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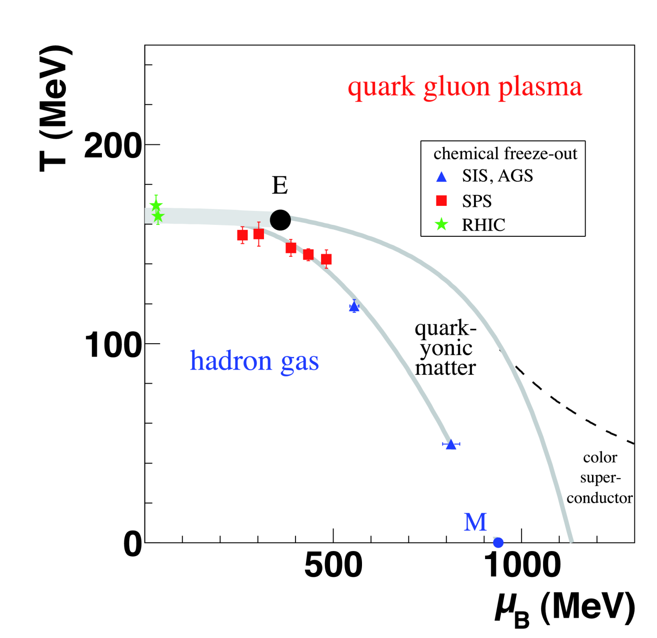
Hadronization, chemical freeze-out and polarization

OUTLINE

- Chemical freeze-out, hadronization and QCD crossover line
- Λ polarization in relativistic heavy ion collisions

Introduction

- Determining the hadronization conditions of the Quark Gluon Plasma is a major goal of experimental and theoretical work
- It has been long believed that at the chemical freeze-out the system is a (locally) equilibrated hadron gas, with an extra strangeness suppression which can be accounted for by residual peripheral NN collisions (corona effect)
- Chemical freeze-out = chemical equilibrium $\simeq$ hadronization $\neq$ QCD critical line



New data on antiproton from SPS and LHC
led us to conclude that
Chemical freeze-out $\neq$ chemical equilibrium $\cong$ hadronization = critical line
(please note that R. Stock, F.B. et al., arXiv:0911.5705 – fortunately unpublished- is obsolete)

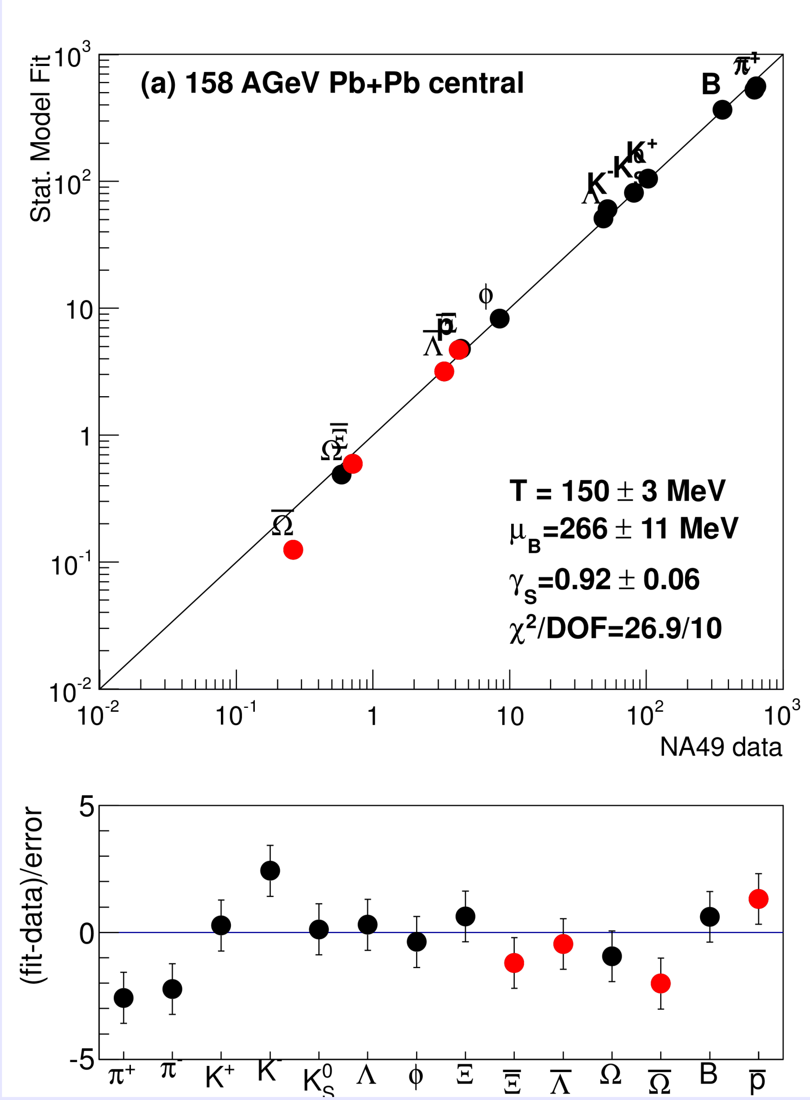
SPS energy

A recently published $\bar{p}$ yield by NA49 in Pb-Pb at 17.2 GeV turned out to be consistently lower than the predicted by SHM.

Predicted: 6.86 (F.B., J. Manninen and M. Gazdzicki, Phys. Rev. C 73 (2006) 044905)
Measured: 4.23±0.35

