# STRANGENESS AND THE DISCOVERY OF QUARK GLUON PLASMA

Bloomington, November 30, 2004

**Deconfinement of quarks and gluons into a plasma (QGP) at high temperature is a predicted paradigm shifting feature of strong interactions. The production of strange particles in relativistic heavy ion collisions at CERN and BNL confirms that a new phase of matter with the expected properties is being formed. I will survey the key theoretical predictions and the related experimental results. Time permitting, I will discuss how the newly gained knowledge leads to the study of the hot nearly matter-antimatter symmetric post quark-gluon Universe. +50% of content is for STUDENTS.**

**BONUS material after 50 transparencies: THE QUARK UNIVERSE**

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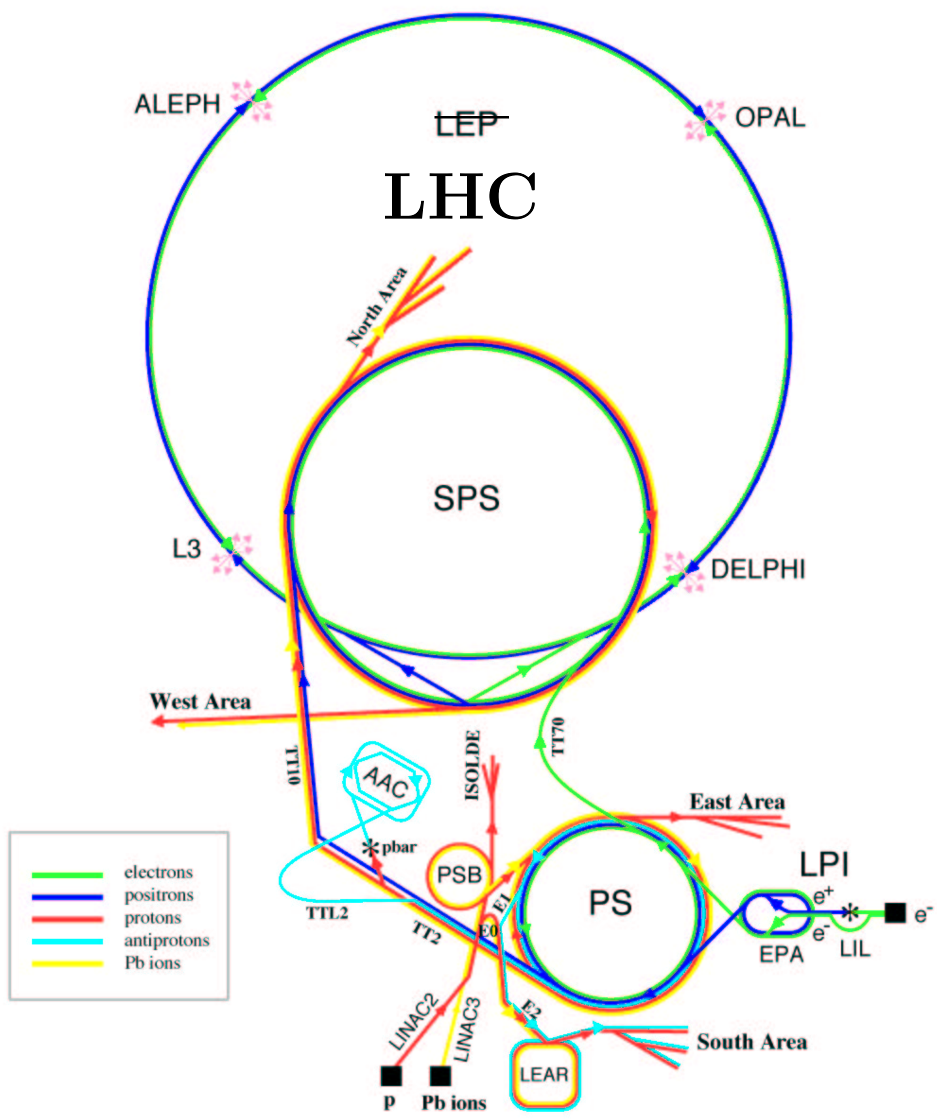
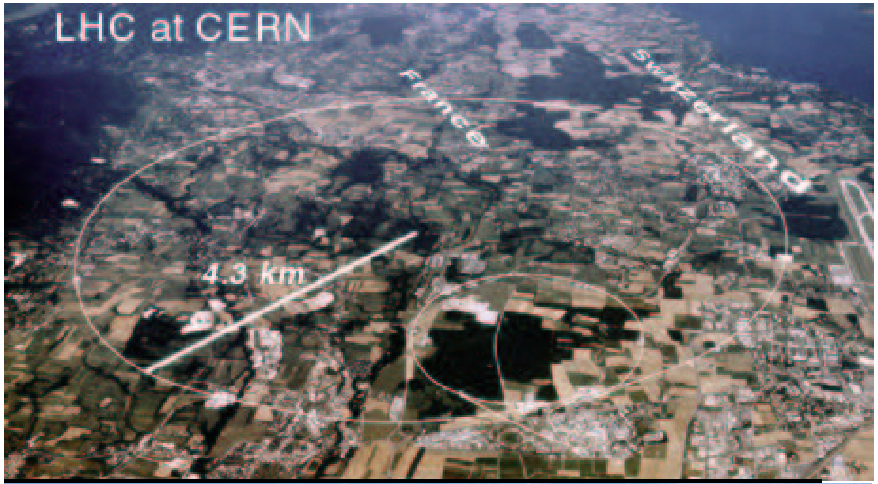
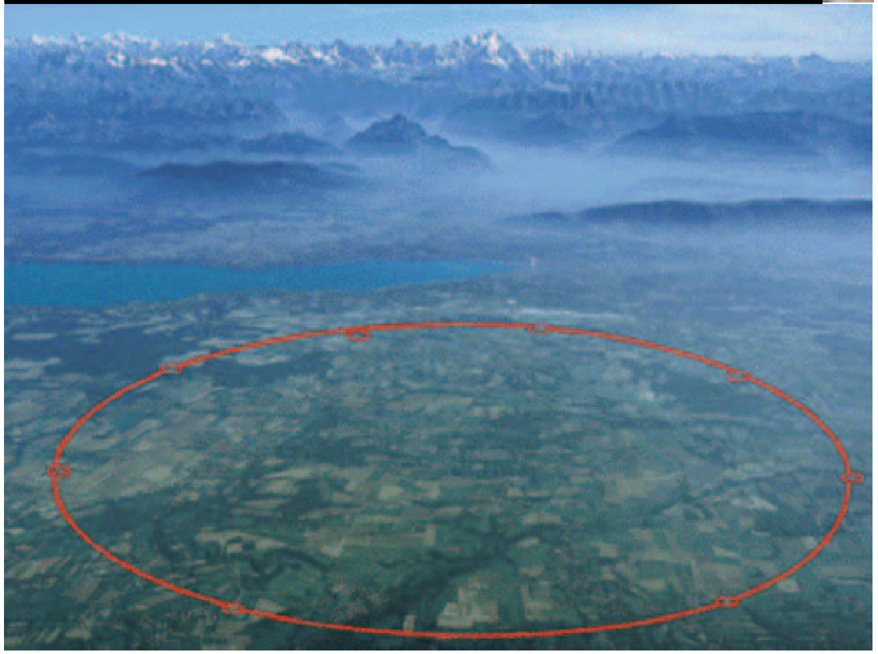
# EXPERIMENTAL HEAVY ION PROGRAM





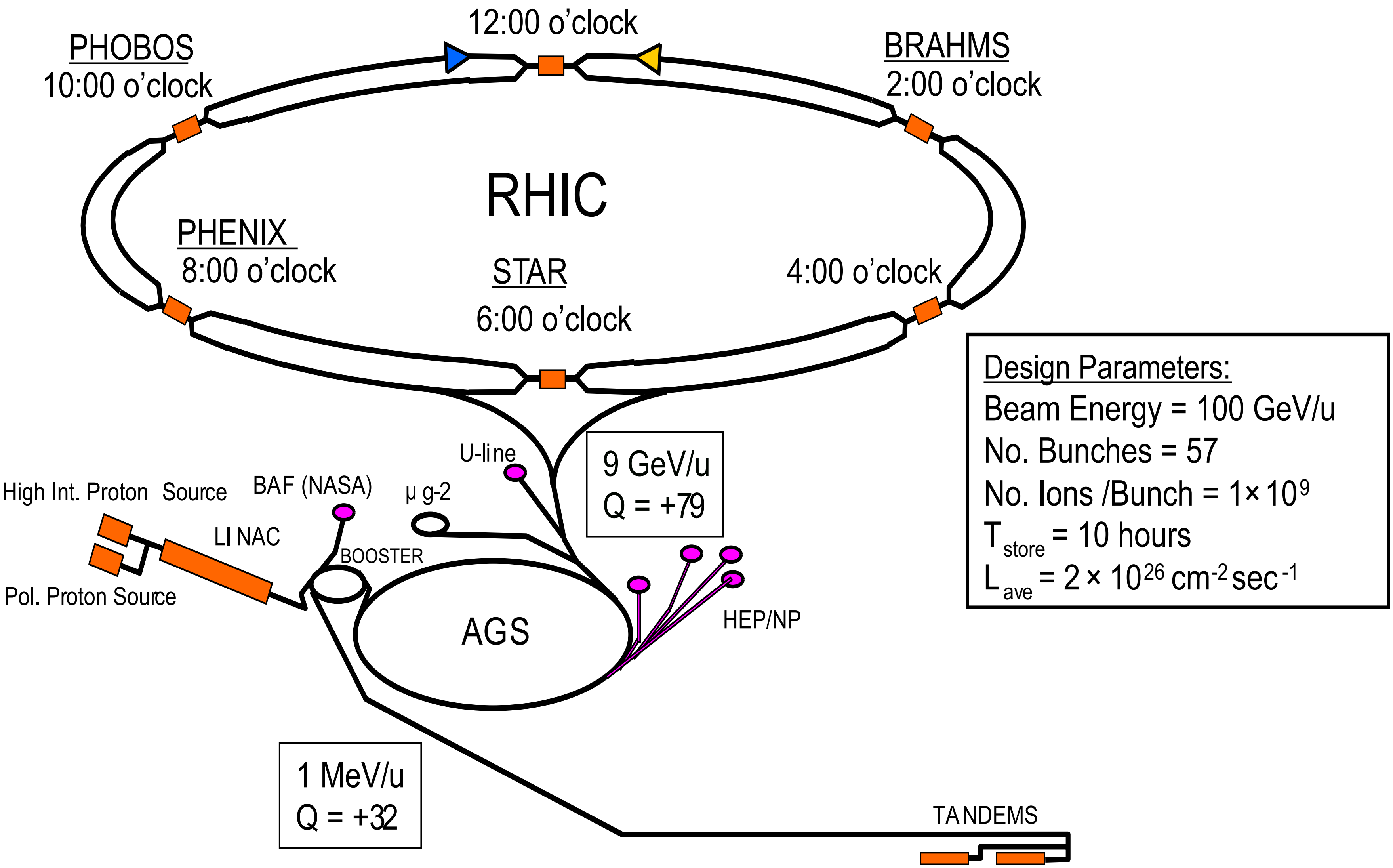


**CERN: LHC opens after 2007 and SPS resumes after 2009**

# ...and at BROOKHAVEN NATIONAL LABORATORY

Relativistic Heavy Ion Collider: RHIC

# BROOKHAVEN NATIONAL LABORATORY



**Design Parameters:**

Beam Energy = 100 GeV/u

No. Bunches = 57

No. Ions /Bunch = $1\times10^{9}$

$T_{store}$ = 10 hours

$L_{ave} = 2\times10^{26}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$

## Relativistic Heavy Ion Collider: RHIC

# The origin of this research program

## STRUCTURED VACUUM:

**Melt the vacuum structure and demonstrate mobility of quarks – ‘deconfinement’. This demonstrates that the vacuum is a key component in the understanding of what we observe in terms of the fundamental laws of nature. This leads to understanding of the origin of 99% of the rest mass present in the Universe – The Higgs mechanism covers the remaining 1% (or less).**

## EARLY UNIVERSE:

**Recreate and understand the high energy density conditions prevailing in the Universe when nucleons formed from elementary degrees of freedom (quarks, gluons) at about 10-40$\mu$s after big bang. Hadronization of the Universe led to nearly matter-antimatter symmetric state, the sequel annihilation left the small $10^{-10}$ matter asymmetry, the world around us.**

# What is deconfinement?

**A domain of (space, time) much larger than normal hadron size in which color-charged quarks and gluons are propagating, constrained by external 'frozen vacuum' which abhors color.**

**We expect a pronounced boundary in temperature and density between confined and deconfined phases of matter: phase diagram. Deconfinement expected at both:**

**high temperature and at high matter density.**

**In a finite size system not a singular boundary, a 'transformation'.**

**THEORY FUTURE What we need as background knowledge:**

**1) Hot QCD in/out of equilibrium (QGP from QCD-lattice)**
**2) Understanding from first principles and not as descriptive method of hadronization dynamics and final hadron yields,**
**3) More sensitive (hadronic and other) signatures of deconfinement**
**beware: final particles always hadrons, many decay into leptons**

**DECONFINEMENT NOT A 'NEW PARTICLE',**
**there is no answer to journalists question:**

**How many new vacuua have you produced today?**

# Vacuum structure

**Quantum vacuum is polarizable: see atomic vac. pol. level shifts**
**Quantum structure of gluon-quark fluctuations:**
**glue and quark condensate evidence from LGT, 'onium sum rules**
**Permanent fluctuations/structure in 'space devoid of matter':**

**even though** $\langle V|G^a_{\mu\nu}|V\rangle = 0,$ **with** $G^2 \equiv \sum_a G^a_{\mu\nu}G_a^{\mu\nu} = 2\sum_a[\vec{B}_a^{\,2} - \vec{E}_a^{\,2}]\,,$

**we have** $\langle V|\frac{\alpha_s}{\pi}G^2|V\rangle \simeq (2.3 \pm 0.3)10^{-2}\mathrm{GeV}^4 = [390(12)\,\mathrm{MeV}]^4\,,$

**and** $\langle V|\bar{u}u + \bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.$

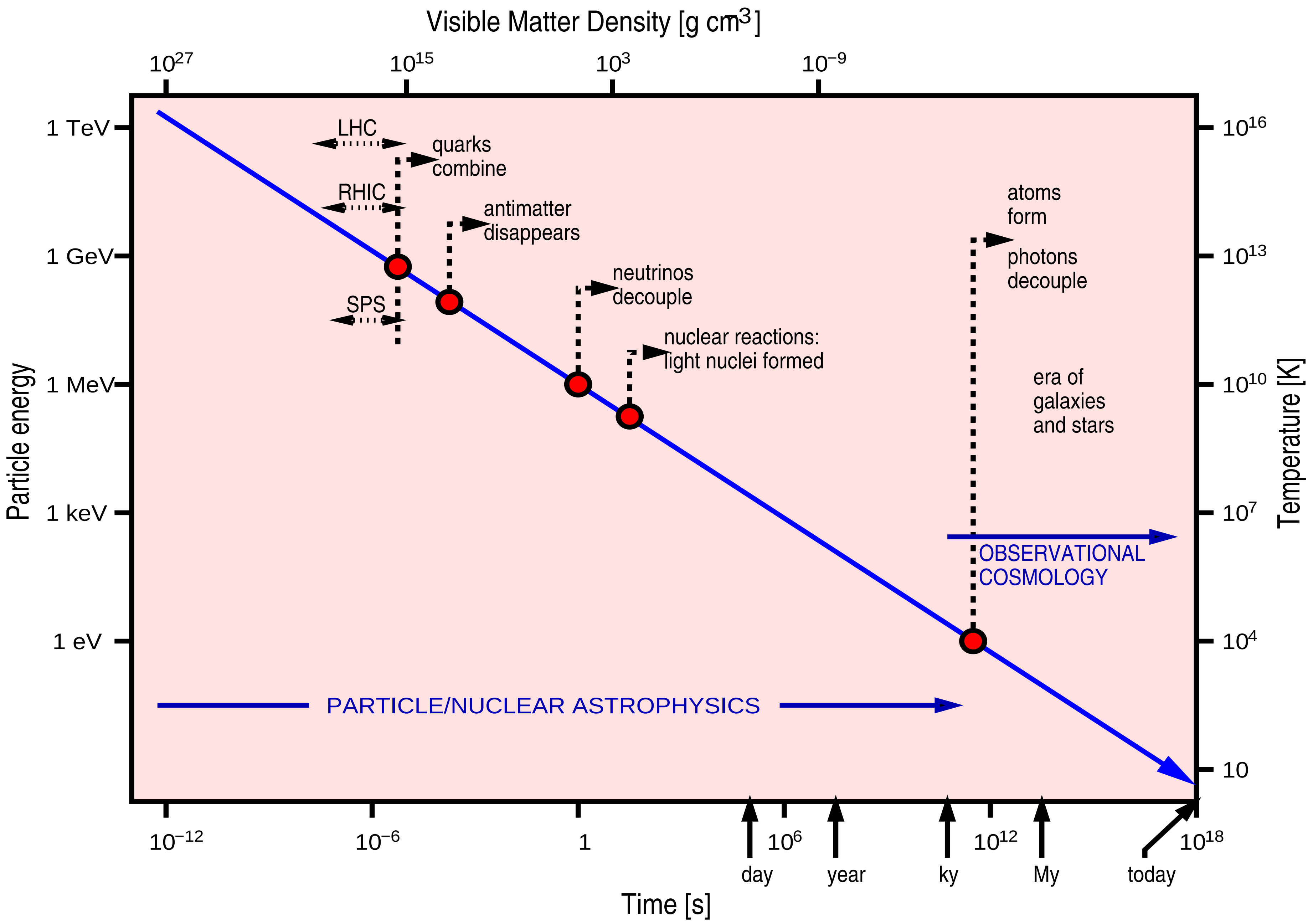
## Vacuum and Laws of Physics

**Vacuum structure controls early Universe properties**
**Vacuum determines inertial mass of 'elementary' particles by the way of the Higgs mechanism,**

