Strangeness:
a diagnostic tool of QGP

CIPPQG, September 5, 2001

WHY is strangeness a popular QGP diagnostic tool

EXPERIMENTAL REASONS

- **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;**
- **There are many strange particles allowing to study different physics questions.**

THEORETICAL CONSIDERATIONS

- **'Accidental' coincidence of scales:** $\boxed{m_s \simeq T_c} \rightarrow \boxed{\tau_s \simeq \tau_{\rm QGP}} \rightarrow$ **strangeness a clock for reaction**
- **production of strangeness in gluon fusion** $\boxed{GG \rightarrow s\bar{s}}$ **strangeness linked to gluons from QGP;**
- **At SPS energy in baryon rich environment** $\boxed{\bar{s} > \bar{q}} \rightarrow$ **strange antibaryon enhancement and at RHIC (anti)hyperon dominance of (anti)baryons.**

FORMATION OF STRANGENESS DENSE PHASE

NEAR Chemical strangeness equilibrium REQUIRES QGP: ⇒

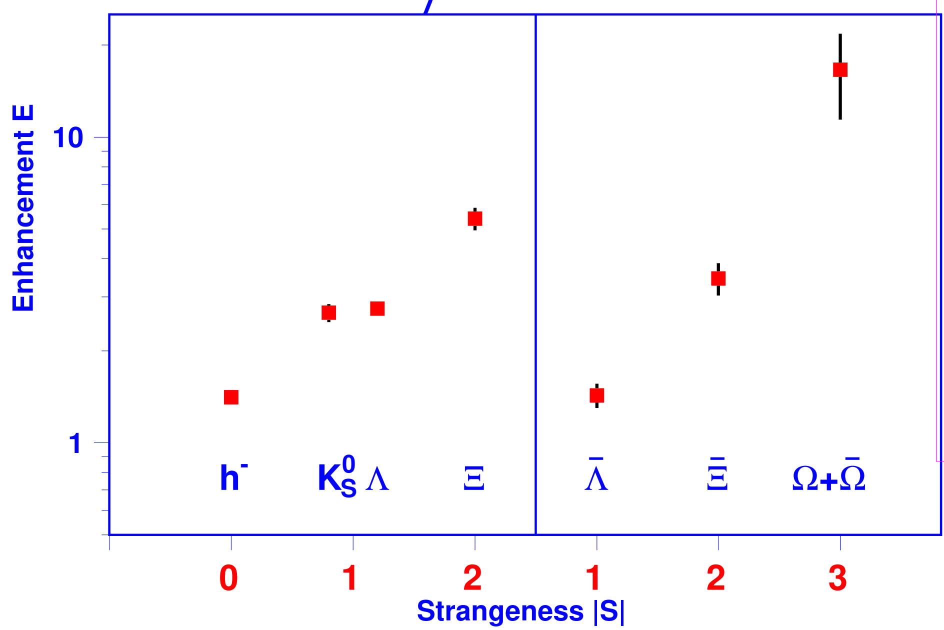
And produces observable excess of strangeness, and STRANGE ANTIBARYONS

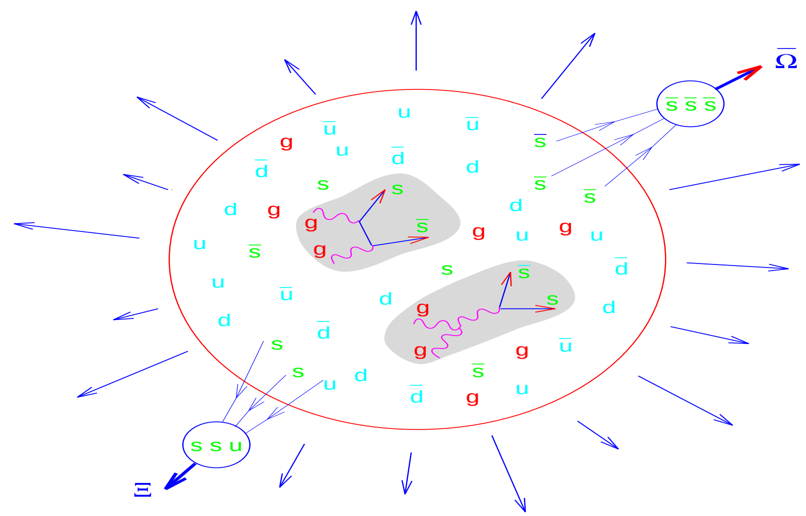
(Rafelski 1980–82: summary in Phys. Rep. 88 (1982) 331)

How produced: In thermal QGP phase strangeness is dominantly produced by gluon fusion reactions $GG \to s\bar{s}$ (Rafelski/Müller, PRL48 (1982) 1066)

Kinetic processes in Hadron Gas too slow (Koch/Rafelski, NP A444(1985) 678)

WA97-SPS/CERN Results





Kinetic description of strangeness production

Kinetic equilibration is faster than chemical, use thermal particle distributions. Strange quark pair production dominated by gluon fusion: $G + G \to s\bar{s}$, add also some $q\bar{q} \to s\bar{s}$,. Solve momentum-integrated Boltzmann equation:

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

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

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

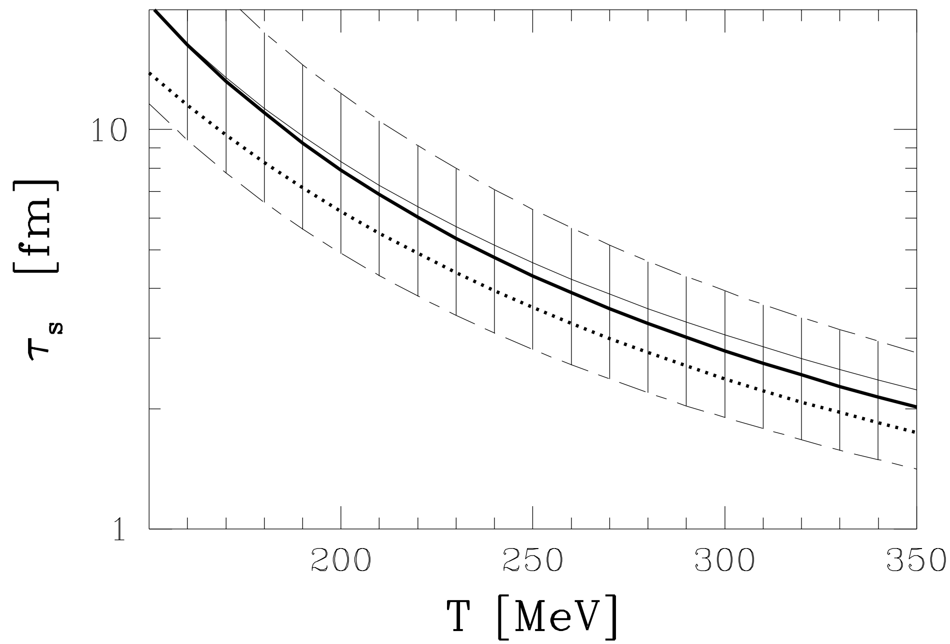
Exponential approach to chemical equilibrium $n_s(t)/n_s^\infty \to 1 - e^{-t/\tau_s}$ defines the characteristic time constant τ_s:

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

$1/(1+\delta_{1,2})$ introduced to compensate double-counting for identical particle pairs. ENTROPY CONSERVING expansion i.e. 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 γ_s known, $\langle s(t)\rangle = \langle\bar{s}(t)\rangle = \int dx^3 n_s^\infty(T(t,x))\gamma_s(T(t,x),\dot{T}(t,x))$; evolution till $t \to t_f$,but effectively production stops for $T < 180$ MeV.



$\sigma_{\rm QCD}^{\to s\bar s}$ gives τ_s similar to lifespan of the plasma phase! The generic angle averaged cross sections for (heavy) flavor s, $\bar s$ production processes $g+g\to s+\bar s$ and $q+\bar q\to s+\bar s$,

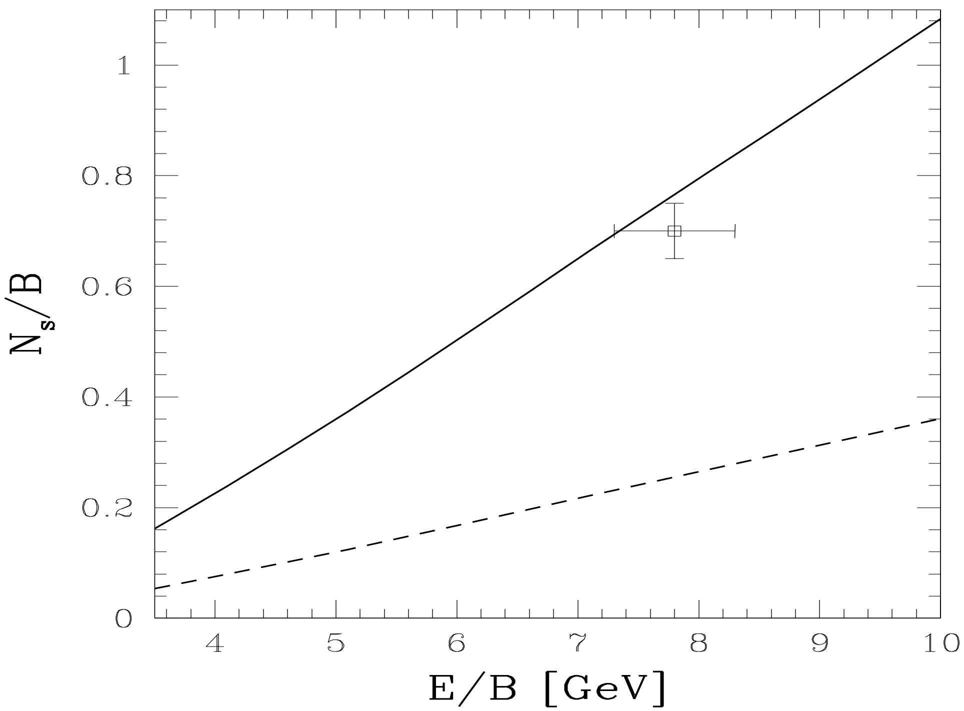
$$\bar\sigma_{gg\to s\bar s}(s)=\frac{2\pi\alpha_{\rm s}^2}{3s}\left[\left(1+\frac{4m_{\rm s}^2}{s}+\frac{m_{\rm s}^4}{s^2}\right)\tanh^{-1}W(s)-\left(\frac{7}{8}+\frac{31m_{\rm s}^2}{8s}\right)W(s)\right],$$

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

Infinite QCD resummation: running $\alpha_{\rm s}$ and $m_{\rm s}$ taken at the energy scale $\mu\equiv\sqrt{s}$.
USED: $m_s(M_Z)=90\pm20\%$ MeV $m_s(1\mathbf{GeV})\simeq 2.1 m_s(M_Z)\simeq 200$**MeV.**

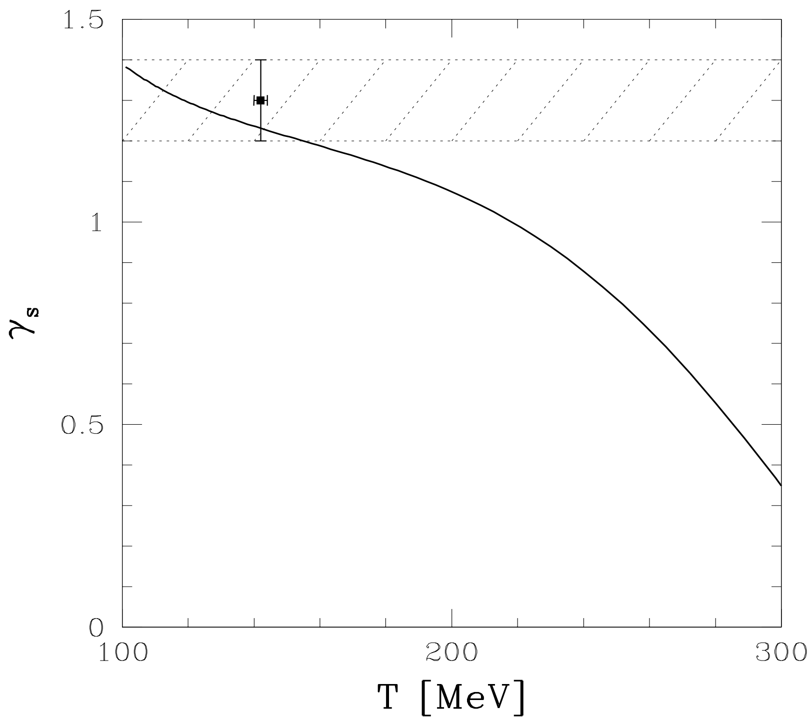
Predictions of Kinetic Theory

SPECIFIC STRANGENESS YIELD



s/B as function of energy per baryonE/B in the QGP fireball. The open square with error bars is result of our experimental data analysis. Dashed curve: qualitative background illustration, given factor three central rapidity strangeness enhancement reported by WA97.

