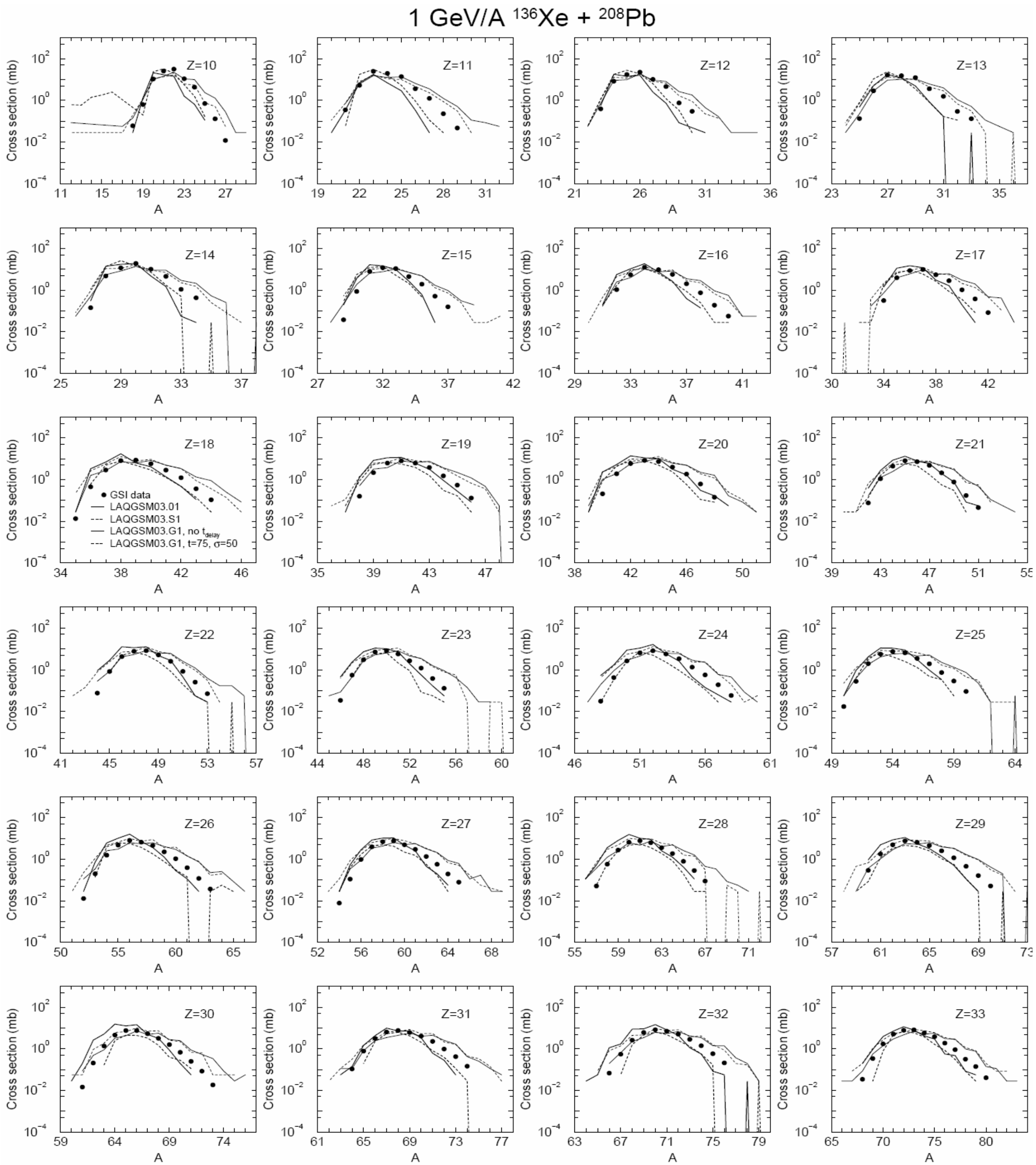
Teresa Kurtukian Nieto, PhD thesis, University of Santiago de Compostela, Spain, March 18, 2007; http://www-w2k.gsi.de/charms/theses.htm

1000 MeV p + ^{56}Fe



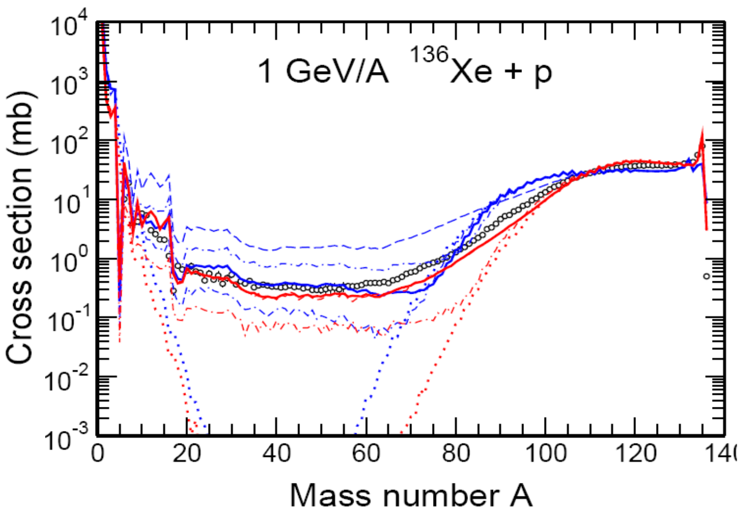
GSI data (symbols):

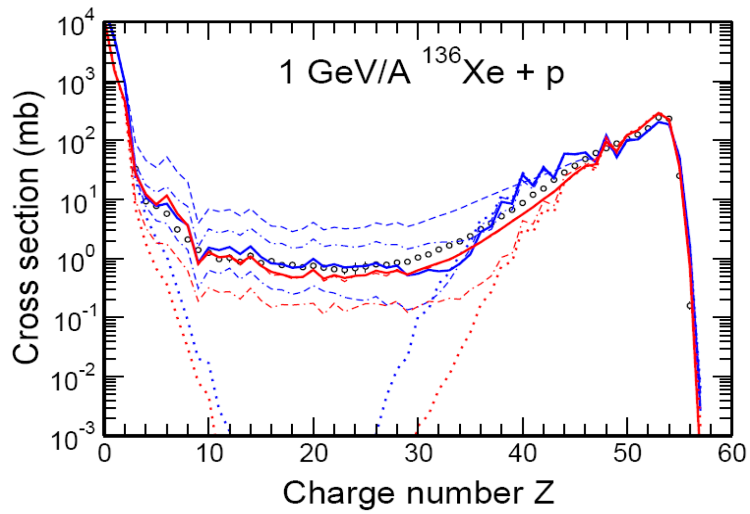
Carmen Villagrasa-Canton,
PhD thesis, Universite de Paris XI, France, December 2003;
Paolo Napolitani,
PhD thesis, Université Paris XI, France, September 2004;
http://www-w2k.gsi.de/charms/theses.htm
Phys. Rev. C 70 (2004) 054607;
Phys. Rev. C75 (2007) 044603

