Analytic model studies of polarized baryon production

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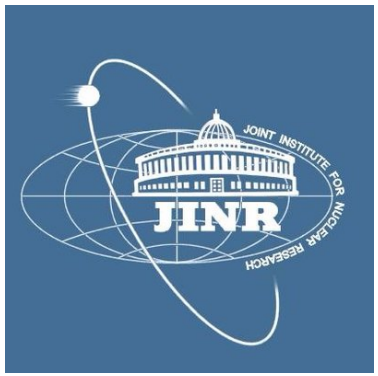
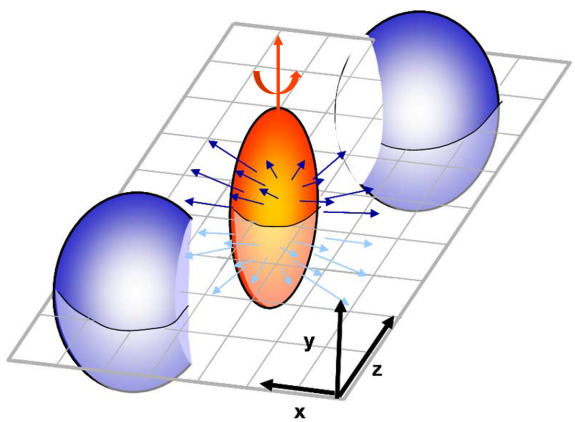


Aims

- QGP: hot expanding perfect fluid $\rightarrow$ hydrodynamical modelling
- Polarization can be calculated in exact hydro solutions
- Polarization is proportional: vorticity of $u^\mu / T(x)$

  F. Becattini *et al.*, Annals Phys. 338, 32 (2013)
- Measurements in STAR: polarization of Λ-baryons (2017)
  $\rightarrow$ analytical solutions are also interesting
- Phenomenological study; analytic formulas
  $\rightarrow$ possibility to get some information of the EoS
- Rotation, acceleration and temperature gradient



Hydro solutions

- Many numerical simulations
- Importance of analytic solutions
- Connection between the initial and final state
- Self-similar expanding solution (Hubble-flow)

  T. Csörgő *et al.*, Acta Phys. Hung. A 21 (2004) 73
- Rotating and accelerating expanding solution

  M. I. Nagy, Phys. Rev. C83, 054901 (2011)
- Buda–Lund model

  M. Csanád, T. Csörgő and B. Lörstad, Nucl. Phys. A **742** (2004) 80

Single particle momentum distribution and polarization

- Cooper–Frye-formula:

  F. Cooper and G. Frye, Phys. Rev. D 10, 186 (1974).

$$E\frac{\mathrm{d}N}{\mathrm{d}^3\boldsymbol{p}} = \int \mathrm{d}^3\Sigma_\nu p^\nu f(x,p), \quad \text{where } f \text{ is the source function}$$

$$f(x,p) \propto \frac{1}{e^{p_\mu\beta^\mu-\mu/T}+1} \ll 1 \quad \Rightarrow \quad f(x,p) = \frac{n}{4\pi T^3}\exp\left(-p_\mu\beta^\mu\right).$$

- Polarization four-vector:

$$\langle S(x,p)\rangle^\mu = \frac{1}{8m}\varepsilon^{\mu\nu\rho\sigma}(1-f(x,p))p_\sigma\partial_\nu\beta_\rho \approx \frac{1}{8m}\varepsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho,$$

  which can be integrated over the freeze-out hypersurface:

$$\langle S(p)\rangle^\mu = \frac{\int \mathrm{d}^3\Sigma_\nu p^\nu f(x,p)\langle S(x,p)\rangle^\mu}{\int \mathrm{d}^3\Sigma_\nu p^\nu f(x,p)} \approx \frac{1}{8m}\varepsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho\Big|_{\mathbf{r}=\mathbf{R_0}}.$$

  F. Becattini and I. Karpenko, Phys. Rev. Lett. 120, no. 1, 012302 (2018)

Spherical symmetric self-similar flow

Aim: polarization four-vector

- no rotation $\rightarrow$ **zero polarization**? $(\mathbf{S} = \mathbf{0})$

Velocity, particle density and temperature fields:

$$u^\mu = \frac{x^\mu}{\tau}, \qquad n = n_0 \left(\frac{\tau_0}{\tau}\right)^3 \mathcal{V}(S), \qquad T = T_0 \left(\frac{\tau_0}{\tau}\right)^{\frac{3}{\kappa}} \frac{1}{\mathcal{V}(S)}.$$

- S: scale function, e.g. $S(\tau) = \frac{r_x^2}{\dot{X}_0^2 \tau^2} + \frac{r_y^2}{\dot{Y}_0^2 \tau^2} + \frac{r_z^2}{\dot{Z}_0^2 \tau^2}$.
- $\mathcal{V}(S) = 1$: spherical symmetric case
- $\tau = \tau_0 =$ const. freeze-out hypersurface.
- saddle-point: $\mathbf{R_0} = \frac{\tau_0}{m}\mathbf{p}$

Polarization

$$\langle S(p) \rangle^\mu = 0.$$

Rotating and accelerating expanding solution

Velocity, particle density and temperature fields

$$\boldsymbol{v} = \frac{2t\boldsymbol{r} + \rho^2 \boldsymbol{\Omega} \times \boldsymbol{r}}{t^2 + r^2 + \rho^2}, \quad n = n_0 \left(\frac{T}{T_0} \right)^3, \quad T = \frac{T_0 \tau_0^2}{\sqrt{(t^2 - r^2 + \rho^2)^2 + 4\rho^2 r^2 - \rho^4 (\boldsymbol{\Omega} \times \boldsymbol{r})^2}}.$$

- $\boldsymbol{\Omega}$: angular velocity vector (y axis)
- $\tau = \tau_0 =$ const. freeze out hypersurface.
- Momentum spectrum:

$$E \frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} \propto \sqrt{\frac{\pi^3 T_0^3 \tau_0^3}{32 p (m + E)}} \exp\left(-\frac{E_{eff}}{T_0} \right), \quad \text{where}$$

$$E_{eff} = m + \frac{\rho^2 E}{\tau_0^2} + \frac{\rho^4 (\mathbf{p} \times \boldsymbol{\Omega})^2}{4 p^2 \tau_0^2} (E - m)$$