PHASE SPACE OCCUPANCY



Result of experimental data analysis compared to theory for γ_s, as function of temperature T, for $158A$ GeV Pb–Pb.

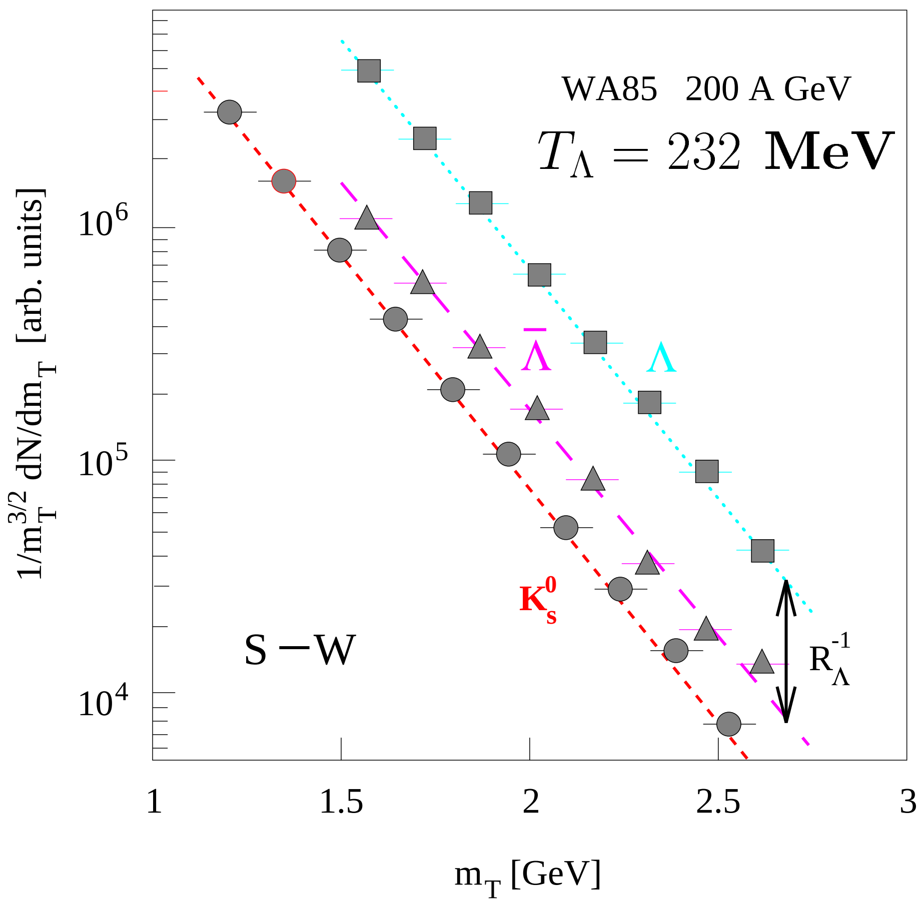
Key exp.result: High $m_\perp$ slope universality

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

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

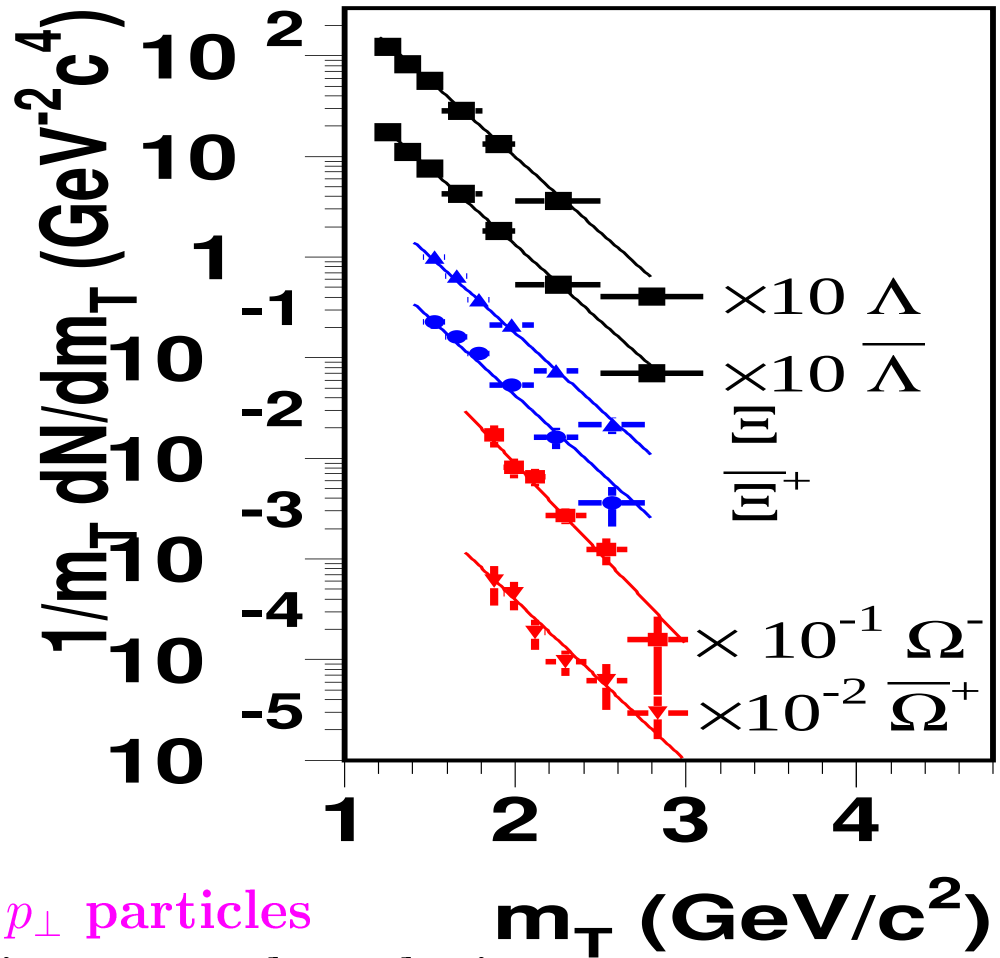
Why is the slope of different particles in same m_t range the same?

Anaysis+Hypothesis 1991: QGP quarks coalescing in SUDDEN hadronization (JR, PLB 262 (1991) 333.)



This allows to study 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**



Λ within 1% of $\overline{\Lambda}$

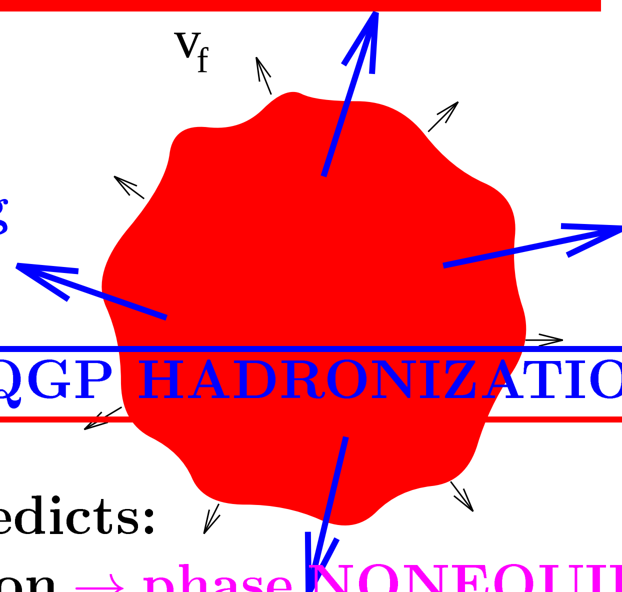
Kaon – hyperon difference:
EXPLOSIVE FLOW effect
Difference between $\Omega+\overline{\Omega}$:
presence of an excess of low $p_\perp$ particles
we will return to study this in spectral analysis

1. Chemical freeze-out (T_f):
condition at which particle number stops changing
similar to early universe nucleosynthesis abundance freeze-out

2. Later: Thermal (kinetic) freeze-out (T_k):
condition at which particle momentum distribution stops evolving
similar to decoupling of cosmic background photons at $T = 3000K$
Since 1991: strange (anti)baryon production does not in detail follow hadron gas pattern: $\rightarrow$ appear to be emitted directly by QGP

Potential to observe chemical properties of QGP

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



Orient analysis towards SUDDEN QGP HADRONIZATION reaction

BUT: Phase equilibrium hydro predicts:
a slow transformation= contradiction $\rightarrow$ phase NONEQUILIBRIUM

Super-cooling of a fast expanding fireball requires 1st order phase transition

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} **:**

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

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:**

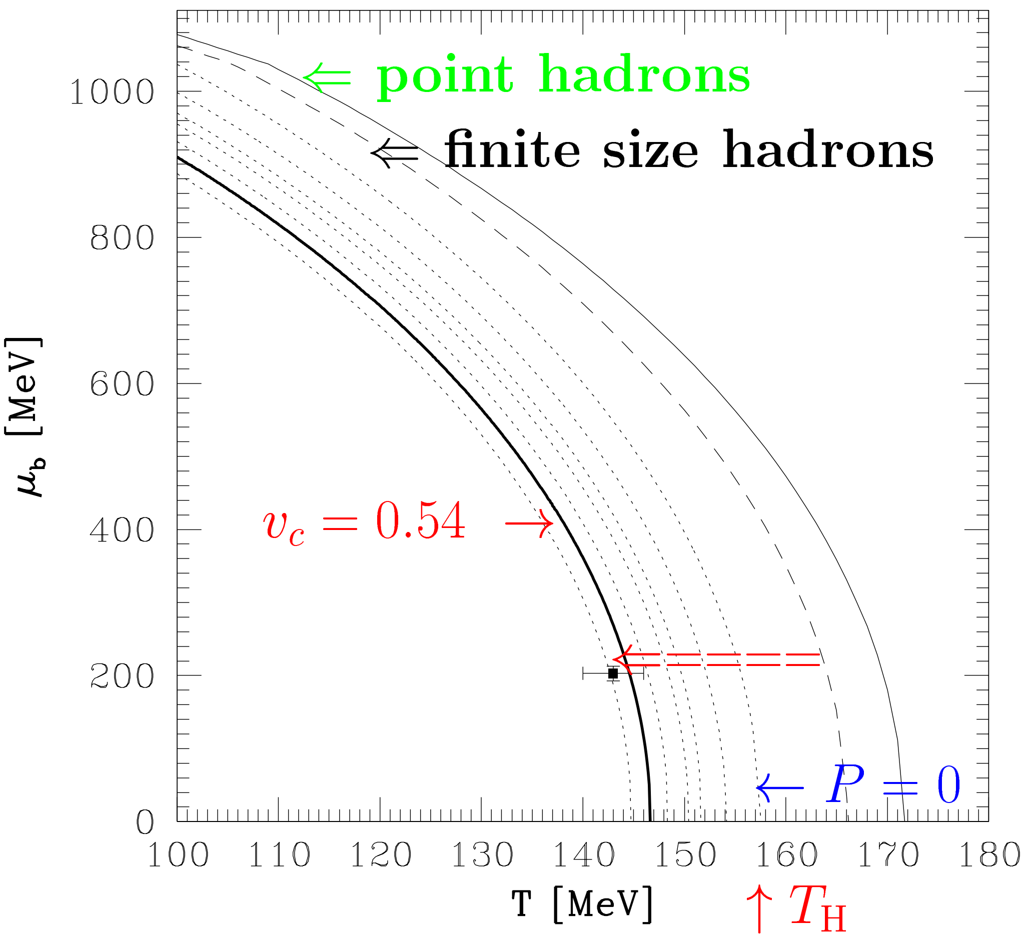
$$\mathcal{B}\vec{n} = P_{\rm p}\vec{n} + (P_{\rm p}+\varepsilon_{\rm p})\frac{\vec{v}_{\rm c}\,\vec{v}_{\rm c}\cdot\vec{n}}{1-v_{\rm c}^2}\,,$$

