# Flow and hyperon polarization from 3-fluid dynamical model MUFFIN

**2023**

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# Motivation

**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)
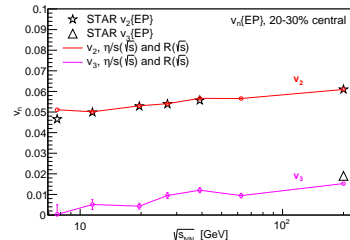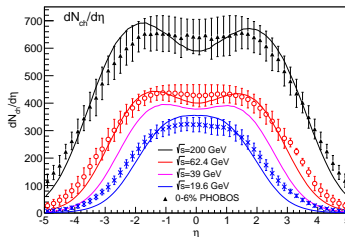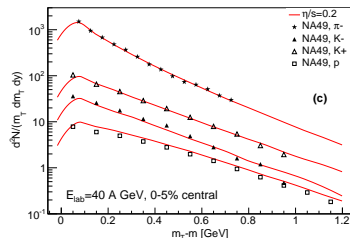
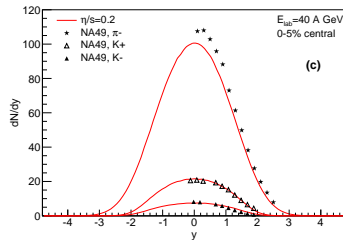- Nonzero baryon and electric charge densities
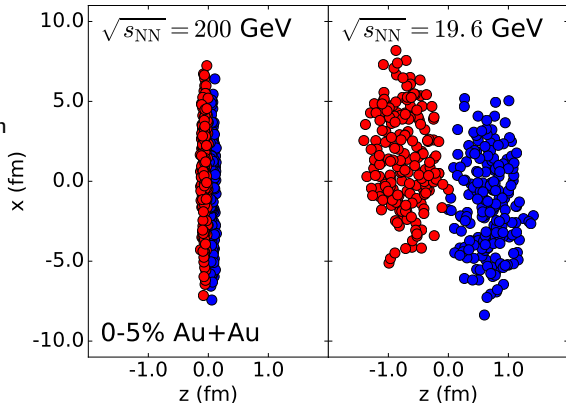


picture credit: C. Shen, B. Schenke, Phys. Rev. C 97, 024907 (2018)

# Our first shot at RHIC BES: UrQMD + vHLLE + UrQMD

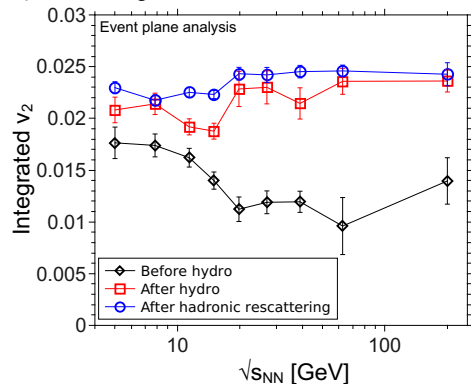- ⇒ decent agreement with a mix of RHIC BES + NA49 + PHOBOS data

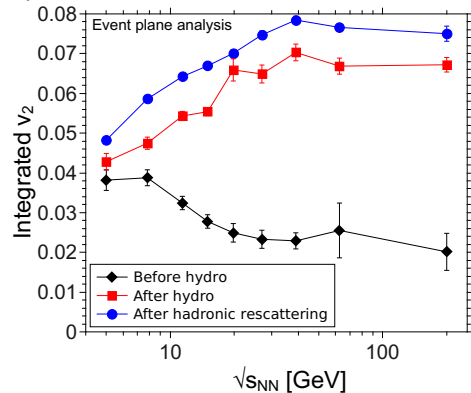From a parallel development of hybrid UrQMD by Jussi Auvinen:

**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
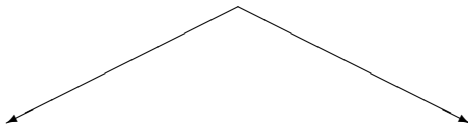


a) Charged hadrons, b = 0 - 3.4 fm

b) Charged hadrons, b = 8.2 - 9.4 fm

Why is that? At lower $\sqrt{s_{NN}}$, pre-hydro stage becomes as long as hydro stage itself.

