Relativistic magneto-hydrodynamics in heavy ion collisions

Gabriele Inghirami
University of Jyväskylä, Dept. of Physics, Jyväskylä, Finland
Helsiki Institute of Physics, Helsinki, Finland

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Why are magnetic fields in HIC so interesting?

- Influence on the elliptic flow
  Bali, Bruckmann, Endrődi and Schäfer - Phys. Rev. Lett. 112 (2014)
  Pang, Endrődi and Petersen - Phys. Rev. C 93, 044919 (2016)
- Influence on directed flow
  Gürsoy, Kharzeev and Rajagopal - Phys. Rev. C 89 (2014)
  Gürsoy, Kharzeev, Marcus, Rajagopal, Shen - Phys. Rev. C 98, 055201 (2018)
  Das, Plumari, Chatterjee, Alam, Scardina, Greco - Phys. Lett. B 768, 260 (2017)
  ALICE Collaboration - arXiv:1910.14406
- The Chiral Magnetic Effect
  Kharzeev, McLerran, Warringa - Nuclear Physics A 803 (2008)
  Wen (STAR Collaboration) - J. Phys.: Conf. Ser.779, 012067 (2017)
  CMS Collaboration - Phys. Rev. C 97, 044912 (2018)
- Contribution to Λ - $\bar{\Lambda}$ polarization
  STAR Collaboration - Nature 548, 62–65 (2017)
  Becattini, Karpenko, Lisa, Upsal, Voloshin - Phys. Rev. C 95, 054902 (2017)
  Guo, Shi, Feng, Liao - arXiv:1905.12613
- Pressure anisotropy in QGP Bali, Bruckmann, Endrődi et al. - Journal of High Energy Physics 08 177 (2014)
- A shift in meson masses and quarkonia states
  Andersen - Phys. Rev. D 86, 025020 (2012), Suzuki and Yoshida - Phys. Rev. D 93, 051502 (2016)
- Shift of the Critical Temperature Bali, Bruckmann, Endrődi et al. - Journal of High Energy Physics 02 044 (2012)
- Very low p_T charmonium photoproduction Shi, Zha, Chen - Phys.Lett. B 777, 399-405 (2018)
- $\gamma\gamma \rightarrow e^+e^-$ Breit-Wheeler process STAR Collaboration - arXiv:1910.12400

Inghirami, Mace, Hirono, Del Zanna, Kharzeev, Bleicher - arXiv:1908.07605

ECHO-QGP code, MHD version

Inghirami, Del Zanna, Beraudo, Haddadi Moghaddam, Becattini, Bleicher - EPJC 76 n.12, 659 (2016)

Fundamental assumptions:

- Energy and momentum conservation: $d_\mu T^{\mu\nu} = 0$
- Baryonic number conservation: $d_\mu N^\mu = 0$
- Second law of thermodynamics: $d_\mu s^\mu \geq 0$
- Maxwell equations: $d_\mu F^{\mu\nu} = -I^\nu,\ (d_\mu I^\mu = 0),\ d_\mu F^{\star\mu\nu} = 0$
- NO: dissipation, polarization, magnetization
- Infinite electrical conductivity: Ohm's law: $I^\mu = \tilde{\rho}_e u^\mu + j^\mu; \quad j^\mu = \sigma^{\mu\nu} e_\nu$ $\Rightarrow e^\mu = 0$ (LRF) $\Rightarrow \vec{E} = -\vec{v} \times \vec{B}$ (lab frame)

Energy-momentum tensor components:

$\mathcal{E} \equiv -T^0_0 = (e+p)\gamma^2 - p + \frac{1}{2}(E_k E^k + B_k B^k)$

$S_i \equiv T^0_i = (e+p)\gamma^2 v_i + \varepsilon_{ijk} E^j B^k$

$T^i_j = (e+p)\gamma^2 v^i v_j + (p + \frac{1}{2}(E_k E^k + B_k B^k))\delta^i_j$
$- E^i E_j - B^i B_j$

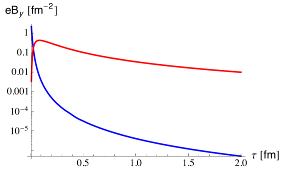
Evolution equations:

$$\partial_0 \mathbf{U} + \partial_i \mathbf{F}^i = \mathbf{S}$$

$$\mathbf{U} = |g|^{\frac{1}{2}} \begin{pmatrix} \gamma n \\ S_j \equiv T^0_j \\ \mathcal{E} \equiv -T^0_0 \\ B^j \end{pmatrix}, \quad \mathbf{F}^i = |g|^{\frac{1}{2}} \begin{pmatrix} \gamma n v^i \\ T^i_j \\ S^i \equiv -T^i_0 \\ v^i B^j - B^i v^j \end{pmatrix}$$

