

STRANGENESS AND THE DISCOVERY OF QUARK-GLUON PLASMA

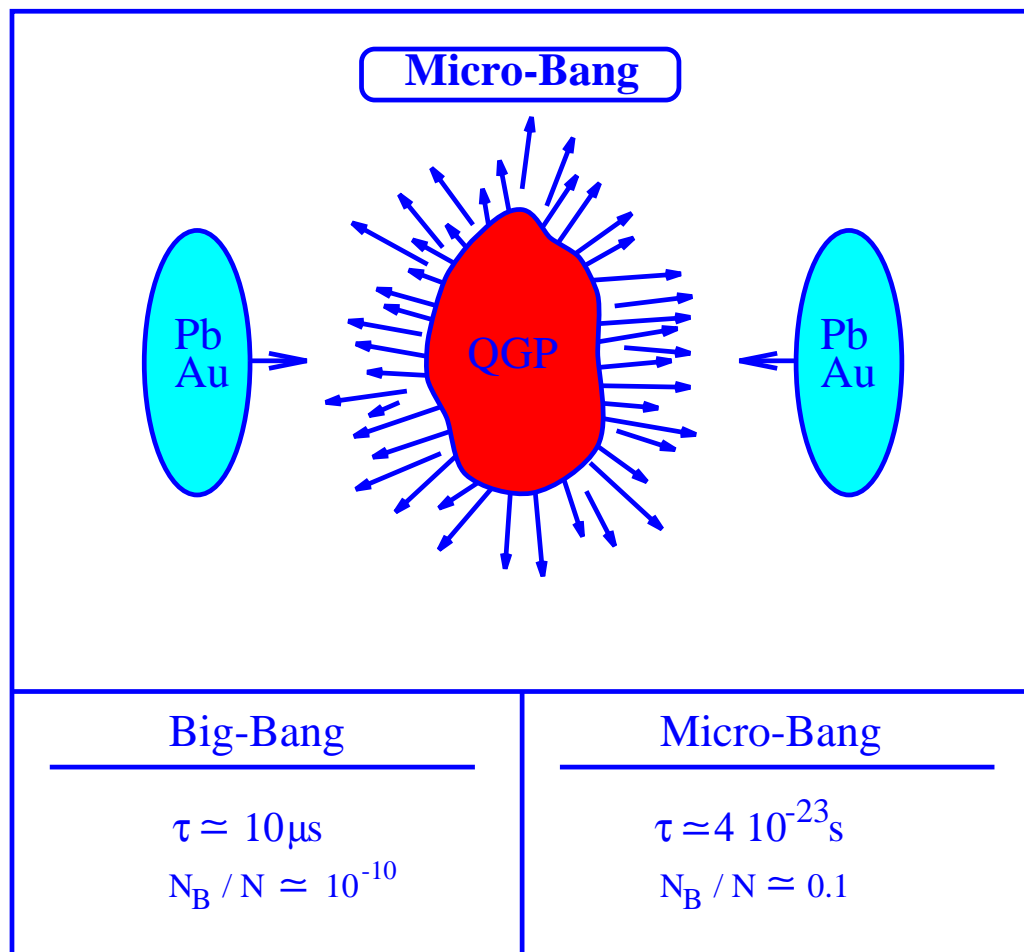
Beijing, August 10, 2004

- [I] **Why make the effort:** Study early Universe; Probe the vacuum; Energy to matter: the (al)chemy of particle production:
- [II] **Measurements:** Strangeness: yield enhancement, strange antibaryons, spectra
- [III] **Statistical hadronization:** methods, importance, results
- [IV] **Strangeness and entropy: deep probes of QGP**

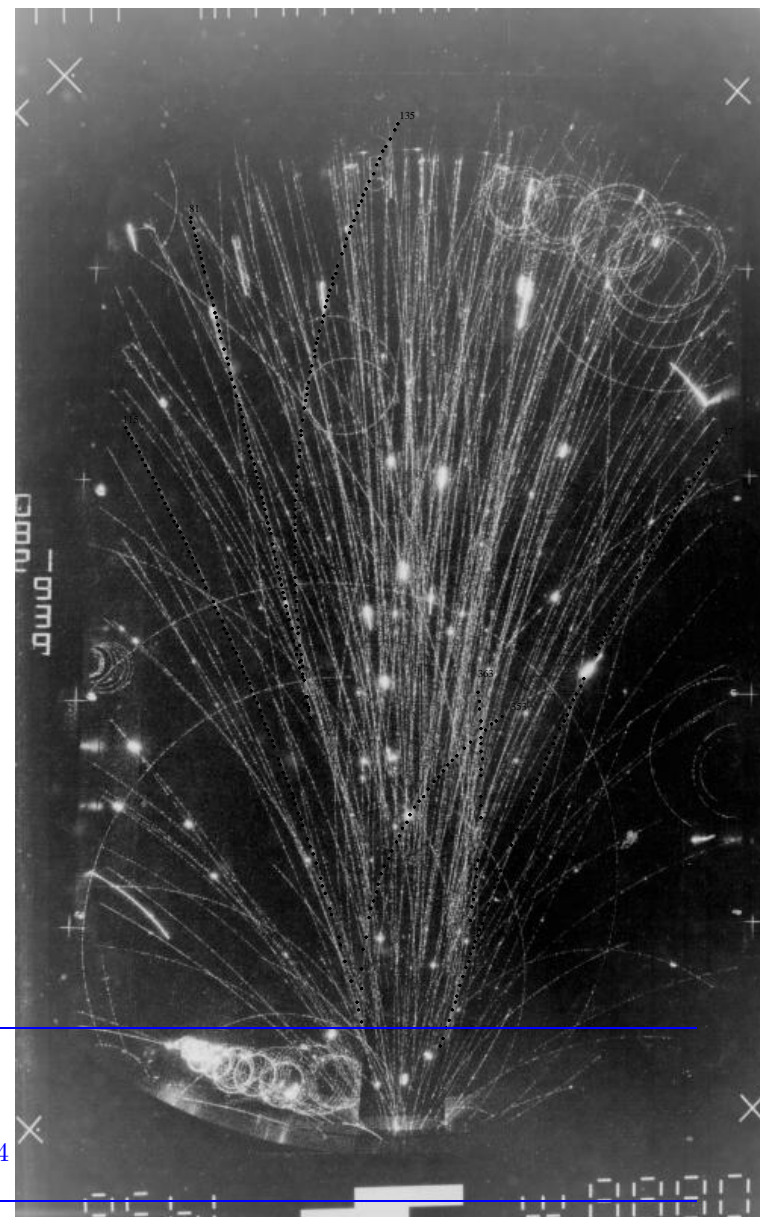
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20 YEARS OF RESEARCH: THE EARLY UNIVERSE IN THE LABORATORY



