Strangeness Physics at RHIC

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RHIC Physics in the Context of the Standard Model:
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Outline

- Strange Particles as Diagnostic Tools
  - Strange Particles in the Standard Model
  - Strange Particles beyond
- Strangeness Production in Hot Matter
  - Strangeness Production and Deconfinement
  - Strangeness Production and Chiral Symmetry
- Summary and Conclusion: A Strange Puzzle?

Strange Particles as Diagnostic Tools

RHIC data on strange particles (incomplete)

Impressive data on strange particle produced at RHIC!

- particle production, m_t-spectra for stable particles: K, $\bar{K}$, Λ,$\bar{\Lambda}$, Ξ, $\bar{\Xi}$, Ω, $\bar{\Omega}$
- strangeness enhancement (centrality dependence, particle ratios)
- elliptic flow (v_2) for K^0, $\Lambda + \bar{\Lambda}$, $\Xi + \bar{\Xi}$, $\Omega + \bar{\Omega}$, ...
- nuclear modification factor (R_{cp}): K^0, Λ, Ξ^-, Ω^-, ...
- correlations for Λ, $\bar{\Lambda}$, K^0

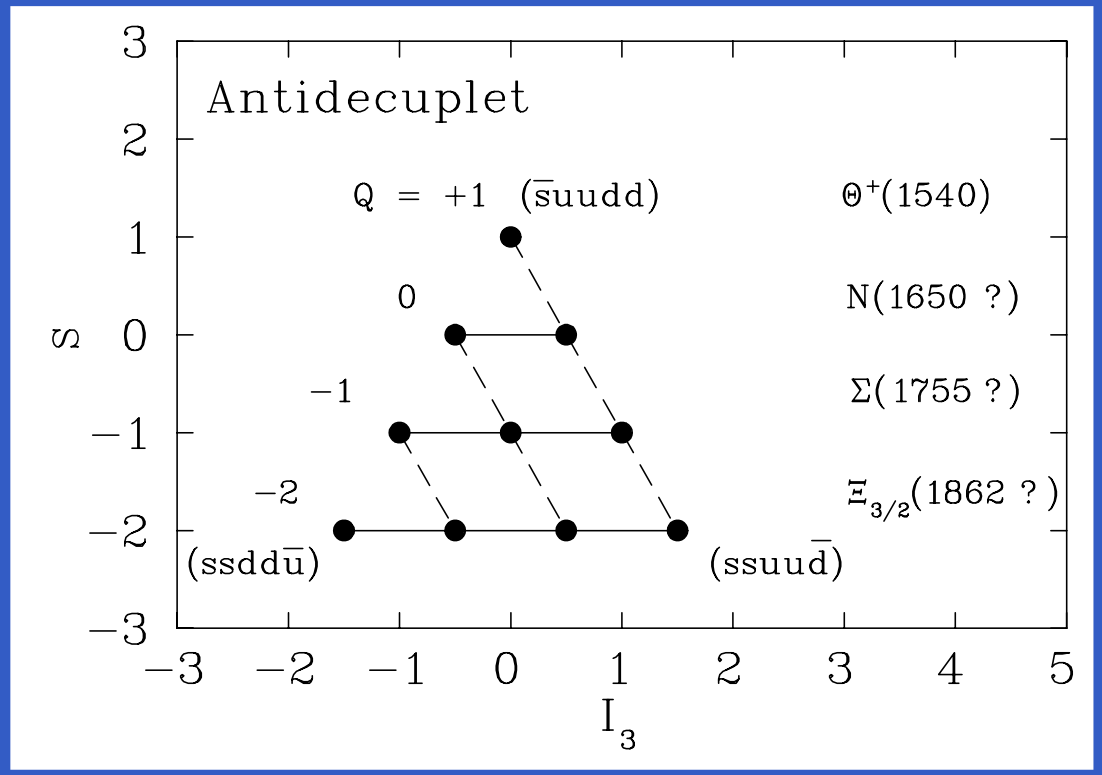
strangeness established mass ordering at low p_t, baryon-meson scaling at high p_t!

RHIC data on strange resonances (incomplete)

- resonances measured so far: $\eta \to 2\gamma$ or $\mu^+\mu^-$ (mainly strange!), $K^*(892) \to K + \pi$, $\phi(1020) \to K\bar{K}$ or $e^+e^-, \mu^+\mu^-$! $\Sigma^*(1385) \to \Lambda + \pi$, $\Lambda(1520) \to N + \bar{K}$
- particle production, m_t-spectra for stable particles: η, $K^*(892)$, $\phi(1020)$, $\Sigma^*(1385)$, $\Lambda^*(1520)$
- elliptic flow (v_2) for $K^*(892)$, $\phi(1020)$, $\Sigma^*(1385)$
- nuclear modification factor (R_{cp}): $K^*(892)$, $\phi(1020)$, $\Sigma^*(1385)$
- stunning data on strange resonances (compare to nonstrange resonances as Δ, ρ, ...) bolstering mass scaling/quark number scaling!
- other possible strange resonances to be measured: $\Xi^*(1530) \to \Xi + \pi$, $\Xi(1820) \to \Lambda + \bar{K}$?

