SIMULATION OF NEUTRON PRODUCTION IN HADRON-NUCLEUS AND NUCLEUS-NUCLEUS INTERACTIONS IN GEANT4

A. Galoyan, V. Uzhinsky and A. Ribon

BES program of RHIC, , NICA/MPD, FAIR/CBM, PANDA

Geant4 FTF, Bertini, Binary Cascade models are used.

Original Fritiof model FTF is based on Fritiof model of LUND university.

B. Andersson et al., Nucl. Phys. B281 (1987) 289;

B. Nilsson-Almquist and E. Stenlund, Comp. Phys. Commun. 43 (1987) 387.

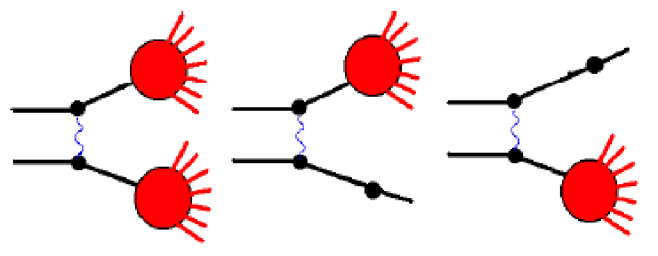
FTF model in Geant4. "Recent developments in Geant4."

J.Allison et al.. 2016. 40 pp., Nucl.Instrum.Meth. A835 (2016) 186-225

1. Main assumptions of the FTF model
2. Reggeon cascading in hadron-nucleus interactions in the FTF model
3. Analysis of ITEP exp.data on neutron production with energies 7.5 – 190 MeV in reactions p+A->n+X».
4. Description of Neutron-Production Double-Differential Cross Sections for nuclear spallation reaction induced by 3.0 GeV Protons.
5. Spallation neutron production by 1.2 GeV and 1.6 GeV protons on various targets
6. Neutron production in anti-proton – nucleus interactions, LEAP exp. data
7. Neutron production in Collisions of H-1, H-2, He-4, and C-12 Nuclei with various nuclei at 1–2 GeV per Nucleon

Simulation of inelastic nucleon-nucleon interactions

Fritiof model



Hadron-hadron interactions are modeled as binary reactions

$a + b \to a' + b'$, $m_a' > m_a$ $m_b' > m_b$

where a' and b' are excited states of the initial hadrons a and b.

$$dW \propto \frac{dM_1}{M_1}, \qquad dW \propto \frac{dM_2}{M_2}$$

$NN \to N\Delta_{1232}$

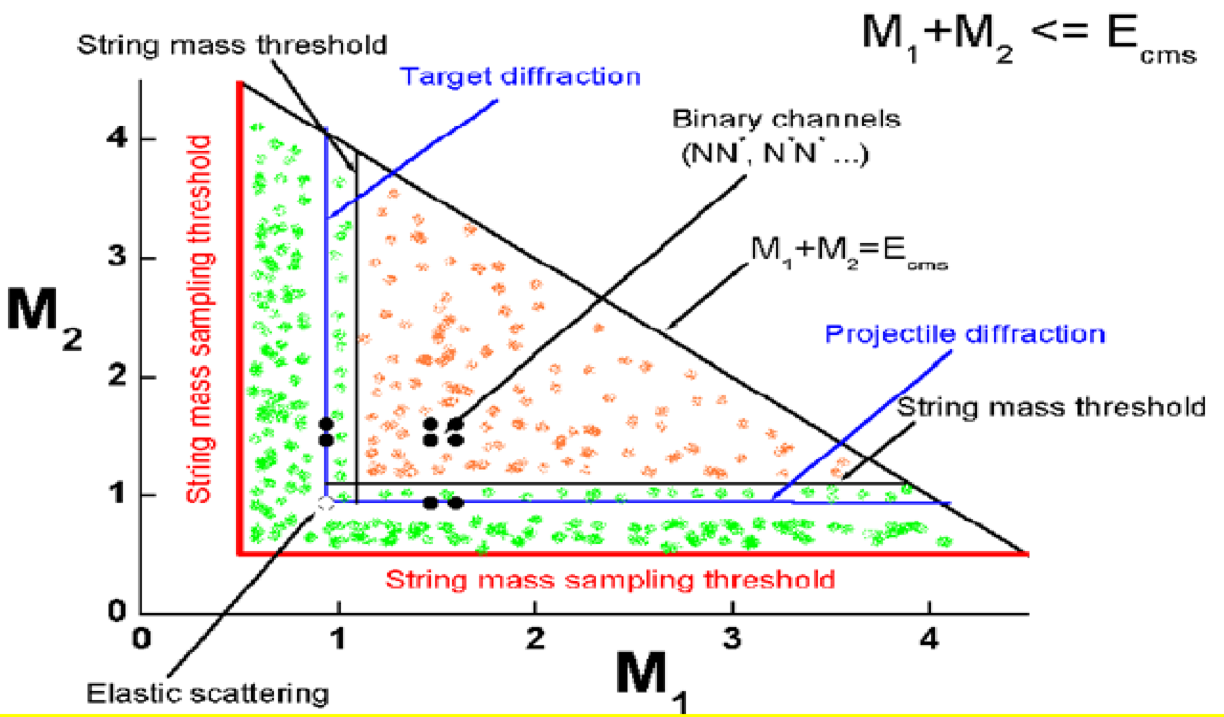
$NN \to NN^*$

$NN \to N\Delta^*$

$NN \to \Delta_{1232}N^*$

$NN \to \Delta_{1232}\Delta^*$

$NN \to \Delta\Delta$ excitation



UrQMD Md=1.46

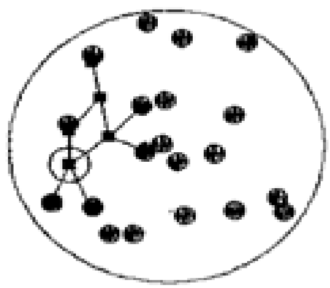
Fritiof 1.6 Md=1.2
Fritiof 7.0 Md=1.2
Hijing Md~2;
FTF – 1.16

Reggeon theory inspired model of nuclear destruction in FTF model

Glauber approach implemented in FTF is not sufficient for a destruction of a nucleus. Thus a reggeon cascading model of nuclear destruction was applied.

Model of nuclear disintegration in high-energy nucleus nucleus interactions.
K. Abdel-Waged, V.V. Uzhinsky Phys.Atom.Nucl.60:828-840,1997, Yad.Fiz.60:925-937,1997.

Probability to involve a spectator nucleon having coordinates b*i* by a participating nucleon with coordinates b*j* – *Pij*



$$P_{ij} = C_{nd} e^{-|\mathbf{b}_i - \mathbf{b}_j|^2/R^2}, \qquad R \simeq 1.2 \text{ fm}, \qquad (1)$$

$$C_{nd} = 0.00481 A e^{4(y_p - 2.1)}/(1 + e^{4(y_p - 2.1)}). \qquad (2)$$

Here, A is the mass number of the target nucleus and y_p is the rapidity of the projectile in the target nucleus rest frame.

$$P(p_z, \mathbf{p}_T) \propto e^{-|\mathbf{p}_T|^2/\langle|\mathbf{p}_T|^2\rangle} e^{-(x^- - 1/N_N)^2/(0.3/N_N)^2}, \qquad (3)$$

$$x^- = (E - p_z)/(E_N - P_N),$$

$$\langle|\mathbf{p}_T|^2\rangle = 0.035 + 0.04 e^{4(y_p - 2.5)}/(1 + e^{4(y_p - 2.5)}) \ (\text{GeV}/c)^2. \qquad (4)$$

Here, N_N is the multiplicity of the involved and participating nucleons, x^- is the light-cone momentum fraction, E_N and P_N are the re-defined energy and momentum of the interacting nucleons of the target

Analysis of ITEP experimental data on neutron production

Yu.D. Bayukov et al., ITEP preprint No 172 (1983)