To explore the effects of EoS, **one needs to start hydro description early!**

**Multi-fluid dynamics**

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)**

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)?

Multi-fluid model discussed in this talk:
**MUFFIN: MUlti Fluid simulation for Fast IoN collisions**

Think of it as a reincarnation of multi-fluid model for ion-ion collisions.

# Equations of motion in multi-fluid dynamics
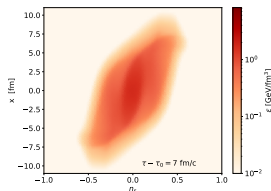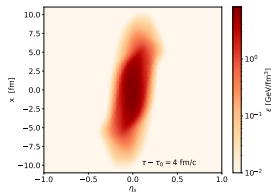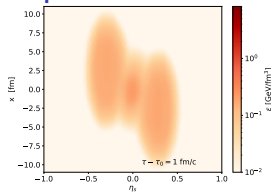


Incoming nuclei = projectile (p) and target (t) fluids.
Friction $\rightarrow$ creation of a third fluid (f).

$$\partial_\mu T_p^{\mu\nu}(x) = -F_p^\nu(x) + F_{fp}^\nu(x),$$
$$\partial_\mu T_t^{\mu\nu}(x) = -F_t^\nu(x) + F_{ft}^\nu(x),$$
$$\partial_\mu T_f^{\mu\nu}(x) = F_p^\nu(x) + F_t^\nu(x) - F_{fp}^\nu(x) - F_{ft}^\nu(x),$$

The total energy of all 3 fluids is conserved:

$$\partial_\mu \left[ T_p^{\mu\nu}(x) + T_t^{\mu\nu}(x) + T_f^{\mu\nu}(x) \right] = 0.$$

the friction terms are $F_p^\mu$ and $F_t^\mu$ for projectile-target friction acting on p- and t-fuids, respectively, and $F_{fp}^\mu$, $F_{ft}^\mu$ for projectile-fireball and target-fireball friction.

Following an assumption from the reference(s) on the next slide, **there is no transfer of conserved charge between the fluids**.

## Friction terms

**Projectile-target friction** [Ivanov, Russkikh, Toneev, Phys.Rev.C 73 (2006) 044904]:
Derived based on average energy-momentum transfer in $NN$ scattering [L.M. Satarov,
Sov. J. Nucl. Phys. 52, 264 (1990)]

$$F_\alpha^\nu = \vartheta^2 \rho_p^\xi \rho_t^\xi m_N V_{\text{rel}}^{pt}[(u_\alpha^\nu - u_{\bar\alpha}^\nu)\sigma_P(s_{pt}) + (u_p^\nu + u_t^\nu)\sigma_E(s_{pt})]$$

**Fireball-projectile/target friction** [same reference]:

$$F_{f\alpha}^\nu = \rho_\alpha^b \xi_{f\alpha}(s_{f\alpha}) V_{\text{rel}}^{f\alpha} \frac{T_{f(eq)}^{0\nu}}{u_f^0} \sigma_{\text{tot}}^{N\pi \to R}(s_{f\alpha}),$$

where:

- $\rho_p^\xi, \rho_t^\xi$ are generalised densities of constituents in the projectile and target fluids,
- $u_\alpha$, $\alpha = p, t$, $\bar\alpha = t, p$ or $u_f$ are 4-velocities of the projectile, target or fireball fluid cells,
- $\sigma_P, \sigma_E$ are cross-sections for momentum and energy transfer, in $NN$ scattering.
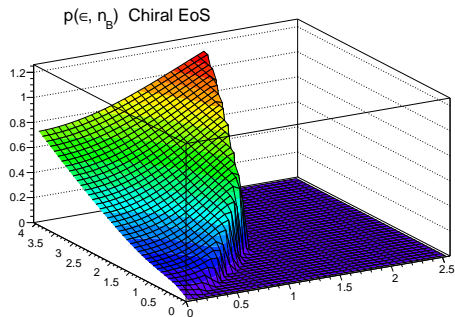
⇒ **talk by Boris Tomášik, Wed 9:30 am** at collective dynamics

