Effect of hadronic interactions on Lambda polarization

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With

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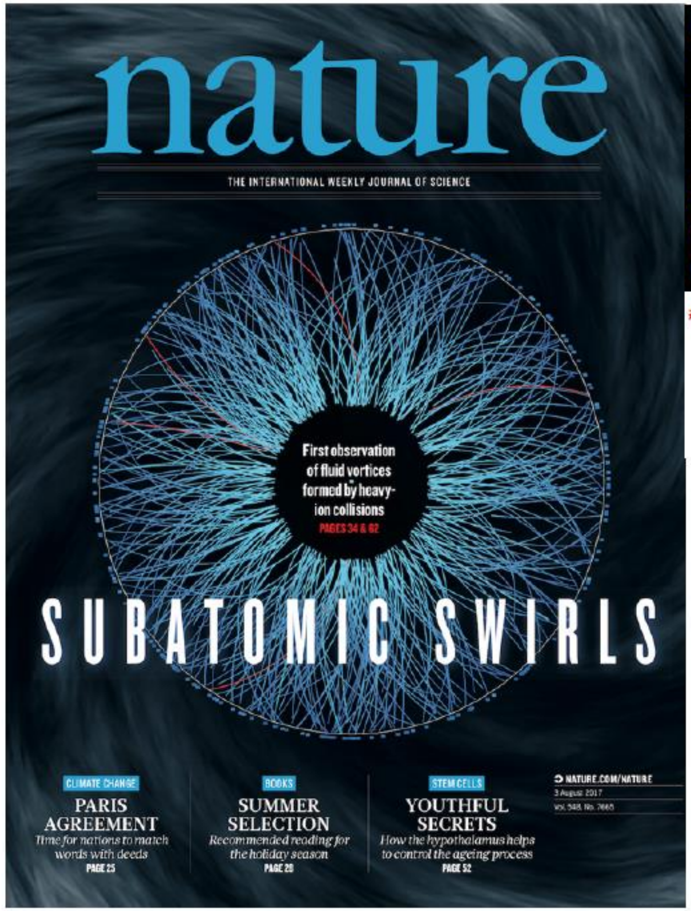
ECT* Workshop on Spin and Hydrodynamics in Relativistic Nuclear Collisions

1. **Experiments and some explanations**
2. **The meson field mechanism**
3. **Simulation and results**
4. **Summary**

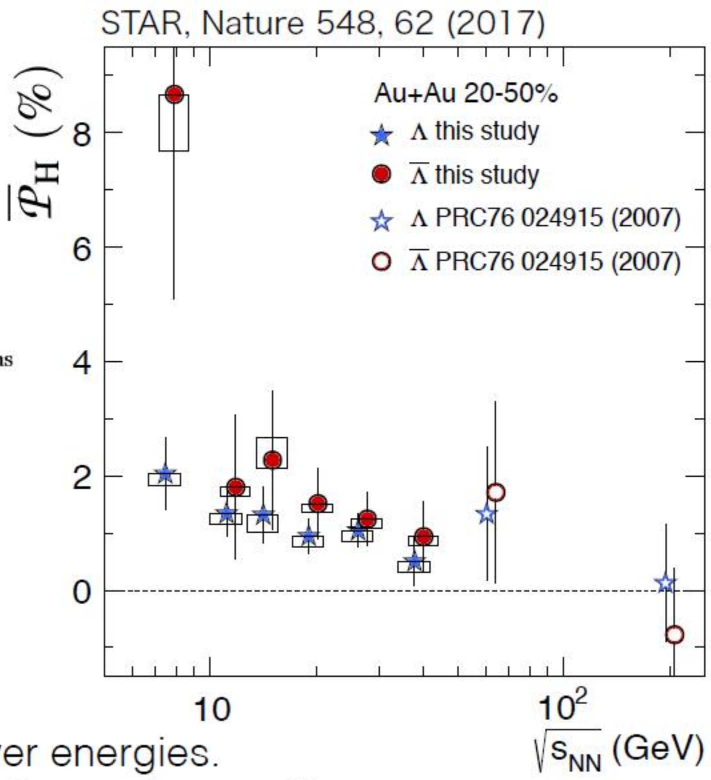
Experiments： RHIC Au+Au collisions

- Global polarization measurements by RHIC BES II programe: Au-Au collisions at energies of 7.7, 11.5, 14.5, 19.6, 27.0, 39.0, 62.4, and 200 GeV



$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar \sim 10^{22}\ s^{-1}$$

(T=160 MeV)

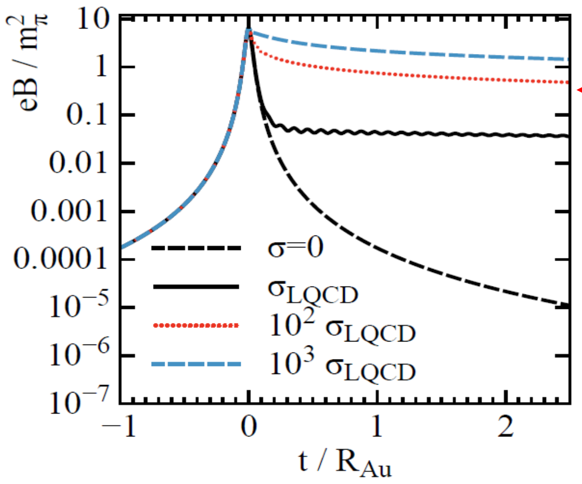


Positive signal at lower energies.
The most vortical fluid ever observed!

Earlier explanations to Polarization Splitting

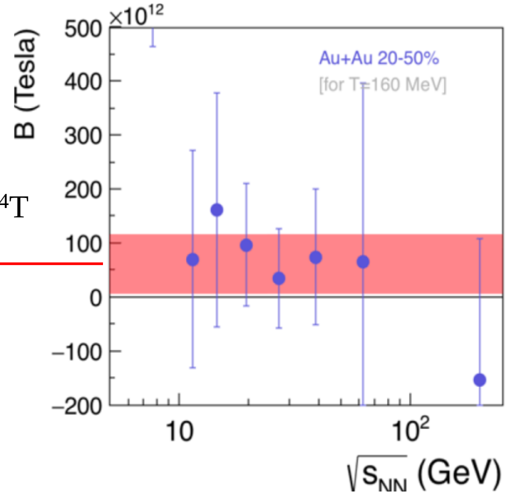
- Why is the anti-Λ's polarization larger than Λ polarization?