Polarization in rotating and accelerating expanding solution

Polarization four-vector

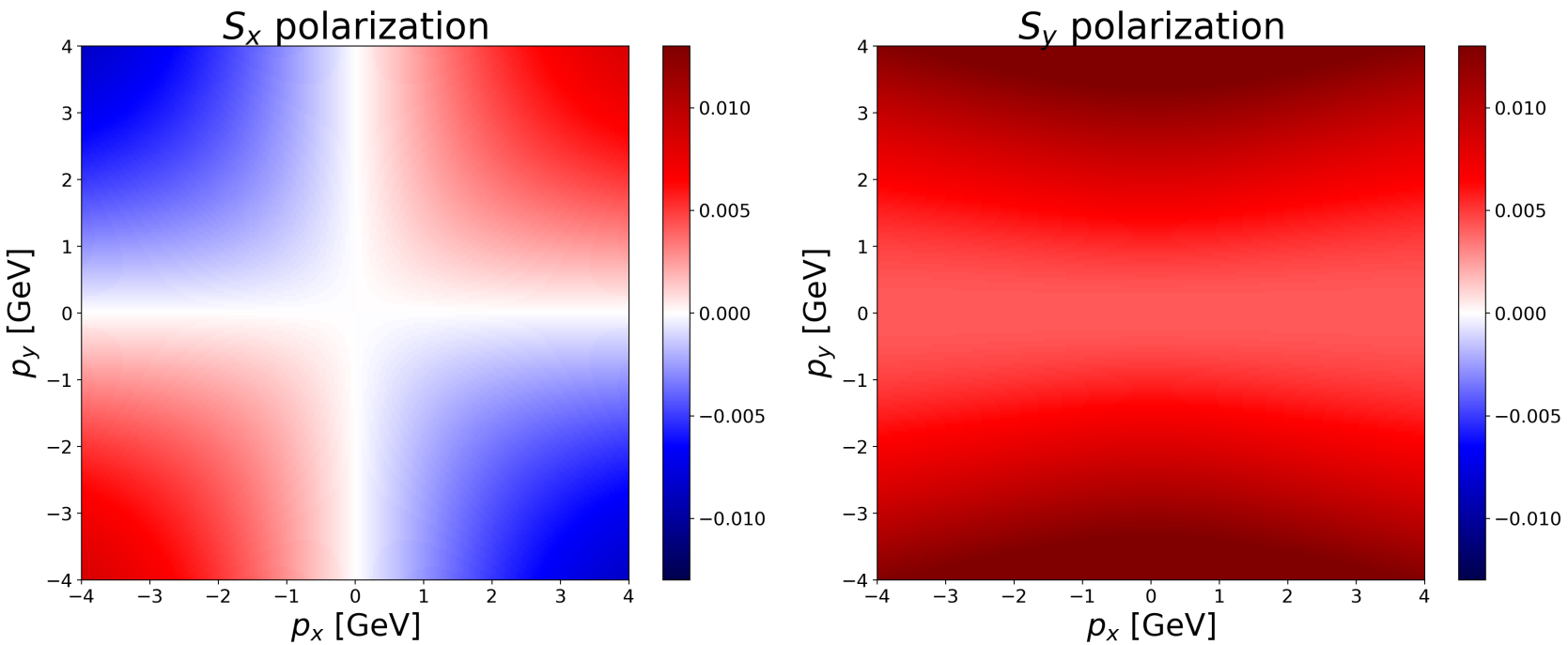
$$\langle S(\mathbf{p})\rangle^{\mu} = \frac{1}{8mT_0}\begin{pmatrix} \mathbf{p\Omega} \\ m\mathbf{\Omega} + \frac{E-m}{p^2}(\mathbf{\Omega p})\mathbf{p} \end{pmatrix}$$

- First analytical result for the polarization
- With no rotation ($\mathbf{\Omega} = \mathbf{0}$) zero polarization
  $\rightarrow$ rotation causes the polarization.

Local rest frame of the particle

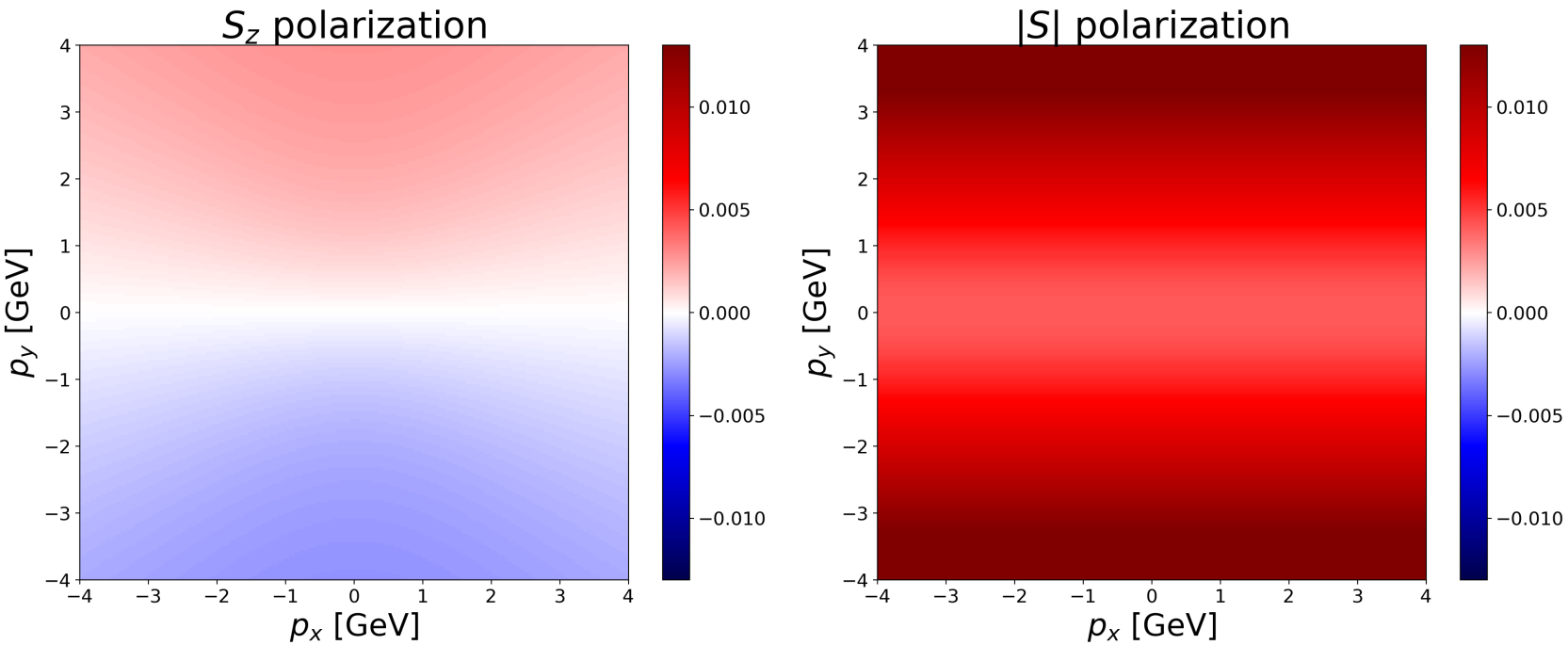
$$\langle S(\mathbf{p})\rangle^{\mu}_{\text{r.f.}} = \begin{pmatrix} 0 \\ \frac{1}{8T_0}\mathbf{\Omega} \end{pmatrix}.$$