New fit to Pb-Pb mult's at 17.2 GeV

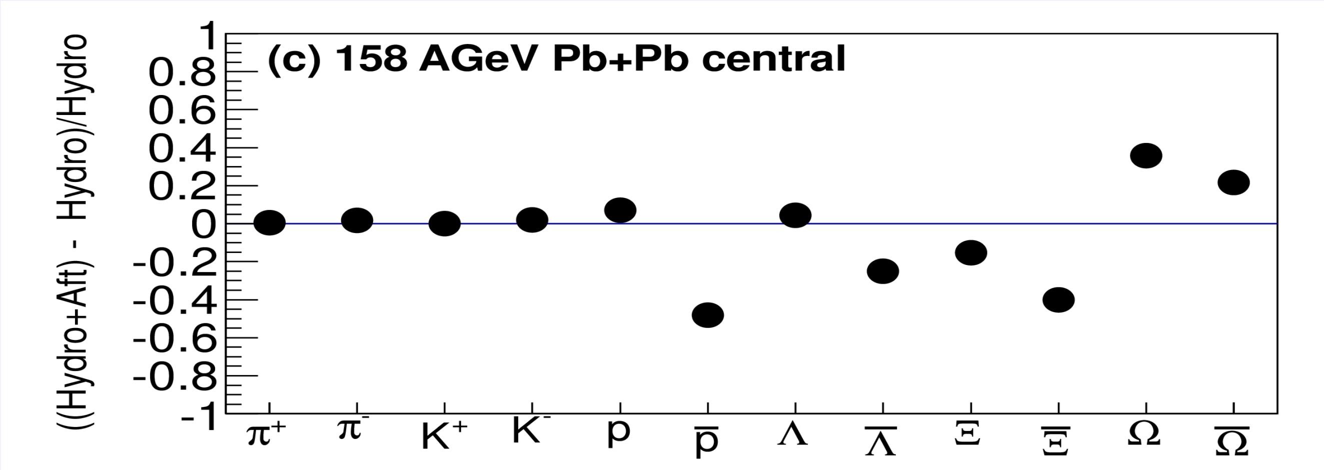
Lower T, lower quality



F. B., M. Bleicher, T. Kollegger, M. Mitrovski, T. Schuster and R. Stock Phys. Rev. C 85 (2012) 044921

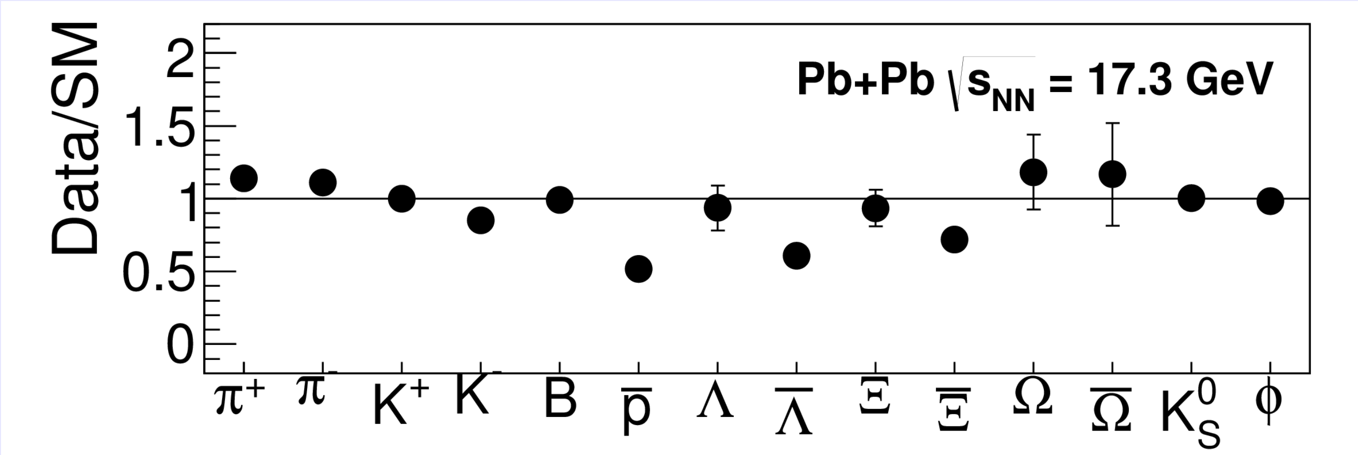
Possible explanation: the effect of post-hadronization rescattering

F. Becattini, M. Bleicher, T. Kollegger, M. Mitrovski, T. Schuster and R. Stock Phys. Rev. C 85 (2012) 044921



Effect of UrQMD afterburning on initial statistical hadronic yields from a hydro code

See also S. Bass and A. Dumitru, Phys. Rev. C 61 (2000) 064909



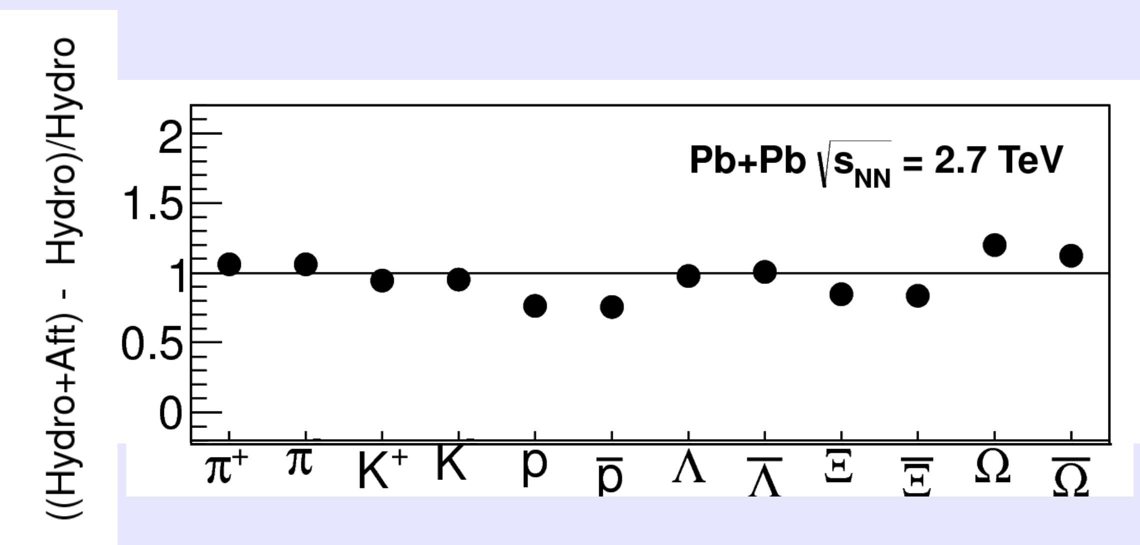
Residual distribution of a fit to hadronic yields excluding anti-baryons