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 outwards is torn apart in a rapid instability. This can arise since matter presses again the vacuum which is not subject to collective dynamics.**

Phase transition and SUDDEN breakup temperatures



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 $\simeq 166$

Perturbative QCD EoS improved to agree with Lattice-QCD

$$\frac{T}{V}\ln \mathcal{Z}_{QGP} \equiv P = -\mathcal{B} + \frac{8}{45\pi^2}c_1(\pi T)^4 + \frac{n_\mathrm{q}}{15\pi^2}\left[\frac{7}{4}c_2(\pi T)^4 + \frac{15}{2}c_3\left(\mu_\mathrm{q}^2(\pi T)^2 + \frac{1}{2}\mu_\mathrm{q}^4\right)\right],$$

$$c_1 = 1 - \frac{15\alpha_s}{4\pi}, \quad c_2 = 1 - \frac{50\alpha_s}{21\pi}, \quad c_3 = 1 - \frac{2\alpha_s}{\pi}.$$

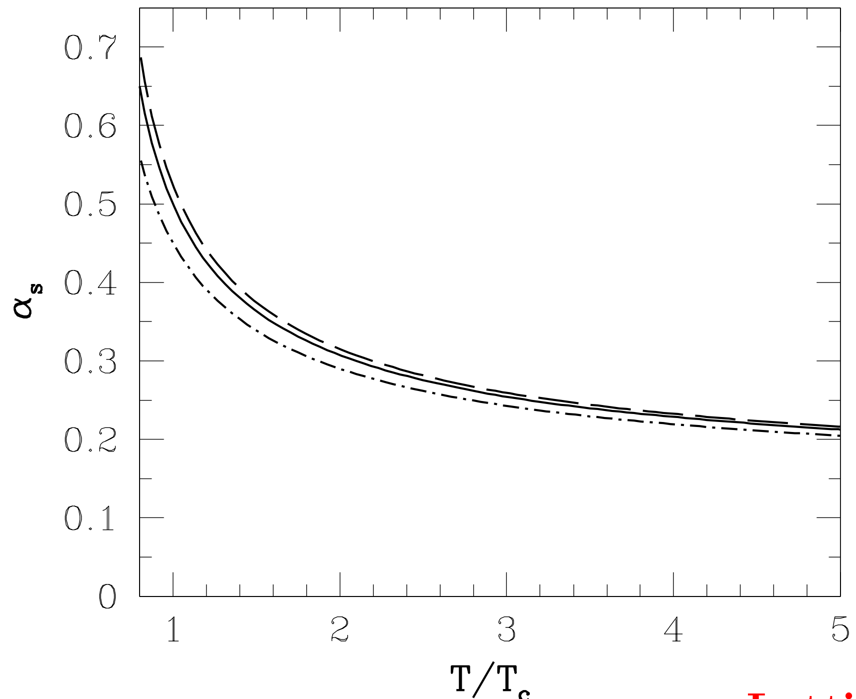
$$\mu\frac{\partial\alpha_s}{\partial\mu} = -b_0\alpha_s^2 - b_1\alpha_s^3 + \ldots \equiv \beta_2^\mathrm{pert}, \quad b_0 = \frac{11 - 2n_\mathrm{f}/3}{2\pi}, \quad b_1 = \frac{51 - 19n_\mathrm{f}/3}{4\pi^2}.$$

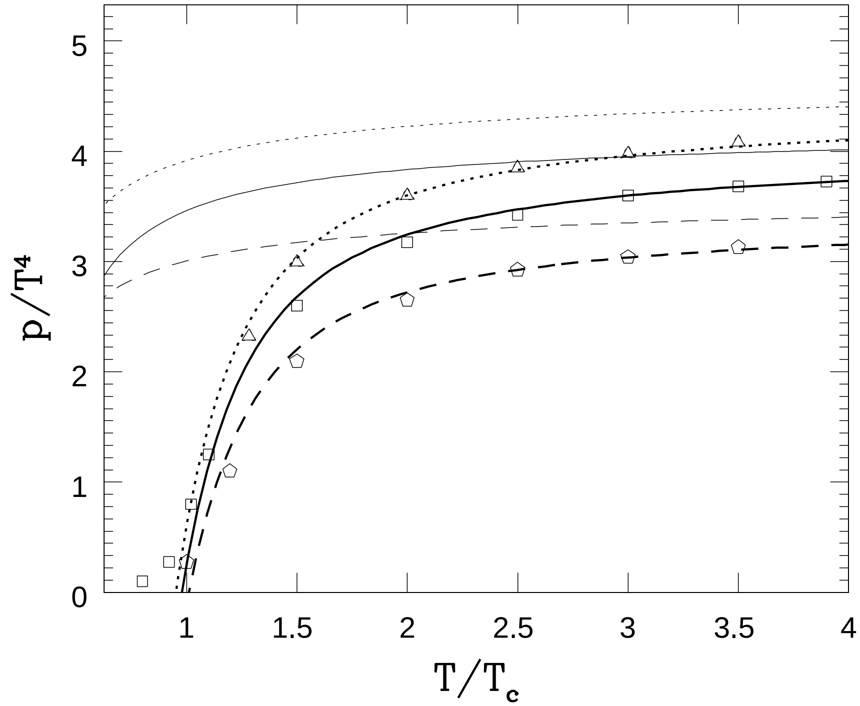
where $\alpha_s(\mu = M_Z) = 0.118 + 0.001 - 0.0016$**.** $\alpha_s/\pi < 0.22$

$$\mu = 2\pi\beta^{-1}\sqrt{1 + \frac{1}{\pi^2}\ln^2\lambda_\mathrm{q}} = 2\sqrt{(\pi T)^2 + \mu_\mathrm{q}^2}.$$

just a little WORK to test how this compares to lattice ($\mu_b = 0$)

Pressure of QGP-Liquid





$\alpha_s(2\pi T)$ **for** $T_c = 0.16$ **GeV.**
Dashed line: $\alpha_s(M_Z) = 0.119$**;**
solid line $= 0.118$**;**
dot-dashed $= 0.1156$**.**

Lattice-QCD results F. Karsch, E. Laermann and A. Peikert *Phys. Lett.* **B 478, 447-455, (2000);** **Quark-gluon liquid model at** $\lambda_q = 1$ **(thick lines) and with** $\mu = 2\pi T = \kappa T/T_c, \kappa = 1$ **GeV.** $\mathcal{B} = 0.19$ **GeV/fm**^{3}**.**
Solid line 2+1 flavors ($m_s/T = 1.7$**), dotted 3 flavors, dashed 2 flavors.**

Thin lines: with approximate 2nd order α_s **(often used comparison):**

Extension to finite baryon density

To relate the QCD scale to the temperature $T = 1/\beta$ we use

$$\mu = 2\sqrt{(\pi T)^2 + \mu_q^2} = 2\pi\beta^{-1}\sqrt{1 + \frac{1}{\pi^2}\ln^2\lambda_q}\,.$$

A convenient way to obtain entropy and baryon density uses the thermodynamic potential $\mathcal{F}$:

$$\frac{\mathcal{F}(T,\mu_q,V)}{V} = -\frac{T}{V}\ln\mathcal{Z}(\beta,\lambda_q,V)_{QGP} = -P_{QGP}\,.$$

The entropy density is:

$$s_{QGP} = -\frac{d\mathcal{F}}{VdT} = \frac{32\pi^2}{45}c_1T^3 + \frac{n_{\rm f}7\pi^2}{15}c_2T^3 + n_{\rm f}c_3\mu_{\rm q}^2T + A\frac{\pi^2T}{\pi^2T^2+\mu_{\rm q}^2}\,.$$

Noting that baryon density is 1/3 of quark density, we have:

$$\rho_{\rm B} = -\frac{1}{3}\frac{d\mathcal{F}}{Vd\mu_{\rm q}} = \frac{n_{\rm f}}{3}c_3\left\{\mu_{\rm q}T^2 + \frac{1}{\pi^2}\mu_{\rm q}^3\right\} + \frac{1}{3}A\frac{\mu_{\rm q}}{\pi^2T^2+\mu_{\rm q}^2}\,.$$

$$A = A_g + A_q + A_s;\qquad A_g = (b_0\alpha_s^2 + b_1\alpha_s^3)\frac{2\pi}{3}T^4$$

$$A_{i=q,s} = (b_0\alpha_s^2 + b_1\alpha_s^3)\left[\frac{n_{\rm i}5\pi}{18}T^4 + \frac{n_{\rm i}}{\pi}\left\{\mu_{\rm i}^2T^2 + \frac{1}{2\pi^2}\mu_{\rm i}^4\right\}\right]\,.$$

OBJECTIVE: is to describe the phase space of hadronic particles in great precision, not to fit the data. Physics in parameters of the phse space, thus χ^2/dof must promise physical relevance.

Chemical Freeze-Out: FERMI 2001 MODEL

The thermal emitted particles production yield dN_i within the time

$T_{\rm f}$	Local rest frame chemical freeze-out temperature
v_h,$v_{\rm f}$	Hadronization, Local flow speed of emitting source
$\lambda_{\rm s}$, $\lambda_{\rm q}$	Chemical fugacities describe conserved quantum number
$\gamma_{\rm s}$, $\gamma_{\rm q}$	Phase space occupancies describe quark pair yield

dt **from a locally at rest surface element dS:**

$$dN_i = \frac{dSd^3p}{(2\pi)^3} A_i v_i dt\,.$$

$v_i = dz/dt$ **is the particle velocity normal to the surface element dS. In a thermal quark-gluon source, phase space factor A_i is:**

$$A_i = g_i \lambda_i \gamma_i e^{-E_i/T}\,, \qquad \lambda_i = \prod_{j\in i} \lambda_j\,, \quad \gamma_i = \prod_{j\in i} \gamma_j\,, \quad E_i = \sum_{j\in i} E_j\,,$$

g_i **is the degeneracy of the produced particle, and E_i its energy:**

$$E_j = \sqrt{m_j^2 + p^2} = \sqrt{m_j^2 + p_\perp^2}\cosh(y - y_{\rm CM})\,.$$

HOW DOES THE MODEL WORK?

$$R_\Lambda = \left.\frac{\overline{\Lambda}}{\Lambda}\right|_{m_\perp} = \frac{\overline{\Lambda} + \overline{\Sigma}^0 + \overline{\Lambda}^* + \cdots}{\Lambda + \Sigma^0 + \Lambda^* + \cdots} = \frac{\bar{s}\bar{q}\bar{q}}{sqq} = \lambda_{\rm s}^{-2}\lambda_{\rm q}^{-4}\,.$$

$$R_\Xi = \left.\frac{\overline{\Xi^-}}{\Xi^-}\right|_{m_\perp} = \frac{\overline{\Xi^-} + \cdots}{\Xi^- + \cdots} = \frac{\bar{s}\bar{s}\bar{q}}{ssq} = \lambda_{\rm s}^{-4}\lambda_{\rm q}^{-2}\,.$$

$$\left.\frac{\Xi^-(dss)}{\Lambda(dds)}\right|_{m_\perp} = \frac{g_\Xi\gamma_d\gamma_s^2\lambda_d\lambda_s^2}{g_\Lambda\gamma_d^2\gamma_s\lambda_d^2\lambda_s}\,.$$

g_i are the spin statistical factors of the states considered.

$$\left.\frac{\overline{\Xi^-(dss)}}{\overline{\Lambda(dds)}}\right|_{m_\perp} = \frac{g_\Xi\gamma_d\gamma_s^2\lambda_d^{-1}\lambda_s^{-2}}{g_\Lambda\gamma_d^2\gamma_s\lambda_d^{-2}\lambda_s^{-1}}\,.$$

EXAMPLE: Pb–Pb ANALYSIS Fermi-2000 Model

Pb–Pb 158A GeV WA97 (top) and NA49 (bottom) S'2000 revised data particle ratios by:

Ratios	Ref.	Exp. Data	$\mathrm{Pb}\|_v^{s,\gamma_q}$	$\mathrm{Pb}\|_v^{\gamma_q}$
Ξ/Λ	[1]	0.099 ± 0.008	0.098	0.096
$\overline{\Xi}/\bar{\Lambda}$	[1]	0.203 ± 0.024	0.199	0.201
$\bar{\Lambda}/\Lambda$	[1]	0.124 ± 0.013	0.122	0.121
$\overline{\Xi}/\Xi$	[1]	0.255 ± 0.025	0.248	0.253
$\frac{(\Xi+\bar{\Xi})}{(\Lambda+\bar{\Lambda})}$	[2]	0.13 ± 0.03	0.111	0.110
~~K_s^0/ϕ~~	~~[3]~~	~~11.9 ± 1.5~~	13.0	13.4
ϕ/π^-	[5]	0.0125 ± 0.0018	0.0127	0.0124
K^+/K^-	[4]	1.80± 0.10	1.757	1.790
$p/\bar{p}$	[6]	18.1 ±4.	16.00	16.50
~~$\bar{\Lambda}/\bar{p}$~~	~~[7]~~	~~3. ± 1.~~	0.53	0.54
K^-/π^-		0.082±0.012	0.81	0.080
K_s^0/B	[8]	0.183 ± 0.027	0.188	0.192
h^-/B	[9]	1.97 ± 0.1	1.782	1.829
	χ^2_{T}		2.25	1.36
	$N;p;r$		10;3;2	10;4;2
χ^2_{T}/dof	LESS	than	0.25	0.15

References

[1] I. Králik, WA97, *Nucl. Phys.* A 638,115, (1998).

