Resolving the $\bar{p}$-Puzzle in High-Energy Heavy-Ion Collisions

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1.) Introduction

2.) Thermal $\bar{p}$-Production and Fugacities

3.) $\bar{p}p \to n\pi$ Annihilation

4.) $\bar{p}$-(Thermo-) Dynamics

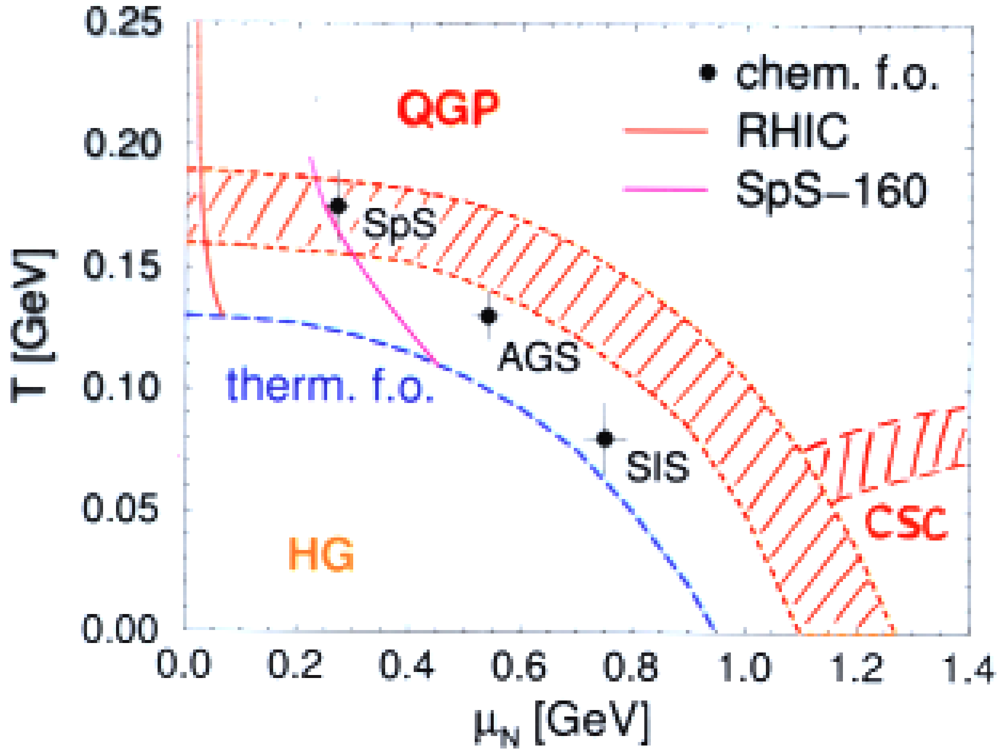
- SpS
- RHIC

5.) Summary

based on: R.R. + E.V. Shuryak, hep-ph/0008326

1.) Introduction I: Thermalization in URHIC's?

→ necessary to address phase diagram!



→ tested through consistent description of (all) observables

Evidences (SpS)

