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ITEP experiments with thin targets irradiated by upto 2.6 GeV protons

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M o s c o w

Russian Federation

ITEP experiments with thin targtets irradiated by upto 2.6GeV protons

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Content:

1. Residual nuclides measurements
    - ITEP accelerator
    - γ-spectrometry
    - Experimental uncertainties
    - Review of experiments performed
2. Comparison with other experiments
3. Comparison with codes
4. Conclusions

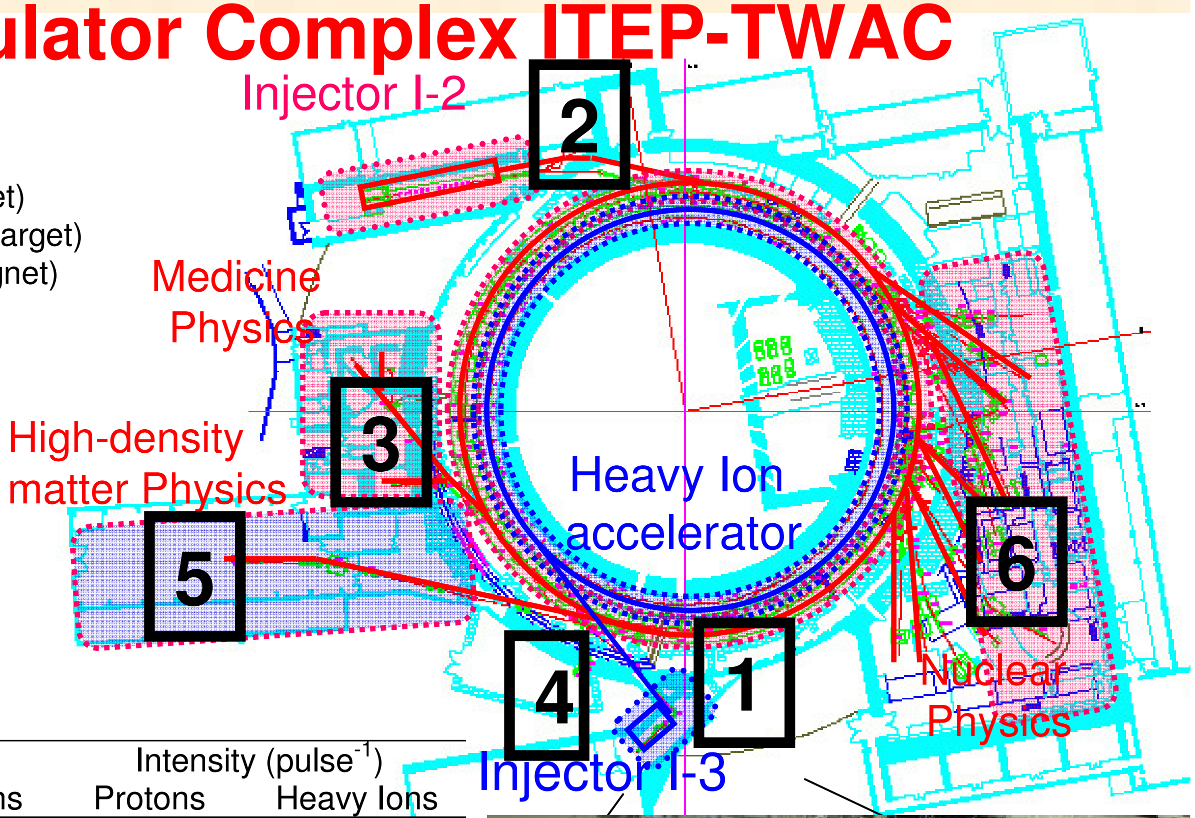
Accelerator-Accumulator Complex ITEP-TWAC

Main parameters:

Energy: Any from 25MeV to 9.3GeV
Intensity: <1E12 p/pulse (fast via kicker magnet)
~1E5-1E6 p/pulse (slow via internal target)
~1E10 p/pulse (slow via septum magnet)
Pulse rate: ~15pulses/min
Pulse Duration: ~100ns (fast)
up to ~500ms (slow)

Species:

Proton – since 1961
^{12}C – since 2002
^{27}Al – to be put in ~Dec2007
^{56}Fe – to be put in ~Mar2008
^{238}U – to be put ~Dec2008



Beam parameters:

№	Site	Energies		Intensity (pulse^{-1})	
		Protons	Heavy Ions	Protons	Heavy Ions
1	I-3: Heavy Ion injector	-	$^{12}C^{6+}$, $^{56}Fe^{15+}$, $^{238}U^{28+}$, 0.1-2 MeV/A	-	~10^9 -10^{11}
2	I-2: Proton Injector	<25MeV	-	~$1*10^{12}$	-
3	Medical beam	<250MeV	-	≤$1*10^{10}$	-
4	Fast extraction , Magnet Hall	<4GeV/c	<4ZGeV/c	≤$1*10^{12}$	~10^9 -10^{11}
5	Fast extraction , Experimental Hall #120	<4GeV/c	<4ZGeV/c	-	~$1*10^8$ (up to $1*10^{10}$ in future)
6	Slow extraction, Main Exp Hall	<10GeV/c	<10ZGeV/c	10^5-10^6	-/-

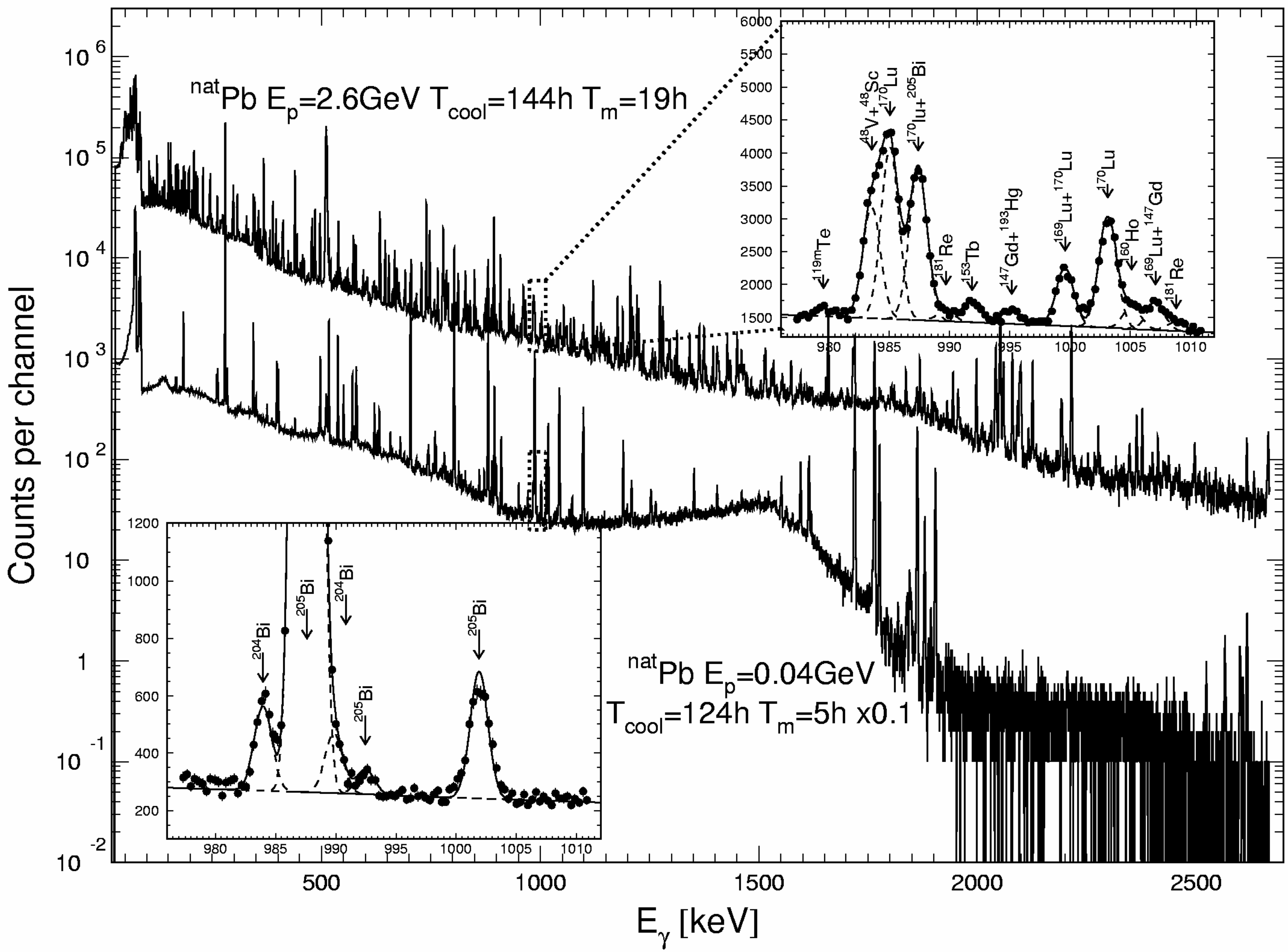
Targets Irradiation

U10 Synchrotron at ITEP:

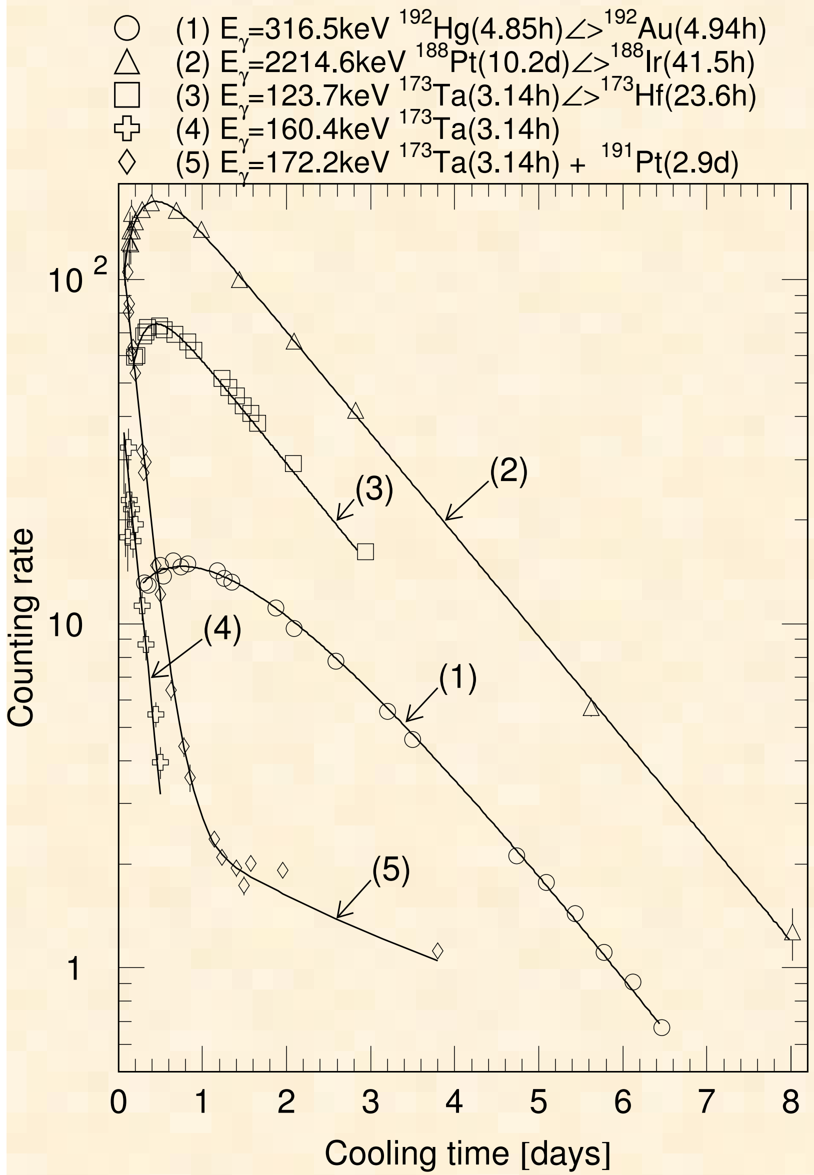
- Proton energy: 40-10000 MeV;
- Beam section: a circle of ~10 mm diameter;
- Intensity: ~$1 \cdot 10^{11}$ protons per pulse;
- Extraction runs: 4 100-ns bunches of 1 μs total duration.

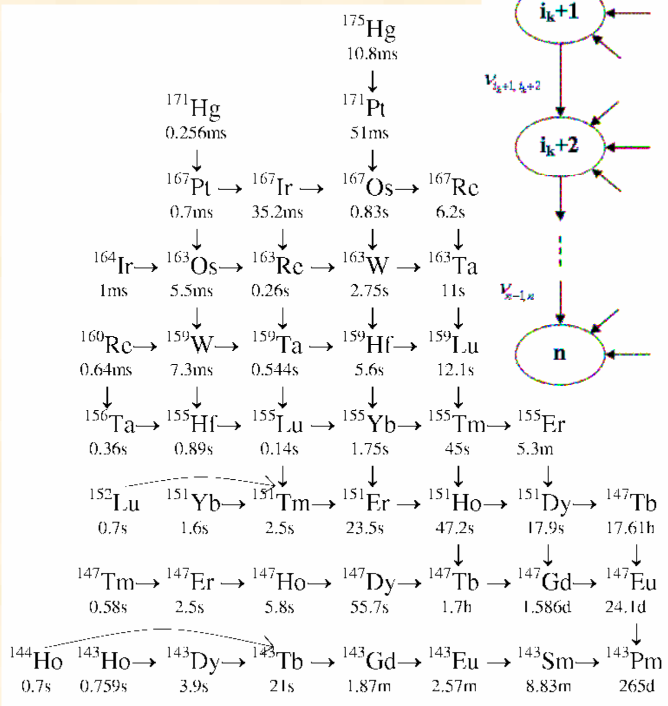
The transport channel schematic together with the elements of proton beam fast extraction.
1 - The table to place the irradiated samples. 2 – Current transformer. 3 – Outlet flange of the vacuum proton guide. 4 – Bending magnet. 5,6 – The doublet of quadrupole lenses to provide beam focusing. 7 – Septum magnet. 8,9 – Magnetic units of the accelerating ring. 10 – Kicker magnet with a 15 mrad bending angle

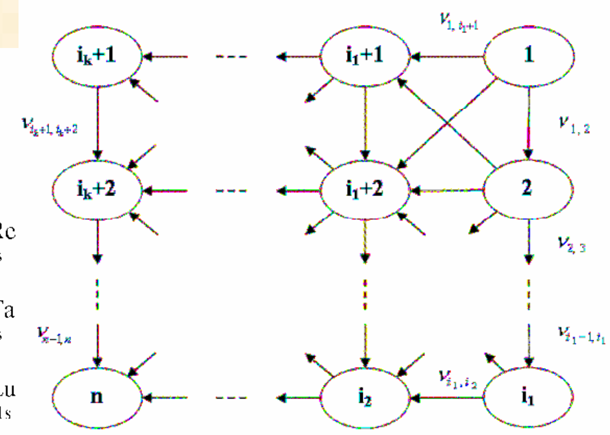
Gamma – spectra measurements



Determination of cross sections







^{143}Pm decay chain

$$R_1^{cum/ind} = \frac{1}{N_{Tag}\eta_2\varepsilon_2}\cdot\frac{B_1^*}{F_1}\cdot\frac{1}{\nu_{12}}\left(1-\frac{\lambda_1}{\lambda_2}\right),$$

$$R_2^{ind} = \frac{1}{N_{Tag}\eta_2\varepsilon_2}\left[\frac{B_2^*}{F_2}+\frac{B_1^*}{F_1}\frac{\lambda_1}{\lambda_2}\right],$$

$$R_2^{cum} = R_2^{ind}+\nu_{12}R_1^{cum/ind} = \frac{1}{N_{Tag}\eta_2\varepsilon_2}\left[\frac{B_1^*}{F_1}+\frac{B_2^*}{F_2}\right]$$

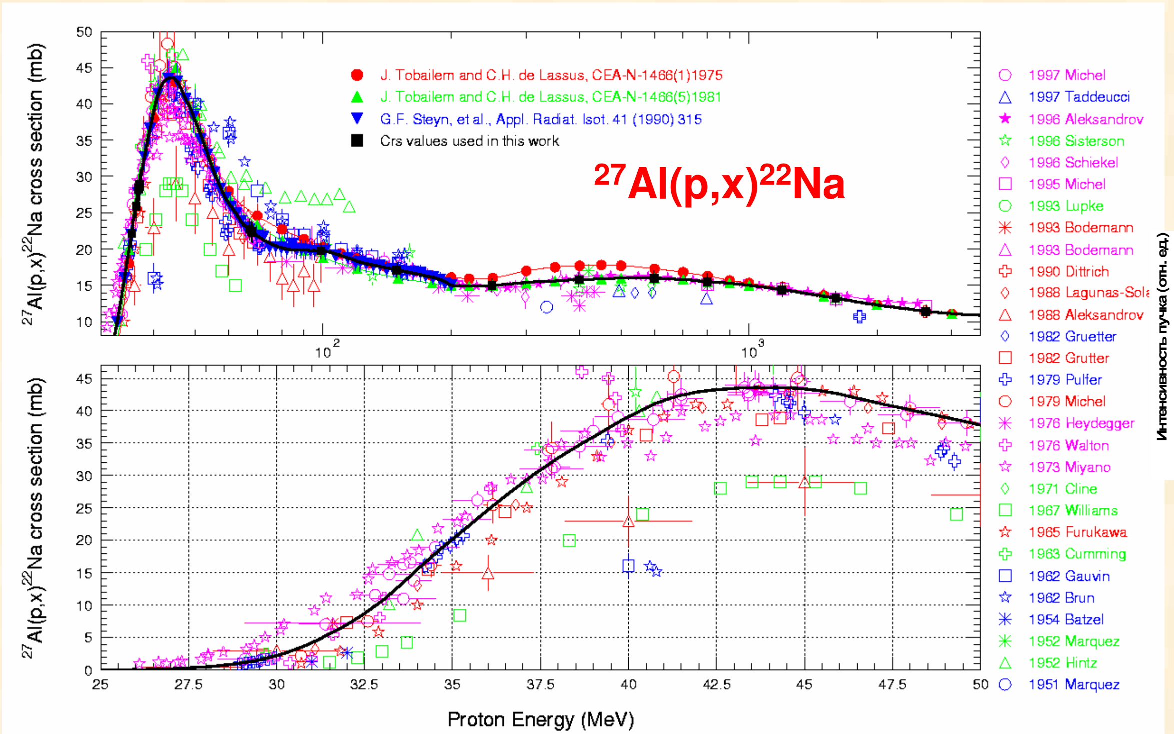
$$\sigma = R/\Phi_p$$

Proton flux determination

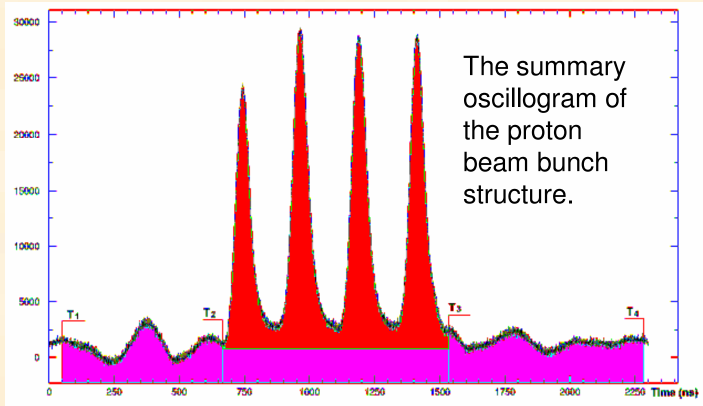
Monitor reaction techniques

$$\hat{\Phi} = \frac{R_{st}^{cum}}{\sigma_{st}^{cum}}$$

$$\frac{\Delta\hat{\Phi}}{\hat{\Phi}} = \sqrt{\left(\frac{\Delta R_{st}^{cum}}{R_{st}^{cum}}\right)^2 + \left(\frac{\Delta\sigma_{st}^{cum}}{\sigma_{st}^{cum}}\right)^2}$$

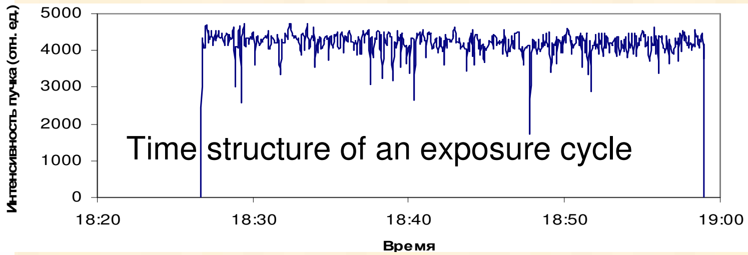


Fast Current Transformer techniques



Proton flux by FCT:

$$\Phi_{FCT} = \frac{I \cdot t \cdot k_{flux}}{K \cdot z \cdot e \cdot T_{irr} \cdot S}$$

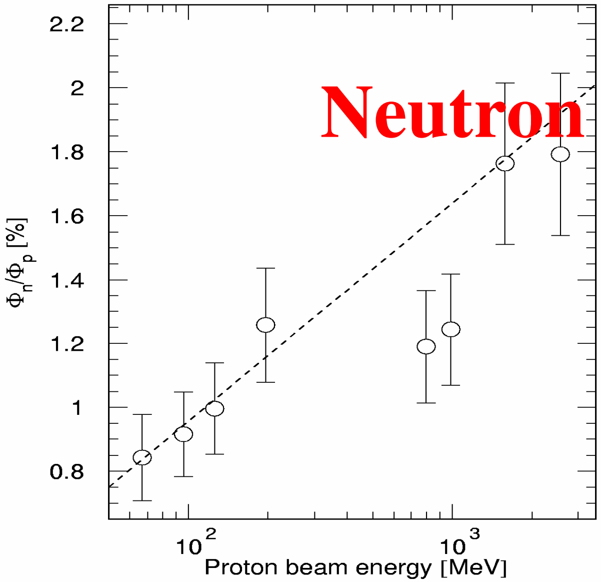


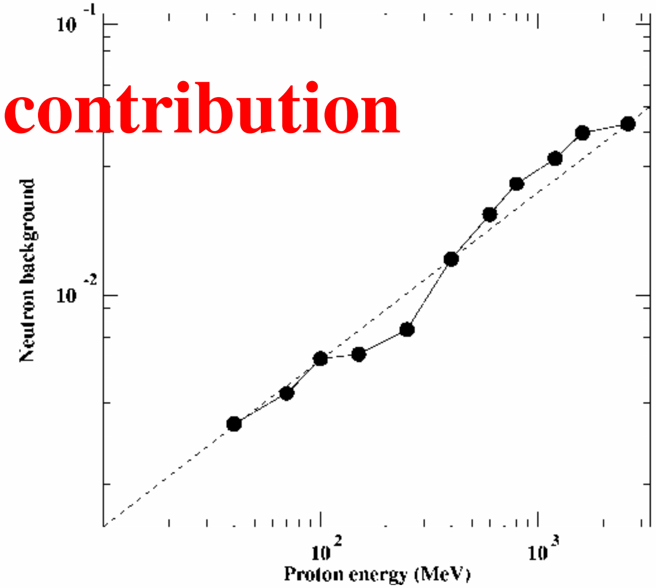
Correction factor to allow decay of short-lived nuclides:

$$k_{f(t)} = \frac{\left(1 - e^{-\lambda \cdot t_{irr}}\right) \cdot \sum_{j=1}^{K} \Phi_j}{\lambda \cdot t_{irr} \cdot \left(\sum_{j=1}^{K} \Phi_j \cdot e^{-\lambda (t_{irr} - t_j)}\right)}$$

