# Reminder of the **Excluded Volume Effects** at the Chemical Freeze-out

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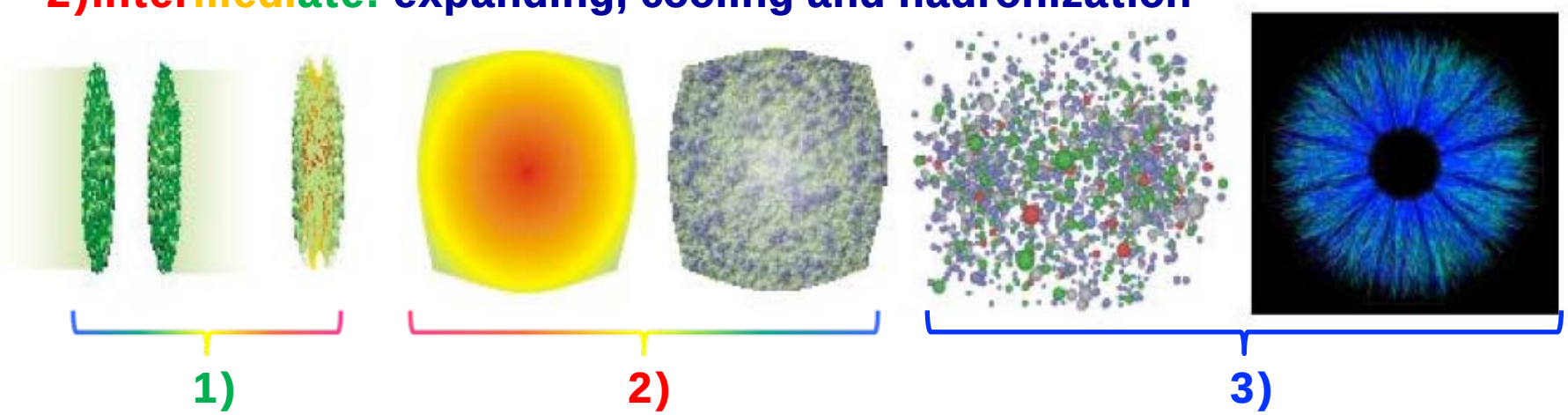
# Motivation

