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华南理工大学
South China University of Technology

Strangeness production and hypernuclear formation in hadron induced reactions

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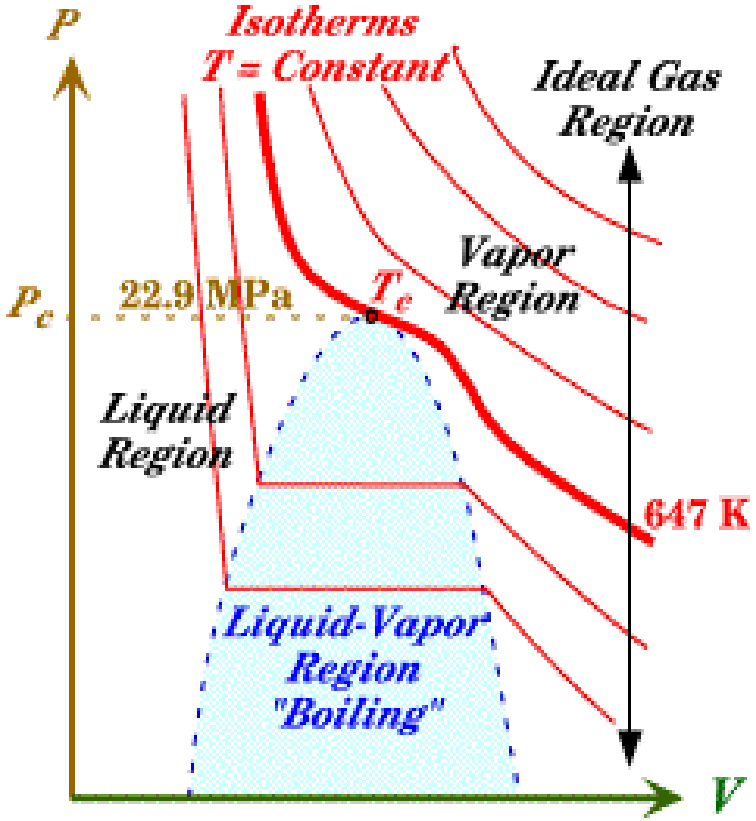
OUTLINE

- Introduction and motivation
- Transport approach for hadron induced nuclear reactions (LQMD)
- Strangeness production and in-medium effect
- Nuclear fragmentation and hypernuclear formation
- Summary

I. Introduction

状态方程(EOS-Equation of State):

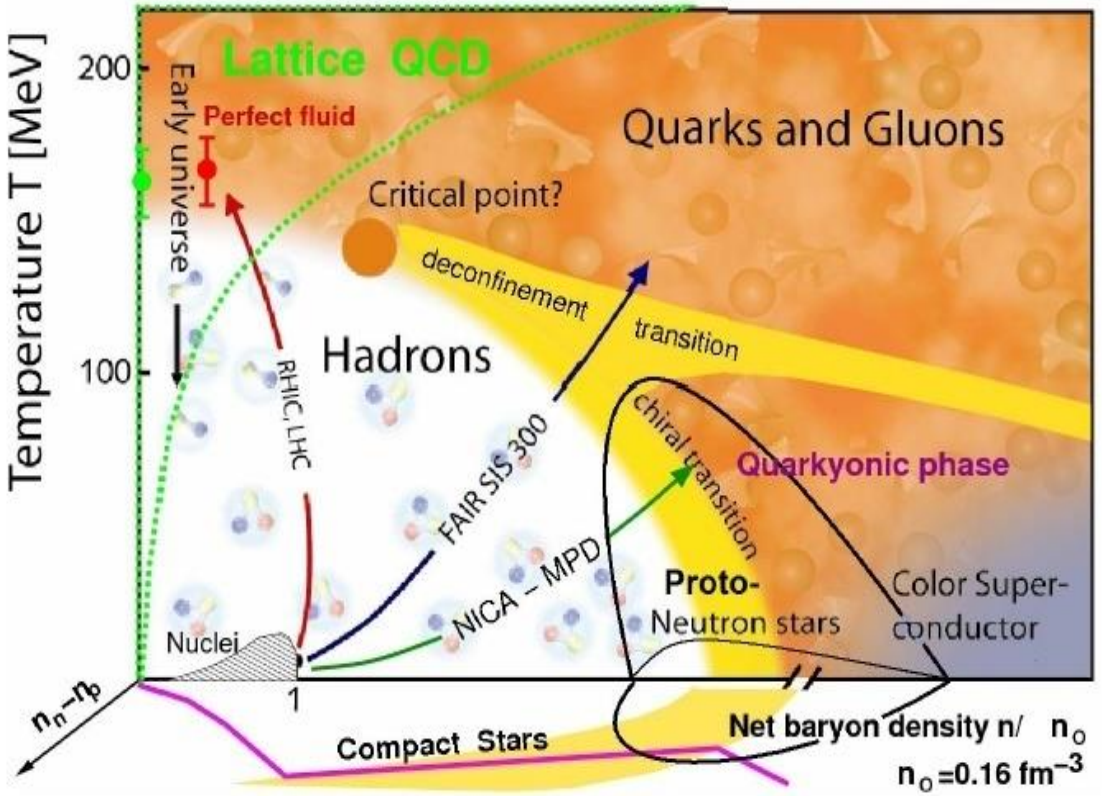
范德瓦尔斯方程：$[p + a(\frac{n}{\mathrm{v}})^2](\mathrm{v} - nb) = nRT$



由中子和质子构成的物质如何随温度、密度变化？

核物质状态方程

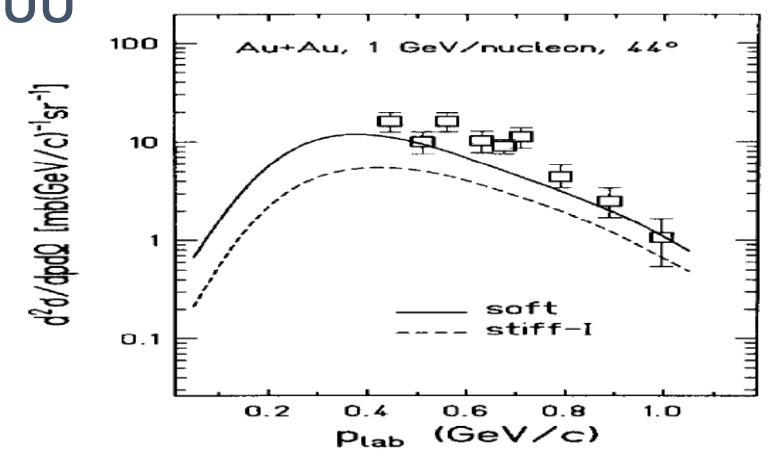
$$E(\rho,\delta) = E(\rho,0) + E_{\mathrm{sym}}(\rho)\delta^2 + O(\delta^4), \quad \delta = (\rho_n - \rho_p)/\rho$$



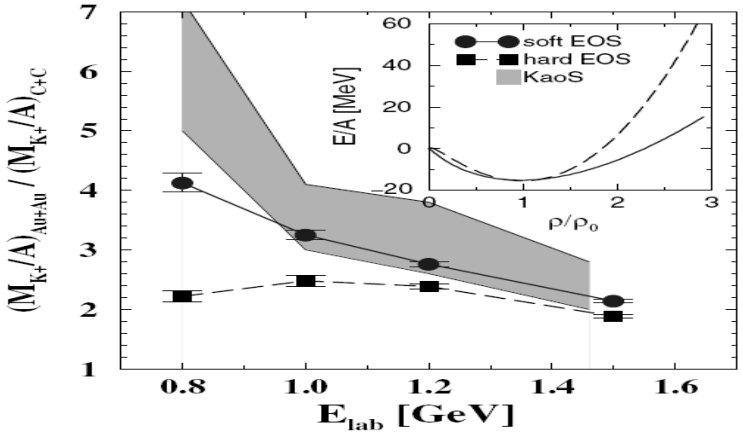
K介子产生探针核物质状态方程

G.Q. Li, C. M. Ko, PLB349(1995)405.

BUU

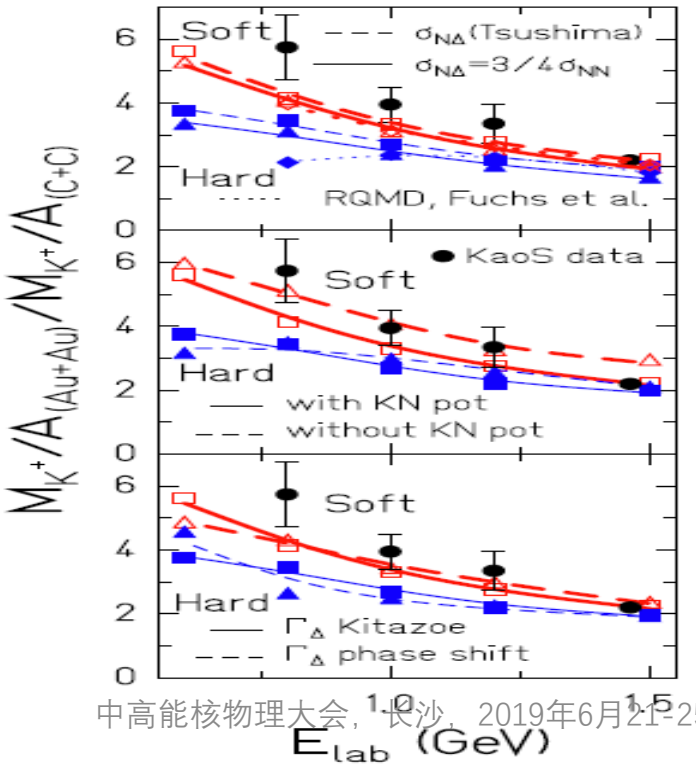


C. Fuchs et al., PRL86(2001)1974. **QMD**

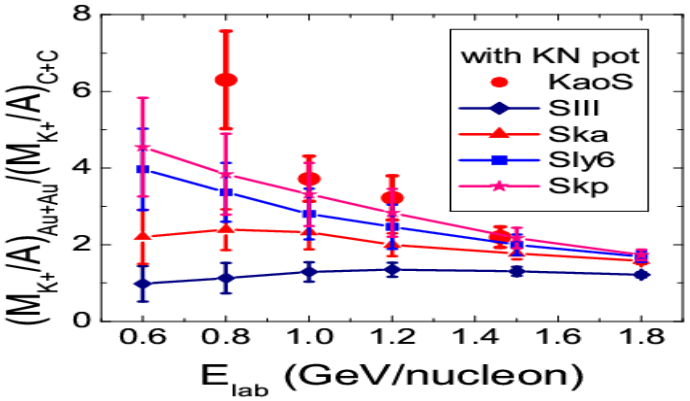


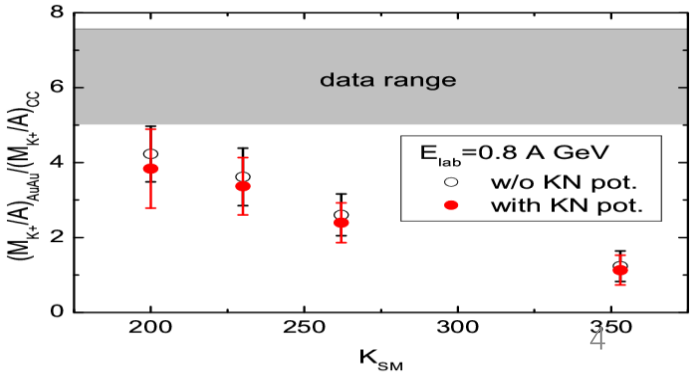
Ch. Hartnack et al., PRL96 (2006) 012302.

IQI



Z. Q. Feng, PRC 83 (2011) 067604. **LQMD**





VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

J. Aichelin and Che Ming Ko[(a)]

Joint Institute for Heavy Ion Research, Holifield Heavy Ion Research Facility, Oak Ridge, Tennessee 37831

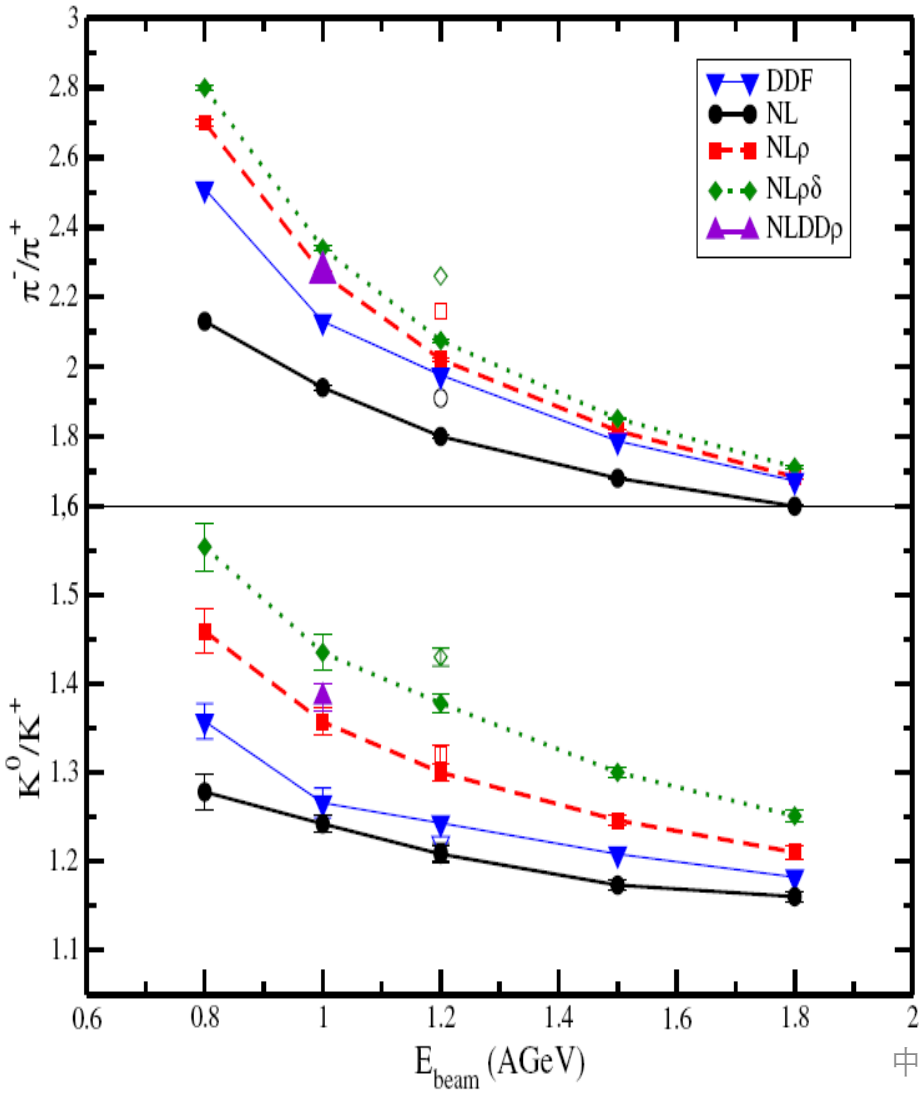
(Received 11 June 1985; revised manuscript received 23 September 1985)

The production of kaons at subthreshold energies from heavy-ion collisions is sensitive to the nuclear equation of state. In the Boltzmann-Uehling-Uhlenbeck model, the number of produced kaons from central collisions between heavy nuclei at incident energies around 700 MeV/nucleon can vary by a factor of ~3, depending on the equation of state.

PACS numbers: 25.70.-z, 21.65.+f

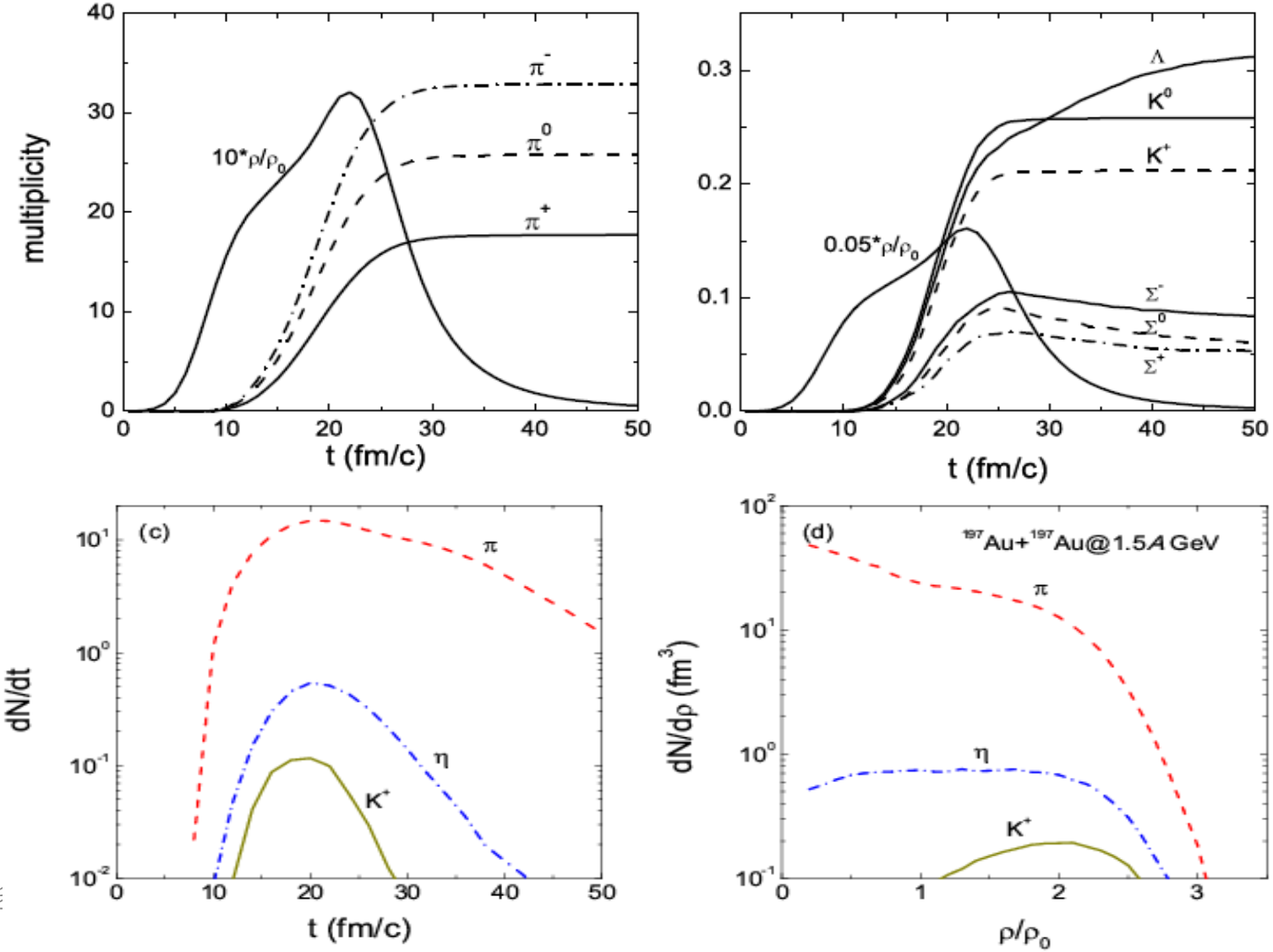
重离子碰撞中的奇异粒子产生探针高密对产能

Symmetry energy from K^0/K^+ production in HIC's around threshold energies (RBUU: PRL97(2006)202301)