- Hadro-Chemistry, -Spectra, -Flow patterns

  'chem.' freezeout ⟹ 'therm.' freezeout

  $T_{ch} \simeq 170$ MeV   5-10 fm/c $T_{th} \simeq 120$ MeV

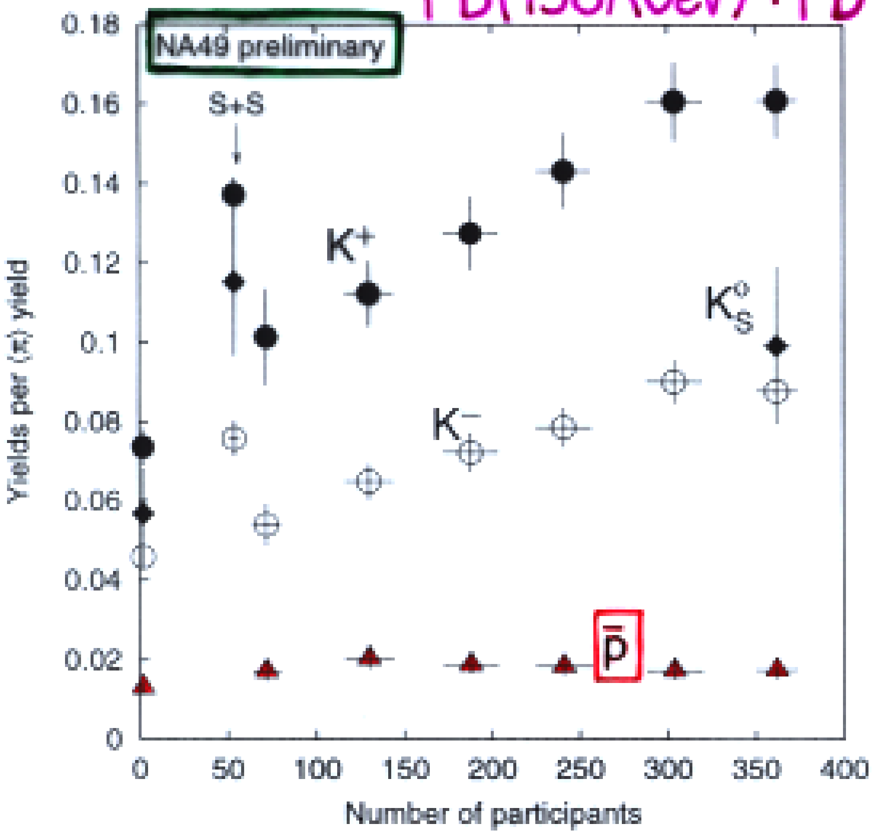
- Electromagnetic Probes
  - dilepton enhancement (thermal radiation) at $2m_\pi \leq M \leq m_{J/\Psi}$
  - direct photons

- J/Ψ suppression (⟺ thermal production at T_{ch} ?!)

Introduction II: Antiprotons

- QGP signature if $\bar{p}/p$-ratio exceeds chemical-equilibrium HG value [U. Heinz et al. '86, P. Koch et al. '88]
- in-medium dynamics of $p\bar{p}$ annihilation

Pb(158AGeV)+Pb



$$\frac{\bar{p}}{p} = (5.5 \pm 1)\%$$ [NA44]

consistent with chem. f.o.:

$$\frac{\bar{p}}{p} = \exp[-2\mu_N/T] \simeq 4.7\%$$

$T_{ch} \simeq 170$ MeV, $\mu_N^{ch} \simeq 260$ MeV

[Braun-Munzinger + Stachel, ...]

<u>however</u>: large $p\bar{p}$ annihilation Xsection in hadronic phase ($\sigma_{p\bar{p}}^{ann} \simeq 50-100$ mb)

<u>Explanation suggestions in transport calculations</u>:

- 'shielding' of annihilation [ARC '97]
- enhanced $\bar{p}$ production [UrQMD '00]

} <u>problem:</u> no backward reaction $n\pi \to p\bar{p}$

2.) Thermal $\bar{p}$-Production

Rate Equation for $p\bar{p} \leftrightarrow n\pi$

$$R_{th} = \int d^3\tilde{k}_p \, d^3\tilde{k}_{\bar{p}} \, d^3\tilde{k}_1 \cdots d^3\tilde{k}_n \, \delta^{(4)}(K) \, |M_n|^2 \left\{ z_\pi^n e^{-(\omega_1+\ldots+\omega_n)/T} - z_p z_{\bar{p}} e^{-(E_p+E_{\bar{p}})/T} \right\}$$

fugacities: $z_i = \exp(\mu_i/T)$

chemical relaxation time:

$$R_{th} = \frac{d\varrho_{\bar{p}}}{dt} \simeq \frac{\varrho_{\bar{p}}}{\tau_{\bar{p}}^{chem}} \left(\frac{z_\pi^n}{z_p z_{\bar{p}}} - 1 \right)$$

$$\tau_{\bar{p}}^{chem} = \frac{1}{\sigma_{p\bar{p}}^{ann}(E_p^{th}) \, v_{th} \, \varrho_B} \simeq 3\,\mathrm{fm/c} \lesssim \tau_{FB} \qquad \left\{ \begin{array}{l} \sigma_{p\bar{p}}^{ann} \simeq 50\,\mathrm{mb}, \; E_p^{th} \simeq \frac{3}{2} kT \\ \varrho_B \simeq \frac{3}{4}\varrho_0 , \; T = 150\,\mathrm{MeV} \end{array} \right.$$