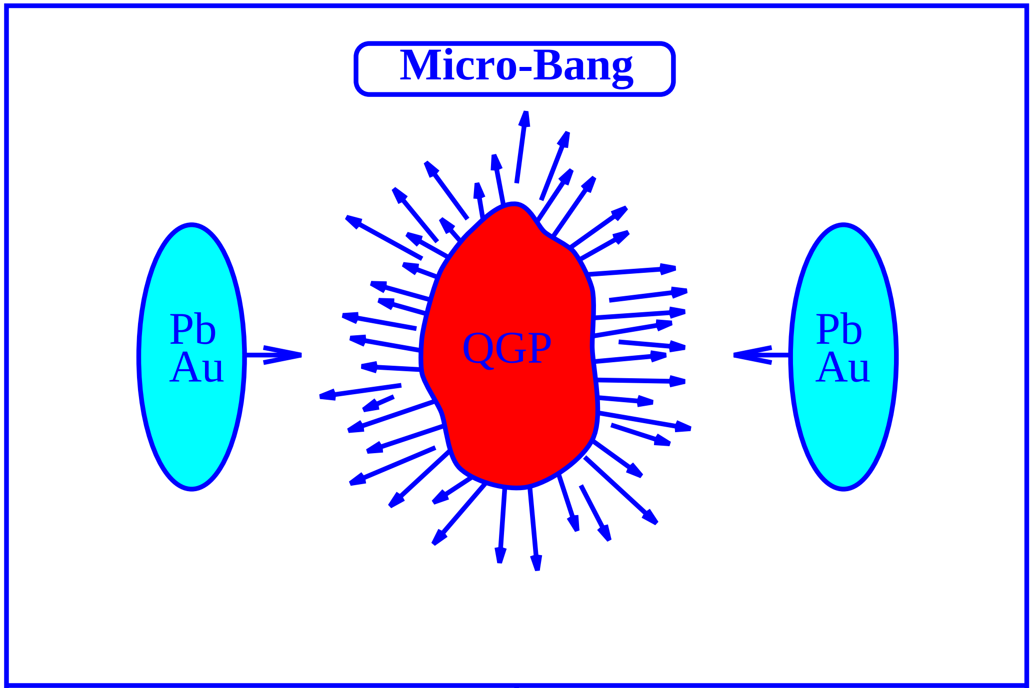
$$m_i = g_i\langle V|h|V\rangle\,,$$

**Vacuum is thought to generate color charge confinement:**
**hadron mass originates in QCD vacuum structure.**
**Vacuum determines interactions, symmetry breaking, etc.....**
**DO WE REALLY UNDERSTAND HOW THE VACUUM CONTROLS INERTIA (RESISTANCE TO CHANGE IN VELOCITY)??**

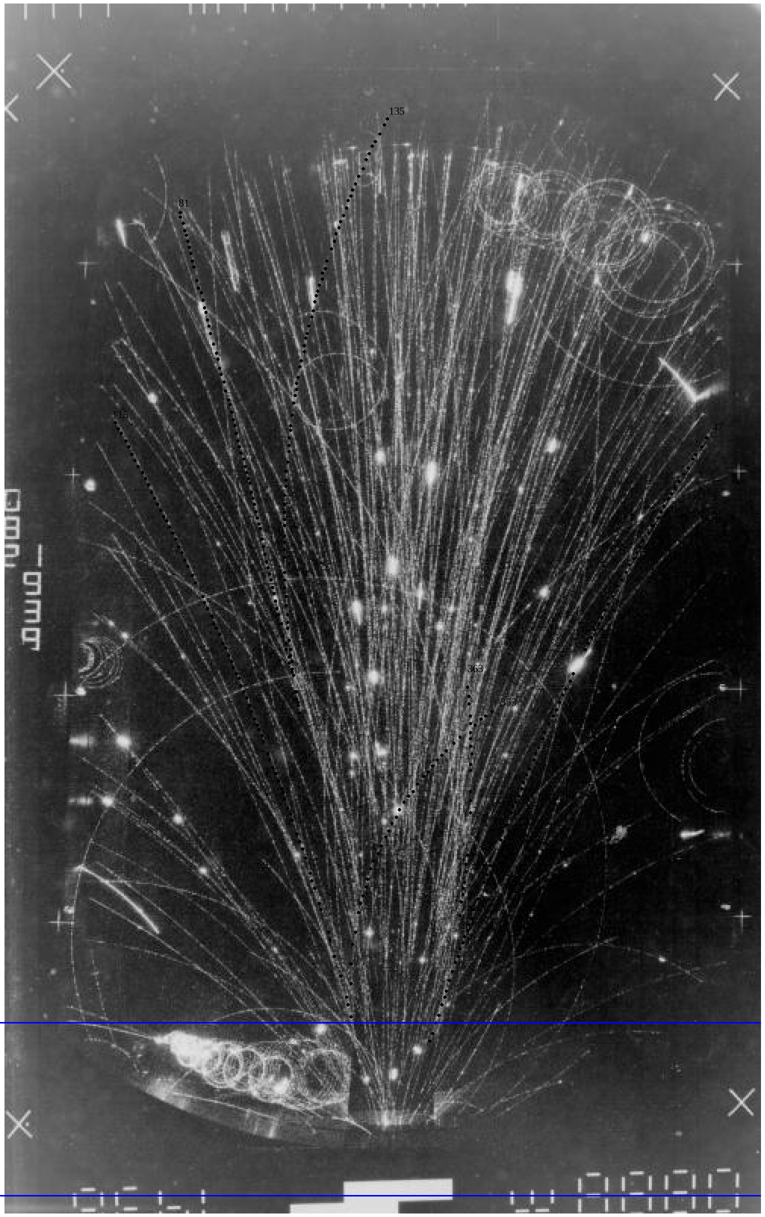
# Do we understand how annihilation of almost all matter-antimatter occurs?



# CERN SPS: THE FIRST LOOK AT DECONFINED UNIVERSE IN THE LABORATORY



| Big-Bang | Micro-Bang |
|---|---|
| $\tau \simeq 10\mu s$ | $\tau \simeq 4\ 10^{-23} s$ |
| $N_B / N \simeq 10^{-10}$ | $N_B / N \simeq 0.1$ |

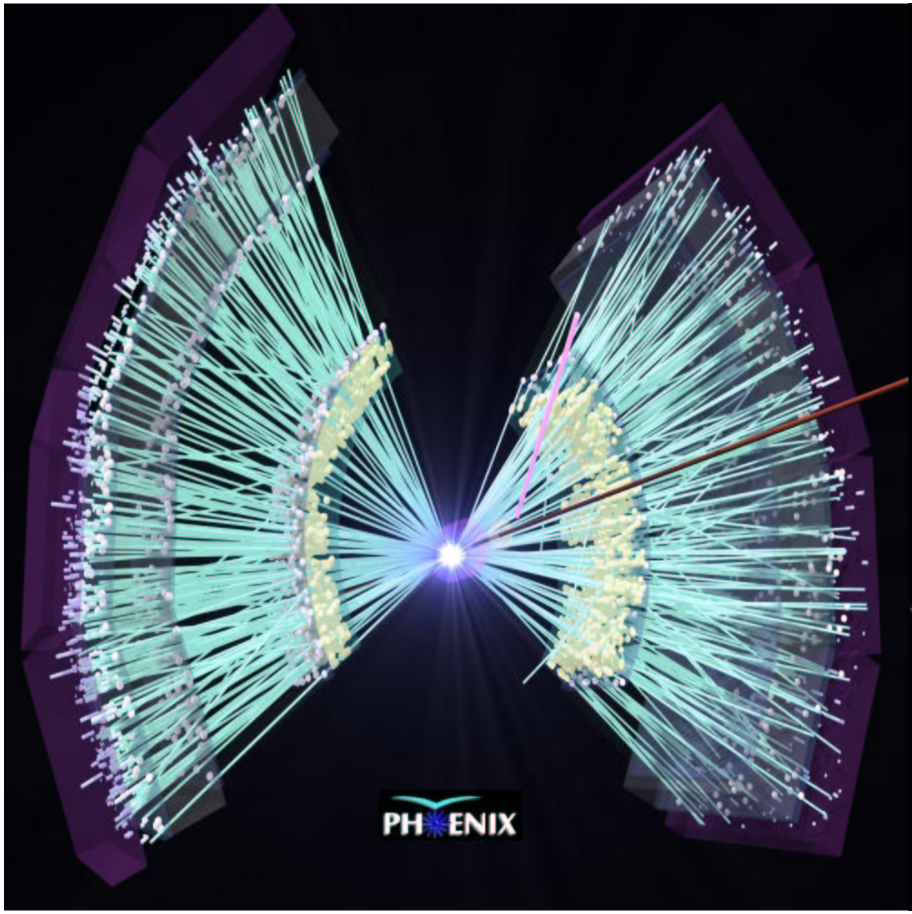


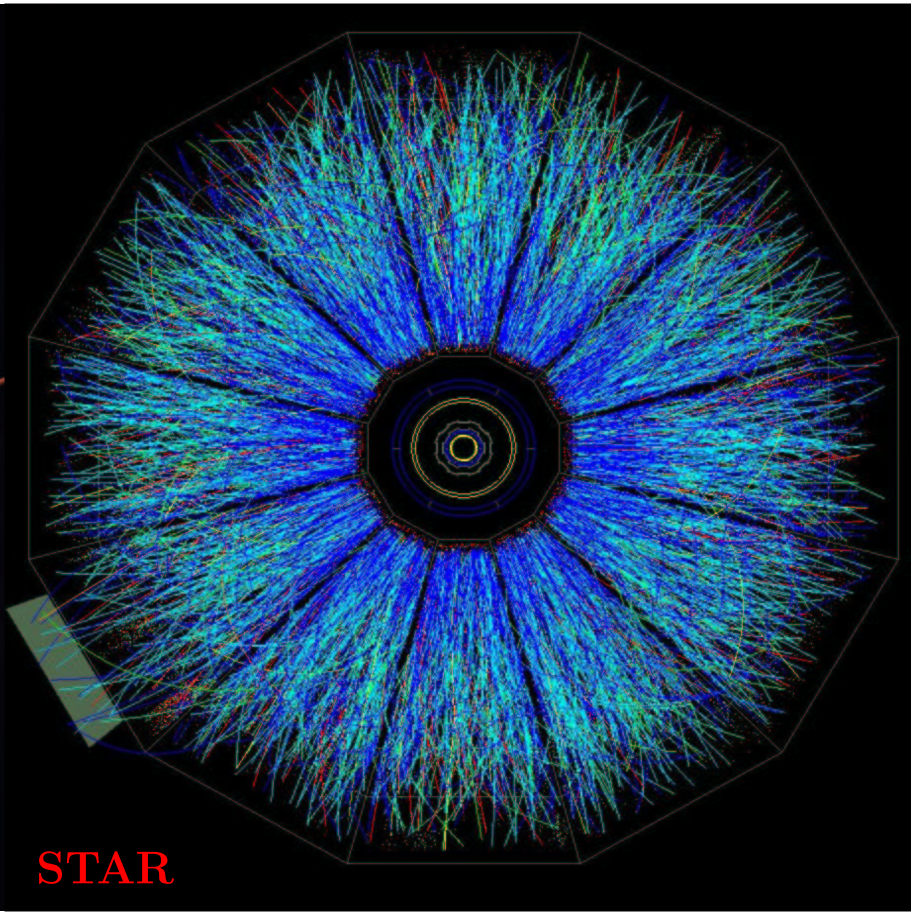
**NA35 1986: S–Ag at 200$A$GeV**

**Order of Magnitude**

| | | |
|---|---|---|
| **ENERGY density** | $\epsilon$ | $\simeq 1$–$5\mathrm{GeV/fm}^3 = 1.8$–$9\ 10^{15}\mathrm{g/cc}$ |
| **Latent vacuum heat** | $B$ | $\simeq 0.1$–$0.4\mathrm{GeV/fm}^3 \simeq (166$–$234\mathrm{MeV})^4$ |
| **PRESSURE** | $P$ | $= \frac{1}{3}\epsilon = 0.52\ 10^{30}$ barn |
| **TEMPERATURE** | $T_0, T_f$ | **300–250, 175–145 MeV;** $300\mathrm{MeV} \simeq 3.5\ 10^{12}\mathrm{K}$ |

# THE EARLY UNIVERSE AT RHIC

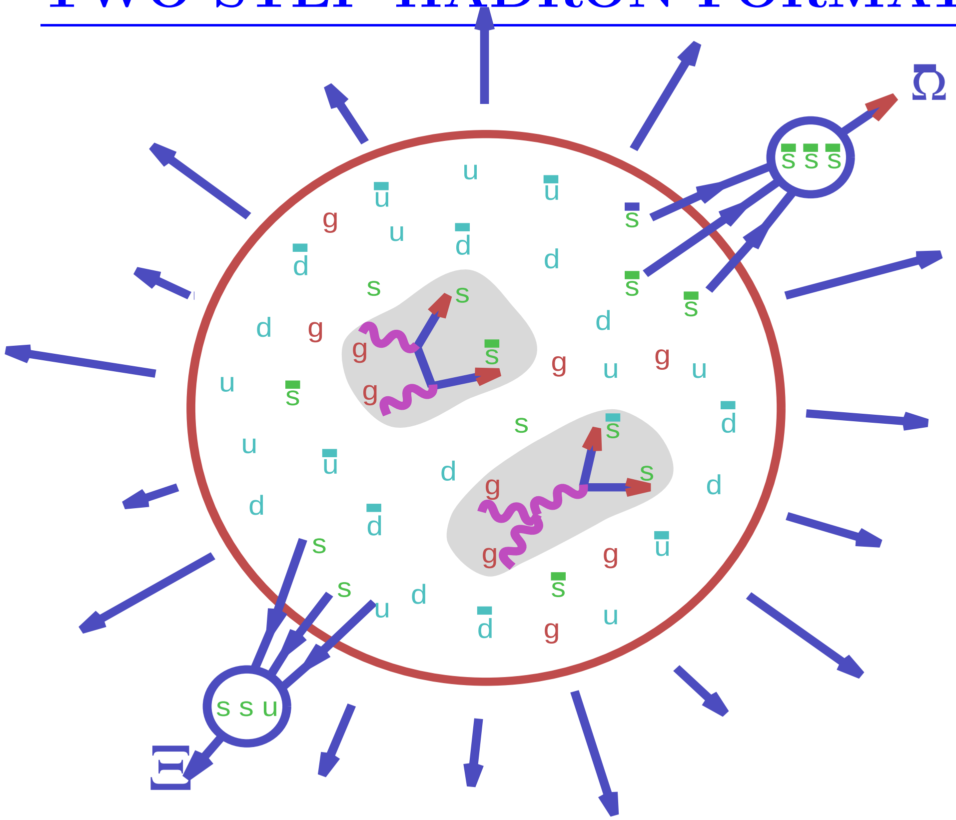




**. . . and BRAHMS, PHOBOS: How is this maze of tracks of newly produced particles telling us what we want to know about the early Universe and its properties?**

**Study of patterns in particle production: correlations, new flavors (strangeness, charm), resonances, etc..**

# TWO STEP HADRON FORMATION MECHANISM IN QGP



1. $GG \to s\bar{s}$ (thermal gluons collide)
   $GG \to c\bar{c}$ (initial parton collision)
   gluon dominated reactions
2. hadronization of pre-formed
   $s$, $\bar{s}$, $c$, $\bar{c}$ quarks

Formation of complex rarely produced (multi)exotic flavor (anti)particles from QGP enabled by coalescence between $s$, $\bar{s}$, $c$, $\bar{c}$ quarks made in different microscopic reactions; this is signature of quark mobility and independent action, thus of deconfinement. Enhancement of flavored (strange, charm) antibaryons progressing with 'exotic' flavor content.

