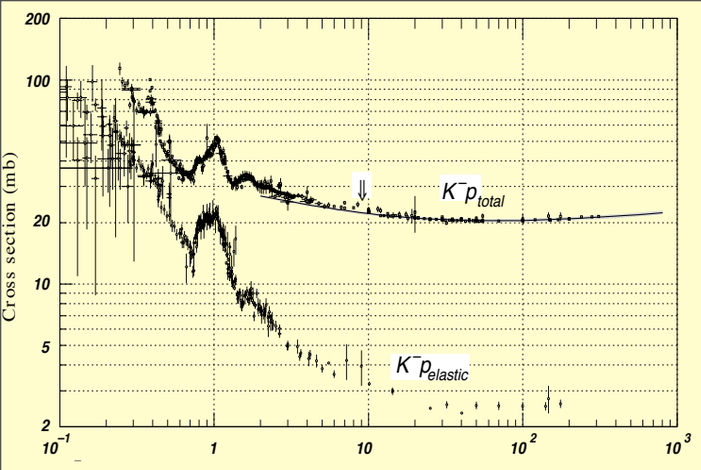
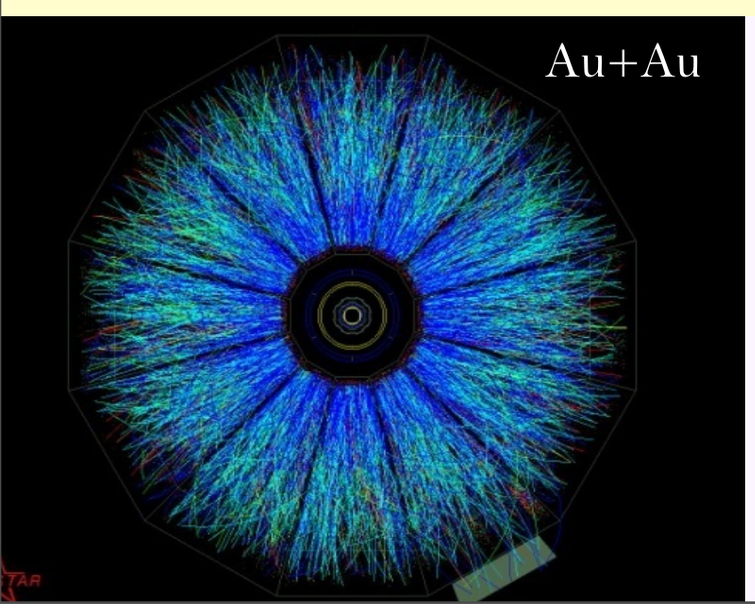


THE ROLE OF RESONANCES IN HOT HADRONIC MATTER

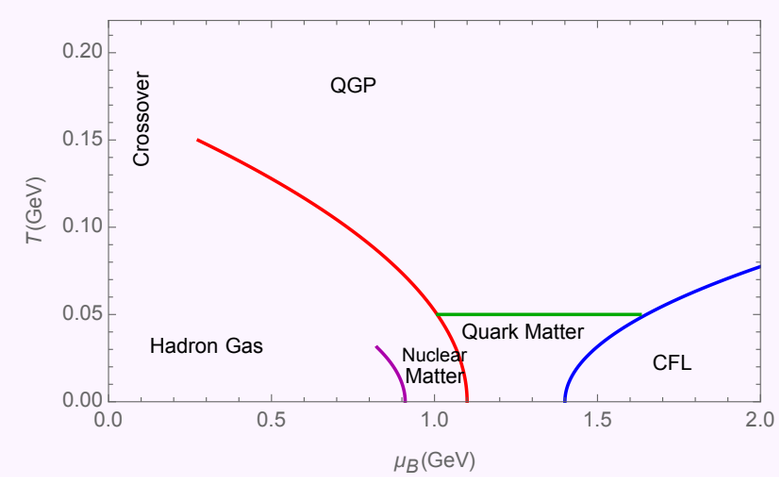
Jose L. Goity

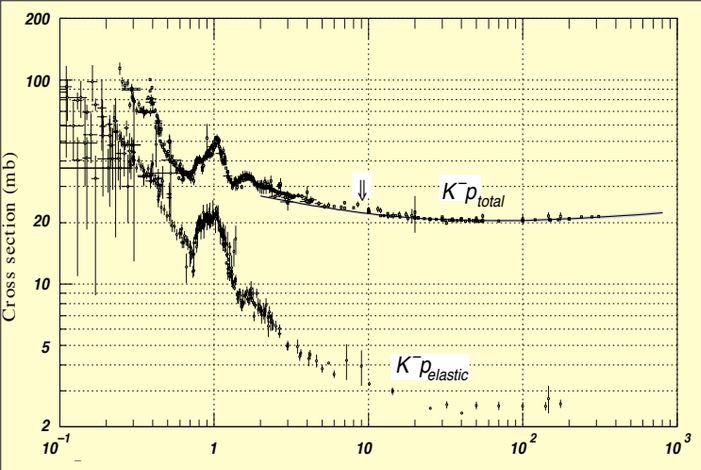
Hampton University and Jefferson Lab

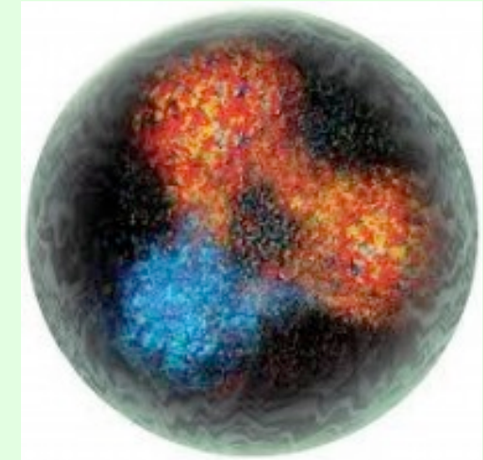


HIPS 2017

New Opportunities with High-Intensity Photon Sources







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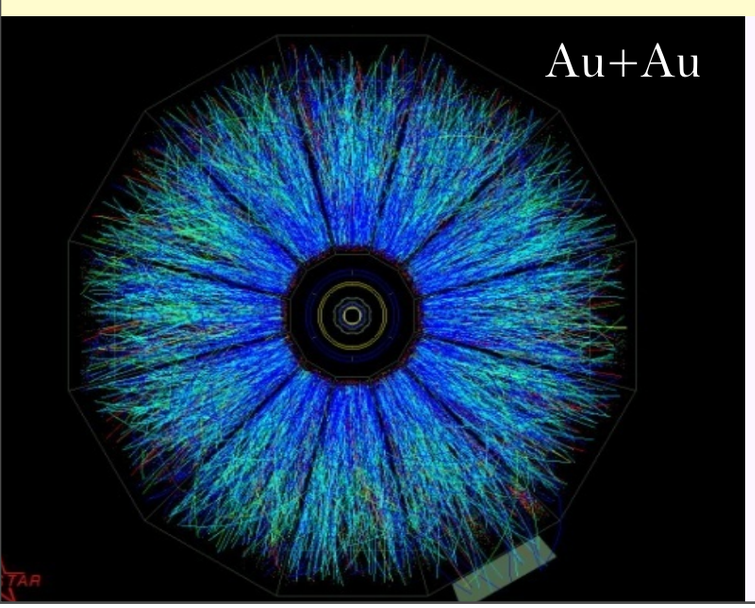

HIPS 2017

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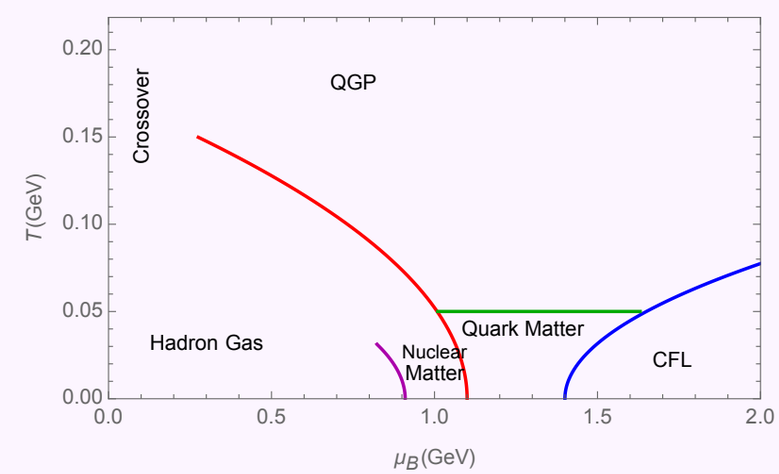

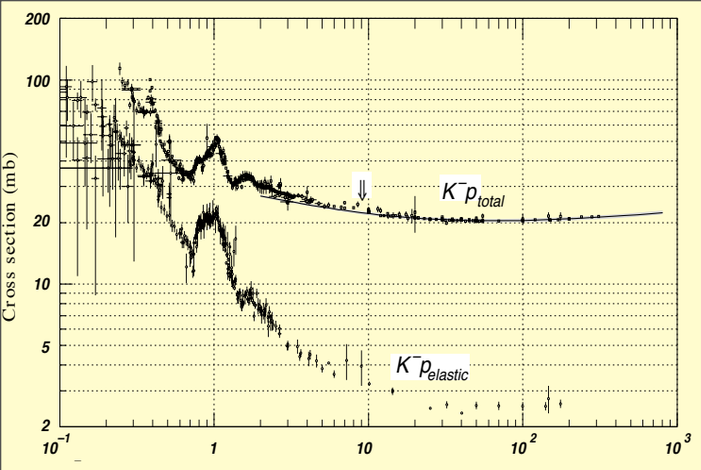

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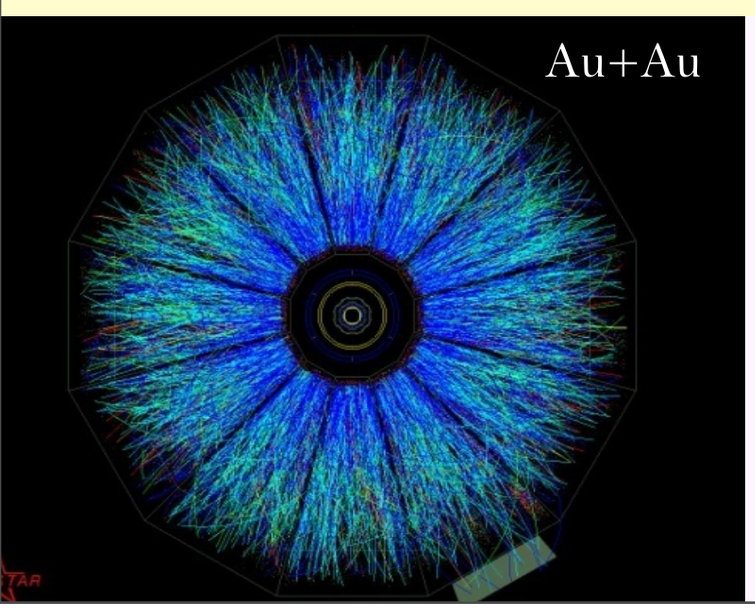
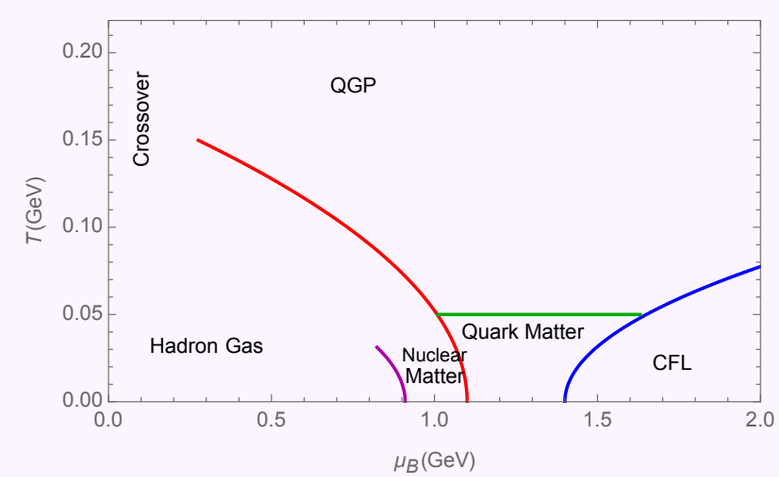