Pentaquark/Multiquark candidates

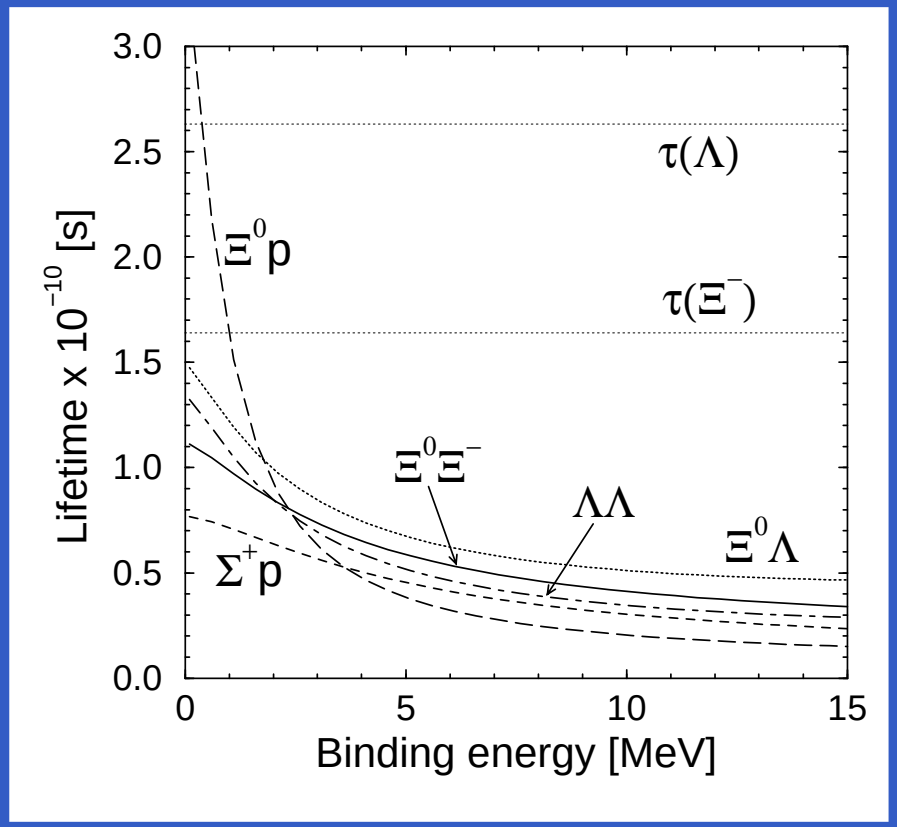
light pentaquark antidecuplet



- $\Theta^{++}(uuud\bar{s})(1530) \rightarrow p + K^{+}$ seen by STAR in dAu data? (not seen in pp, AuAu)
- possibly $N^{0}(udsd\bar{s})/\Xi^{0}(udss\bar{d})(1730) \rightarrow \Lambda + K_{s}^{0}$ detected?
- H dibaryon (uuddss) signal observed by STAR? (PhD thesis of Renaud Vernet)!