## AVAILABLE RESULT (SPS, RHIC):

**Enhancement of strange (anti)baryons progresses with strangeness content.**

# Why Strangeness is a diagnostic tool

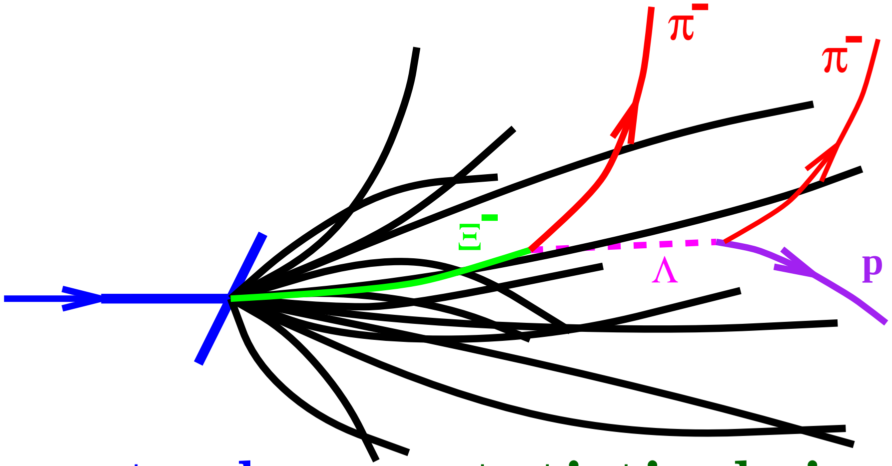
## EXPERIMENTAL REASONS

- There are many strange particles allowing to study different physics questions $(q = u, d)$:

$$\phi(s\bar{s}),\quad K(q\bar{s}),\quad \overline{K}(\bar{q}s),\quad \Lambda(qqs),\quad \overline{\Lambda}(\bar{q}\bar{q}\bar{s}),$$

$$\Xi(qss),\quad \overline{\Xi}(\bar{q}\bar{s}\bar{s}),\quad \Omega(sss),\quad \overline{\Omega}(\bar{s}\bar{s}\bar{s})\quad \ldots\textbf{resonances}\ldots$$

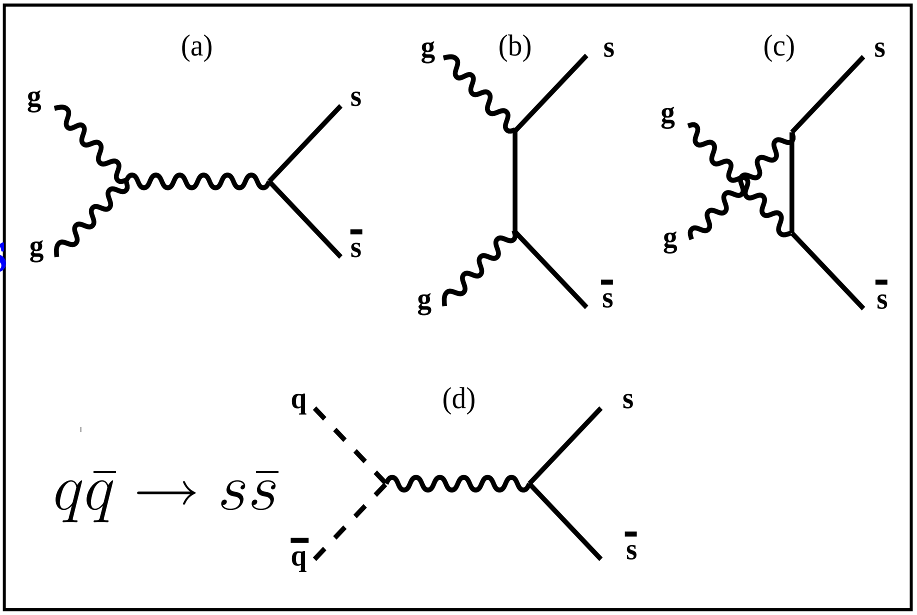
- Strange hadrons are subject to a self analyzing decay within a few cm from the point of production;



- Production rates hence statistical significance is high; (strong interaction reaction cross sections)

# THEORETICAL CONSIDERATIONS

- production of strangeness in gluon fusion $\boxed{GG \rightarrow s\bar{s}}$
  strangeness linked to gluons from QGP;



**dominant processes:**

$$GG \rightarrow s\bar{s}$$

**abundant strangeness**
**=evidence for gluons**

**10–15% of total rate:**

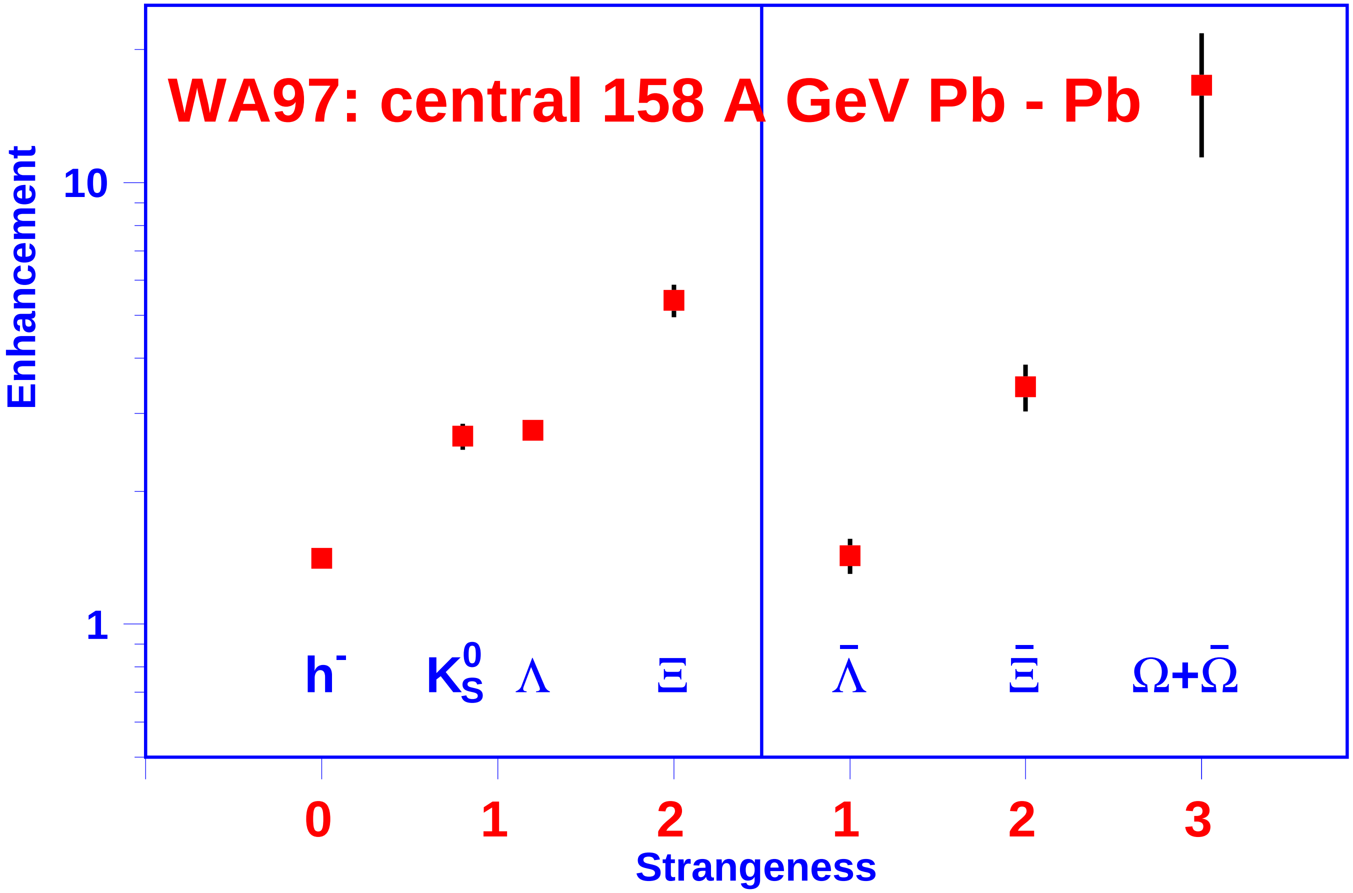
- coincidence of scales:

$$\boxed{m_s \simeq T_c} \rightarrow \boxed{\tau_s \simeq \tau_{\rm QGP}} \rightarrow$$

strangeness a clock for QGP phase

- $\boxed{\bar{s} \simeq \bar{q}} \rightarrow$ strange antibaryon enhancement
  at RHIC (anti)hyperon dominance of (anti)baryons.

# (MULTI)STRANGE (ANTI)HYPERON ENHANCEMENT

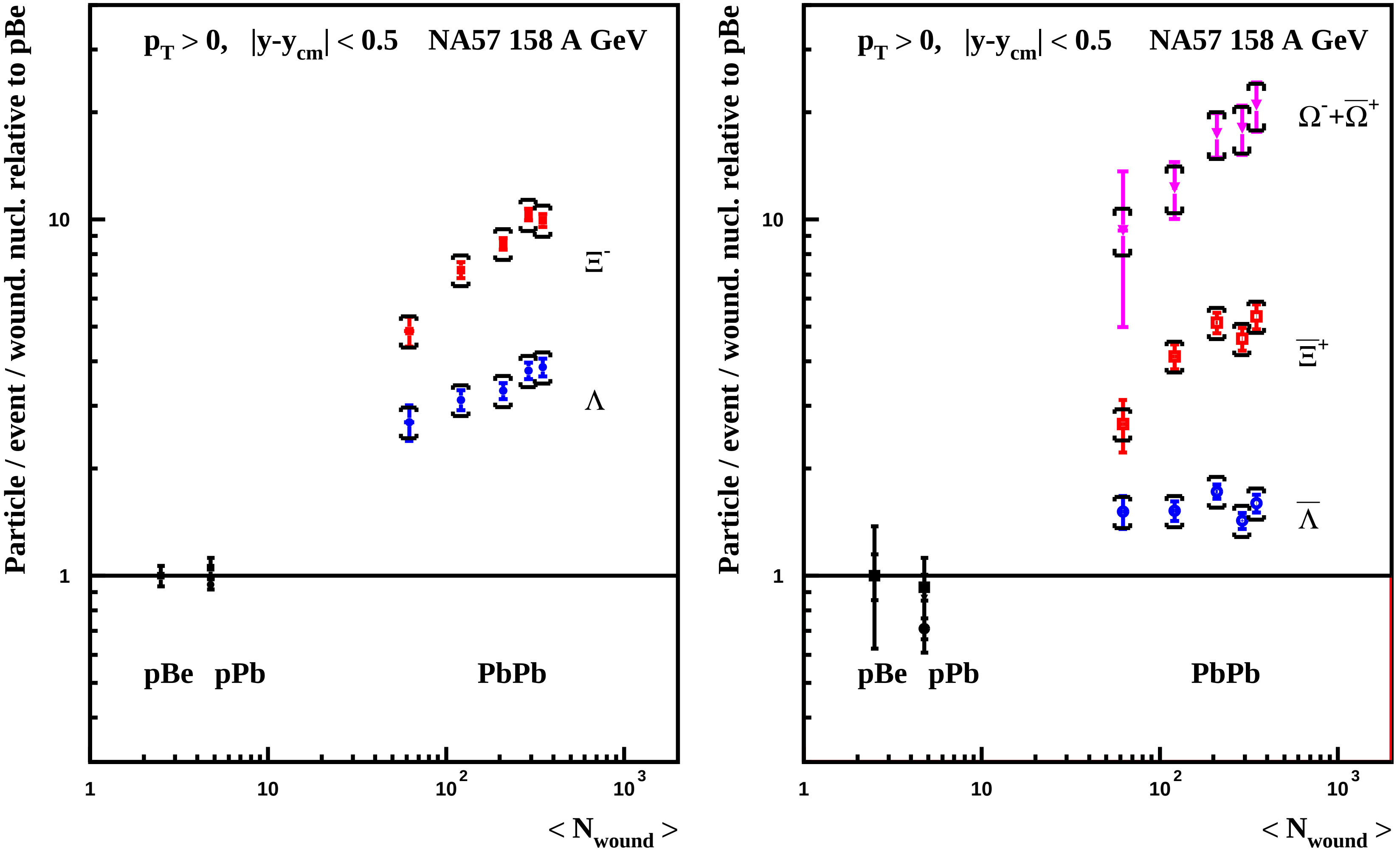


**Enhancement GROWTH with**

**strangeness** **antiquark content.**

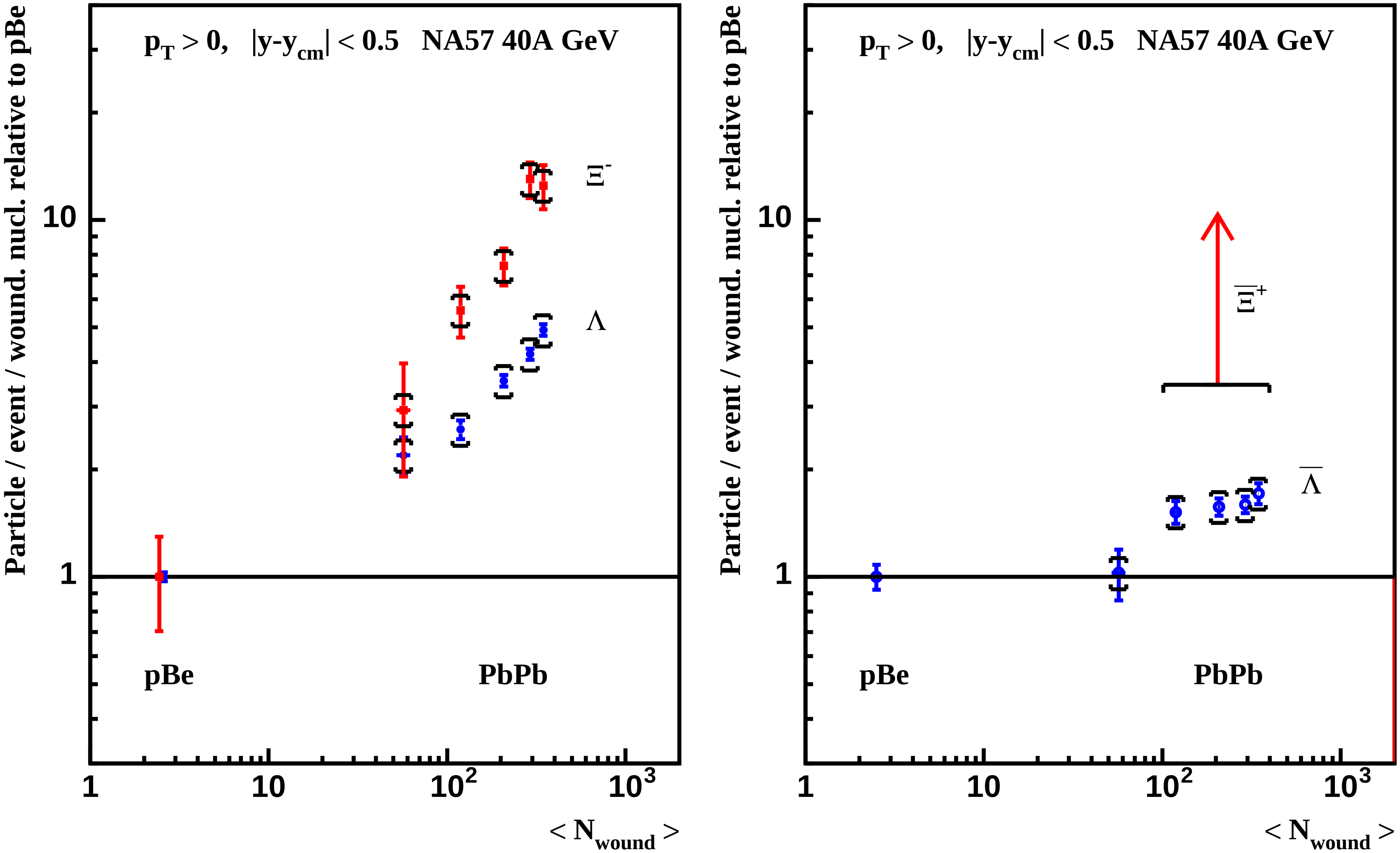
**Enhancement is here defined with respect to the yield in p–Be collisions, scaled up with the number of collision 'wounded' nucleons.**

# ENHANCEMENT AS FUNCTION OF REACTION VOLUME



Note the gradual onset of enhancement with reaction volume. “Canonical enhancement” (a hadronic equilibrium model) is grossly inconsistent with these results. Gradual enhancement shown predicted by kinetic strangeness production.