Polarization vector plots: rotating and expanding solution



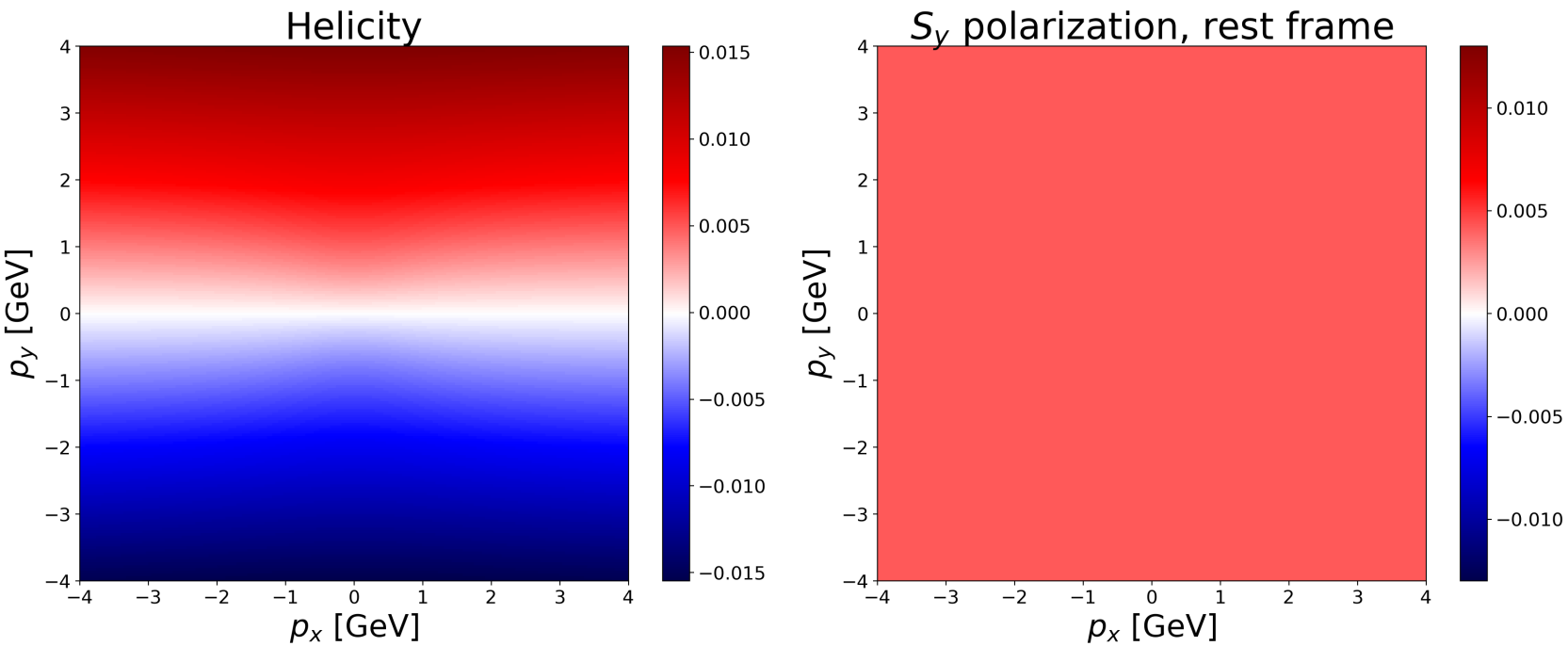
- S_x: the sign depends on the sign of the momentum components
- S_y: mostly p_y dependence

Polarization vector plots: rotating and expanding solution



- S_z: mostly p_y dependence

Helicity and polarization in the rest frame



- Helicity: $\Lambda_s := \frac{\mathbf{pS}}{p} = \frac{E}{8mpT_0}\mathbf{p\Omega}$
- S_y constant in the rest frame, other components zero

Buda–Lund model

Relativistic parameterization of the self-similiar ellipsoidal flows

Four-velocity

$$u^\mu(x) = \begin{pmatrix} \gamma \\ \frac{\dot{X}(t)}{X(t)} r_x + \Omega(t) \frac{R(t)}{Z(t)} r_z \\ \frac{\dot{Y}(t)}{Y(t)} r_y \\ \frac{\dot{Z}(t)}{Z(t)} r_z - \Omega(t) \frac{R(t)}{X(t)} r_x \end{pmatrix}, \quad \text{where} \quad R(t) \equiv \frac{X(t)+Z(t)}{2},$$

and γ from $u_\mu u^\mu = 1$.

Temperature field and scale function

$$\frac{1}{T(x)} = \frac{1}{T_0}\left(1+a^2 S\right)\left(1+\alpha^2 \frac{(\tau-\tau_0)^2}{2(\Delta\tau)^2}\right), \quad \text{where} \quad a^2 \equiv \frac{T_0-T_s}{T_s}, \quad \alpha^2 \equiv \frac{T_0-T_e}{T_e},$$

$$S = \frac{r_x^2}{2X^2} + \frac{r_y^2}{2Y^2} + \frac{r_z^2}{2Z^2}.$$

Buda–Lund model

- Well describes many observables $\rightarrow$ realistic
- Analitic solution
- Rotating generalization
- Freeze-out: Gaussian

$$H(\tau) = \frac{1}{\sqrt{2\pi(\Delta\tau)^2}} \exp\left(-\frac{(\tau-\tau_0)^2}{2(\Delta\tau)^2}\right) \quad \Rightarrow \quad H(\tau) = \delta(\tau-\tau_0).$$

Saddle-point

$$r_x = \frac{p_x X\dot{X} - p_z \Omega R X}{T_0 b^2 + E(a^2 + \dot{X}^2 + \Omega^2 R^2)},$$

$$r_y = \frac{p_y Y\dot{Y}}{T_0 b^2 + E(a^2 + \dot{Y}^2)},$$

$$r_z = \frac{p_z Z\dot{Z} + p_x \Omega R Z}{T_0 b^2 + E(a^2 + \dot{Z}^2 + \Omega^2 R^2)}.$$

Polarization in Buda–Lund model

Polarization four-vector:

$$\langle S(\mathbf{p})\rangle^{\mu} = \frac{1}{8m}\varepsilon^{\mu\nu\rho\sigma} p_\sigma \partial_\nu \beta_\rho \Big|_{\mathbf{r}=\mathbf{R}_0}.$$

Polarization four-vector

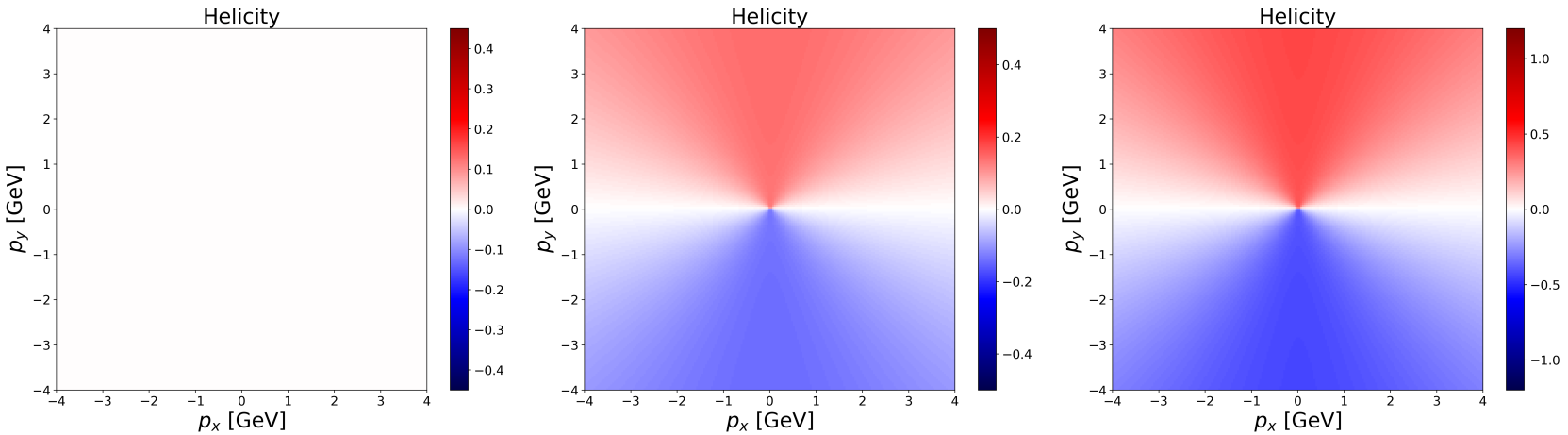
$$\langle S(\mathbf{p})\rangle^{0} = -\frac{1}{8m}\varepsilon_{klm}\mathbf{p}_m\partial_k\beta_l = -\frac{1}{8m}\mathbf{p}\,(\nabla\times\boldsymbol{\beta})$$