HIPS 2017

New Opportunities with High-Intensity Photon Sources



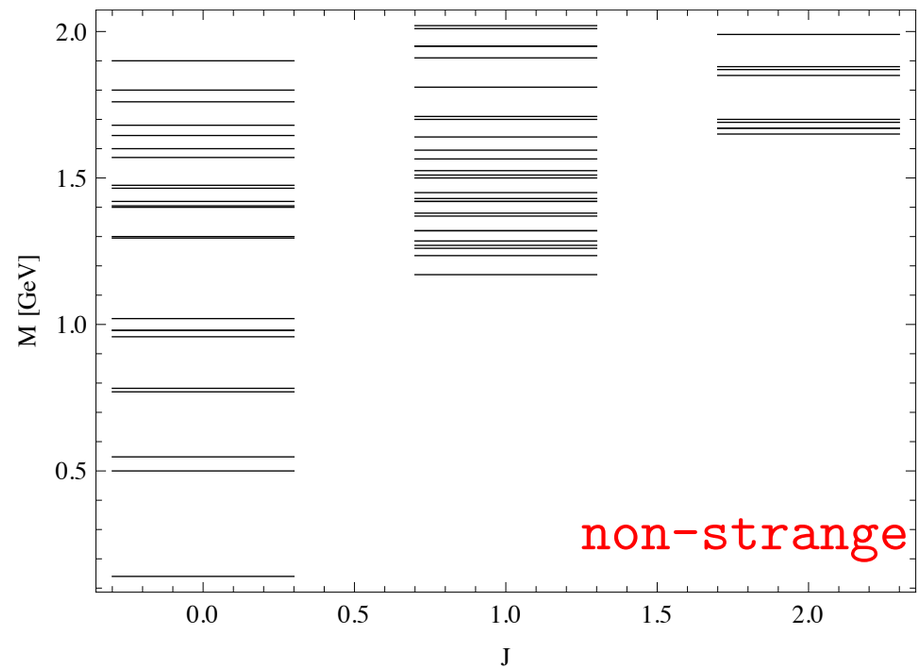
Outline

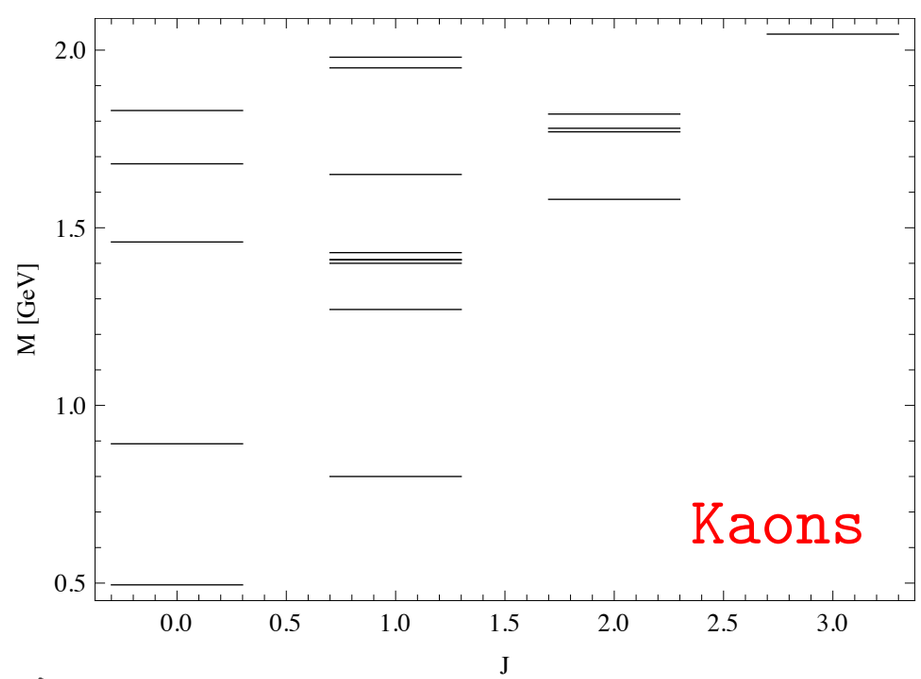
- Missing hadrons
- Hot hadronic matter
- The hot Hadron Resonance Gas
- HRG and LQCD
- HRG and heavy ion collisions
- Hyperon effects in the HRG
- Remarks and conclusions

Missing hadrons: Mesons in PDG

non-strange

Meson	I	S	L	J	P	0.001 Mass[GeV]	nπDecay
π[140]	1	0	0	0	-1	0.14	1
f0[500]	0	0	0	0	1	0.5	2
η[548]	0	0	0	0	-1	0.548	1
ω[782]	0	1	0	1	-1	0.782	3
ρ[770]	1	1	0	1	-1	0.77	2
ηp[958]	0	0	0	0	-1	0.958	1
f0[980]	0	0	0	0	1	0.98	2
a0[980]	1	0	0	0	1	0.98	2
ϕ[1020]	0	1	0	1	-1	1.02	2
h1[1170]	0	1	1	1	1	1.17	3
b1[1235]	1	0	1	1	1	1.235	4
a1[1260]	1	1	1	1	1	1.26	3
a2[1320]	1	1	1	2	1	1.32	3.
f2[1270]	0	1	1	2	1	1.27	2
f1[1285]	0	1	1	1	1	1.285	4
η[1295]	0	0	0	0	-1	1.295	3
π[1300]	1	0	0	0	-1	1.3	3
a2[1320]	1	1	1	2	1	1.32	3
f0[1370]	0	1	1	0	1	1.37	4
h1[1380]	0	0	1	1	1	1.38	3.
π1[1400]	1	1	0	1	-1	1.4	2
η[1405]	0	0	0	0	-1	1.405	2
f1[1420]	0	0	1	1	1	1.42	3
ω[1420]	0	1	0	1	-1	1.42	3
f2[1430]	0	2	1	2	1	1.43	2.
a0[1450]	1	1	1	0	1	1.45	2
ρ[1450]	1	1	0	1	-1	1.465	2
η[1475]	0	0	0	0	-1	1.475	3
f0[1500]	0	0	1	0	1	1.5	3
f2p[1525]	0	1	1	2	1	1.525	2
f1[1510]	0	0	1	1	1	1.51	3.
f2[1565]	0	1	1	2	1	1.565	2
ρ[1570]	1	1	0	1	-1	1.57	3
h1[1595]	0	0	1	1	1	1.595	3.
π1[1600]	1	1	0	1	-1	1.6	3
f2[1640]	0	1	1	2	1	1.64	2
η2[1645]	0	1	0	2	-1	1.645	3.
ω[1650]	0	1	2	1	-1	1.65	3
ω3[1670]	0	1	2	3	-1	1.67	3
π2[1670]	1	0	2	2	-1	1.67	3.
ϕ[1680]	0	1	0	1	-1	1.68	3
ρ3[1690]	1	1	2	3	-1	1.69	4
ρ[1700]	1	1	2	1	-1	1.7	4
a2[1700]	1	1	1	2	1	1.7	3
f0[1710]	0	1	1	0	1	1.71	2
η[1760]	0	0	0	0	-1	1.76	3
π[1800]	1	0	0	0	-1	1.8	3
f2[1810]	0	1	1	2	1	1.81	2
a1[1420]	1	0	1	1	1	1.42	3
ϕ3[1850]	0	1	2	3	-1	1.85	2
η2[1870]	0	0	2	2	-1	1.87	3.
π2[1880]	1	0	2	2	-1	1.88	3.
ρ[1900]	1	1	0	1	-1	1.9	2
f2[1910]	0	1	1	2	1	1.91	3
a0[1950]	1	1	1	0	1	1.95	2
f2[1950]	0	1	1	2	1	1.95	2
ρ3[1990]	1	1	2	3	-1	1.99	2
f2[2010]	0	1	1	2	1	2.01	2
f0[2020]	0	1	1	0	1	2.02	3





Kaons

Meson	I	S	L	J	P	0.001 Mass[GeV]	nπdecay
K	$\frac{1}{2}$	0	0	0	-1	0.495	1
K[800]	$\frac{1}{2}$	1	1	0	1	0.8	2
K[892]	$\frac{1}{2}$	1	0	1	-1	0.892	2
K1[1270]	$\frac{1}{2}$	0	1	1	1	1.27	3
K1[1400]	$\frac{1}{2}$	0	1	1	1	1.4	3
K[1410]	$\frac{1}{2}$	1	1	1	1	1.41	3
K0[1430]	$\frac{1}{2}$	1	1	0	1	1.41	2
K2[1430]	$\frac{1}{2}$	1	1	2	1	1.43	2
K[1460]	$\frac{1}{2}$	0	0	0	-1	1.46	3
K2[1580]	$\frac{1}{2}$	0	2	2	-1	1.58	3
K[1650]	$\frac{1}{2}$	0	1	1	1	1.65	3
K[1680]	$\frac{1}{2}$	1	0	1	-1	1.68	2
K2[1770]	$\frac{1}{2}$	0	2	2	-1	1.77	3
K3[1780]	$\frac{1}{2}$	1	2	3	-1	1.78	3
K2[1820]	$\frac{1}{2}$	1	2	2	-1	1.82	3
K[1830]	$\frac{1}{2}$	0	0	0	-1	1.83	3
K0[1950]	$\frac{1}{2}$	1	1	0	1	1.95	2
K2[1980]	$\frac{1}{2}$	1	1	2	1	1.98	2
K4[2045]	$\frac{1}{2}$	1	3	4	1	2.045	2