1. Polarization induced by magnetic field might split the vorticity induced polarization?



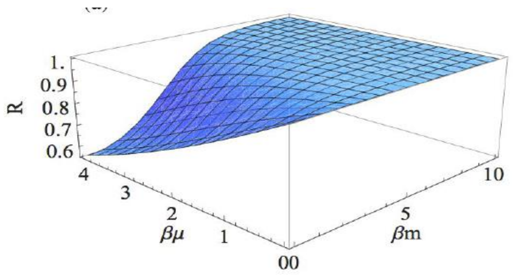
[L. McLerran, V. Skokov, Nucl.Phys. A929 (2014) 184-190]

$m_\pi^2/e \approx 10^{14}$T



[M.A. Lisa, invited talk in Zimany School, Amesterdam 2017]

2. Effect of baryon chemical potential : accounts for only 1%



$$\beta = \frac{1}{T}$$

$$\left.\begin{aligned} \beta\mu &\approx \frac{150\ \text{MeV}}{150\ \text{MeV}} = 1 \\ \beta m &\approx \frac{1100\ \text{MeV}}{150\ \text{MeV}} \approx 7 \end{aligned}\right\} 1 - \frac{1}{R} < 1\%$$

$$n_F(x,p) = \frac{1}{e^{\beta(p^\mu u_\mu \mp \mu)} + 1}$$

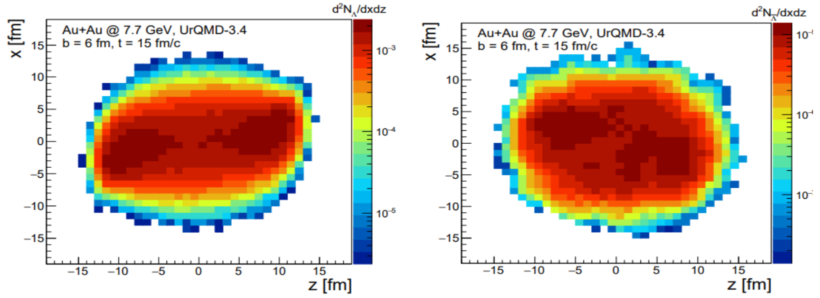
R.H. Fang, et al., PRC 94 (2016) 024904;
M.A. Lisa, invited talk in WPCF, Budapest 2017

3. Axial Anomaly Charge: The same for Λs and anti-Λs. But $N_\Lambda > N_{\bar{\Lambda}}$

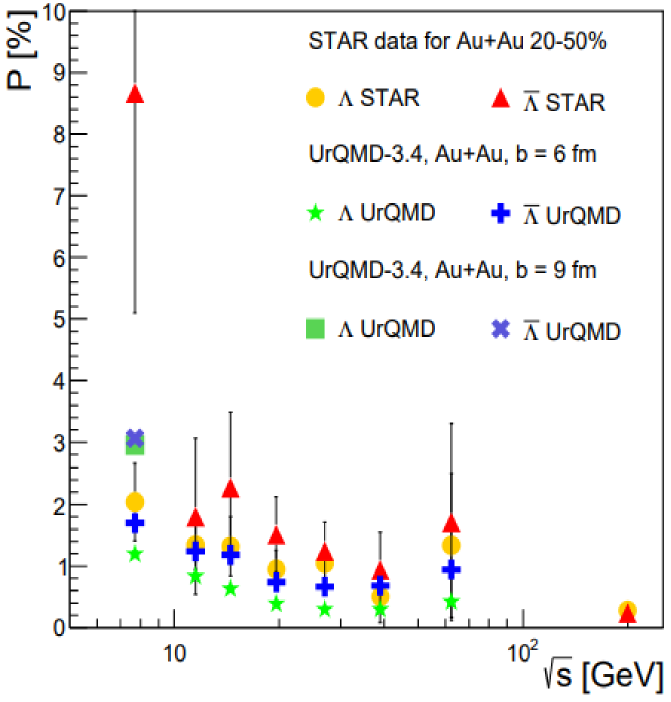
A. Sorin, O. Teryaev, PRC 94 011902(R) (2017)

Recent explanations

Different Space-time freeze-out of Λ and anti- Λ, results into polarization difference?



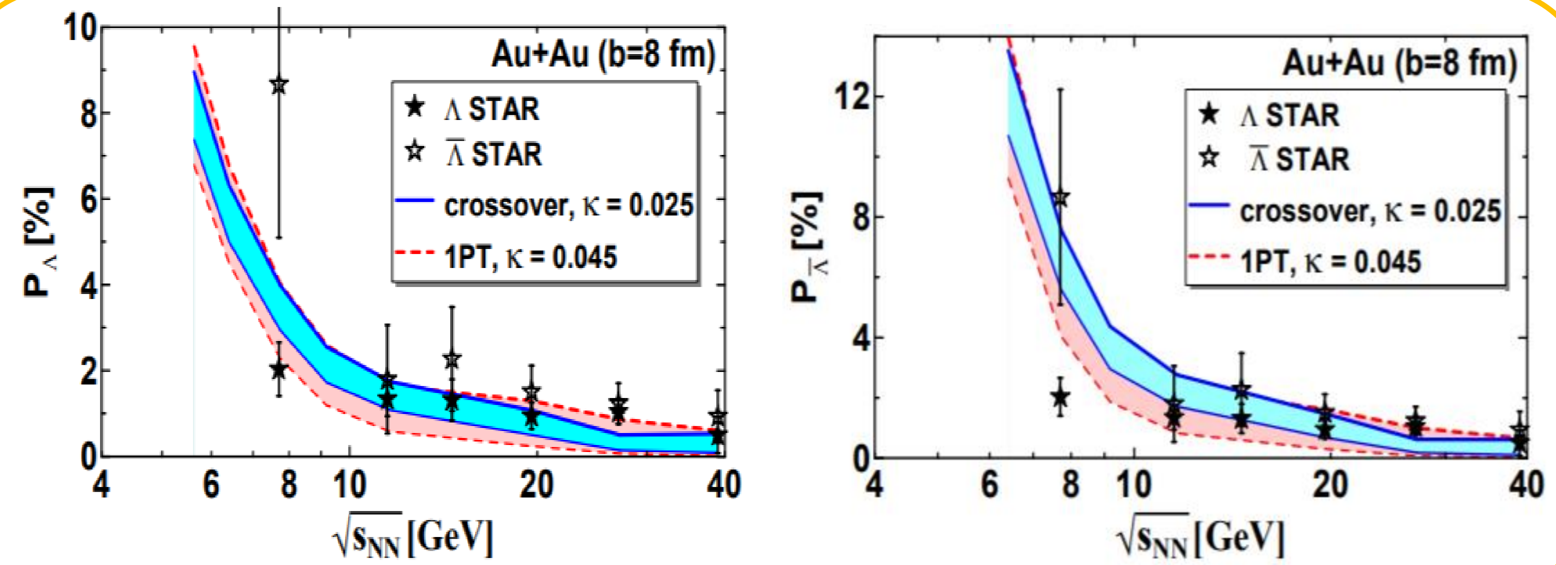
$\sqrt{s}$ (GeV)	7.7	11.5	14.5	19.6
$\langle t_{\Lambda}^{FO} \rangle$ (fm/c)	21.3009	21.9568	23.066	24.3462
$\langle t_{\bar{\Lambda}}^{FO} \rangle$ (fm/c)	19.7806	21.0302	21.959	23.1288



[O. Vitiuk, L.V. Bravina, E. E. Zabrodin, PLB 803, 135298 (2020).]