Strange Dibaryons – Candidates and Lifetime

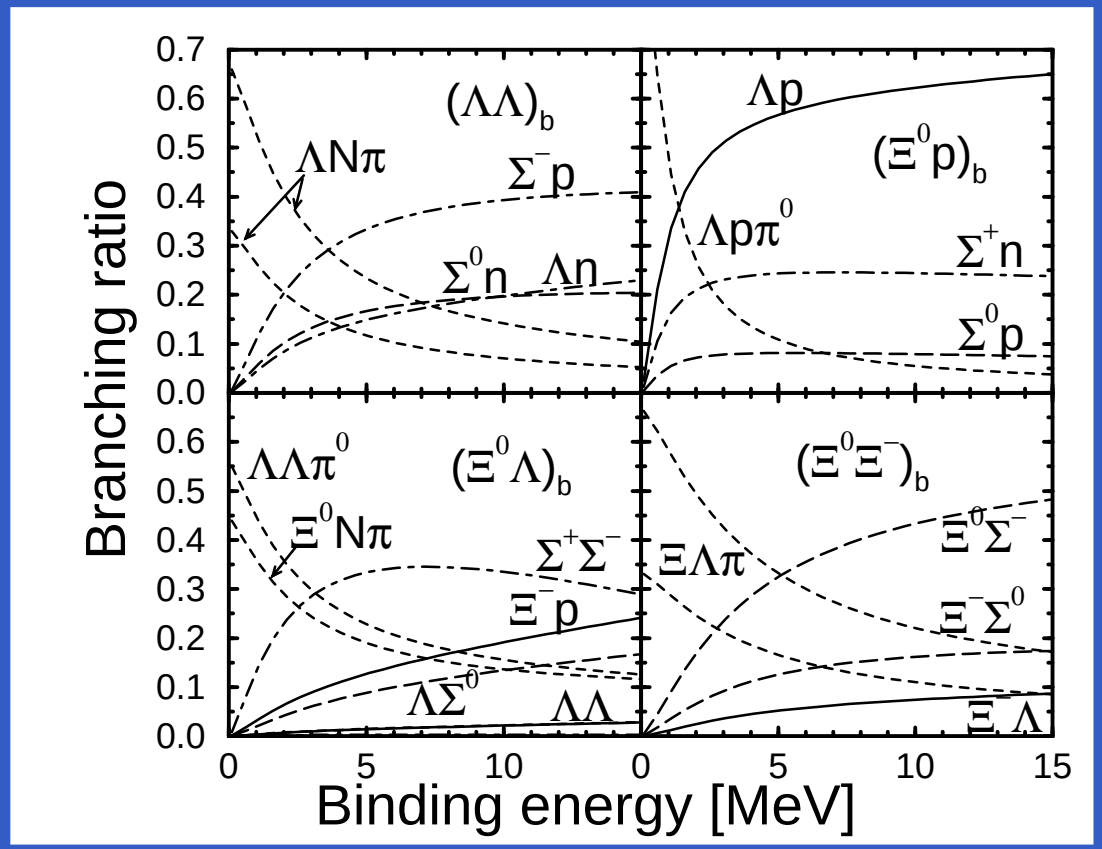
(JSB, Mattiello, Sorge, PRL 84 (2000) 4305)



- best observable dibaryon decay products: p, Λ, Ξ^- only!
- corresponding bound candidates: $(\Sigma^+ p)_b \to p + p$, $(\Xi^0 p)_b \to \Lambda + p$, $(\Lambda\Xi^0)_b \to \Lambda + \Lambda$ or $\Xi^- + p$, $(\Xi^-\Xi^0)_b \to \Xi^- + \Lambda$
- lifetime estimates: $c\tau = 1 - 5$ cm (only slightly smaller than hyperon lifetimes) depending on binding energy

Strange Dibaryons – Branching Ratios

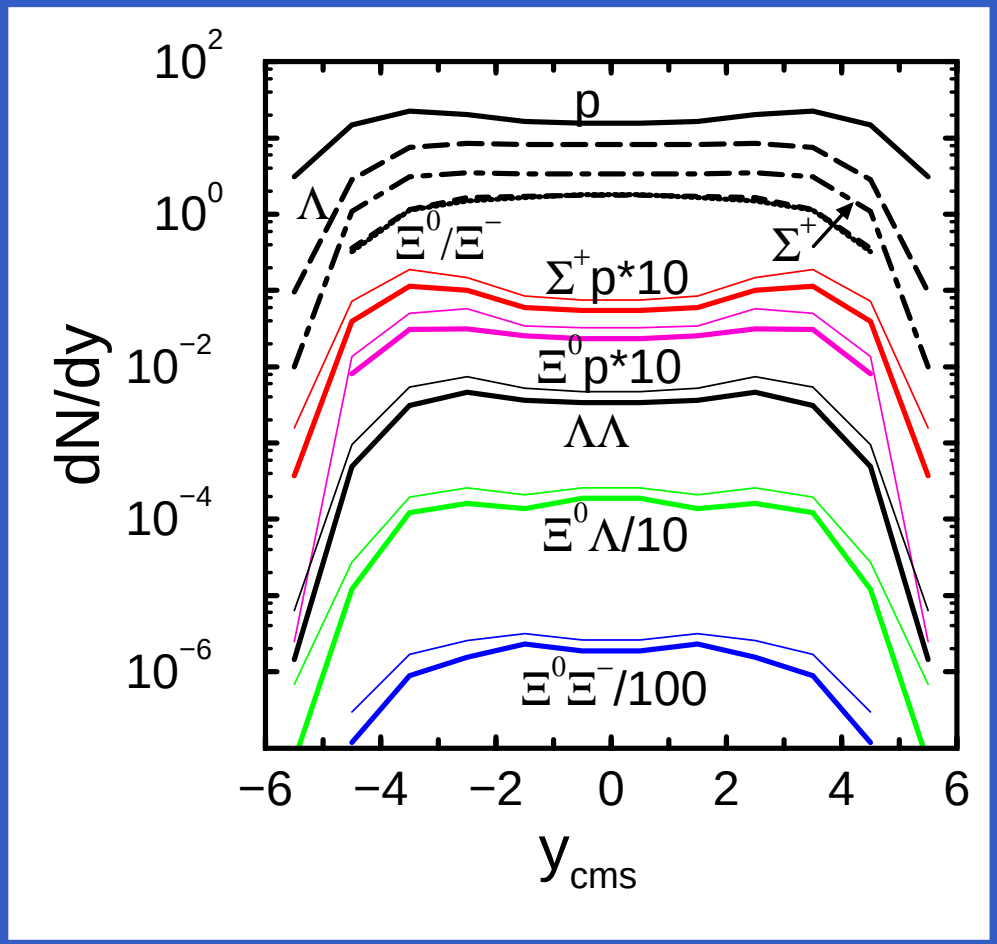
(JSB, Mattiello, Sorge, PRL 84 (2000) 4305)



