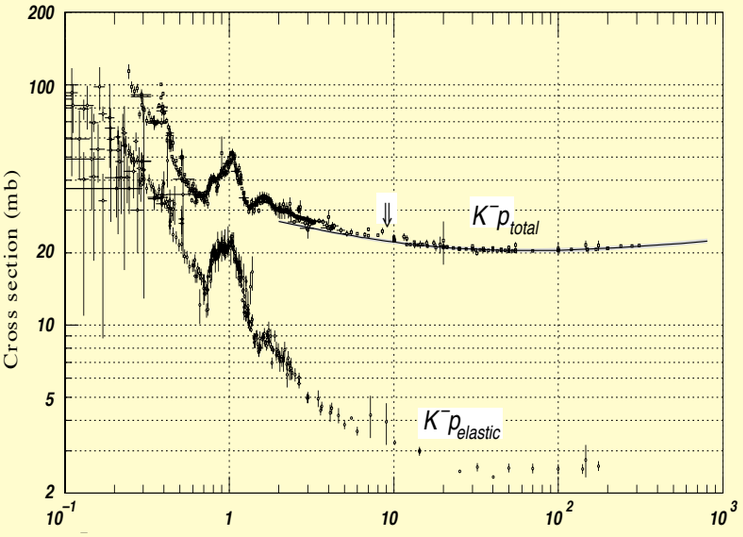
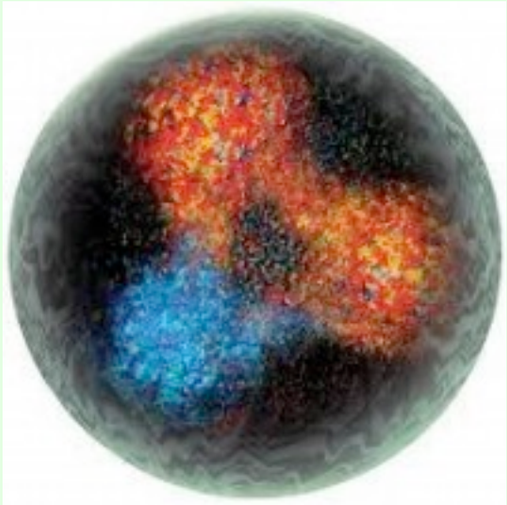
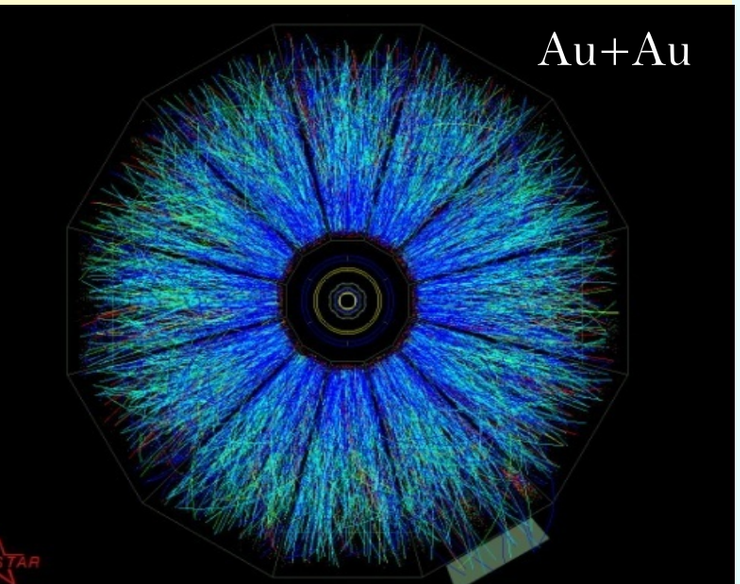




THE ROLE OF BARYON RESONANCES IN HOT HADRONIC MATTER

Jose L. Goity

Hampton University and Jefferson Lab



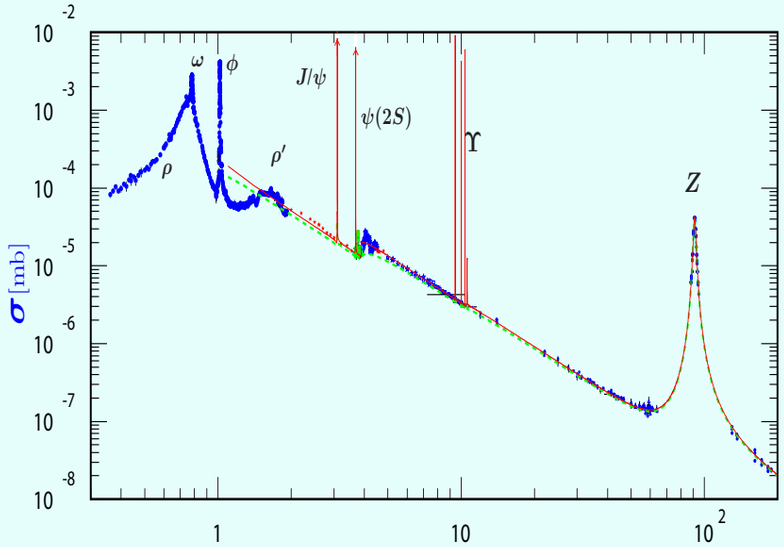
YSTAR 2016

Excited Hyperons in QCD Thermodynamics at Freeze-Out

NOVEMBER 16 - 17, 2016

Jefferson Lab

Newport News, Virginia



Outline

- Missing hyperons
- The hot Hadron Resonance Gas
- HRG and LQCD
- HRG and heavy ion collisions
- Hyperon effects in the HRG
- Remarks and conclusions

Talks related to this one

hot matter:

Rene Bellwied
Benjamin Doenigus
Claudia Ratti
Pasi Huovinen
Jacquelyn Noronha
Enrique Ruiz Arriola
Paolo Alba

resonances:

Fred Myhrer
Simon Capstick

LQCD:

Robert Edwards

Missing states 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

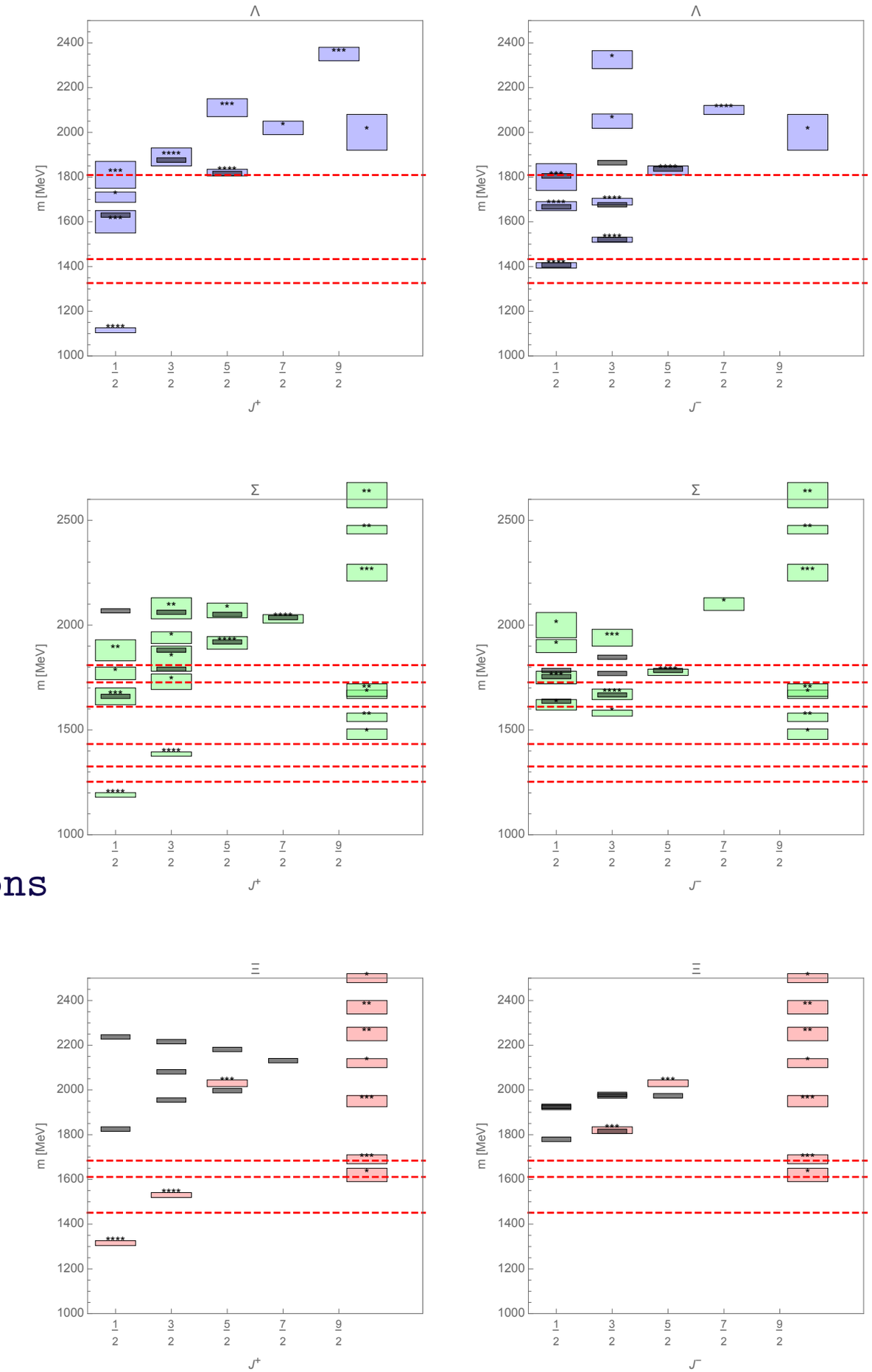
- Test the existence of complete SU(3) multiplets
- Study SU(3) breaking effects in excited baryons
- Test the indications that excited baryons form SU(6)xO(3) multiplets
- Important source of information to test the 1/Nc expansion of QCD in baryons
- Possible role of hyperons in high energy heavy ion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



Hot hadronic matter:
Ideal Hadron Resonance Gas -- IHRG

dof: meson-, baryon- and antibaryon- stable states and resonances
only light quarks here

EoS

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

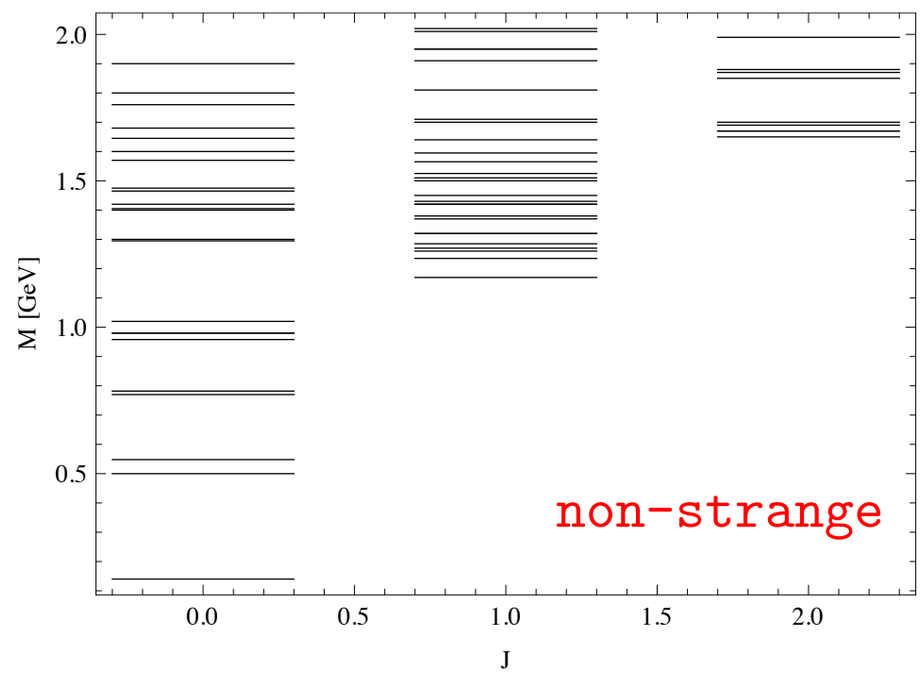
$$B(n) = \texttt{Baryon number}, \quad d(n) = (2J_n+1)(2I_n+1)$$