**Each high energy heavy ion collision pass three main stages:**

**1)initial: individual collisions merge and form a new state of matter, probably Quark Gluon Plasma**

**2)intermediate: expanding, cooling and hadronization**

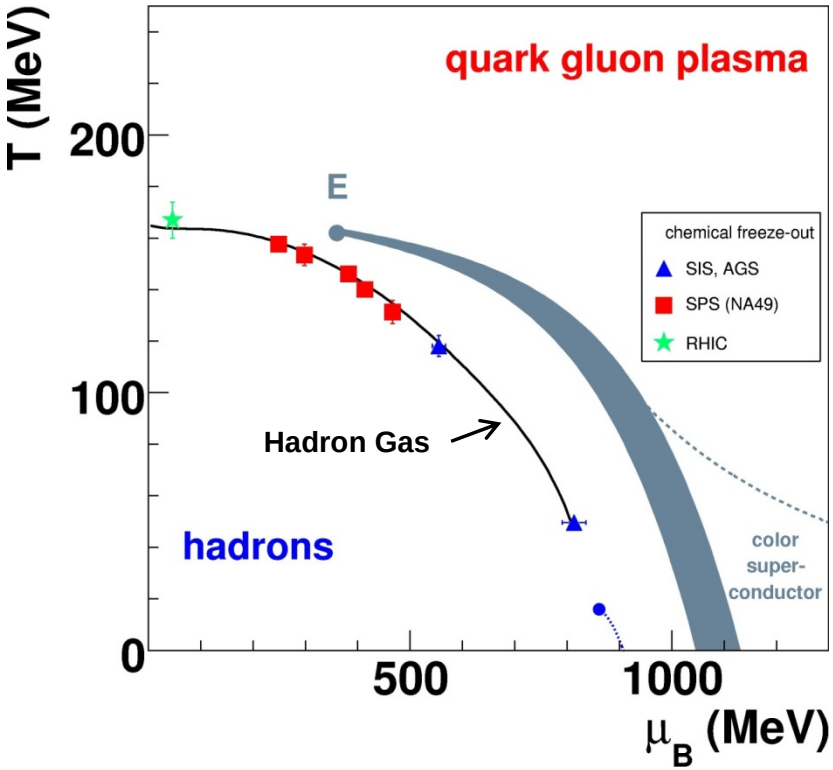


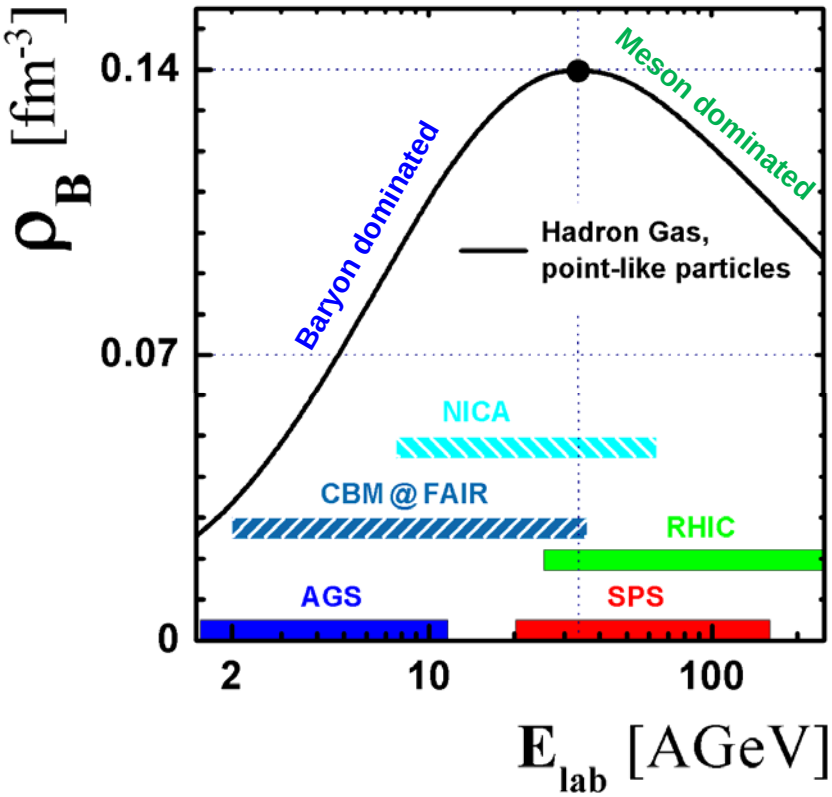

**3)final: particle composition and moments “freeze”, free particles fly to detectors**

**We take into account proper volume of particles in the Hadron Gas model of the final stage for more realistic estimation of the achieved densities**