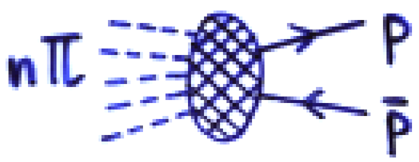
$\Rightarrow$ $\bar{p}B \leftrightarrow n\pi$ stays in chemical equilibrium !

at thermal freezeout:

$$\left. \begin{array}{l} \mu_B^{th} \simeq 400\,\mathrm{MeV} \\ T_{th} \simeq 120\,\mathrm{MeV} \end{array} \right\} \quad \frac{\bar{p}}{p} = \frac{z_{\bar{p}}}{z_p} = e^{-2\mu_N/T} \simeq 0.1\,\% \quad !$$

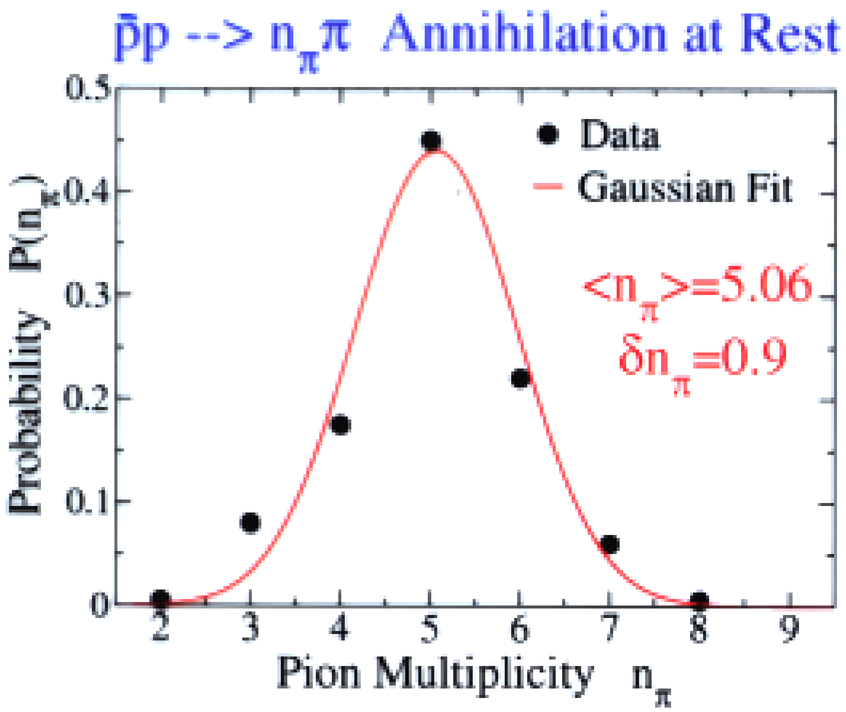
but: π-number $\sim$ conserved from $T_{ch} \to T_{th}$ $\left(\tau_\pi^{chem} \gg \tau_{FB}\right)$