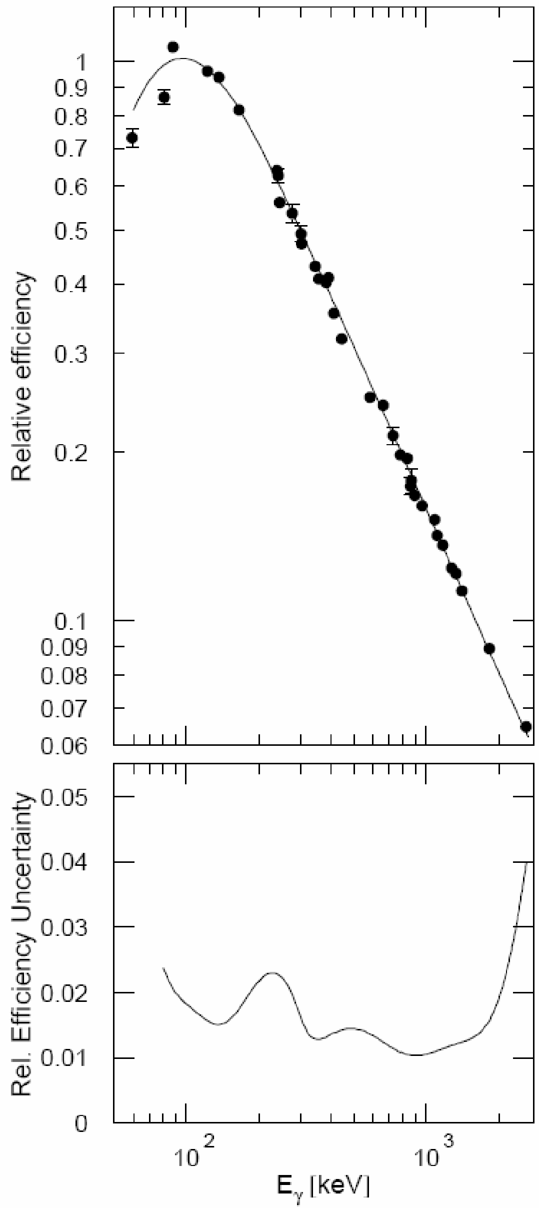
Specific uncertainties

Neutron contribution

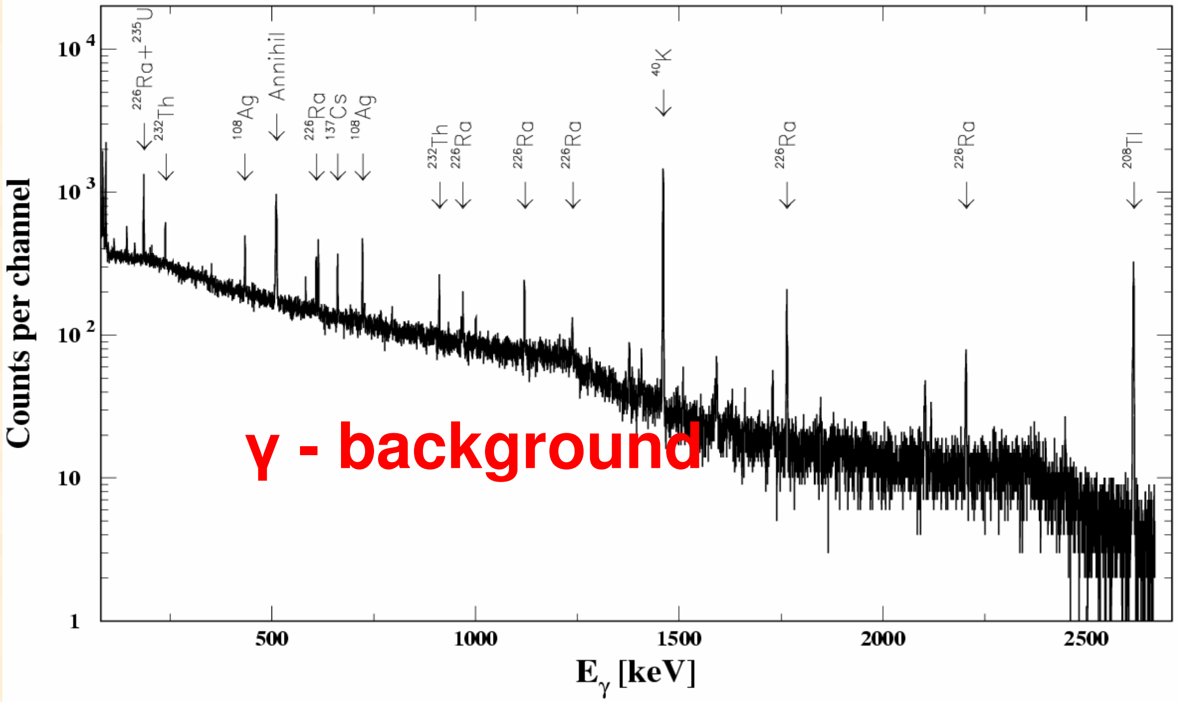




HPGe-efficiency



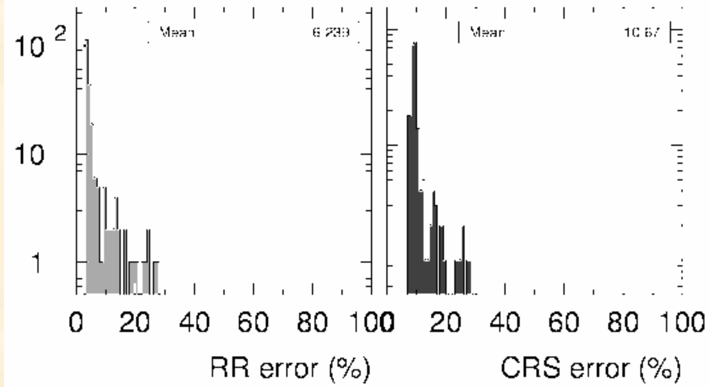
γ - background



Experimental uncertainties

$$\overline{R}_i^{cum/ind} = \frac{{}^{rel}\overline{R}_{ij}^{cum/ind}}{k_{\gamma_i}\cdot k_{\varepsilon}\cdot N_{tag}}$$

$$\Delta\overline{R}_i^{cum/ind} = \overline{R}_i^{cum/ind}\cdot\sqrt{\left(\frac{\Delta\,{}^{rel}\overline{R}_i^{cum/ind}}{{}^{rel}\overline{R}_i^{cum/ind}}\right)^2+\left(\frac{\Delta k_{\gamma_i}}{k_{\gamma_i}}\right)^2+\left(\frac{\Delta k_{\varepsilon}}{k_{\varepsilon}}\right)^2+\left(\frac{\Delta N_{tag}}{N_{tag}}\right)^2}$$



Sources of errors	Value in % in case of ^{56}Fe(p,x)	
	Experim. samples	Monitor samples
Statistical error of count rate in total absorption peak with due allowance for correction of unresolved γ-lines under the peak, for γ-spectrum transients, and for the spectrometer dead time and count loss.	1.1 – 27	0.79 – 3.5
Uncertainty in the correction for γ-absorption in samples.	0.03 – 0.07	0.01 – 0.02
Uncertainty in the absolute spectrometer detection effectiveness with due allowance for uncertainty in cascade summation effects and in contributions from the peaks of double and single ejections.	3.3 – 3.4	3.3
Uncertainty in the relative spectrometer detection effectiveness and in the relative-to-absolute effectiveness scaling factor.	1.05 – 1.5 0.71	-
Uncertainty in the γ-abundances. Uncertainty in the γ-abundance to relative yield scaling factor.	0 – 7.1	0.01
Uncertainty in the number of experimental sample nuclei.	0.05	0.05
Total uncertainty of measured Reaction Rates	3.3 - 28	3.4 – 4.8
Uncertainty in the ^{27}Al(p,x)^{22}Na monitor reaction cross section	6.3 - 7.9	
Uncertainty of Proton Flux	7.1 – 9.2	
Total uncertainty of measured Cross Sections	8 - 29	

ISTC Project #839 (1997-1998; 1999-2000, Japan, EU, Norway)

Experimental and Theoretical Study of the Residual Product Nuclide Yields in Thin Targets Irradiated with 100-2600 MeV Protons

Proton Energy [GeV]	Targets																			
	^{56}Fe	^{58}Ni	^{59}Co	^{63}Cu	^{65}Cu	^{93}Nb	^{99}Tc	^{182}W	^{183}W	^{184}W	^{186}W	^{nat}W	^{nat}Hg	^{206}Pb	^{207}Pb	^{208}Pb	^{nat}Pb	^{209}Bi	^{232}Th	^{nat}U
0.1			25	11	6		18						44	22	22	20		26	87	108
0.2			29	29	29		39	32	35	36	36		65						128	123
0.8							72	70	76	77	62								130	195
1.0							64									114				
1.2			41	47	54		67						103						214	226
1.5				35	36									92	93	94	93	99		
1.6			41	42	47		78	109	111	114	119		141						212	231
2.6	36	38	41	42	48	85	85					129								
ADS element	SM, Sh, TM	SM	SM	SM	SM	SM	FP	TM	TM	TM	TM	TM	TM	TM	TM	TM	TM	TM	Th-cycle	Fuel

SM – Structure Material; **Sh** – Shielding Material; **FP** – Fission Product;
TM - Target material; **Th** - Th fuel cycle, breeding; **Fuel** - Fuel compositions

More than 5000 products were determined. Final Technical Report is available via http://www-nds.iaea.org/reports/indc-ccp-434.pdf; EXFOR Data files#: O0781, O0782, O0978-O0987, O1018-O1021

ISTC Project #2002 (2002-2004, funded by EC)

Experimental and theoretical studies of the yields of residual product nuclei produced in thin Pb and Bi targets irradiated by 40-2600 MeV protons

Target	Proton Energy (GeV)										
	0.04	0.07	0.1	0.15	0.25	0.4	0.6	0.8	1.2	1.6	2.6
^{nat}Pb	18	28	43	63	95	116	141	154	171	181	178
^{208}Pb	8	28	36	63	94	113	141	154	170	182	172
^{207}Pb	9	29	42	65	94	112	140	152	170	180	171
^{206}Pb	13	28	46	65	94	112	139	156	170	180	171
^{209}Bi	13	35	50	71	106	128	147	162	183	192	198

***TOTAL number of measured yields: 5972** (+11 ^{194}Hg)*

- Detailed information on reaction rates per each gamma-line presented!
- Decay chains description presented

- Isotopic composition of targets

Targets	Isotopic composition, %				
	^{204}Pb	^{206}Pb	^{207}Pb	^{206}Pb	^{209}Bi
^{208}Pb	<0.01	0.87	1.93	97.2	-
^{207}Pb	<0.01	1.39	93.2	5.41	-
^{206}Pb	0.19	92.3	5.1	2.41	-
^{nat}Pb	1.4	24.1	22.1	52.4	-
^{209}Bi	-	-	-	-	>99.9

Final Technical report: http://www.nea.fr/html/science/egsaatif/ISTC2002-final-report.pdf

ISTC Project #3266 (2006-2009, funded by EC)

Experimental and theoretical study of the residual nuclide production in 40-2600 MeV proton-irradiated thin targets of ADS structure materials

Targets	Proton energies (MeV)										
	40	70	100	150	250	400	600	800	1200	1600	2600
^{56}Fe +	x	x	x	x	I	I	I	38	39	38	40
^{nat}Cr	x	x	x	x	I	I	I	30	31	32	32
^{nat}Ni	x	x	x	x	I	I	I	43	42	46	46
^{93}Nb	x	x	x	x	I	I	I	105	110	123	128
^{181}Ta	x	x	x	x	I	I	I	I	I	I	I
^{nat}W	x	x	x	x	I	I	I	I	I	I	I

^{56}Fe is also measured at 300, 500, 750, 1000, and 1500 MeV to be compared with recent GSI measurements (P. Napolitani et al., PRC (2007)

Isotopic composition of the targets

Isotope	Number of samples	Isotopic composition, %
^{56}Fe	15	^{54}Fe-0.3, ^{56}Fe-99.5±0.1, ^{57}Fe-0.2, ^{58}Fe-<0.05.
^{nat}Cr	11	^{50}Cr-4.345 , ^{52}Cr-83.789 , ^{53}Cr-9.501, ^{54}Cr-2.365 .
^{nat}Ni	11	^{58}Ni-68.077, ^{60}Ni-26.223, ^{61}Ni-1.140, ^{62}Ni-3.634, ^{64}Ni-0.926
^{93}Nb	10	^{93}Nb > 99.9
^{181}Ta	15	^{180}Ta-0.012, ^{181}Ta-99,988.
^{nat}W	14	^{180}W-0.12, ^{182}W-26.50, ^{183}W-14.31, ^{184}W-30.64, ^{186}W – 28.43.

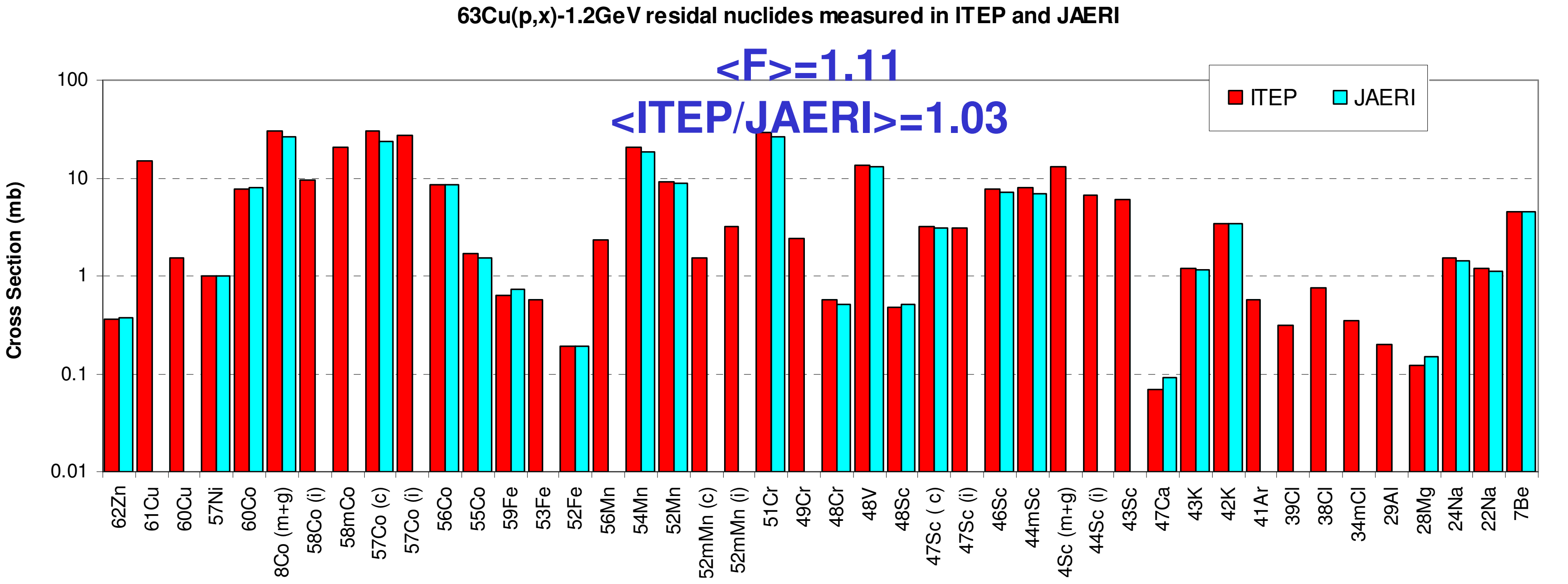
List of irradiation runs for alpha-active nuclide (^{148}Gd) production measurements.

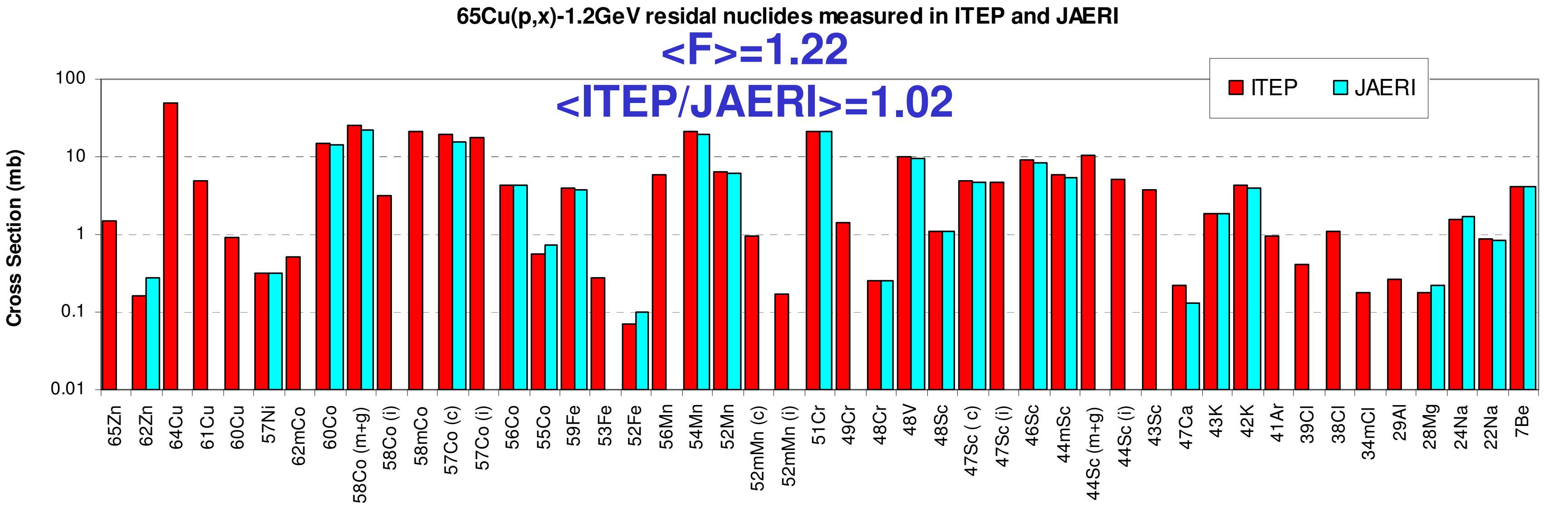
Targets	Proton energies (MeV)			
	600	800	1600	2600
^{181}Ta	I	I	I	I
^{nat}W	i	i	i	i

Comparison with other experiments

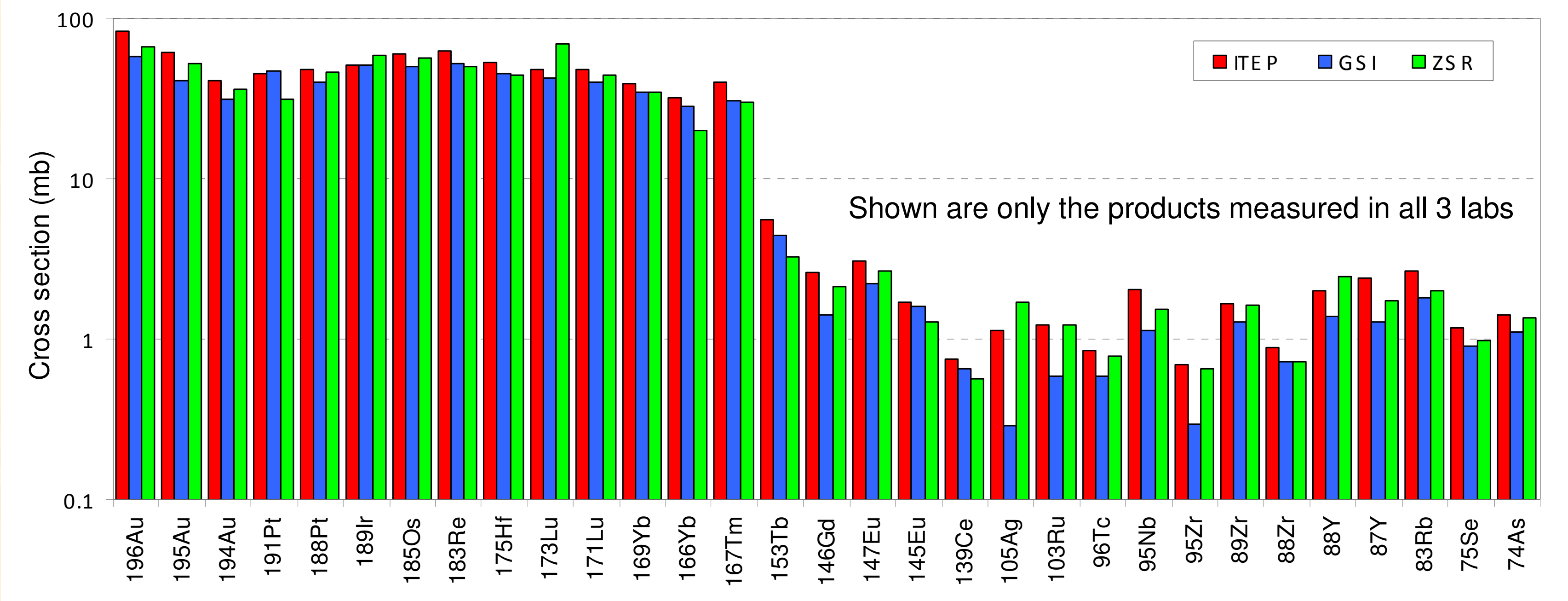
- ITEP and JAERI intercalibration on ^{63}Cu and ^{65}Cu irradiated with 1.2 GeV protons;
- ITEP / GSI comparison for the residual nuclide yields in ^{56}Fe irradiated with 0.3, 0.5, 0.75, 1.0, 1.5 GeV protons (C. Villagrasa-Canton et al., PRC 75 (2007) 044603);
- ITEP / GSI / ZSR comparison ^{197}Au, ^{208}Pb, and ^{238}U irradiated with 0.5, 0.8, and 1.0 GeV protons (Nucl. Phys. A686, 481 (2001), Nucl. Instr. Meth., A464, 593 (2001))