Number of PDG dof: 469

SU(3) octets $\Longrightarrow$ # Kaons=# non-strange mesons

Missing baryons in PDG

$SU(3)$	PDG
$\#\Sigma = \#\Xi = \#N + \#\Delta$	$26; 12; 49$
$\#\Omega = \#\Delta$	$4; 22$
$\#\Lambda = \#N + \#\text{singlets}$	$18; 29$

All listed

SU(3): # Y= 3(# N+ # Δ)+singlets

Important aspects of excited hyperon physics

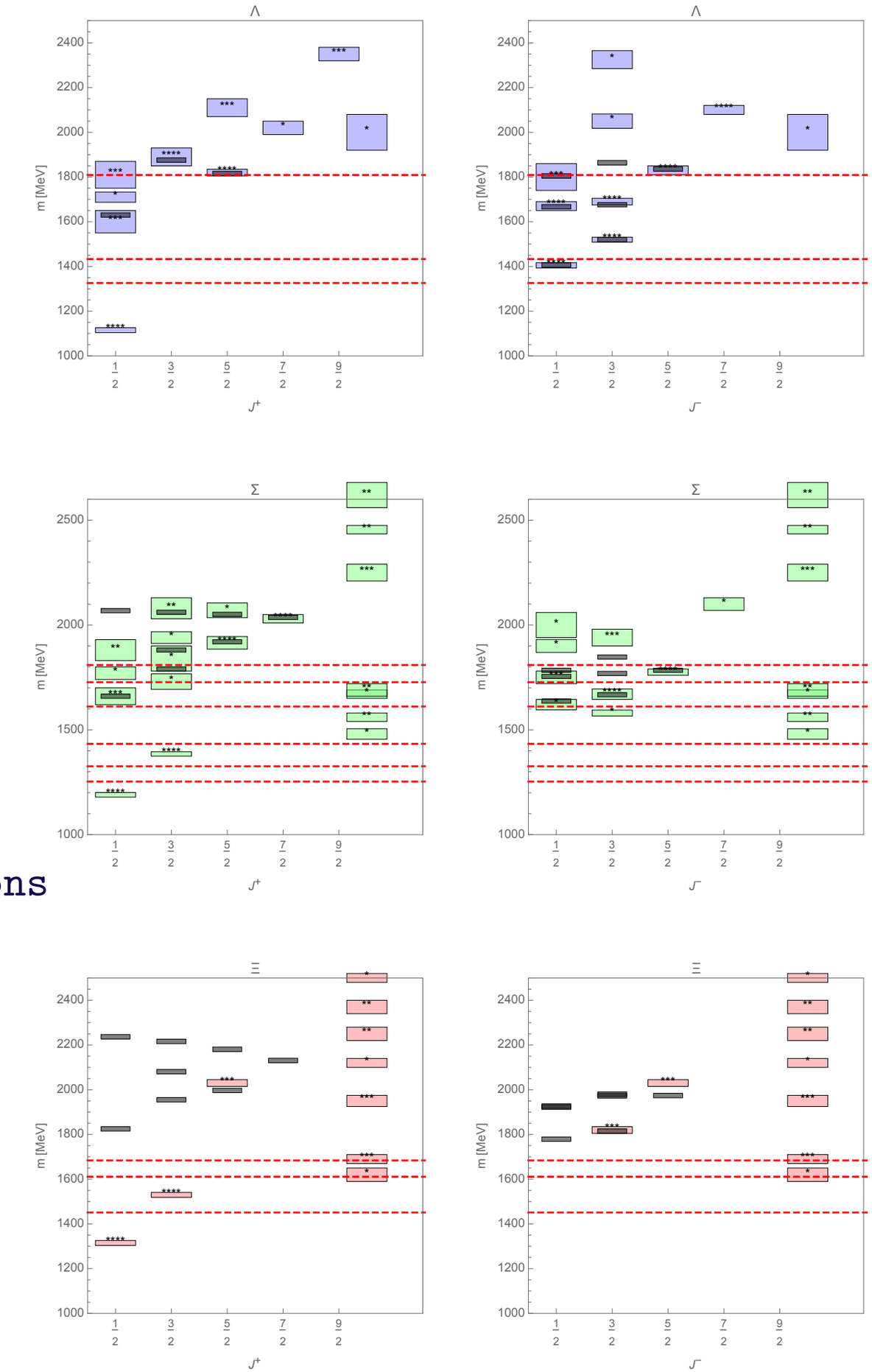
- Test the existence of complete SU(3) multiplets
- Study SU(3) breaking effects in excited baryons
- Test the indications that excited baryons form SU(6)xO(3) multiplets
- Important source of information to test the 1/Nc expansion of QCD in baryons
- Possible role of hyperons in high energy heavy ion collisions

Present status of hyperons from PDG

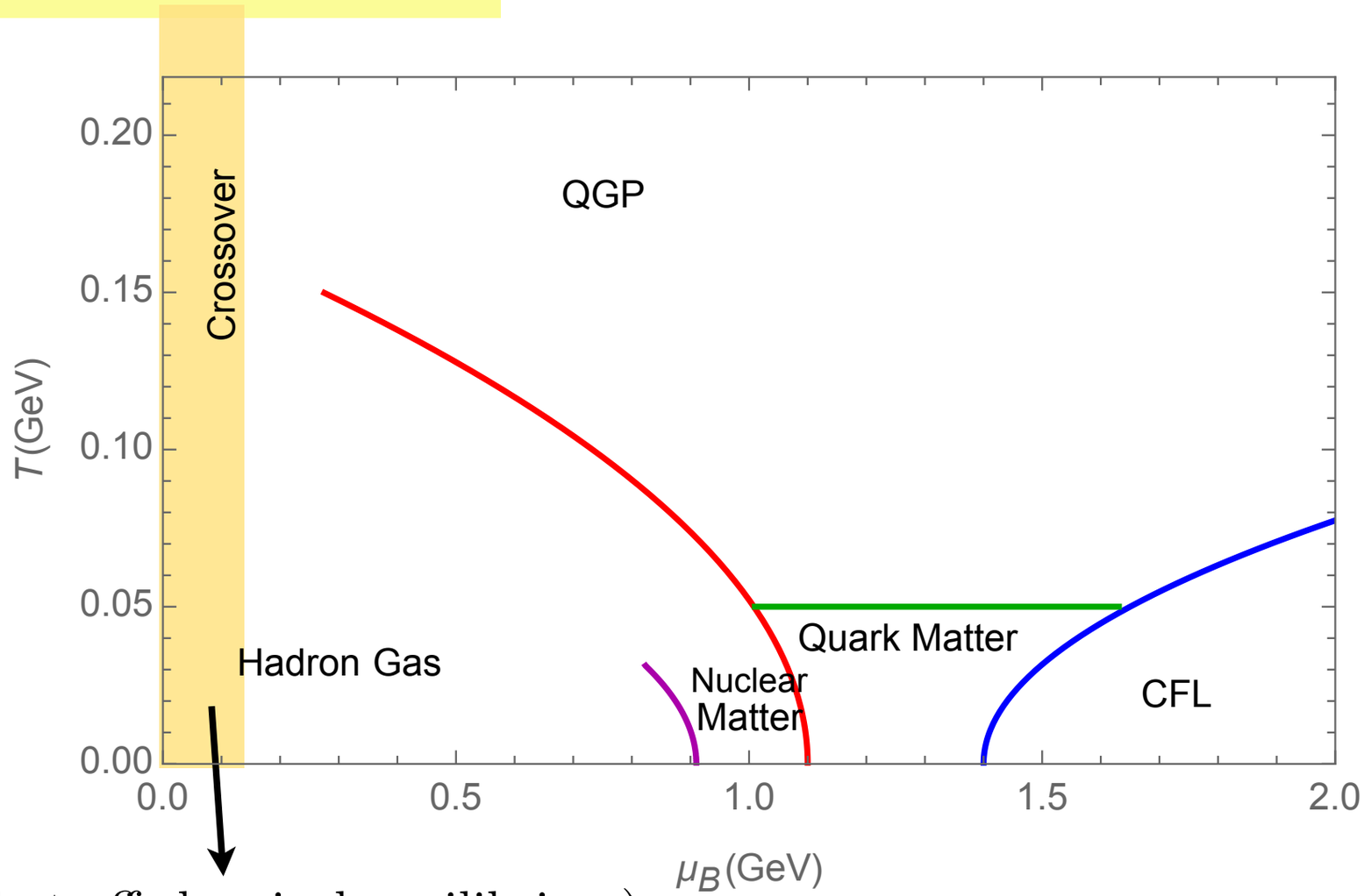
1/Nc baryon mass formulas

for 56-plets $\ell = 0, 2 : 24$ excited hyperons

for 70-plet $\ell = 1 : 23$ excited hyperons



Phases of QCD



LQCD, RHIC (but off chemical equilibrium)

LQCD thermodynamics gives results at vanishing or small chemical potentials: this is the QCD thermo of the early universe!

RHIC gives results in a range of μ_B down to zero, but at freeze out system is well off chemical equilibrium: QGP phase as in early universe, but not so the hadronic phase.

What can QCD thermodynamics tell about missing hadrons?

We need to investigate the hadronic phase

Framework is needed to try to answer the question: model of hadronic phase

Compare with LQCD: it gives only thermodynamics observables

Compare with RHICs: it gives lots of detail from where one can derive thermodynamics, but lots of uncertainties

What thermodynamic observables need to be looked at?

