Hadron resonance gas is a bad model

for hadronic matter in strong magnetic field

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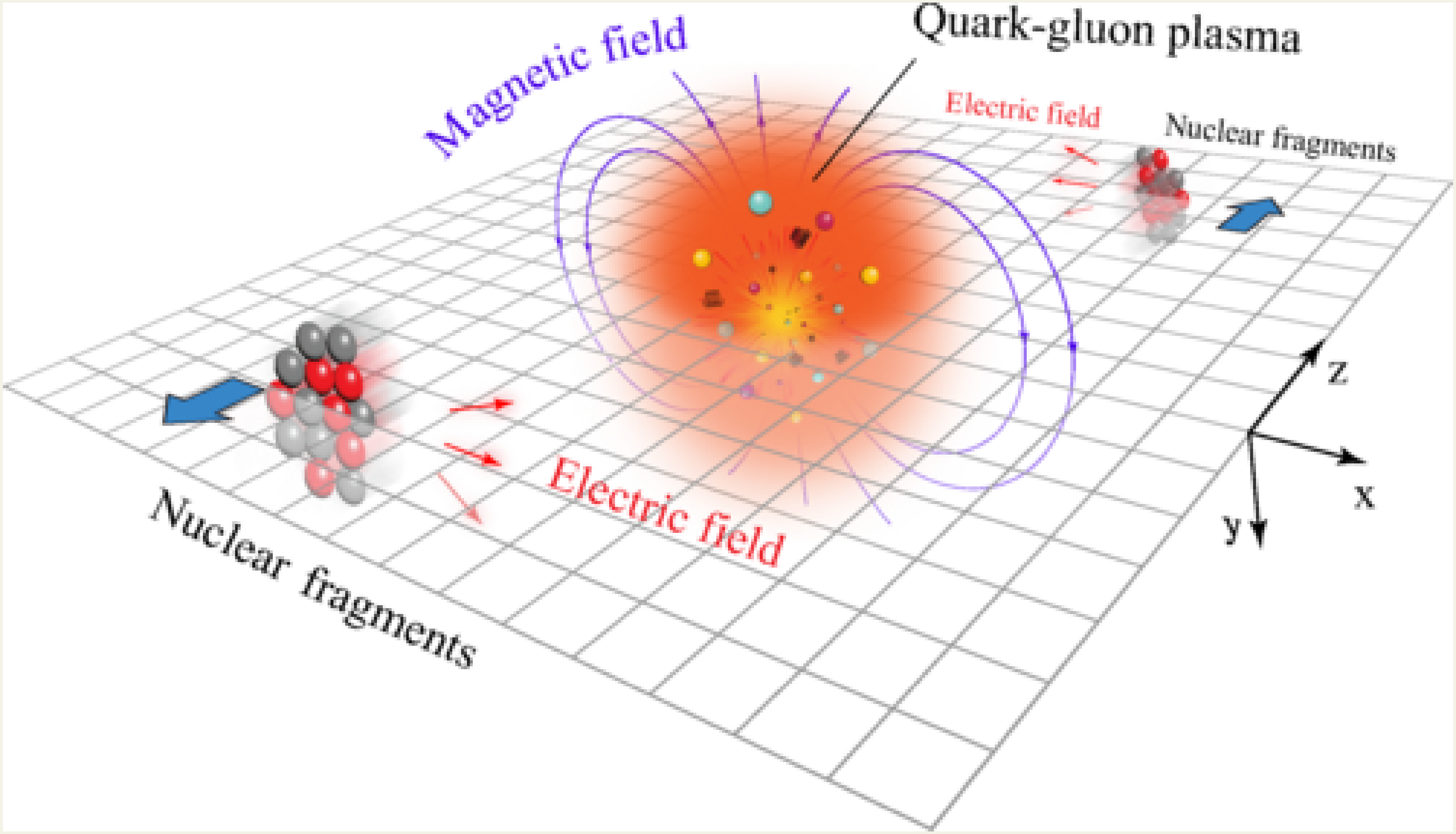
Strong magnetic field in HIC



Hadron Resonance Gas

- **EoS of interacting hadron gas approximated by non-interacting gas of hadrons and resonances**

$$P(T) = \sum_i P_i(T) = \sum_i \pm g_i T \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \ln(1 \pm f_i(E,T))$$