^{63,65}Cu(p,x)-1.2GeV: ITEP vs. JAERI





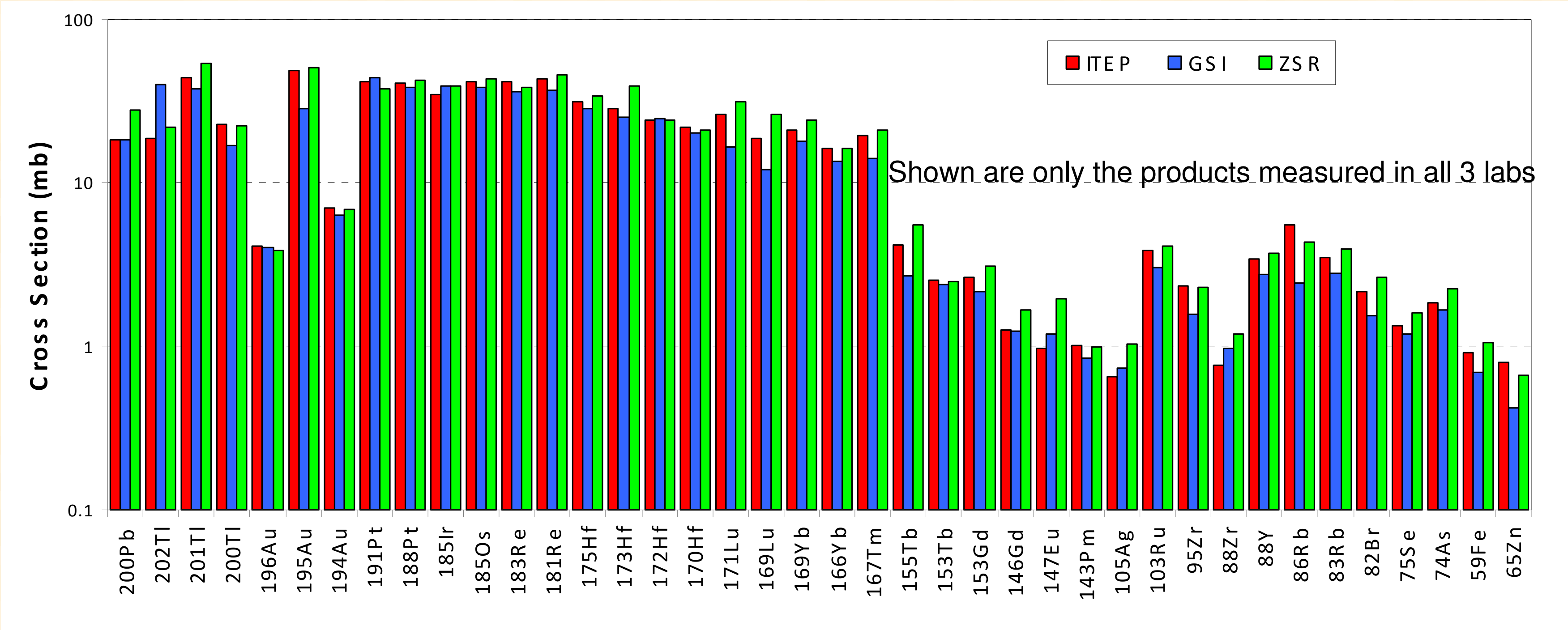
Au(p,x)-0.8GeV: ITEP; GSI; ZSR



	<F>	$<\sigma_{1,i} / \sigma_{2,i}>$
ITEP/GSI	1.54	1.45
GSI/ZSR	1.56	0.88
ITEP/ZSR	1.28	1.17

GSI < ZSR< ITEP

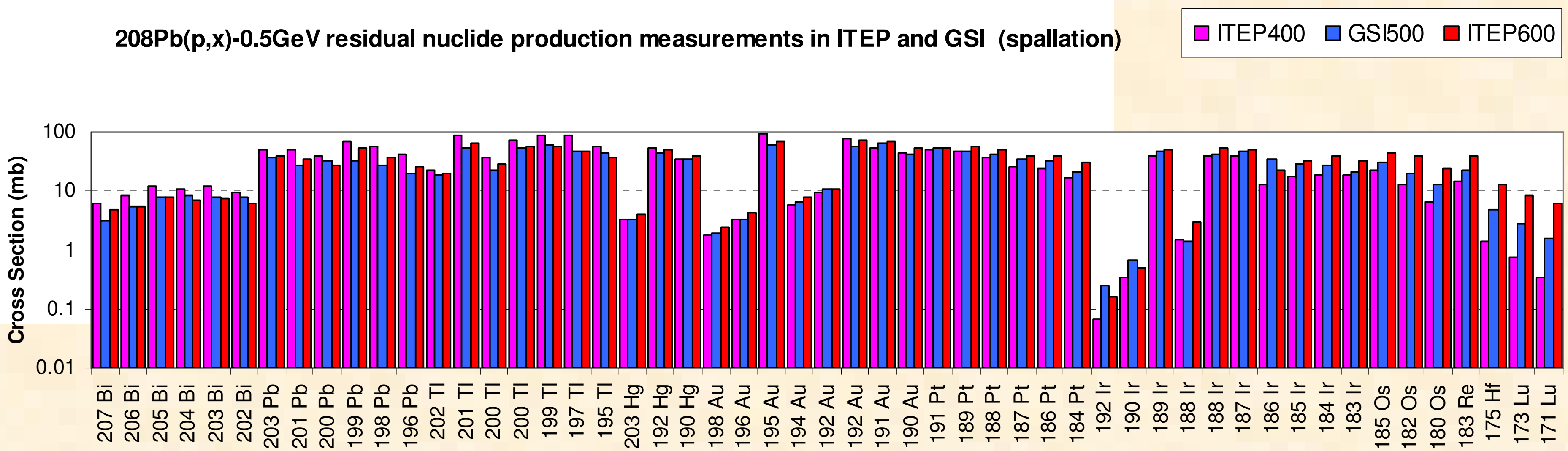
^{208}Pb(p,x)-1.0GeV: ITEP; GSI; ZSR



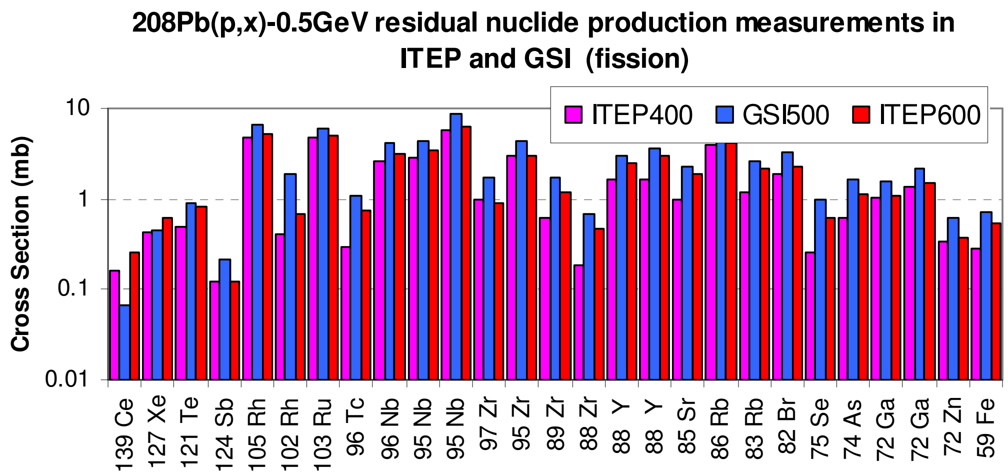
	<F>	$<\sigma_{1,i} / \sigma_{2,i}>$
ITEP/GSI	1.35	1.20
GSI/ZSR	1.45	0.79
ITEP/ZSR	1.25	0.90

GSI < ITEP < ZSR

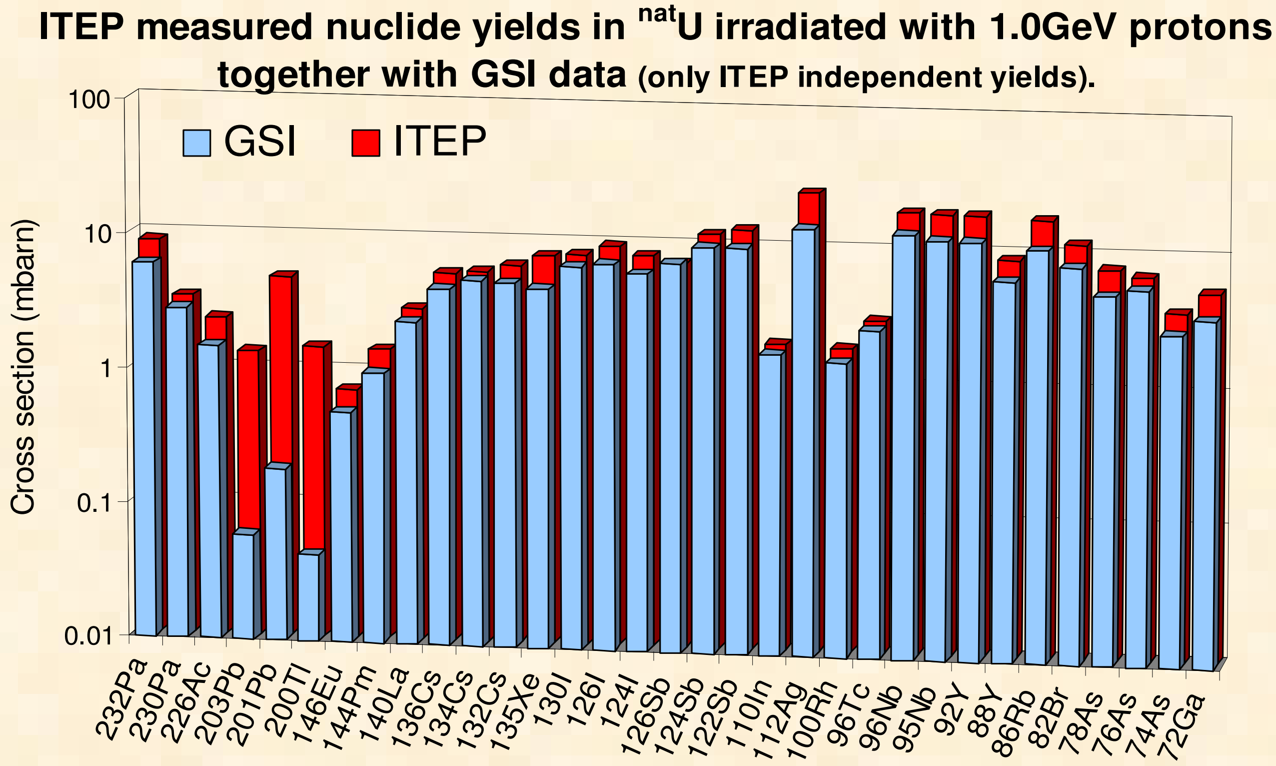
^{208}Pb(p,x)-0.5GeV: ITEP, GSI



	<F>	<ITEP/GSI>
All products	1.51	0.98
Spallation pr.	1.32	1.12
Fission pr.	1.81	0.71



^{238}U(p,x)-1.0GeV: ITEP, GSI



	<F>	<ITEP/GSI>
All products – ^{203}Pb, ^{201}Pb, ^{200}Tl	1.39	1.35

Conclusion on exp-comparisons

- A large set of comparisons between ITEP, GSI and ZSR data is shown.

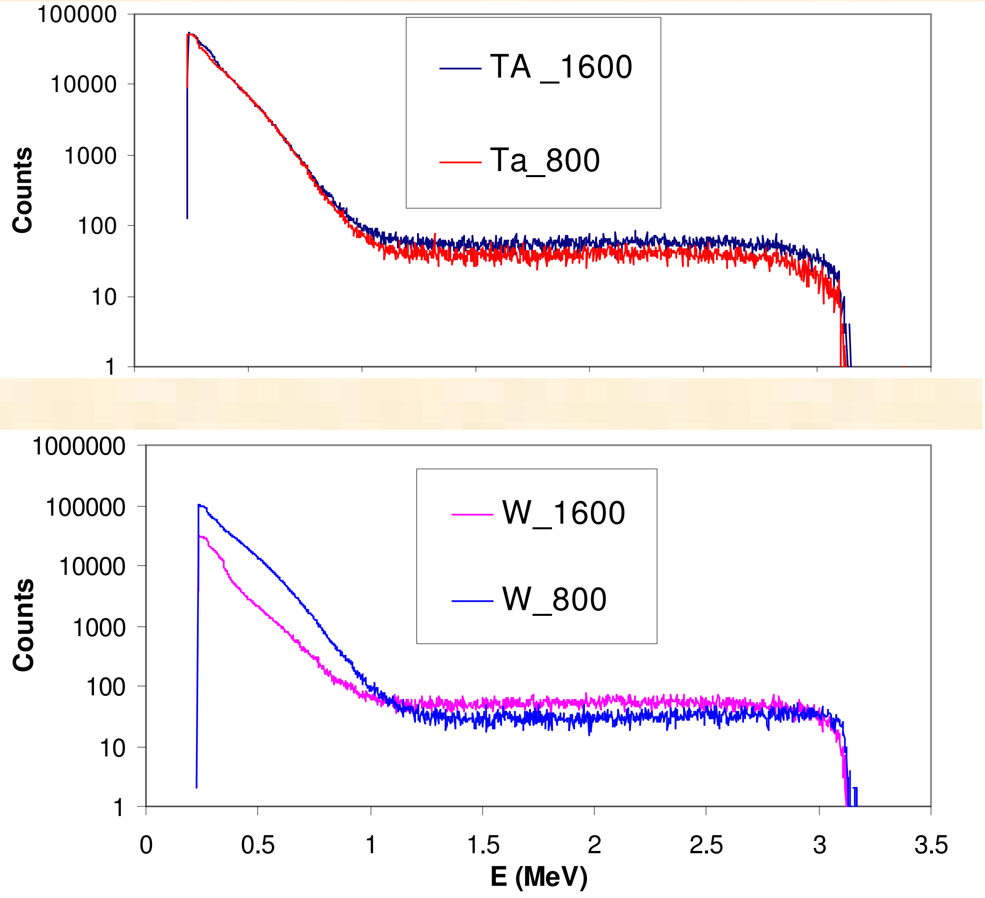
Target	Energy (GeV)	set	<F>	$\langle\sigma_{1,i} / \sigma_{2,i}\rangle$
^{63}Cu ^{65}Cu	1.2GeV	ITEP/JAERI	1.11 1.22	1.03 1.02
^{56}Fe	0.3, 0.5, 0.75 1.0, 1.5	ITEP/GSI	1.36	
^{197}Au	0.8GeV	ITEP/GSI GSI/ZSR ITEP/ZSR	1.54 1.56 1.28	1.45 0.88 1.17
^{208}Pb	0.5GeV	ITEP/GSI	1.51 – all products 1.32 – spallation pr. 1.81 – fission pr.	0.98 – all products 1.12 – spallation pr. 0.71 – fission pr.
	1.0GeV	ITEP/GSI GSI/ZSR ITEP/ZSR	1.35 1.45 1.25	1.20 0.79 0.90
^{238}U	1.0GeV	ITEP/GSI	1.39	1.35

- <F> varies from ~1.1 to ~1.5:
  - ITEP/JAERI – 1.1-1.2
  - ITEP/ZSR – 1.2-1.3
  - ITEP/GSI – 1.4-1.5
  - ZSR/GSI – 1.5

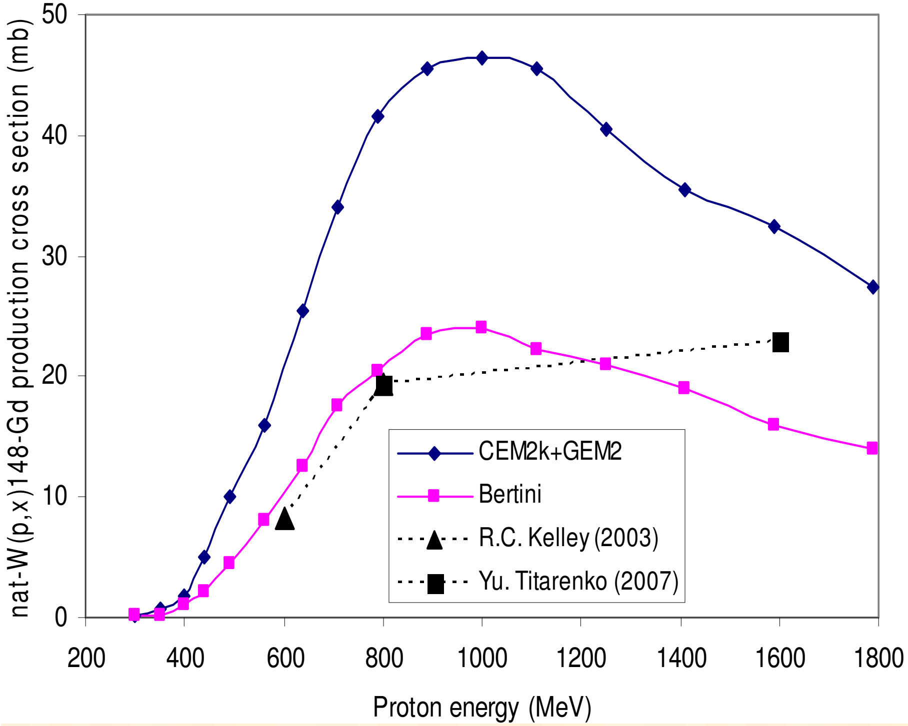
The data from the same type of experimental methods agree better than from the different

1) Inverse kinematics data (GSI) data are valuable for theory modifications
2) Gamma-spectroscopy (ITEP,ZSR) data are valuable for testing codes for applications

α-active ^{148}Gd measurements in Ta,W(p,x) reactions

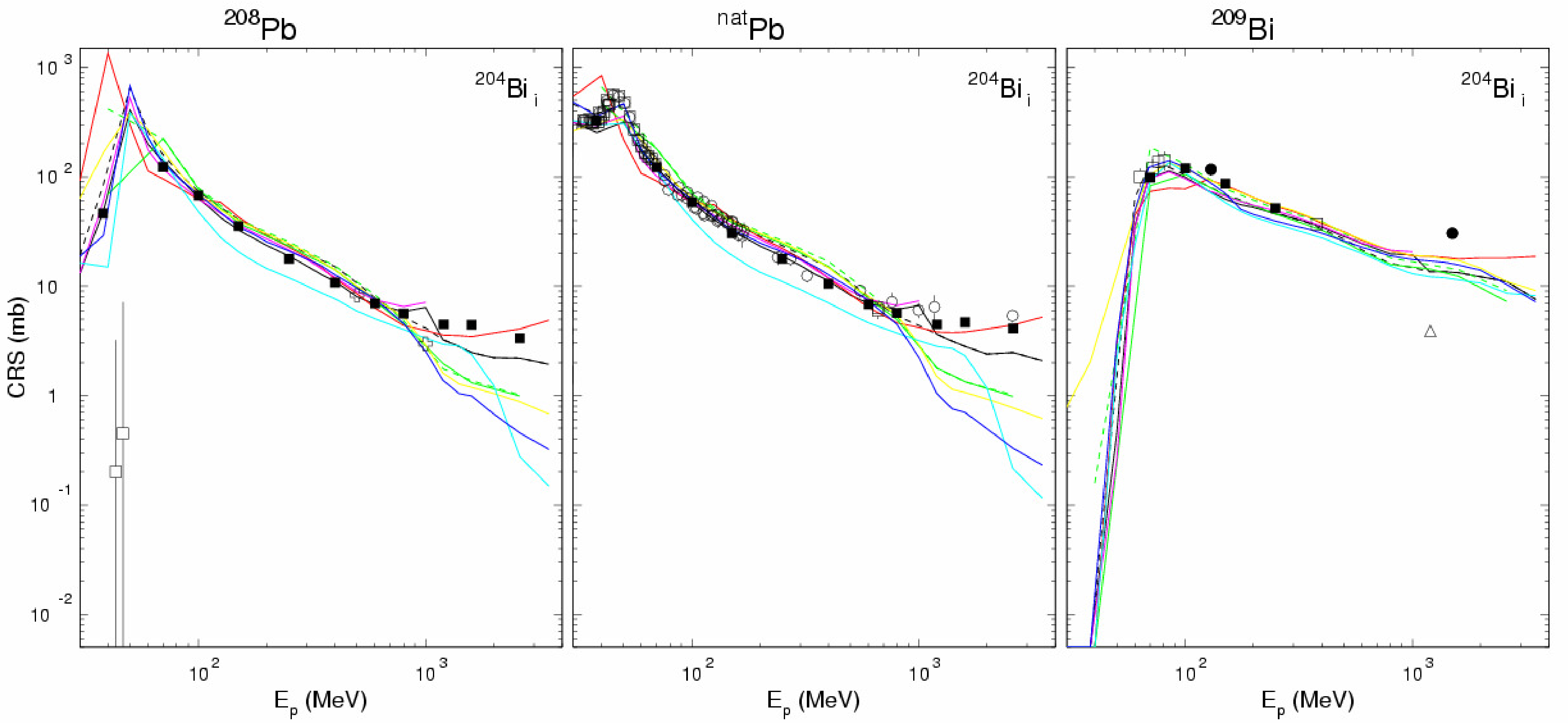


α- + β-spectra from irradiated Ta and W with 800 and 1600 MeV protons



Excitation functions of 148Gd production in W(p,x) measured and predicted via CEM2k+GEM2 and MCNPX(Bertini) codes.