# Motivation

**Hadron Gas model allows to connect the results of different experiments by the Freeze-out line $T(\mu_B)$**

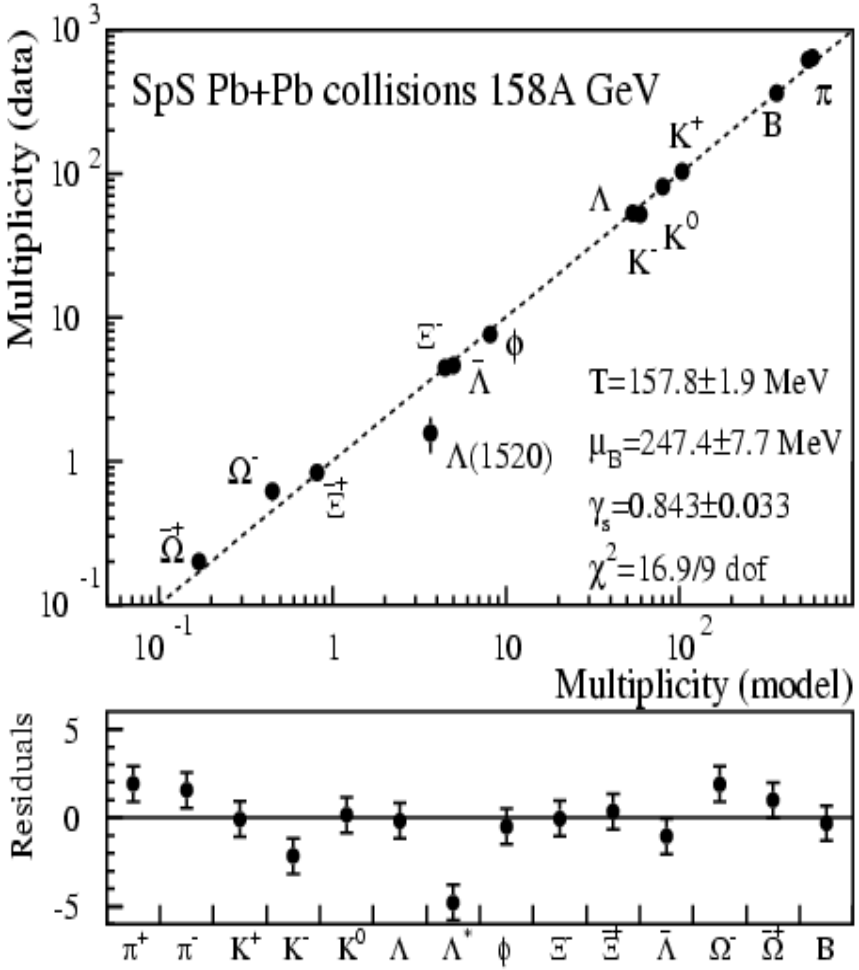



**The maximum in baryon density and the exact point of the transition from baryon to meson domination may depend on excluded volume**

**New accelerators are constructed to study Compressed Baryonic Matter**

# Hadron Gas model



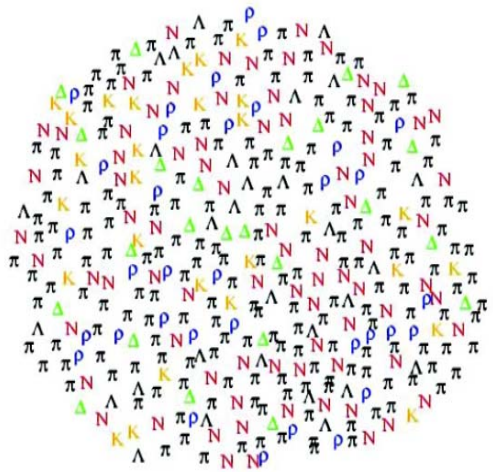

Becattini, Gazdzicki, Keranen, Manninen, Stock, PRC 2004

$$\langle N_i \rangle \equiv \sum_{\mathbf{p}} \langle n_{\mathbf{p},i} \rangle \simeq \frac{g_i V}{2\pi^2} \int_0^\infty p^2 dp \, \langle n_{p,i} \rangle \, ,$$

$$\langle N^+ \rangle = \sum_{i, q_i > 0} \langle N_i \rangle \, ,$$

$$\langle n_{\mathbf{p},i} \rangle = \frac{1}{\exp\left[\left(\sqrt{\mathbf{p}^2 + m_i^2} - \mu_i\right)/T\right] - \gamma_i} \, ,$$

