THE FUTURE OF RELATIVISTIC HEAVY ION COLLISIONS

Workshop on "Future of Nuclear Collisions at High Energy", Kielce, October 14-17, 2004

This is not a workshop summary. I describe major accomplishments (some not yet mentioned) and offer implied and/or explicit challenges. +50% of content is for STUDENTS who ARE actually THE FUTURE of relativistic heavy ion nuclear collisions.

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The origin of this research program

to move on with other issues in fundamental understanding of the world around us, we need to make this 'next step'

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 10-40μs 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 $\langle V|\bar{u}u + \bar{d}d|V\rangle = -2[225(9)\,\mathrm{MeV}]^3\,.$

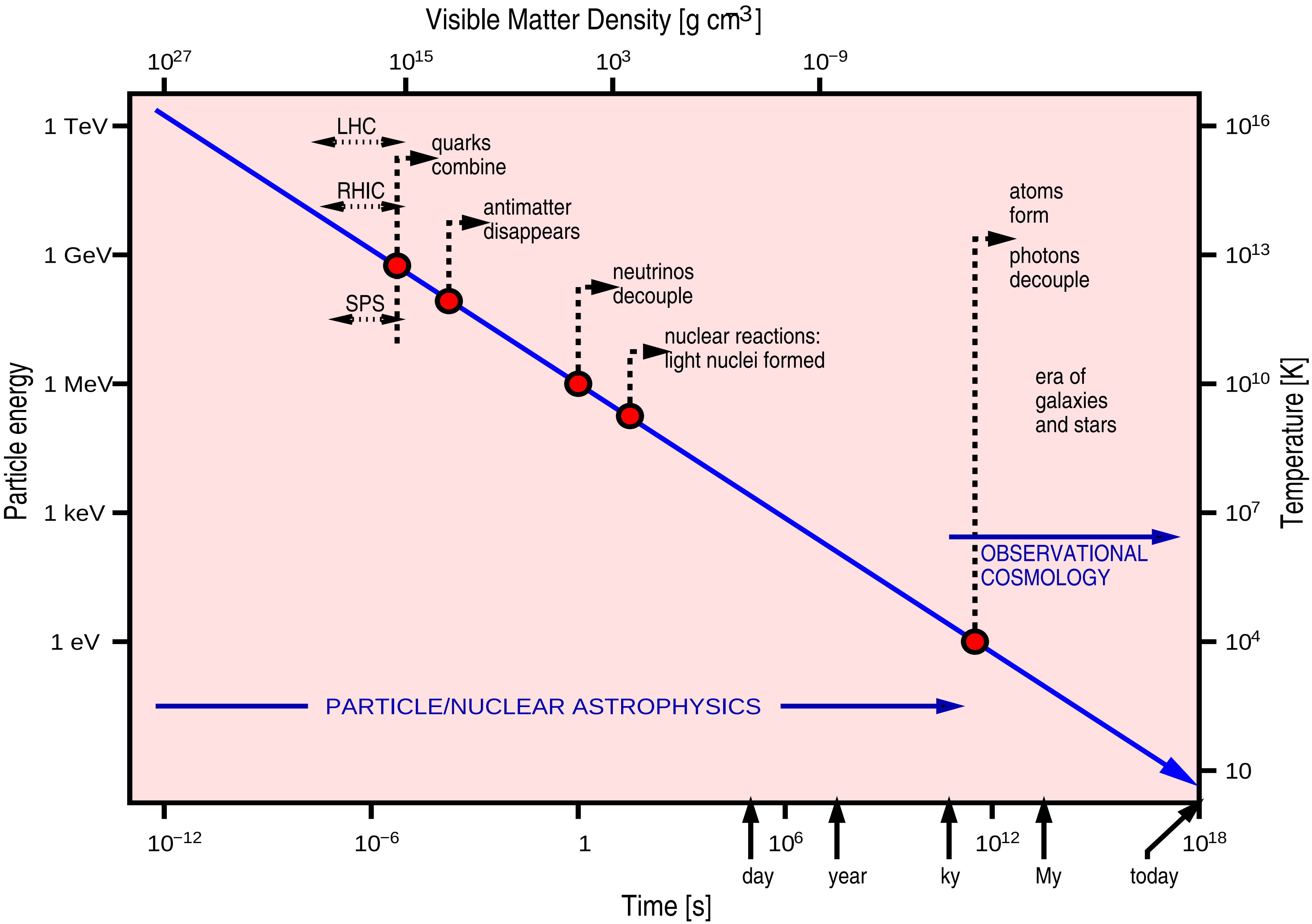
Vacuum and Laws of Physics

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

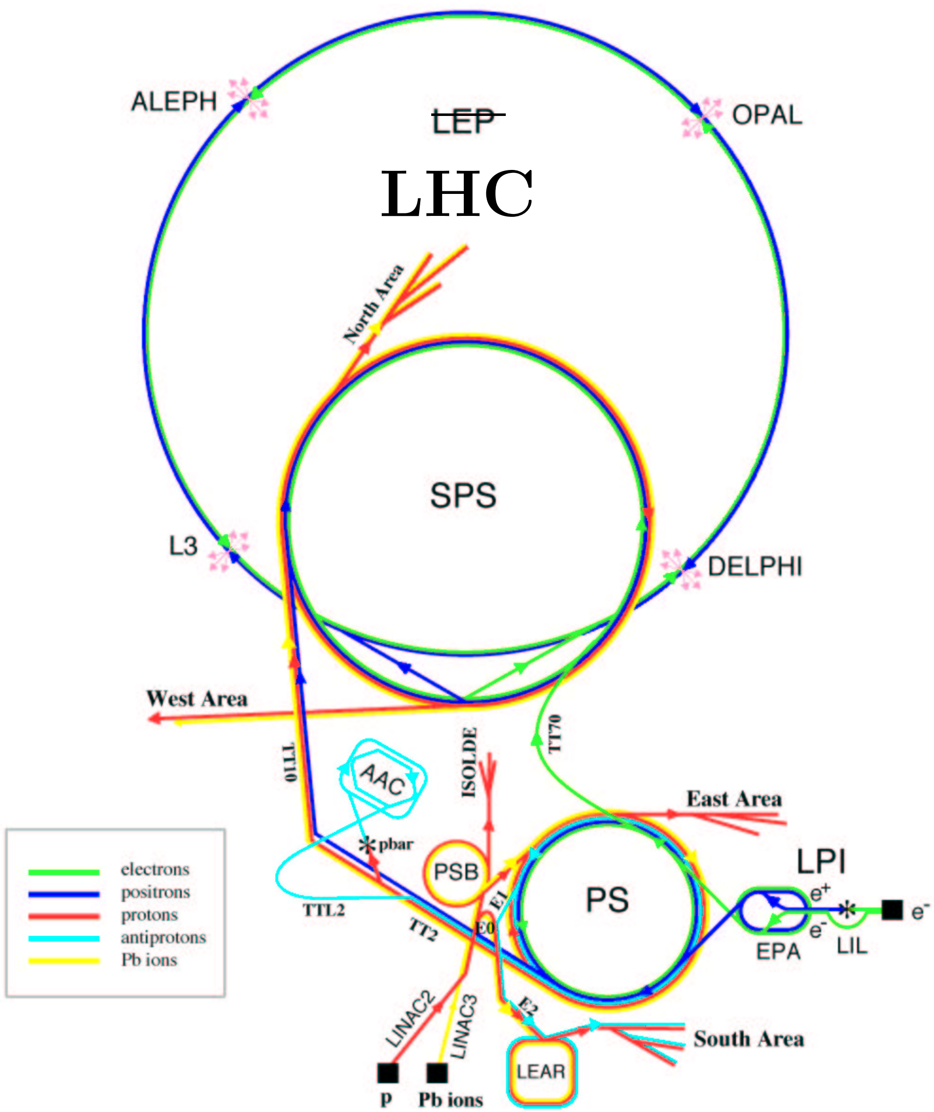
$$m_i = g_i\langle V|h|V\rangle\,,$$

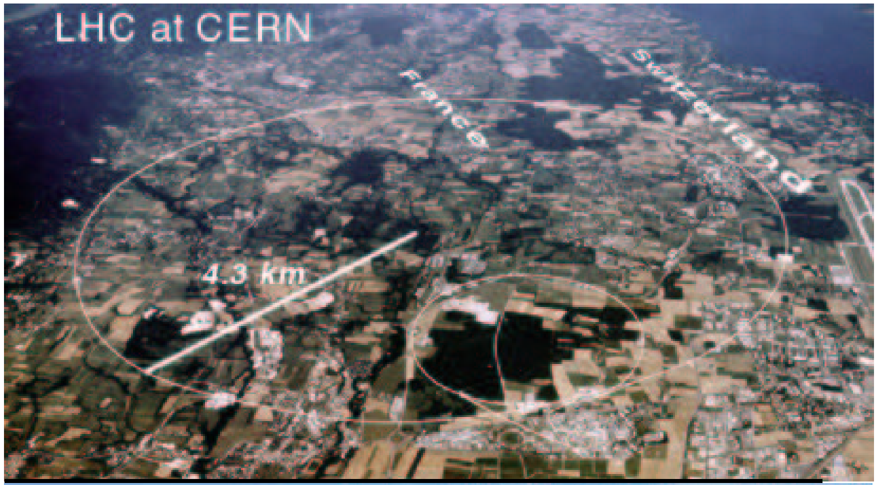
Vacuum is thought to generate color charge confinement:
hadron mass originates in QCD vacuum structure.
Vacuum determines interactions, symmetry breaking, etc.....
DO WE REALLY UNDERSTAND HOW THE VACUUM CONTROLS INERTIA (RESISTANCE TO CHANGE IN VELOCITY)??