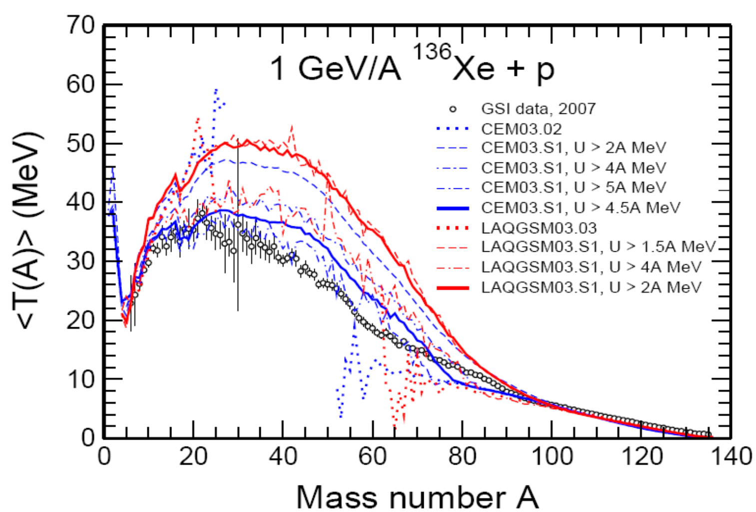


GSI data (symbols):

Daniela Henzlova ,
PhD thesis, Czech Technical University Prague, Faculty of Nuclear Science and Physical Engineering, Czech Republic, March 2006
http://www-w2k.gsi.de/charms/theses.htm

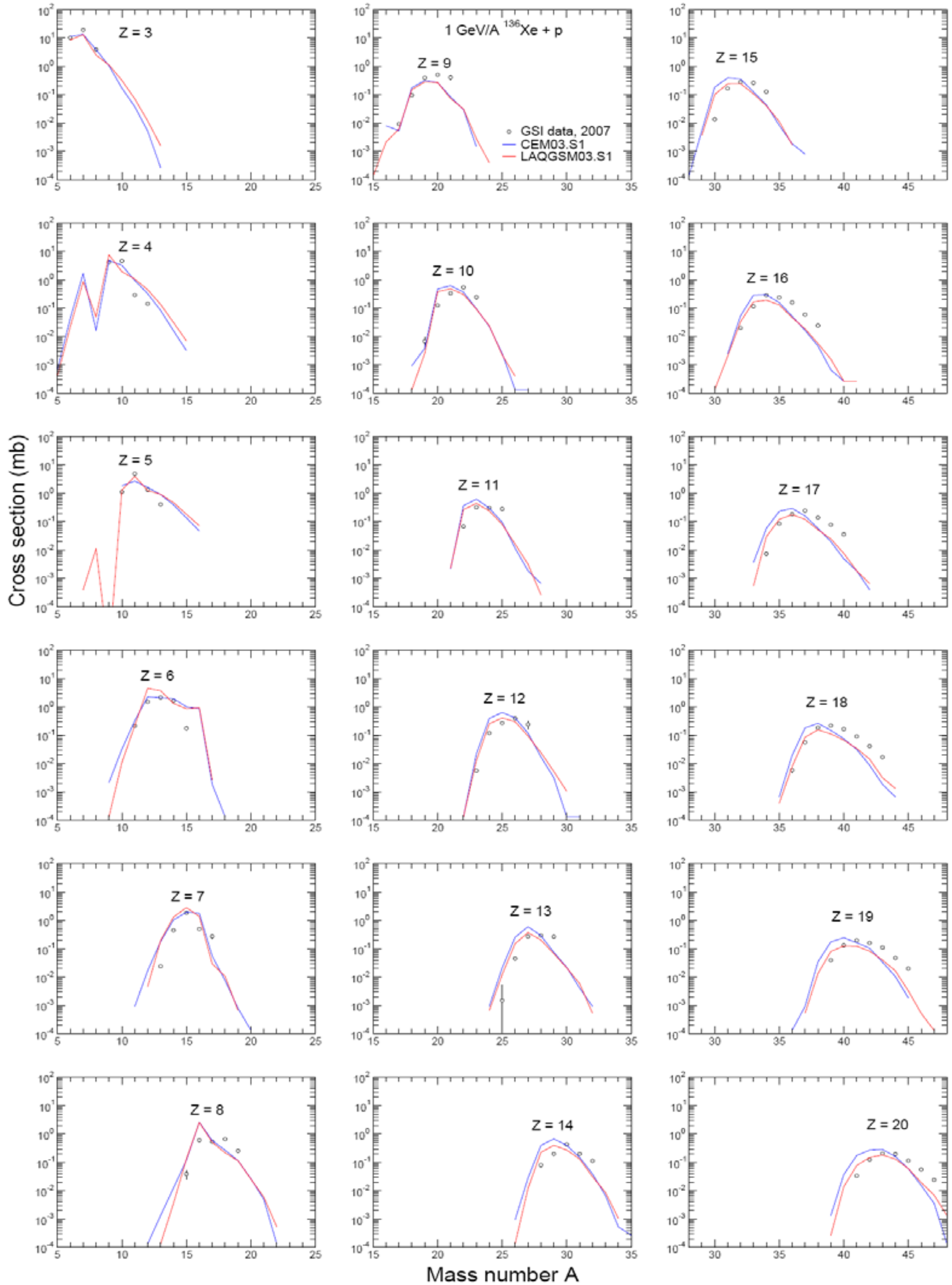






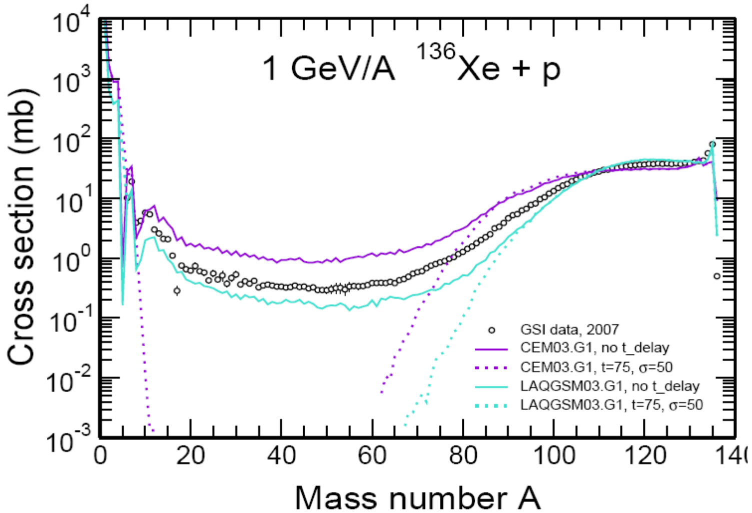
GSI data (symbols):

