Flow and hyperon polarization from 3-fluid dynamical model MUFFIN

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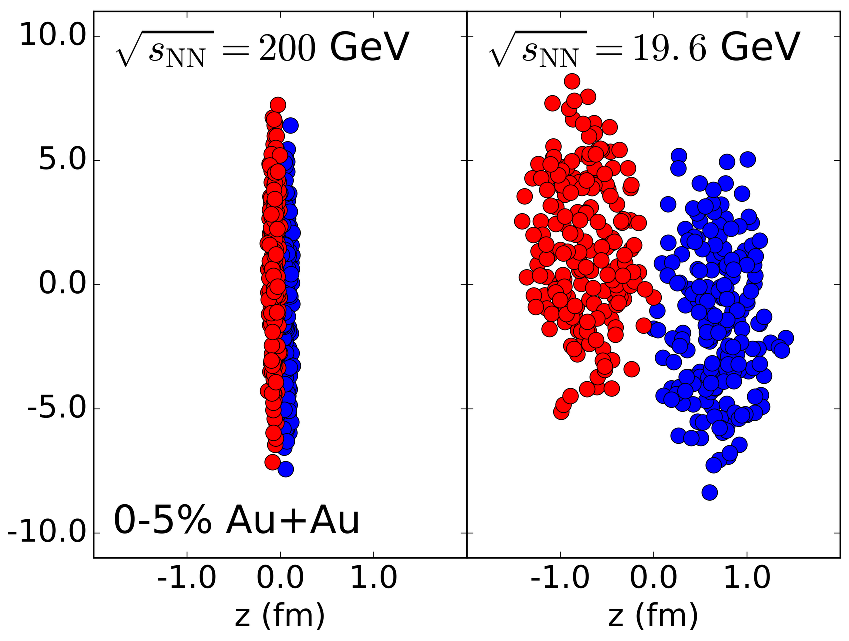
MOTIVATION: Why 3-fluid dynamics?

1) When simulating heavy-ion collisions at lower energies, the paradigm of "thin pancakes" gradually loses its applicability.

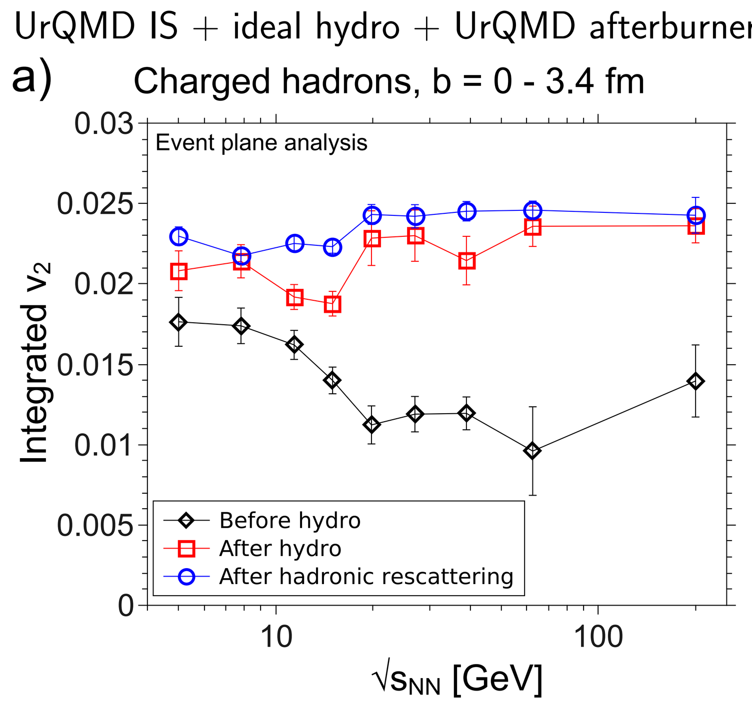
- Initial state: thick pancakes
  - boost invariance is not a good approximation → need for 3 dimensional initial state
  - previous-gen IP-Glasma, EKRT are formulated for mid-rapidity (but there is development of 3D IP-Glasma and EKRT)
- Nonzero baryon and electric charge densities