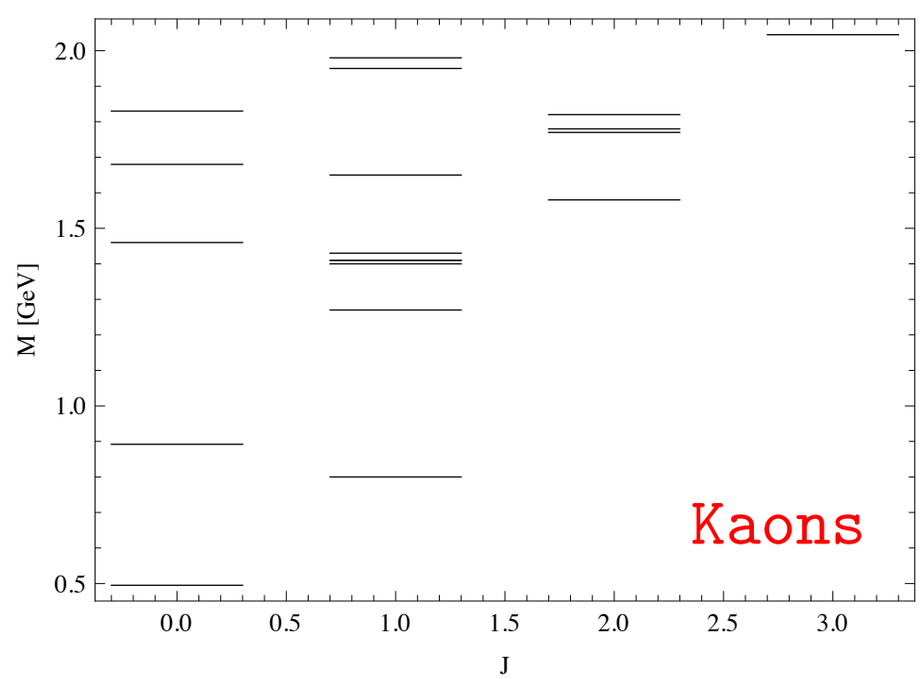
In chemical equilibrium: μ_s, μ_B

for all hadrons use the relativistic EoS

Mesons

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





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 dof: 469

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

mass formulas: neglect spin-orbit splittings

JLG & N.Matagne

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

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

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

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

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

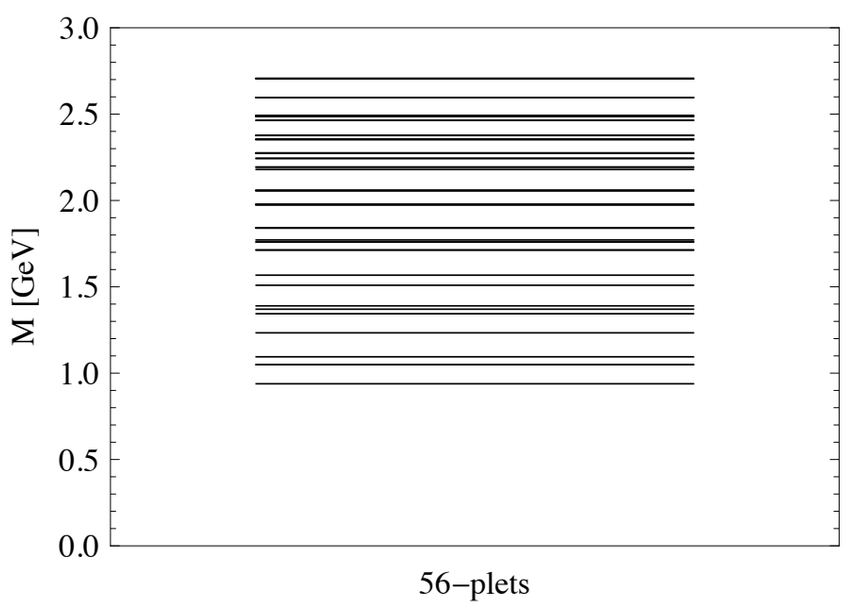
$$M_{70}(S=I-1,\mathcal{S}) = m_0 + \frac{1}{3}c_{HF}\left(S(S+2) - \frac{3}{4}\right) - c_{\mathcal{S}}\mathcal{S}$$

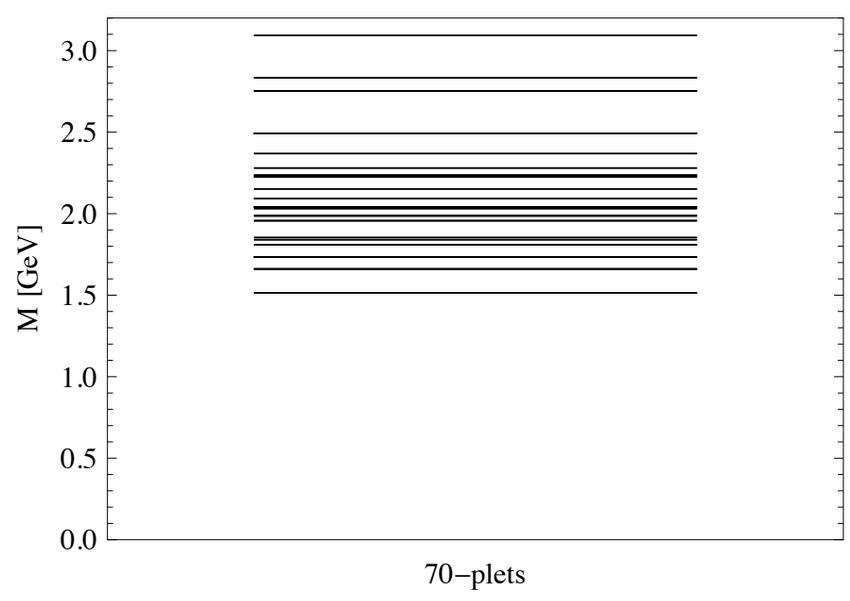
$$M_{70}(S=I+1,\mathcal{S}) = m_0 + \frac{1}{3}c_{HF}\left(S^2 - \frac{7}{4}\right) - c_{\mathcal{S}}\mathcal{S}$$

