STRANGENESS AND THE DISCOVERY OF QUARK-GLUON PLASMA

Bergen, 11 June, 2004

[I] **Why the effort:** **Recreate early Universe; Probe the vacuum; Energy to matter: the (al)chemy of particle production:**

[II] **Accelerators and measurements:** **CERN, BNL, Strangeness: yield enhancement, strange antibaryons, spectra**

[III] **Statistical hadronization:** **methods, importance, results**

[IV] **Strangeness and entropy: deep probes of QGP**

[V] **So what, there is QGP?** **a little excursion into the early Universe**

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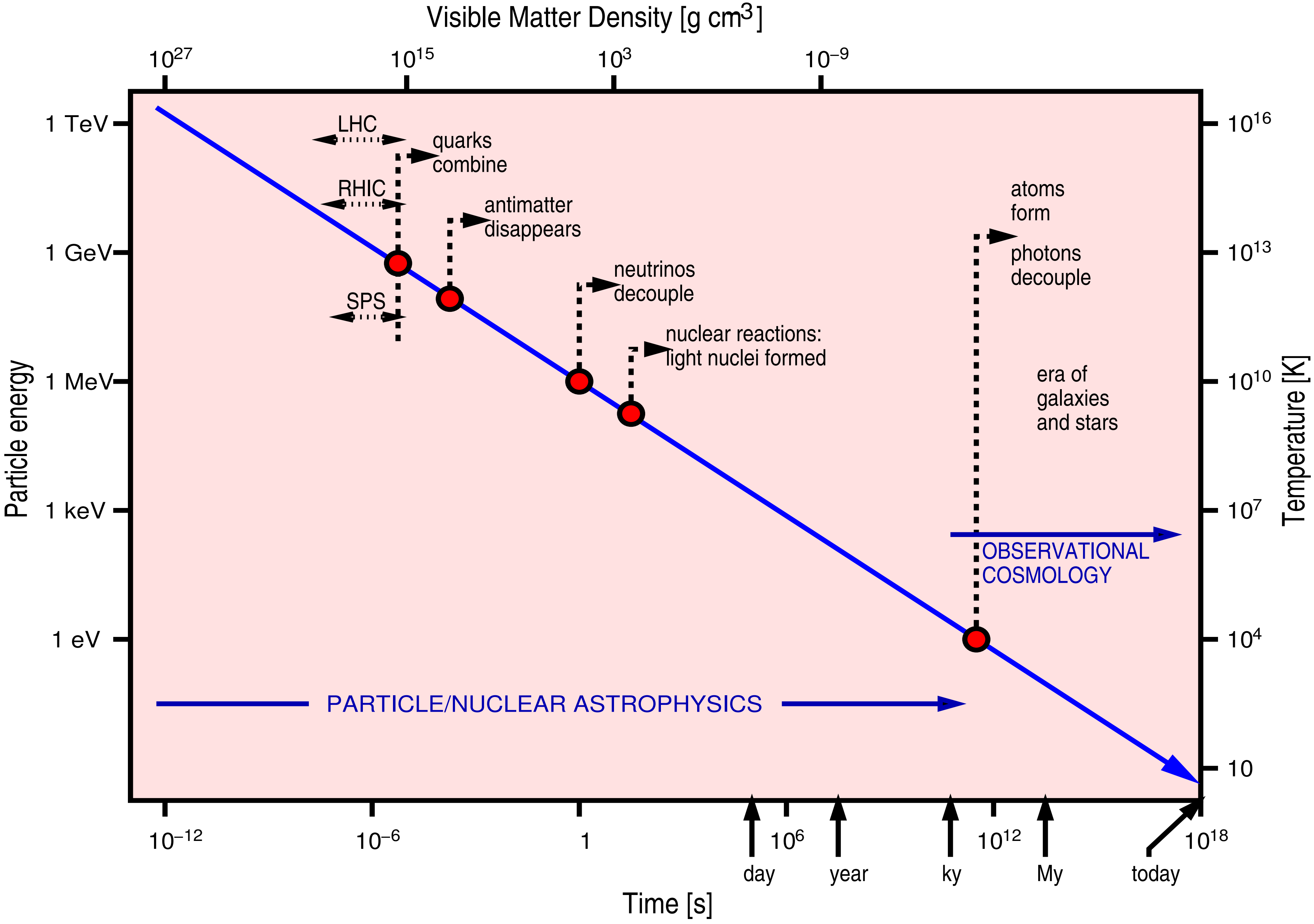
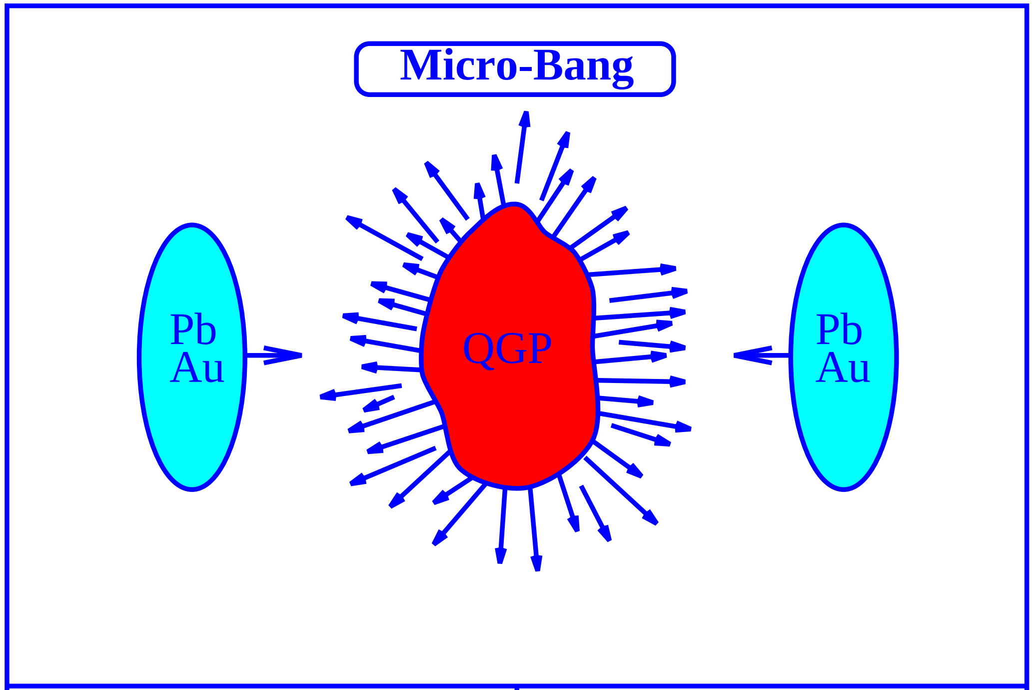
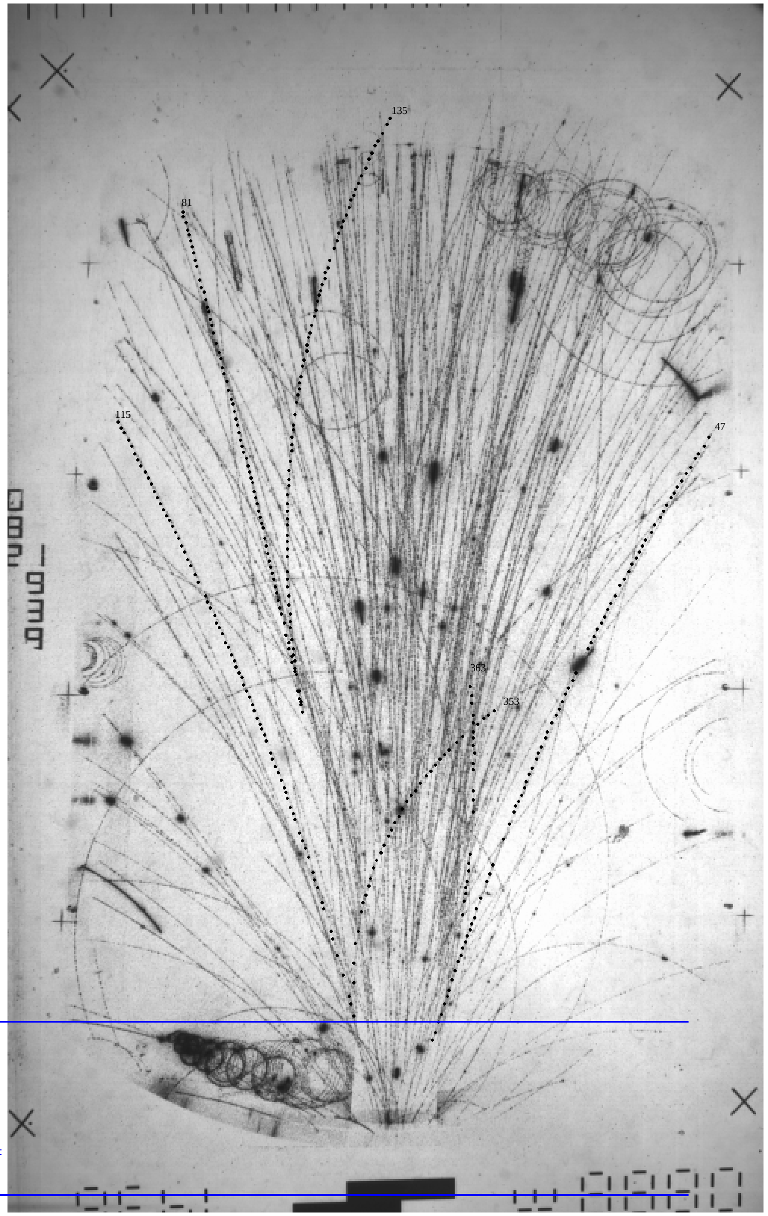
Particle/nuclear evolution of the Universe