[2] G.J. Odyniec, NA49, *J. Phys.* G 23, 1827 (1997).

[3] F. Pühlhofer, NA49, *Nucl. Phys.* A 638, 431,(1998).

[4] C. Bormann, NA49, *J. Phys.* G 23, 1817 (1997).

[5] S.V. Afanasiev, NA49, *Phys. Lett.* B 491 59 (2000).

[6] G.J. Odyniec, *Nucl. Phys.* A 638, 135, (1998).

[7] D. Röhrig, NA49, in EPS-HEP Conf. Jerusalem, Aug. 1997.

[8] P.G. Jones, NA49, *Nucl. Phys.* A 610, 188c (1996).

[9] H. Appelshäuser *et al.*, NA49, *Phys. Rev. Lett.* 82, 2471 (1999).

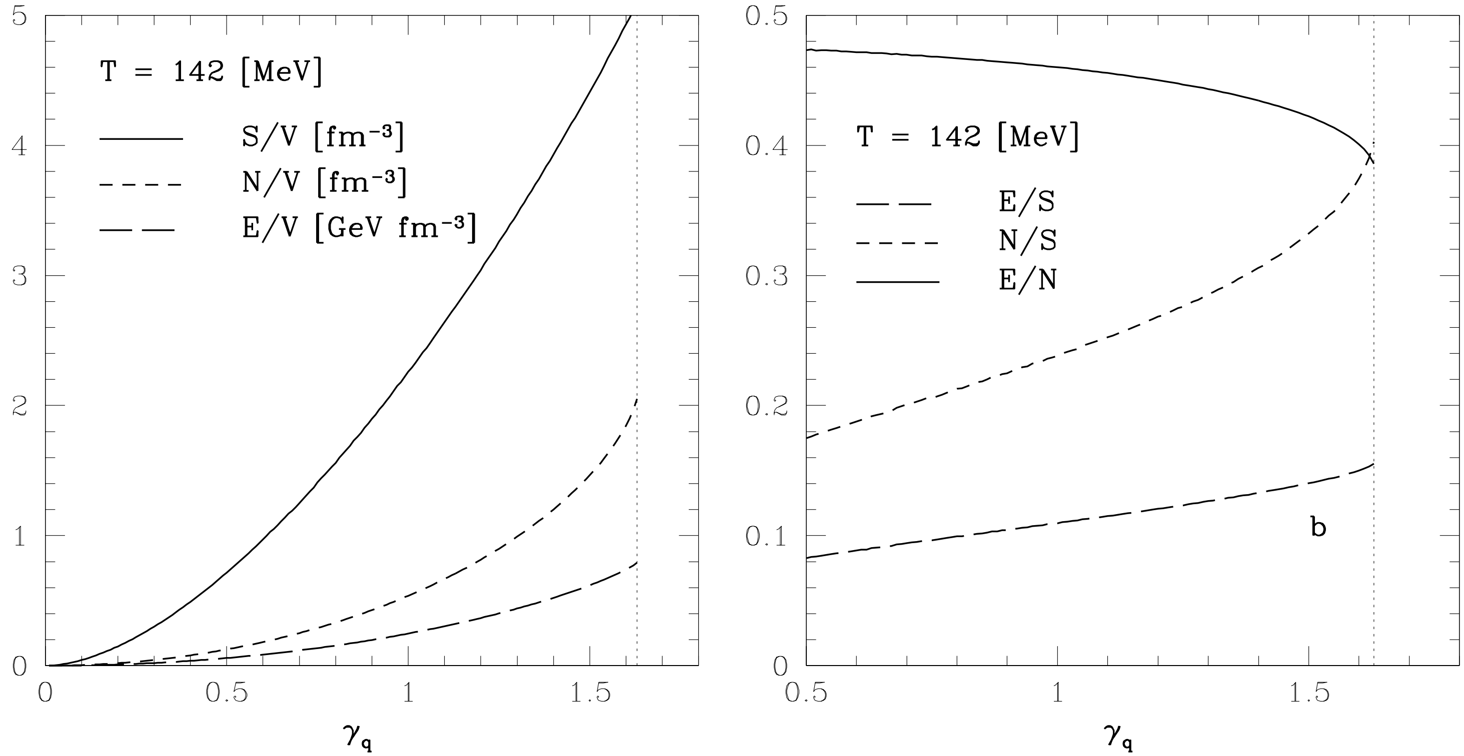
Chemical and Physical Properties for Pb–Pb and for S–Au/W/Pb

$\chi^2_{\rm T}$; $N; p; r$	$\mathbf{Pb}\vert_v^{s,\gamma_q}$ 1.48; 11; 3; 2	$\mathbf{Pb}\vert_v^{\gamma_q}$ 0.76; 11; 4; 2	$\mathbf{S}\vert_v$ 6.2; 16; 6; 6
T_f [MeV]	151 ± 3	147 ± 5.5	144 ± 2
v_c	0.57 ± 0.05	0.52 ± 0.09	0.49 ± 0.02
λ_q	1.618 ± 0.026	1.625 ± 0.025	1.51 ± 0.02
λ_s	1.101*	1.093 ± 0.02	1.00 ± 0.02
γ_q	$\gamma_q^{c*} = e^{m_\pi/2T_f}$=1.59	$\gamma_q^{c*} = e^{m_\pi/2T_f}$=1.62	1.41 ± 0.08
γ_s/γ_q	1.04 ± 0.05	1.05 ± 0.06	0.69 ± 0.03
E_f^{in}/S_f	0.163 ± 0.01	0.158 ± 0.01	0.186 ± 0.01
s_f/b	0.68 ± 0.05	0.69 ± 0.05	0.73 ± 0.05
$(\bar{s}_f - s_f)/b$	0*	0.05 ± 0.05	0.17 ± 0.05

WHY $\gamma_q \simeq 1.6$? **A striking feature of the data analysis is the 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.**



CONCLUSION: excess of QGP entropy pumped into pions

The Omega Question **Chemical analysis DOES NOT INCLUDE Ω-yield. Thermal analysis shows excess of Ω and $\overline{\Omega}$ at soft momentum, This means that these MOST RARELY produced strange hadrons are sensitive to NEW formation channells beyond the statistical Fermi model hadron phase space.**

Significant contributions can arise from:

1. in source $(ss)_{\bar{3}}$ and $(\bar{s}\bar{s})_3$ clusters (predicted);

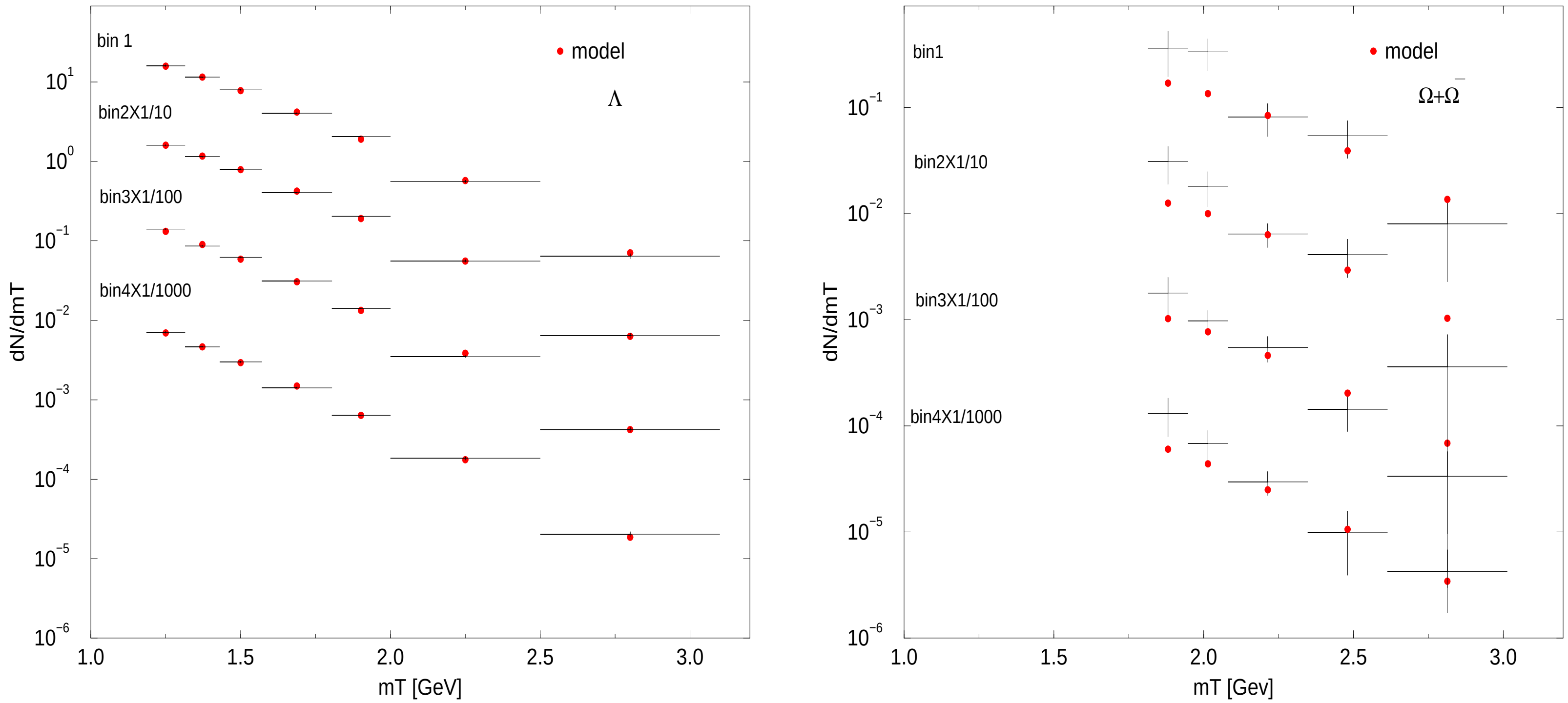
2. formation in final state fragmentation $(\bar{s}\bar{s})_3 + G \to (\bar{s}\bar{s}\bar{s}) + X$;

3. chiral disoriented strangeness vacuum (Kapusta/Wang PRL);

A way to see if two first hypothesis for extra Ω and $\overline{\Omega}$ can work is to see if one extra parameter explains 3 data points (ratios $\overline{\Omega}/\Omega$, Ω/Ξ, $\overline{\Omega}/\overline{\Xi}$). We find that $40 \pm 10\%$ of Ξ and $\overline{\Xi}$ clusters has to turn into Ω and $\overline{\Omega}$ to obtain the required additional yields ($\chi^2 \simeq 0.1$!)

None of the global properties (strangeness conservation etc) is affected by this 'inperfection' of the statistical phase space hadronization model.

COMPARE $m_\perp$ SPECTRA



Thermal analysis of Λ (left) and $\Omega+\overline{\Omega}$ (right) m_T spectra. 'dots' theoretical values; Histogram lines: WA97 DATA obtained in different centrality bins. Note for $\Omega+\overline{\Omega}$ at low $m_\perp$ the systematic difference between thermal de facto prediction and experiment.