Recent explanations

Axial Anomaly Charge: The same for Λs and anti-Λs. But $N_\Lambda > N_{\bar{\Lambda}}$



$$P_\Lambda = \int d^3x\,(J^0_{5s}/u_y)/(N_\Lambda + N_{\bar{K}^*}),$$

$$P_{\bar{\Lambda}} = \int d^3x\,(J^0_{5s}/u_y)/(N_{\bar{\Lambda}} + N_{K^*}),$$

[Yu. B. Ivanov, arXiv:2006.14328, accepted by PRC]

Meson field in rotating system

Considering the system during hadron rescattering, the strong interactions between Λ and baryons are mediated by the scalar meson σ and vector meson V^{μ}

$$\mathcal{L}_{\text{eff}} = \sum_i \bar{\psi}_i (i \not{\partial} - m_i + g_{\sigma i}\sigma - g_{Vi} \not{V}) \psi_i$$
$$+ \tfrac{1}{2} \left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) - \tfrac{1}{4} V^{\mu\nu} V_{\mu\nu} + \tfrac{1}{2} m_V^2 V_\mu V^\mu \, .$$

$$H^V_{\text{spin}} = -\frac{g_{VH}}{M_H} \beta\, \boldsymbol{S} \cdot \boldsymbol{B}_V - i \frac{g_{VH}}{4M_H^2} \boldsymbol{S} \cdot \boldsymbol{\nabla} \times \boldsymbol{E}_V - \frac{g_{VH}}{2M_H^2} \boldsymbol{S} \cdot \boldsymbol{E}_V \times \boldsymbol{p}$$

Dirac 4 × 4 matrix: $\beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$$\boldsymbol{B}_V = \frac{\bar{g}_V}{m_V^2} (\boldsymbol{\nabla} \times \boldsymbol{J}_B)$$

------ Foldy-Wouthuysen Hamiltonian

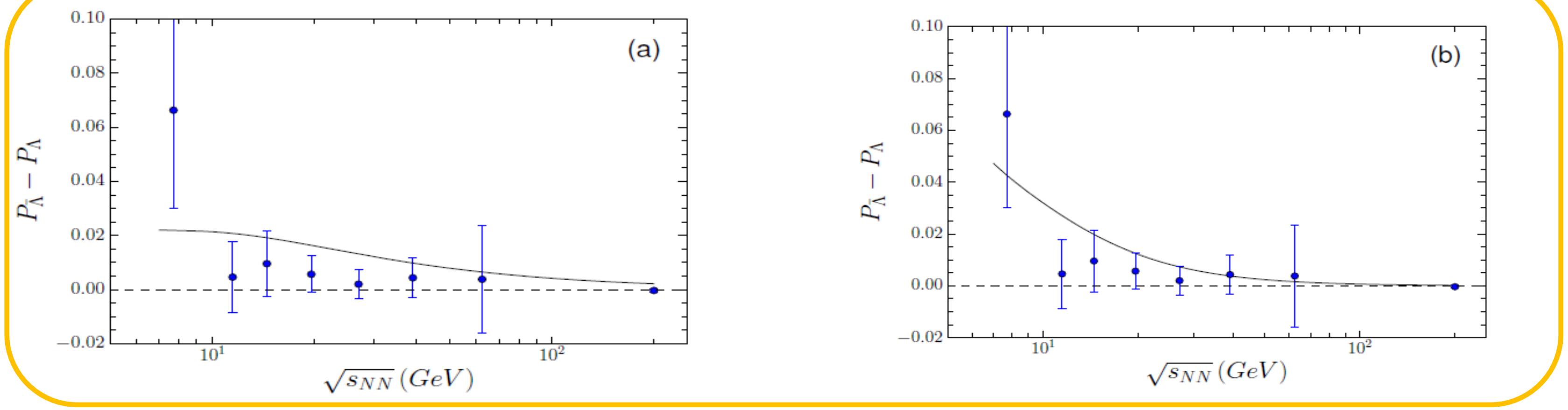
[L.P. Csernai, J. Kapusta, et al, PRC 99, 021901(R) (2019)]

Meson field in rotating system

In conclusion, the baryons (fermions) with vorticity will induce vector meson (bosons) magnetic field, this magnetic&electric field would interact with the Λ's spin, resulting into the polarization and polarization difference between Λ and anti- Λ.

$$P_y = \beta \frac{g_{V\Lambda}}{m_\Lambda}\frac{|\boldsymbol{B}_V|}{2T} = g_{V\Lambda}\bar{g}_V \frac{n_B(t_{ch})}{m_\Lambda m_V^2}\frac{\Delta c\,\beta}{2t_{ch}T(t_{ch})}.$$

$$P_{\bar{\Lambda}} - P_\Lambda = C\left(\frac{n_B(t_{ch})}{0.15/\mathrm{fm}^3}\right)\left(\frac{140\ \mathrm{MeV}}{T(t_{ch})}\right).$$



[L.P. Csernai, J. Kapusta, et al, PRC 99, 021901(R) (2019)]

Meson field in rotating system

We modify the polarization splitting formula therein, by removing the free parameter C and explicitly bringing out the vorticity, which is essential in polarization study.