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

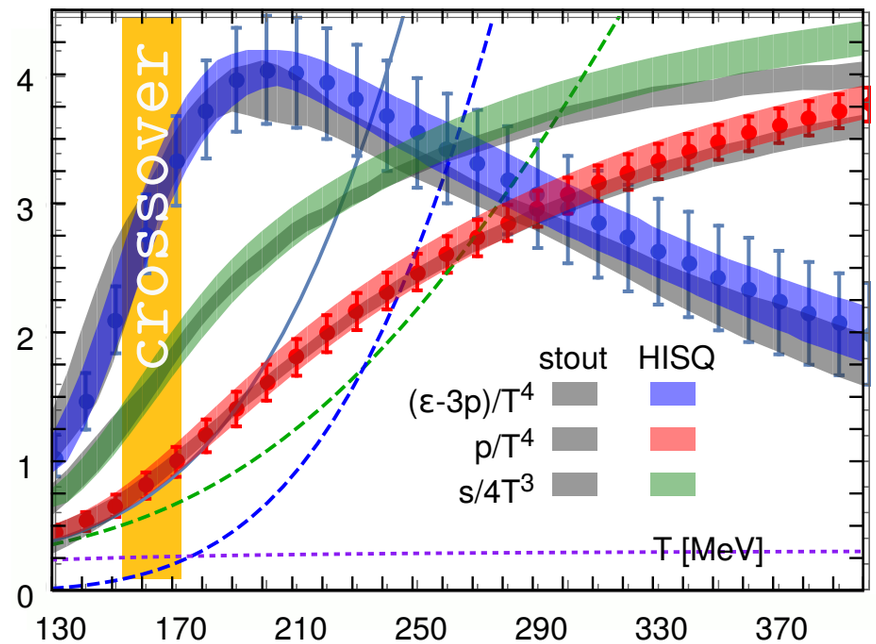
... or use QM

talks by Manley, Myhrer, Capstick





IHRG and LQCD

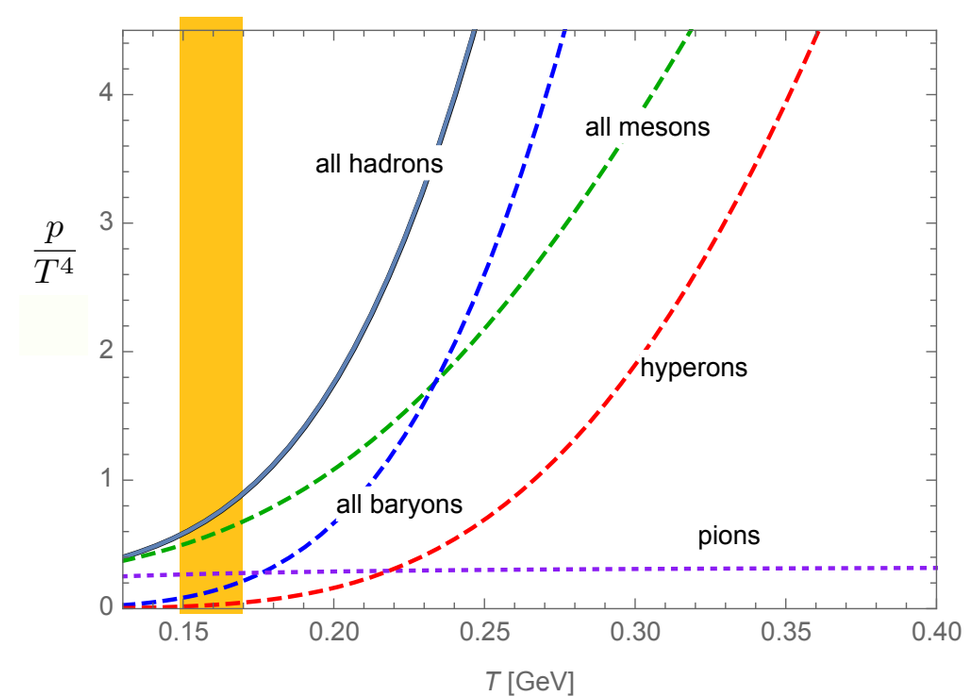


A. Bazavov et al

R.A. Soltz et al.

$\mu_S = \mu_B = 0$

different contributions to pressure



Early Universe at $T < T_c$

chemically equilibrated HRG

meson dominated HRG

talks by Ratti, Ruiz Arriola

Hot hadronic matter in heavy ion collisions

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

Rapp & Shuryak

stable hadrons develop effective chemical potentials

resonances have chemical potentials given by:

$$\mu_{R^*} = \sum_h d^h_{R^*}\,\mu_h$$

Chemical potentials

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

detailed balance

$$\left.\begin{array}{l} \pi\pi \leftrightarrow \pi\pi \\ \pi K \leftrightarrow \pi K \\ \pi\pi \leftrightarrow K\bar{K} \\ \pi\pi \leftrightarrow \rho \\ \text{etc} \end{array}\right\} \qquad \mu_\pi = \mu_K = \mu_\eta = \frac{\mu_\rho}{2} = \frac{\mu_\omega}{3} = \cdots = \mu_M$$

approximation of SU(3) symmetry

$$MB \leftrightarrow M'B' \qquad \mu_N = \mu_\Sigma = \mu_\Xi = \cdots = \mu_B$$

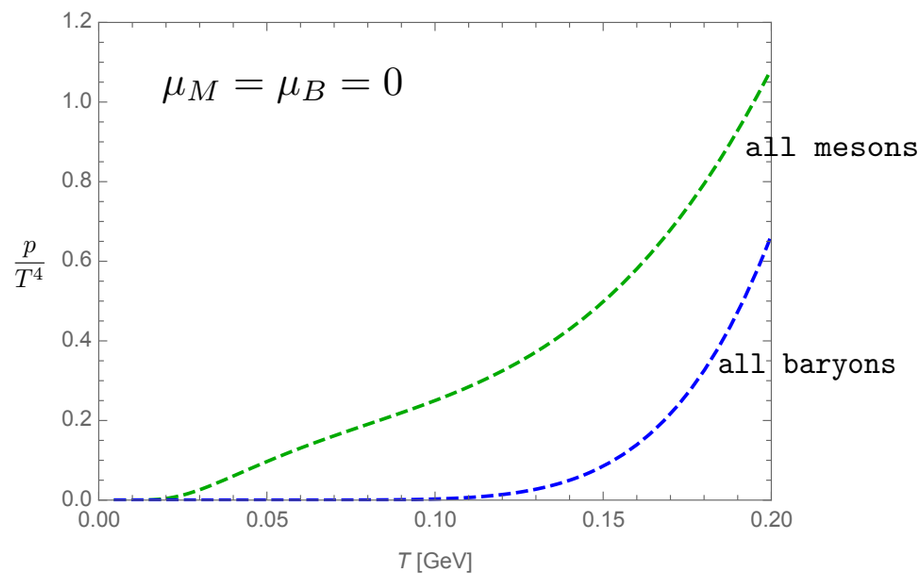
$$MB \leftrightarrow B^* \qquad \mu_{B^*} = \mu_B + \mu_M$$

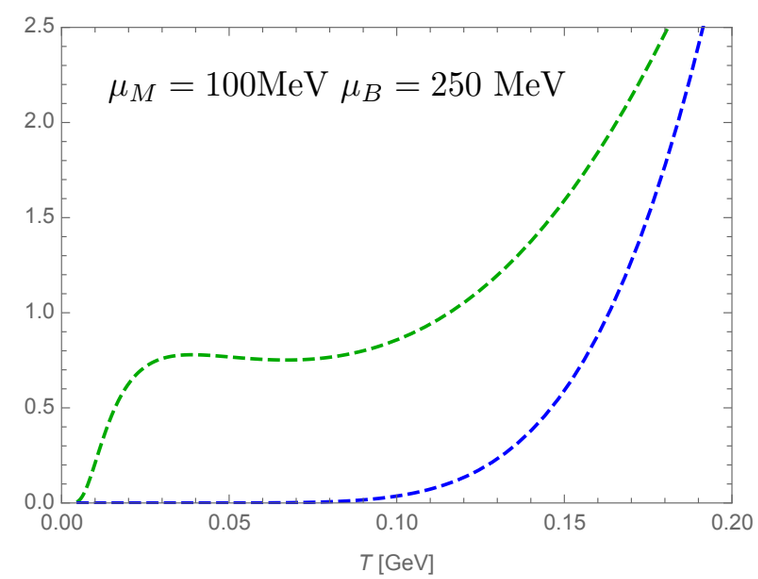
assume dominance of 2-body resonance decay as approximation

