Magnetic field effect on hadron yield ratios and fluctuations in a hadron resonance gas

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FIAS Frankfurt Institute for Advanced Studies

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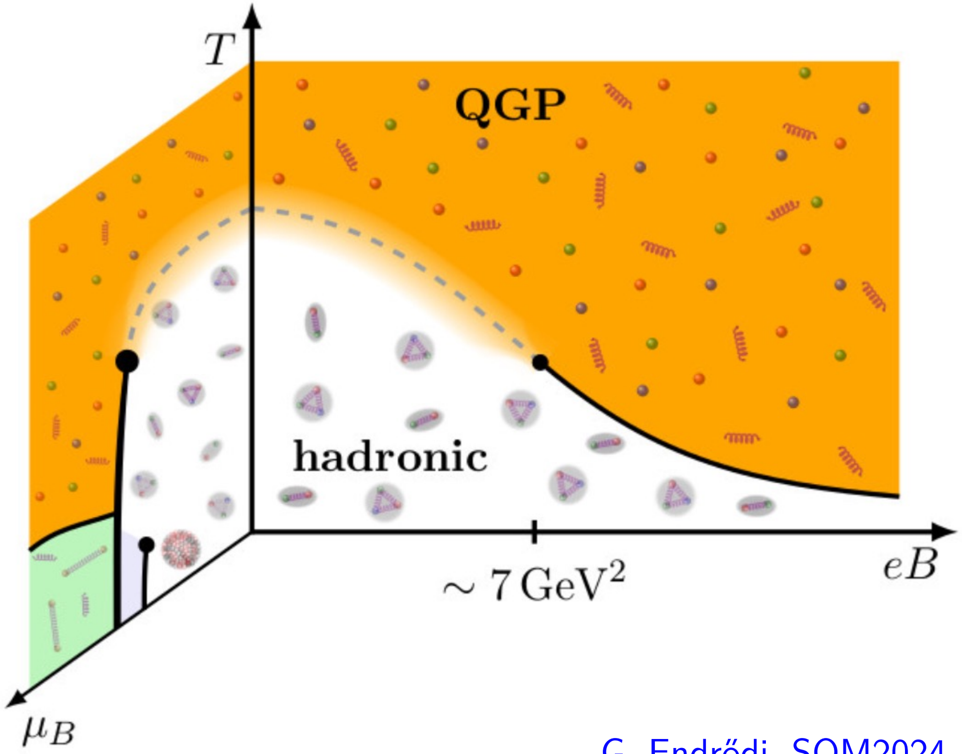
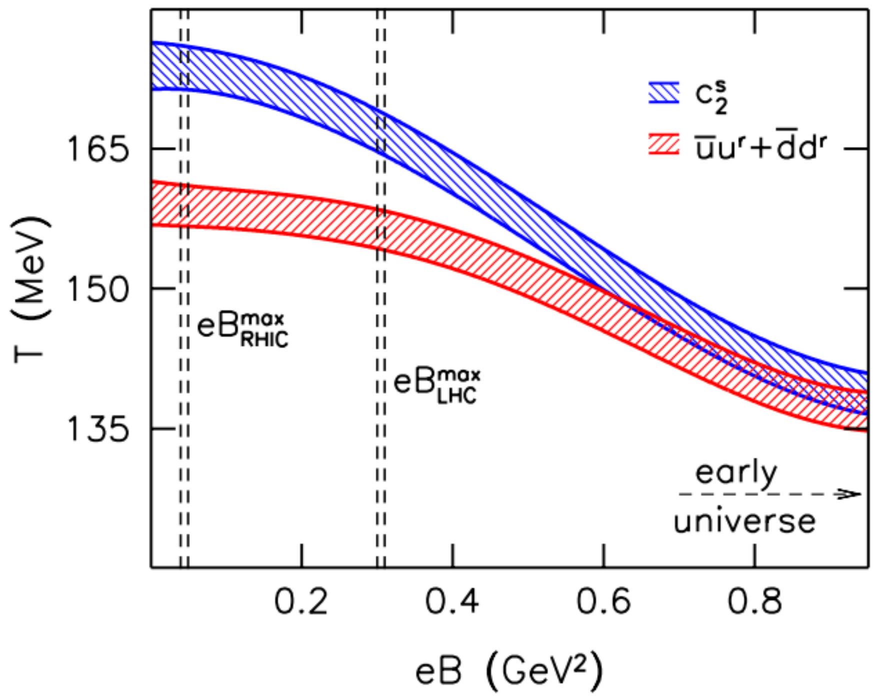
QCD in external magnetic fields

Phase diagram



G. Endrődi, SQM2024

Transition temperature

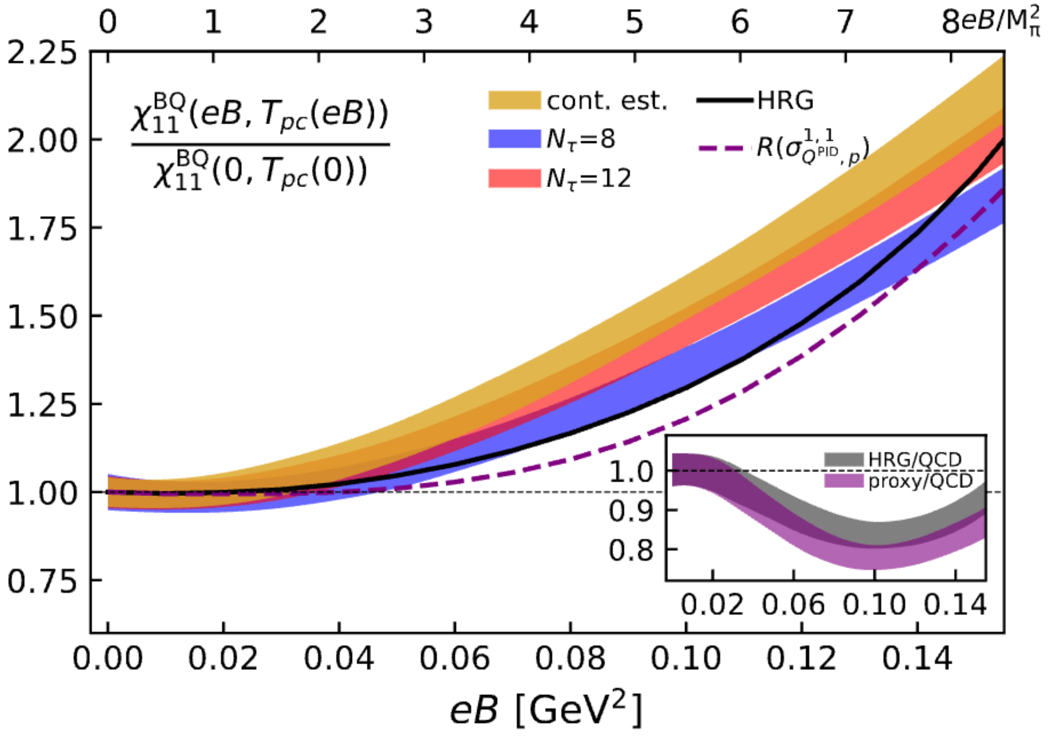


Lattice QCD: Bali et al., JHEP 02, 044 (2012)