- **Dashen-Ma-Bernstein: exact when**

- interactions mediated by resonances
- resonances have zero width

Landau quantization

- **energy of charged structureless spin-0 or spin-1/2 particle**

$$E_c = \sqrt{p_z^2 + m^2 + 2|Q|B\left(l + \frac{1}{2} - s_z\right)}$$

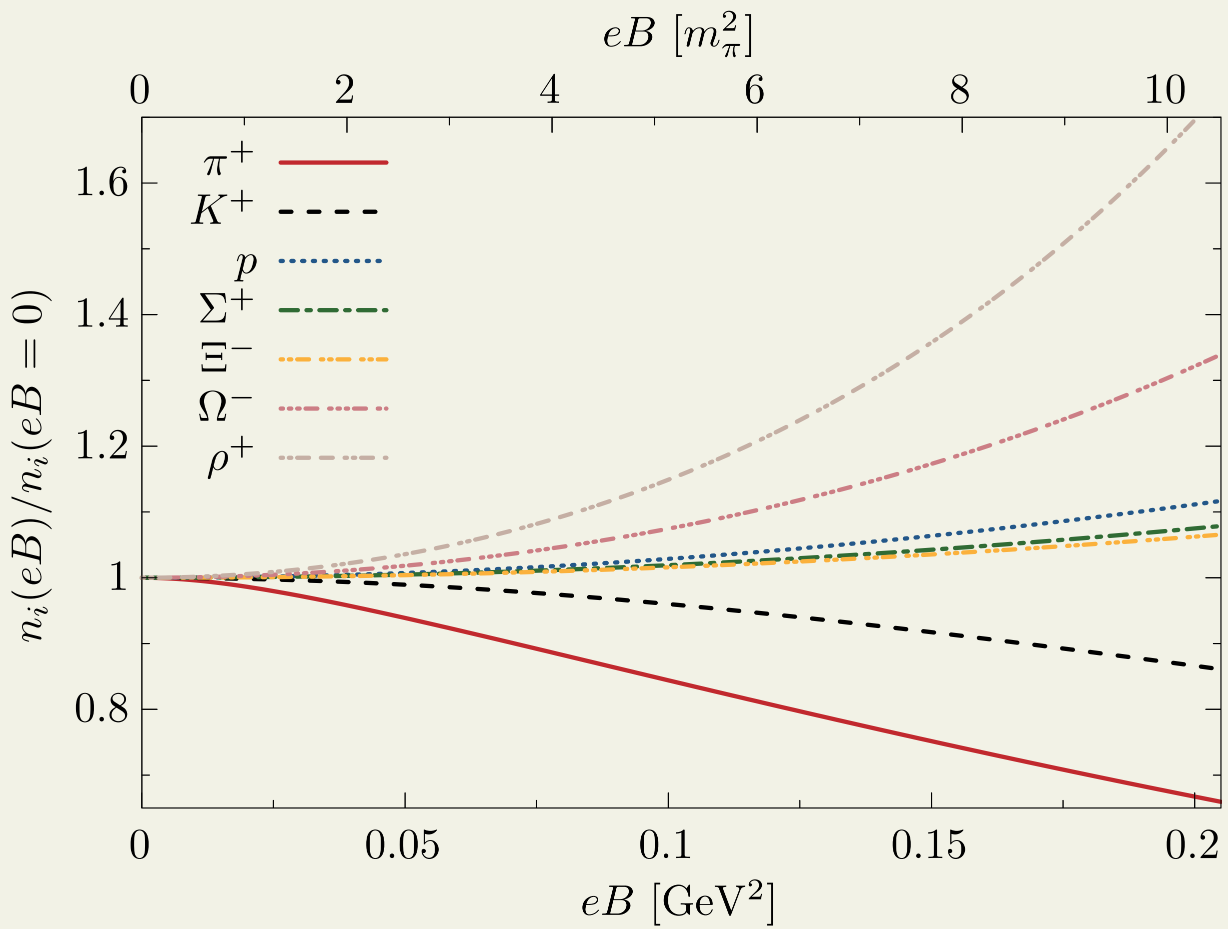
number density

