# Probing neutron-skin thickness via the antiproton and pion induced reactions

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# OUTLINE

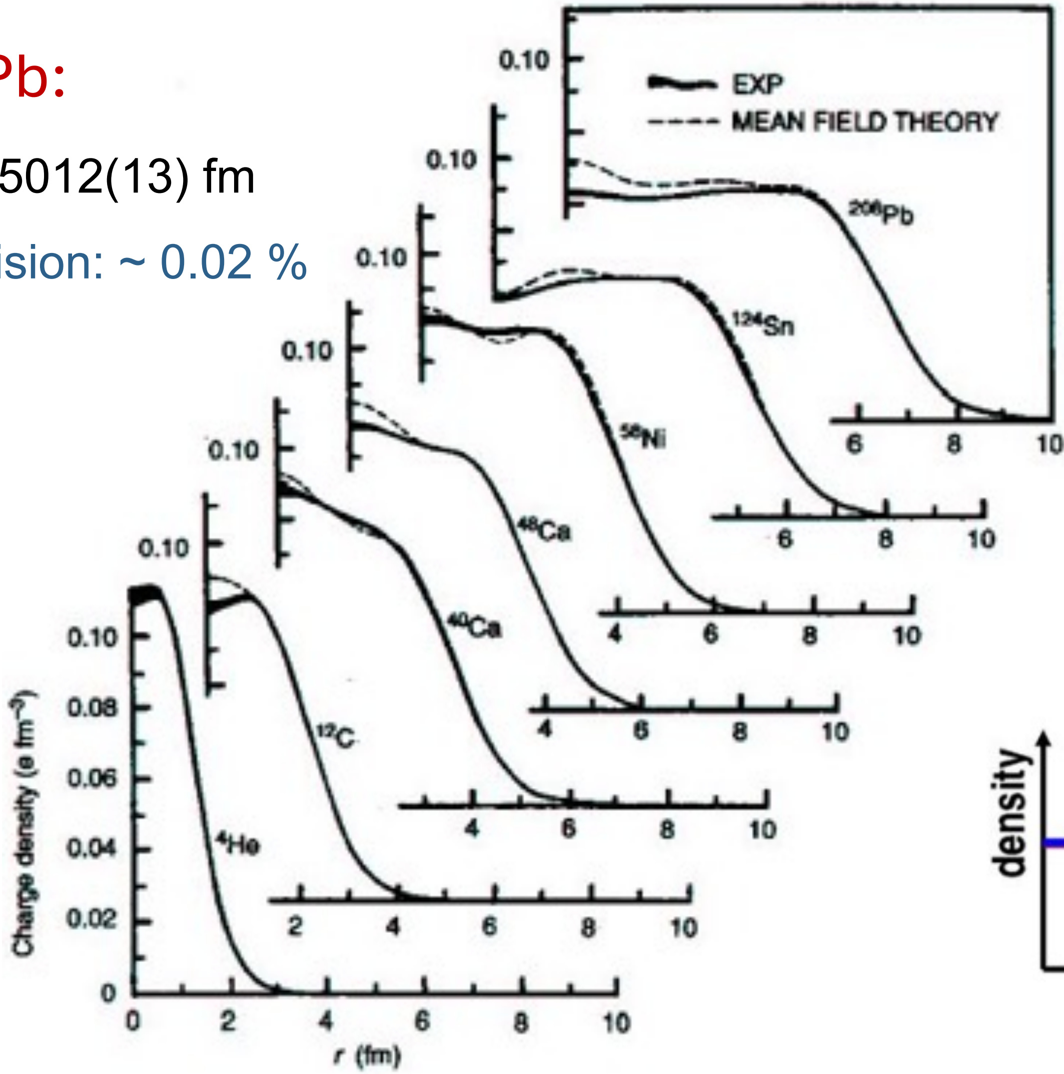
1. Introduction and motivation
2. Transport approach (LQMD)
3. Results and discussion
4. Summary

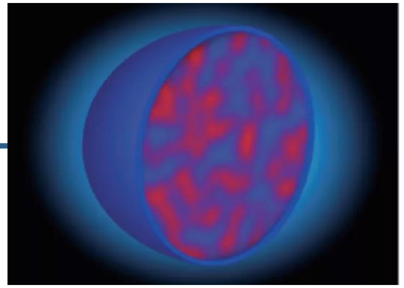
# Introduction and motivation

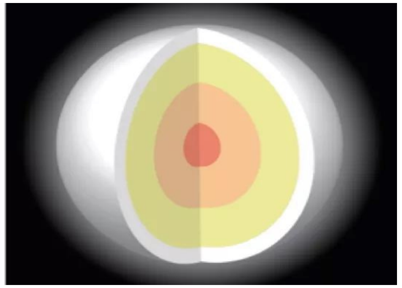
$^{208}$Pb:

$R_{ch}$ = 5.5012(13) fm

high precision: ~ 0.02 %





$^{208}$Pb

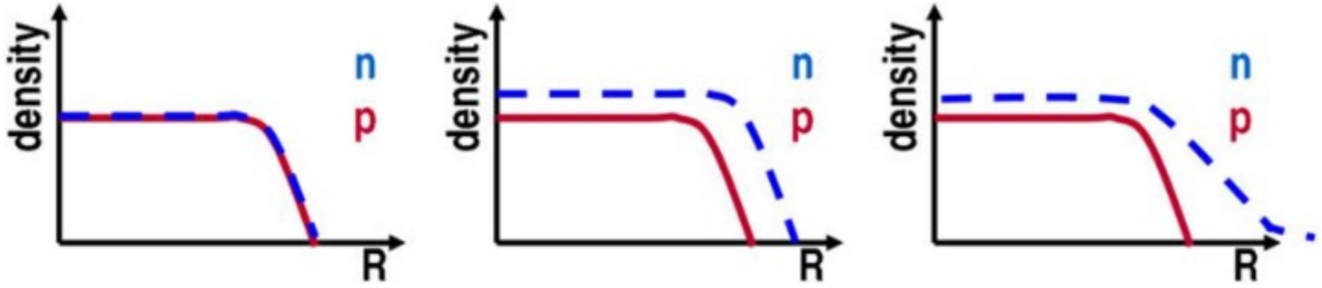
Neutron stars

**Neutron-skin thickness**：

$$\Delta r_{np} = r_n^{rms} - r_p^{rms}$$

$r_n^{rms}$ : rms radii of the neutron

$r_p^{rms}$ : rms radii of the proton




J. Phys. G: Nucl. Part. Phys. 46 (2019) 093003 (38pp)

# Introduction and motivation

**Equation of state :**

$$E(\rho,\delta) = E(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}\left(\frac{3}{2}\pi^2\rho\right)^{2/3} + E_{sym}^{loc}(\rho) + E_{sym}^{mom}(\rho)$$