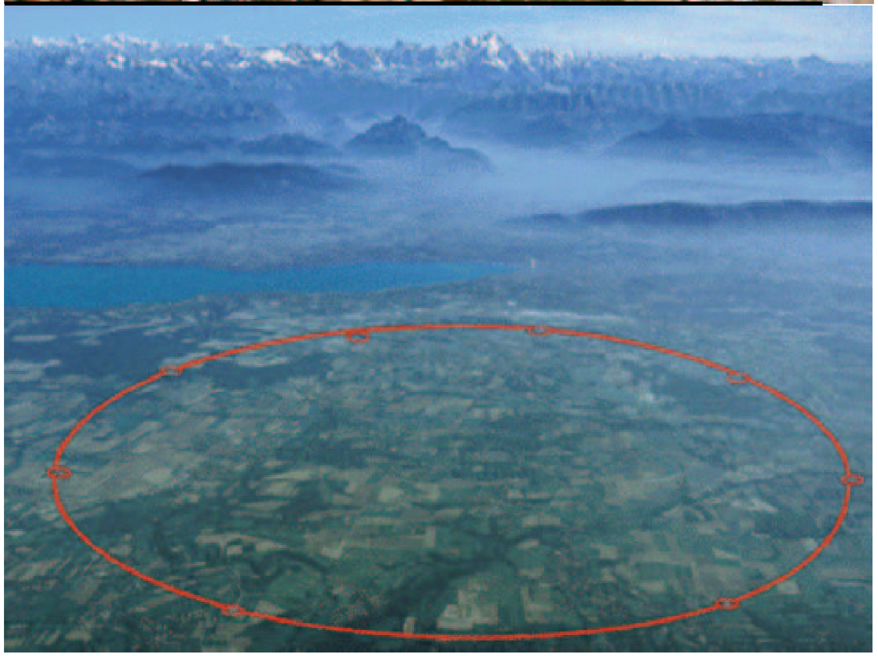
Do we really understand how annihilation of almost all matter-antimatter occurs?