$$n_i(T) = \frac{g_i}{(2\pi)^3}\int \mathrm{d}^3p\, f(E,T)$$

becomes

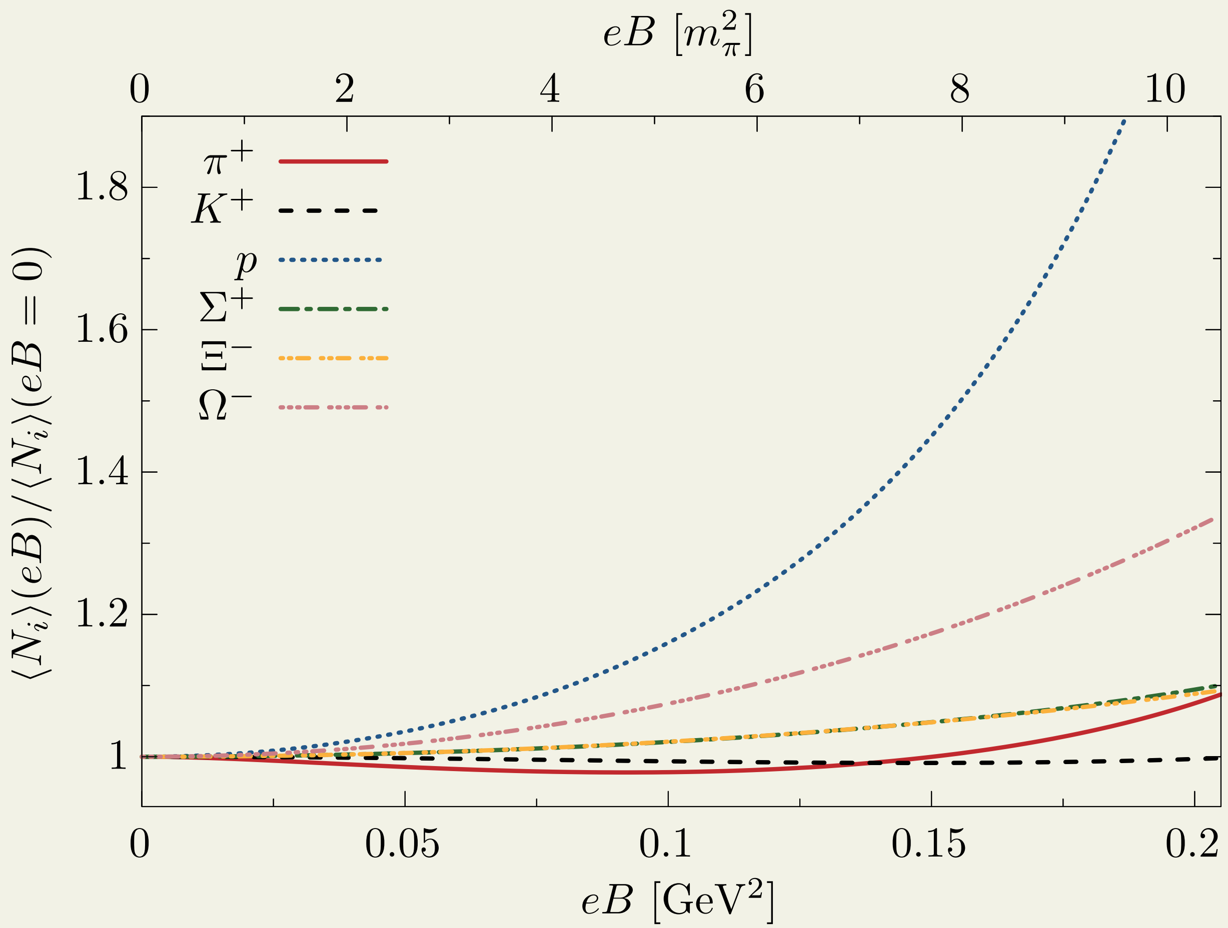
$$n_c(T) = \frac{|Q|B}{2\pi^2}\sum_{s_z}\sum_{l=0}^{\infty}\int \mathrm{d}p_z\, f(E(B),T)$$

Particle densities at $T = 155$ MeV



- **pion density drops**
- **proton density slightly increases**
- **large increase of high-spin particles**