# Equations of state in the fluid stage

**Chiral model**

J. Steinheimer, et al, J. Phys. G 38, 035001 (2011)

- good agreement with lattice QCD at $\mu_B = 0$
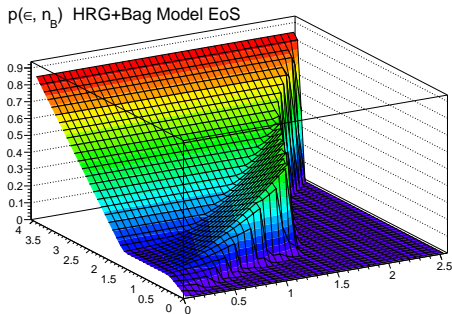- crossover type PT between confined and deconfined phases at all $\mu_B$

**Hadron resonance gas + Bag Model**

P.F. Kolb, et al, Phys.Rev. C 62, 054909 (2000)
(a.k.a. EoS Q)

- hadron resonance gas made of $u, d$ quarks including repulsive meanfield
- Maxwell construction resulting in $1^{st}$ order PT



$p(\epsilon, n_B)$ Chiral EoS



$p(\epsilon, n_B)$ HRG+Bag Model EoS

# The core part: vHLLE

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 $\Rightarrow$ easy to plug in new IS/EoS

✓ multi-fluid evolution added with very little overhead $\Rightarrow$ see a fork by Jakub Cimerman

✓ using vHLLE as a library: possible (WIP)

# Fluid-to-particle transition (particlization)

- Diagonalize $T_p^{\mu\nu}(x) + T_t^{\mu\nu}(x) + T_f^{\mu\nu}(x)$

  $\Rightarrow$ extract energy density $\varepsilon_{sw}$
- construct a hypersurface of fixed $\varepsilon_{sw} = 0.5$ GeV/fm$^3$ using `CORNELIUS`.
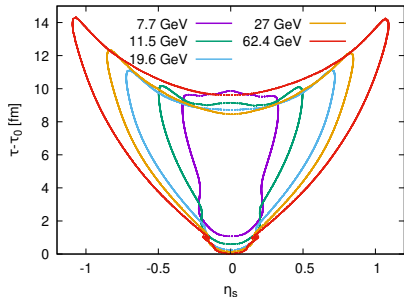


- Exclude parts of hypersurface which corresponds to matter flowing in:

$$d\Sigma^\mu d\Sigma_\mu > 0 \quad \text{and} \quad d\Sigma_0 < 0,$$

$$d\Sigma^\mu d\Sigma_\mu < 0 \quad \text{and} \quad d\Sigma_\mu T^{\mu 0} < 0$$

- distribution function on the particlization surface:

$$f(x,p) = f_p(x,p) + f_t(x,p) + f_f(x,p)$$

- Hadron sampling according to Cooper-Frye, using `SMASH-hadron-sampler`
- Sampled hadrons +spectator nucleons