$$\langle S(\mathbf{p})\rangle^{k} = \frac{1}{8m}\Big((\partial_0\boldsymbol{\beta})\times\mathbf{p}\Big)_k - \frac{1}{8m}(\nabla\beta_0\times\mathbf{p})_k - \frac{p_0}{8m}(\nabla\times\boldsymbol{\beta})_k.$$

Rest frame

$$\mathbf{S}_{\text{r.f.}} = \frac{1}{8m}\left\{(\partial_0\boldsymbol{\beta}-\nabla\beta_0)\times\mathbf{p} - E(\nabla\times\boldsymbol{\beta}) + \frac{E-m}{p^2}(\mathbf{p}(\nabla\times\boldsymbol{\beta}))\mathbf{p}\right\}.$$

Helicity in the Buda–Lund model



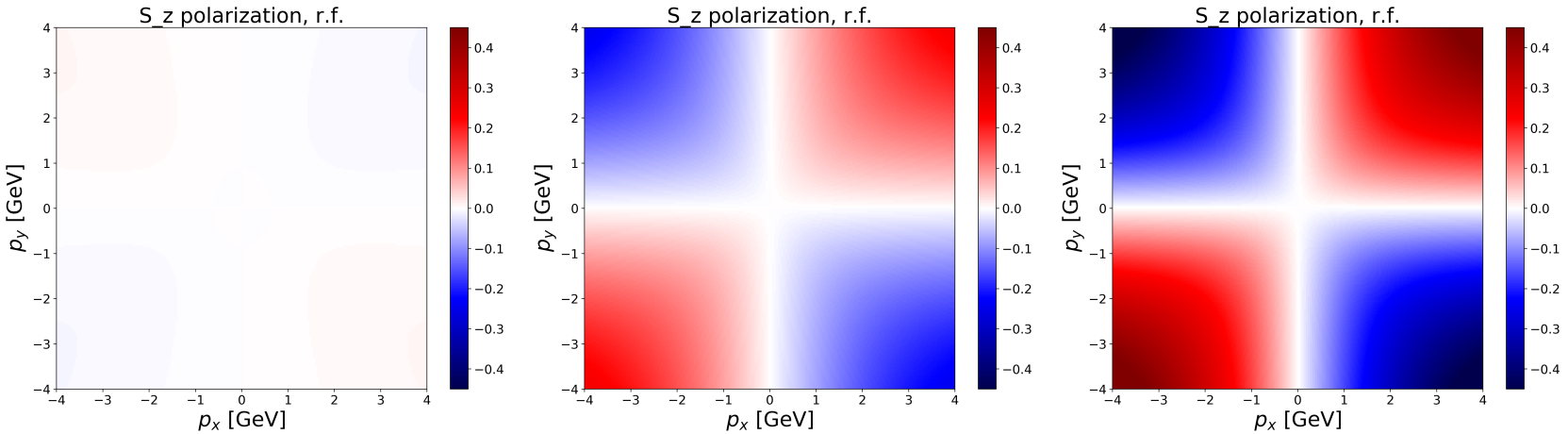
(a) $\Omega = 0$ (b) $\Omega = 0.1$ (c) $\Omega = 0.3$

Helicity:

$$\Lambda_s = \frac{\mathbf{pS}_{\text{r.f.}}}{p} = -\frac{1}{8p}\mathbf{p}(\nabla \times \boldsymbol{\beta}).$$

- Same 'pattern' for different rotation, acceleration and temperature gradient values
- Rotation plays a significant role

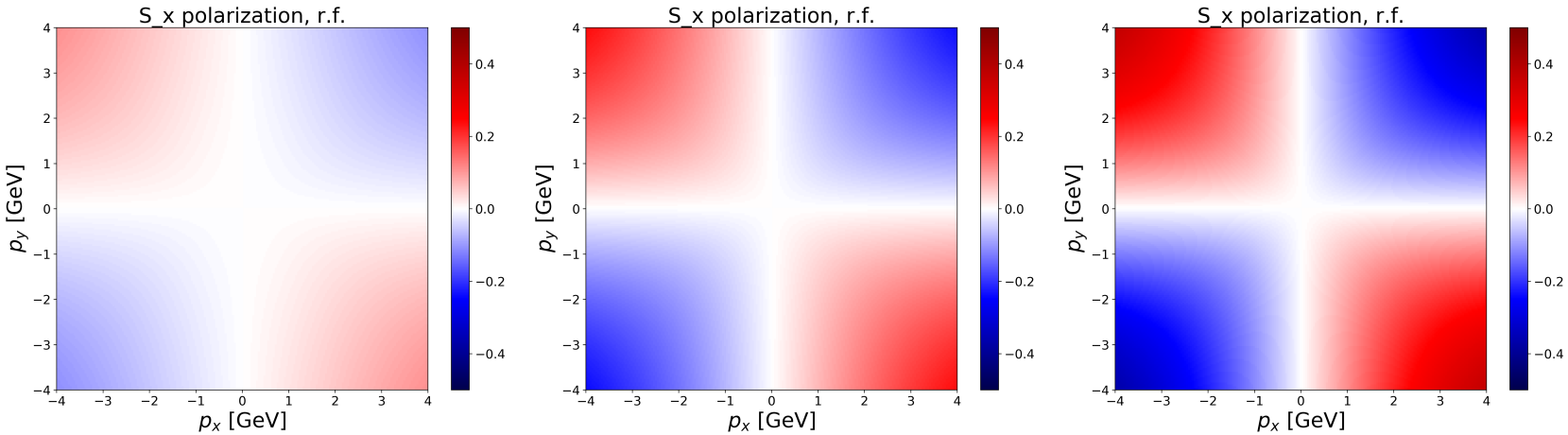
Polarization vector plots: Buda–Lund model, S_z, $\Omega = 0$



(a) $\zeta = 0$ (b) $\zeta = 0.5$ (c) $\zeta = 1$

- $\Omega = 0$: zero rotation; $a^2 = 0$: zero temperature gradient
- ζ: acceleration
- Large increase in the value of polarization with growing acceleration
- If $\Omega = 0$: other components zero