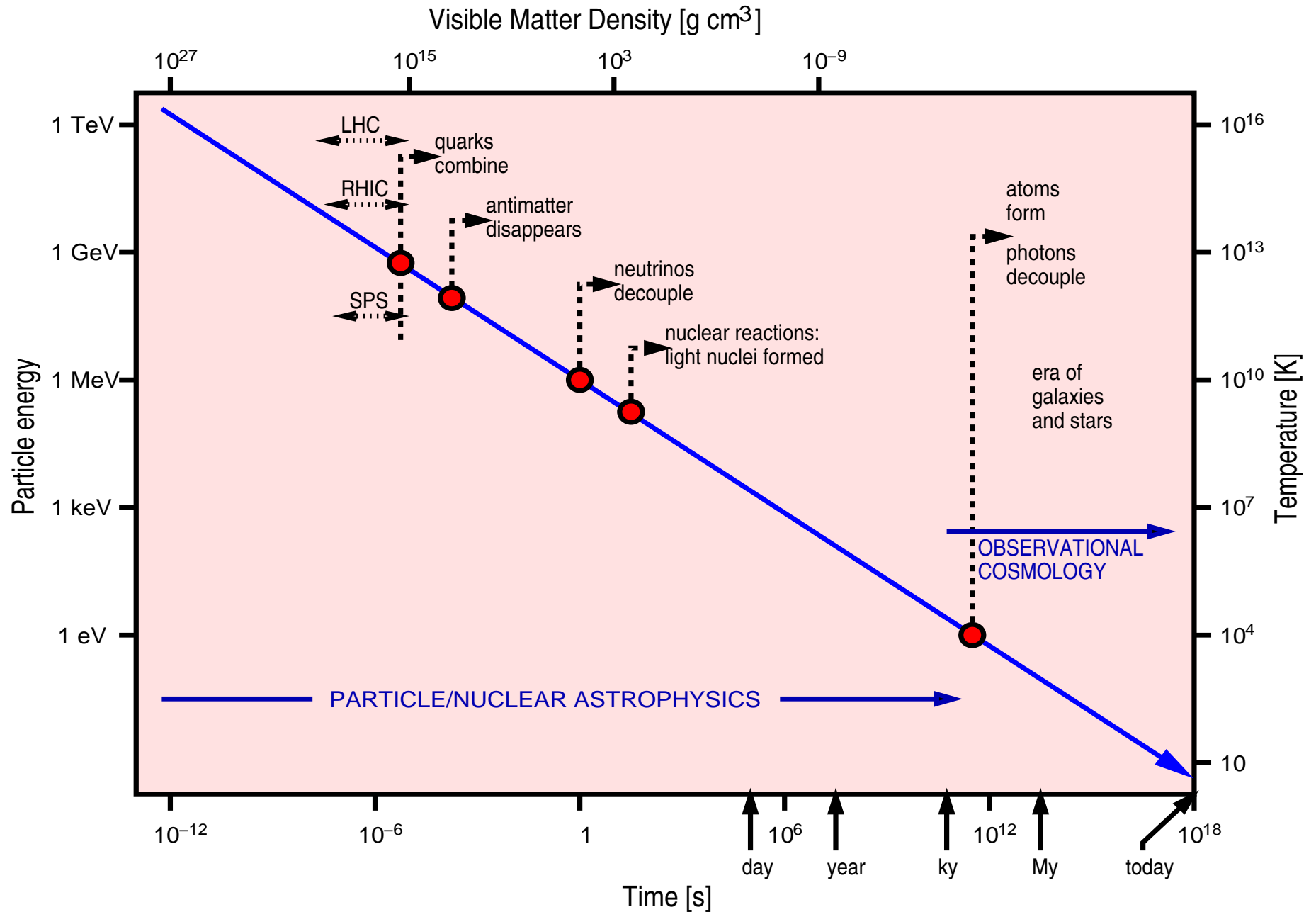
Order of Magnitude



S-Ag Reaction at 200A GeV

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

Particle/nuclear era in the evolution of the Universe



Vacuum and RHIC

We aim to verify the new paradigm: the Vacuum structure causes quark confinement and determines hadron structure (masses etc).

Quantum fluctuations/structure is present in 'space devoid of matter'

Quantum vacuum is polarizable: see atomic level shifts

Quantum structure of gluon-quark fluctuations:
glue and quark condensate

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

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

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

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.....

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. In finite size systems always a 'transformation', not a sharp boundary.

What we need as background knowledge:

- 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

Strangeness: a sensitive QGP diagnostic tool

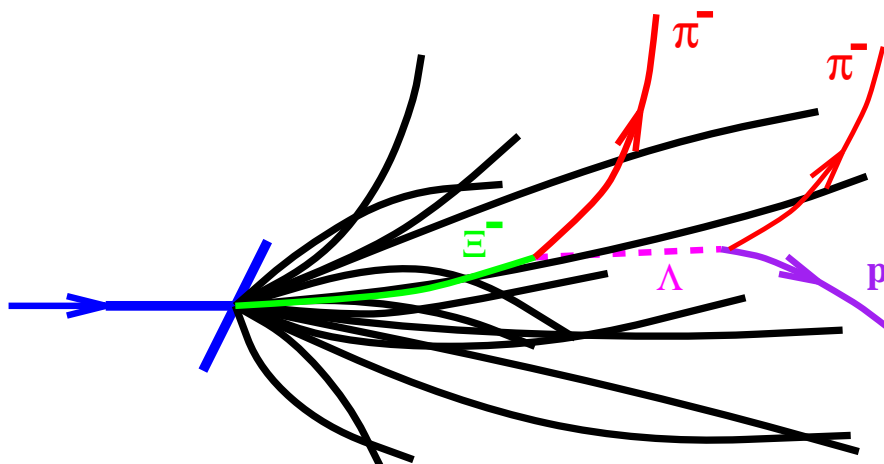
EXPERIMENTAL REASONS

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

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

$$\Xi(qss), \quad \bar{\Xi}(\bar{q}\bar{s}\bar{s}), \quad \Omega(sss), \quad \bar{\Omega}(\bar{s}\bar{s}\bar{s}) \quad \dots \text{resonances} \dots$$

- 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

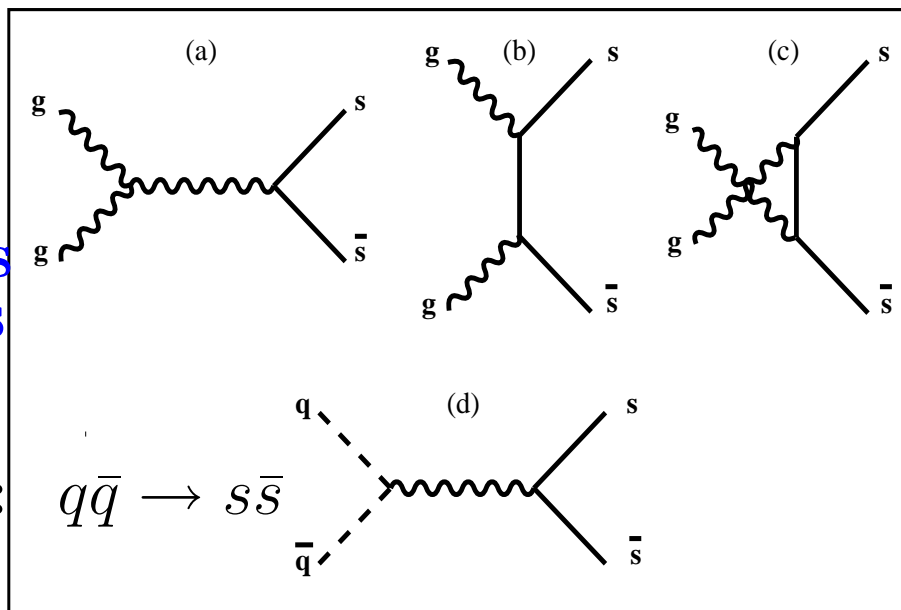
- production of strangeness in gluon fusion $GG \rightarrow s\bar{s}$
 strangeness linked to gluons from QGP;

dominant processes:

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

abundant strangeness
 =evidence for gluons

10–15% of total rate:



- coincidence of scales:

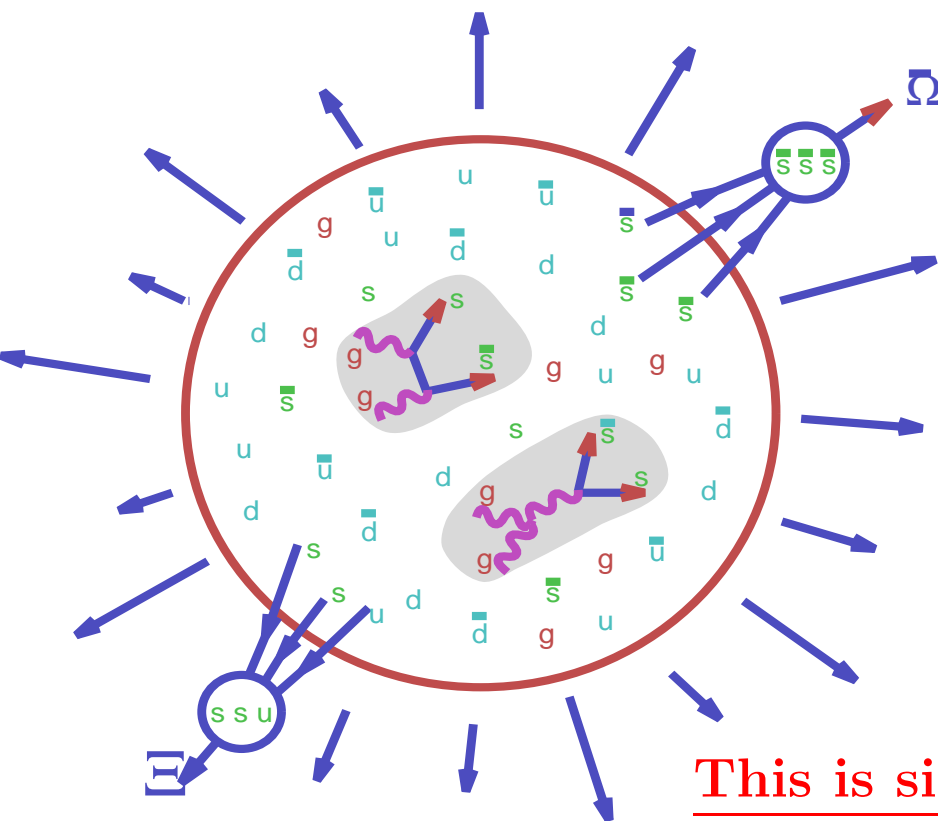
$$\boxed{m_s \simeq T_c} \rightarrow \boxed{\tau_s \simeq \tau_{\text{QGP}}} \rightarrow$$

strangeness a clock for QGP phase

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

(Al)chemistry of particle production: STRANGENESS AND ENTROPY

Stable matter is made of only up and down quarks, strange flavor is always almost all newly made.