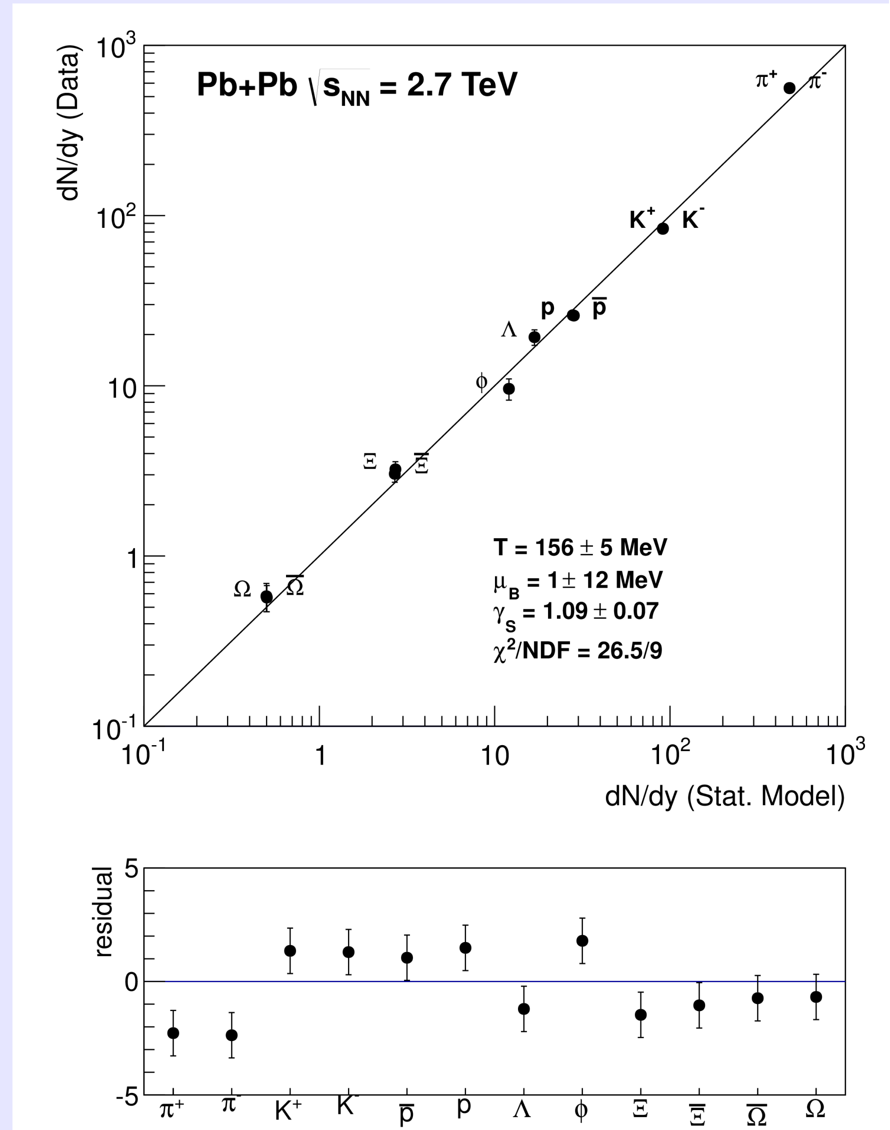
LHC energy

The p ($\bar{p}$)/p yield in PbPb at 2.76 TeV is lower than predicted by the statistical hadronization model by 40% (by A. Andronic et al., J.Phys. G38 (2011) 124081)

Advocated as an effect of post-hadronization rescattering:

J. Steinheimer, J. Aichelin and M. Bleicher, Phys. Rev. Lett. 110 (2013) 042501
Y. Pan and S. Pratt, *Baryon Annihilation in Heavy Ion Collisions* arXiv:1210.1577 [nucl-th]

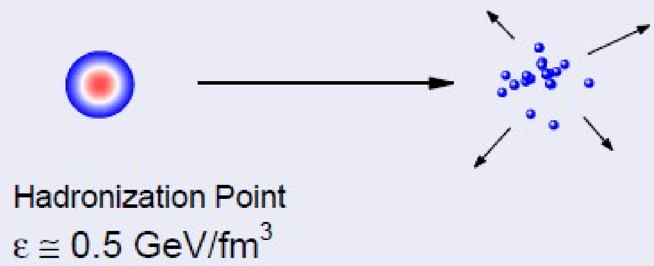




F. Becattini, M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, *Hadron Formation in Relativistic Nuclear Collisions and the QCD Phase Diagram*," arXiv:1212.2431 [nucl-th].

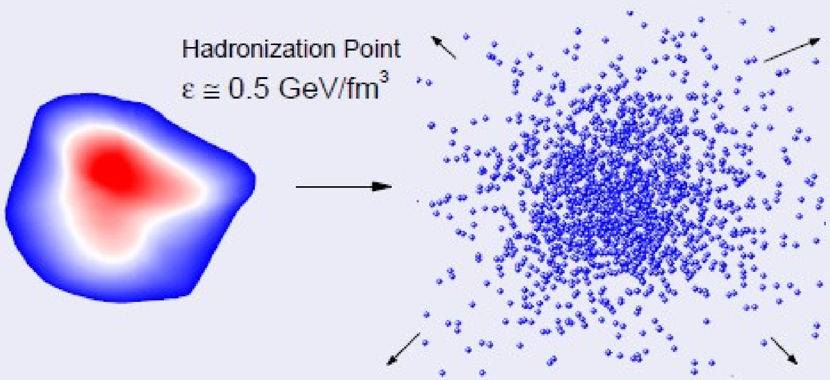
Physical picture

Elementary Collisions



- Hadrons are born into equilibrium.
- They are few and escape the reaction volume immediately.

Heavy Ion Collisions

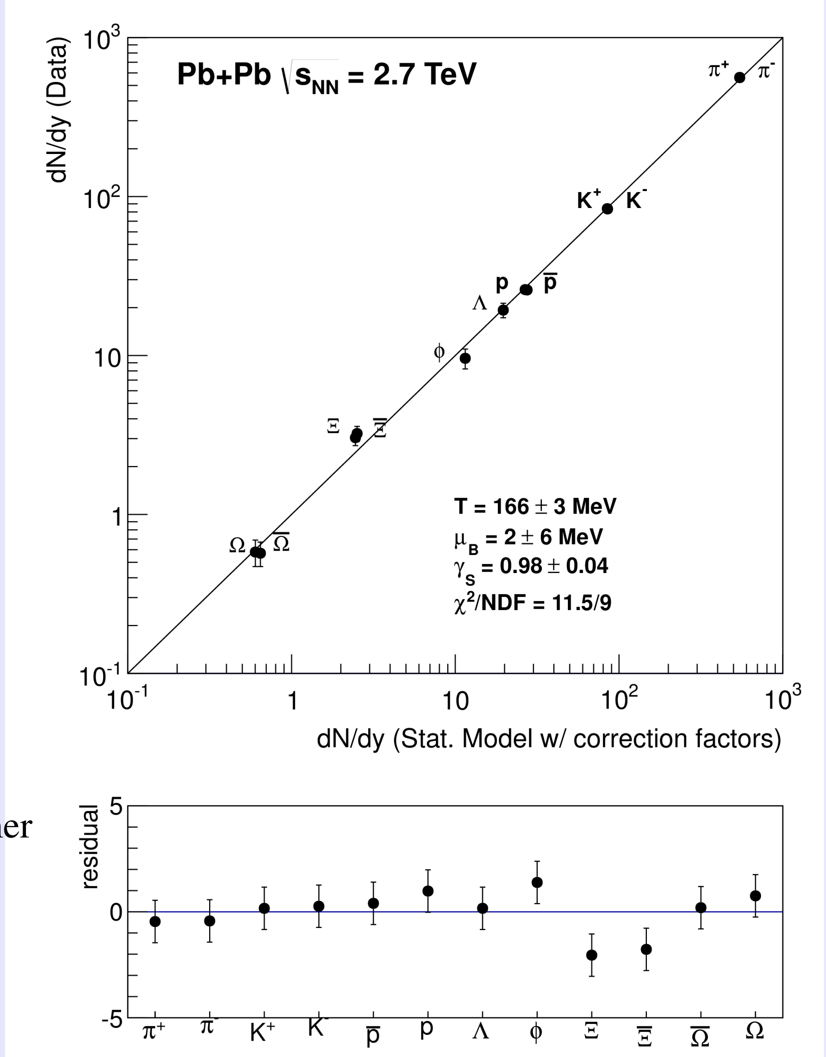


- Hadrons are born into equilibrium.
- They need more time to escape the reaction volume.
- They can undergo inelastic collisions.