RECREATING THE EARLY UNIVERSE IN THE LABORATORY



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

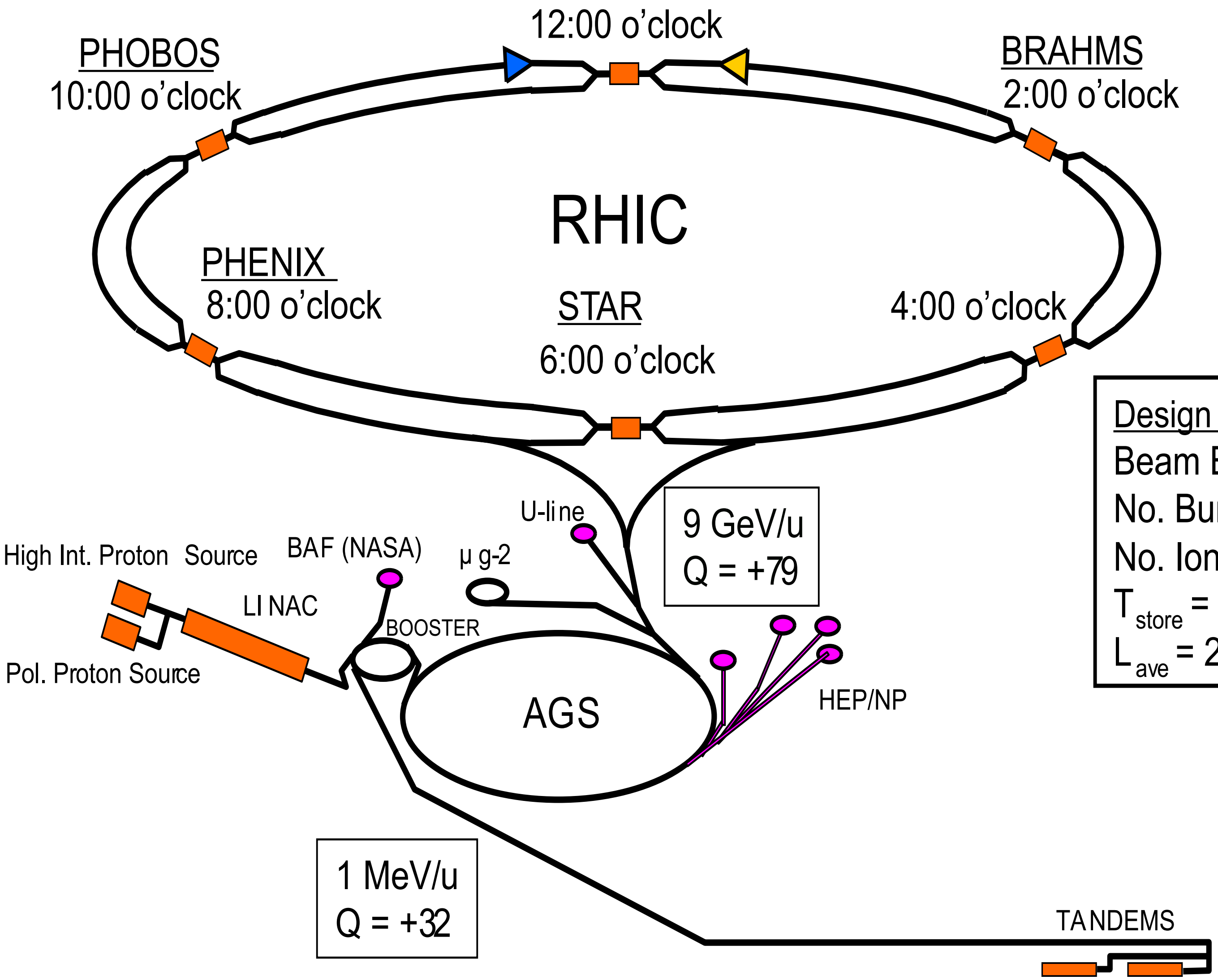


S–Ag Reaction at 200 AGeV

Order of Magnitude

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

BROOKHAVEN NATIONAL LABORATORY



Design Parameters:

Beam Energy = 100 GeV/u

No. Bunches = 57

No. Ions /Bunch = 1×10^{9}

T_{store} = 10 hours

$L_{ave} = 2\times 10^{26}\ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$

Relativistic Heavy Ion Collider: RHIC

What is QGP, and how we go about to find it

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.

What we need:

1) QGP equilibrium properties from QCD-lattice,
2) Understanding how to adapt these to the environment of heavy ion reactions,
3) Model of QGP hadronization into final particles,
4) Sensitive signatures of deconfinement: final particles always hadrons.

NOT A SINGLE SMOKING GUN type observation, NOT a'new' particle.
We need to pursue global, systematic and physics-consistent understanding of all experimental results. Where we are not able (yet) to evaluate results in detail, at least in principle interpretation should be available.

When reaching a consensus about discoveries, we are also remembering the difference between: verified predictions, accompanied by expected global behavior, and inventive/clever often negative post-dictions, limited in scope to punctual experimental data interpretation.

QGP is FULL OF STRANGENESS AND ENTROPY

Vacuum and QCD

Quantum vacuum is polarizable: see atomic level shifts
Quantum fluctuations/structure in 'space devoid of matter'
Quantum structure of gluon-quark fluctuations:
glue and quark condensate

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

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

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

We aim to verify the new paradigm: the Vacuum structure a key element for quark confinement and hadron structure (masses etc).

Vacuum and Laws of Physics

Vacuum structure controls early Universe properties
Vacuum determines inertial mass of all matter particles

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

Vacuum determines interactions, symmetry breaking, etc.....

Strangeness: a practical QGP diagnostic tool

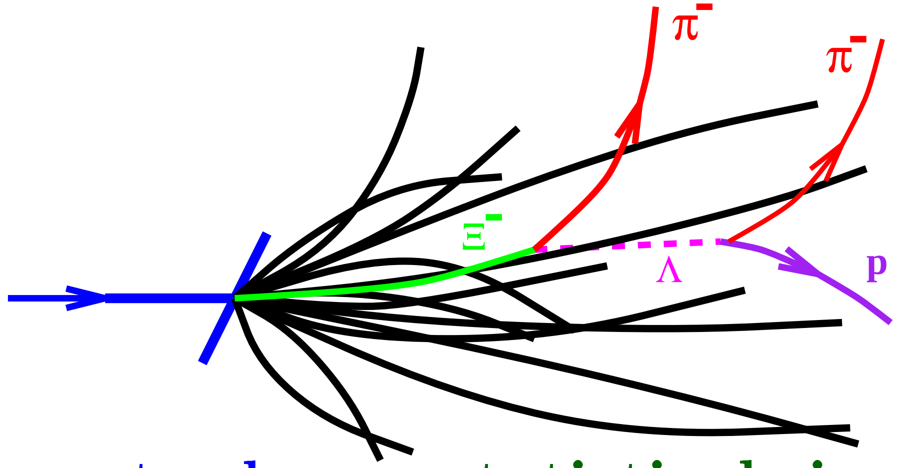
EXPERIMENTAL REASONS

- **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

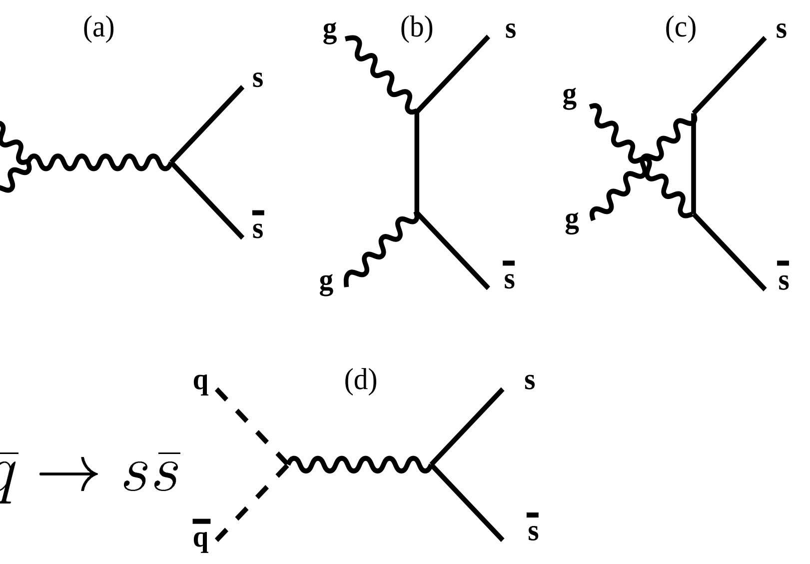
- **production of strangeness in gluon fusion** $\boxed{GG \to s\bar{s}}$
  strangeness linked to gluons from QGP;

dominant processes:

$$GG \to s\bar{s}$$

abundant strangeness =evidence for gluons

10–15% of total rate: $q\bar{q} \to s\bar{s}$



- **coincidence of scales:**

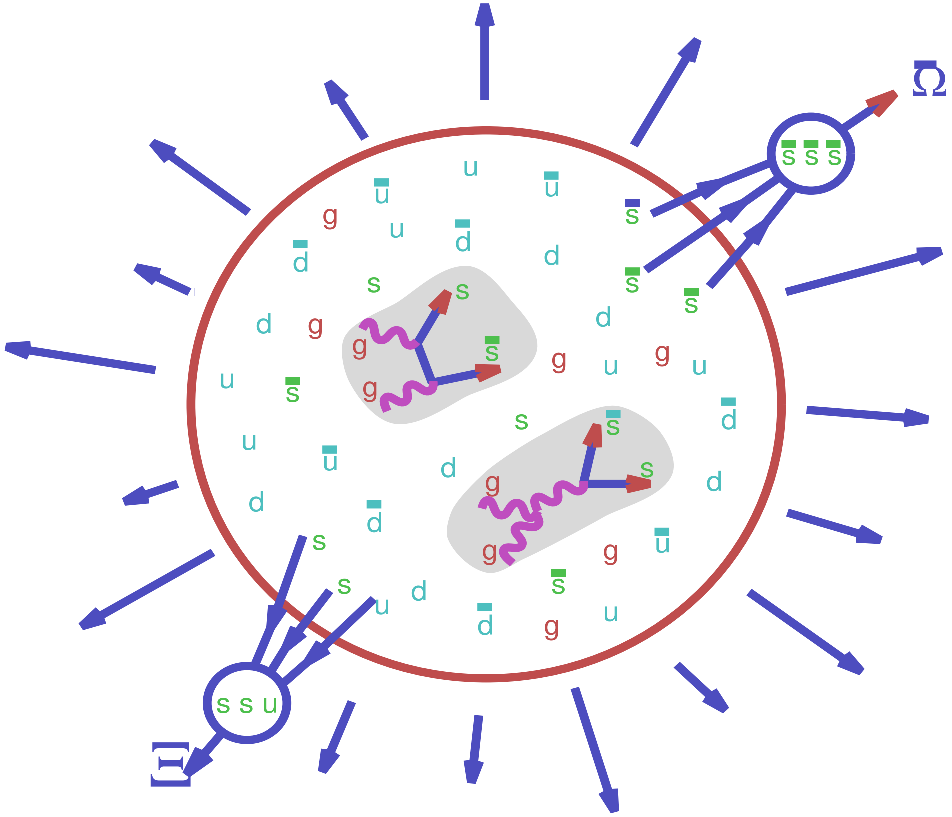
$$\boxed{m_s \simeq T_c} \to \boxed{\tau_s \simeq \tau_{\mathrm{QGP}}} \to$$

strangeness a clock for QGP phase

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

(Al)chemy of particle production: STRANGENESS AND ENTROPY

Stable matter is made of up and down quarks, there are further (listed by increasing mass) STRANGE, CHARM, BEAUTY AND TOP quarks which decay by weak interactions into lighter quarks.