In the QGP hadrons are dissolved into an entropy rich partonic liquid. TWO STEP MECHANISM of (strange) hadron formation from QGP:

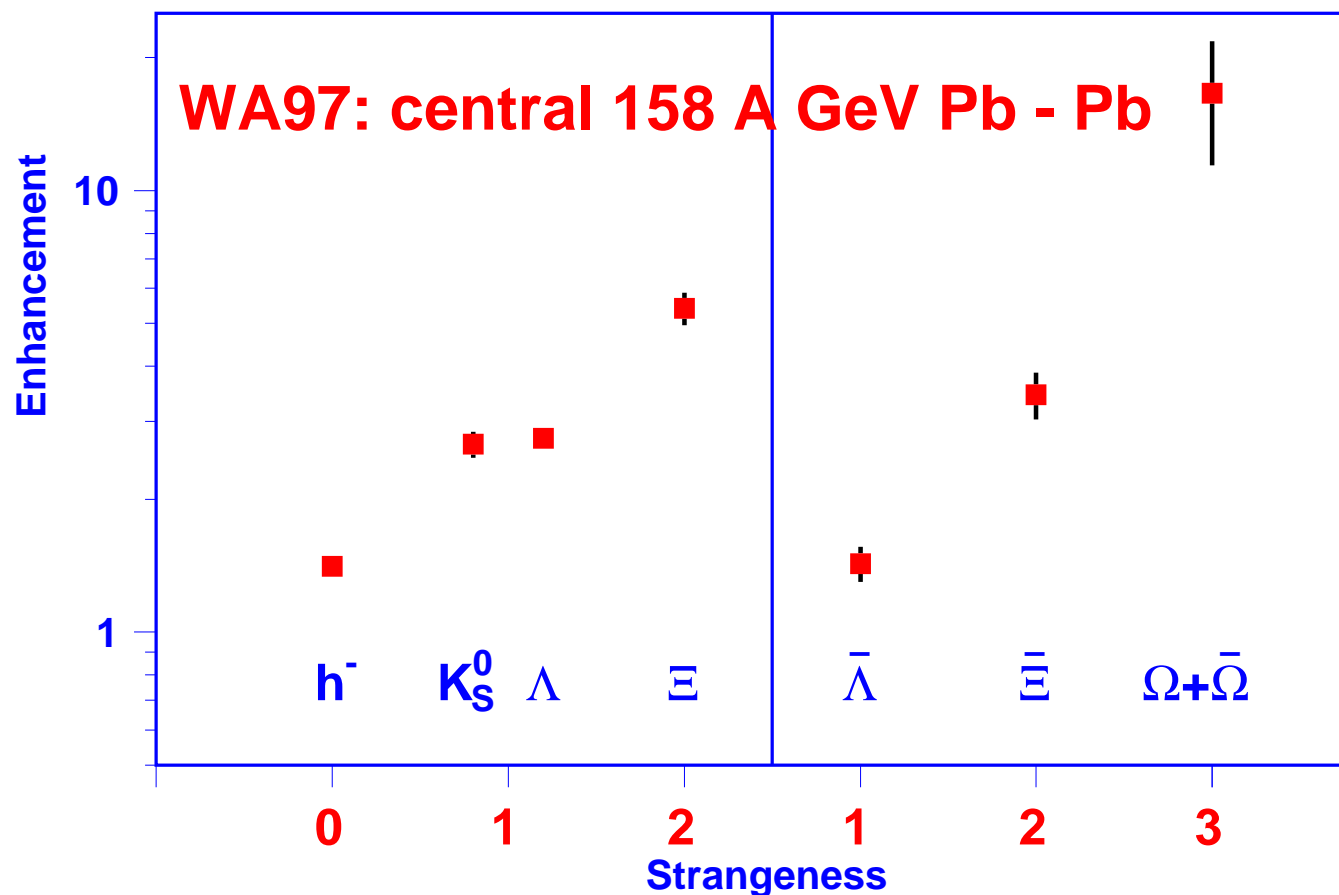
1. $GG \rightarrow s\bar{s}$ in QG-plasma
2. hadronization of pre-formed s, \bar{s} quarks

Formation of complex rarely produced multi strange (anti)particles from QGP enabled by coalescence between s, \bar{s} quarks made earlier in QCD based microscopic reactions.

This is signature of quark mobility in the source.

Experimental observable: Enhanced production of strange anti-baryons, progresses strongly with strangeness content of the particle, increases gradually with reaction volume and energy. First seen at SPS at CERN by WA97, recent work by NA57, NA49, and STAR at RHIC collaborations. Predictions developed in detail 1981–1991 prior to experimental results.

MULTISTRANGE (ANTI)HYPERON ENHANCEMENT I



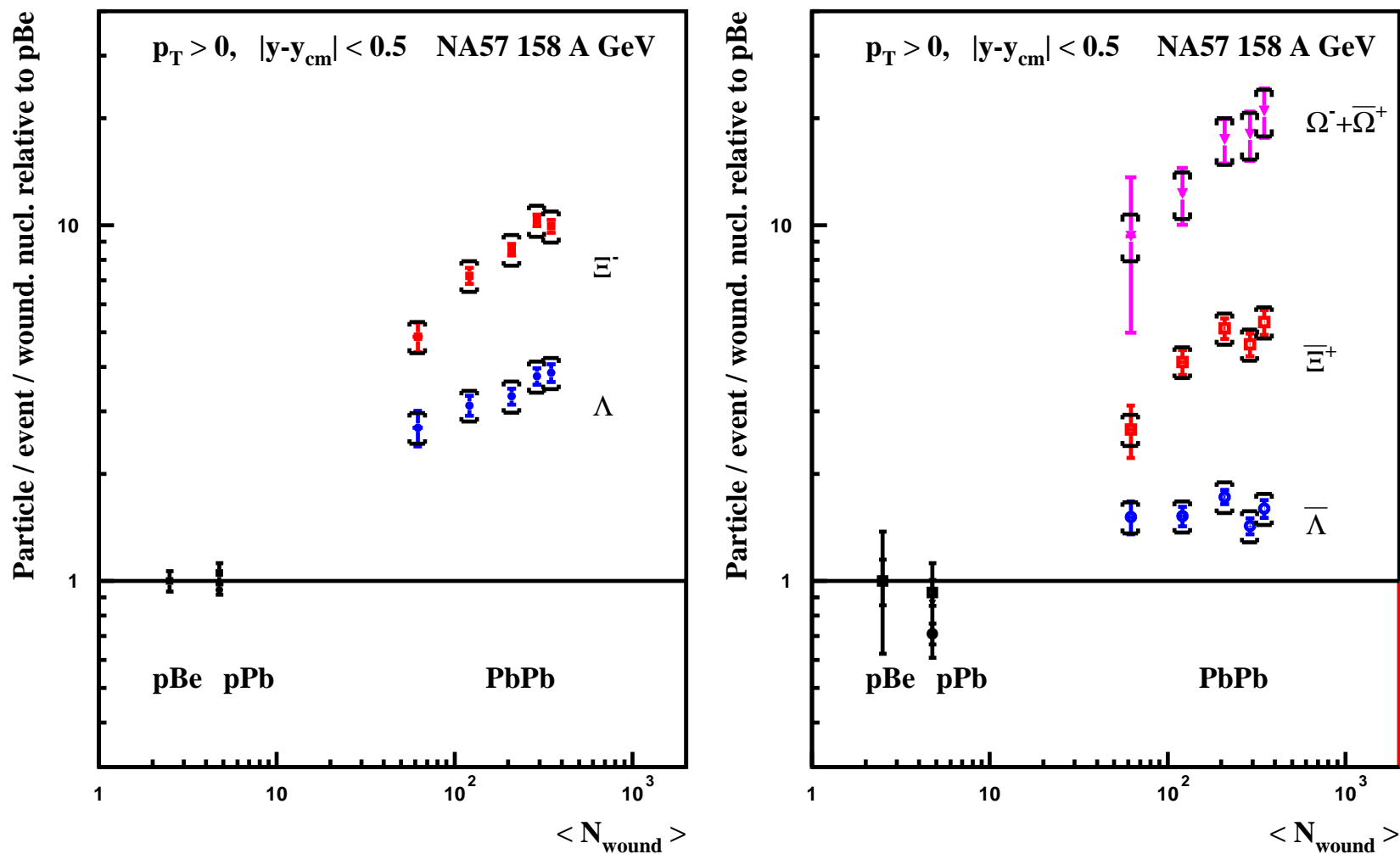
Enhancement GROWTH with

strangeness

antiquark content.