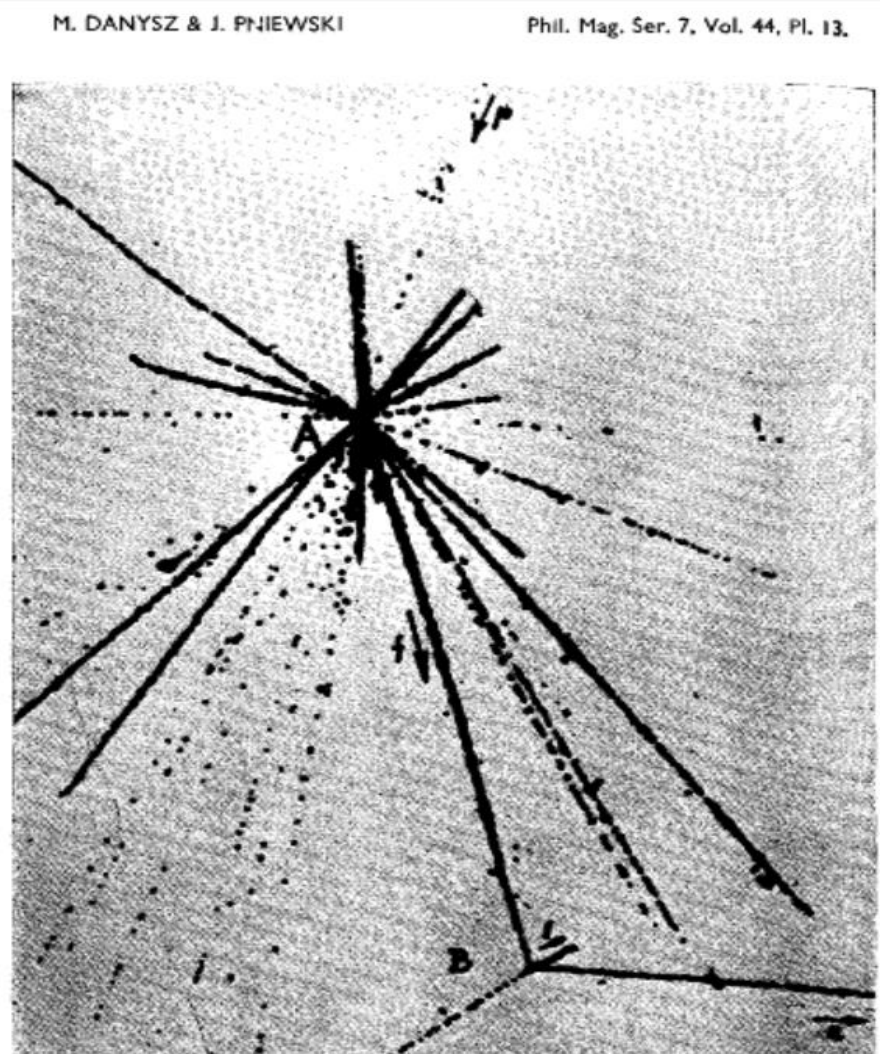
中高能

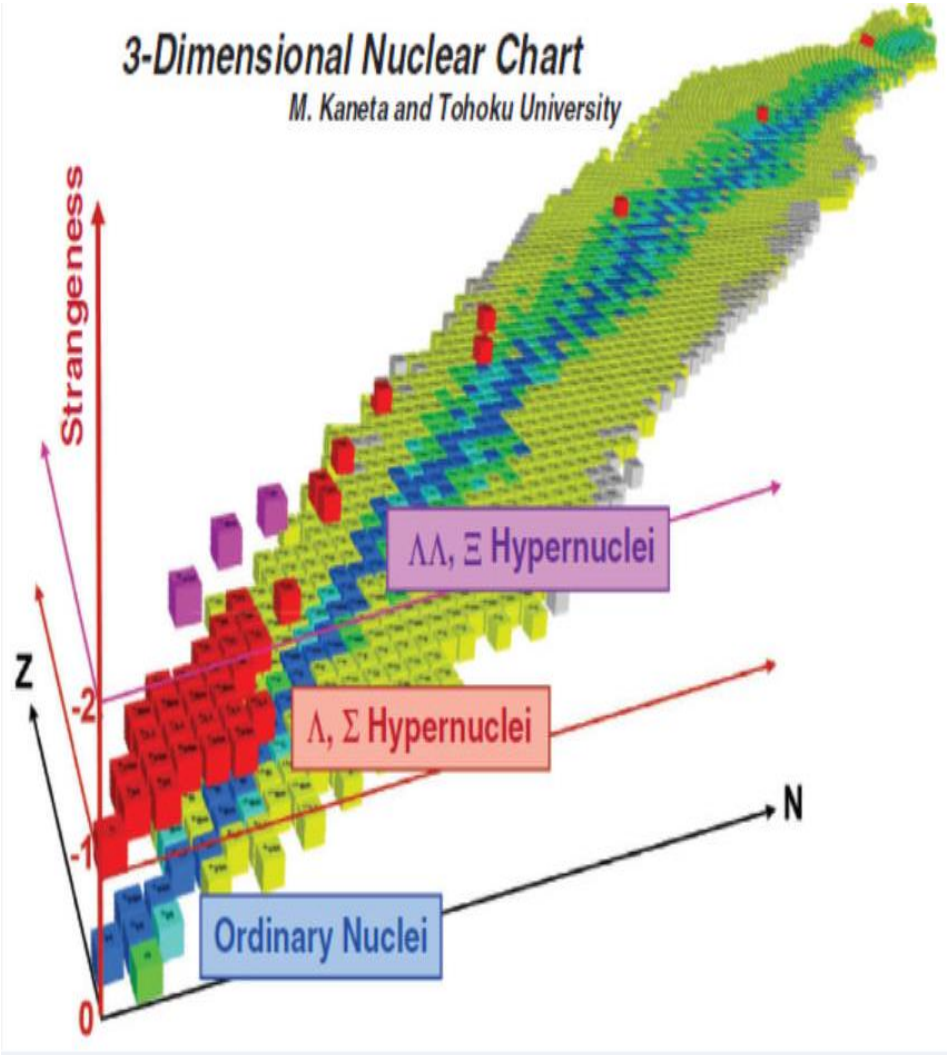
Time evolutions of pion, kaon and sigma in $^{197}Au+^{197}Au$ at 1.5A GeV by LQMD model (Phys. Rev. C 82 (2010) 057901)



1953年波兰物理学家M. Danysz和J. Pniewski
在宇宙线乳胶实验中首次发现Λ超核

H. Tamura, *Prog. Theor. Exp. Phys*. (2012) 02B012

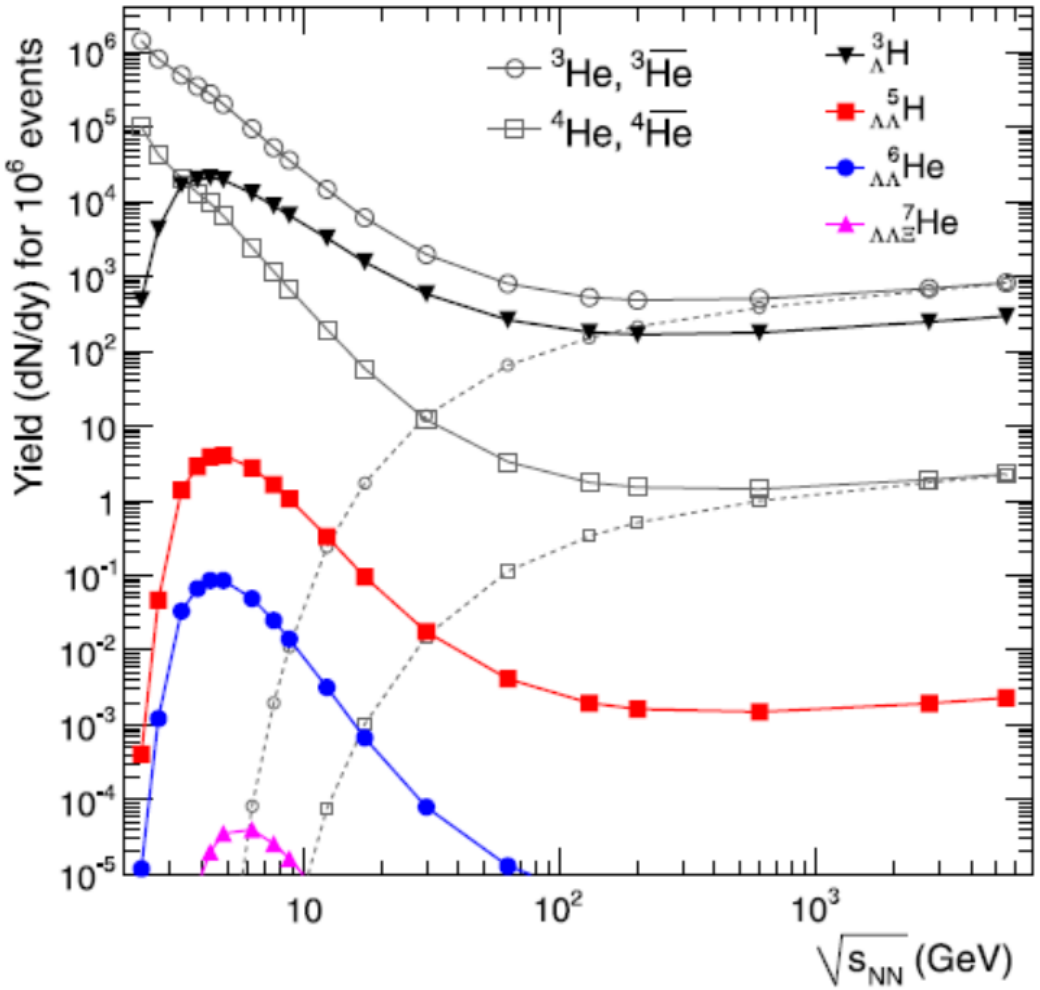




A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, Physics Letters B 697 (2011) 203–207

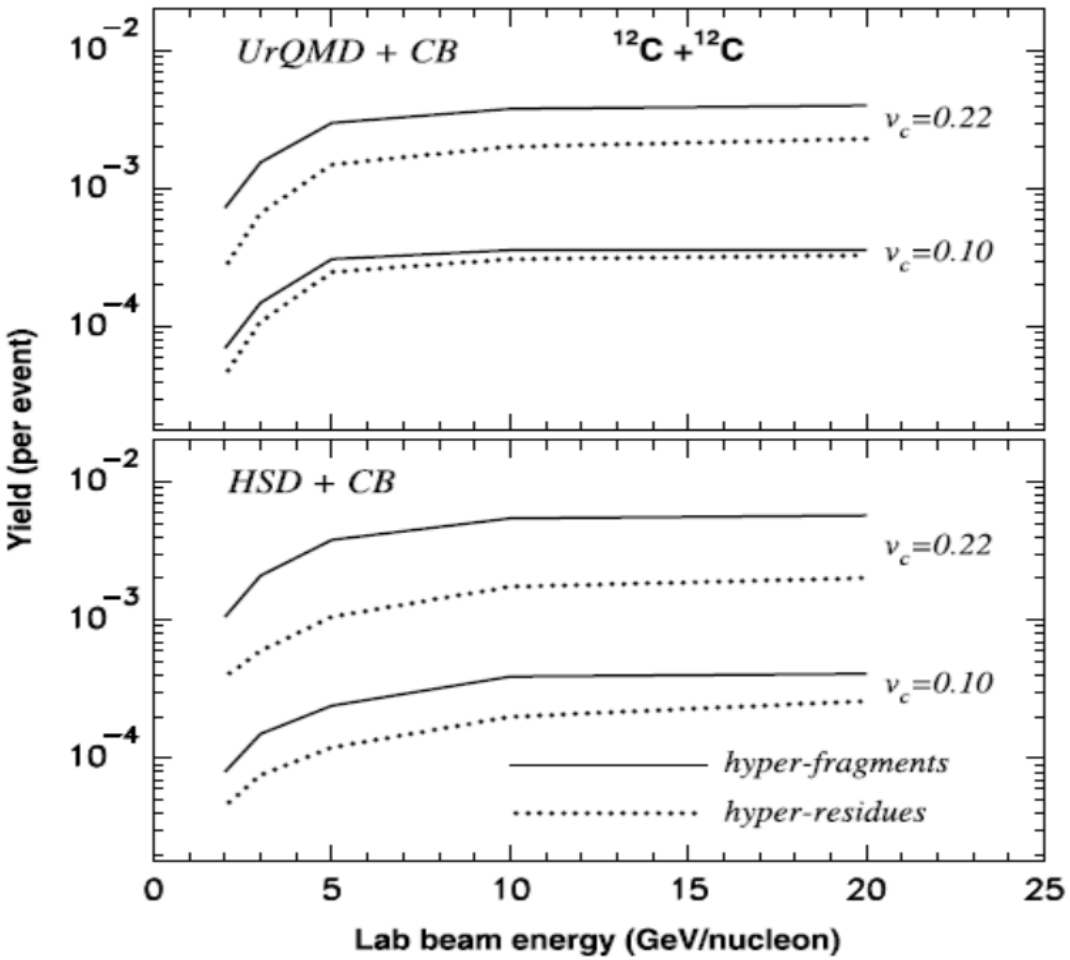
Pb+Pb

statistical model



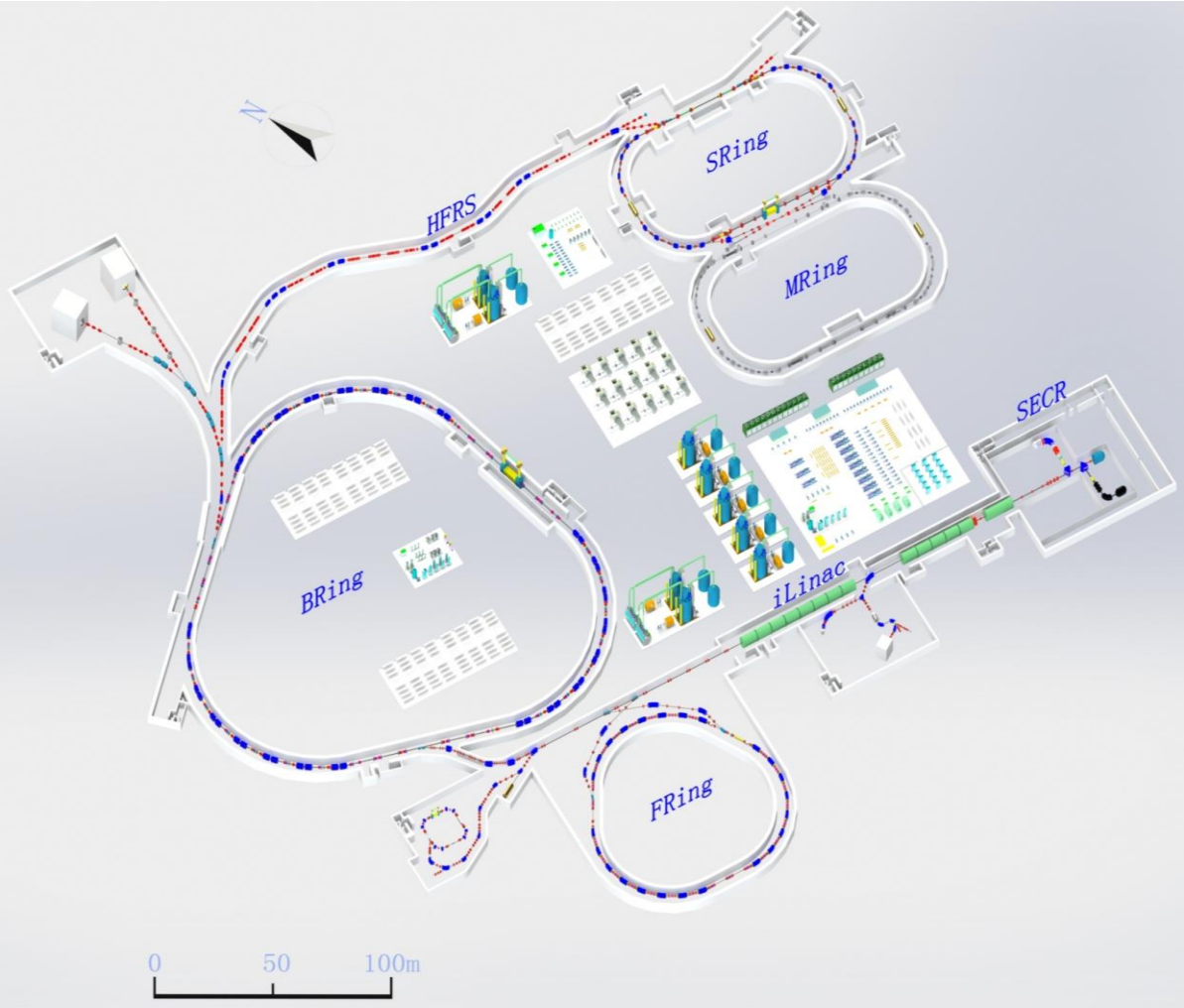
A.S. Botvina, J. Steinheimer, E.Bratkovskaya et al., Physics Letters B 742 (2015)7–14

transport model+coalescence approach



HIAF (*High-Intensity Heavy Ion Accelerator Facility*)

Provided by Jian-Cheng Yang

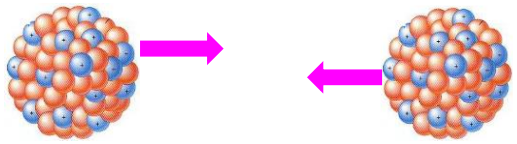


	Ions	Energy	Intensity
SECR	$^{238}U^{35+}$	14 keV/u	0.05-0.1 pmA
iLinac	$^{238}U^{35+}$	17 MeV/u	0.028-0.05 pmA
FRing	$^{238}U^{35+}$	0.35 GeV/u	~2.0×10^{11} ppp
BRing	$^{238}U^{35+}$	1.0 GeV/u	~1.0×10^{12} ppp
	$^{238}U^{92+}$	**3.8 GeV/u**	**~5.0×10^{11} ppp**
SRing	RIBs: **neutron-rich, proton-rich**	0.84 GeV/u(A/q=3)	~$10^{9\text{-}10}$ ppp
	Fully stripped heavy ions H-like, He-like heavy ions	0.8 GeV/u($^{238}U^{92+}$)	~$10^{11\text{-}12}$ ppp

II. Lanzhou Quantum Molecular Dynamics (LQMD) transport model

Nuclear dynamics from 5 MeV/nucleon – 10 GeV/nucleon for HICs, antiproton (proton, π, K, etc)

- **Dynamics of low-energy heavy-ion collisions** (dynamical interaction potential, barrier distribution, neck dynamics, fusion/caption excitation functions etc)
- **Isospin physics at intermediate energies** (constraining nuclear symmetry energy at sub- and supra-saturation densities in HICs and probing isospin splitting of nucleon effective mass from HICs)
- **In-medium properties of hadrons in dense nuclear matter from heavy-ion collisions** (extracting optical potentials, i.e., Δ(1232), N*(1440), N*(1535)), hyperons (Λ,Σ,Ξ,Ω) and mesons (π,K,η,ρ,ω,ϕ…), hypernucleus dynamics)
- **Hadron (antiproton, proton, $\pi^{\pm}$, $K^{\pm}$) induced reactions** (hypernucleus production, e.g., Λ(Σ)X, ΛΛX, ΞX, $\bar{\Lambda}$X(S=1), in-medium modifications of hadrons, cold QGP)



Density, isospin and momentum-dependent single-nucleon potential

$$U_\tau(\rho,\delta,\mathbf{p}) = \alpha\frac{\rho}{\rho_0} + \beta\frac{\rho^\gamma}{\rho_0^\gamma} + E_{\rm sym}^{\rm loc}(\rho)\delta^2 + \frac{\partial E_{\rm sym}^{\rm loc}(\rho)}{\partial\rho}\rho\delta^2 + E_{\rm sym}^{\rm loc}(\rho)\rho\frac{\partial\delta^2}{\partial\rho_\tau}$$

$$+\frac{1}{\rho_0}C_{\tau,\tau}\int d\mathbf{p}'\, f_\tau(\mathbf{r},\mathbf{p})[\ln(\epsilon(\mathbf{p}-\mathbf{p}')^2+1)]^2$$

$$+\frac{1}{\rho_0}C_{\tau,\tau'}\int d\mathbf{p}'\, f_{\tau'}(\mathbf{r},\mathbf{p})[\ln(\epsilon(\mathbf{p}-\mathbf{p}')^2+1)]^2.$$

$$C_{\tau,\tau} = C_{mom}(1+x),\ C_{\tau,\tau'} = C_{mom}(1-x)\ (\tau\neq\tau')$$

ZQF, Phys. Rev. C 84 (2011) 024610

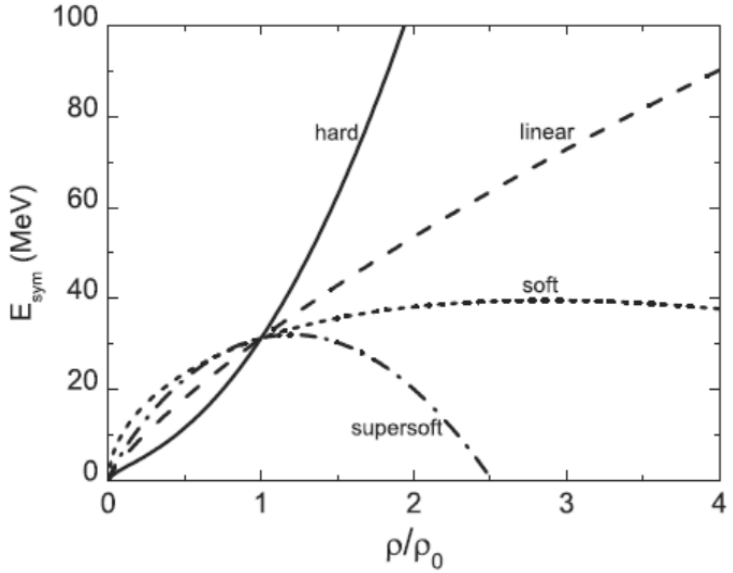


Table 1: The parameters and properties of isospin symmetric EoS used in the LQMD model at the density of 0.16 fm^{-3}.

Parameters	α (MeV)	β (MeV)	γ	C_{mom} (MeV)	ϵ (c^2/MeV^2)	m^*_∞/m	K_∞ (MeV)
PAR1	-215.7	142.4	1.322	1.76	5×10^{-4}	0.75	230
PAR2	-226.5	173.7	1.309	0.	0.	1.	230

Particle production channels in the LQMD model

π and resonances (Δ(1232), N*(1440), N*(1535), …) production:

$$NN \leftrightarrow N\Delta, \quad NN \leftrightarrow NN^*, \quad NN \leftrightarrow \Delta\Delta, \quad \Delta \leftrightarrow N\pi,$$
$$N^* \leftrightarrow N\pi, \quad NN \leftrightarrow NN\pi(s-state), \quad N^*(1535) \leftrightarrow N\eta$$

Collisions between resonances,

NN*↔NΔ, NN*↔NN*

Strangeness channels:

$$BB \rightarrow BYK, \quad BB \rightarrow BBK\overline{K}, \quad B\pi \rightarrow YK,$$
$$B\pi \rightarrow NK\overline{K}, \quad Y\pi \rightarrow N\overline{K}, \quad N\overline{K} \rightarrow Y\pi, \quad YN \rightarrow \overline{K}NN$$

Reaction channels with antiproton:

$$\bar{p}N \rightarrow \overline{N}N, \quad \overline{N}N \rightarrow \overline{N}N, \overline{N}N \rightarrow \overline{B}B, \overline{N}N \rightarrow \overline{Y}Y$$
$$\overline{N}N \rightarrow \mathtt{annihilation}(\pi, \eta, \rho, \omega, K, \overline{K}, K^*, \overline{K}^*, \phi)$$

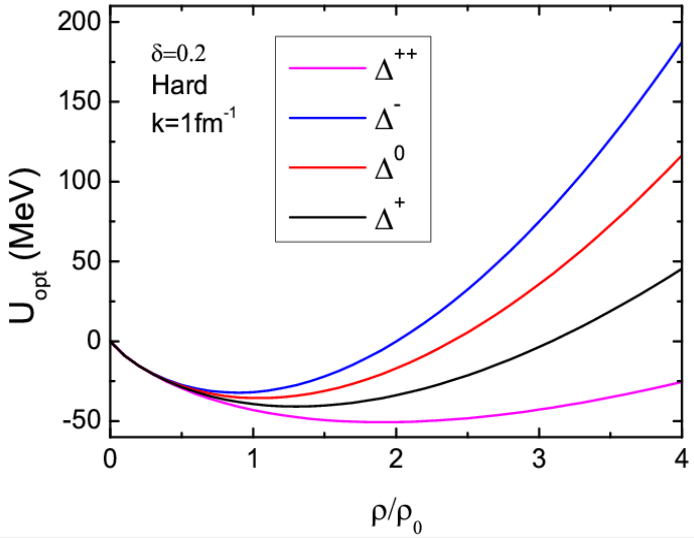
Statistical model with SU(3) symmetry for annihilation
(E.S. Golubeva et al., Nucl. Phys. A 537, 393 (1992))

The **PYTHIA** and **FRITIOF** code are used for baryon(meson)-baryon and antibaryon-baryon collisions at high invariant energies

Mean-field potentials for resonances, hyperons and mesons

1. Mean-field potentials for resonances (Δ(1232), N*(1440), …) are considered based on nucleon potentials, but distinguishing isospin effect.