The model for Hot hadronic matter: Hadron Resonance Gas -- HRG

dof: meson-, baryon- and antibaryon- stable states and resonances
only light quarks here (heavy hadrons give very small contributions)

EoS

$$p_n(T,\mu) = \frac{(-1)^{1+B(n)} d(n)}{(2\pi)^3} T \int d^3p \log\left(1 + (-1)^{1+B(n)} \exp\left(-\frac{\sqrt{p^2+m_n^2}-\mu}{T}\right)\right)$$

$$B(n) = \texttt{Baryon number}, \quad d(n) = (2J_n+1)(2I_n+1)$$

or expansion in Bessel functions

$$p_n(T,\mu) = T^2 d(n) \frac{m_n^2}{2\pi^2} \sum_k (-1)^{B_n(k+1)} \frac{1}{k^2} K_2(k m_n/T) \exp(k\mu/T)$$

In chemical equilibrium: $\mu_s, \ \mu_B$

HRG determined by spectrum of QCD

Baryons: states up to ~2.7 GeV

$SU(6) \times O(3)$ `Multiplets`

$[56, \ell = 0]$ `ground state`

$[56, \ell = 0, 2, 4]$

$[70, \ell = 1, 2, 3]$

Number of dof: 1946

many missing states: in SU(3) multiplets and also spin-flavor multiplets (QM & LQCD)

use simple mass formulas fitted to known states to provide masses for the missing states

mass formulas: neglect spin-orbit splittings

JLG & N.Matagne

$$M_{56,GS}(S=1/2,\mathcal{S}) = m_0 - \frac{1}{2}c_{HF} - c_{\mathcal{S}}\mathcal{S}$$

$$M_{56,GS}(S=3/2,\mathcal{S}) = m_0 + \frac{1}{2}c_{HF} - c_{\mathcal{S}}\mathcal{S}$$

$$M_{56}(S=1/2,\mathcal{S}) = m_0 - \frac{1}{6}c_{HF} - c_{\mathcal{S}}\mathcal{S}$$

$$M_{56}(S=1/2,\mathcal{S}) = m_0 + \frac{1}{6}c_{HF} - c_{\mathcal{S}}\mathcal{S}$$

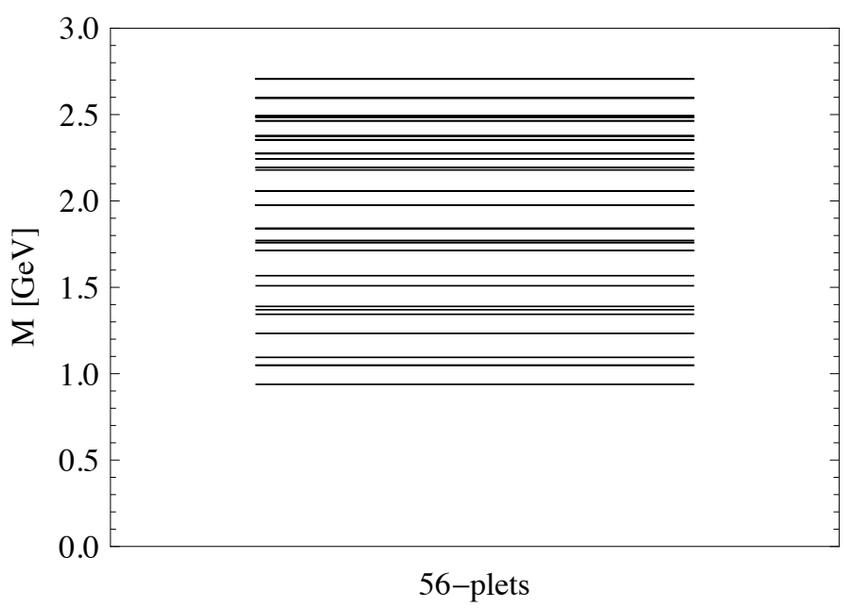
$$M_{70}(S=I,\mathcal{S}) = m_0 + \frac{1}{3}c_{HF}\left(\frac{5}{3}S(S+1) - \frac{7}{4}\right) - c_{\mathcal{S}}\mathcal{S}$$

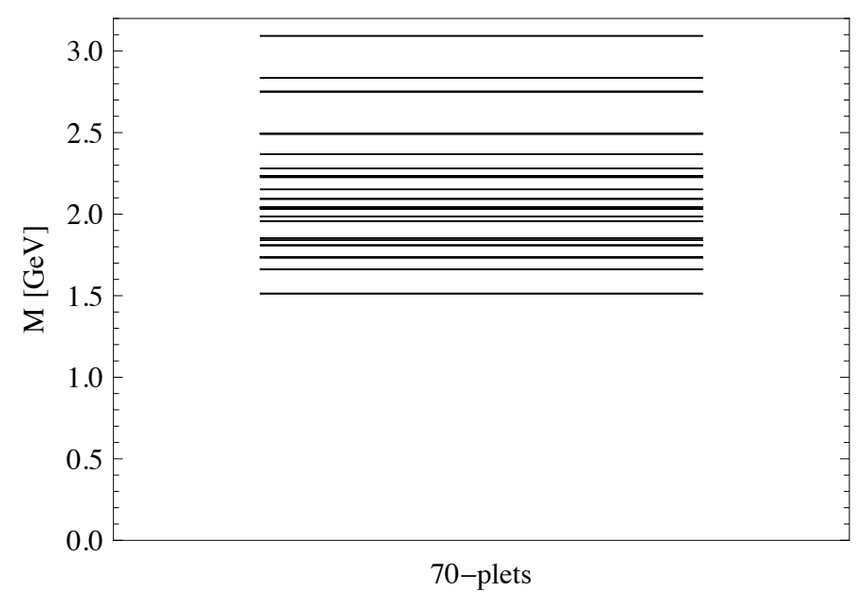
$$M_{70}(S=I-1,\mathcal{S}) = m_0 + \frac{1}{3}c_{HF}\left(S(S+2) - \frac{3}{4}\right) - c_{\mathcal{S}}\mathcal{S}$$

$$M_{70}(S=I+1,\mathcal{S}) = m_0 + \frac{1}{3}c_{HF}\left(S^2 - \frac{7}{4}\right) - c_{\mathcal{S}}\mathcal{S}$$

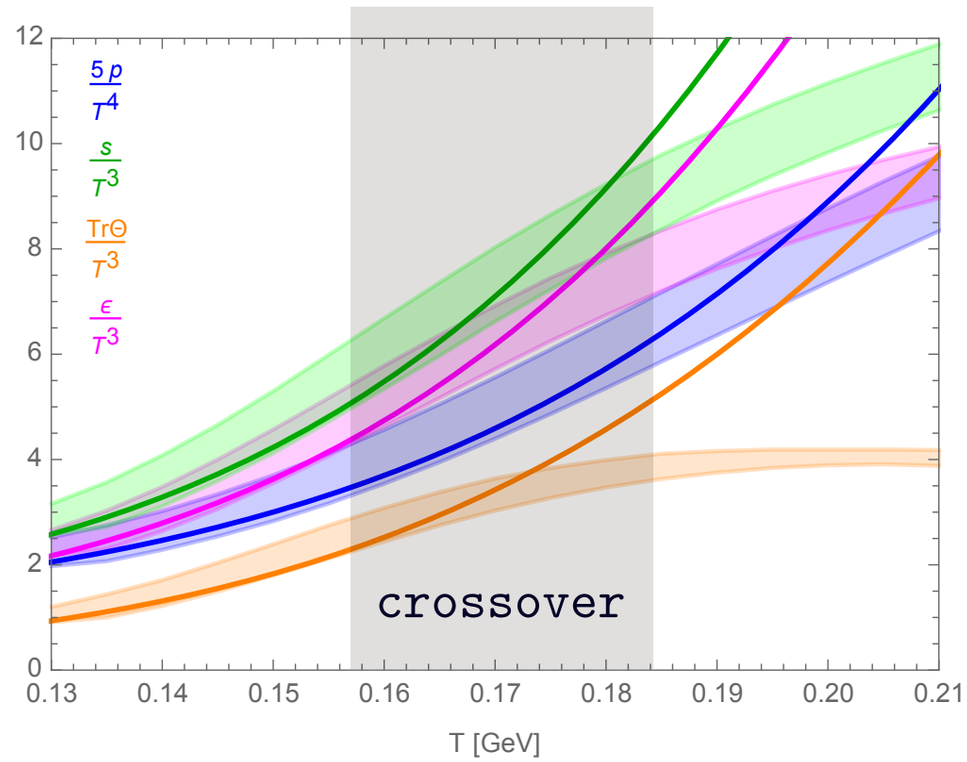
$$\Lambda^1_{70} = m_0 - \frac{1}{2}c_{HF} + c_{\mathcal{S}}$$