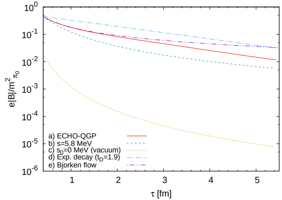
$$\mathbf{S} = |g|^{\frac{1}{2}} \begin{pmatrix} 0 \\ \frac{1}{2} T^{ik} \partial_j g_{ik} \\ -\frac{1}{2} T^{ik} \partial_0 g_{ik} \\ 0 \end{pmatrix}$$

Pb+Pb collision at $\sqrt{s}_{\rm NN}$=2.76 TeV, b=7 fm



Blue line: vacuum Red line: $\sigma = 4.5\,\mathrm{MeV}$

Gürsoy, Kharzeev, Rajagopal - Phys. Rev. C 89, 054905 (2014)

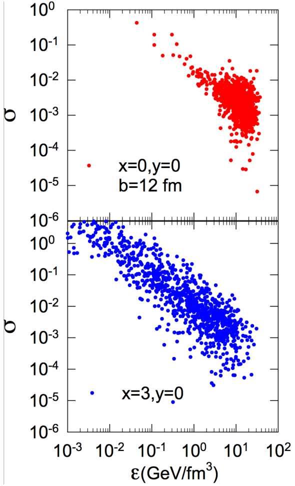


Au+Au @ $\sqrt{s_{NN}} = 200\,\mathrm{AGeV}$, b=10 fm

$\sigma = 5.8\,\mathrm{MeV}$, $\varepsilon_0 = 55\,\mathrm{GeV/fm^3}$

Inghirami, Del Zanna, Beraudo, Haddadi Moghaddam, Becattini, Bleicher - EPJC 76 n.12, 659 (2016)

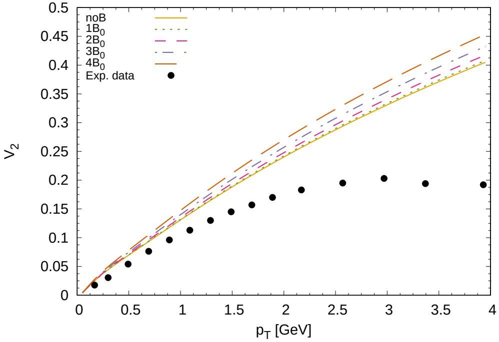
Au-Au at $\sqrt{s}_{\rm NN}$=200 GeV, Glauber-M.C., $t = 0.5\,\mathrm{fm}$

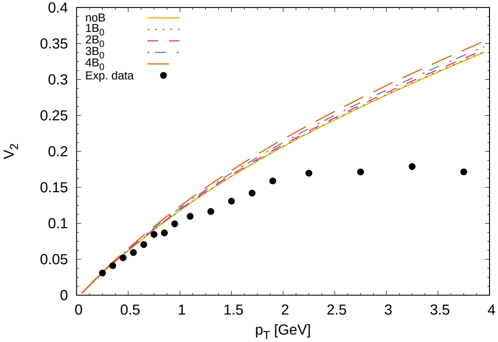


$$\sigma(x,y,\vec{b}) = \frac{B^2(x,y,\vec{b})}{2\varepsilon(x,y,\vec{b})}$$

Roy, Pu - Phys. Rev. C 92, 064902 (2015)

Initial conditions for the $\vec{B}$ field as in:
Li, Sheng and Wang, Phys. Rev. C 94, 044903 (2016) - Tuchin, Phys. Rev. C 88 (2013)