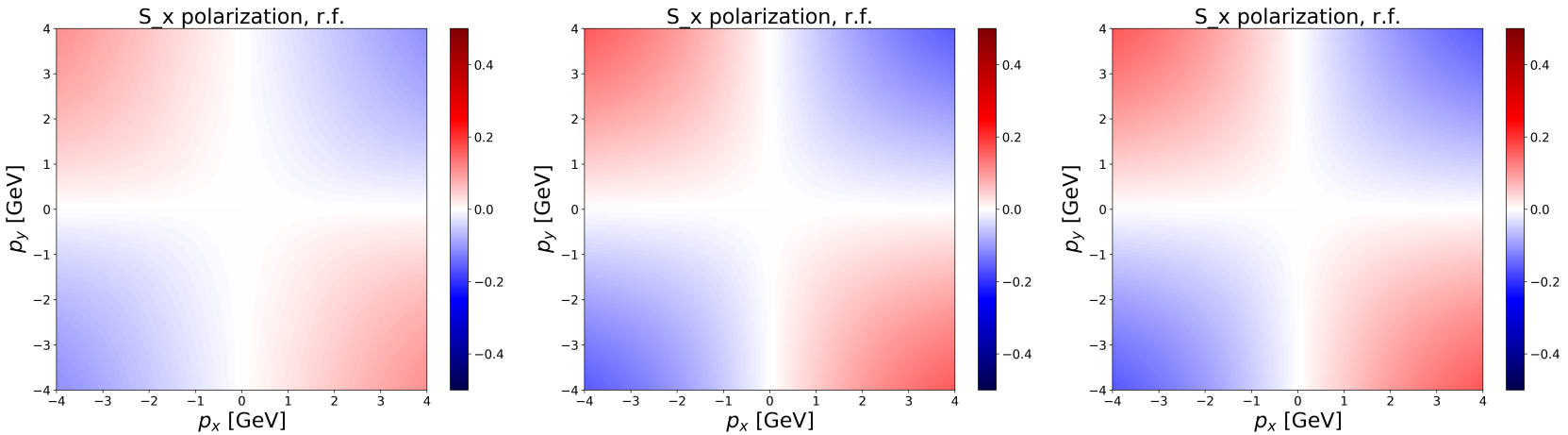
Polarization vector plots: Buda–Lund model, S_x, $\Omega = 0.1$



(a) $\zeta = 0$ (b) $\zeta = 0.5$ (c) $\zeta = 1$

- $\Omega = 0.1$: rotation, $a^2 = 0$: zero temperature gradient
- ζ: acceleration
- Large acceleration $\rightarrow$ greater polarization

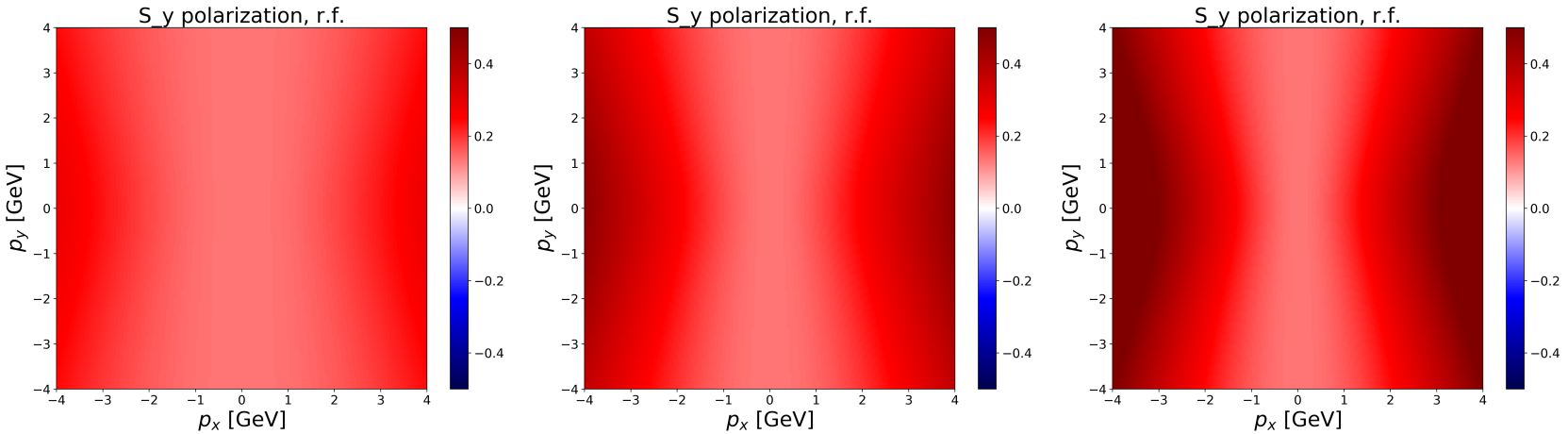
Polarization vector plots: Buda–Lund model, S_x, $\Omega = 0.1$



(a) $a^2 = 0$ (b) $a^2 = 0.5$ (c) $a^2 = 1$

- $\Omega = 0.1$: rotation, $\zeta = 0$: zero acceleration
- a^2: temperature gradient
- Bigger temperature gradient $\rightarrow$ small increase in the polarization

Polarization vector plots: Buda–Lund model, S_y, $\Omega = 0.1$



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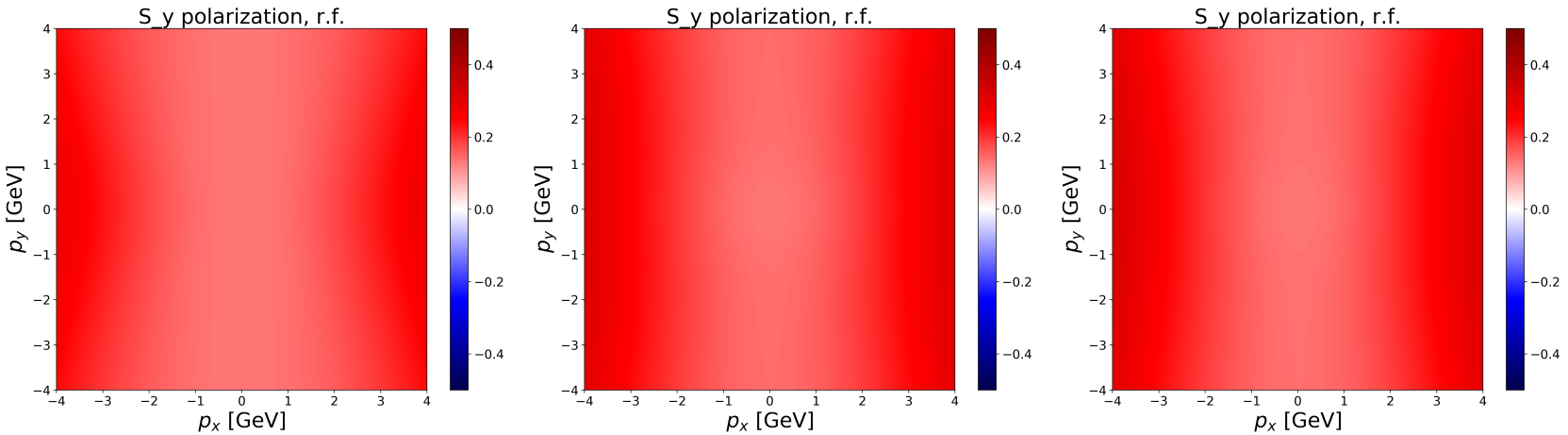
Polarization vector plots: Buda–Lund model, S_y, $\Omega = 0.1$