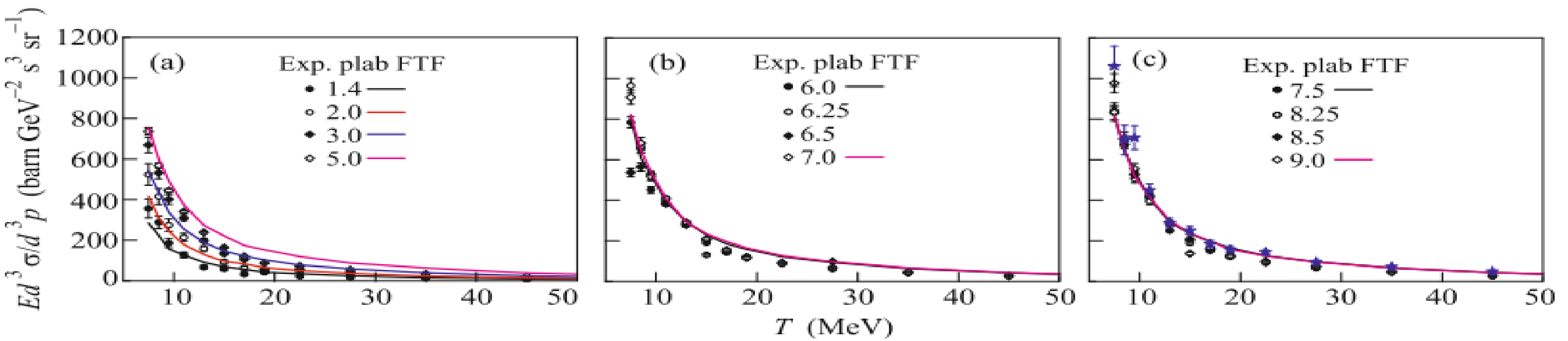
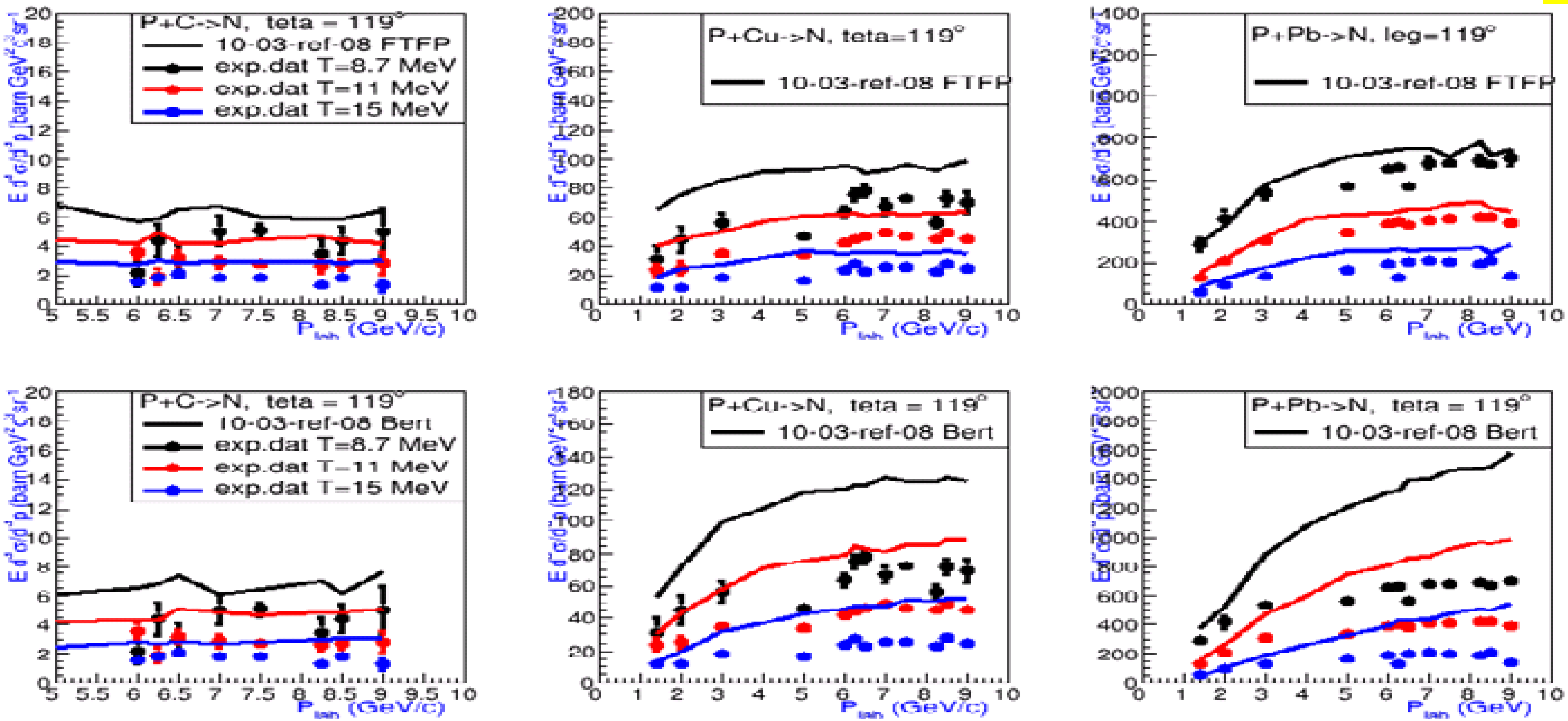
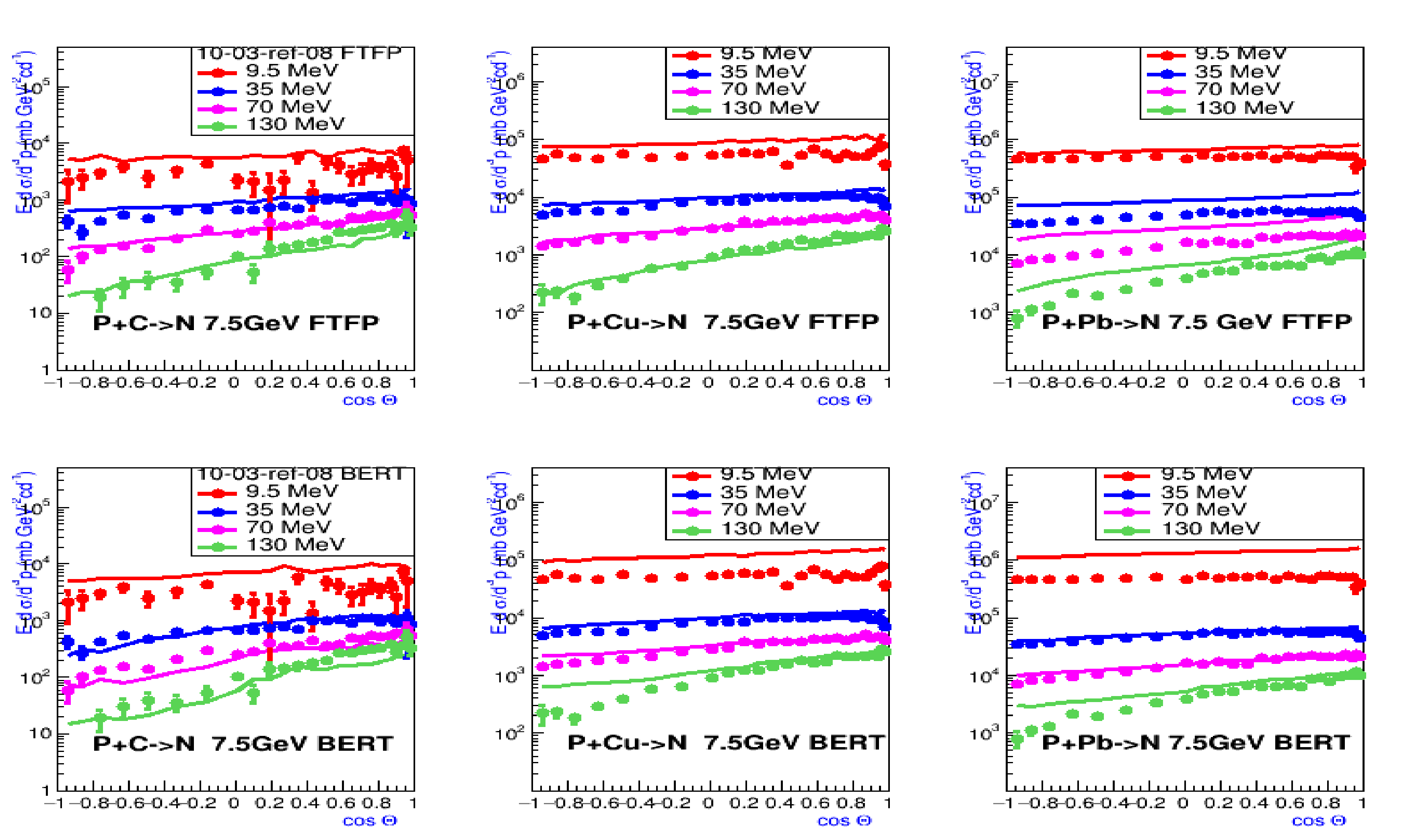


Fig. 1. (Color online) Inclusive neutron production cross sections in p + Pb interactions at various projectile momenta (a) 1.4, 2, 3, and 5 GeV/c; (b) 6, 6.25, 6.5, and 7 GeV/c; and (c) 7.5, 8.25, 8.5, and 9 GeV/c. Points are experimental data [8]. Lines are FTF model calculations.



Analysis of ITEP experimental data on neutron production

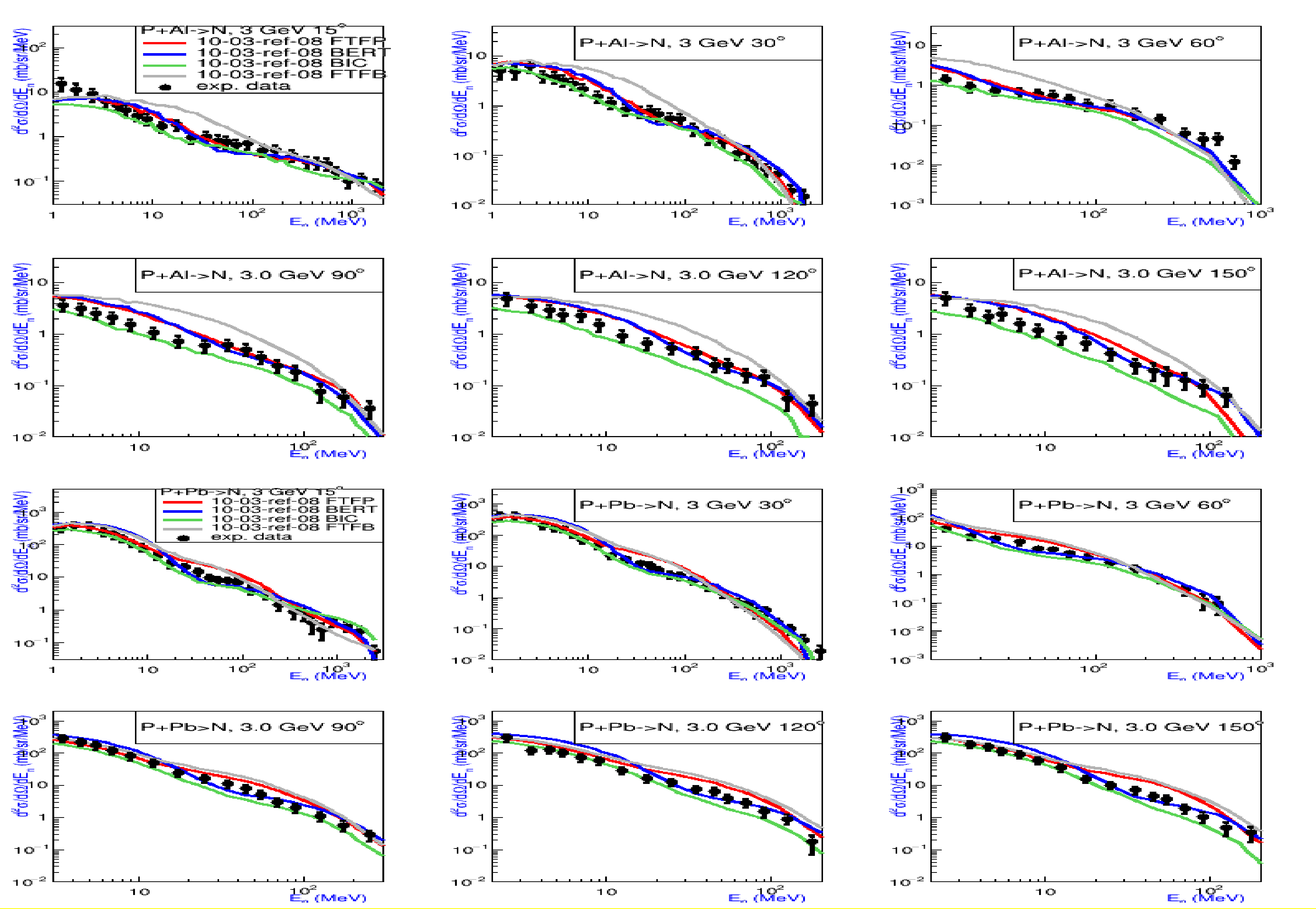
Yu.D. Bayukov et al., ITEP preprint No 172 (1983) «Cross sections of neutron production with energies 7.5 – 190 MeV in reactions p+A->n+X».