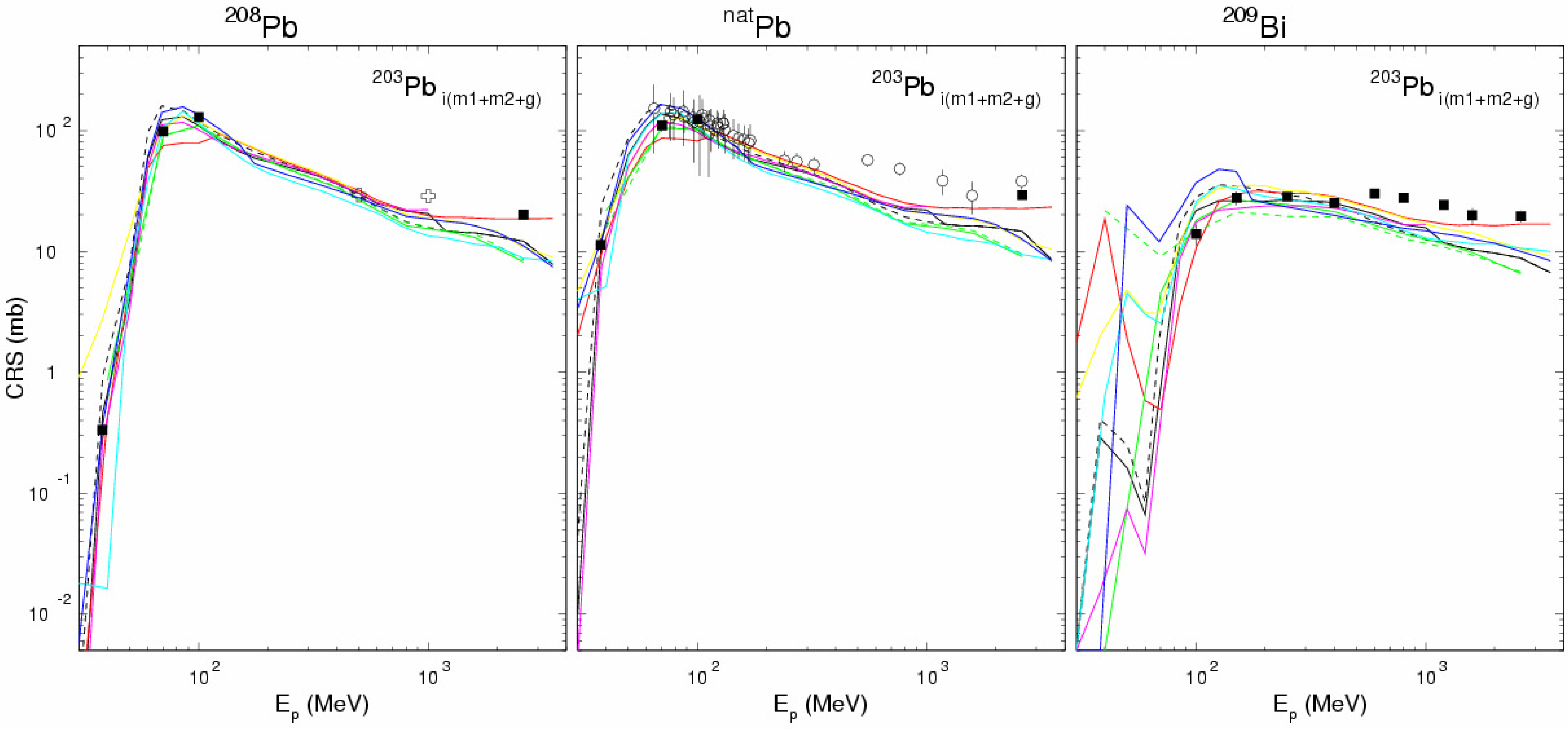
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Spallation products (1)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✣ - *GSI*, □ - *others*

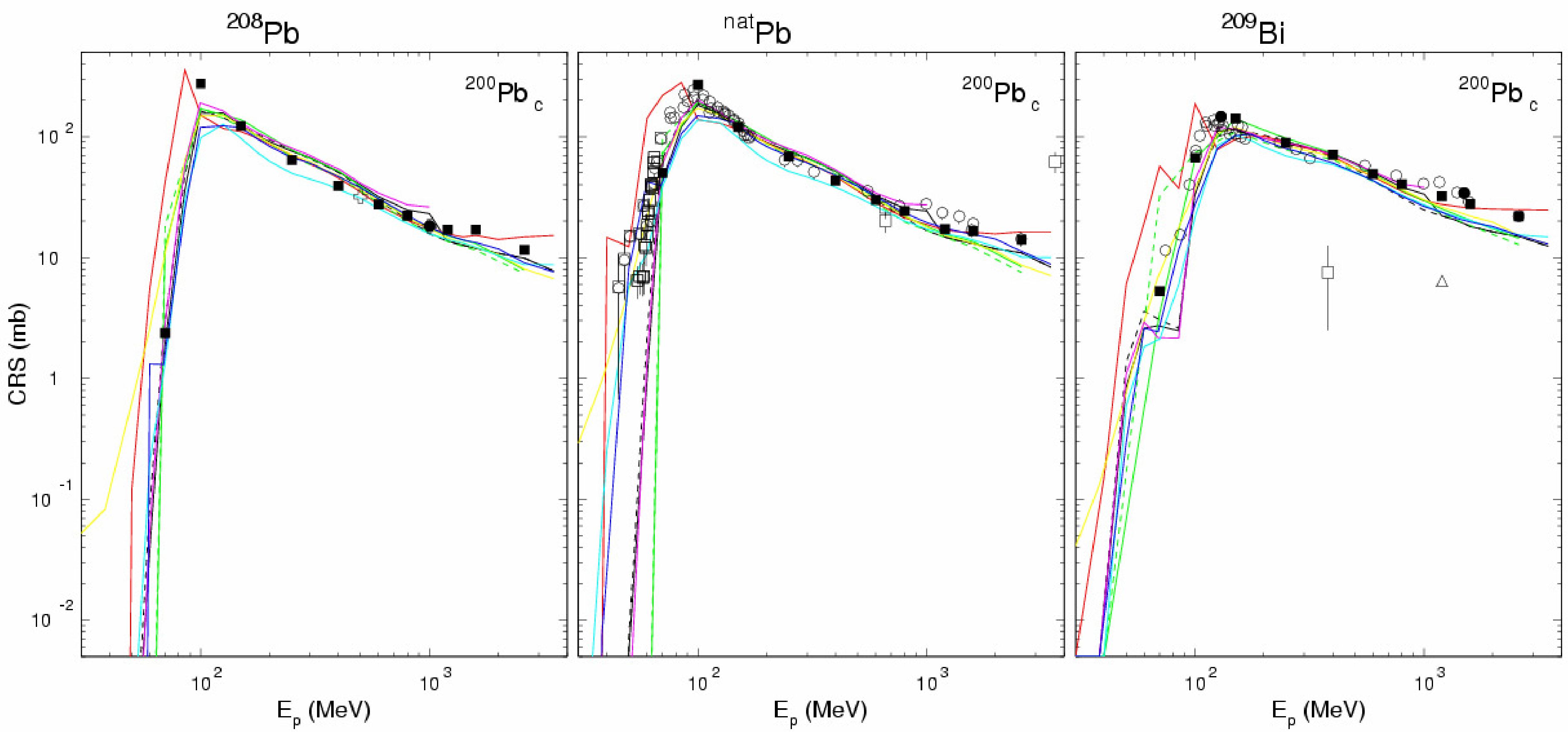
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions Spallation products (2)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✥ - *GSI*, □ - *others*

^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions Spallation products (3)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
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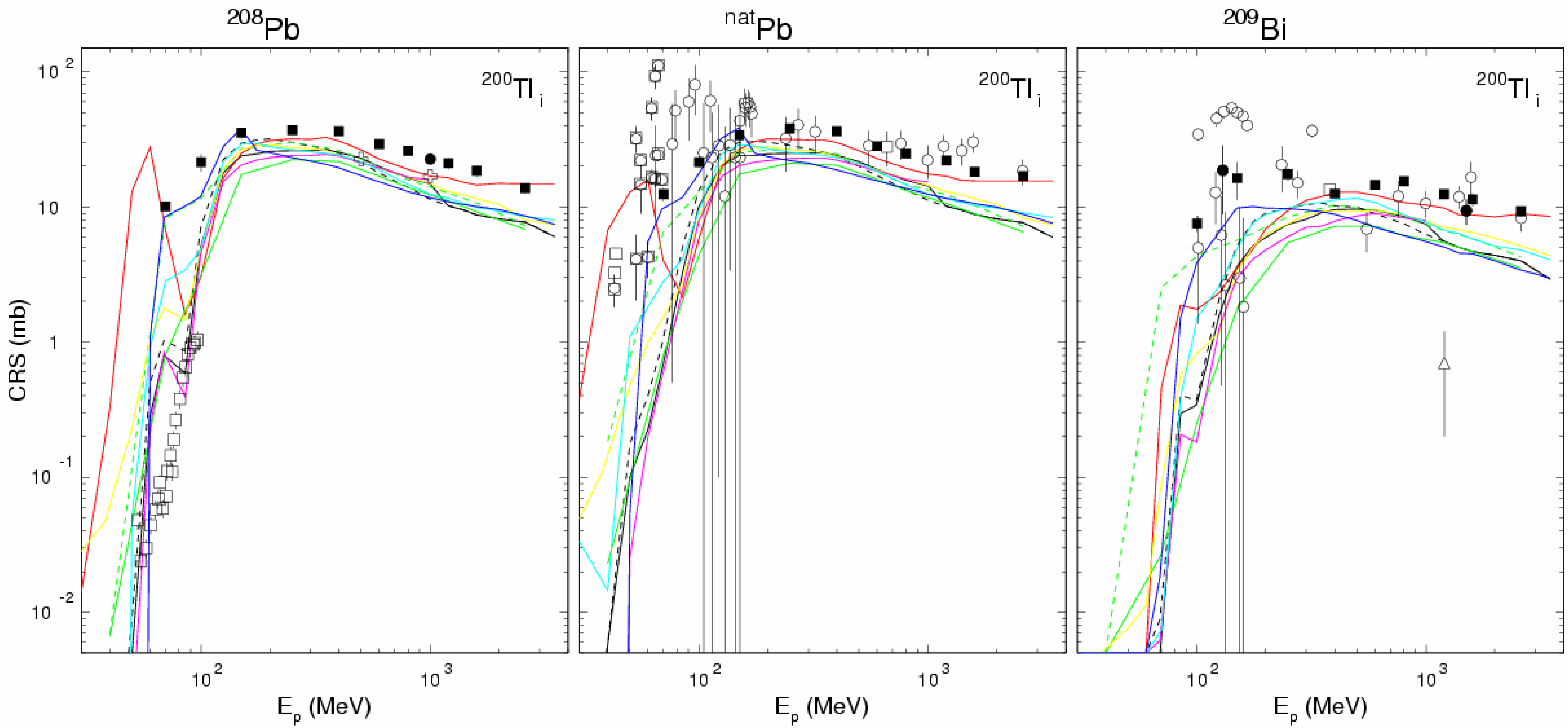
LAQGSM+GEM2 LAHETO CASCADO

■ - ***ITEP***, ○ - ***ZSR***, ✢ - ***GSI***, □ - ***others***

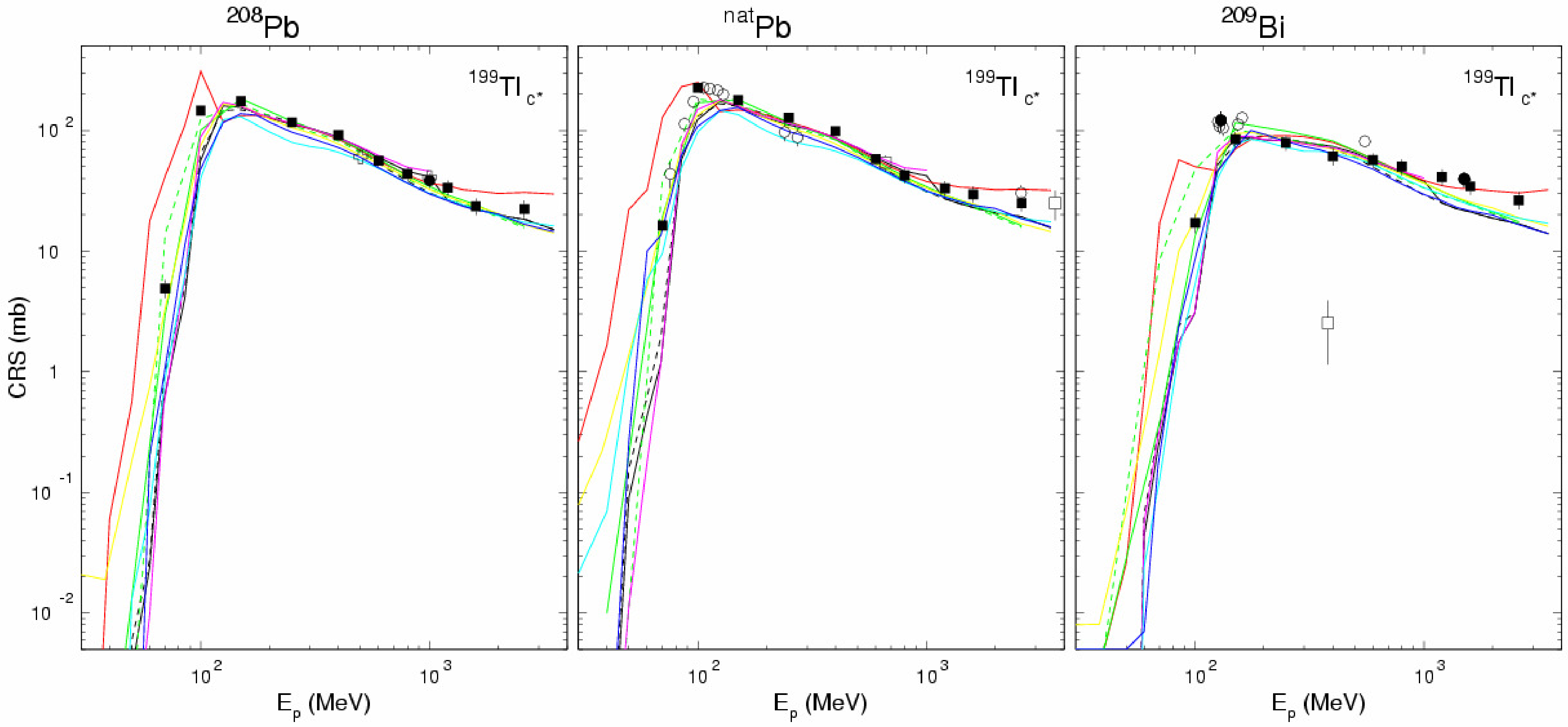
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions
Spallation products (4)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✙ - *GSI*, □ - *others*

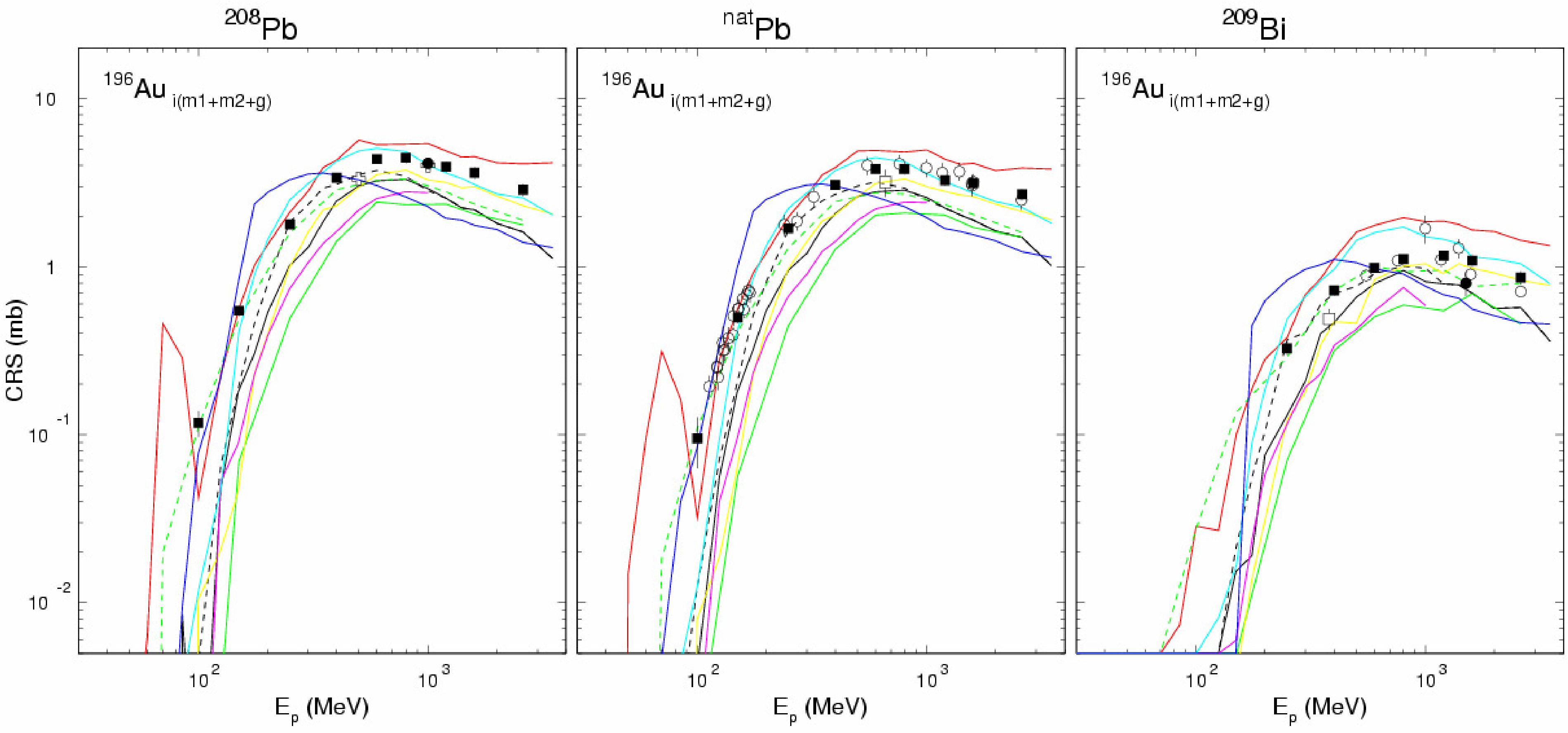
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions Spallation products (5)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - ITEP, ○ - ZSR, ✚ - GSI, □ - others

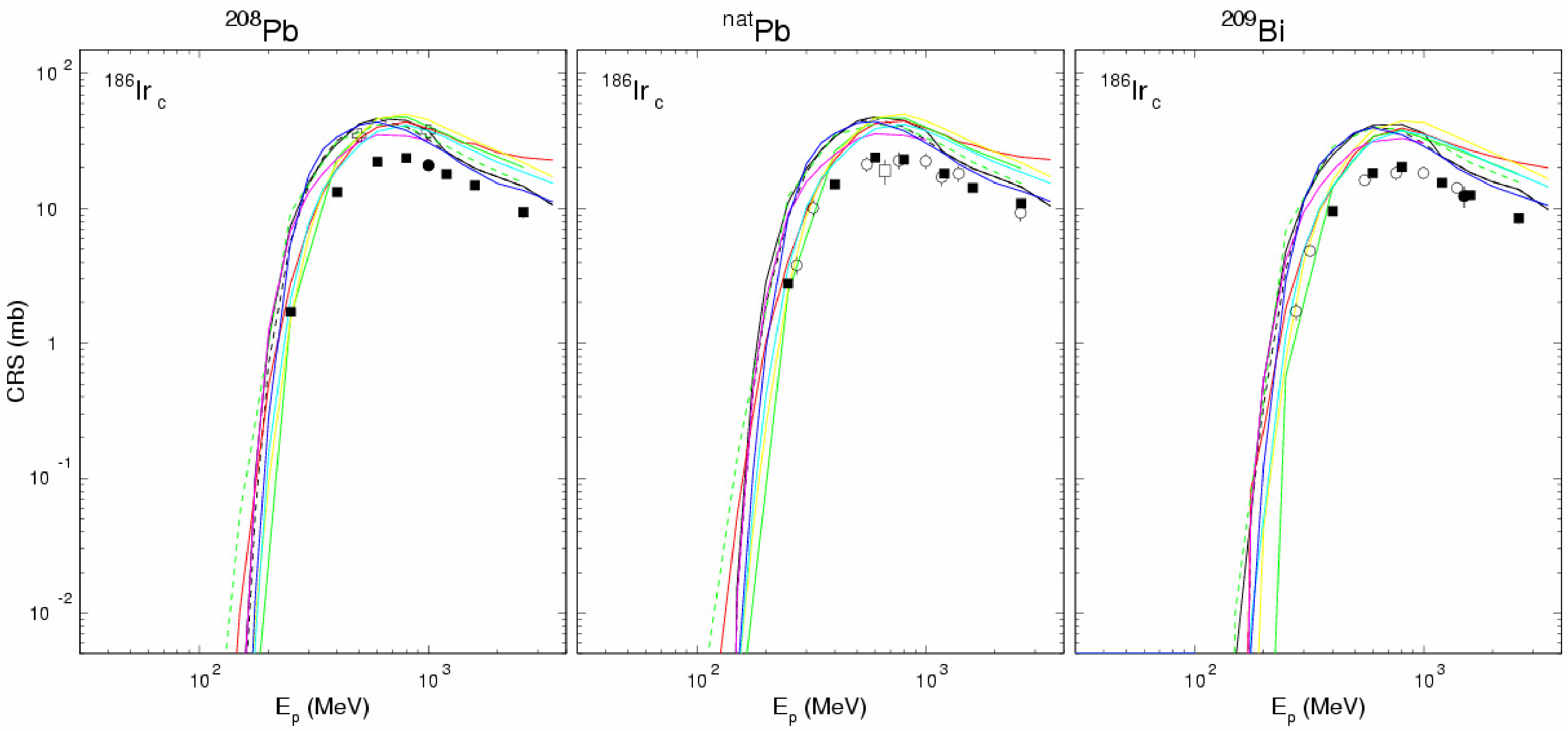
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions Spallation products (6)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✙ - *GSI*, □ - *others*