TOPIS FOR DISCUSSION:HOW STRANGENESS DEFINES QGP

In past 20 years we reached understanding of strangeness kinetic evolution

Dynamics: SUPERCOOLED QGP FIREBALL BREAKS SUDDENLY

Analysis of data: PRECISE DESCRIPTION OF FINAL STATE REQUIRED
YIELD NON-EQUILIBRIUM REQUIRES PARTICLE ABUNDANCES PARAMETERS

CHEMICAL PROPERTIES IN SUDDEN BREAKUP:

$$\tilde{\lambda}_s = 1, \qquad \gamma_q \to e^{m_\pi/T}, \quad \gamma_s > 1$$

conservation of strangeness and maximum of entropy lead to these values
Evidence for non-statistical production of $\Omega(sss)$

CHEMICAL AND THERMAL FREEZE-OUT ANALYSIS COINCIDE

STRANGE HADRON RESONANCE DIAGNOSIS OF SUDDEN HADRONIZATION

RHIC HADRONS SIMILAR TO SPS BUT EXPECT BARYONS DOMINATED BY HYPERONS

Remember: universality of baryon/antibaryon slopes before asking a question

Thermal FREEZE-OUT Analysis

Hadron $m_\perp$-spectra are result of flow and thermal motion and are strongly influenced by resonance decays. The Flow-Boltzmann distribution we adapt with two velocities, one local temperature:

$$\frac{d^2N}{dm_T dy} \propto \left(1 - \frac{\vec{v}_f^{\,-1} \cdot \vec{p}}{E}\right) \gamma\, m_T \cosh y\, e^{-\gamma \frac{E}{T}\left(1 - \frac{\vec{v}\cdot\vec{p}}{E}\right)}\,, \qquad \gamma = 1/\sqrt{1-v^2}$$

Resonance 2-body decay contribution:

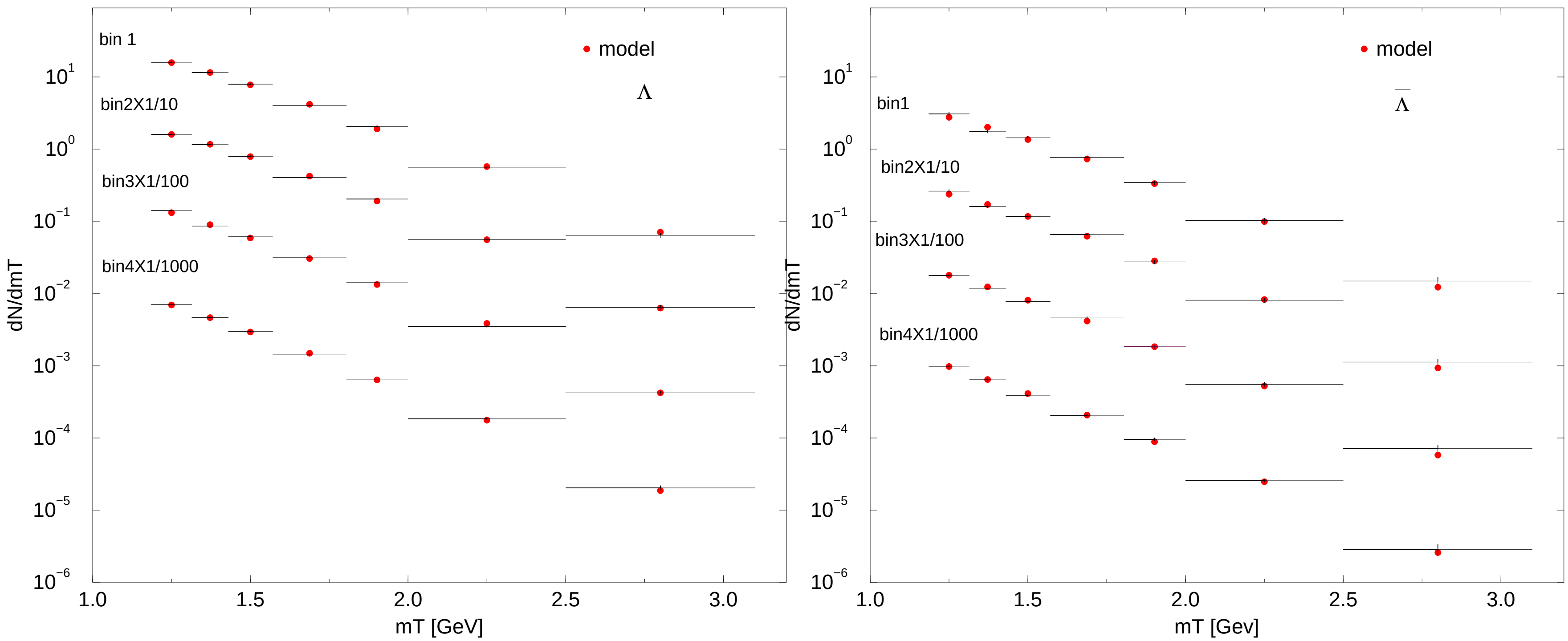
$$\frac{dN_X}{dm_\perp} = \frac{dN_X}{dm_\perp}\Big|_{\rm direct} + \sum_{\forall R\to X+2+\dots} \frac{dN_X}{dm_\perp}\Big|_{R\to X+2+\dots}\,, \quad \frac{dN_X}{dm_\perp^2 dy} = \frac{g_r b}{4\pi p^*}\int_{Y_-}^{Y_+} dY \int_{M_{T_-}}^{M_{T_+}} dM_T^2\, J\, \frac{d^2N_R}{dM_T^2 dY}\,.$$

$$J = \frac{M}{\sqrt{P_T^2 p_T^2 - \{M E^* - M_T m_T \cosh \Delta Y\}^2}}\,, \Delta Y = Y - y\,, E^* = (M^2 - m^2 - m_2^2)/2M\,,$$

$$p^* = \sqrt{E^{*2} - m^2}$$

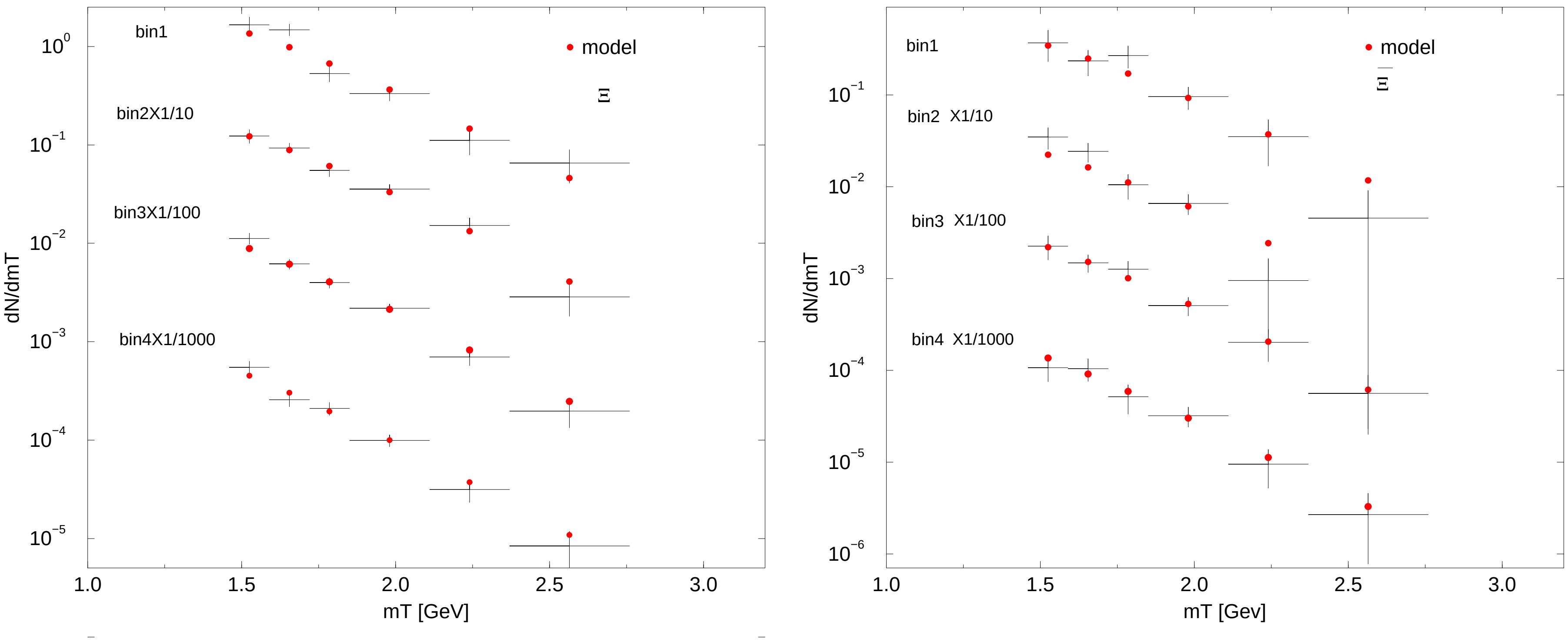
$$Y_\pm = y \pm \sinh^{-1}\left(\frac{p^*}{m_T}\right)\,, \qquad M_{T_\pm} = M\frac{E^* m_T \cosh \Delta Y \pm p_T\sqrt{p^{*2} - m_T^2 \sinh^2 \Delta Y}}{m_T^2 \sinh^2 \Delta Y + m^2}$$

Λ and $\overline{\Lambda} - m_\perp$ SPECTRA



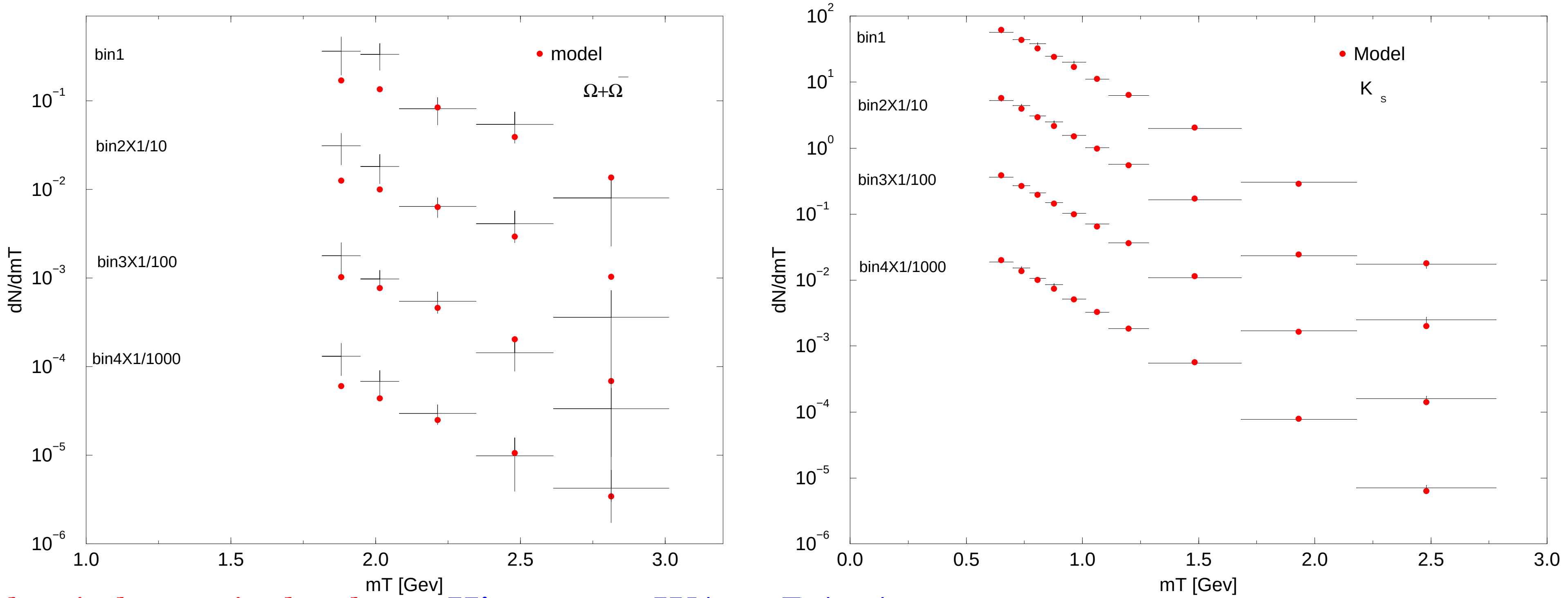
Thermal analysis m_T spectra: Λ (left) and $\overline{\Lambda}$ (right) for 4 different centralities.
'dots' theoretical values; HISTOGRAM: WA97 data in different centrality bins.