$$\mu_i = q_i \, \mu_Q + b_i \, \mu_B + s_i \, \mu_S ,$$



$Q/B = 0.4 \Rightarrow \mu_Q(T, \mu_B)$

$S = 0 \Rightarrow \mu_S(T, \mu_B)$

# Excluded Volume Effects, Density

$$V - \sum_i v_i \cdot N_i$$

**Particle volume**

$$v_i = 4 \cdot \frac{4}{3} \pi r_i^3$$

**Density**

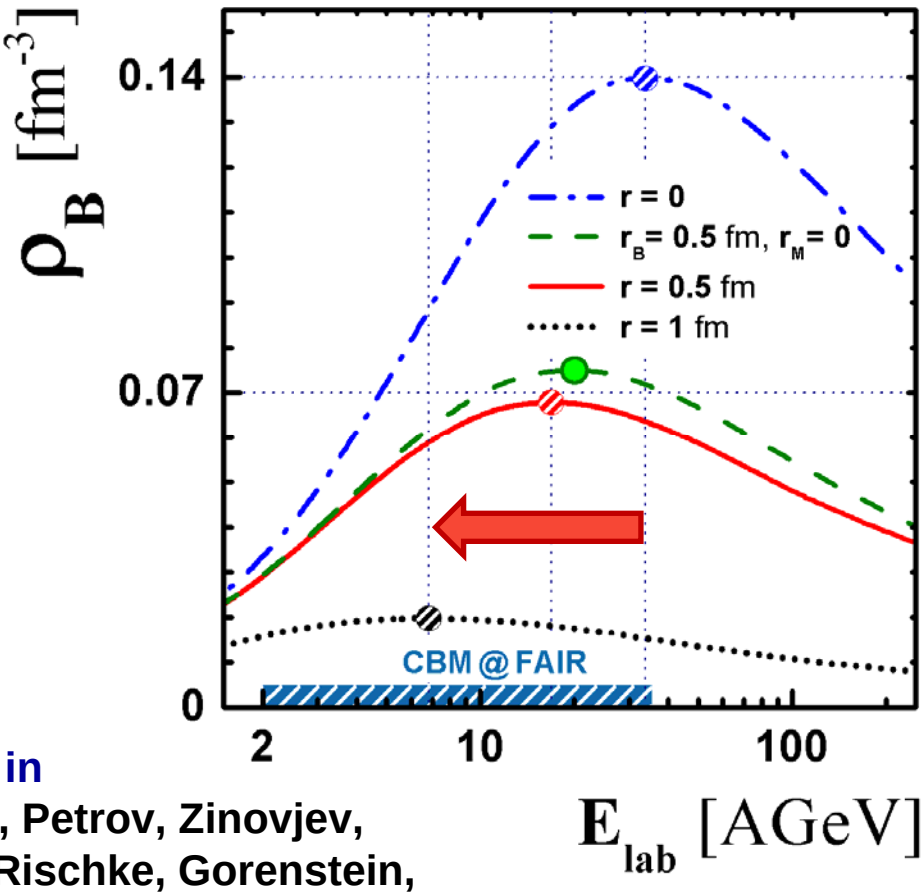
$$n_i = \frac{n_i^{id}(T, \tilde{\mu}_i)}{1 + \sum_i v_i \, n_i^{id}(T, \tilde{\mu}_i)}$$