... or use QM

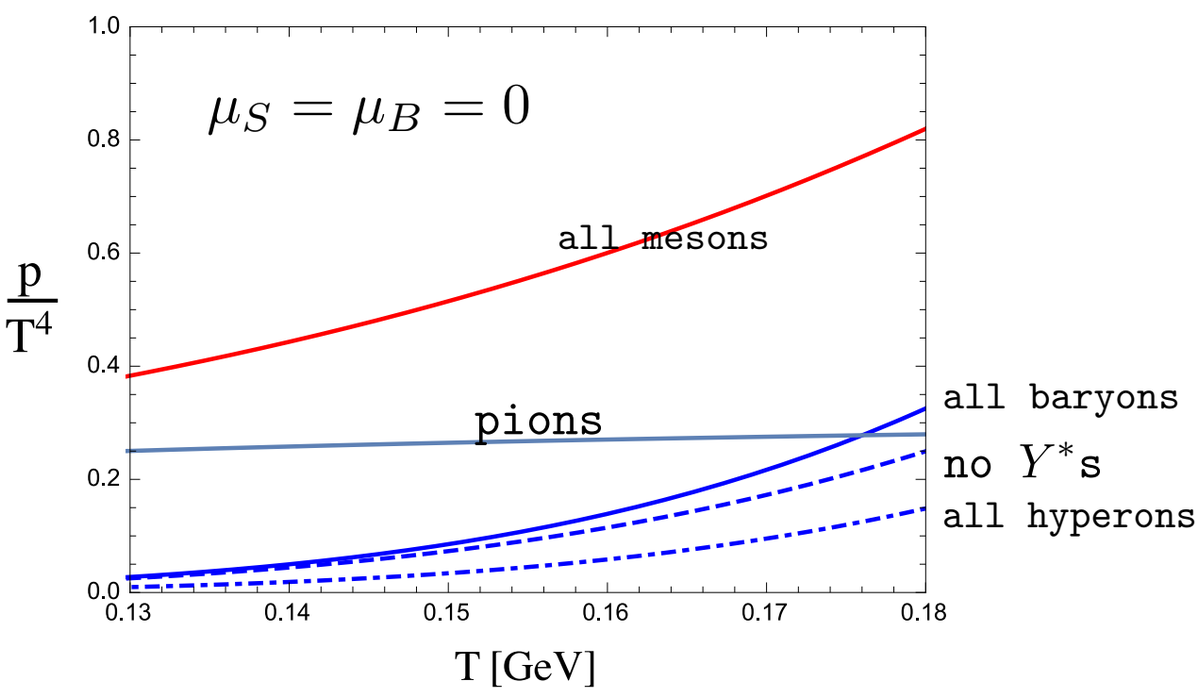




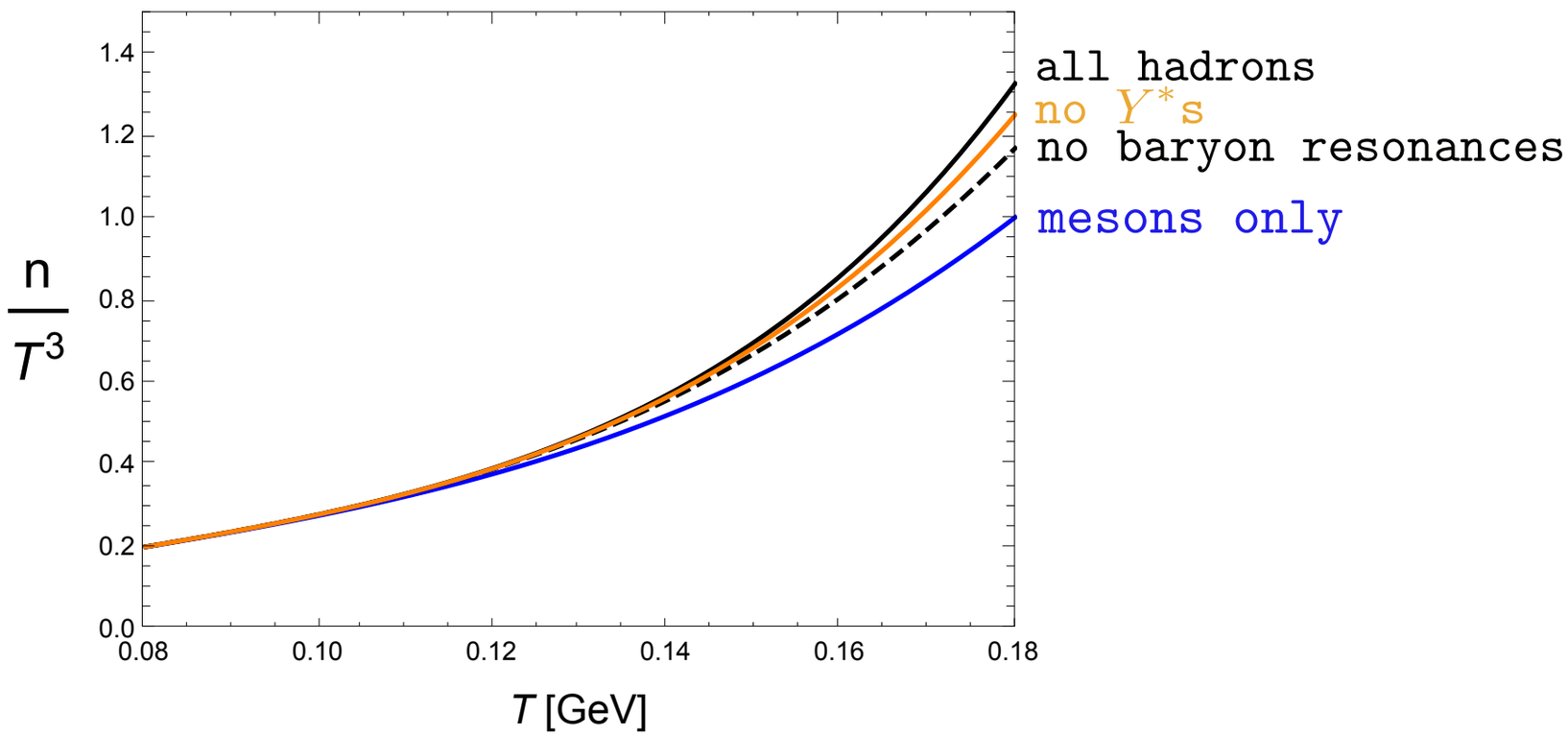
HRG and LQCD



A. Bazavov et al



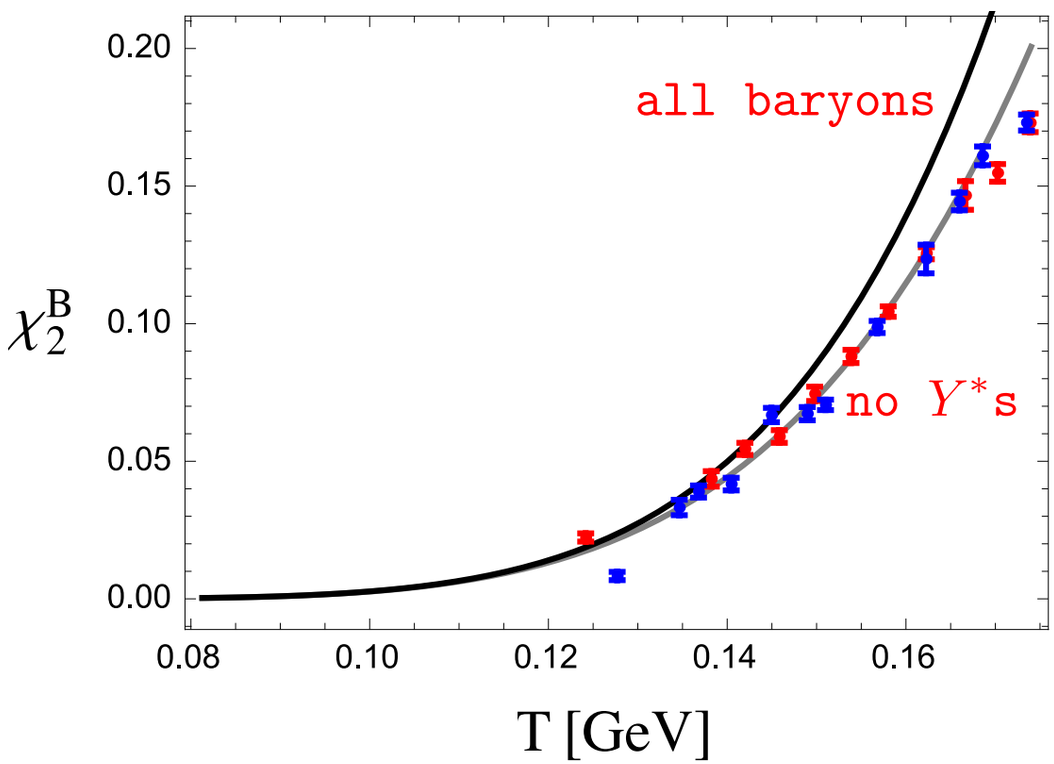
early universe at $T < T_c$:
chemically equilibrated
meson dominated HRG

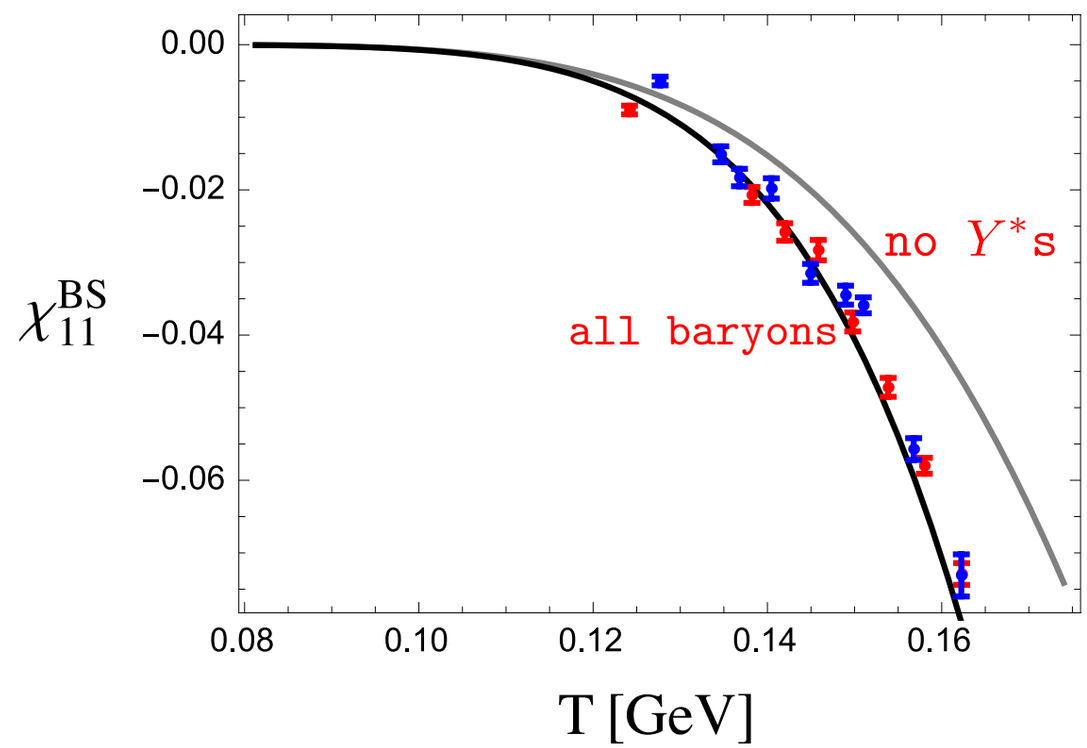


at the crossover there are about 0.5 hadrons/fm^3

More sensitive probes: correlations

$$\chi_2^{ij} = \frac{1}{T^2}\frac{\partial^2 p}{\partial\mu_i \partial\mu_j} \qquad i,j: \quad Q,\ S,\ B$$