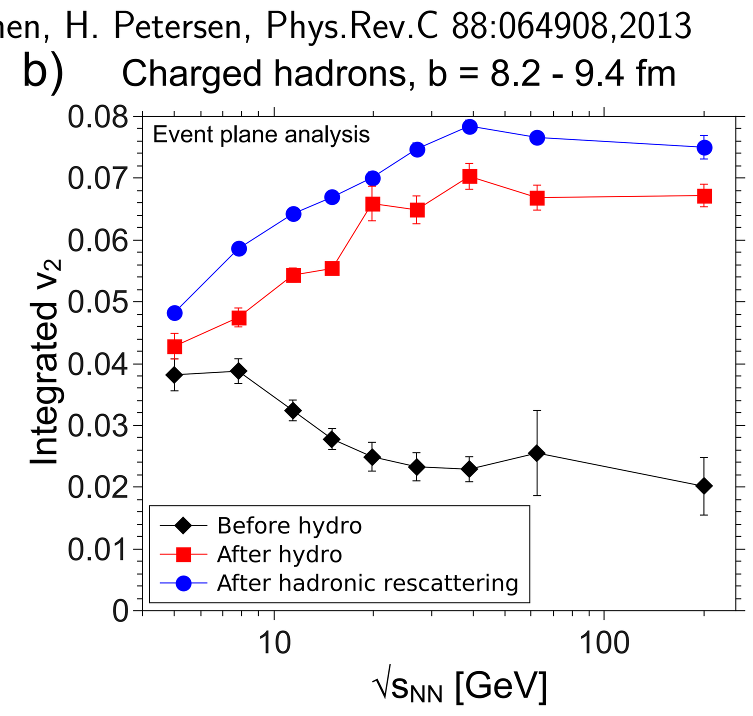


picture taken from: C. Shen, B. Schenke, Phys. Rev. C 97, 024907 (2018)

2) A lot of evolution is happening before the nuclei have completely passed through each other

UrQMD IS + ideal hydro + UrQMD afterburner, J. Auvinen, H. Petersen, Phys.Rev.C 88:064908,2013





⇒ **One must start hydro description early!** ⇐

Multi-fluid dynamics (3 fluids)
(this and #140 poster by Jakub Cimerman)

Hydrodynamic description starts from the very beginning of the collision.

Difficulty: reasonability of fluid description at the very start of heavy ion collision?

Dynamical fluidization (1 fluid)
(Poster # 154 by Renan Hirayama's, which I should also be co-authoring)

Regions of fluid phase are created dynamically, where (and when) the density is large enough.

Difficulty: how to treat non-fluid and fluid phase together (in the intial state)?

Equations of motion in multi-fluid dynamics ⇒ poster by Jakub Cimerman

The incoming nuclei are represented by two blobs of cold baryon-rich fluids: projectile (p) and target (t) fluids. As the fluids inter-penetrate each other, local friction forces start to develop. The kinetic energy lost to friction is channeled into creation of a third fluid (f). The third, or fireball, fluid vaguely correspond to mesons and baryons+anti-baryons produced in the reaction.

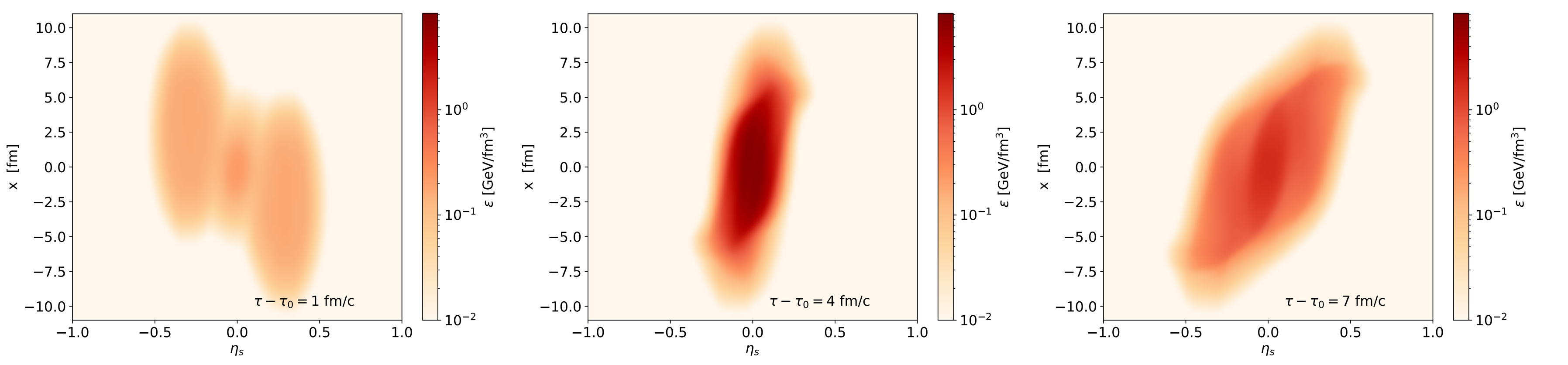
$$\partial_\mu T^{\mu\nu}_{\rm p}(x) = -F^\nu_{\rm p}(x) + F^\nu_{\rm fp}(x),$$
$$\partial_\mu T^{\mu\nu}_{\rm t}(x) = -F^\nu_{\rm t}(x) + F^\nu_{\rm ft}(x),$$
$$\partial_\mu T^{\mu\nu}_{\rm f}(x) = F^\nu_{\rm p}(x) + F^\nu_{\rm t}(x) - F^\nu_{\rm fp}(x) - F^\nu_{\rm ft}(x),$$