# ENHANCEMENT at low SPS Energy



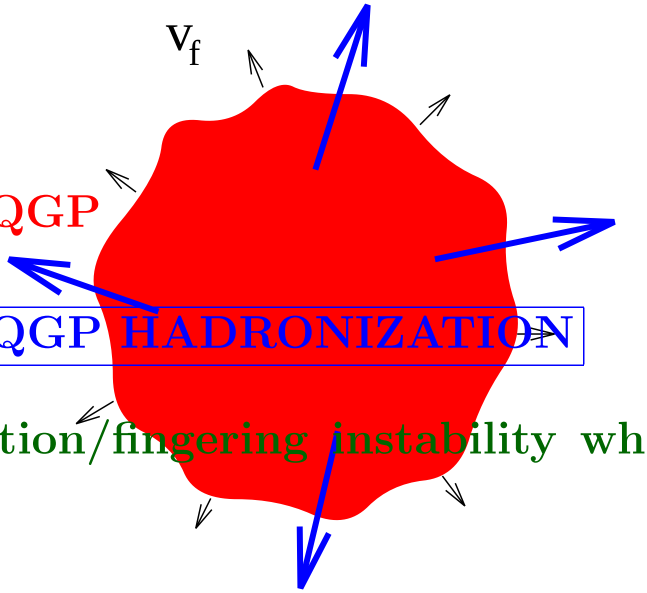
**At 40$A$ GeV we still see a strong volume dependent hyperon enhancement, in agreement with expectations for deconfined state formation.**

# REACTION MECHANISM OF PARTICLE PRODUCTION

**several CERN experiments since 1991 demonstrate symmetry of $m_\perp$ spectra of strange baryons and antibaryons in baryon rich environment, now also observed at RHIC.**

**Interpretation: Common matter-antimatter particle formation mechanism, little reannihilation in sequel evolution.**

**Appears to be emission by a quark source into vacuum.**
**Fast hadronization confirmed by abundant yield of hadron resonances at RHIC and HBT particle correlation analysis: same size pion source at all energies**



**Practically no hadronic 'phase'!**
**No 'mixed phase' either!**
**Direct emission of free-streaming**
**hadrons from exploding filamenitating QGP**

**Develop analysis tools viable in SUDDEN QGP HADRONIZATION**

**Proposed reaction mechanism: filamentation/fingering instability when in expansion pressure reverses.**

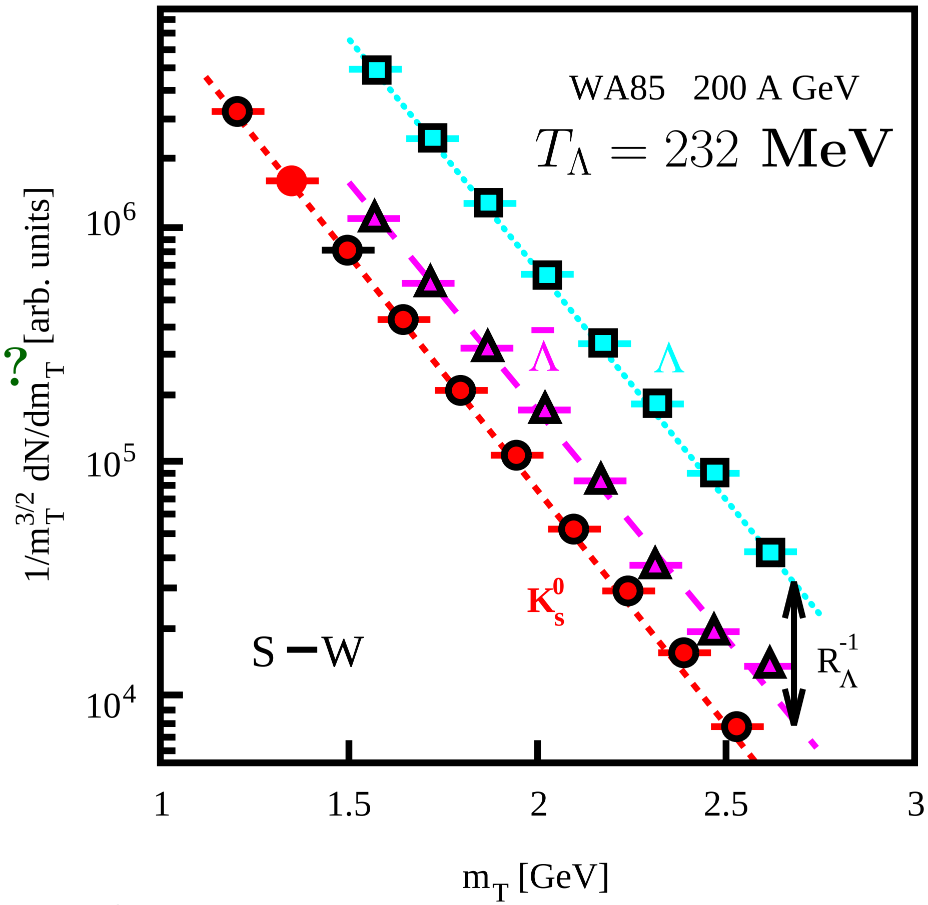
# High $m_\perp$ slope universality

**Discovered in S-induced collisions, pronounced in Pb-Pb Interactions.**

**Why is the slope of baryons and antibaryons in baryon-rich environment precisely the same?**

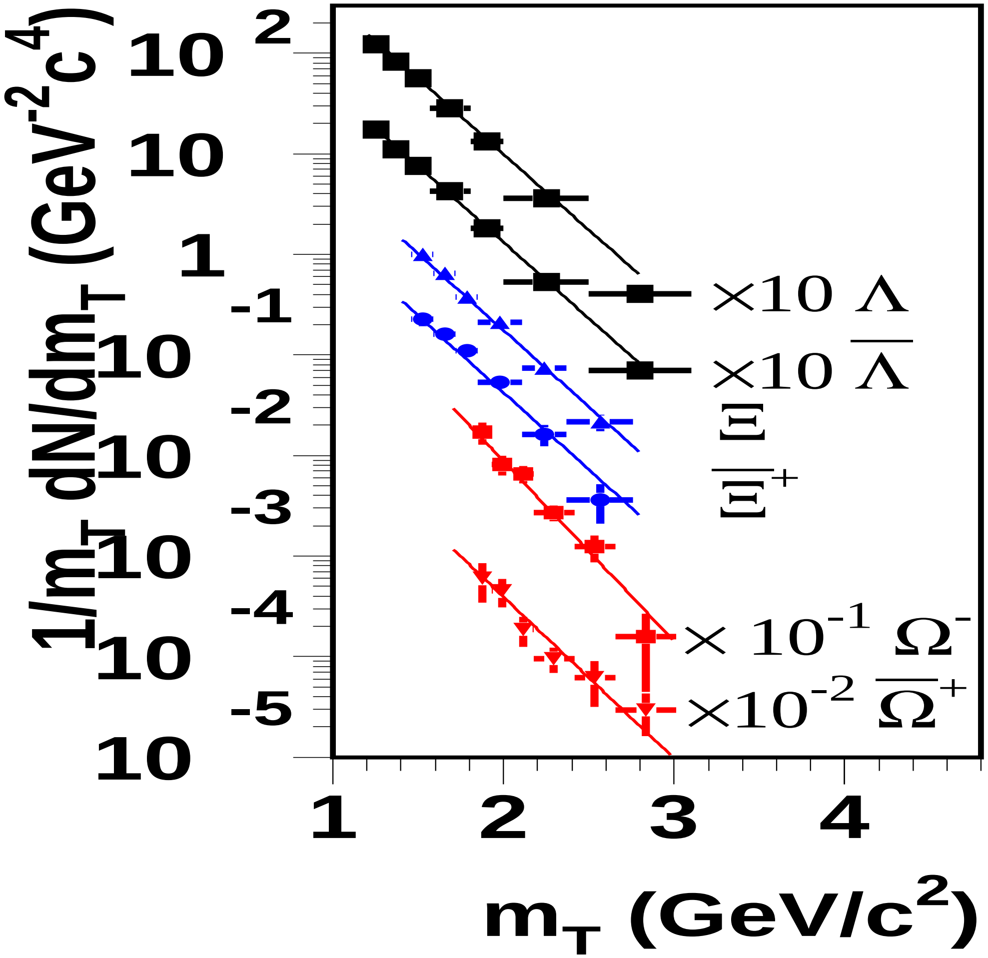
**Why is the slope of different hyperons in same $m_t$ range the same?**

**Analysis+our hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization**



**This allowed the study of ratios of particles measured only in a fraction of phase space**

| **WA97** | $T_\perp^{\rm Pb}$ [MeV] |
|---|---|
| $T^{\rm K^0}$ | **230 ± 2** |
| $T^{\Lambda}$ | **289 ± 3** |
| $T^{\overline{\Lambda}}$ | **287 ± 4** |
| $T^{\Xi}$ | **286 ± 9** |
| $T^{\overline{\Xi}}$ | **284 ± 17** |
| $T^{\Omega+\overline{\Omega}}$ | **251 ± 19** |



**$\Lambda$ within 1% of $\overline{\Lambda}$**

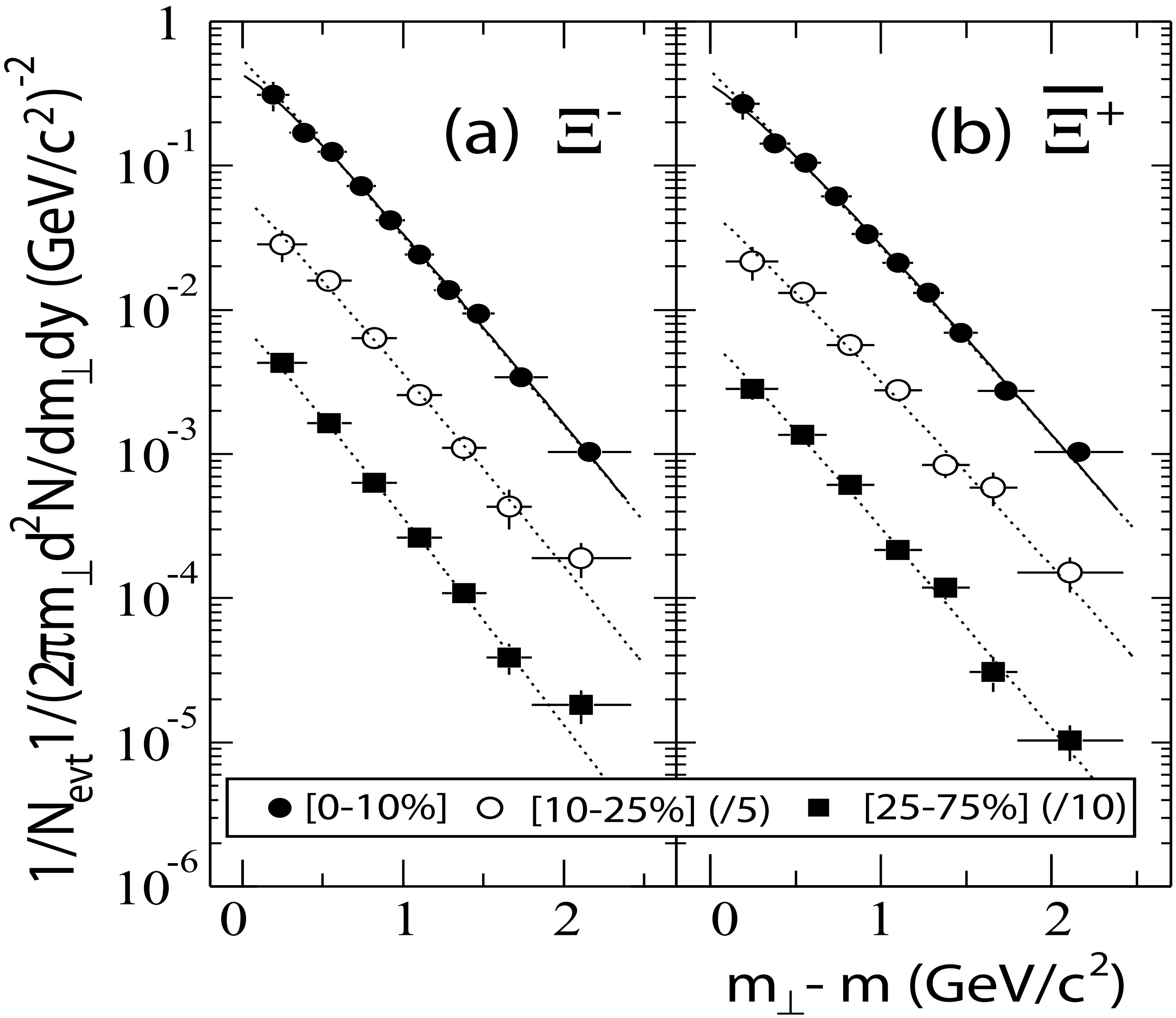
**Kaon – hyperon difference: EXPLOSIVE FLOW effect**

# Spectra at RHIC-STAR 130+130 A GeV show the same effect

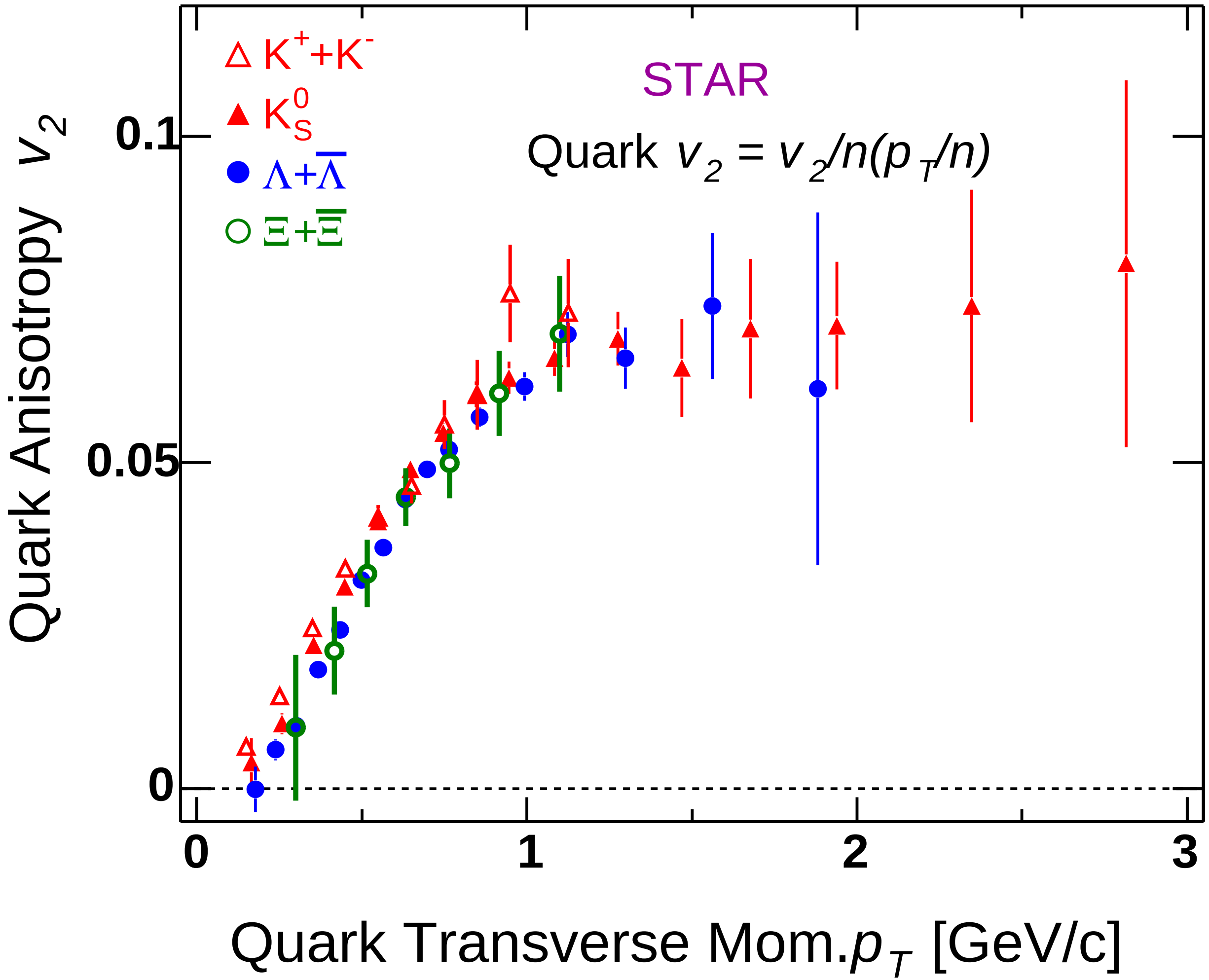
| $h^-$ |  | Exponential Fit |  | Boltzmann Fit |  |
|---|---|---|---|---|---|
| centrality |  | $dN/dy$ | $T_{\rm E}$(MeV) | $dN/dy$ | $T_{\rm B}$(MeV) |
| 260.3±7.5 | $\Xi^-$ | 2.16±0.09 | 338±6 | 2.06±0.09 | 296±5 |
|  | $\bar{\Xi}^+$ | 1.81±0.08 | 339±7 | 1.73±0.08 | 297±5 |
| 163.6±5.2 | $\Xi^-$ | 1.22±0.11 | 335±16 | 1.18±0.11 | 291±13 |
|  | $\bar{\Xi}^+$ | 1.00±0.10 | 349±17 | 0.97±0.10 | 302±13 |
| 42.5±3.0 | $\Xi^-$ | 0.28±0.02 | 312±12 | 0.27±0.02 | 273±10 |
|  | $\bar{\Xi}^+$ | 0.23±0.02 | 320±11 | 0.22±0.02 | 280±9 |

**$m_\perp$ spectra of $\Xi^-,\overline{\Xi^-}$, for three centrality bins 0-10%, 10-25% and 25-75% with $h^-$=$dN_{h^-}/\mathrm{d}\eta|_{|\eta|<0.5}$. Statistical and $p_\perp$ dependent systematic uncertainties are presented.The $p_\perp$ independent systematic uncertainties are 10%. (STAR Collaboration, PRL92 (2004) 182301)**

# $\Xi^-, \overline{\Xi^-}$ Spectra RHIC-STAR 130+130 A GeV



# Discovery of early thermalization: Azimuthal asymmetry



Evidence for common bulk $q, \bar{q}, s, \bar{s}$-partonic matter flow. The absence of gluons at hadronization is consistent with the absence of charge fluctuations, Quark scaling: Paul Sorenson and Huan-Zhong Huang. A superb confirmation that dynamics of the fireball is in thermal partonic degrees of freedom, and quarks hadronize.