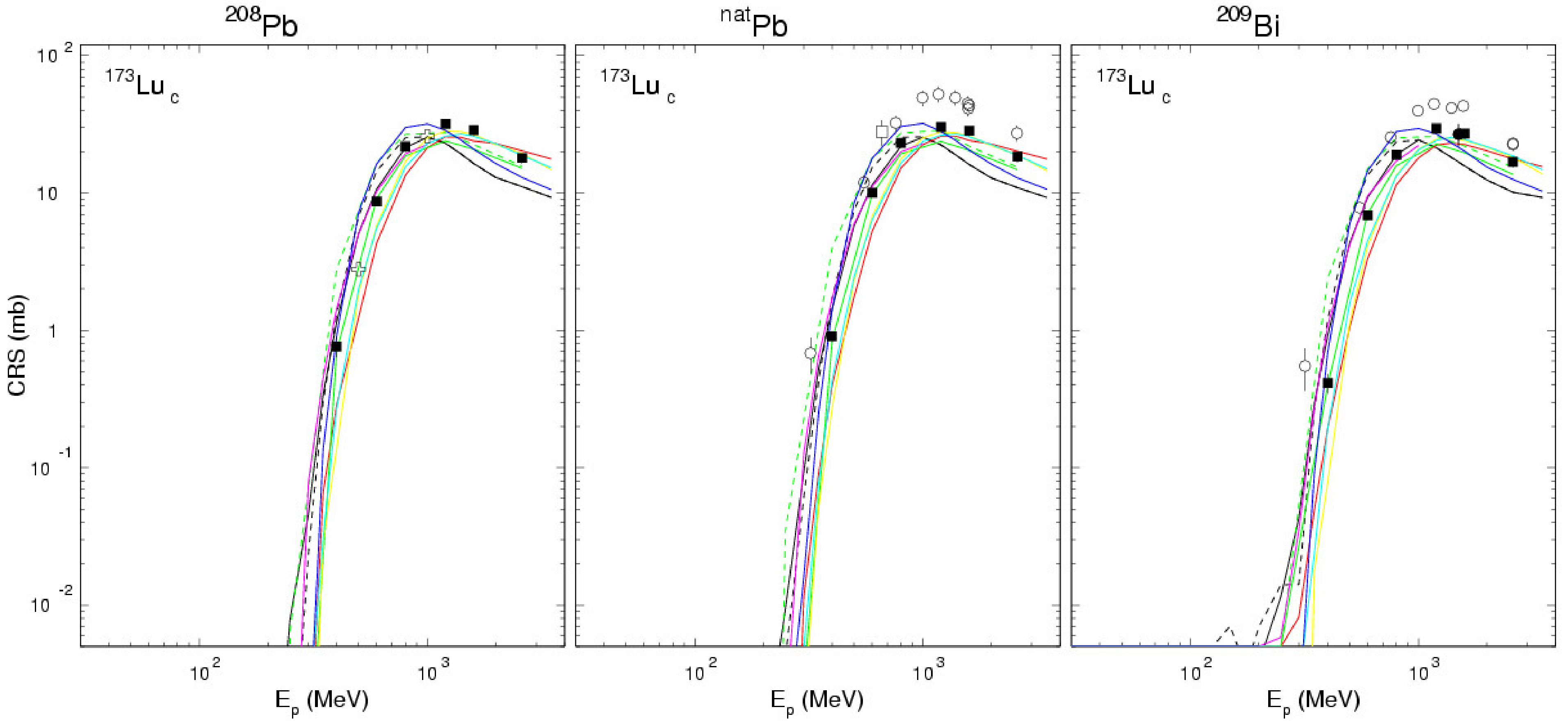
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions
Spallation products (7)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - ITEP, ○ - ZSR, ✣ - GSI, □ - others

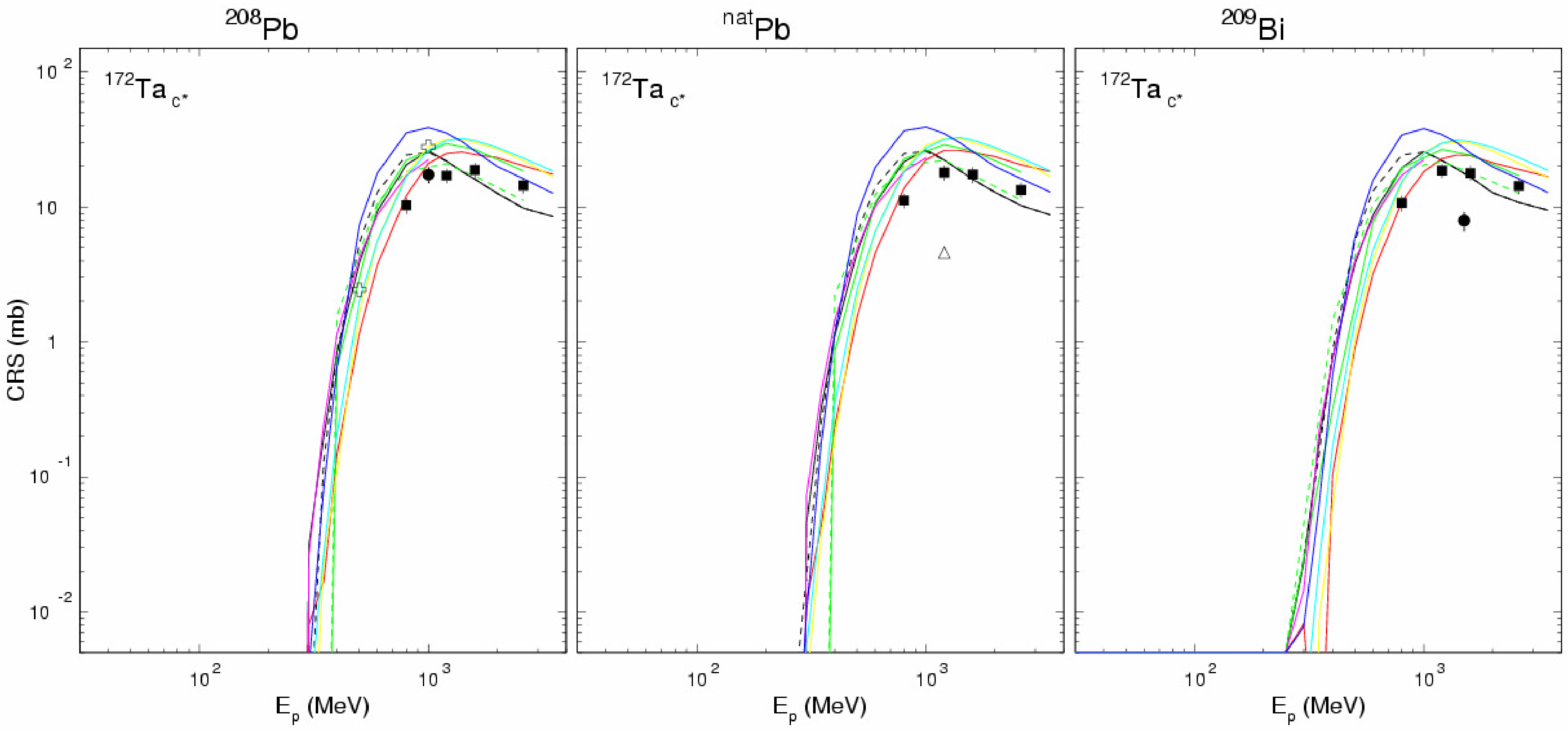
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions
Spallation products (9)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✙ - *GSI*, □ - *others*

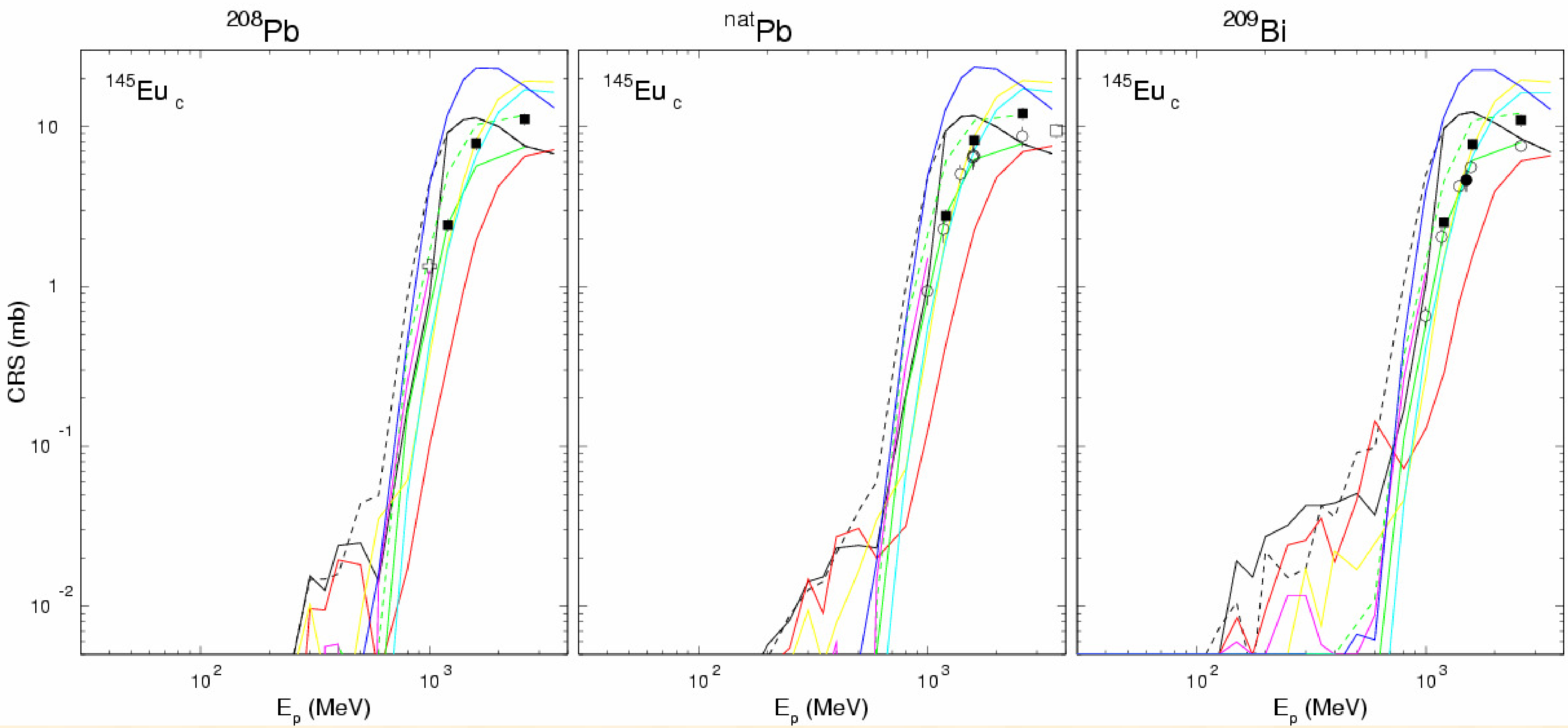
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions Spallation products (8)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✚ - *GSI*, □ - *others*

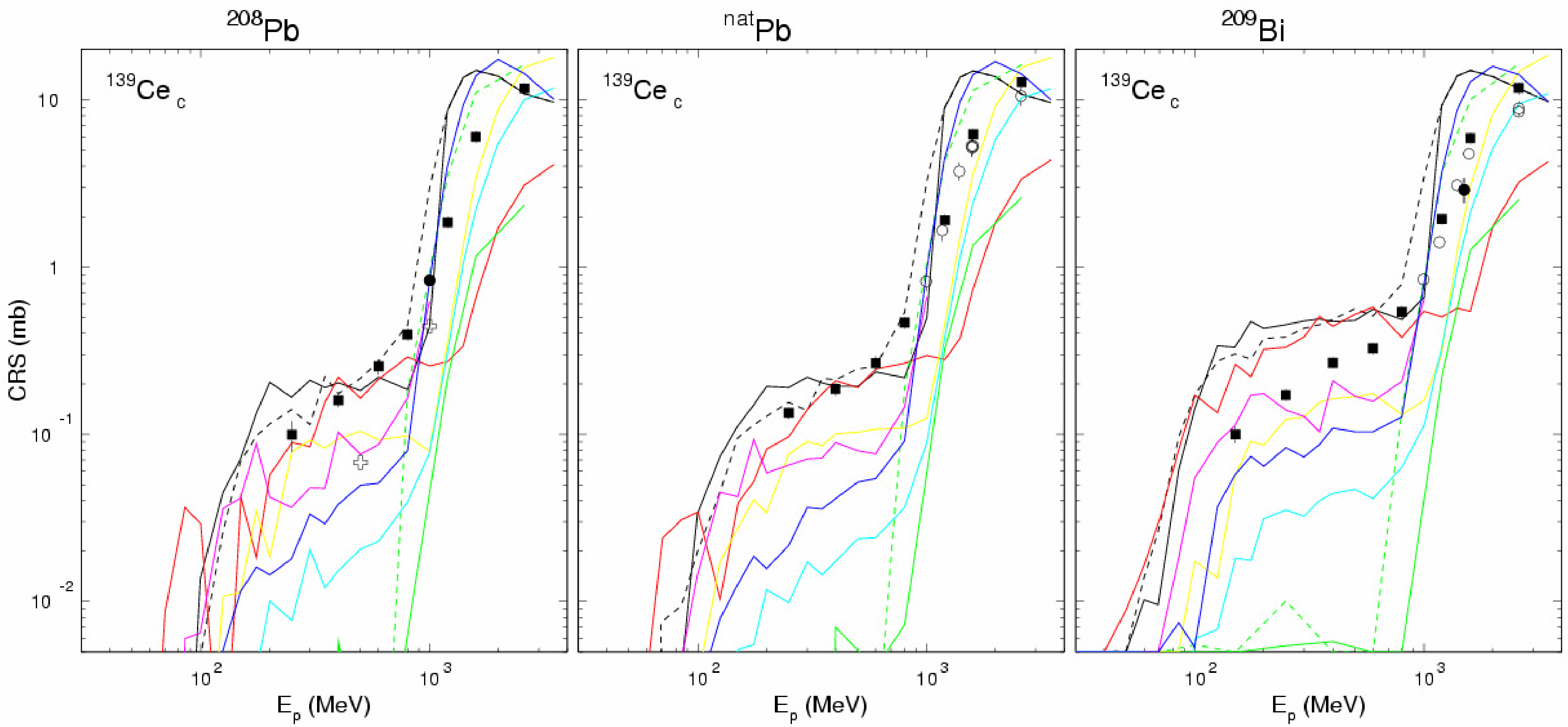
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Spallation+Fission products (1)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✣ - *GSI*, □ - *others*

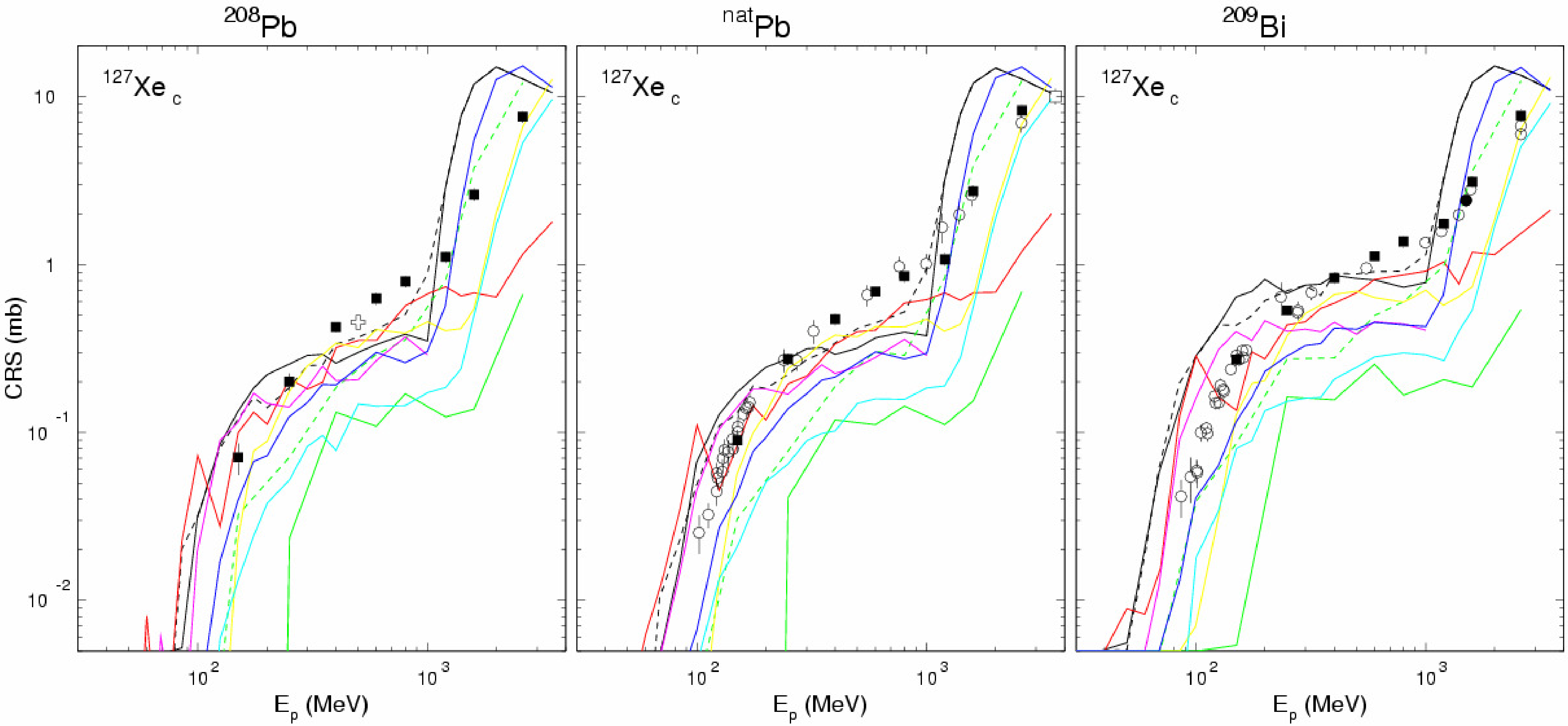
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Spallation+Fission products (2)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✚ - *GSI*, □ - *others*

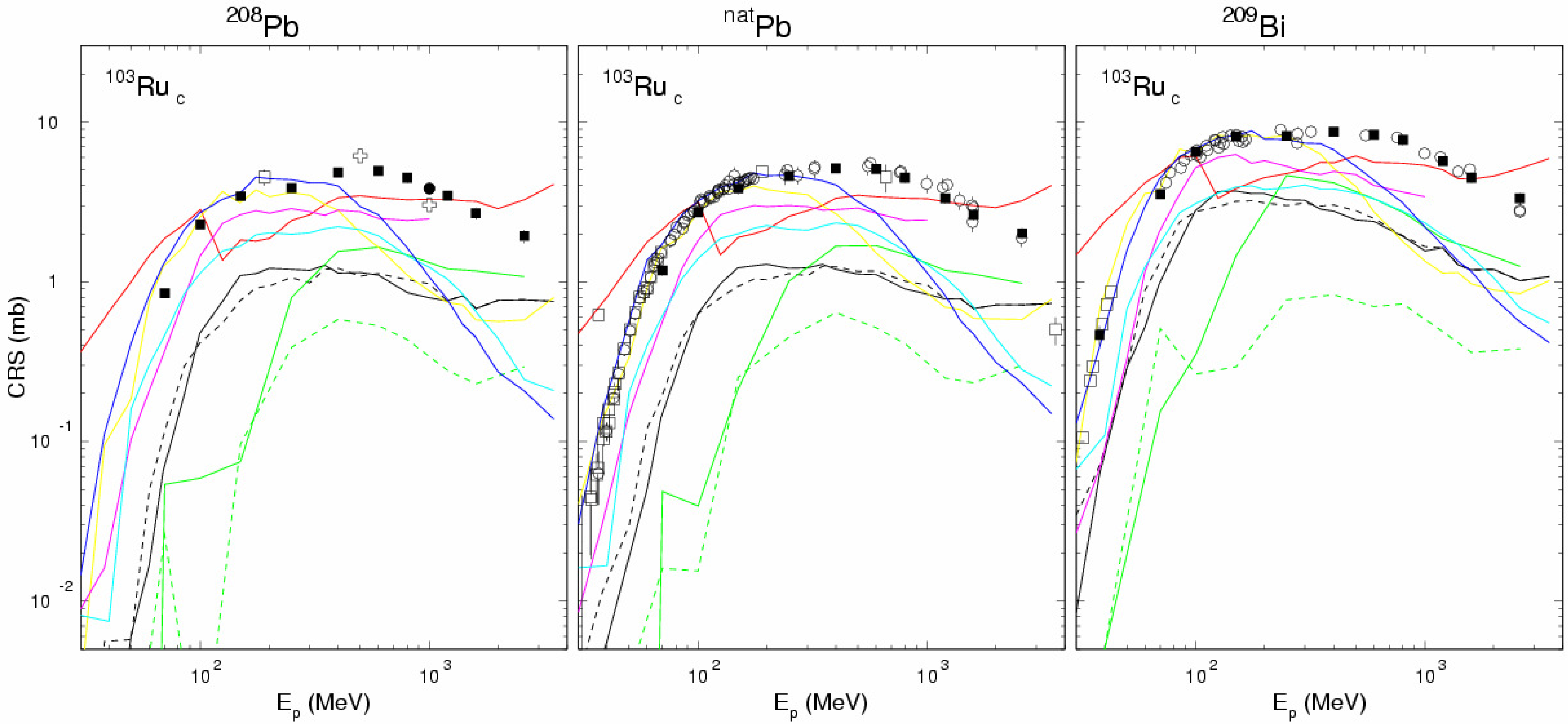
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Spallation+Fission products (3)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✥ - *GSI*, □ - *others*