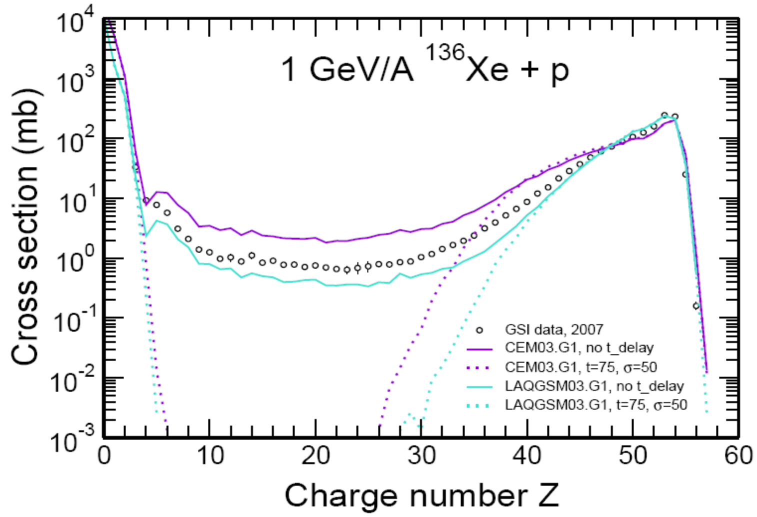
P. Napolitani *et al.*,
arXiv:0706.064v1
[nucl-ex] 5 Jul 2007

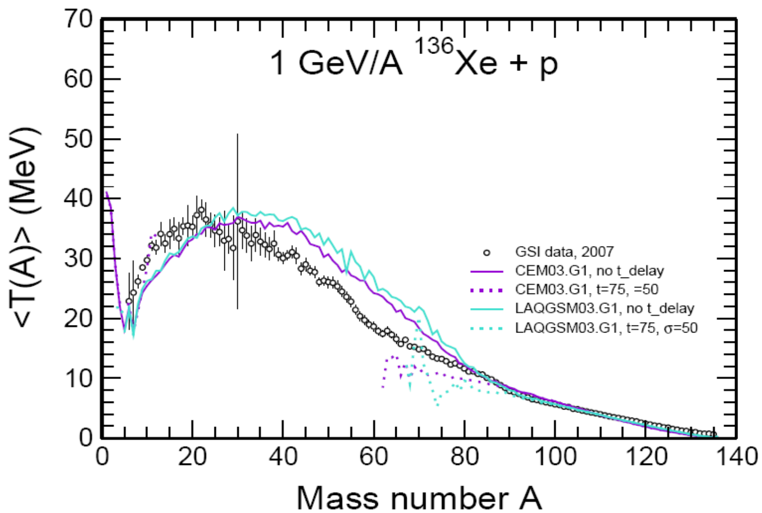


GSI data (symbols):

P. Napolitani *et al.*,
arXiv:0706.064v1
[nucl-ex] 5 Jul 2007







GSI data (symbols):

P. Napolitani *et al.*,
arXiv:0706.064v1
[nucl-ex] 5 Jul 2007

Summary

- CEM03.02 and LAQGSM03.02(03) and their "S" and "G" versions describe various nuclear reactions much better than their precursors
- CEM03.01 is available now to users from Oak Ridge as the RSICC code package PSR-532, RSICC package id: P00532MNYCP00
- CEM03.01 and LAQGSM03.01 are being (were) incorporated into MCNP6, MCNPX, and MARS15, to be available to users from RSICC
- However, there are still many problems to be solved ...

- **Thank you for your attention !**

Thank the NUFRA2007 Organizers for inviting me to present this talk and for financial support !