- decay can be mesonic (three-body decay) or nonmesonic (two-body decay!)
- $(\Lambda\Lambda)_b \to \Sigma^- + p$ dominant decay for $E_b > 4$ MeV (similar to H dibaryon!)
- $(\Xi^0 p)_b \to \Lambda + p$ main decay channel for $E_b > 2$ MeV
- for $(\Lambda\Xi^0)_b$ the branching ratio for $\Xi^- + p$ is larger than for $\Lambda + \Lambda$

Strange Dibaryons – Production Rates at RHIC

(JSB, Mattiello, Sorge, PRL 84 (2000) 4305)

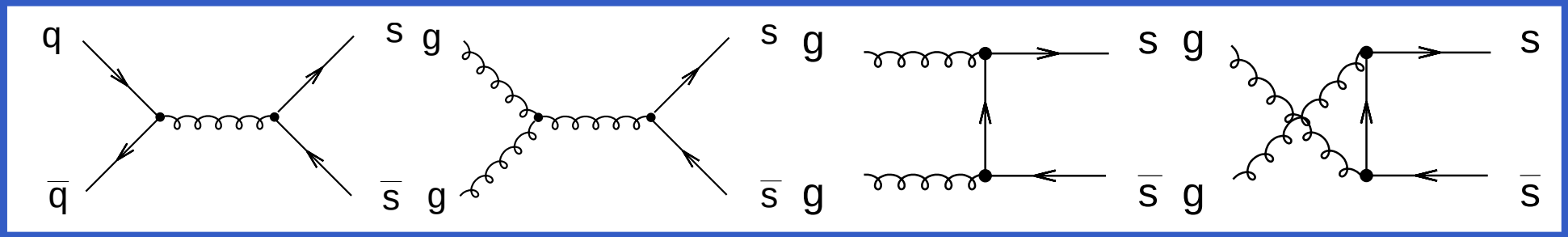


- using RQMD2.4 ($b < 3$ fm) with phase-space wave-function coalescence
- production rates for dihyperons are between 10^{-2} to 10^{-4} per event
- flat rapidity dependence $\rightarrow$ detection at forward/backward rapidity?

Strangeness Production in Deconfined Matter

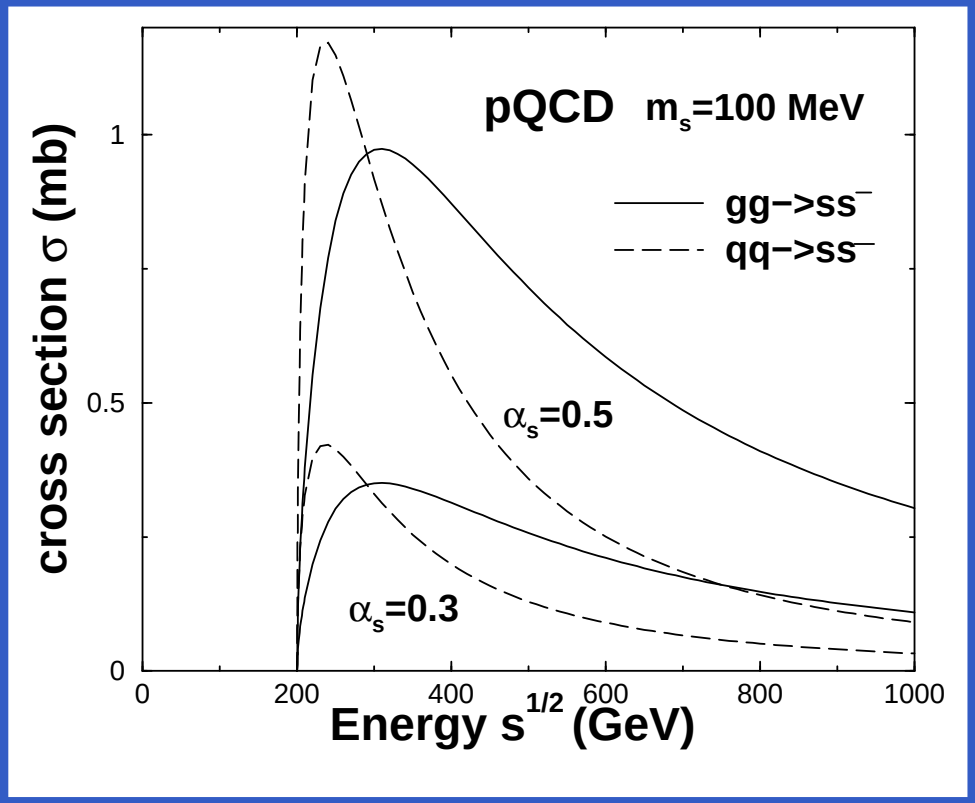
Strangeness enhancement in the quark-gluon plasma