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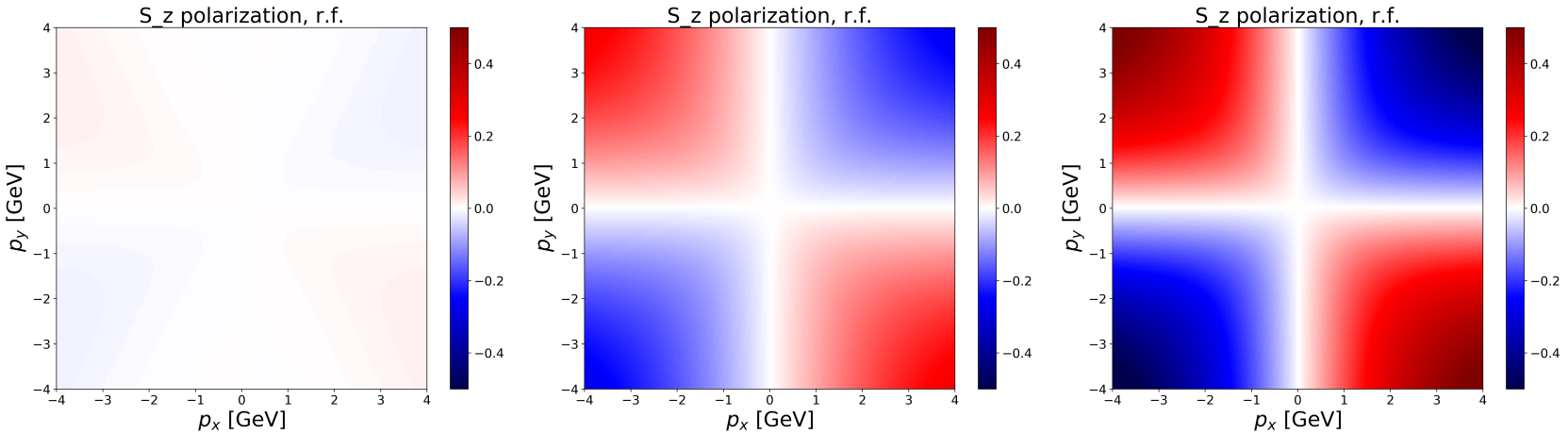
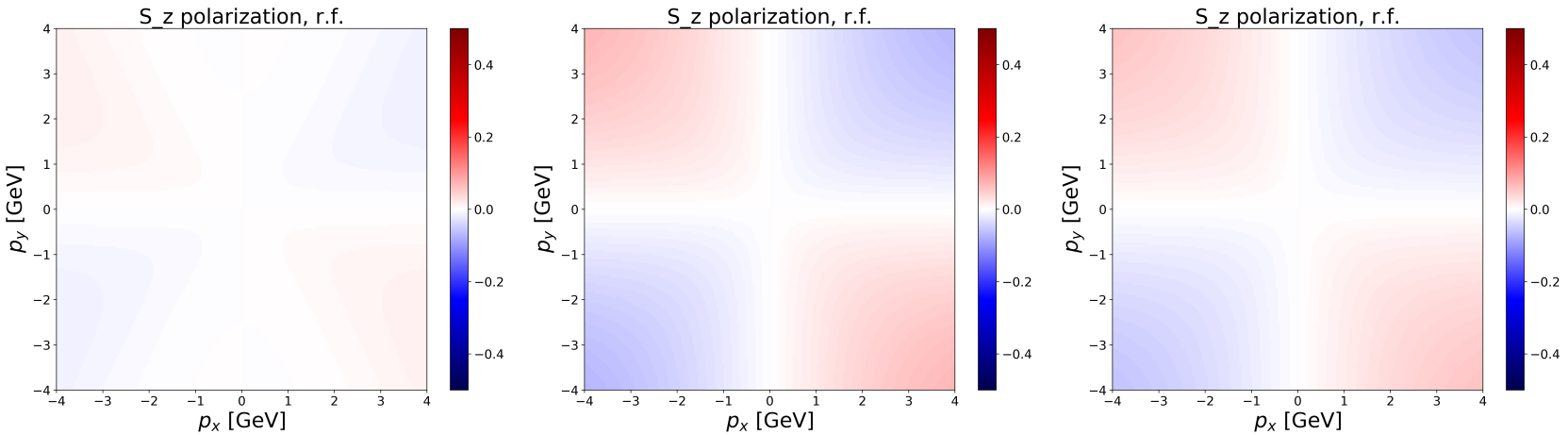
Polarization vector plots: Buda–Lund model, S_z, $\Omega = 0.1$



(a) $\zeta = 0$ (b) $\zeta = 0.5$ (c) $\zeta = 1$

- $\Omega = 0.1$: rotation, $a^2 = 0$: zero temperature gradient
- ζ: acceleration
- Large acceleration $\rightarrow$ greater polarization

Polarization vector plots: Buda–Lund model, S_z, $\Omega = 0.1$



(a) $a^2 = 0$ (b) $a^2 = 0.5$ (c) $a^2 = 1$

- $\Omega = 0.1$: rotation, $\zeta = 0$: zero acceleration
- a^2: temperature gradient
- Bigger temperature gradient $\rightarrow$ small increase in the polarization

Conclusion

Determination of the polarization:

Spherical symmetric self-similar flow

$$\langle S(p)\rangle^{\mu} = 0$$

Rotating and accelerating expanding solution

$$\langle S(p)\rangle^{\mu} = \frac{\rho^2}{8m}\begin{pmatrix}\mathbf{p\Omega}\\ E\mathbf{\Omega}\end{pmatrix}, \qquad \langle S(p)\rangle^{\mu}_{\text{r.f.}} = \frac{\rho^2}{8m}\begin{pmatrix}0\\ (m-E)\dfrac{\mathbf{p}(\mathbf{p\Omega})}{p^2} + E\mathbf{\Omega}\end{pmatrix}.$$

B. Boldizsár, M. I. Nagy and M. Csanád, Universe **5** (2019) no.5, 101

Buda–Lund model

$$\mathbf{S}_{\text{r.f.}} = \frac{1}{8m}\left\{(\partial_0\boldsymbol{\beta} - \nabla\beta_0)\times\mathbf{p} - E(\nabla\times\boldsymbol{\beta}) + \frac{E-m}{p^2}(\mathbf{p}(\nabla\times\boldsymbol{\beta}))\mathbf{p}\right\}.$$

- First analytical formulas for the polarization

Single particle distribution

Half spin particles:

- Single particle distribution: Fermi–Dirac statistics

$$f(x,p) \propto \frac{1}{\exp\left\{p_\mu \beta^\mu - \frac{\mu(x)}{T(x)}\right\} + 1},$$

where $\beta^\mu = \frac{u^\mu}{T(x)}$ is the so called inverse temperature field.