Back up slides

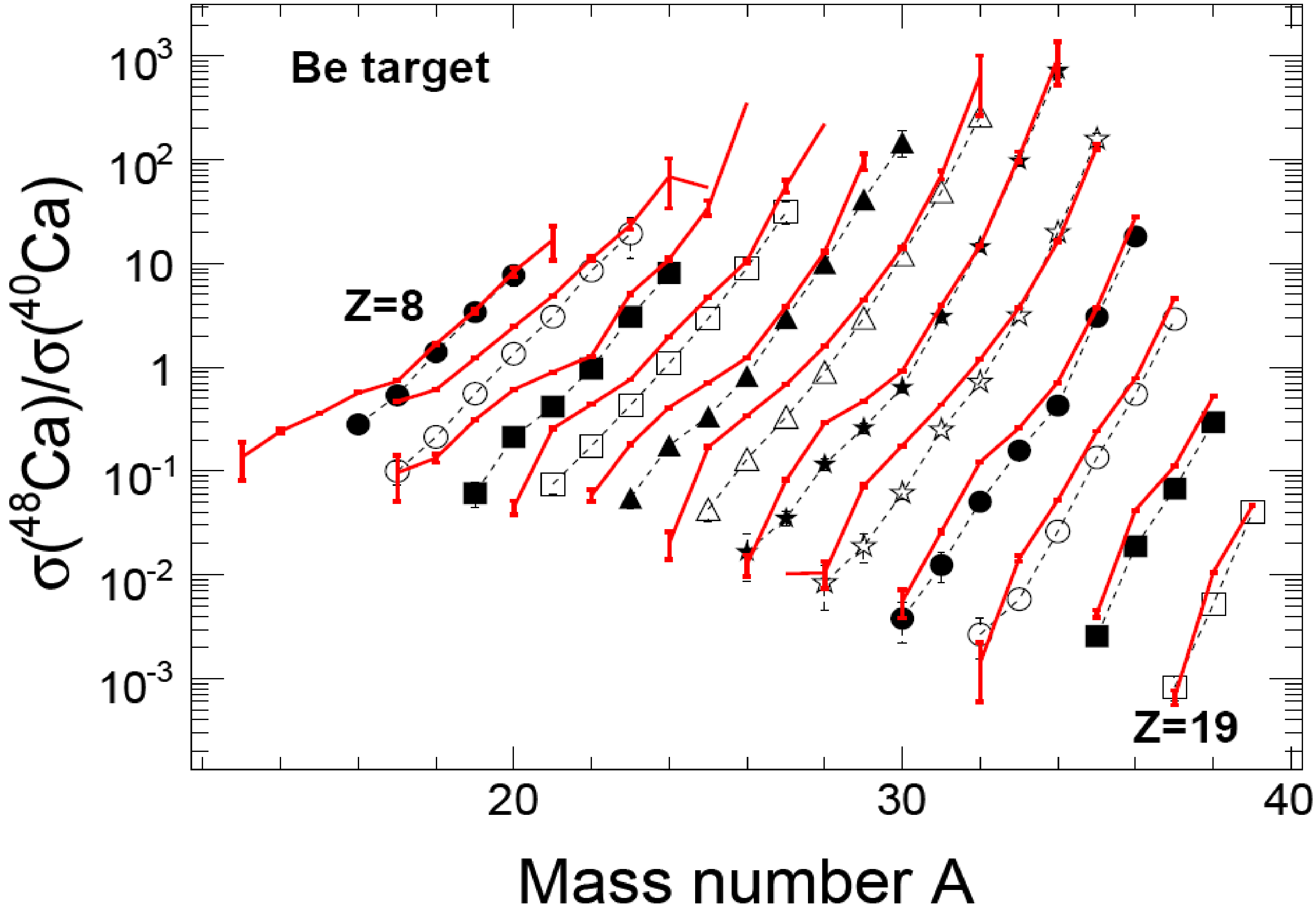
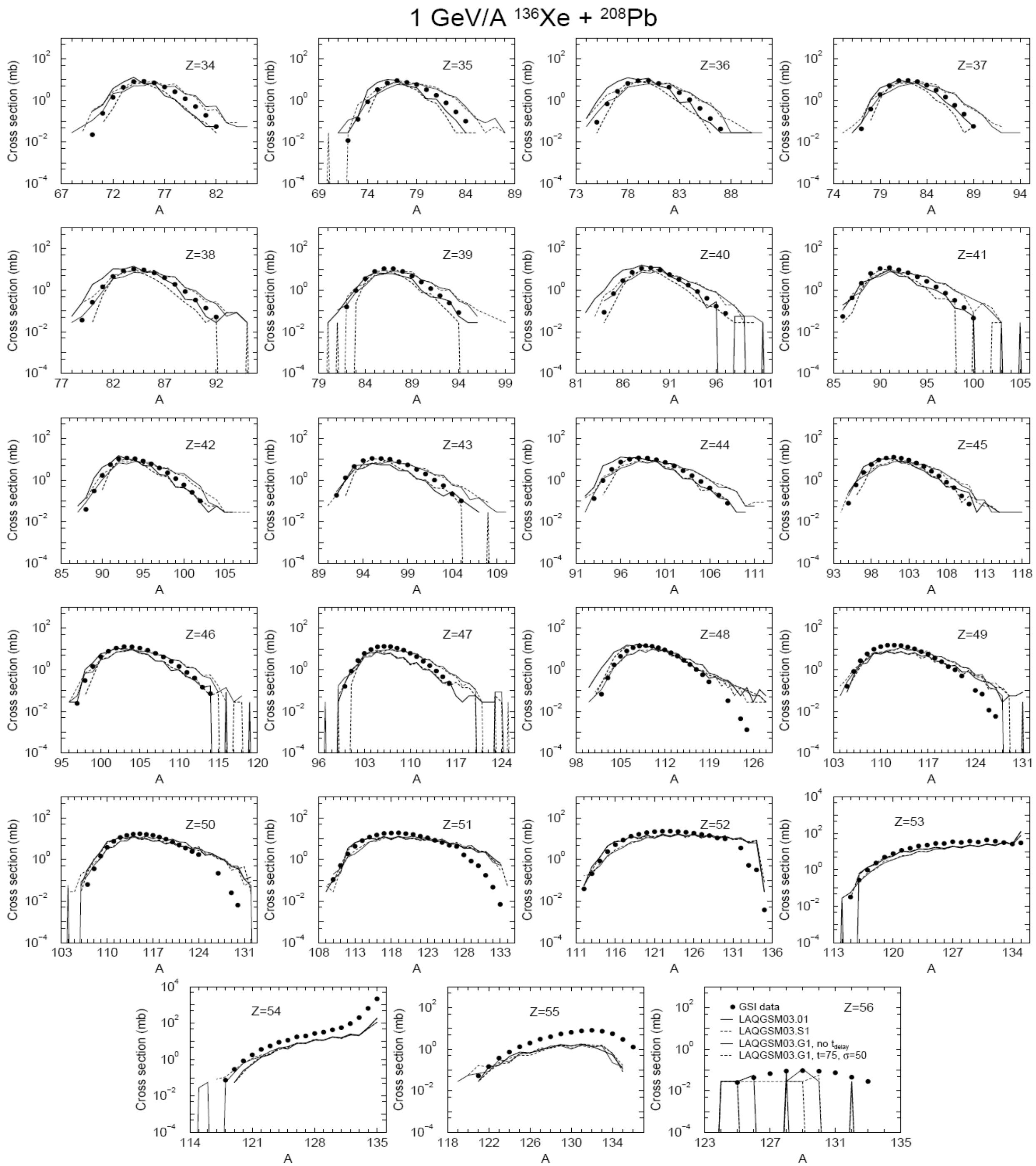


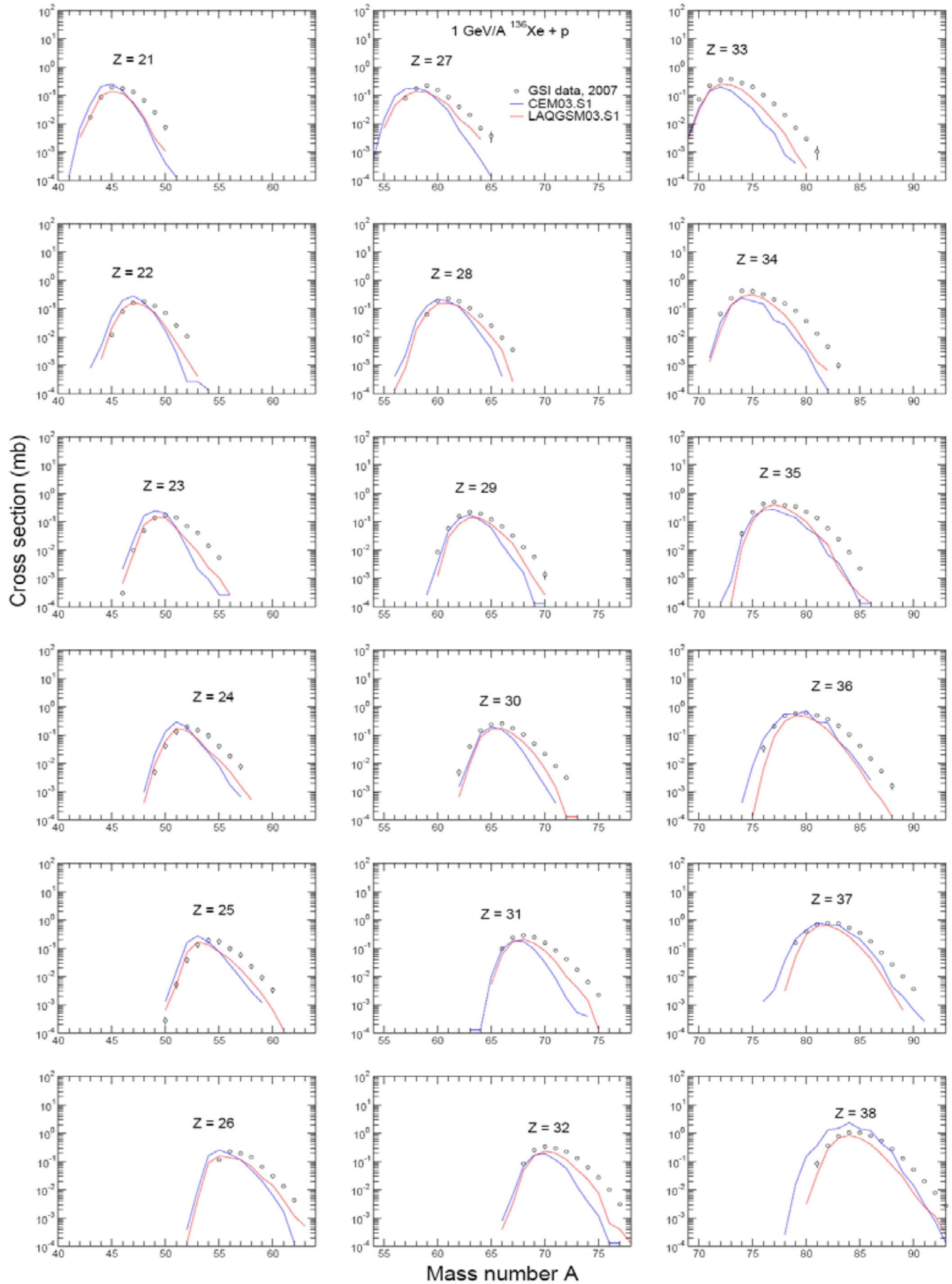
Figure 16: Projectile ratios for the CaBe reaction systems. Data are depicted as markers and the LAQGSM calculation as a red line.