How to reconstruct hadronization conditions?

Strictly speaking, the *latest chemical equilibrium point*

- Excluding the most affected particles from the SHM fit
- Estimating the effect of the afterburning with an analytical calculation (e.g. Pratt) or a Monte-Carlo (UrQMD)

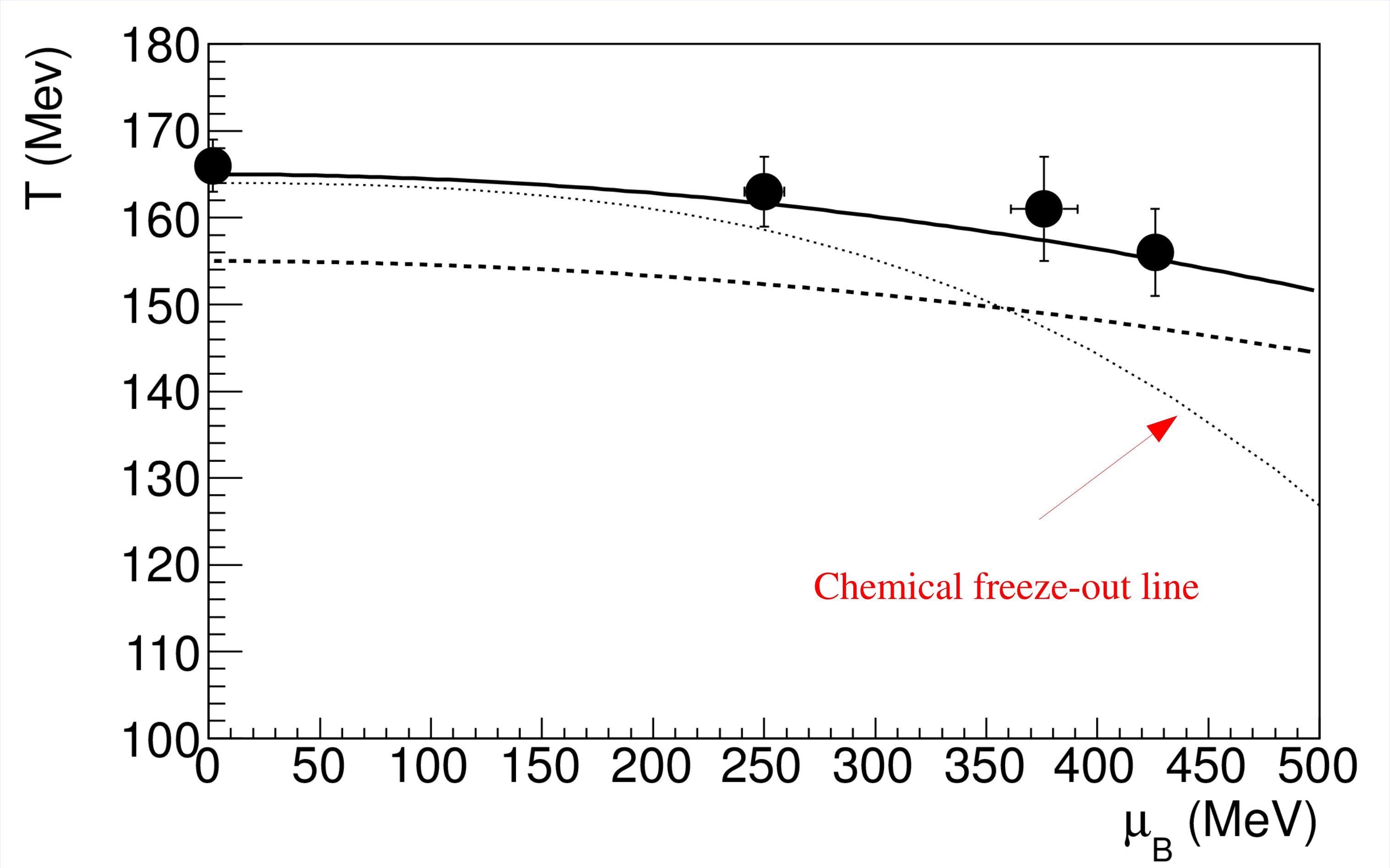


"Corrected" fit to ALICE data

Higher T, much better quality

F. Becattini, M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, *Hadron Formation in Relativistic Nuclear Collisions and the QCD Phase Diagram*," arXiv:1212.2431.

Comparing reconstructed LCHP's with lattice QCD



Lattice calculations from

F. Karsch, J. Phys. G 38, 124098 (2011); S. Borsanyi et al., ibidem 124101
G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP 1104, 001 (2011)

See also: *The critical line of two-flavor QCD at finite isospin or baryon densities from imaginary chemical potentials.* P. Cea, L. Cosmai, M. D'Elia, A. Papa, F. Sanfilippo, Phys.Rev. D85 (2012) 094512

Polarization in relativistic heavy ion collisions

Recently, we extended the Cooper-Frye formula to particles with spin ½

F. B., V. Chandra, L. Del Zanna, E. Grossi, arXiv:1303.3431

$$f(x,p)_{rs} = \frac{1}{2m}\bar{u}_r(p)\left(\exp[\beta(x)\cdot p - \xi(x)]\exp\left[-\frac{1}{2}\varpi(x)_{\mu\nu}\Sigma^{\mu\nu}\right] + I\right)^{-1} u_s(p)$$

$$\bar{f}(x,p)_{rs} = -\frac{1}{2m}\bar{v}_s(p)\left(\exp[\beta(x)\cdot p + \xi(x)]\exp\left[\frac{1}{2}\varpi(x)_{\mu\nu}\Sigma^{\mu\nu}\right] + I\right)^{-1} v_r(p)$$

$$\beta^\mu = \frac{1}{T_0}u^\mu \qquad \xi = \mu_0/T_0$$

$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu) + \mathcal{O}(\partial^2\beta)$$

"Thermal vorticity"

$$\varepsilon\frac{\mathrm{d}N_{rs}}{\mathrm{d}^3\mathrm{p}} = \int_\Sigma \mathrm{d}\Sigma_\mu p^\mu f_{rs}(x,p)$$

The total number of particles is given by the trace over polarization indices

Polarization in relativistic heavy ion collisions - 2

There have been several papers in the past years about this subject:

A. Ayala et al., Phys. Rev. C 65 024902 (2002)
Z. T. Liang, X. N. Wang, Phys. Rev. Lett. 94 102301 (2005) and others
B. Betz, M. Gyulassy and G. Torrieri, Phys. Rev. C 76 044901 (2007)
F. B., F. Piccinini and J. Rizzo, Phys. Rev. C 77 024906 (2008)

yet no definite formula connecting the polarization of hadrons to the hydrodynamical model. Now we have it:

$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int \mathrm{d}\Sigma_\lambda p^\lambda \, n_F (1-n_F) \partial^\rho \beta^\sigma}{\int \mathrm{d}\Sigma_\lambda p^\lambda \, n_F}$$

$$n_F = \frac{1}{\mathrm{e}^{\beta(x)\cdot p - \xi(x)} + 1}$$

and we can use it to predict Λ polarization in peripheral heavy ion collisions
(F.B., L. Csernai, D.J. Wang, arXiv:1304.4427)

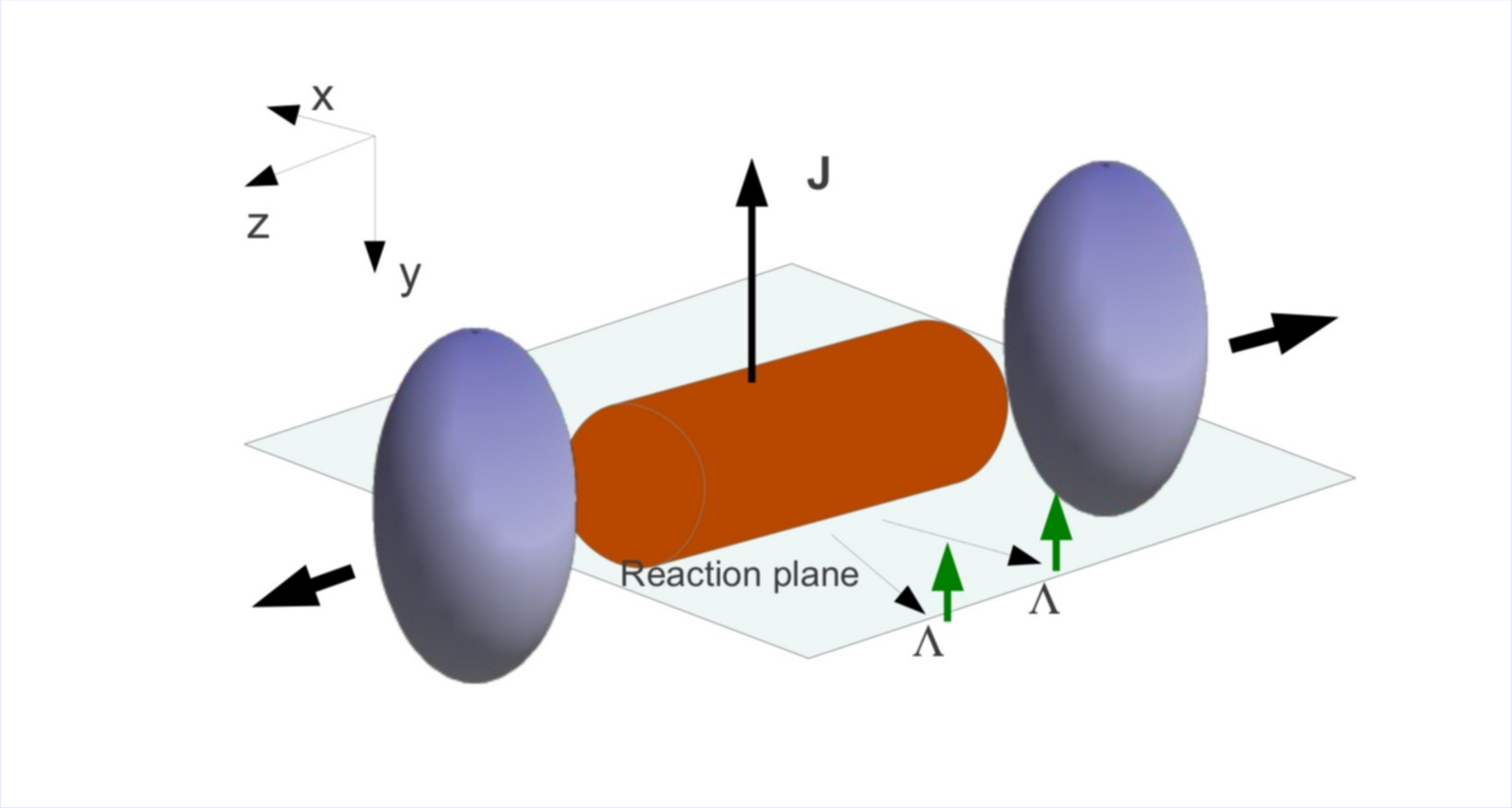
Distribution of protons in the Λ rest frame

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha\, \mathbf{\Pi}_0 \cdot \hat{\mathbf{p}}^*\right) \qquad \mathbf{\Pi}_0(p) = \mathbf{\Pi}(p) - \frac{\mathbf{p}}{\varepsilon(\varepsilon+m)} \mathbf{\Pi}(p)\cdot\mathbf{p}$$

Because of the parity symmetry of the collision

$$\mathbf{\Pi}(p) = \frac{\varepsilon}{8m} \frac{\int \mathrm{d}V \, n_F (\nabla \times \boldsymbol{\beta})}{\int \mathrm{d}V \, n_F}$$

The most polarized Λ are those in the reaction plane (normal to angular momentum).