# SUDDEN MECHANISM: Super-cooling COLOR WIND of an exploding fireball

$P$ **and** $\varepsilon$**: local in QGP particle pressure, energy density,** $\vec{v}$ **local flow velocity. The pressure component in the energy-momentum tensor:**

$$T^{ij} = P\delta_{ij} + (P+\varepsilon)\frac{v_i v_j}{1-\vec{v}^{\,2}}\,.$$

**The rate of momentum flow vector** $\vec{\mathcal{P}}$ **at the surface of the fireball is obtained from the energy-stress tensor** $T_{kl}$ **:**

$$\vec{\mathcal{P}} \equiv \widehat{\mathcal{T}}\cdot\vec{n} = P\vec{n} + (P+\varepsilon)\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-\vec{v}_{\rm c}^{\,2}}\,.$$

**The pressure and energy comprise particle and the vacuum properties:** $P = P_{\rm p} - \mathcal{B}\,, \quad \varepsilon = \varepsilon_{\rm p} + \mathcal{B}\,.$ **Condition** $\vec{\mathcal{P}} = 0$ **reads:**

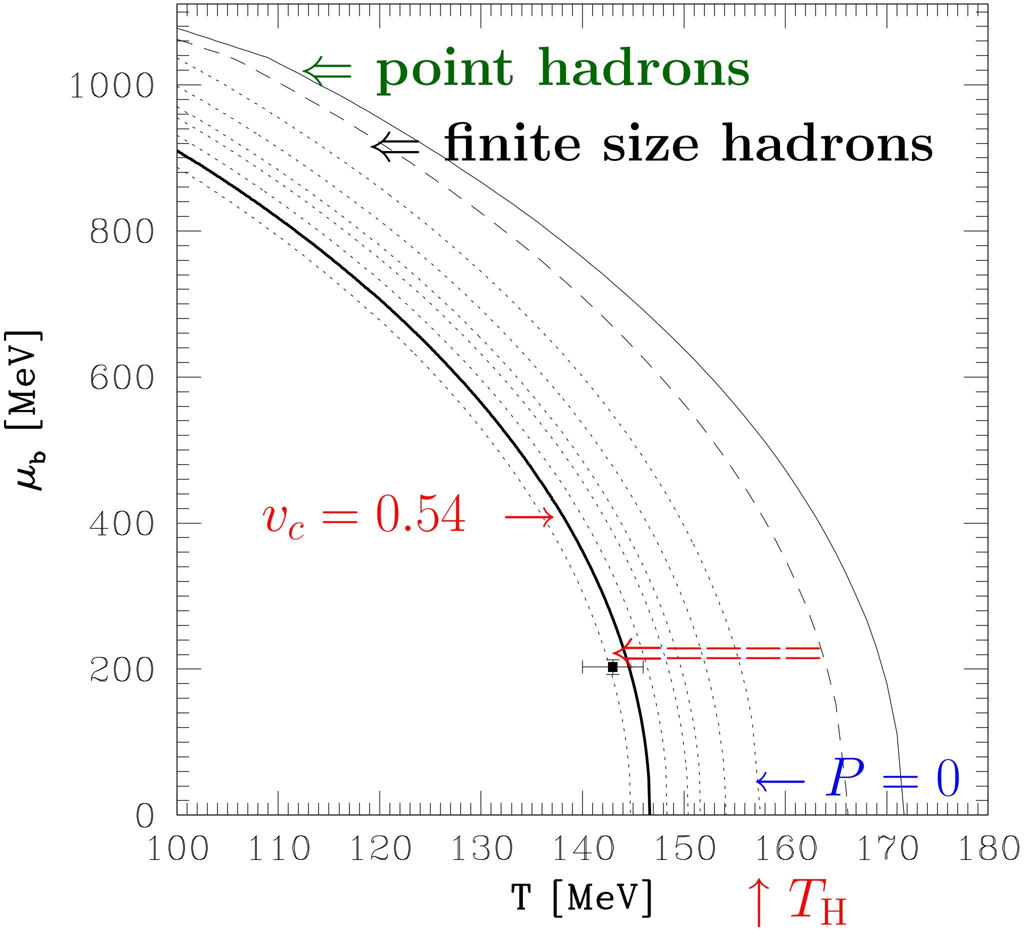
$$\mathcal{B}\vec{n} = P_{\rm p}\vec{n} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-v_{\rm c}^2}\,,$$

**Multiplying with** $\vec{n}$**, we find,**

$$\mathcal{B} = P_{\rm p} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\kappa v_{\rm c}^2}{1-v_{\rm c}^2}\,, \qquad \kappa = \frac{(\vec{v}_{\rm c}\cdot\vec{n})^2}{v_{\rm c}^2}\,.$$

**This requires** $P_{\rm p} < \mathcal{B}$**: QGP phase pressure** $P$ **must be NEGATIVE. A fireball surface region which reaches** $\mathcal{P} \to 0$ **and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses again the vacuum which is not subject to collective dynamics.**

# Phase boundary and ‘wind’ of flow of matter



**Solid: point hadrons $T_p$**

**Dashed: finite size**

**Dotted: $T_c(\mu_{\rm b})|_{P_{eff}-\mathcal{B}=0}$ for $v^2 = 0, 1/10, 1/6, 1/5, 1/4, 1/3$.**

**Thick solid: breakup with $v = 0.54$ ($\kappa = 0.6$)**

**PRL 85 (2000) 4695**

**DEEP SUPERCOOLING by 20 MeV**

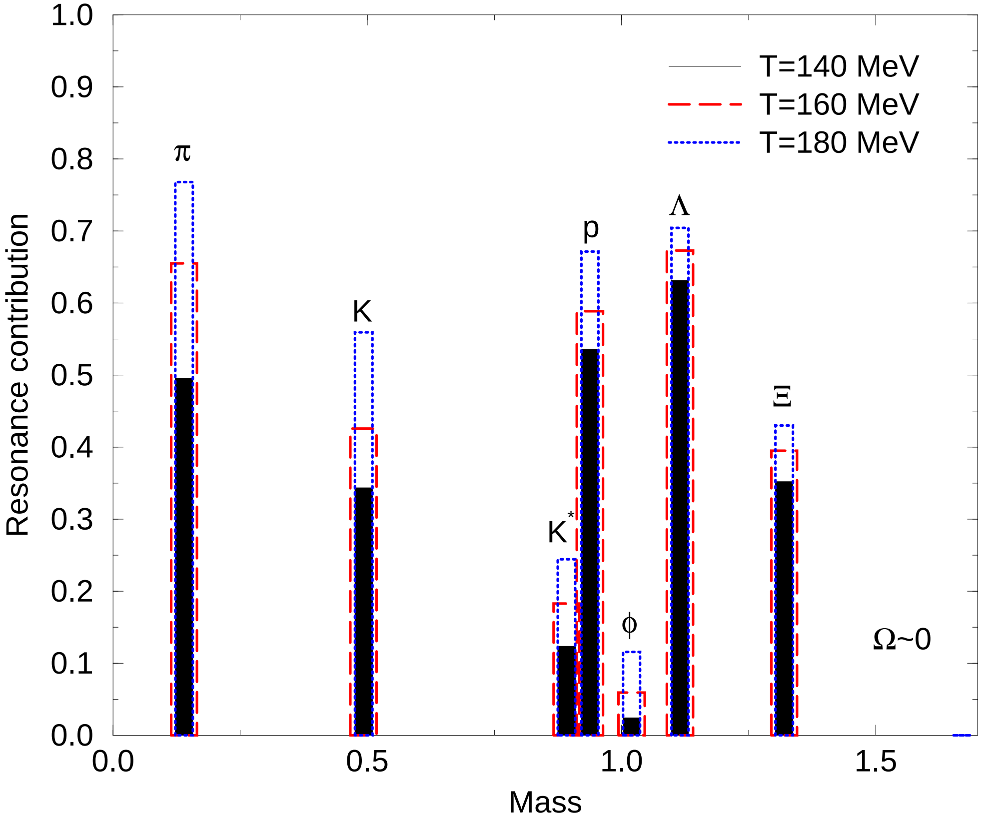
$T_{\rm H} = 158$ **MeV Hagedorn temperature where $P = 0$, no hadron $P$**

$T_f \simeq 0.9 T_H \simeq 143$ **MeV is where supercooled QGP fireball breaks up**

**equilibrium phase transformation is at $\simeq 166$.**

# STATISTICAL HADRONIZATION AND RESONANCES

**Fermi (micro canonical)-Hagedorn (grand canonical) particle 'evaporation' from hot fireball:particles produced into accessible phase space, yields and spectra thus predictable.**



## HOW TO TEST SH:

**Study of particle yields with same quark content, e.g. the relative yield of $\Delta(1230)/N$ , $K^*/K$, $\Sigma^*(1385)/\Lambda$, etc, which is controlled by chemical freeze-out temperature $T$:**

$$\frac{N^*}{N} = \frac{g^*(m^*T)^{3/2}e^{-m^*/T}}{g(mT)^{3/2}e^{-m/T}}$$

**Resonances decay rapidly into 'stable' hadrons and dominate the yield of most stable hadronic particles.**

**Resonances test both statistical hadronization principle and perhaps more importantly, due to their short and diverse lifespan characterize the dynamics of QGP hadronization.**

# OBSERVABLE RESONANCE YIELDS

**Invariant mass method: construct invariant mass from decay products:**

$$M^2 = (\sqrt{m_a^2+\vec{p}_a^{\,2}} + \sqrt{m_b^2+\vec{p}_b^{\,2}} + \ldots)^2 - (\vec{p}_a + \vec{p}_b + \ldots)^2$$

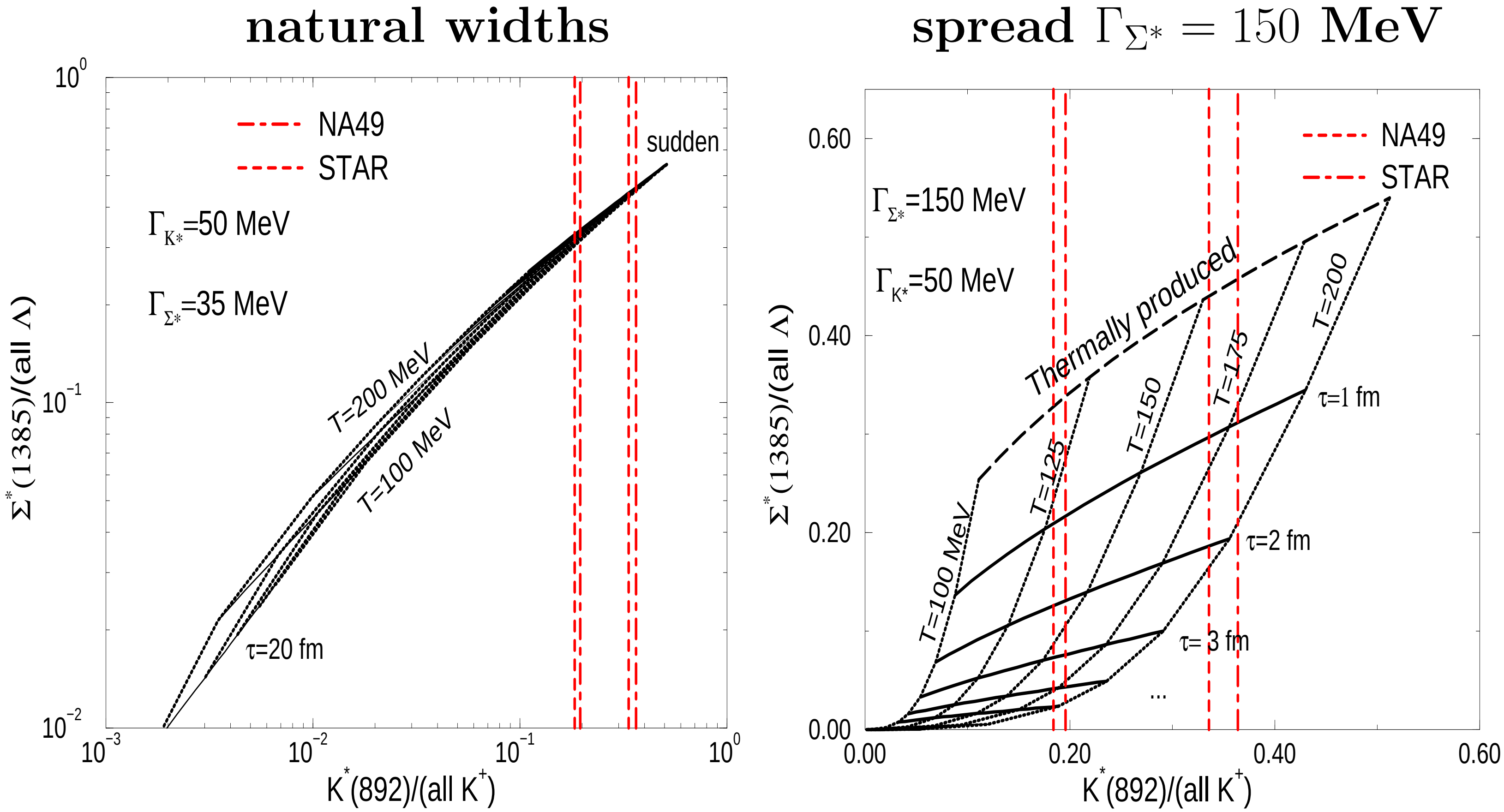
**If one of decay products rescatter the reconstruction not assured.**

**Strongly interacting matter essentially non-transparent. Simplest model: If resonance decays $N^* \to D + \ldots$ within matter, resonance can disappear from view. Model implementation:**

$$\frac{dN^*}{dt} = -\Gamma N^* + R, \qquad \frac{dD}{dt} = \Gamma N^*, \qquad \frac{dN^*_{\rm rec}}{dt} = \Gamma N^* - D\sum_j \langle \sigma_{Dj} v_{Dj}\rangle \rho_j(t)$$

**$\Gamma$ is $N^*$ in matter width, $N^*(t=0), D(t=0)$ from statistical hadronization, and $\rho_j(t)$ is the time dependent particle '$j$' density: To obtain the observable resonance yield $N^*_{\rm rec}$ we integrate to the time $t=\tau$ spend by $N^*$ in the opaque matter, and add the remainder from free space decay. Regeneration term $R \propto \langle \sigma_{Di}^{INEL} v_{Di}\rangle \rho_i$ negligible since production reactions very much weaker than scattering, $\{i\} \ll \{j\}$. Hadronic matter acts as black cloud, practically all in matter decays cannot be reconstructed.** **Giorgio Torrieri**

# TWO resonance ratios combined



**natural widths** | **spread $\Gamma_{\Sigma^*} = 150$ MeV**

**Dependence of the combined $\Sigma^*/(\text{all }\Lambda)$ with $K^*(892)/(\text{all K})$ signals on the chemical freeze-out temperature and HG phase lifetime.**

**Even the first rough measurement of $K^*/K$ indicates that there is no long lived hadron phase. In matter widening makes this conclusion stronger.**

**J.R., J. Letessier and G. Torrieri, Phys. Rev. C64, 054907 (2001); C65, 069902(E) (2002)**

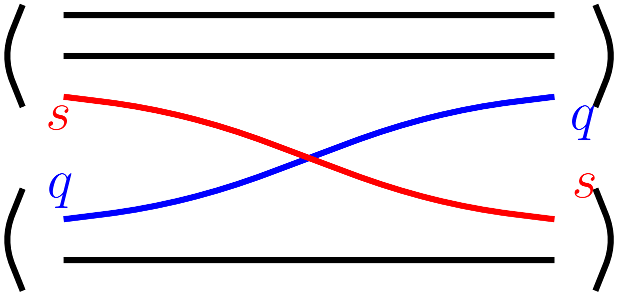
# QUARK CHEMISTRY

**When we compare yields of particles of different quark content we need to consider chemical potentials, in principle one poitential for each hadron! Simplification: follow quark content and rememe br that quarks are produced in pairs.**

# FOUR QUARKS: $s, \bar{s}, q, \bar{q} \rightarrow$ FOUR CHEMICAL PARAMETERS

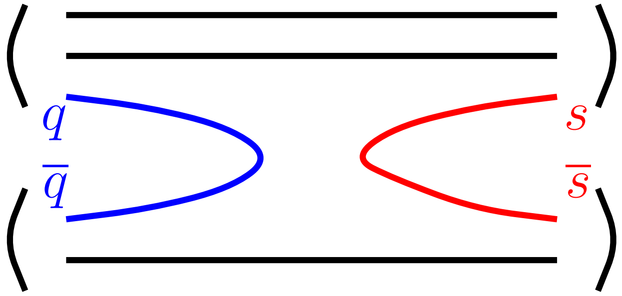
| | |
|---|---|
| $\gamma_i$ controls overall abundance of quark $(i = q, s)$ pairs | Absolute chemical equilibrium |
| $\lambda_i$ controls difference between strange and non-strange quarks $(i = q, s)$ | Relative chemical equilibrium |

**HG-EXAMPLE: redistribution,**
**Relative chemical equilibrium**



**EXCHANGE REACTION**
$\lambda_i$

**production of strangeness**
**Absolute chemical equilibrium**



**PAIR PRODUCTION REACTION**
$\gamma_i$

# Particle yields in chemical (non)equilibrium

**The counting of hadrons is conveniently done by counting the valence quark content ($u, d, s, \ldots$), and it leads to characterization of HG equivalent to QGP phase. There is a natural relation of quark fugacities with hadron fugacities, for particle 'i'**

$$\Upsilon_i \equiv \Pi_i \gamma_i^{n_i} \lambda_i^{k_i} = e^{\sigma_i/T}$$

**but for one complication: for historical reasons hyperon number is opposite to strangeness, thus $\mu_S = \frac{\mu_b}{3} - \mu_s$, where $\lambda_q^3 = e^{\mu_b/T}, \lambda_q^2 = \lambda_u \lambda_d$.**