EXPERIMENTAL HEAVY ION PROGRAM





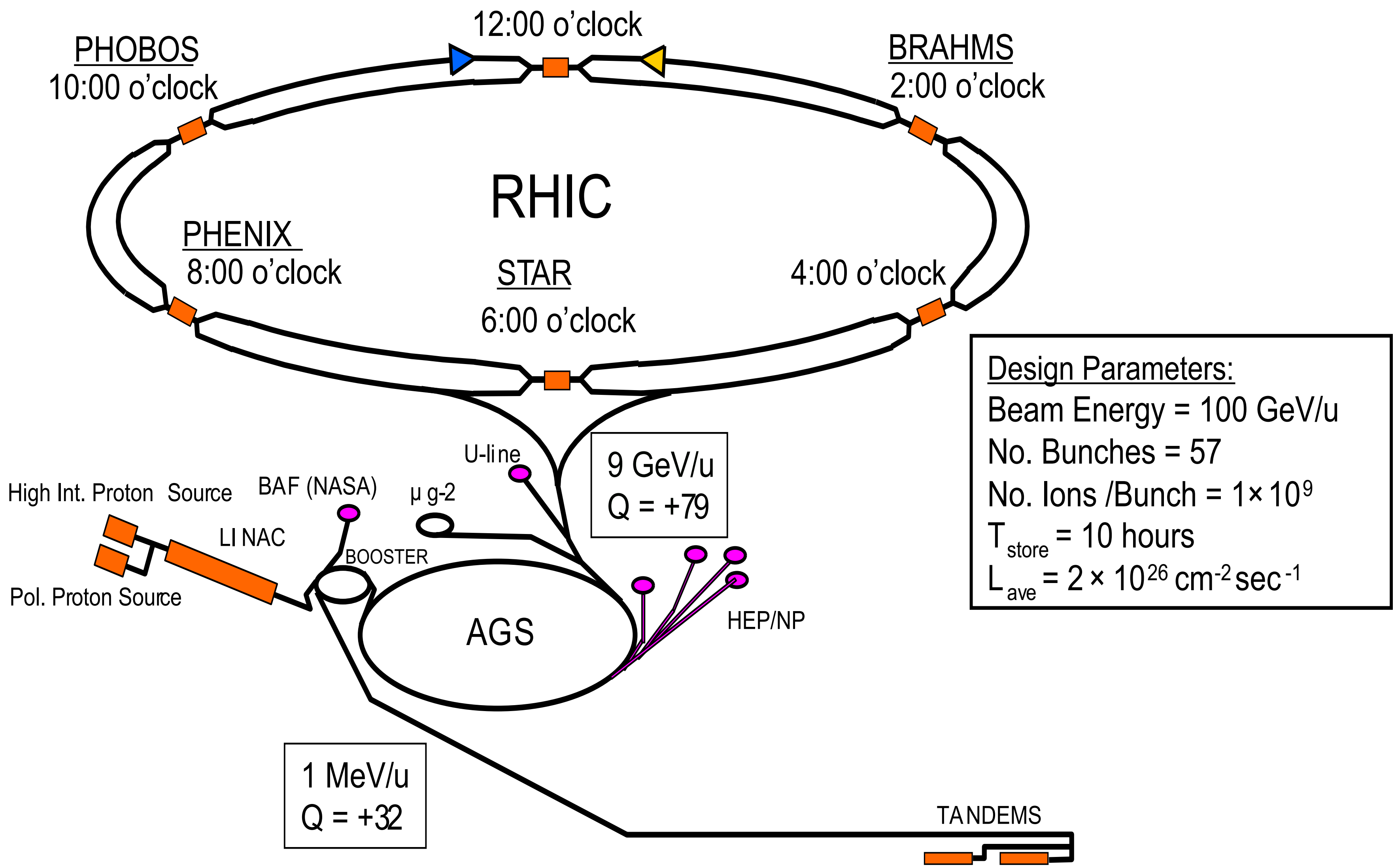


AT CERN: LHC opens after 2007 and SPS resumes after 2009

...and at BROOKHAVEN NATIONAL LABORATORY

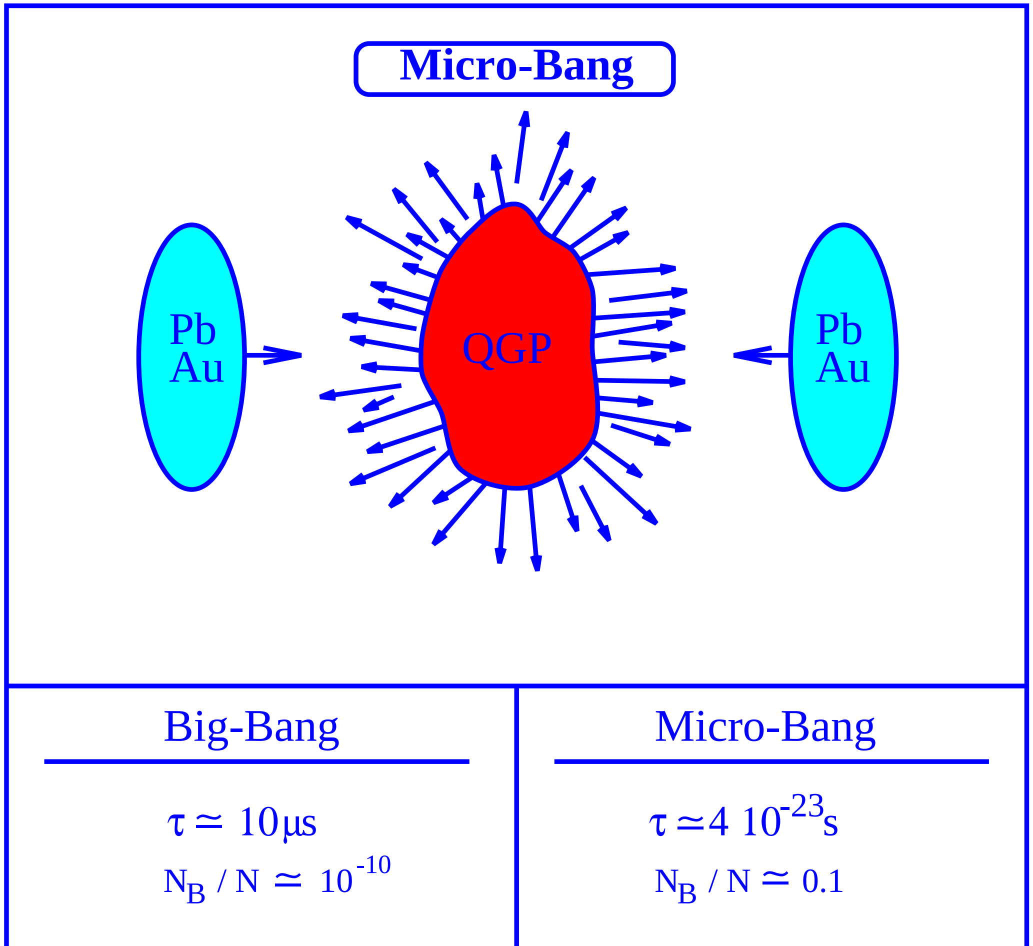
Relativistic Heavy Ion Collider: RHIC

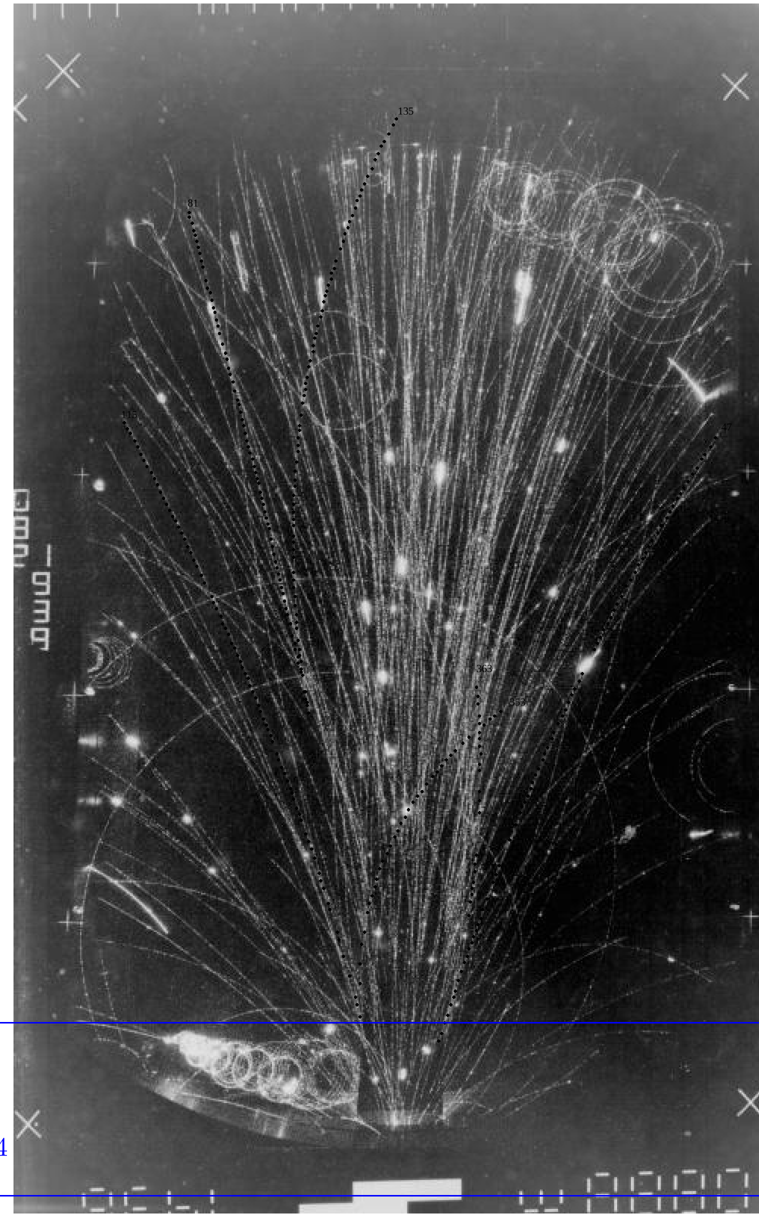
BROOKHAVEN NATIONAL LABORATORY



Relativistic Heavy Ion Collider: RHIC

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



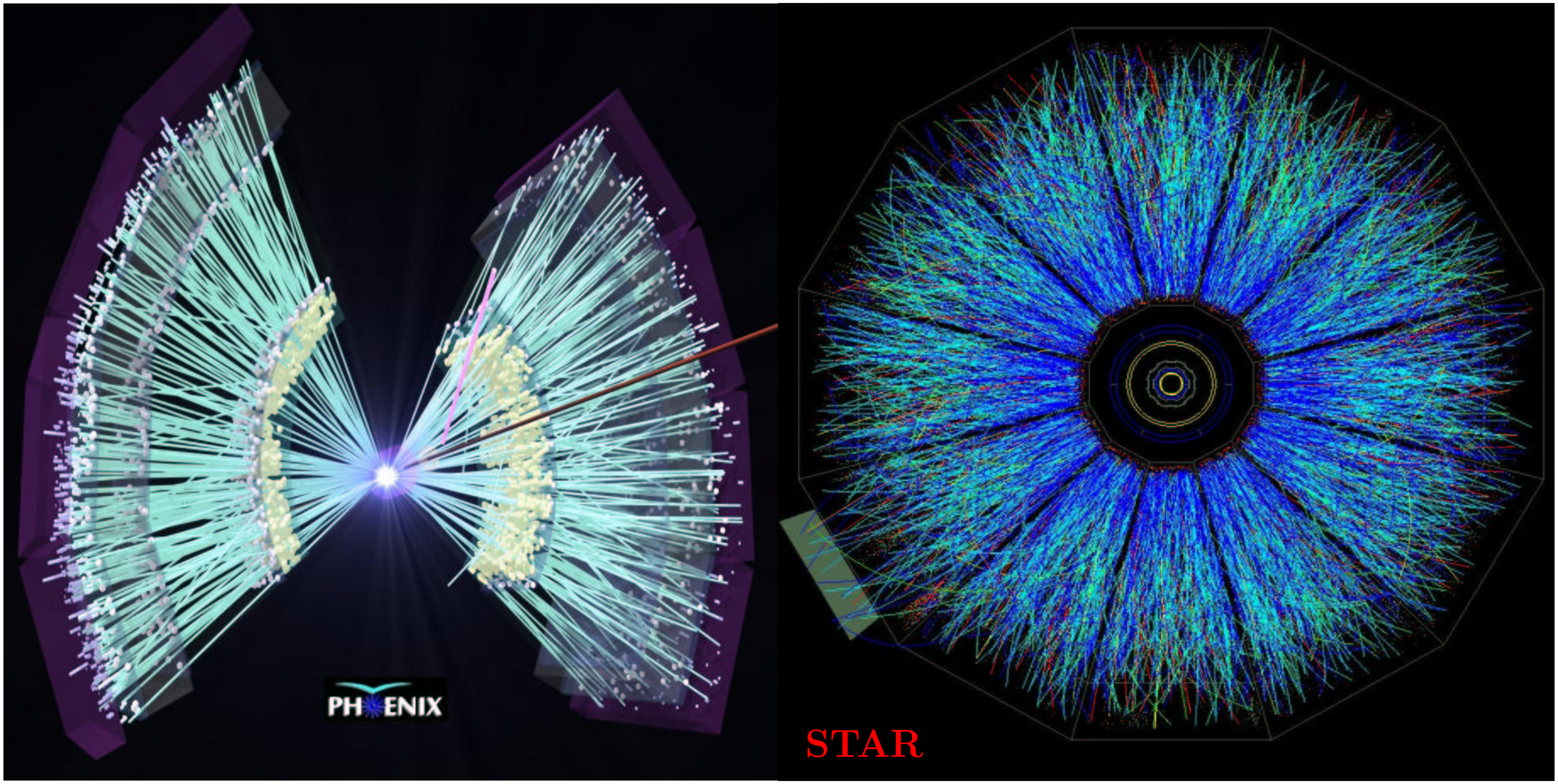


Peter Seyboth, NA35 1986: S–Ag at 200AGeV

Order of Magnitude

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

THE EARLY UNIVERSE AT RHIC



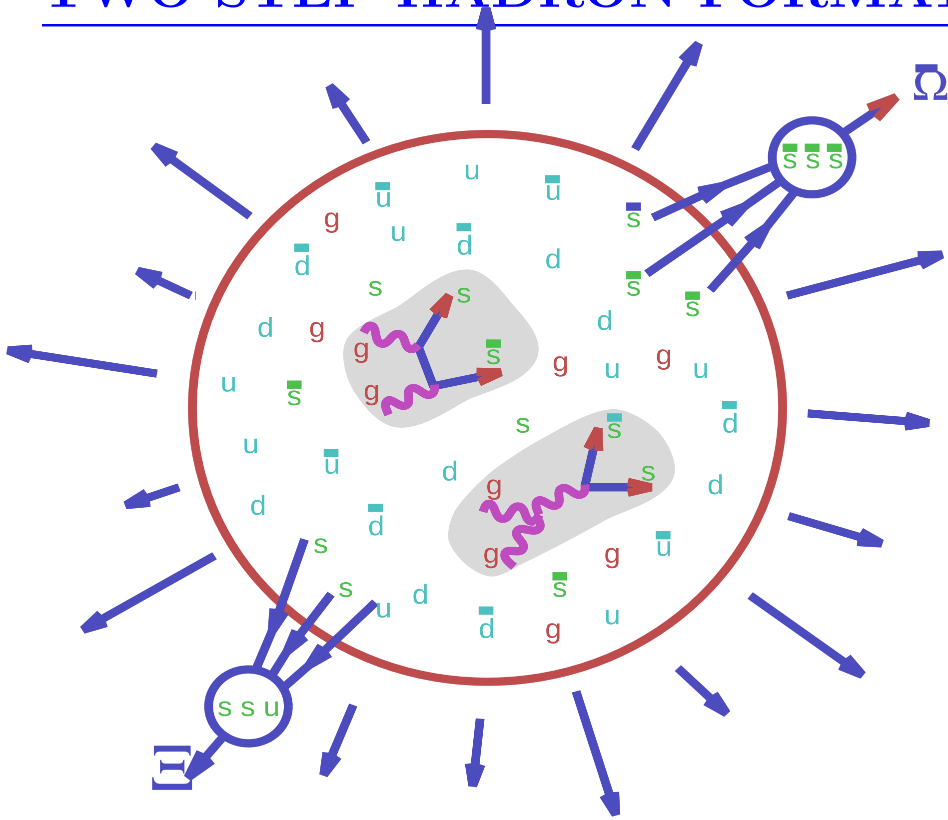
. . . and BRAHMS, PHOBOS: How is this maze of tracks of newly produced particles telling us what we want to know about the early Universe and its properties?
Study of patterns in particle production: correlations, new flavors (strangeness, charm), resonances, etc..

