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Overview and Validation of the CEM03.01 and LAQGSM03.01 Event Generators for MCNP6, MCNPX, and MARS15

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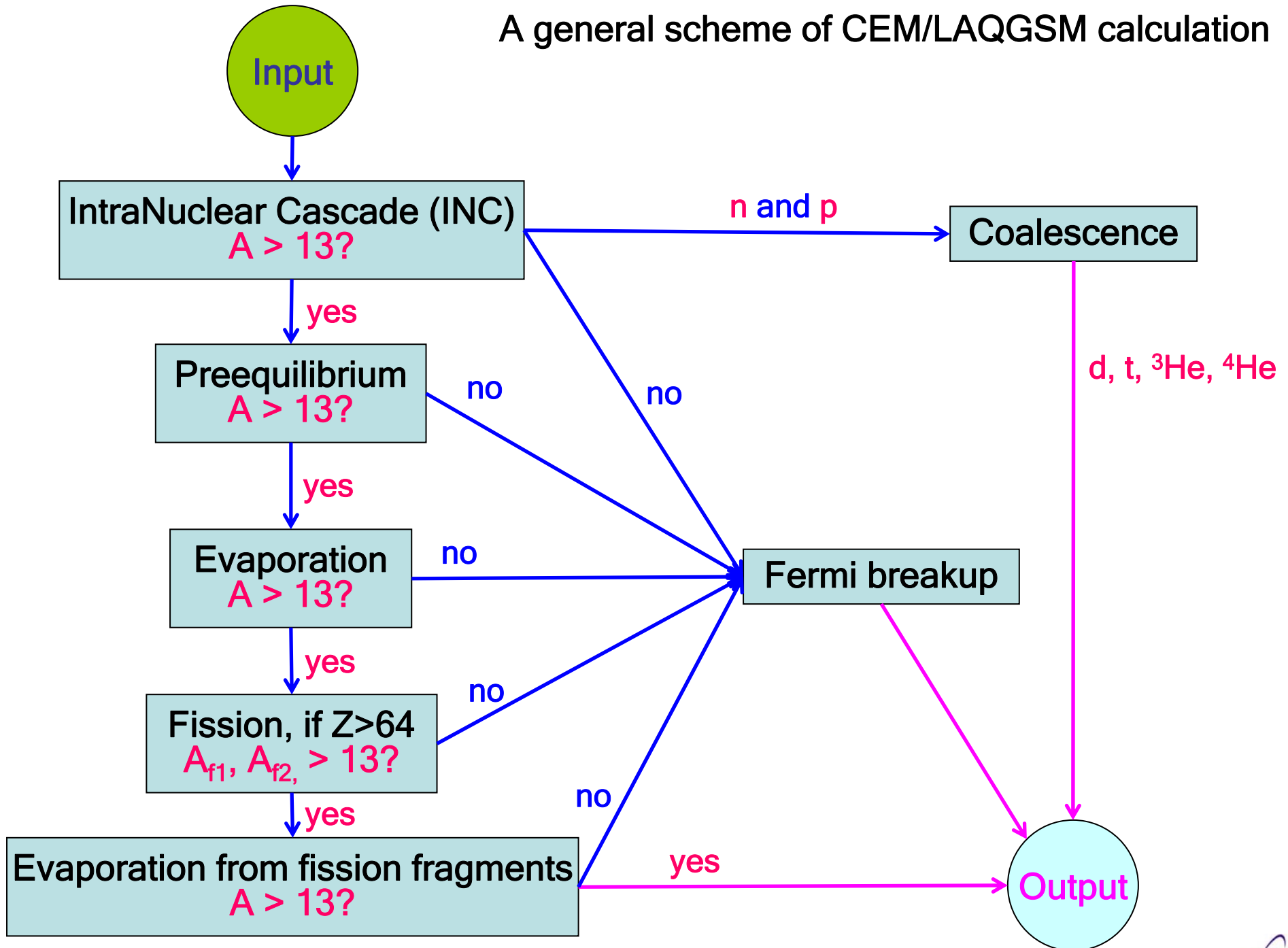
³Fermi National Accelerator Laboratory, Batavia, IL, USA



- Introduction
- INC of CEM03.01 and LAQGSM03.01
- 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 CEM03.01 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 Polonica 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

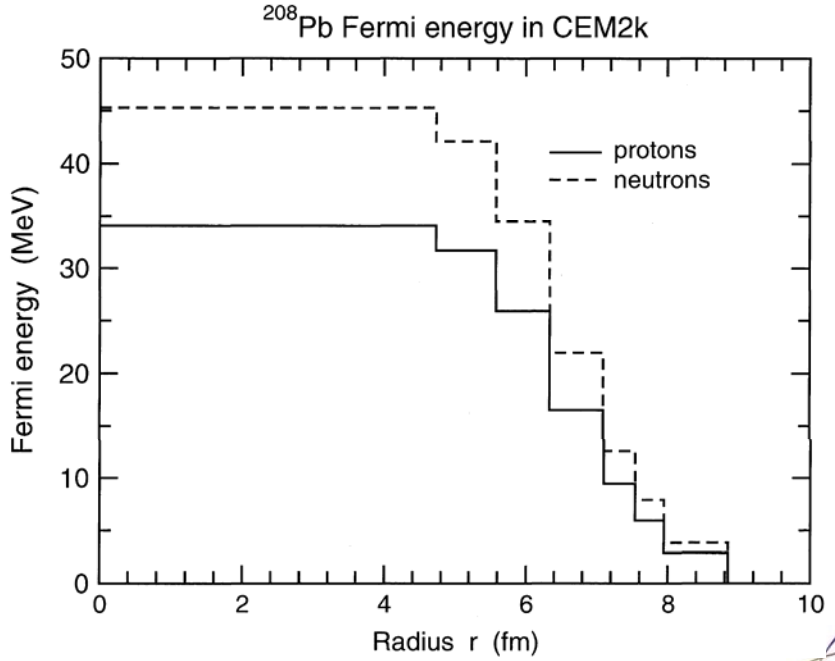
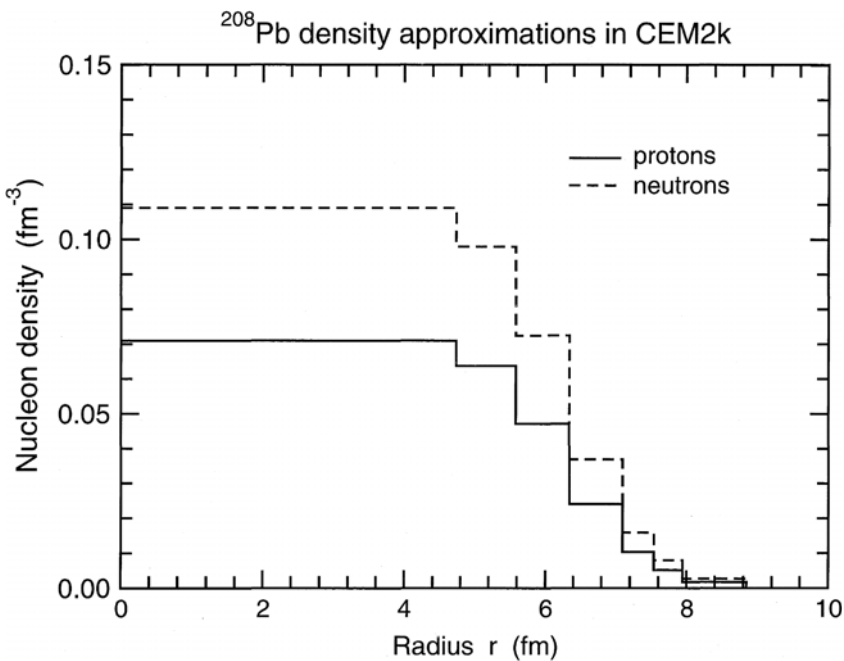
$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0 \{1 + \exp[(r - c)/a]\}$$

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 $T_F(r) = \hbar^2[3\pi^2\rho(r)]^{2/3}/(2m_N)$





$$\begin{aligned}
 NN &\rightarrow NN, & NN &\rightarrow \pi NN, & NN &\rightarrow \pi_1, \dots, \pi_i NN \\
 \pi N &\rightarrow \pi N, & \pi N &\rightarrow \pi_1, \dots, \pi_i N & (i \geq 2)
 \end{aligned}$$

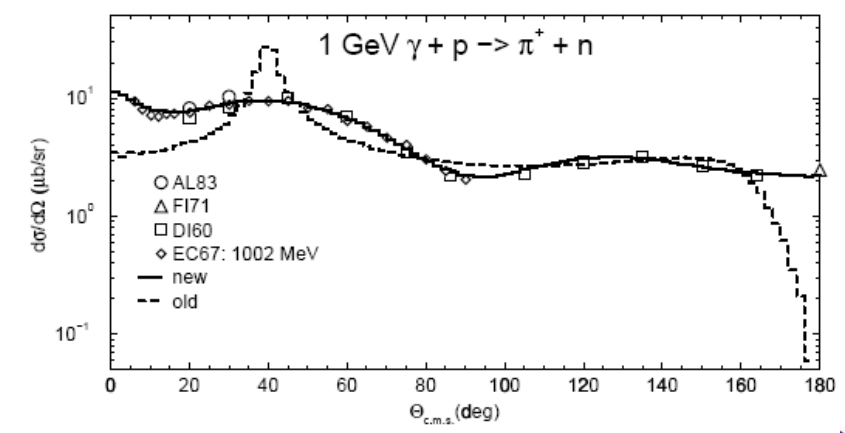
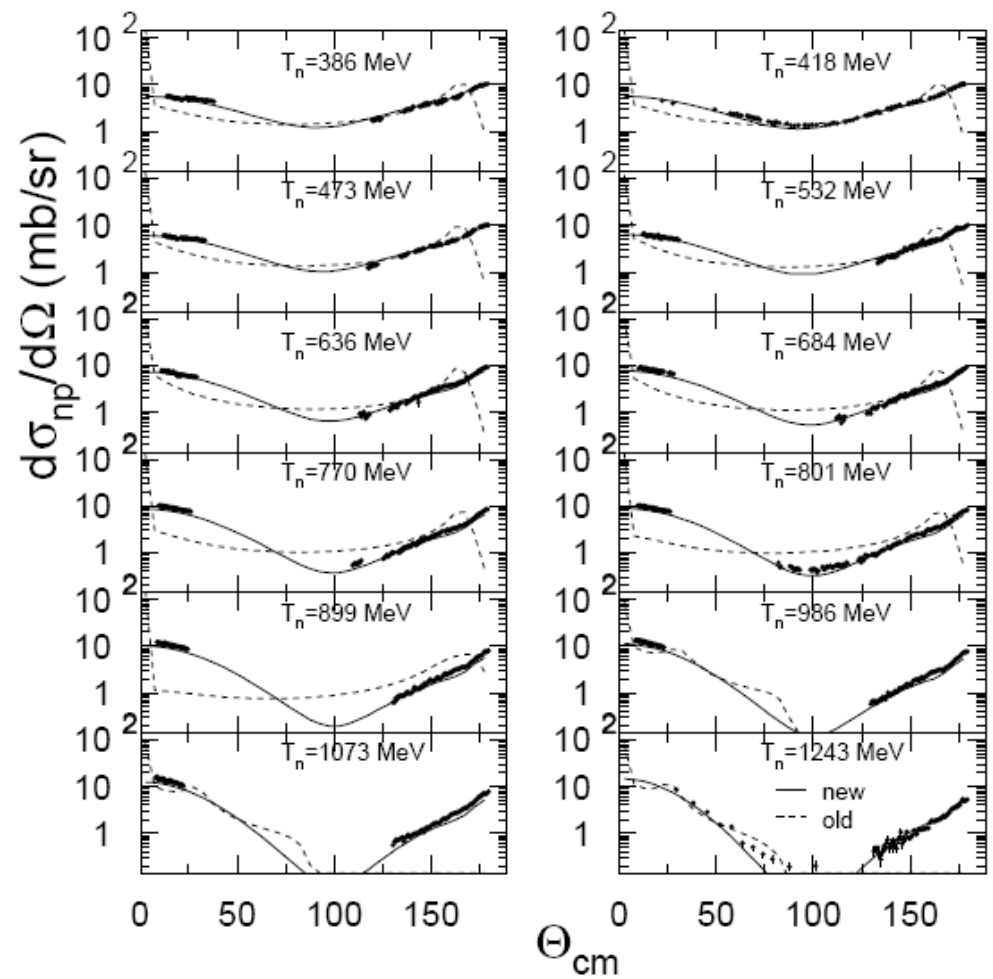
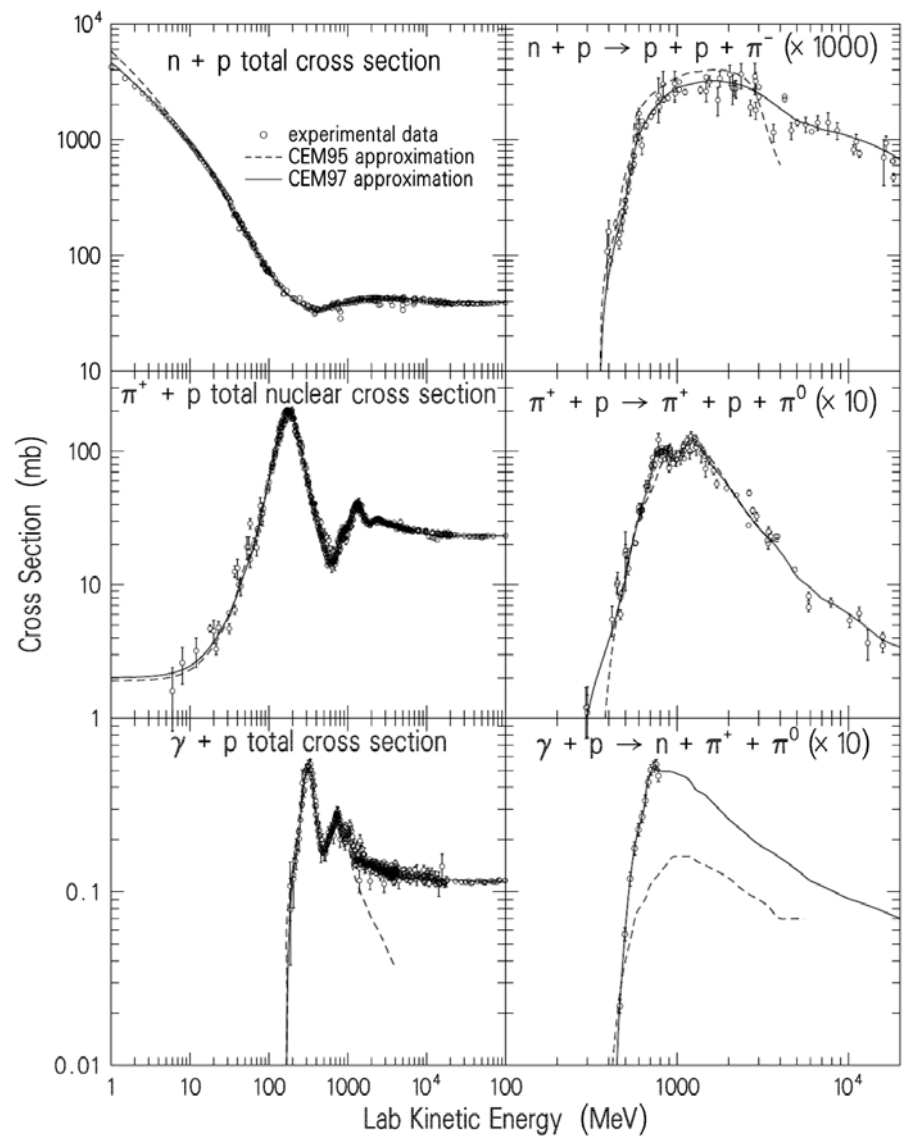
$$\pi NN \rightarrow NN$$

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

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

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

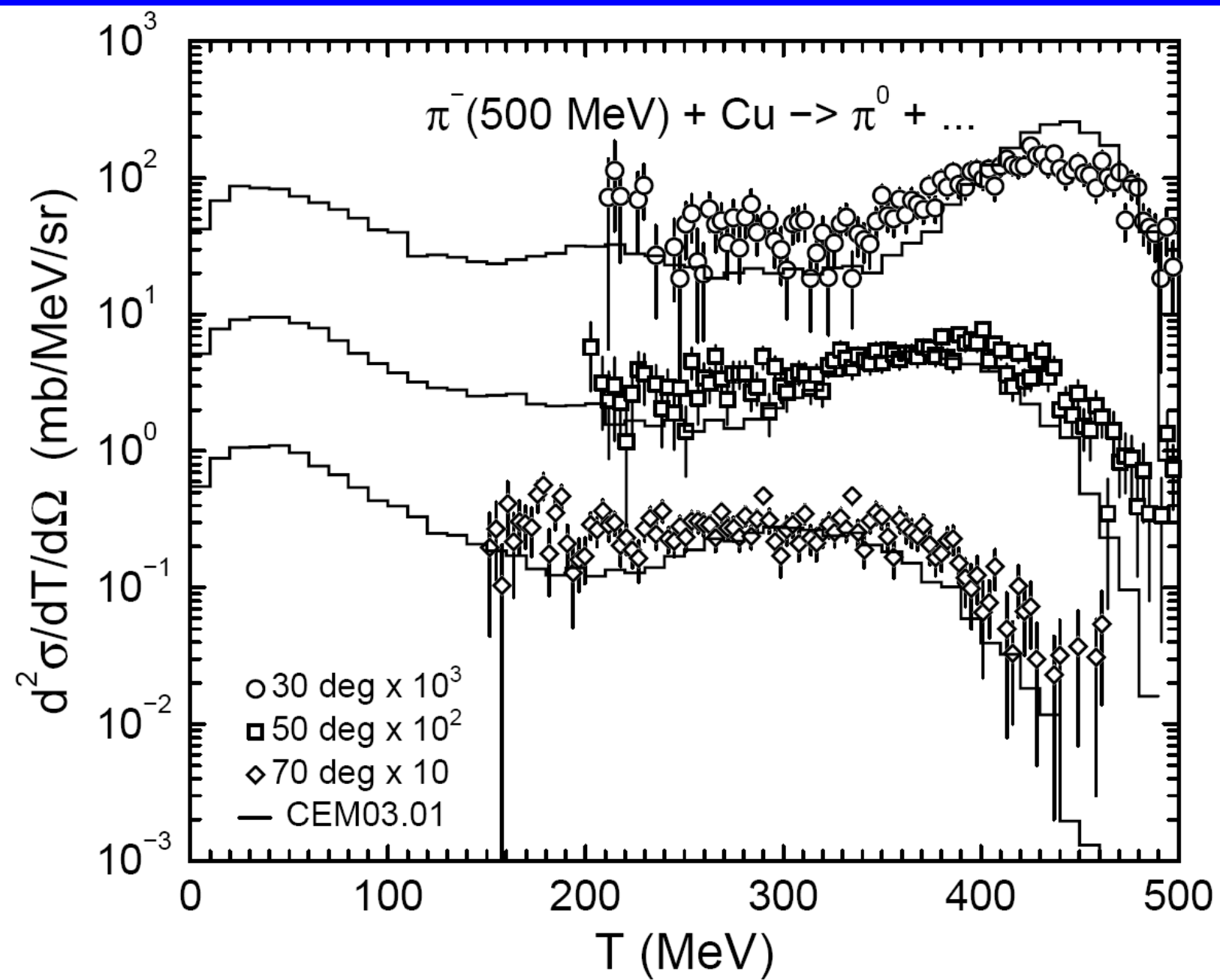
Pauli principle forbids a number of intranuclear collisions





In comparison with the initial version [1,2] of INC, in CEM03.01 we have:

- 1) developed better approximations for the total 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
- 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 **LAQGSM03.01** with a recently improved version [1] of the time-dependent 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.