$U_{\Delta++} = U_p(\rho, p)$, $U_{\Delta+} = 2U_p(\rho, p)/3 + U_n(\rho, p)/3$, $U_{\Delta0} = U_p(\rho, p)/3 + 2U_n(\rho, p)/3$, $U_{\Delta-} = U_n(\rho, p)$

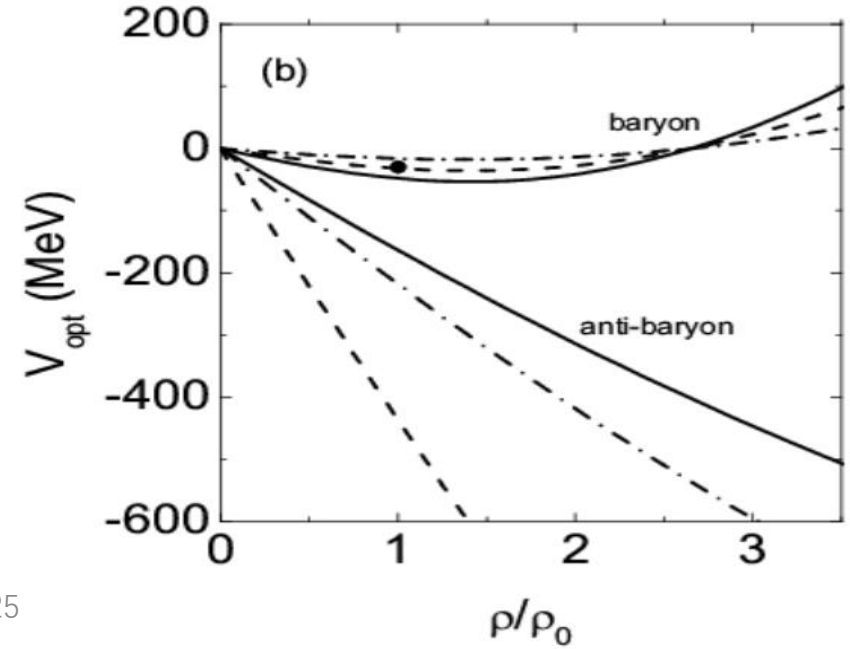


2. Mean-field potentials for hyperons and antiprotons in nuclear medium

$$H_M = \sum_{i=1}^{N_M} \left(V_i^{\mathrm{Coul}} + \omega(\mathbf{p}_i, \rho_i) \right)$$

$$\omega(\mathbf{p}_i, \rho_i) = \sqrt{\left(m_H + \Sigma_S^H\right)^2 + \mathbf{p}_i^2} + \Sigma_V^H$$

$$V_{opt}(\mathbf{p}, \rho) = \omega(\mathbf{p}, \rho) - \sqrt{\mathbf{p}^2 + m^2}$$



3. Mean-field potentials for kaons and antikaons

J.Schaffner-Bielich et al., Nucl. Phys. A 625 (1997) 325, Z. Q. Feng, Nucl. Phys. A 919 (2013) 32-45

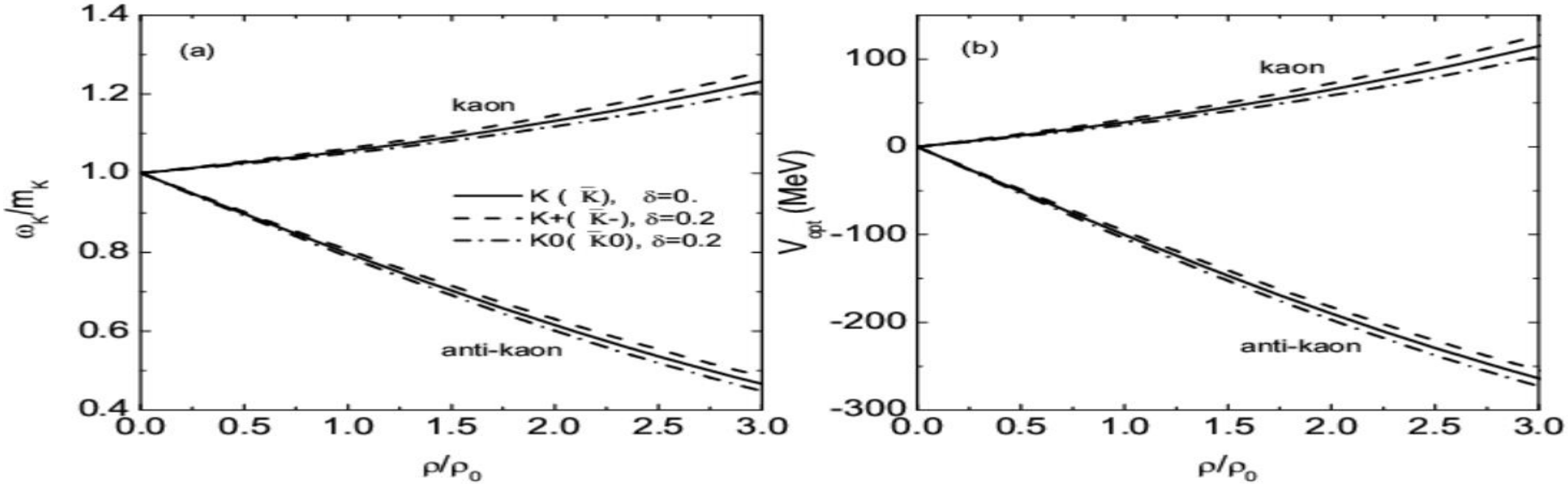
$$\omega_K(\mathbf{p}_i,\rho_i) = \left[m_K^2 + \mathbf{p}_i^2 - a_K\rho_i^S - \tau_3 c_K \rho_{i3}^S + (b_K\rho_i + \tau_3 d_K \rho_{i3})^2\right]^{1/2} + b_K\rho_i + \tau_3 d_K \rho_{i3}$$

$$\omega_{\overline{K}}(\mathbf{p}_i,\rho_i) = \left[m_{\overline{K}}^2 + \mathbf{p}_i^2 - a_{\overline{K}}\rho_i^S - \tau_3 c_K \rho_{i3}^S + (b_K\rho_i + \tau_3 d_K \rho_{i3})^2\right]^{1/2} - b_K\rho_i - \tau_3 d_K \rho_{i3}$$

$b_K = 3/(8f_\pi^{*2}) \approx 0.333$ GeV fm^3 with assuming $f_\pi^* = f_\pi$, the a_K and $a_{\overline{K}}$ are 0.18 GeV^2 fm^3 and 0.31 GeV^2 fm^3, respectively,

The parameters $c_K = 0.0298$ GeV^2 fm^3 and $d_K = 0.111$ GeV fm^3

$$\frac{d\mathbf{p}_i}{dt} = -\frac{\partial V_i^{\rm Coul}}{\partial \mathbf{r}_i} - \frac{\partial \omega_{K(\overline{K})}(\mathbf{p}_i,\rho_i)}{\partial \mathbf{r}_i} \pm \mathbf{v}_i \frac{\partial \mathbf{V}_i}{\partial \mathbf{r}_i}$$

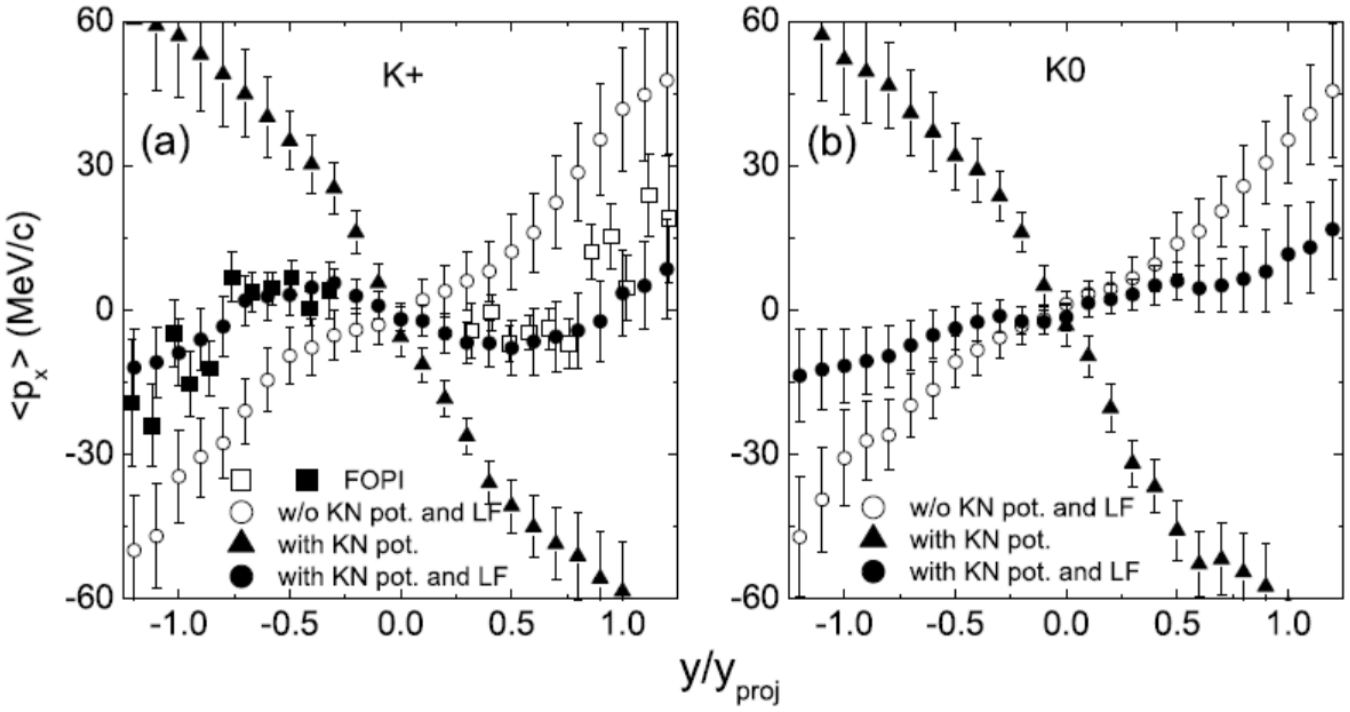


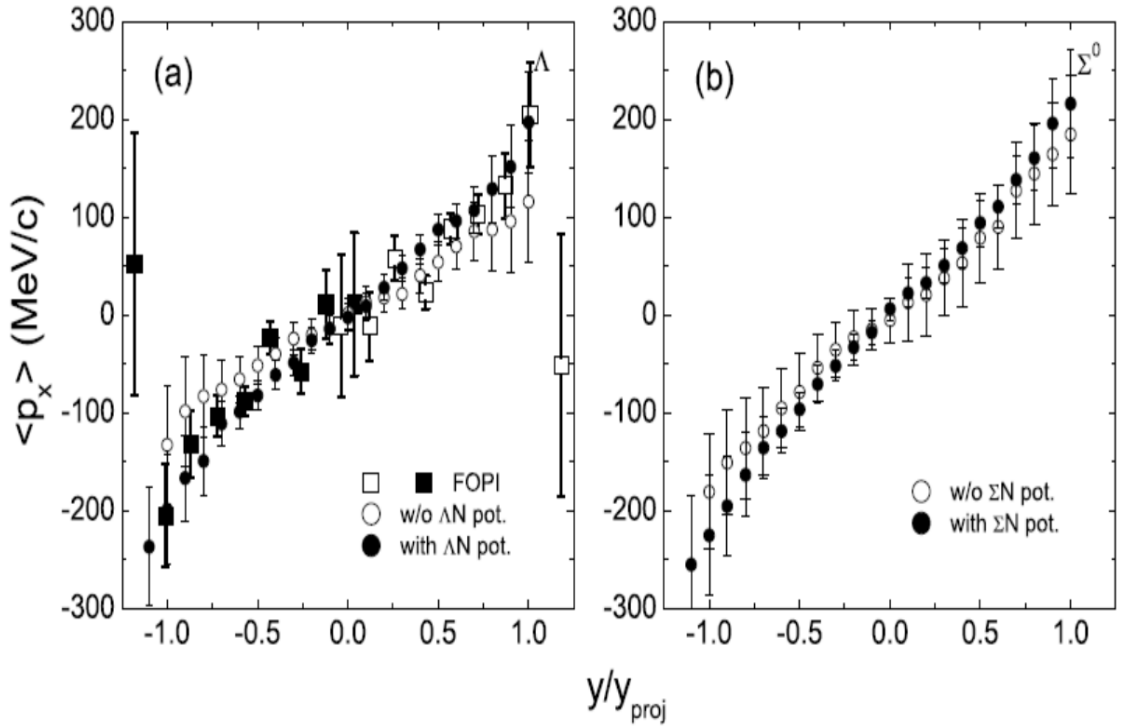
$V_{K+}(\rho_0)$= 28 MeV, $V_{K-}(\rho_0)$= -100 MeV

III Results and discussion: 1. Strangeness production in HICs

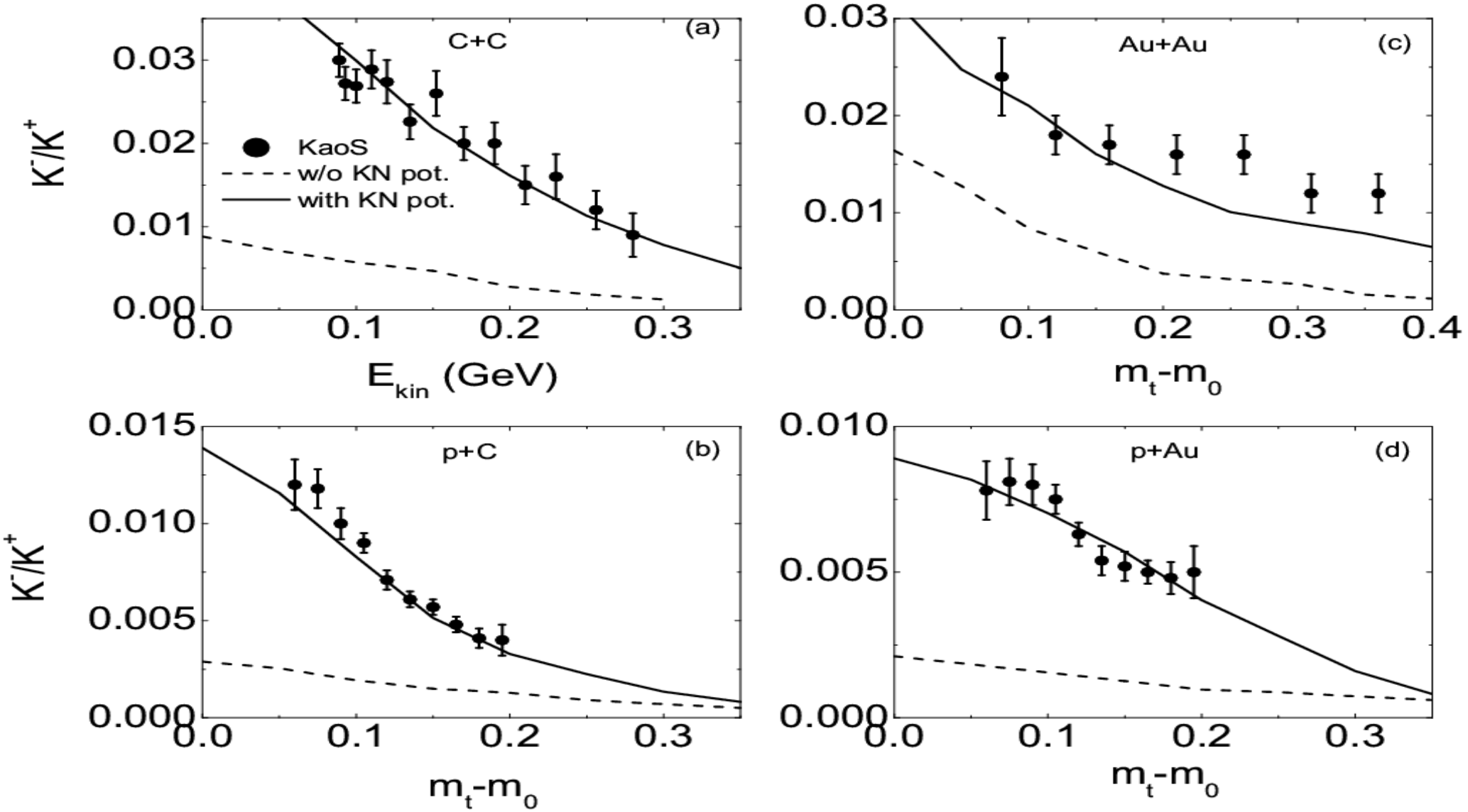
Exp. data: H. Herrmann, FOPI Collaboration, Prog. Part. Nucl. Phys. 42 (1999) 187; J. L. Ritman, FOPI Collaboration, Z. Phys. A 352 (1995) 355.

Z.-Q. Feng / Nuclear Physics A 919 (2013) 32–45





The ratio of K^-/K^+ as a function of transverse mass (kinetic energy) in collisions of $^{12}C + ^{12}C$ and protons on ^{12}C and ^{197}Au at the beam energies of 1.8*A* GeV and 2.5 GeV, respectively.

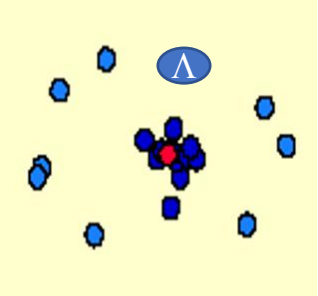


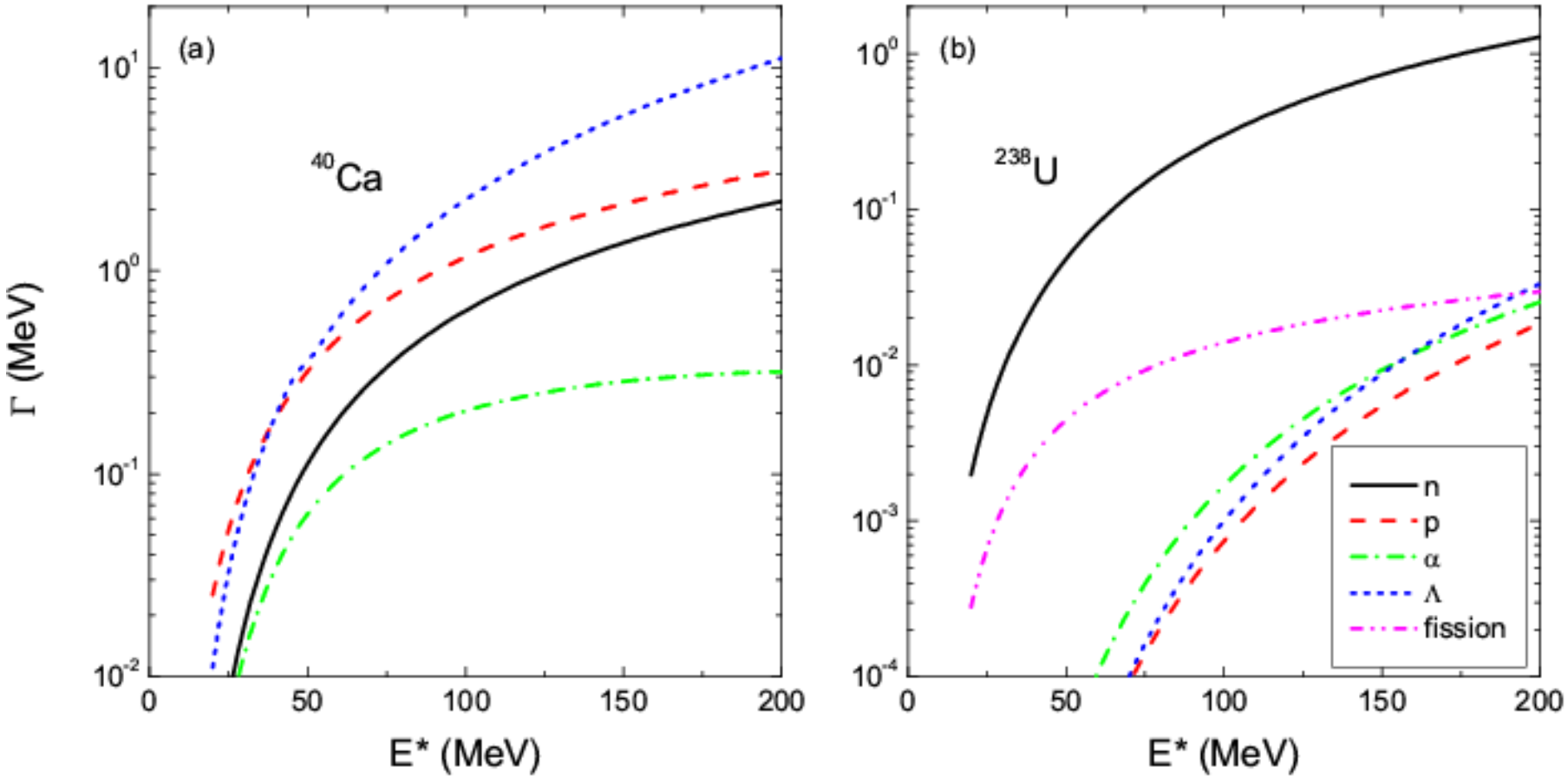
$V_{K+}(\rho_0)$= 28 MeV, $V_{K-}(\rho_0)$= -100 MeV

2. Coalescence approach for hypernuclear formation

Classical coalescence approach in phase space

$|r_i - r_j| \leq 3$ fm, $|r_i - r_Y| \leq 4.5$ fm , $|p_i - p_j| \leq 3$ GeV/c





The rapidity and kinetic energy distributions of nucleonic fragments, Λ-hypernuclide fragments and free hyperons

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论 文
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中高能重离子碰撞中奇异粒子产生和超核形成机制