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/Ψ 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

TWO STEP HADRON FORMATION MECHANISM IN QGP



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

$GG \to c\bar{c}$

reaction gluon dominated

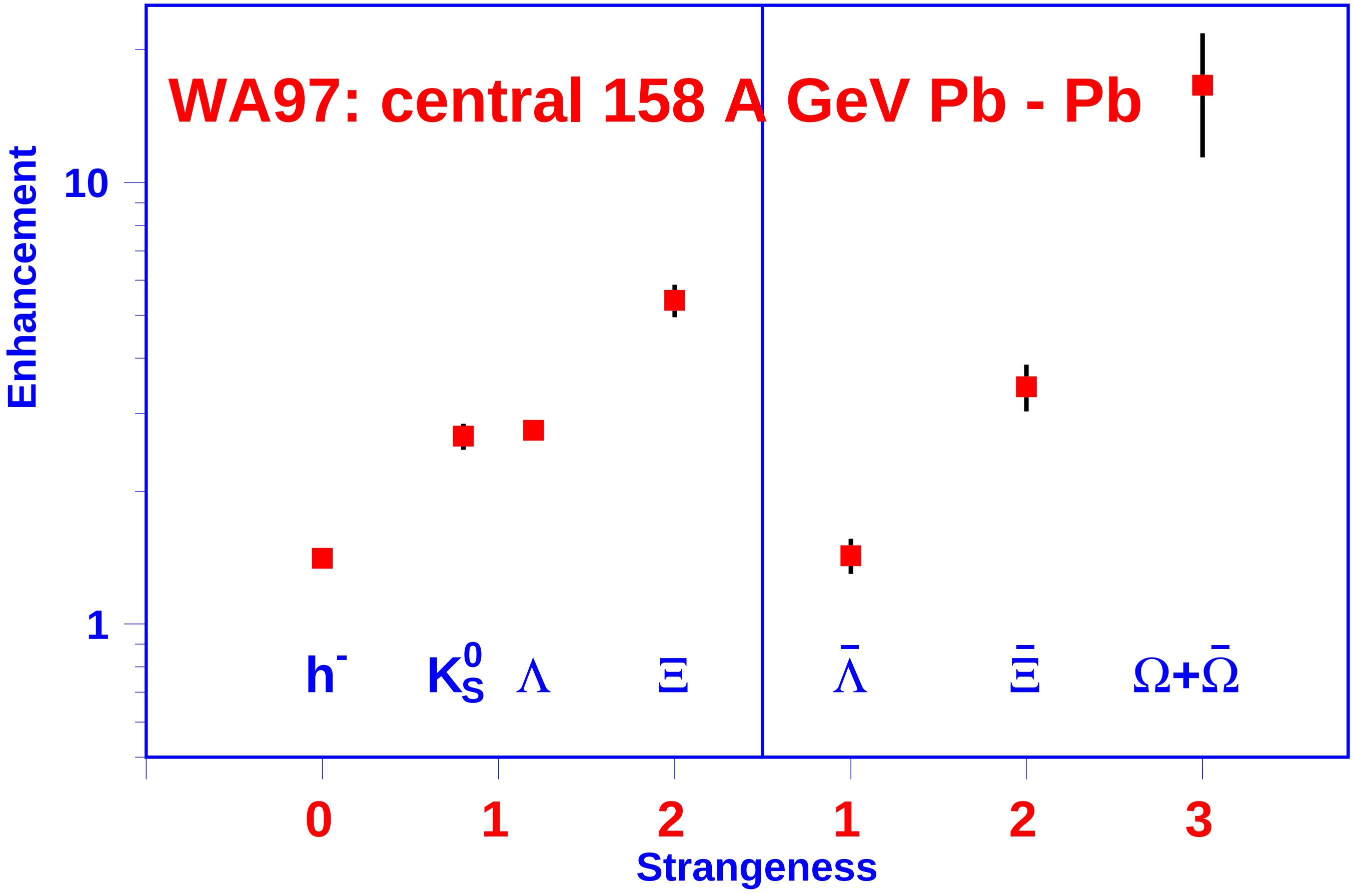
2. hadronization of pre-formed s, $\bar{s}$, c, $\bar{c}$ **quarks**

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.

(MULTI)STRANGE (ANTI)HYPERON ENHANCEMENT

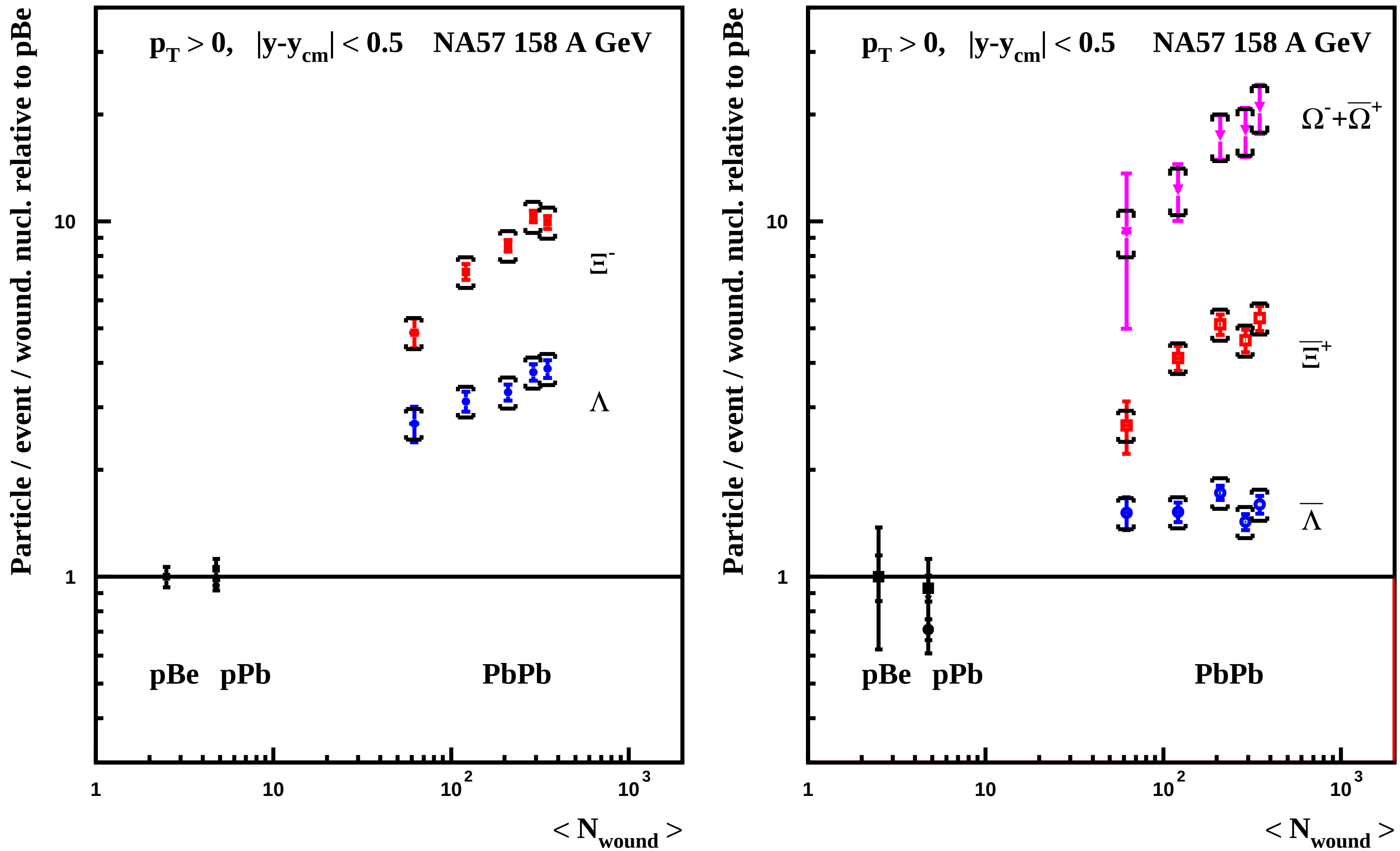


Enhancement GROWTH with

strangeness antiquark content.

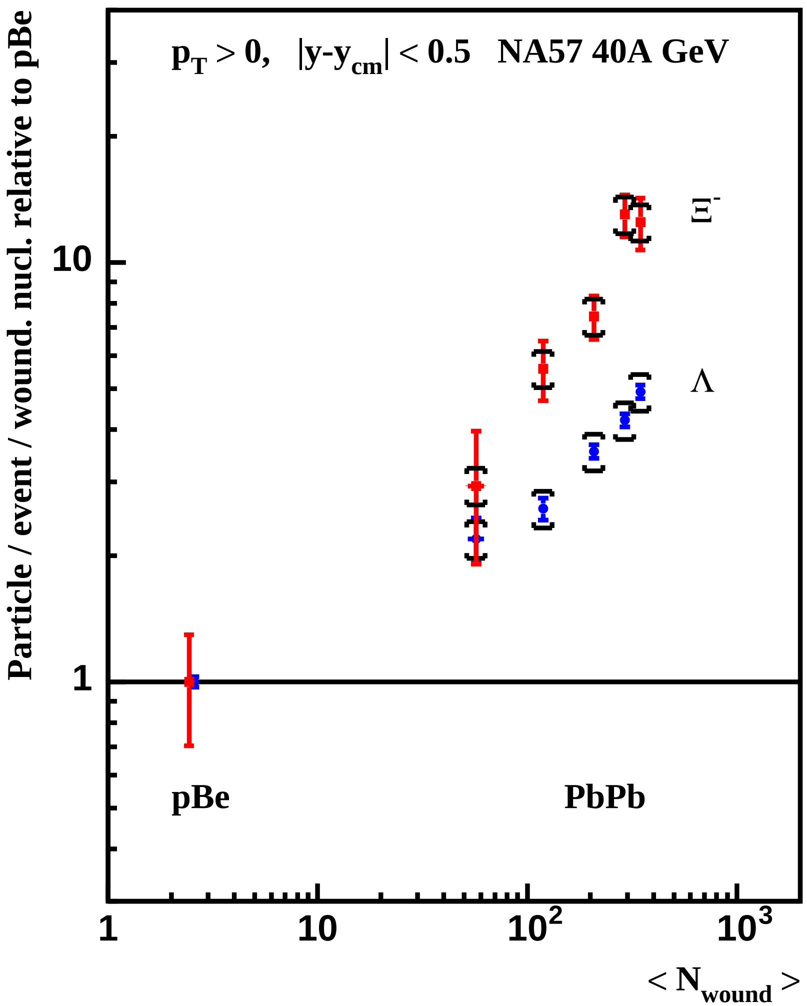
Enhancement is here defined with respect to the yield in p–Be collisions, scaled up with the number of collision 'wounded' nucleons.