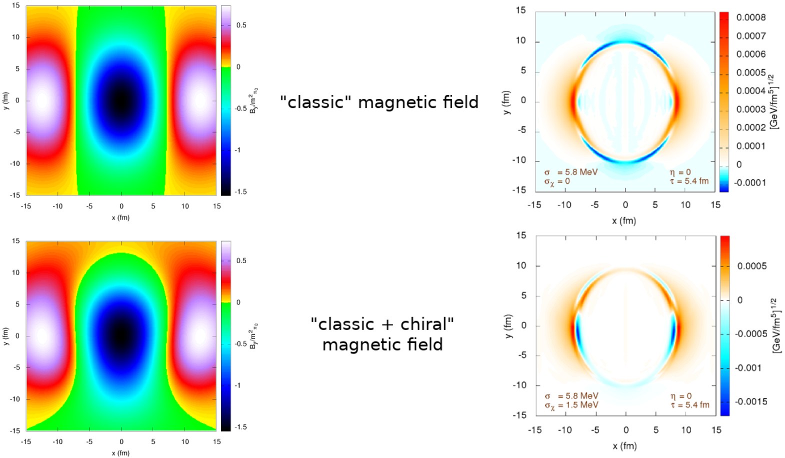


v_2 of $\pi^{\pm}$ (RHIC)
Au+Au @ $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, b=8 fm,
$\sigma = 5.8\,\mathrm{MeV}$, $\sigma_\chi = 1.5\,\mathrm{MeV}$, $\tau_0 = 0.4\,\mathrm{fm}/c$,
Exp. data from Phys. Rev., C 72:014904 (2005)

v_2 of $\pi^{\pm}$ (LHC)
Pb+Pb @ $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$, b=8 fm,
$\sigma = 5.8\,\mathrm{MeV}$, $\sigma_\chi = 1.5\,\mathrm{MeV}$, $\tau_0 = 0.2\,\mathrm{fm}/c$,
Exp. data from Phys. Rev. L., 105:252302 (2010)

Inghirami, Mace, Hirono, Del Zanna, Kharzeev, Bleicher - arXiv:1908.07605

Initial $\vec{B}$ fields from axial charges produce a charge density asymmetry w. respect to the reaction plane



Left: initial B_y at $\tau = 0.4\,\mathrm{fm}$ at $\eta = 0$, right: electric charge density in the fluid LRF at $\tau = 5.4\,\mathrm{fm}$ at $\eta = 0$.

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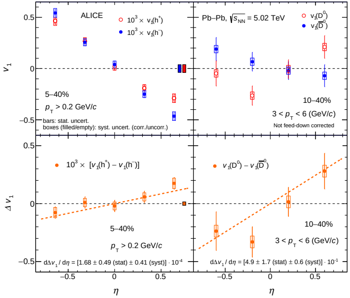
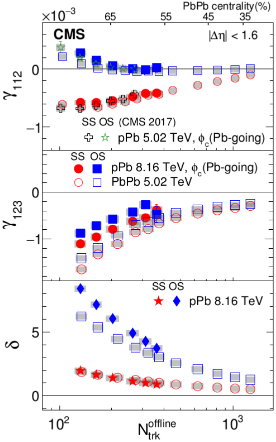
The next steps

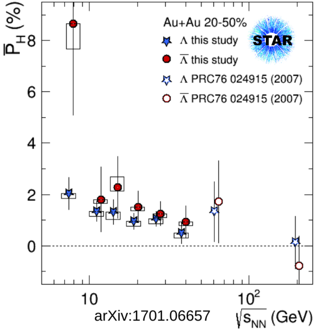
- Resistive-“chiral” MHD:
  $\partial \boldsymbol{E} - \nabla \times \boldsymbol{B} = \boldsymbol{J}_{\mathrm{Ohm}} + \boldsymbol{J}_{\mathrm{CME}} = \sigma \boldsymbol{E} + \sigma_{\mathrm{A}} \boldsymbol{B}$
  Del Zanna & Bucciantini, MNRAS, 479, 1 (2018)
- Explicit electric charge evolution:
  Denicol, Huang, Molnár, Monteiro, **Niemi**, Noronha, Rischke, Wang - Phys. Rev. D 98, 076009 (2018)
- Explicit axial charge evolution:
  $\partial_\mu J^A = -C_A E_\mu B^\mu, \quad J_A^\mu = n_A u^\mu + J_{A(1)}^\mu$
  $E_{(1)}^\mu = -\frac{1}{\sigma}[C_A \mu_A B^\mu + T \epsilon^{\mu\nu\alpha\beta} u_\nu \partial_\alpha (\frac{H_\beta}{T})]$
  Warning: only first order. Second order under development.
  Hattori, Hirono, Yee, Yin - Phys. Rev. D 100, 065023 (2019)
- Re-inclusion of viscosity
  Del Zanna, Chandra, **Inghirami**, Rolando, Beraudo, De Pace, Pagliara, Drago, Becattini - Eur.Phys.J. C73 (2013)
- Reconsider initial conditions and final hadronic phase
  Eskola, Niemi, Paatelainen - Phys. Rev. C 93, 024907 (2016)



ALICE collaboration
arXiv:1910.14406



CMS collaboration
P.R.C. 97, 044912 (2018)



STAR collab., Nature 548, 62 (2017)