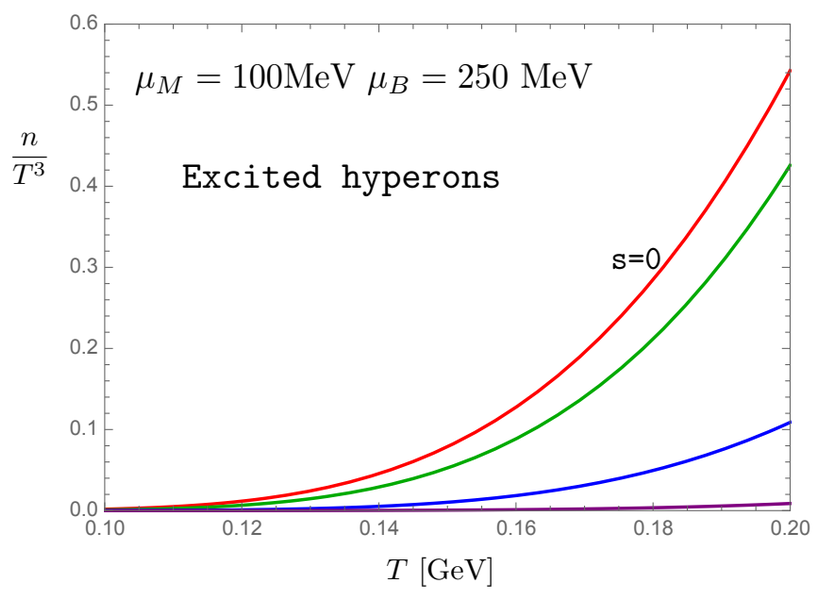
baryon annihilation

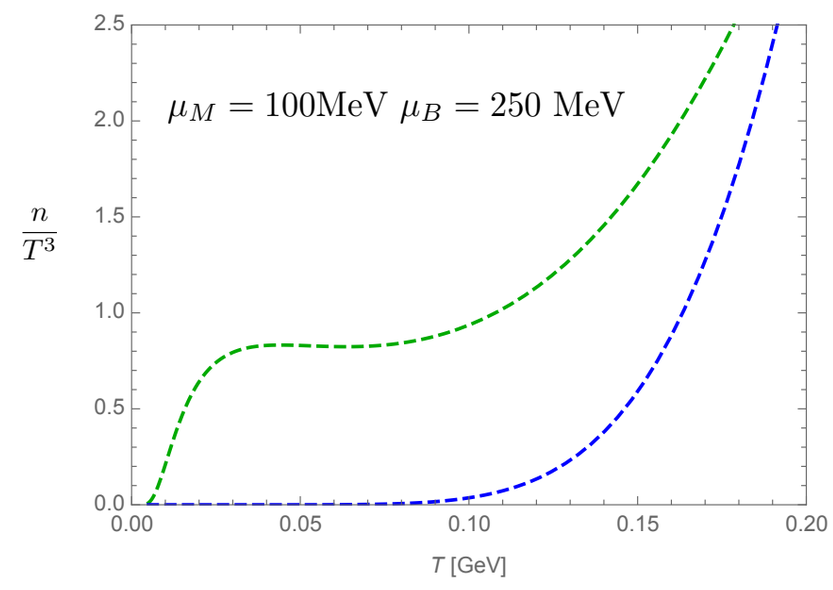
$$B\bar{B} \leftrightarrow nM \qquad \mu_B = \frac{\bar{n}}{2}\,\mu_M$$

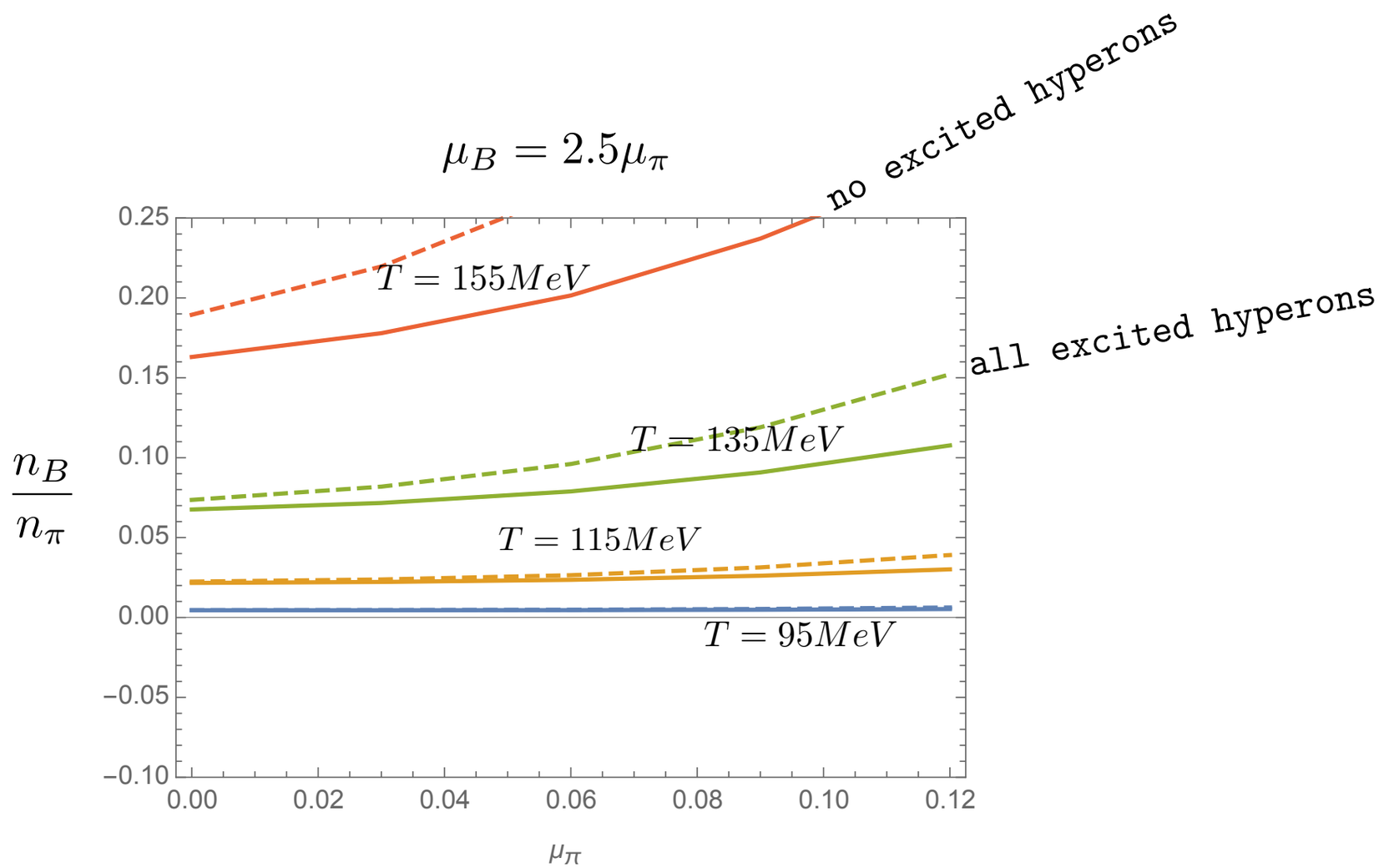
Effects of chemical potentials











decreasing number density of Y^* wrt non-strange baryons as T drops

Simple model of fireball expansion for assessing the possible role of hyperon resonances