QGP is an entropy rich gas in which hadrons are dissolved into constituents.

TWO STEP MECHANISM IN QGP

Hadron formation:

1. $GG \to s\bar{s}$ in QG-plasma
2. hadronization of pre-formed s, $\bar{s}$ quarks

Formation of complex rarely produced multi strange (anti)particles from QGP enabled by coalescence between s, $\bar{s}$ quarks made in different microscopic reactions; Enhancement of strange antibaryons progressing with strangeness content.

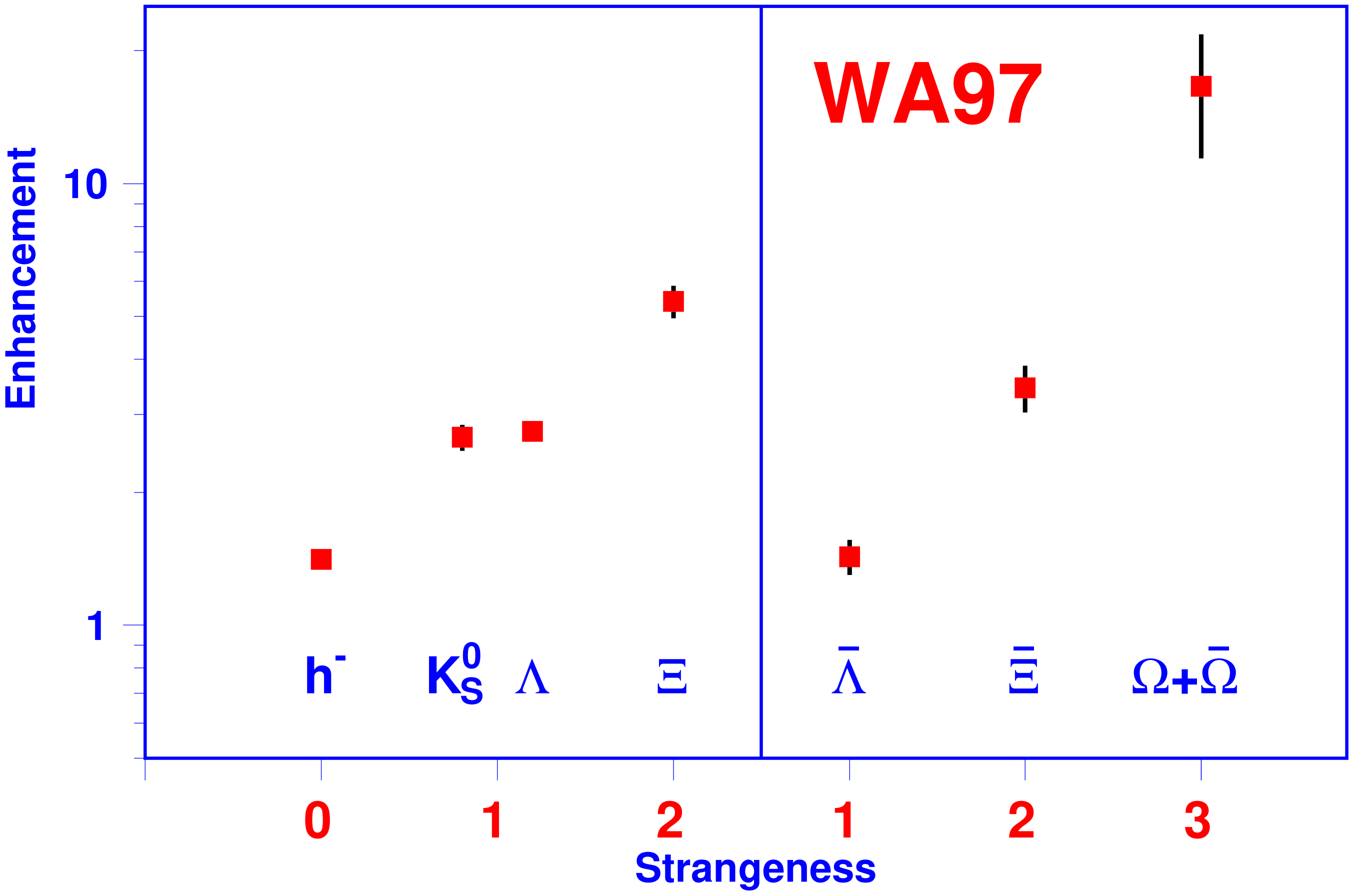
This is signature of quark mobility in the source.

RESULT: Enhancement of strange (anti)baryons progresses with strangeness content. First seen at CERN by WA97,work in progress by NA57, NA49, STAR at RHIC collaborations.

Study of QUARK-GLUON PLASMA properties at its final moments is possible

Retrospective: Strangeness Predictions/Discoveries

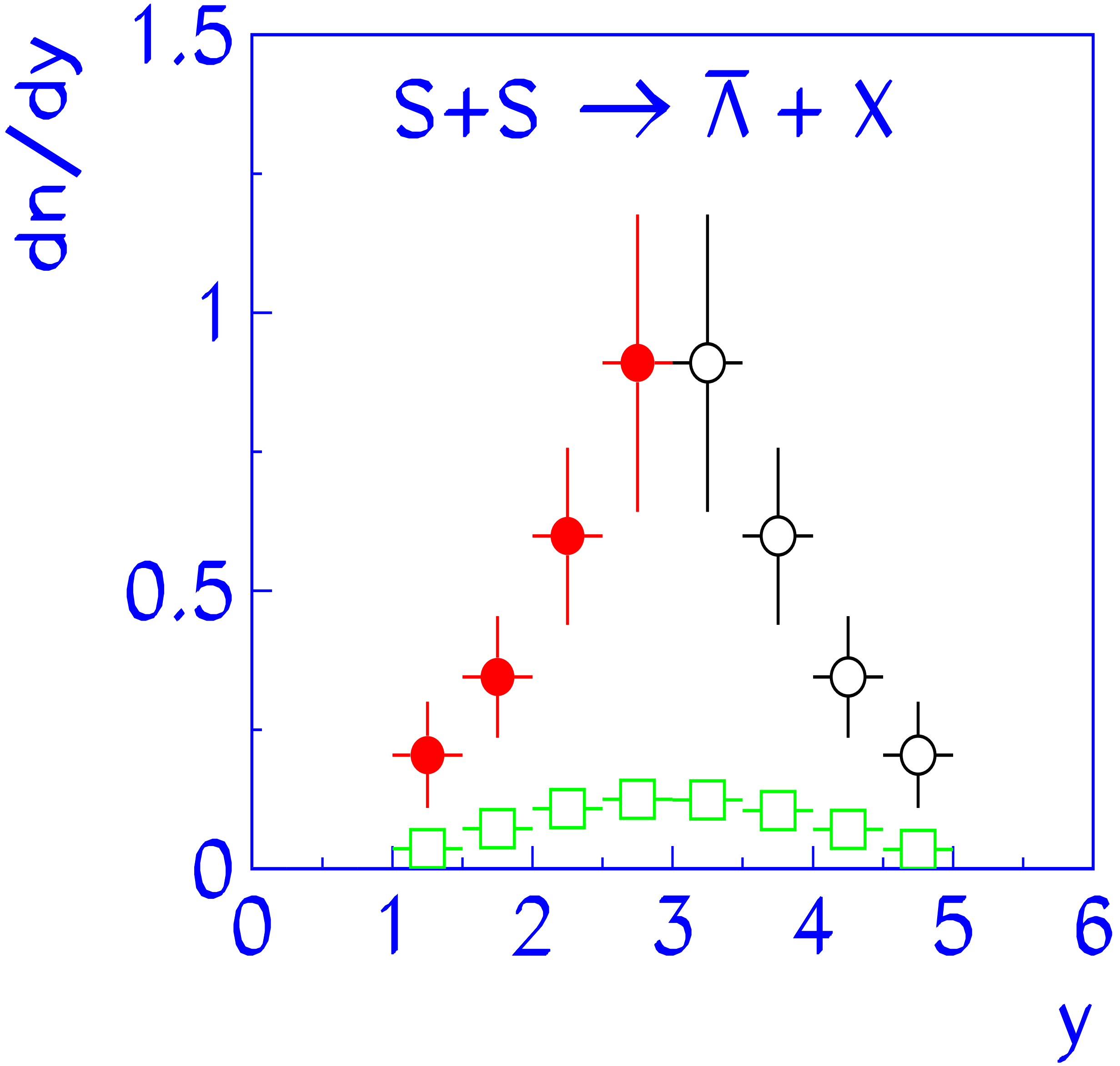
MULTISTRANGE (ANTI)HYPERON ENHANCEMENT



Enhancement GROWTH with
strangeness antiquark content.