- Possibly rich phase structure, including a critical point in T-eB plane
- Can be probed by heavy-ion collisions

Fluctuations of conserved charges

Baryon-charge correlator



H.-T. Ding et al., PRL 132, 201903 (2024)

(Non-central) heavy-ion collisions

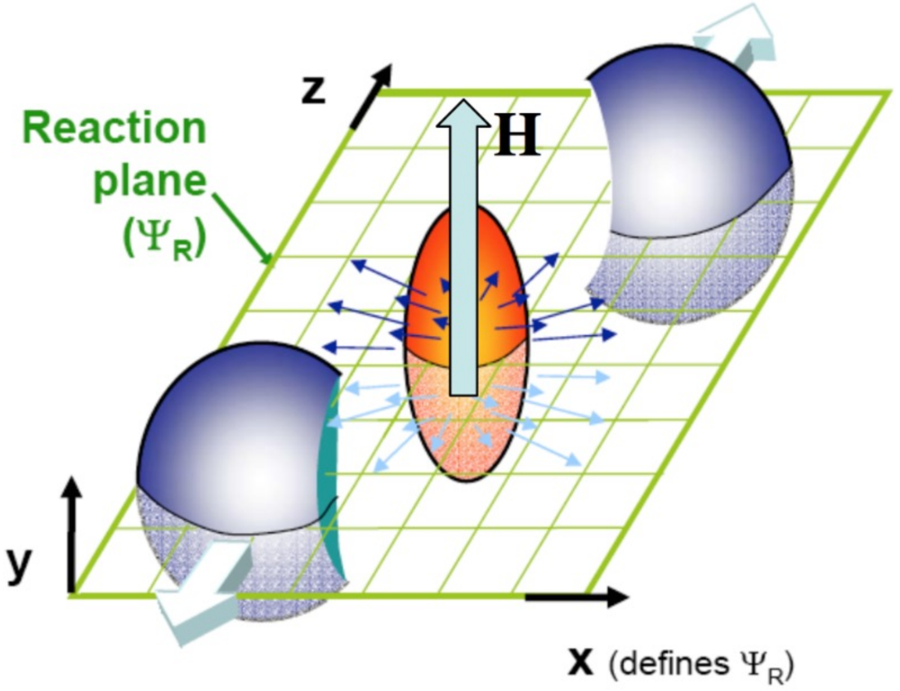


Figure from Kharzeev, PPNP 75, 133 (2014)

- Baryon-charge correlator suggested as magnetometer in heavy-ion collisions*
- If the magnetic field is relevant at freeze-out, how does it affect hadrochemistry?

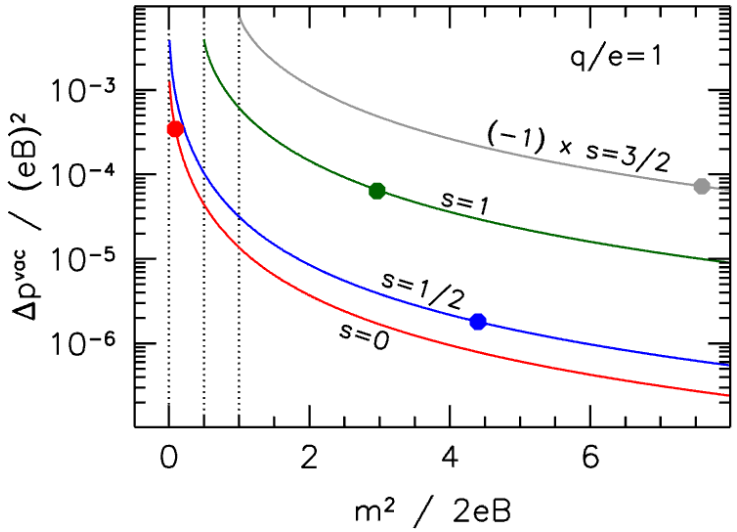
*In heavy-ion collisions one uses proton-charge correlator as a proxy

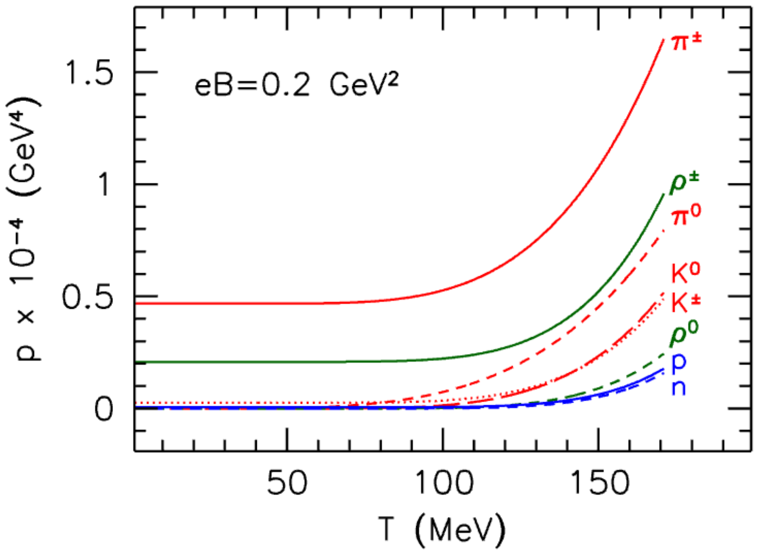
HRG model in external magnetic field

Hadron resonance gas (HRG) description applies at not too large eB

- Discretization of transverse momenta $(2s+1)\int \frac{d^3\mathbf{p}}{(2\pi)^3} \to \frac{|q|B}{2\pi}\sum_{s_z=-s}^{s}\sum_{l=0}^{\infty}\int\frac{dp_z}{2\pi}$

- Energy levels of charged hadrons $E_c(p_z,l,s_z)=\sqrt{p_z^2+m^2+2|q|B(l+1/2-s_z)}$