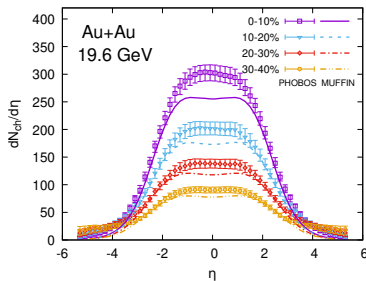$$\Downarrow$$

`SMASH` for rescatterings and resonance decays

# Basic observables vs. the data: $dN/d\eta$, net protons
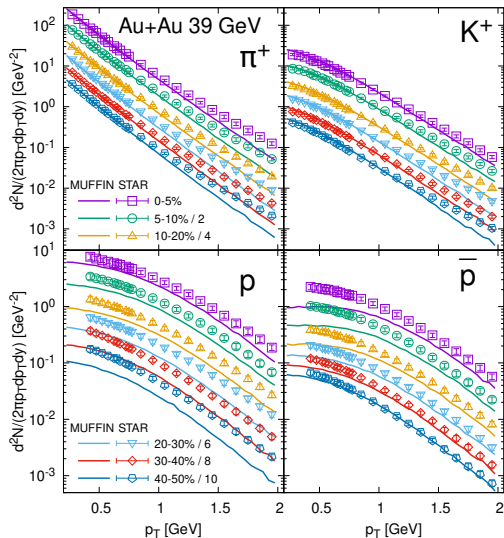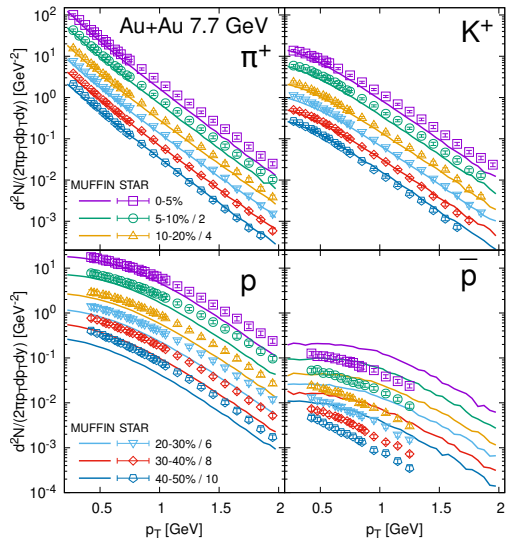
Fitting parameters in the model:

## Friction Terms

(both their functional form and the amplitudes)

We fix the functional form and vary the $\xi_{pt}(\sqrt{s_{NN}})$, $\xi_{f\alpha}(\sqrt{s_{NN}})$ to get overall agreement with the data $\Rightarrow$
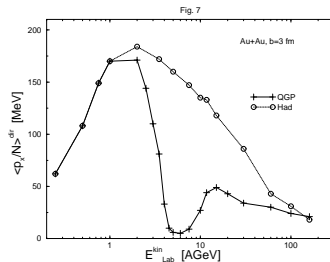
# Basic observables vs. the data: $dN/dp_T$



Jakub Cimerman, IK, Boris Tomasik, Pasi Huovinen, Phys.Rev. C **107** (2023) 4, 044902 [2301.11894 [nucl-th]]
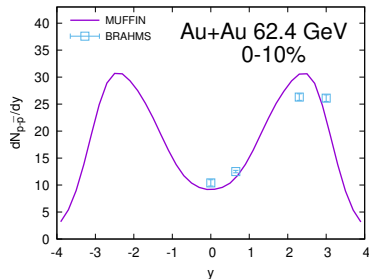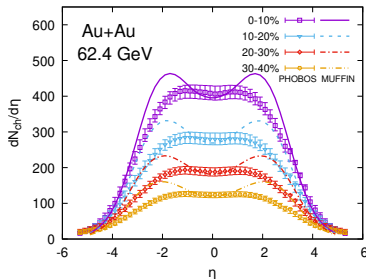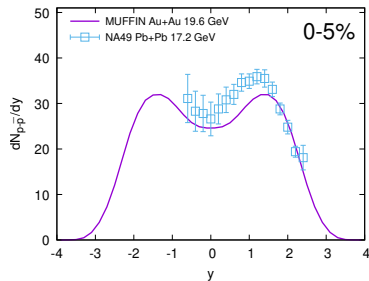
# Directed flow and Polarization

# Directed flow: origins

Rischke, Puersuen, Maruhn, Stoecker, Greiner,

Acta Physica Hungarica: 1, 309–322 (1995)

[nucl-th/9505014]

Brachmann, Soff, Dumitru, Stöcker, Maruhn, Greiner, Rischke,

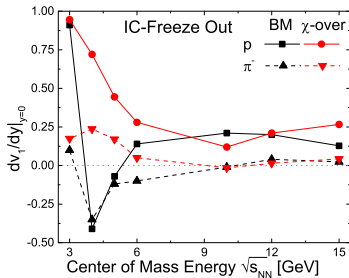Phys. Rev. C61 (2000) 024909

[nucl-th/9908010]
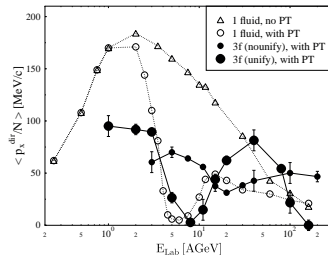
The conclusion was clear: non-monotonic dependence of $v_1$ → phase transition.