(J. Rafelski and B. Müller, PRL 48 (1982) 1066)



- producing strangeness via quarks:
  $q + \bar{q} \leftrightarrow s + \bar{s}$, $q = u, d$ quarks
- and gluons: $g + g \leftrightarrow s + \bar{s}$
- Q-value of reaction: $Q_{qgp} = 2m_s \approx 200$ MeV, comparable to critical temperature T_c!
- Q-value for hadron gas (associated production):
  $NN \rightarrow N\Lambda K$, $Q_{hg} = m_\Lambda + m_K - m_N \approx 670$ MeV!

Cross section within perturbative QCD



$$\sigma_{q\bar{q}\to s\bar{s}} = \frac{8\pi\alpha_s^2}{27s^2}\left(s+2m_s^2\right)\chi, \qquad \chi = \sqrt{1-\frac{4m^2}{s}}$$

$$\sigma_{gg} = \frac{\pi\alpha_s^2}{3s}\left[\left(1+\frac{4m_s^2}{s}+\frac{m_s^4}{s^2}\right)\ln\left(\frac{1+\chi}{1-\chi}\right)-\left(\frac{7}{4}+\frac{31}{4}\frac{m_s^2}{s}\right)\chi\right]$$

cross section peaks at a temperature of 200–250 MeV, gluonic processes dominate at higher temperature

Equilibration timescales in pQCD

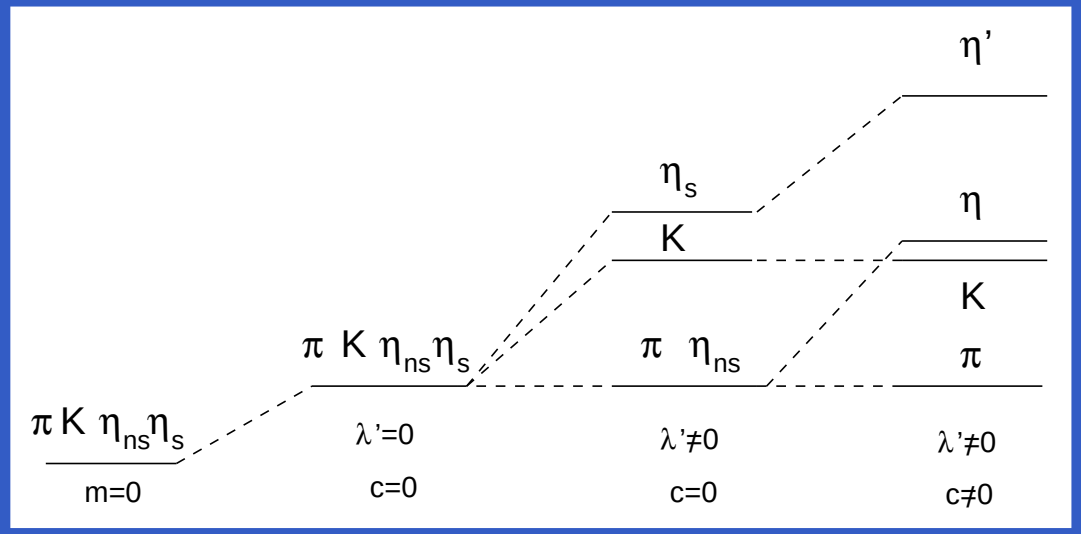
equilibration timescale: form rate per unit time and volume A (thermal average of cross section) and solve the master equation

$$\frac{dn_s}{dt} = A \cdot \left\{ 1 - \left(\frac{n_s(t)}{n_s^{\rm eq}} \right)^2 \right\}, \qquad \tau_{\rm eq} = \frac{1}{n_s^{\rm eq} \cdot A} \Longrightarrow \tau_{\rm eq}^{\rm qgp} \approx 10 \text{ fm}$$

- no dynamical effects taken into account!
- caveats: we know that perturbative QCD fails at T_c from lattice data!
- resummation techniques: allow for massive gluons to decay directly to strange quarks (Rischke, Biro, Levai, Müller, Altherr, Seibert, Bilic, Cleymans, Dadic, Hislop)
- no overall consistent picture yet, so far equilibration times seem to stay above 10 fm! Effects from color-glass condensate?