- Negative vacuum pressures from $S=3/2$ channels, indicating instability
- Hadrons acquire effective mass $m_{\rm eff}\sim\sqrt{m^2+|q|B(1-2s_z)}$

G. Endrődi, JHEP 04 (2013) 023

HRG model in external magnetic field: implementation

$$p = \sum_{i \in neutral} p_n^i + \sum_{i \in charged} p_c^i$$

neutral hadrons | **charged hadrons**

Pressure:

$$p_n^i = \eta_i \frac{(2s_i+1)T}{2\pi^2} \int_0^\infty dp\, p^2 \ln\left[1 + \eta_i e^{-(E_n-\mu_i)/T}\right]$$

$$p_c^i = \eta_i \frac{|q_i| BT}{2\pi^2} \sum_{s_z=-s}^{s} \sum_{l=0}^{\infty} \int_{-\infty}^{\infty} dp_z \ln\left[1 + \eta_i e^{-(E_c-\mu_i)/T}\right]$$

Density:

$$n_n^i = \frac{(2s_i+1)}{2\pi^2} \int_0^\infty dp\, p^2 \left[\exp\left(\frac{E_n-\mu_i}{T}\right) + \eta_i\right]^{-1}$$

$$n_c^i = \frac{|q_i| B}{2\pi^2} \sum_{s_z=-s}^{s} \sum_{l=0}^{\infty} \int_{-\infty}^{\infty} dp_z \left[\exp\left(\frac{E_c-\mu_i}{T}\right) + \eta_i\right]^{-1}$$

Susceptibilities:

$$\chi_{lmn}^{BQS} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_B/T)^l\, \partial(\mu_Q/T)^m\, \partial(\mu_S/T)^n} = \sum_i b_i^l\, q_i^m\, s_i^n \frac{\partial(p_{n/c}^i/T^4)}{\partial(\mu_i/T)}$$

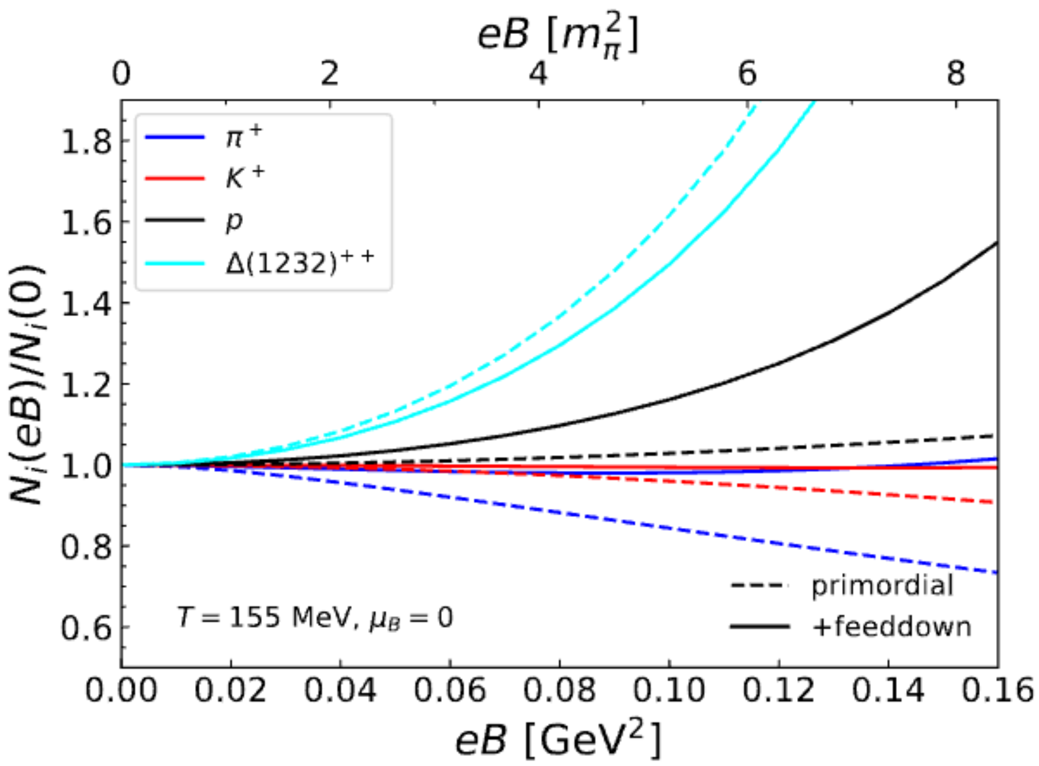
Implemented in **`Thermal-FIST`*** as of version 1.5

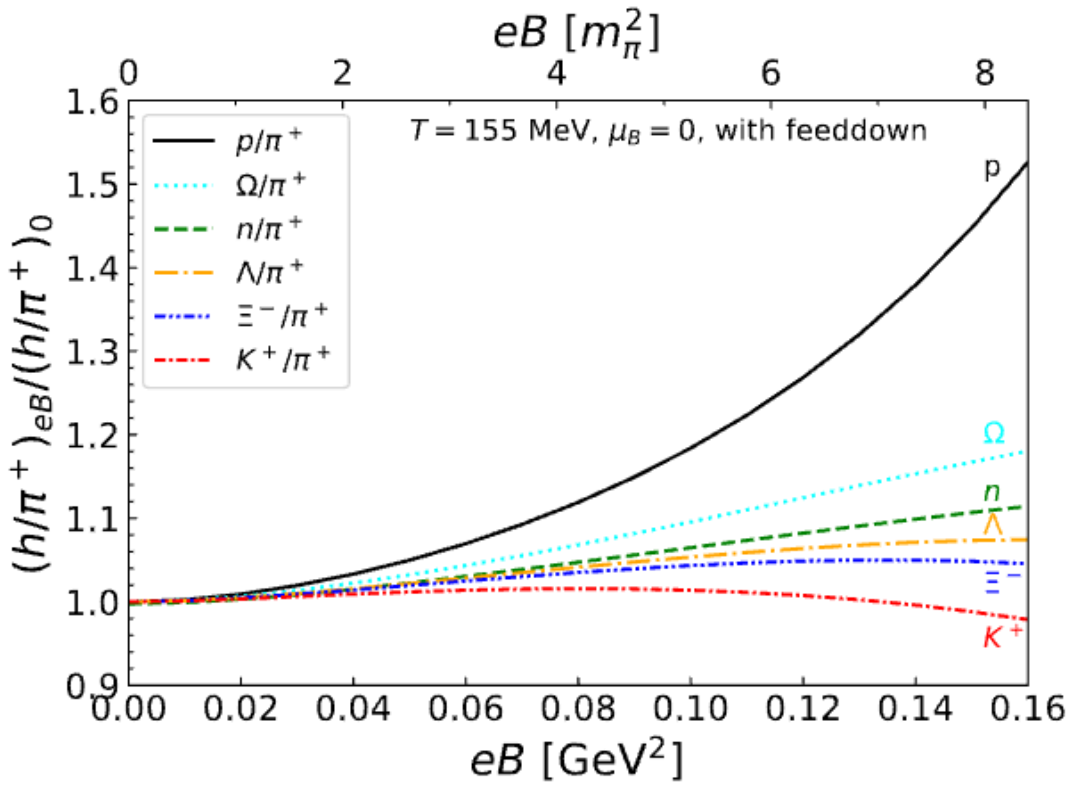
- Study effect of $eB \neq 0$ on heavy-ion hadron yields, susceptibilities, van der Waals interactions etc.
- No vacuum contribution (does not depend on chemical potentials thus hadrochemistry is unaffected)