Vorticity in relativistic heavy ion collisions
3+1 D ideal calculation

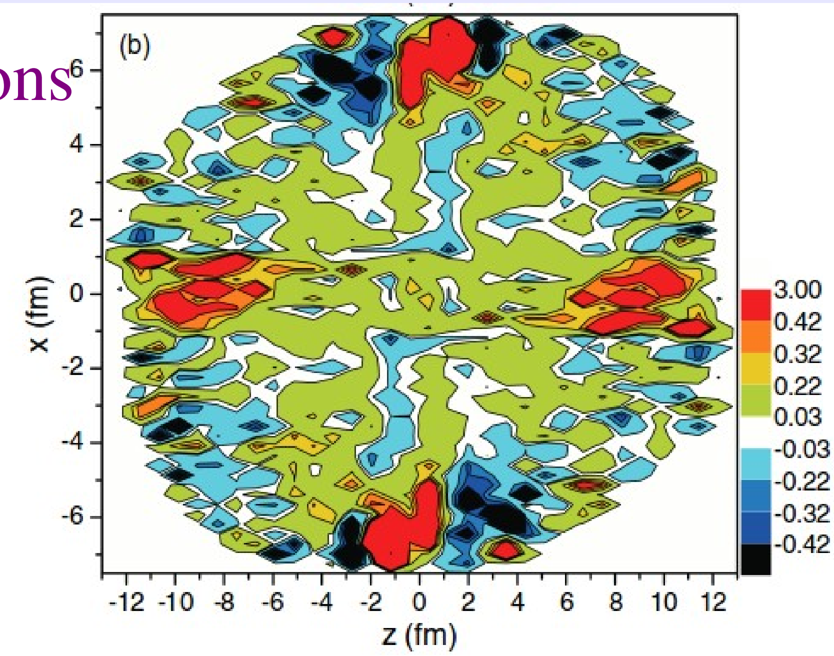


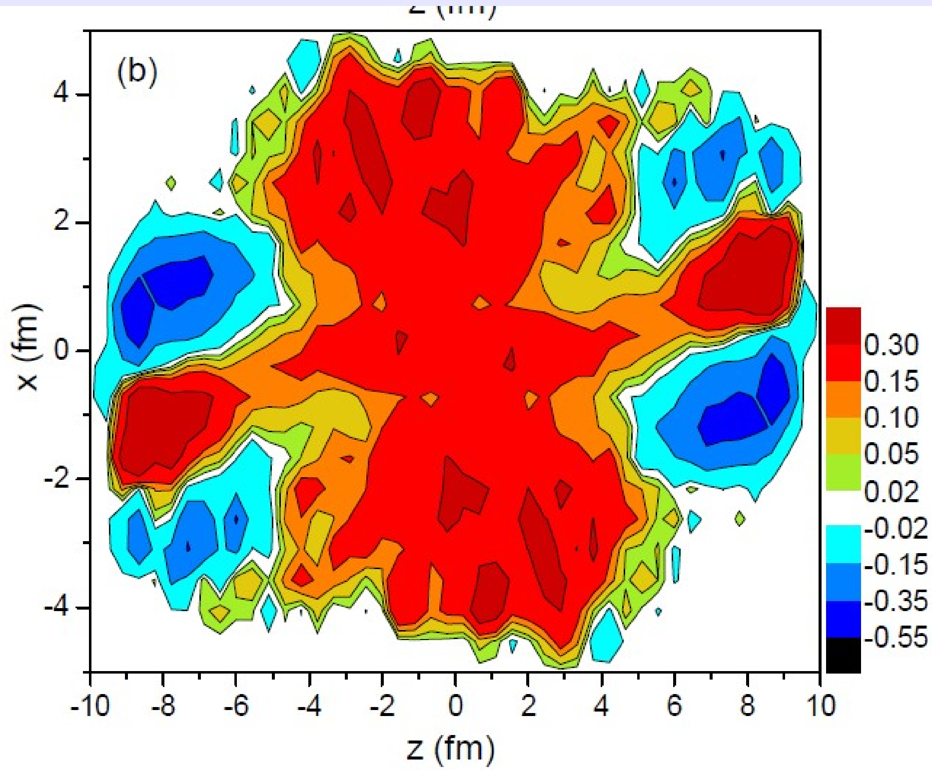
FIG. 6. (Color online) The classical (a) and relativistic (b) weighted vorticity Ω_{zx} (c/fm), calculated in the reaction xz plane at $t = 6.94$ fm/c. The collision energy is $\sqrt{s_{NN}} = 2.76$ TeV and $b = 0.7\, b_{\max}$; the cell size is $dx = dy = dz = 0.4375$ fm. The average vorticity in the reaction plane is 0.01555 (0.05881) c/fm for the classical (relativistic) weighted vorticity respectively.

Vorticity of the *u* field

L. Csernai, V. Magas, D.J. Wang,
Phys. Rev. C 87 034906 (2013)

Vorticity of the β field (thermal vorticity)