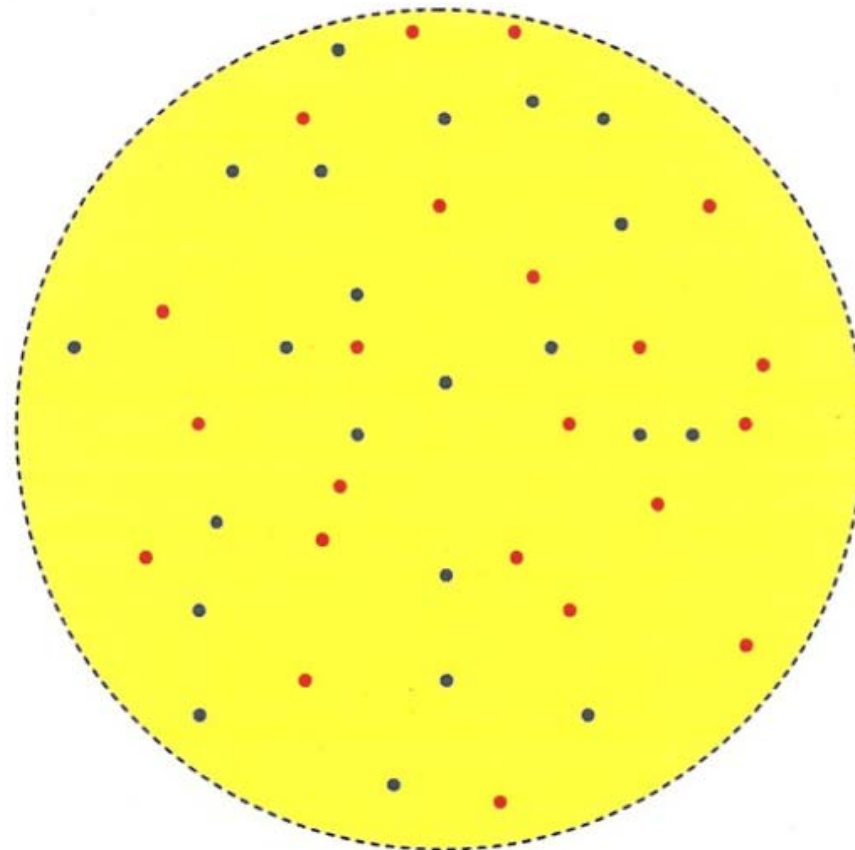
[3] N.S. Amelin, K.K. Gudima, V.D. Toneev, Sov. J. Nucl. Phys. 51 (1990) 327; ibid. 51 (1990) 1730; ibid. 52 (1990) 172;
N. S. Amelin, CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland (1999).



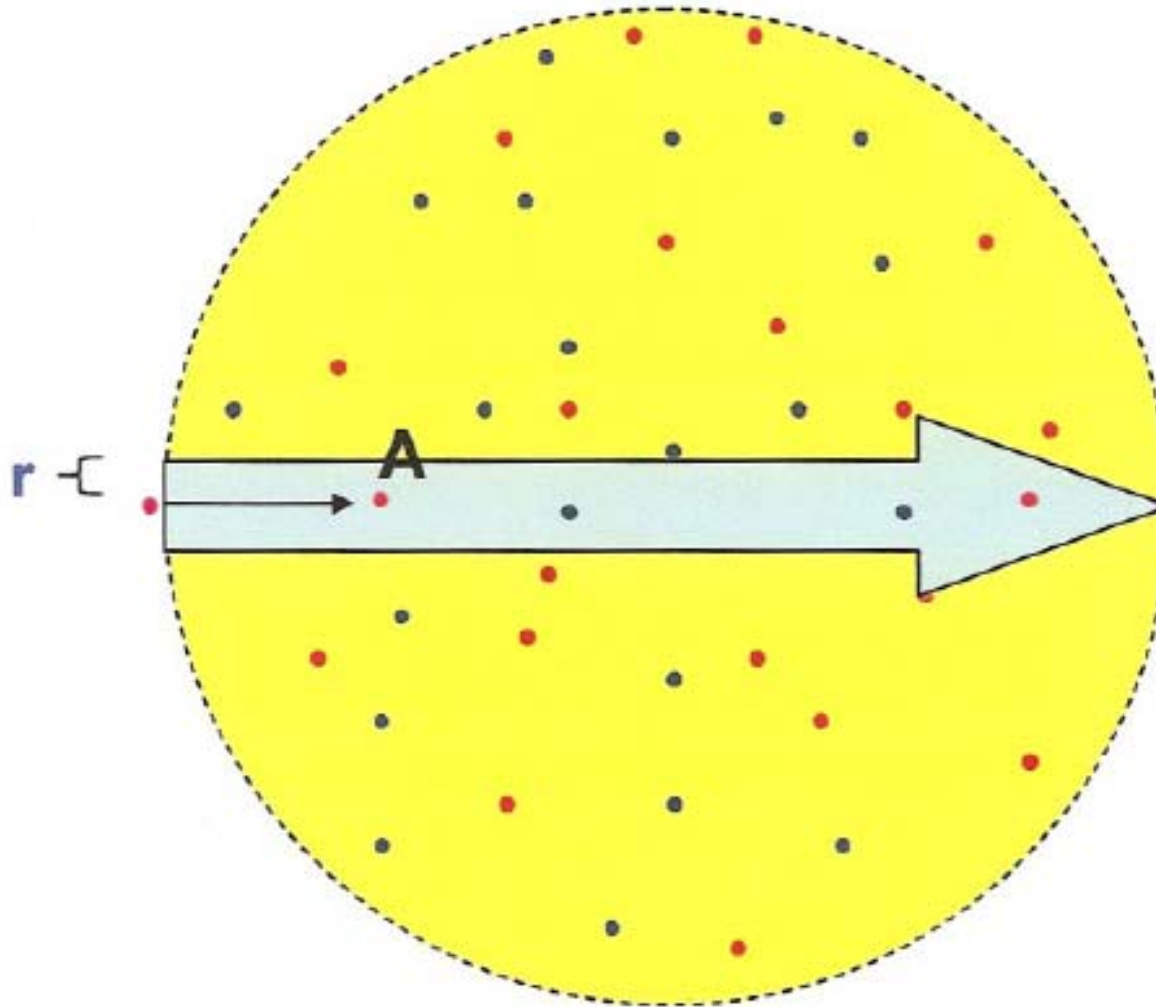
LAQGSM uses a continuous nuclear distribution (no “zones”)

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

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

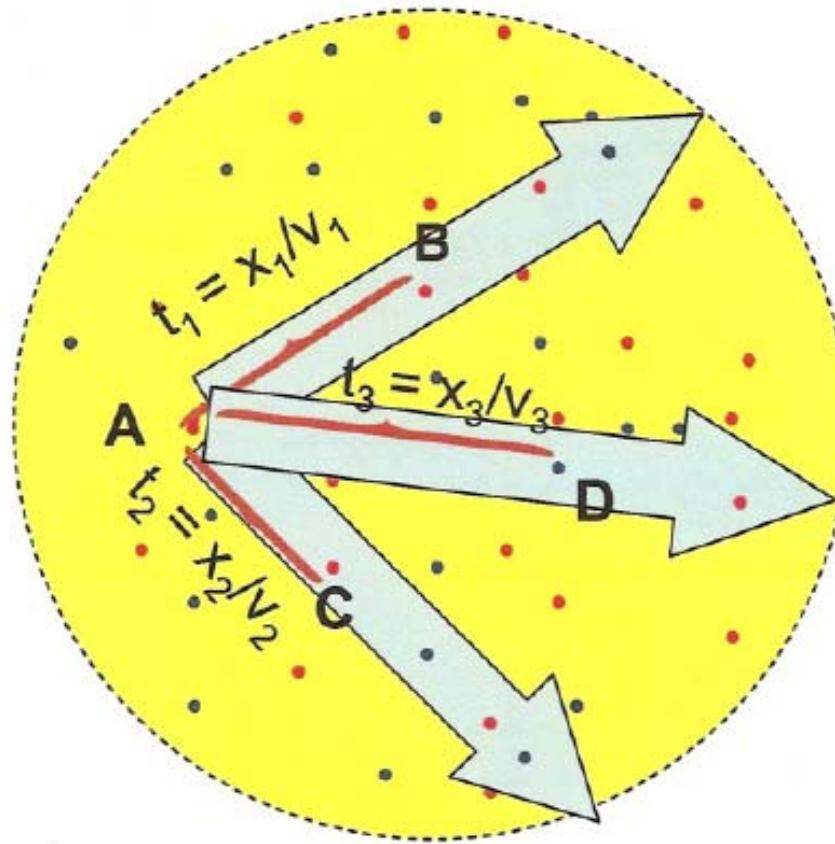


Before starting to simulate an INC event, position of all IntraNuclear nucleons are simulated and “frozen”



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

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



$t_{1(2,3,...)}^f$ is the **formation** time of the cascade particle #1(2,3,...)

If $t_2 < t_1$, $t_2 < t_3, \dots$, and $t_2 > t_2^f$, 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)

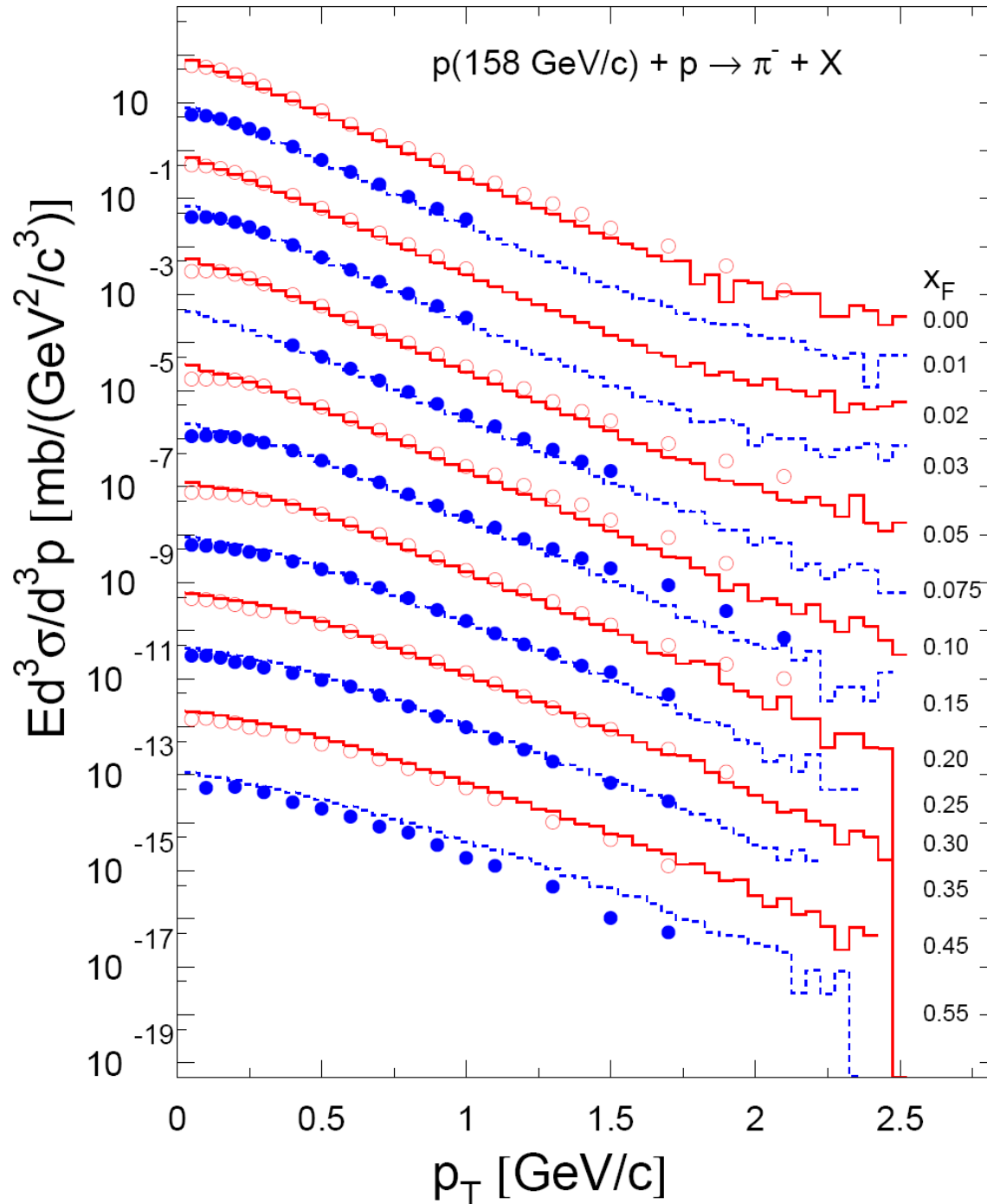
The **formation** time: $t^f = (E/m)t_f^0$; $t_f^0 = C_t \hbar/m_\pi$;