$$E_{sym}^{loc}(\rho) = \frac{1}{2}C_{sym}(\rho/\rho_0)^{\gamma_s}$$

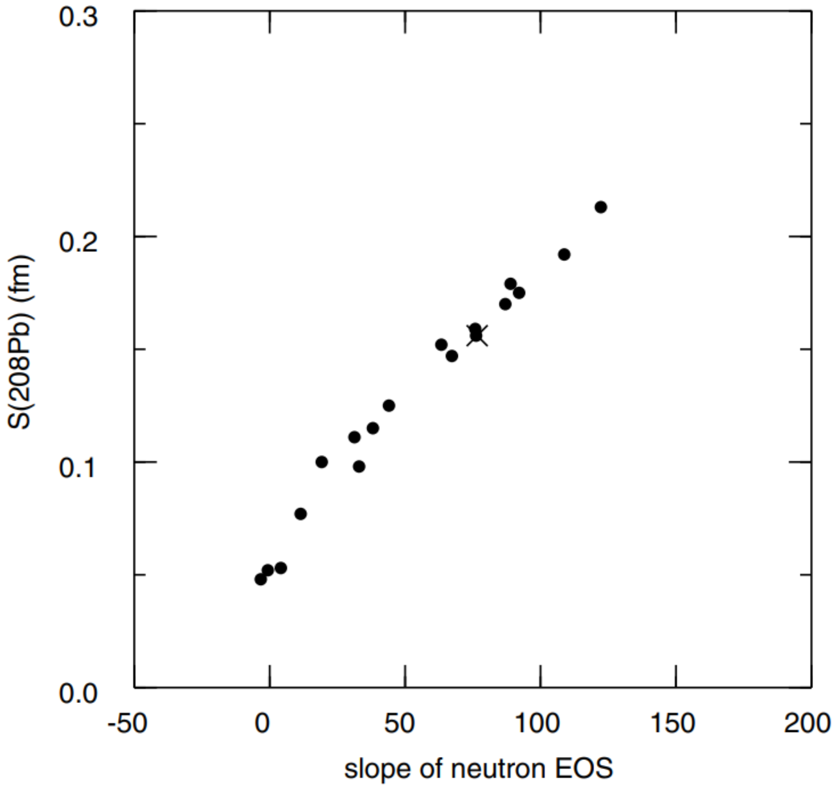
**Curvature of symmetry energy:**

$$K_{sym} = 9\rho_0^2\frac{\partial^2 E_{sym}(\rho)}{\partial^2\rho}|_{\rho=\rho_0}.$$

**Slope of symmetry energy:**

$$L = 3\rho_0\frac{\partial E_{sym}(\rho)}{\partial\rho}|_{\rho=\rho_0},$$

## Neutron skin and equation of state parameter

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# Transport approach

## Lanzhou Quantum Molecular Dynamics (LQMD)

- **Gaussian wave-packet**

$$\phi_i(\mathbf{r},t)=\frac{1}{(2\pi L)^{\frac{3}{4}}}\exp\left[-\frac{-(\mathbf{r}-\mathbf{r}_i(t))^2}{4L}+\frac{i\mathbf{p}_i(t)\cdot\mathbf{r}}{\hbar}\right]$$

$$U_{loc}=\int V_{loc}[\rho(\boldsymbol{r})]d\boldsymbol{r}$$

- **Temporal evolution:**

$$\dot{\boldsymbol{r}}_i=\frac{\partial\langle H\rangle}{\partial\boldsymbol{p}_i},\qquad \dot{\boldsymbol{p}}_i=-\frac{\partial\langle H\rangle}{\partial\boldsymbol{r}_i}$$

$$V_{loc}=\frac{\alpha}{2}\frac{\rho^2}{\rho_0}+\frac{\beta}{1+\gamma}\frac{\rho^{1+\gamma}}{\rho_0^{\gamma}}+\boxed{E_{sym}^{loc}}(\rho)\rho\delta^2+\frac{g_{sur}}{2\rho_0}(\nabla\rho)^2+\frac{g_{sur}^{iso}}{2\rho_0}[\nabla(\rho_n-\rho_p)]^2$$

- **Hamiltonian of baryons:**

$$H_B=\sum_i\sqrt{\mathbf{p}_i^2+m_i^2}+U_{int}+U_{mom}$$

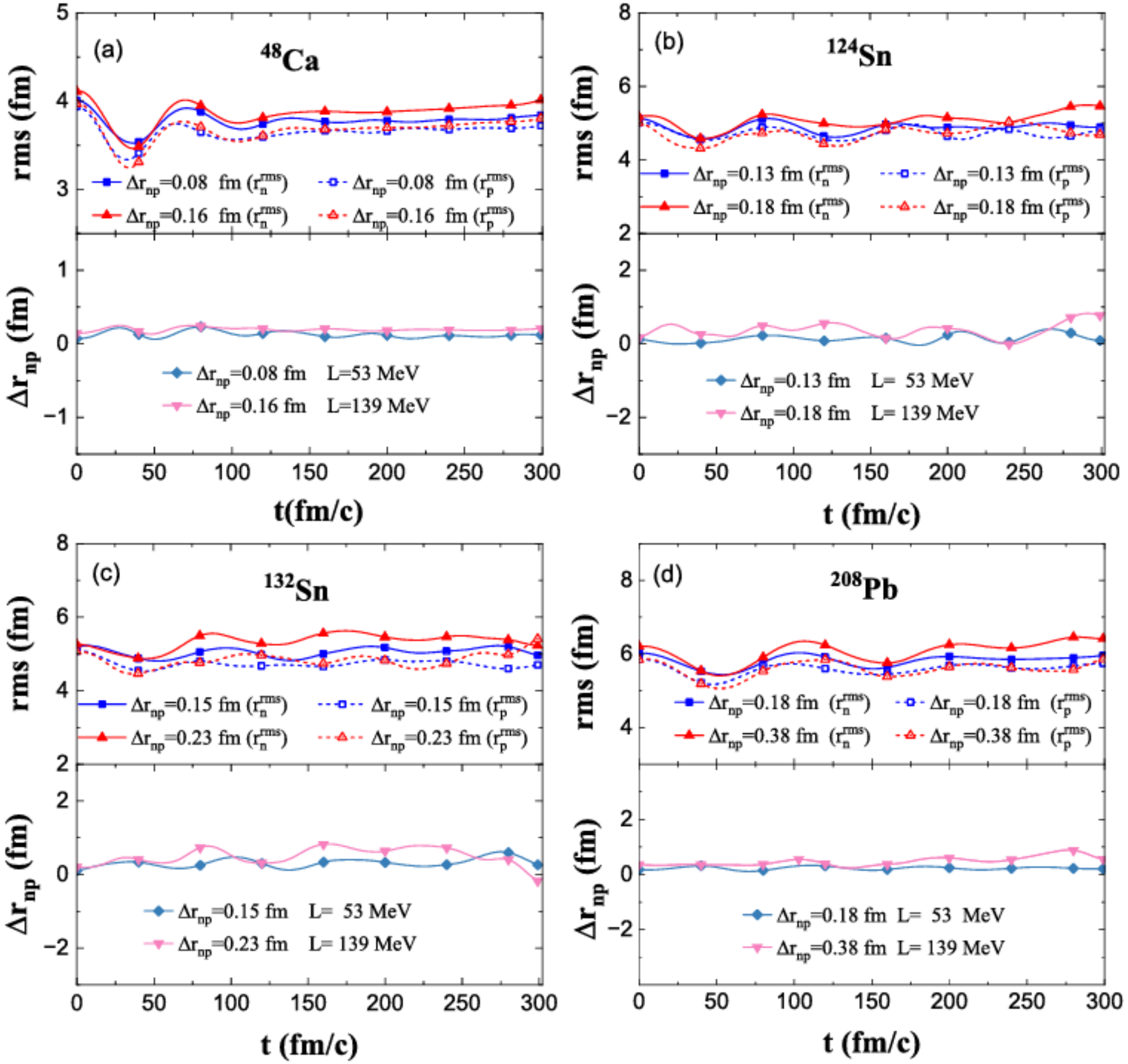
$$\boxed{U_{\mathrm{coul}}+U_{\mathrm{loc}}}$$