The total energy of all 3 fluids is conserved:

$$\partial_\mu \left[T^{\mu\nu}_p(x) + T^{\mu\nu}_t(x) + T^{\mu\nu}_f(x)\right] = 0.$$

the friction terms are $F^\mu_{\rm p}$ and $F^\mu_{\rm t}$ for projectile-target friction acting on p- and t-fuids, respectively, and $F^\mu_{\rm fp}$, $F^\mu_{\rm ft}$ for projectile-fireball and target-fireball friction. More details in Jakub Cimerman's poster.

Snapshots of multi-fluid evolution in x-η_s plane, Au-Au collision at $\sqrt{s_{NN}} = 7.7$ GeV



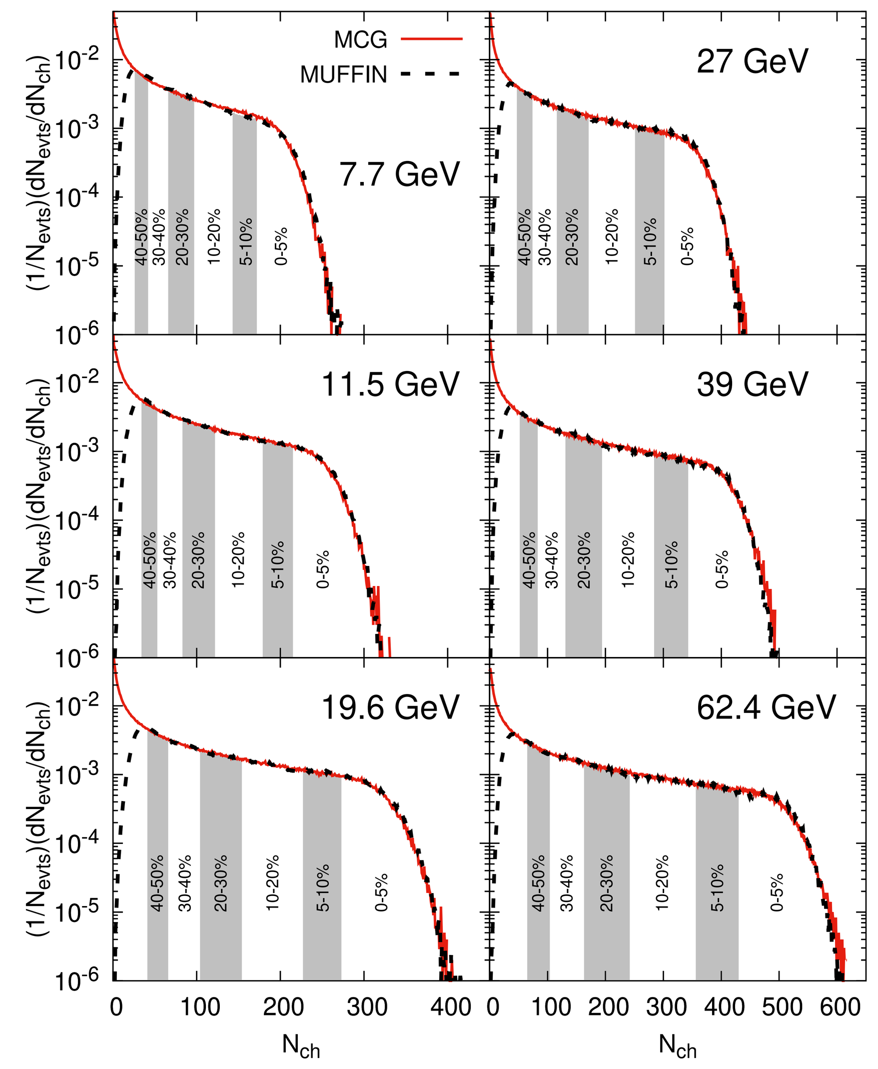
Centrality determination in MUFFIN vs. "Monte Carlo Glauber"