**Example of NUCLEONS:**

**two particles $N, \overline{N}$ → two chemical factors, with $\lambda_q^3 = e^{\mu_b/T}, \gamma_N = \gamma_q^3$;**

$$\sigma_N \equiv \mu_b + T \ln \gamma_N, \qquad \sigma_{\overline{N}} \equiv -\mu_b + T \ln \gamma_N;$$

$$\Upsilon_N = \gamma_N e^{\mu_b/T}, \qquad \Upsilon_{\overline{N}} = \gamma_N e^{-\mu_b/T}.$$

**Meaning of parameters from e.g. the first law of thermodynamics:**

$$\begin{aligned} dE + P\,dV - T\,dS &= \sigma_N\,dN + \sigma_{\overline{N}}\,d\overline{N} \\ &= \mu_b(dN - d\overline{N}) + T \ln \gamma_N (dN + d\overline{N}). \end{aligned}$$

**The (baryo)chemical potential $\mu_b$ controls the particle difference = baryon number. $\gamma$ regulates the number of particle-antiparticle pairs present.**

# STRANGENESS PRODUCTION: Theoretical perspective

## STRANGENESS / NET BARYON NUMBER $s/b$

**Baryon number $b$ is conserved, strangeness could increase slightly in hadronization. $s/b$ ratio probes the mechanism of primordial fireball baryon deposition and strangeness production. Ratio eliminates dependence on reaction geometry.**

## STRANGENESS / ENTROPY CONTENT $s/S$

**Strangeness $s$ and entropy $S$ produced predominantly in early hot parton phase. Ratio eliminates dependence on reaction geometry. Strangeness and entropy could increase slightly in hadronization. $s/S$ relation to $K^+/\pi^+$ is not trivial when precision better than 25% needed.**

## HADRON PHASE SPACE OVERPOPULATION

**$\gamma_s,\ \gamma_q$ allow correct measure of yields of strangeness and baryon number, probe dynamics of hadronization, allow fast breakup without ‘mixed phase’**

# STRANGENESS YIELD IN QGP and $\gamma_{\rm s}^{\rm QGP}/\gamma_{\rm q}^{\rm QGP}$

$$\frac{\rho_{\rm s}}{\rho_{\rm b}} = \frac{s}{q/3} = \frac{\gamma_{\rm s}^{\rm QGP}\frac{3}{\pi^2}T^3(m_{\rm s}/T)^2K_2(m_{\rm s}/T)}{\gamma_{\rm q}^{\rm QGP}\frac{2}{3}\left(\mu_{\rm q}T^2+\mu_{\rm q}^3/\pi^2\right)}\,, \rightarrow \frac{s}{b} \simeq \frac{\gamma_{\rm s}^{\rm QGP}}{\gamma_{\rm q}^{\rm QGP}}\frac{0.7}{\ln\lambda_{\rm q}+(\ln\lambda_{\rm q})^3/\pi^2}\,.$$

**assumption: $\mathcal{O}(\alpha_s)$ interaction effects cancel out between $b, s$**

**We consider $m_{\rm s}=200$ MeV and hadronization $T=150$ MeV,**

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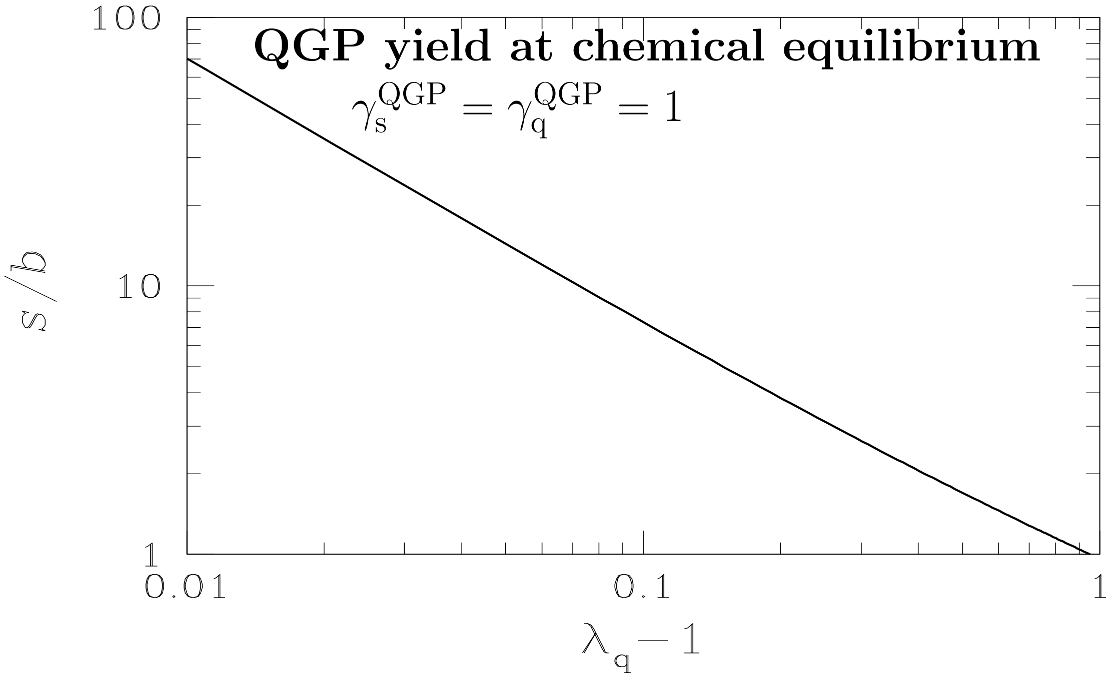


**At SPS $\lambda_q$=1.5–1.6, implies $s/b \simeq 1.5$.**

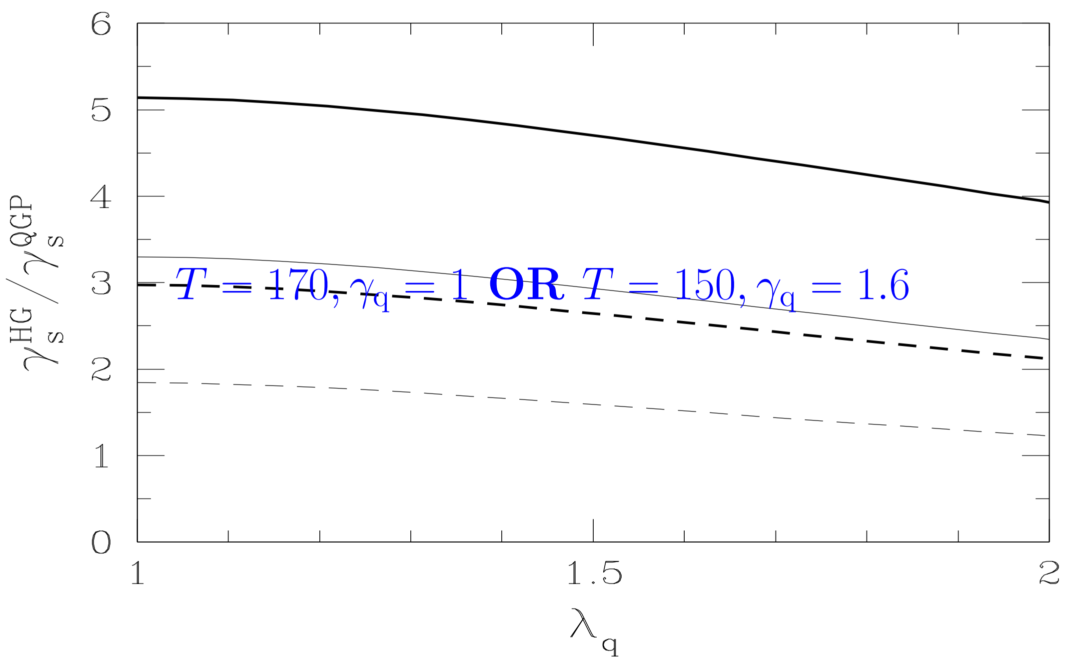
**Observation: $s/b \simeq 0.75 \rightarrow \gamma_{\rm s}^{\rm QGP}/\gamma_{\rm q}^{\rm QGP}=0.5$ at SPS**

**Similarly for RHIC at $\sqrt{s_{\rm NN}} \geq 130$ GeV we have $1 \leq \lambda_q \leq 1.1$ and a comparison of the actual $s/b$ yield allows to estimate $\gamma_{\rm s}^{\rm QGP}/\gamma_{\rm q}^{\rm QGP}$=0.7–0.8 at RHIC-130.**

# CAN WE ESTIMATE THE EXPECTED $\gamma_s^{\rm HG}$?

## COMPUTE EXPECTED RATIO OF $\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$

**In sudden hadronization, $V^{\rm HG} \simeq V^{\rm QGP}$, $T^{\rm QGP} \simeq T^{\rm HG}$, the chemical occupancy factors accommodate the different magnitude of particle phase space.**

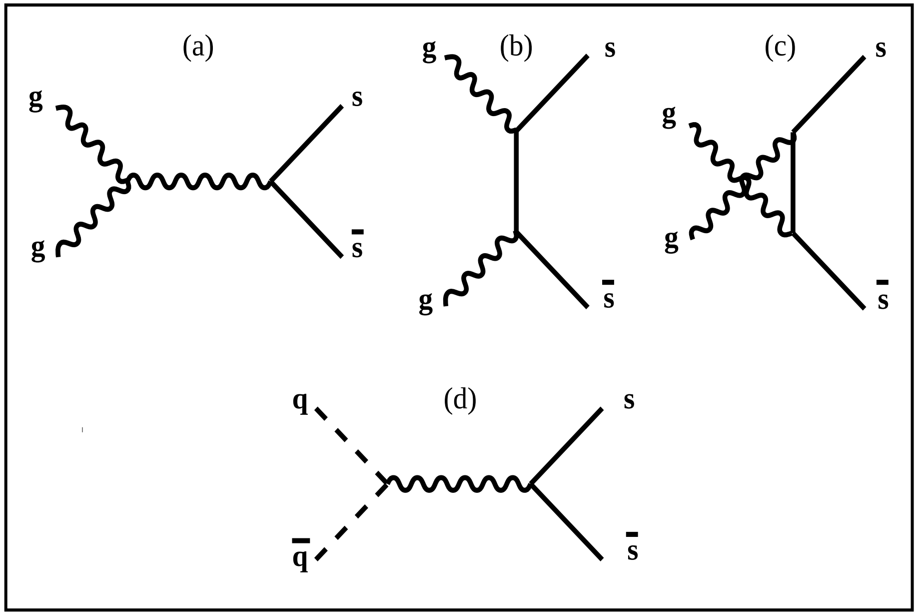


→ $T = 170$, $\gamma_{\rm q} = 1$ **OR** $T = 150$, $\gamma_{\rm q} = 1.6$

**$\gamma_{\rm s}^{\rm HG}/\gamma_{\rm s}^{\rm QGP}$ in sudden hadronization as function of $\lambda_{\rm q}$. Solid lines $\gamma_{\rm q} = 1$, and short dashed $\gamma_{\rm q} = 1.6$. Thin lines for $T = 170$ and thick lines $T = 150$ MeV, common to both phases.**

$$\boxed{\gamma_s^{\rm HG} \simeq 2...5\gamma_s^{\rm QGP}}$$

# Kinetic description of strangeness production



**The generic angle averaged cross sections for (heavy) flavor $s$, $\bar{s}$ production processes $g+g \rightarrow s+\bar{s}$ and $q+\bar{q} \rightarrow s+\bar{s}$, are:**

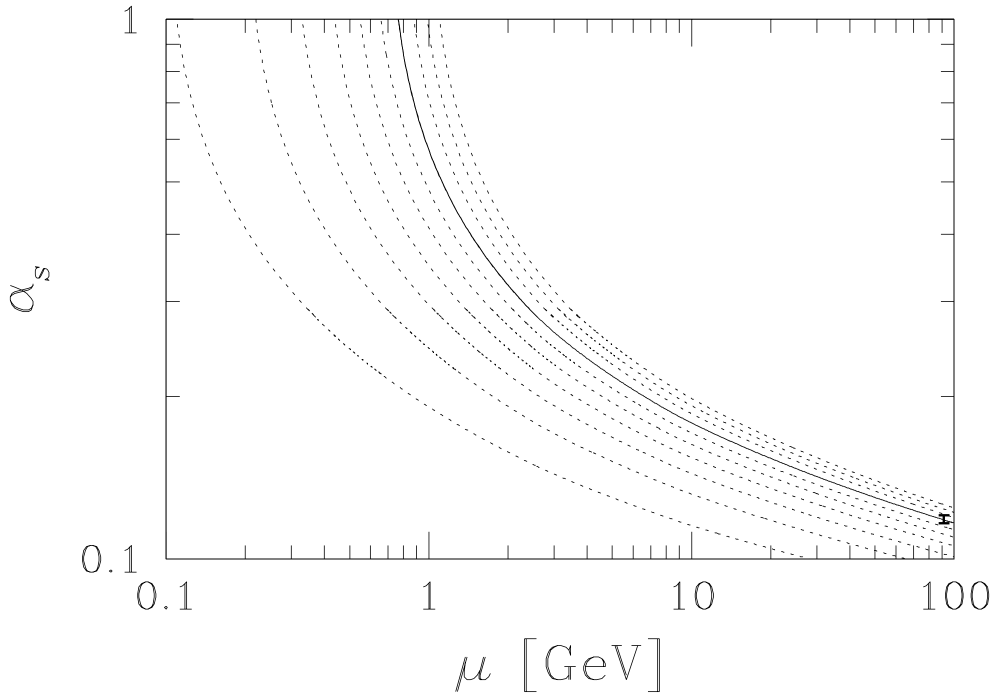
$$\bar{\sigma}_{gg\to s\bar{s}}(s) = \frac{2\pi\alpha_{\rm s}^2}{3s}\left[\left(1+\frac{4m_{\rm s}^2}{s}+\frac{m_{\rm s}^4}{s^2}\right)\tanh^{-1}W(s) - \left(\frac{7}{8}+\frac{31m_{\rm s}^2}{8s}\right)W(s)\right],$$

$$\bar{\sigma}_{q\bar{q}\to s\bar{s}}(s) = \frac{8\pi\alpha_{\rm s}^2}{27s}\left(1+\frac{2m_{\rm s}^2}{s}\right)W(s). \qquad W(s)=\sqrt{1-4m_{\rm s}^2/s}$$

**Infinite QCD resummation: running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu \equiv \sqrt{s}$.**
**USED: $m_s(M_Z) = 90 \pm 20\%$ MeV** **$m_s(1\mathbf{GeV}) \simeq 2.1 m_s(M_Z) \simeq 200$MeV.**

# WHY PERTURBATIVE STRANGENESS WORKS

**An essential prerequirement for the perturbative theory of strangeness production in QGP, is the relatively small experimental value $\alpha_s(M_Z) \simeq 0.118$, which has been experimentally established in recent years.**



**$\alpha_s^{(4)}(\mu)$ as function of energy scale $\mu$ for a variety of initial conditions. Solid line: $\alpha_s(M_Z) = 0.1182$ (experimental point, includes the error bar at $\mu = M_Z$).**

**At the scale of just above 1 GeV where typically thermal strangeness production in RHIC QGP occurs, perturbative theory makes good sense but is not completly reliable. Had $\alpha_s(M_Z) > 0.125$ been measured 1996 than our approach from 1982 would have been invalid.**

# Thermal averge of (strangeness p[roduction) reaction rates

**Kinetic (momentum) equilibration is faster than chemical, use thermal particle distributions $f(\vec{p}_1, T)$ to obtain average rate:**

$$\langle \sigma v_{\rm rel} \rangle_T \equiv \frac{\int d^3p_1 \int d^3p_2 \sigma_{12} v_{12} f(\vec{p}_1, T) f(\vec{p}_2, T)}{\int d^3p_1 \int d^3p_2 f(\vec{p}_1, T) f(\vec{p}_2, T)} \, .$$

**Invariant reaction rate in medium:**

$$A^{gg\to s\bar{s}} = \frac{1}{2}\rho_g^2(t)\, \langle \sigma v \rangle_T^{gg\to s\bar{s}} , \qquad A^{q\bar{q}\to s\bar{s}} = \rho_q(t)\rho_{\bar{q}}(t)\langle \sigma v \rangle_T^{q\bar{q}\to s\bar{s}} , \qquad A^{s\bar{s}\to gg,q\bar{q}} = \rho_s(t)\, \rho_{\bar{s}}(t)\, \langle \sigma v \rangle_T^{s\bar{s}\to gg,q\bar{q}} .$$

$1/(1+\delta_{1,2})$ **introduced for two gluon processescompensates the double-counting of identical particle pairs, arising since we are summing independently both reacting particles.**

**This rate enters the momentum-integrated Boltzmann equation which can be written in form of current conservation with a source term**

$$\partial_\mu j_s^\mu \equiv \frac{\partial \rho_s}{\partial t} + \frac{\partial \vec{v} \rho_s}{\partial \vec{x}} = A^{gg\to s\bar{s}} + A^{q\bar{q}\to s\bar{s}} - A^{s\bar{s}\to gg,q\bar{q}}$$

# Strangeness density time evolution

**in local restframe ($\vec{v}$) we have :**

$$\frac{d\rho_s}{dt}=\frac{d\rho_{\bar{s}}}{dt}=\frac{1}{2}\rho_g^2(t)\,\langle\sigma v\rangle_T^{gg\to s\bar{s}}+\rho_q(t)\rho_{\bar{q}}(t)\langle\sigma v\rangle_T^{q\bar{q}\to s\bar{s}}-\rho_s(t)\,\rho_{\bar{s}}(t)\,\langle\sigma v\rangle_T^{s\bar{s}\to gg,q\bar{q}}$$