Data: 140 MeV/A ^{48}Ca and ^{40}Ca + Be, M. Mocko *et al.*, Phys. Rev. C74 (2006) 054612



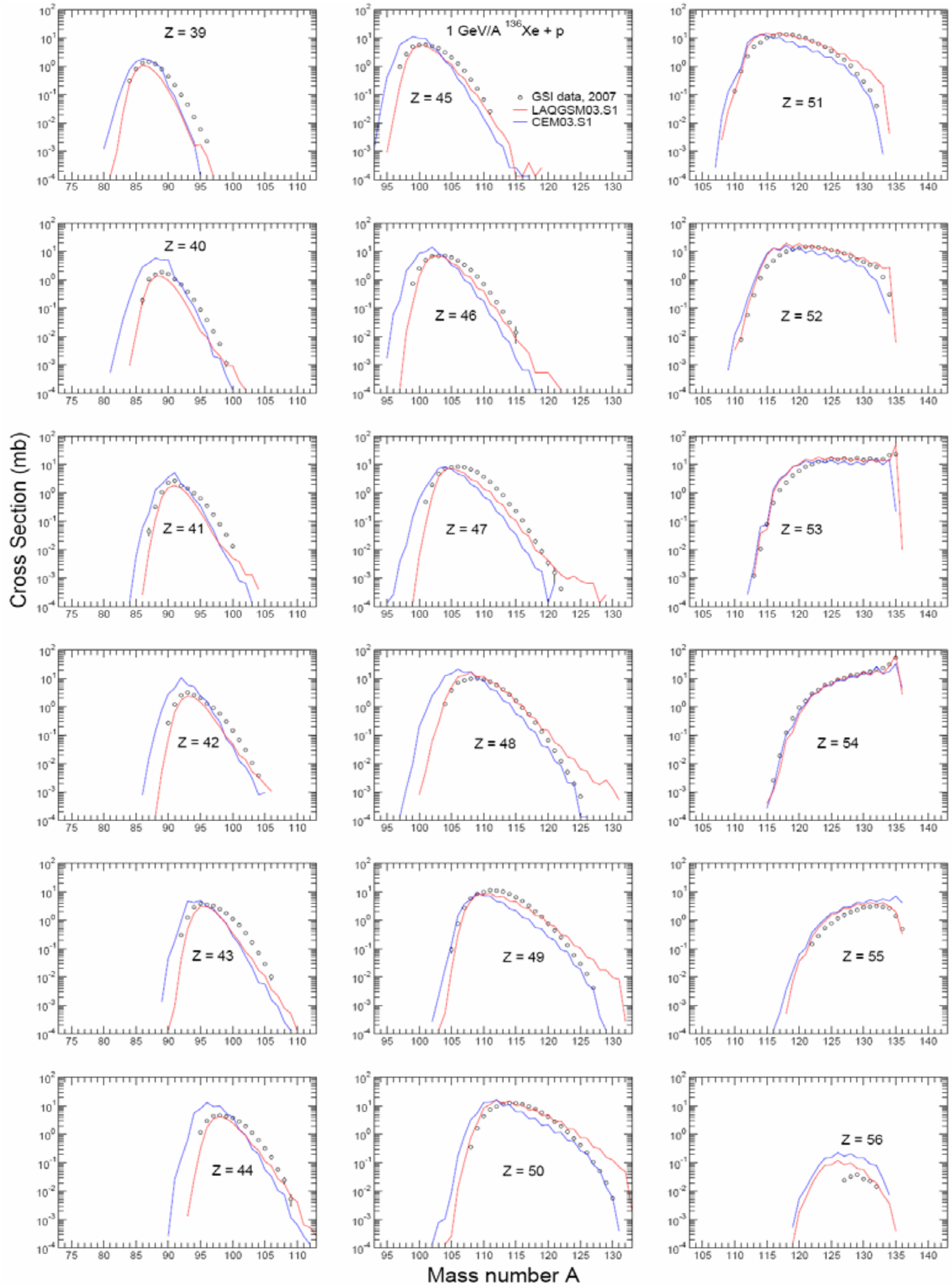
GSI data (symbols):

Daniela Henzlova ,
PhD thesis, Czech Technical University Prague, Faculty of Nuclear Science and Physical Engineering, Czech Republic, March 2006
http://www-w2k.gsi.de/charms/theses.htm