**Cross section of pion-nucleon scattering:**

$$\sigma_{\pi N\to R}(\sqrt{s})=\sigma_{\max}(|\mathbf{p}_0/\mathbf{p}|)^2\frac{0.25\Gamma^2(\mathbf{p})}{0.25\Gamma^2(\mathbf{p})+(\sqrt{s}-m_0)^2}$$

# Transport approach

Lanzhou Quantum Molecular Dynamics (LQMD)




| | $\rho_{0p}(\mathrm{fm}^{-3})$ | $\rho_{0n}(\mathrm{fm}^{-3})$ | $R_p(\mathrm{fm})$ | $R_n(\mathrm{fm})$ | $a_p(\mathrm{fm})$ | $a_n(\mathrm{fm})$ | $L(\mathrm{MeV})$ |
|---|---|---|---|---|---|---|---|
| $^{48}$Ca | 0.0731 | 0.0872 | 3.790 | 4.062 | 0.54 | 0.49 | 53 |
| | 0.0731 | 0.0854 | 3.790 | 4.062 | 0.54 | 0.53 | 139 |
| $^{124}$Sn | 0.0648 | 0.0964 | 5.576 | 5.492 | 0.44 | 0.57 | 53 |
| | 0.0648 | 0.0951 | 5.576 | 5.502 | 0.44 | 0.59 | 139 |
| $^{132}$Sn | 0.0620 | 0.0994 | 5.670 | 5.650 | 0.43 | 0.54 | 53 |
| | 0.0620 | 0.0957 | 5.670 | 5.710 | 0.43 | 0.57 | 139 |
| $^{208}$Pb | 0.0633 | 0.090 | 6.638 | 6.780 | 0.506 | 0.57 | 53 |
| | 0.0633 | 0.090 | 6.638 | 6.730 | 0.506 | 0.66 | 139 |

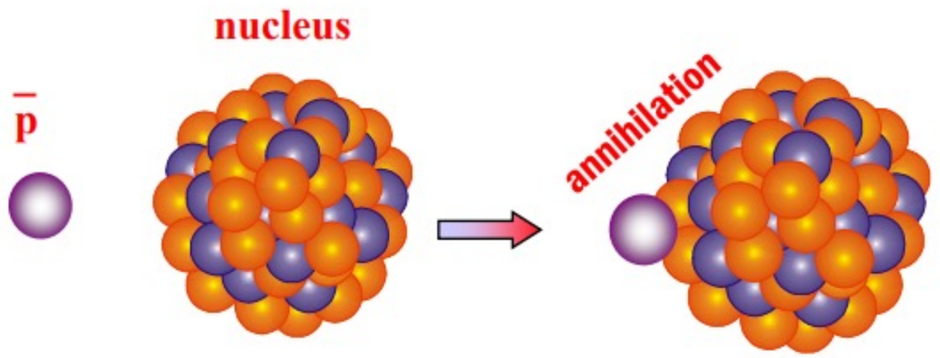
$$\rho_i = \frac{\rho_{0i}}{1+\exp(\frac{r-R_i}{a_i})}, i = n,p \quad N = \int \rho_n(r) d^3r, Z = \int \rho_p(r) d^3r$$

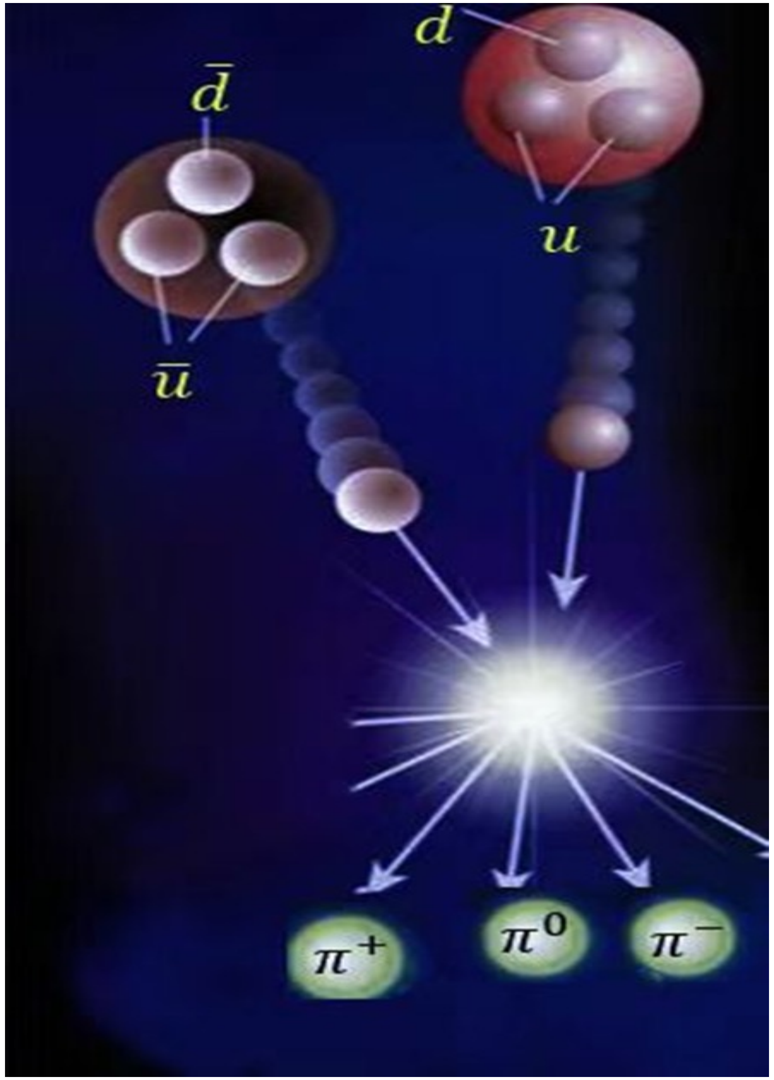
$$\Delta r_{np} = r_n^{rms} - r_p^{rms}$$

$$r_n^{rms} = \frac{1}{N}\left[\int r^2 \rho_n(r) d^3r\right]^{\frac{1}{2}} \quad r_p^{rms} = \frac{1}{Z}\left[\int r^2 \rho_p(r) d^3r\right]^{\frac{1}{2}}$$

# Antiproton-nucleus collisions

Ban Zhang and Zhao-Qing Feng, PRC 111, 014607 (2025)