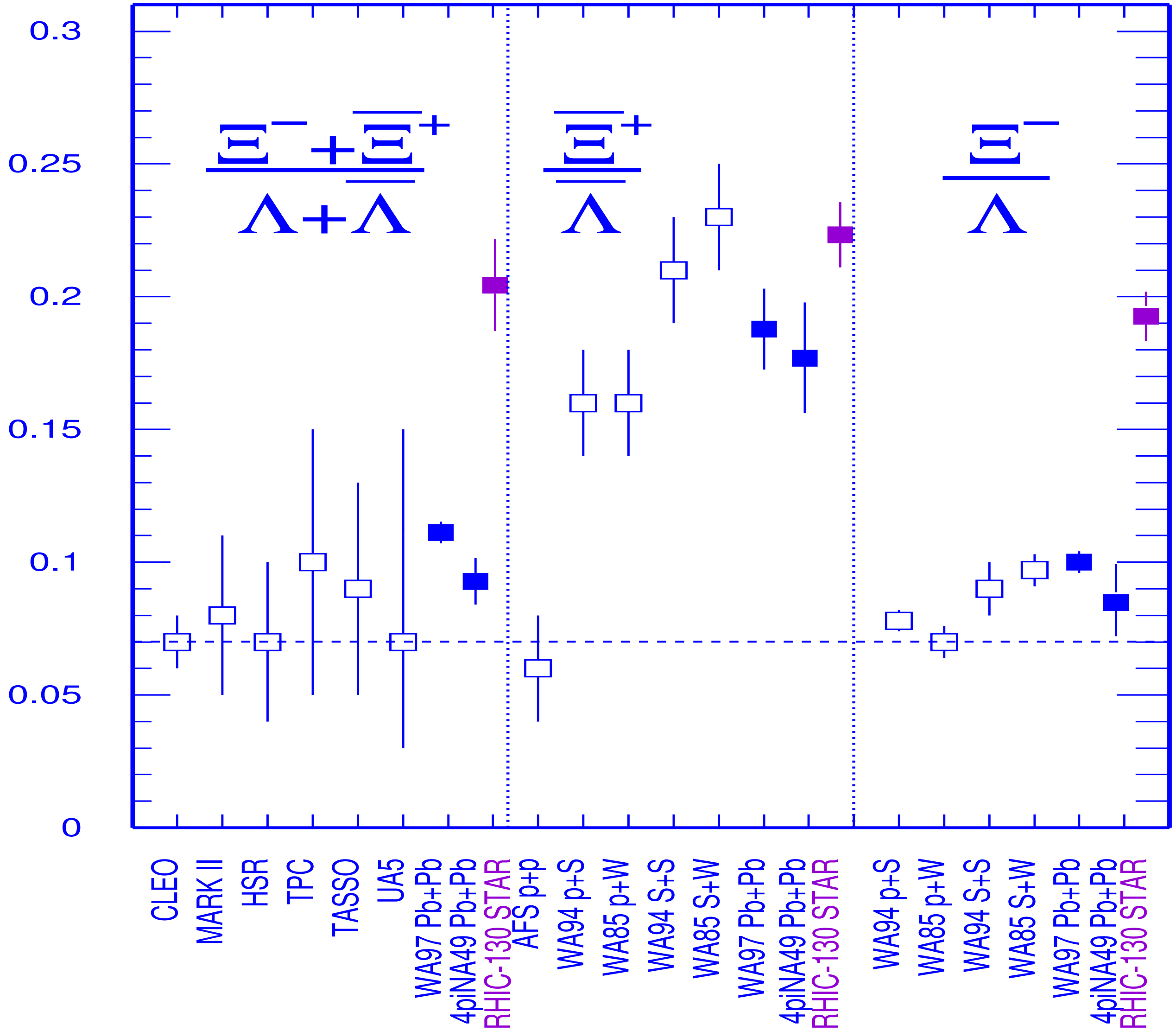
Enhancement is here defined with respect to the yield in p–Be collisions, scaled up with the number of collision 'wounded' nucleons.

Antibaryon excess IS at central CM rapidity



NA35II EXCESS $\overline{\Lambda}$ emitted from a central well localized source.
Background (squares) from multiplicity scaled NN reactions
forward (open circles) points: reflection at CM rapidity

MULTISTRANGE ANTI-HYPERON RATIOS:



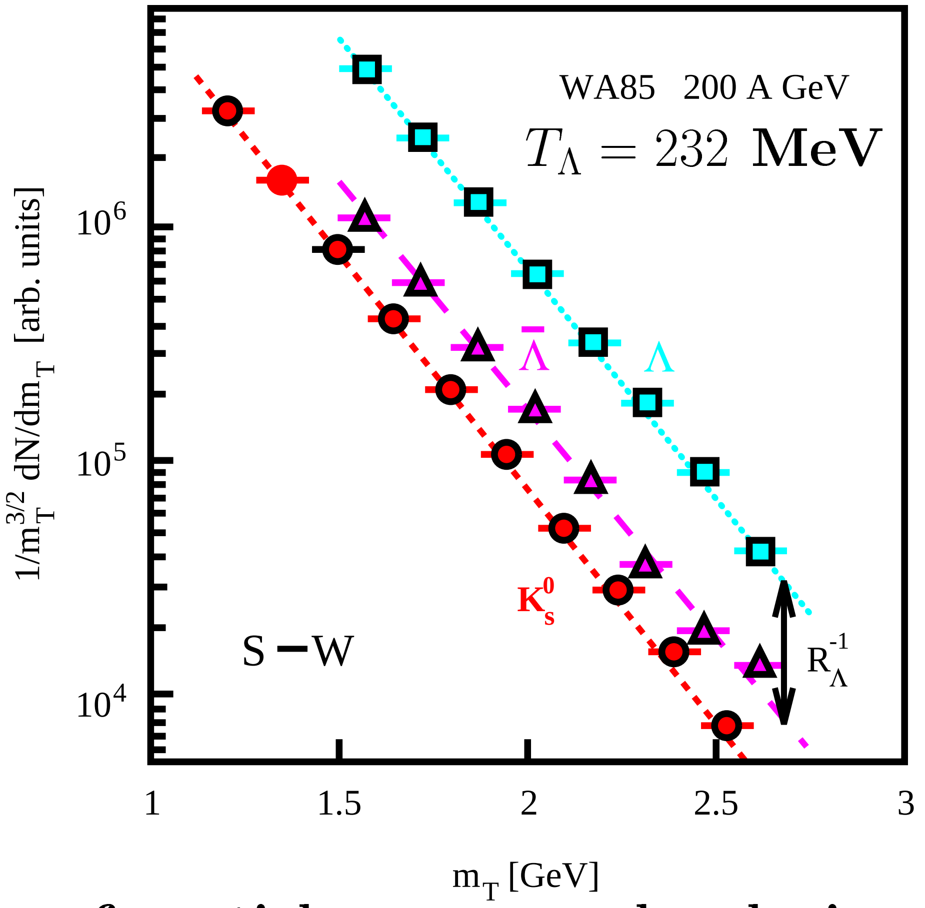
High $m_\perp$ slope universality

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

Why is the slope of baryons and antibaryons precisely the same?

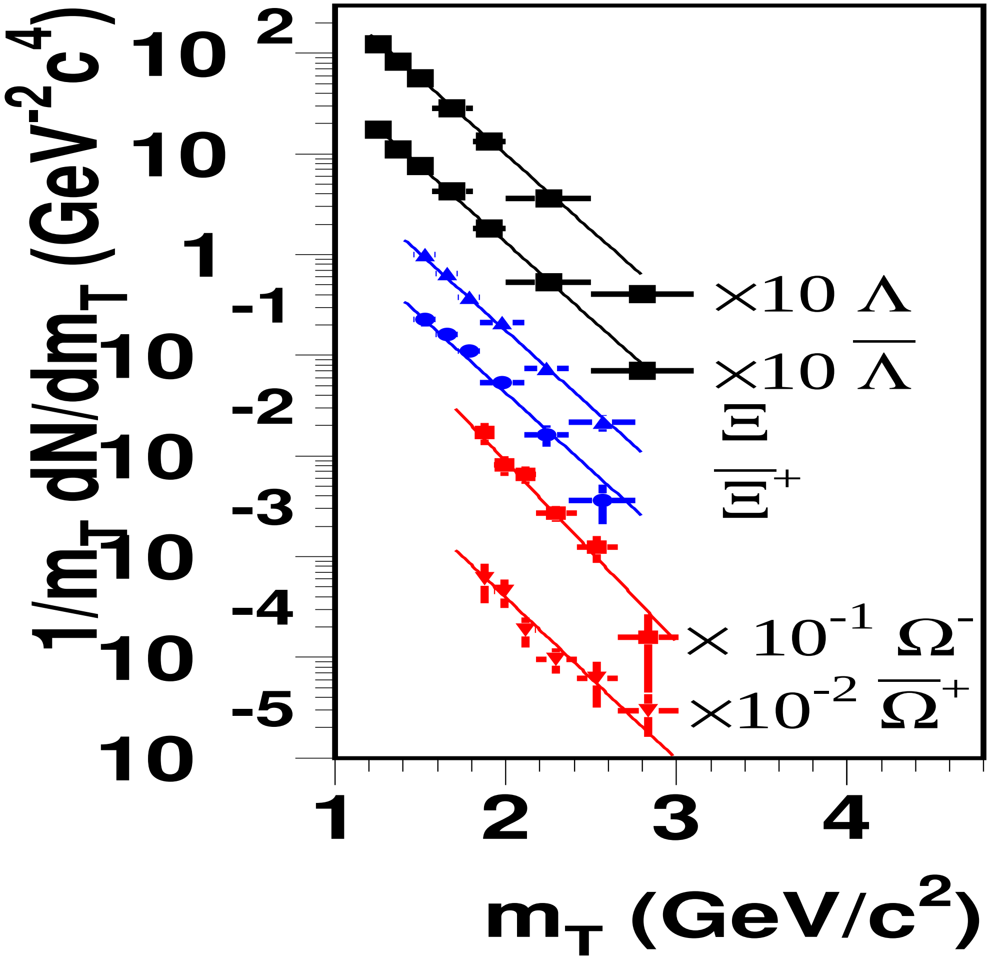
Why is the slope of different hyperons in same m_t range the same?