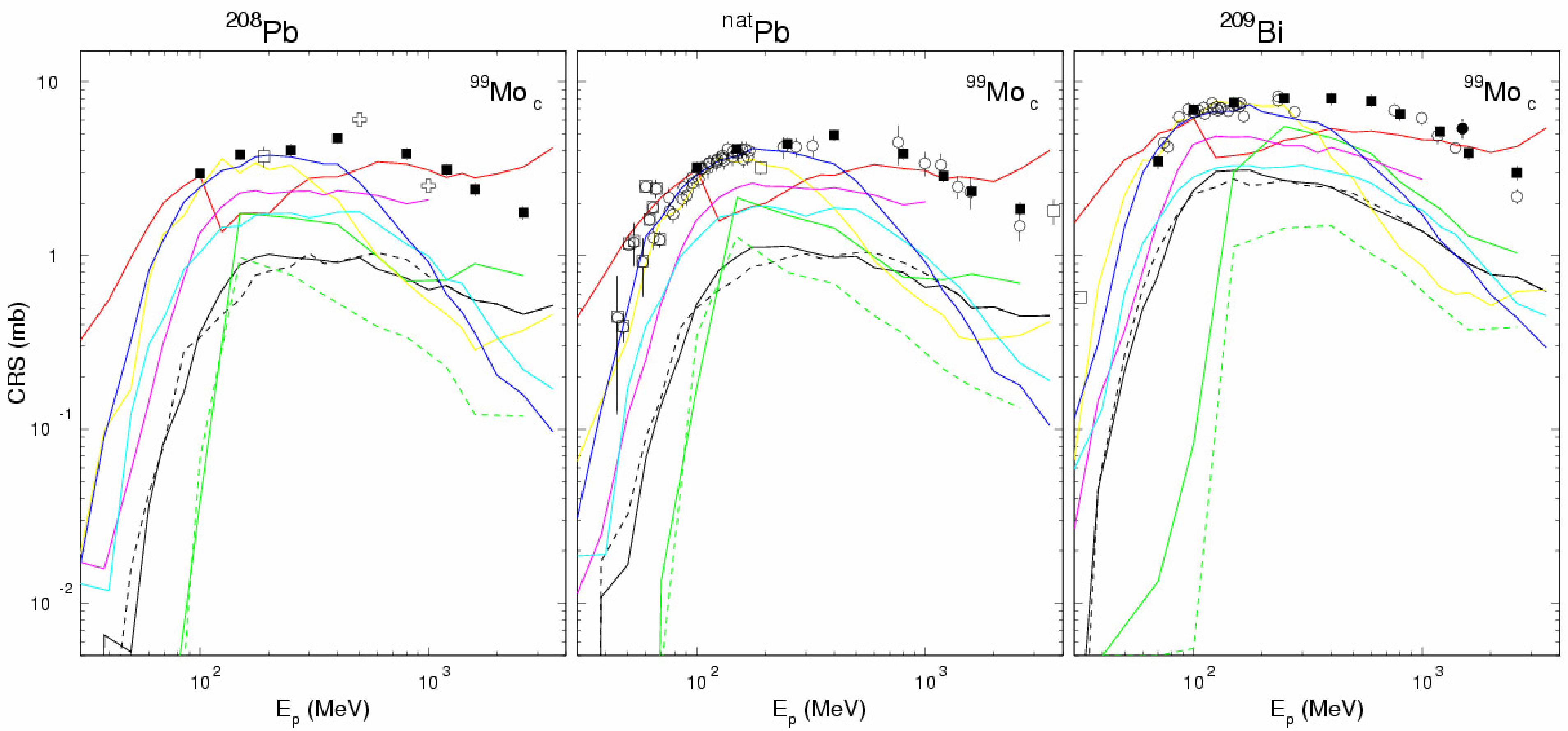
^{208}Pb-, ^{nat}Pb-, and $^{209}Bi(p,x)$ excitation functions: Fission products (1)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✢ - *GSI*, □ - *others*

^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fission products (2)



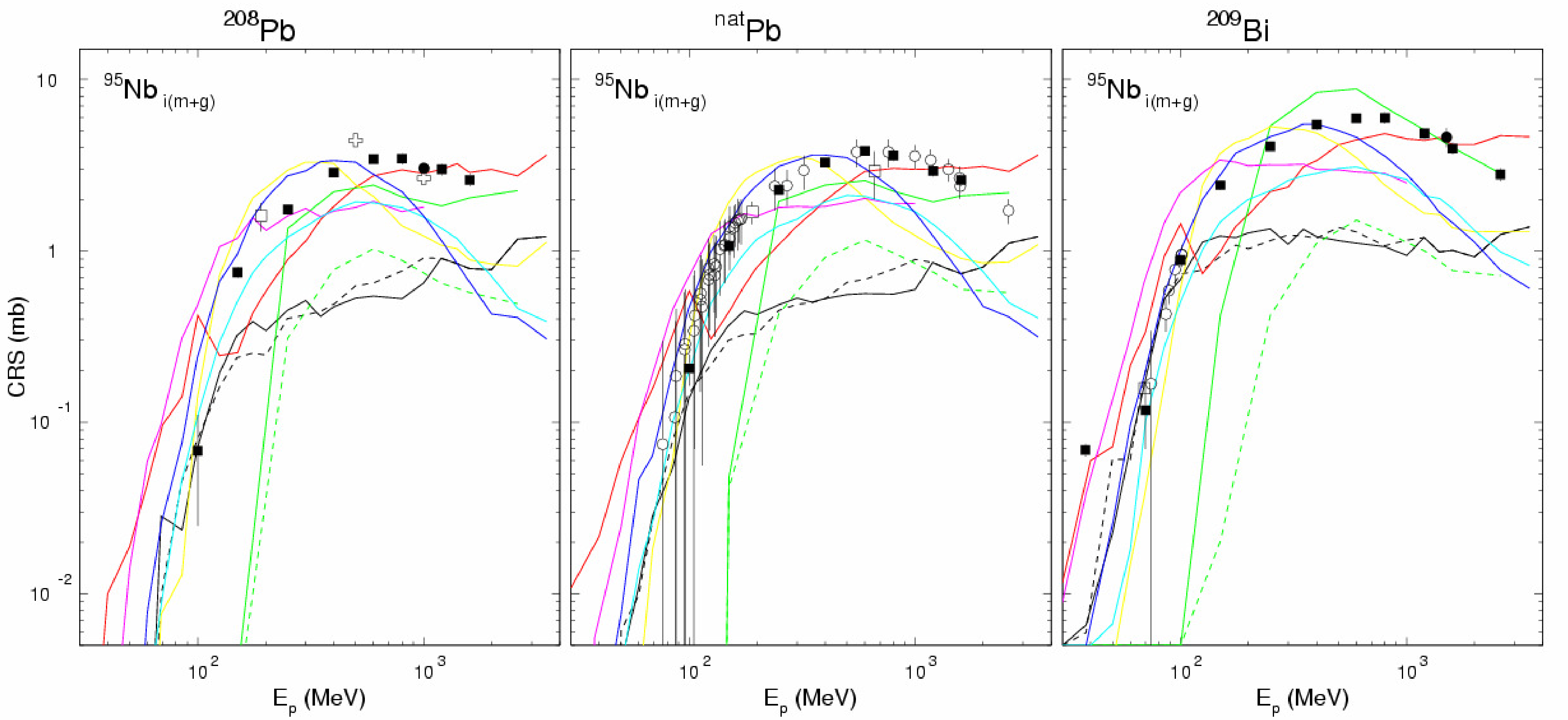
LAHET(ISABEL-solid; BERTINI-dashed) CEM03

INCL4+ABLA CASCADE(2004-solid; 2002-dashed)

LAQGSM+GEM2 LAHETO CASCADO

■ - ***ITEP***, ○ - ***ZSR***, ✙ - ***GSI***, □ - ***others***

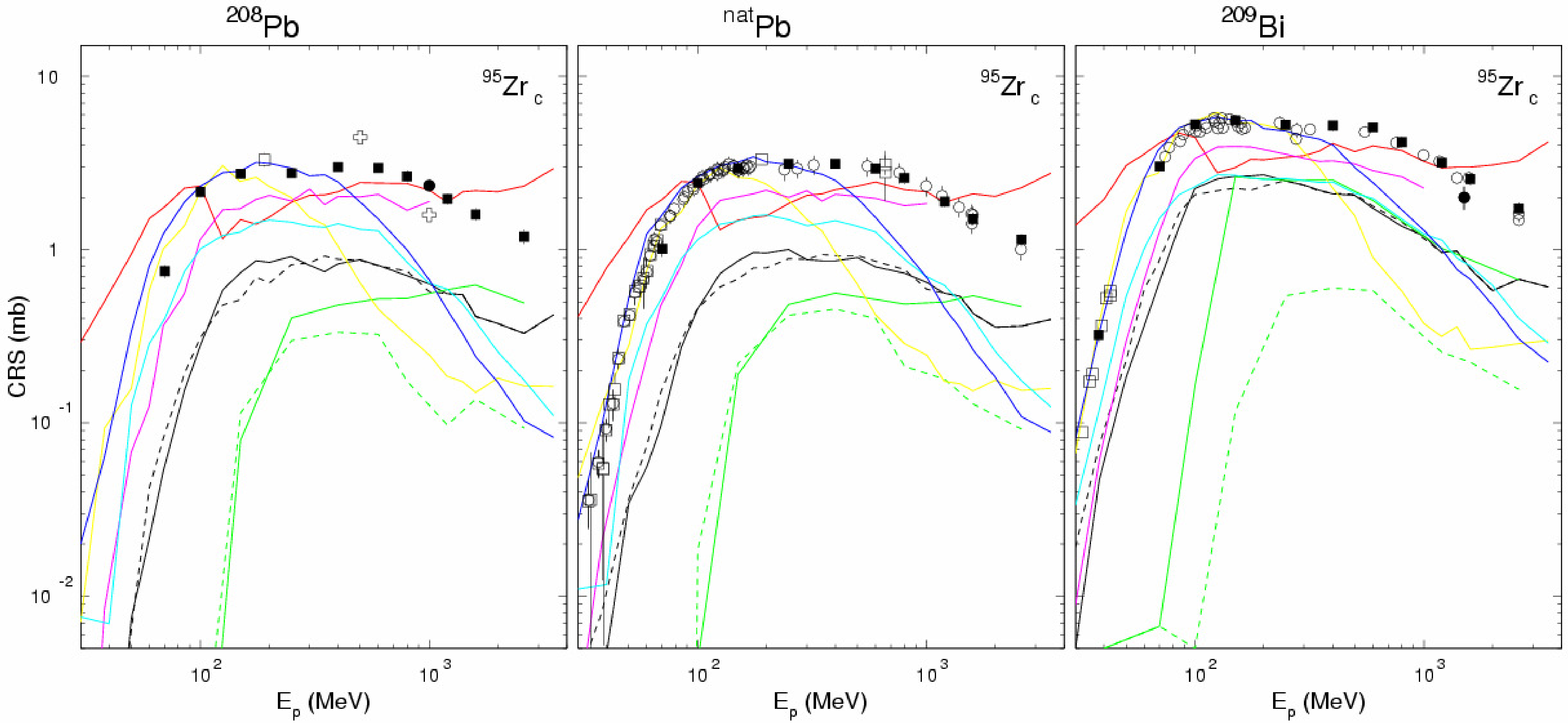
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fission products (3)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - ITEP, ○ - ZSR, ✚ - GSI, □ - others

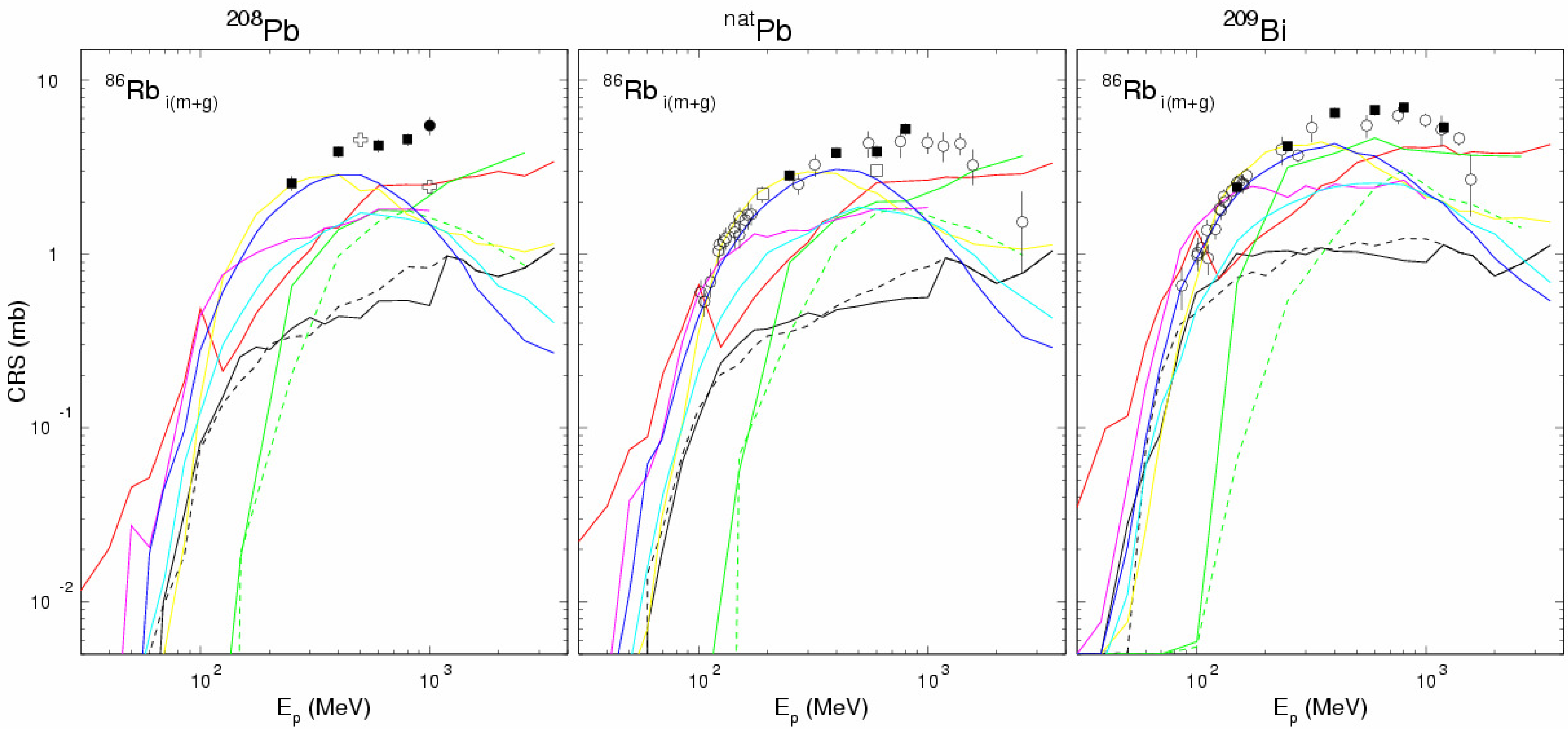
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fission products (4)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✣ - *GSI*, □ - *others*

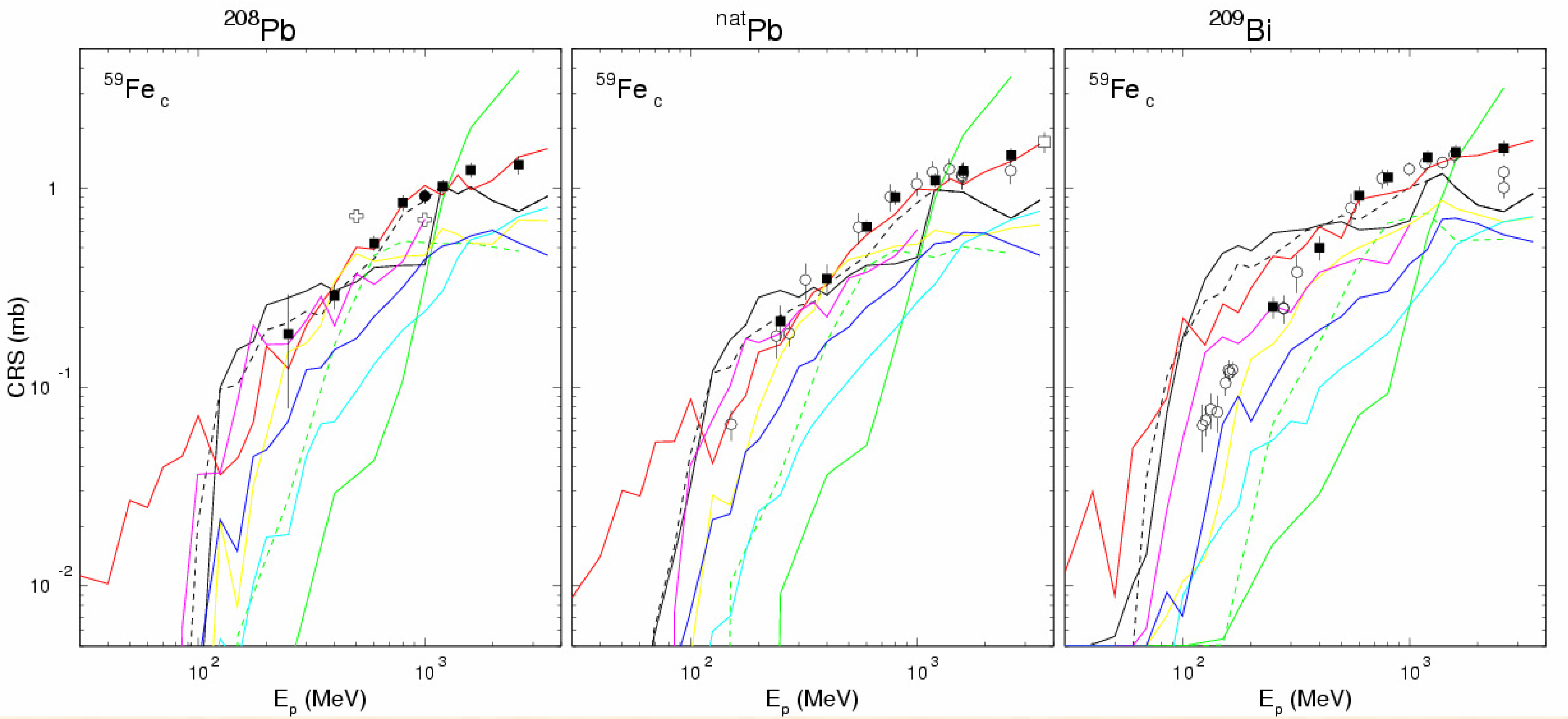
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fission products (5)



LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✣ - *GSI*, □ - *others*

^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fission+Fragmenation products



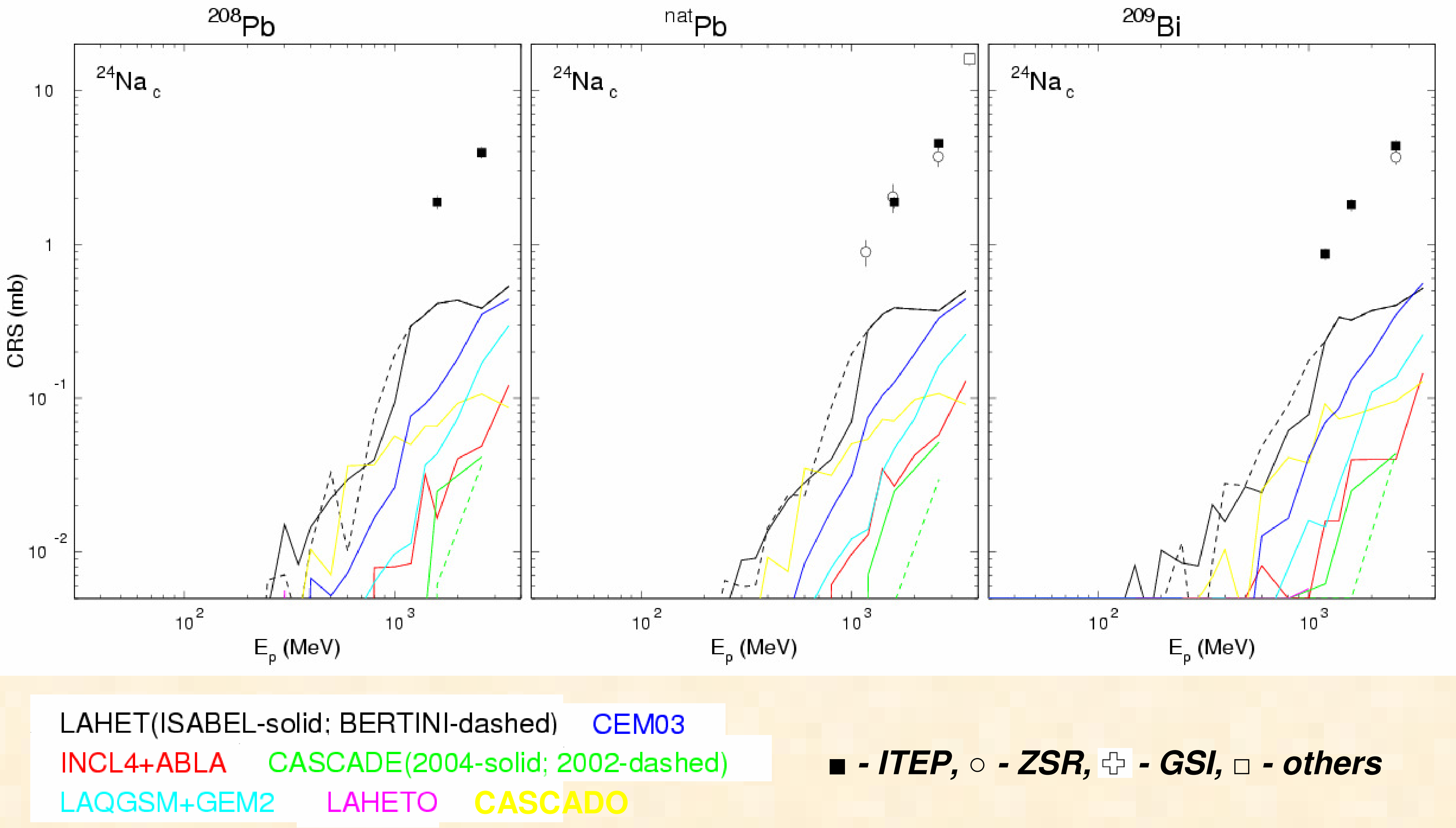
LAHET(ISABEL-solid; BERTINI-dashed) CEM03

INCL4+ABLA CASCADE(2004-solid; 2002-dashed)