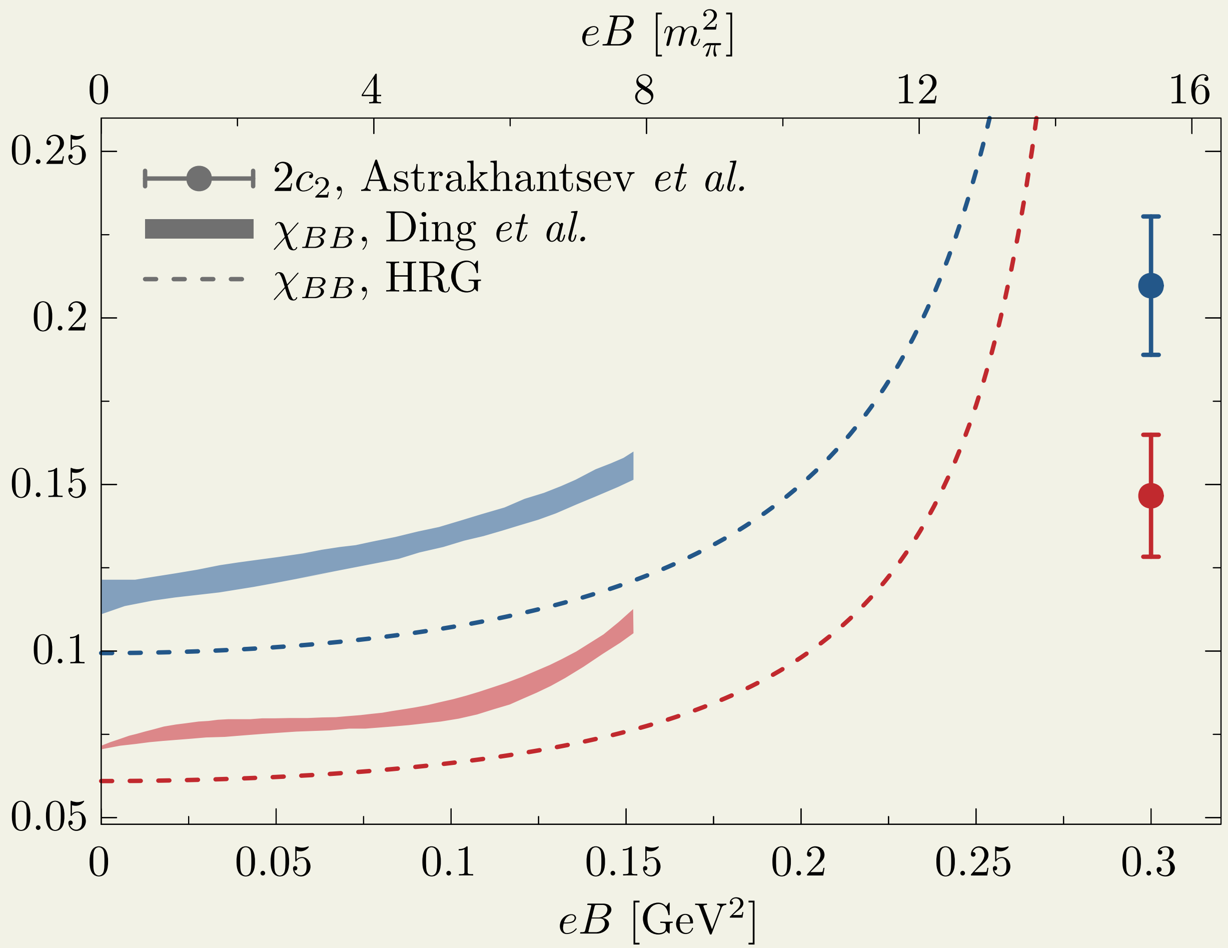
Yields after decays at $T = 155$ MeV



- **large increase in proton yield due to resonance decays**

Baryonic susceptibility

$$\chi_{BB} = \left.\frac{\partial^2 (P/T^4)}{\partial (P/T^4)^2}\right|_T \qquad T = 145\,\mathrm{GeV} \qquad T = 155\,\mathrm{GeV}$$



- **below lattice at weak field, overshoots at strong field**

Decays?