## Reaction channels with antiproton:

$$\bar{p}N \to \bar{N}N,\ \bar{N}N \to \bar{N}N,\ \bar{N}N \to \bar{B}B,\ \bar{N}N \to \bar{Y}Y,$$

$$\bar{N}N \ \to annihilation(\pi,\eta,\rho,\omega,K,\bar{K},K^*,\phi)$$

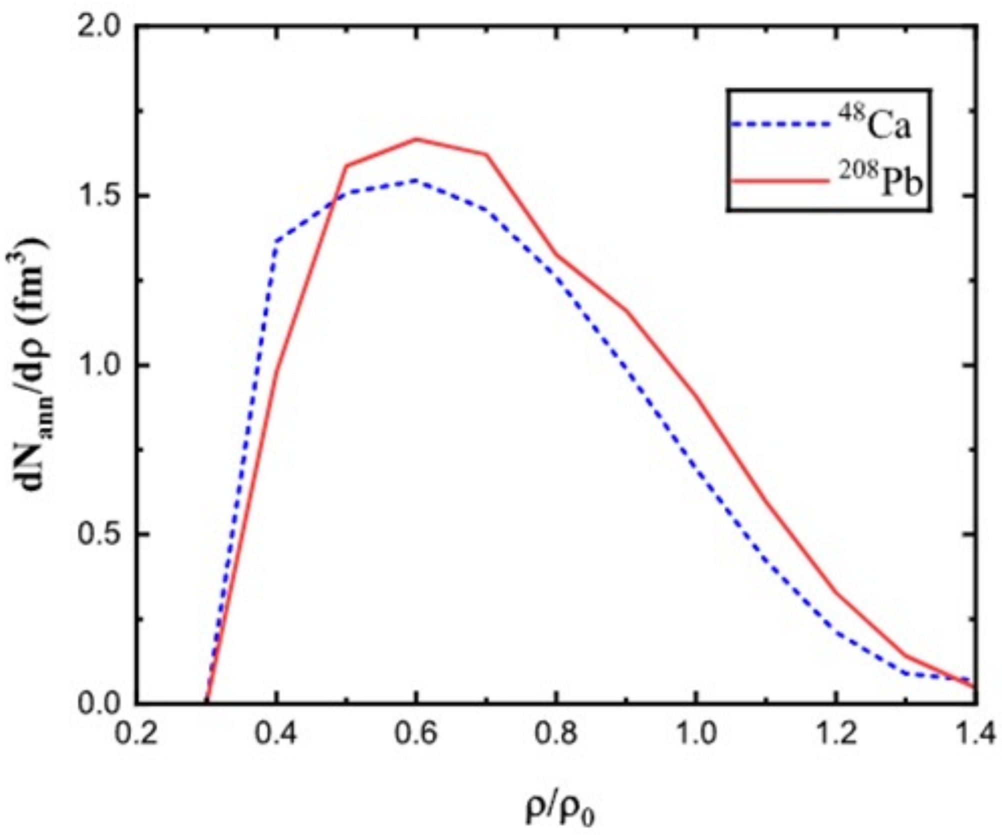
# Results and discussion

Ban Zhang and Zhao-Qing Feng, PRC 111, 014607 (2025)