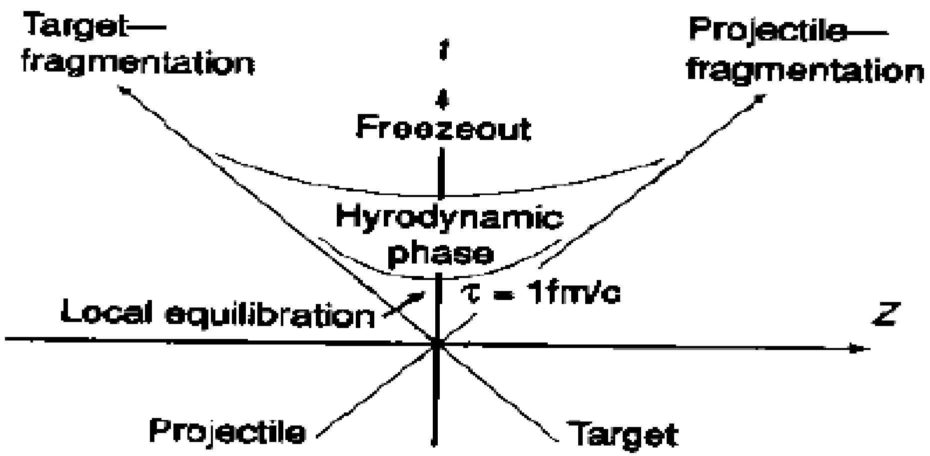
$$\boldsymbol{P} = 2\boldsymbol{S} = \tanh\left(\frac{\Omega}{2T}\right)\hat{\boldsymbol{\Omega}} \simeq \frac{\boldsymbol{\Omega}}{2T} = -\beta\frac{g_{\mathrm{VH}}}{M_{\mathrm{H}}}\frac{\boldsymbol{B}_{\mathrm{V}}}{T}$$

$$\begin{aligned}\Delta\boldsymbol{P}_J = \langle C\frac{\boldsymbol{\nabla}\times\boldsymbol{J}_{\mathrm{B}}}{T}\rangle &= C\langle\frac{\rho_{\mathrm{B}}\,\boldsymbol{\omega}}{T}\rangle + C\langle\frac{\boldsymbol{\nabla}\rho_{\mathrm{B}}\times\boldsymbol{v}}{T}\rangle \\ &= \Delta\boldsymbol{P}_\omega + \Delta\boldsymbol{P}_\rho.\end{aligned}$$

where $C = 2(g_{\mathrm{VH}}\,\bar{g}_{\mathrm{V}})/(M_{\mathrm{H}}m_{\mathrm{V}}^2)$ is a coefficient determined by the strong coupling constants, hyperon mass and meson mass.

Assumption: the post-freeze-out system is near Boltzmann limit and Λ particles are non-relativistic

Hydrodynamic Simulation



Space-time evolution in Bjorken model

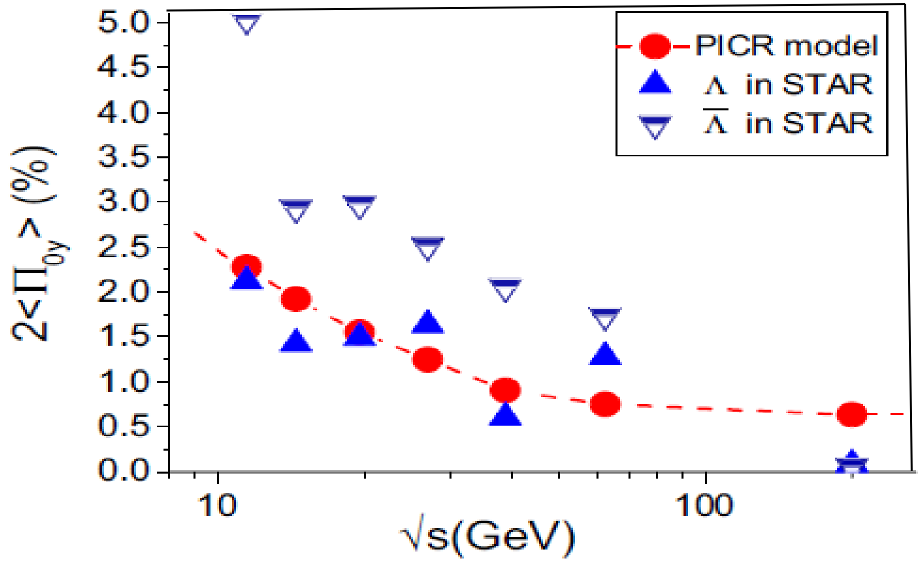
- ❑ An initial state based on Yang-Mills fields (flux tube) is formed after Lorentz contracted nuclei penetrate each other, then system evolves with a (3+1)D fluid dynamics: the high resolution Particle-In-Cell Relativistic (PICR) hydrodynamic model.

- ❑ The major part of freeze out hypersurface is assumed to be time like here. We use the ideal-gas post-FO distribution. The precise FO prescription in Hydro fluid dynamics was discussed in Ref. [Yu Cheng, 2010].

[Yun Cheng, et al., Phys. Rev. C **81**, 064910 (2010)]

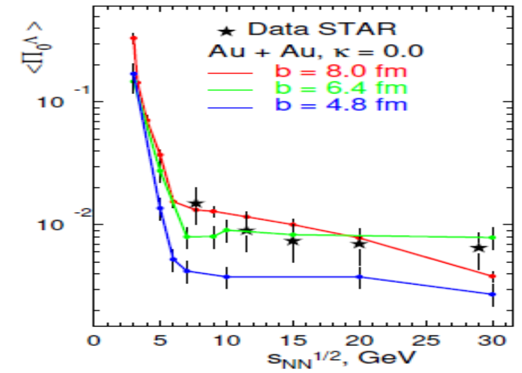
Previous simulation

[Y.L. Xie et al., PRC 93, 031901(R) (2017)]



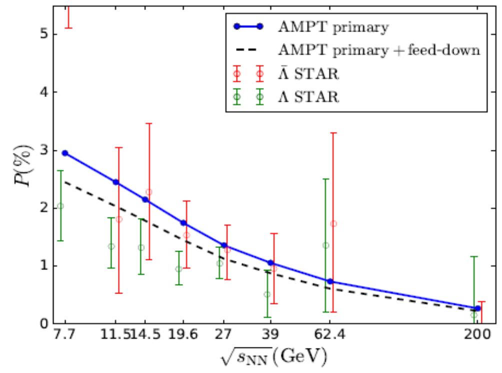
The global polarization, $2\langle\Pi_{0y}\rangle p$, in our PICR model (red circle) and STAR BES experiments (green triangle), at energies √s of 11.5, 14.5, 19.6, 27.0, 39.0, 62.4, and 200 GeV.

$$\langle \Pi_{0y} \rangle_p = \frac{\int dpdx\,\Pi_{0y}(p,x)n_F(x,p)}{\int dpdx\; n_F(x,p)} = \frac{\int dp\,\Pi_{0y}(p)n_F(p)}{\int dp\; n_F(p)}$$



