Hadron resonance gas is a bad model

for hadronic matter in strong magnetic field

Pasi Huovinen

Incubator of Scientific Excellence—Centre for Simulations of Superdense Fluids

University of Wrocław

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with M. Marczenko, M. Szymański, B. Karmakar,
and P.M. Lo, C. Sasaki, K. Redlich

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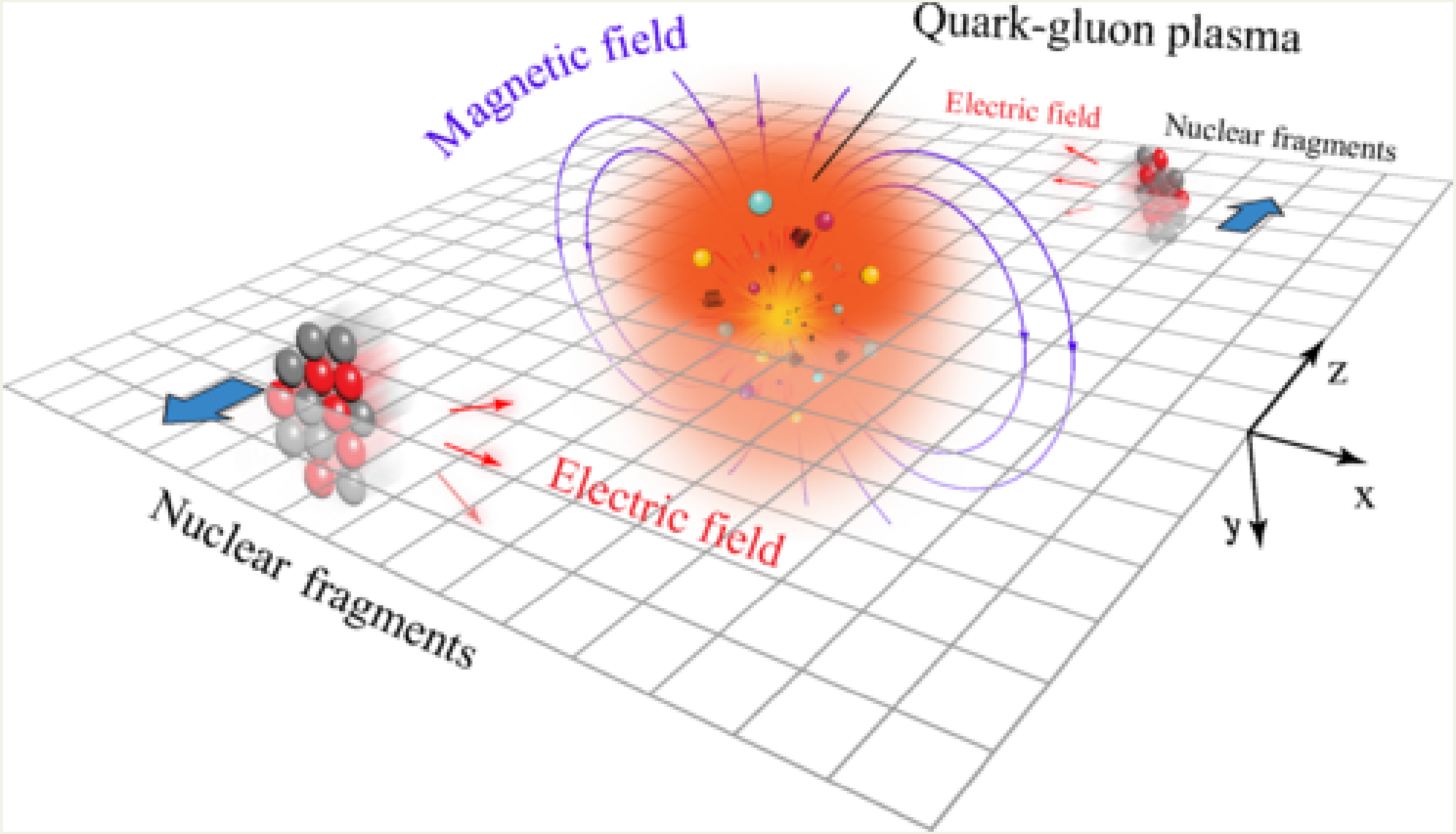
Strong magnetic field in HIC