*Vovchenko, Stoecker, Comput. Phys. Commun. 244, 295 (2019); v1.5 available in `devel` branch at https://github.com/vlvovch/Thermal-FIST

Effect on hadron yields

Feeddown: $\langle N_i^{tot} \rangle = \langle N_i^{th} \rangle + \sum_R BR(R \to i) \langle N_R^{th} \rangle$

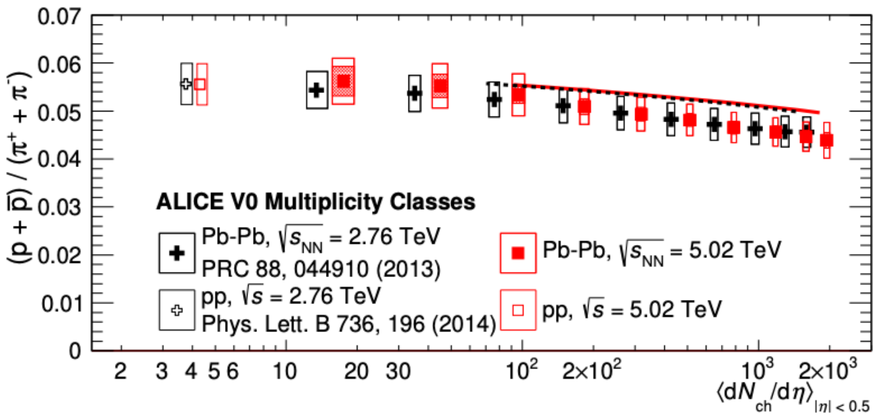




- Strong enhancement of doubly charged, spin-3/2 $\Delta(1232)^{++}$
- Enhancement of the proton yield through decay feeddown $\Delta^{++} \to p + \pi^+$
- Breaks isospin symmetry (smaller enhancement of neutrons)

Proton yields at the LHC: 5 TeV data

ALICE Collaboration, Phys. Rev. C 101 (2020) 044907



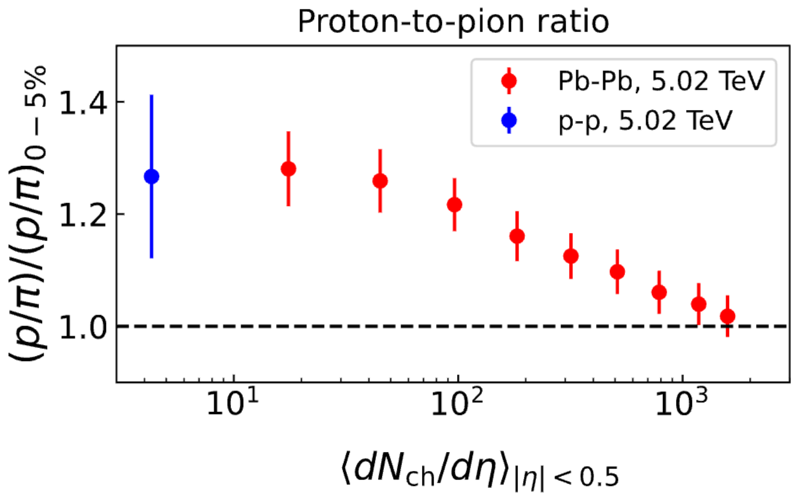


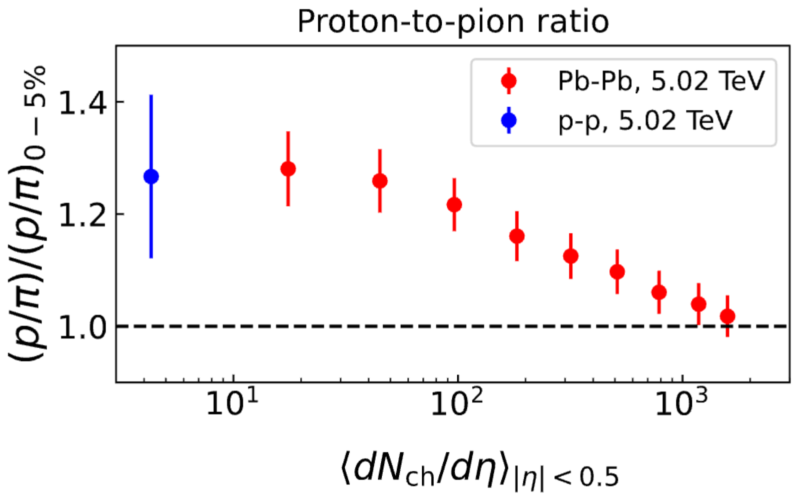
Figure 7: Transverse momentum integrated K/π (top) and p/π (bottom) ratios as a function of $\langle dN_{ch}/d\eta \rangle$ in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, compared to Pb–Pb at 2.76 TeV [14]. The values in pp collisions at $\sqrt{s}$ = 5.02 and 2.76 TeV are also shown. The empty boxes show the total systematic uncertainty; the shaded boxes indicate the contribution uncorrelated across centrality bins (not estimated in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV).