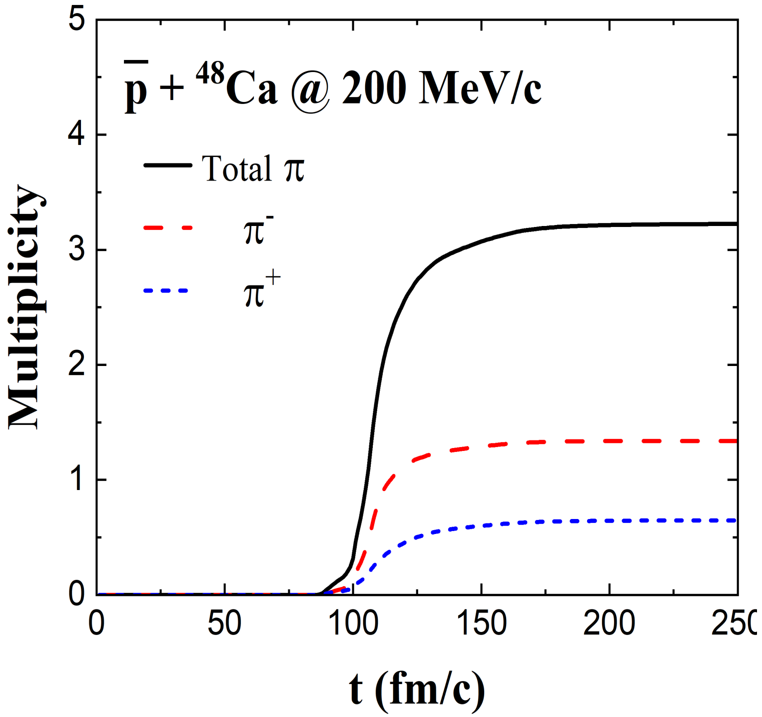
**antiproton-nucleus**

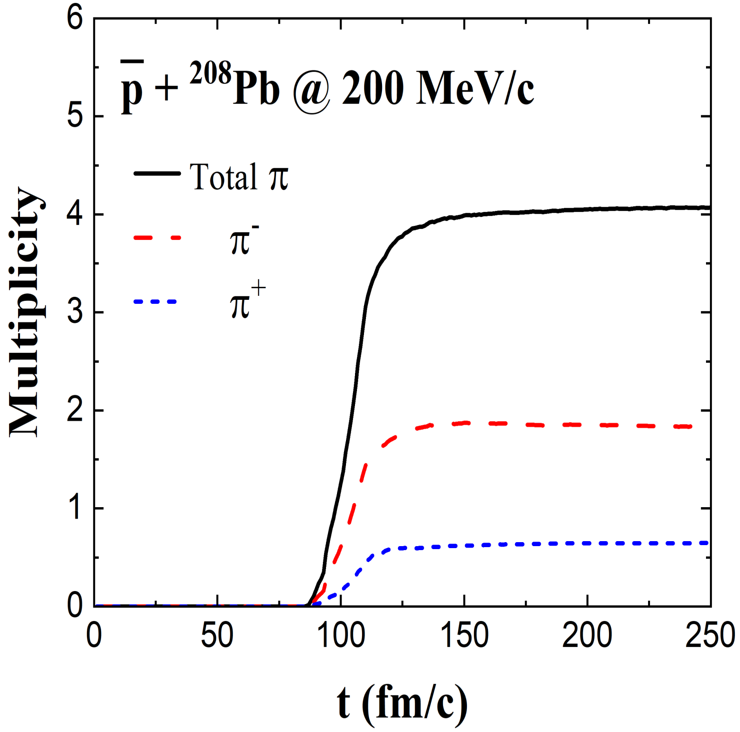
## Density profiles at the annihilation

$0.4\rho_0 - 0.8\rho_0$




## Temporal evolution of the pions



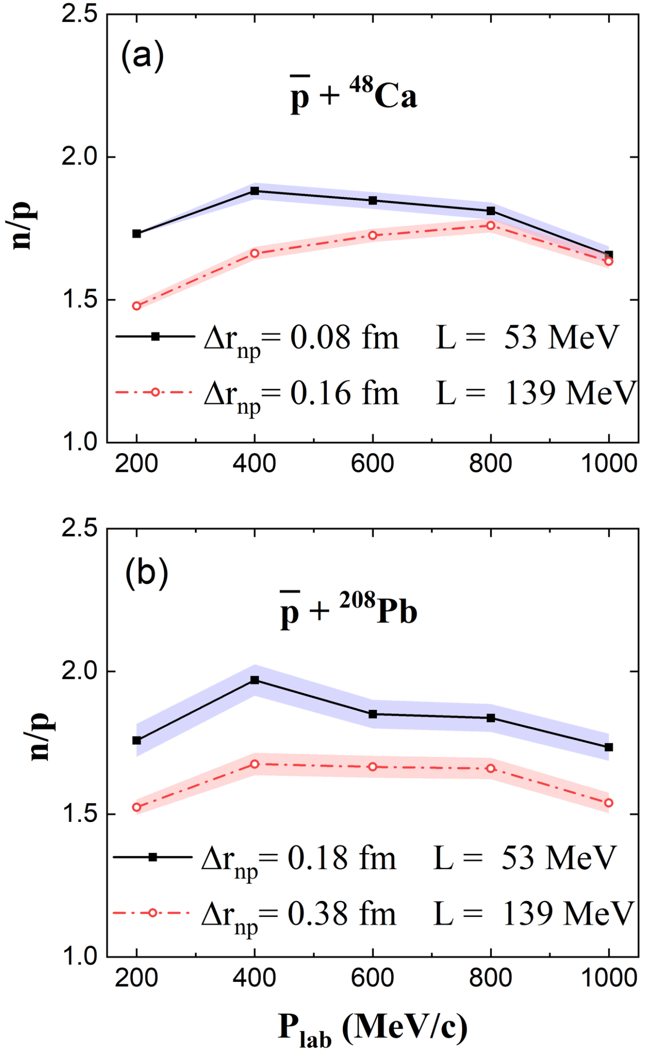



# Results and discussion

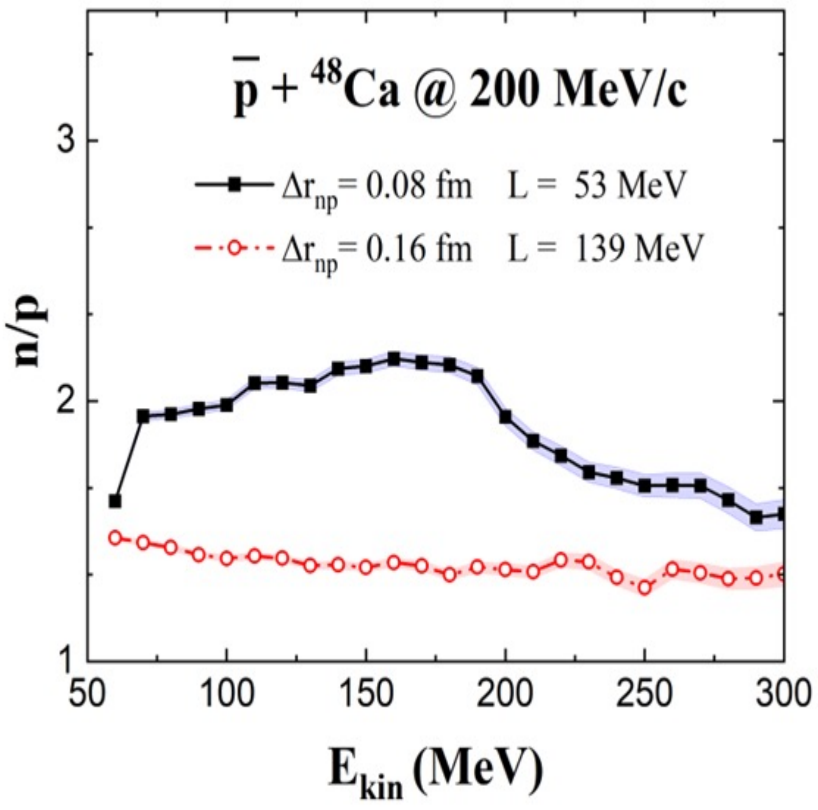
Ban Zhang and Zhao-Qing Feng, PRC 111, 014607 (2025)