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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 quantisation

- **energy of charged structureless particle**

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

minimal extension of HRG
•no change in widths (still zero)
•no change in masses (vacuum pole masses)

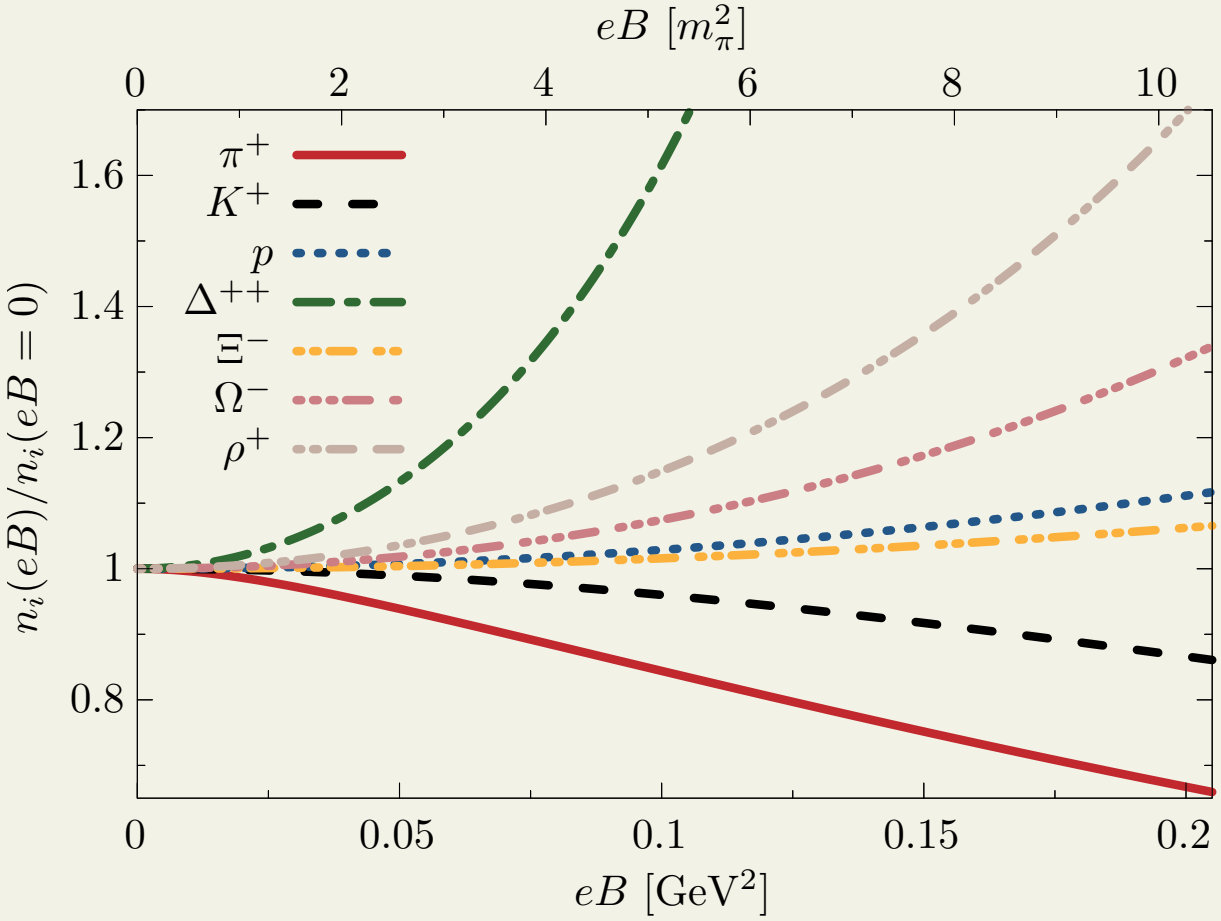
number density

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

becomes

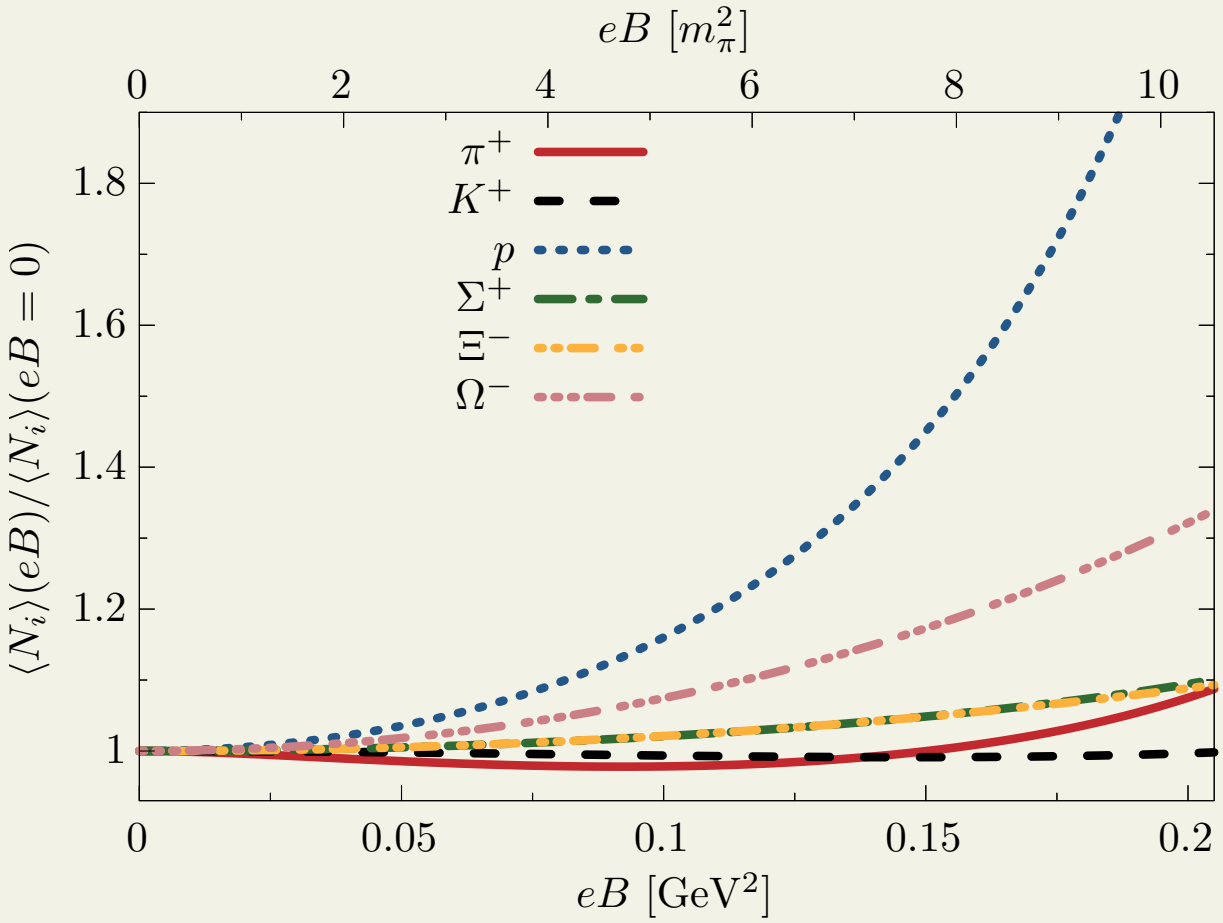
$$n_c(T) = \frac{|Q|B}{2\pi^2}\sum_{s_z}\sum_{l=0}^{\infty}\int \mathrm{d}p_z\, f(E(B),T)$$