$\Rightarrow$ build up finite μ_π, enters with large power



enhanced by $\boxed{z_\pi^n = e^{n\mu_\pi/T}}$

3.) Features of $\bar{p}p \to n\pi$



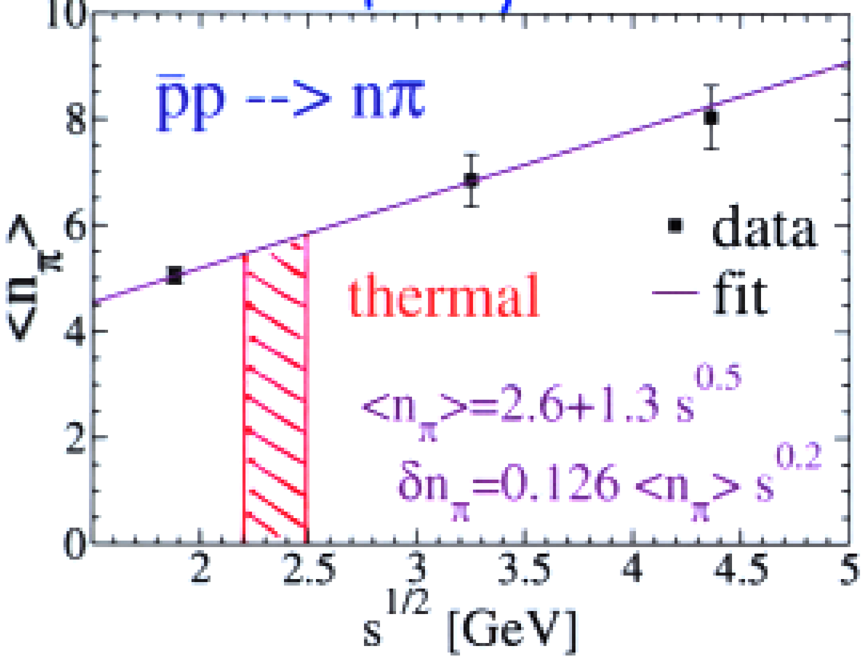
Pion Multiplicities

→ Gaussian

$$P(n_\pi) = \frac{1}{\sqrt{2\pi}\,\delta n_\pi} \exp\left[-\frac{(n_\pi - \langle n_\pi\rangle)^2}{2\delta n_\pi^2}\right]$$

Energy Dependence

Multiplicity



total Ann.-Xsection

$$\sigma^{ann}_{\bar{p}p} \simeq \left(\frac{40}{P_{lab}^{0.5}} + \frac{24}{P_{lab}^{1.1}}\right) \text{mb}$$

↳ thermal enhancement factor

$$\langle Z_\pi^n \rangle = \sum_n P(n)\, e^{n\mu_\pi/T}$$

4.) $\bar{p}$ - Thermodynamics at SpS

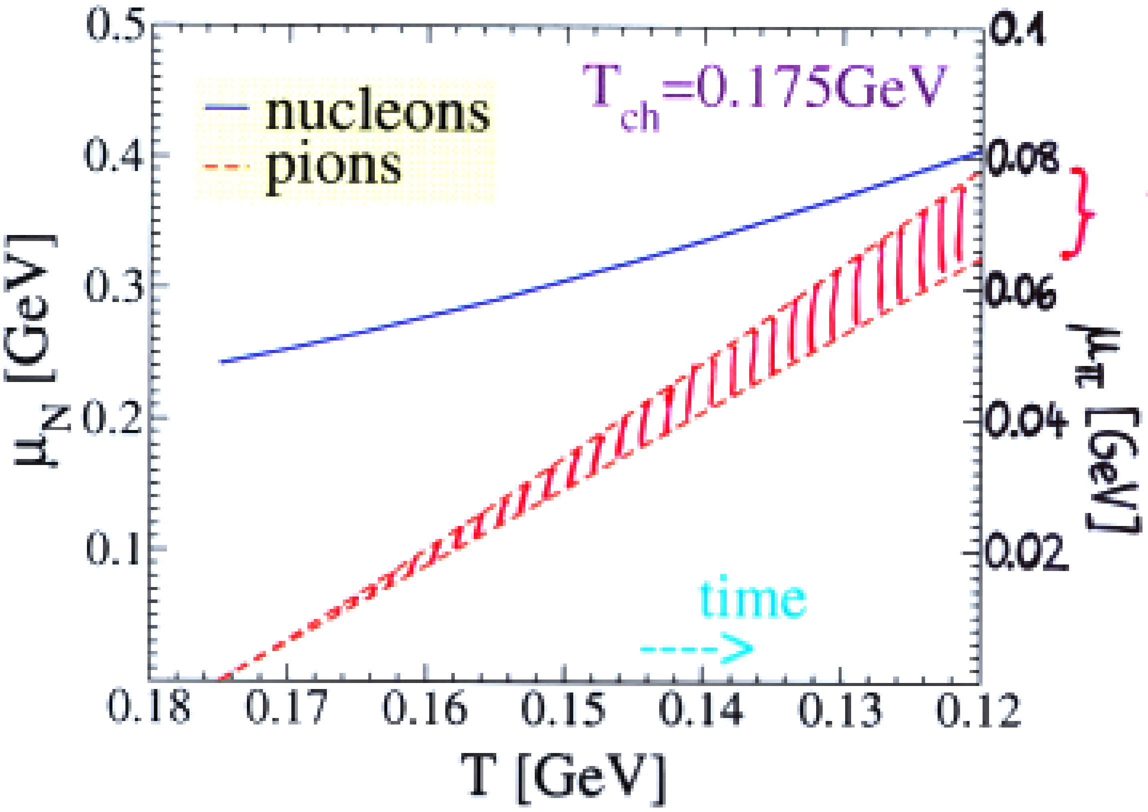
$$R_{\bar{p}} = \int |M_n|^2 \left\{ \langle z_\pi^n \rangle e^{-(\omega_1+\ldots+\omega_n)/T} - z_p z_{\bar{p}} e^{-(E_p+E_{\bar{p}})/T} \right\} \delta^{(4)}(\ldots)$$