F.B., L. Csernai, D.J. Wang, arXiv 1304.4427



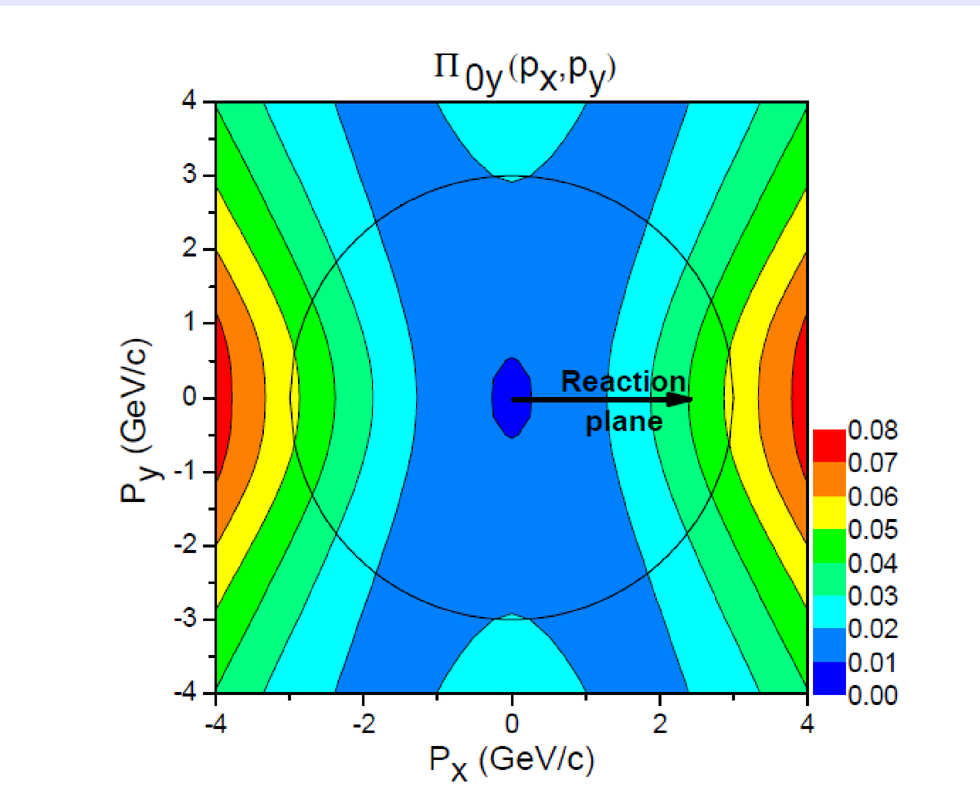
b=7fm √s = 2.76 TeV

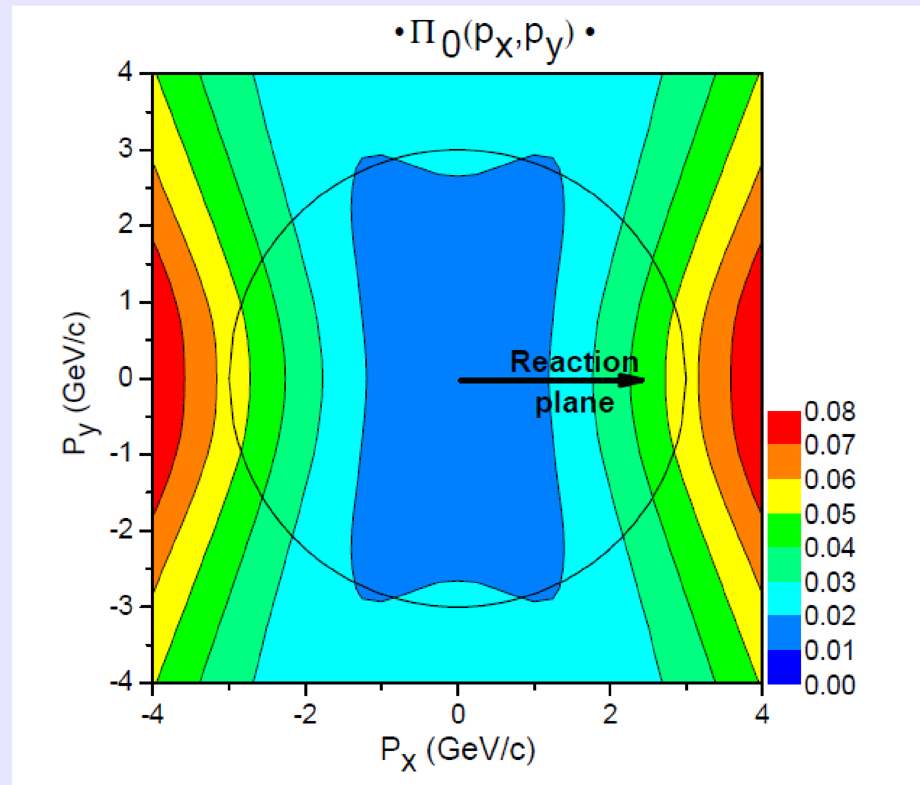
Thermal vorticity decays much slower than usual vorticity (1/T factor)

$$\mathbf{\Pi}_0(p) = \mathbf{\Pi}(p) - \frac{\mathbf{p}}{\varepsilon(\varepsilon+m)}\mathbf{\Pi}(p)\cdot\mathbf{p}$$

Average polarization consistent with the bound set by RHIC (<0.02).

F.B., L. Csernai, D.J. Wang arXiv 1304.4427

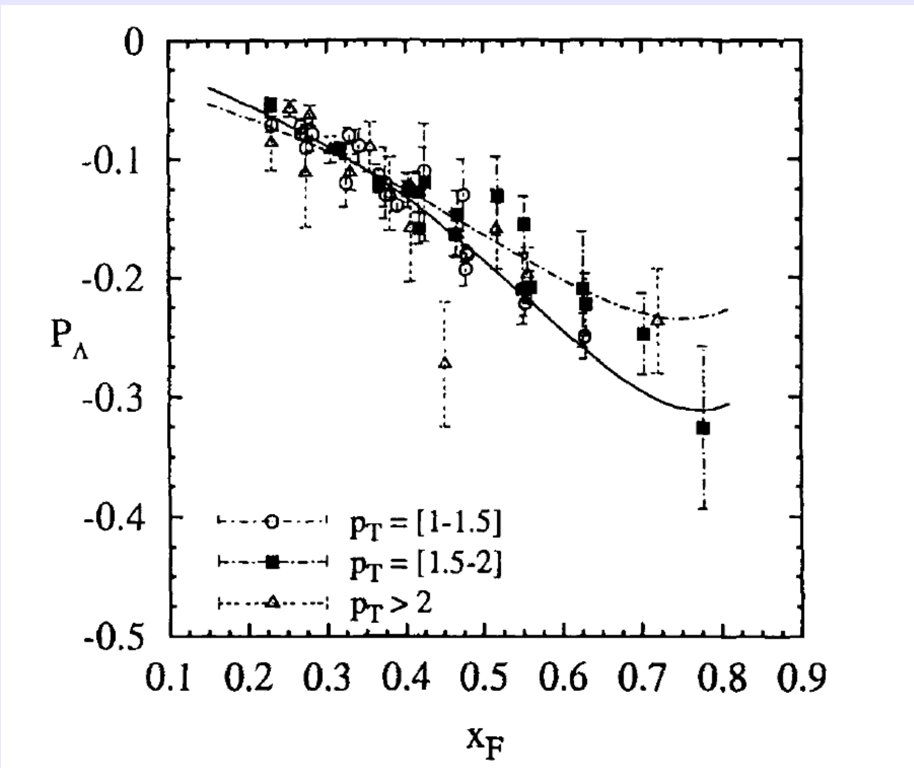


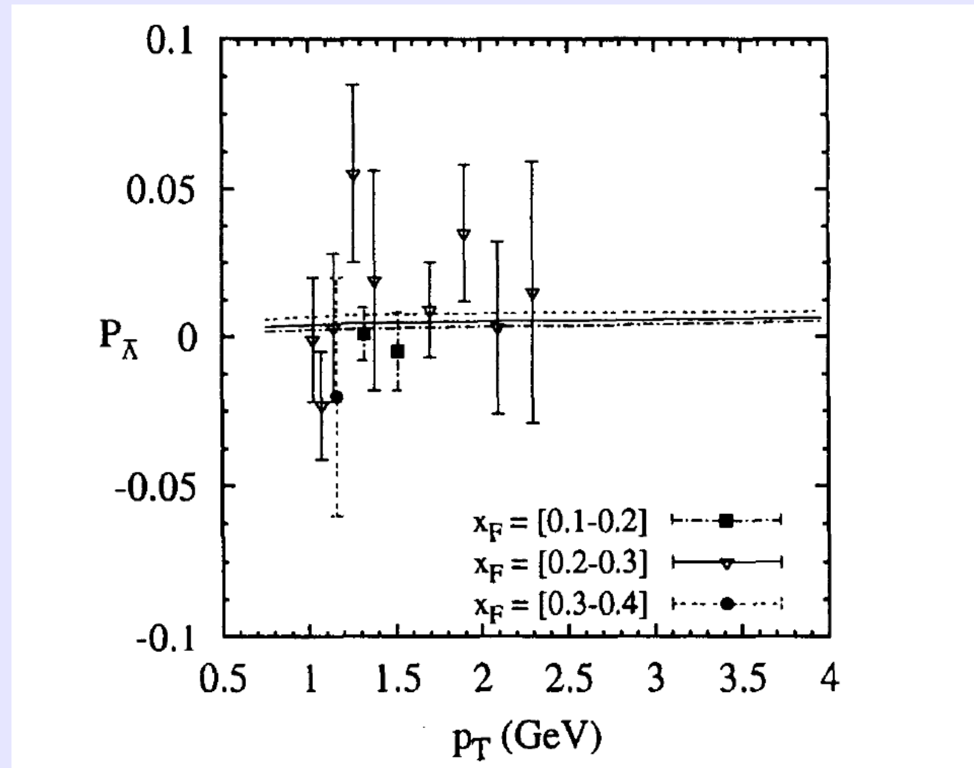


NOTE: the polarization owing to the spectator's magnetic field (E. Bratkovskaya et al.) is at least 4 orders of magnitude less than the one shown above

Background

The main background are polarized Λ from “corona” NN collisions





We estimated a contribution of 0.002 to the observed polarization of Λ

Conclusions

- There is further evidence of a post-hadronization inelastic scattering stage in hadronic multiplicities.