Particle densities at $T = 155$ MeV



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

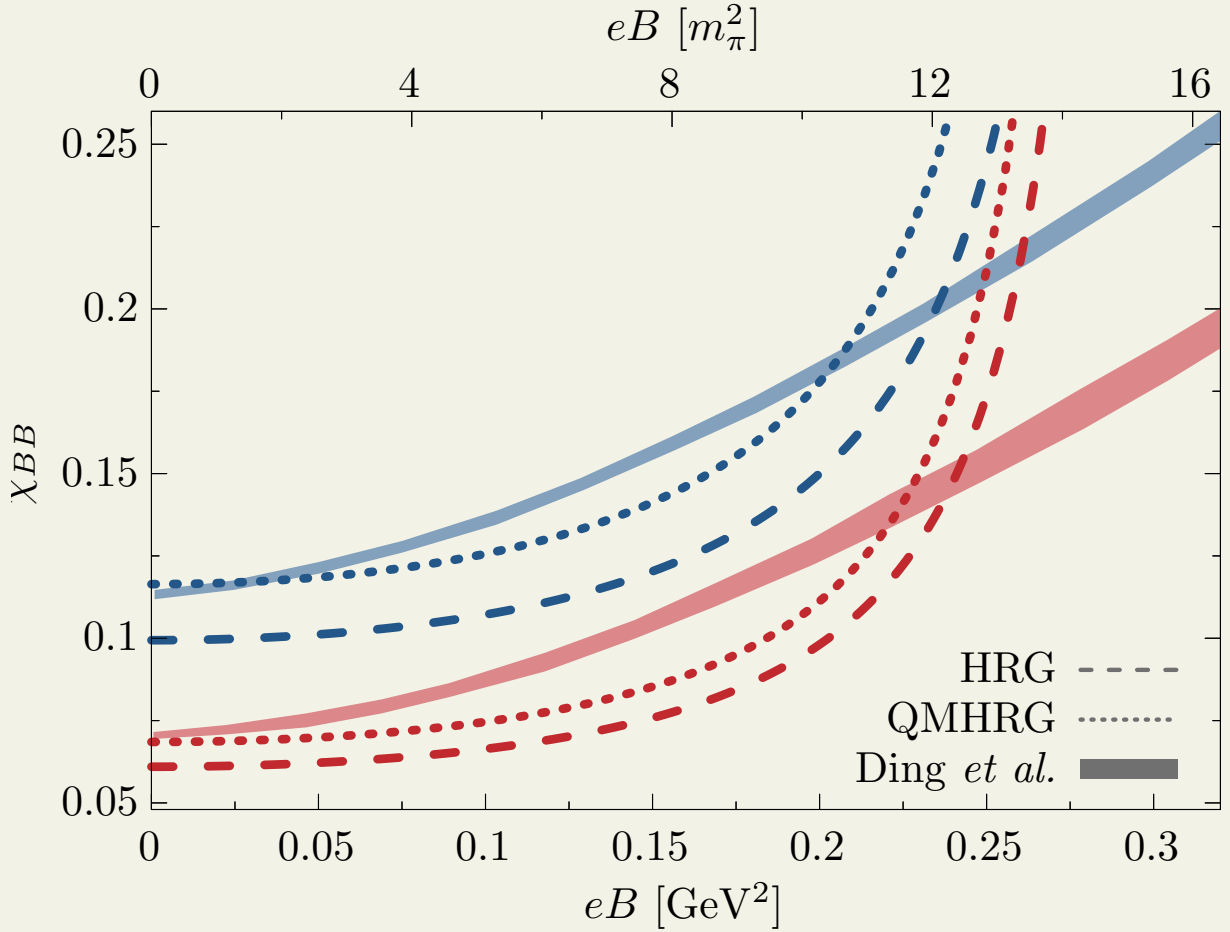
Yields after decays at $T = 155$ MeV



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

Baryonic susceptibility

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



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

Decays?