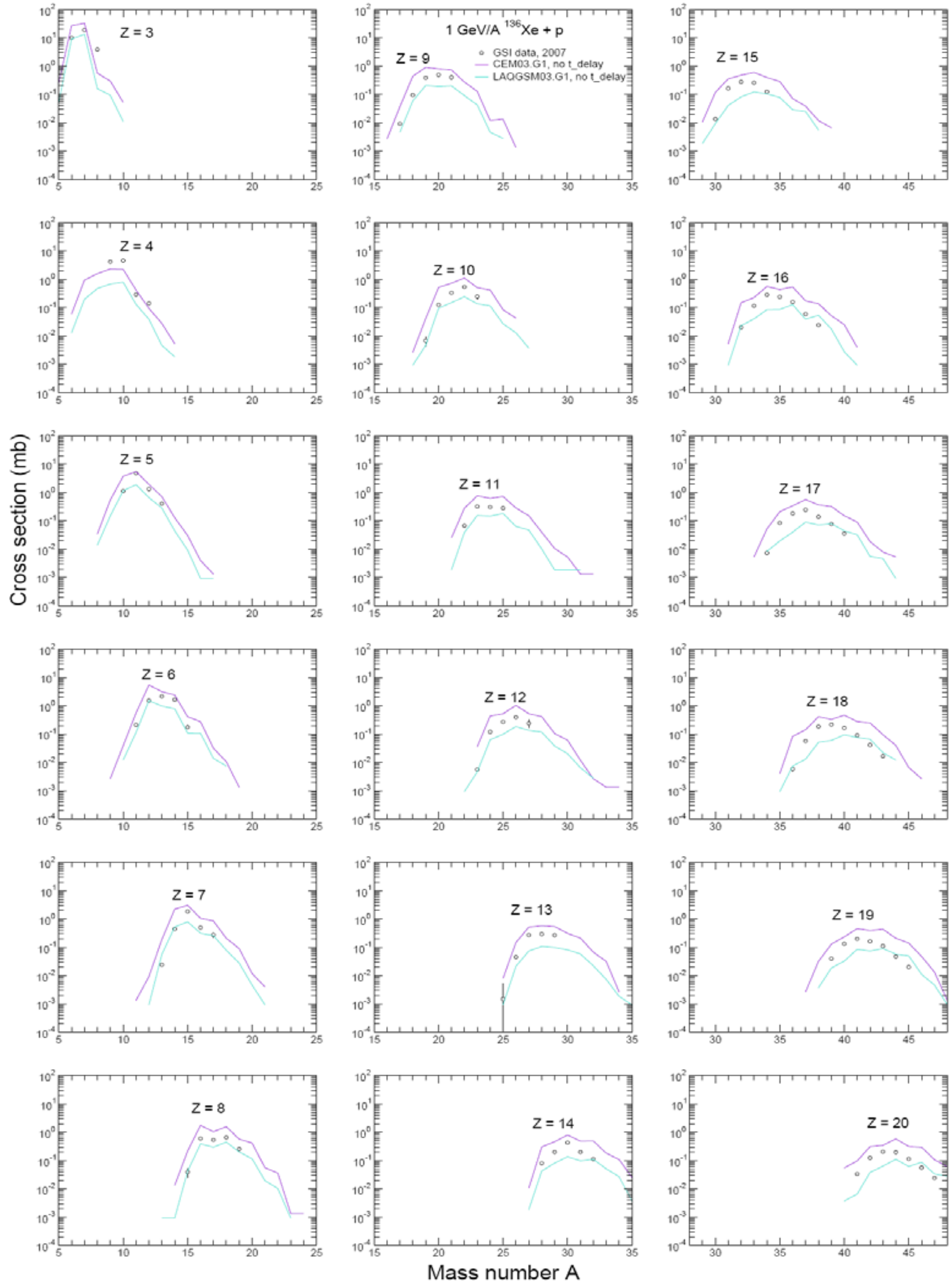
GSI data (symbols):

P. Napolitani *et al.*,
arXiv:0706.064v1
[nucl-ex] 5 Jul 2007



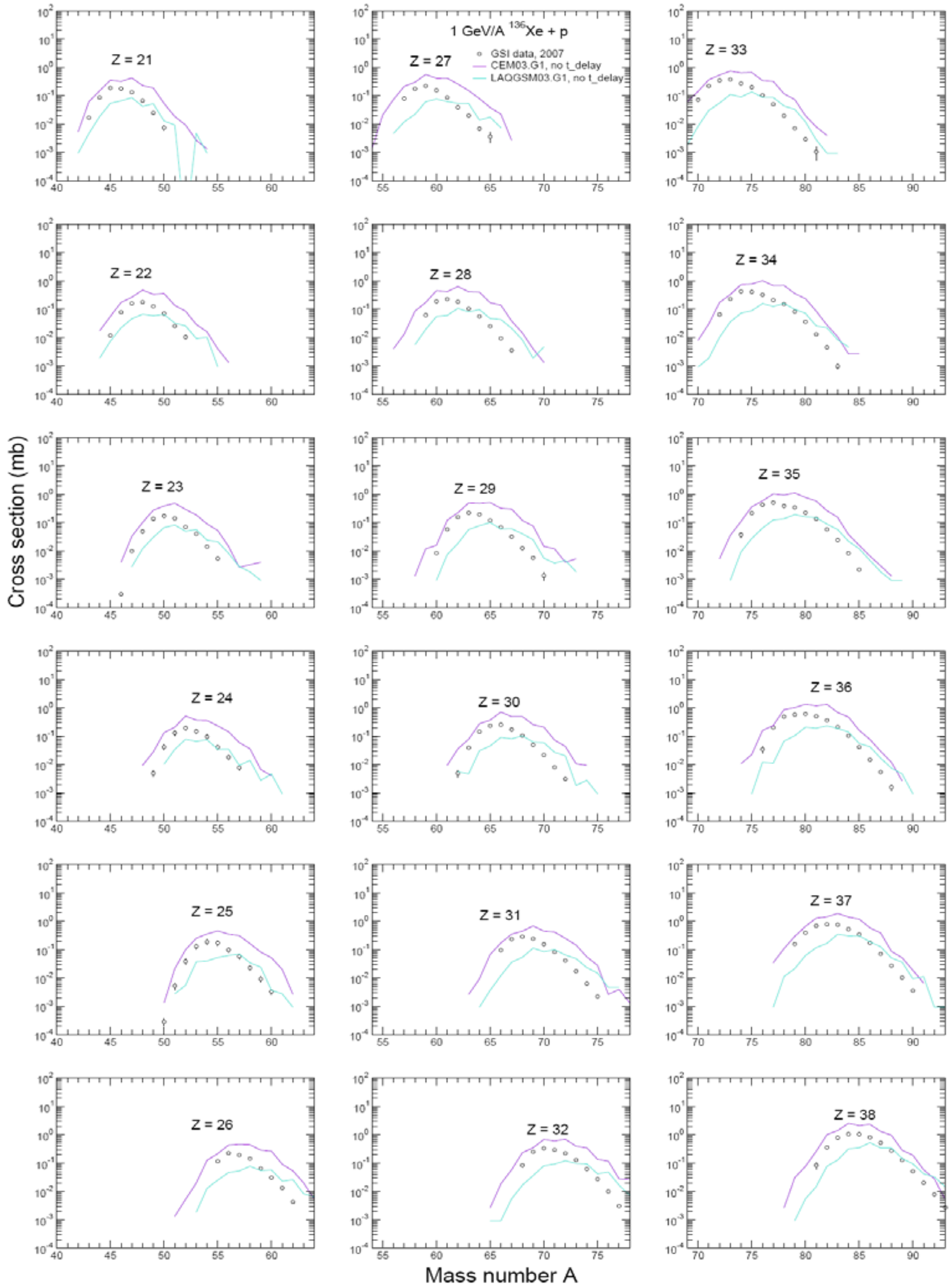
GSI data (symbols):