A.S. Galoyan, A. Ribon, and V.V. Uzhinsky “Scaling and Asymptotic Properties…”
JETP Letters, 2015, Vol. 102, No. 6, pp. 324

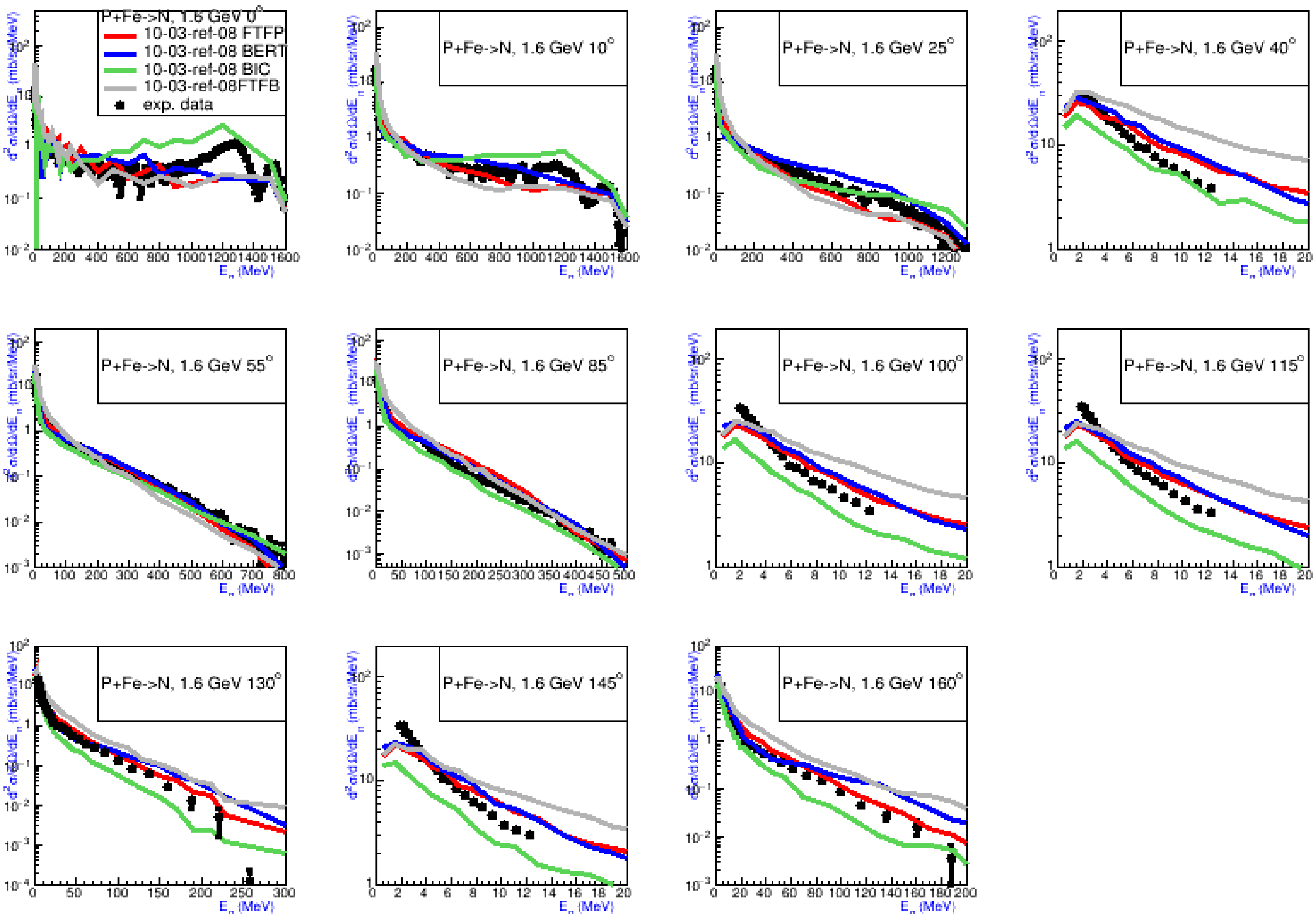
Current status of neutron production in FTF model

K. Ishibashi et al., J.Nucl. Sci. Tech., Vol.34, N6 (1997) 529-537



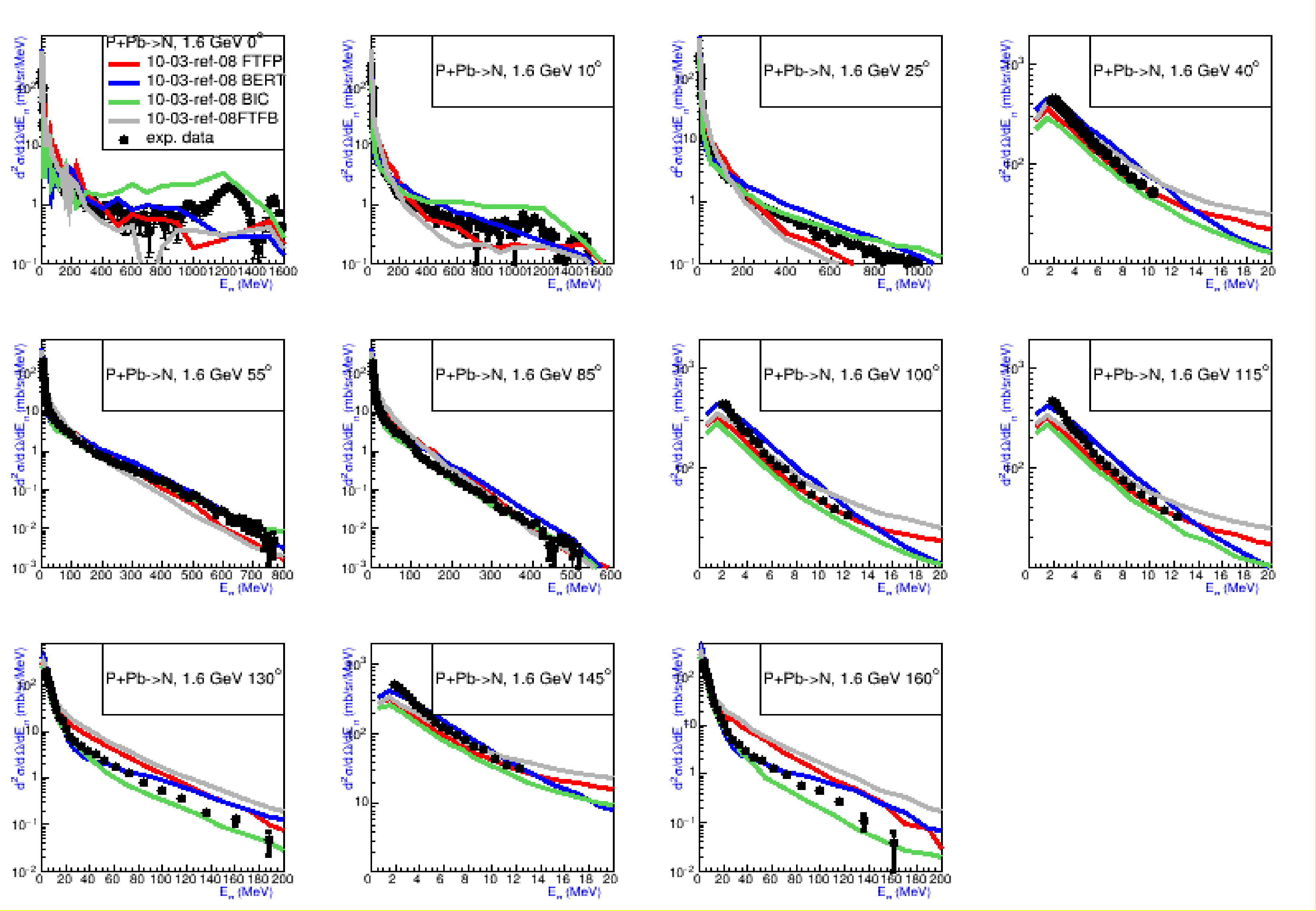
Current status of neutron production in FTF, Bertini, BIC models