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

requires

$$E_{\Delta^{++}} \geq E_p + E_{\pi^+}$$

but

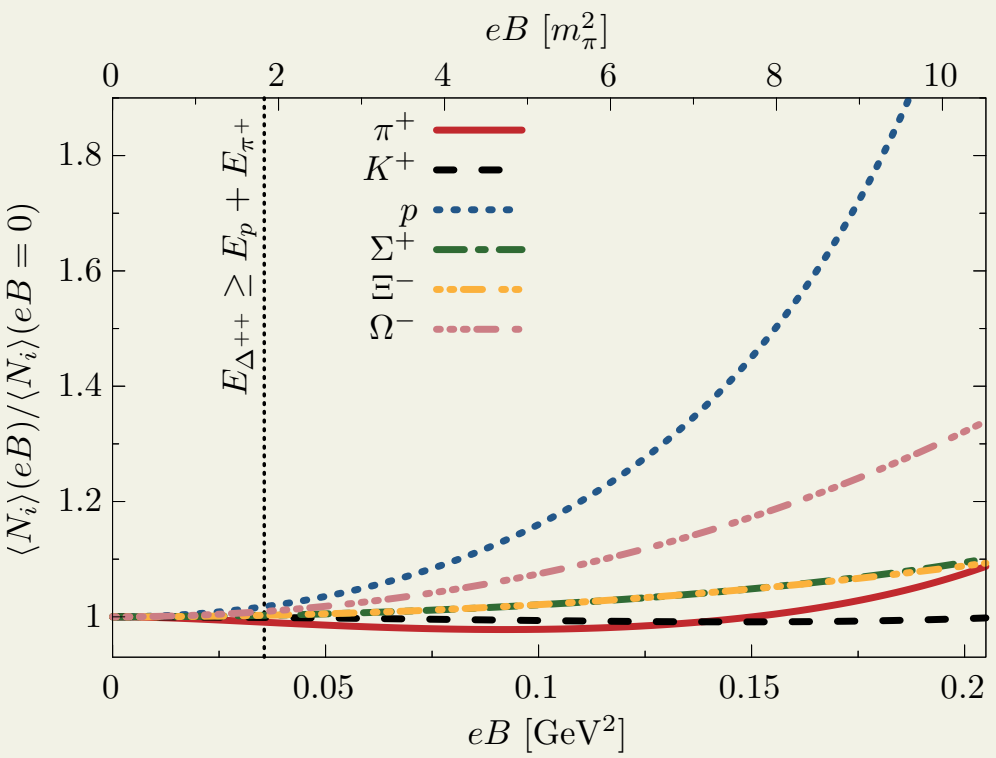
$$\begin{aligned} E_{\Delta^{++}} &= \sqrt{m_\Delta^2 - 4eB} \\ E_p &= m_p \\ E_{\pi^+} &= \sqrt{m_\pi^2 + eB} \end{aligned}$$