- By using hadronic transport codes we can reconstruct the primordial chemical equilibrium
•conditions which overlap with the lattice QCD extrapolated critical line temperature.

- We have obtained a formula to *quantitatively* determine polarization of baryons in peripheral relativistic heavy ion collisions at the freeze-out and its momentum dependence.

- The detection of a polarization pattern in agreement with the prediction of the hydro model would be a striking confirmation of the local thermodynamical equilibrium picture and it would be a probe (and a gauge) of the vorticous flow in peripheral relativistic heavy ion collisions.

http://www.hadrons.to.infn.it/QGP_School/Home.html

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The School aims at providing a general background on the theory and phenomenology of Quark Gluon Plasma built on the expertise developed at SPS, RHIC and the LHC, also in view of the future GSI and next LHC run data.
It is suitable for undergraduate, graduate and postdoctoral students who plan to actively engage in this area of research, as well as for those who specialize in the nearby fields of strong interactions and nuclear physics.

Canonical spin tensor

$$\mathcal{S}^{\lambda,\mu\nu}(x) \equiv \frac{1}{2}\langle : \overline{\Psi}(x)\{\gamma^\lambda, \Sigma^{\mu\nu}\}\Psi(x) : \rangle = \frac{1}{2}\int \frac{\mathrm{d}^3\mathrm{p}}{2\varepsilon}\mathrm{tr}_2\left(f(x,p)\bar{U}(p)\{\gamma^\lambda, \Sigma^{\mu\nu}\}U(p)\right) - \mathrm{tr}_2\left(\bar{f}^T(x,p)\bar{V}(p)\{\gamma^\lambda, \Sigma^{\mu\nu}\}V(p)\right)$$

...tracing the γ's, expanding in $\varpi(x)$ which is usually a small number (at global equilibrium $\hbar\omega/KT \ll 1$)...

$$\frac{\mathrm{d}\mathcal{S}^{\lambda,\rho\sigma}(x)}{\mathrm{d}^3 p} \simeq \frac{1}{2\varepsilon}\left(p^\lambda n_F(1-n_F)\varpi^{\rho\sigma} + \text{rotation of indices}\right)$$

$$n_F = \frac{1}{\mathrm{e}^{\beta(x)\cdot p - \xi(x)} + 1}$$

Polarization four-vector in the LAB frame

Final formulae:

$$\langle \Pi_\mu(x,p) \rangle \simeq \frac{1}{16} \epsilon_{\mu\rho\sigma\tau} \, (1-n_F) \, (\partial^\rho \beta^\sigma - \partial^\sigma \beta^\rho) \, \frac{p^\tau}{m} = \frac{1}{8} \epsilon_{\mu\rho\sigma\tau} \, (1-n_F) \partial^\rho \beta^\sigma \frac{p^\tau}{m}$$

$$\Pi = (\Pi^0, \mathbf{\Pi}) = \frac{1-n_F}{8m} ((\nabla \times \boldsymbol{\beta}) \cdot \mathbf{p}, \varepsilon (\nabla \times \boldsymbol{\beta}) - \frac{\partial \boldsymbol{\beta}}{\partial t} \times \mathbf{p} - \nabla \beta^0 \times \mathbf{p})$$

As a by-product, a new effect is predicted: particles in a steady temperature gradient (here with $\boldsymbol{v} = 0$) should be transversely polarized:

$$\Pi = (\Pi^0, \mathbf{\Pi}) = (1-n_F) \frac{\hbar p}{8mKT^2} (0, \nabla T \times \hat{\mathbf{p}})$$

Cooper-Frye for polarization

$$\langle \Pi_\mu(p) \rangle \equiv \frac{\displaystyle\int \mathrm{d}\Sigma_\lambda \, \frac{p^\lambda}{\varepsilon} (-1/2) \epsilon_{\mu\rho\sigma\tau} \frac{\mathrm{d}\mathcal{S}^{0,\rho\sigma}}{\mathrm{d}^3\mathrm{p}} \frac{p^\tau}{m}}{\displaystyle\int \mathrm{d}\Sigma_\lambda \, \frac{p^\lambda}{\varepsilon} \mathrm{tr}_2 f(x,p)} = -\frac{1}{4} \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{m} \frac{\displaystyle\int \mathrm{d}\Sigma_\lambda \, p^\lambda \, \Theta^{\rho\sigma}}{\varepsilon \dfrac{\mathrm{d}N}{\mathrm{d}^3\mathrm{p}}}$$

$$\langle \Pi_\mu(p) \rangle \simeq -\frac{1}{4} \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{m} \frac{\displaystyle\int \mathrm{d}\Sigma_\lambda \, p^\lambda \, n_F (1-n_F) \varpi^{\rho\sigma}}{\varepsilon \dfrac{\mathrm{d}N}{\mathrm{d}^3\mathrm{p}}} \simeq \frac{1}{8} \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{m} \frac{\displaystyle\int \mathrm{d}\Sigma_\lambda \, p^\lambda \, n_F (1-n_F) \partial^\rho \beta^\sigma}{\displaystyle\int \mathrm{d}\Sigma_\lambda \, p^\lambda n_F}$$

Polarization in a relativistic fluid

Definition:

$$\Pi_\mu = -\frac{1}{2}\epsilon_{\mu\rho\sigma\tau}S^{\rho\sigma}\frac{p^\tau}{m}$$

also known as Pauli-Lubanski vector

should be the total angular momentum vector of the particle

For a kinetic system

$$\langle \Pi_\mu(x,p)\rangle = -\frac{1}{2}\frac{1}{\mathrm{tr}_2 f}\epsilon_{\mu\rho\sigma\tau}\frac{\mathrm{d}\mathcal{J}^{0,\rho\sigma}(x,p)}{\mathrm{d}^3p}\frac{p^\tau}{m}$$

Total angular momentum tensor

$$\mathcal{J}^{\lambda,\rho\sigma}(x) = x^\rho T^{\lambda\sigma}(x) - x^\sigma T^{\lambda\tau}(x) + \mathcal{S}^{\lambda,\rho\sigma}(x)$$

$$\frac{\mathrm{d}\mathcal{J}^{0,\rho\sigma}(x)}{\mathrm{d}^3p} = (x^\rho p^\sigma - x^\sigma p^\rho)\mathrm{tr}_2 f(x,p) + \frac{\mathrm{d}\mathcal{S}^{\lambda,\rho\sigma}(x)}{\mathrm{d}^3p}$$

vanished by the Levi-Civita symbol