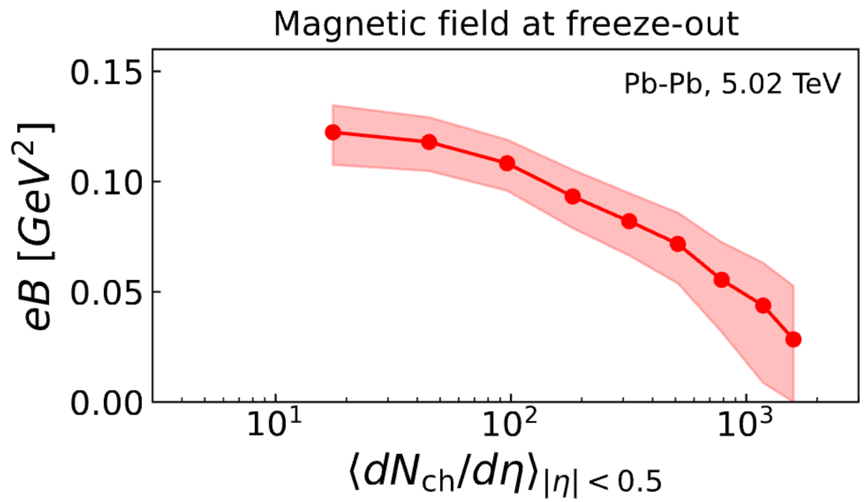
- Evidence for suppression of p/π ratio in central collisions (~20%, $>4\sigma$ level)
- Arguably a hadronic phase effect (baryon annihilation) Vovchenko, Koch, Phys Lett B 835, 137577 (2022)
- Could strong magnetic field in non-central collisions play a role?

Proton-to-pion ratio as a magnetometer

Assumptions:

- Centrality dependence driven solely by the changing magnetic field
- $eB = 0$ in central collisions





Maximum magnetic field at freeze-out: $eB \approx 0.12\, GeV^2 \approx 6.3 m_\pi^2$ in peripheral collisions

Proton-to-pion ratio as a magnetometer: Caveats

Caveats:

- Assumed constant magnetic field in whole fireball at freeze-out
- The likely strong event-by-event fluctuations of magnetic field neglected

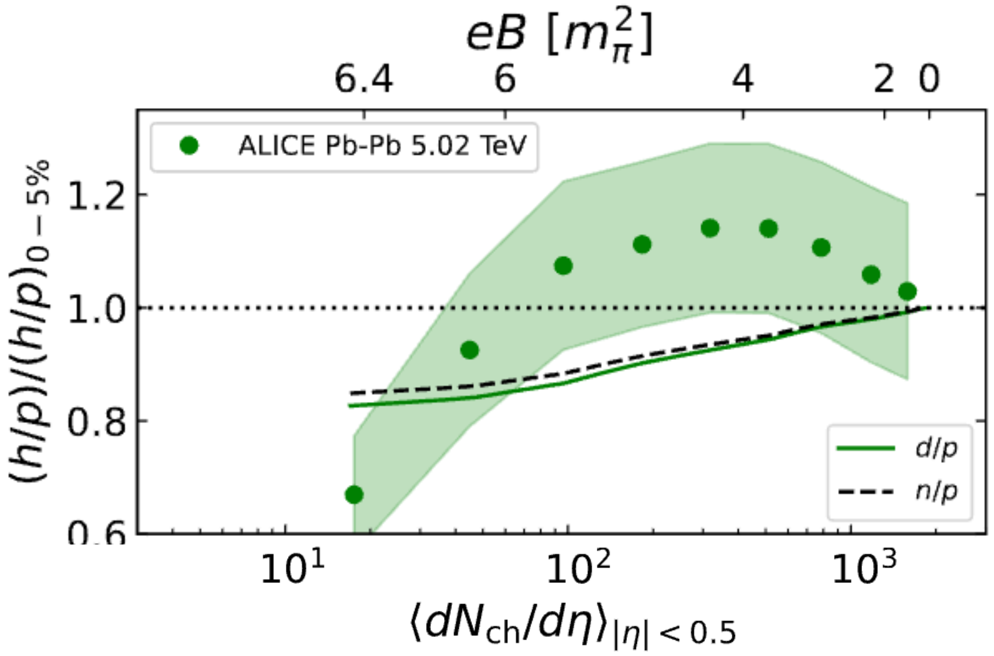
  Bzdak, Skokov, PLB 710, 171 (2012)
  Deng, Huang, PRC 85, 044907 (2012)
- ALICE data on p/π ratio in p-p collisions $(eB\sim0)$ is in better agreement with peripheral Pb-Pb than central Pb-Pb

  ALICE Collaboration, Phys. Rev. C 101 (2020) 044907
- Other QCD processes can change p/π ratio but were neglected
  - In particular, baryon annihilation in the hadronic phase

  Steinheimer, Aichelin, Bleicher, PRL 110 (2013) 042501
  Becattini et al., PRC 90 (2014) 054907
  Vovchenko, Koch, Phys Lett B 835, 137577 (2022)
- Need an improved treatment of higher-spin states and decays/regeneration of resonances at $eB \neq 0$