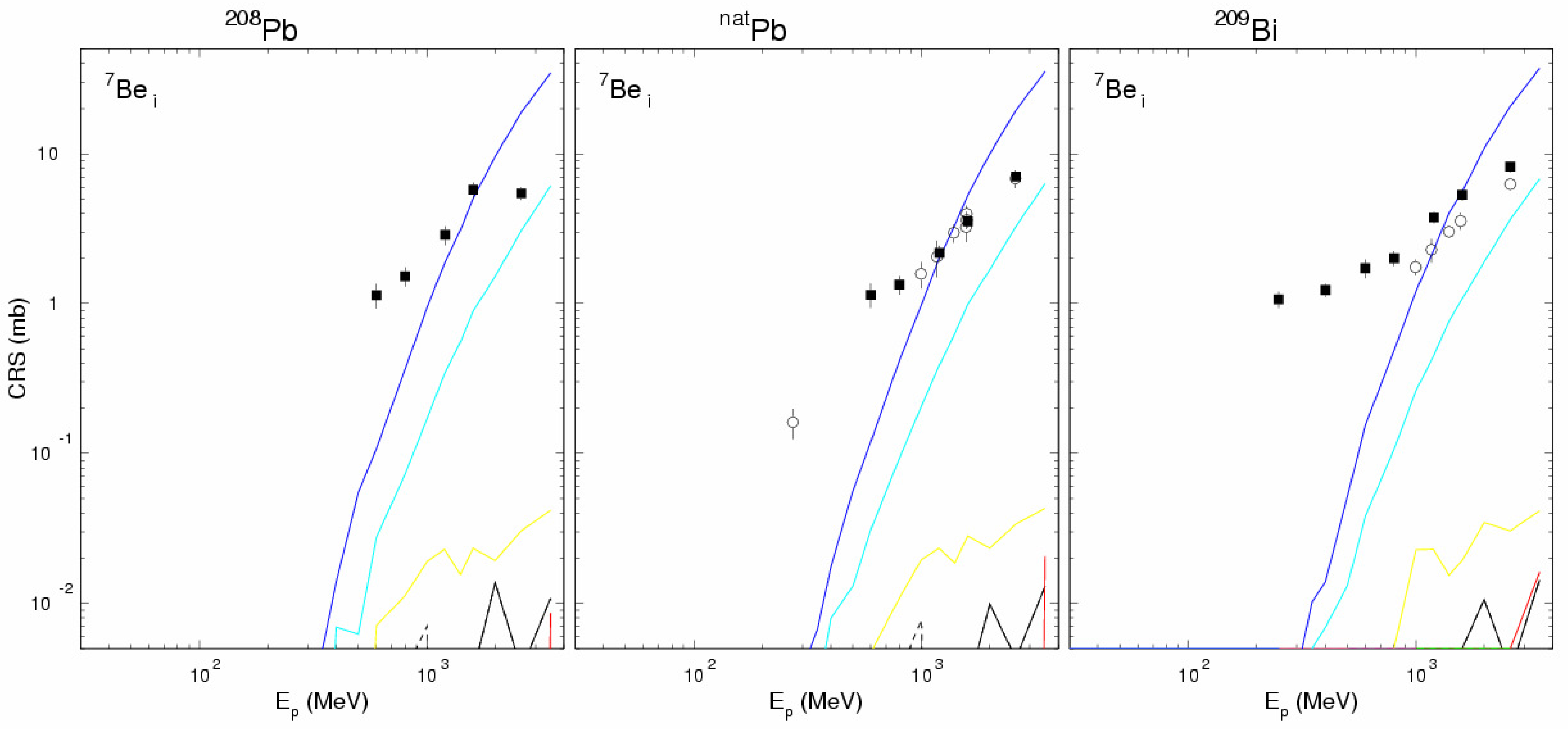
LAQGSM+GEM2 LAHETO CASCADO

■ - *ITEP*, ○ - *ZSR*, ✙ - *GSI*, □ - *others*

^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fragmentation products (1)



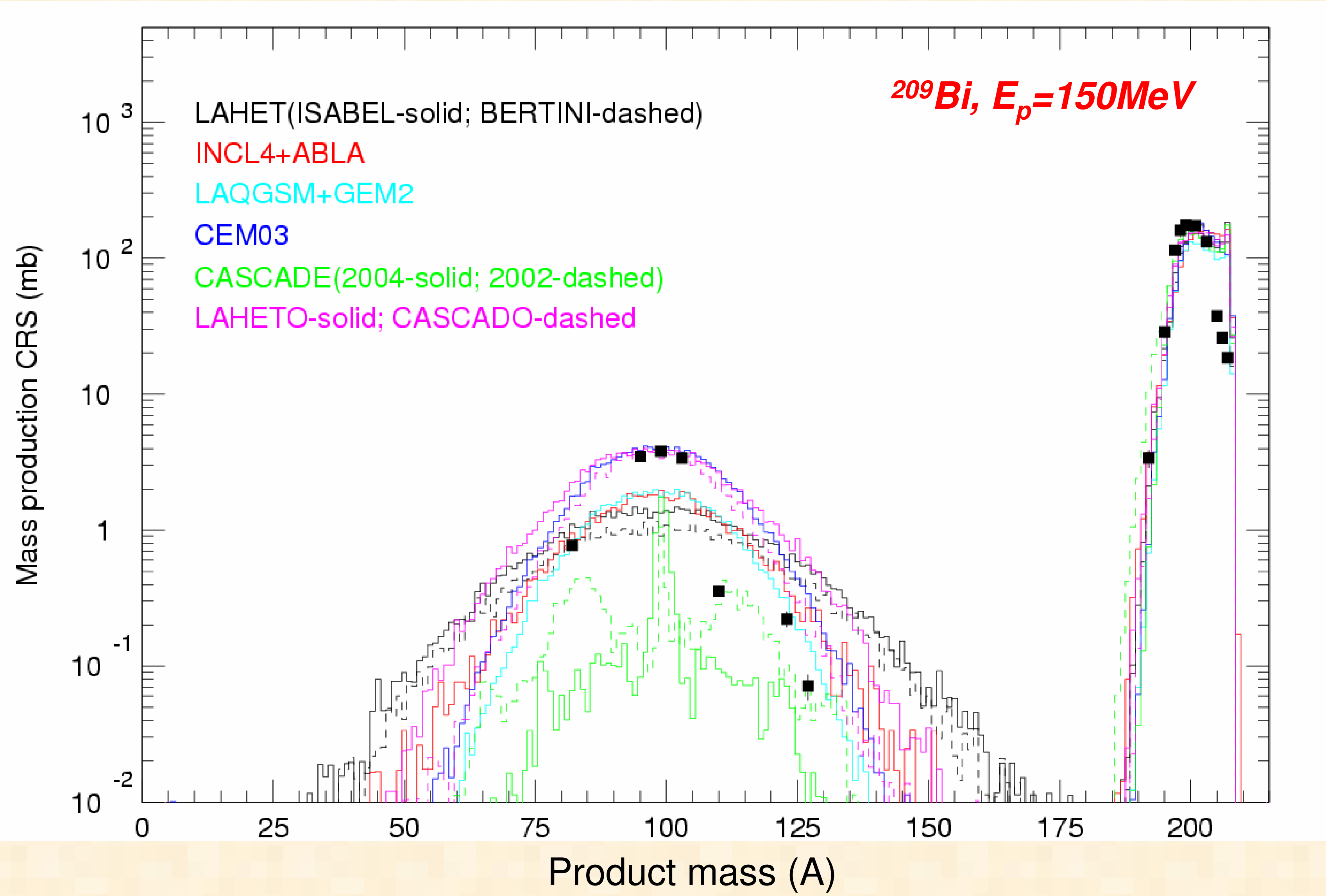
^{208}Pb-, ^{nat}Pb-, and ^{209}Bi(p,x) excitation functions: Fragmentation products (2)



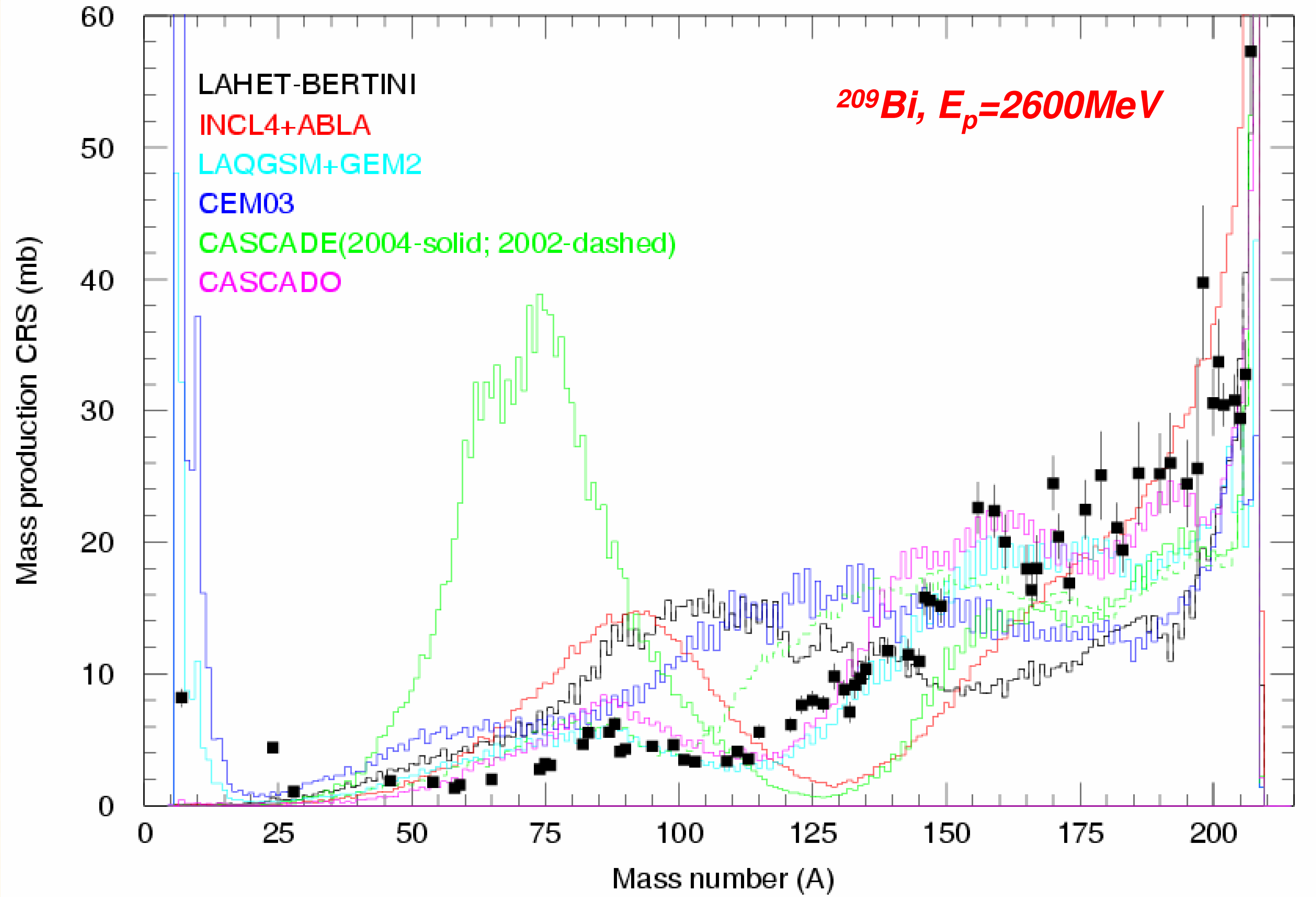
LAHET(ISABEL-solid; BERTINI-dashed) CEM03
INCL4+ABLA CASCADE(2004-solid; 2002-dashed)
LAQGSM+GEM2 LAHETO CASCADO

■ - ***ITEP***, ○ - ***ZSR***, ✙ - ***GSI***, □ - ***others***

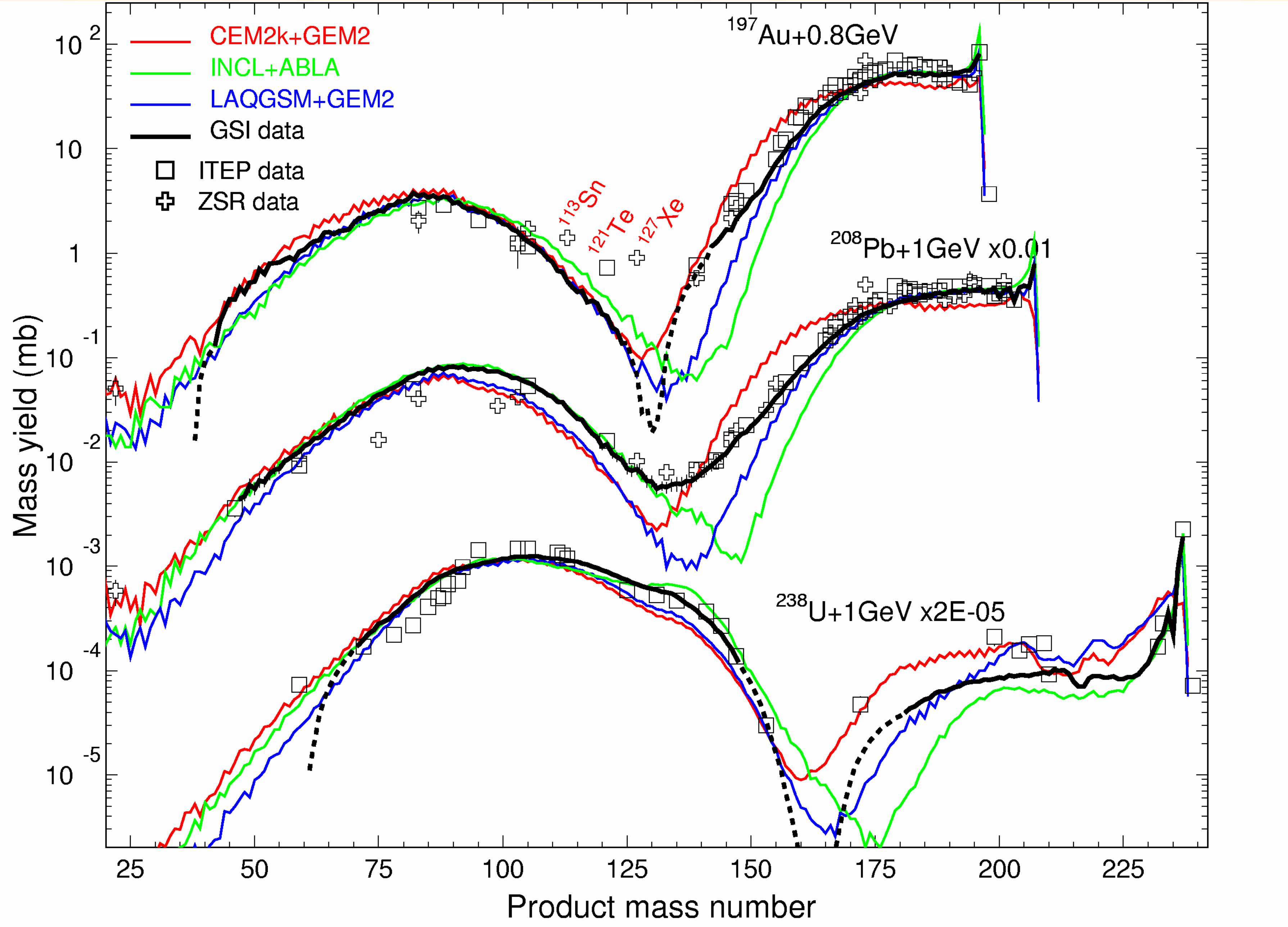
Mass production at low energy (150MeV)



Mass production at high energy (2600MeV)



Product mass distributions (GSI, ITEP, ZSR)



The simulation codes prediction power

Mean squared deviation factor <F>

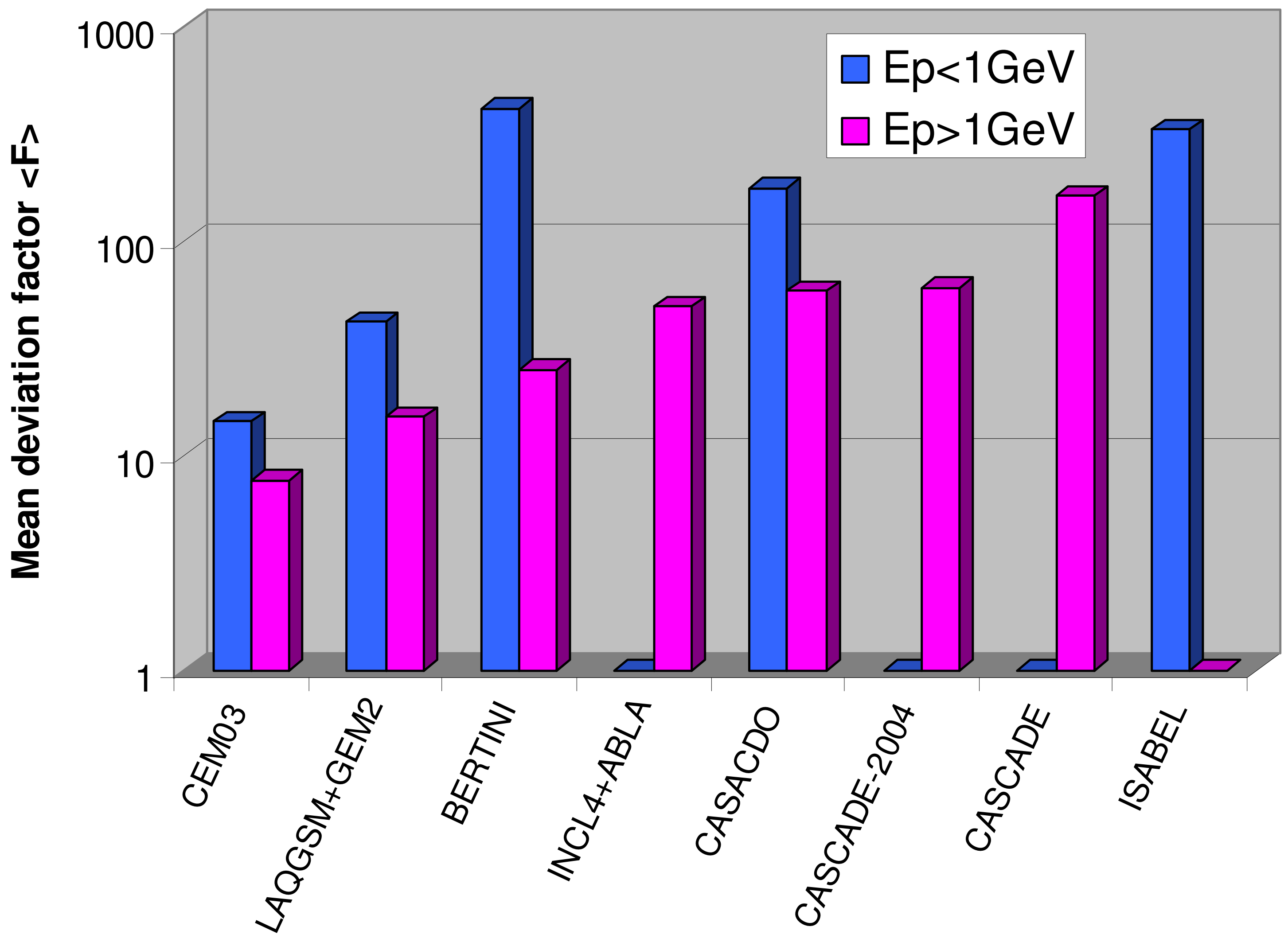
$$< F >= 10^{\sqrt{A}},$$

$$A = < (\lg(\sigma_{cal,i} / \sigma_{\exp,i}))^2 >$$

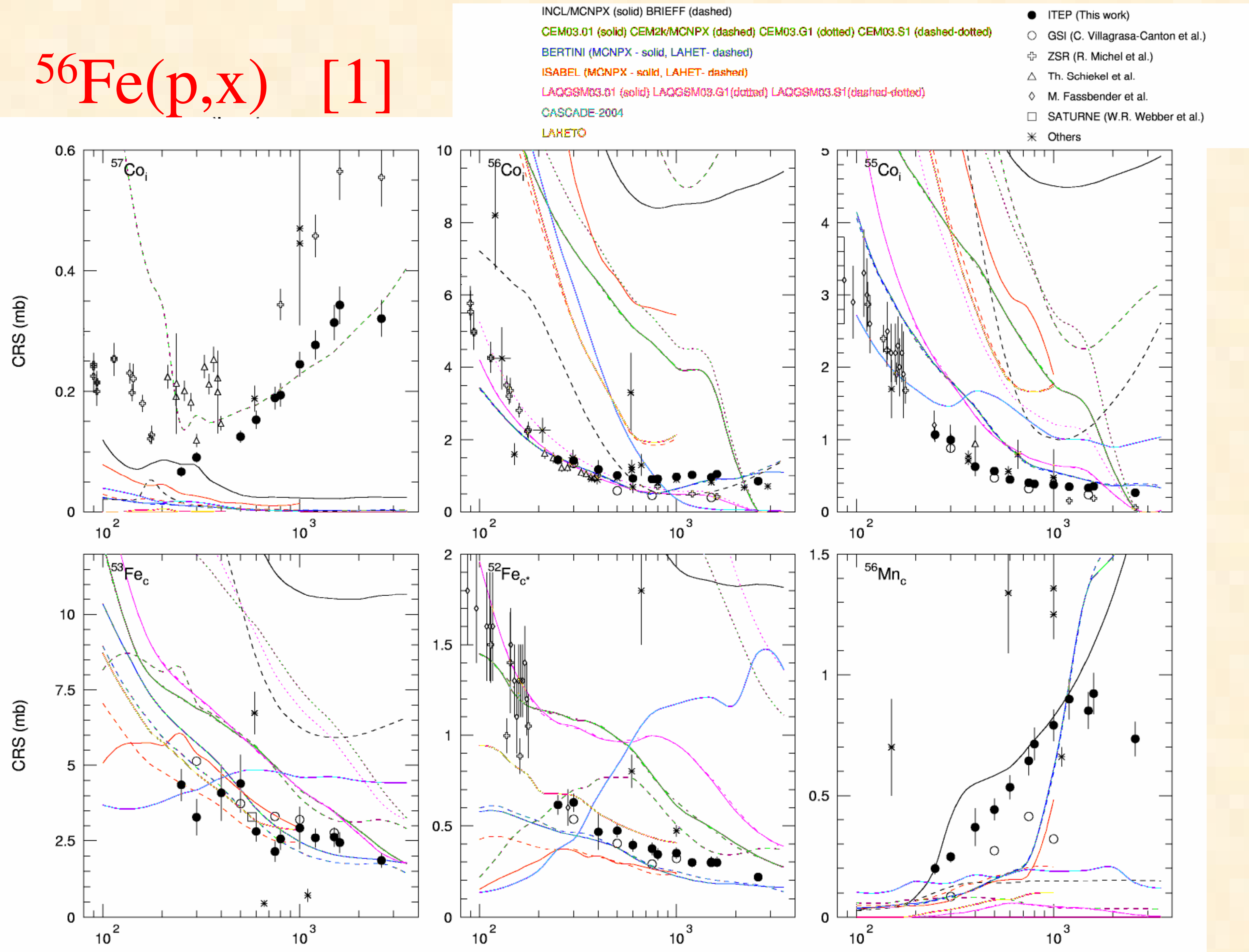
Table 44: Mean squared deviation factors <F> separately for different energy groups and ranges of products (A>30) and for all comparisons as well.