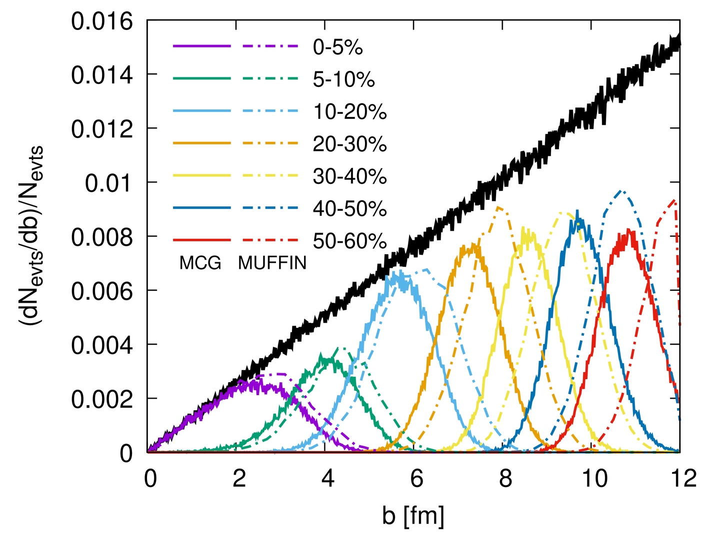
A two-component model for particle production, where $N_{\rm part}$ and $N_{\rm coll}$ come from a Monte Carlo Glauber sampling:

$$\frac{dN_{\rm ch}}{d\eta} = n_{pp}\left[(1-x)\frac{\langle N_{\rm part}\rangle}{2} + x\langle N_{\rm coll}\rangle\right]$$

$$P_{\rm NBD}(n_{pp}, k; n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)}\frac{(n_{pp}/k)^n}{(n_{pp}/k+1)^{n+k}}$$

"MCG" fits the $N_{\rm ch}$ distribution from a semi-minbias MUFFIN simulation with $b = 0 - 12$ fm (see the plot ⇒), however the resulting impact parameter is systematically smaller in MUFFIN (see the plot ⇓)





Similar findings: arXiv:2303.07919 by Kuttan, Steinheimer, Zhou, Bleicher and Stoecker

Basic observables ⇒ Jakub Cimerman's poster

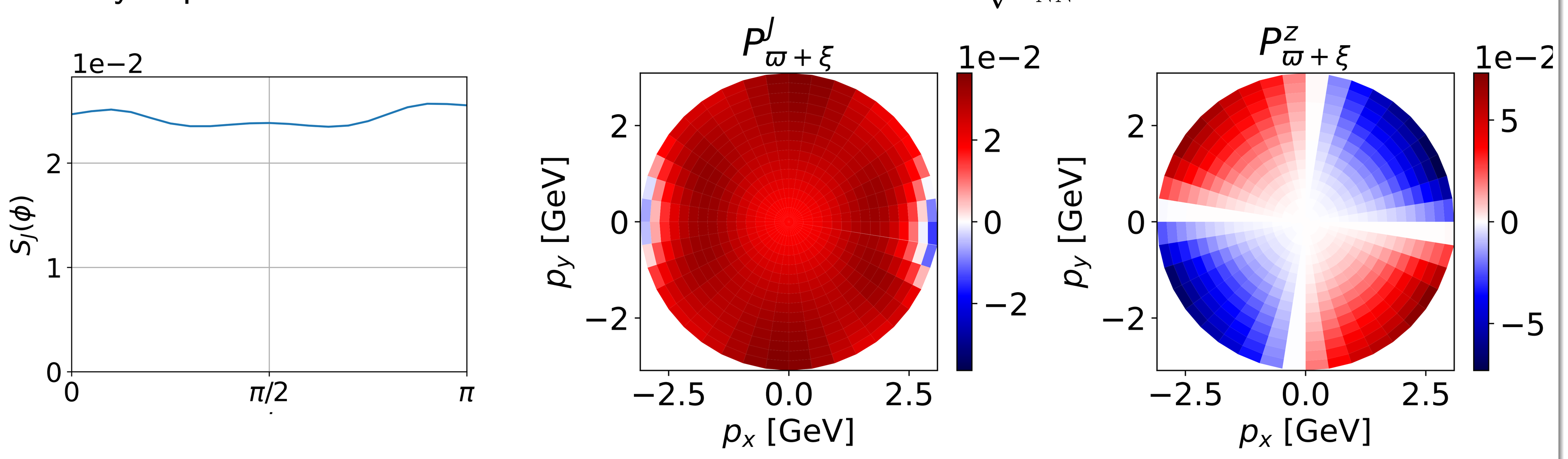
Hyperon polarization from 3-fluid dynamics