**Chemical potential**

$$\tilde{\mu}_i = \mu_i - v_i \, p$$

**Pressure**

$$p = \sum_i p_i^{id}(T, \tilde{\mu}_i)$$

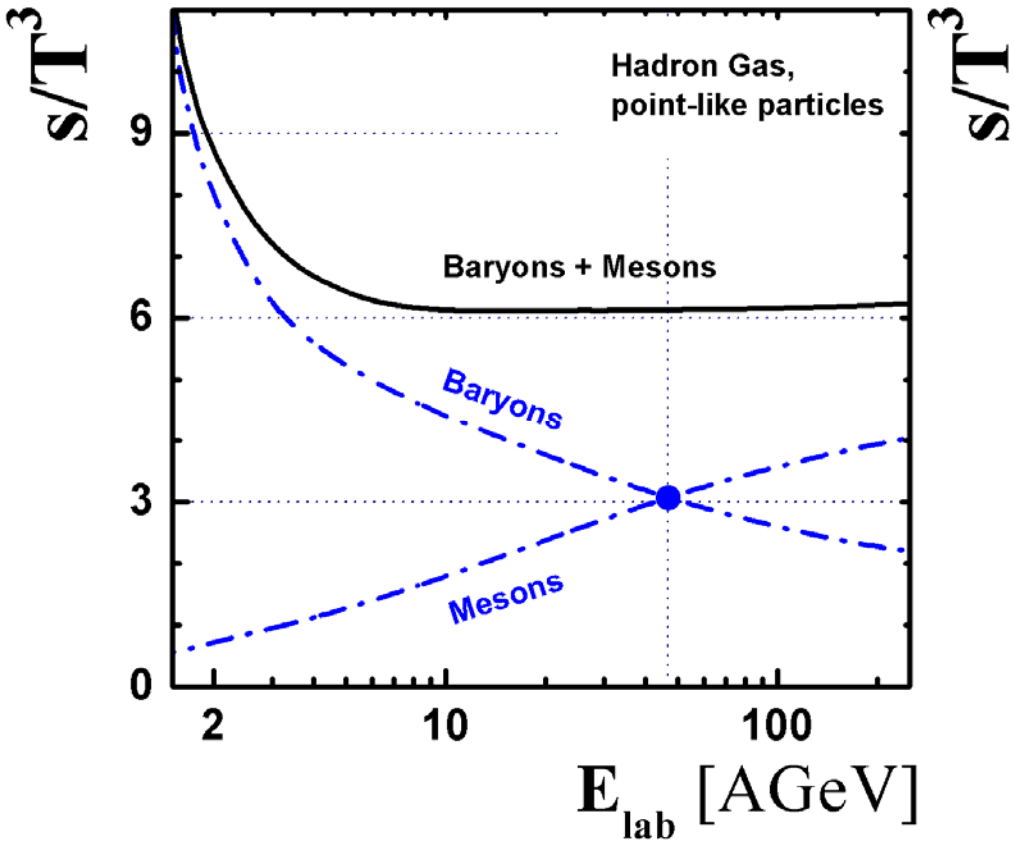


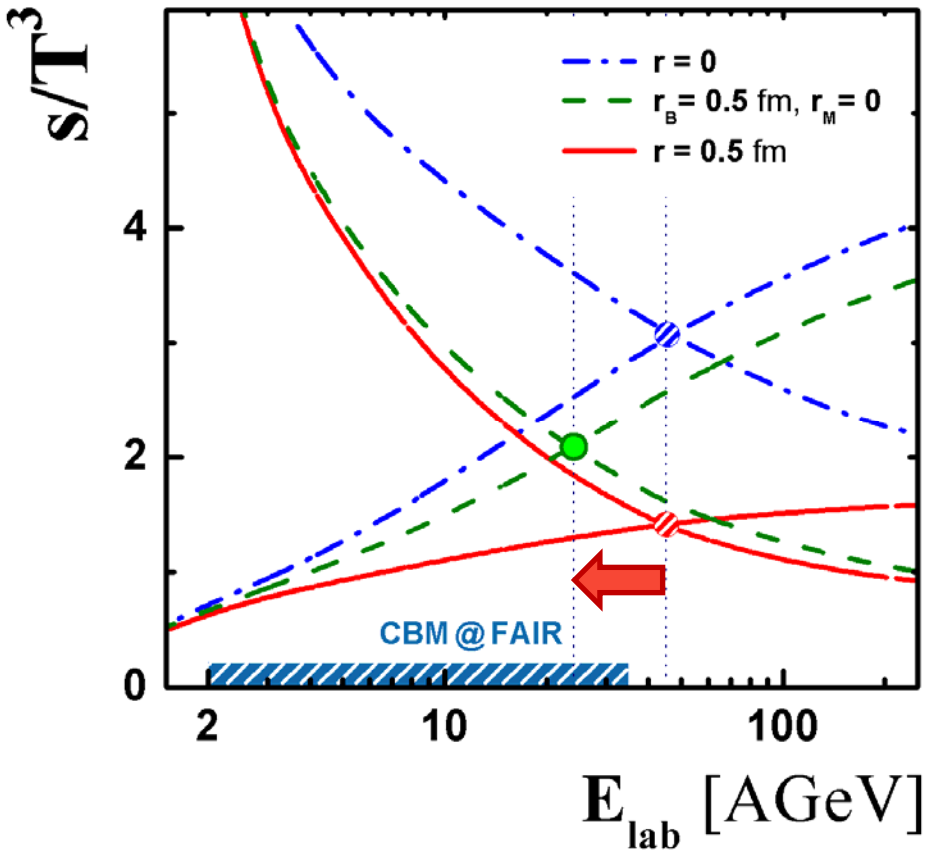

**Introduced in**
Gorenstein, Petrov, Zinovjev, PLB 1981; Rischke, Gorenstein, Stocker, Greiner, ZPC 1991

**Implemented in THERMUS:** Wheaton, Cleymans, Comput. Phys. 2009 [hep-ph/0407174]

**Begun, Gazdzicki, Gorenstein, in preparation**

# Excluded Volume Effects, Entropy



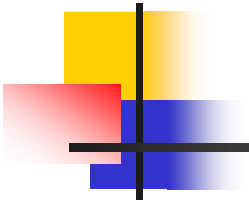




**The transition point of baryon / meson domination moves to lower energies only for different meson and baryon radiuses**

**Begun, Gazdzicki, Gorenstein, in preparation**

# Conclusions:

- Excluded Volume effects lead to smaller particle number and entropy densities
- The position of the density maximum moves to lower energies
- The transition point from baryon to meson domination lies at higher energies than density maximum
- The transition point moves to lower energies only for different meson and baryon radiuses in the system