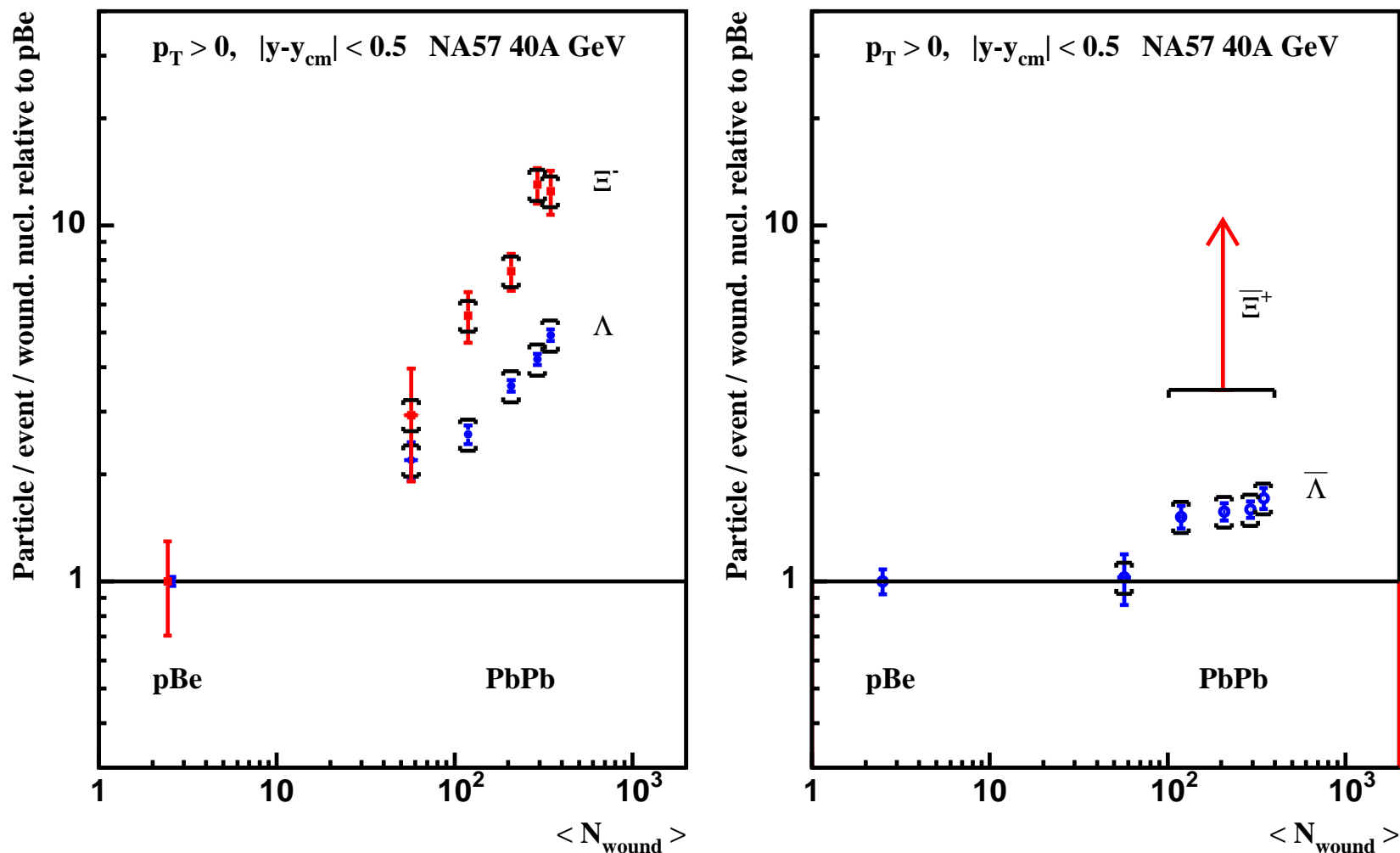
Enhancement is here defined with respect to the yield in p-Be collisions, scaled up with the number of collision 'wounded' nucleons.

MULTISTRANGE (ANTI)HYPERON ENHANCEMENT II



Note the gradual onset of enhancement with reaction volume.
 “Canonical enhancement” (a hadronic equilibrium model) is grossly inconsistent with these results.

MULTISTRANGE (ANTI)HYPERON ENHANCEMENT III



At 40A GeV we still see a strong hyperon enhancement, inconsistent with the canonical enhancement model but in agreement with expectations for deconfined state formation.

MULTISTRANGE (ANTI)HYPERON ENHANCEMENT IV

At RHIC similar enhancement but I have no access to these results which are being elaborated by the STAR collaboration.

REACTION MECHANISM OF PARTICLE PRODUCTION

Since 1982 we assumed sudden breakup of QGP into hadrons and thus preservation of hadronic signatures of deconfinement. Other workers explored a range of alternate models, and there were speculations that there would be an extremely long lived transformation stage. **HOW CAN ONE DECIDE THIS EXPERIMENTALLY??**

Experiments since 1991 (WA85, WA97) see identical shape of m_{\perp} spectra of strange baryons and antibaryons, obtained in central reactions at CM rapidity, also observed by NA49, and very precisely at RHIC.

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

Appears to be **DIRECT** emission by a quark source into vacuum. Fast hadronization confirmed today by HBT particle correlation analysis, which yields a nearly energy independent size of hadron fireball with short lifespan of pion production.

High m_{\perp} slope universality

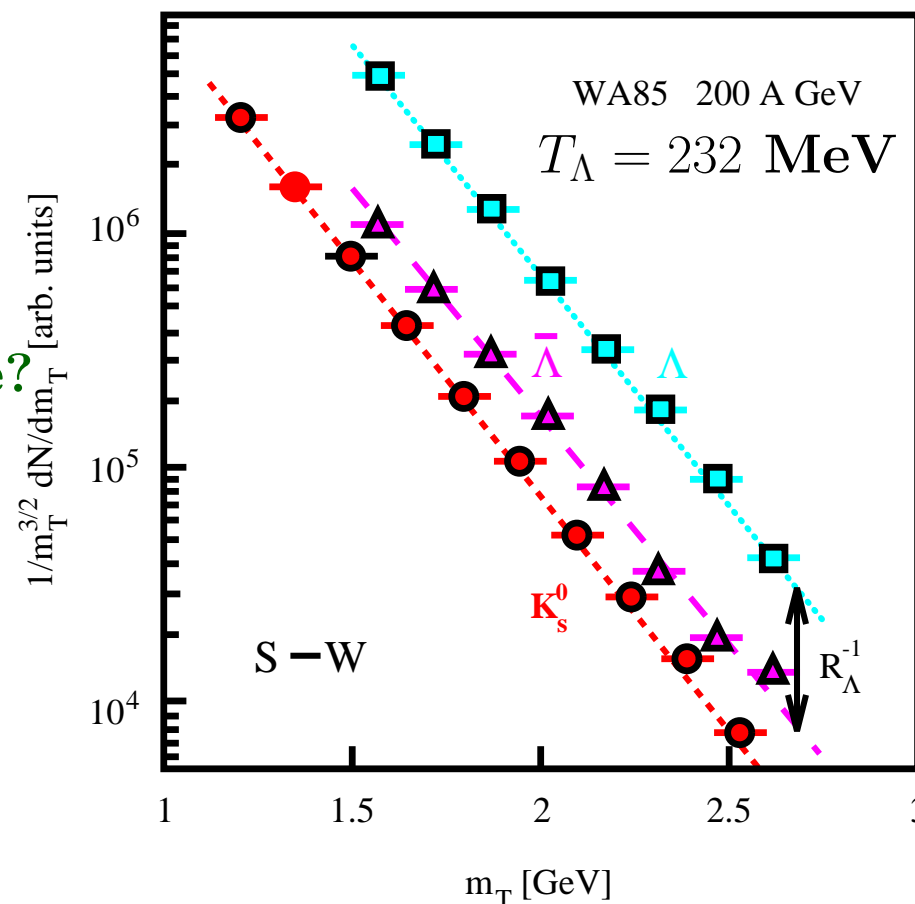
Discovered in S-induced collisions, pronounced in Pb-Pb Interactions.

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

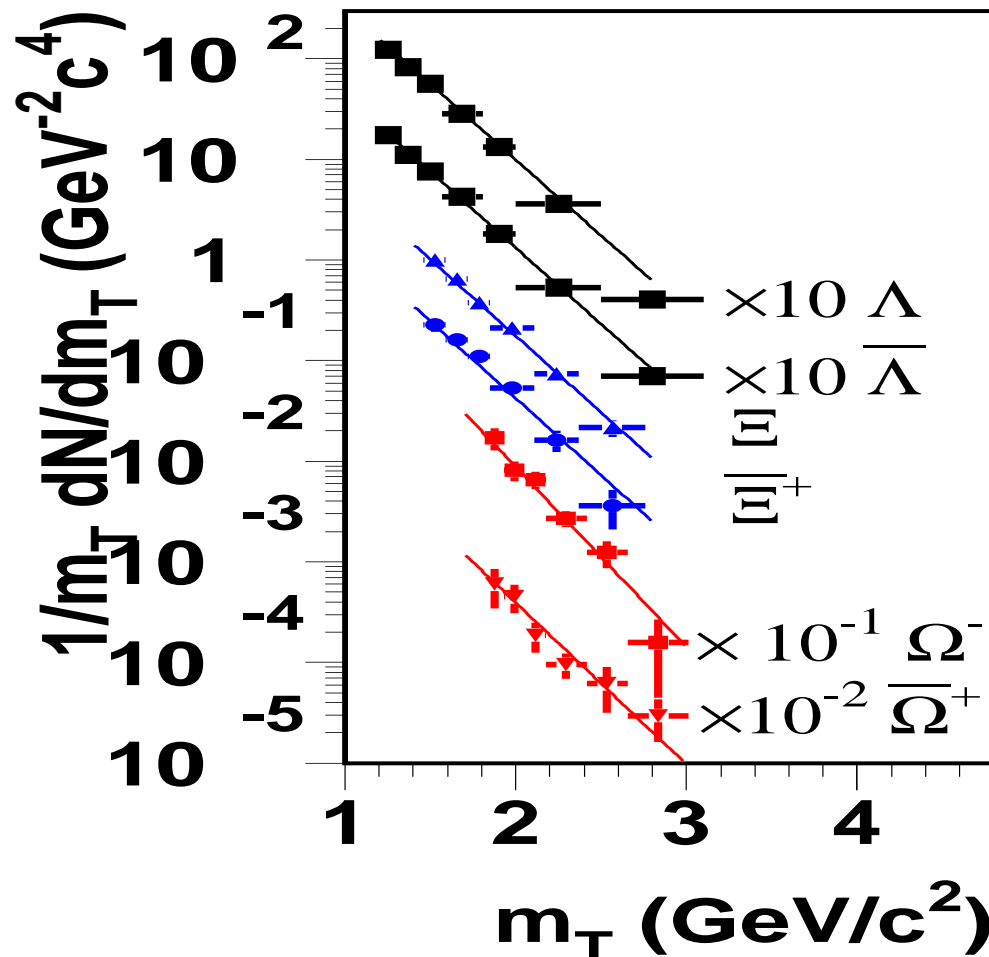
This allowed the study of ratios of particles measured only in a fraction of phase space