We employ the standard formula to compute polarization of spin $1/2$ hadrons produced at fluid dynamical freeze-out:

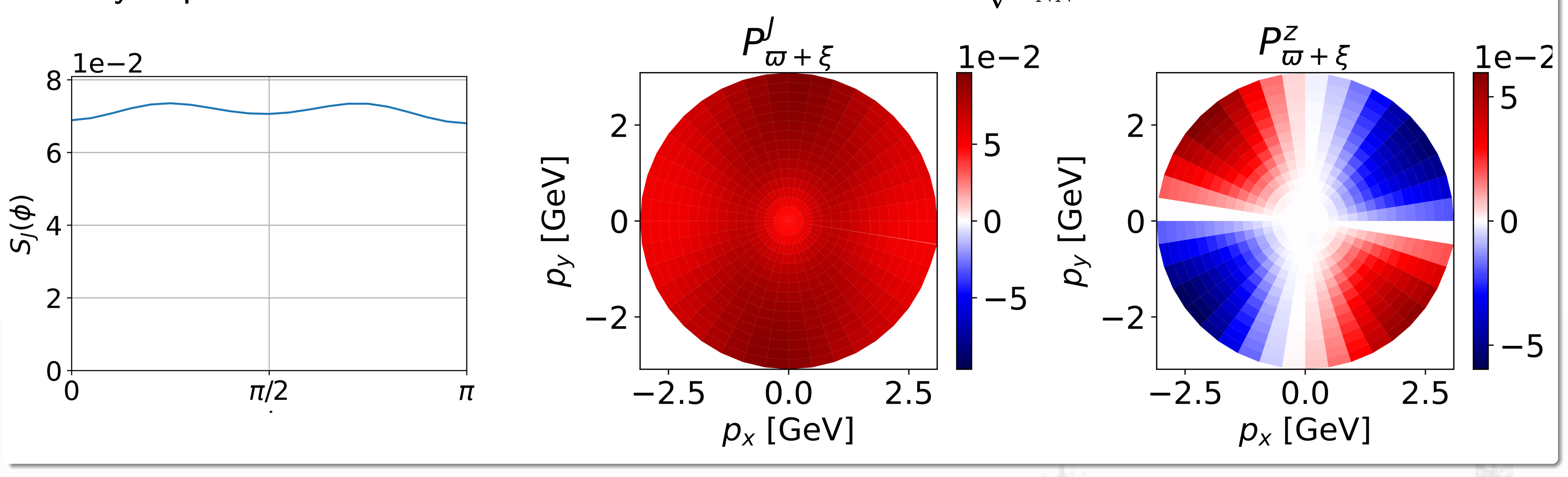
$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\sigma\frac{\int d\Sigma\cdot p\, n_F(1-n_F)[\varpi_{\nu\rho} + 2\hat{t}_\nu\xi_{\lambda\rho}\frac{p^\lambda}{\varepsilon}]}{\int d\Sigma\cdot p\, n_F}.$$

with contributions from thermal vorticity $\varpi_{\nu\rho}$ and thermal shear $\xi_{\lambda\rho}$.

Primary Λ polarization in 20-50% central Au-Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV:



Primary Λ polarization in 20-50% central Au-Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV:



vHLLE: a versatile 3 dimensional relativistic viscous hydro code for all of the mentioned projects

`https://github.com/yukarpenko/vhlle`

Comput. Phys. Commun. 185 (2014), 3016 [arXiv:1312.4160]
(this reference paper is outdated!)

✓ shear and bulk viscosity in "Israel-Stewart" with cross-terms
✓ $\tau - \eta$ (hyperbolic), as well as Cartesian coordinate frames (separate branches of the code)
✓ grid resize to optimize CPU time
✓ several initial state, EoS modules. All realized via classes ⇒ easy to plug in new IS/EoS
✓ multi-fluid evolution added with very little overhead ⇒ see a fork by Jakub Cimerman
✓ using vHLLE as a library: possible (WIP)

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