$$\Delta^{++} \Longrightarrow p + \pi^{+}$$

requires

$$E_\Delta \leq E_p + E_\pi$$

but

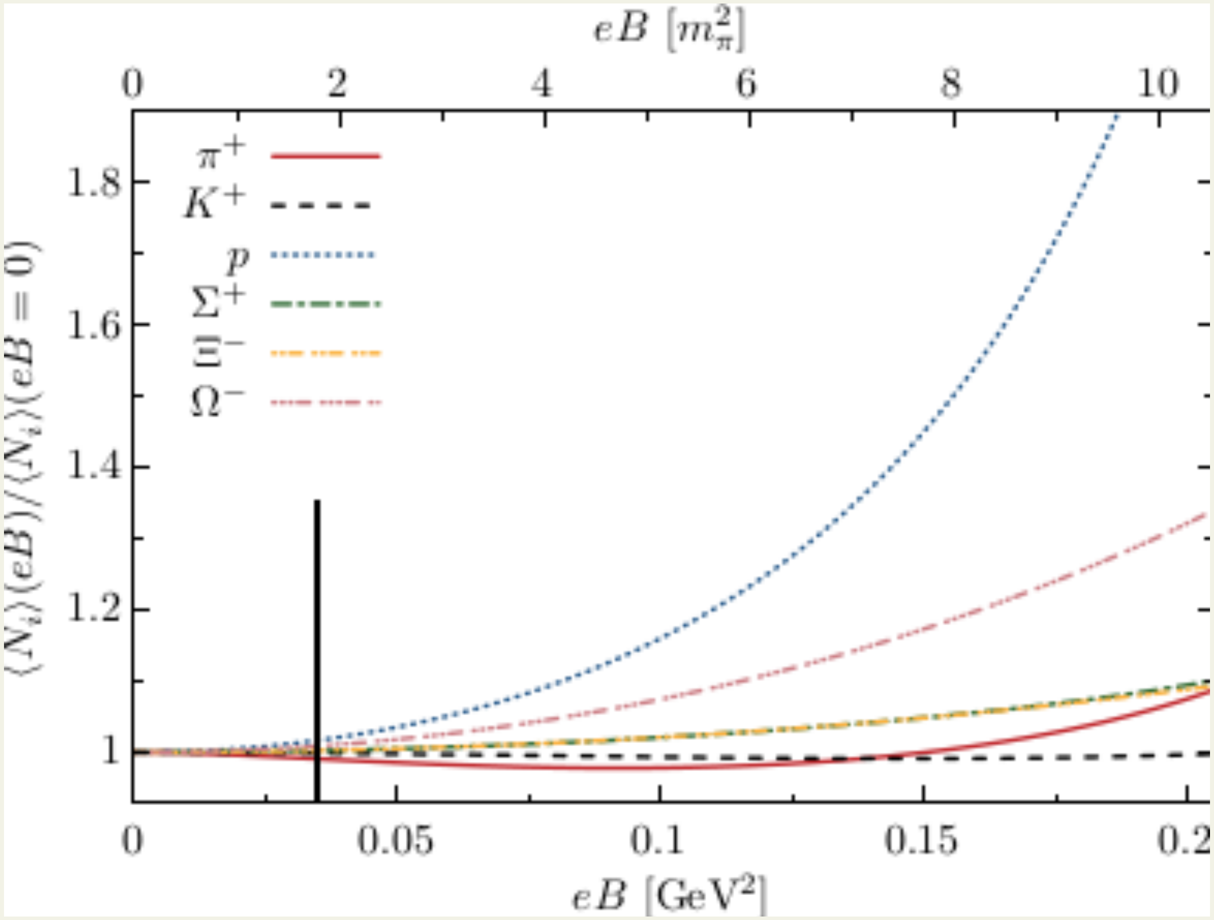
$$\begin{aligned} E_\Delta &= \sqrt{m_\Delta^2 - 4eB} \\ E_p &= m_p \\ E_\pi &= \sqrt{m_\pi^2 + eB} \end{aligned}$$

Therefore

$$eB \lesssim 0.0356\,\mathrm{GeV}^2$$

What is ground state beyond that??