Ξ and $\overline{\Xi}$ – $m_\perp$ SPECTRA



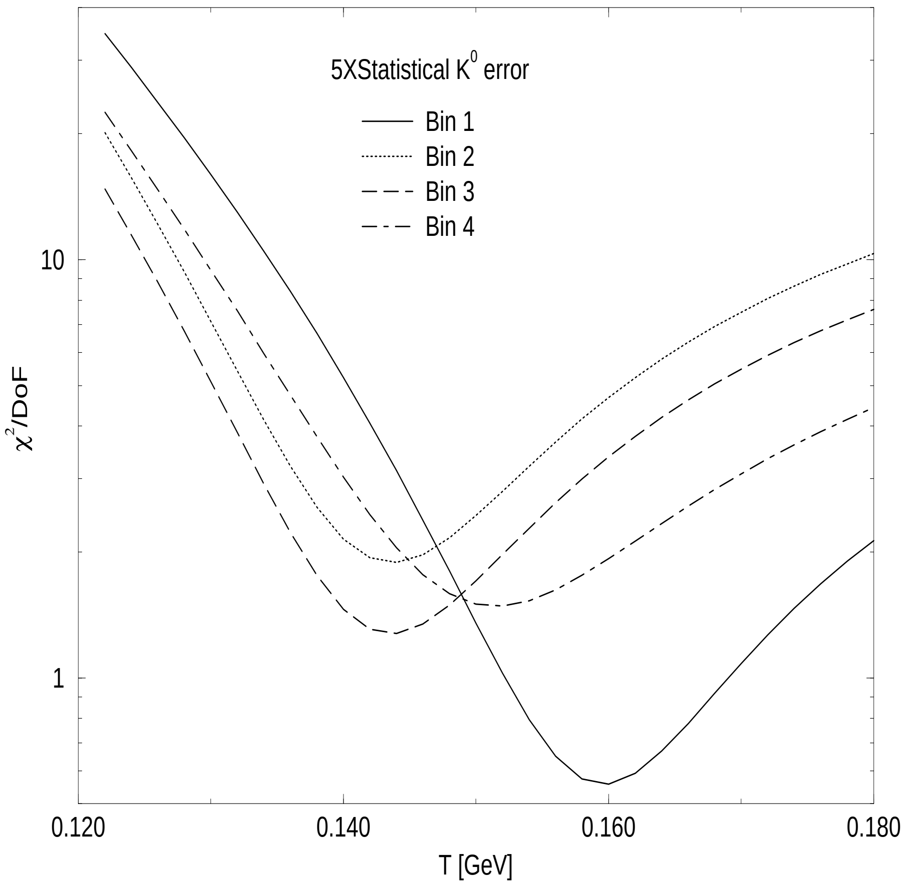
Thermal analysis m_T spectra: Ξ (left) and $\overline{\Xi}$ (right) for 4 different centralities.
'dots' theoretical values; Histogram lines: WA97 data in different centrality bins.

$\Omega + \overline{\Omega} - m_{\perp}$ and K_s-SPECTRA

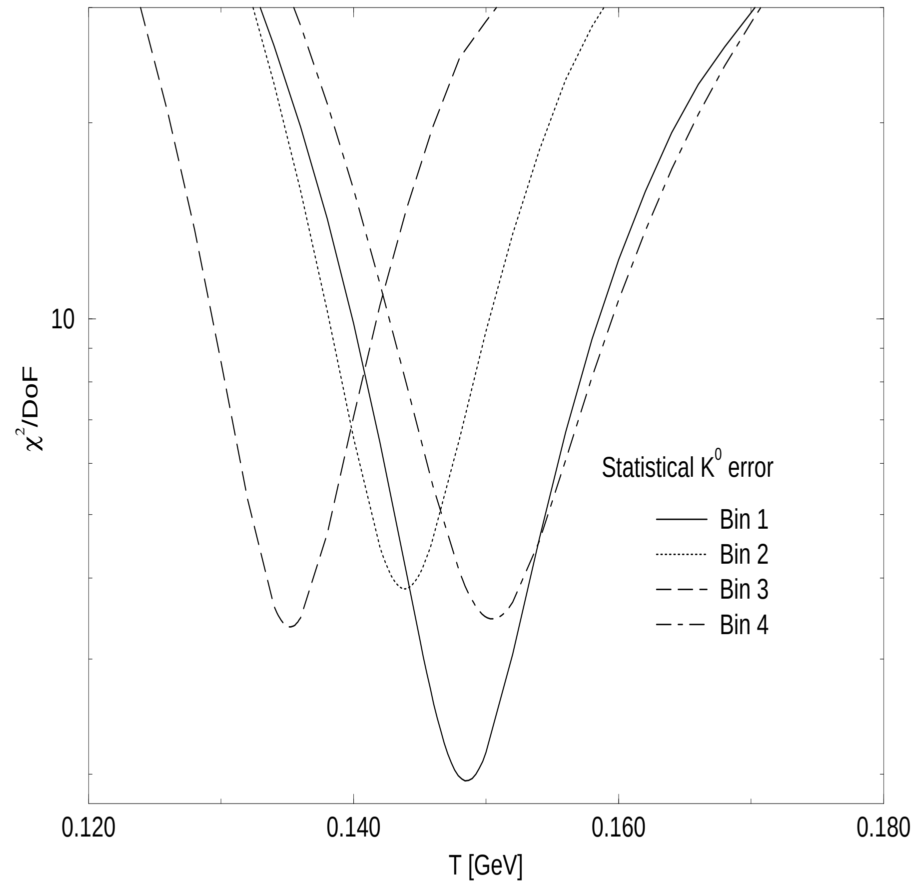


'dots' theoretical values; Histogram WA97 DATA
We systematically under predict $\Omega + \overline{\Omega}$ for the two lowest $m_{\perp}$ data points. We recall that there is a disagreement with the Omega yields in the chemical analysis, here we see that this disagreement is arising at low momentum. NEED: a soft momentum secondary source.

The χ^2 profiles show good significance, here TEMPERATURE T: Total error divided by degrees of freedom for five centrality bins

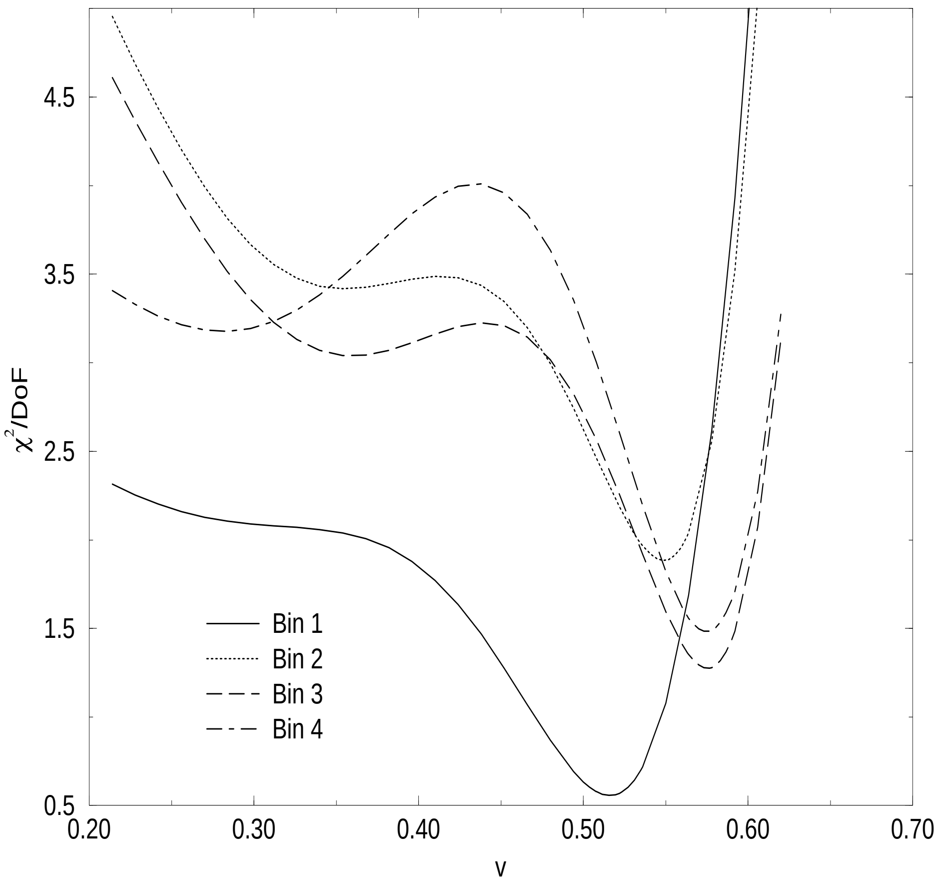


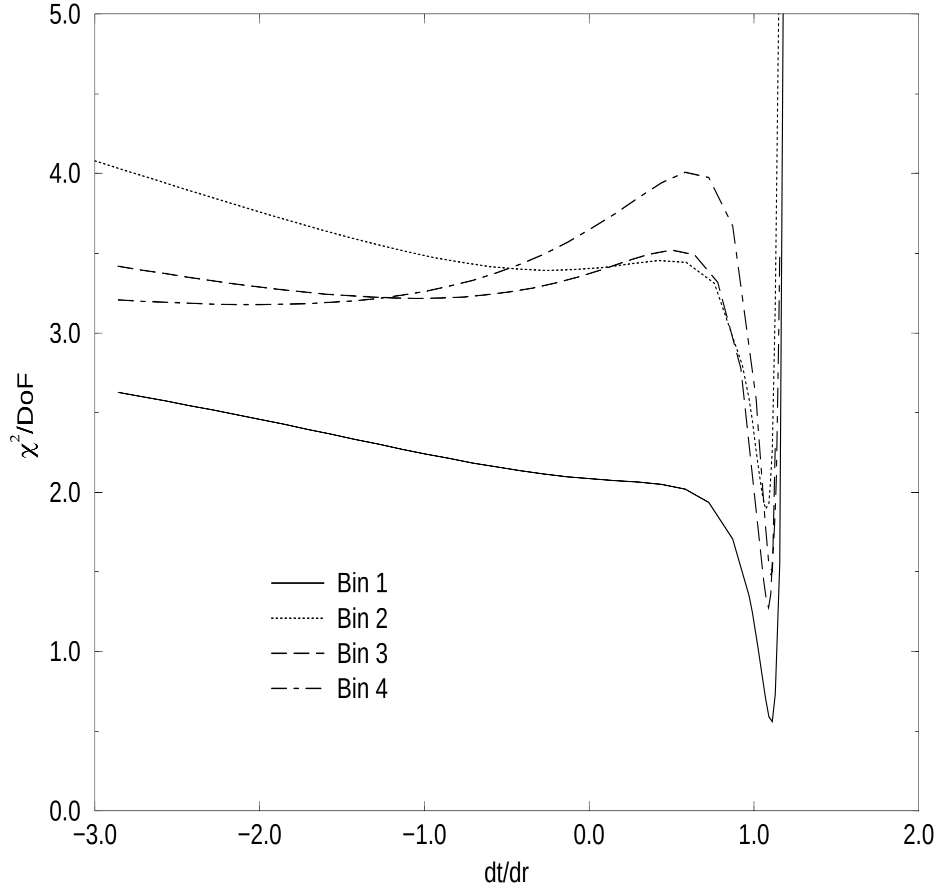
5 times enlarged K^0 stat. error



experimental stat. K^0 error.