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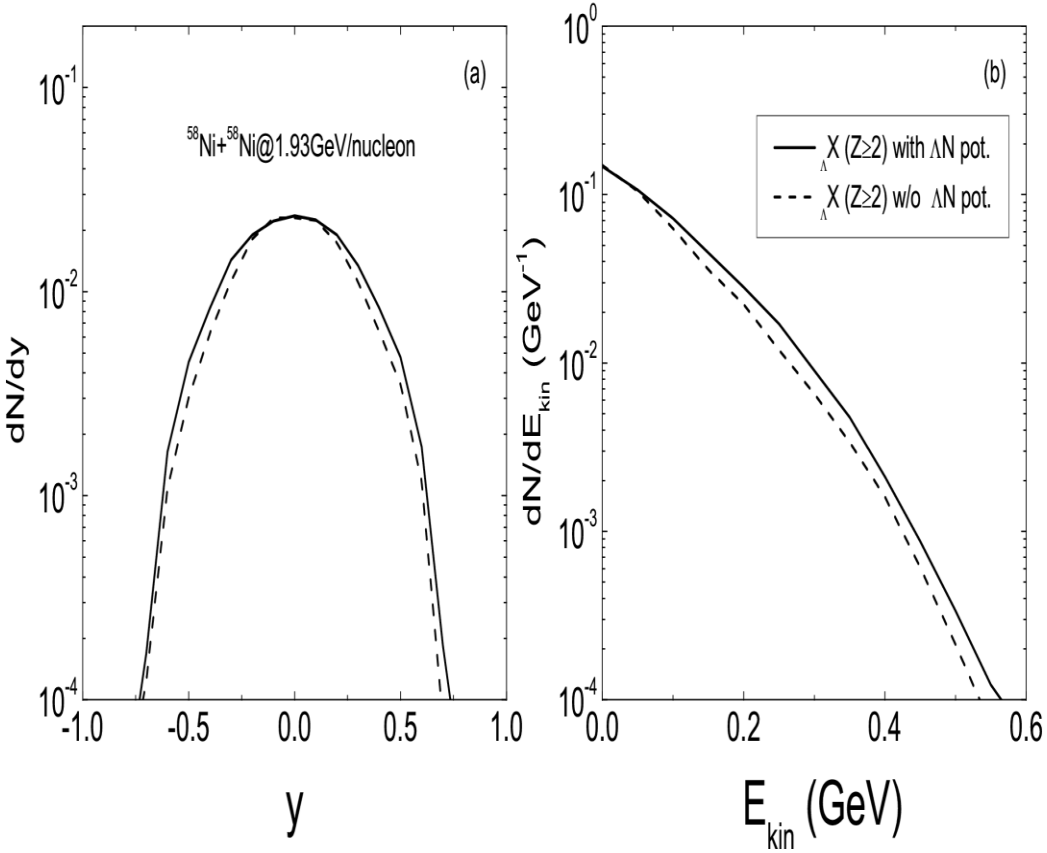
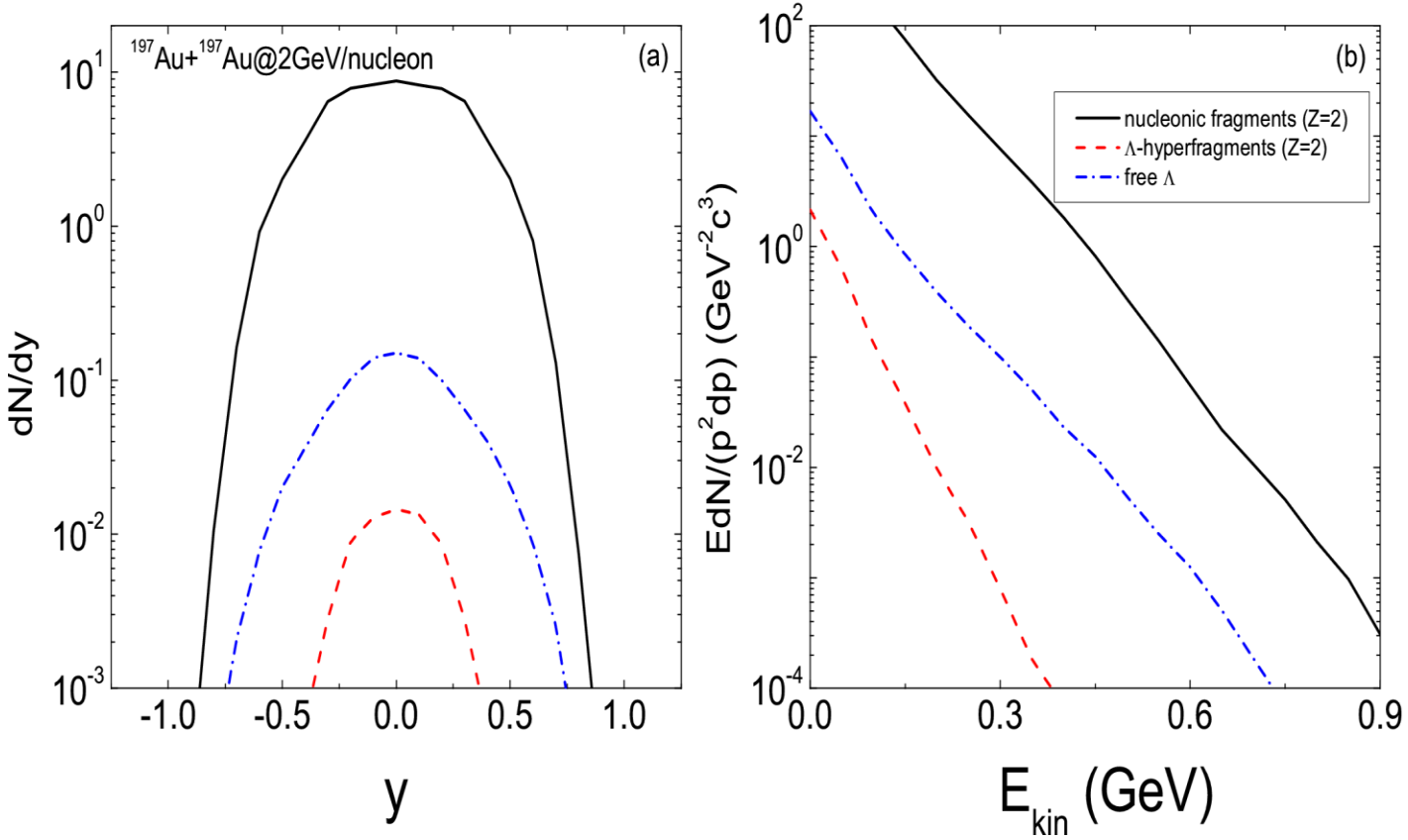
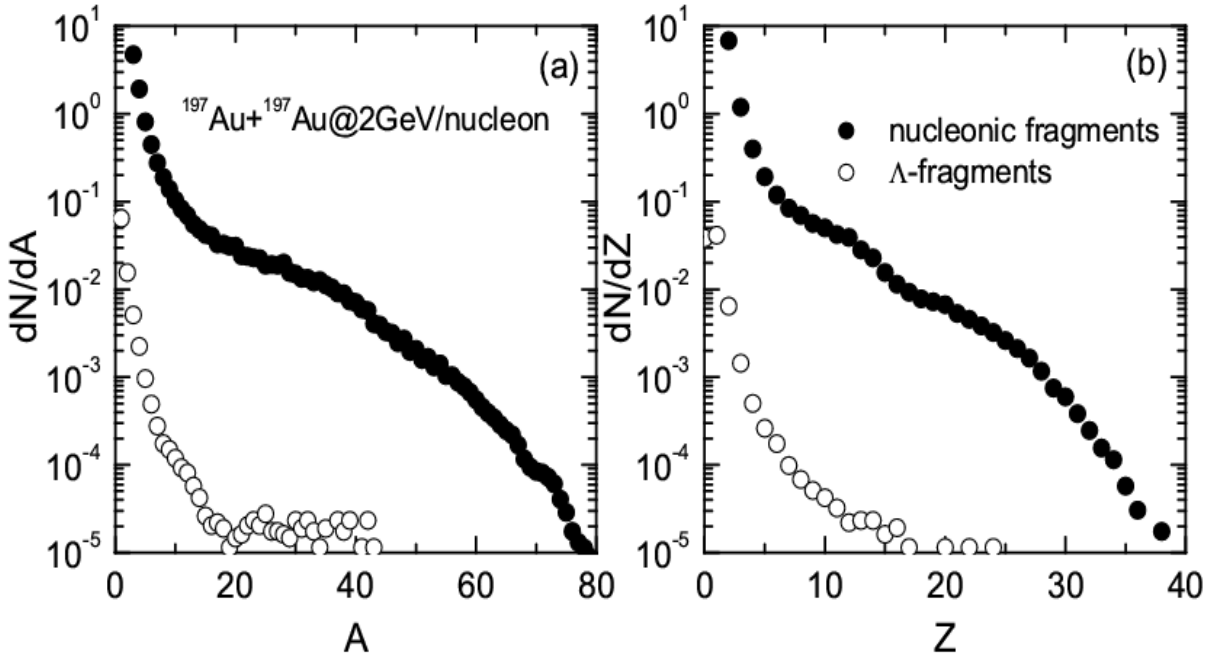
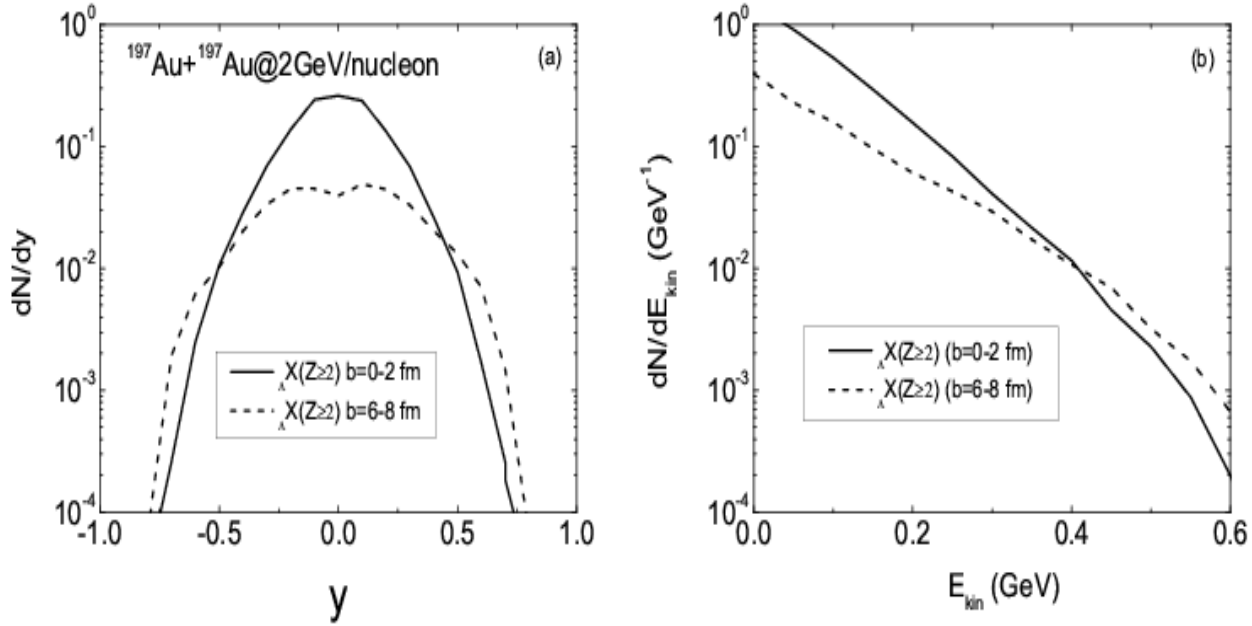


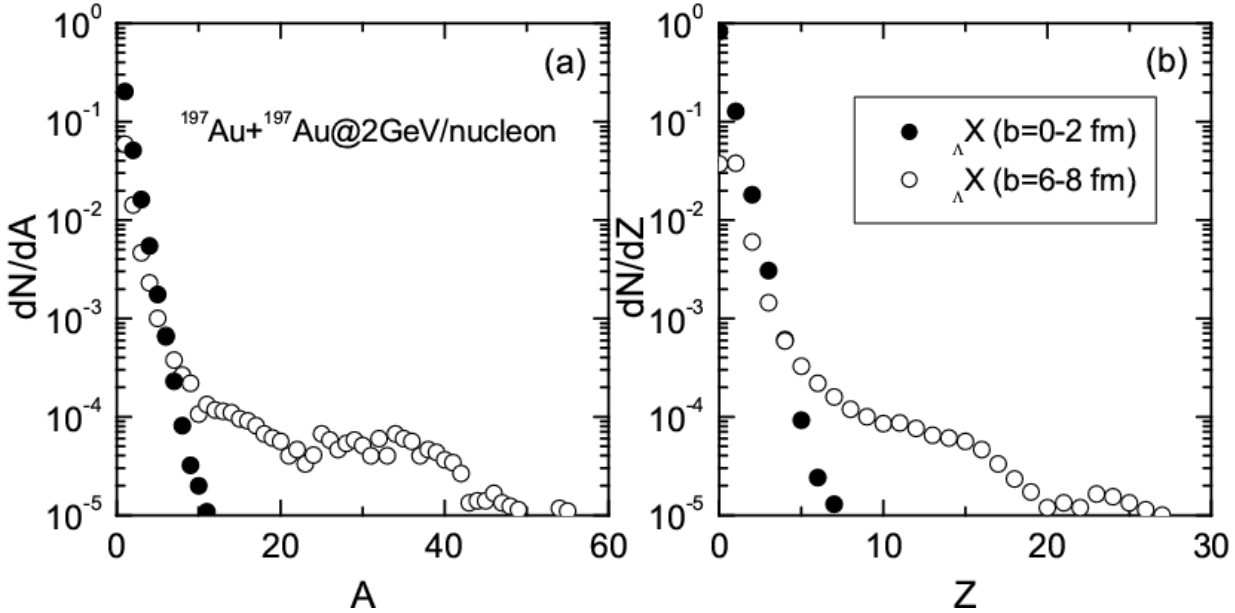


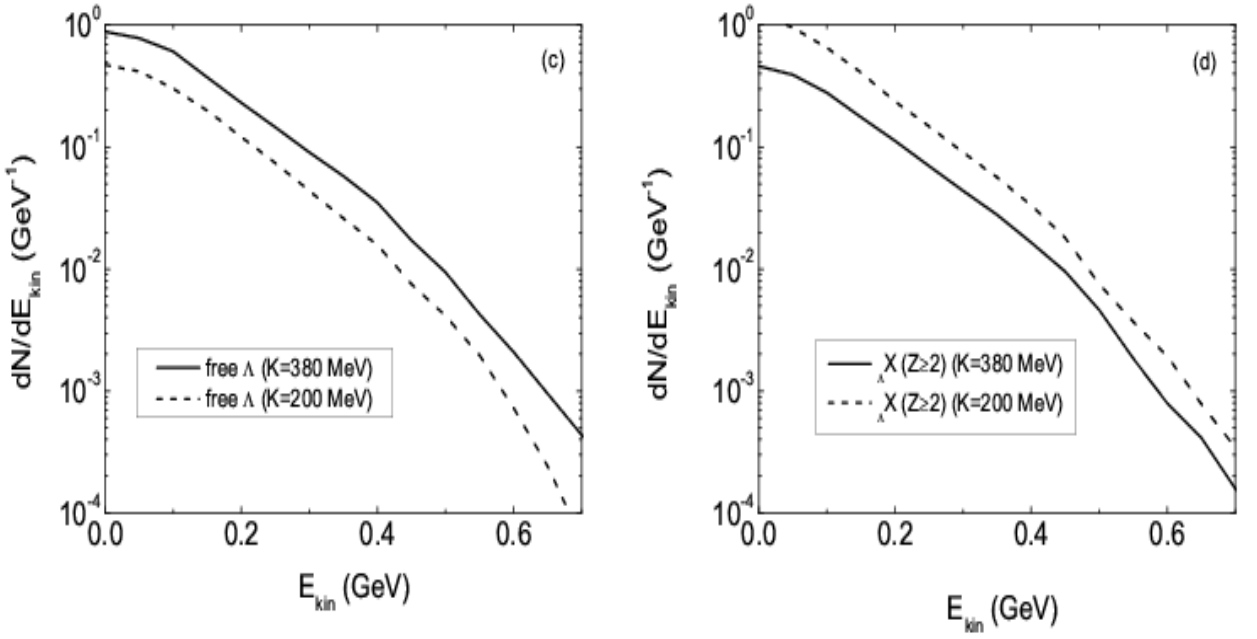
Production of Λ-hypernuclide in $^{197}Au+^{197}Au$ at the beam energy of 2 GeV/nucleon

Nuclear Science and Techniques 29 (2018) 40







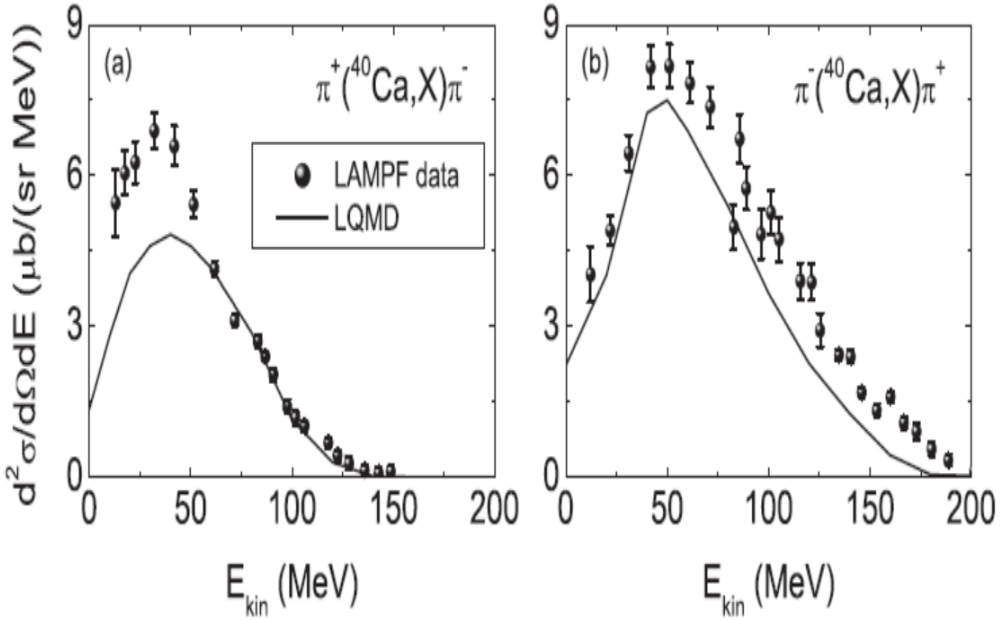


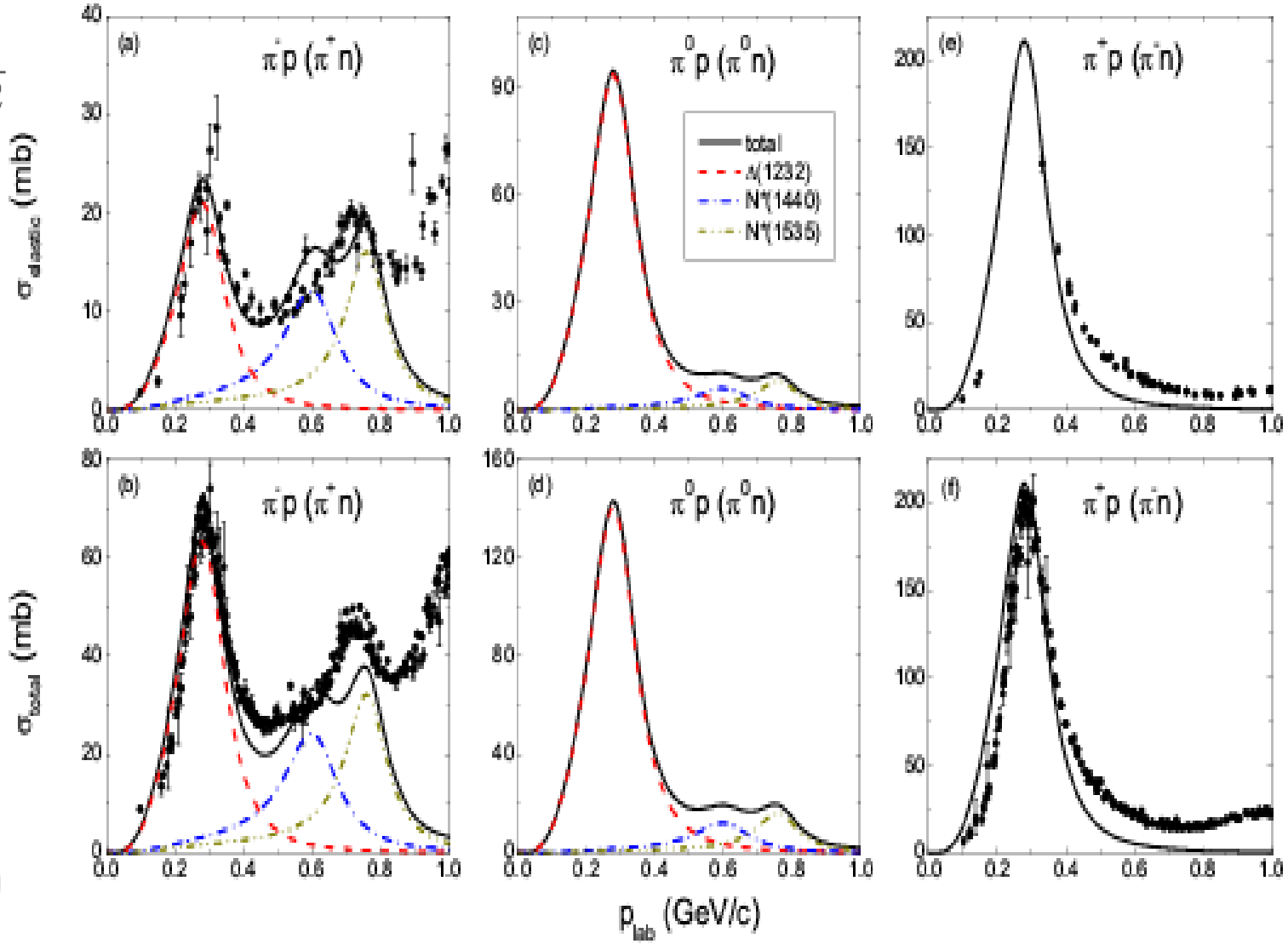
3. Pion-nucleus scattering

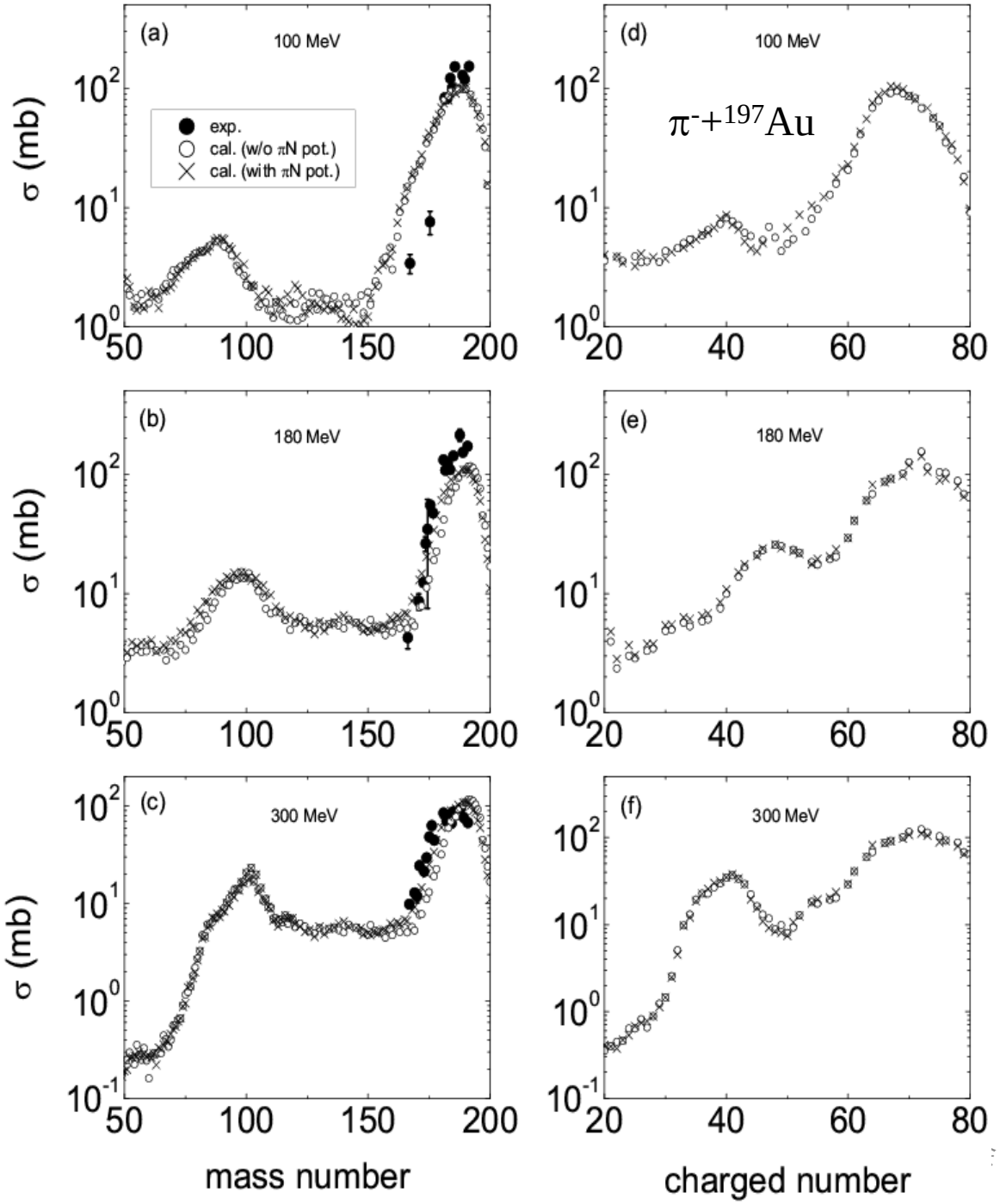
Z. Q. Feng, Phys. Rev. C 94, 054617 (2016)