$C_t = 1.0$ for mesons and ~ 0.0 for baryons



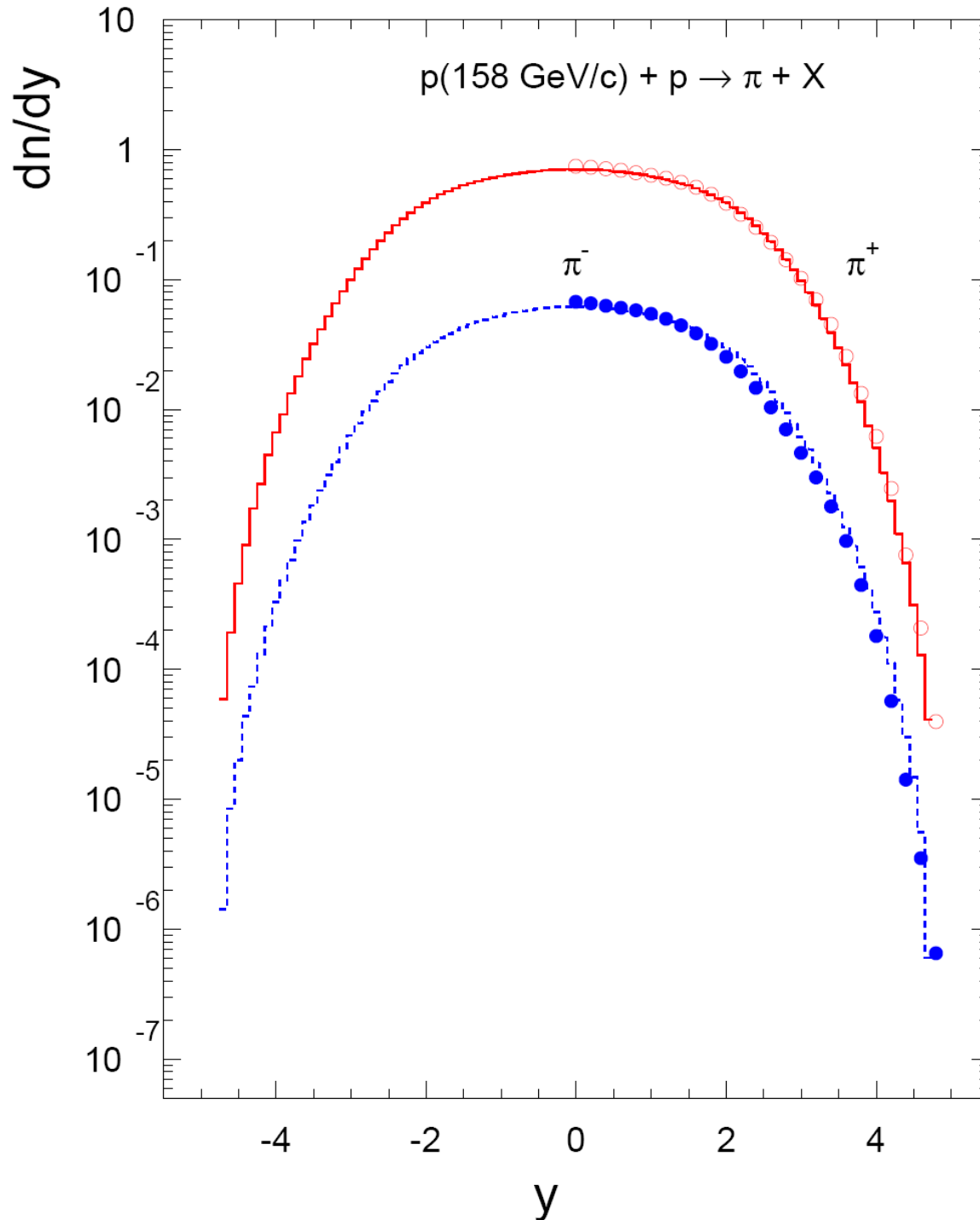
#	γp -interactions	γn -interactions
1	$\gamma p \rightarrow \pi^+ n$	$\gamma n \rightarrow \pi^- p$
2	$\gamma p \rightarrow \pi^0 n$	$\gamma n \rightarrow \pi^0 n$
3	$\gamma p \rightarrow \Delta^{++} \pi^-$	$\gamma n \rightarrow \Delta^+ \pi^-$
4	$\gamma p \rightarrow \Delta^+ \pi^0$	$\gamma n \rightarrow \Delta^0 \pi^0$
5	$\gamma p \rightarrow \Delta^0 \pi^+$	$\gamma n \rightarrow \Delta^- \pi^+$
6	$\gamma p \rightarrow \rho^0 p$	$\gamma n \rightarrow \rho^0 n$
7	$\gamma p \rightarrow \rho^+ n$	$\gamma n \rightarrow \rho^- p$
8	$\gamma p \rightarrow \eta p$	$\gamma n \rightarrow \eta n$
9	$\gamma p \rightarrow \omega p$	$\gamma n \rightarrow \omega n$
10	$\gamma p \rightarrow \Lambda K^+$	$\gamma n \rightarrow \Lambda K^0$
11	$\gamma p \rightarrow \Sigma^0 K^+$	$\gamma n \rightarrow \Sigma^0 K^0$
12	$\gamma p \rightarrow \Sigma^+ K^0$	$\gamma n \rightarrow \Sigma^- K^+$
13	$\gamma p \rightarrow \eta' p$	$\gamma n \rightarrow \eta' n$
14	$\gamma p \rightarrow \phi p$	$\gamma n \rightarrow \phi n$
15	$\gamma p \rightarrow \pi^+ \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^- n$
16	$\gamma p \rightarrow \pi^0 \pi^+ n$	$\gamma n \rightarrow \pi^0 \pi^- p$
17	$\gamma p \rightarrow \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 n$
18	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 n$
19	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 n$
20	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 p$
21	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- p$
22	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 n$
23	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 n$
24	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- n$
25	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 p$
26	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 p$
27	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
28	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 n$
29	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$
30	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$
31	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$
32	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- p$

#	γp -interactions	γn -interactions
33	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
34	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 n$
35	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$
36	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- n$
37	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$
38	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$
39	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 p$
40	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
41	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 n$
42	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 n$
43	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 n$
44	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$
45	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 p$
46	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 \pi^0 p$
47	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- p$
48	$\gamma p \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
49	$\gamma p \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 n$
50	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 n$
51	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 \pi^0 n$
52	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^- p$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^- n$
53	$\gamma p \rightarrow \pi^+ \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$	$\gamma n \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 \pi^0 p$
54	$\gamma p \rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 \pi^0 p$
55	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0 \pi^0 \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 \pi^0 \pi^0 p$
56	$\gamma p \rightarrow \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 n$	$\gamma n \rightarrow \pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^- \pi^0 p$



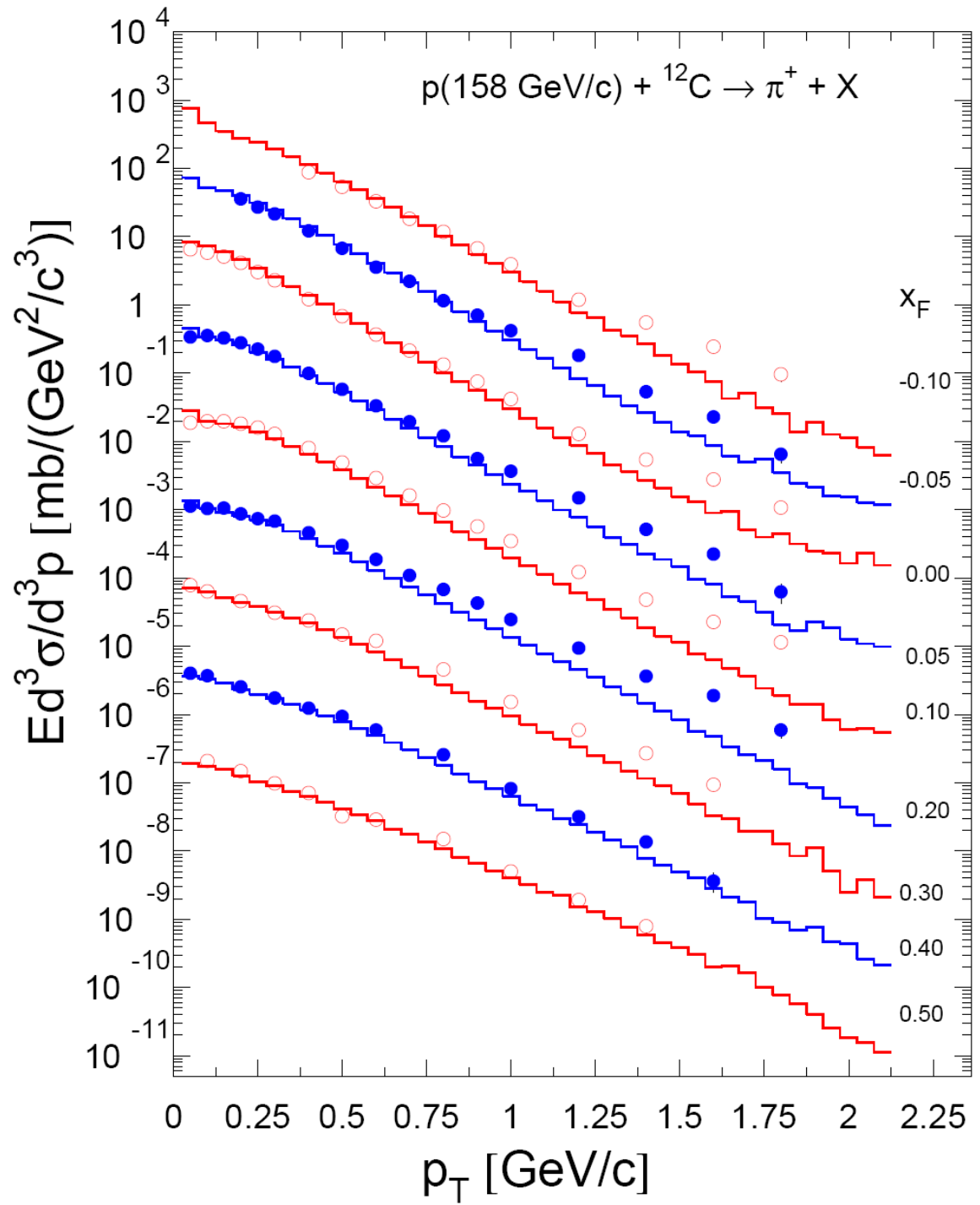
NA49 data (symbols):
 C. Alt et al.,
 Eur. Phys. J.
C45 (2006) 343-381;

LAQGSM03.01 results:
 histograms



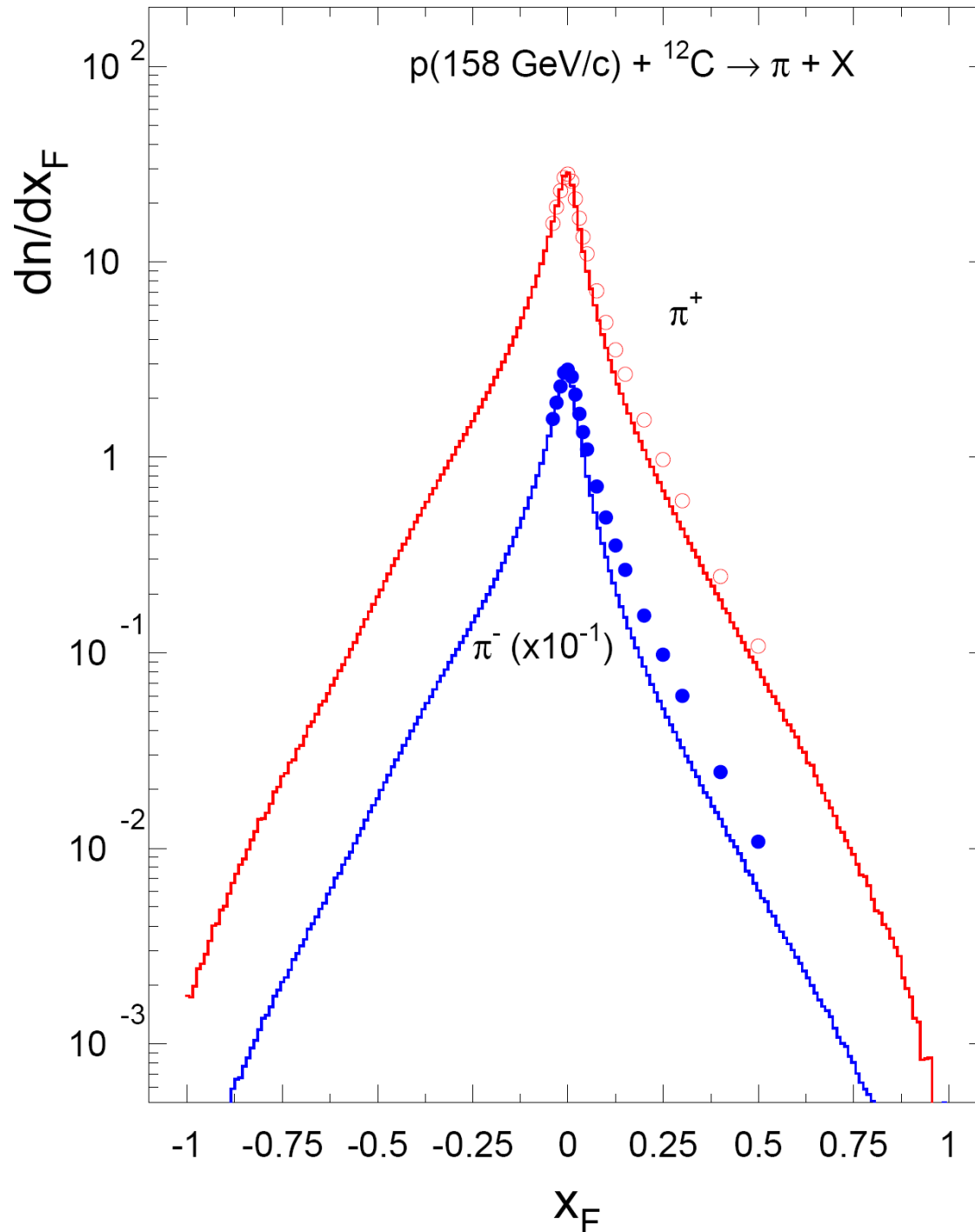
NA49 data (symbols):
C. Alt et al.,
Eur. Phys. J.
C45 (2006) 343-381;

LAQGSM03.01 results:
histograms



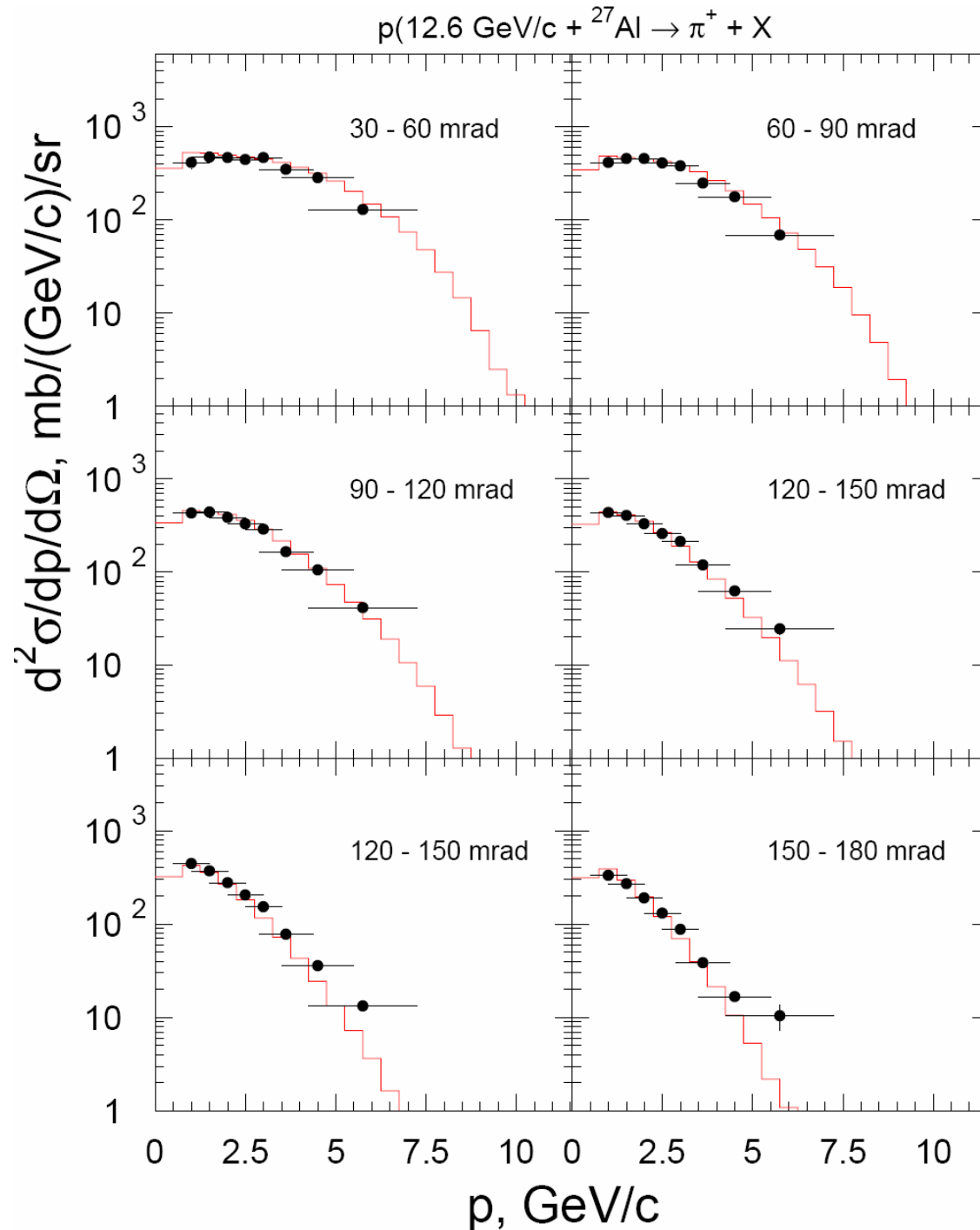
NA49 data (symbols):
C. Alt et al.,
E-print: hep-ex/0606028,
submitted to
Eur. Phys. J. ;