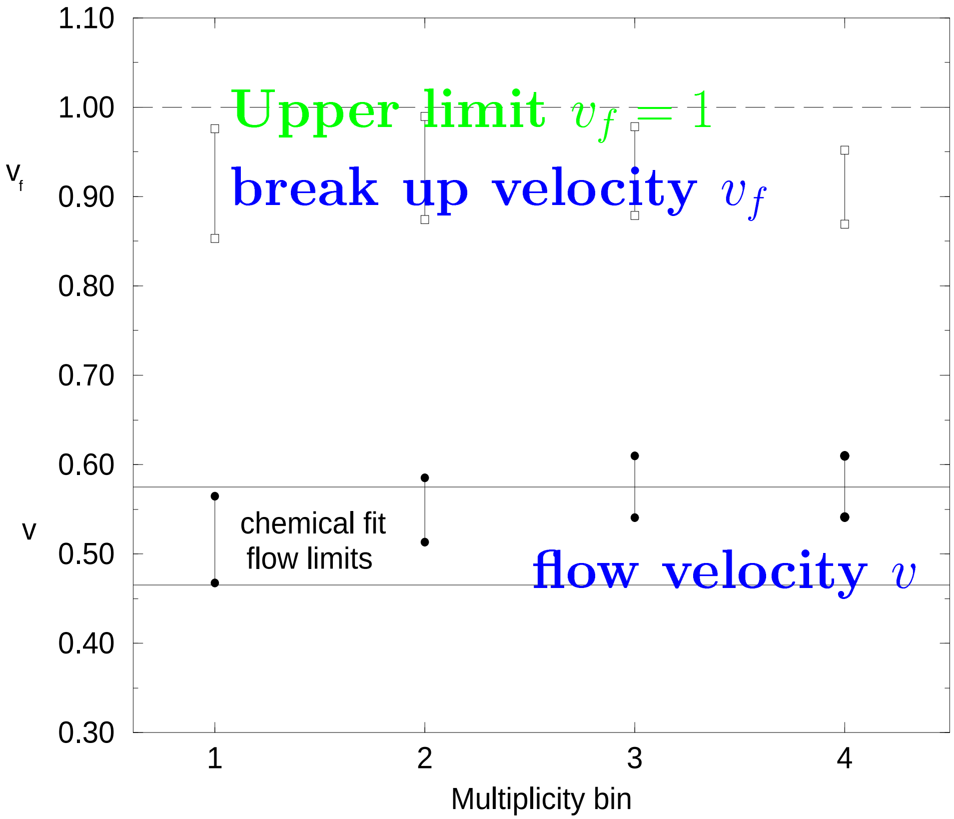
here v on LEFT and $\partial t_f/\partial r_f = 1/v_f$ on RIGHT

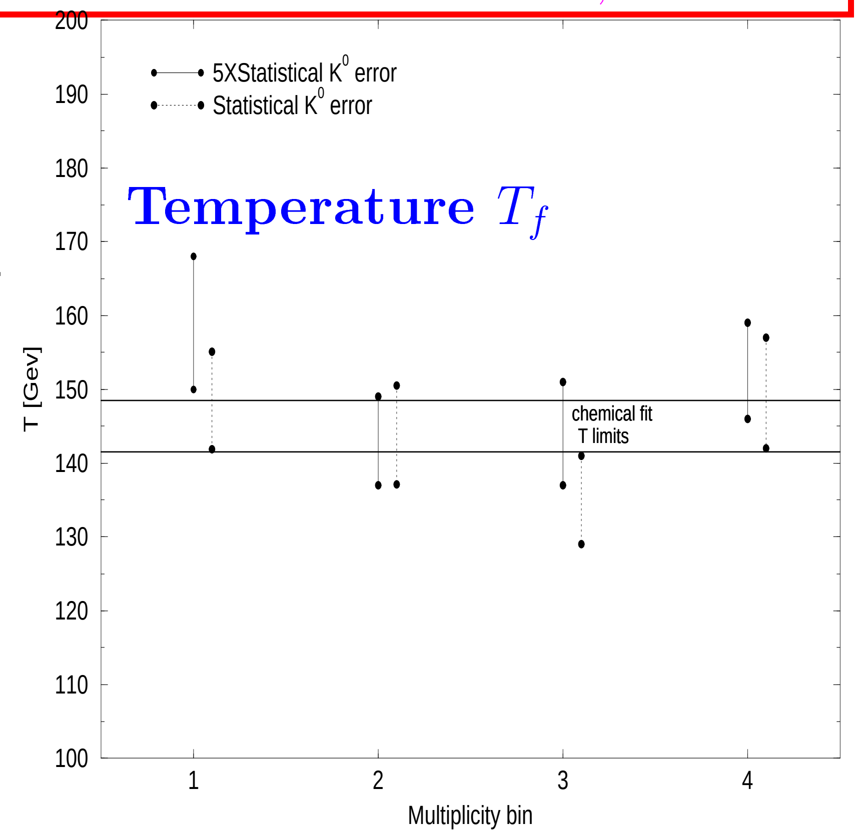




regular experimental stat. K^0 error.

Pb–Pb 158 A GeV CHEMICAL AND THERMAL FREEZE-OUT T, v AGREE

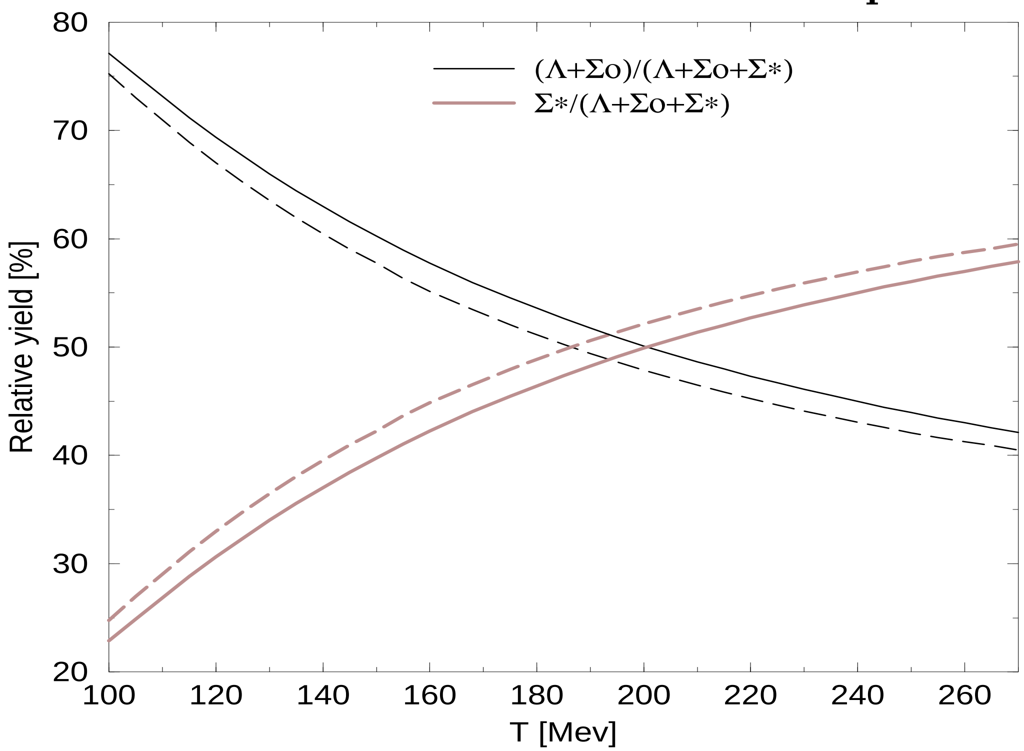




5 different collision centrality bins. We note flow velocity increase (withn errors) with increasing size (centrality). Aside of this, there is no indication of a significant or systematic change of T, v, v_f with centrality, e.g. new state of matter is formed in all 4 centrality bins ($A > 100$). It will be interesting to see if the low centrality $A \simeq 50$ studied by experiment WA57 will show different freeze-out properties.

Strange hadron resonances PROBE sudden hadronization

direct experimental measurement!



$\Sigma^*(1385) \to \Lambda + \pi$ **resonance decay contributes significantly to** Λ **yield. The decay width of** $\Gamma_{\Sigma^*} = 35$**MeV=1/(5.6 fm) assures that some decays occur within, and some outside the hadron matter – those within matter would be practically all unreconstructable. Candidates for study** $\Gamma_{\Lambda(1520)} = 15.6$**MeV=1/(12.6 fm);** $\Gamma_{K^*(892)} = 50$ **MeV=1/(4 fm) and** $\Gamma_{\Sigma^*(1385)} = 35$**MeV=1/(5.6 fm). Complication: quenching.**

RESONANCE QUENCHING

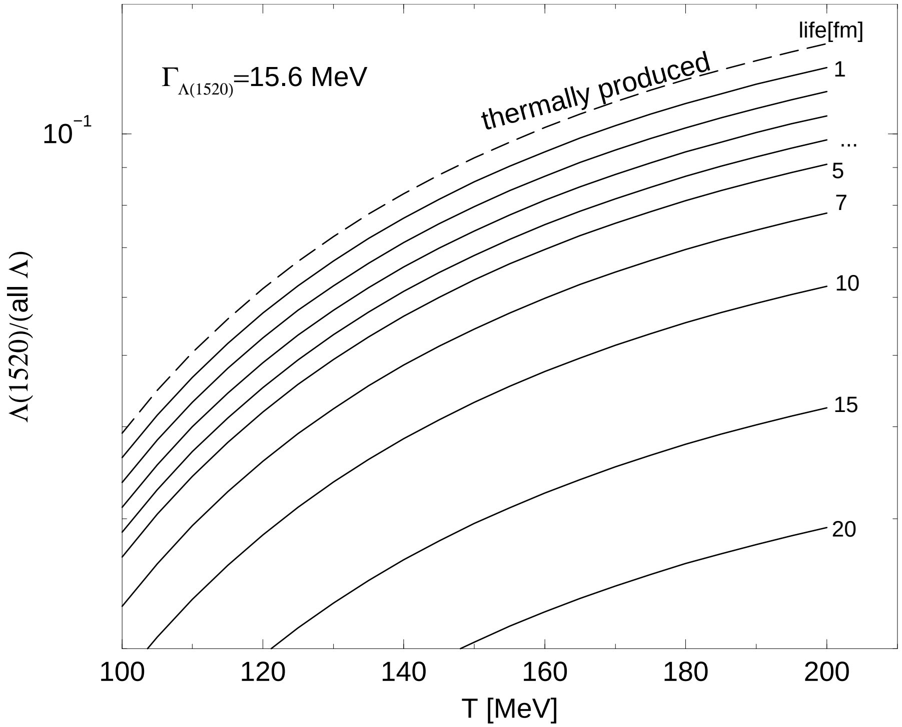
IF DECAY IN FREE SPACE IS BLOCKED BY SUPERSELCTION RULE, QUENCHING IS EFFECTIVE! A possible explanation of $\Lambda(1520)$ suppression reported by NA49.

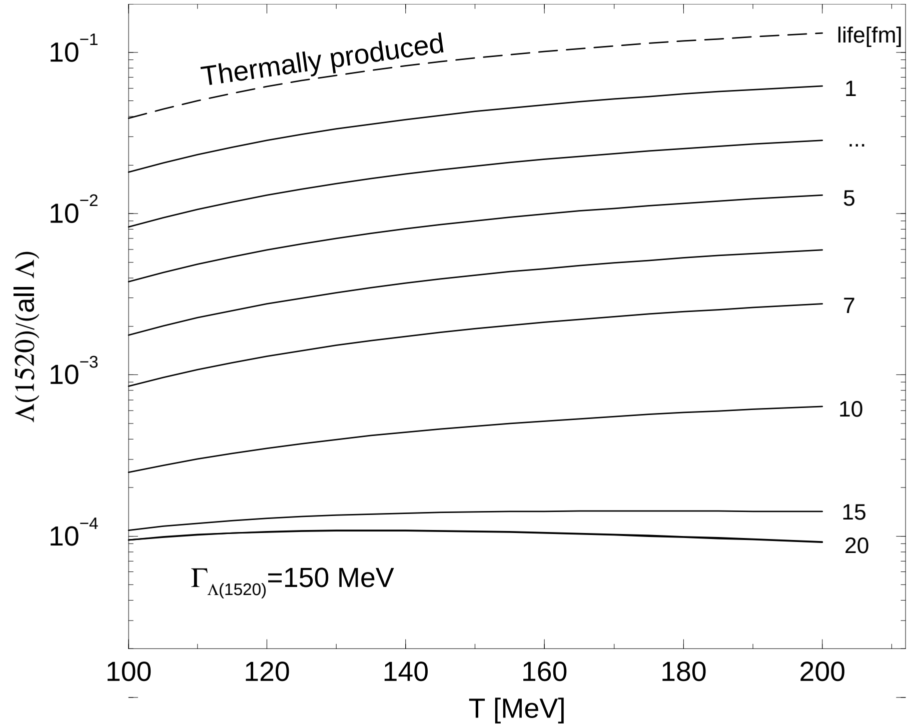
$$\pi + \Lambda(1520) \to \Sigma^* \to \pi + \Lambda\,,$$

Possible since $\Gamma_{\Lambda(1520)}$ is small due to need for angular $L = 2$ partial wave in its decay. Collisional widening of a metastable state is a familiar phenomenon explored in several areas of physics. The decay of the $\phi(s\bar{s})$ has been the 'usual suspect' in search for such a quenching, given the proximity of the $K\overline{K}$ mass threshold. NOTE: reconstructed line shape will always have the natural width, since rapid in-matter-decay products rescatter not allowing $\Lambda(1520)$ reconstruction!