S. Leray (DAPNIA, Saclay) et al., PRC 65(2002)044624



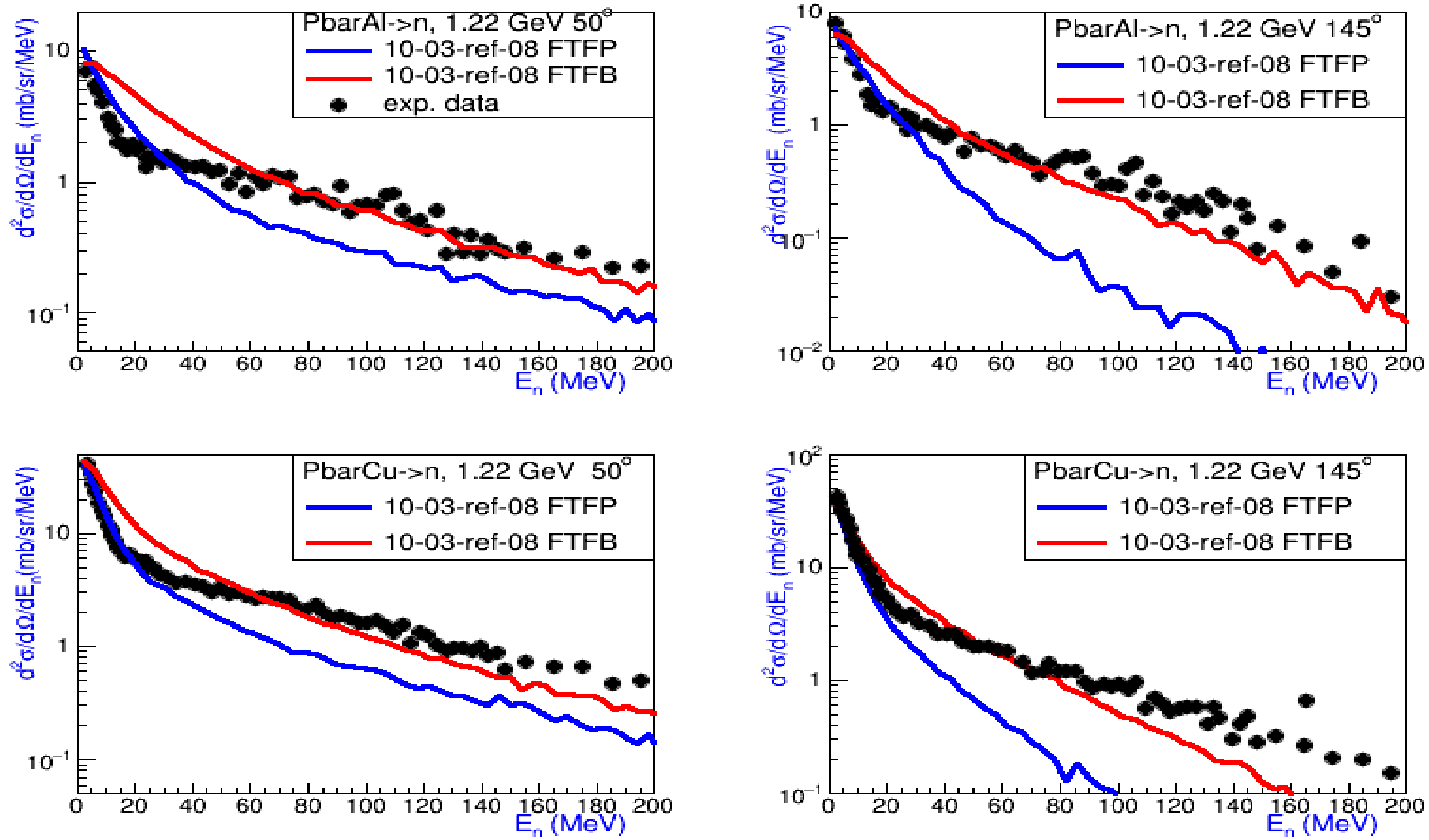
Current status of neutron production in FTF, Bertini, BIC models

S. Leray (DAPNIA, Saclay) et al., PRC 65(2002)044624



Results of FTF validation for AntiProton–Nucleus reactions inflight

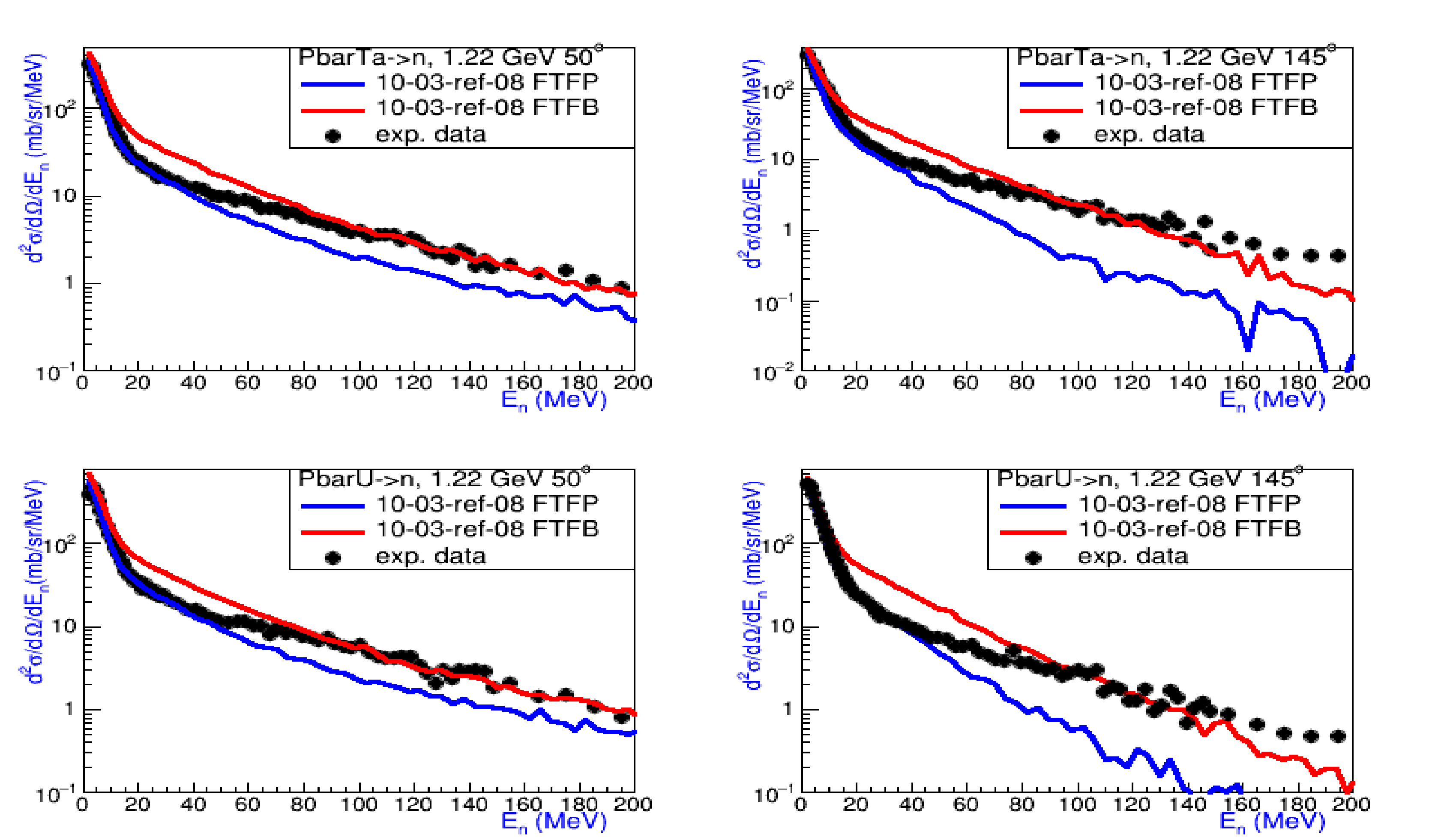
Kinetic energy spectra of neutrons produced in Pbar-Al, Pbar-Cu at projectile momenta 1.22 GeV/c



T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000) LEAR collab. data

Results of FTF validation for AntiProton–Nucleus reactions inflight

Kinetic energy spectra of neutrons produced in Pbar-Ta, Pbar-U at projectile momenta 1.22 GeV/c



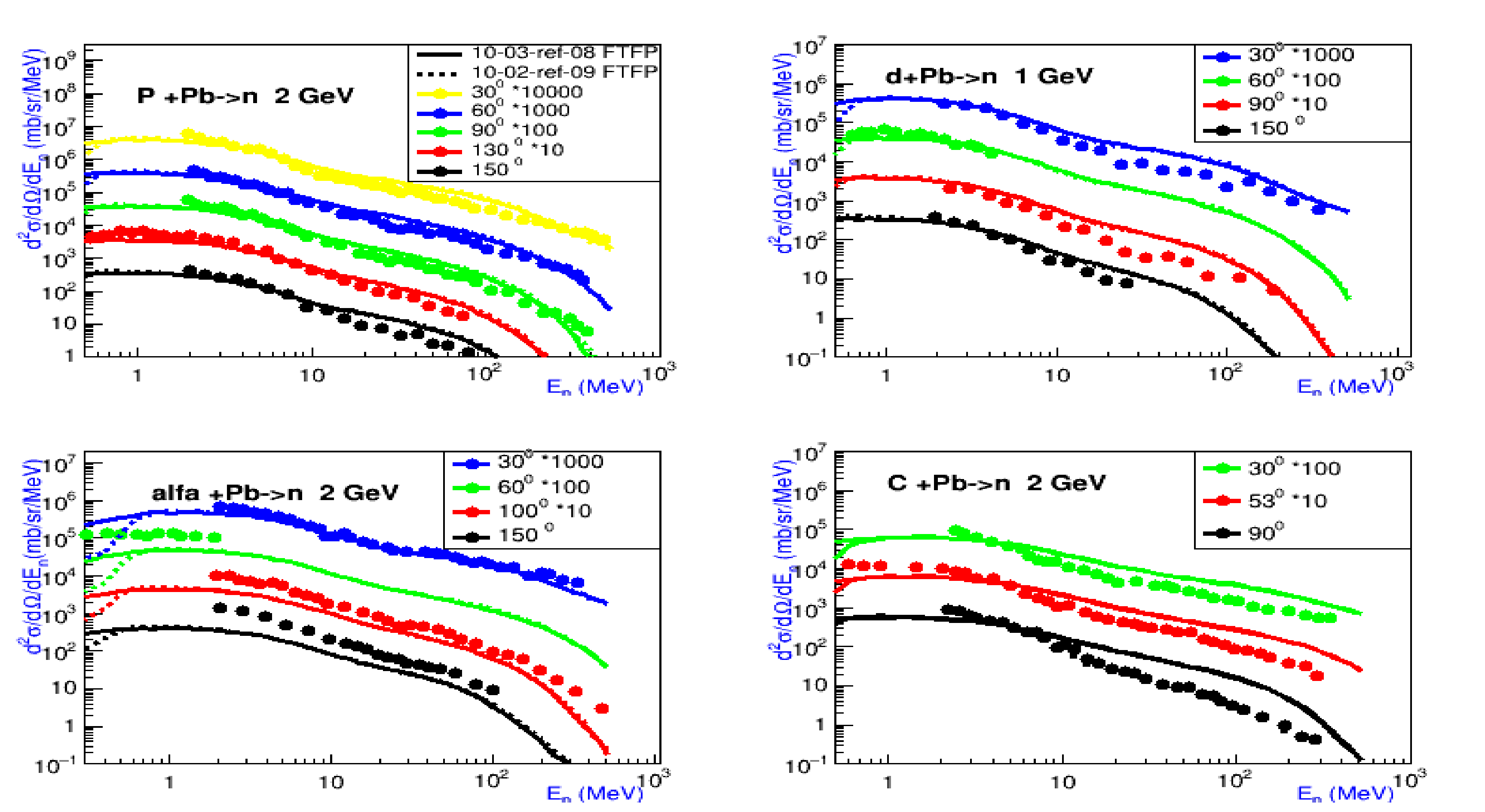
T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000) LEAR collab. data