- adiabatic expansion Bebie,Gerber,JLG & Leutwyler
- several scenarios:

1) $B\bar{B} \leftrightarrow nM$ in equilibrium

$$\frac{\bar{n}\, n_B + n_M}{s} = \text{const}$$

2) $B\bar{B} \leftrightarrow nM$ off equilibrium

$$\frac{n_B}{s} = \text{const}, \quad \text{and} \quad \frac{n_M}{s} = \text{const}$$

3) $2) +$ $K\bar{K} \leftrightarrow \pi\pi$ off equilibrium

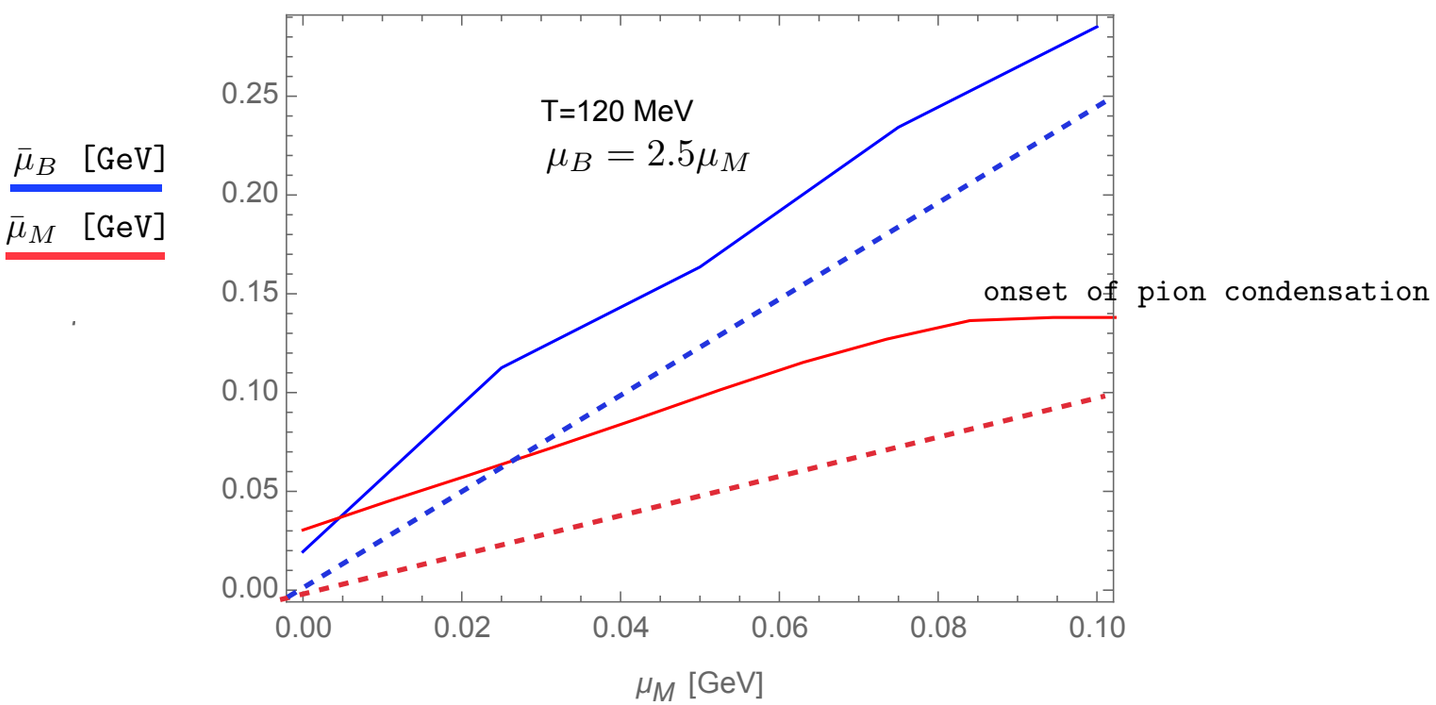
$$\frac{n_K}{s} = \text{const}, \quad \frac{n_\pi}{s} = \text{const}, \quad \text{etc}$$

I discuss simplest case 1) (real life is more like 3))

Freeze out

at freeze out all resonances decay and change the chemical potentials of the stable hadrons

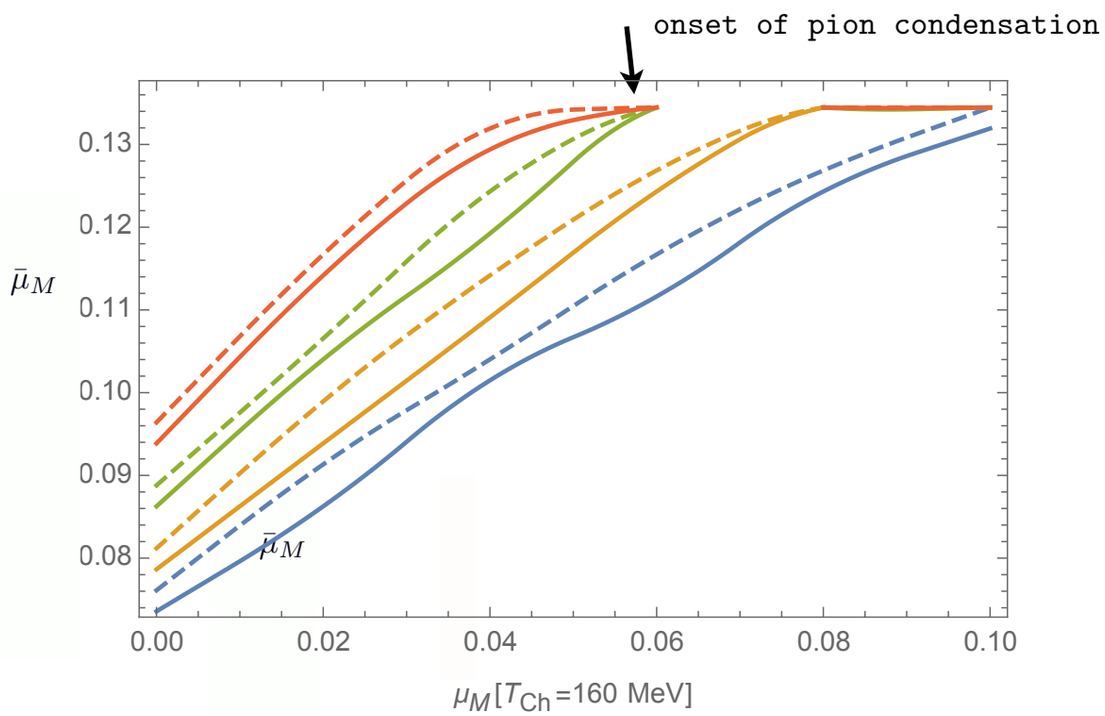
effective chemical potentials at freeze out