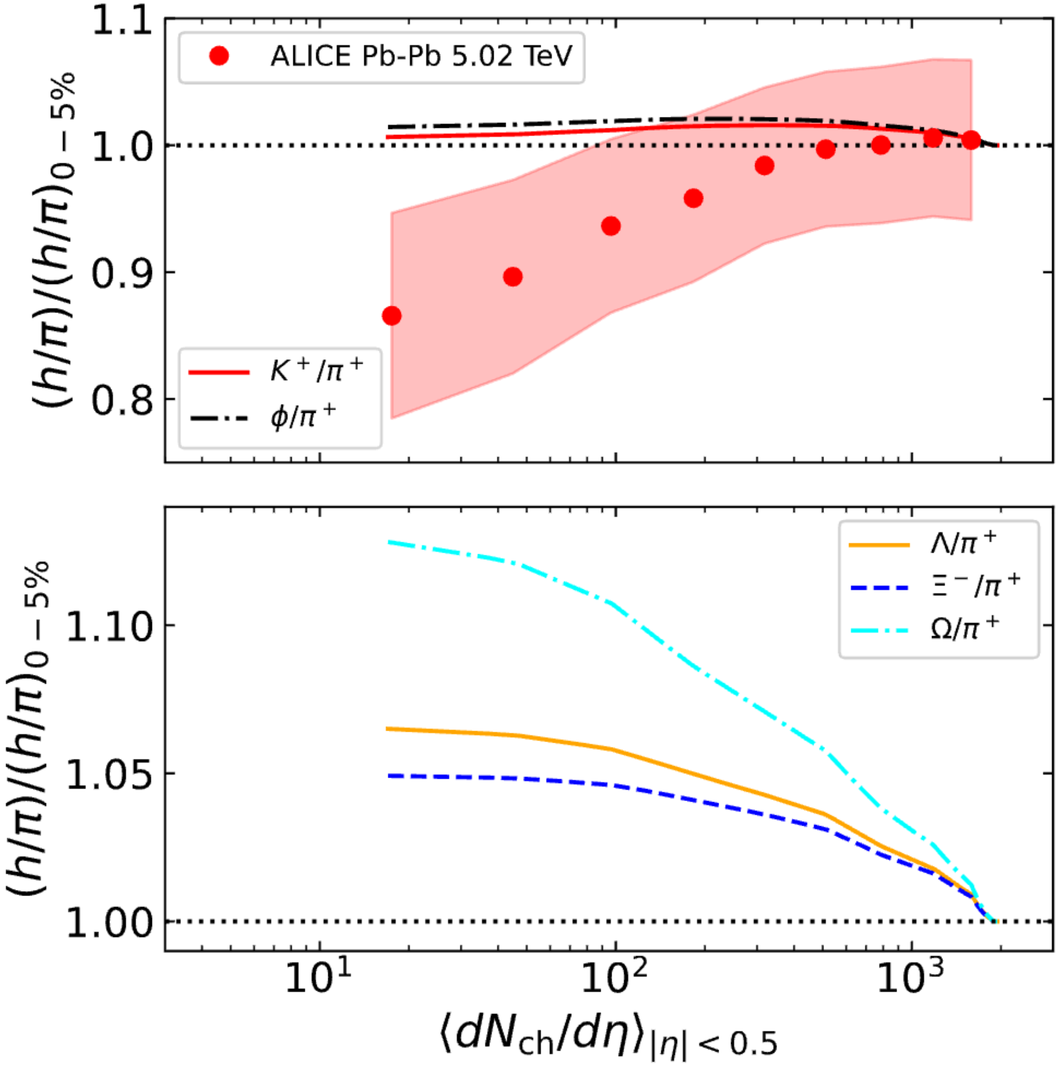
  Marczenko et al., 2405.15745

Other yield ratios



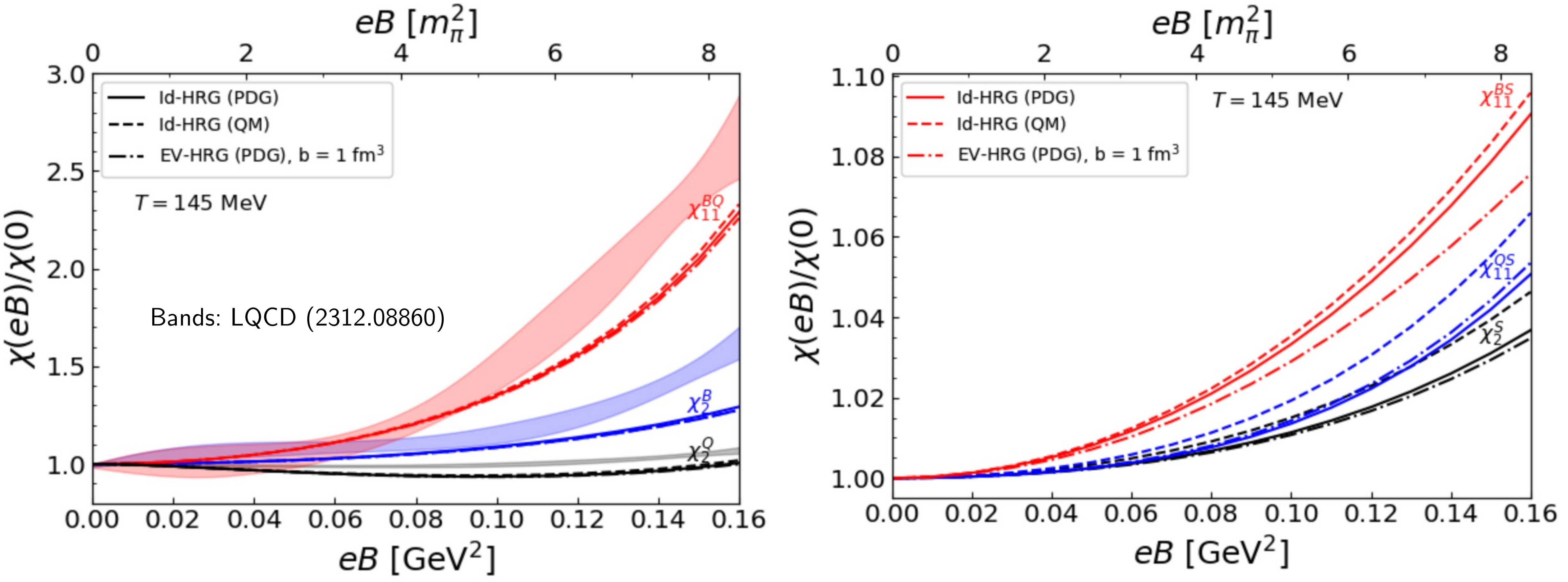
- Suppression of the d/p ratio by the magnetic field in non-central collisions
  - No clear evidence from data
  - However, conclusion relies on applying thermal production mechanism to light nuclei
- Suppression of the n/p ratio
  - An isospin symmetry breaking effect and perhaps a clearer signature than p/π ratio
  - Challenging to measure neutrons