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^{Λ}	**289 ± 3**
$T^{\overline{\Lambda}}$	**287 ± 4**
T^{Ξ}	**286 ± 9**
$T^{\overline{\Xi}}$	**284 ± 17**
$T^{\Omega+\overline{\Omega}}$	**251 ± 19**



<u>Λ **within 1% of** $\overline{\Lambda}$</u>

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

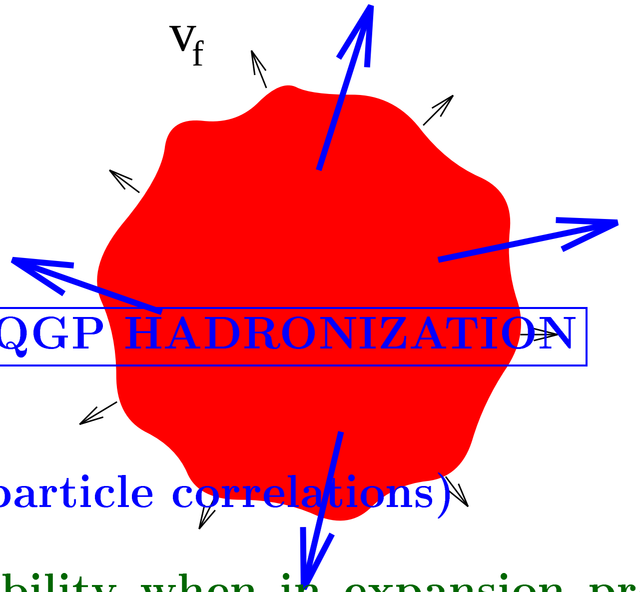
REACTION MECHANISM OF PARTICLE PRODUCTION

Bergen/Oslo experiments since 1991 (WA85, WA97) see symmetry of $m_\perp$ spectra of strange baryons and antibaryons, now also observed by NA49 and at RHIC.

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

Appears to be emission by a quark source into vacuum.
Fast hadronization confirmed today by HBT particle correlation analysis

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



Develop analysis tools viable in SUDDEN QGP HADRONIZATION

SLOW transformation is in contradiction to experiment (single particle spectra, 2-particle correlations)

Reaction mechanism: filamentation instability when in expansion pressure reverses (L. Csernai, Bergen et al, JR et al).

NEXT:
production of final state particles in Statistical Hadronization

HOW DOES STATISTICAL HADRONIZATION WORK?

For the 4π particle yields the particle abundance is proportional to phase space integrals – no influence of matter flow dynamics.

$$\frac{N_\pi}{V} = C g_\pi \int \frac{d^3p}{(2\pi)^3} \frac{1}{\gamma_q^{-2} e^{\sqrt{m_\pi^2+p^2}/T} - 1}, \qquad \gamma_q^2 < e^{m_\pi/T} \simeq (1.6)^2$$

$$\frac{N}{V} = C g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{1 + \gamma_q^{-3}\lambda_q^{-3} e^{E/T}} \qquad \frac{\overline{N}}{V} = C g_N \int \frac{d^3p}{(2\pi)^3} \frac{1}{1 + \gamma_q^{-3}\lambda_q^{+3} e^{E/T}}$$

Integrals easily computed. Proportionality constant C NOT A VOLUME for a dynamically evolving system.

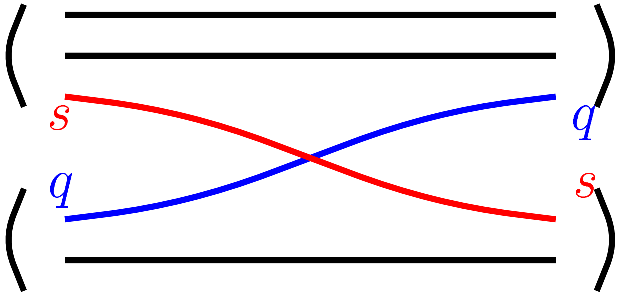
From study of particle yields and their fits to data we can not only extract the statistical parameters but also learn about unobserved particle yields. This allows to evaluate global properties of the system, such as strangeness, energy, entropy etc.

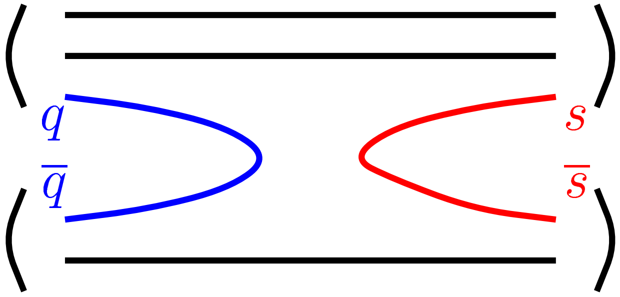
FOUR QUARKS: $s, \bar{s}, q, \bar{q} \rightarrow$ FOUR CHEMICAL PARAMETERS

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

HG-EXAMPLE: redistribution, production of strangeness

Relative chemical equilibrium **Absolute chemical equilibrium**





EXCHANGE REACTION λ_i

PAIR PRODUCTION REACTION γ_i

RATIOS OF PARTICLE YIELDS FIX CHEMICAL PARAMETERS

$$R_\Lambda = \frac{\overline{\Lambda}}{\Lambda} = \frac{\overline{\Lambda} + \overline{\Sigma}^0 + \overline{\Sigma}^* + \cdots}{\Lambda + \Sigma^0 + \Sigma^* + \cdots} = \frac{\bar{s}\bar{q}\bar{q}}{sqq} = \lambda_{\rm s}^{-2}\lambda_{\rm q}^{-4} = e^{2\mu_{\rm S}/T} e^{-2\mu_b/T}\,.$$

$$R_\Xi = \frac{\overline{\Xi^-}}{\Xi^-} = \frac{\overline{\Xi^-} + \overline{\Xi^*} + \cdots}{\Xi^- + \Xi^* + \cdots} = \frac{\bar{s}\bar{s}\bar{q}}{ssq} = \lambda_{\rm s}^{-4}\lambda_{\rm q}^{-2} = e^{4\mu_{\rm S}/T} e^{-2\mu_b/T}\,.$$

Sensitivity to nonequilibrium occupancy factors γ_i derives from comparison of hadron yields with differing q, s quark content e.g.:

$$\frac{\Xi^-(dss) + \Xi * + \ldots}{\Lambda(dds) + \Lambda * + \ldots..} \propto \frac{\gamma_d\gamma_s^2}{\gamma_d^2\gamma_s}\,\frac{g_\Xi\lambda_d\lambda_s^2}{g_\Lambda\lambda_d^2\lambda_s}\,.$$

note: $\gamma_q^2 \equiv \gamma_u\gamma_d, \quad \gamma_u \simeq \gamma_d$. Observation of $\gamma_q > 1, \gamma_s > 1$ implies rapid expansion of near equilibrium QGP, with final hadrons emitted directly from deconfined state.

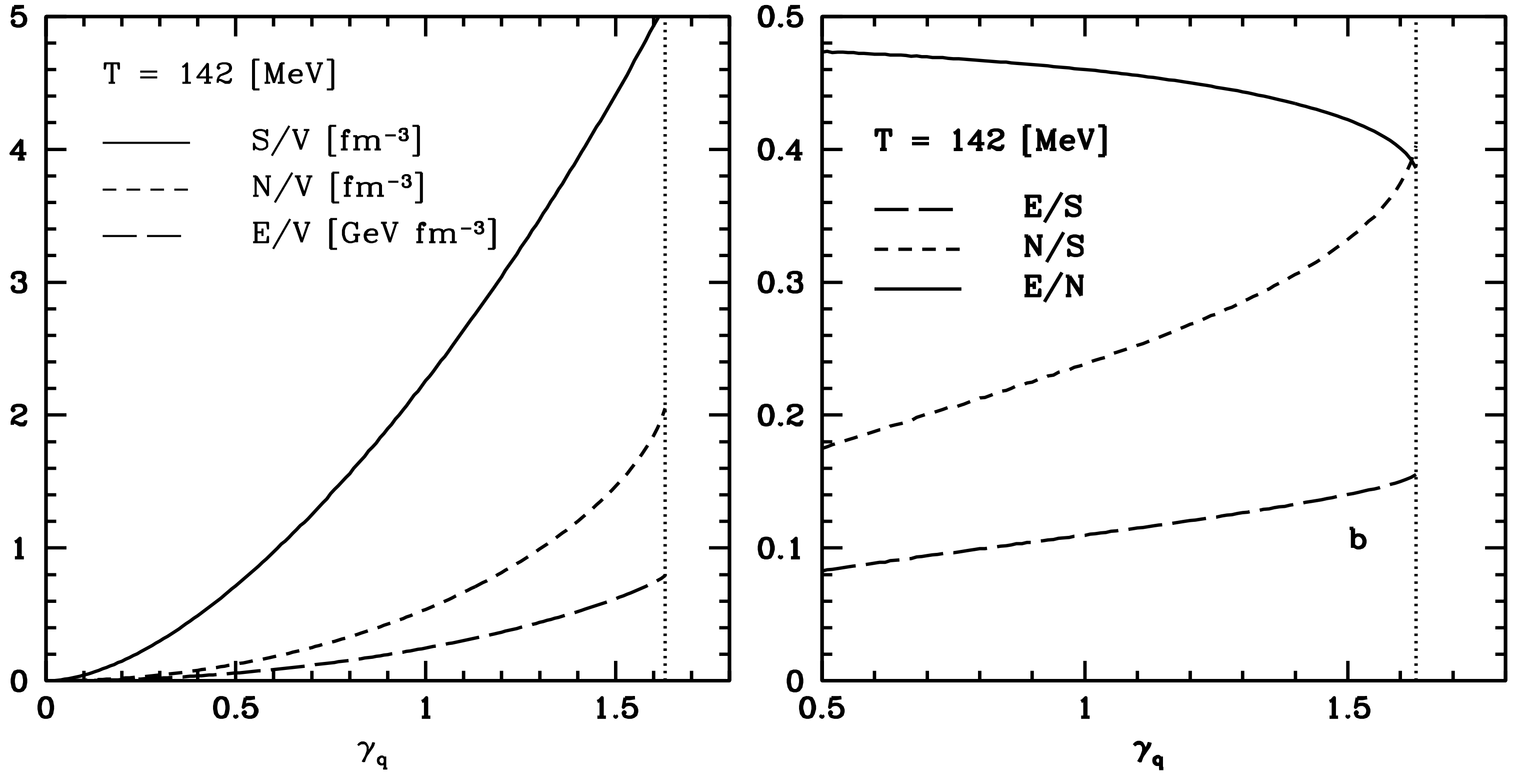
Note the presence of resonance decays. Full analysis requires a significant effort with 1000's of decaying states. A public package SHARE Statistical Hadronization with REsonances is available at http://www.physics.arizona.edu/˜torrieri/SHARE/share.html developed by Kraków-Tucson collaboration.