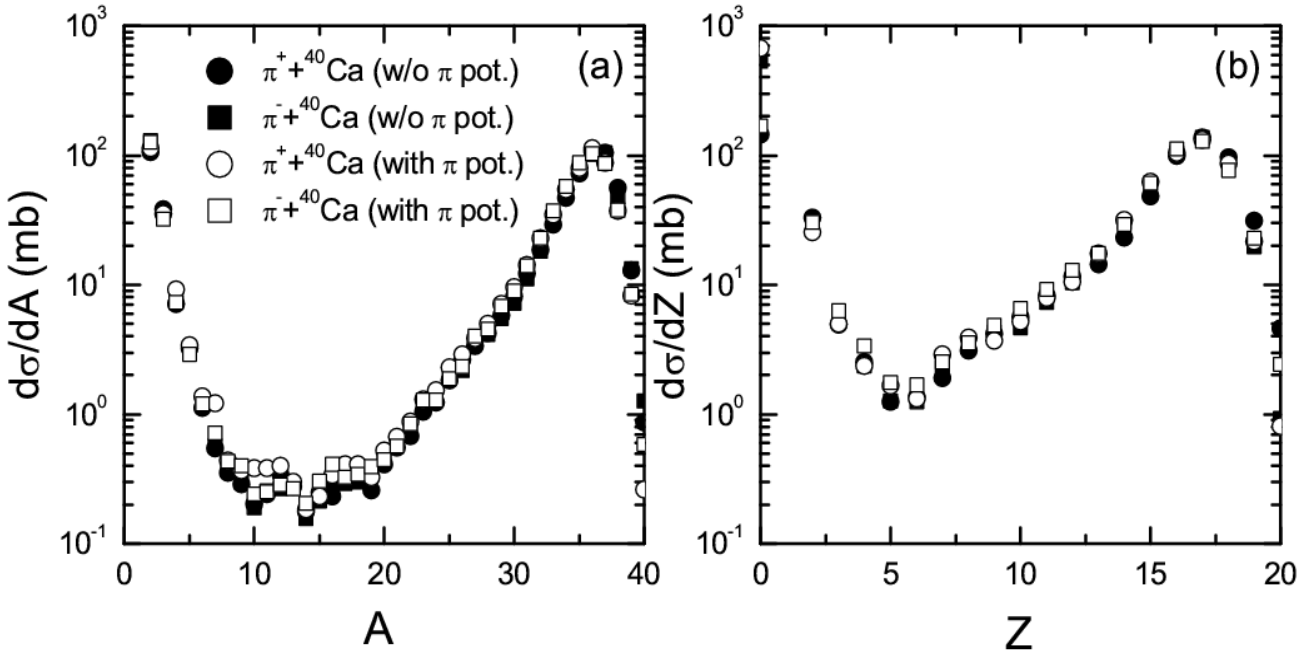
$$\sigma_{\pi N\to R}(\sqrt{s}) = \sigma_{\max}(|p_0/p|)^2 \frac{0.25\Gamma^2(p)}{0.25\Gamma^2(p)+(\sqrt{s}-m_0)^2}$$

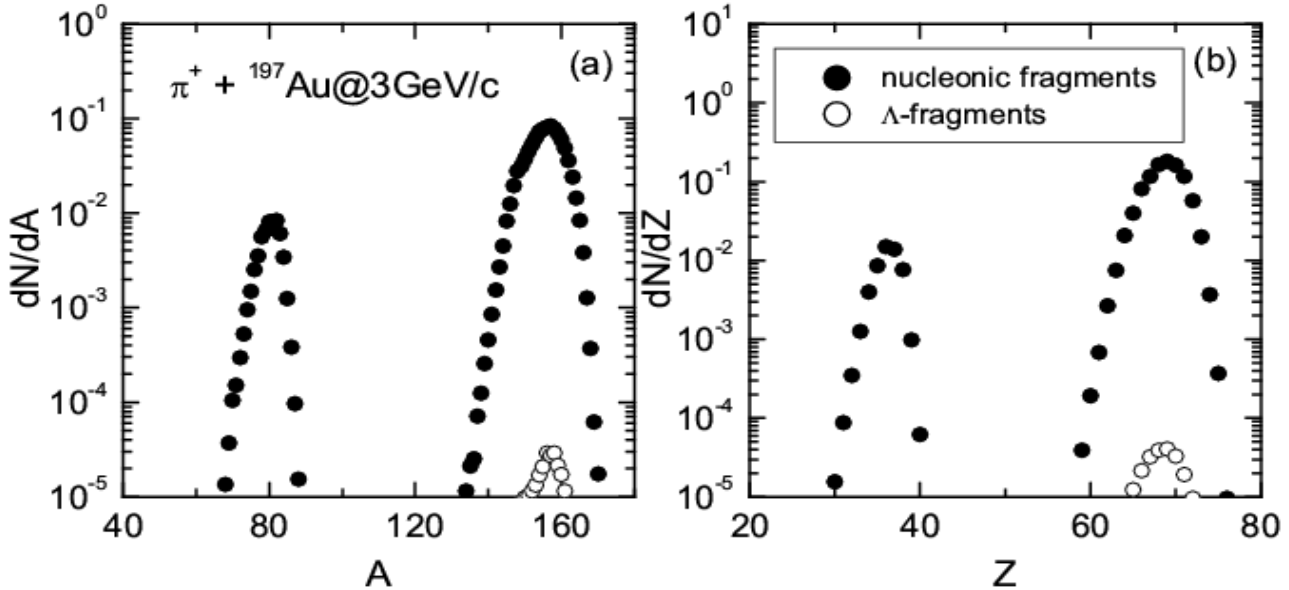
σ_{max}= 200, 133.3, and 66.7 mb for $\pi^+ + p \to \Delta^{++}$ ($\pi^- + n \to \Delta^-$), $\pi^0 + p \to \Delta^+$ ($\pi^0 + n \to \Delta^0$), and $\pi^- + p \to \Delta^0$ ($\pi^+ + n \to \Delta^+$), respectively.



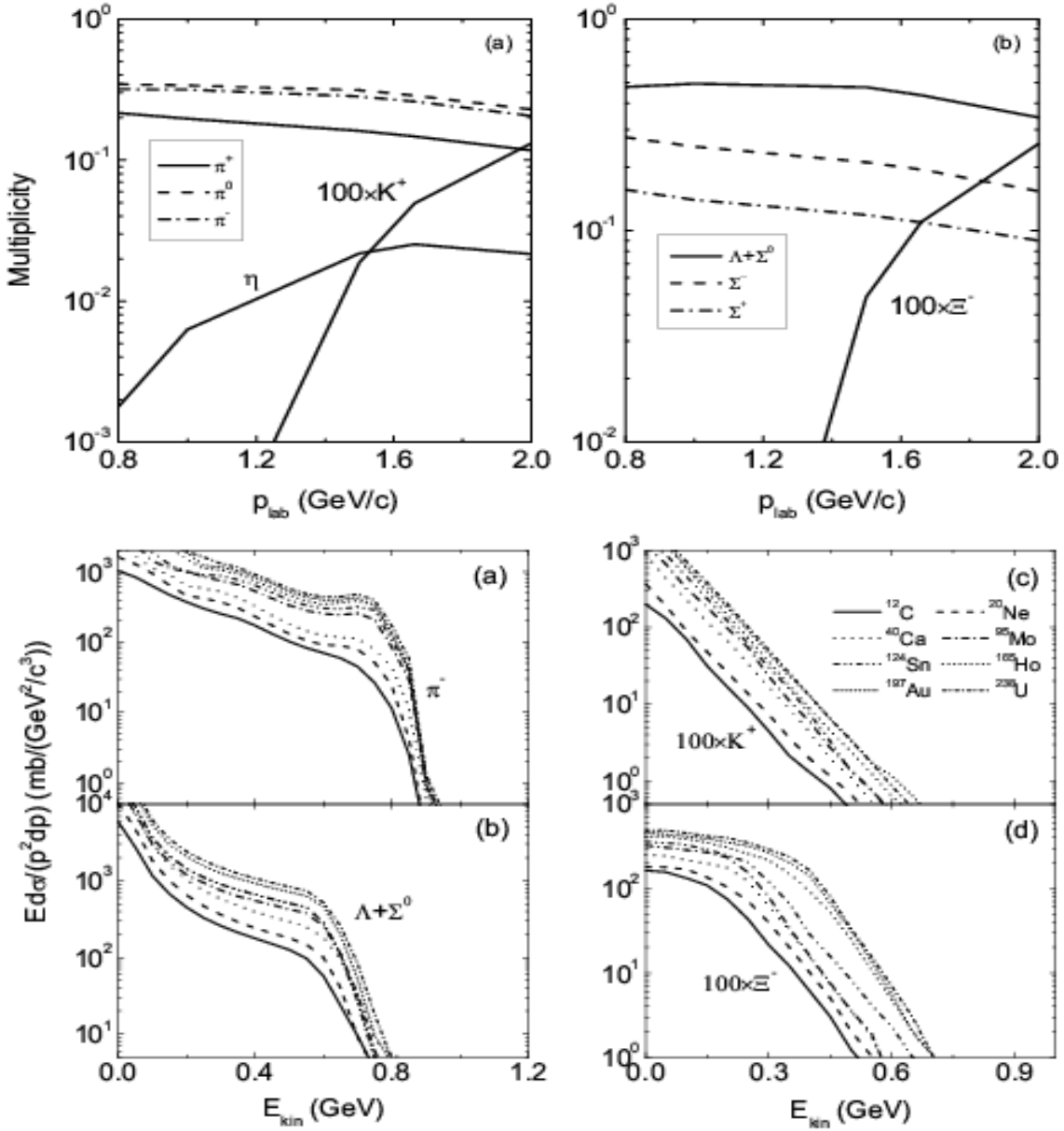


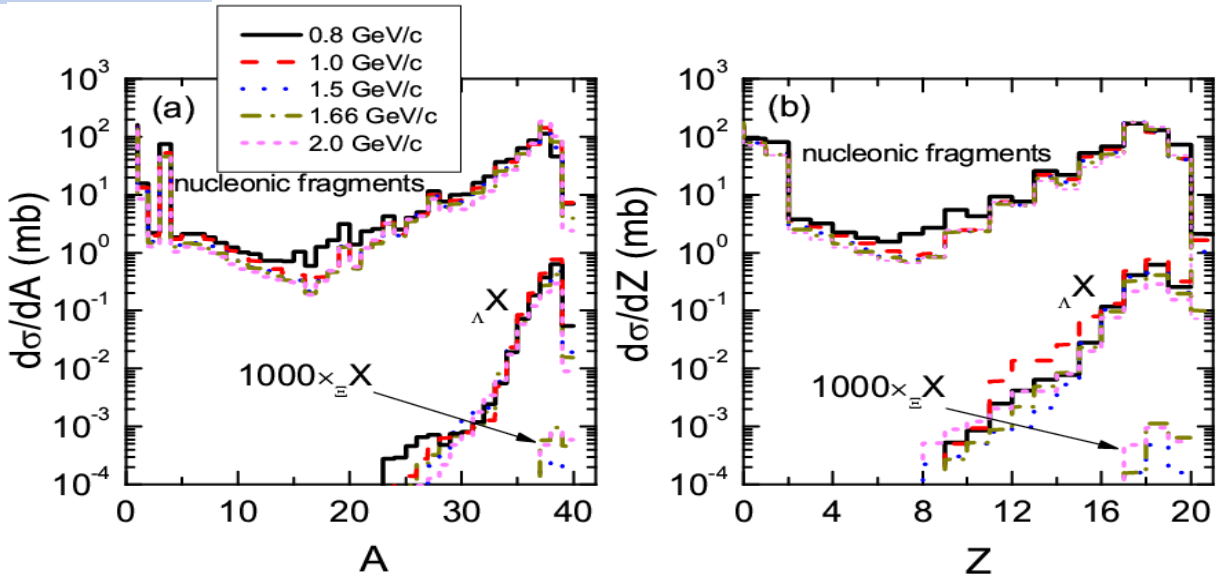

(a)
100 MeV
exp.
cal. (w/o πN pot.)
cal. (with πN pot.)
(d)
100 MeV
π⁻+197Au
(b)
180 MeV
(e)
180 MeV
(c)
300 MeV
(f)
300 MeV
σ (mb)
mass number
charged number

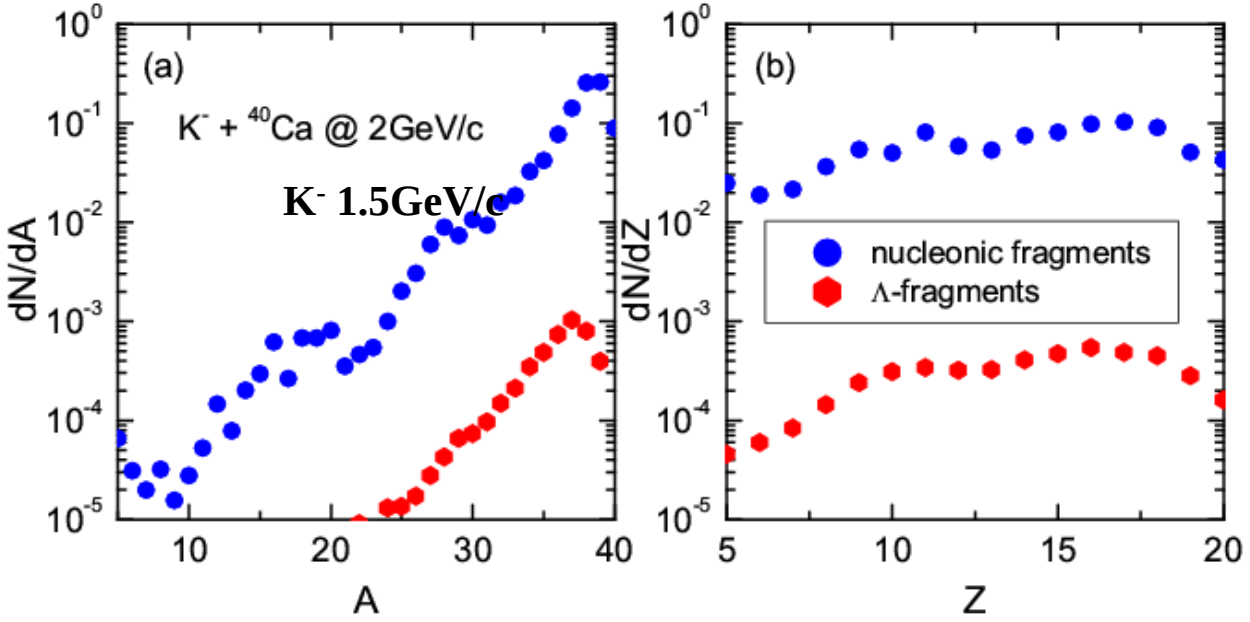

π⁺+40Ca (w/o π pot.)
π⁻+40Ca (w/o π pot.)
π⁺+40Ca (with π pot.)
π⁻+40Ca (with π pot.)
(a)
(b)
dσ/dA (mb)
dσ/dZ (mb)
A
Z


π⁺ + 197Au@3GeV/c
(a)
(b)
nucleonic fragments
Λ-fragments
dN/dA
dN/dZ
A
Z

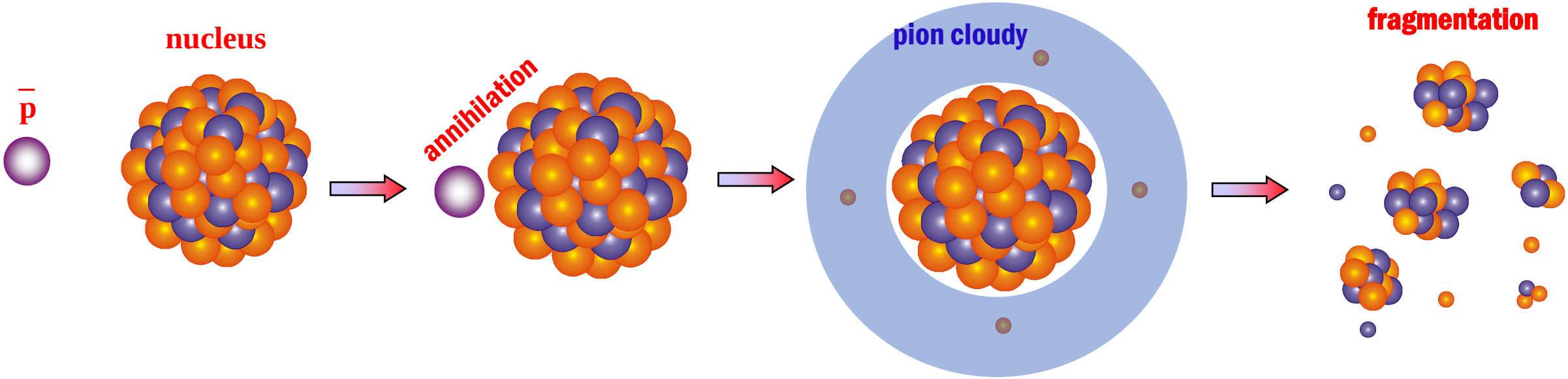
4. Hypernuclear formation in meson K⁻ induced reactions







5. Nuclear dynamics induced by antiprotons



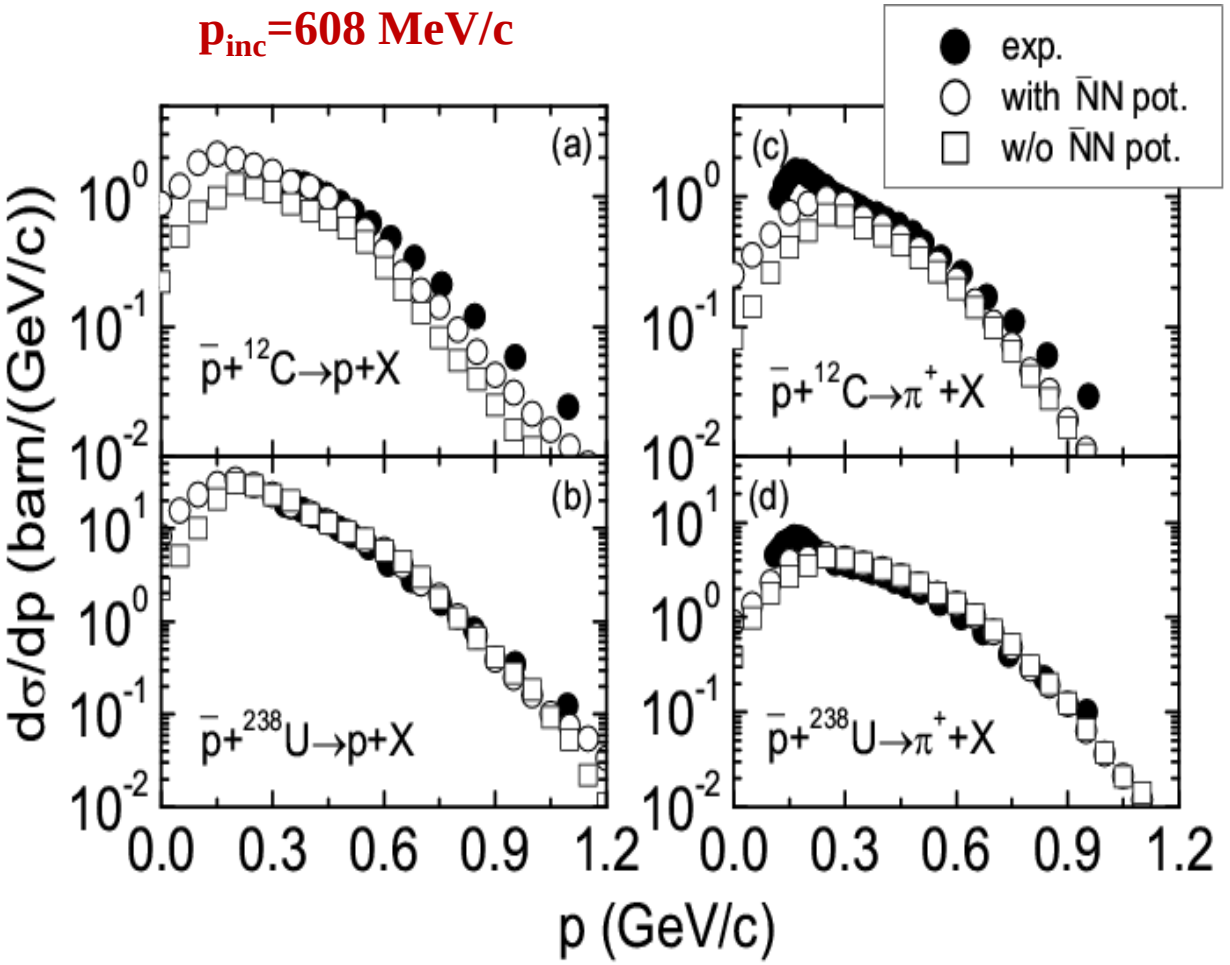
Particle multiplicities on different nuclei at stopped energy