**Evolution for $s$ and $\bar{s}$ identical, which allows to set $\rho_s(t)=\rho_{\bar{s}}(t)$.**
**Use detailed balance to simplify**

$$\frac{d\rho_s}{dt}=A\left(1-\frac{\rho_s^2(t)}{\rho_s^2(\infty)}\right)\,,\qquad A=A^{gg\to s\bar{s}}+A^{q\bar{q}\to s\bar{s}}$$

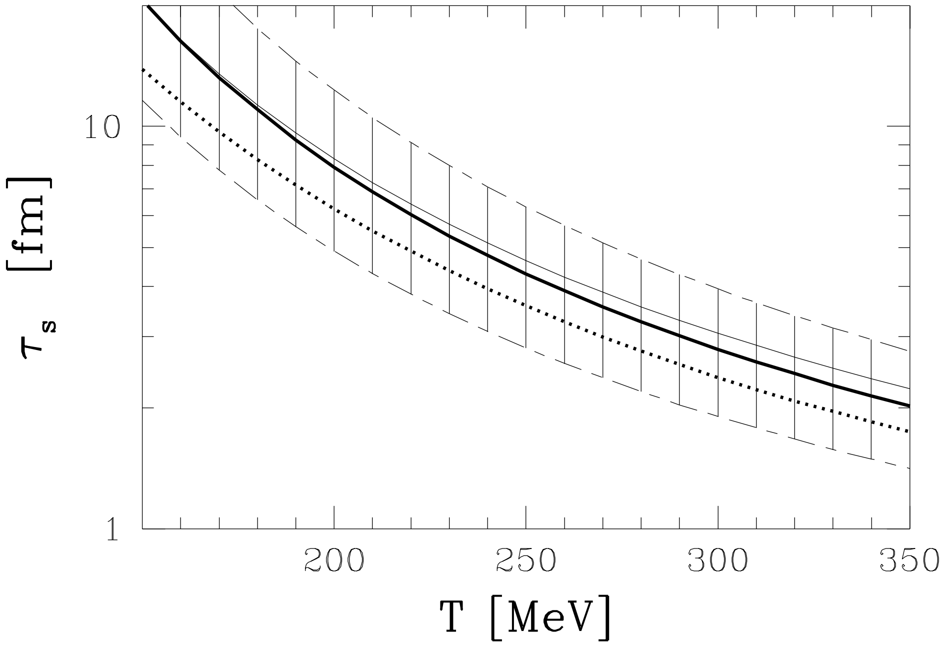
**The generic solution at fixed $T$ ($\rho\propto\tanh$) implies that in all general cases there is an exponential approach to chemical equilibrium**

$$\frac{\rho_s(t)}{\rho_s^\infty}\longrightarrow 1-e^{-t/\tau_s}$$

**with the characteristic time constant $\tau_s$:**

$$\boxed{\tau_s\equiv\frac{1}{2}\frac{\rho_s(\infty)}{(A^{gg\to s\bar{s}}+A^{q\bar{q}\to s\bar{s}}+\ldots)}}\qquad\boxed{A^{12\to 34}\equiv\frac{1}{1+\delta_{1,2}}\rho_1^\infty\rho_2^\infty\langle\sigma_s v_{12}\rangle_T^{12\to 34}\,.}$$

# Characteristic time constant and $\gamma_s$-evolution



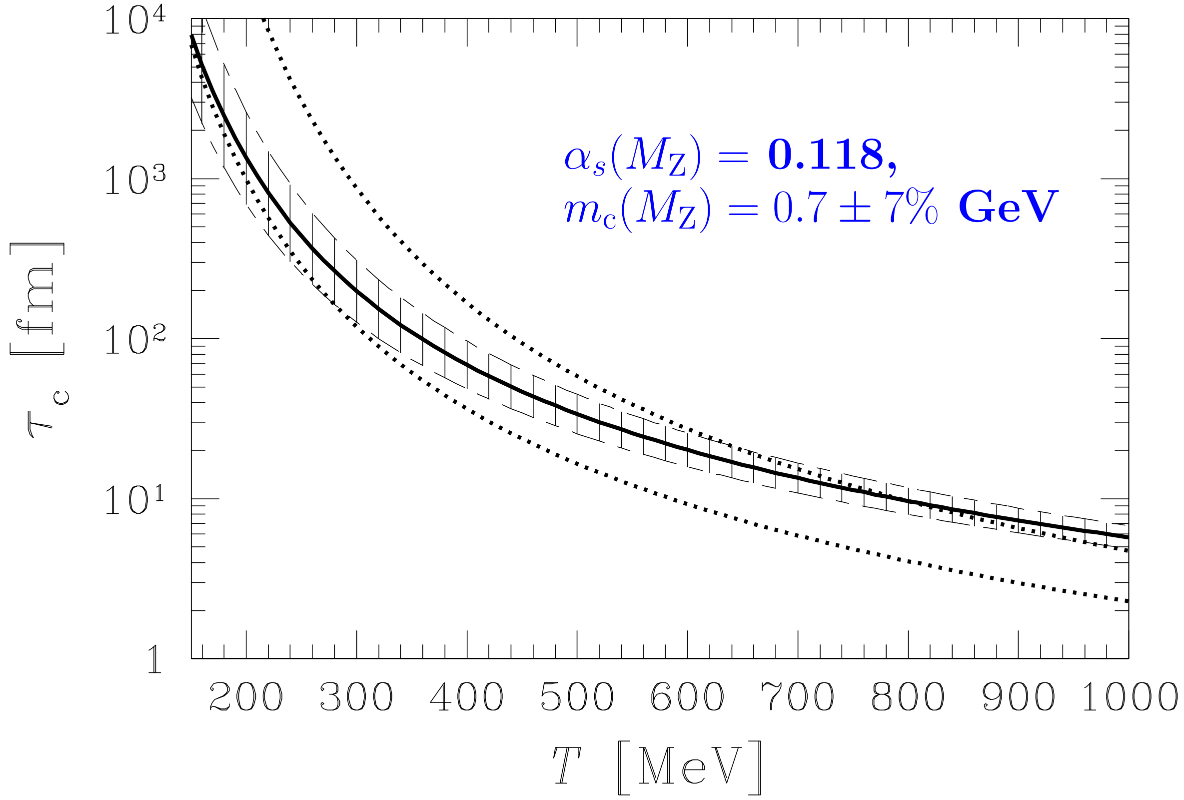
**$\sigma_{\rm QCD}^{\to s\bar{s}}$ gives $\tau_s$ similar to lifespan of the plasma phase!**
**Strange quark pair production dominated by gluon fusion: $G+G \to s\bar{s}$, also some (10%) $q\bar{q} \to s\bar{s}$, present; this is due to gluon collision rate.**
**ENTROPY CONSERVING expansion i.e. at SPS $T^3V$ =Const. (not yet long. scaling):**

$$2\tau_s \frac{dT}{dt}\left(\frac{d\gamma_s}{dT} + \frac{\gamma_s}{T} z \frac{K_1(z)}{K_2(z)}\right) = 1 - {\gamma_s}^2 , \quad \gamma_s(t) \equiv n_s(t)/n_s^\infty , \quad z = \frac{m_s}{T} , \quad K_i : \text{Besself}.$$

**Once $\gamma_s$ known, $\langle \rho_s(t)\rangle = \langle \bar{\rho}_s(t)\rangle = \int dx^3 \rho_s^\infty(T(t,x))\gamma_s(T(t,x),\dot{T}(t,x))$;**
**evolution till $t \to t_f$,but effectively production stops for $T < 180$ MeV.**

# What about charm? $m_s \to m_c$

**We expect that thermal charm production is of relevance only for $T \to m_c(1\,\mathbf{GeV}) \simeq 1.5\,\mathbf{GeV}$, probably not accessible.**



**Lower dotted line: for fixed $m_c = 0.9\,\mathbf{GeV}$, $\alpha_s = 0.35$;**
**upper doted line: for fixed $m_c = 1.5\,\mathbf{GeV}$, $\alpha_s = 0.4$ .**
**Equillibrium density for $\rho_c^\infty(m_c \simeq 1.5\,\mathbf{GeV})$.**

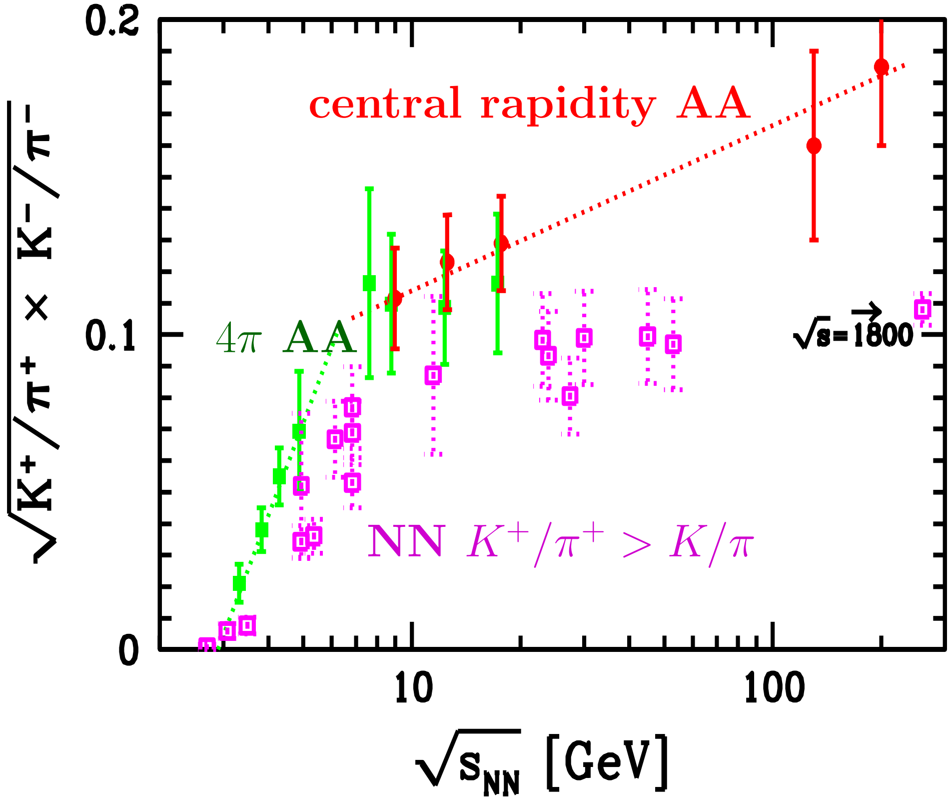
**Charm is produced relatively abundantly in first parton collisions. Benchmark: 10 $c\bar{c}$ pairs in central Au–Au at RHIC-200. This yield is greater than the expected thermal equilibrium yield at hadronization of QGP. Charmonium enhancement by recombination.**

# Probing strangeness excitation by ratio $K/\pi$

**The particle yield products**

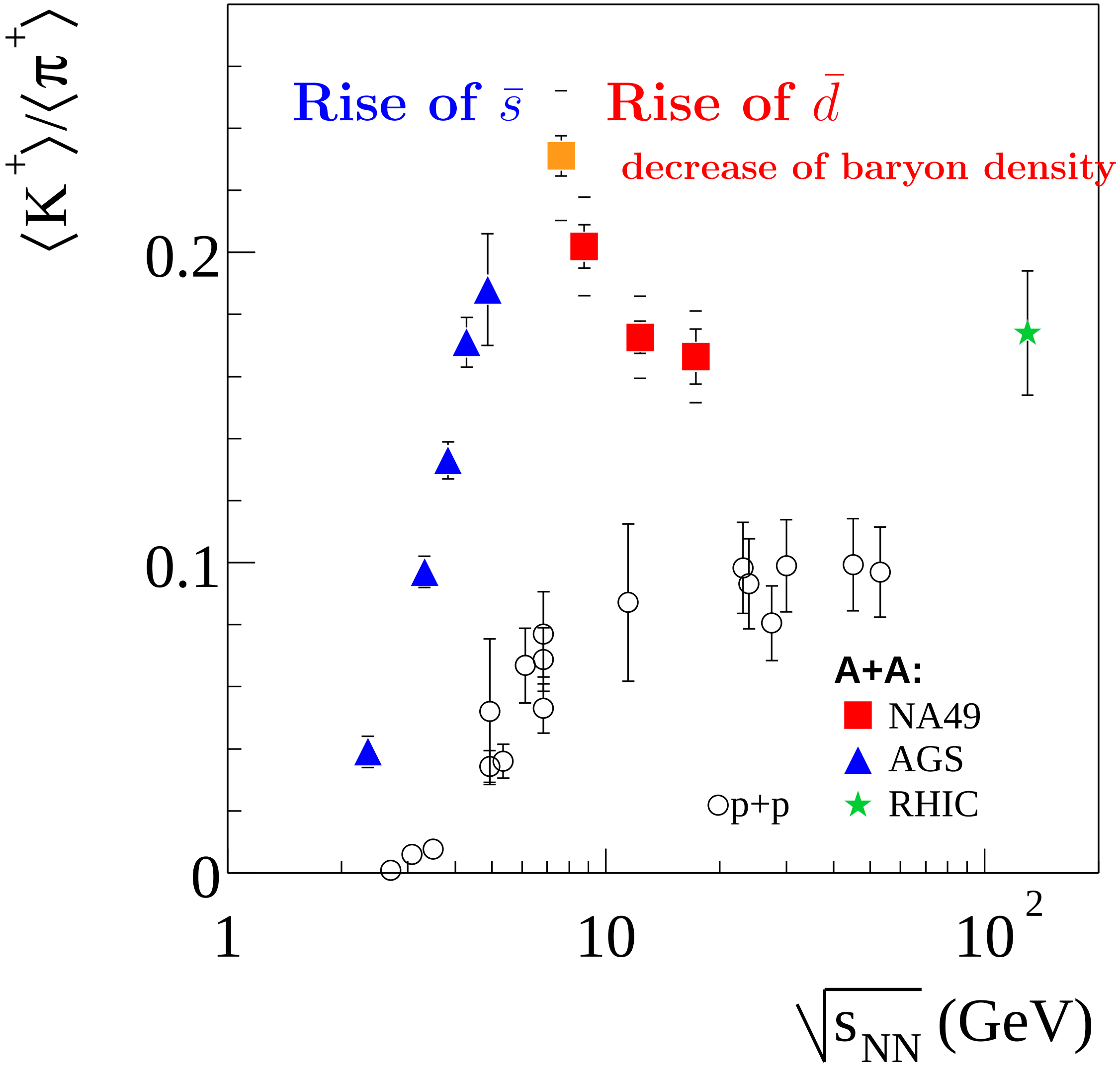
$$K \equiv \sqrt{K^+(u\bar{s})K^-(\bar{u}s)} \propto \sqrt{\lambda_u/\lambda_s\ \lambda_s/\lambda_u} \qquad \pi \equiv \sqrt{\pi^+(u\bar{d})\pi^-(\bar{u}d)} \propto \sqrt{\lambda_u/\lambda_d\ \lambda_d/\lambda_u}$$

**are much less dependent on chemical conditions including baryon density.**



**There is a notable enhancement in $K/\pi$ above the $K^+/\pi^+$ ratio recorded in $pp$ reactions, which provides an upper limit on $K/\pi$. There is a clear change in the speed of rise in the $K/\pi$ ratio at the lower energy limit at SPS; This combined with change in nuclear compression results in a peak in the $K^+/\pi^+$.**

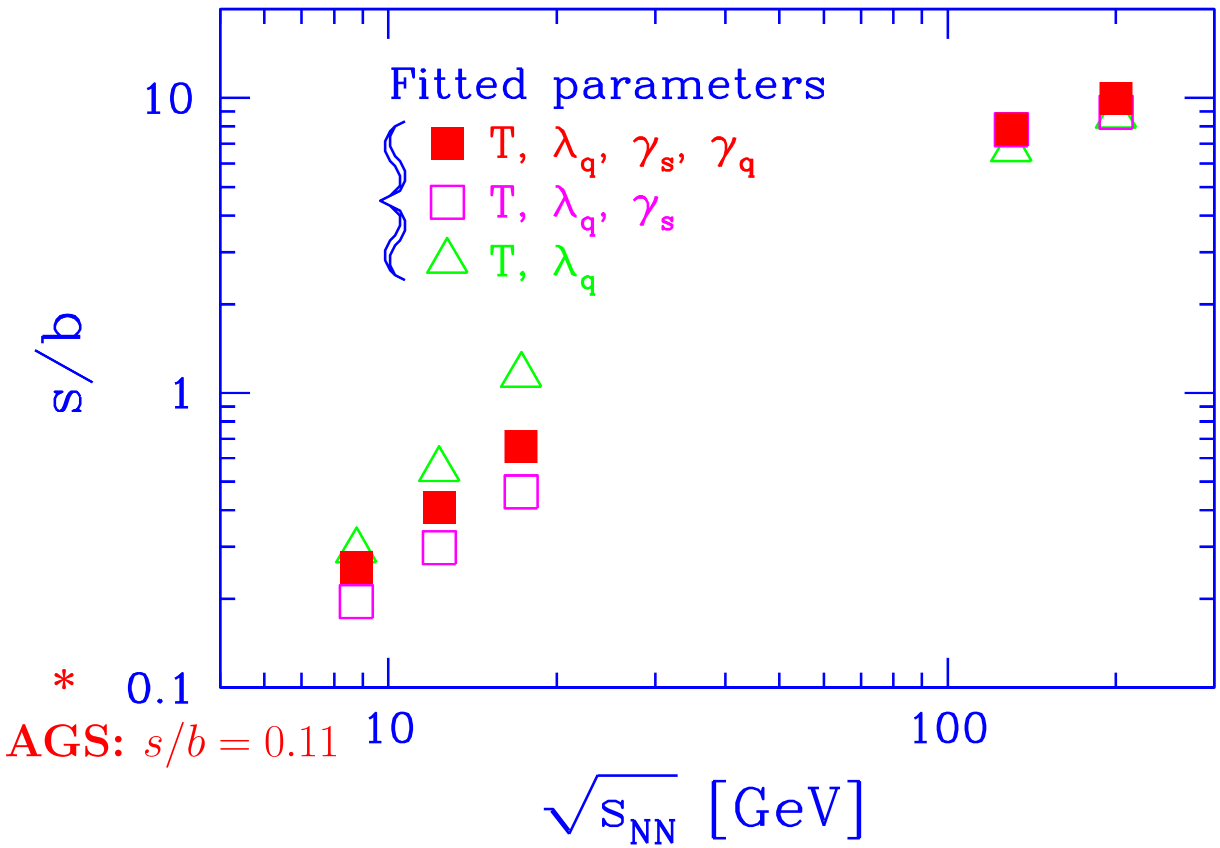
# More SPECTACULAR: Marek Gaździcki study of $\bar{s}/\bar{d}$