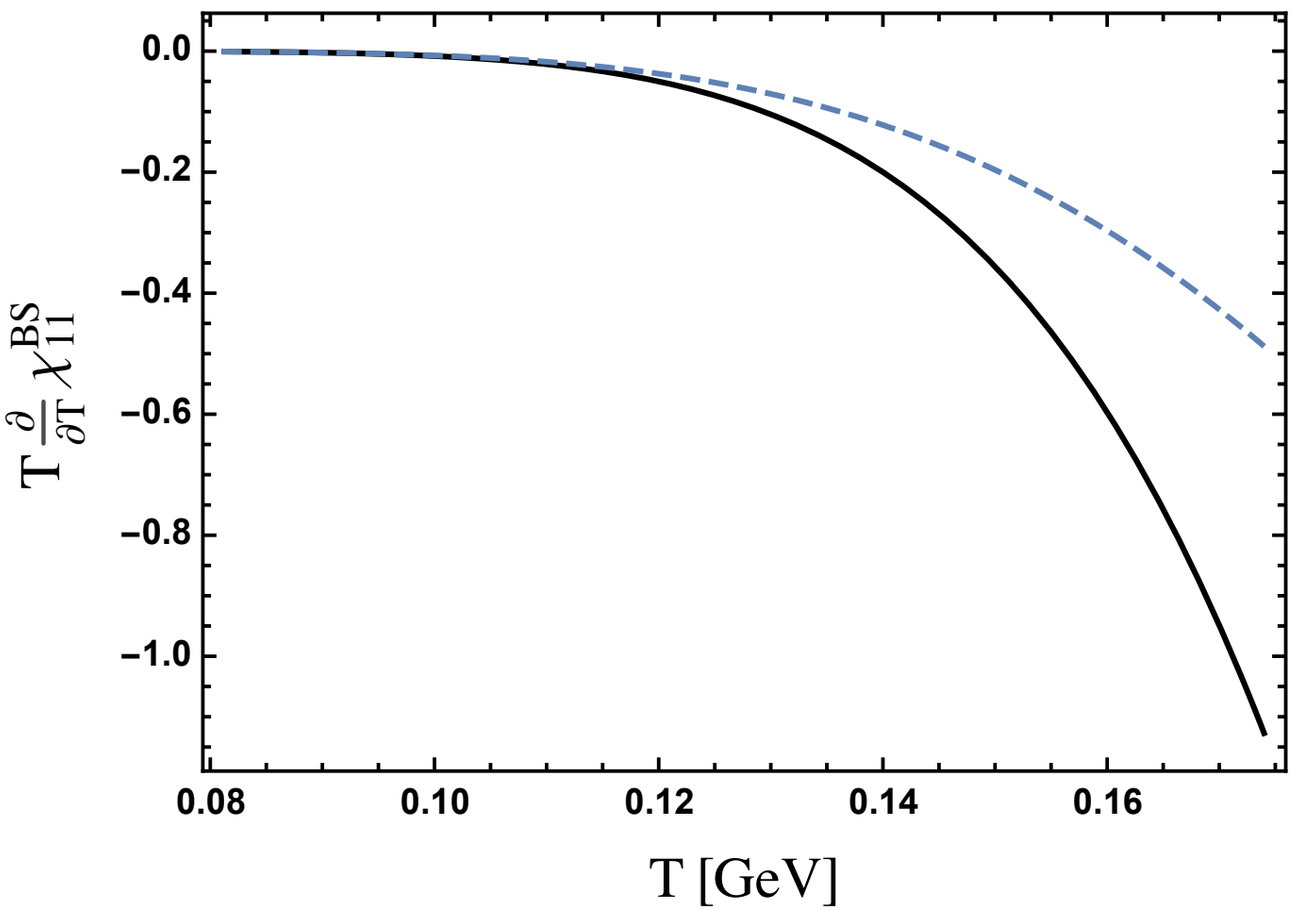




LQCD results: Bazavov et al.

Correlations in the Entropy

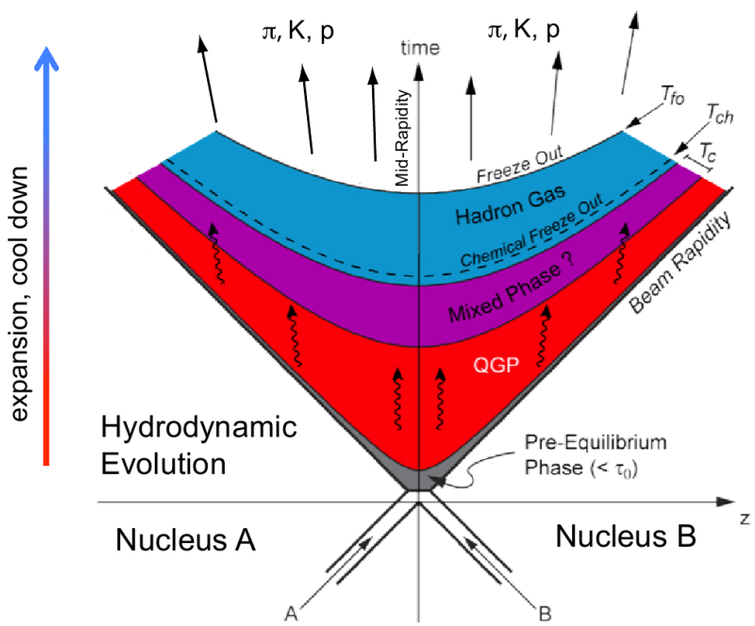
Entropy weighs heavier states more than pressure does.

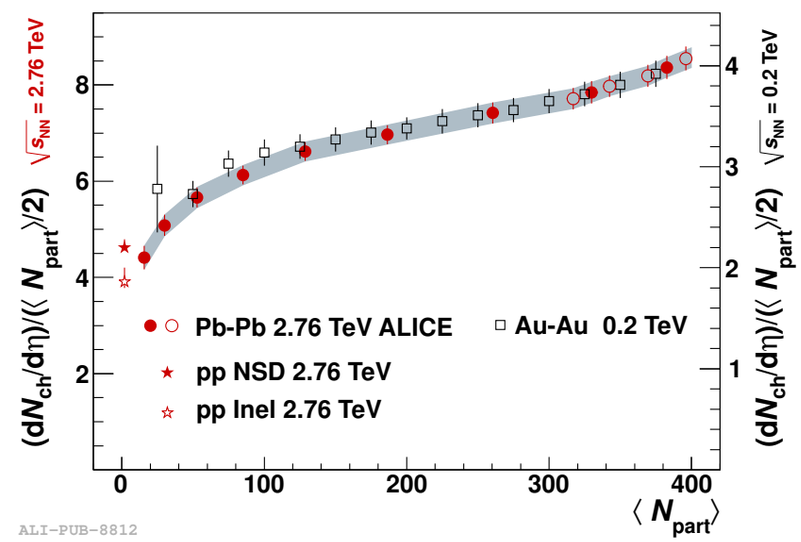


In principle accessible in LQCD, but calculations need results at more temperatures: very crude results with available data, or study correlations involving trace anomaly

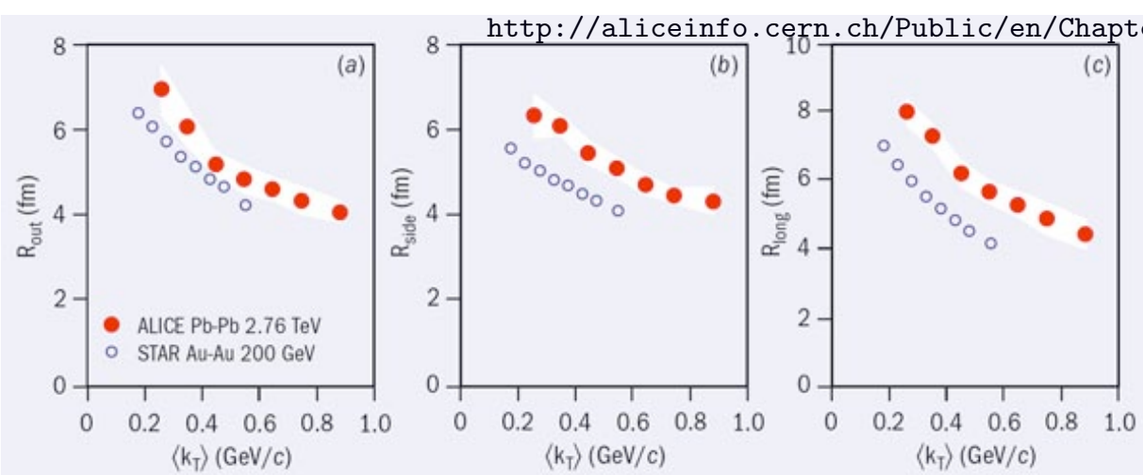
Hot hadronic matter in heavy ion collisions

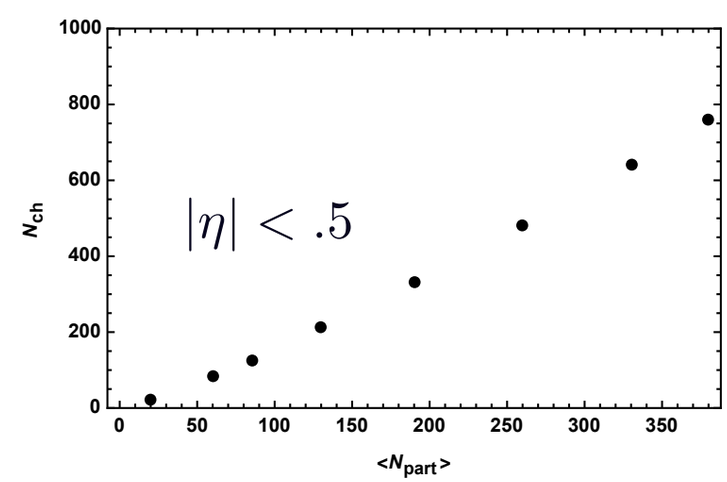
RHICs produce around central rapidity a fireball that starts as a ~thermalized QGP which expands crossing over to a hadronic fireball





http://aliceinfo.cern.ch/Public/en/Chapter1/results.html





size of pion source meassured via HBT interferometry

central Au-Au @ 2.76 TeV:
total charged particle multiplicity

key characteristic of fireball: it is off chemical equilibrium

$$\tau_{\rm ch} \sim \frac{1}{\sigma_{\rm ann}\,\rho\,v_{\rm th}}$$

Inelastic collision rates are low and
hadron gas is off chemical equilibrium

$\tau_{\rm ch}$ can be very large $> 10's$ fm

Bebie et al; Shuryak; JLG; Koch et al;...

$N\bar{N} \to n\pi$ is not that slow and should be
taken into account at early stages of hadronization

Rapp & Shuryak

Chemical potentials

for HRG off chemical equilibrium one assigns chemical potentials to all hadrons

detailed balance

$$A + B \leftrightarrow C + D \Longrightarrow \mu_C + \mu_D = \mu_A + \mu_B$$

stable hadrons develop effective chemical potentials

$$\mu_\pi,\ \mu_K,\ \mu_N,\ \mu_\Sigma,\ \mu_\Xi,\ \mu_\Omega$$

baryon annihilation

$$B\bar{B} \leftrightarrow nM \qquad\qquad \mu_B = \frac{\bar{n}}{2}\,\mu_M$$

assume dominance of 2-body

resonance decay as approximation

$$\mu_i^{M^*} = \sum_{j=\pi,K} \nu_{ij}^{M^*}\mu_j \ , \qquad \mu_i^{B^*} = \sum_{j=N,\Sigma,\Lambda,\Xi,\Omega} \nu_{ij}^{B^*}(\mu_j + \delta_{S_i\,S_j}\,\mu_\pi + \delta_{S_i\,(S_j\pm 1)}\,\mu_K)$$

$$\nu_{ij}^{M^*} = \delta_{S_i 0}\, \delta_{j\pi}\, \overline{\eta}_i + \delta_{S_i\, \pm 1}\, (\delta_{jK} + (\overline{\eta}_i - 1)\delta_{j\pi})$$

$$\nu_{ij}^{B^*} = \delta_{S_i 0}\, \delta_{S_j 0} + \delta_{|S_i| 3}\, \delta_{|S_j| 2} + \sum_{S=1,2} \delta_{S\, |S_i|} \left(r_i \delta_{S_i\, S_j} + \frac{1 - r_i}{2} \delta_{S_i\, (S_j \pm 1)} \right) \quad , \qquad \sum_j \nu_{ij}^{B^*} = 1$$