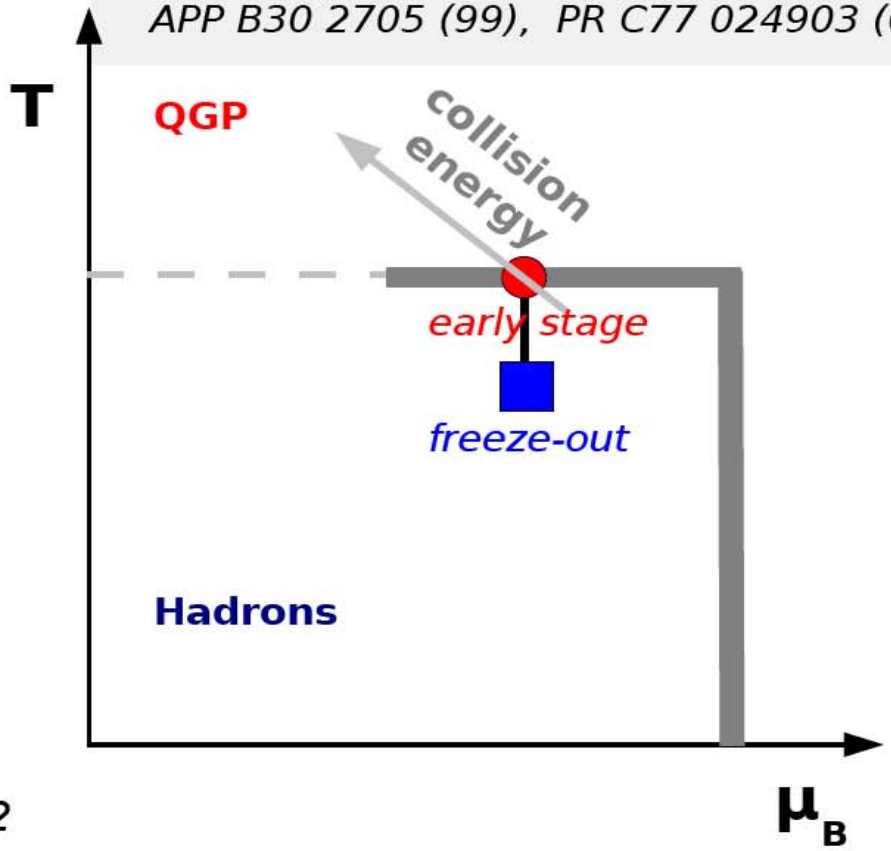


# Extra Slides

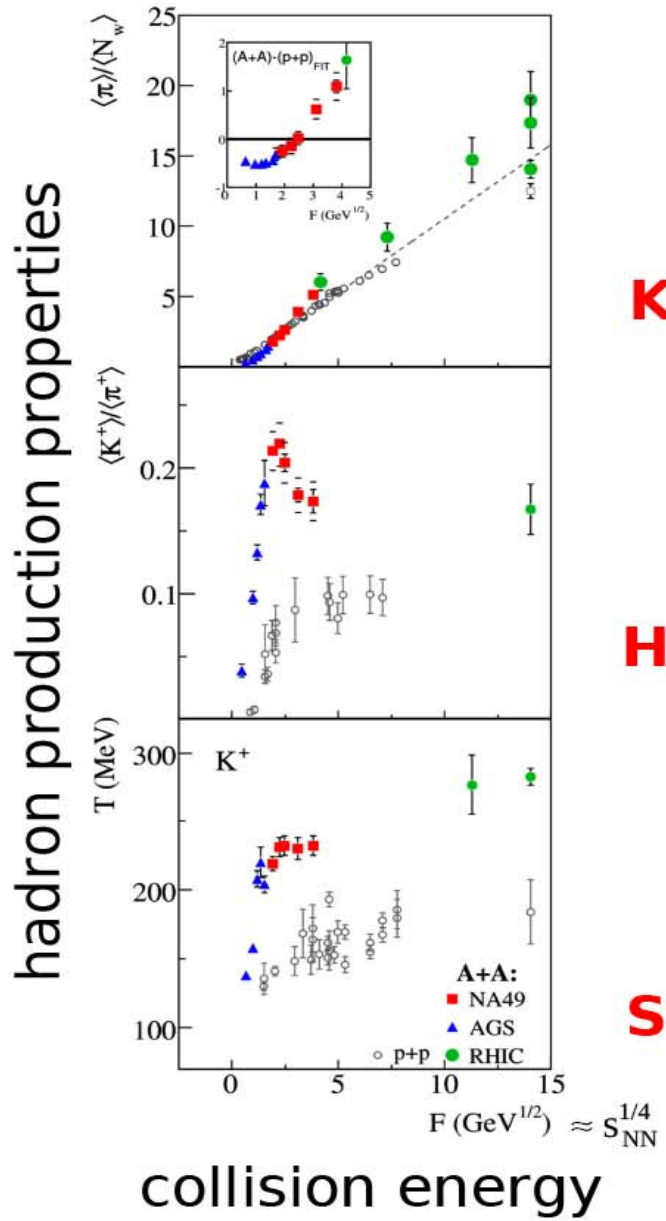
# Onset of deconfinement: NA49 evidence in single particle yields and spectra

**Onset of Deconfinement:**
**early stage hits transition line,**
**observed signals: kink, horn, step**

*Predictions SMES:* *Results:*
*APP B30 2705 (99), PR C77 024903 (08)*




AGS SPS RHIC ..LHC




**Kink**

**Horn**

**Step**



slide from M. Gazdzicki talk at QM 2011