LAQGSM03.01 results:
histograms



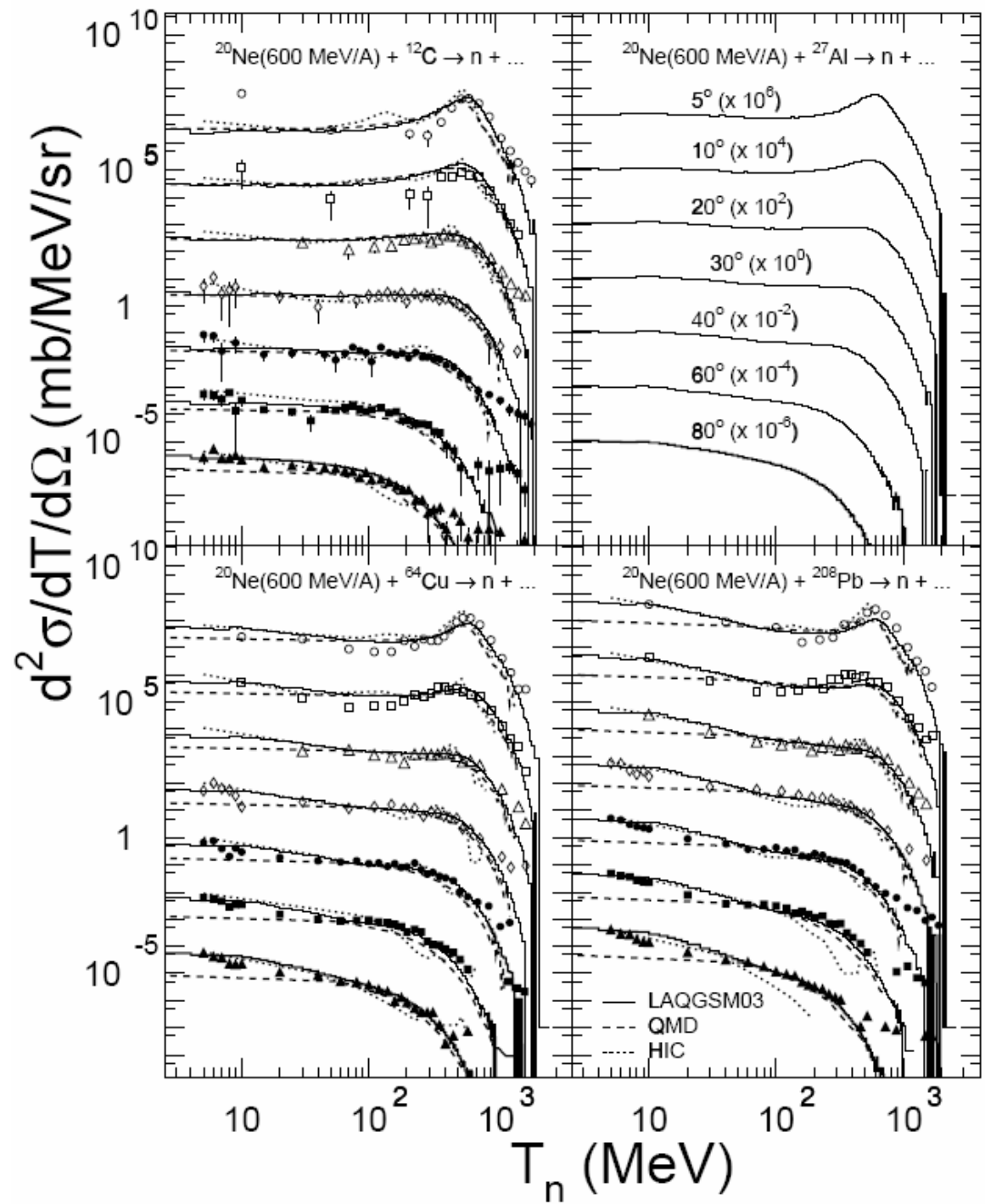
NA49 data (symbols):
 C. Alt et al.,
 E-print: hep-ex/0606028,
 submitted to
 Eur. Phys. J. ;

LAQGSM03.01 results:
 histograms

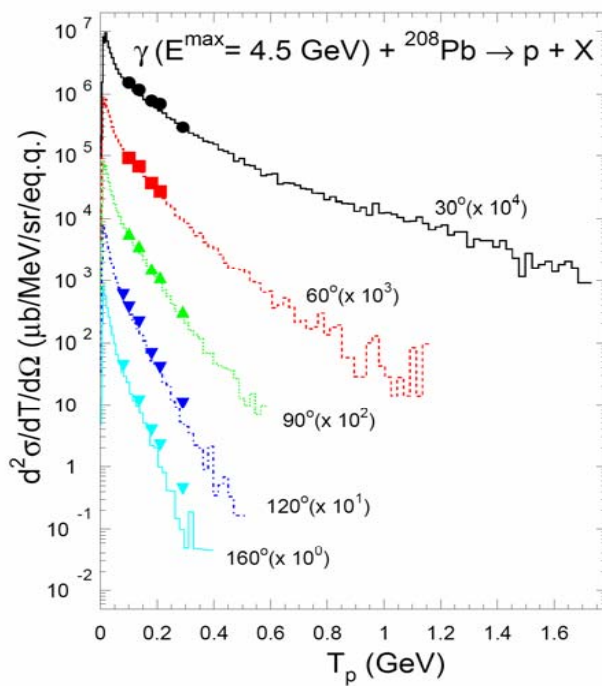
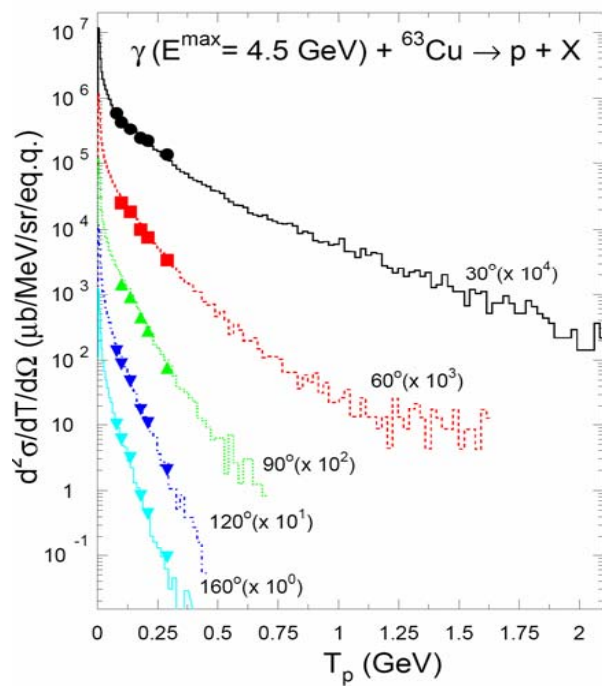
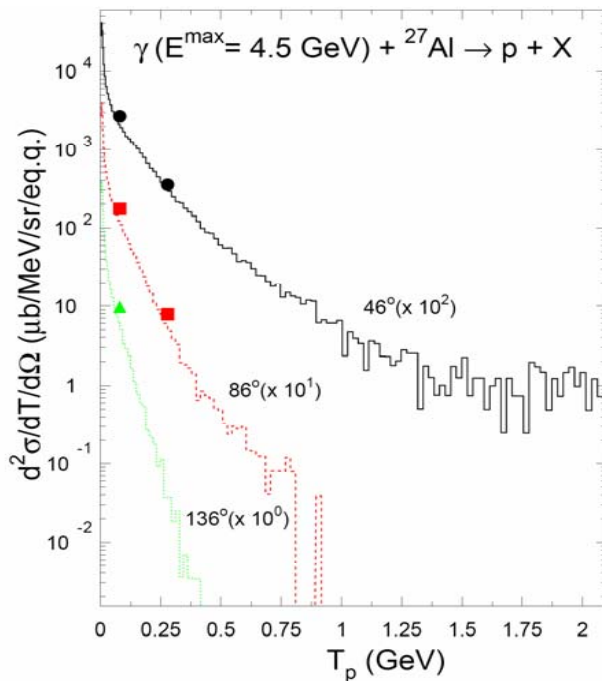
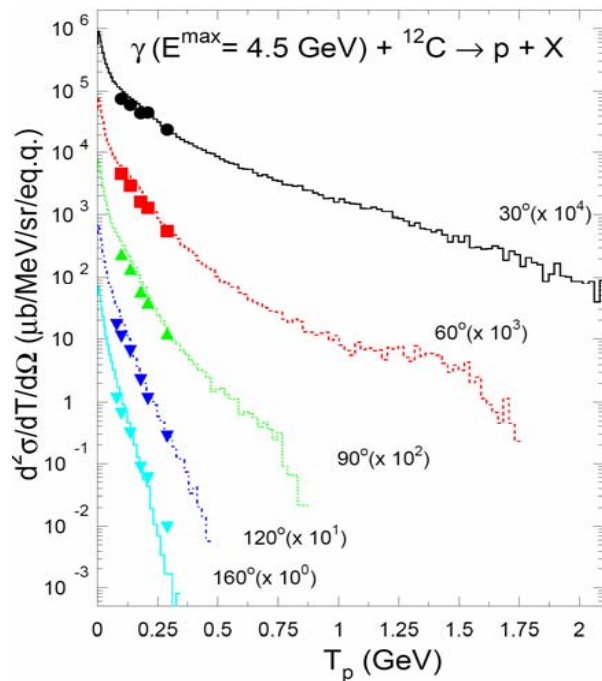


HARP data (symbols):
 M. G. Catanesi et al.,
 Nucl. Phys. **B 732**
 (2006) 1-45;

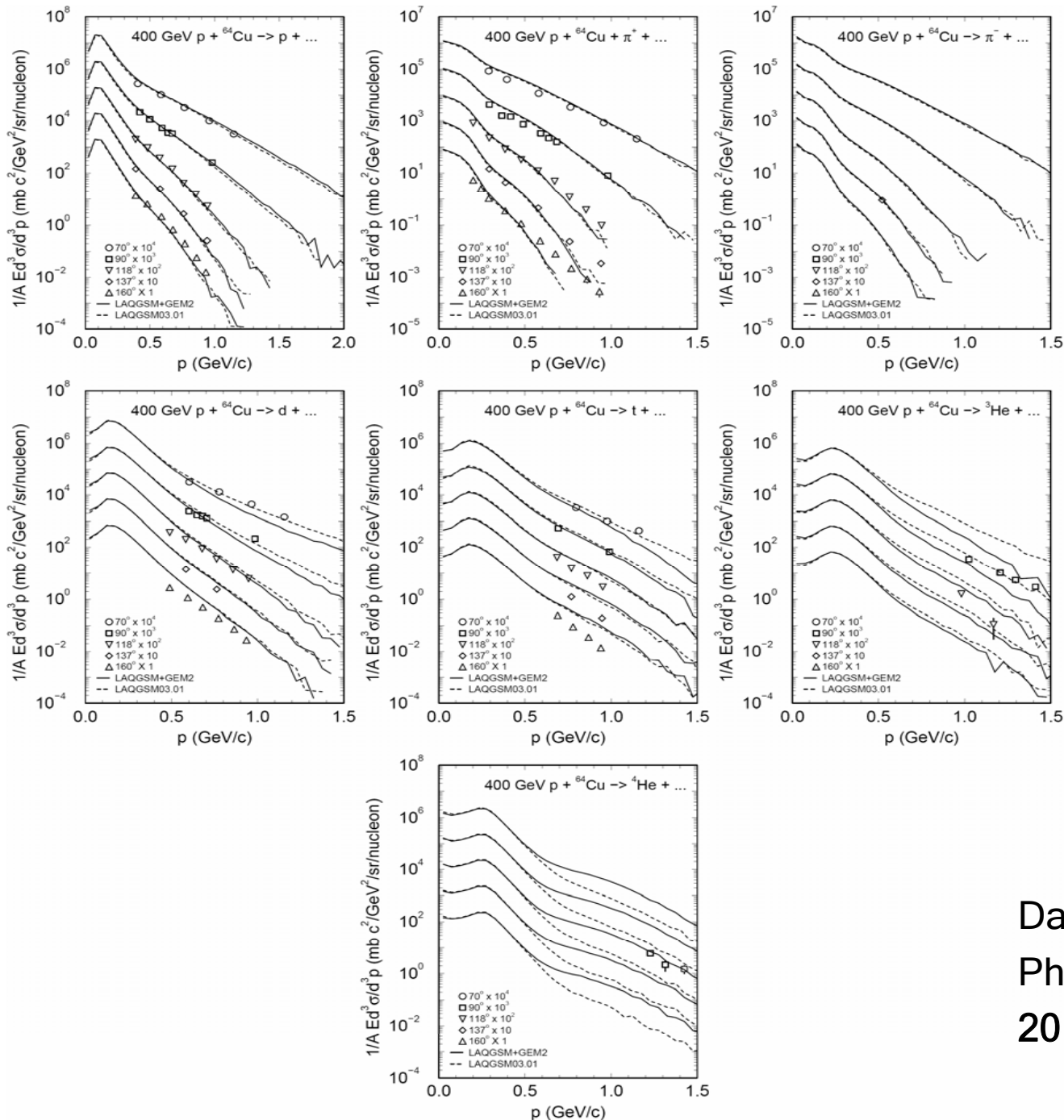
LAQGSM03.01 results:
 histograms



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)



Data: K. V. Alanakyan *et al.*,
 Sov. J. Nucl. Phys.
 25 (1977) 292; 34 (1981) 828;
 Nucl. Phys. A367 (1981) 429



Data: Y. D. Bayukov *et al.*,
 Phys. Rev. C 20 (1979) 764;
 20 (1979) 2257; 22 (1980) 700



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 ${}^4\text{He}$ 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.

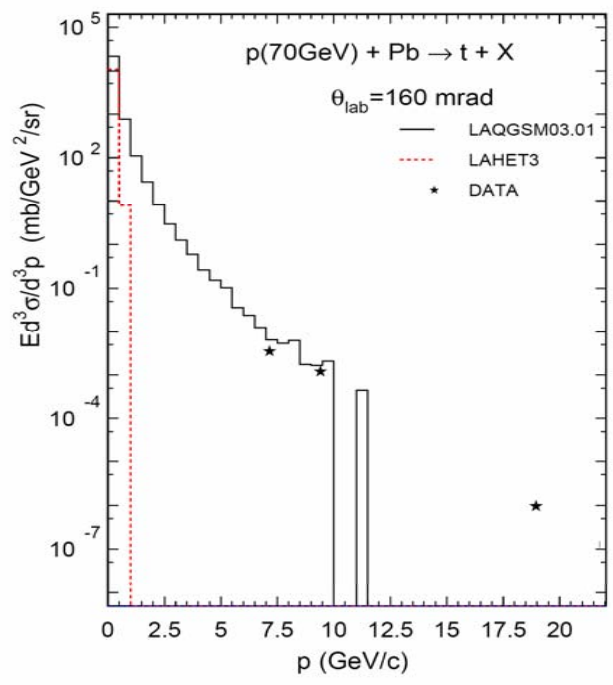
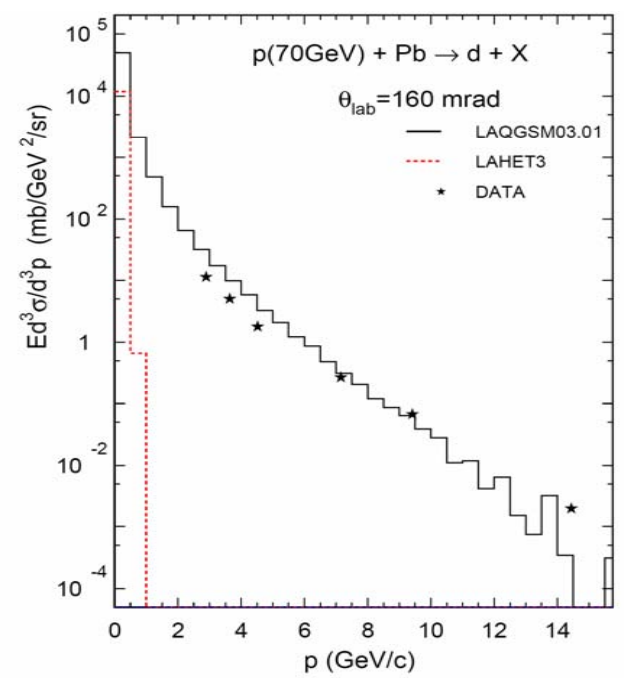
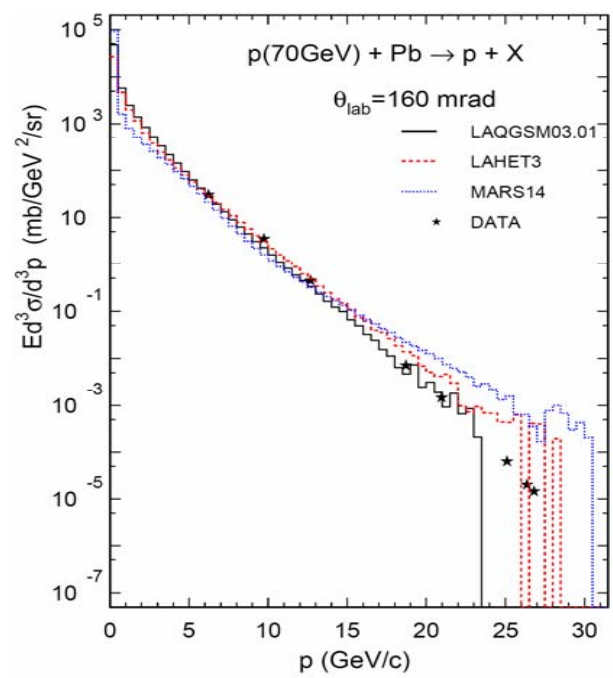
$$W_d(\vec{p}, b) = \int \int d\vec{p}_p d\vec{p}_n \rho^C(\vec{p}_p, b) \rho^C(\vec{p}_n, b) \delta(\vec{p}_p + \vec{p}_n - \vec{p}) \Theta(p_c - |\vec{p}_p - \vec{p}_n|)$$

LAQGSM:

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

CEM:

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



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.