FTF is installed in PandaRoot for simulations of PbarP and Pbar-Nucleus simulations

Neutron production in nucleus-nucleus interactions in FTF model

Yurevich, R.M. Yakovlev, V. G. Lyapin (JINR, RI St.Peterburg)

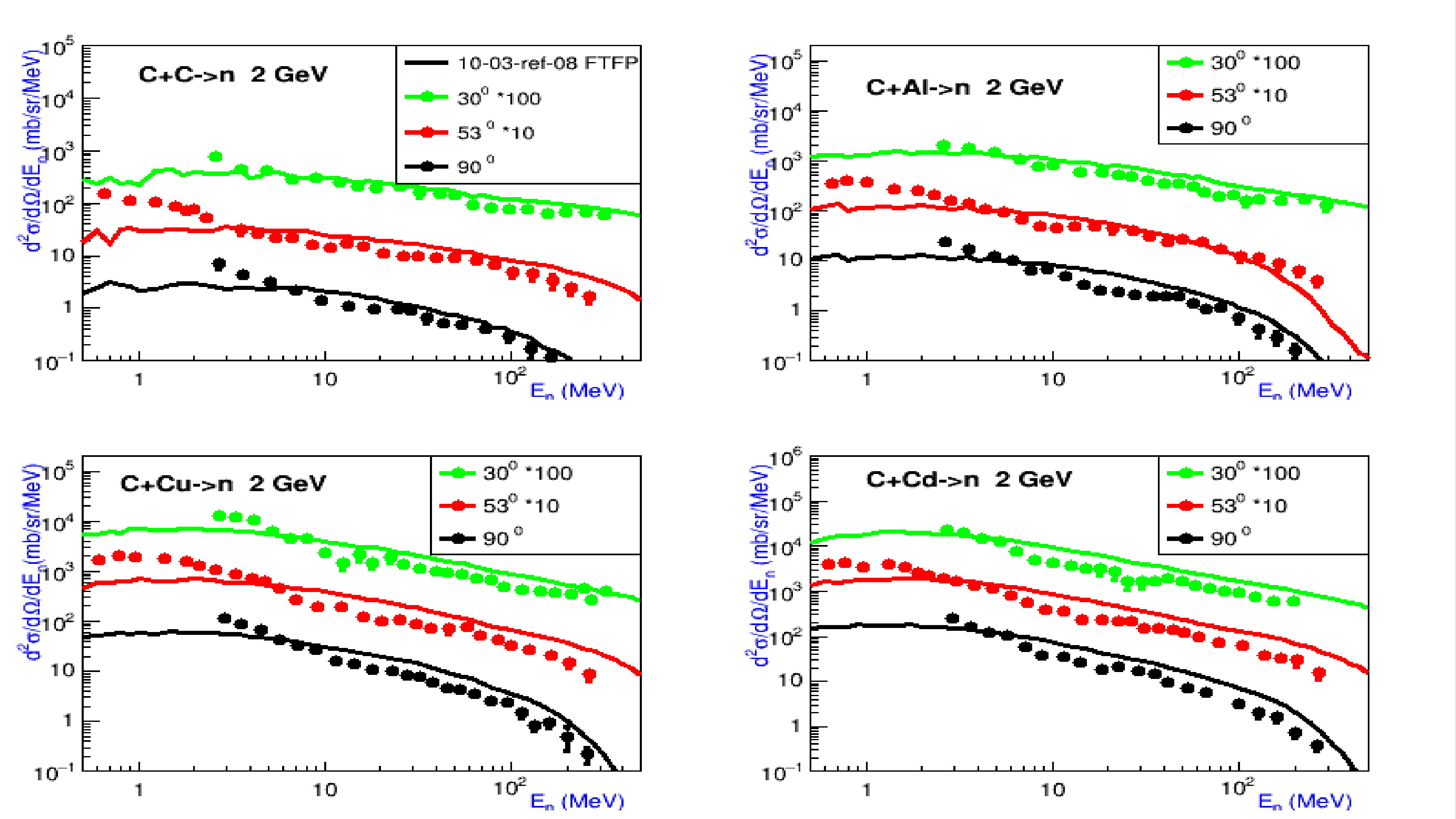
Physics of Atomic Nuclei, 2006, Vol. 69, No. 9, pp. 1496–1509 «Neutron Emission in Interactions of H-1, H-2, He-4, and C-12 Nuclei with Lead Nuclei at 1–2 GeV per Nucleon».



A.S. Galoyan, A. Ribon, and V.V. Uzhinsky "Scaling and Asymptotic Properties…"
JETP Letters, 2015, Vol. 102, No. 6, pp. 324

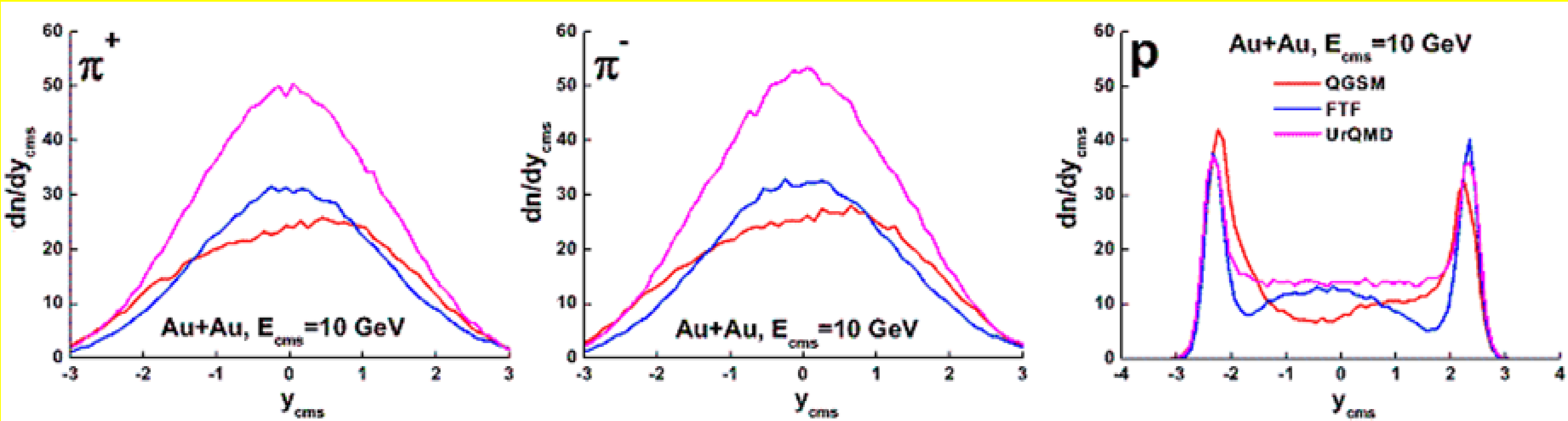
Neutron production in nucleus-nucleus interactions in FTF model

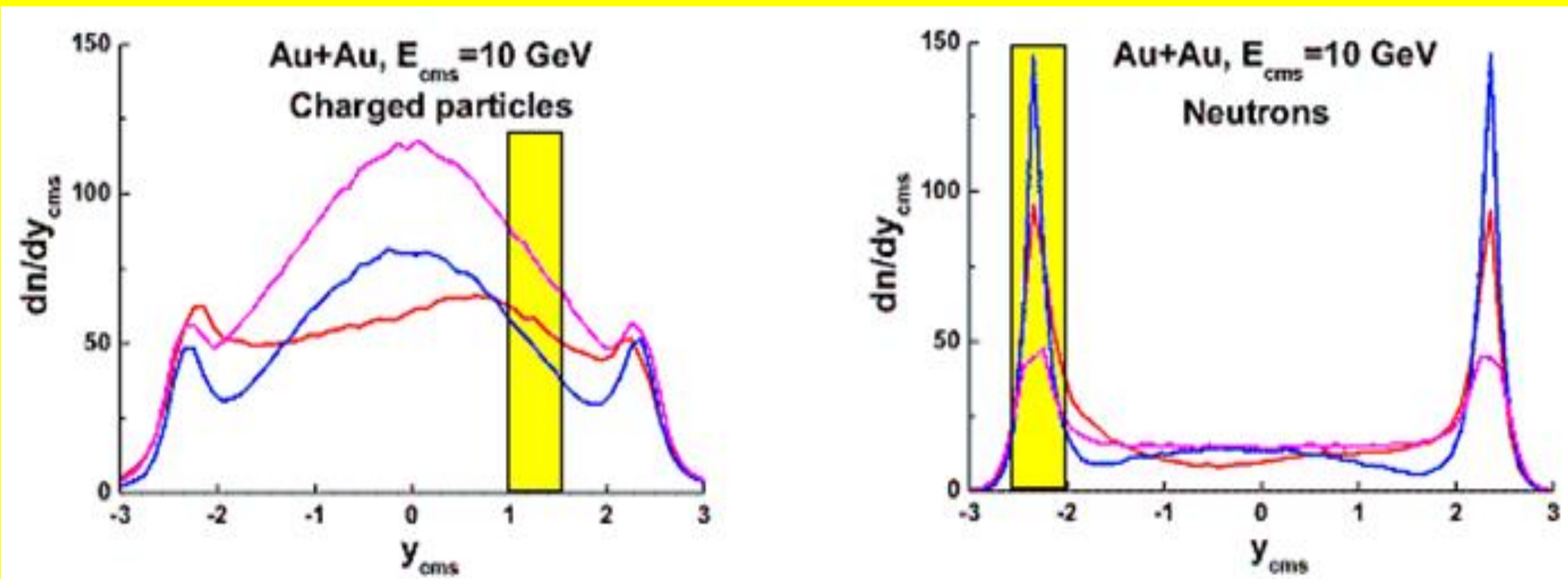
Yurevich, R.M. Yakovlev, V. G. Lyapin (JINR, RI St.Peterburg) Physics of Atomic Nuclei, *2012, Vol 75, No 2, pp191-202.* *«Neutron production in Collisions between Carbon Nuclei of Energy 2 GeV per Nucleon and Carbon, Aluminium, Cadmium and Lead Nuclei».*