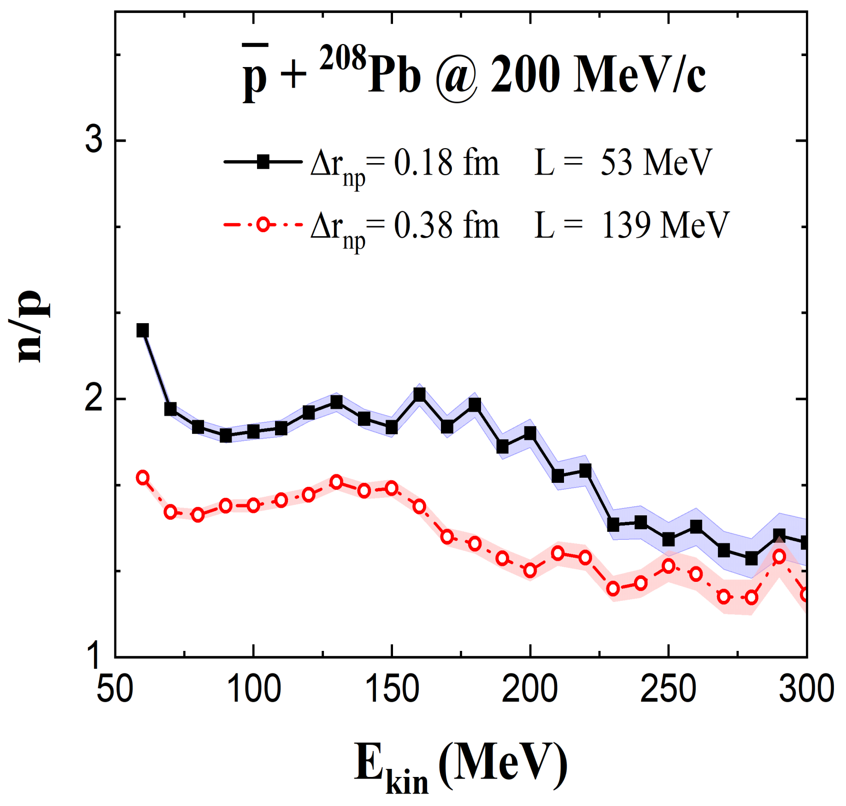
## antiproton-nucleus

The free n/p ratio as a function of incident momentum




The kinetic energy spectra of free n/p ratio



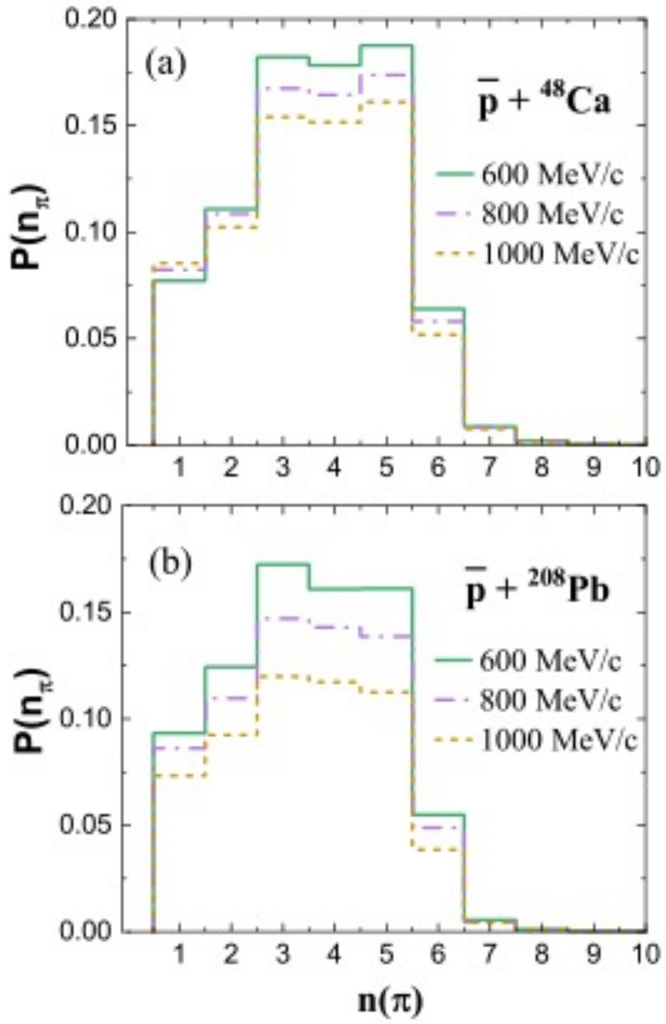



# Results and discussion

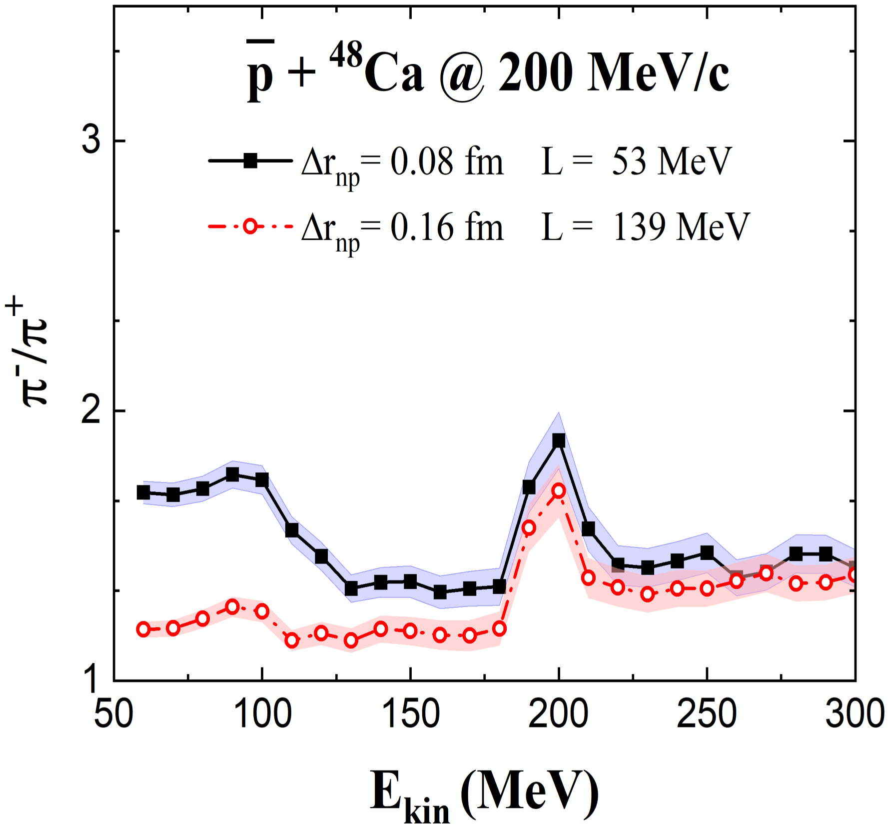
Ban Zhang and Zhao-Qing Feng, PRC 111, 014607 (2025)

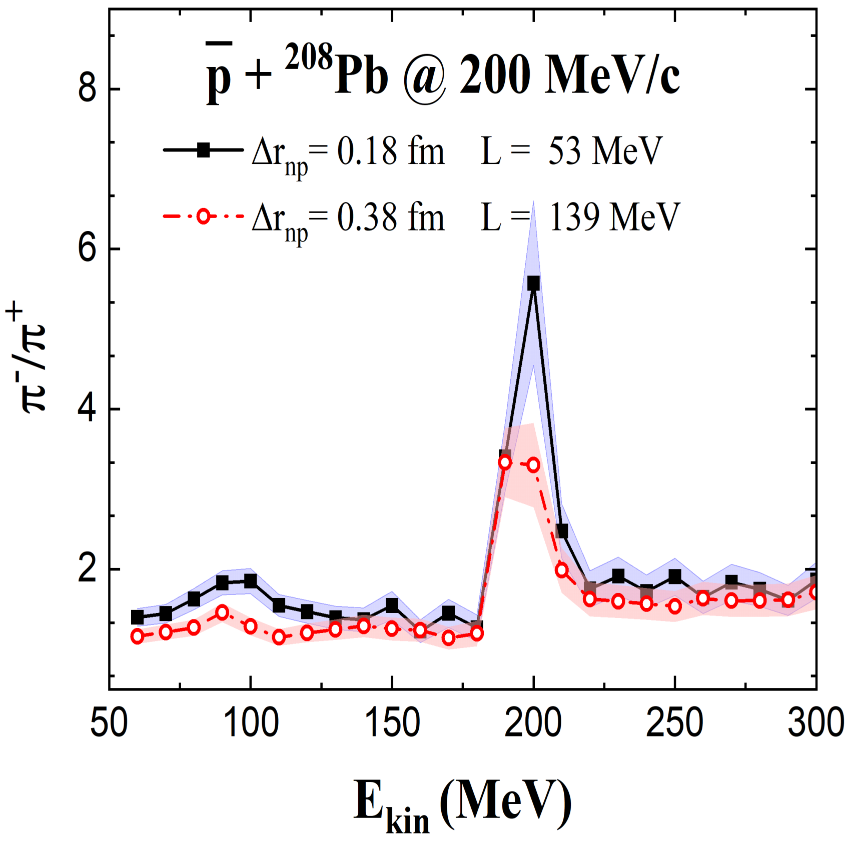
**antiproton-nucleus**

**Distribution of the pion numbers(2-8)**




**The kinetic energy spectra of π−/π+ ratio**



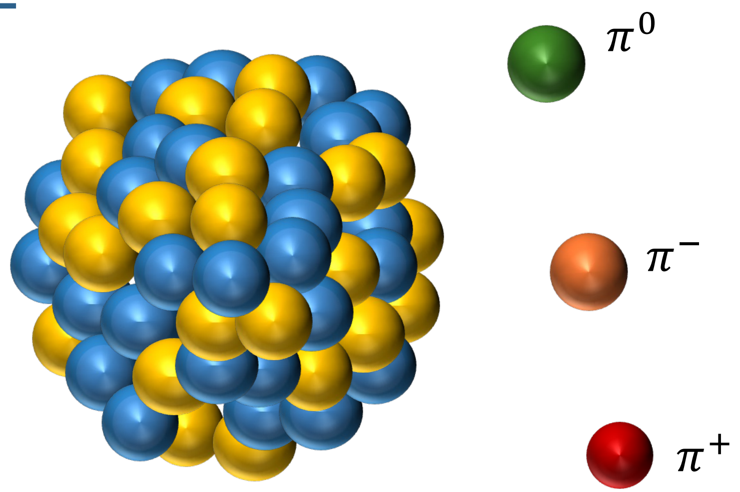
# Pion-nucleus collisions

Ban Zhang, Zhao-Qing Feng, arXiv:2505.02341, PRC (in review)

$\pi$ and resonances ($\Delta(1232)$, $N^*(1440)$, $N^*(1535)$) production:

$NN \leftrightarrow N\Delta$ ,  $NN \leftrightarrow NN^*$, $NN \leftrightarrow \Delta\Delta$, $\Delta \leftrightarrow N\pi$,

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




实验：pion工厂

Los Alamos Meson Physics Facility (LAMPF)
Paul Scherrer Institute (PSI)
Tri-University Meson Facility (TRIUMF)
superconducting kaon spectrometer (SKS)

理论:

BUU
Giessen BUU

**Pion-nucleus**

fast nucleon emission
particle evaporation
intermediate-mass fragments
fission

**Transport approach**—LQMD

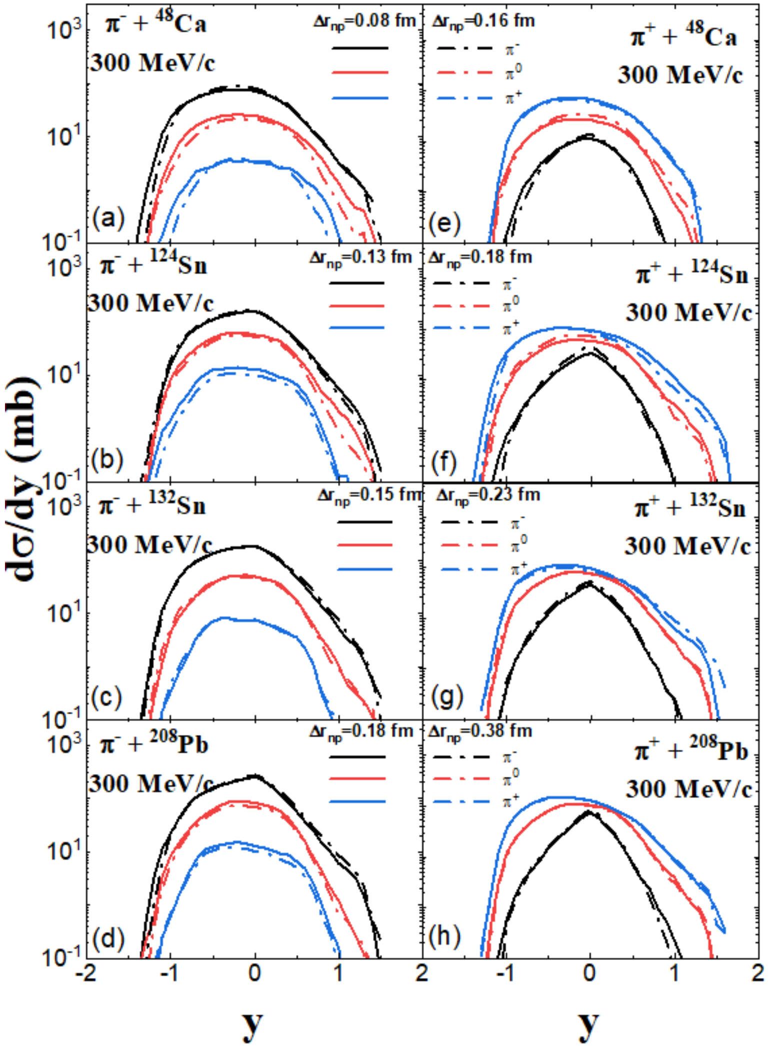
**Double charge exchange**

# Results and discussion

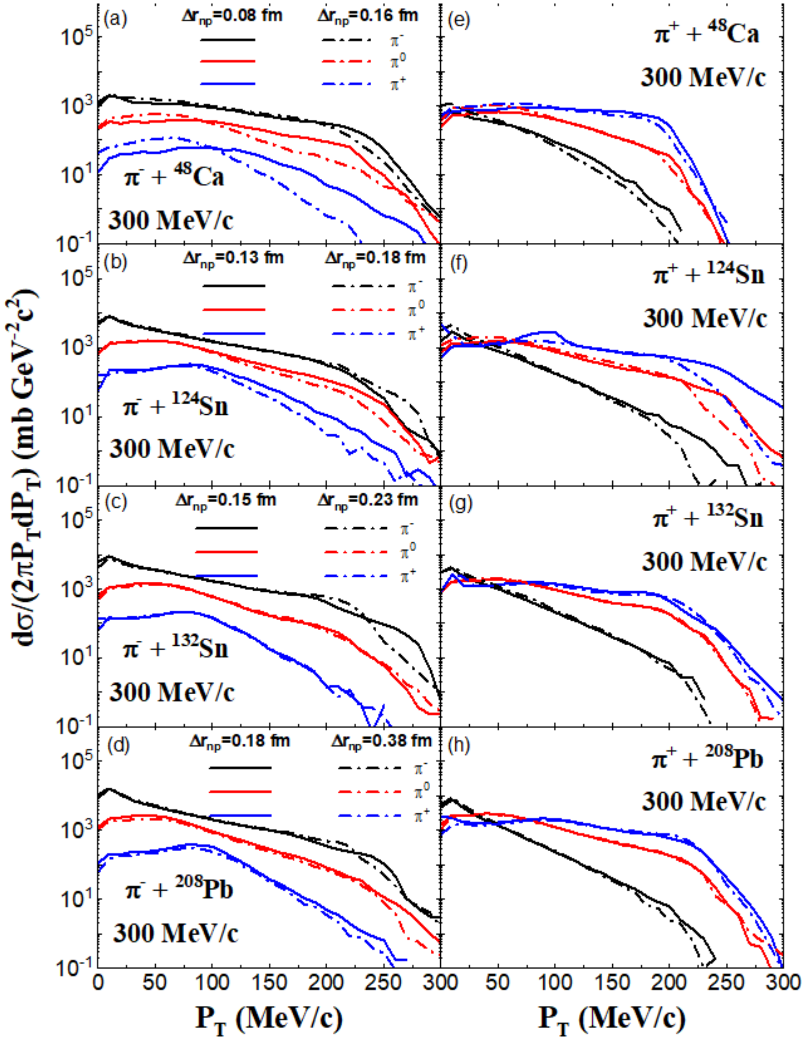
Ban Zhang, Zhao-Qing Feng, arXiv:2505.02341, PRC (in review)