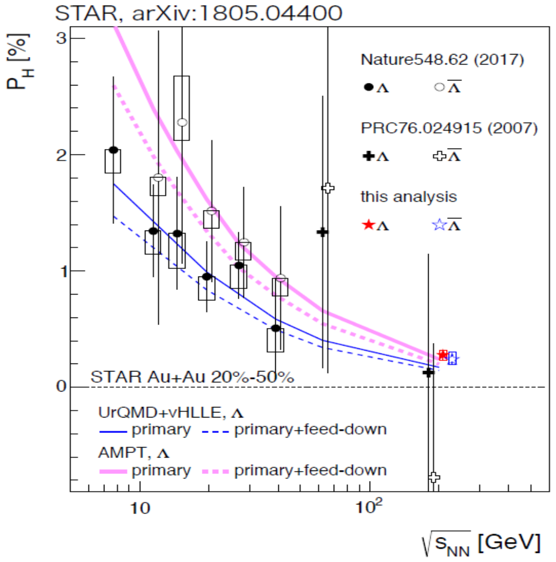
QGSM+Axial Vortrical Effect

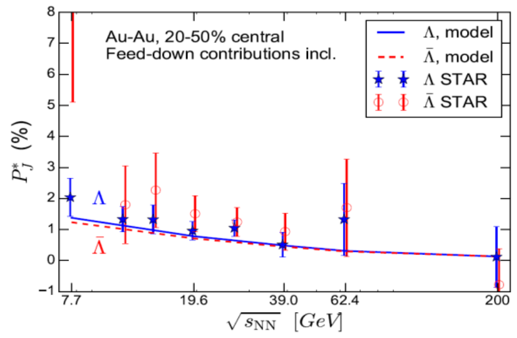
M. Baznat, et al., arXiv:1701.00923.



AMPT+Spin-Vorticity Coupling

H. Li, X.N. Wang et al., PRC 96,054908 (2017).



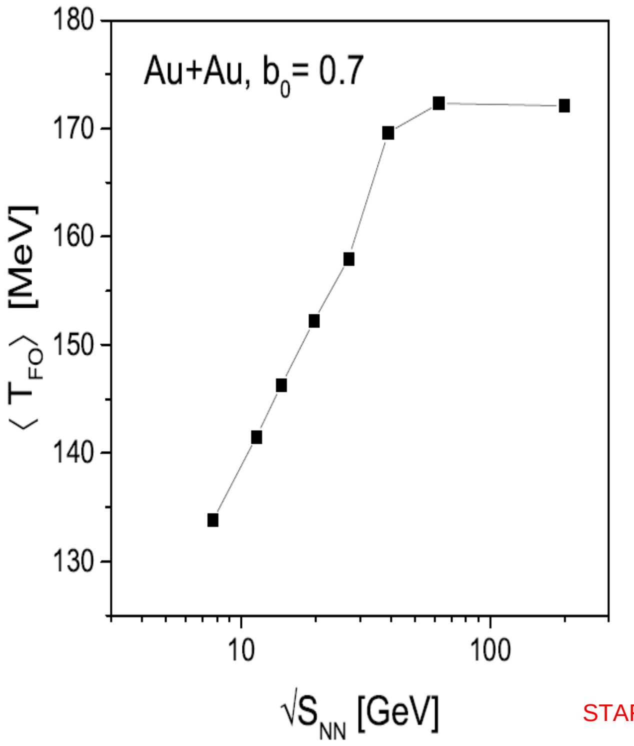


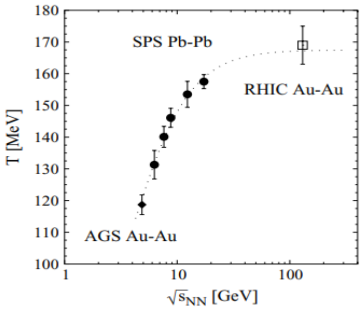
UrQMD-vHLLE hybrid Model

I. Karpenko, F. Becattini, et al., Eur. Phys. J. C 77, 213 (2017).

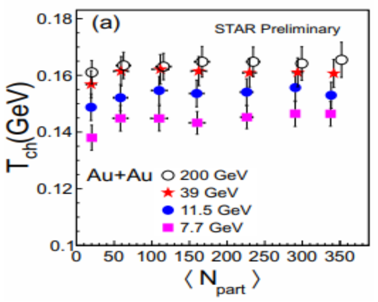
We use the same simulation data, but vary the freeze-out time for different collision energies.

Simulation and results

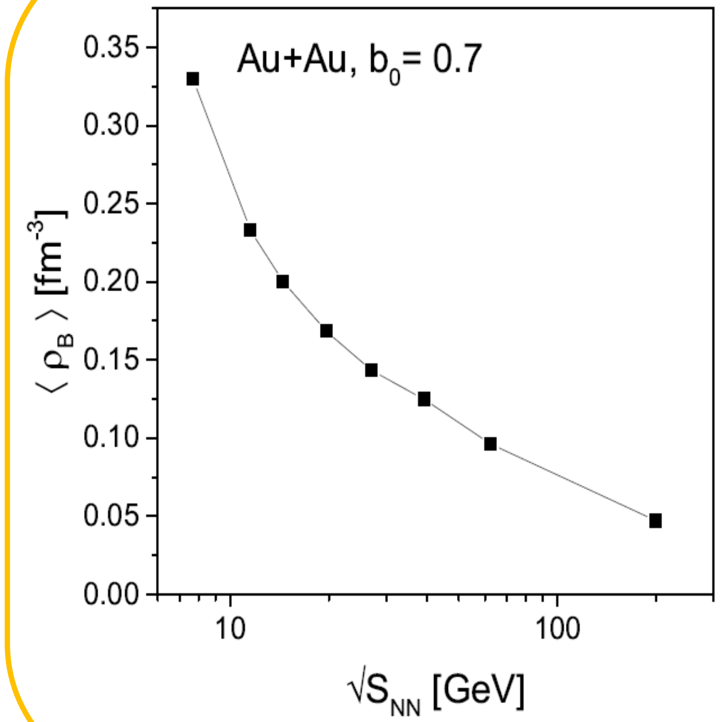


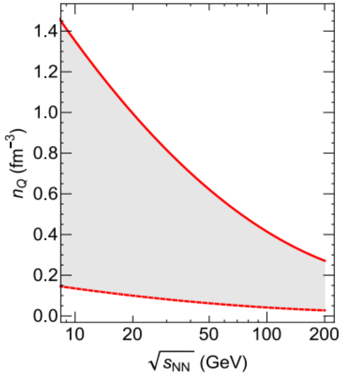


F. Becattini et al., PRC 73, 044905 (2006)



STAR Collaboration, NPA 904-905, 891c (2013).