$\gamma_q^2 \to e^{m_\pi/T}$: A way to 'consume' excess of QGP entropy

Maximization of entropy density in pion: gas. $E_\pi = \sqrt{m_\pi^2 + p^2}$

$$S_{\rm B,F} = \int \frac{d^3p\, d^3x}{(2\pi\hbar)^3} \left[\pm(1 \pm f)\ln(1 \pm f) - f \ln f\right], \qquad f_\pi(E) = \frac{1}{\gamma_q^{-2} e^{E_\pi/T} - 1}.$$

Pion gas properties: ***N*-particle, *E*-energy, *S*-entropy, *V*-volume as function of γ_q.**



Strangeness measurement in QGP

1. **TOTAL STRANGENESS YIELD:** $\boxed{s\text{trangeness}/b\text{aryon}}$ **depends primarily on initial conditions and (less) on evolution dynamics**
(how long the system is at which T)

$\boxed{\gamma_s^{\rm QGP}:}$ **is QGP near chemical equilibrium?**

$$\gamma_{\rm s,q}^{\rm QGP} = \left.\frac{n_{\rm s,q}(t,T(t))}{n_{\rm s,q}(\infty,T(t))}\right|_{\rm QGP} \to 1?$$

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2. **Strangeness overpopulation at QGP BREAK-UP:**
QGP phase space is squeezed into a smaller number of HG phase space cells: $\boxed{\gamma_{\rm s}^{HG} \simeq 2\gamma_{\rm s}^{\rm QGP}}$

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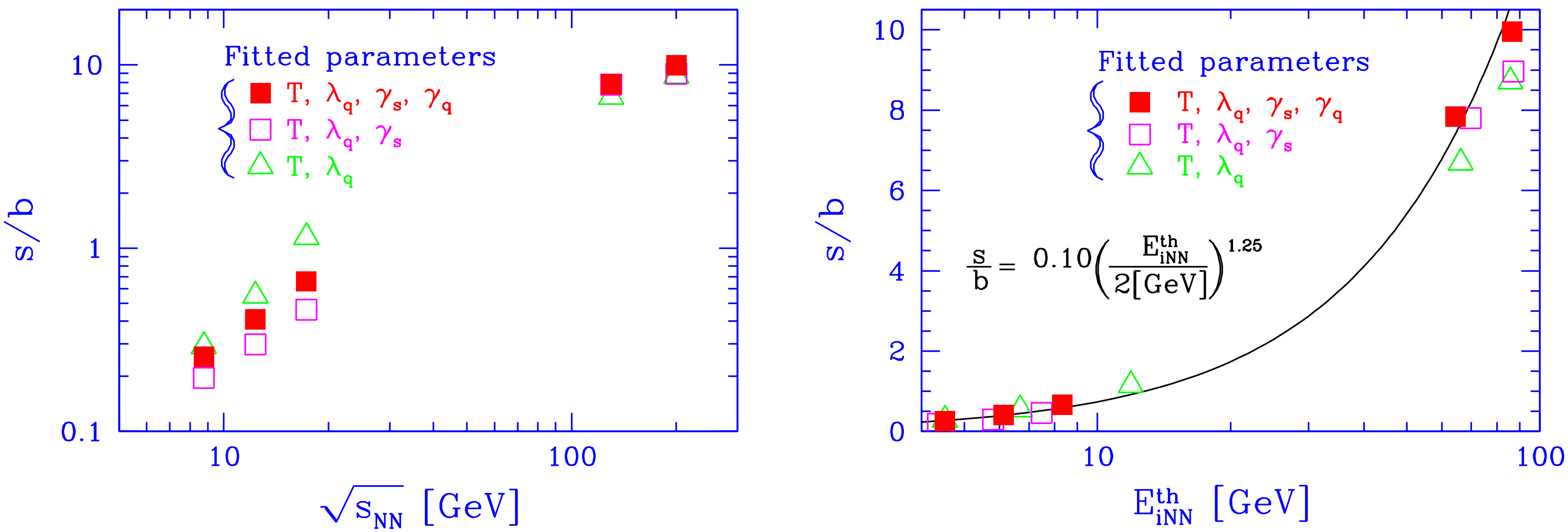
3. **WE NEED ALSO TO CONSIDER QGP ENTROPY enhancement expressed in** $\boxed{e^{m_\pi/(2T)} > \gamma_q^{\rm HG} > 1}$
over population of pion phase space is ENTROPY enhancement

FROM SPS to RHIC: STRANGENESS vs NET BARYON CONTENT



Strangeness per thermal baryon participating in the reaction grows rapidly and continuously. Gluon based thermal production mechanism UNDERSTOOD.

Strangeness production rises faster than entropy.

YIELD MUCH GREATER THAN IN NN-REACTIONS

OUTLOOK:

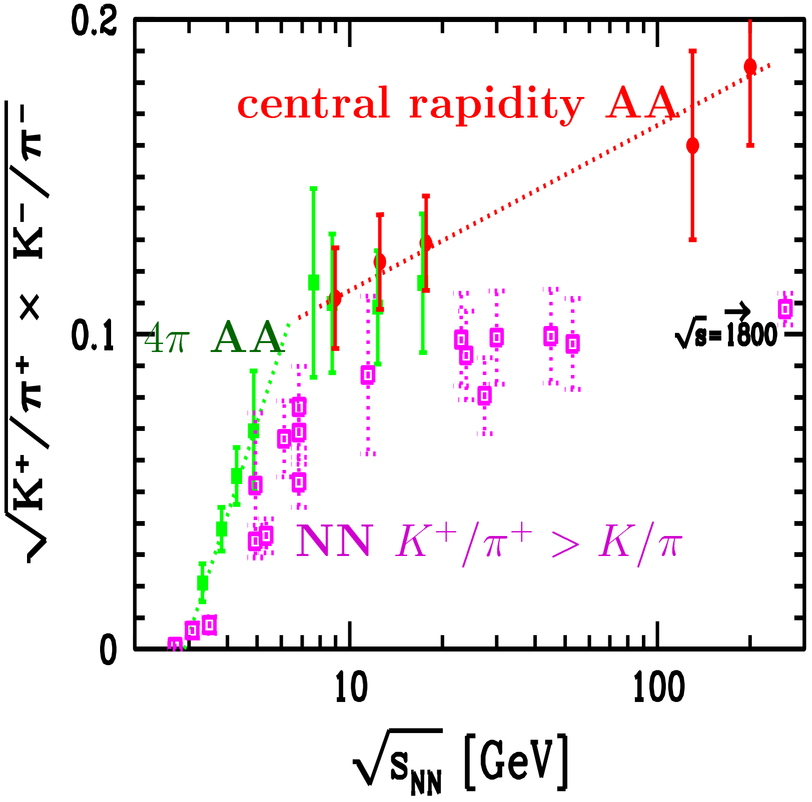
Soon at LHC – charm takes over from strangeness – an experimental challenge

Probing strangeness excitation by ratio K/π

The particle yield products

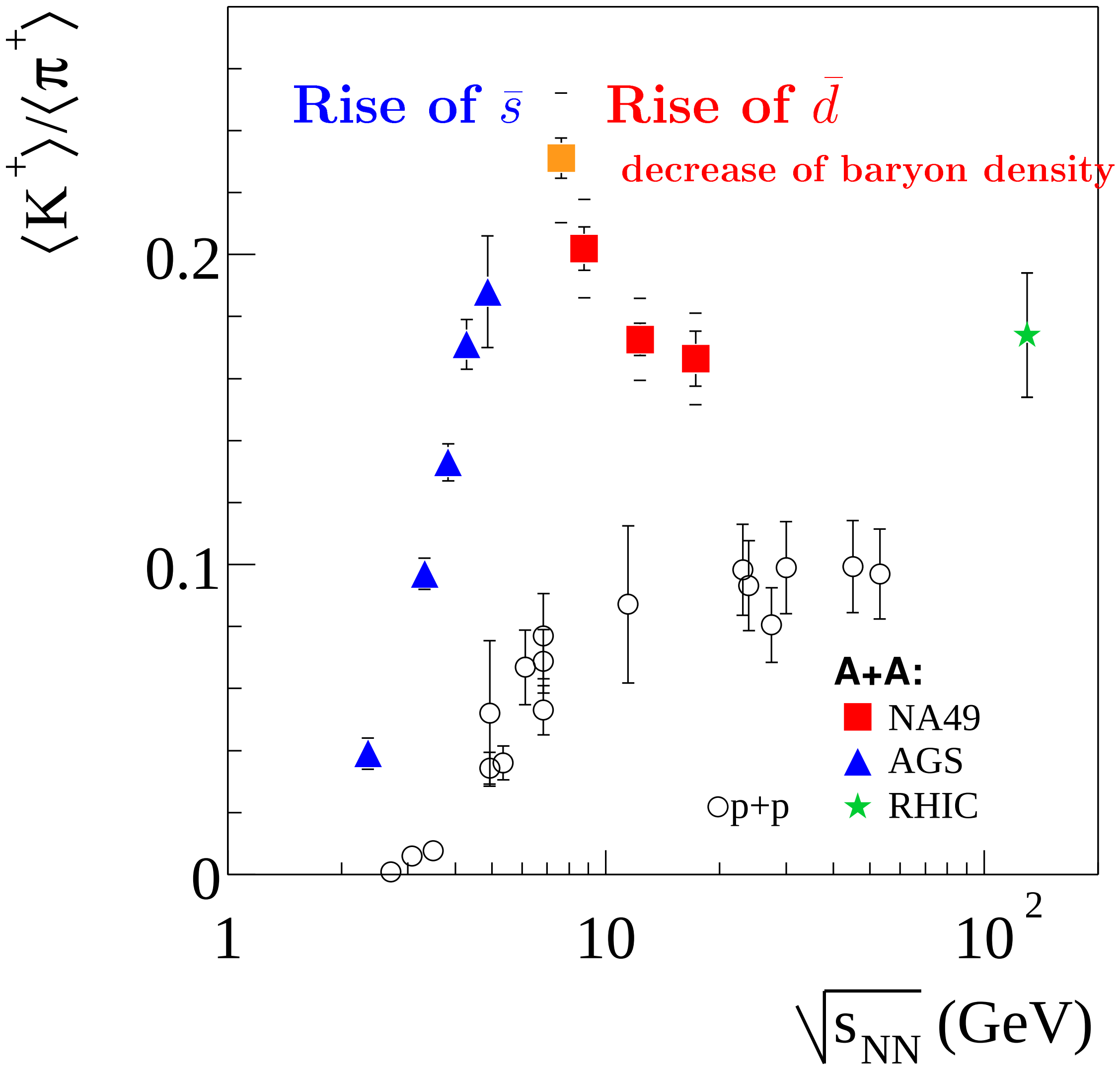
$$K \equiv \sqrt{K^+(u\bar{s})K^-(\bar{u}s)} \propto \sqrt{\lambda_u/\lambda_s\ \lambda_s/\lambda_u} \qquad \pi \equiv \sqrt{\pi^+(u\bar{d})\pi^-(\bar{u}d)} \propto \sqrt{\lambda_u/\lambda_d\ \lambda_d/\lambda_u}$$

are less dependent on chemical conditions including baryon density.