Other yield ratios: Strangeness



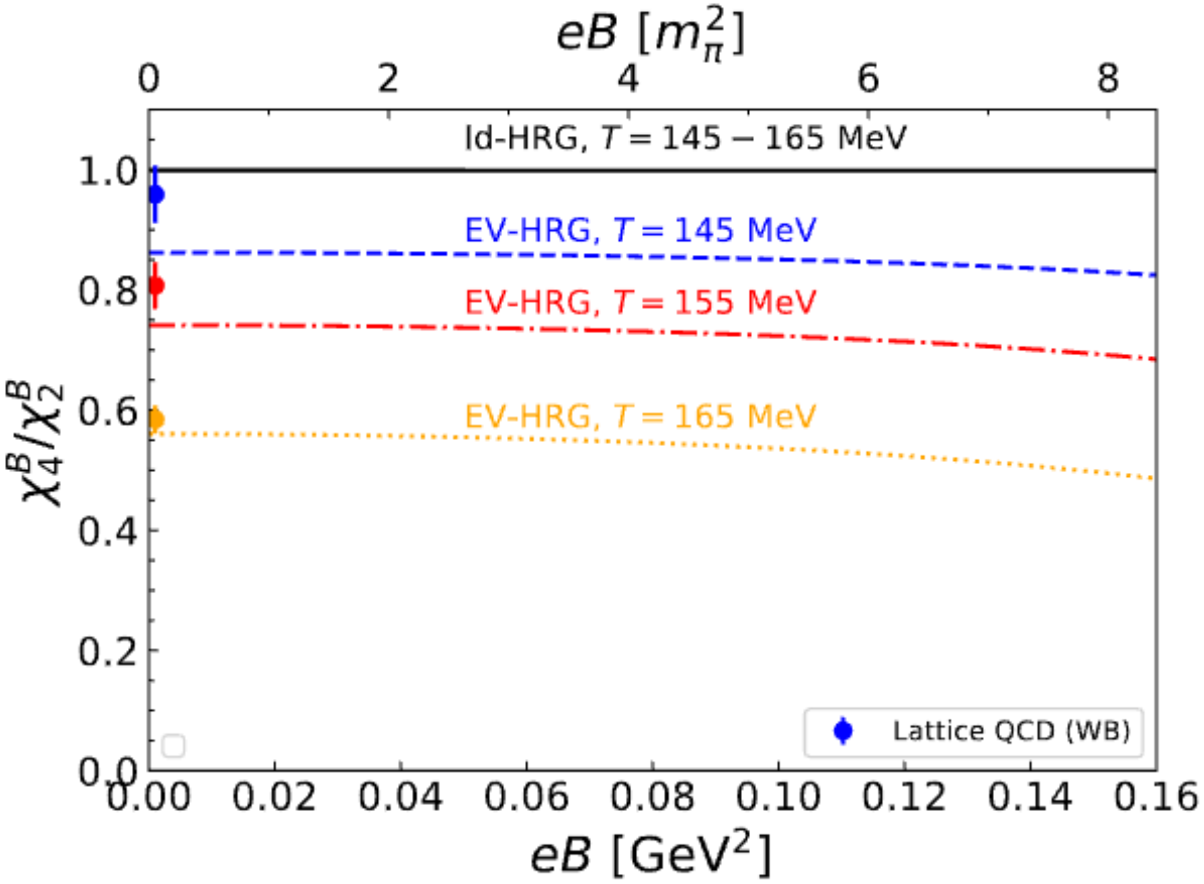
- Weak effect on kaons and phi
- Certain hierarchy for hyperons to be probed by future data

Fluctuations of conserved charges



- Qualitative (but not quantitative) agreement with lattice QCD
- Weak dependence of the normalized susceptibilities on the particle list (PDG vs QM) and baryon excluded volume (EV-HRG) effects

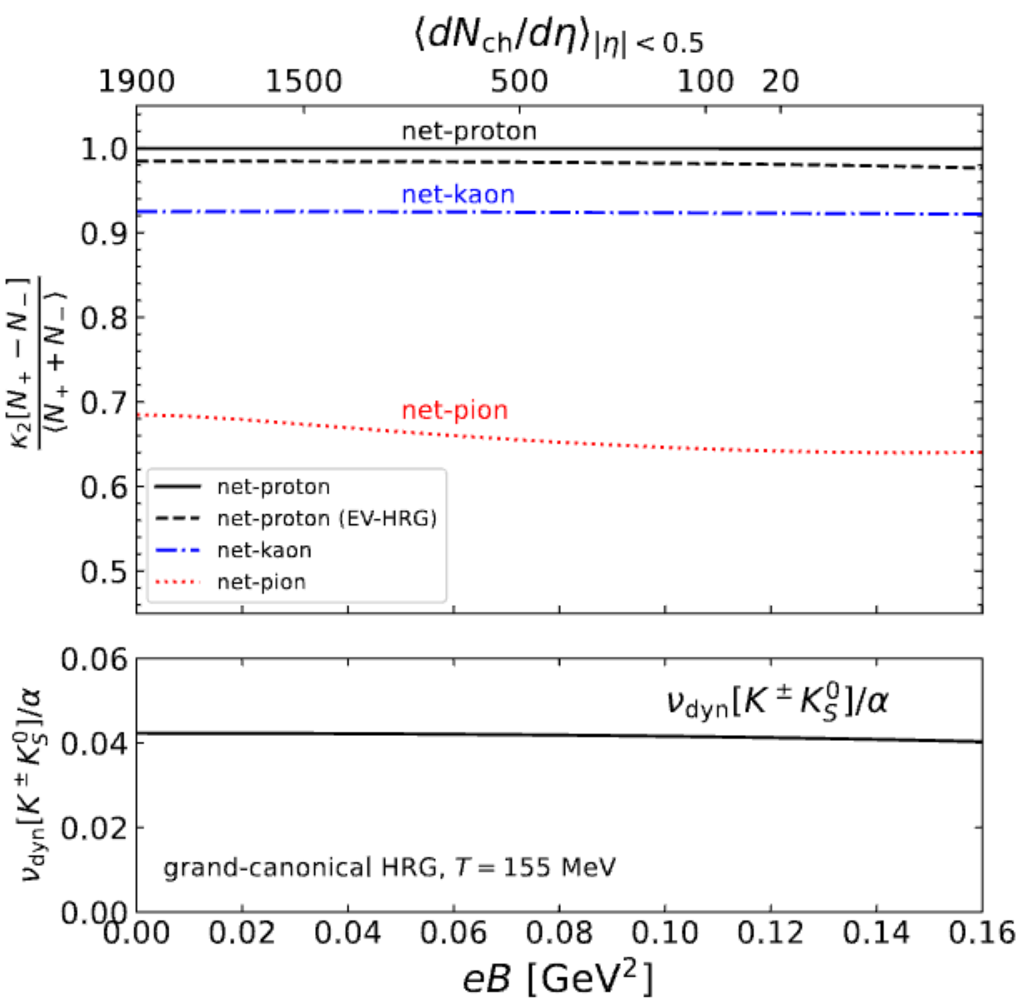
Fluctuations of conserved charges: high-order cumulants



- Net-baryon kurtosis stays χ_4^B/χ_2^B=1 in ideal HRG (Id-HRG) for any $eB \neq 0$
  - No dynamical fluctuations induced by the magnetic field
- Weakly affects χ_4^B/χ_2^B in HRG with baryon repulsion (EV-HRG)

Fluctuations in heavy-ion collisions

kappa2-over-Skellam



- Heavy-ion collisions measure non-conserved quantities
  - Incorporate probabilistic decays