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

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

$$\langle \sigma \rangle \rightarrow \langle \sigma \rangle F(\Omega) ,$$

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

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

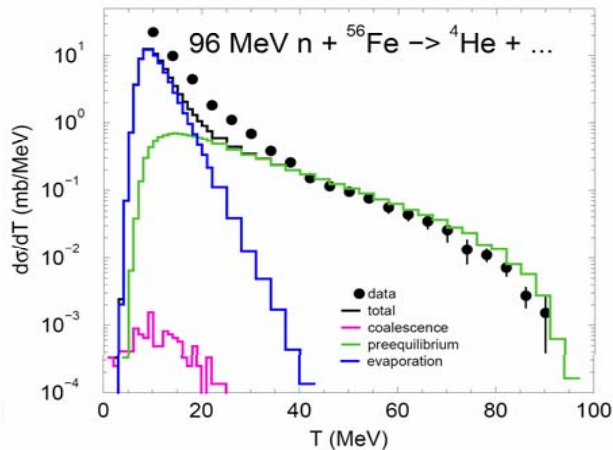
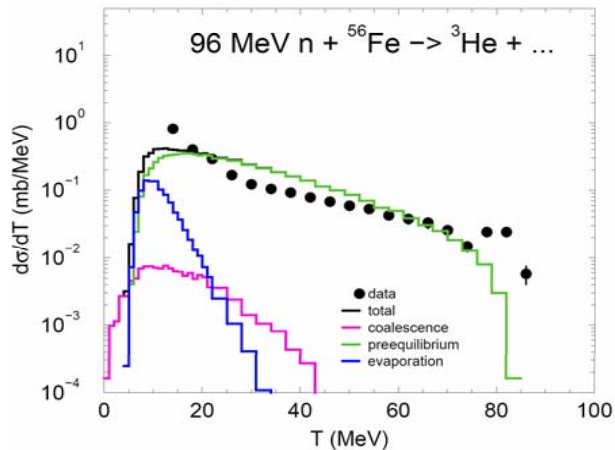
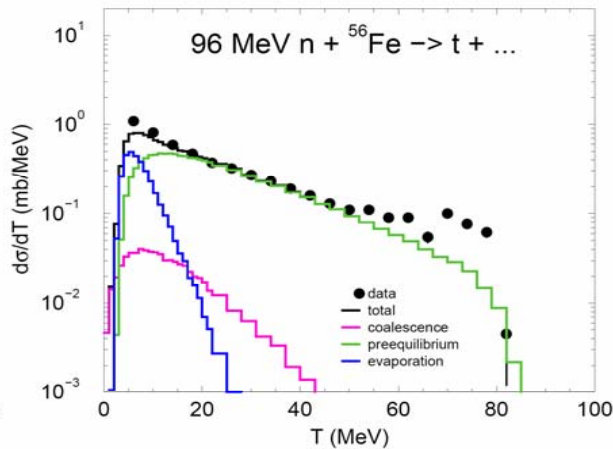
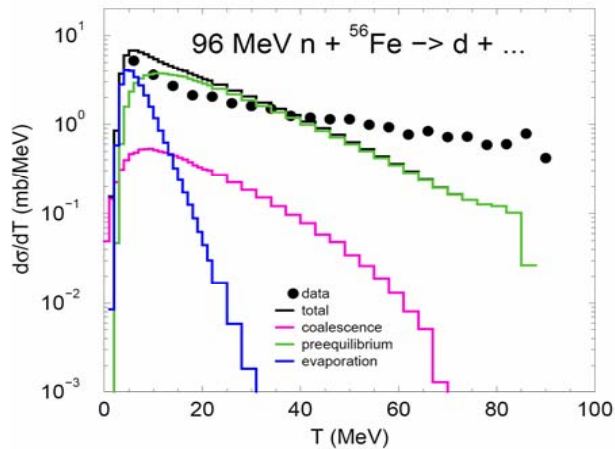
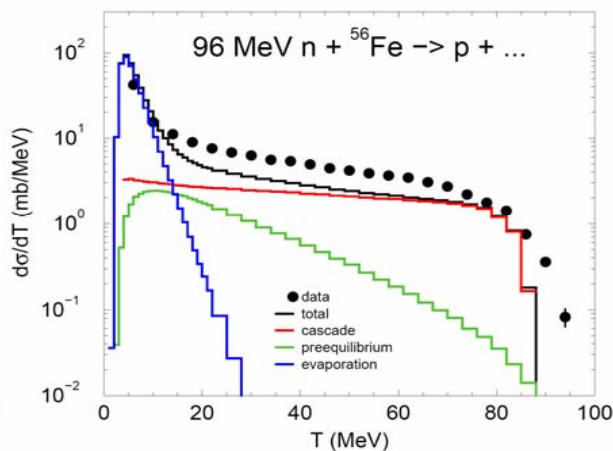
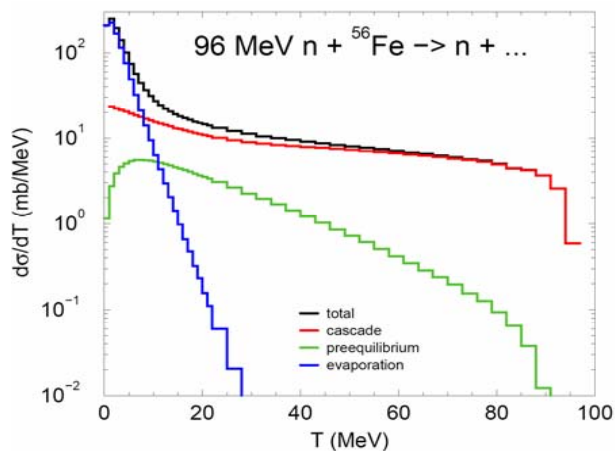
1) χ_j was fitted for proton-induced reactions

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

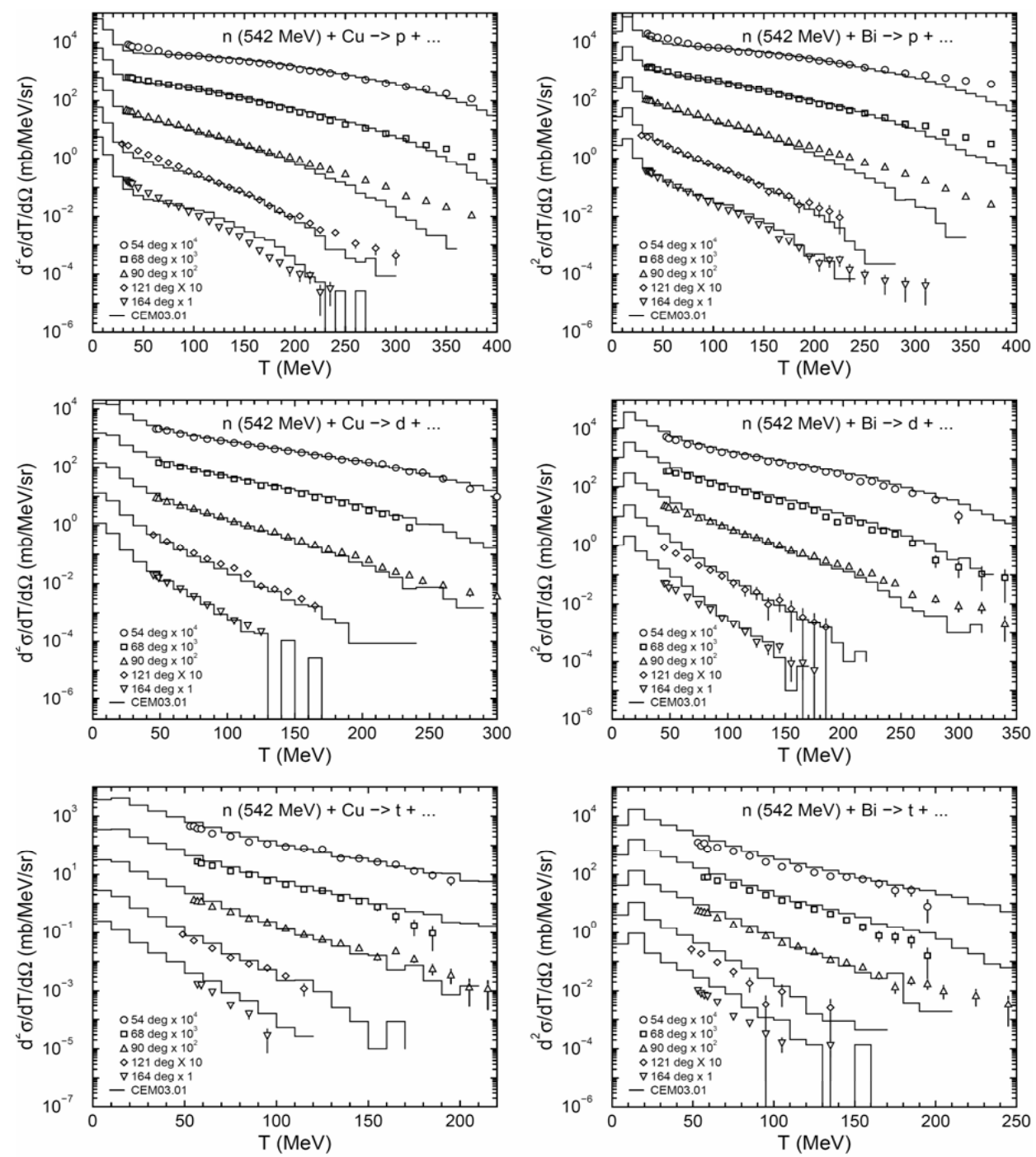


In comparison with the initial version [2] of CEM, the **preequilibrium (PREC)** part of CEM03.01 have been changed:

- 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



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



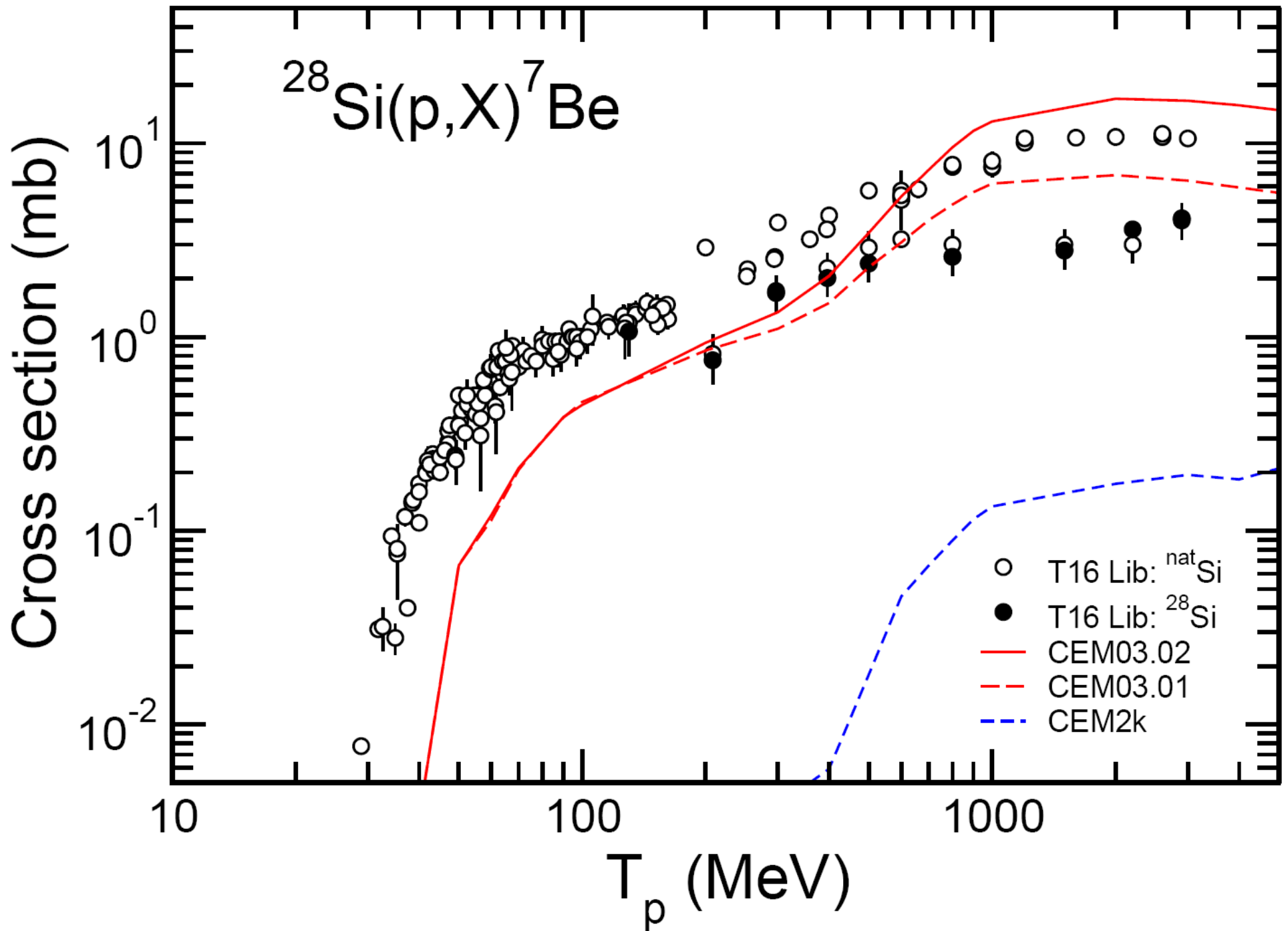
Data: J. Franz *et al.*,
Nucl. Phys. A510 (1990) 774

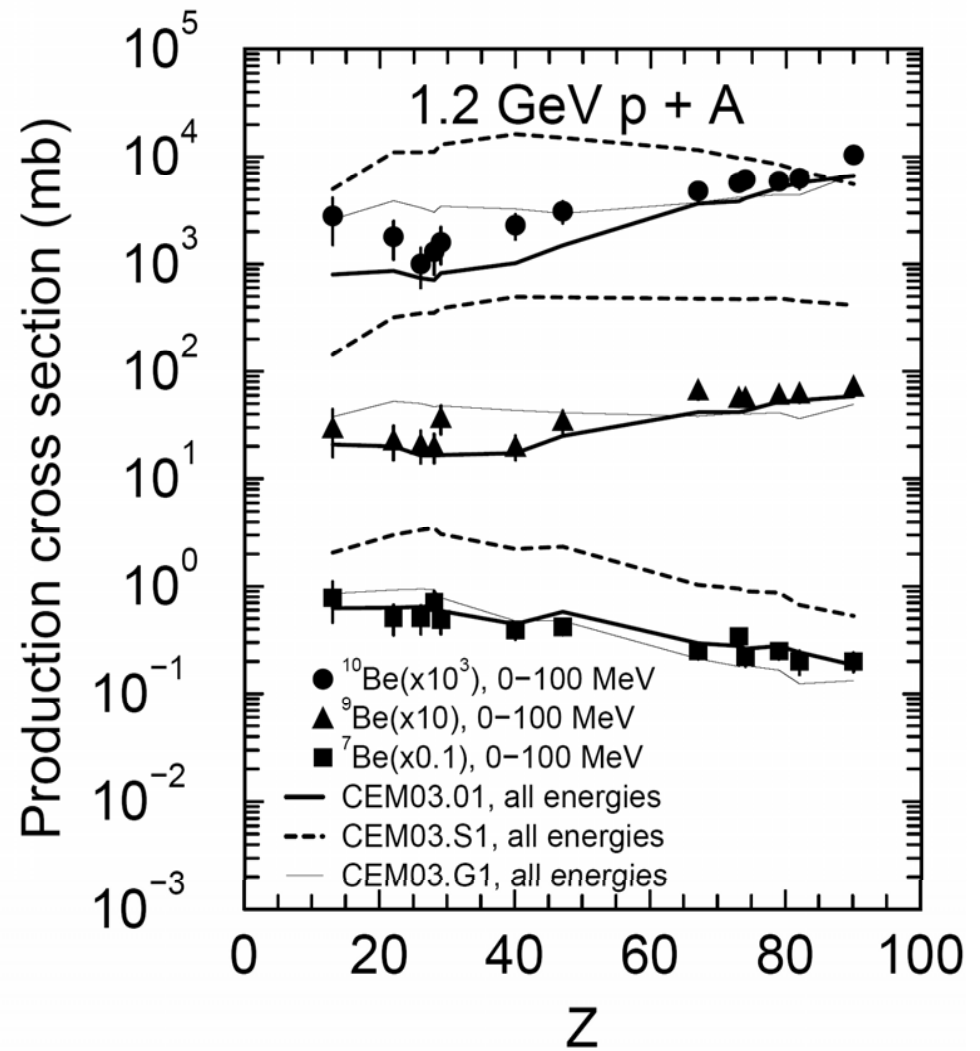
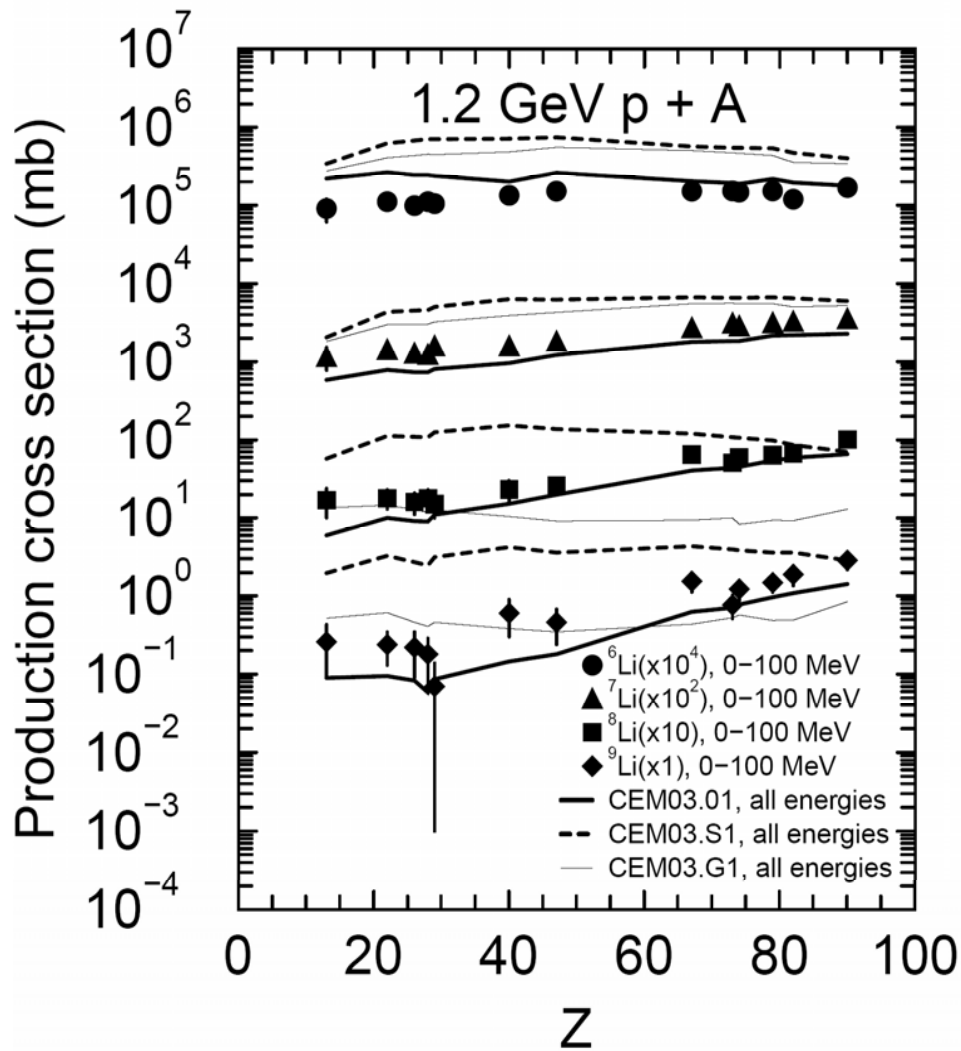


The **evaporation** stages of reactions is calculated with an improved version of the **Generalized Evaporation Model (GEM2)** by Furihata (several routines by Furihata from GEM2 were slightly modified in CEM03.01/LAQGSM03.01; some bugs found in GEM2 were fixed).