- Maxwell–Boltzmann distribution:

$$f(x^\mu, p^\mu) = \frac{n}{4\pi T^3} \exp\left(-p_\mu \beta^\mu\right).$$

Saddle-point integration method

Approximating method for the calculation

- product of a 'flat' function and one with a 'sharp maximum'
- flat function: constant
- function with a sharp maximum: Gauss

Determine the following integration:

$$\int g(\mathbf{r})h(\mathbf{r})\mathrm{d}^3\mathbf{r} \approx g(\mathbf{R_0})h(\mathbf{R_0}) \int \mathrm{d}^3\mathbf{r} \exp\left\{-\frac{1}{2}(\mathbf{r}-\mathbf{R_0})\mathbf{M}(\mathbf{r}-\mathbf{R_0})\right\} =$$

$$= g(\mathbf{R_0})h(\mathbf{R_0})\sqrt{\frac{(2\pi)^3}{\det \mathbf{M}}}.$$

$\mathbf{R_0}$: saddle-point
$\mathbf{M}$: second derivative matrix

Self similarly expanding solution

- Momentum spectrum:

$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} = \frac{n_0}{4}\sqrt{\frac{\pi\tau_0^3}{mT_0^3}}\exp\left(-\frac{\tau_0 m}{T_0}\right)$$

- For the polarization four-vector we need to determine the $\partial_\nu\beta_\rho$ derivative:

$$\partial_\nu\beta_\rho = \frac{g_{\nu\rho}}{\sqrt{\tau_0^2+r^2}\,T_0} + \frac{x_\nu x_\rho}{(\tau_0^2+r^2)^{3/2}\,T_0}$$

- Using the fact that $\varepsilon^{\mu\nu\rho\sigma}$ is anti-symmetric and $\partial_\nu\beta_\rho$ symmetric:

$$\langle S(p)\rangle^0 = 0, \qquad \langle S(p)\rangle^i = 0 \quad \Rightarrow \quad \langle S(p)\rangle^\mu = 0$$

Further investigations

- Self-similar expanding solution

  T. Csörgő *et al.*, Acta Phys. Hung. A 21 (2004) 73

$$u^\mu = \frac{x^\mu}{\tau}, \qquad n = n_0 \left(\frac{\tau_0}{\tau}\right)^3 \mathcal{V}(S), \qquad T = T_0 \left(\frac{\tau_0}{\tau}\right)^{\frac{3}{\kappa}} \frac{1}{\mathcal{V}(S)},$$

  where

$$\mathcal{V}(S) = 1 + bS, \qquad S(\tau) = \frac{r_x^2}{\dot{X}_0^2 \tau^2} + \frac{r_y^2}{\dot{Y}_0^2 \tau^2} + \frac{r_z^2}{\dot{Z}_0^2 \tau^2}.$$

- Rotating Hubble-like solution

  M. I. Nagy, Phys. Rev. C83, 054901 (2011)

$$\mathbf{v} = \frac{\mathbf{r} + \mathbf{E}t + \mathbf{B} \times \mathbf{r}}{t + (\mathbf{E}\mathbf{r})}, \qquad n = n_0 \left(\frac{T}{T_0}\right)^\kappa,$$

$$T = \frac{T_0 \tau_0}{\sqrt{t^2 - r^2 + (\mathbf{B}\mathbf{r})^2 - B^2 r^2 - E^2 t^2 + (\mathbf{E}\mathbf{r})^2}}$$

Rotating and expanding solution

Velocity, particle density and temperature fields

$$\boldsymbol{v} = \frac{2t\boldsymbol{r} + \tau_0^2 \boldsymbol{\Omega} \times \boldsymbol{r}}{t^2 + r^2 + \rho_0^2}, \quad n = n_0 \left(\frac{T}{T_0}\right)^3, \quad T = \frac{T_0 \tau_0^2}{\sqrt{(t^2 - r^2 + \rho_0^2)^2 + 4\rho_0^2 r^2 - \tau_0^4 (\boldsymbol{\Omega} \times \boldsymbol{r})^2}}.$$

- $\tau = \tau_0 = \text{const.}$ freeze-out hypersurface.
- saddle-point: $\mathbf{R_0} = \alpha \mathbf{p} + \beta \tau_0^2 (\mathbf{p} \times \boldsymbol{\Omega})$,

$$\alpha = 2\beta\tau_0 \sqrt{\frac{1 + \beta^2 \tau_0^2 (\mathbf{p} \times \boldsymbol{\Omega})^2}{1 - 4\beta^2 p^2}} \qquad \text{and} \qquad \beta = \frac{E - m}{2p^2}.$$

- Momentum spectrum:

$$E \frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} \propto \sqrt{\frac{\pi^3 T_0^3 \tau_0^3}{32p(m + E)}} \exp\left(-\frac{E_{eff}}{T_0}\right), \quad \text{where}$$

$$E_{eff} = m + \frac{\rho_0^2 E}{\tau_0^2} + \frac{\tau_0^2 (\mathbf{p} \times \boldsymbol{\Omega})^2}{4p^2} (E - m)$$

Buda–Lund model: Saddle-point

Implicit system of equations

$$\frac{r_x}{X} = \frac{p_x\dot{X} - p_z\Omega R + r_z\dfrac{E\Omega}{Z\gamma}R(\dot{Z}-\dot{X})}{\dfrac{T_0}{1+a^2A}\left(\dfrac{p_\mu u^\mu}{T_0}a^2+b^2\right)+\dfrac{E}{\gamma}\left\{\dot{X}^2+\Omega^2R^2\right\}},$$

$$\frac{r_y}{Y} = \frac{p_y\dot{Y}}{\dfrac{T_0}{1+a^2A}\left(\dfrac{p_\mu u^\mu}{T_0}a^2+b^2\right)+\dfrac{E}{\gamma}\dot{Y}^2},$$

$$\frac{r_z}{Z} = \frac{p_z\dot{Z} + p_x\Omega R + r_x\dfrac{E\Omega}{X\gamma}R(\dot{Z}-\dot{X})}{\dfrac{T_0}{1+a^2A}\left(\dfrac{p_\mu u^\mu}{T_0}a^2+b^2\right)+\dfrac{E}{\gamma}\left\{\dot{Z}^2+\Omega^2R^2\right\}},$$

Buda–Lund model: derivatives

$$\partial_0\beta_k = -\frac{1}{T}\begin{pmatrix} \frac{\dot{X}}{X}r_x + \Omega\frac{R}{Z}r_z \\ \frac{\dot{Y}}{Y}r_y \\ \frac{\dot{Z}}{Z}r_z - \Omega\frac{R}{X}r_x \end{pmatrix} \cdot \left\{ -\frac{1}{1+a^2S}\left(\frac{\dot{X}}{X^3}r_x^2 + \frac{\dot{Y}}{Y^3}r_y^2 + \frac{\dot{Z}}{Z^3}r_z^2 \right) \right\} +$$

$$+\frac{1}{T_0}\left(1+a^2S\right)\begin{pmatrix} \left(\frac{\ddot{X}}{X} - \frac{\dot{X}^2}{X^2}\right)r_x + \frac{(\dot{\Omega R})}{Z}r_z - \Omega R\frac{\dot{Z}}{Z^2}r_z \\ \left(\frac{\ddot{Y}}{Y} - \frac{\dot{Y}^2}{Y^2}\right)r_y \\ \left(\frac{\ddot{Z}}{Z} - \frac{\dot{Z}^2}{Z^2}\right)r_z - \frac{(\dot{\Omega R})}{X}r_x - \Omega R\frac{\dot{X}}{X^2}r_x \end{pmatrix},$$