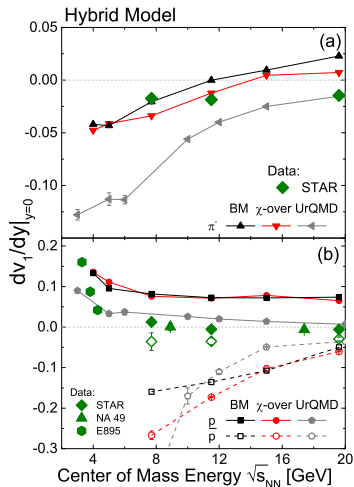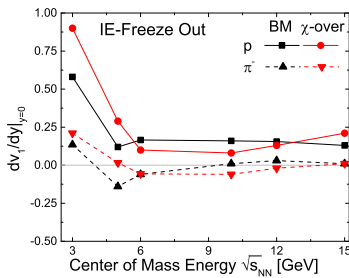This conclusion is essentially obsolete since already 10 years (see next slide).

# Directed flow: further developments circa 2014

- 1-fluid model with iso-time freezeout:
  sign change of $dv_1/dy$ with $1^{st}$-order PT EoS

- 1-fluid model with iso-T freezeout:
  NO sign change of $dv_1/dy$ with $1^{st}$-order PT EoS

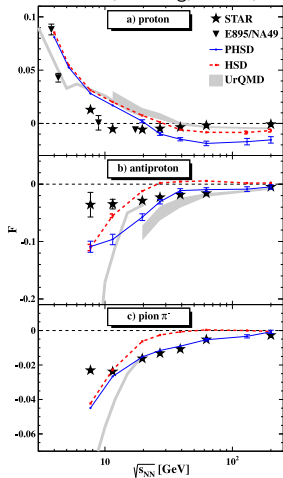

- Full hybrid model: no sign change of $dv_1/dy$, weak EoS dependence and no agreement with the data

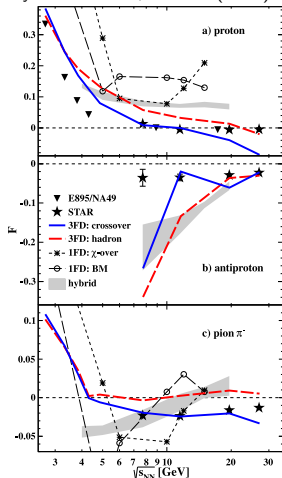# Full-fledged models generally struggle to reproduce the $v_1$

**PHSD/HSD/UrQMD models:**

Konchakovski, Cassing, Ivanov, Toneev,
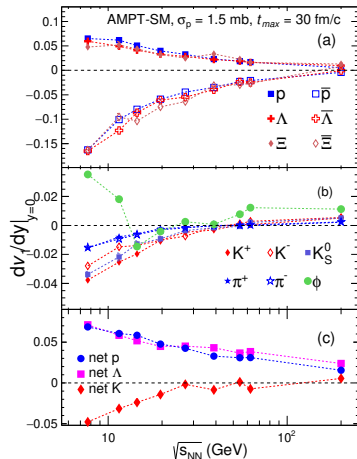
**3-fluid/1-fluid models:**
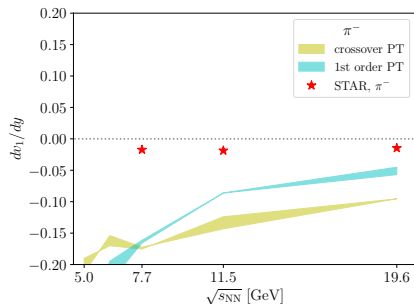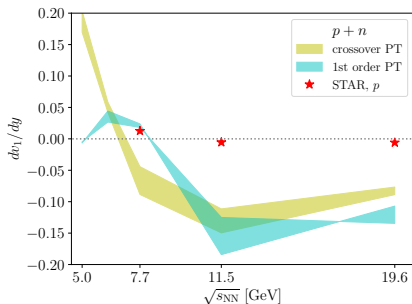
Phys. Rev. C 90, 014903 (2014)