Strangeness Production in Chirally Restored Matter

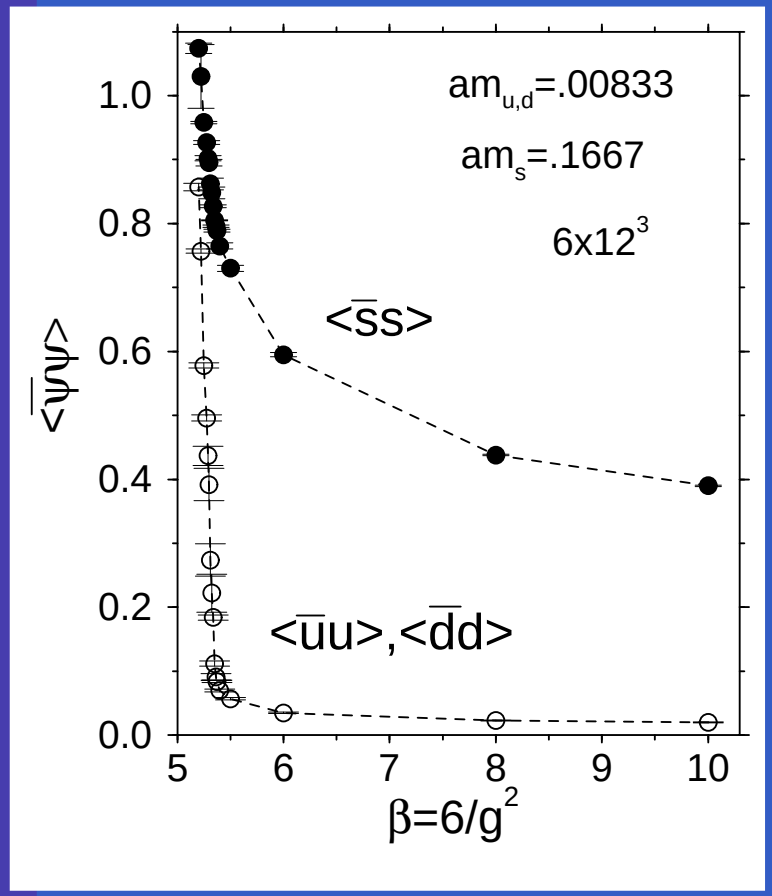
SU(3) chiral effective Lagrangian



$$\mathcal{L} = \mathcal{L}_{\rm kin} + \frac{1}{2}\mu^2 {\rm Tr} M^\dagger M - \lambda \cdot {\rm Tr}\left(M^\dagger M M^\dagger M\right) - \lambda' \cdot \left({\rm Tr} M^\dagger M\right)^2 + c \cdot \left(\det M + \det M^\dagger\right) + \epsilon \cdot \sigma + \epsilon' \cdot \zeta$$

- hadrons involved: pseudoscalar mesons (π,K,η,η') and their chiral partners, the scalar mesons (σ,κ,a_0,f_0)
- mass splittings: complete degeneracy without mass or interaction terms
- $\lambda' \neq 0$ breaks O(18) symmetry, mass splitting according to strangeness
- the $U_A(1)$ anomaly ($c \neq 0$) breaks $\eta_{ns} - \pi$ degeneracy, heavy η'!

Which chiral symmetry is restored at T_c?