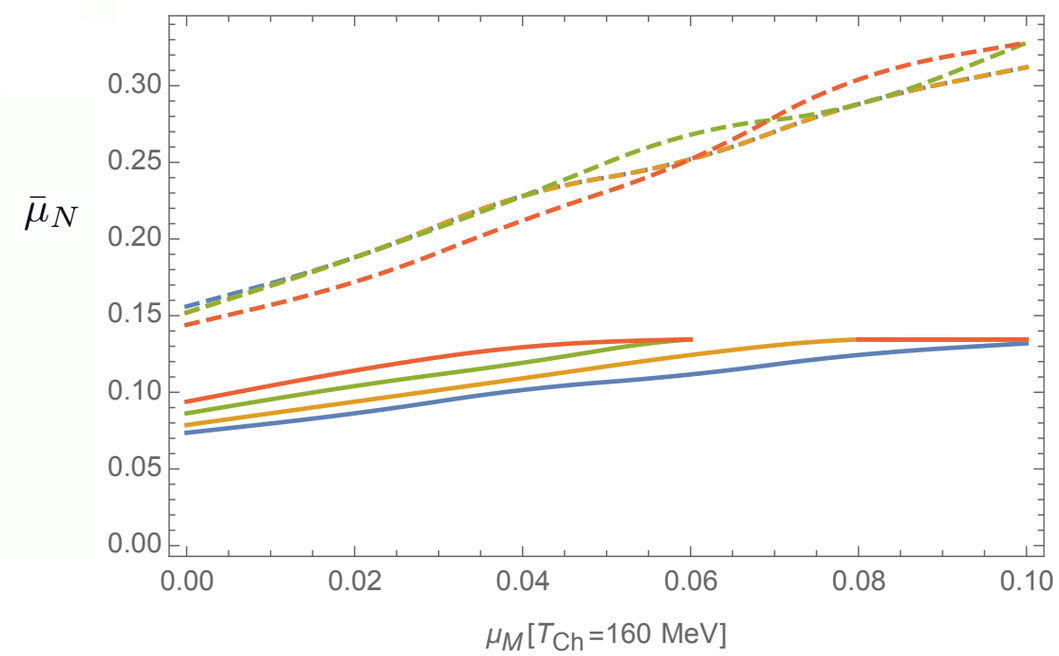


pion and nucleon effective chemical potential at freeze out

$\mu_B = 2.5\ \mu_M$

$T_{\rm FO} = \{90, 100, 110, 120\}$ MeV

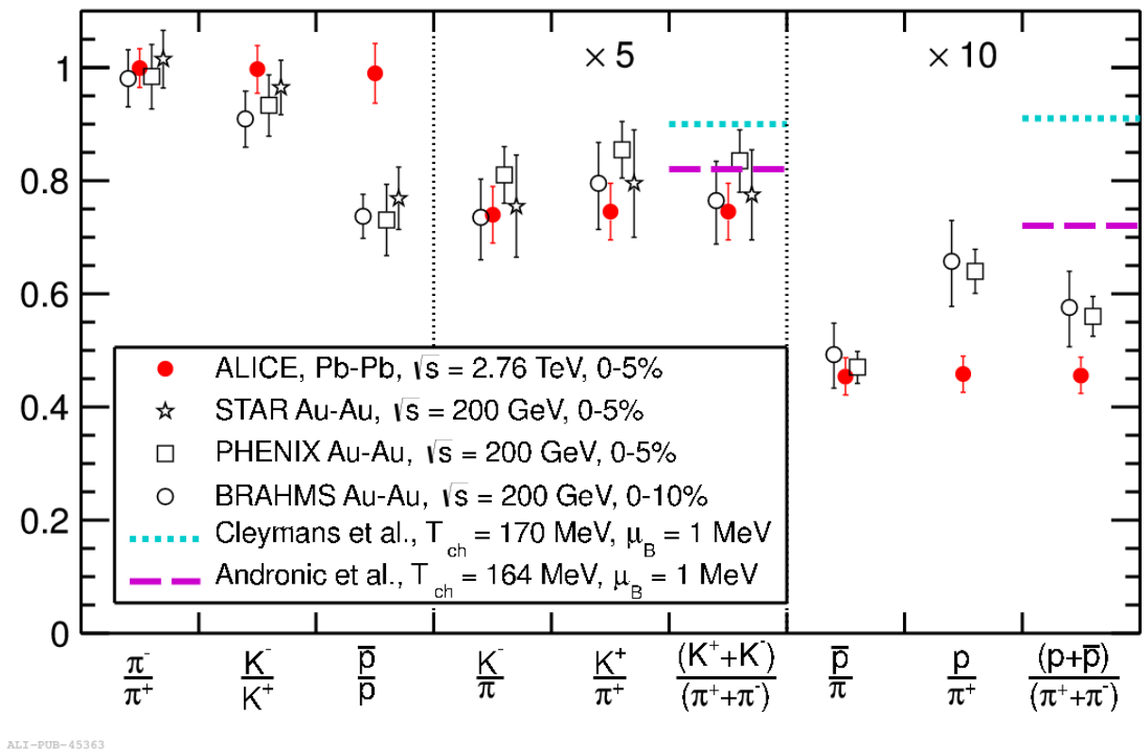




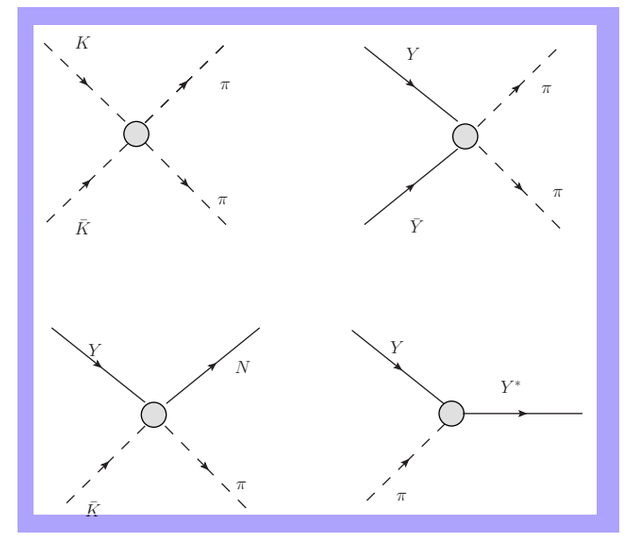
$Y^{*\prime}s$ included no $Y^{*\prime}s$