Properties of particles produced nucleus-nucleus interactions at 10 GeV/Nucleon

Predictions for the NICA/MPD experiment at JINR





Conclusion

1. **Studying experimental data obtained at ITEP on neutron production in interactions of protons with various nuclei in the energy range from 747 MeV up to 8.1 GeV, we have found that slow neutron spectra have scaling and asymptotic properties. Particularly, the spectra for various nuclei are similar, and can be approximately described by the function $A^n f(E)$.**

2. **At comparison of improved FTF and Bertini results with ITEP experimental data, it was obtained that FTF model better describes slow neutron production in P-Cu and P-Pb interactions than Bertini model. Calculations by Bertini model overestimate essentially production of slow neutrons**

3. **At comparison with exp. data, it was shown that improved FTF model gives acceptable results for neutron production in proton-nucleus interactions at projectile energies more than 1.0 GeV. Good agreement were reached for neutron spectra in pA-interactions at projectile momenta 3 GeV/c. FTF model works as well as Bertini one.**

4. **For neutron production in antiproton-nucleus interactions, FTF+BIC calculation results are in a good agreement with exp. data of LEAR collaboration.**

5. **FTF model gives quite reasonable results for neutron production in nucleus - nucleus interactions at projectile energy 1-2 GeV per nucleon.**

SIMULATION OF NEUTRON PRODUCTION IN HADRON-NUCLEUS AND NUCLEUS-NUCLEUS INTERACTIONS IN GEANT4

A. Galoyan, V. Uzhinsky and A. Ribon

1. **Yu.D. Bayukov et al., ITEP preprint No 172 (1983)** ***«Cross sections of neutron production with energies 7.5 – 190 MeV in reactions p+A->n+X».***

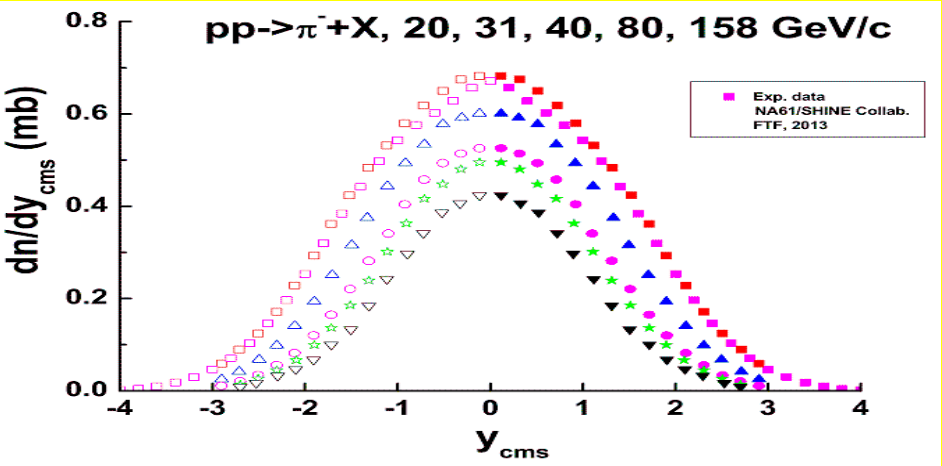
2. **K. Ishibashi et al., J.Nucl. Sci. Tech., Vol.34, N6 (1997) 529-537*«Measurement of Neutron-Production Double-Differential Cross Sections for Nuclear Spallation Reaction Induced by 0.8, 1.5 and 3.0 GeV Protons».***

3. **S. Leray (DAPNIA, Saclay) et al., PRC *65(2002) , 044624***
«Spallation neutron production by 0.8 GeV, 1.2 GeV and 1.6 GeV protons on various targets».

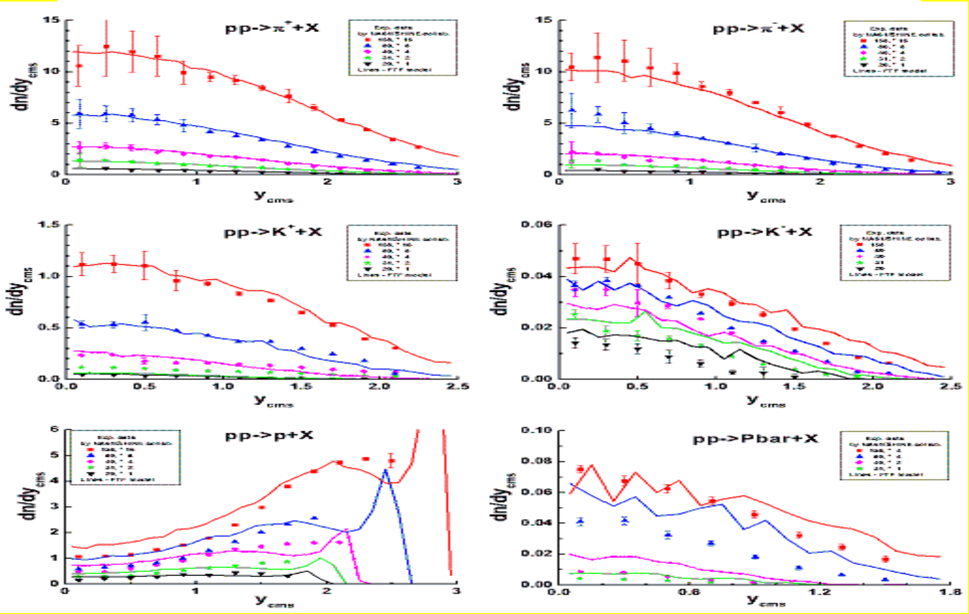
4. **Neutron production in antiproton-nucleus interactions.**
T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000) LEAR collab. data

5. **V. I. Yurevich, R.M. Yakovlev, V. G. Lyapin (JINR, RI St.Peterburg)**
Physics of Atomic Nuclei, 2006, Vol. 69, No. 9, pp. 1496–1509. *«Neutron Emission in Interactions of H-1, H-2, He-4, and C-12 Nuclei with Lead Nuclei at 1–2 GeV per Nucleon». Physics of Atomic Nuclei, 2012, Vol 75, No 2, pp191-202. «Neutron production in Collisions between Carbon Nuclei of Energy 2 GeV per Nucleon and Carbon,Aluminium ... Nuclei».*