$$\simeq \left\{ \langle z_\pi^n \rangle - z_p z_{\bar{p}} \right\} I_0(T)$$

equilibrium: $z_p z_{\bar{p}} = \langle z_\pi^n \rangle$

$$\boxed{z_{\bar{p}} = \frac{\langle z_\pi^n \rangle}{z_p}}$$

μ_π, μ_N determined by (isentropic) fireball expansion (resonance HG EoS)

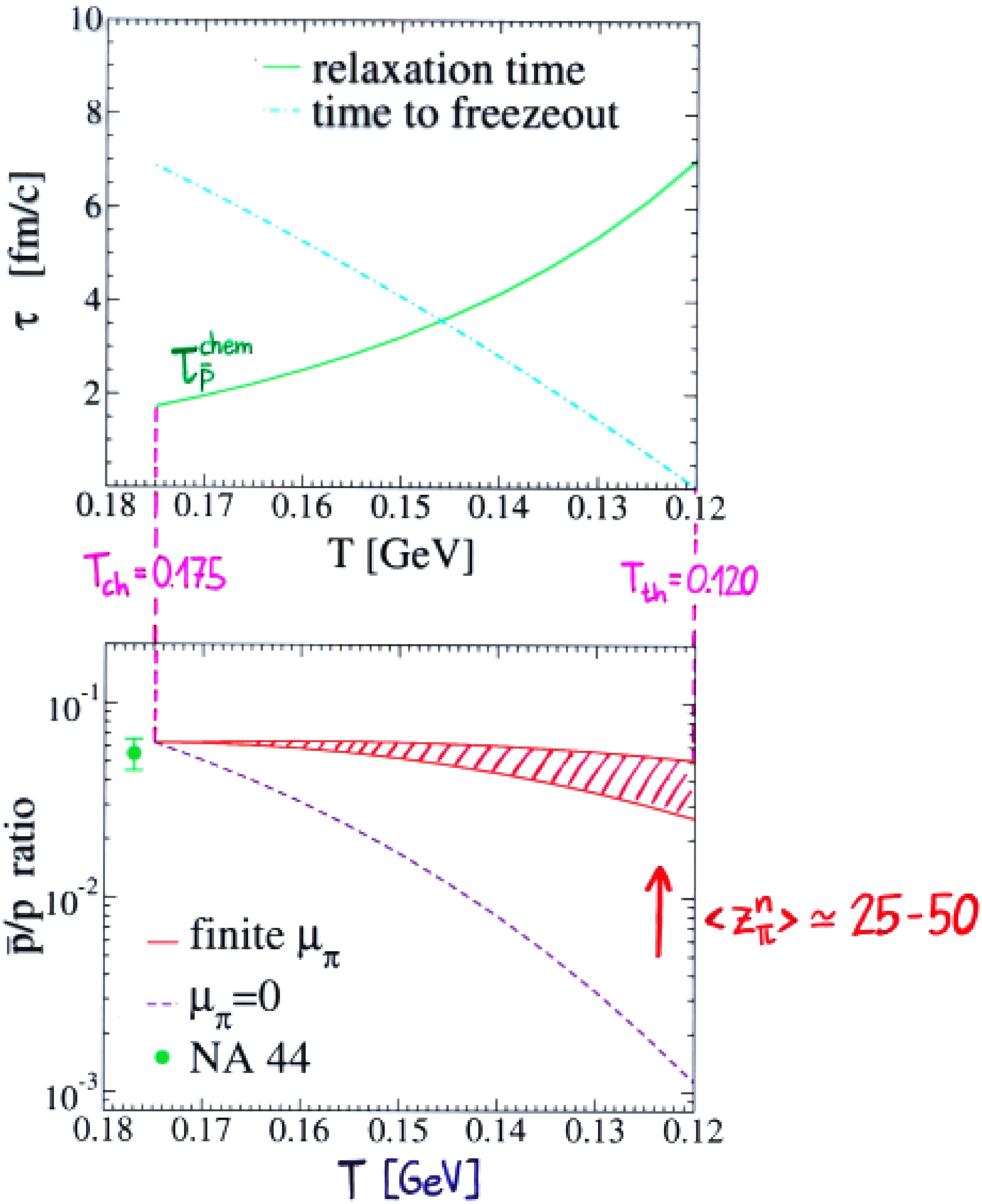


$\mu_\pi(T_{th}) \simeq$ (65-80) MeV

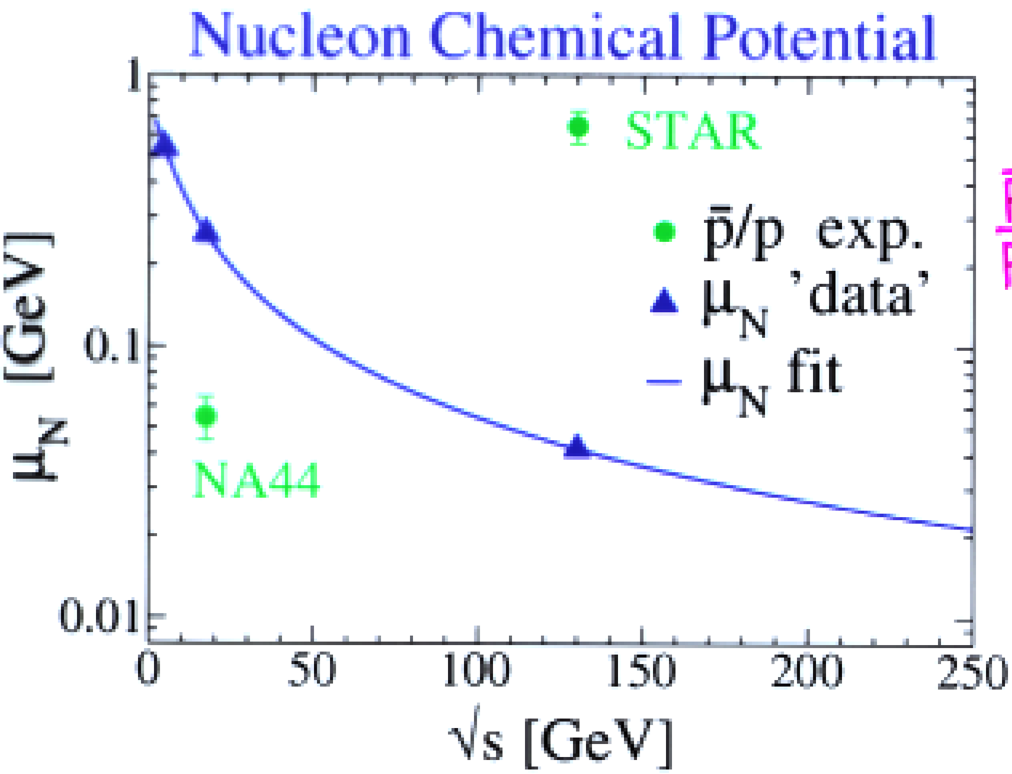
$$\Rightarrow \boxed{\bar{p}/p = \exp[-2\mu_N/T] \, \langle z_\pi^n \rangle}$$