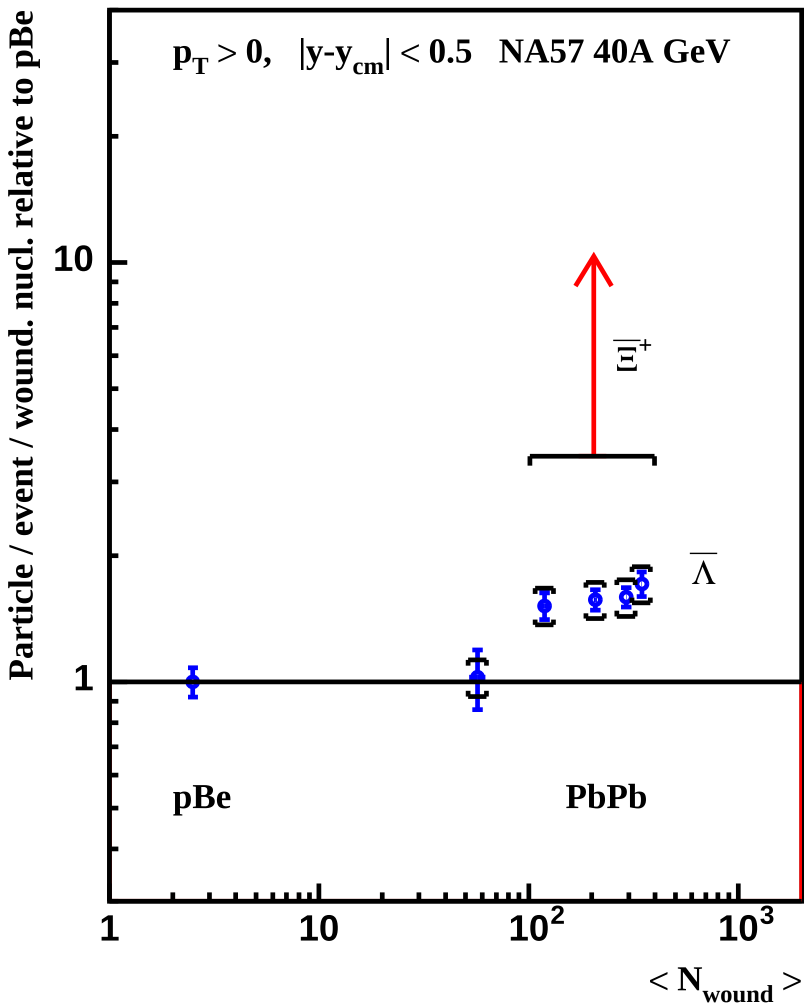
ENHANCEMENT AS FUNCTION OF REACTION VOLUME



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

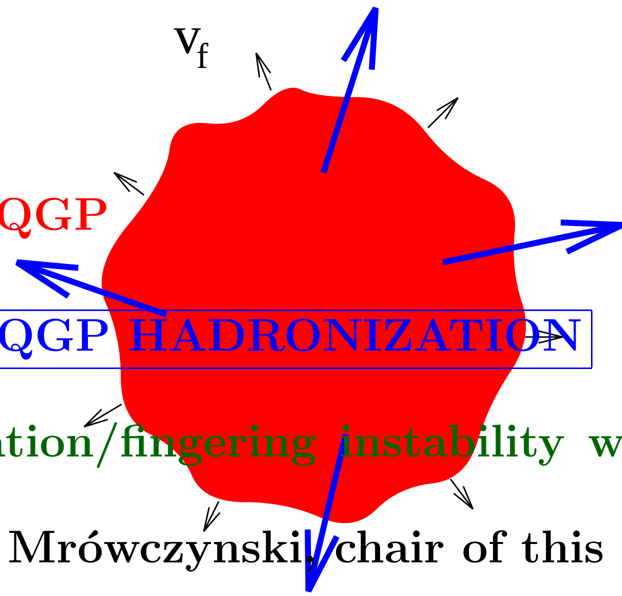
REACTION MECHANISM OF PARTICLE PRODUCTION

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 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

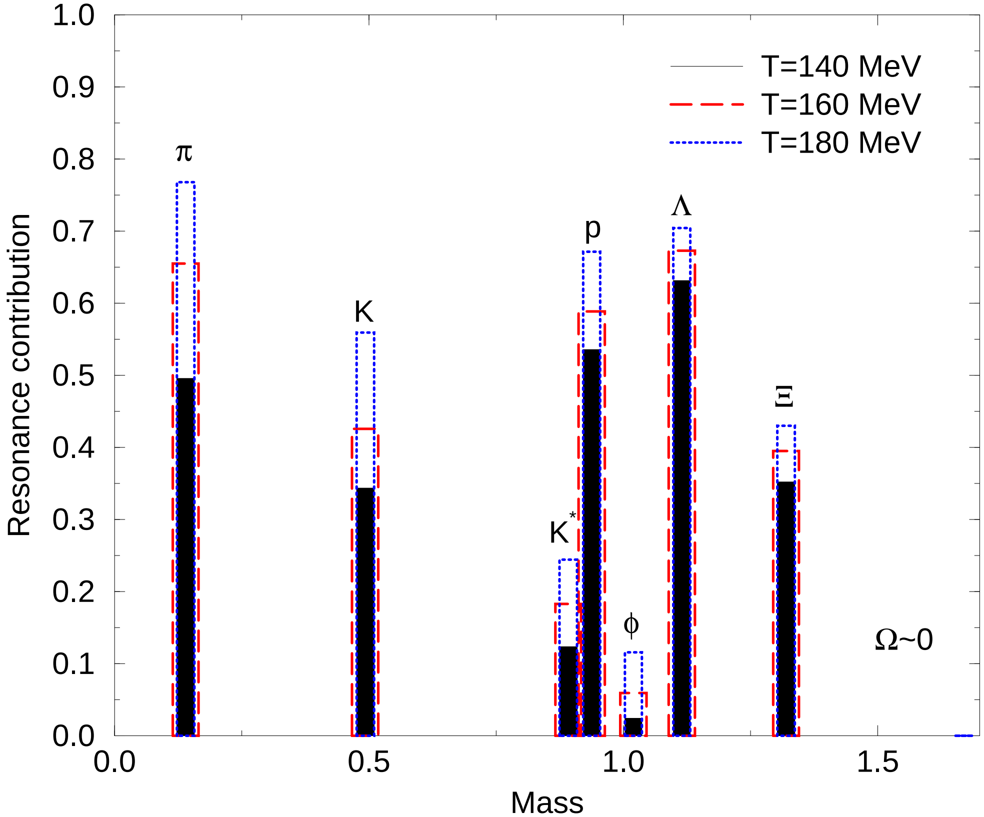


Develop analysis tools viable in SUDDEN QGP HADRONIZATION

Proposed reaction mechanism: filamentation/fingering instability when in expansion pressure reverses.
A big player is filamentation is Stanislaw Mrówczynski, chair of this meeting

STATISTICAL HADRONIZATION: 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.

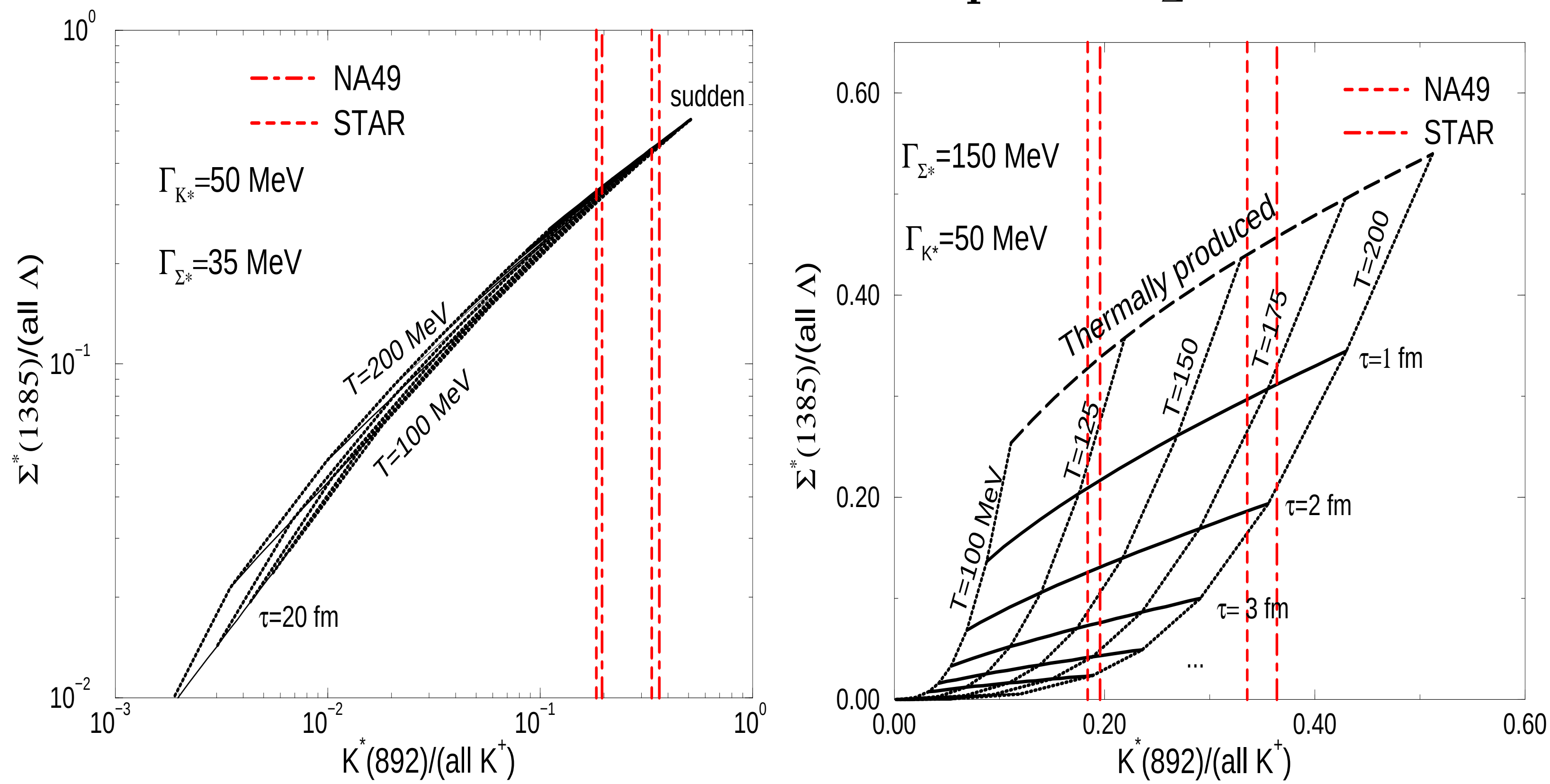
Strongly interacting matter essentially non-transparent. Simplest model: If resonance decays $N^* \to D + \ldots$ within matter, resonance can disappear from view. Model implementation:

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

Γ 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.**

TWO resonance ratios combined

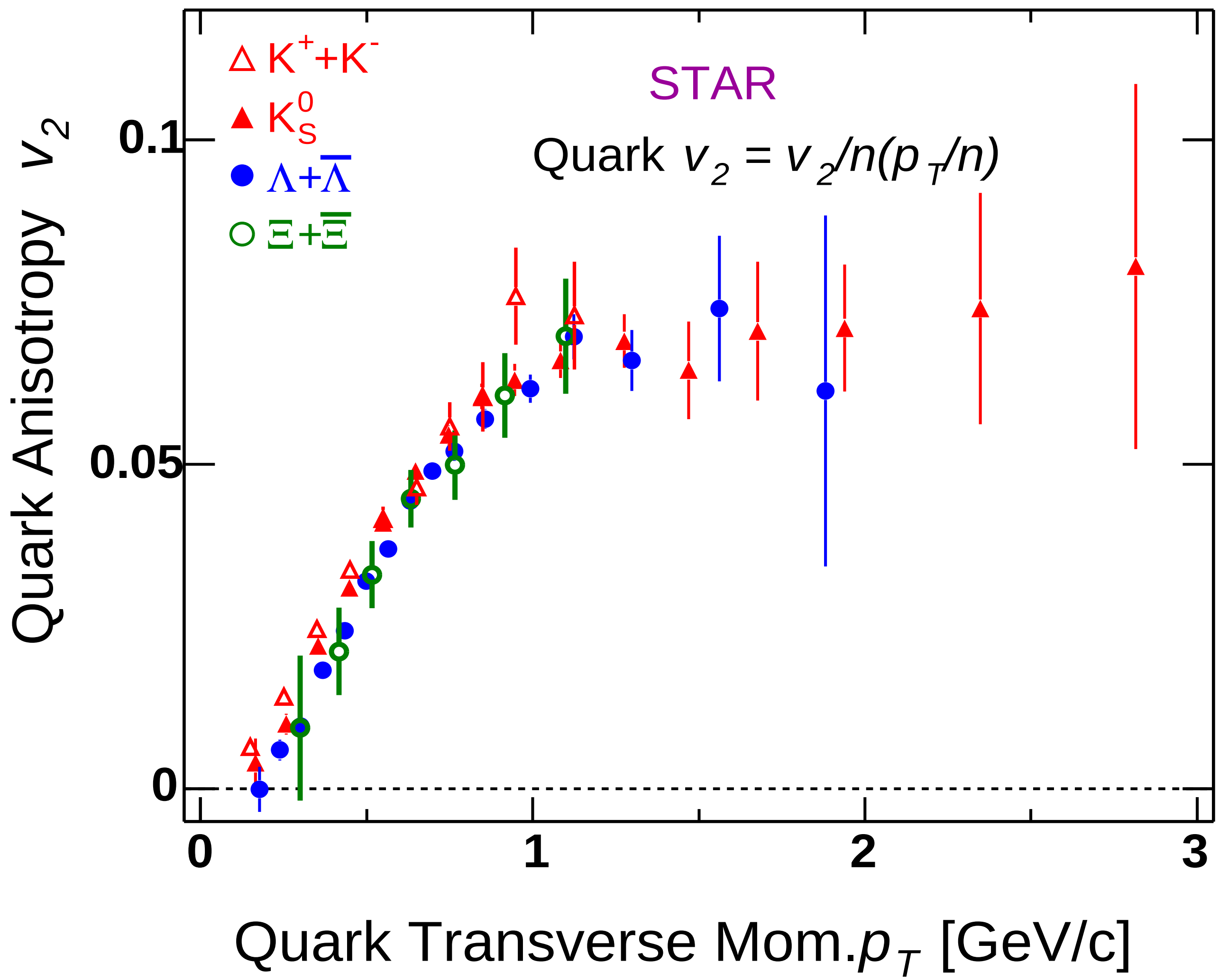
natural widths **spread $\Gamma_{\Sigma^*} = 150$ MeV**



Dependence of the combined Σ^*/(all Λ) with $K^*(892)$/(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.

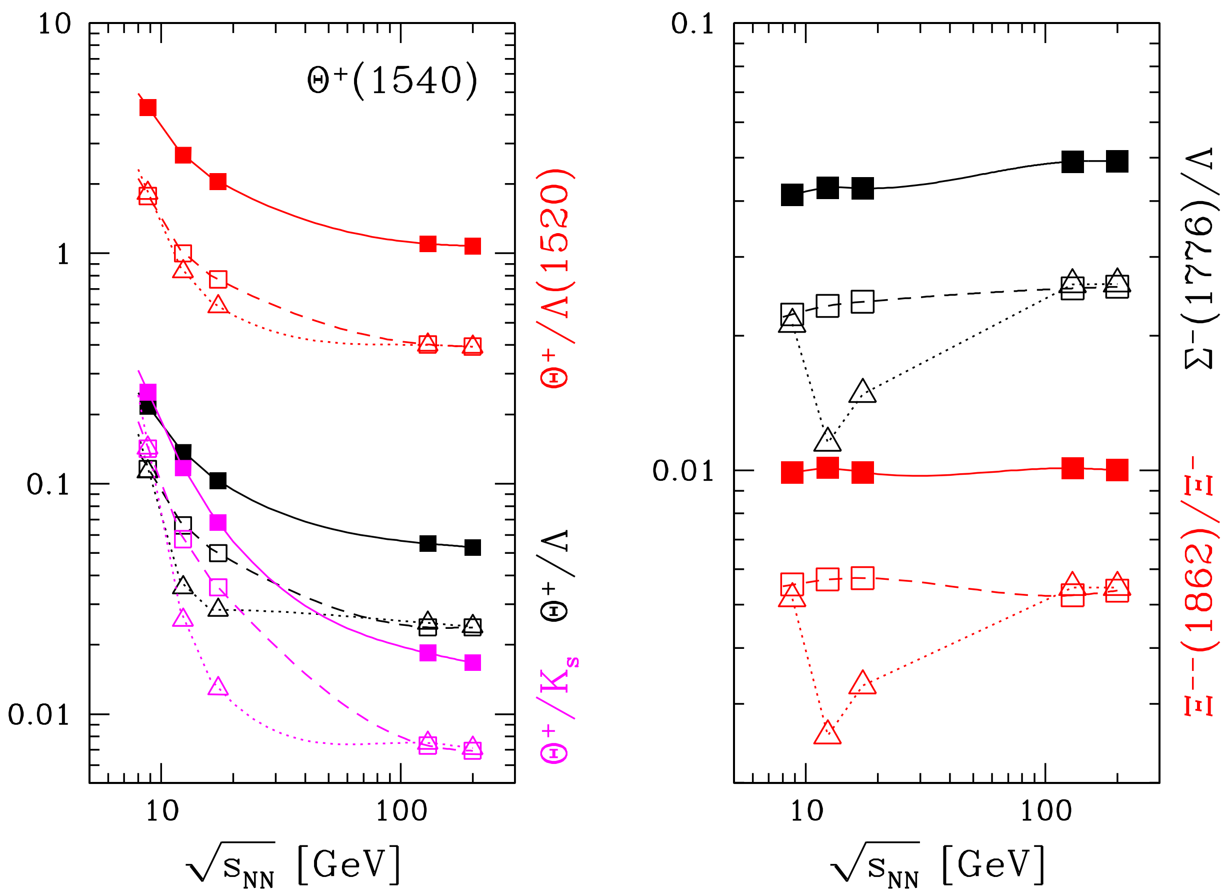
Discovery: Azimuthal asymmetry of particle spectra



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, observed B. Wosiek. **Quark scaling: Paul Sorenson and Huan-Zhong Huang. Idea due to J.-Y. Ollitrault.**

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 γ_s and γ_q fitted; dashed lines γ_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 γ_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 (see talk by W. Broniowski)**

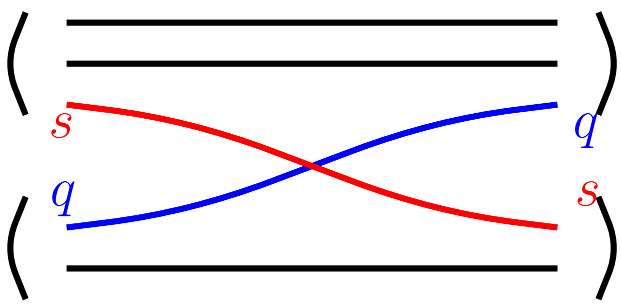
IN FUTURE: we hope that the more accurate, standardized and debugged hadronization studies will reduce misunderstandings

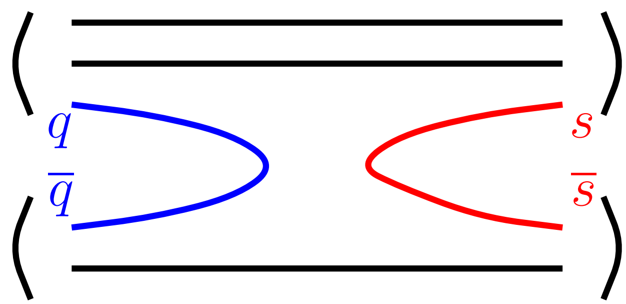
FOUR QUARKS: $s, \bar{s}, q, \bar{q} \rightarrow$ FOUR CHEMICAL PARAMETERS

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 **PAIR PRODUCTION REACTION**

λ_i γ_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 $N, \overline{N} \rightarrow$ 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 μ_b controls the particle difference = baryon number. γ 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.