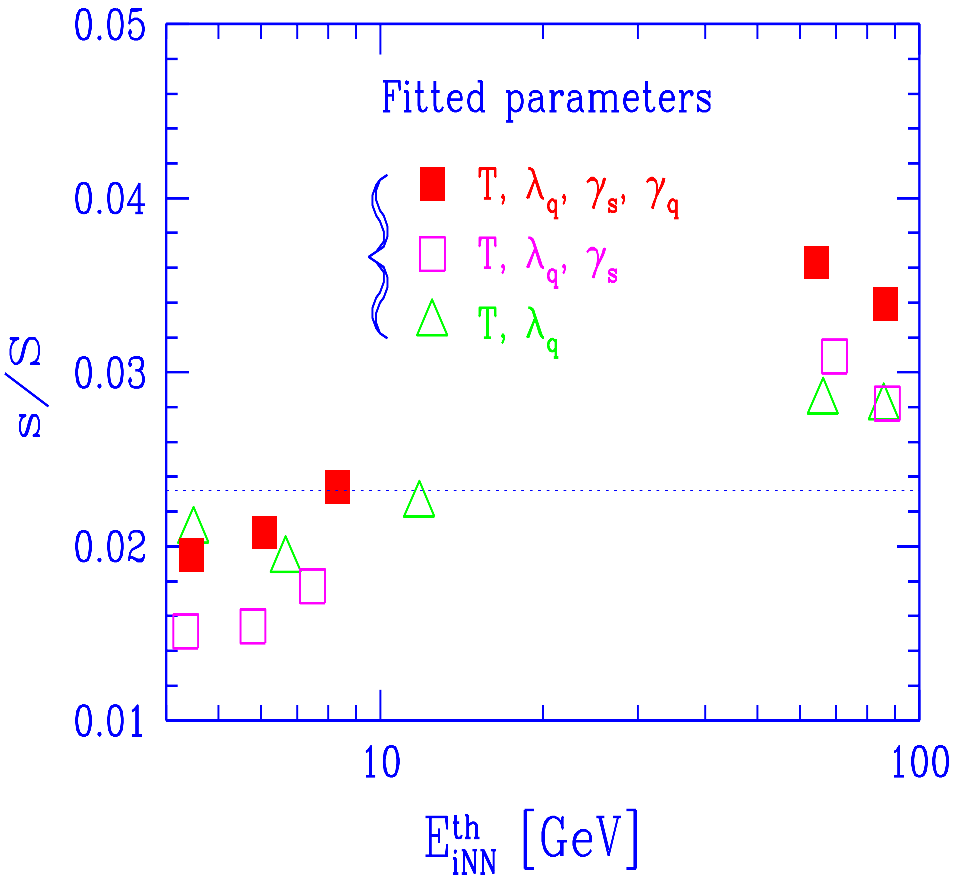


There is a notable enhancement in K/π above the K^+/π^+ ratio recorded in pp reactions, which provides an upper limit on K/π. There is a clear change in the speed of rise in the K/π ratio at the lower energy limit at SPS; This combined with change in nuclear compression results in a peak in the K^+/π^+.

NA49/Marek Gaździcki STUDY $\bar{s}/\bar{d}$ ENHANCEMENT



YET MORE INTERESTING: STRANGENESS/ENTROPY CONTENT



From AGS to SPS: step up by 50% (not shown) and second step-up by 50% in strangeness per entropy between SPS and RHIC
Strangeness production rises with energy faster than production of entropy.

New physics at RHIC compared to SPS
New physics at SPS compared to AGS.

Is QGP discovered??

Predicted QGP behavior confirmed by strangeness and strange antibaryon enhancement experiments, verifies strange quark mobility. Enhanced source entropy content consistent with gluon degrees of freedom, expected given strangeness enhancement. Chemical properties consistent with sudden hadron production in fast breakup of QGP.

Furthermore: quark coalescence explains features of non-azimuthally symmetric strange particle production. Early thermalization and strange quark participation in matter flow.

Strangeness excitation function fingerprints QGP as the new state of matter:
Probable onset of 'valon' quark deconfinement at AGS;
between SPS and RHIC entropy and strangeness change 2nd time
we need to scan this energy range for transformation to 'free' QGP

SO WHAT??

This is not the end of the story, but its beginning. Back in time, how did the quark-gluon Universe hadronizes and the antimatter component disappear?

Hadronization of the Quark Universe

The expanding hot deconfined Universe cools, the hot quark-gluon plasma freezes into individual hadrons. In laboratory we do this suddenly, in the early Universe slowly as seen on time scale of strong interactions.

STRONG INTERACTIONS TIME CONSTANT:
Nucleon size / light velocity $\simeq 10^{-23}$**s**

UNIVERSE HADRONIZATION TIME CONSTANT:

$$\tau_{\mathrm{U}} = \sqrt{\frac{3c^2}{32\pi G\mathcal{B}}} = 36\,\mu\mathbf{s}\ \sqrt{\frac{\mathcal{B}_0}{\mathcal{B}}}, \qquad \mathcal{B}_0 = 0.19\,\frac{\mathbf{GeV}}{\mathbf{fm}^3}$$

$4\mathcal{B}$ **is energy density inside particles like protons, and is the amount of energy required per unit of volume to deconfine quarks.**

Production of Matter of our cosmic era

Our objective is to understand the chemical conditions at the emergence of matter as we know it today in the early Universe period at hadronization of quark-gluon plasma. This establishes the initial particle densities which can be followed to the end of the hadron gas era.

Quantitative Tasks

1) Identify the chemical conservation laws constraining potentials $\mu(T)$ and the pertinent conservation laws;

2) Trace out chemical potentials as function of temperature, which itself we can study separately as function of time (see above) – this separation is convenient given the lack of knowledge about dark matter;

3) Evaluate the chemical (particle) flavor composition of the Universe during evolution toward the condition of neutrino decoupling at

$$T \simeq 1\,\mathbf{MeV} \qquad t \simeq 10\,s$$

4) Explore the quark-hadron phase transformation dynamics, and establish potential for conserved quantum (baryon, electrical charge) number distillation;

Constraint conditions in hadronization of the early Universe

The three chemical potentials not constrained by chemical reactions are obtained from the physical constraints:

i. *Local electrical charge neutrality* **($Q = 0$):**

$$n_Q \equiv \sum_i Q_i\, n_i(\mu_i, T) = 0,$$

where Q_i and n_i are the charge and number density of species i.

ii. *Net lepton number equals net baryon number* **($L = B$):**

$$n_L - n_B \equiv \sum_i (L_i - B_i)\, n_i(\mu_i, T) = 0,$$

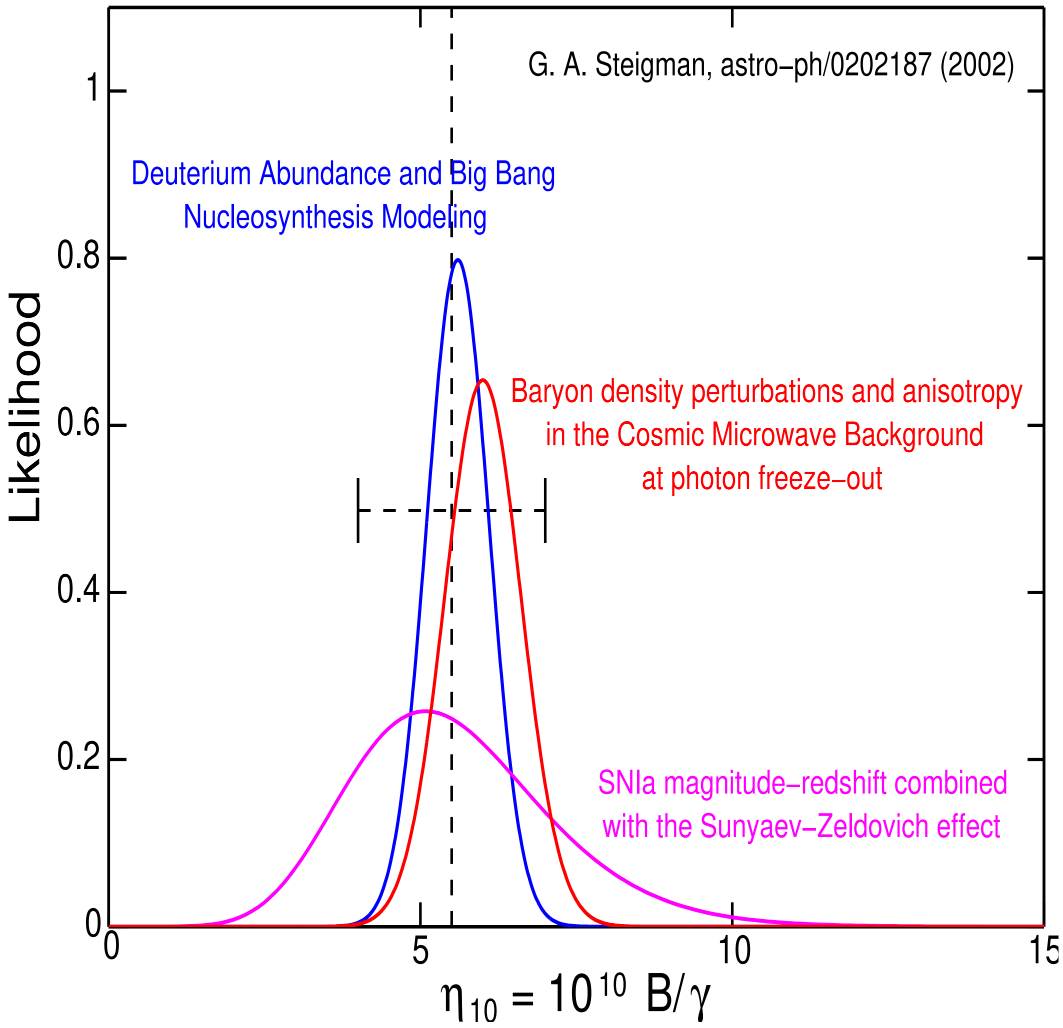
(standard condition in baryo-genesis models, generalization to finite $B - L$ easily possible)

iii. Universe evolves adiabatically i.e. at *constant in time entropy-per-baryon S/B*

$$\frac{\sigma}{n_B} \equiv \frac{\sum_i \sigma_i(\mu_i, T)}{\sum_i B_i\, n_i(\mu_i, T)} = 1.3 \pm 0.1 \times 10^{10} \quad \Longleftarrow \quad \textit{how do we know this?}$$