Code	Product mass (A)			Proton energy (E_p, GeV)			**Total**
	A>170	140<A<170	30<A<140	E_p <0.1	0.1<E_p <1.0	E_p >1.0	
ISABEL	1.81	1.81	2.87	4.88	2.13	–	**2.16**
BERTINI	1.75	1.93	2.75	4.26	2.06	1.97	**2.10**
INCL4+ABLA	1.90	3.74	2.22	4.63	2.18	2.13	**2.25**
CASCADE	1.77	2.01	6.93	4.93	3.93	2.44	**3.25**
CASCADE-2004	1.93	1.47	5.54	6.54	3.23	2.42	**2.94**
LAQGSM+GEM2	1.98	2.32	2.71	3.03	2.35	2.09	**2.26**
CEM03	1.98	2.07	2.25	2.08	1.77	2.39	**2.07**
CASCADO	1.99	2.22	2.83	2.69	2.33	2.22	**2.29**
LAHETO	1.99	1.96	1.98	4.85	1.76	–	**1.98**

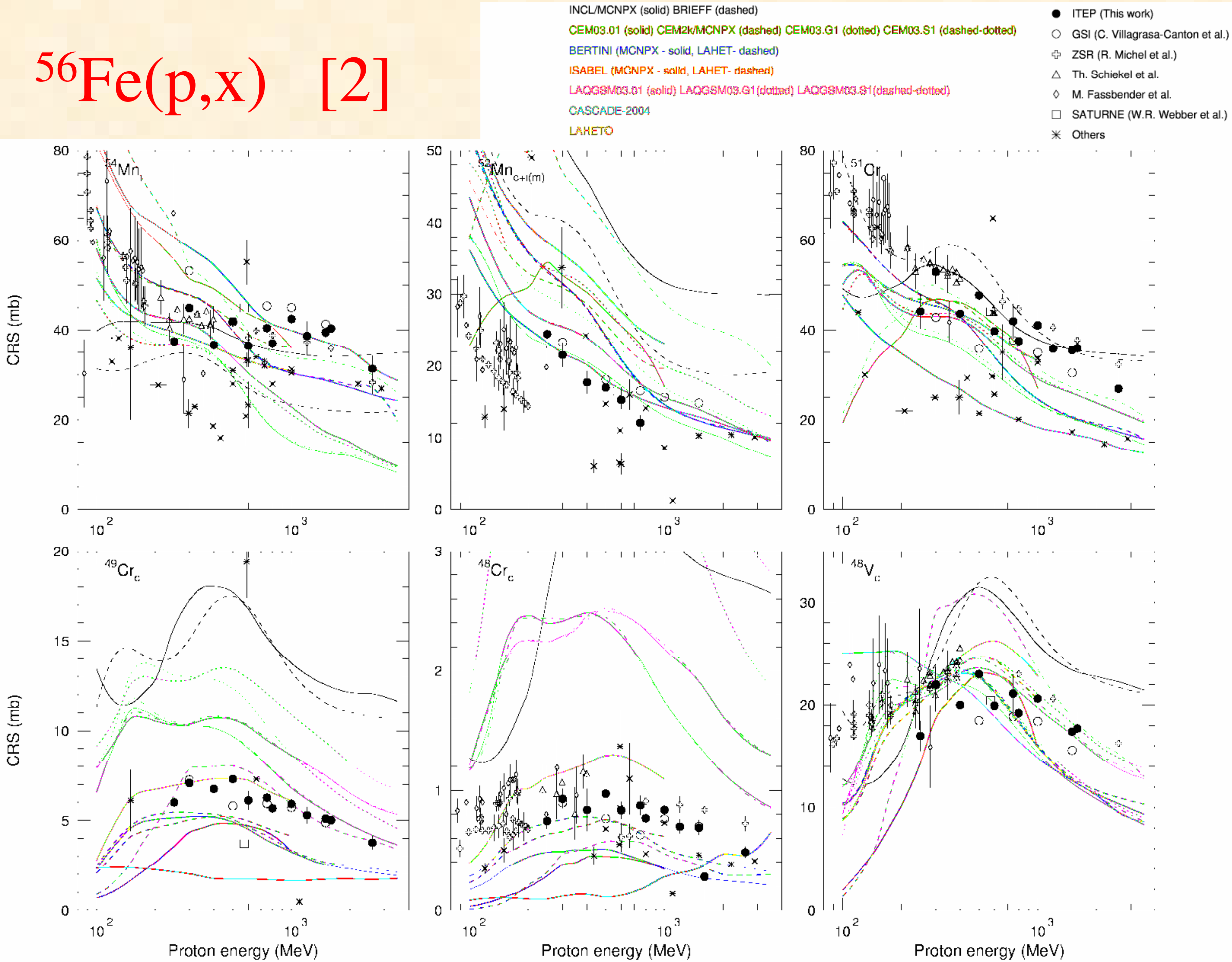
Mean squared deviation factor <F> for products from Pb's&Bi with A below 30



$^{56}Fe(p,x)$ [1]

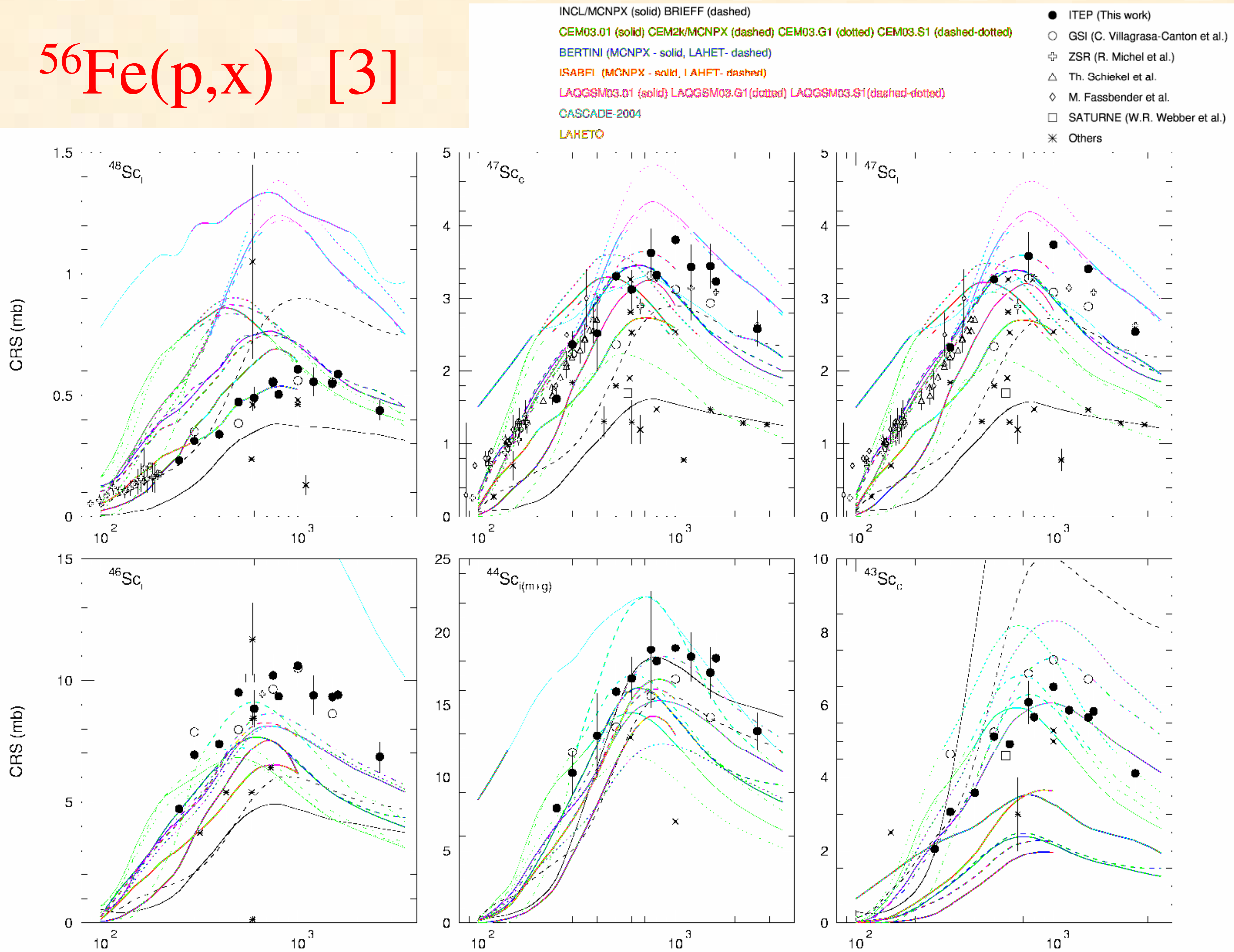

INCL/MCNPX (solid) BRIEFF (dashed)
CEM03.01 (solid) CEM2k/MCNPX (dashed) CEM03.G1 (dotted) CEM03.S1 (dashed-dotted)
BERTINI (MCNPX - solid, LAHET- dashed)
ISABEL (MCNPX - solid, LAHET- dashed)
LAQGSM03.01 (solid) LAQGSM03.G1(dotted) LAQGSM03.S1(dashed-dotted)
CASCADE-2004
LAHETO
ITEP (This work)
GSI (C. Villagrasa-Canton et al.)
ZSR (R. Michel et al.)
Th. Schiekel et al.
M. Fassbender et al.
SATURNE (W.R. Webber et al.)
Others
CRS (mb)
57Coi
56Coi
55Coi
53Fec
52Fec*
56Mnc

^{56}Fe(p,x) [2]

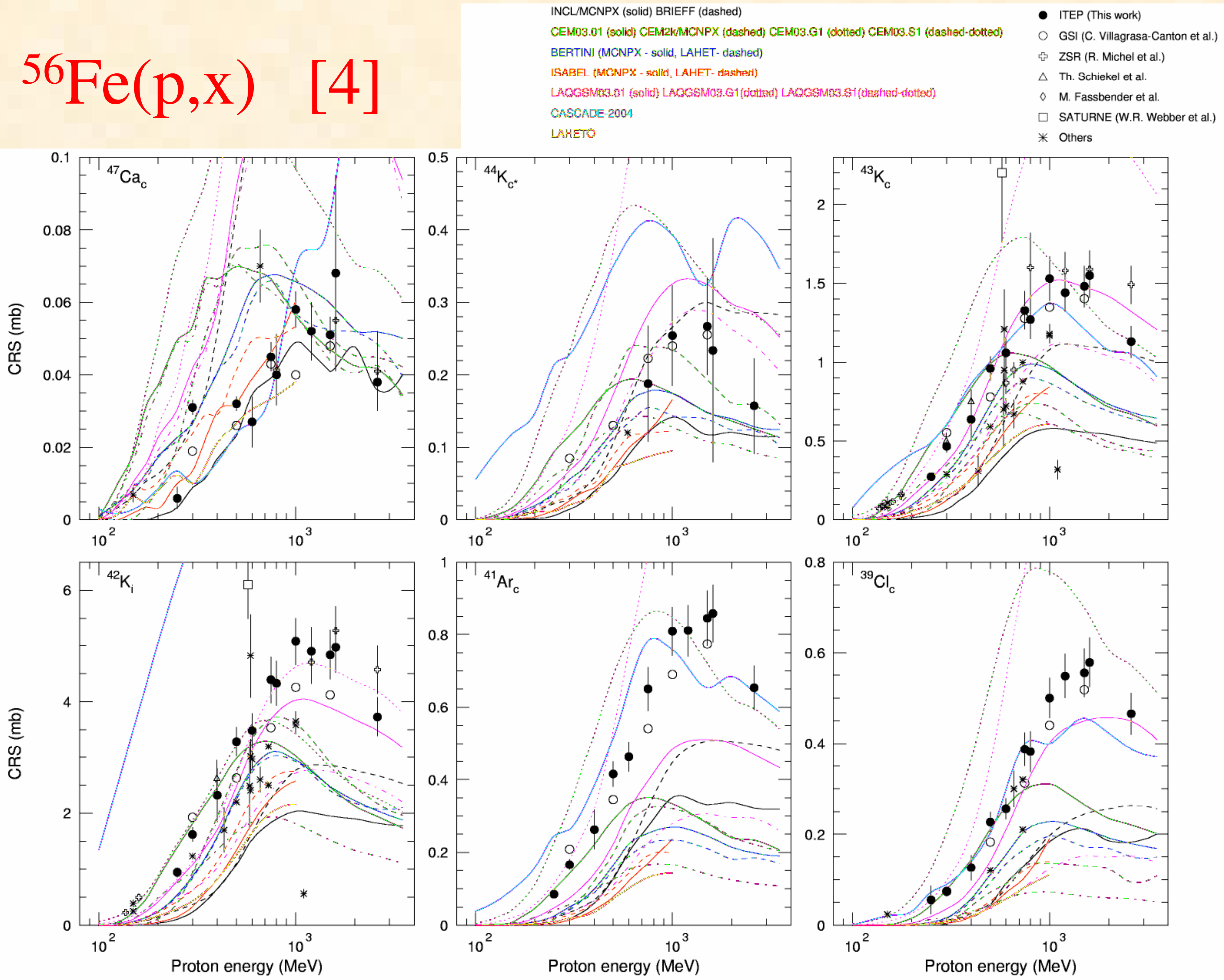


INCL/MCNPX (solid) BRIEFF (dashed)
CEM03.01 (solid) CEM2k/MCNPX (dashed) CEM03.G1 (dotted) CEM03.S1 (dashed-dotted)
BERTINI (MCNPX - solid, LAHET- dashed)
ISABEL (MCNPX - solid, LAHET- dashed)
LAQGSM03.01 (solid) LAQGSM03.G1(dotted) LAQGSM03.S1(dashed-dotted)
CASCADE-2004
LAHETO
ITEP (This work)
GSI (C. Villagrasa-Canton et al.)
ZSR (R. Michel et al.)
Th. Schiekel et al.
M. Fassbender et al.
SATURNE (W.R. Webber et al.)
Others
54Mn
52Mn c+i(m)
51Cr
49Cr c
48Cr c
48V c
CRS (mb)
Proton energy (MeV)

$^{56}Fe(p,x)$ [3]

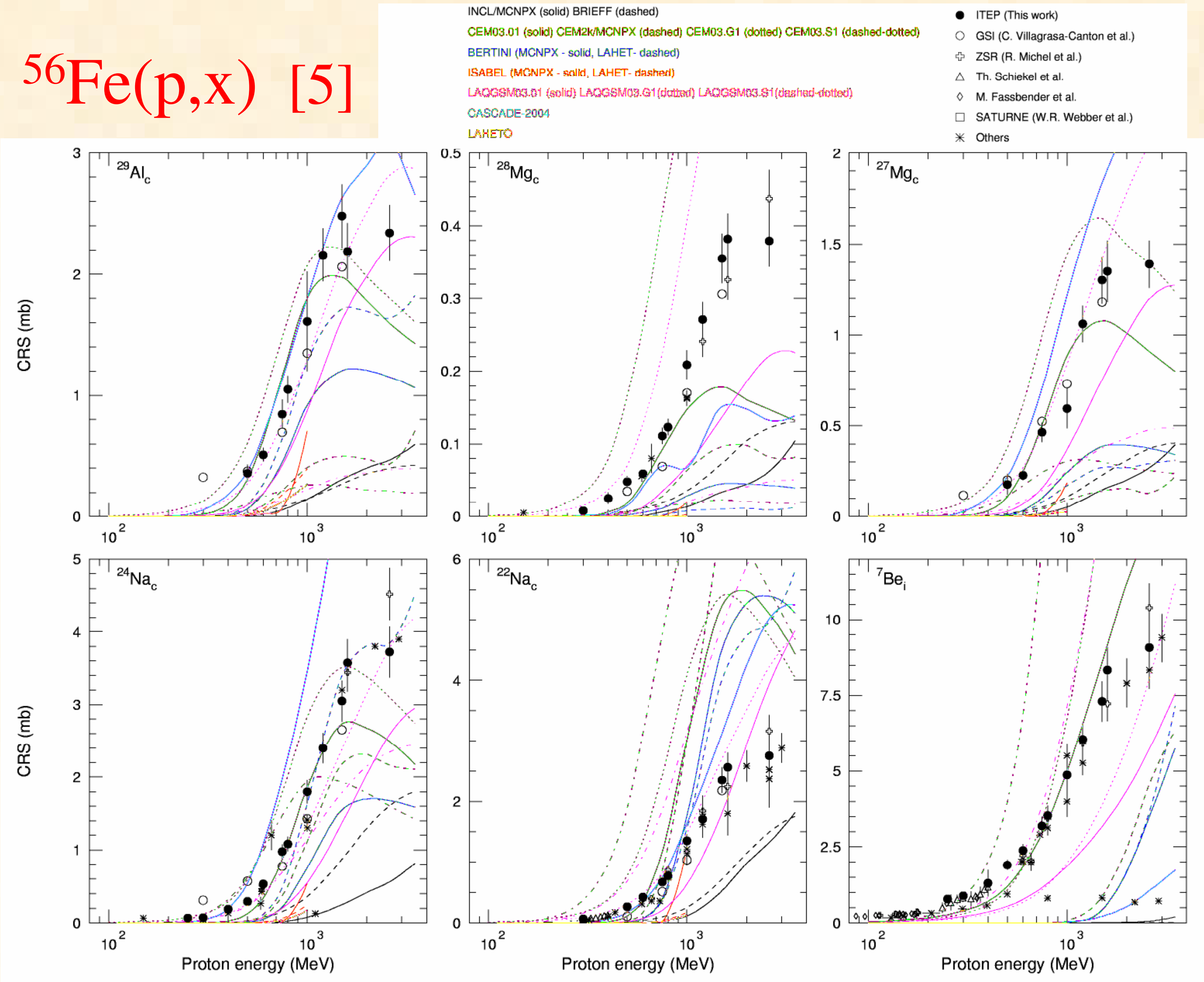

INCL/MCNPX (solid) BRIEFF (dashed)
CEM03.01 (solid) CEM2k/MCNPX (dashed) CEM03.G1 (dotted) CEM03.S1 (dashed-dotted)
BERTINI (MCNPX - solid, LAHET- dashed)
ISABEL (MCNPX - solid, LAHET- dashed)
LAQGSM03.01 (solid) LAQGSM03.G1(dotted) LAQGSM03.S1(dashed-dotted)
CASCADE-2004
LAHETO
ITEP (This work)
GSI (C. Villagrasa-Canton et al.)
ZSR (R. Michel et al.)
Th. Schiekel et al.
M. Fassbender et al.
SATURNE (W.R. Webber et al.)
Others
CRS (mb)
48Sc_i
47Sc_c
47Sc_i
46Sc_i
44Sc_i(m+g)
43Sc_c

$^{56}Fe(p,x)$ [4]



INCL/MCNPX (solid) BRIEFF (dashed)
CEM03.01 (solid) CEM2k/MCNPX (dashed) CEM03.G1 (dotted) CEM03.S1 (dashed-dotted)
BERTINI (MCNPX - solid, LAHET- dashed)
ISABEL (MCNPX - solid, LAHET- dashed)
LAQGSM03.01 (solid) LAQGSM03.G1(dotted) LAQGSM03.S1(dashed-dotted)
CASCADE-2004
LAHETO
ITEP (This work)
GSI (C. Villagrasa-Canton et al.)
ZSR (R. Michel et al.)
Th. Schiekel et al.
M. Fassbender et al.
SATURNE (W.R. Webber et al.)
Others
47Ca_c
44K_c*
43K_c
42K_i
41Ar_c
39Cl_c
CRS (mb)
Proton energy (MeV)

$^{56}Fe(p,x)$ [5]



INCL/MCNPX (solid) BRIEFF (dashed)
CEM03.01 (solid) CEM2k/MCNPX (dashed) CEM03.G1 (dotted) CEM03.S1 (dashed-dotted)
BERTINI (MCNPX - solid, LAHET- dashed)
ISABEL (MCNPX - solid, LAHET- dashed)
LAQGSM03.01 (solid) LAQGSM03.G1(dotted) LAQGSM03.S1(dashed-dotted)
CASCADE-2004
LAHETO
ITEP (This work)
GSI (C. Villagrasa-Canton et al.)
ZSR (R. Michel et al.)
Th. Schiekel et al.
M. Fassbender et al.
SATURNE (W.R. Webber et al.)
Others
29Alc
28Mgc
27Mgc
24Nac
22Nac
7Bei
CRS (mb)
Proton energy (MeV)

Conclusions

- 11'962 residual CRS's have been measured at ITEP during 1/10/1997 - 1/01/2008. At least 3 data sets (^{nat}Pb, ^{181}Ta, ^{56}Fe) measured at permanent energy list can well be used in Model Intercomparison. ^{181}Ta, ^{56}Fe data will be finished and available by 1/03/2009.

Target	Proton Energy (GeV)										
	0.04	0.07	0.1	0.15	0.25	0.4	0.6	0.8	1.2	1.6	2.6
^{209}Bi	13	35	50	71	106	128	147	162	183	192	198
^{nat}Pb	**18**	**28**	**43**	**63**	**95**	**116**	**141**	**154**	**171**	**181**	**178**
^{208}Pb	8	28	36	63	94	113	141	154	170	182	172
^{207}Pb	9	29	42	65	94	112	140	152	170	180	171
^{206}Pb	13	28	46	65	94	112	139	156	170	180	171
^{nat}W	x	x	x	x	i	i	i	i	i	i	i
^{181}Ta	**x**	**x**	**x**	**x**	**i**	**i**	**i**	**i**	**i**	**i**	**i**
^{93}Nb	x	x	x	x	i	i	i	105	110	123	128
^{nat}Ni	x	x	x	x	i	i	i	43	42	46	46
^{56}Fe +	**x**	**x**	**x**	**x**	**i**	**i**	**i**	**38**	**39**	**38**	**40**
^{nat}Cr	x	x	x	x	i	i	i	30	31	32	32

- To get smooth excitation function the codes should provide simulations for extended list of energies, e.g. 20, 25, 30, 35, 40, 45, 50, 60, 70, 85, 100, 125, 150, 175, 200, 250, 300, 350, 400, 500, 600, 700, 800, 1000, 1200, 1400, 1600, 2000, 2600, 3000 (or 3500) MeV. (30 energies)
- Statistics of simulations should not be less $N_{inter}(min) = \sim 100 * \sigma_{in} / \sigma_i(min) = 100 * 1000mb/0.01mb = 10 \cdot 10^6$ interactions (~30energies*3sets*10M=1B interactions for each code)
- Mean squared deviation factor <F> should be estimated separately for low energy proton range (e.g. $20 \le E_p \le 200$MeV (15 energies) and $200 < E_p \le 3000$MeV (15 energies))
- ITEP experience in calculation cumulative yields can be used
- Future ITEP experiments are planned to include Zr, Mo, Ti, Th, U.