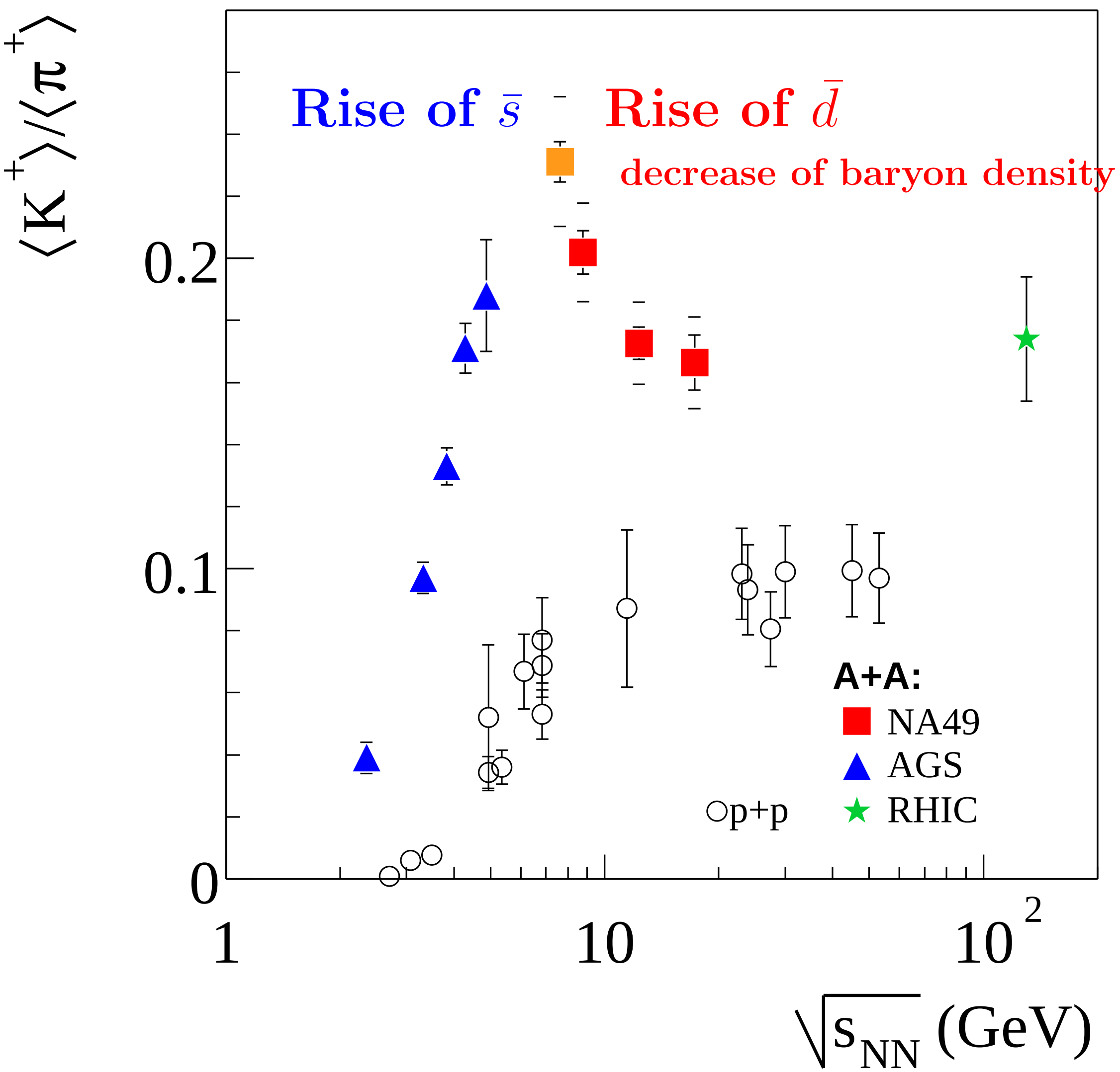
STRANGENESS / ENTROPY CONTENT s/S

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^+/π^+ is not trivial when precision better than 25% needed.

HADRON PHASE SPACE OVERPOPULATION

γ_s, γ_q allow correct measure of yields of strangeness and baryon number, probe dynamics of hadronization, allow fast breakup without 'mixed phase'

Instead: Marek Gaździcki study of $\bar{s}/\bar{d}$



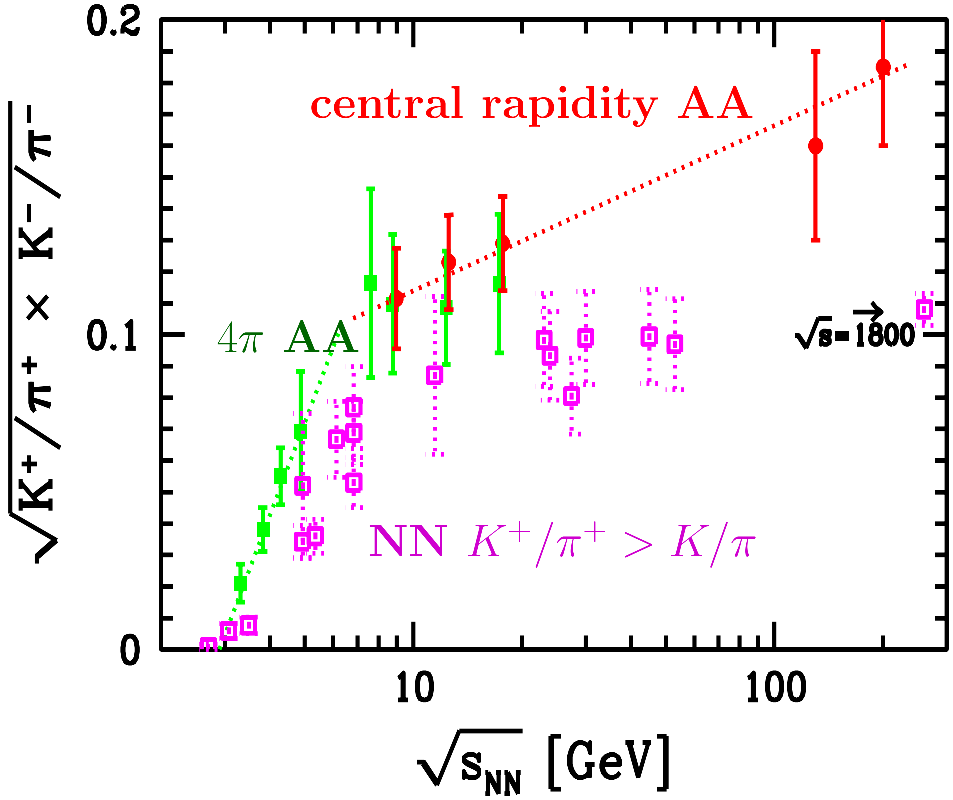
The 'peak' is result of two effects: approach to saturation of strangeness, followed by reduction of baryon density which allows growth of $\bar{d}$.
To confirm this let us eliminate from the presented measurement the last effect:

Probing strangeness excitation by ratio K/π

The particle yield products

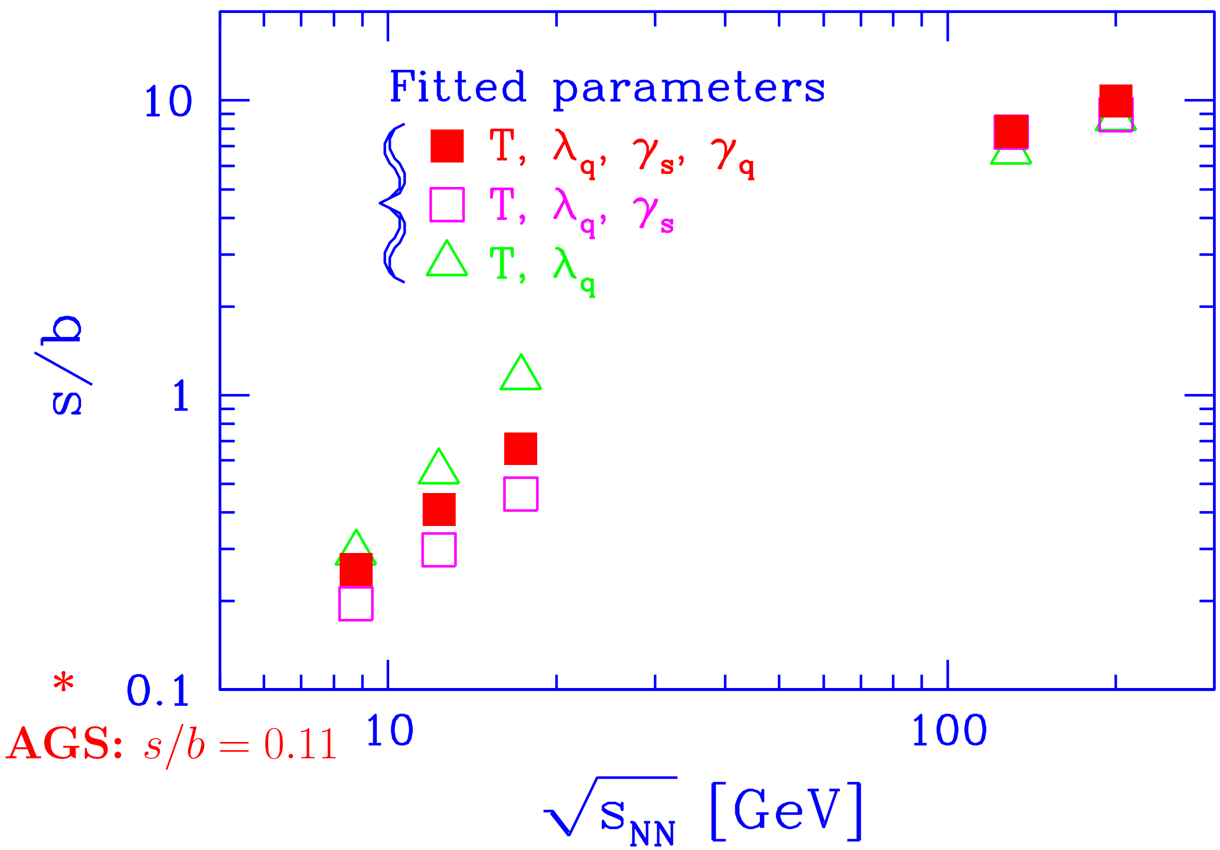
$$K \equiv \sqrt{K^+(u\bar{s})K^-(\bar{u}s)} \propto \sqrt{\lambda_u/\lambda_s\ \lambda_s/\lambda_u} \qquad \pi \equiv \sqrt{\pi^+(u\bar{d})\pi^-(\bar{u}d)} \propto \sqrt{\lambda_u/\lambda_d\ \lambda_d/\lambda_u}$$

are much 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^+.

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.

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?

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

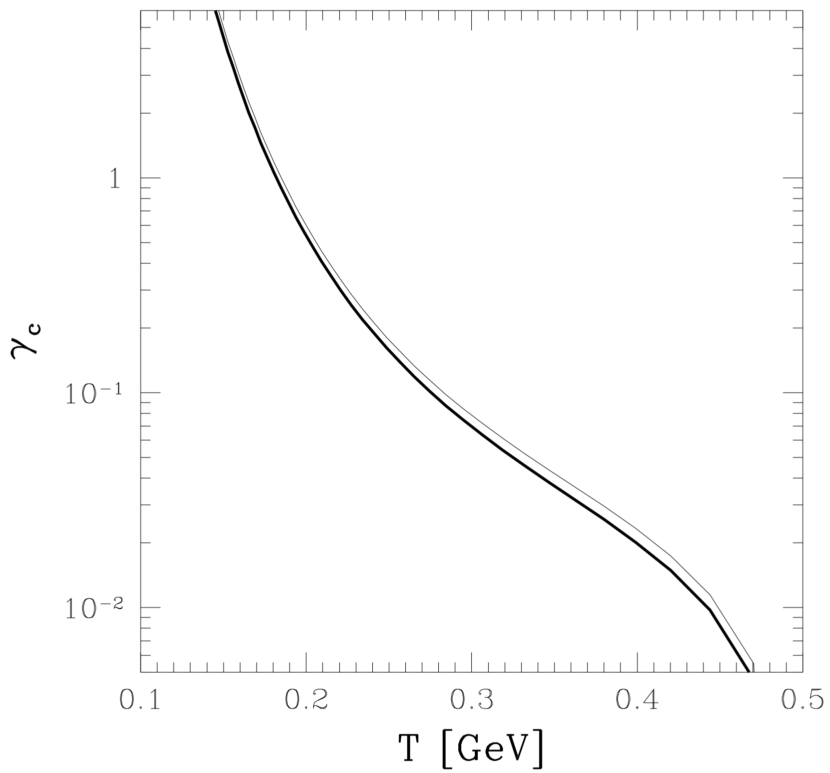
Precise prediction is a challenge to nLO pQCD since it requires parton distribution and initial time evolution within colliding nuclei. Thermal yields are at 10-30% for charm, negligible for $b\bar{b}$.

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:

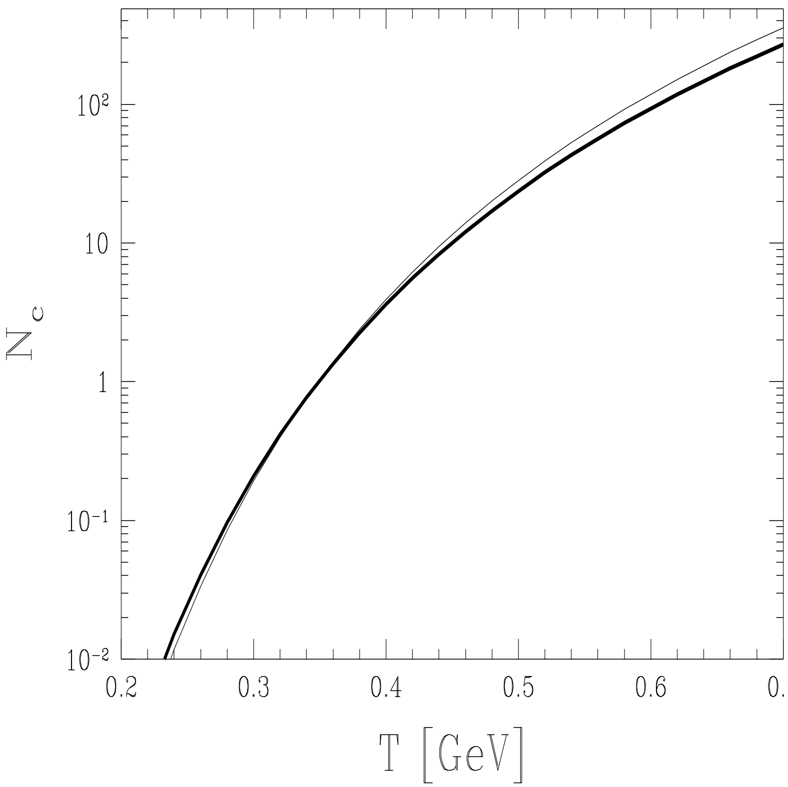
$$N_c = k\,VT^3\,\gamma_c(t)\,\sqrt{\left(\frac{m}{T(t)}\right)^3}\,e^{m/T(t)}, \qquad VT^3 = \textbf{Const.}, \qquad k = \frac{g}{2\pi^2}\sqrt{\frac{\pi}{2}}.$$

Since at hadronization $m_c/T \simeq 10$ and $m_b/T \simeq 30$ the thermal yields need to be multiplied by large γ_c, or resp. γ_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



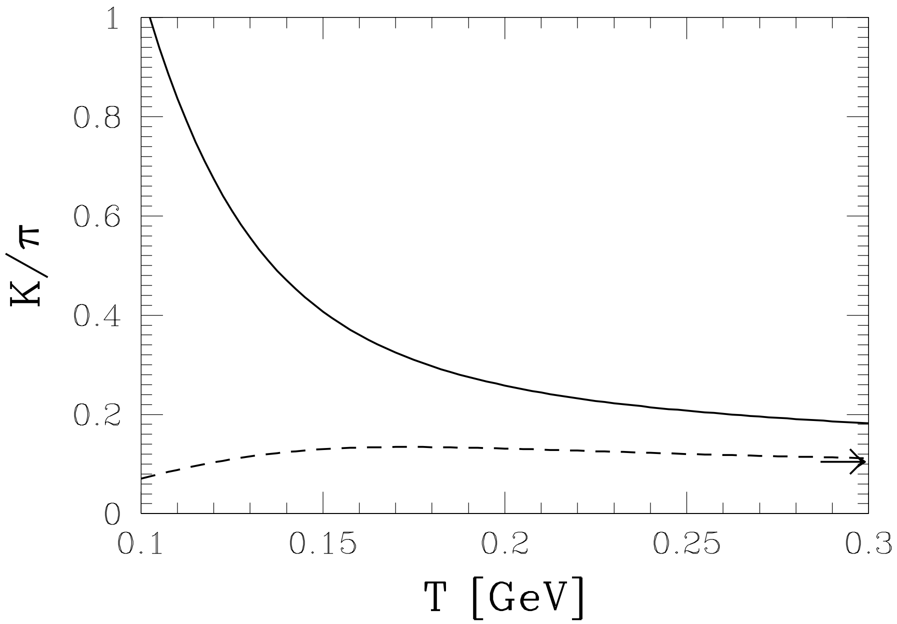
thermal charm as function T, the time dependent local temperature.



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: $\pi : \gamma_q^2 \leq e^{\frac{m_\pi}{T}}, K : \gamma_s\gamma_q \leq e^{\frac{m_K}{T}} \rightarrow \gamma_s/\gamma_q \leq e^{\frac{m_K - m_\pi}{T}} \rightarrow K/\pi$



Expect a shift toward strange meson production. Aside of K/π **shown, the enhanced** γ_s/γ_q **will enhance other strange particles.**

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.

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.

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

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

Immediate FUTURE

Wojtek Broniowski presents a vote of thanks