Nuclei	π^+	π^0	π^-	K^+/K^0	$K^-/\bar{K}^0$	$\Lambda+\Sigma^0$	Σ^+	Σ^-
^{12}C	0.6	1.2	1.5	0.027/0.034	0.013/0.008	0.021	0.009	0.01
^{197}Au	0.8	1.4	1.6	0.045/0.051	0.01/0.007	0.051	0.011	0.017

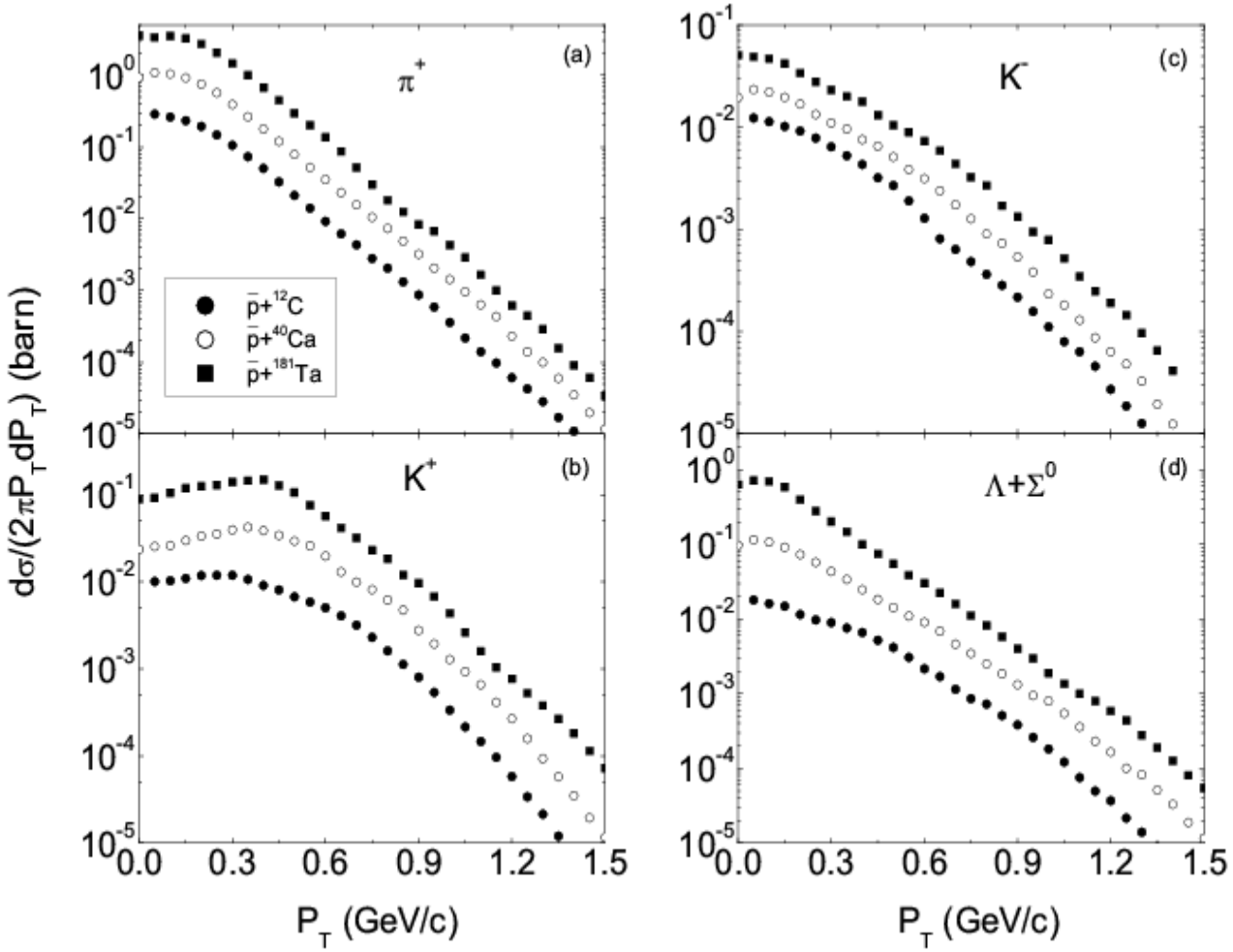
(1) Particle production in antiproton-nucleus collisions

Z. Q. Feng and H. Lenske, Phys. Rev. C 89, 044617 (2014)

p_{inc}=608 MeV/c



p_{inc}=4 GeV/c



LEAR (Low-Energy Antiproton Ring) **at CERN** (P. L. McGaughey et al., Phys. Rev. Lett. 56, 2156 (1986))

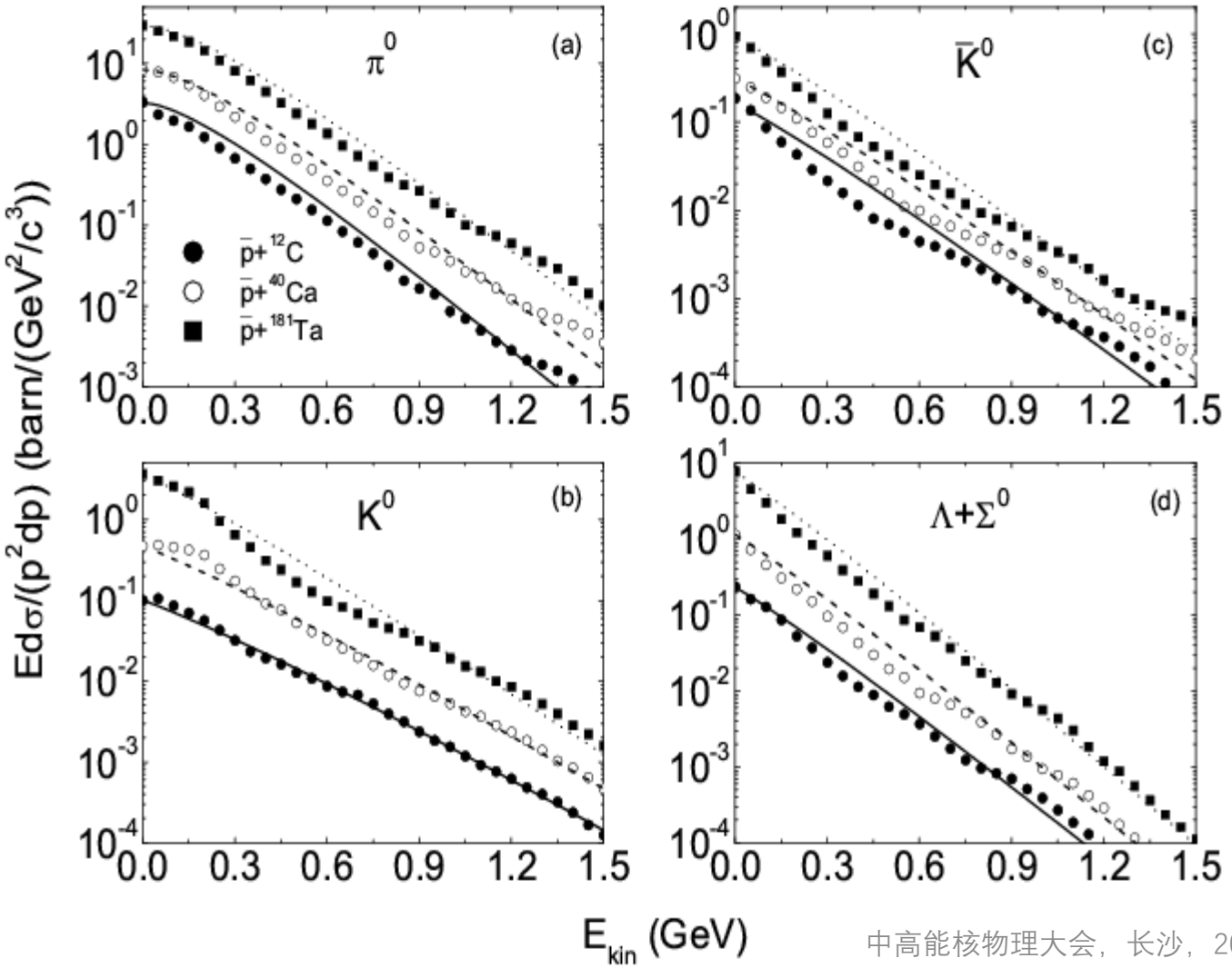
Slope parameters: 105 MeV (pion), 140 MeV (kaon), 125 MeV (antikaon) and 95 MeV (hyperon)

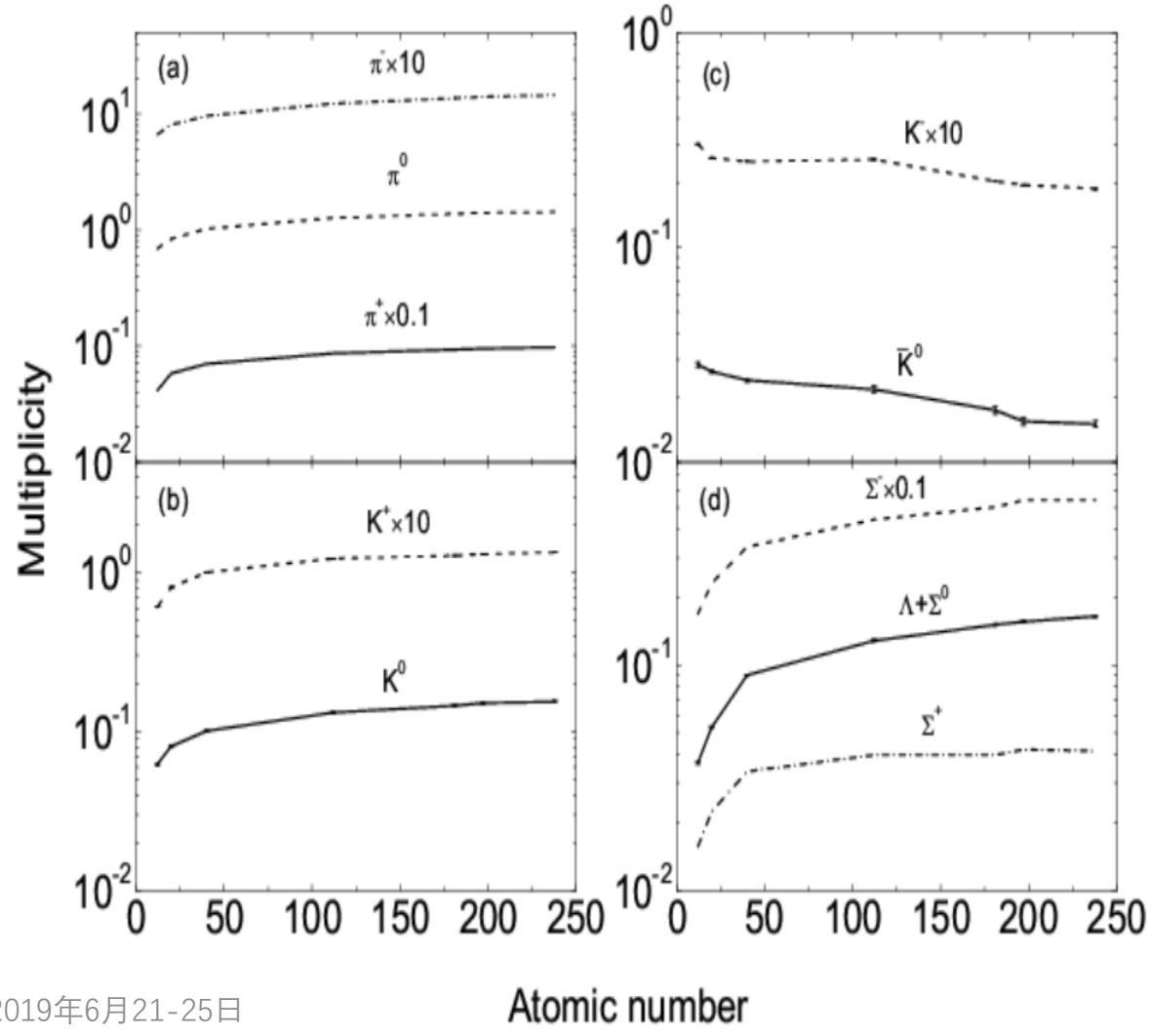
KEK data: 135±13 MeV (K^0_S), 97±6 MeV (Λ)

(Phys. Rev. C 38 (1988) 2788)

$$\frac{E\,d\sigma}{p^2\,dp} = C\,E\exp(-E_{kin}/T)$$

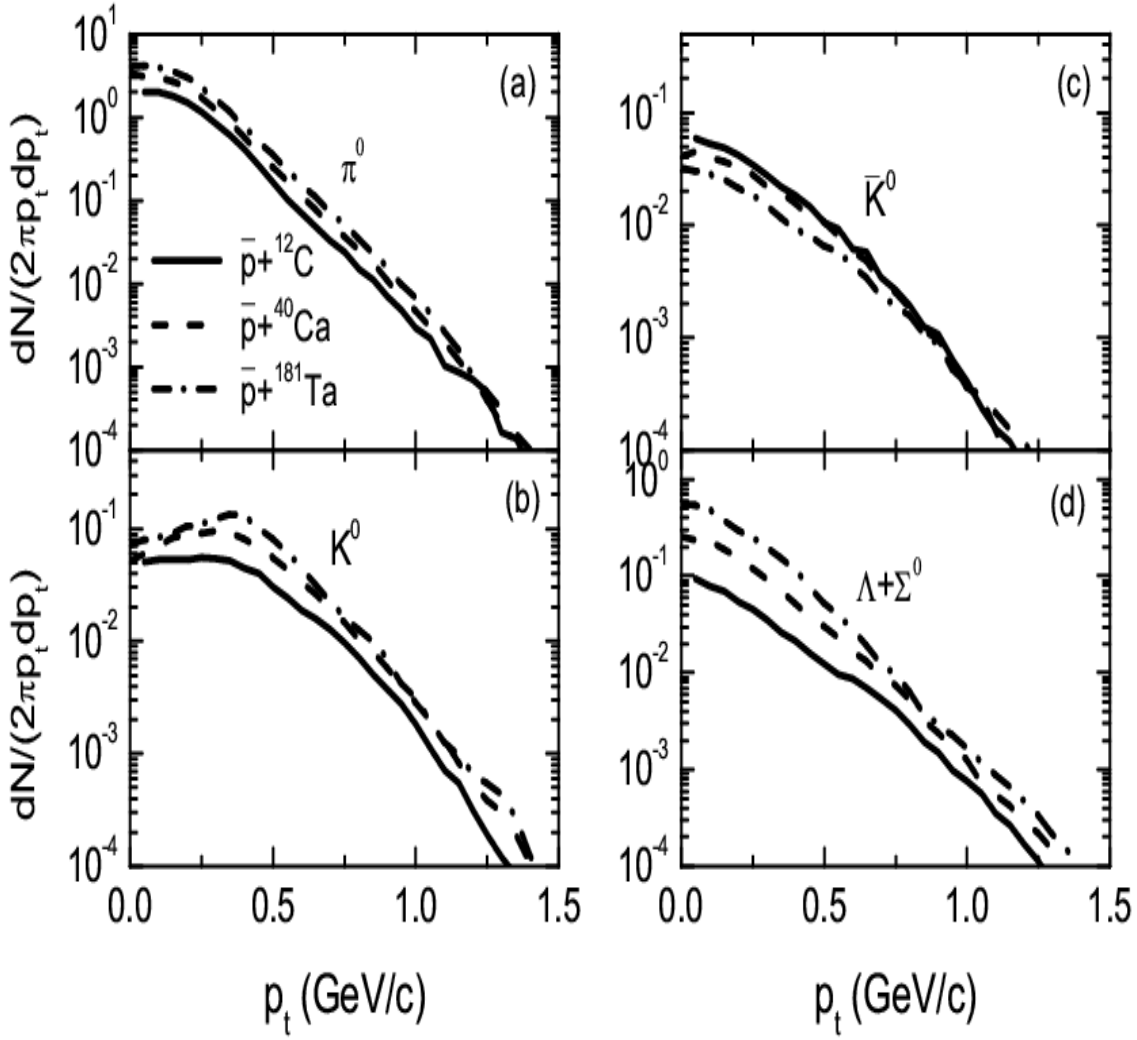
Multiplicities of particles $\bar{p}$+ ^{12}C, ^{20}Ne, ^{40}Ca, ^{112}Sn, ^{181}Ta, ^{197}Au and ^{238}U at 4 GeV/c

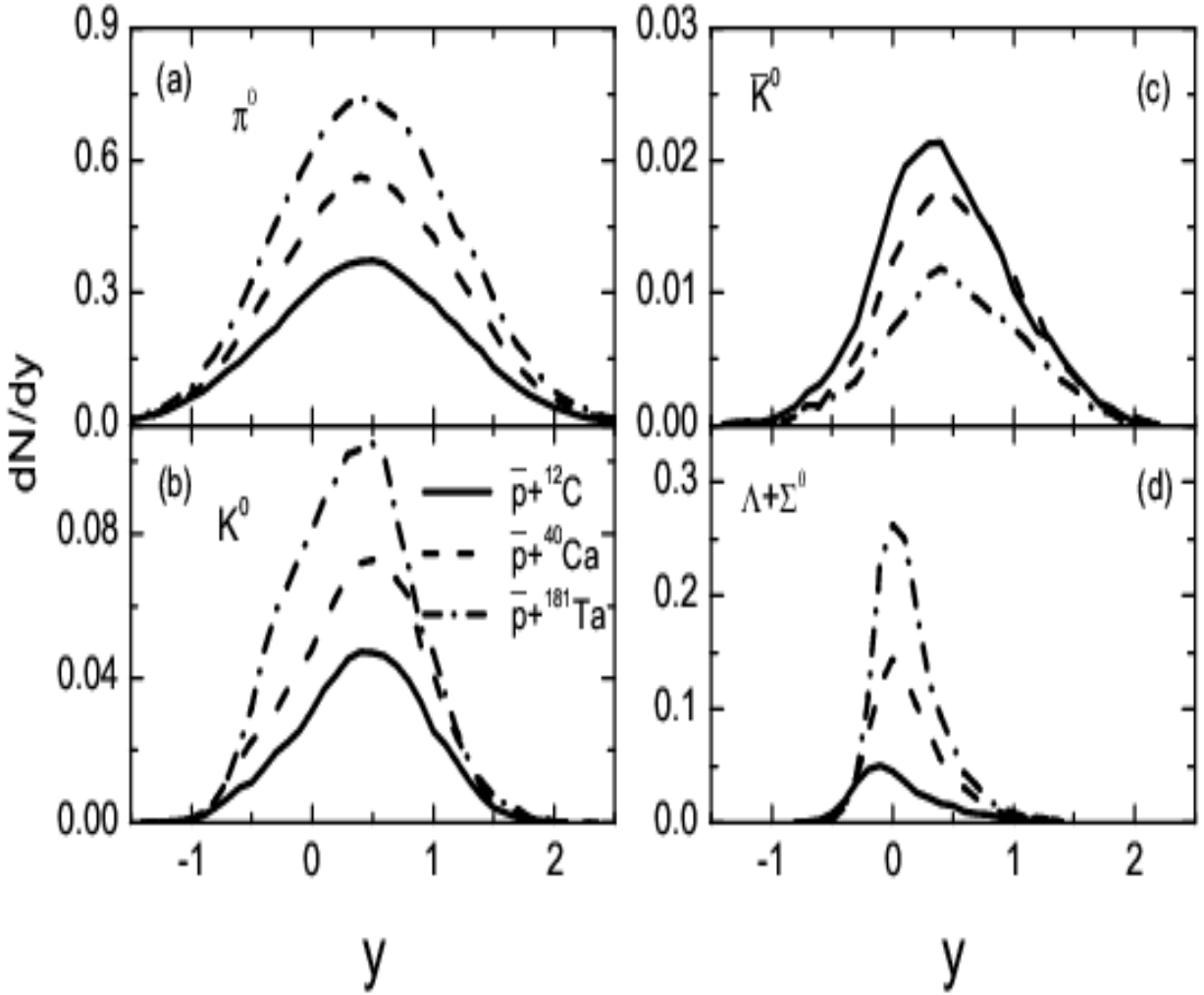




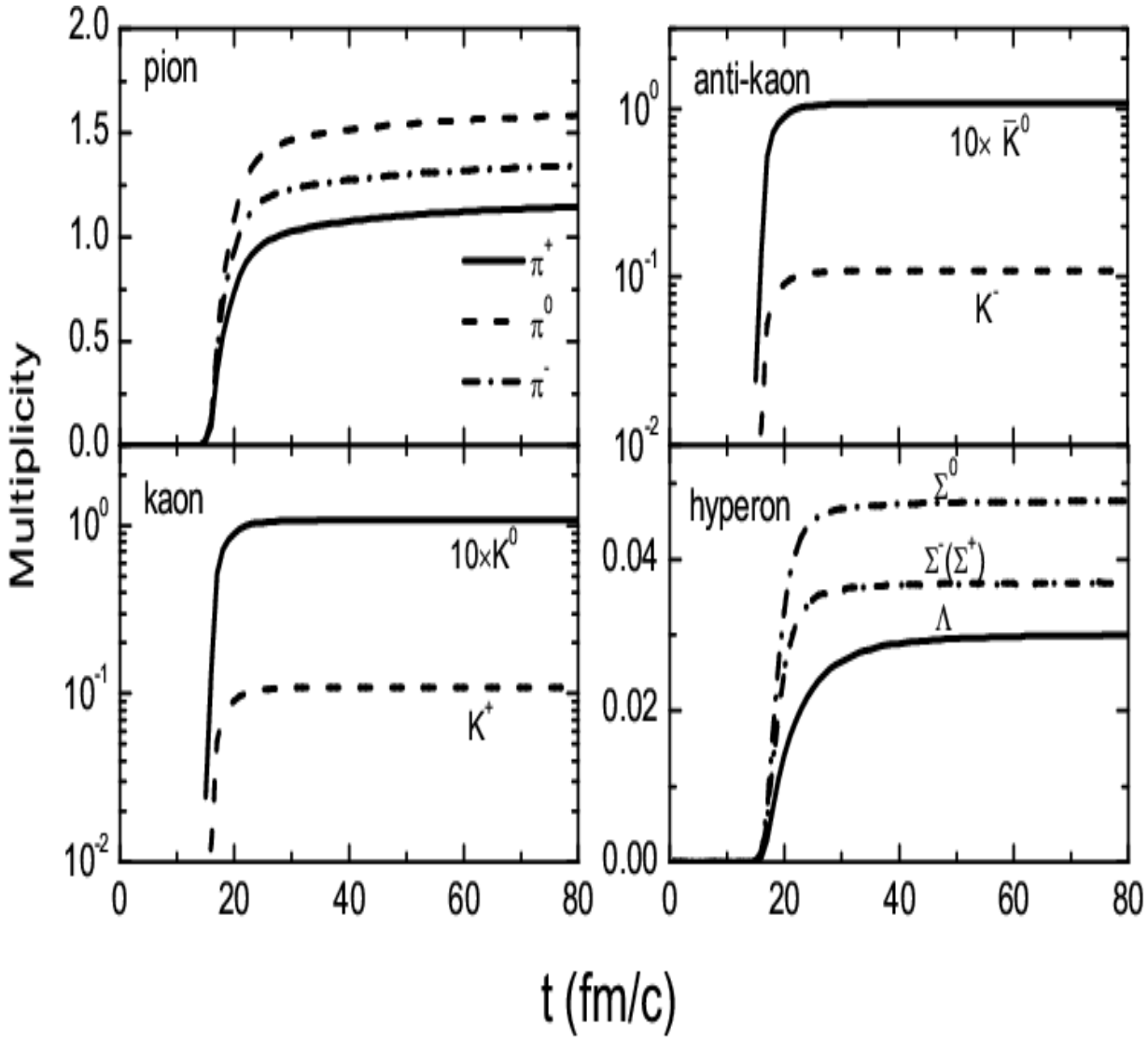
System size dependence of neutral particles at incident momentum of 4 GeV/c