Baryon to photon ratio in the Universe

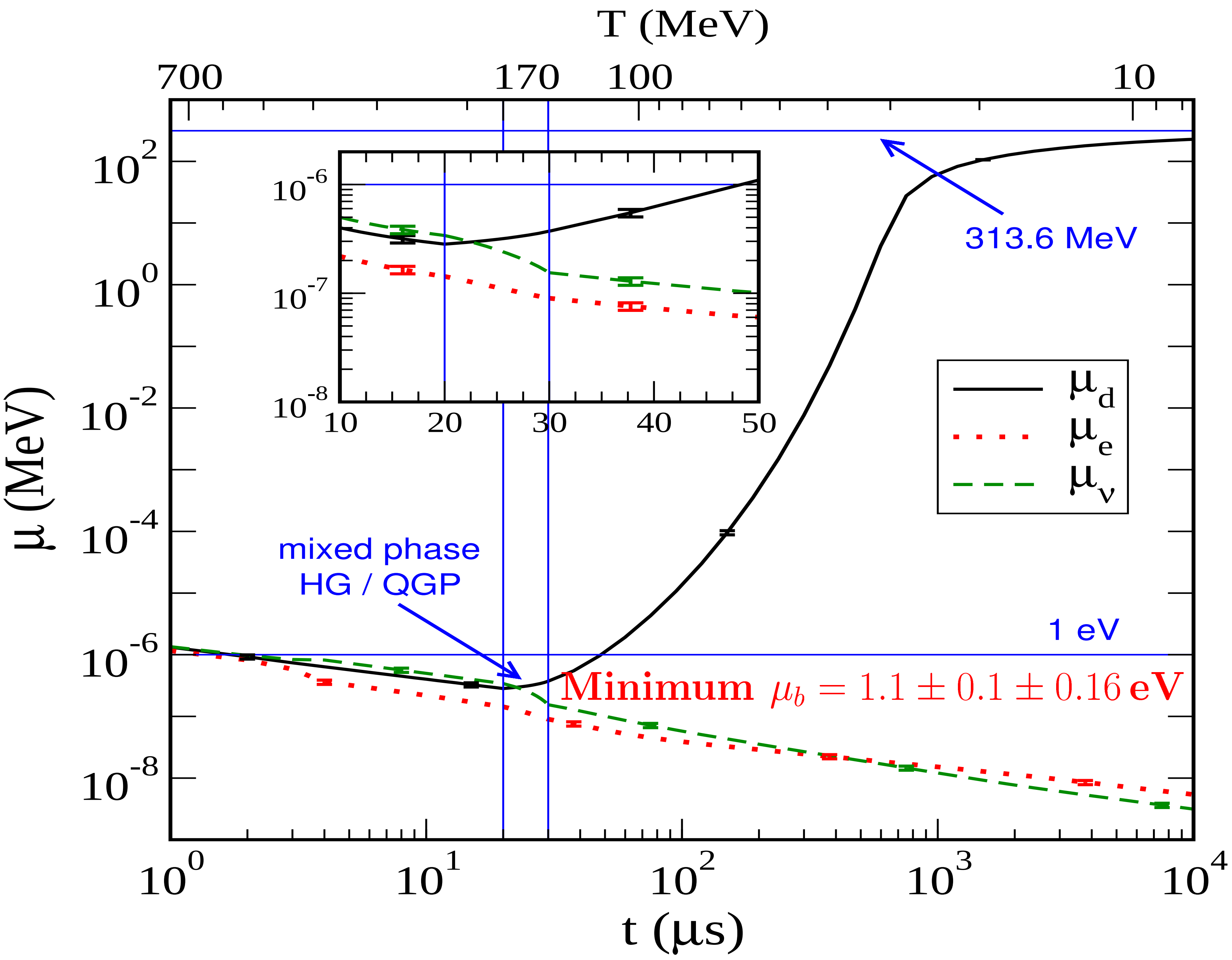
OLD: $\eta \equiv n_{\rm B}/n_\gamma = 5.5 \pm 1.5 \times 10^{-10}$; **W-MAP:** $\eta = 6.1^{+0.3}_{-0.2} \times 10^{-10}$;



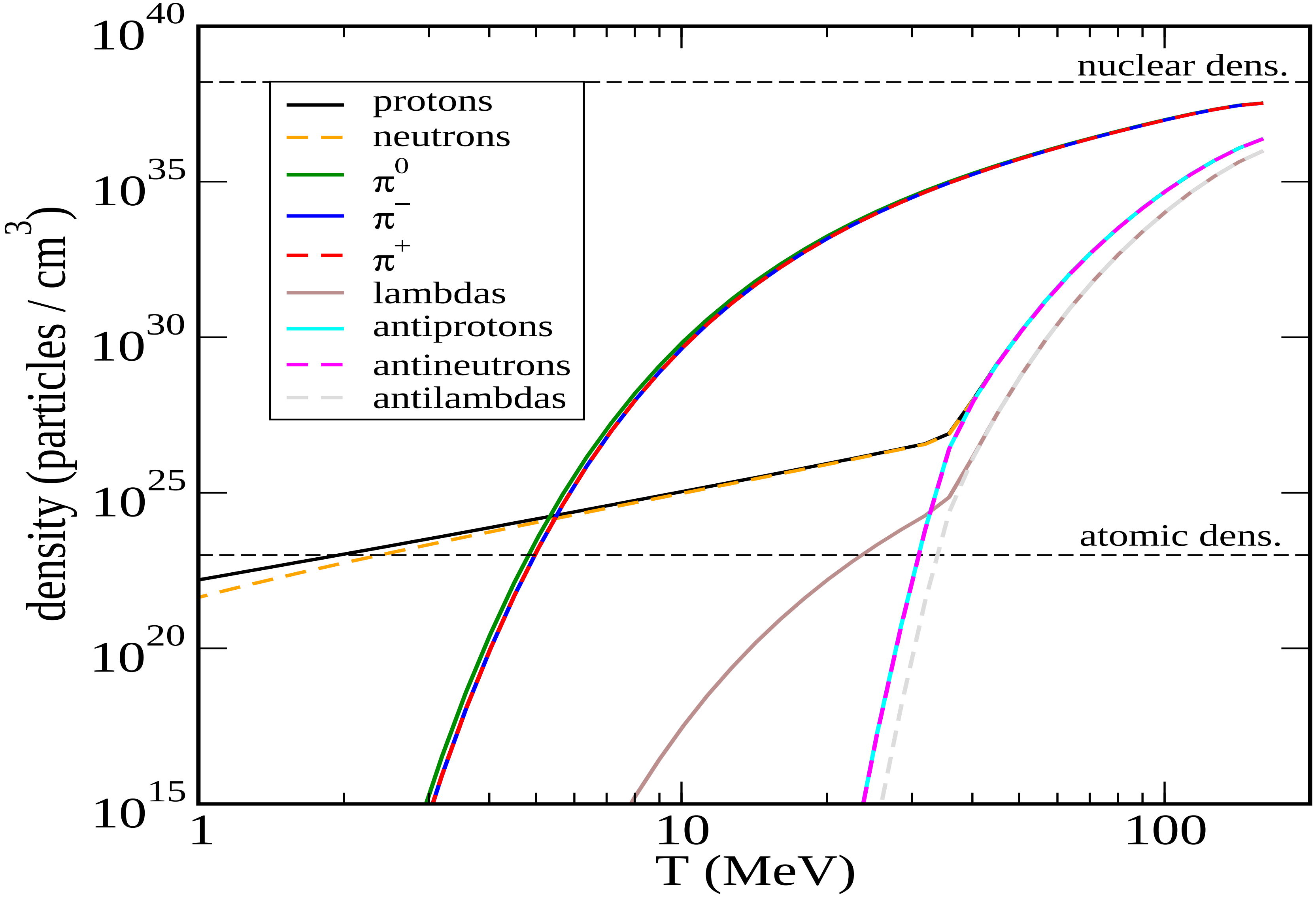
This yields entropy per baryon: $\frac{S}{n_{\rm B}} = \frac{S}{n_\gamma}\frac{n_\gamma}{n_{\rm B}} = \frac{8.0}{\eta} = 1.3 \pm 0.1\, 10^{10}$

$(S_\gamma + S_\nu + S_i)/n_\gamma$ **is evaluated using stat.mech. and remembering** e^+e^- **reheating of photons.**

TRACING μ_d IN THE UNIVERSE



Hadronic Particle Densities



Note the baryon freeze-out at $T \simeq 37$ MeV and that pion density remains at baryon density down to $T \simeq 4.5$ MeV

FINAL REMARKS

The deconfinement specific hadronic 'deep' probes are entropy and strangeness. These probes are fully consistent with deconfinement/QGP at SPS and at RHIC

We have control of statistical models and chemical potentials, particle abundances, but not yet of phase transformation dynamics.

Theoretical study of the QGP phase and hadronization of the early Universe beginning at $t = 10\,\mu s$ is possible