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

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	





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 CEM03.01/LAQGSM03.01; some bugs found in GEM2 were fixed.

Fission cross section calculation:

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

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

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

$$J_0 = \frac{(s_n - 1)e^{s_n} + 1}{2a_n},$$

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

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

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



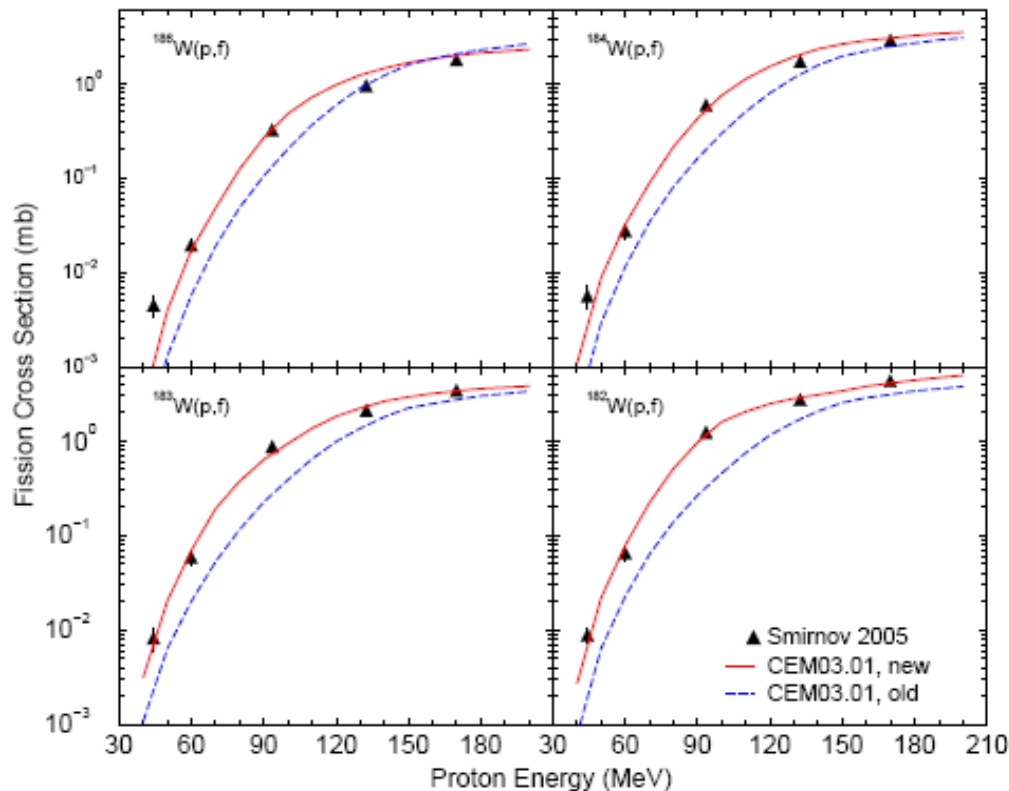
2) $Z_j \geq 89$

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

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

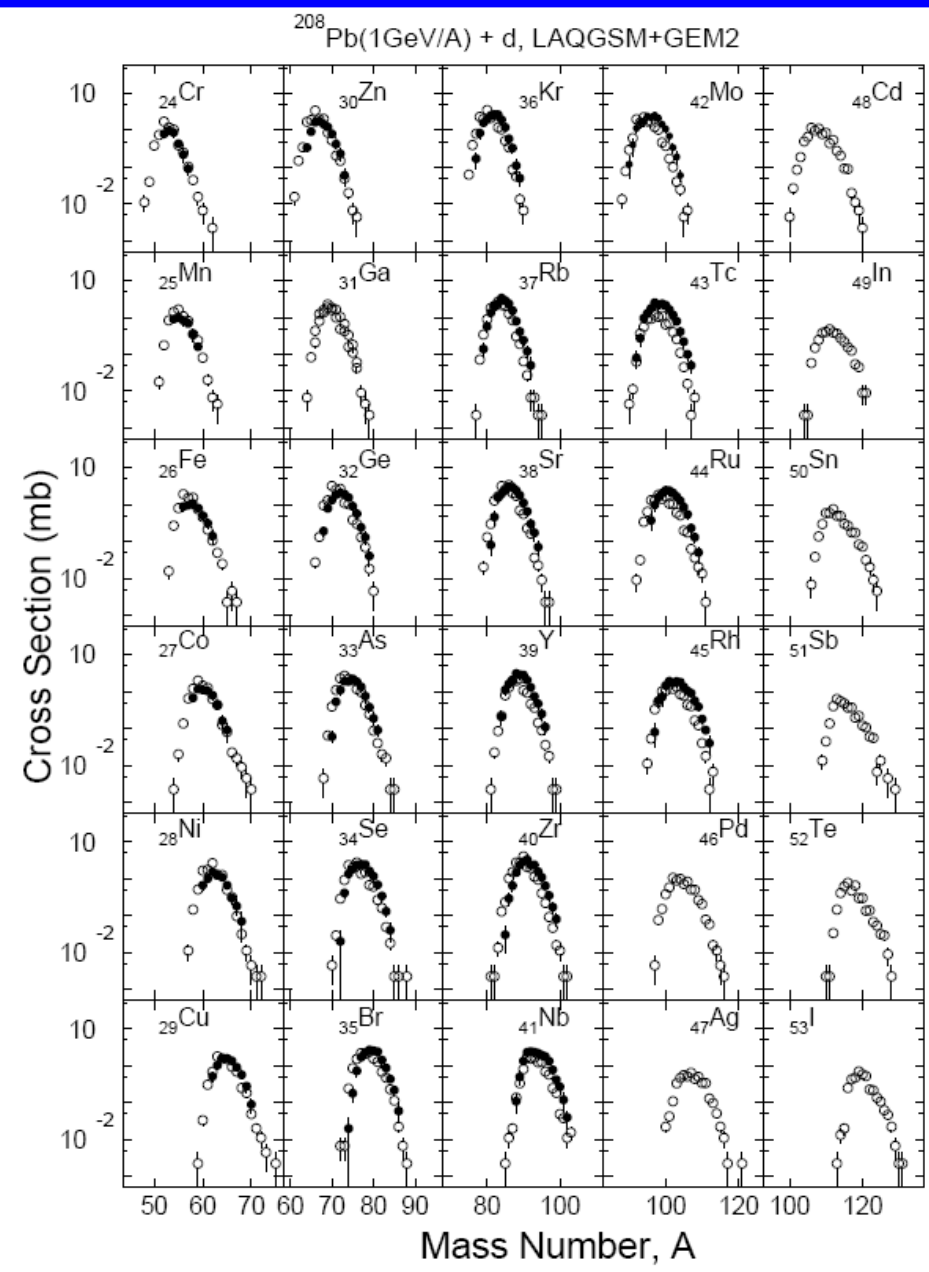
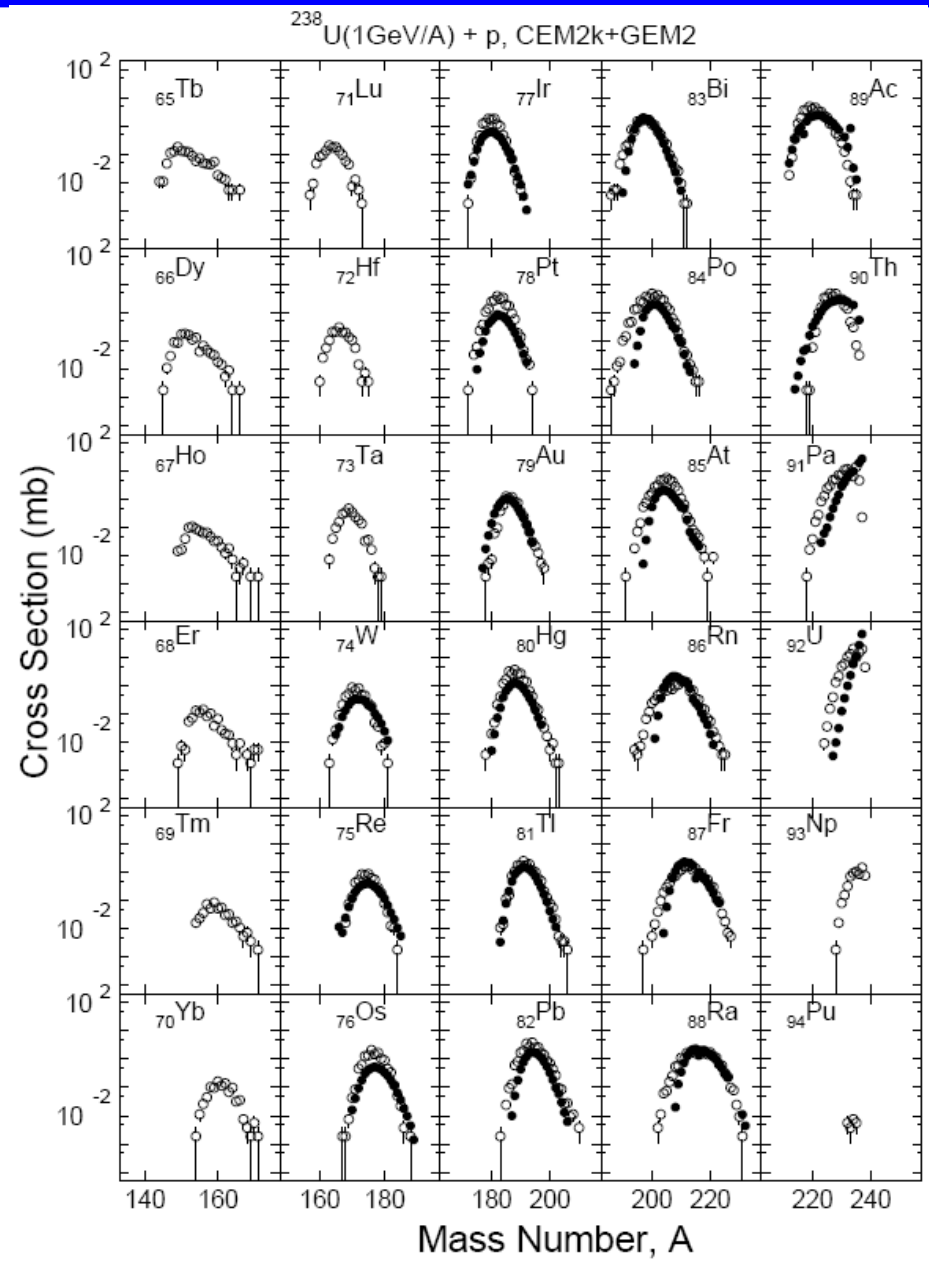
Z	C(Z)	A ₀ (Z)
89	0.23000	219.40
90	0.23300	226.90
91	0.12225	229.75
92	0.14727	234.04
93	0.13559	238.88
94	0.15735	241.34
95	0.16597	243.04
96	0.17589	245.52
97	0.18018	246.84
98	0.19568	250.18
99	0.16313	254.00
100	0.17123	257.80
101	0.17123	261.30
102	0.17123	264.80
103	0.17123	268.30
104	0.17123	271.80
105	0.17123	275.30
106	0.17123	278.80

In CEM03.01 and LAQGSM03.01: $a_f \rightarrow C_a \times a_f$ $C(Z_i) \rightarrow C_c \times C(Z_i)$



S. G. Mashnik, A. J. Sierk,
 K. K. Gudima, M. I. Baznat,
 Proc. NPDC19, Journal of
 Physics: Conference
 Series, 41 (2006) 340-351
 (nucl-th/0510070)

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.



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



The **Fermi breakup model** 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:

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

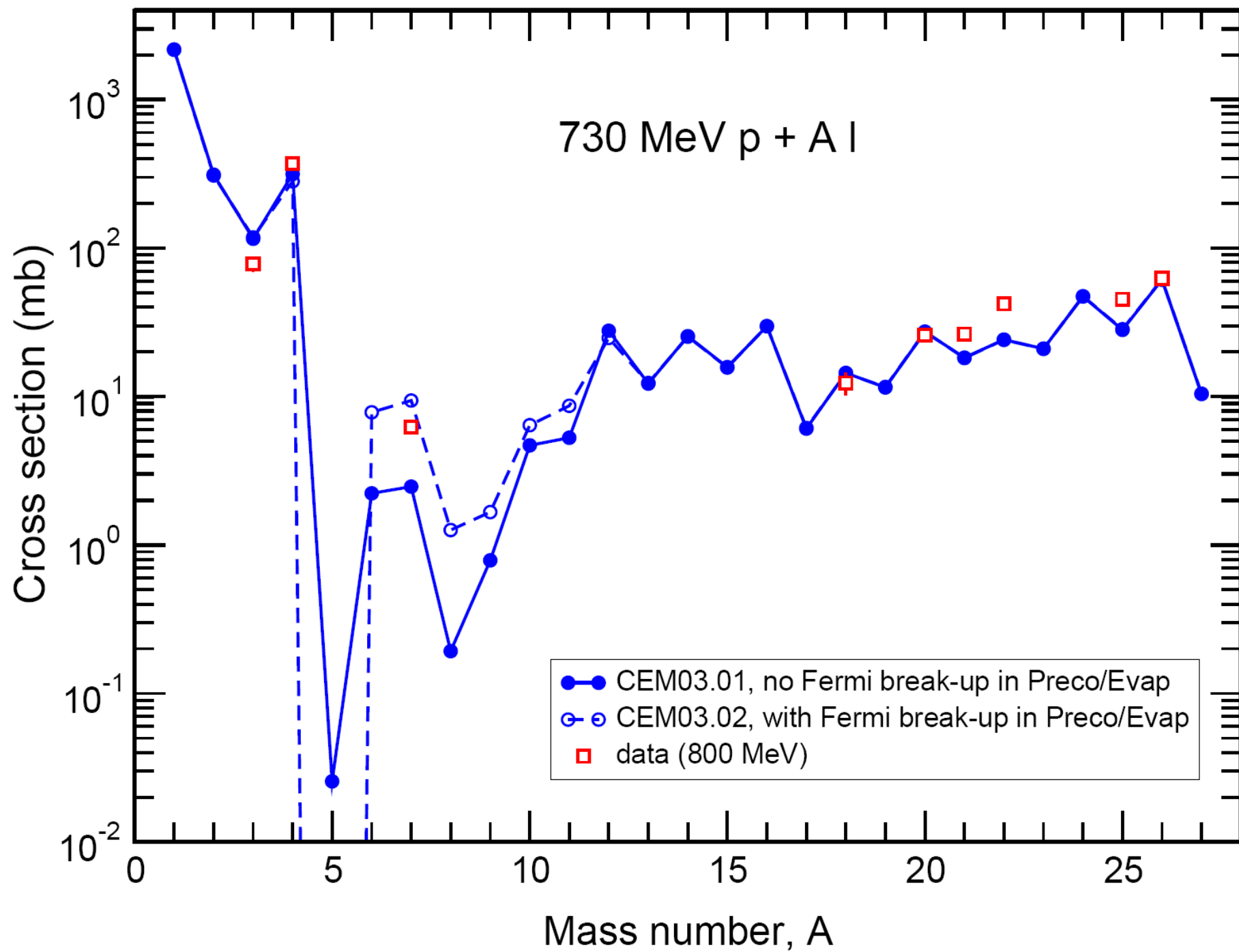
$$V = 4\pi R^3/3 = 4\pi r_0^3 A/3,$$

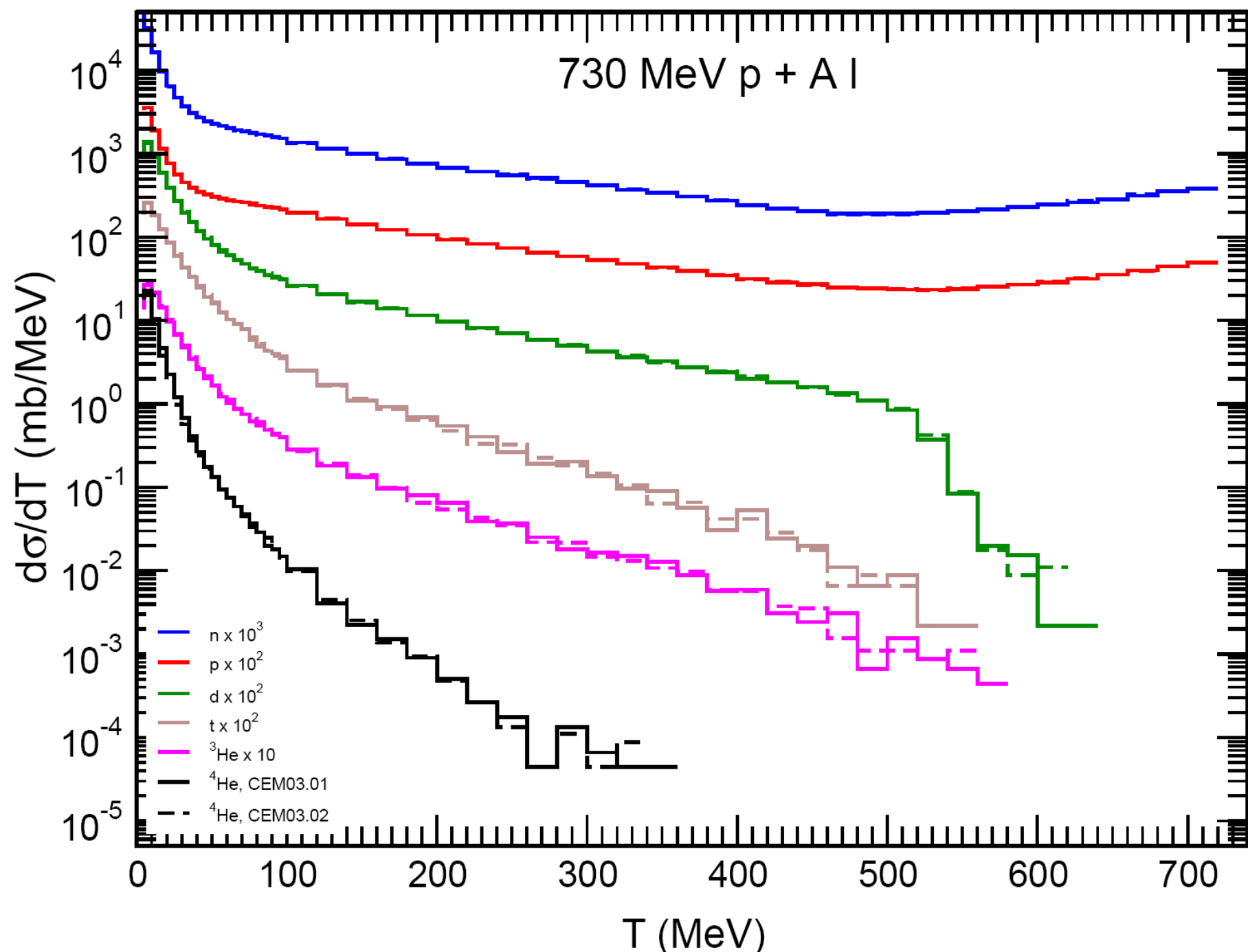
where $r_0 = 1.4$ fm, is the only "free" parameter (fixed) of the model.

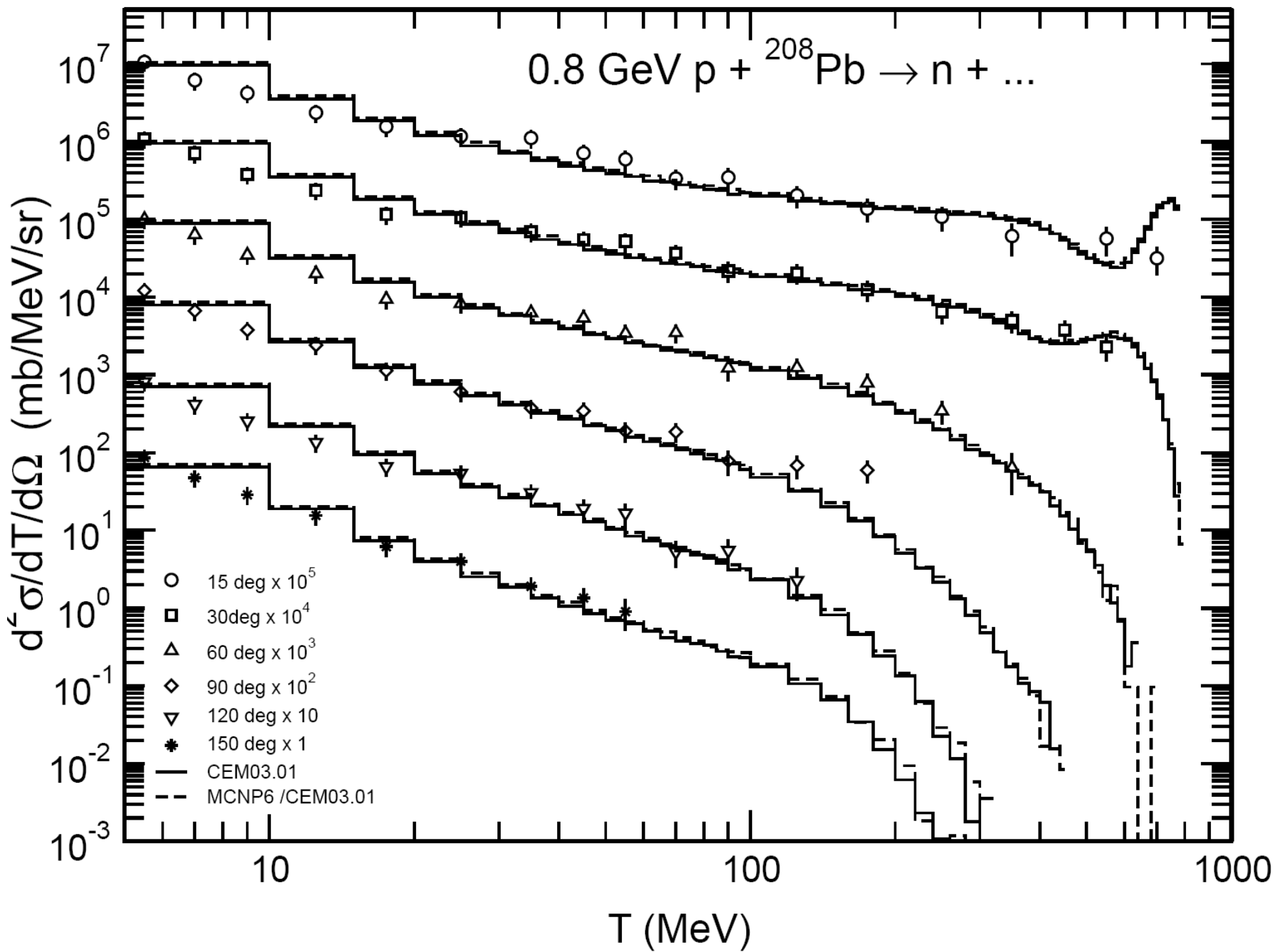


In comparison with its initial version [1] used in QGSM, in the initial version of LAQGSM, and in GEANT4 and SHIELD, we have modified the Fermi breakup model in the last versions of CEM and LAQGSM:

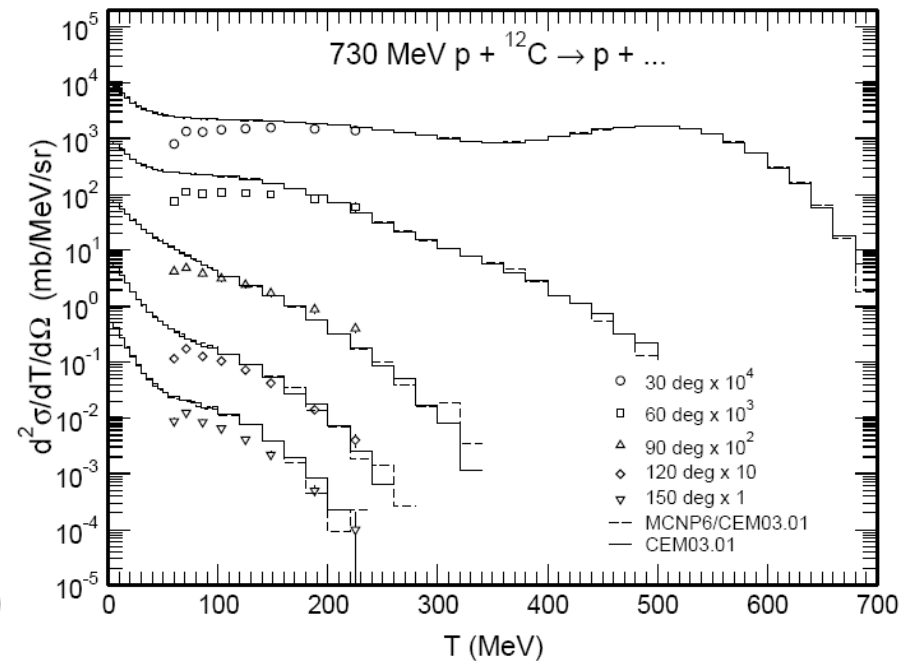
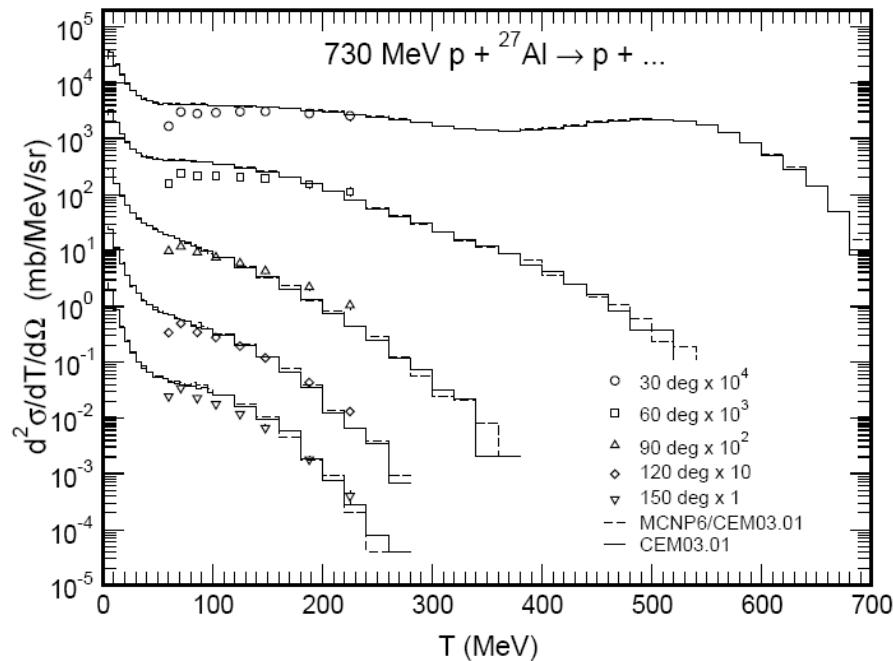
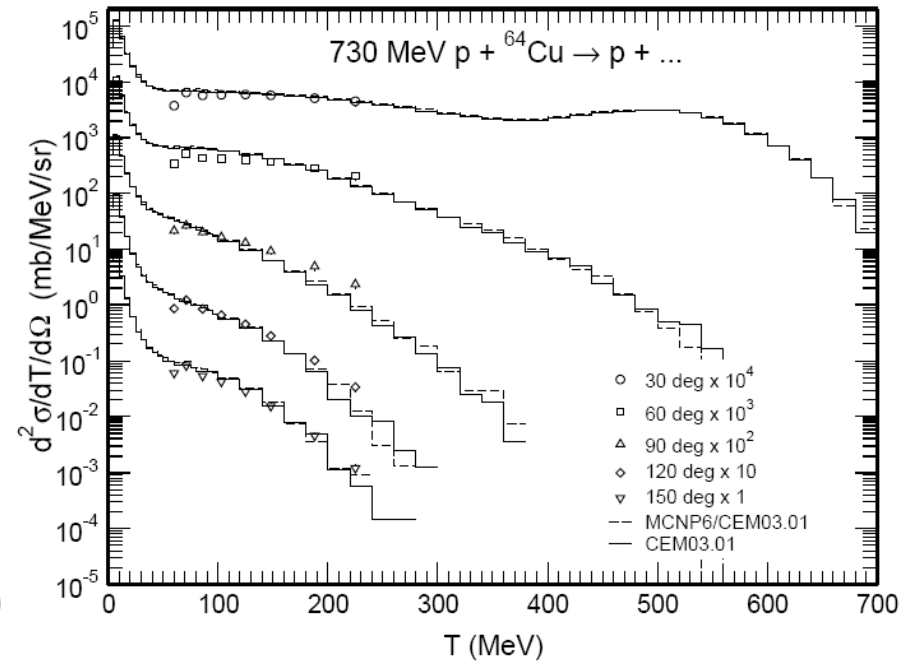
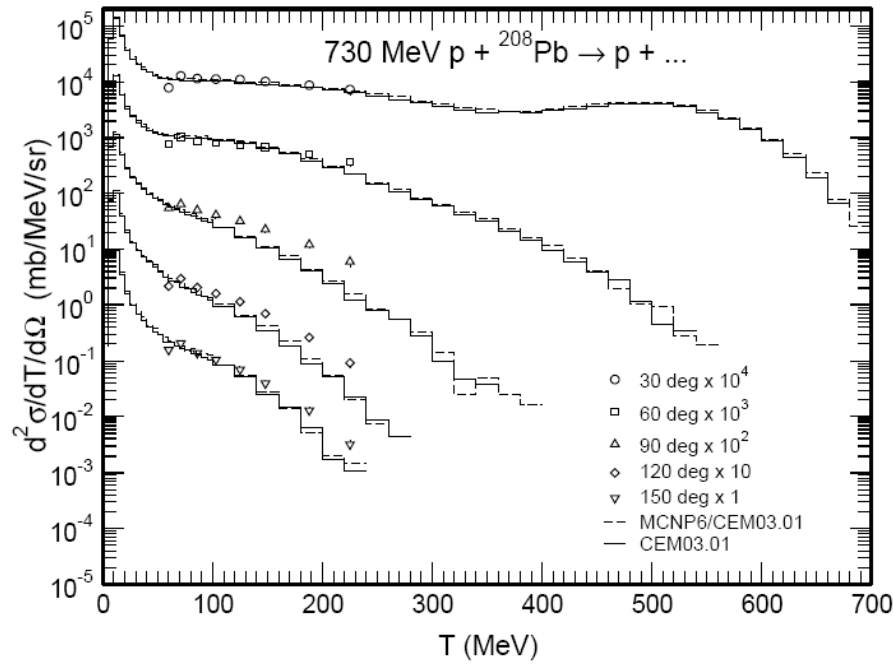
- 1) To decay some unstable light fragments like ${}^5\text{He}$, ${}^5\text{Li}$, ${}^8\text{Be}$, ${}^9\text{B}$, *etc.*, that were produced by the original Fermi breakup model;
- 2) Several bugs/uncertainties observed in the original version [1] were fixed; this solved the problem of the production 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).