Z. Q. Feng, Nuclear Science and Techniques 26 (2015) S20512

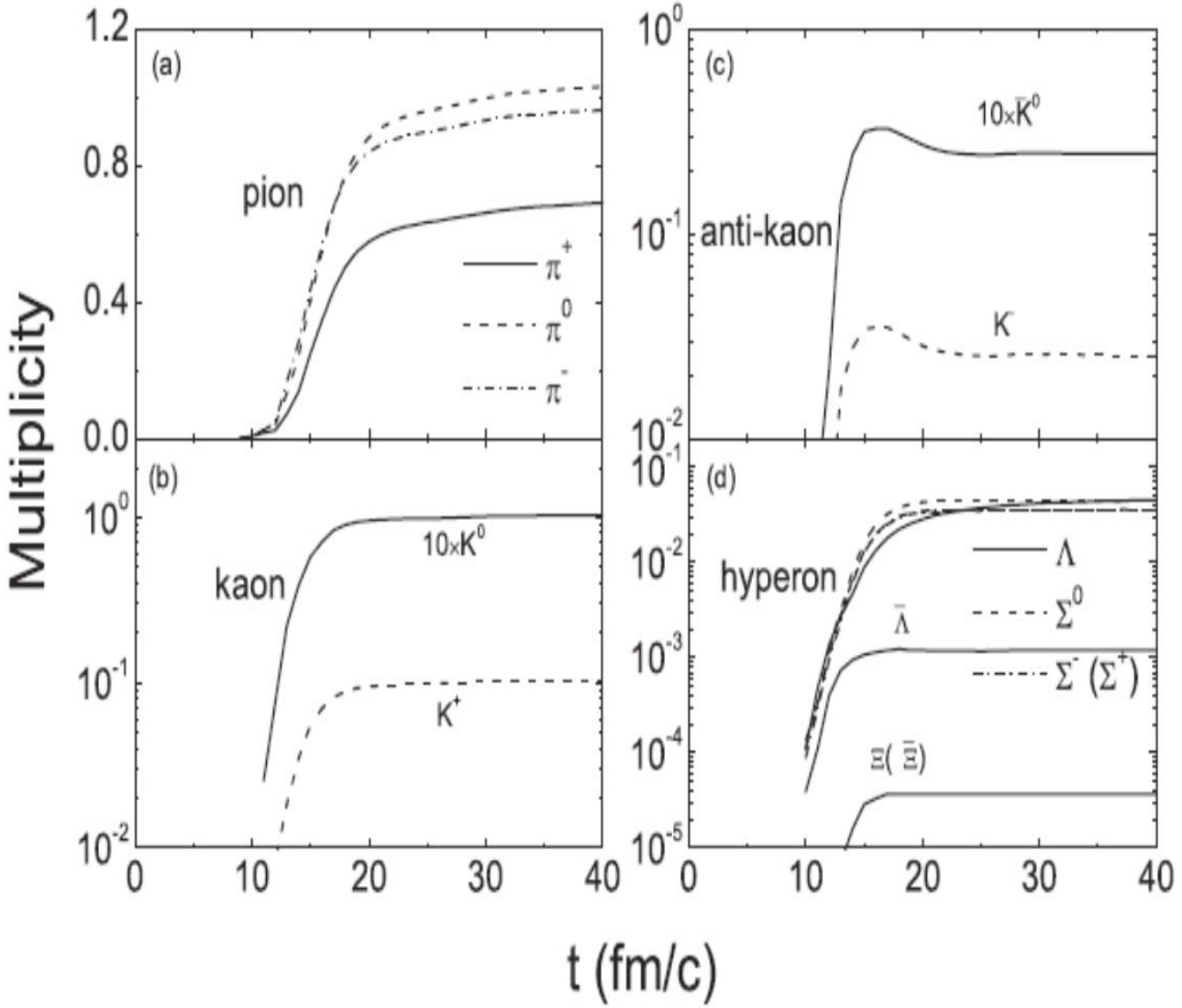




$\bar{p}+^{12}C$, 1 GeV/c

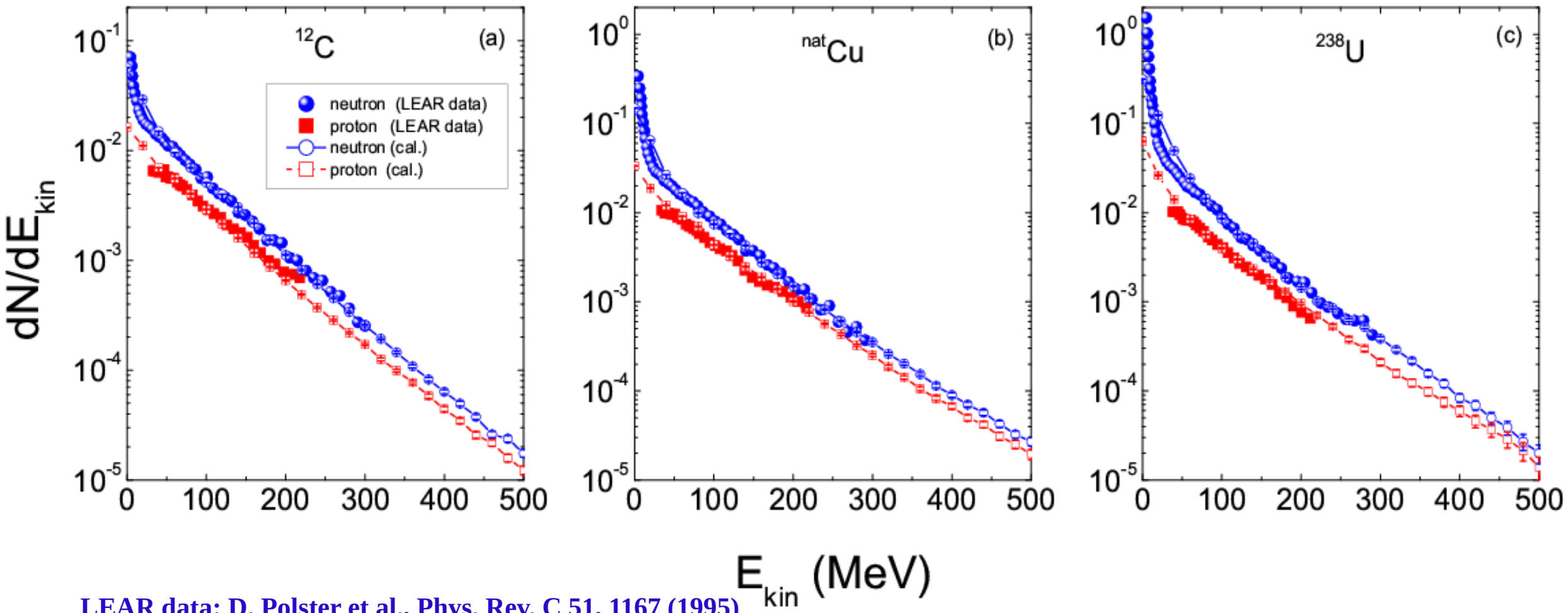


$\bar{p}+^{40}Ca$, 4 GeV/c



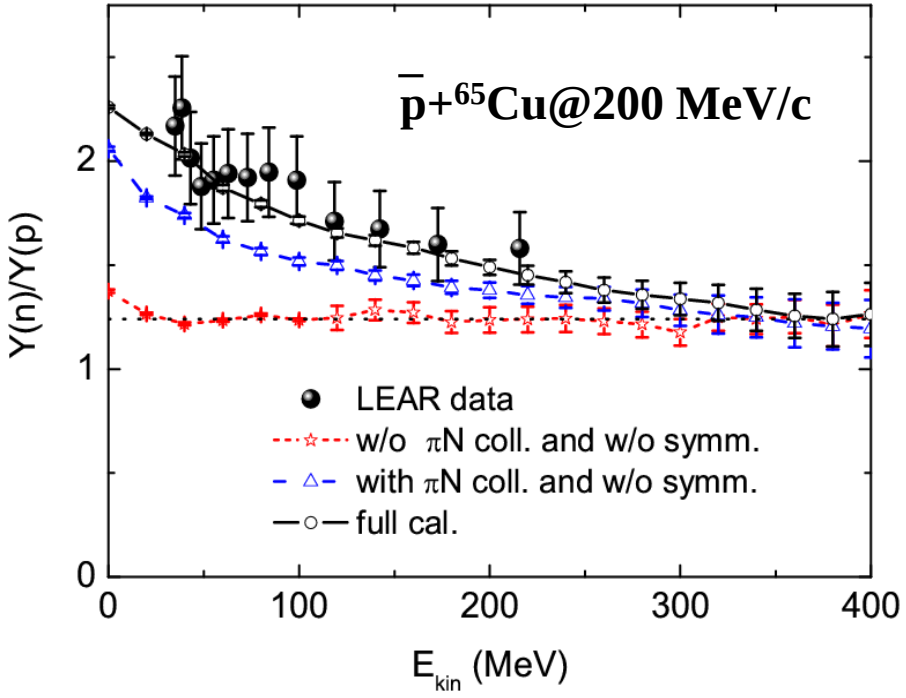
(2) The isospin effect in low-energy antiproton-induced reactions

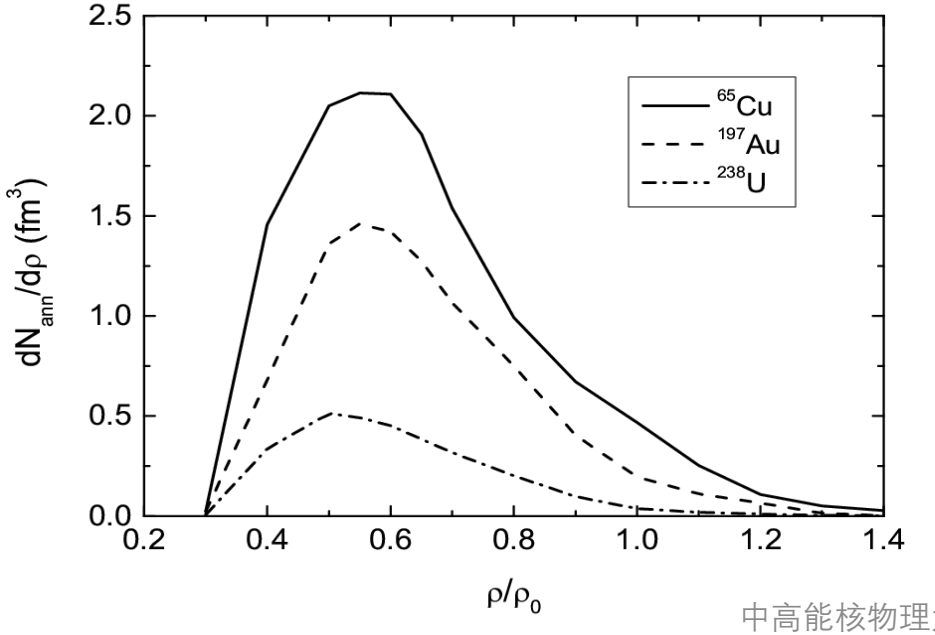
(Z. Q. Feng, Phys. Rev. C 96, 034607 (2017), arXiv: 1701.0630)



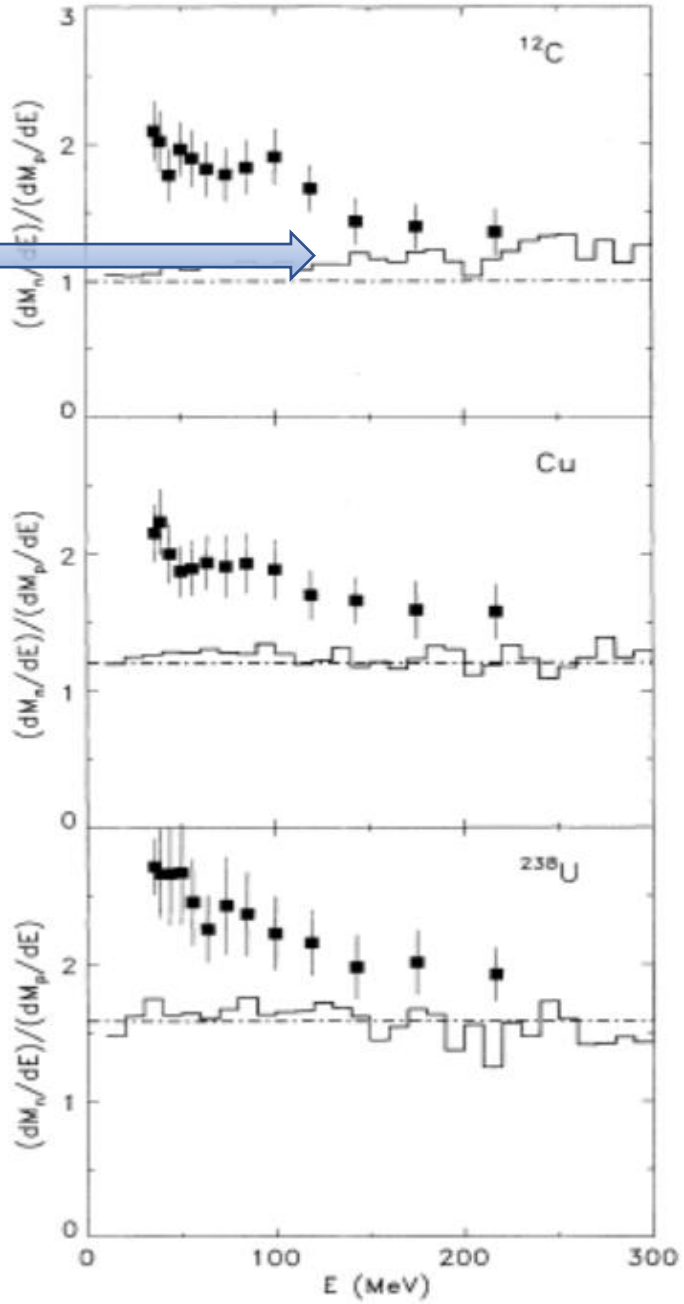
LEAR data: D. Polster et al., Phys. Rev. C 51, 1167 (1995)

D. Polster et al., Phys. Rev. C 51, 1167 (1995)

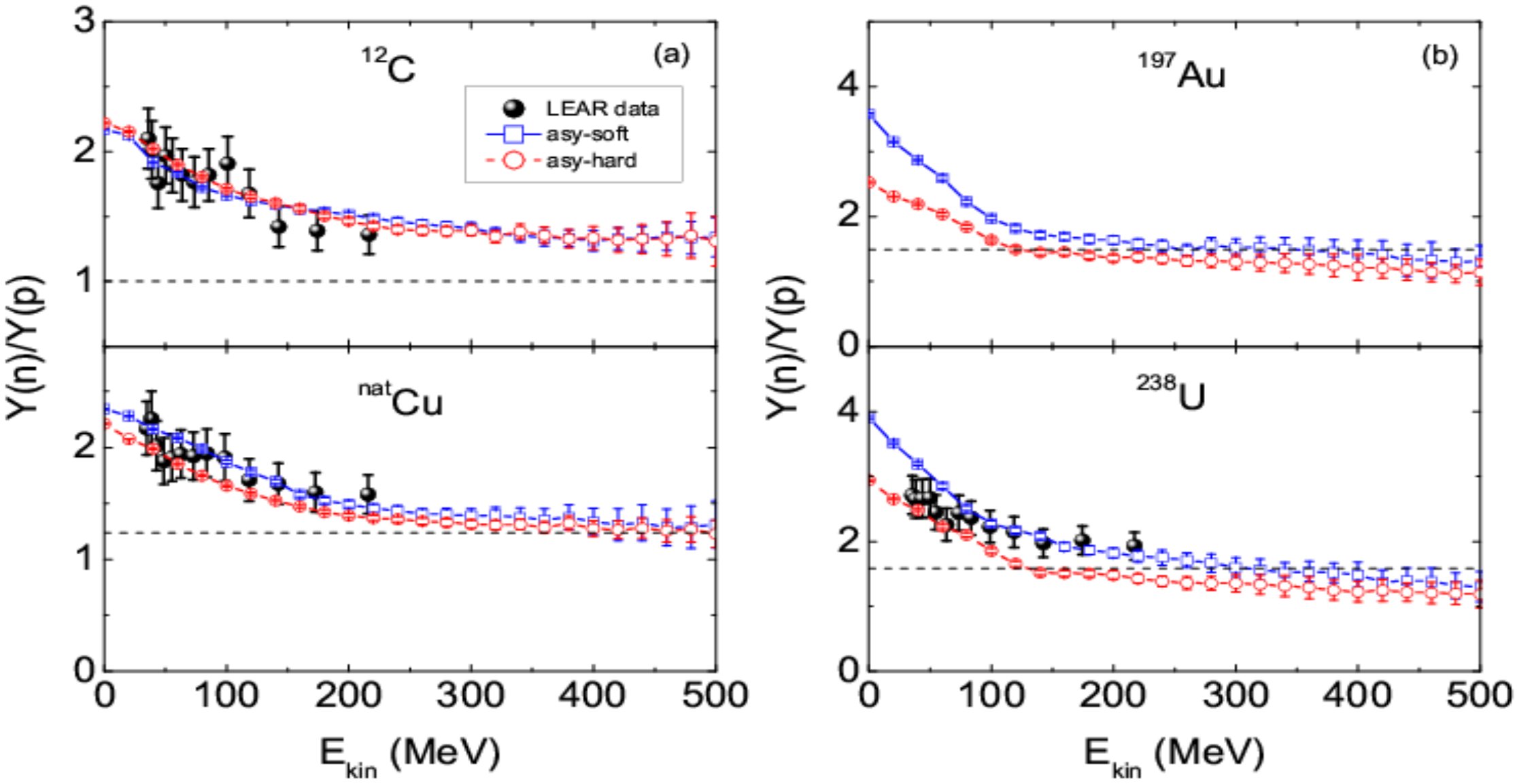




I. A. Pshenichnov, A. S. Iljinov, Y. S. Golubeva, and D. Polster, Phys. Rev. C 52, 947 (1995)

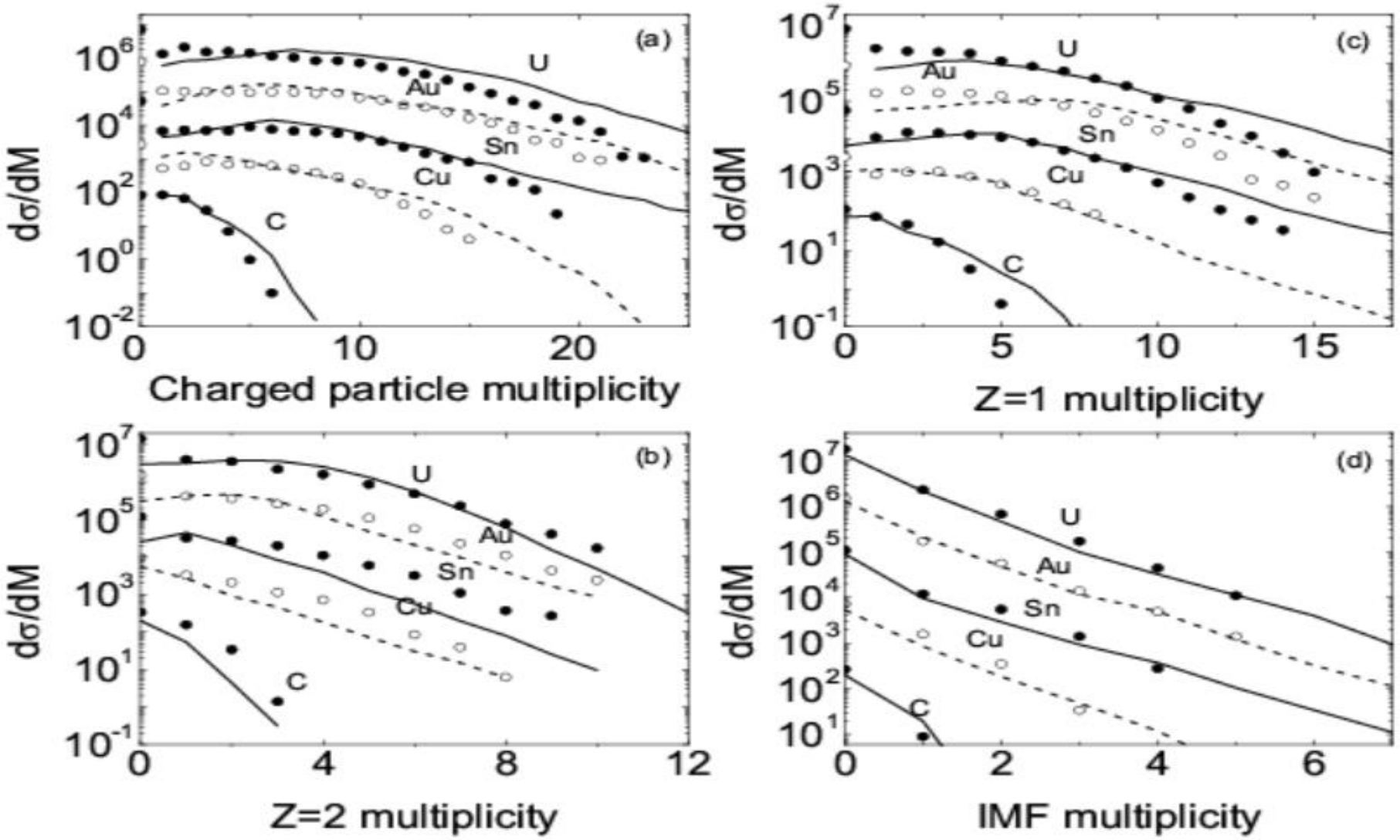


The n/p ratios in antiproton induced reactions with different stiffness of symmetry energies and compared with the LEAR data