**AMPT model:**

K. Nayak, S. Shi, Nu Xu, Zi-Wei Lin,
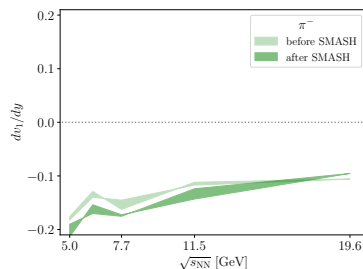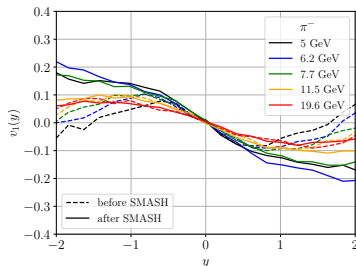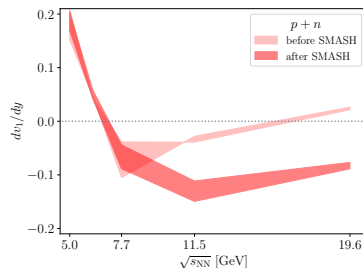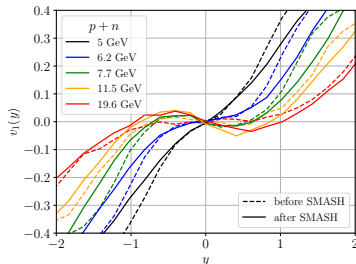
Phys. Rev. C 100, 054903 (2019)

# Where do se stand with MUFFIN



- The directed flow is **much stronger** than what STAR measured
- There is no clear trend in the EoS dependece.
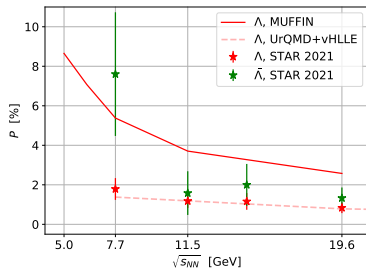
# Directed flow in MUFFIN

effects of hadronic cascade



Final-state hadronic cascade drives the directed flow further away from the data.

# Hyperon polarization

- global polarization in 20-50% central Au-Au

- local polarization in 20-50% central Au-Au at $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV



Mean hyperon polarization is much stronger in MUFFIN as compared to STAR data
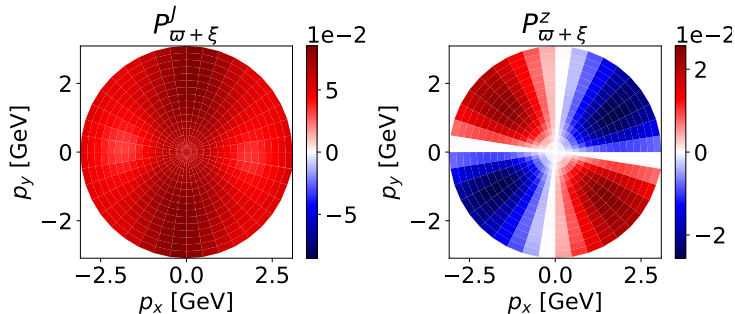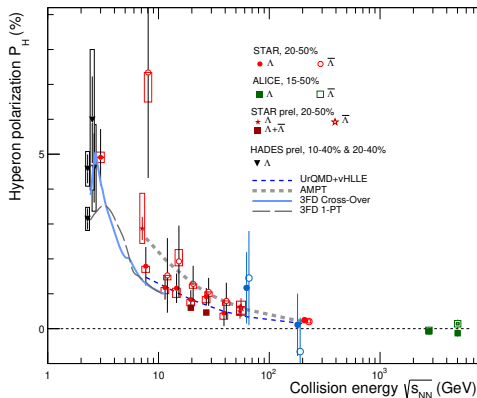
Local polarization: same patterns as observed at high energies