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

Λ within 1% of $\bar{\Lambda}$

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

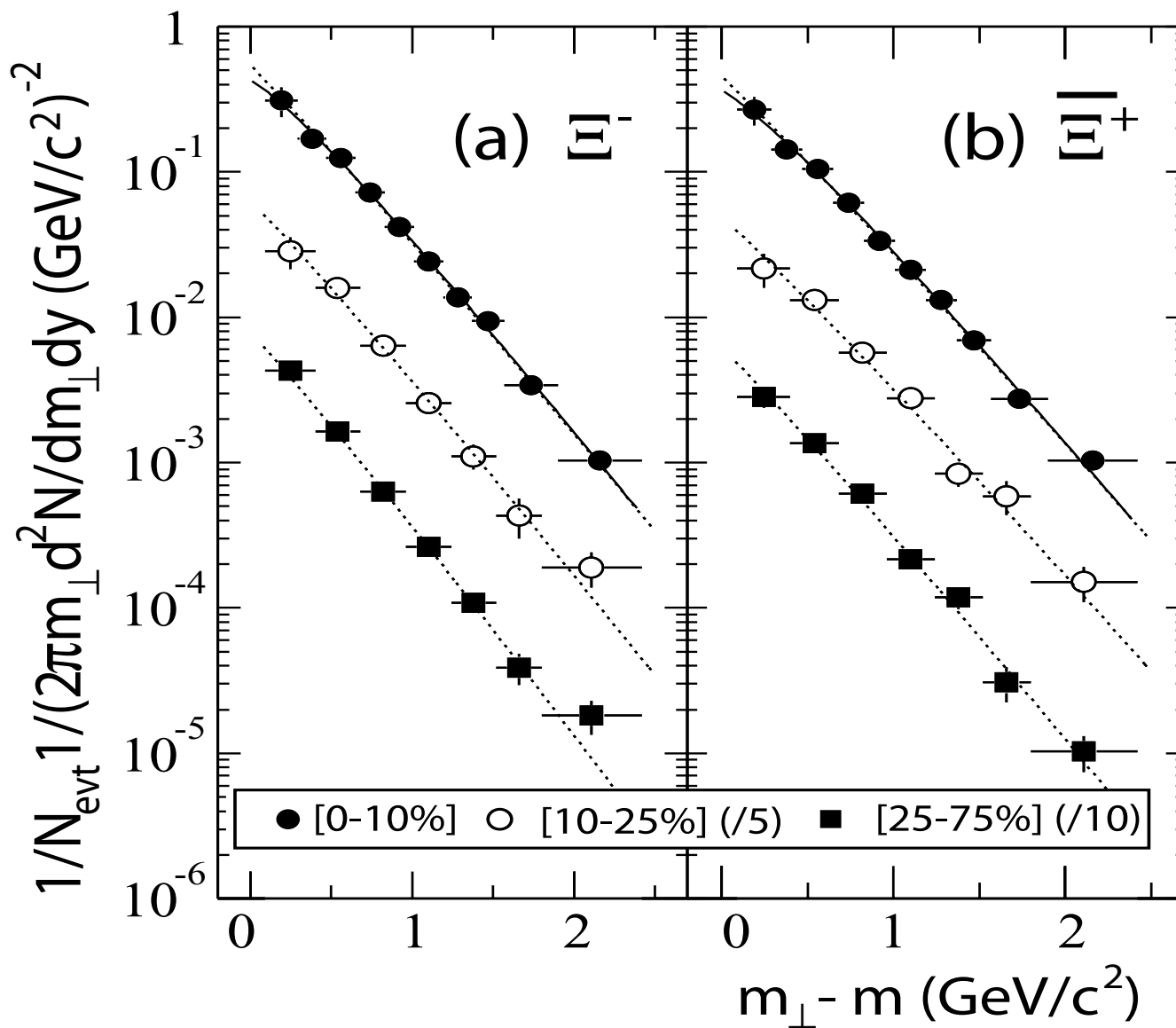


Spectra at RHIC-STAR 130+130 A GeV show the same effect

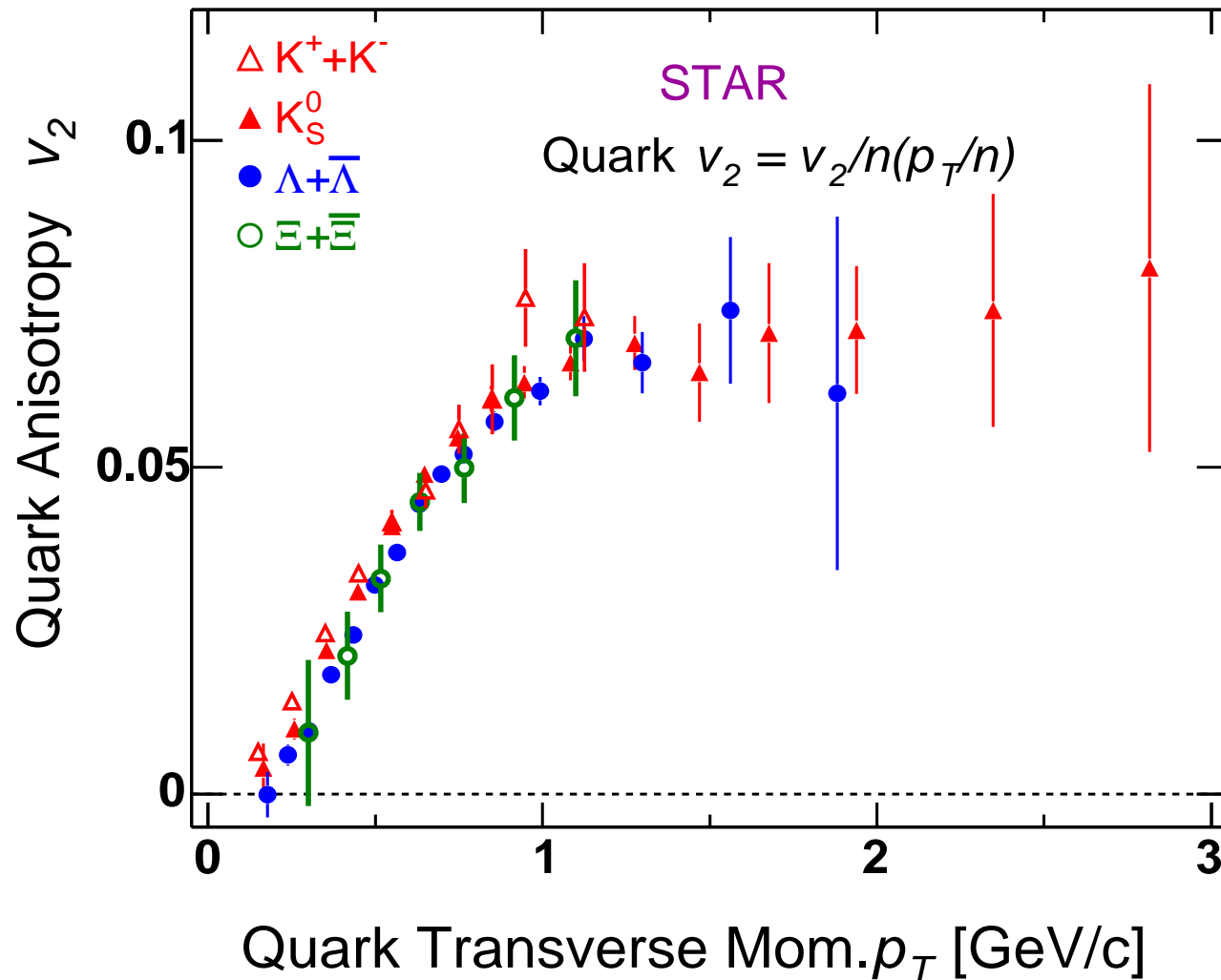
h^-	centrality	Exponential Fit		Boltzmann Fit	
		dN/dy	$T_E(\text{MeV})$	dN/dy	$T_B(\text{MeV})$
Ξ^-	260.3 ± 7.5	2.16 ± 0.09	338 ± 6	2.06 ± 0.09	296 ± 5
	$\bar{\Xi}^+$	1.81 ± 0.08	339 ± 7	1.73 ± 0.08	297 ± 5
Ξ^-	163.6 ± 5.2	1.22 ± 0.11	335 ± 16	1.18 ± 0.11	291 ± 13
	$\bar{\Xi}^+$	1.00 ± 0.10	349 ± 17	0.97 ± 0.10	302 ± 13
Ξ^-	42.5 ± 3.0	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 Ξ^- , $\bar{\Xi}^-$, for three centrality bins 0-10%, 10-25% and 25-75% with $h^- = dN_{h^-}/d\eta|_{|\eta|<0.5}$. Statistical and p_\perp dependent systematic uncertainties are presented. The p_\perp independent systematic uncertainties are 10%. (STAR Collaboration, PRL92 (2004) 182301)

Ξ^-, Ξ^+ Spectra RHIC-STAR 130+130 A GeV



Early Quark Thermalization and COMMON COLLECTIVE FLOW



A superb confirmation that dynamics of the fireball is in partonic degrees of freedom, see lecture by Huan-Zhong Huang

DIRECT PARTICLE PRODUCTION

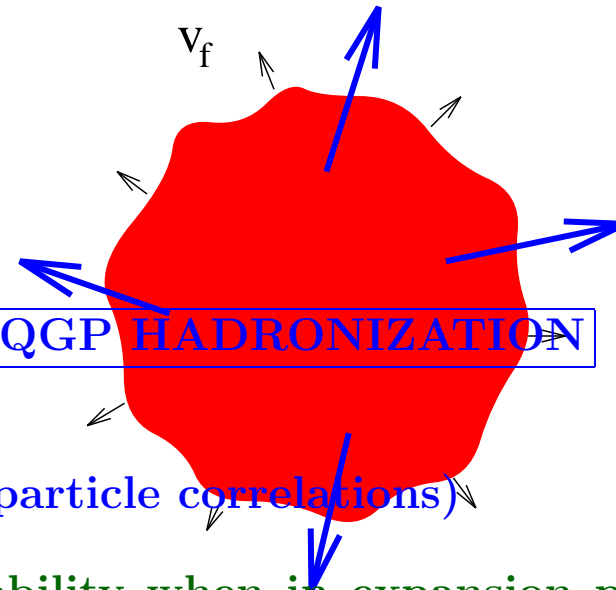
Common formation mechanism for all particles, for antimatter little reannihilation in sequel evolution.