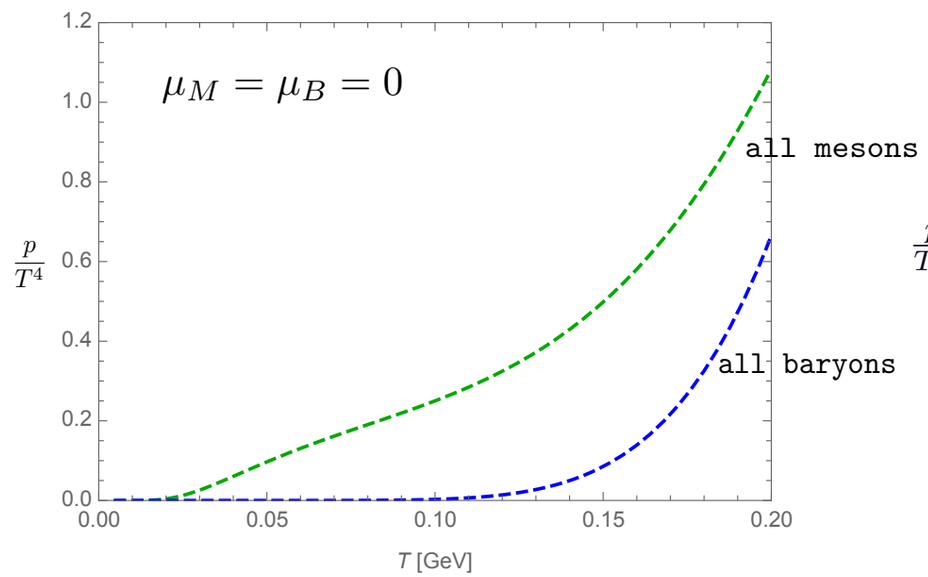
cases considered: $r_i = r, \quad r = 0.5,\ 1$

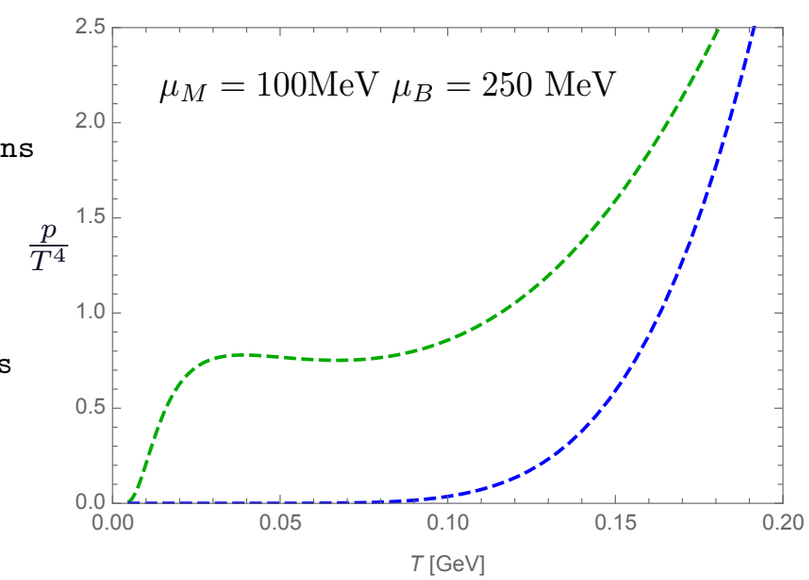
effective particle numbers: stable hadrons at kinetic freeze-out

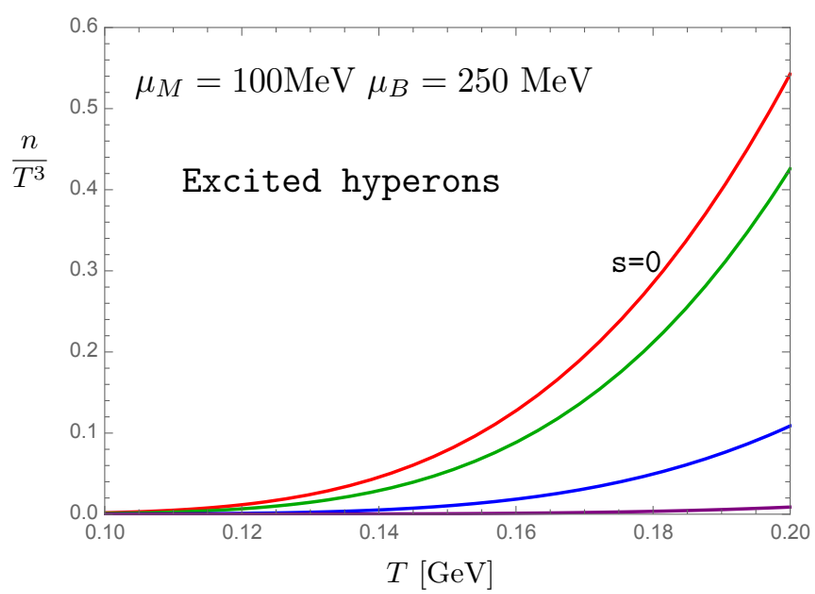
$$\overline{n}_i^M = n_i^M + \sum_j \nu_{ji}^{M^*} n_j^{M^*} \quad , \qquad \overline{n}_i^B = n_i^B + \sum_j \nu_{ji}^{B^*} n_j^{B^*}$$

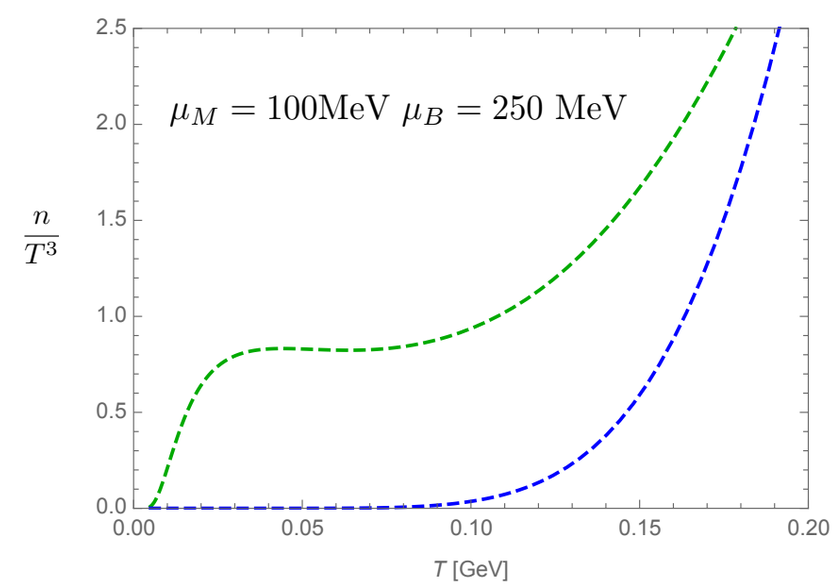
baryon resonance decays affect very little the meson abundance

Effects of chemical potentials









Simple model of hadron fireball expansion for assessing the possible role of baryon resonances

Bebie,Gerber,JLG & Leutwyler

- adiabatic expansion

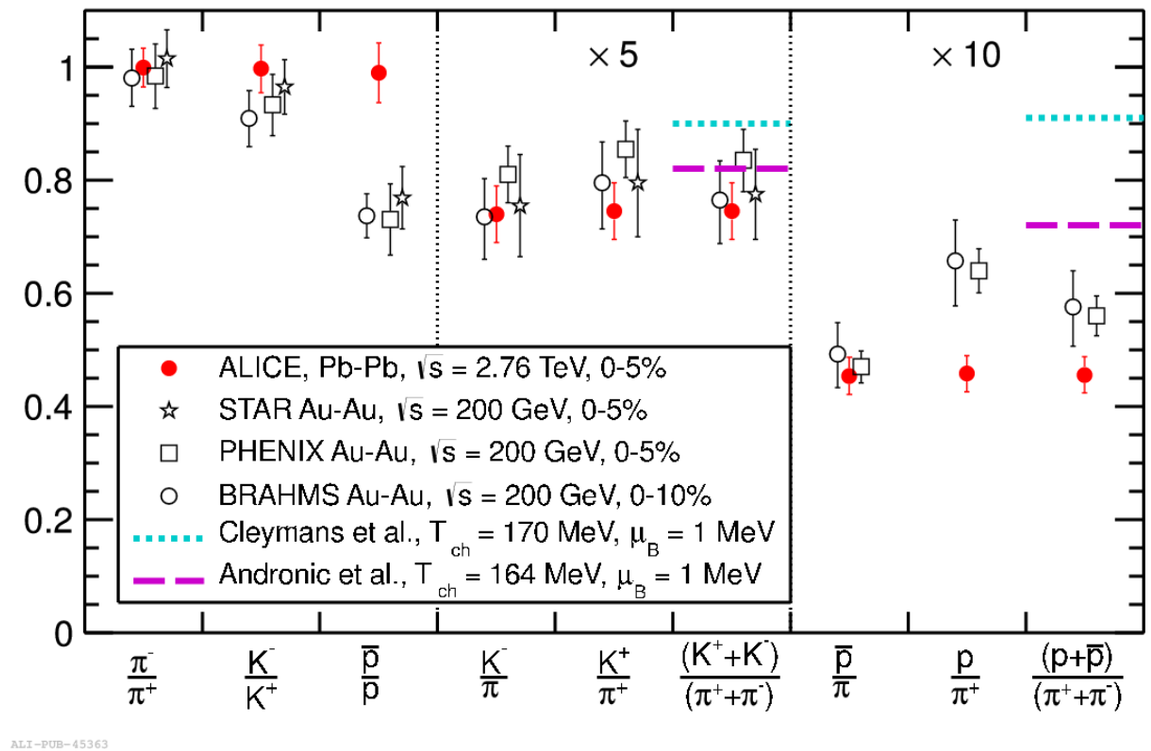
  conservation of $\frac{\bar{n}_i}{s}$ during expansion

- scenario considered: only resonances are kept in chemical equilibrium; two body inelastic reactions of stable hadrons are frozen.