# Hyperon polarization

MUFFIN compared to other models
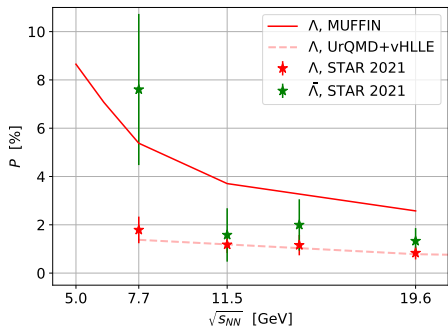
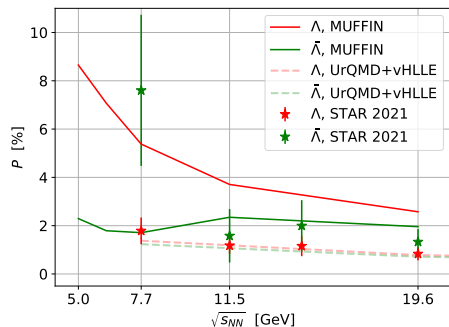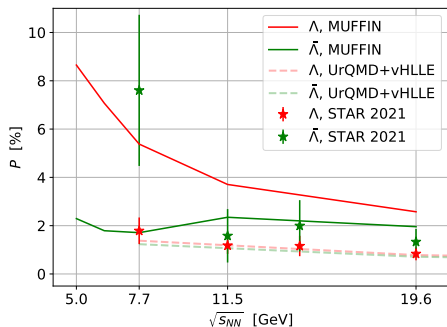Compilation by Subhash Singha @ SQM 2022



Hyperon polarization is stronger in MUFFIN as compared to other hydro models

# Polarization of $\bar{\Lambda}$ vs. $\Lambda$



- MUFFIN produces strong $\Lambda - \bar{\Lambda}$ splitting but with a wrong sign!
- There was a similar but much weaker trend with UrQMD+vHLLE
- Same trend in AMPT+MUSIC,
  Baochi Fu et al, Phys. Rev. C 103, 024903 (2021) [arXiv:2011.03740]

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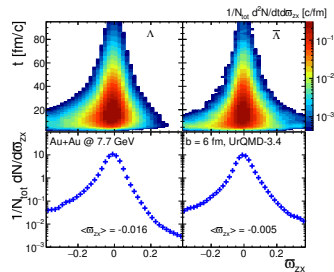
Correct sign of splitting in UrQMD 3.4 + coarse graining:
O. Vitiuk, L. Bravina, E. Zabrodin, Phys. Lett. B 803 (2020), 135298
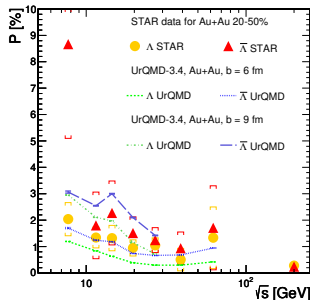


... however the explanation therein sounds confusing since reported $\langle \varpi_{zx} \rangle$ is larger in magnitude for $\Lambda$ than for $\bar{\Lambda}$

# Conclusions

- We present the next incarnation of 3-fluid model for relativistic heavy-ion collisions at RHIC BES/FAIR/... energies.

- Different from the existing model by Ivanov,Toneev,Soldatov, there is fluctuating initial state, shear and bulk viscosities (implemented but not enabled yet), Monte Carlo hadron sampling and hadronic afterburner (SMASH). Equation of state can be easily swapped.

- We fit the $dN/dy$ and $p_T$ distributions of hadrons from RHIC BES.

- $v_2$ is overestimated, which presumably happens due to ideal hydro evolution

- Directed flow is much stronger than the data (same as in other models), and there is no clear EoS trend

- Global polarization is stronger than the data; splitting between $\bar{\Lambda}$ and $\Lambda$ is strong but has a wrong sign. However it challenges the idea that the splitting is mainly due to magnetic field.

- **Outlook:** construct different friction terms based on different underlying assumptions; explore viscous fluid evolution,

- plug in different equations of state to explore sensitivity to the EoS (currently used EoS are outdated).