Limited validity



- **not much happens where HRG is not in trouble**

Detailed balance

- chemical equilibrium: resonances are formed and decay at the same rate

$$\pi^+ + \pi^- \Leftrightarrow \rho^0$$

- magnetic field affects pion densities
- effect on decay rates small
- *assume* effect on production via pion densities only
- deviation from equilibrium density: effective chemical potential

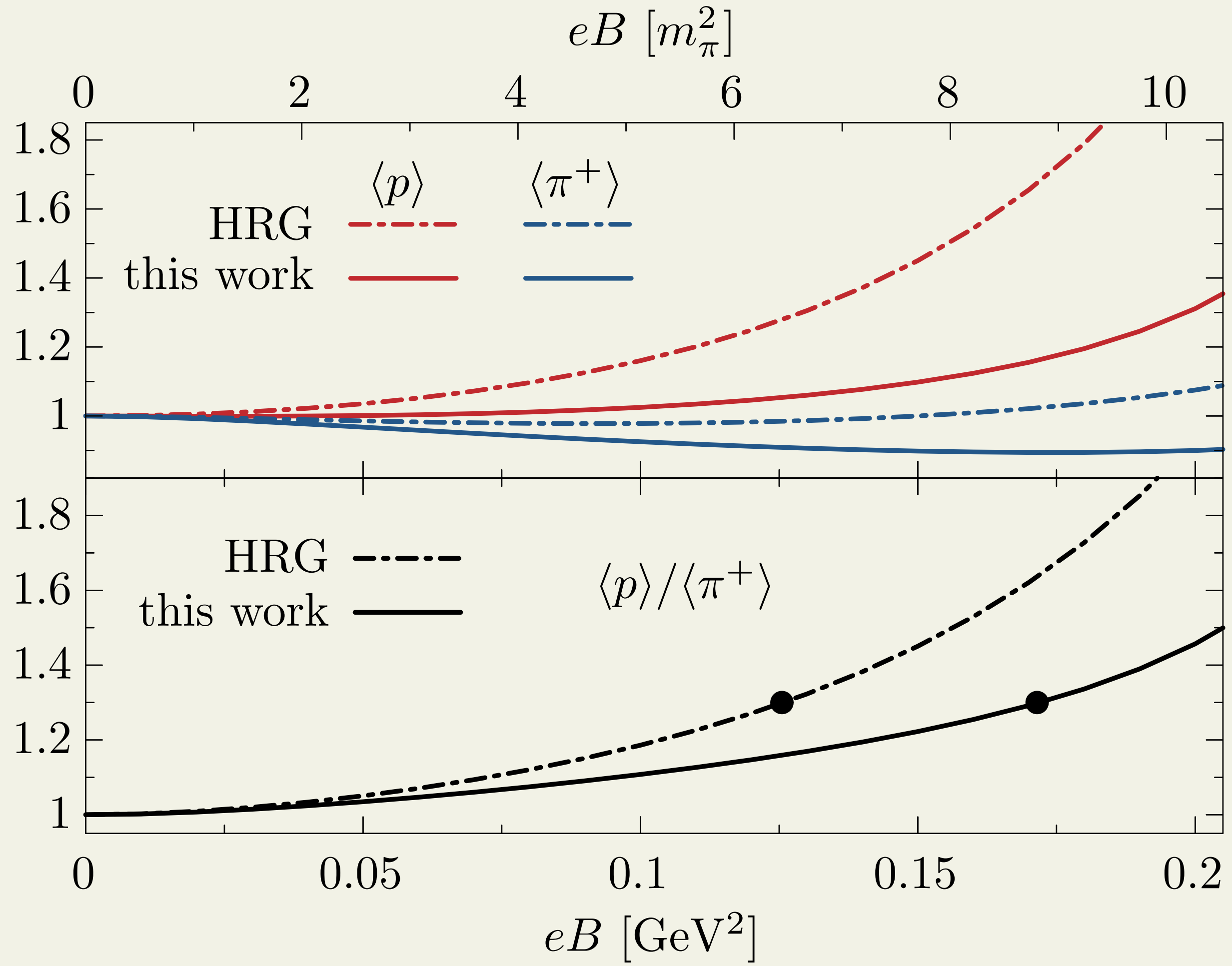
$$n_\pi(T, \mu_\pi, B \equiv 0) = n_\pi(T, B)$$

- relative equilibrium:

$$\mu_\rho = \mu_{\pi^+} + \mu_{\pi^-}$$

$\Longrightarrow$ **neutral resonance density affected!**

Detailed balance: effect on yields



- **both pion and proton yields reduced**
- p/π **ratio reduced**

Summary

- Landau quantization defined for structureless particles
- hadrons have structure

  $\Longrightarrow$ problems ahead latest from $\sqrt{|Q|B} > m_\pi$ on

- magnetic field does not affect neutral particles

  $\Longrightarrow$ spoils detailed balance

- we need better model than HRG