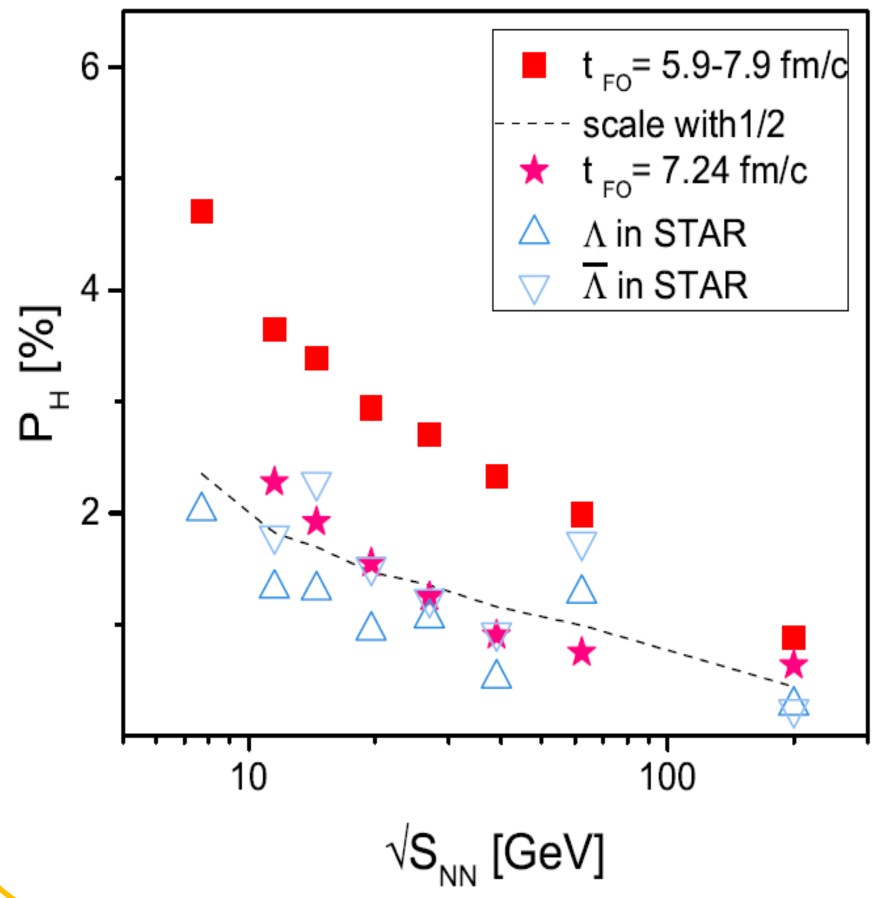




X. Y. Guo et al., arXiv:1904.04704.

The freeze-out time is varied from 5.9 -7.9 fm/c for √s = 7.7-200GeV, so that the freeze-out T and ρ are consistent with theoretical expectations and experiments.

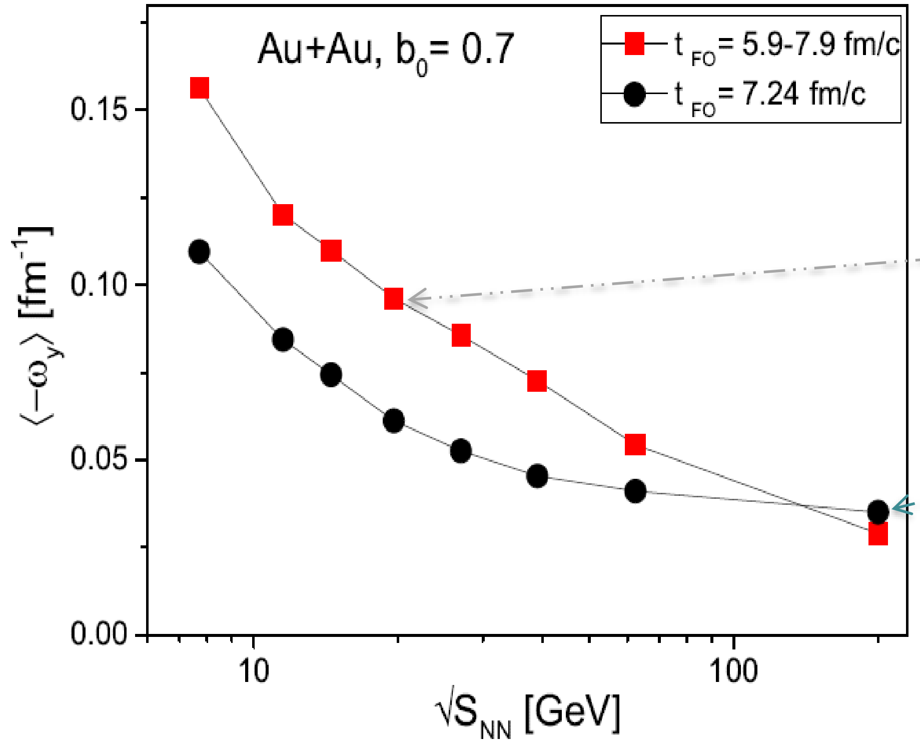
Simulation and results

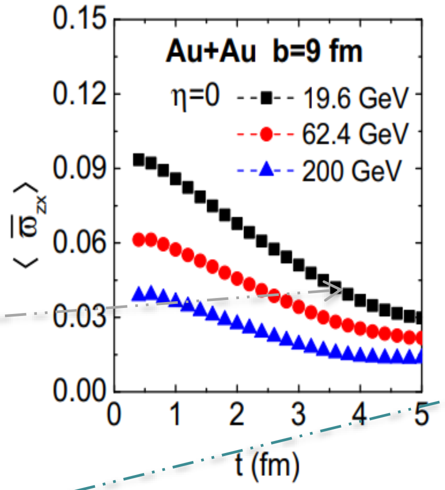


1. New values of polarization are larger than old ones, showing the sensitivity to freeze-out time, while the energy dependence behavior is still kept.