Appears to be direct emission by a quark source into vacuum.

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:

- 1) Flow of matter and supercooling
- 2) Production of final state particles in **Statistical Hadronization**

Super-cooling WIND of a fast expanding fireball

P and ε : 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} :

$$\vec{\mathcal{P}} \equiv \hat{T} \cdot \vec{n} = P\vec{n} + (P + \varepsilon)\frac{\vec{v}_c \vec{v}_c \cdot \vec{n}}{1 - \vec{v}_c^2}.$$

The pressure and energy comprise particle and the vacuum properties: $P = P_p - \mathcal{B}$, $\varepsilon = \varepsilon_p + \mathcal{B}$. Condition $\vec{\mathcal{P}} = 0$ reads:

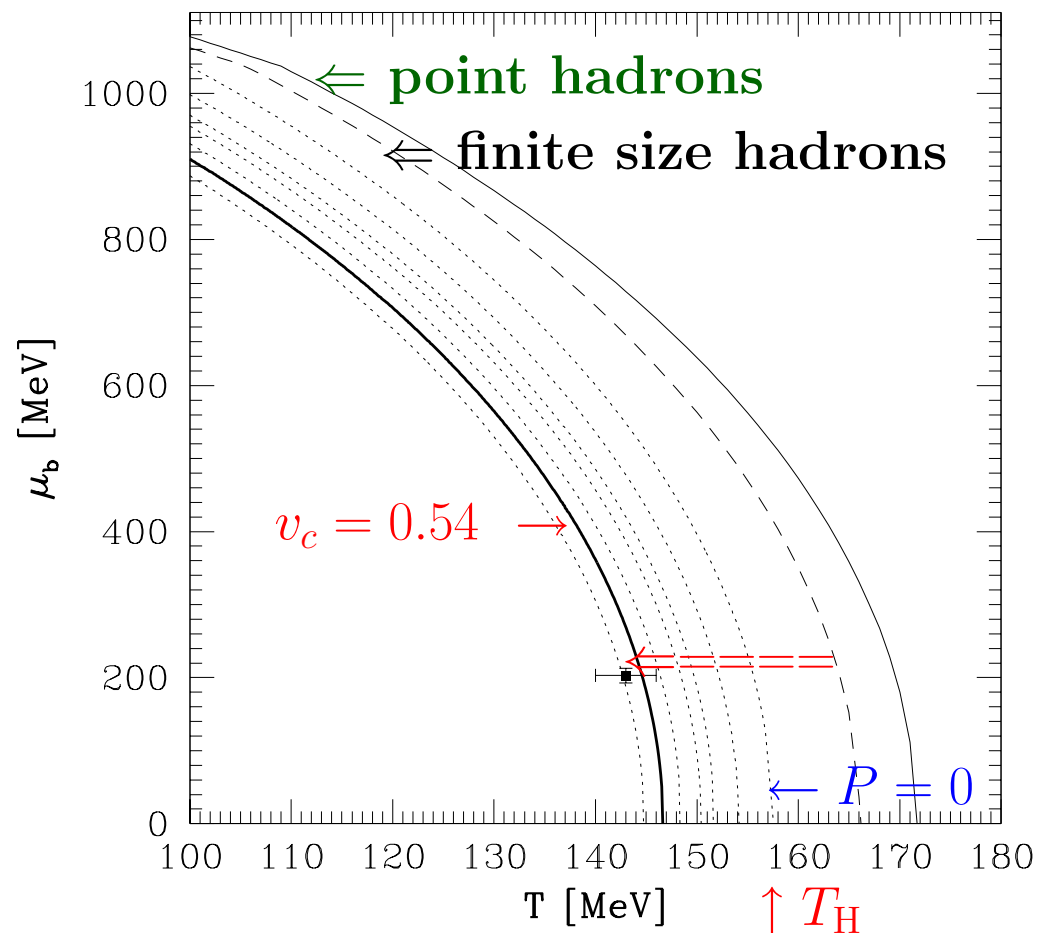
$$\mathcal{B}\vec{n} = P_p\vec{n} + (P_p + \varepsilon_p)\frac{\vec{v}_c \vec{v}_c \cdot \vec{n}}{1 - v_c^2},$$

Multiplying with \vec{n} , we find,

$$\mathcal{B} = P_p + (P_p + \varepsilon_p)\frac{\kappa v_c^2}{1 - v_c^2}, \quad \kappa = \frac{(\vec{v}_c \cdot \vec{n})^2}{v_c^2}.$$

This requires $P_p < \mathcal{B}$: QGP phase pressure P must be NEGATIVE. A fireball surface region which reaches $\mathcal{P} \rightarrow 0$ and continues to flow outward is torn apart in a rapid instability. This can ONLY arise since matter presses against 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: $T_c(\mu_b)|_{P_{eff}-B=0}$ 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

$T_H = 158$ MeV Hagedorn temperature where $P = 0$, no hadron P
 $T_f \simeq 0.9T_H \simeq 143$ MeV is where supercooled QGP fireball breaks up
 equilibrium phase transformation is at $\simeq 166$.

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.

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

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

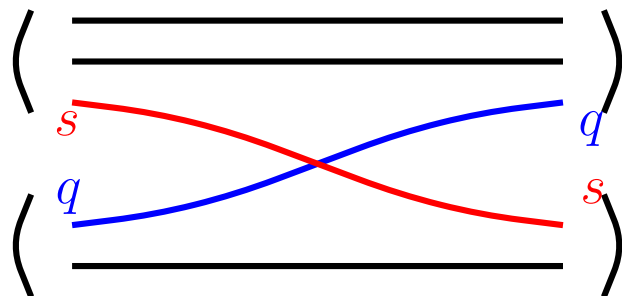
Integrals easily computed. Proportionality constant C NOT A VOLUME for a dynamically evolving system.

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

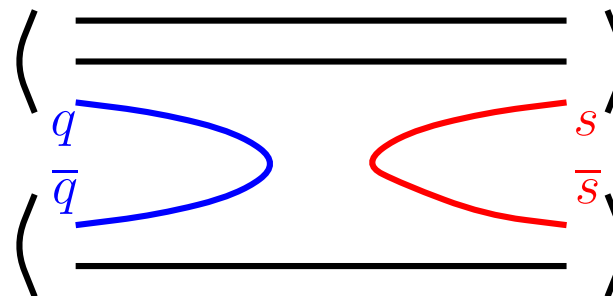
HG-EXAMPLE: redistribution,
Relative chemical equilibrium



EXCHANGE REACTION

λ_i

production of strangeness
Absolute chemical equilibrium



PAIR PRODUCTION REACTION

γ_i

RATIOS OF PARTICLE YIELDS FIX CHEMICAL PARAMETERS

$$R_\Lambda = \frac{\bar{\Lambda}}{\Lambda} = \frac{\bar{\Lambda} + \bar{\Sigma}^0 + \bar{\Sigma}^* + \dots}{\Lambda + \Sigma^0 + \Sigma^* + \dots} = \frac{\bar{s}\bar{q}\bar{q}}{sqq} = \lambda_s^{-2}\lambda_q^{-4} = e^{2\mu_s/T} e^{-2\mu_b/T} .$$

$$R_\Xi = \frac{\bar{\Xi}^-}{\Xi^-} = \frac{\bar{\Xi}^- + \bar{\Xi}^* + \dots}{\Xi^- + \Xi^* + \dots} = \frac{\bar{s}\bar{s}\bar{q}}{ssq} = \lambda_s^{-4}\lambda_q^{-2} = e^{4\mu_s/T} e^{-2\mu_b/T} .$$

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

$$\frac{\Xi^-(dss) + \Xi^* + \dots}{\Lambda(dd)s + \Lambda^* + \dots} \propto \frac{\gamma_d \gamma_s^2}{\gamma_d^2 \gamma_s} \frac{g_\Xi \lambda_d \lambda_s^2}{g_\Lambda \lambda_d^2 \lambda_s} .$$

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

Complete description of all hadron yields

We note above 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. Lead author: **Giorgio Torrieri**.