Toward description of NA61/SHINE data on pp interactions

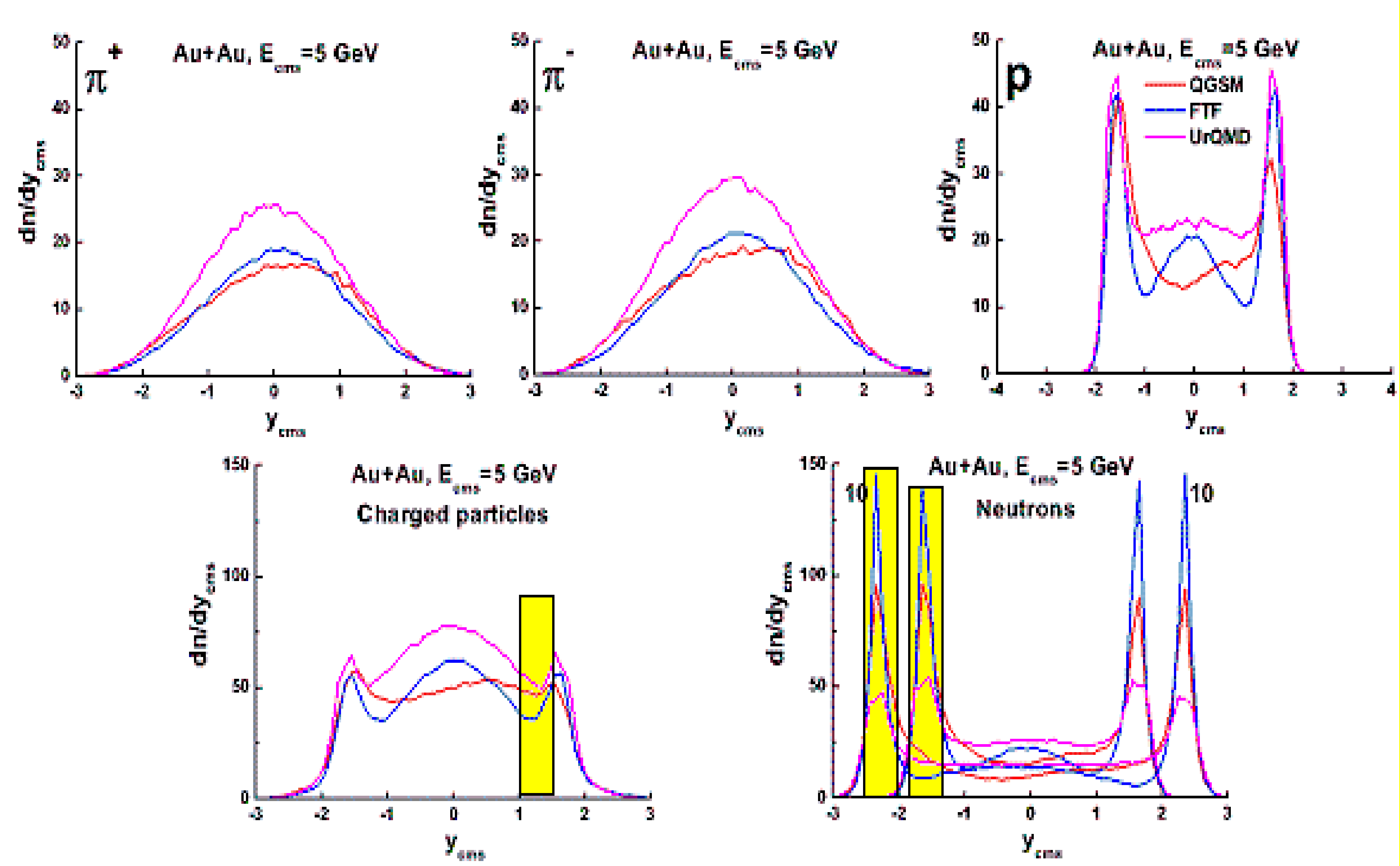


Marek Gazdzeski, D.T. Larsen, 2015



Properties of particles produced nucleus-nucleus interactions at 5 GeV/Nucleon

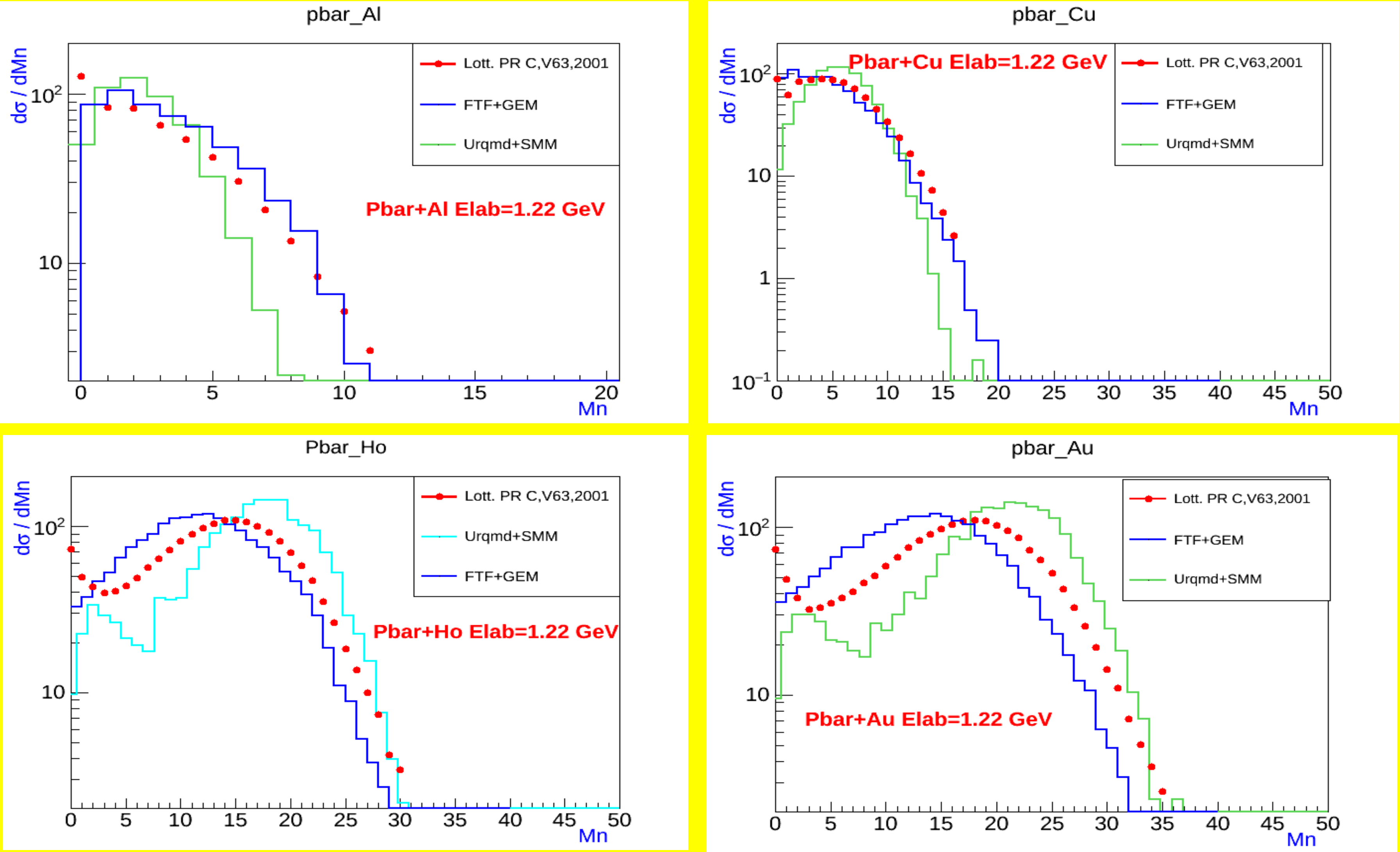
Predictions for the NICA/MPD experiment at JINR



Results of FTF validation for Antiproton–Nucleus reactions

Multiplicity distributions of neutrons produced in Pbar-Nucleus at energy 1.22 GeV in FTF and UrQMD+SMM models

exp.data : B. Lott et al., Phys.Rev.C 63 034616

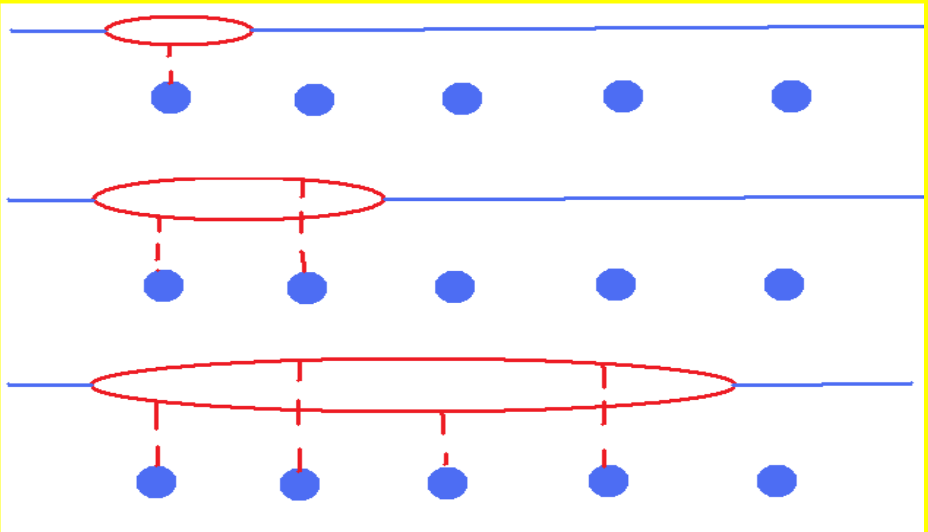


Correction of multiplicity of intra-nuclear collisions

Source of the problem: the AGK cutting rules are asymptotical ones!

Glauber cross section **AGK rules**

$$\sigma_{pA}^{in} = \int d^2b[1 - e^{-\sigma_{pn}^{in} T(\vec{b})}] = \sum_{\nu=1}^{\infty} \int d^2b \frac{[-\sigma_{pn}^{in} T(\vec{b})]^{\nu}}{\nu!} e^{-\sigma_{pN} T(\vec{b})}$$



Low energy, Std. cascade.

Cascade+ QGS

High energy, Std. QGS.

Competition of planar and non-planar diagrams. There was only 1 paper on the subject by K. Boreskov and A. Kaidalov.

Glauber cross section

$$N_{max} = \sigma\rho < \tau > v\gamma = \sigma\rho < \tau > P_{lab}^{proj}/m_{proj} = P_{lab}/P_0$$

$$\sigma_{pA}^{in} = \int d^2b[1 - e^{-\sigma_{pn}^{in} T(\vec{b})}] = \int d^2b[1 - e^{-N_{max}\frac{\sigma_{pn}^{in}}{N_{max}} T(\vec{b})}] =$$

$$\sum_{\nu=1}^{N_{max}} C_{N_{max}}^{\nu} \int d^2b[1 - e^{-\frac{\sigma_{pn}^{in}}{N_{max}} T(\vec{b})}]^{\nu} e^{-(N_{max}-\nu)\frac{\sigma_{pn}^{in}}{N_{max}} T(\vec{b})}$$

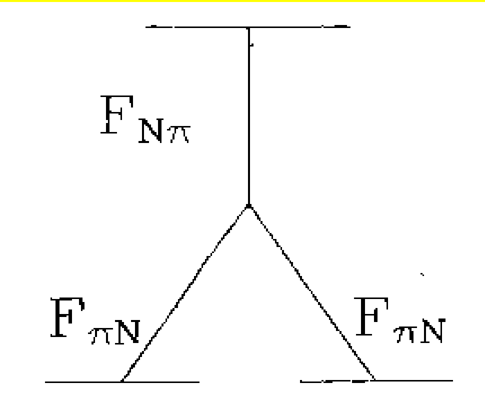
S.Yu. Shmakov, V.V. Uzhinsky, Zeit. fur Phys. C36:77,1987.

Max. cross section method:

W.A. Coleman: Nucl. Sci. Eng. 32 (1968) 76

Uzhi rules

Tuning of reggeon cascading parameters



Glauber approach implemented in FTF and QGS is not sufficient for a destruction of a nucleus. Thus a reggeon cascading model of nuclear destruction was applied.

Model of nuclear disintegration in high-energy nucleus nucleus interactions.
K. Abdel-Waged, V.V. Uzhinsky
Phys.Atom.Nucl.60:828-840,1997, Yad.Fiz.60:925-937,1997.

$$\begin{aligned} Y &= G \int d\xi' d^2b' F_{N\pi}(\vec{b}-\vec{b}', \xi-\xi') \times \\ &\times F_{\pi N}(\vec{b}'-\vec{s}_1, \xi') F_{\pi N}(\vec{b}'-\vec{s}_2, \xi'), \end{aligned}$$

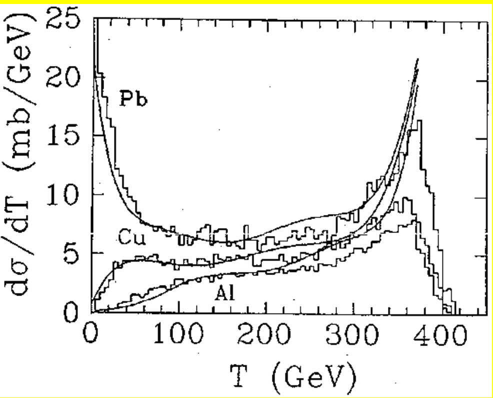
G is 3-pomeron vertex constant, $\vec{b}$- impact parameter of incident hadron, $\vec{s}_1$, $\vec{s}_2$- impact co-ordinates of nuclear nucleons. $\vec{b}'$ is the position of pomeron interactions vertex in the impact parameter plane, ξ'-its rapidity.