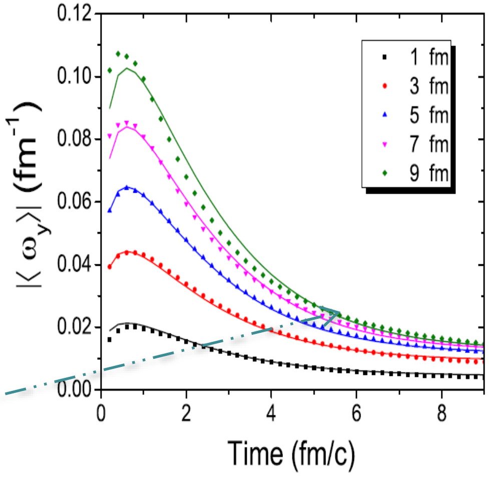
2. Estimates of the global polarization at c=20-50% by scaling of 0.5, is very close to the experimental results.

Simulation and results



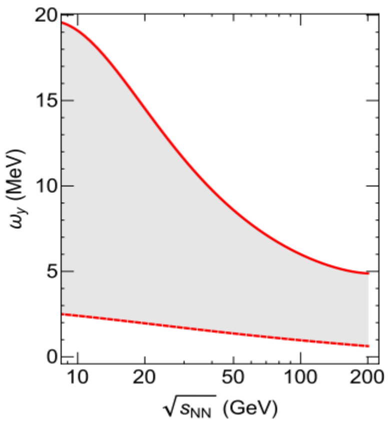


Y. Jiang et al., Phys. Rev. C 94, 044910 (2016).



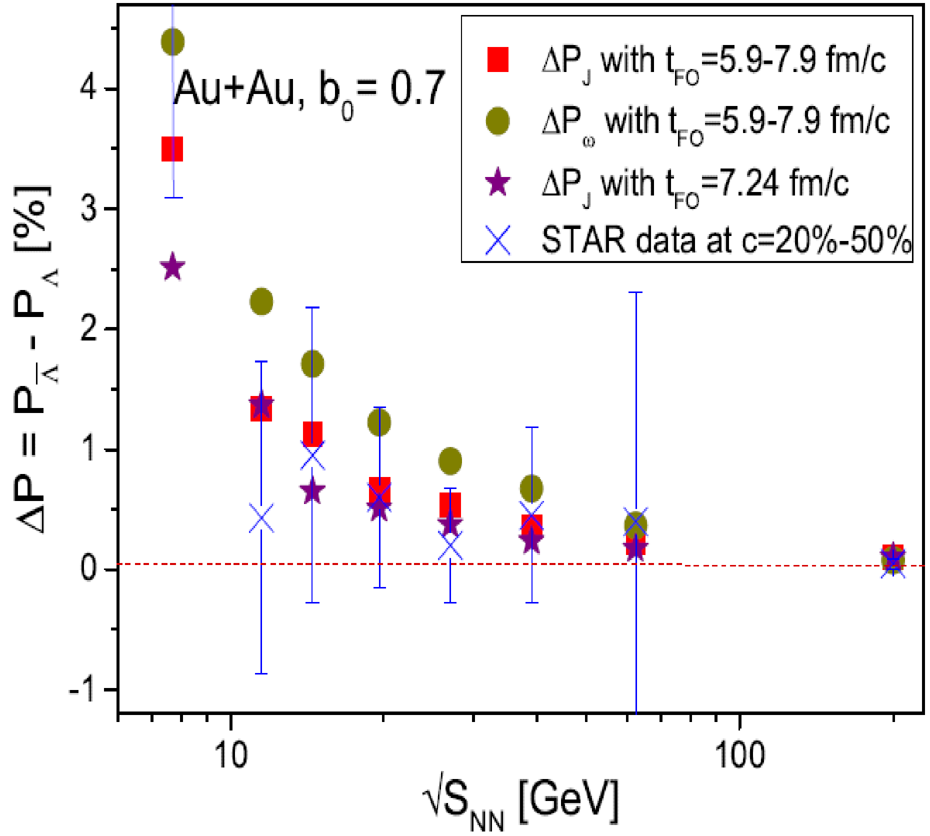
D.-X. Wei et al., PRC 99, 014905 (2019).

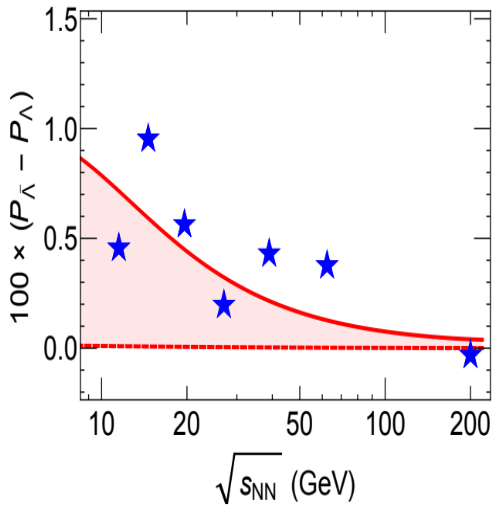
PICR model has similar magnitude of vorticity as the AMPT model

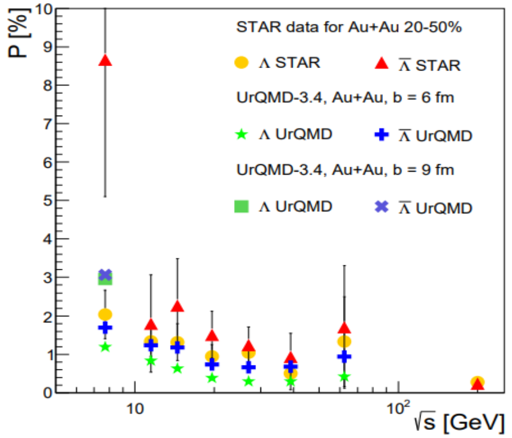


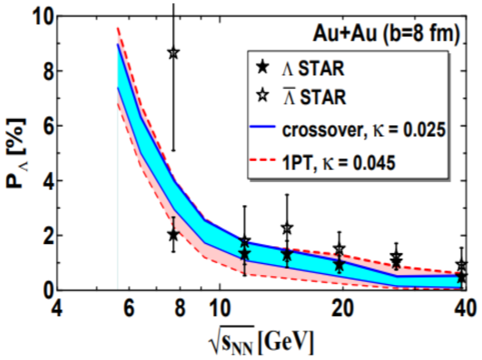
X. Y. Guo et al., arXiv:1904.04704.