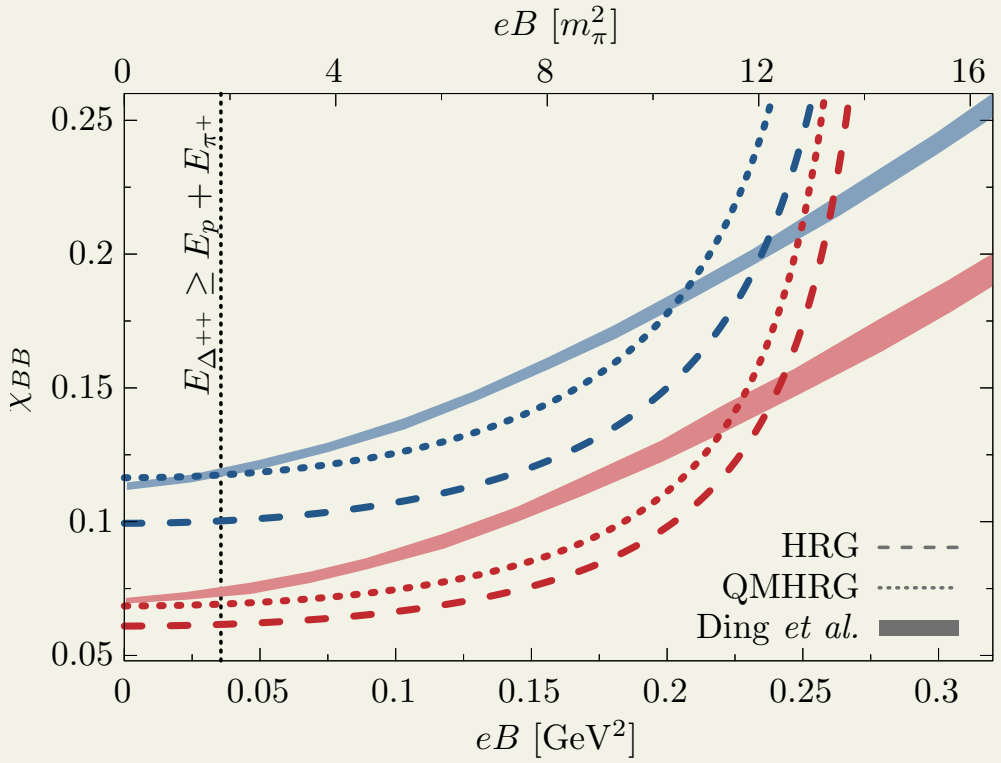
Therefore

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

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**

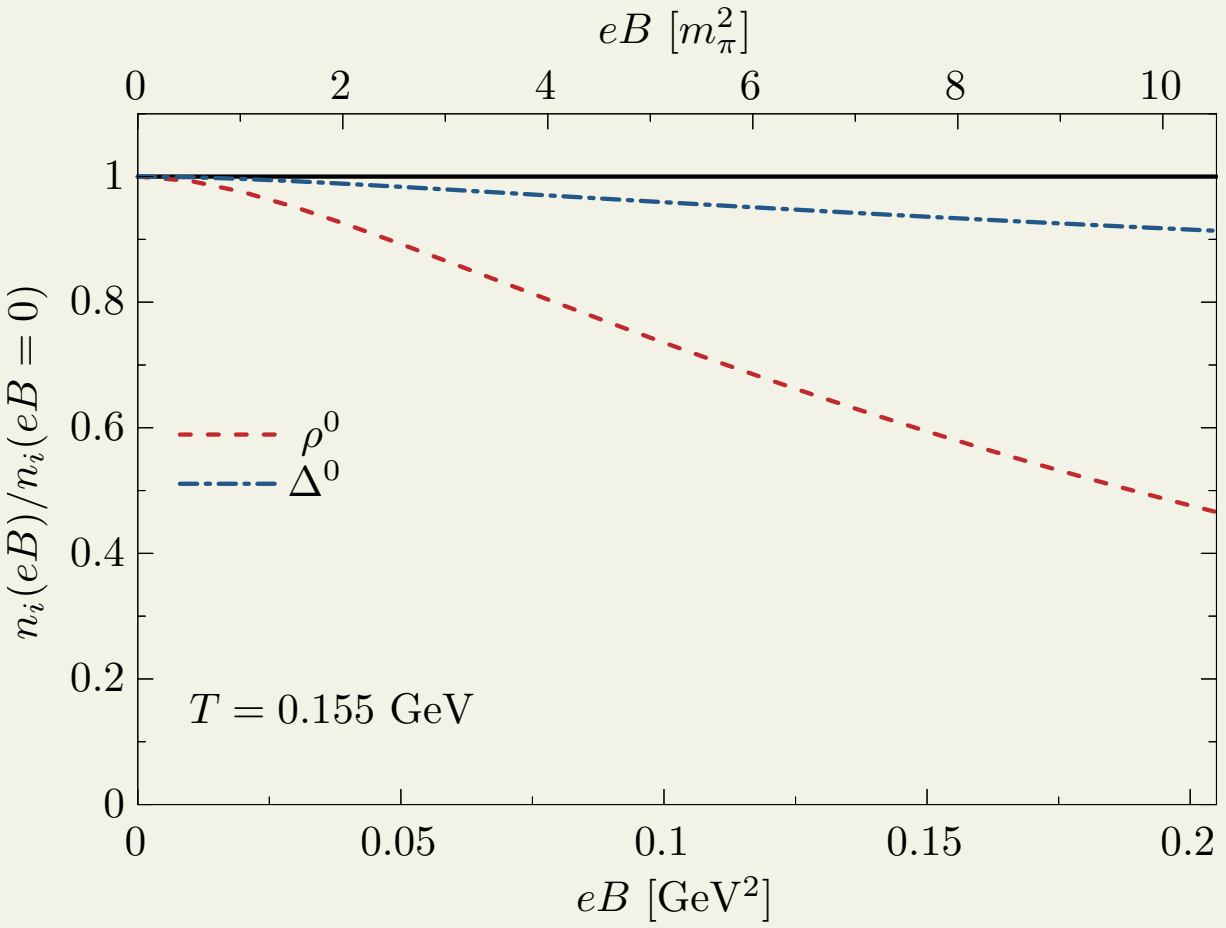
$$n_\pi(T, \mu_\pi, B \equiv 0) = n_\pi(T, B)$$