The **complete** statistical hadronization model allows precise description of all hadron yields, including resonances at all energies. The myth that resonances are not described within the same scheme is due to the limited model applied by some other groups which omits one or more key properties required. We find that Single freeze-out model as proposed in 1991 suffices when we consider:

1. Complete tree of resonance decays **Prof. Xu-Nu please note:**
not only for yields but also most important for **spectra**.
2. **WIDTH** of the resonances (needed to describe resonance yields)
3. Chemical off-equilibrium in hadron yields (if QGP near equilibrium, it is not present in the hadron sector, as the transformation is sudden).

Look for a few publications using the SHARE package on line, and invite **G. Torrieri** to give a lecture!

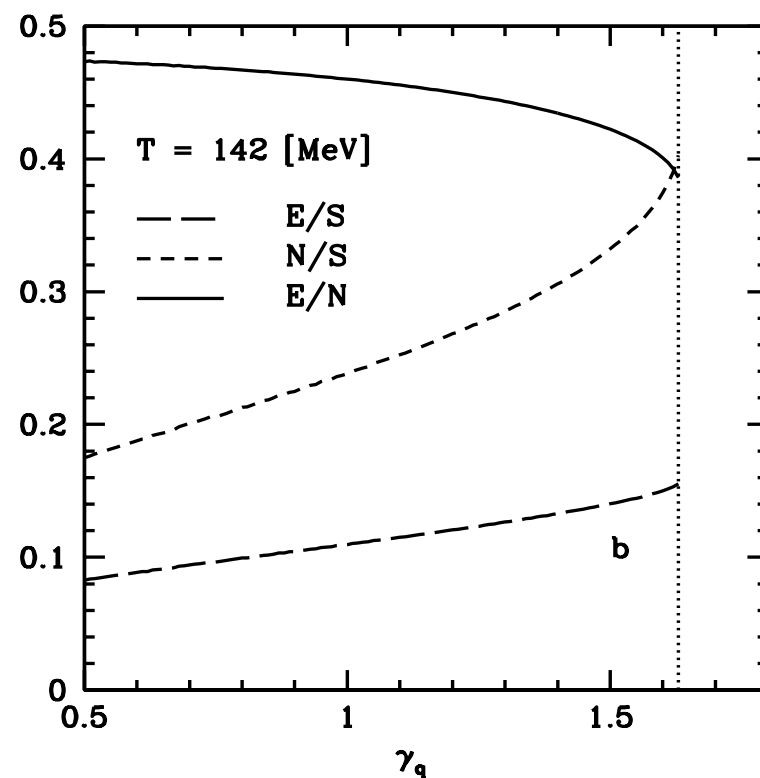
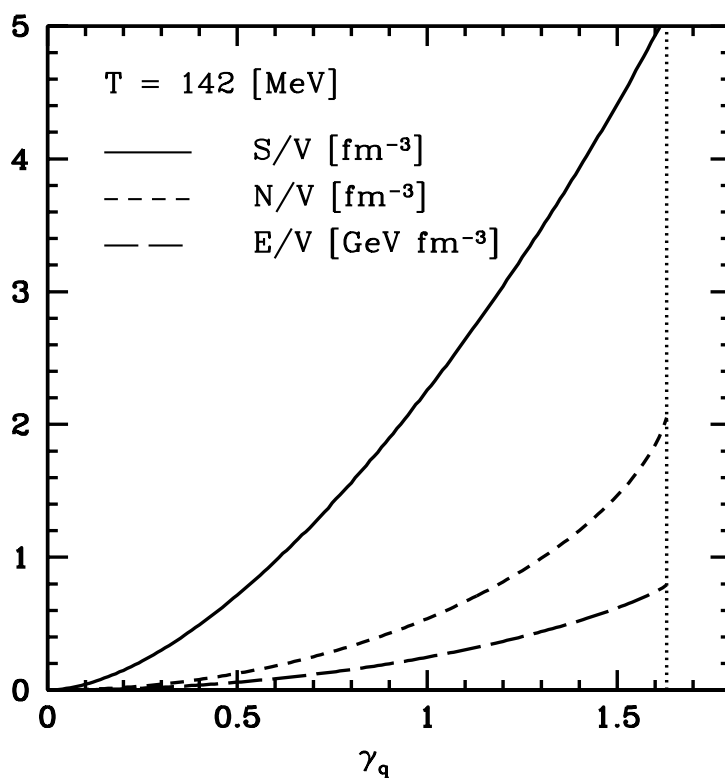
$\gamma_q^2 \rightarrow e^{m_\pi/T}$: A way to ‘consume’ excess of QGP entropy

Maximization of entropy density in pion: gas.

$$E_\pi = \sqrt{m_\pi^2 + p^2}$$

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

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



Strangeness measurement in QGP

1. TOTAL STRANGENESS YIELD: strangeness/*b*aryon depends primarily on **initial** conditions and (less) on **evolution** dynamics
(how long the system is at which *T*)

γ_s^{QGP} :

is QGP near chemical equilibrium?

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

2. Strangeness overpopulation at QGP BREAK-UP:

QGP phase space is squeezed into

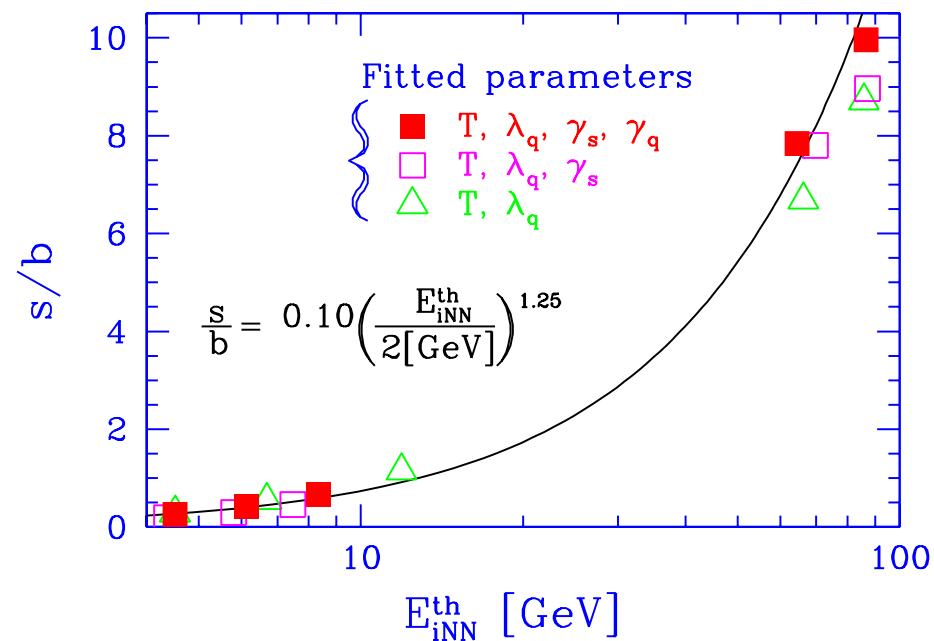
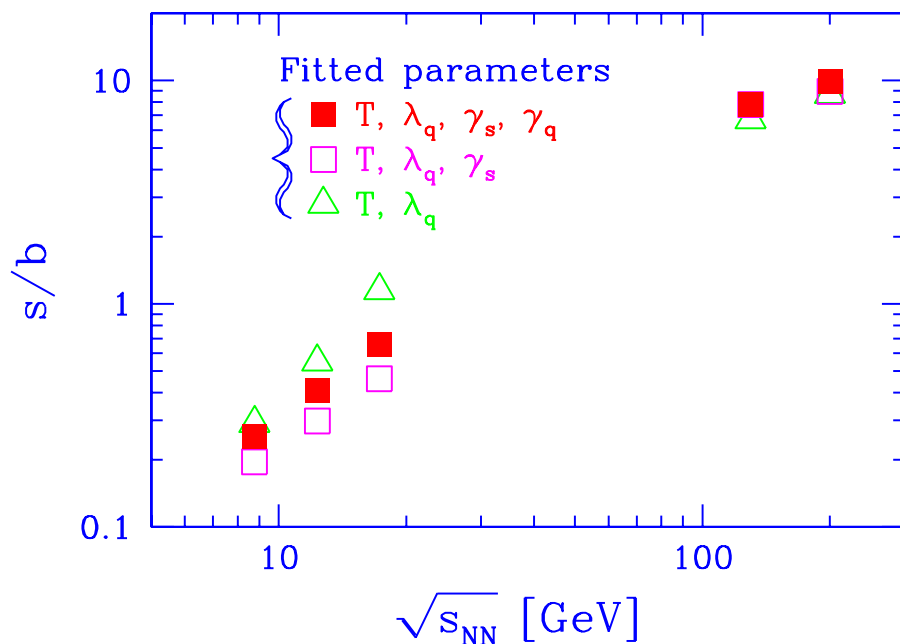
a smaller number of HG phase space cells: $\gamma_s^{\text{HG}} \simeq 2\gamma_s^{\text{QGP}}$

3. WE NEED ALSO TO CONSIDER QGP ENTROPY enhancement expressed

in $e^{m_\pi/(2T)} > \gamma_q^{\text{HG}} > 1$

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:

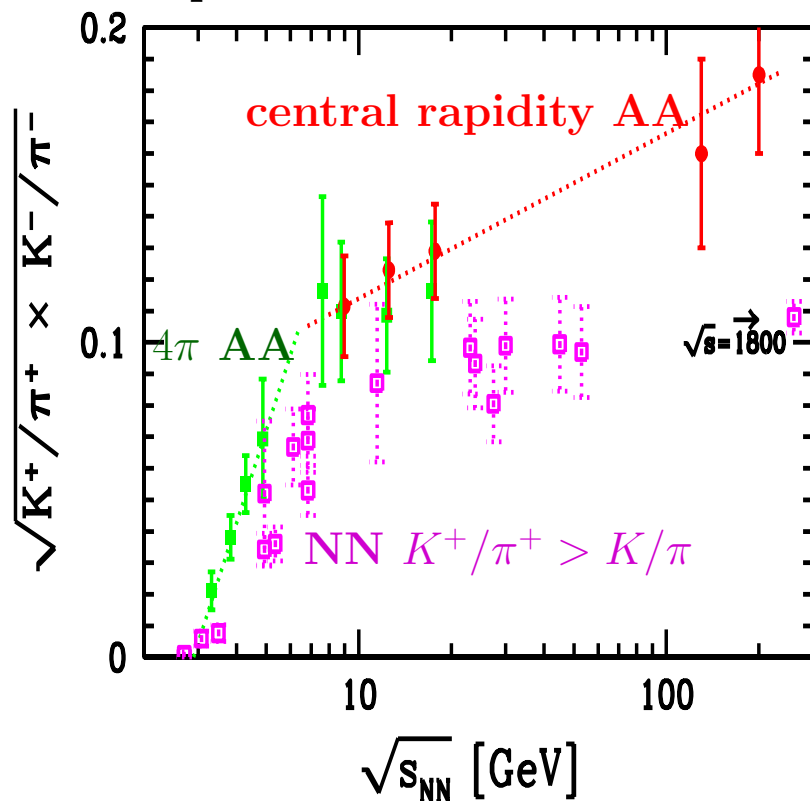
Soon at LHC – charm takes over from strangeness – an experimental challenge

Probing strangeness excitation by ratio K/π

The particle yield products

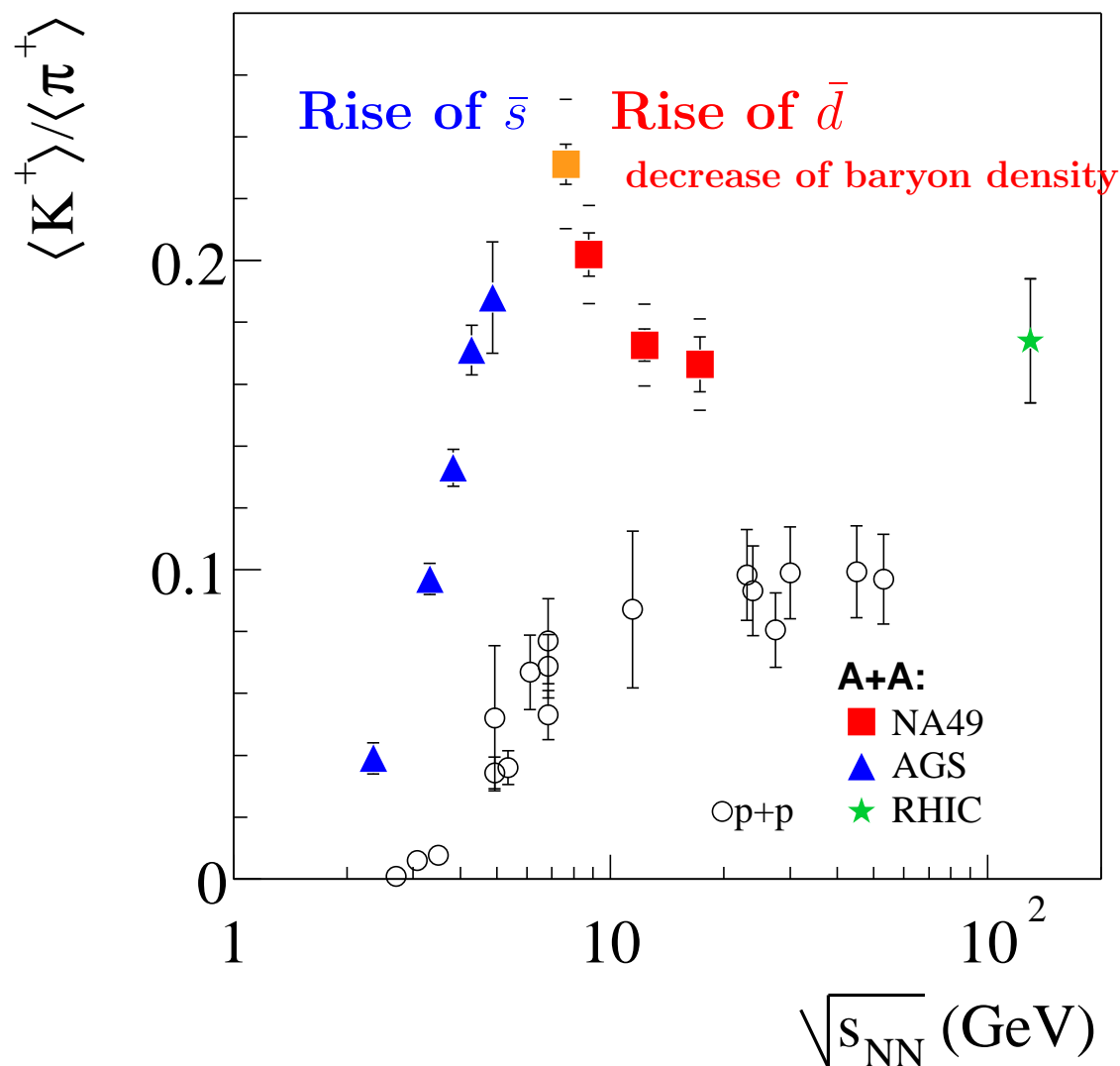
$$K \equiv \sqrt{K^+(u\bar{s})K^-(\bar{u}s)} \propto \sqrt{\lambda_u/\lambda_s \lambda_s/\lambda_u} \quad \pi \equiv \sqrt{\pi^+(u\bar{d})\pi^-(\bar{u}d)} \propto \sqrt{\lambda_u/\lambda_d \lambda_d/\lambda_u}$$

are less dependent on chemical conditions including baryon density.



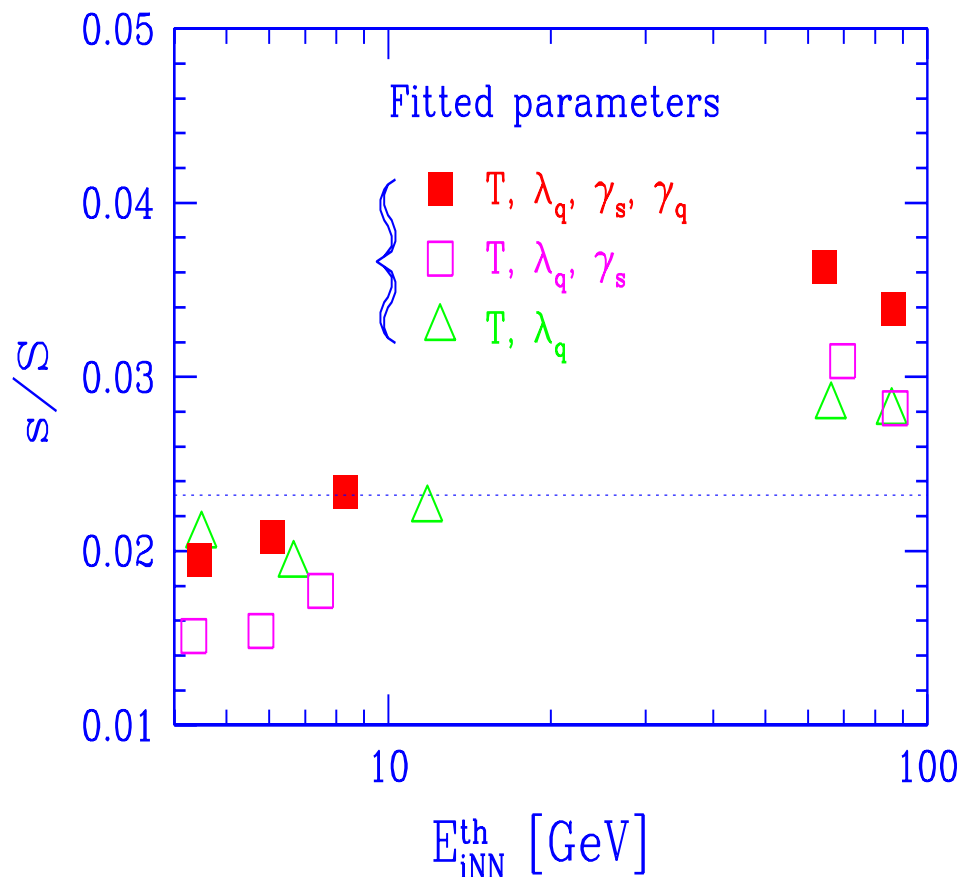
There is a notable enhancement in K/π above the K^+/π^+ ratio recorded in pp reactions, which provides an upper limit on K/π . There is a clear change in the speed of rise in the K/π ratio at the lower energy limit at SPS; This combined with change in nuclear compression results in a peak in the K^+/π^+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

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



The 'peak' is result of two effects: approach to saturation of strangeness, followed by increased baryon transparency signaling a change in reaction mechanism. Possibly, deconfinement!

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

SO WHAT??

This is not the end of the story, but its beginning. We will soon know how did the quark-gluon Universe hadronizes and how did the antimatter component disappear.