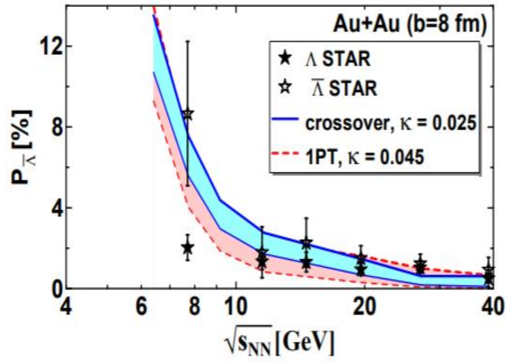
Simulation and results



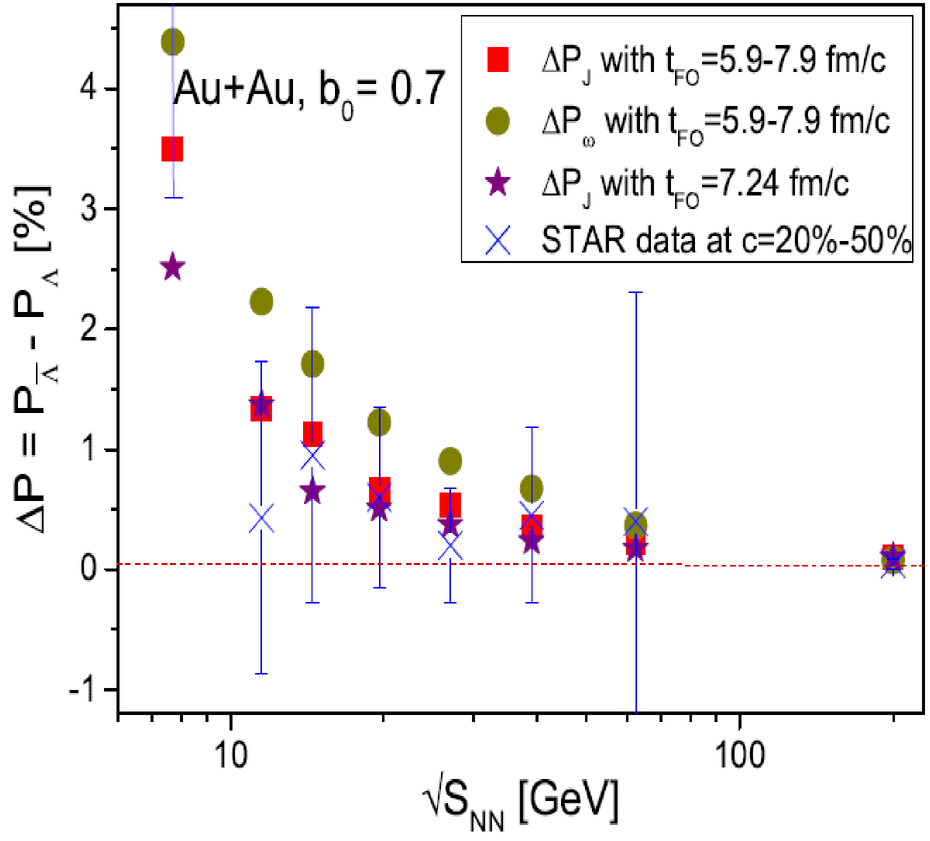








Simulation and results



1. The polarization splitting based on meson field mechanism is larger than many other approaches.
2. $\Delta P_J = \Delta P_\omega + \Delta P_\rho < \Delta P_\omega$, and it means ΔP_ρ is negative, so it decreases the final splitting effect by about 1/3~1/4.

Simulation and results

b_0 (c)	0.45 (20%)	0.6 (36%)	0.7 (49%)
$\langle T_{\rm FO} \rangle$ (MeV)	134.3	134.8	133.8
$t_{\rm FO}$ (fm/c)	4.2 <	5.1 <	5.9
$\langle \rho_{\rm B} \rangle$ (fm^{-3})	0.36	0.345	0.33
$\langle -\omega_y \rangle$ (fm^{-1})	0.140	0.163	0.156
ΔP_ω	4.49% ≈	4.77% ≈	4.39%
ΔP_J	4.28% >	4.12% >	3.49%

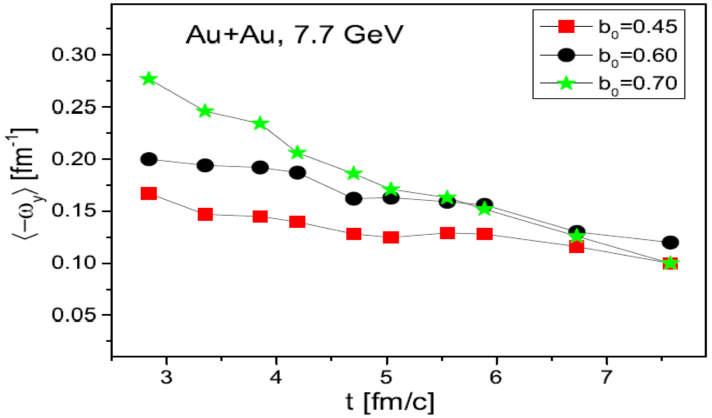
Table 1. The average freeze-out temperature $T_{\rm FO}$, freeze-out time $t_{\rm FO}$, average baryon density $\langle \rho_{\rm B} \rangle$, average vorticity $\langle -\omega_y \rangle$, and ΔP_ω, ΔP_J defined in eq. (15), for Au+Au 7.7 GeV collisions at different centralities $c = 20\%, 36\%, 49\%$.

b_0 (c)	0.45 (20%)	0.7 (49%)
$\langle T_{\rm FO} \rangle$ (MeV)	142.2	141.5
$t_{\rm FO}$ (fm/c)	7.9 >	5.9
$\langle -\omega_y \rangle$ (fm^{-1})	0.140	0.156
ΔP_ω	1.43% <	2.23%
ΔP_J	0.83% <	1.33%

Table 2. The average freeze-out temperature $T_{\rm FO}$, freeze-out time $t_{\rm FO}$, average vorticity $\langle -\omega_y \rangle$, and ΔP_ω, ΔP_J defined in eq. (15), for Au+Au 11.5 GeV collisions at different centalities $c = 20\%, 49\%$.

Things are different for 7.7 GeV case:

1. Freeze-out time is larger in peripheral collisions and the decreasing tendency of vorticity vs time is very mild. Thus similar ΔP_ω
2. The larger fluctuations of baryon density in peripheral collisions lead to larger $|\Delta P_\rho|$. Thus $\Delta P_J = \Delta P_\omega + \Delta P_\rho$ is smaller for peripheral collisions.



Summary

- We have presented the polarization splitting based on the meson field mechanism.

Thank
You

$$\boldsymbol{\Pi}_0(p) = \boldsymbol{\Pi}(p) - \frac{\mathbf{p}}{p^0(p^0+m)}\boldsymbol{\Pi}(p)\cdot\mathbf{p}\ .$$