Try to compare with experiment aside of natural width also a width which is usual for hadronic resonances, $\Gamma_{\Lambda(1520)} = 150$ MeV.

Yields as function of t and T

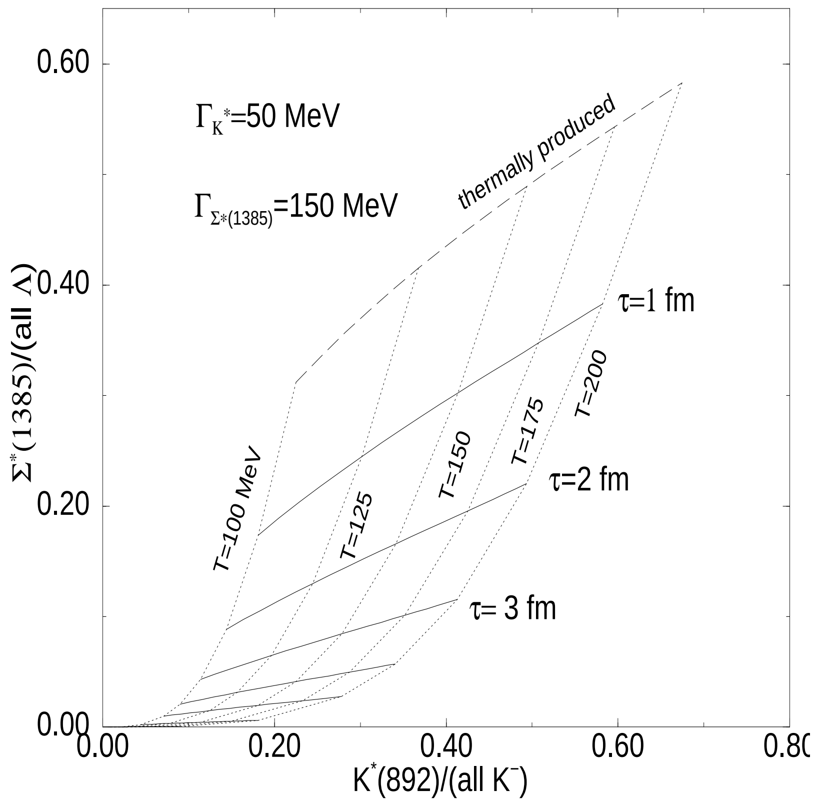


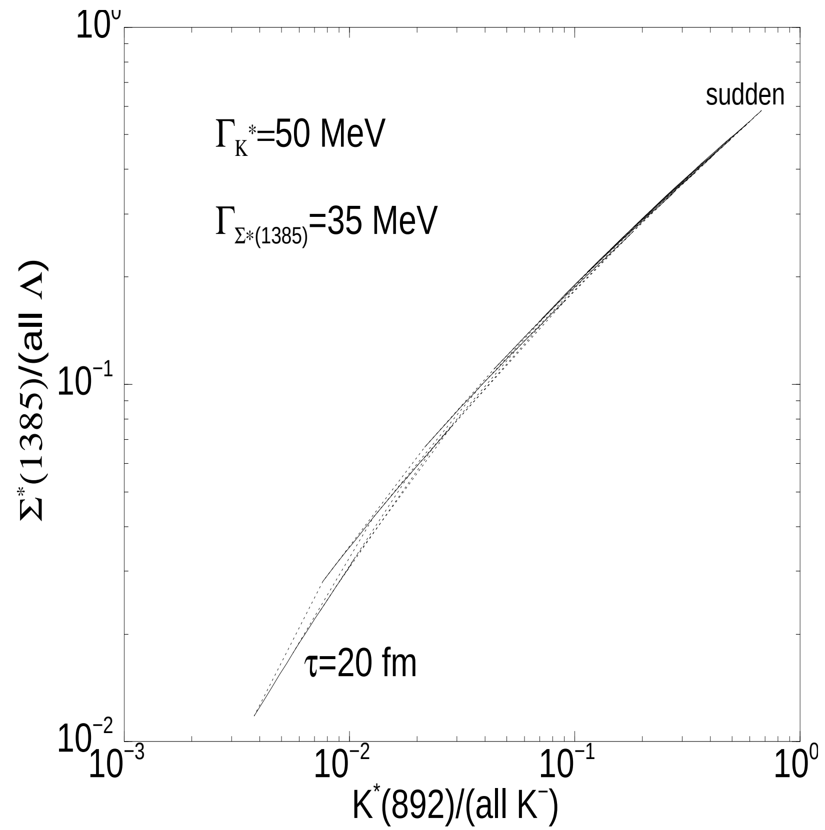


Relative $\Lambda(1520)/$(all Λ) yield as function of freeze-out temperature T. Dashed - thermal yield, solid lines: observable yield for evolution lasting the time shown (1....20 fm) in an opaque medium.
LEFT: natural $\Gamma_{\Lambda(1520)} = 15.6$MeV, RIGHT: quenched $\Gamma^*_{\Lambda(1520)} = 150$MeV.
NA49 measures in $pp \simeq 0.11 \pm 0.02$, in Pb–Pb $\simeq 0.025 \pm 0.008$.

HOW TO FIX value of Γ^*?

Evaluate TWO resonances; EXAMPLE

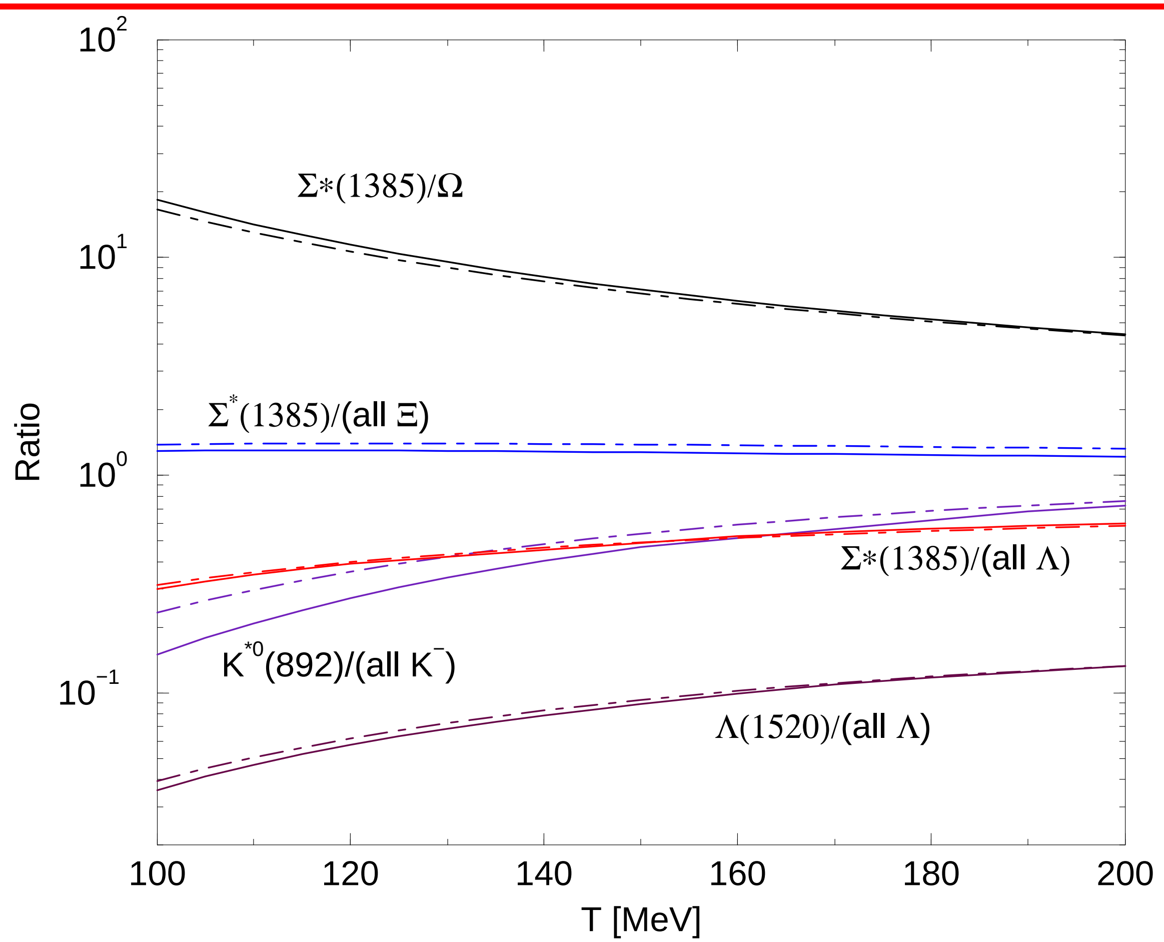




Dependence of the combined Σ^*/(all Λ) with $K^*(892)$/(all K) signals on the chemical freeze-out temperature and HG phase lifetime.

LEFT: quenched $\Gamma_{\Sigma^*} = 150$ **RIGHT natural widths**

Method Sensitivity and Practicability – RELATIVE RESONANCE CONTRIBUTIONS



Temperature dependence: Solid line all rapidity, dashed lines central rapidity $\Delta y = \pm 0.5$. NoteΣ^* is more abundant than all Ξ.

Strangeness at RHIC-130A GeV

$$\frac{dN_{K^+}}{dy}|_{y=0} = 35 \pm 10\%\,, \quad \frac{dN_{K^-}}{dy}|_{y=0} = 30 \pm 10\%\,, \quad \frac{d\bar{s}}{dy}|_{y=0} > 85 \pm 10\%\,.$$

Total strangeness $(\bar{s})$ yield depends on unmeasured hyperons. Model calculations suggest more than 20%. Hence the last result above.

Compare this to

$$\frac{d\pi^+}{dy} \simeq \frac{d\pi^-}{dy} \simeq 235$$

Calculations suggest that $\bar{s}/b \simeq 8$ (11–12 times greater than at 17A GeV SPS Pb–Pb).

EXTREMELY difficult to imagine that among three quarks which coalesce to make a baryon there is no strange quark! Hence we predicted HYPERON DOMINANCE of baryon/antibaryon yields.

Because the hyperon decays are contaminating in a dominant way baryon multiplicity, and K^* yields are AFTER hadronization dedectability attenuation, STUDY OF RHIC MULTIPLICITIES AND INTERPRETATION of particle ratios in terms of statistical parameters is not possible yet in the same way we did this for SPS. We can take a first glimpse:$\rightarrow$

Look at STAR data presented at QM2001:

1) from $\bar{p}/p = 0.6 \pm 0.02 = \lambda_q^{-6}$ **it follows** $\lambda_q = 1.09$**.** $\lambda_s = 1$ **in any FIT STRATEGY!**

2) and hence $\mu_B = 38$**MeV (18% of SPS value) at** $T = 150$ **MeV.**

3) The ratios $\overline{\Lambda}/\Lambda = 0.73 \pm 0.03 = \lambda_s^{-2}\lambda_q^{-4}$**and** $\overline{\Xi}/\Xi = 0.82 \pm 0.08 = \lambda_s^{-2}\lambda_q^{-4}$**are consistent within 1.5% with** $\lambda_s = 1$**, value expected for sudden hadronization.**

4) $K^+/K^- = 0.88 \pm 0.06$ **is also consistent within error with** $\lambda_q = 1.089$**.**

5) On the other hand the ratio $K^*/\overline{K^*} \simeq 1$ **is inconsistent with this analysis and** $K/\overline{K}$**. This suggests that** $K^*, \overline{K^*}$ **yields are influenced by 'in hadronization' decay product rescattering in a asymmetric way and thus:**

6) $K^*, \overline{K^*}$ **MAY NOT be used to fix** T **using the ratios** K^*/h^- **and** $\overline{K^*}/h^-$**.**

7) Ratio $\bar{p}/\pi = 8\%$**cannot be used to fix** T **since yield of** $\bar{p}$ **required large hyperon correction.**

8) The ratio K^-/π^- **DOES NOT SUFFICE TO FIX temperature: we need at least 3 reliable yield ratios as we must also fix** γ_q, γ_s**:** $K^-/\pi^- = 15\% = f(T)\gamma_s/\gamma_d$**.**

First result on chemical potentials, BUT T **and** γ_q, γ_s **cannot yet be fixed.**