- **relative equilibrium:**

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

$$\Longrightarrow \textbf{neutral resonance density affected!}$$

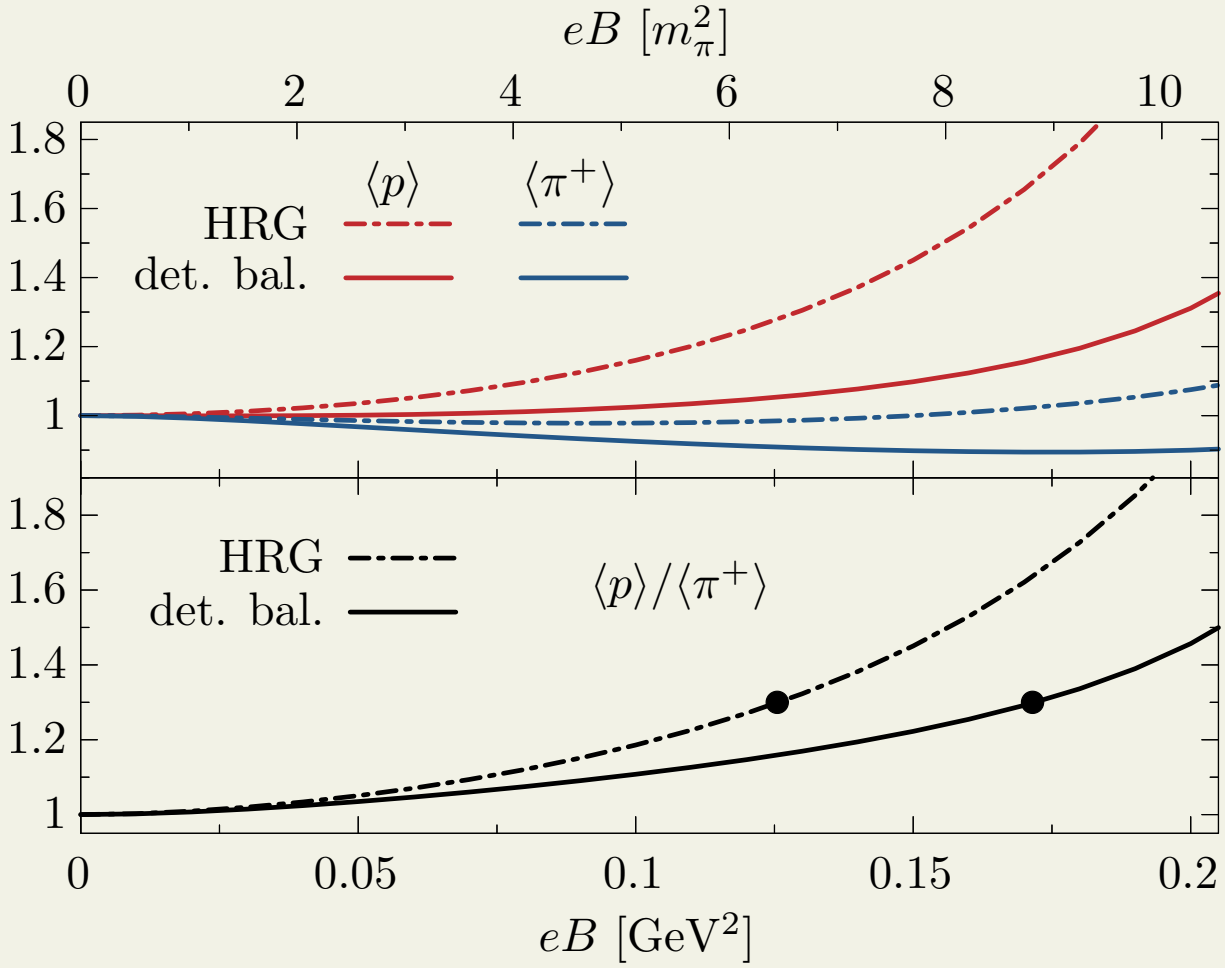
Detailed balance: effect on ρ^0 and Δ^0



- ρ^0 and Δ^0 densities reduced
- charged ρ and Δ densities increased (Landau quantisation)