Thermal Antiproton Dynamics at SpS Energies

Central Pb(158AGeV) + Pb



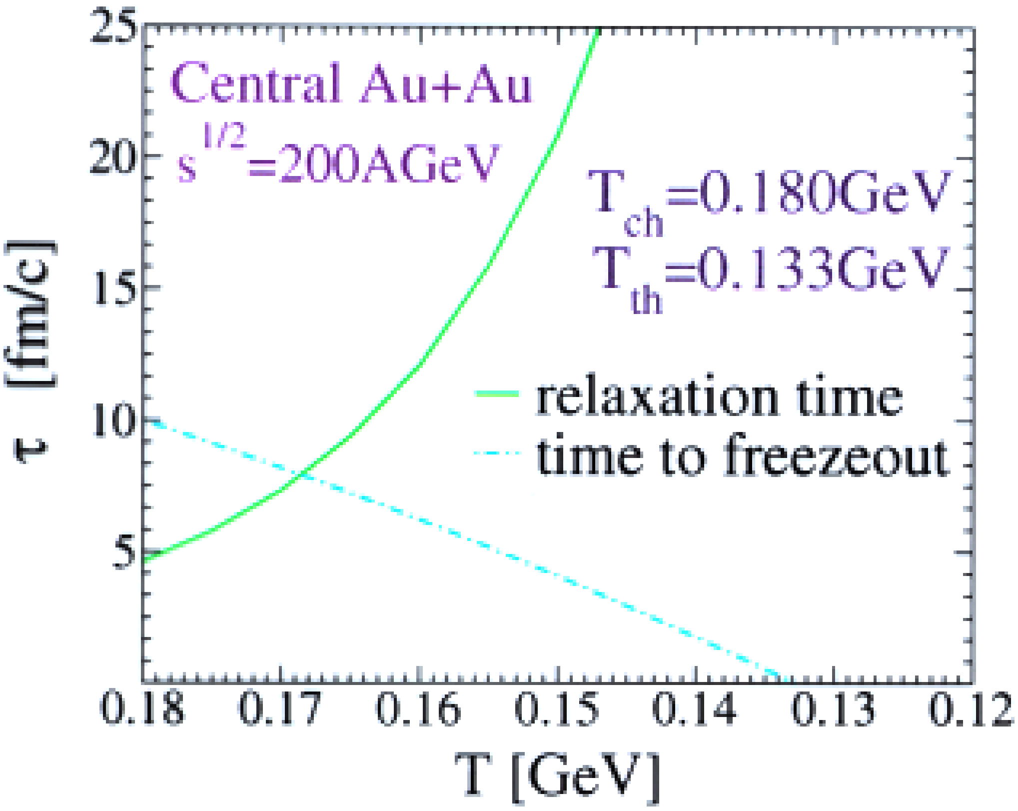
$\bar{p}$ - Thermodynamics at RHIC Energies



$\sqrt{s} = 130$ AGeV:

$\frac{\bar{p}}{p} = (65 \pm 3 \pm 6)\%$ [STAR]

$\Rightarrow \mu_N^{ch} \simeq 40$ MeV



$\mu_\pi^{th} \simeq 10$ MeV

$\frac{\bar{p}}{p} \simeq 75\%$ (~const)

5.) Summary

- $\bar{p}$ - Puzzle at SpS (partially) resolved by backward channel in $p\bar{p} \leftrightarrow n\pi$ ⊕ finite μ_π (centrality dependence ≃ const, following hadro-chemistry)

- Medium effects in $\sigma_{\bar{p}p\to n\pi}$ ('shielding', ...) neither needed nor excluded

- **RHIC**: much longer chemical-equilibration times
  ⇒ $\frac{\bar{p}}{p}$ - ratio more direct reflection of chemical freezeout

- Anti-Hyperons → C. Greiner - talk