Using Gaussian parameterization for $F_{\pi N}$ ($F_{\pi N} = exp(-(|\vec{b}|^2)/(R^2_{\pi N}))$ and neglecting its dependence on energy, we have

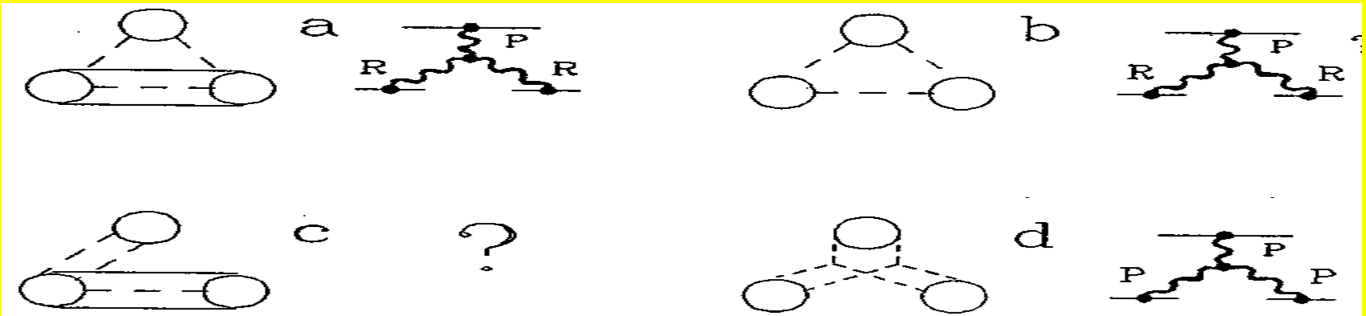
$$\begin{aligned} Y &\simeq G(\xi_0 - 2\epsilon)\frac{R^2_{\pi N}}{3} exp(-(\vec{b}-(\vec{s}_1+\vec{s}_2)/2)^2/3R^2_{\pi N}) \times \\ &\times exp(-(\vec{s}_1-\vec{s}_2)^2/2R^2_{\pi N}), \end{aligned}$$

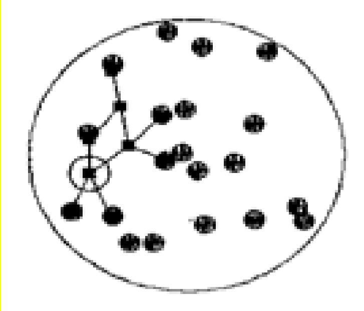
where $R_{\pi N}$ is the pion-nucleon interaction radius. According to (2) the contribution reaches a maximum if the nucleon coordinates $\vec{s}_1$ and $\vec{s}_2$ coincide and decreases very fast with increasing the distance between the nucleons. For reproduction of this behavior we choose ϕ as

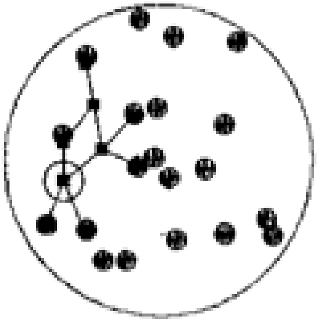
$$\phi(|\vec{s}_i - \vec{s}_j|) = C exp(-\frac{|\vec{s}_i - \vec{s}_j|^2}{r_c^2}).$$



Si+A, 14.7 GeV/N
T – energy in ZDC







Tuning of reggeon cascading parameters

How have we to determine momentum spectra of nucleons?

Complex analysis of gold interactions with photoemulsion nuclei at 10.7-GeV/nucleon within the framework of cascade and FRITIOF models.
By EMU-01 Collaboration (M.I. Adamovich *et al.*). 1997. Zeit. fur Phys.A358:337-351,1997.

In case of dissociation of two compound systems A and B containing A and B constituents respectively, the i-th constituent of system A will be described by

$$x_i^+ = (E_{Ai} + p_{iz})/W_A^+ \quad and \quad \mathbf{p}_{i\perp},$$

and the j-th constituent of system B

$$y_j^- = (E_{Bj} - q_{jz})/W_B^- \quad and \quad \mathbf{q}_{j\perp}.$$

Here, $E_{A_i}(E_{B_i})$ and $\mathbf{p}_i(\mathbf{q}_i)$ are energy and momentum of i-th constituent from $A(B)$.

$$W_A^+ = \sum_{i=1}^{A}(E_{Ai} + p_{iz}); \quad W_B^- = \sum_{i=1}^{B}(E_{Bi} - q_{iz}).$$

Using these variables, let us write the conservation law as

$$\frac{W_A^+}{2} + \frac{1}{2W_A^+}\sum_{i=1}^{A}\frac{m_{i\perp}^2}{x_i^+} + \frac{W_B^-}{2} + \frac{1}{2W_B^-}\sum_{i=1}^{B}\frac{\mu_{i\perp}^2}{y_i^-} = E_A^0 + E_B^0,$$

$$\frac{W_A^+}{2} - \frac{1}{2W_A^+}\sum_{i=1}^{A}\frac{m_{i\perp}^2}{x_i^+} - \frac{W_B^-}{2} + \frac{1}{2W_B^-}\sum_{i=1}^{B}\frac{\mu_{i\perp}^2}{y_i^-} = P_A^0 + P_B^0,$$

$$\sum_{i=1}^{A}\mathbf{p}_{i\perp} + \sum_{i=1}^{B}\mathbf{q}_{i\perp} = 0, \qquad (15)$$

where $m_{i\perp}^2 = m_i^2 + \mathbf{p}_{i\perp}^2$, $\mu_{i\perp}^2 = \mu_i^2 + \mathbf{q}_{i\perp}^2$, and $m_i(\mu_i)$ - mass i-th constituent from system $A(B)$.

System (15) allows us to determine W_A^+, W_B^- and kinematic characteristics all the particles in the finite sets $\{x_i^+, \mathbf{p}_{i\perp}\}$, $\{y_i^-, \mathbf{q}_{i\perp}\}$.

$$W_A^+ = (W_0^- W_0^+ + \alpha - \beta + \sqrt{\Delta})/2W_0^-; \qquad (16)$$

$$W_B^- = (W_0^- W_0^+ - \alpha + \beta + \sqrt{\Delta})/2W_0^+; \qquad (17)$$

$$W_0^+ = (E_A^0 + E_B^0) + (P_{Az}^0 + P_{Bz}^0);$$

$$W_0^- = (E_A^0 + E_B^0) - (P_{Az}^0 + P_{Bz}^0);$$

$$\alpha = \sum_{i=1}^{A}\frac{m_{i\perp}^2}{x_i^+}, \quad \beta = \sum_{i=1}^{B}\frac{\mu_{i\perp}^2}{y_i^-};$$

$$\Delta = (W_0^- W_0^+)^2 + \alpha^2 + \beta^2 - 2W_0^- W_0^+ \alpha - 2W_0^- W_0^+ \beta - 2\alpha\beta;$$

$$p_{iz} = (W_A^+ x_i^+ - \frac{m_{i\perp}^2}{x_i^+ W_A^+})/2; \quad q_{iz} = -(W_B^- y_i^- - \frac{\mu_{i\perp}^2}{y_i^- W_B^-})/2.$$

To reproduce this result the values of $\mathbf{p}_{i\perp}$ for knocked-out nucleons are simulated according to distribution

$$dW \propto \exp(-\mathbf{p}_{i\perp}^2/<p_\perp^2>)d^2p_{i\perp}, \sqrt{<p_\perp^2>} = 0.05. \qquad (18)$$

The sum of transverse momenta (with sign "minus") was ascribed to the residual nucleus.
The chose of x_i^+ is carried out by

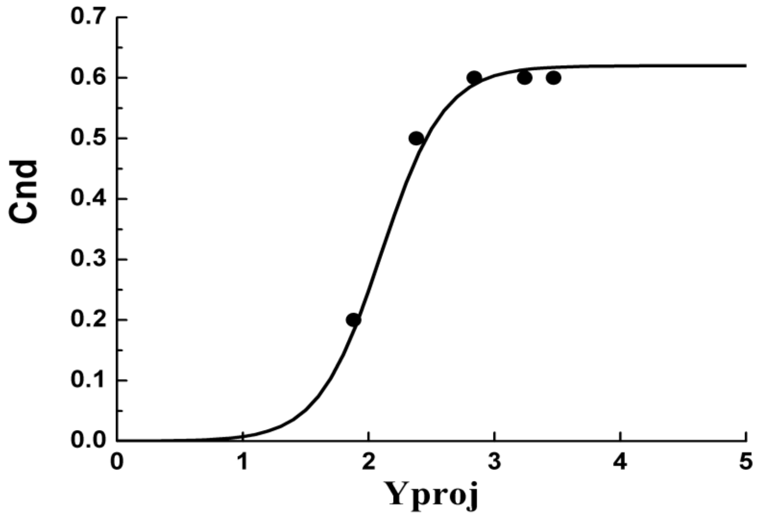
$$dW \propto \exp[-(x_i^+ - 1/A)^2/(d_x/A)^2]dx_i^+, \quad d_x = 0.05. \qquad (19)$$

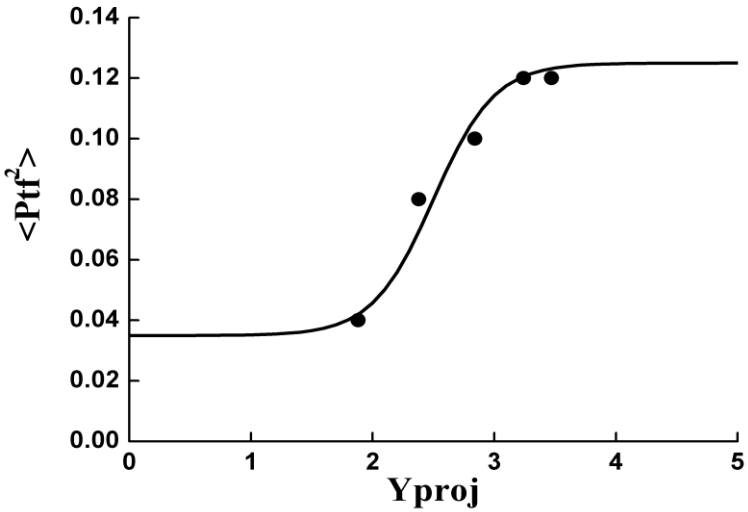
The dispersion of the distribution was defined by fitting the average emission angle of b-particles. x^+ of the residual nucleus was included as $1 - \sum x_i^+$.

Main parameters: Cnd, d_x, p_T^2

Tuning of reggeon cascading parameters

Unexpected results of the tuning!





$$C_{nd} = 0.62 \frac{e^{4(y-2.1)}}{1 + e^{4(y-2.1)}}$$

$$y = 2.1 \; at \; p_{lab} \simeq 4 \; GeV/c$$

$$< P_T^2 >= 0.035 + 0.09 \frac{e^{4(y-2.5)}}{1 + e^{4(y-2.5)}} \; (GeV/c)^2$$

$$y = 2.5 \; at \; p_{lab} \simeq 5.5 \; GeV/c$$

Clear signal of a transition regime!
The transition takes place at Plab= 4-5 GeV/c