Detailed balance: effect on yields

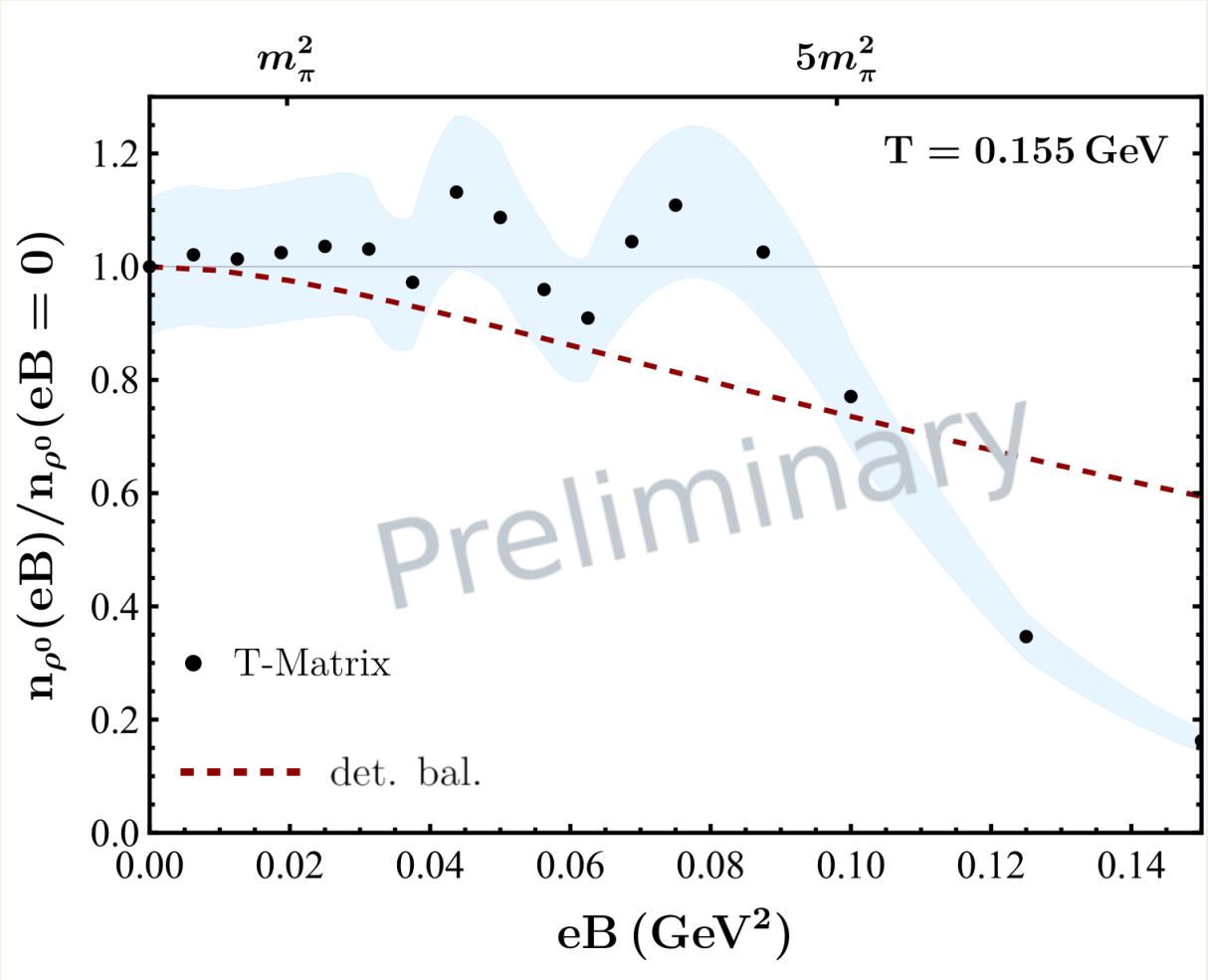
- **all ρ and Δ densities by detailed balance:**



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

T-matrix description of ρ^0

B. Karmakar & P.M. Lo, work in progress



- **both HRG and detailed balance assumption are far too naive!**

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**