(3) Nuclear fragmentation and hyperfragment formation in antiproton-nucleus collisions

(Z. Q. Feng, Phys. Rev. C 93, 041601(R) (2016))

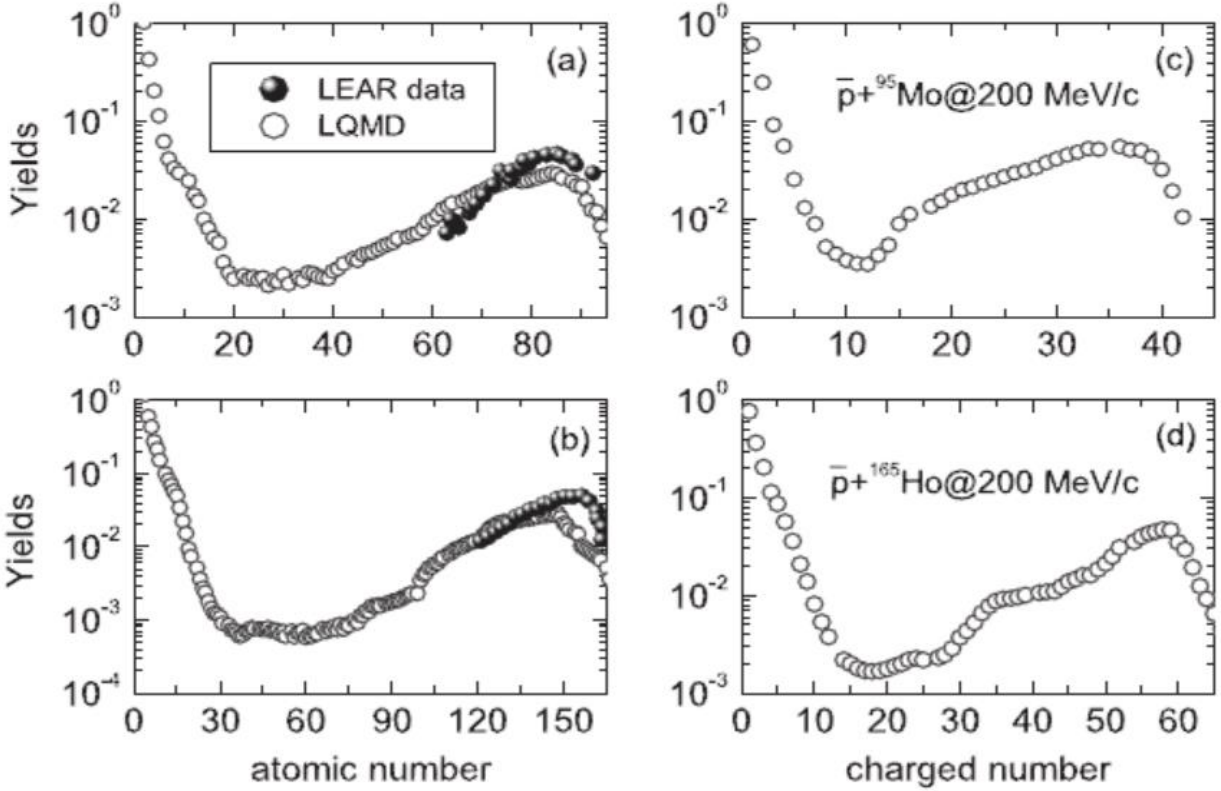


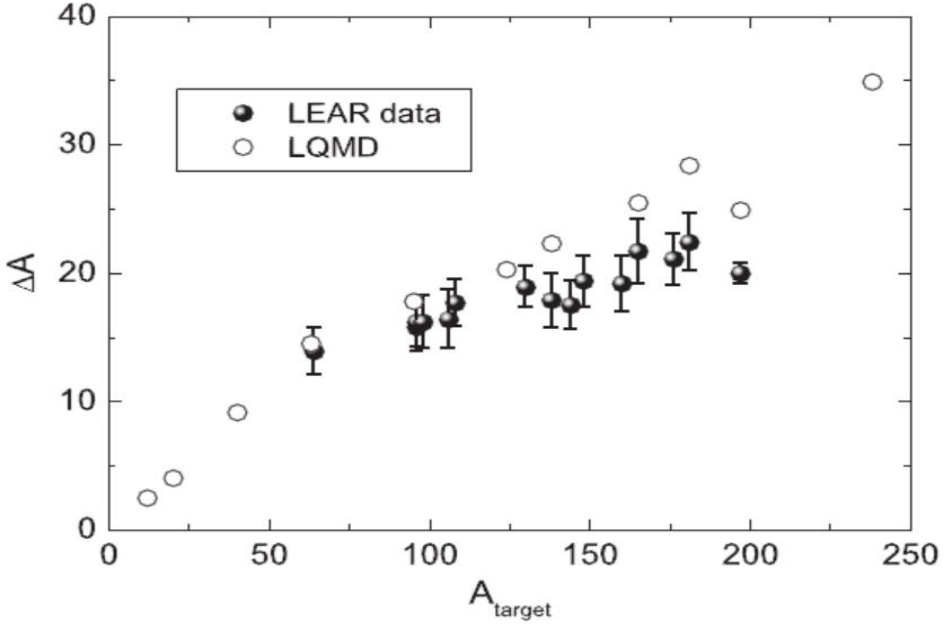
Experimental data: LEAR at CERN, B. Lott *et al.*, Phys. Rev. C 63, 034616 (2001) with 1.22 GeV antiproton

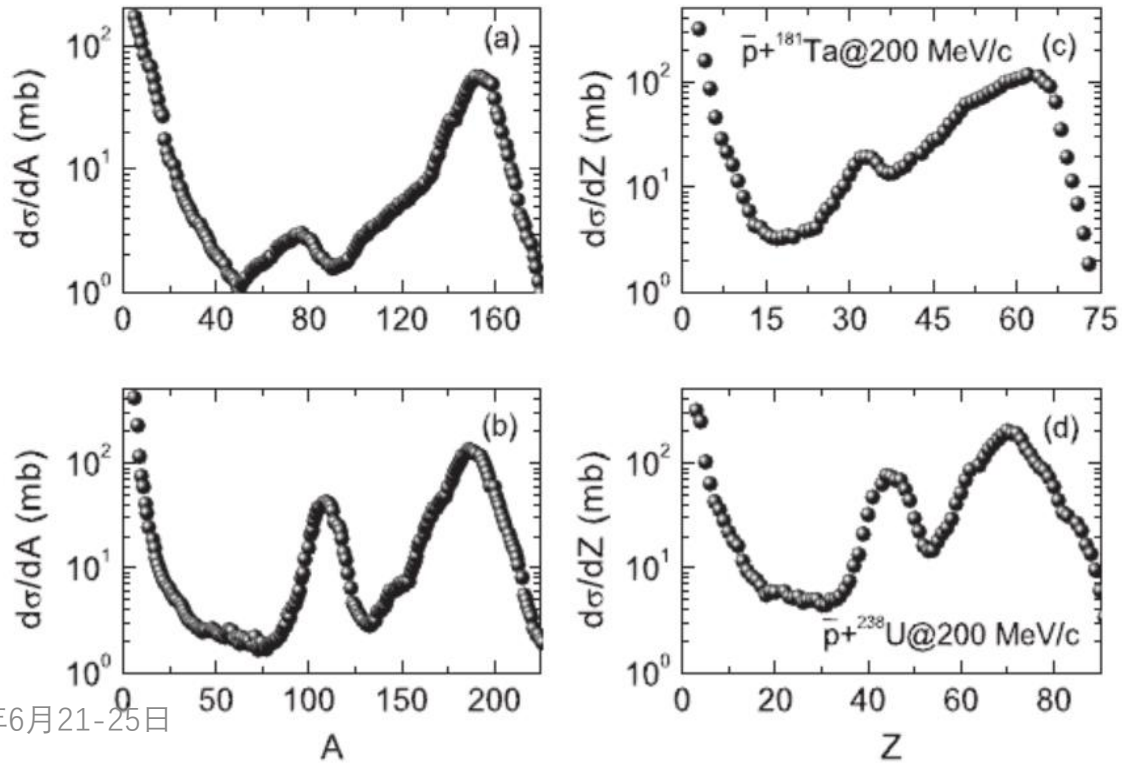
Nuclear fragmentation with low-energy antiproton

Z. Q. Feng, Phys. Rev. C 94, 064601 (2016)

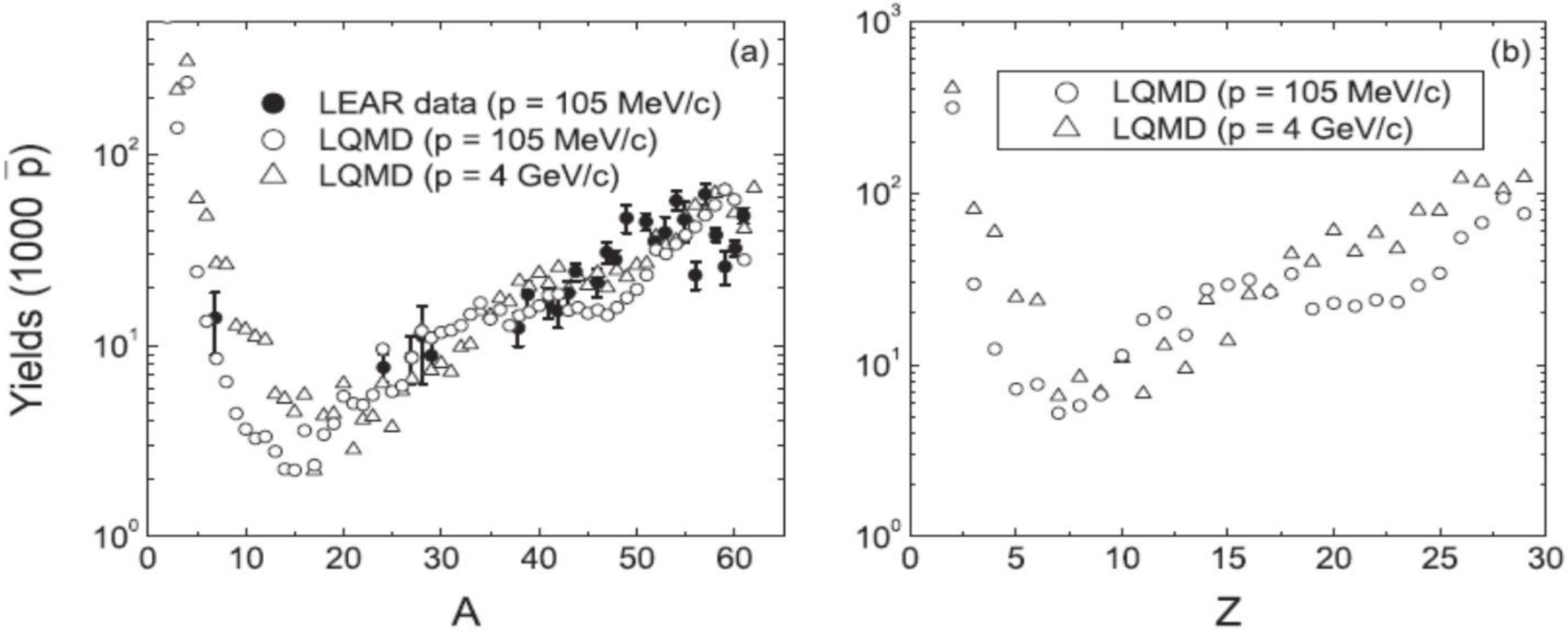
$$\triangle A = A_T - 1 - \int_{A_{\min}}^{A_T-2} \sigma(A) A dA / \int_{A_{\min}}^{A_T-2} \sigma(A) dA$$





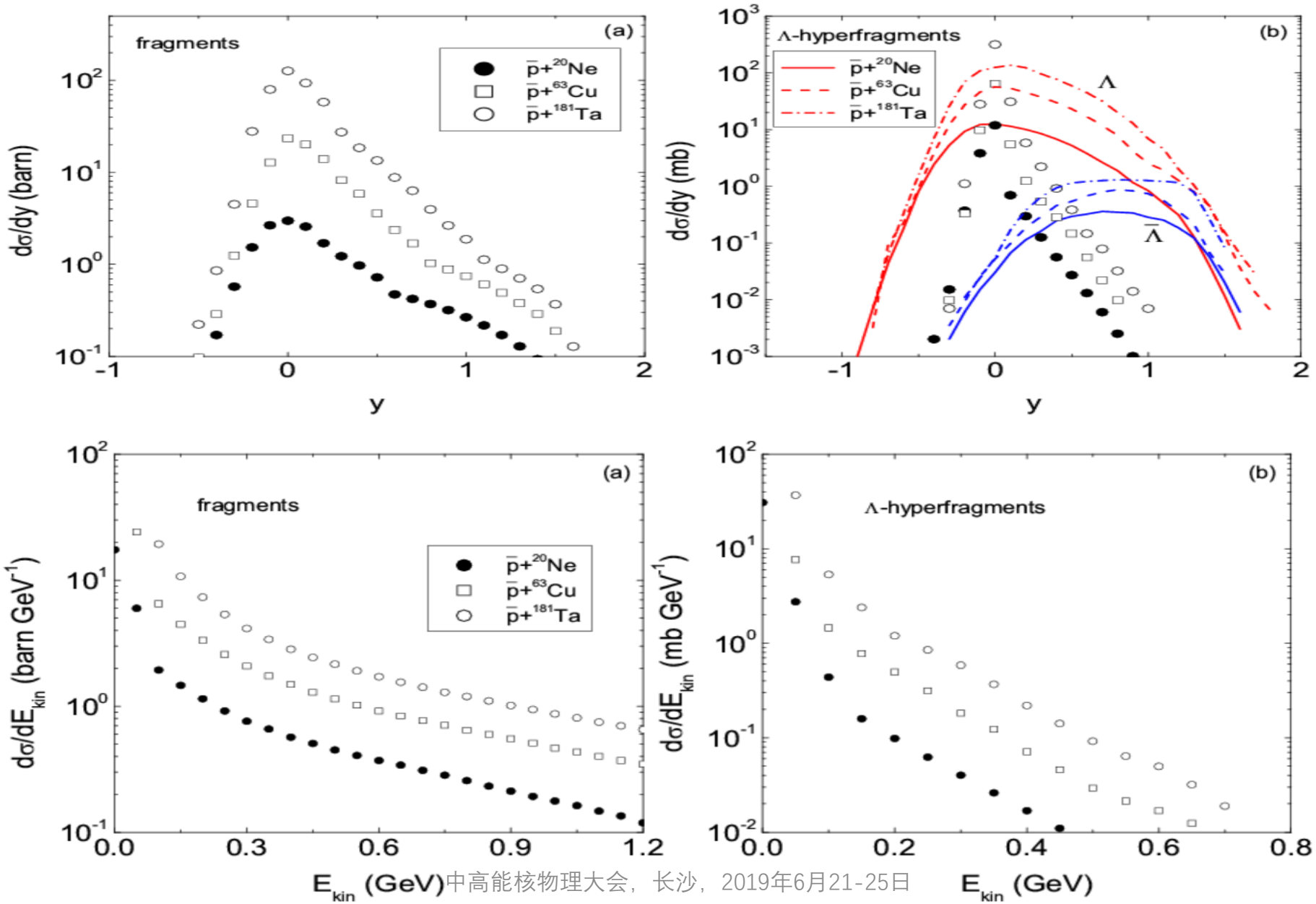


Mass and charge distributions of nucleonic fragments produced in the $\bar{p}$ + 63Cu reaction at incident momenta of 105 MeV/c and 4 GeV/c, respectively



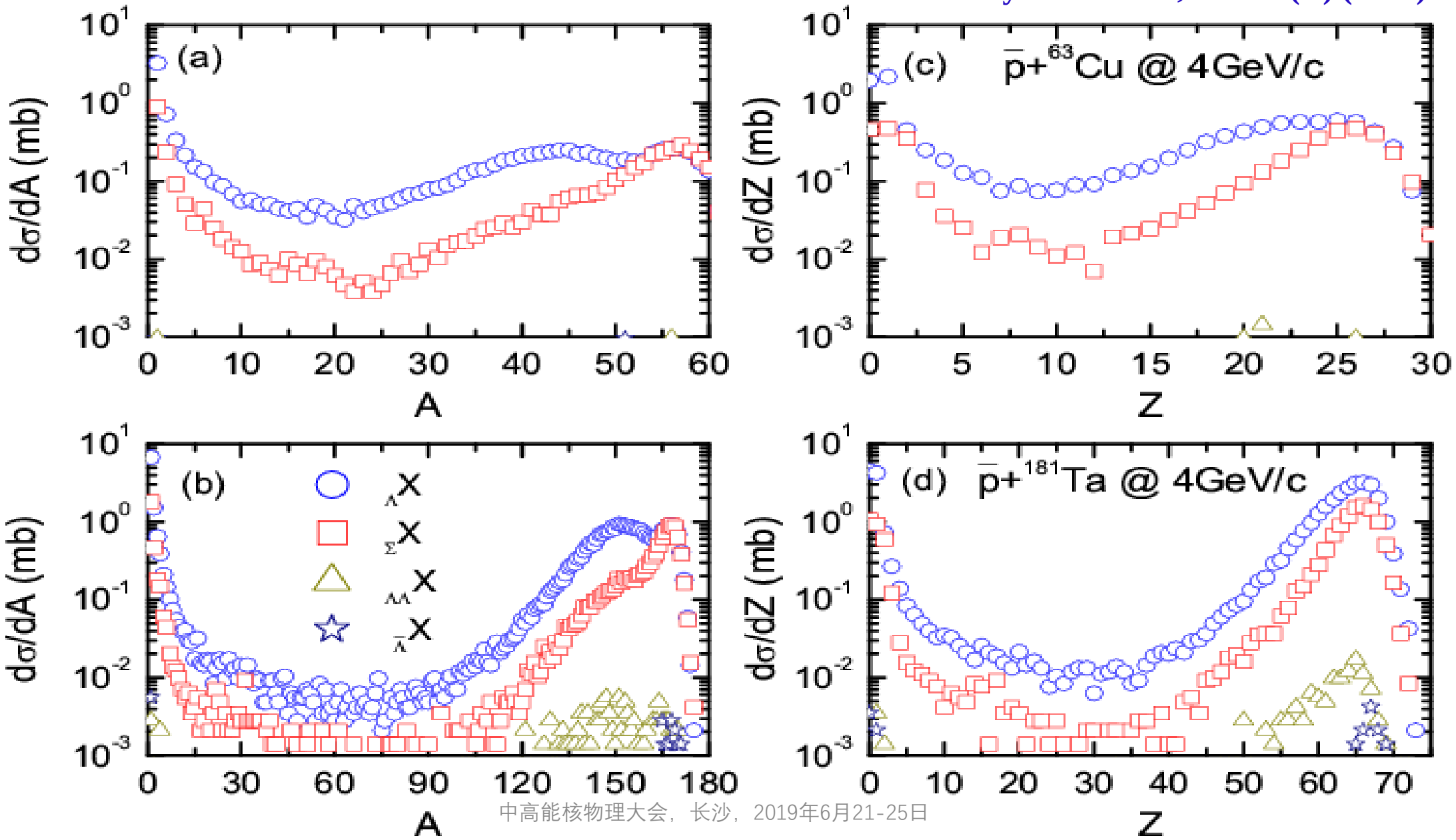
The data from LEAR facility at CERN. J. Jastrzebski *et al.*, Phys. Rev. C 47, 216 (1993)

(4) Hypernuclear formation: Rapidity and kinetic energy distributions



Hyperfragments production in the antiproton induced reactions

Phys. Rev. C 93, 041601(R) (2016)



IV. Summary

- Nuclear dynamics induced by antiprotons has been investigated within the Lanzhou quantum molecular dynamics (LQMD) model.
- In-medium effect of strangeness production is investigated. It is concluded that the weakly repulsive KN potential of $V(\rho_0)$=28 MeV, strongly attractive $\bar{K}N$ potential of $V(\rho_0)$= -100 MeV, weak attractive ΛN potential of $V(\rho_0)$= -32 MeV.
- Hypernuclear dynamics in heavy-ion collisions and in hadron induced reactions has been investigated, in particular for producing the double strangeness ${}_{\Lambda\Lambda}X$.

Thank you for your attention!