presence of Y^*'s tend to reduce the effective FO chemical potentials

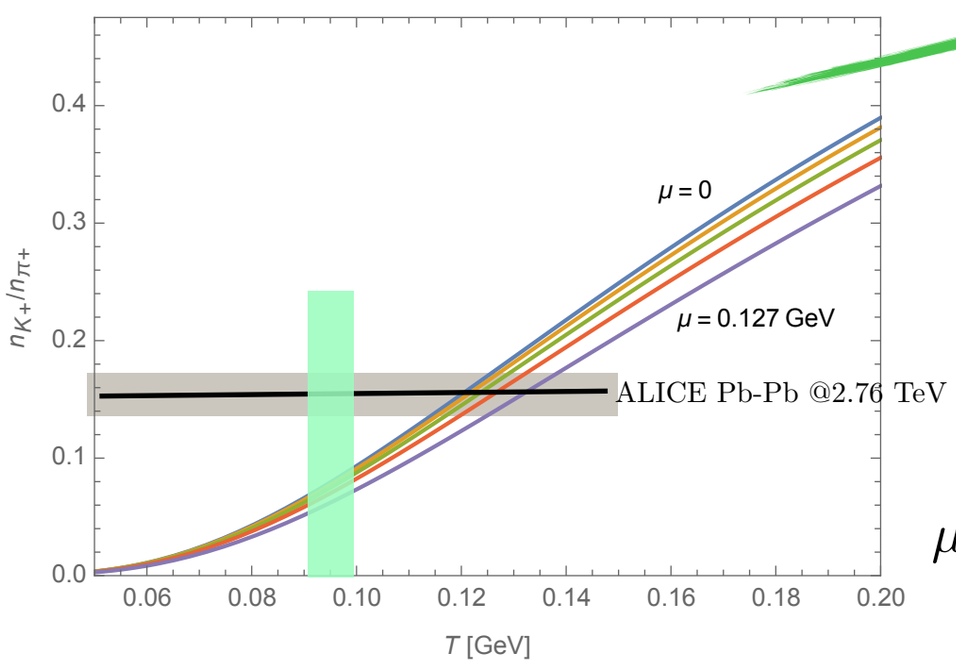
particle yield ratios



[ALICE, PRL 109, 252301 (2012)]



strangeness freeze out

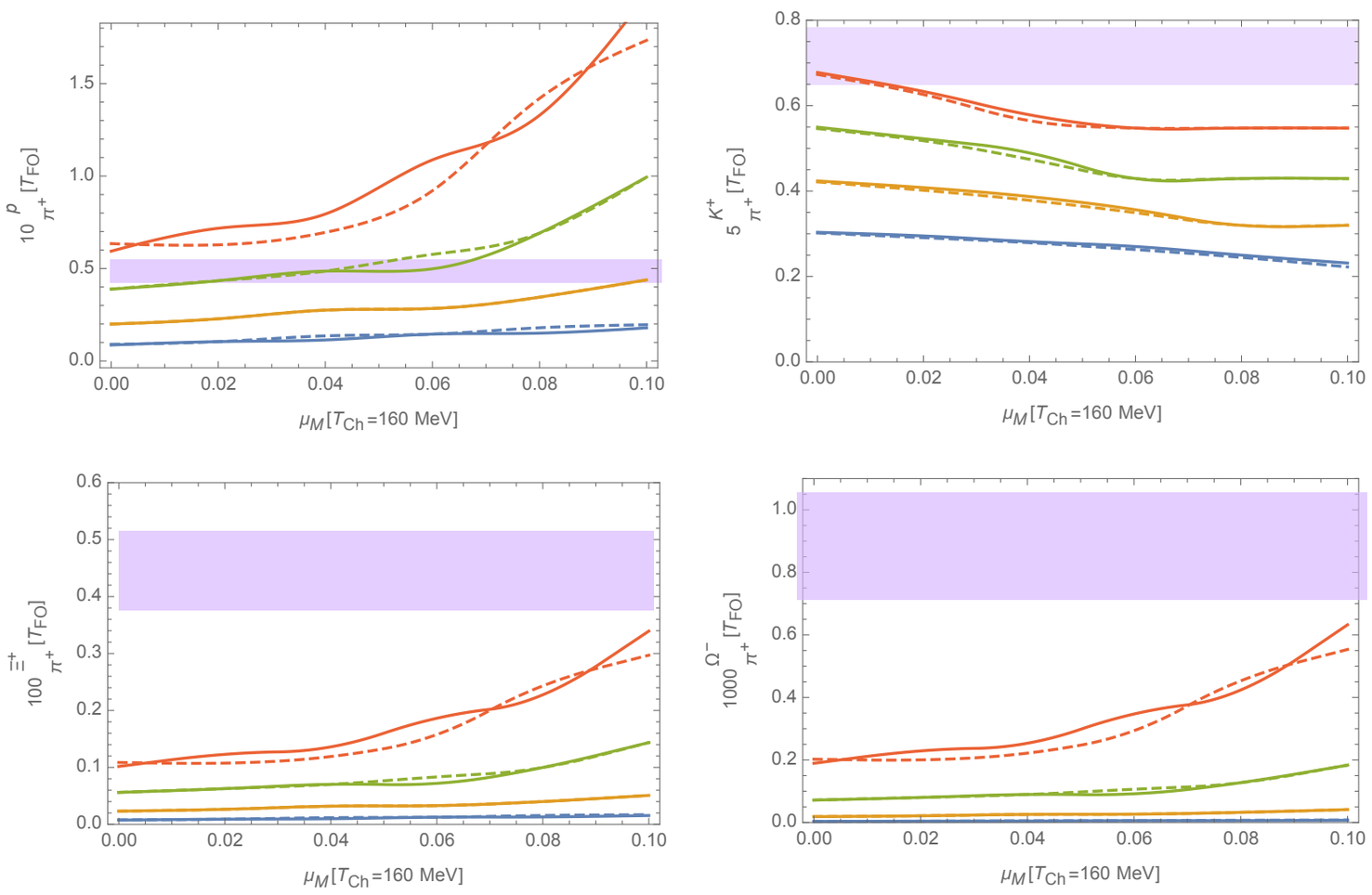


$$\mu_K = \mu_\pi$$

comparing with data

$T_{\rm FO} = \{90, 100, 110, 120\}$ MeV

ALICE Pb-Pb 2.76 TeV



- one more indication of early freeze out of strangeness
- important contribution from the Δ decays for the ratio $\dfrac{p}{\pi^+}$

Remarks

- Effects of excited Y*'s in HRG are not easy to pin down: they make small changes to thermodynamic ratios

- Small chance to determine the effects of Y*s from LQCD calculations of thermodynamic observables: effects are small in that case, although effects of all resonances together are very important.

- HRG off chemical equilibrium may be necessary, but effects of Y*s may be smaller than inherent theoretical uncertainties of the models used to describe the evolution and FO of the hadronic fireball. e.g.,: different scenarios of evolution to freeze out; Van der Waals volume corrections to IHRG, which are likely to be significant; hydrodynamics; etc.

- Early freeze out of strangeness, with expected depletion of Y*s in the HRG through their decay may affect strange particle yields at FO. Ratios of yields seem rather insensitive in the simple model presented.

- What is (are) the best observable(s) to search for effects due to Y*'s ?