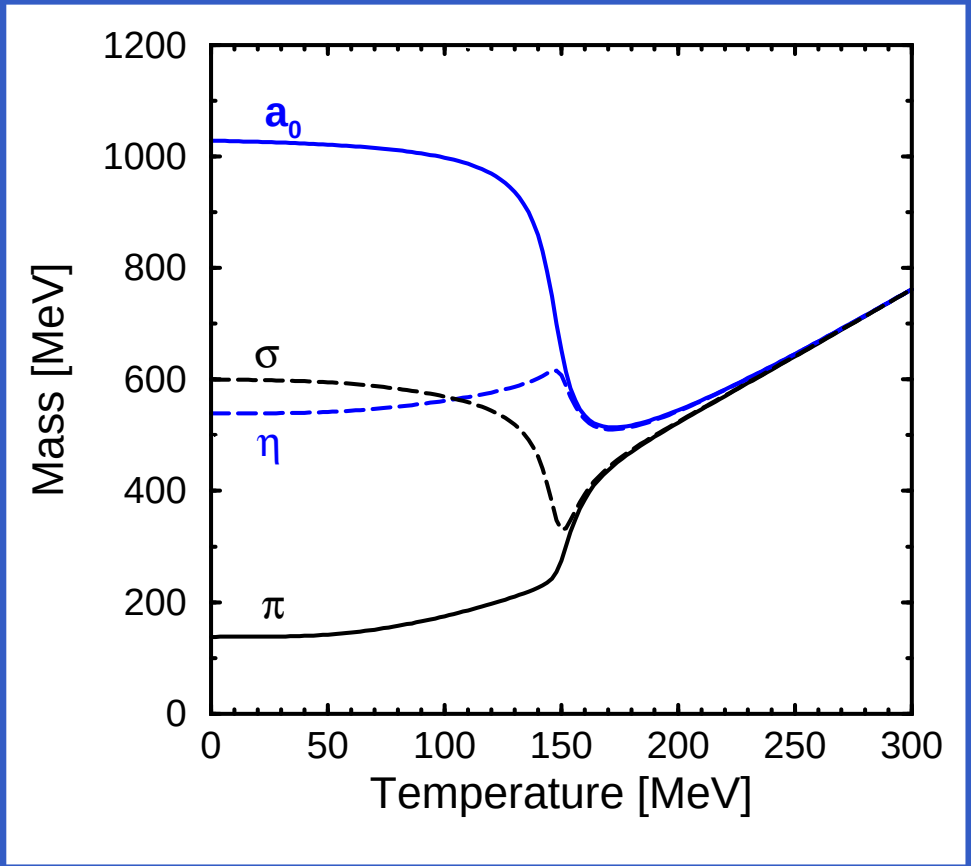


(data taken from Kogut, Sinclair, Wang, PLB 263 (1991) 101)

- restoration of SU(2)xSU(2) symmetry:
  $m_\pi = m_\sigma < m_{\eta_{ns}} = m_{a_0}$
- plus restoration of $U_A(1)$ symmetry:
  $m_\pi = m_\sigma = m_{\eta_{ns}} = m_{a_0}$
- mass splitting of nonstrange partners governed by strange quark condensate ($\delta m^2 \propto c \cdot \zeta$)!
- partial restoration of $U_A(1)$ symmetry seen on the lattice! (Alles et al., Bernard et al., Chandrasekharan et al., ...)

Chiral symmetry restoration I

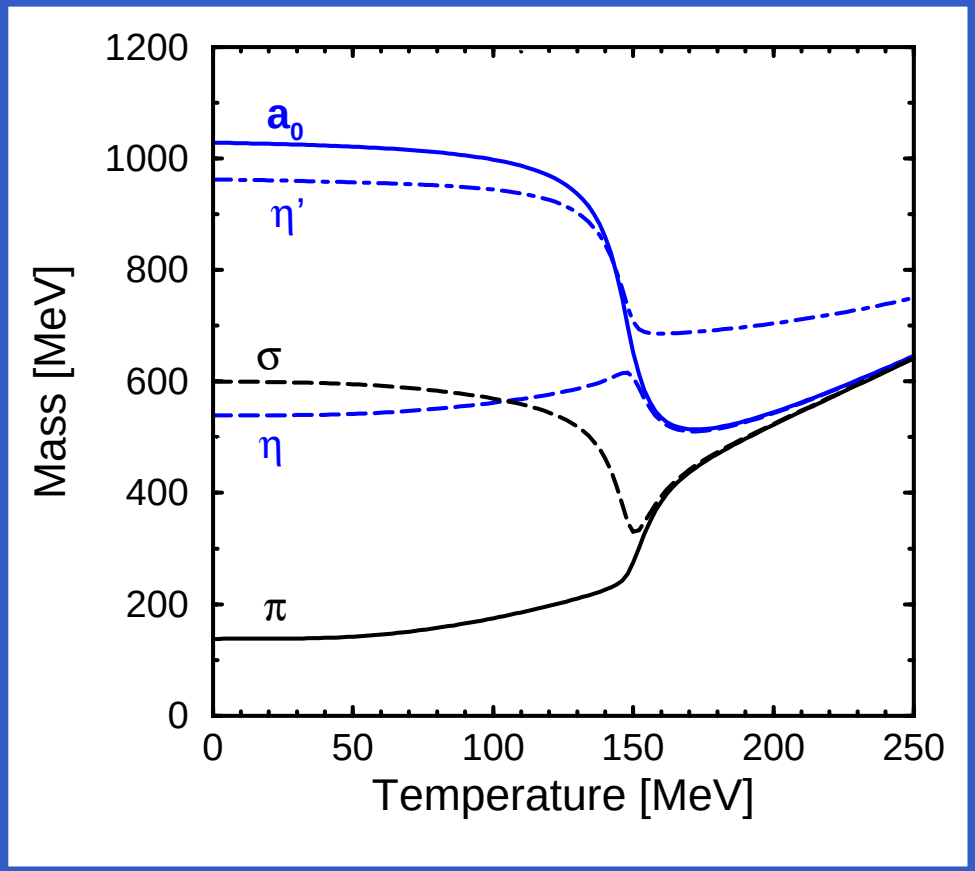
(JSB, PRL 84 (2000) 3261)