**Pion-nucleus**

## Rapidity distributions



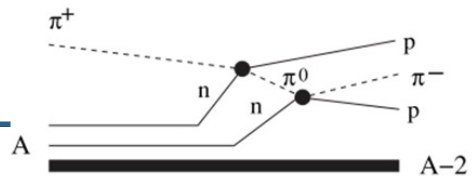

## Transverse momentum distributions



# Results and discussion

## Double charge exchange

### Pion-nucleus

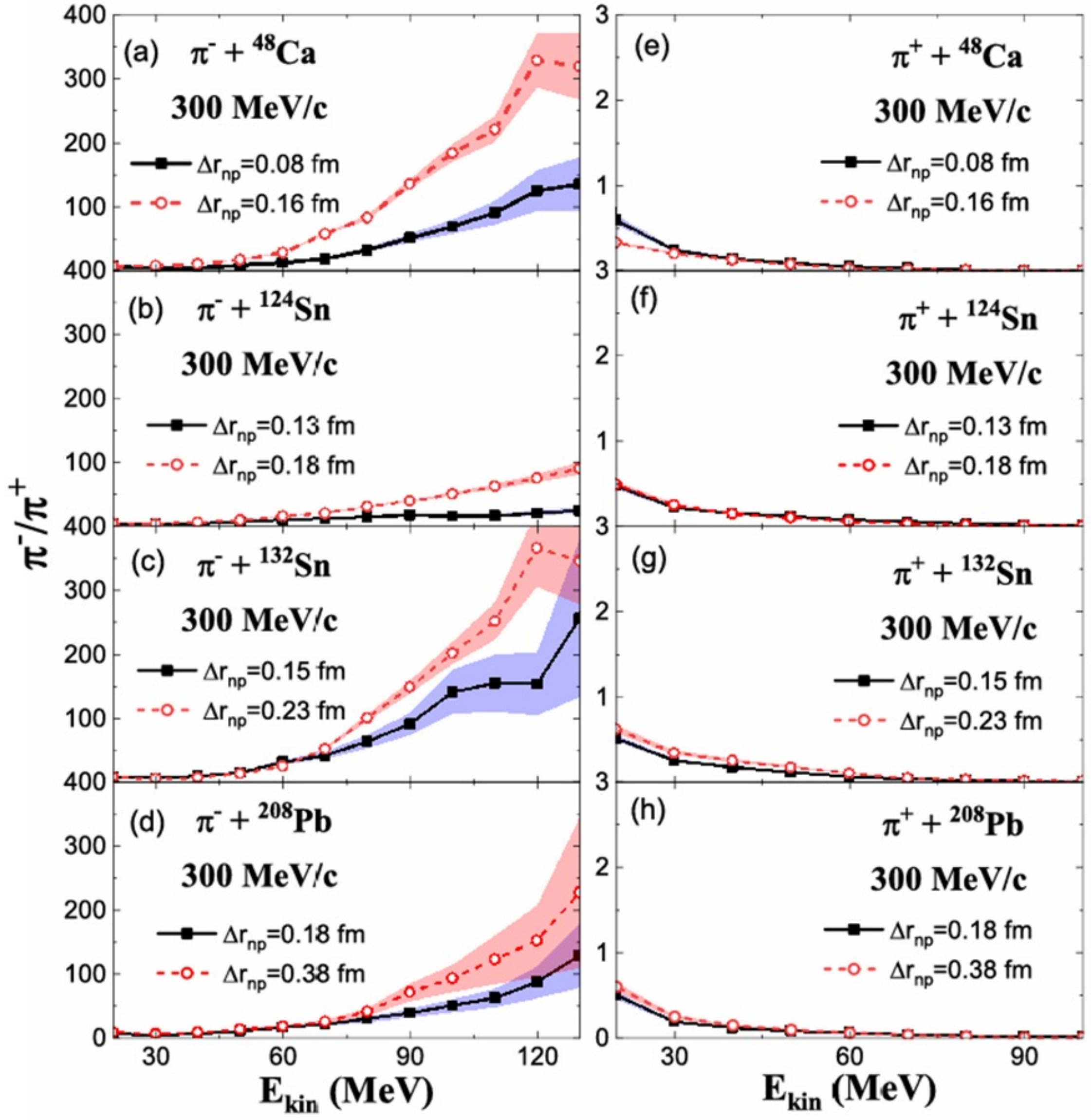


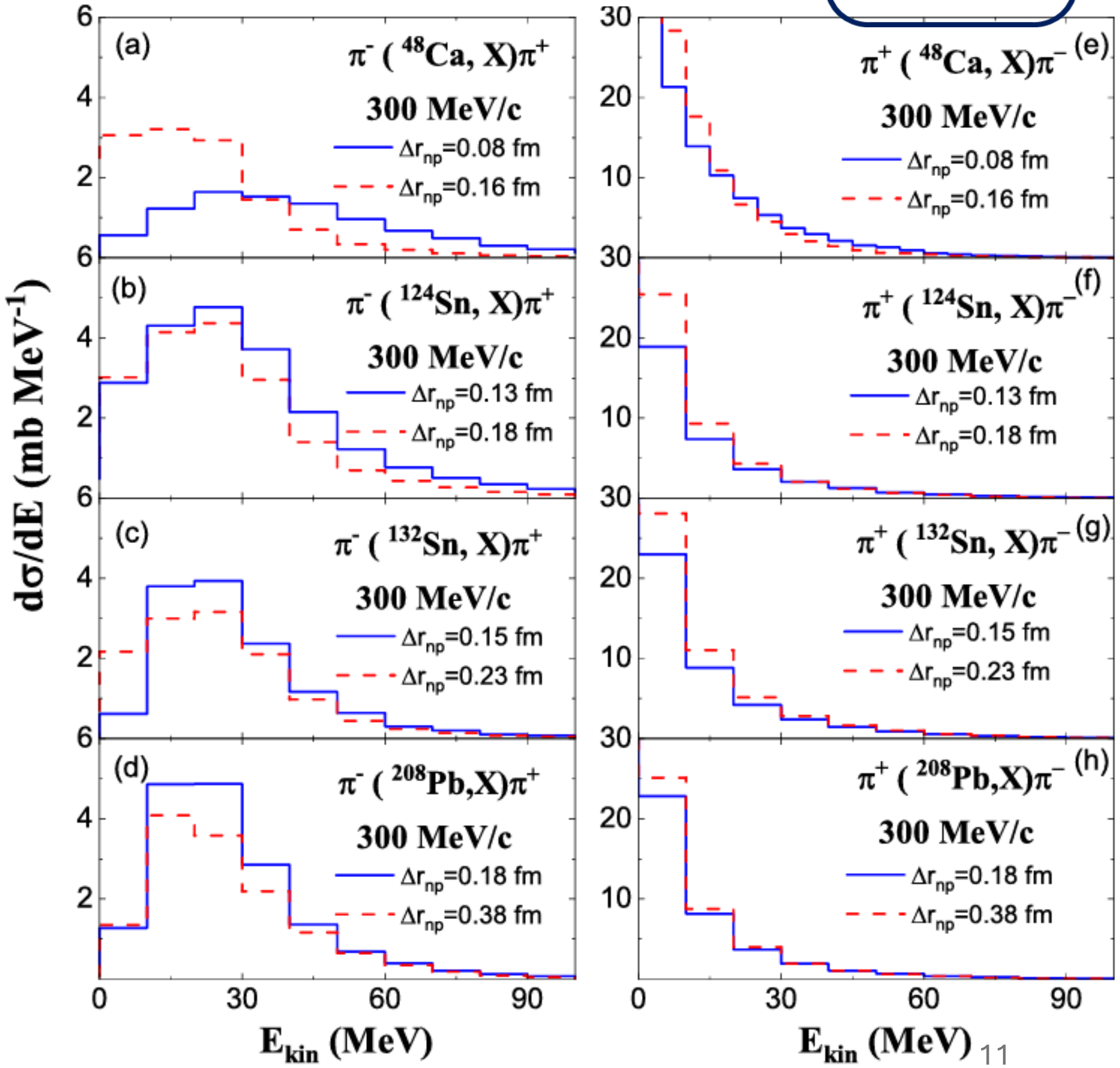

$\pi^- + p \rightarrow \Delta^0$

$\Delta^0 \rightarrow \pi^0 + n$

$\pi^0 + p \rightarrow \Delta^+$

$\Delta^+ \rightarrow \pi^+ + n$



# THANKS