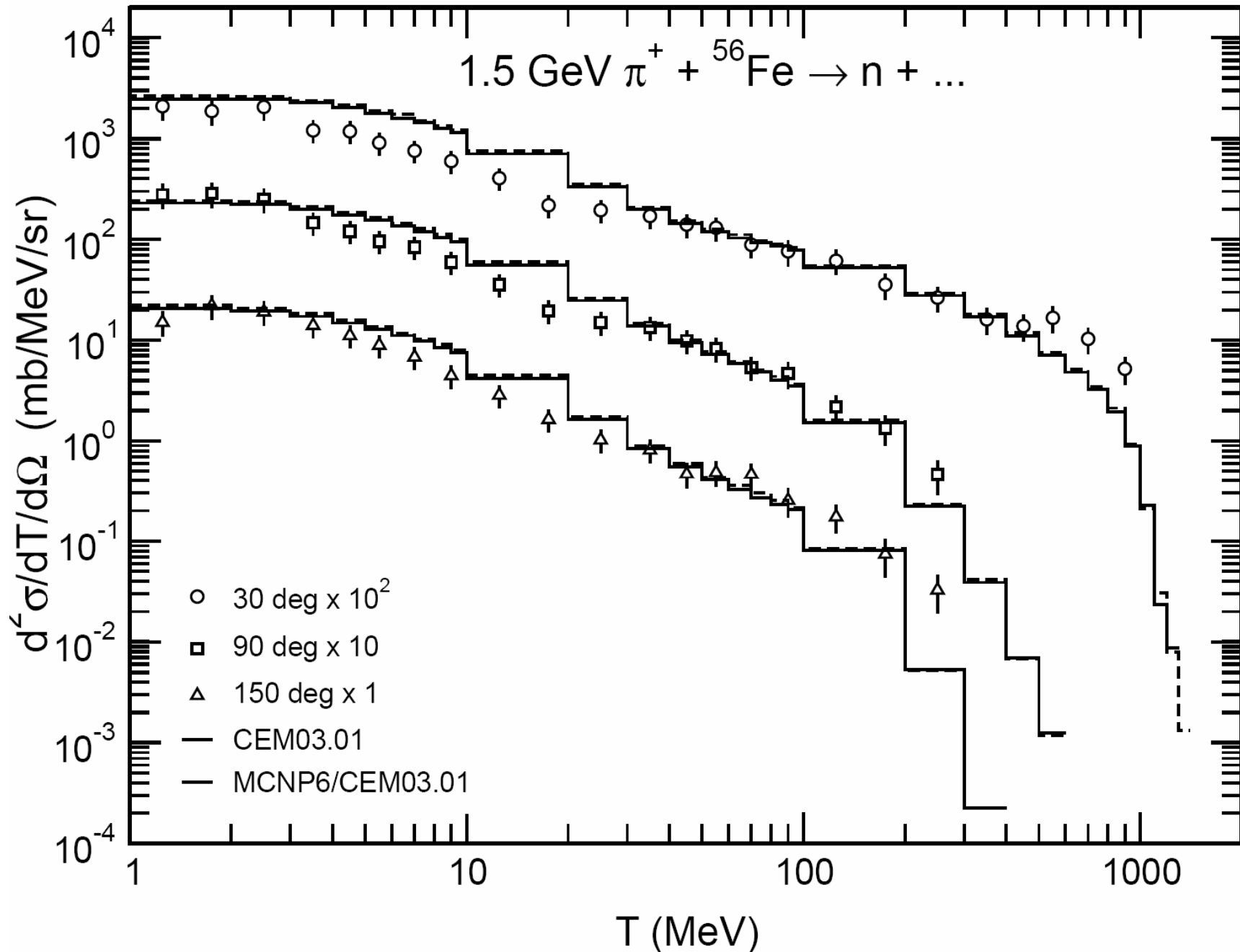




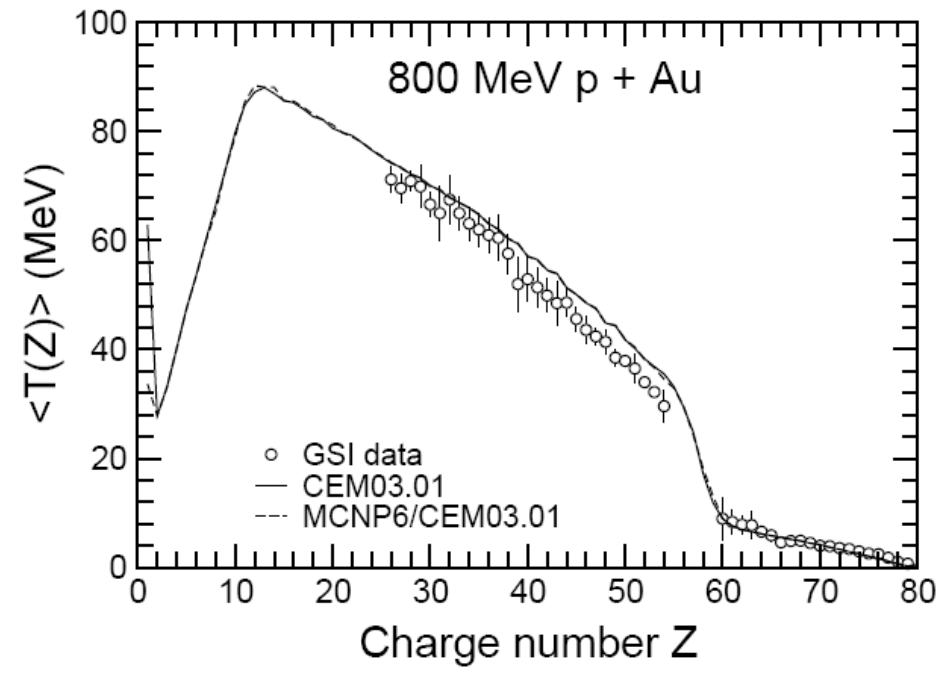
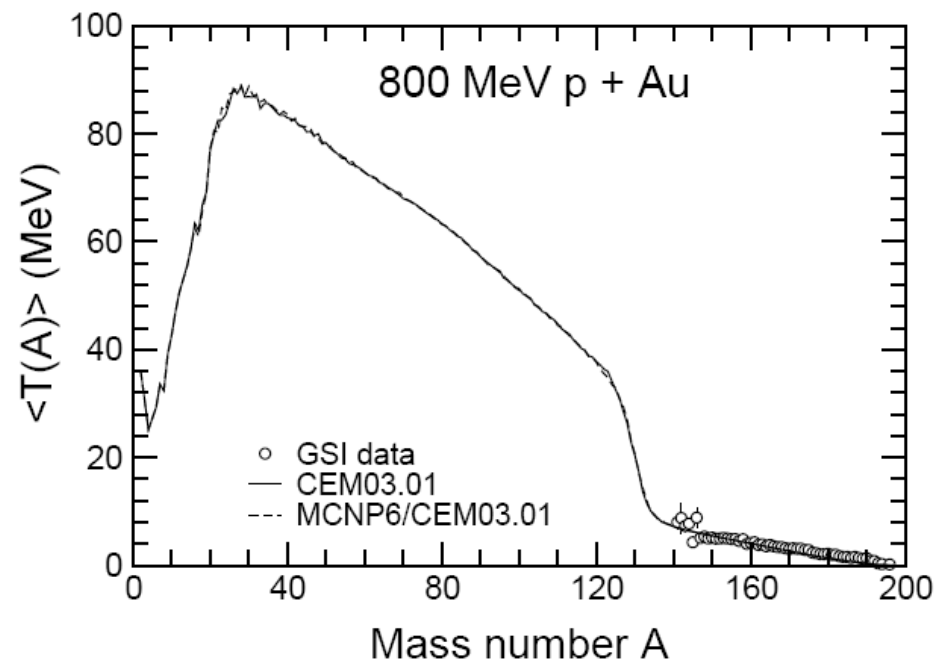
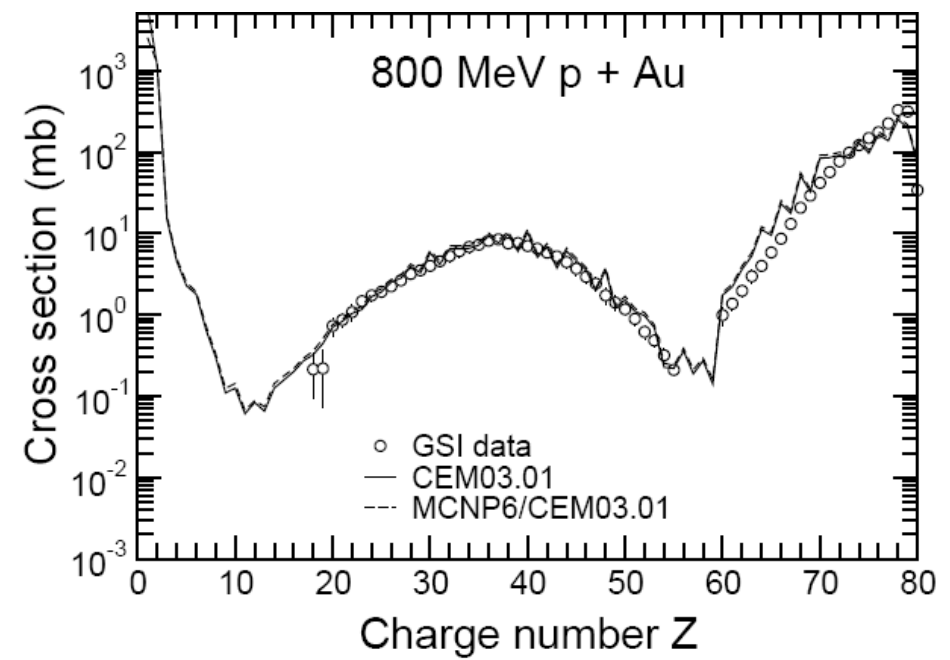
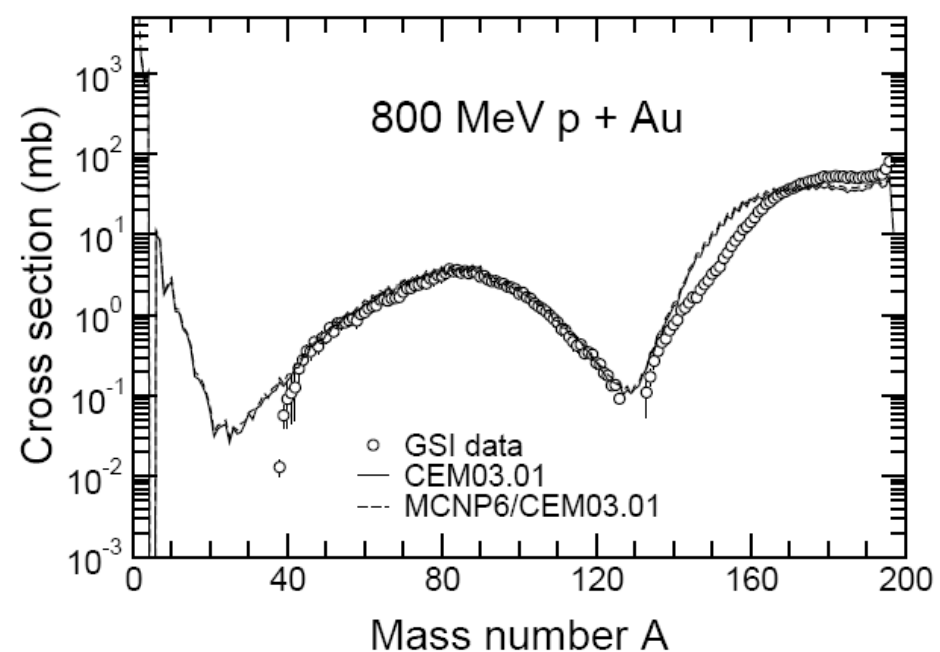
Data (symbols): K. Ishibashi et al., J. Nucl. Sci. Techn., 34 (1997) 529



Data (symbols): D. R. F. Cochran *et al.*, Phys. Rev. 6 (1972) 3085-3116



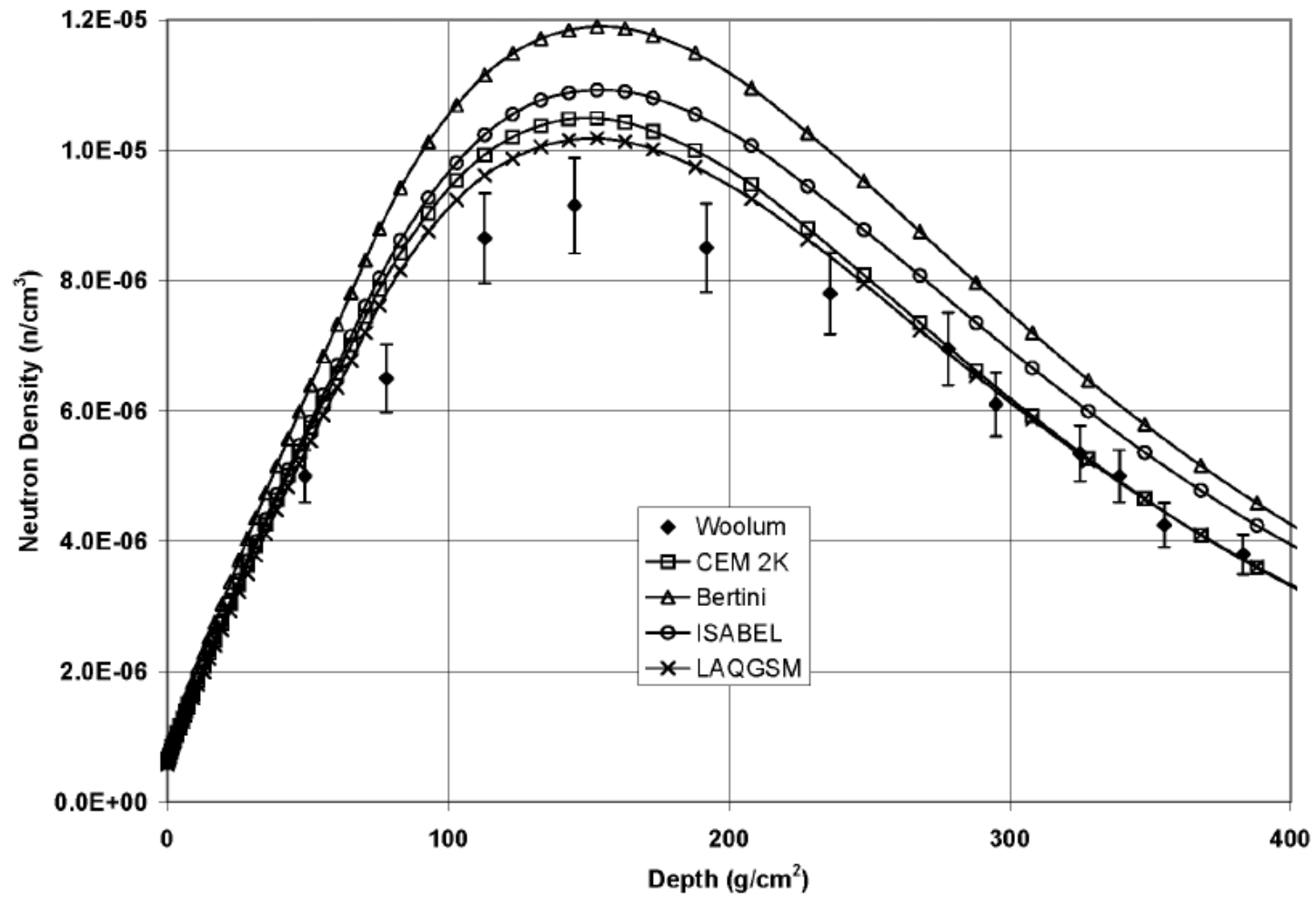
Data (symbols): T. Nakamoto *et. al.*, J. Nucl. Sci. Techn. 34 (1997) 860



GSI data (circles): F. Rejmund *et al.*, Nucl. Phys. **A683** (2001) 540; *ibid.*, p. 513

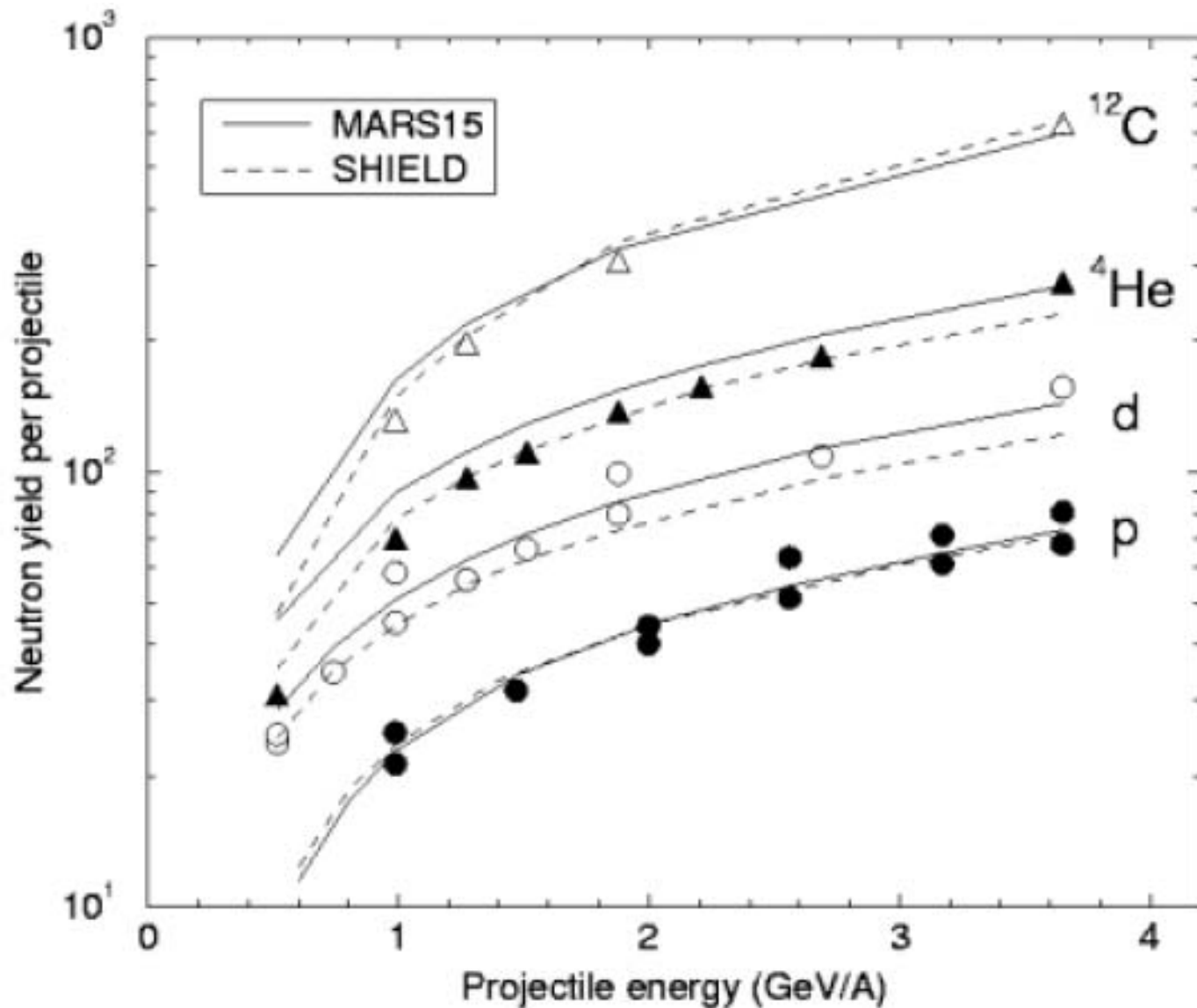


MCKINNEY ET AL.: COSMIC RAY INTERACTIONS WITH THE MOON



G.W. McKinney,
D.J. Lawrence,
T.H. Prettyman,
R.C. Elphic,
W.C. Feldman,
J.J. Hagerty,
J. Geophysical Res.,
Vol. 111, E06005,
Doi:10.1029/2005JE00
2551, 2006

Figure 7. Lunar neutron density profiles for various INC physics models.



N.V. Mokhov,
 K.K. Gudima,
 S.G. Mashnik,
 I.L. Rakhno,
 S.I. Striganov,
 Radiation Protection
 Dosimetry, Vol. 116,
 No. 1-4 (2005) 104-108

Figure 8. Calculated and measured⁽²⁵⁾ total neutron yield ($E < 14.5$ MeV) from a lead cylinder *versus* ion beam energy.



Summary

- CEM03.01 and LAQGSM03.01 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 patience and attention !**