P. Napolitani *et al.*, arXiv:0706.064v1 [nucl-ex] 5 Jul 2007



GSI data (symbols):

P. Napolitani *et al.*,
arXiv:0706.064v1
[nucl-ex] 5 Jul 2007



GSI data (symbols):

P. Napolitani *et al.*,
arXiv:0706.064v1
[nucl-ex] 5 Jul 2007

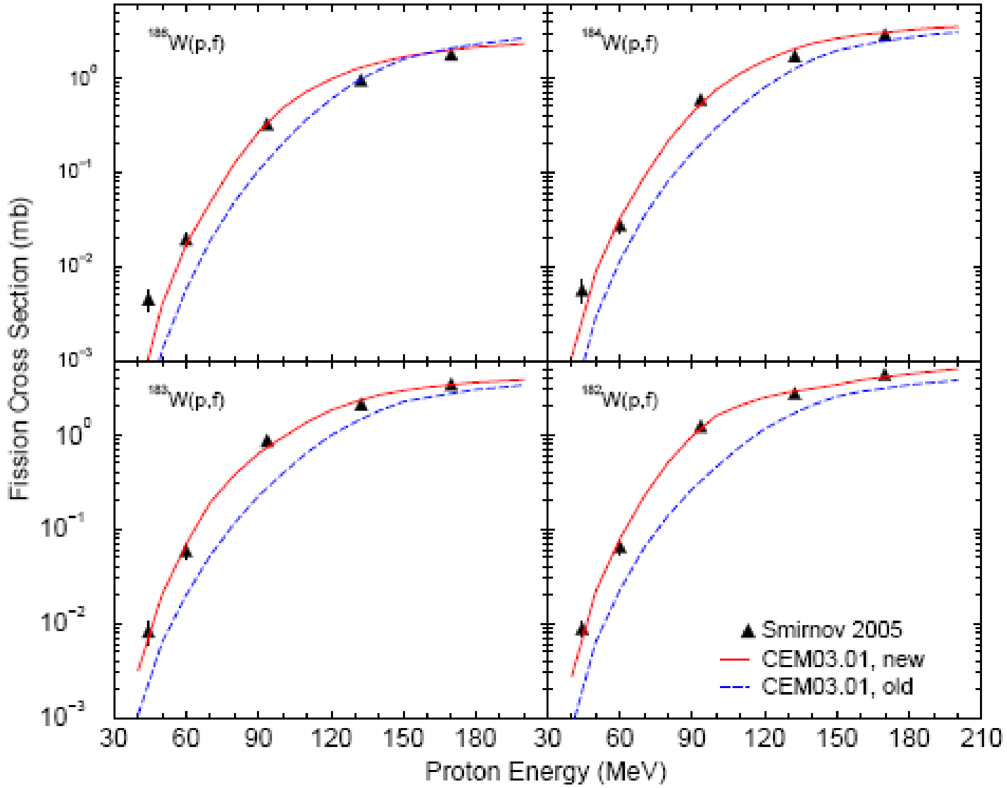


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Figure 3. Experimental [31] proton-induced fission cross sections of ^{186}W, ^{184}W, ^{183}W, and ^{182}W compared with improved (red solid lines) and old (blue dashed lines, from [31]) CEM03.01 calculations.

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Projectile fragmentation of ^{40}Ca, ^{48}Ca, ^{58}Ni, and ^{64}Ni at 140 MeV/nucleon

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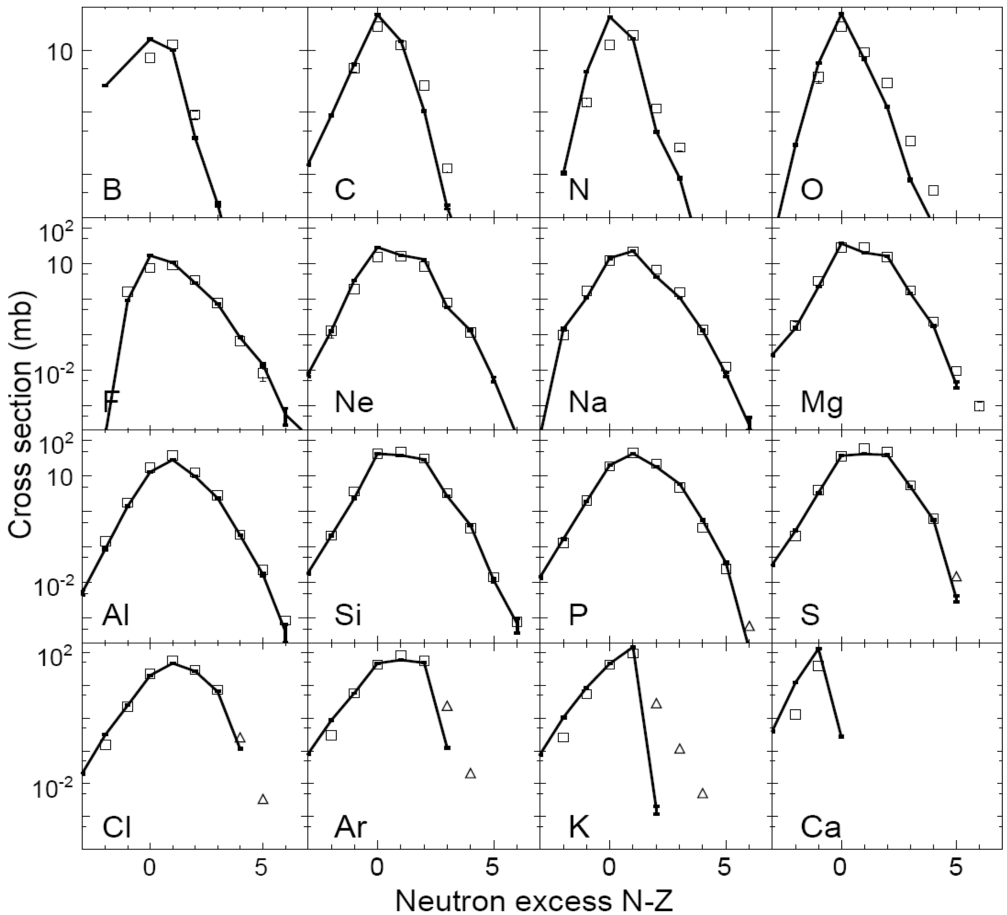


Figure 1: Experimental data for ^{40}Ca+^{9}Be reactions compared to LAQGSM model.