- masses of $\pi - \sigma$ and $\eta - a_0$ equal separately at T_c
- then complete degeneracy due to $U_A(1)$ symmetry restoration
- mass of a_0 decreases drastically around T_c ($a_0 \to \eta + \pi$ closed before T_c)

Chiral symmetry restoration II

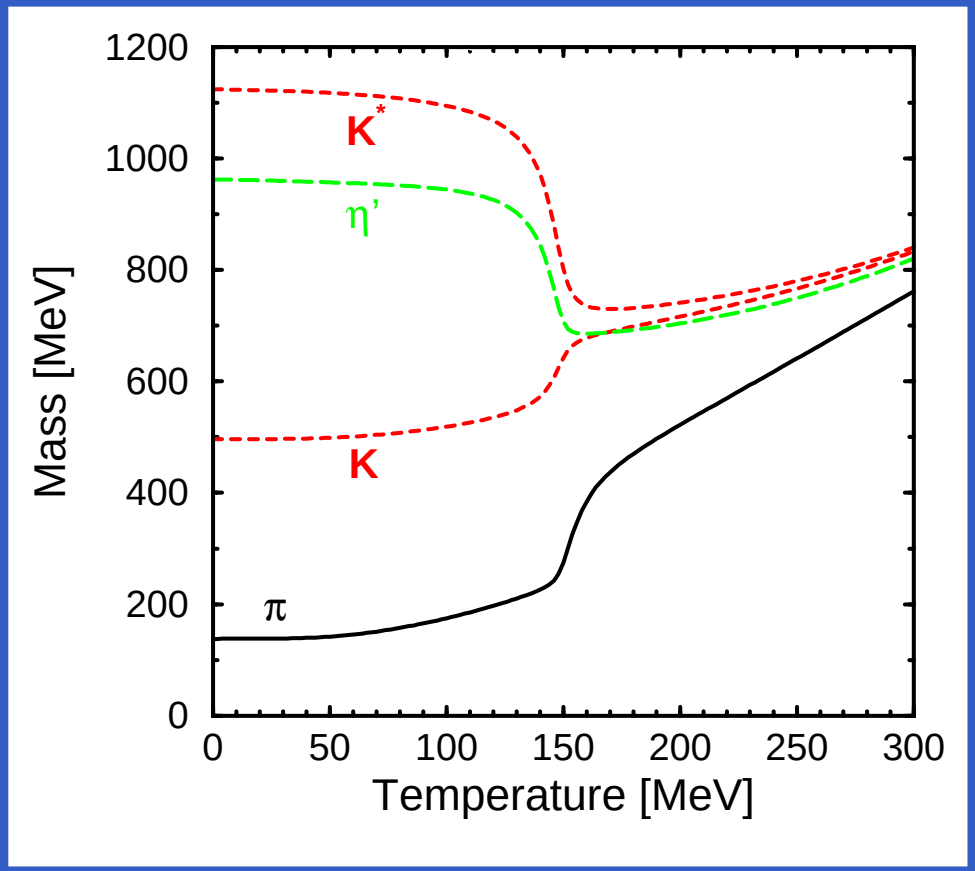
(JSB, PRL 84 (2000) 3261)



- η' becomes degenerate with a_0, not η!
- reflects the fact, that η' is mainly nonstrange
- level crossing visible between η and η' around T_c
- the mesons η and η' switch roles at T_c! (η' enhancement at and above T_c)

Chiral symmetry restoration III

(JSB, PRL 84 (2000) 3261)



- chiral partner of the kaon: the scalar $\kappa(800)$ meson
- slightly changing masses below T_c, mass degeneracy only asymptotically for large temperatures
- sharp drop of the η' and κ mass around T_c ($\kappa \to K + \pi$ closed before T_c)

Summary: A Strange Puzzle and a Strange Conclusion?

- enhanced strangeness production enhanced in the QGP: not yet fully addressed in resummed calculations or taken into account effects from CGC or sQGP!
- SU(3) chiral symmetry restoration predicts huge effects on mass spectrum for mesons
- but measured particle ratios as in (free) phase-space statistical approaches
- where is the interaction? where is chiral symmetry restoration?
- solution 1: there is no deconfined/chirally restored matter formed (we do not want that)
- solution 2: final particle production happens out of equilibrium (but strong collective behaviour observed, elliptic flow)
- $\Longrightarrow$ need a collective out-of-equilibrium process! (reminds one of the physics of the very early universe)