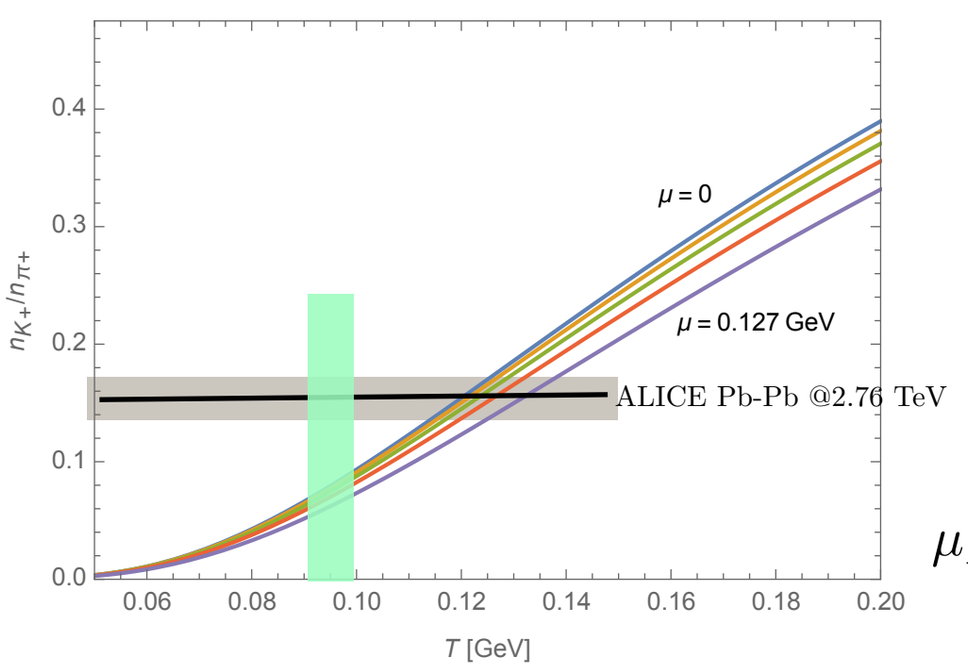
conserved ratios: $\frac{\bar{n}_\pi}{s}, \frac{\bar{n}_K}{s}, \frac{\bar{n}_N}{s}, \frac{\bar{n}_\Sigma}{s}, \frac{\bar{n}_\Xi}{s}, \frac{\bar{n}_\Omega}{s}$

use measured particle yield ratios to set initial conditions of the expansion: one unknown is left, e.g. μ_π

particle yield ratios



[ALICE, PRL 109, 252301 (2012)]



$\mu_K = \mu_\pi$

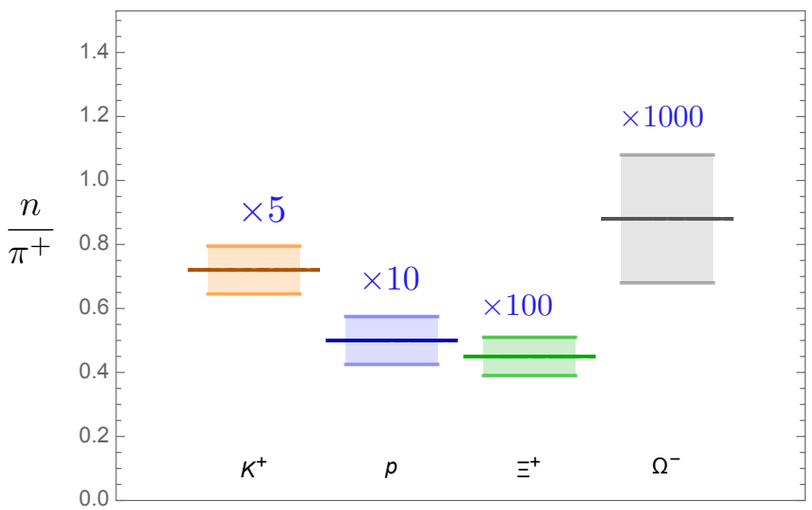
strangeness freeze out

$\frac{n_K}{n_\pi}$ as thermometer to determine freeze-out of $\pi\pi \leftrightarrow K\bar{K}$

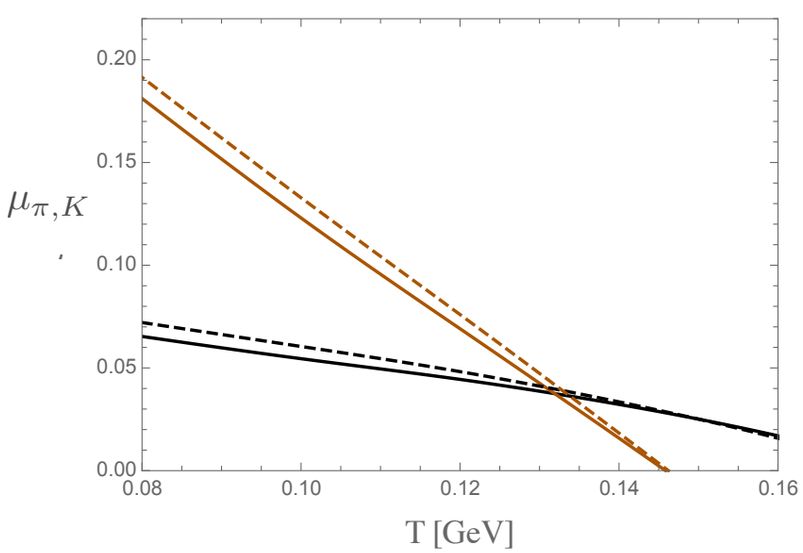
$$\overline{n}_i^M = n_i^M + \sum_j \nu_{ji}^{M^*} n_j^{M^*} \quad , \qquad \overline{n}_i^B = n_i^B + \sum_j \nu_{ji}^{B^*} n_j^{B^*}$$

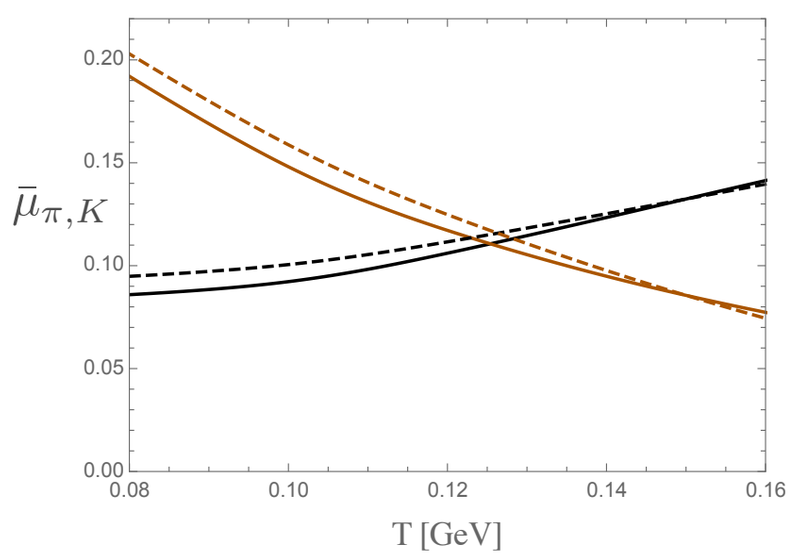
initial conditions @ 0.150 GeV

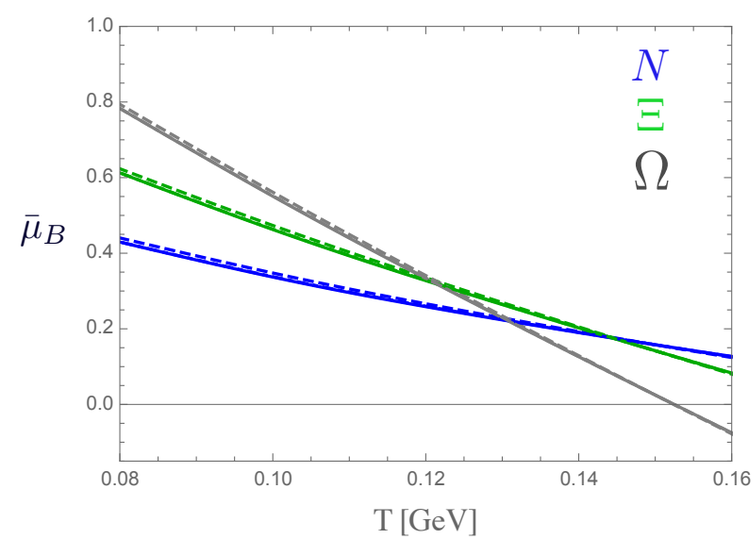
$$\mu_\pi = 0.025 \text{ GeV}$$



fit to freeze-out particle ratios







no clear indication of resonance effects in bulk thermodynamic observables

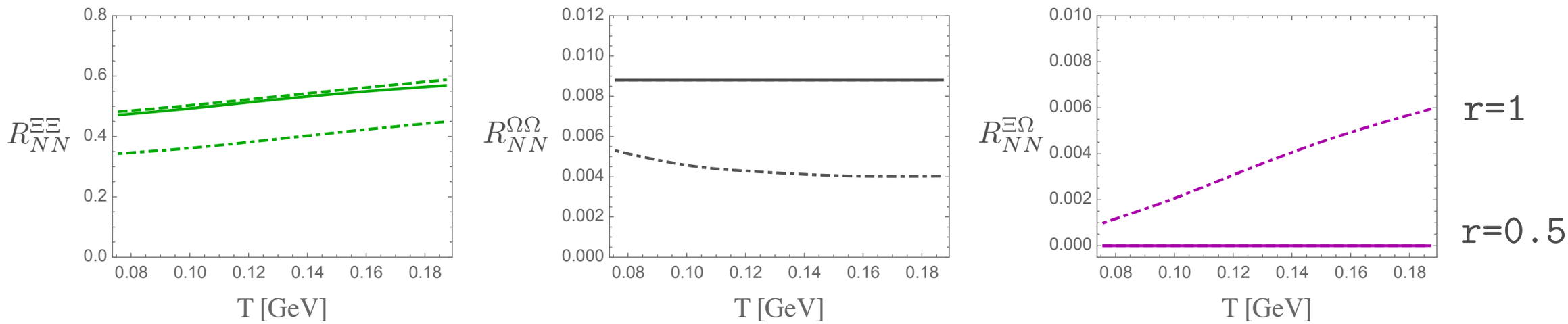
More sensitive probe: correlations in RHICs

define off chemical equilibrium correlations

$$\chi_2^{ij} = \frac{1}{T^2}\frac{\partial^2 p}{\partial\mu_i\partial\mu_j}$$

measurable ratios

$$R_{kl}^{ij} = \frac{\chi_2^{ij}}{\chi_2^{kl}}.$$



sensitive to hyperon resonances when r<1: here r=0.5

what is needed: event by event measurement of N and hyperon yields close to central rapidity

measurements of charge multiplicity moments have been done: STAR @ RHIC

Remarks

- Effects of excited baryons, in particular Y*s, are not easy to pin down in hot QCD: best thermodynamic observables are correlations, which can select conserved or approximately conserved particle numbers.

- LQCD: study of correlations (susceptibilities) is most sensitive tool. HRG model, modulo possible corrections, shows effects of Y*s.

- RHICs: global thermo does not show sensitivity: main reason is lack of chemical equilibrium, which brings in uncertainties. Some details of resonance decay BRs is also needed. Correlations defined off chemical equilibrium are sensitive in principle to baryon resonances.