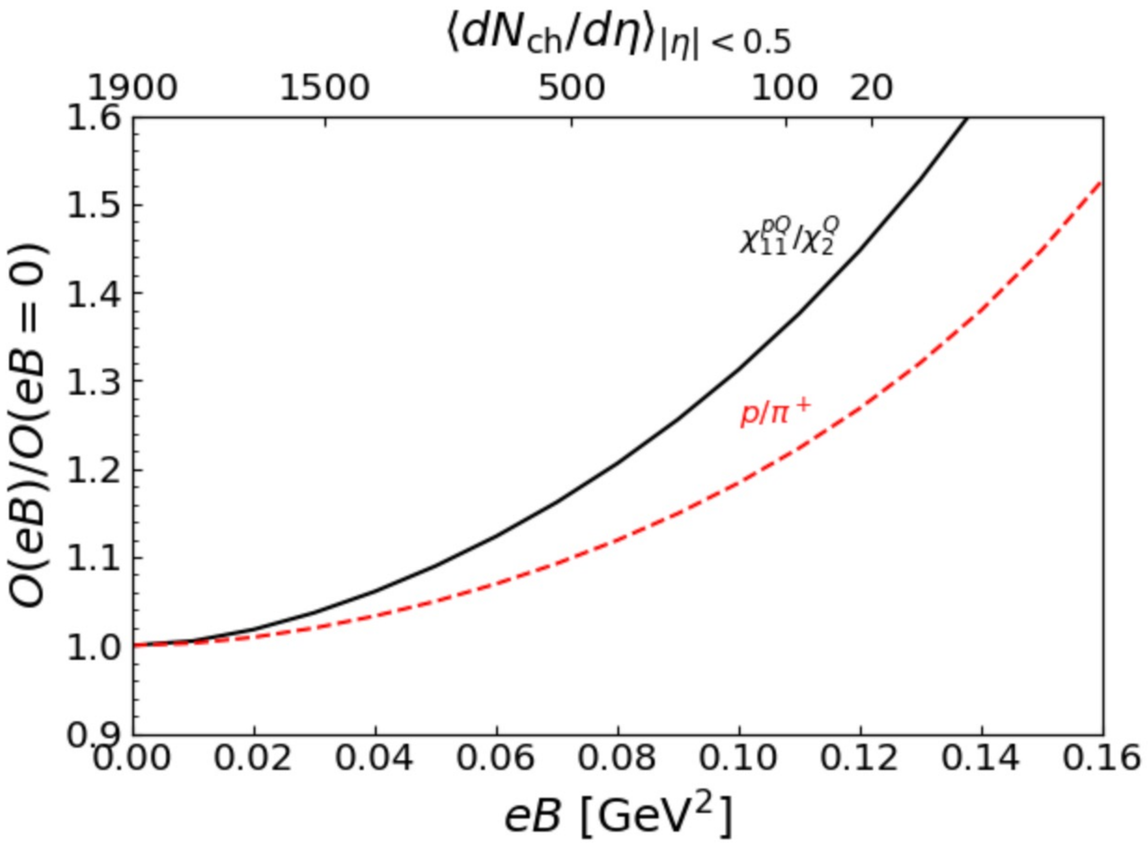
$$\langle \Delta N_i \Delta N_j \rangle_{\rm Id-HRG} = \delta_{ij} \langle N_i^* \rangle + \sum_R \langle N_R^* \rangle \langle n_i \rangle_R \langle n_j \rangle_R + \sum_R \langle N_R^* \rangle \langle \Delta n_i \Delta n_j \rangle_R .$$

Begun et al., PRC 74, 044903 (2006)

- Virtually no magnetic field effect on normalized variance of net-particle numbers
  - *Fluctuations do not carry any additional information not contained in the yields*

- Does not explain "anomalous" kaon correlations

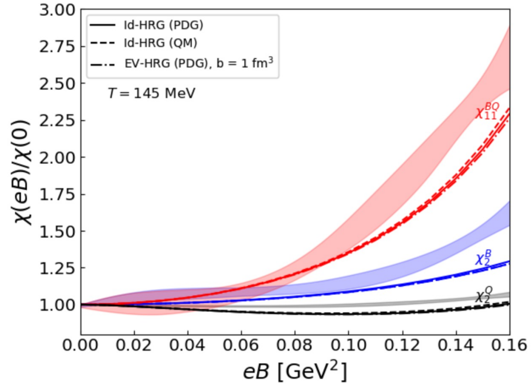
Proton-charge correlator in heavy-ion collisions

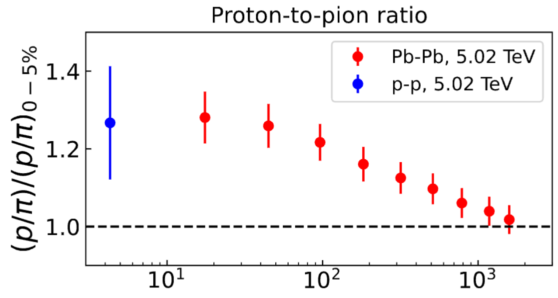


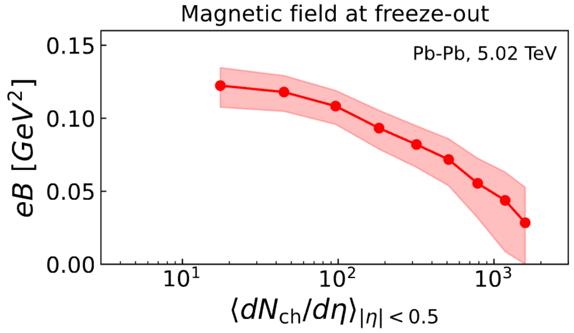
- Enhancement of the p/π ratio mirrors the enhancement of χ_{11}^{pQ}/χ_2^Q
- To leading order χ_{11}^{pQ}~$\langle p \rangle$ and χ_2^Q~$\langle \pi \rangle$
  - It is likely that baryon annihilation leads to the same centrality dependence of χ_{11}^{pQ}/χ_2^Q

Summary

- Sizable magnetic field influences select hadron yields in HRG
  - Strong enhancement of Δ^{++} affects final proton yield through decay feeddown
  - Qualitative (but not quantitative) agreement with lattice
- If strong ($eB \sim 1 - 6\, m_\pi^2$) magnetic field survives to freeze-out
  - p/π ratio can serve as a magnetometer, which can be probed by other ratios such as the isospin symmetry breaking suppression of the n/p ratio
- Fluctuations do not carry additional information not contained in the yields in HRG
- Outlook
  - Improved formalism for higher-spin states, decays, and fluctuations
  - p_T differential analysis and Monte Carlo event generator with `Thermal-FIST`







Thanks for your attention!

Backup slides