**The ‘peak’ is result of two effects: approach to saturation of strangeness, followed by reduction of baryon density which allows growth of $\bar{d}$.**

**To confirm this let us eliminate from the presented measurement the last effect:**

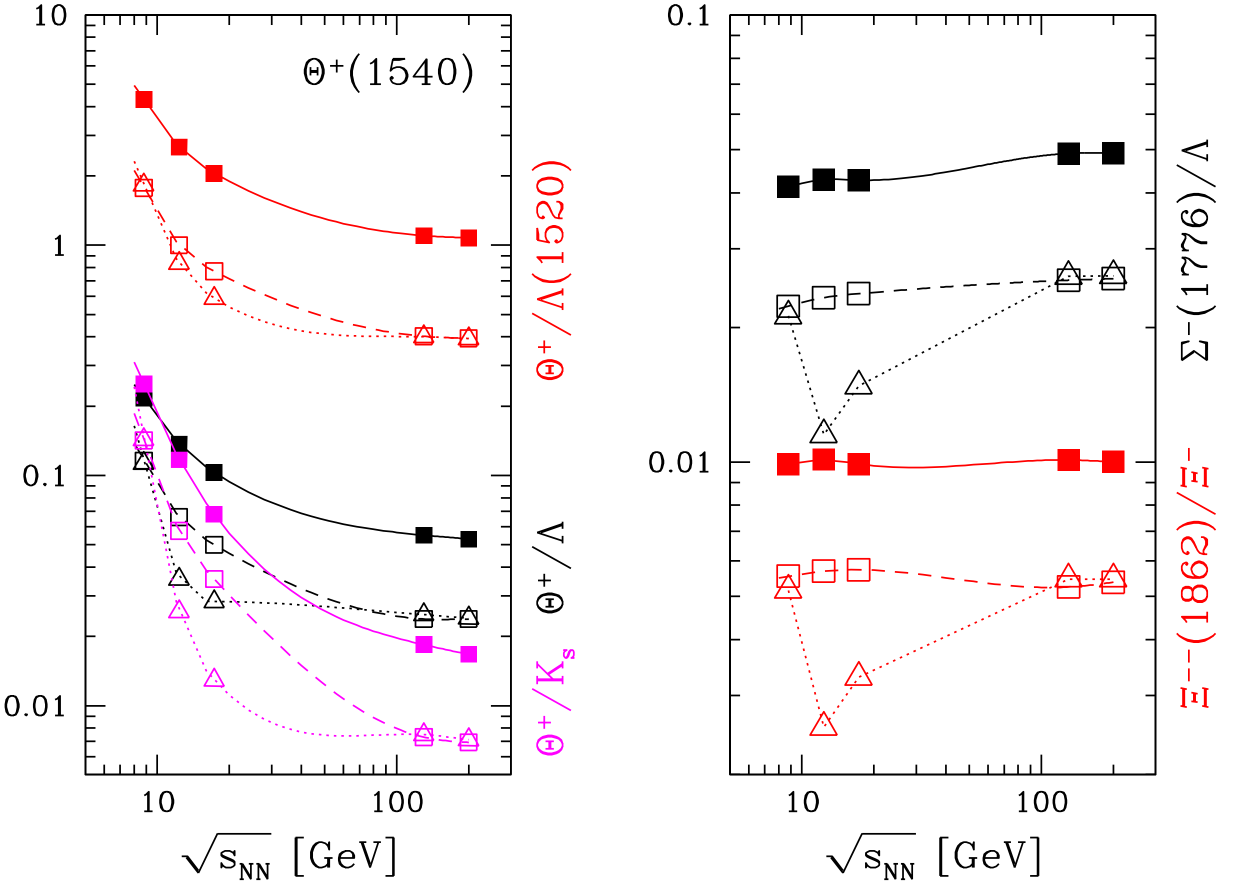
# STRANGENESS vs NET BARYON CONTENT: requires fit to yield data



**Strangeness per thermal baryon deposited within rapidity slice (RHIC) or participating in the reaction (AGS, SPS) grows rapidly and continuously. YIELD MUCH GREATER THAN IN NN-REACTIONS AGS with SHARE, other results with earlier programs, soon SHARE.**

# Excursion to Pentaquarks

**Statistical hadronization allows to explore the rate of production of pentaquarks which are very sensitive to chemical potentials: $\Theta^+(1540)[uudd\bar{s}]$ ('wrong strangeness' baryon) and $\Xi^{--}(1862)[ssqq\bar{q}]$, $\Sigma^-(1776?)[sqqq\bar{q}]$. (PRC68, 061901 (2003), hep-ph/0310188)**



**Expected relative yield of $\Theta^+(1540)$(left); $\Xi^{--}(1862)$ and $\Sigma^-(1776?)$ (right), based on statistical hadronization fits at SPS and RHIC: solid lines $\gamma_s$ and $\gamma_q$ fitted; dashed lines $\gamma_s$ fitted, $\gamma_q = 1$; dotted lines $\gamma_s = \gamma_q = 1$.**

# Some issues in description of hadron yields

1. **FAST phase transformation implies chemical nonequilibrium, see 'Gaździcki horn':** the phase space density is in general different in the two phases. To preserve entropy (valance quark pair number) across the phases need a jump in the phase space occupancy parameters $\gamma_i$. **This replaces the jump in volume in a slow reequilibration with mixed phase.**
2. **Incorporate the complete tree of resonance decays please note: not only for yields but also most important for spectra.**
3. **Production weight with width of the resonances accounts for experimental reaction rates**

**Full analysis of experimental results requires a significant numerical effort.** Short-cut projects produce results which alter physical conclusions. **For this reason the Kraków-Tucson collaboration produced a public package SHARE Statistical Hadronization with Resonances which is available e.g. at http://www.physics.arizona.edu/˜torrieri/SHARE/share.html**

**Lead author: Giorgio Torrieri.**

**IN FUTURE: we hope that the more accurate, standardized and debugged hadronization studies will reduce misunderstandings**

# Charm and bottom at LHC

**Given high energy threshold charm (and certainly bottom)heavy flavor is believed to be produced predominantly in initial parton collisions and not in thermal relatively soft collisions. Will it thermalize?**

$$Y_{c\bar{c}} \simeq 150-300; \qquad Y_{b\bar{b}} \simeq 5-15$$

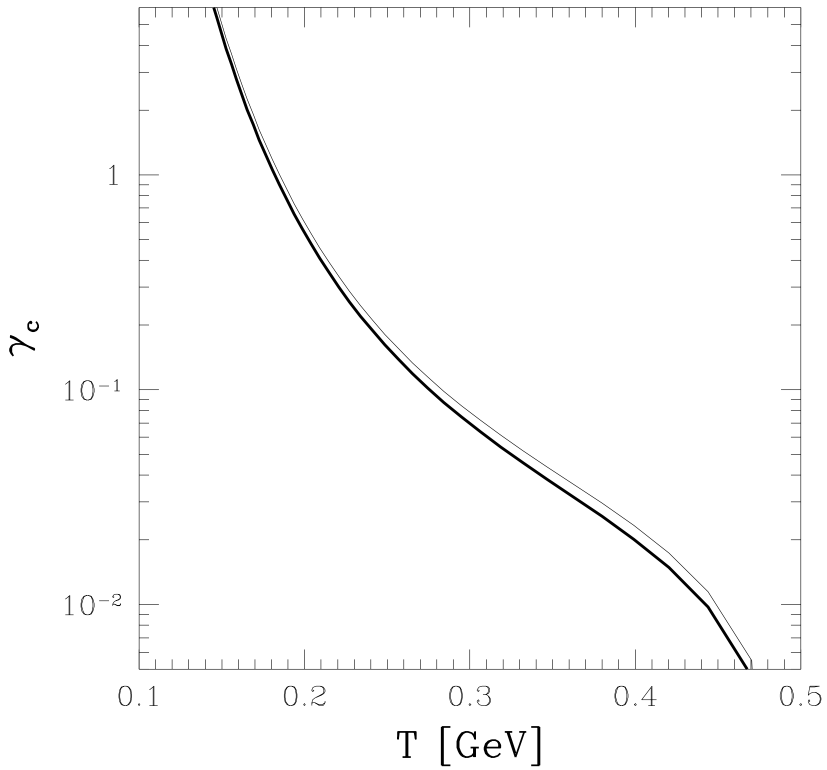
**Precise prediction is a challenge to nLO pQCD since it requires parton distribution and initial time evolution within colliding nuclei. Thermal yields are at 10-30% for charm, negligible for $b\bar{b}$.**

**No significant reannihilation expected in dense matter evolution. The phase space occupancy rises rapidly. The way it works: assuming effective thermalization of local distributions, the integral of the Boltzmann spectrum yields at each local temperature $T$:**

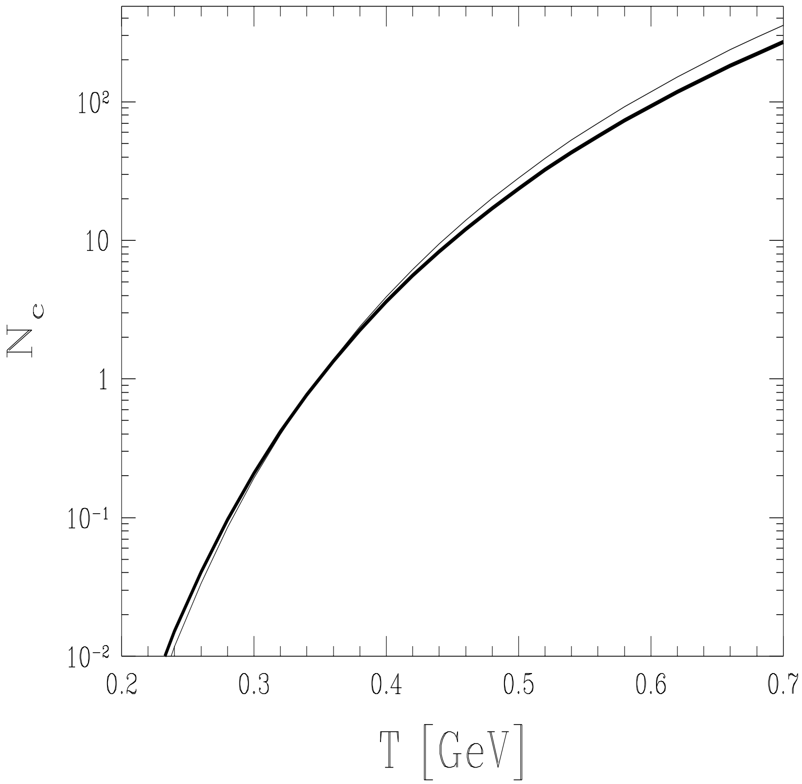
$$N_c = k\,VT^3\,\gamma_c(t)\,\sqrt{\left(\frac{m}{T(t)}\right)^3}\,e^{m/T(t)}, \qquad VT^3 = \textbf{Const.}, \qquad k=\frac{g}{2\pi^2}\sqrt{\frac{\pi}{2}}.$$

**Since at hadronization $m_c/T \simeq 10$ and $m_b/T \simeq 30$ the thermal yields need to be multiplied by large $\gamma_c$, or resp. $\gamma_b$ to maintain the initially produced yield. We expect ABOVE equilibrium yields. Since e.g. $J/\Psi \propto \gamma_c^2$ we expect multi charmed meson, baryon production enhancement.**

# Thermal Charm Example at LHC



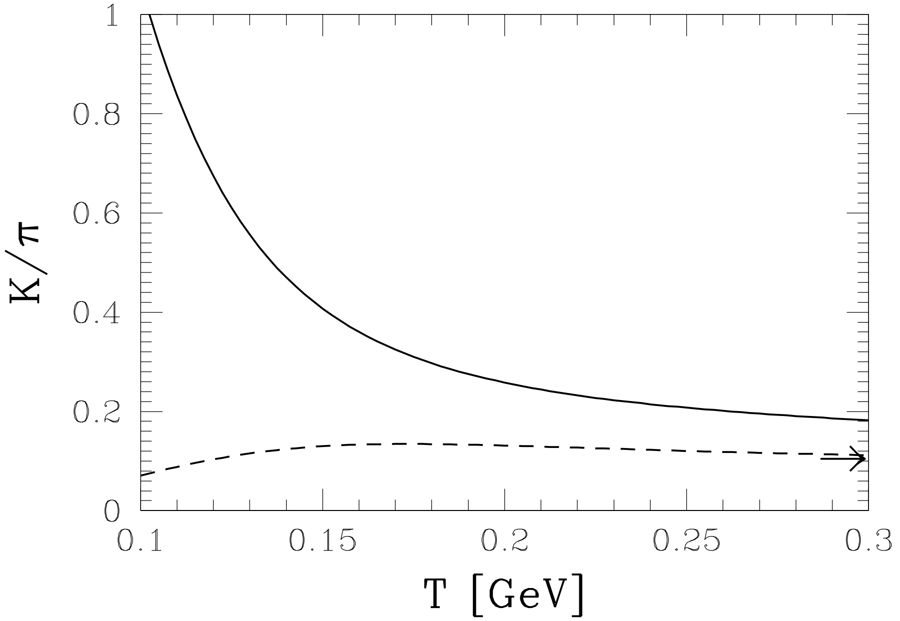
thermal charm as function $T$, the time dependent local temperature.



**Total thermal charm yield as function of initial temperature.**

## Strangeness at LHC has some surprises

**At LHC fast dilution of initial high density phase. Strangeness is slower to reequilibrate chemically. Initial high yield preserved, this leads to overpopulation of phase space at hadronization. Here, let us estimate the maximum possible. Limits generated by condensation boundary. For pions, an kaons limits are:** $\pi : \gamma_q^2 \leq e^{\frac{m_\pi}{T}}$, $K : \gamma_s\gamma_q \leq e^{\frac{m_K}{T}} \to \gamma_s/\gamma_q \leq e^{\frac{m_K - m_\pi}{T}} \to K/\pi$



**Expect a shift toward strange meson production. Aside of $K/\pi$ shown, the enhanced $\gamma_s/\gamma_q$ will enhance other strange particles.**

# Near term tasks for hadronic/flavor QGP signatures

1. **New directions: LHC Flavor signatures = Signatures of flavor**
   - **Mixed charm-bottom states $B_c(b\bar{c})$ etc. will be made extremely abundantly (comparing to $pp$) in the quark soup at LHC, this opens up precision laboratory of atomic QCD**
   - **Charm and bottom yield at LHC: in depth tests of small-$x$ structure functions**
2. **Search for onset of deconfinement as function of energy and of system size Marek Gaździcki with NA49**
3. **Resonances, statistical hadronization, bulk matter dynamics, critical (phase boundary) chemical nonequilibrium**

**Furthermore: recall**
**1) $J/\Psi$ suppression turns into enhancement as soon as ‘enough’ charm pairs per reaction available.**
**2) Hard parton jets: is it absorption of decay products, or energy stopping or both; relation to QGP physics?**
**3) Dileptons and photons are predominantly produced in final state meson decays**

## Is QGP discovered??

**At SPS and RHIC: Predicted QGP behavior confirmed by strangeness and strange antibaryon enhancement which imply strange quark mobility. Enhanced source entropy content consistent with initial state thermal gluon degrees of freedom, also expected given strangeness enhancement. Chemical properties consistent with sudden hadron production in fast, filamenting breakup of QGP.**

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**Furthermore at RHIC: quark coalescence explains features of non-azimuthally symmetric strange particle production. Early thermalization and strange quark participation in matter flow. Jet quenching indicates dense and highly absorptive matter.**

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**Strangeness excitation function fingerprints QGP as the new state of matter: Probable onset of ‘valon’ quark deconfinement at AGS;**

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## NEAR FUTURE

**The deconfinement specific hadronic ‘deep’ probe at LHC is charm and bottom flavor**

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**Search for deconfinement boundary next priority**

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