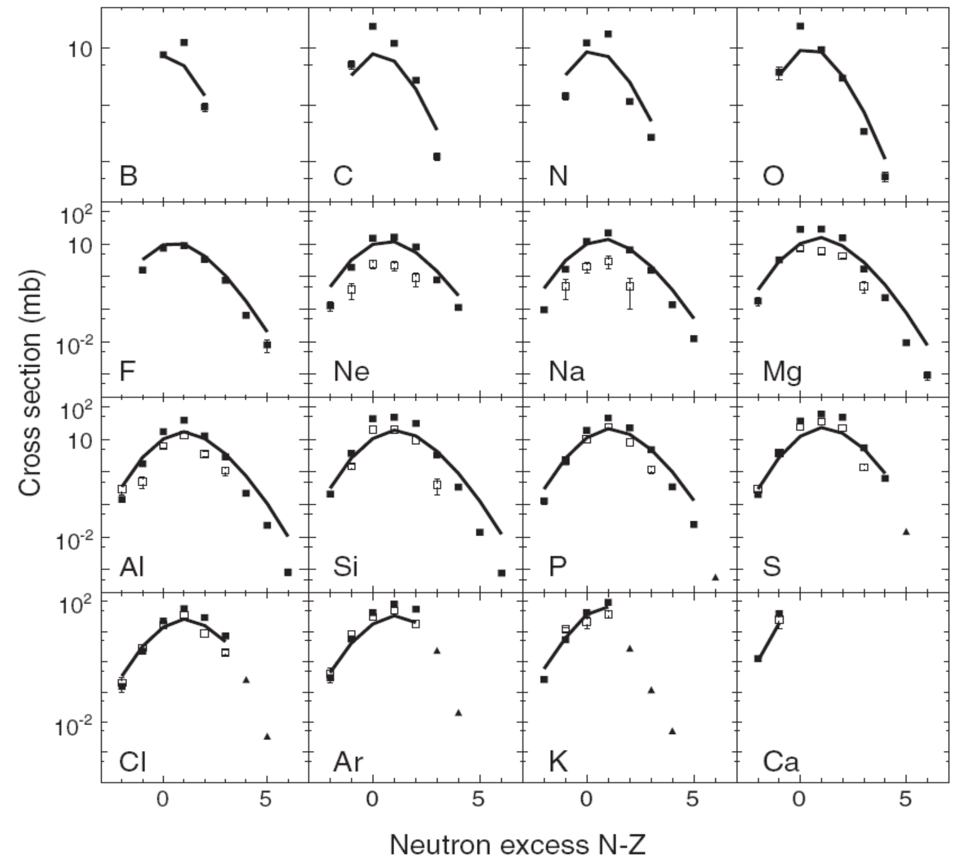
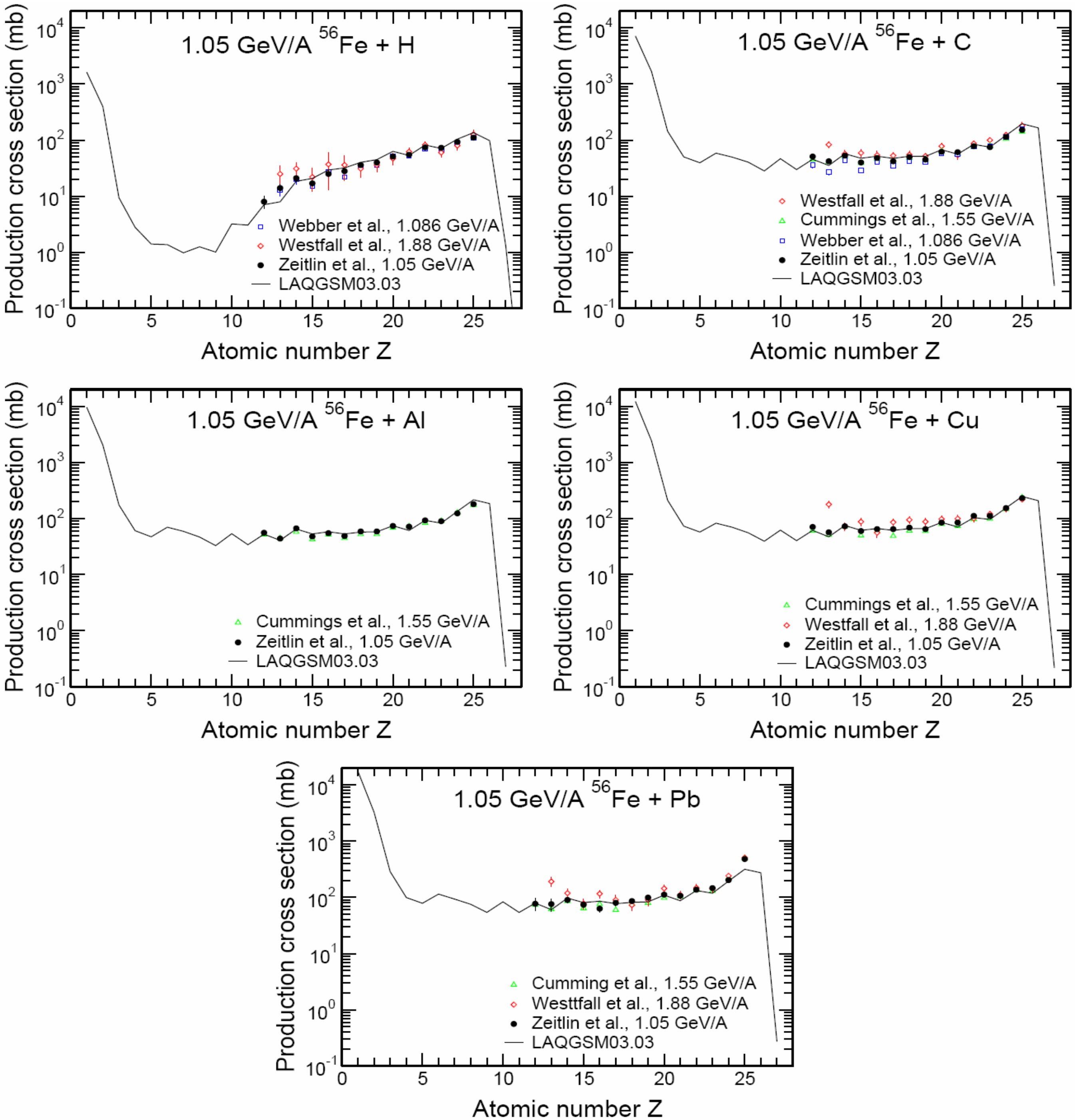


FIG. 6. Measured cross-sections presented as isotope distributions for $5 \leqslant Z \leqslant 20$ elements detected in ^{40}Ca+^{9}Be reactions at 140 MeV/nucleon. Experimental fragmentation data are shown as filled squares. Filled triangles show the cross-sections of nucleon pickup reactions. EPAX predictions are shown as solid lines. Open squares show ^{40}Ca+^{1}H at 356 MeV/nucleon.



Data (symbols):

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