Buda–Lund model: derivatives

$$\partial_k \beta_0 = = \frac{a^2}{T_0}\gamma \begin{pmatrix} \frac{r_x}{X^2} \\ \frac{r_y}{Y^2} \\ \frac{r_z}{Z^2} \end{pmatrix} + \frac{1}{T_0}\left(1 + a^2 A\right)\frac{1}{\gamma} \begin{pmatrix} \frac{\dot{X}^2 + \Omega^2 R^2}{X^2} r_x + \Omega R \frac{\dot{X} - \dot{Z}}{XZ} r_z \\ \frac{\dot{Y}^2}{Y^2} r_y \\ \frac{\dot{Z}^2 + \Omega^2 R^2}{Z^2} r_z + \Omega R \frac{\dot{X} - \dot{Z}}{XZ} r_x \end{pmatrix}.$$

Buda–Lund model: derivatives

$$\nabla \times \boldsymbol{\beta} = \begin{pmatrix} 0 \\ -\omega \dfrac{(X+Z)^2}{2XZ} \\ 0 \end{pmatrix} +$$

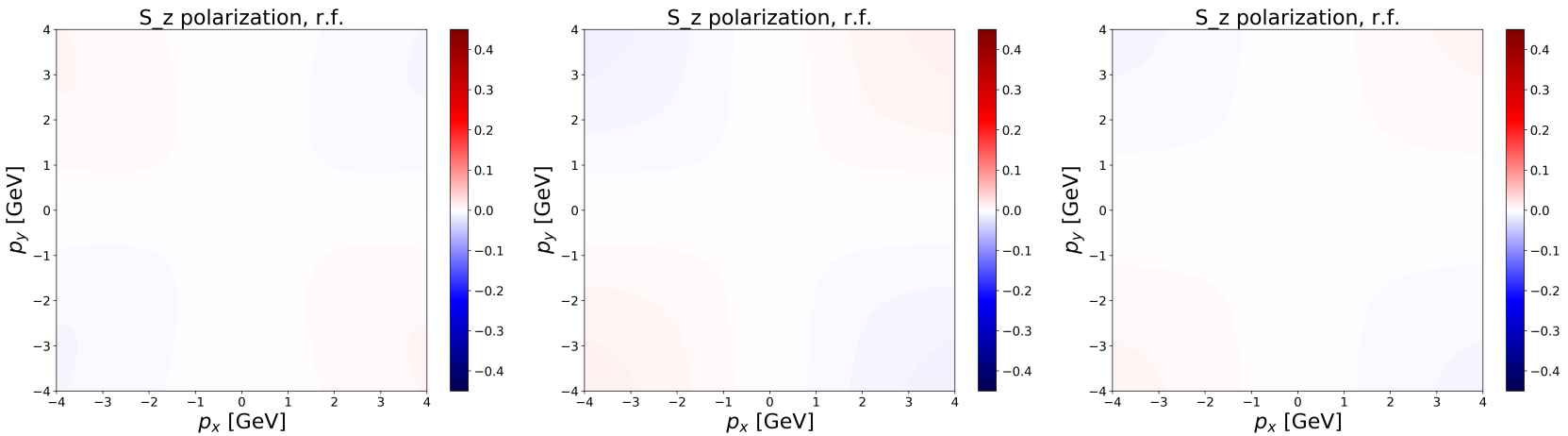
$$+ -\frac{a^2}{T_0} \begin{pmatrix} \dfrac{r_y}{Y^2}\left(\dfrac{\dot{Z}}{Z} r_z - \Omega R \dfrac{r_x}{X}\right) - \dfrac{r_z}{Z^2}\dfrac{\dot{Y}}{Y} r_y \\ \dfrac{r_z}{Z^2}\left(\dfrac{\dot{X}}{X} r_x - \Omega R \dfrac{r_z}{Z}\right) - \dfrac{r_x}{X^2}\left(\dfrac{\dot{Z}}{Z} r_z - \Omega R \dfrac{r_x}{X}\right) \\ \dfrac{r_x}{X^2}\dfrac{\dot{Y}}{Y} r_y - \dfrac{r_y}{Y^2}\left(\dfrac{\dot{X}}{X} r_x + \Omega R \dfrac{r_z}{Z}\right) \end{pmatrix}.$$

Buda–Lund model: parameters for the plots

The parameters for the plot:

X [fm]	6	Ω_x	0
Y [fm]	8	Ω_y	0/0.1/0.3
Z [fm]	10	Ω_z	0
$\dot{X}$ [c]	0.3	T_0 [GeV]	0.2
$\dot{Y}$ [c]	0.4	b^2	0.1
$\dot{Z}$ [c]	0.2	m [GeV/c^2]	1.115
p_z [GeV/c]	0	m_0 [GeV/c^2]	0.140

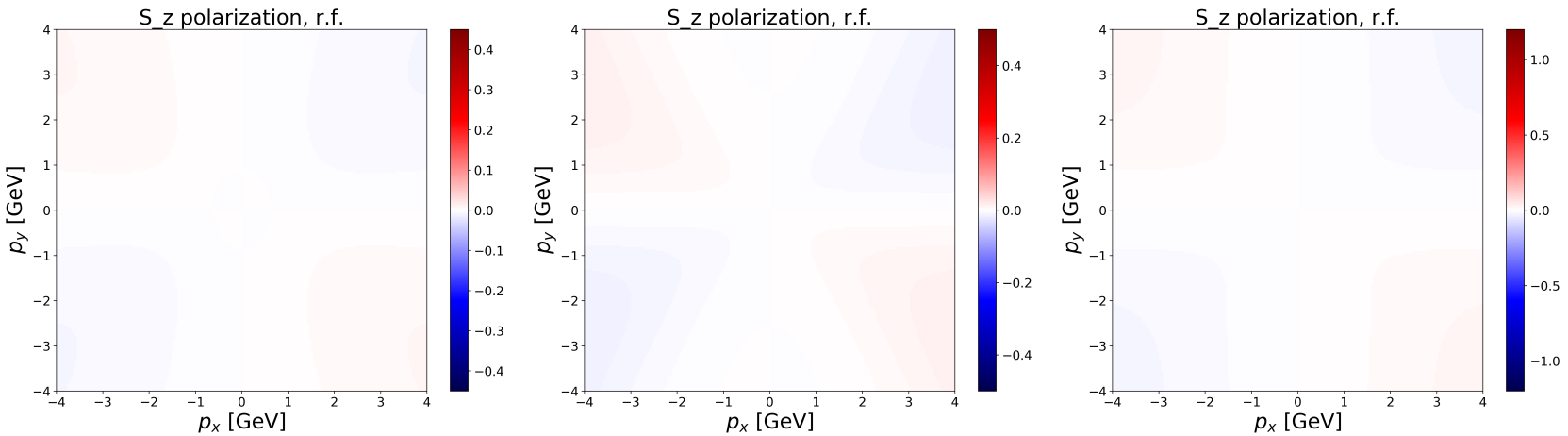
Polarization vector plots: Buda–Lund model, S_z, $\Omega = 0$



(a) $a^2 = 0$ (b) $a^2 = 0.5$ (c) $a^2 = 1$

- $\Omega = 0, \quad \zeta = 0$
- Sign change with growing temperature gradient

Polarization vector plots: Buda–Lund model, S_z



(a) $\Omega = 0$ (b) $\Omega = 0.1$ (c) $\Omega = 0.3$

- $a^2 = 0, \quad \zeta = 0$
- No significant change with growing rotation
  $\rightarrow$ acceleration and temperature gradient also important