Simulating collectivity in dense baryon matter with multiple fluids

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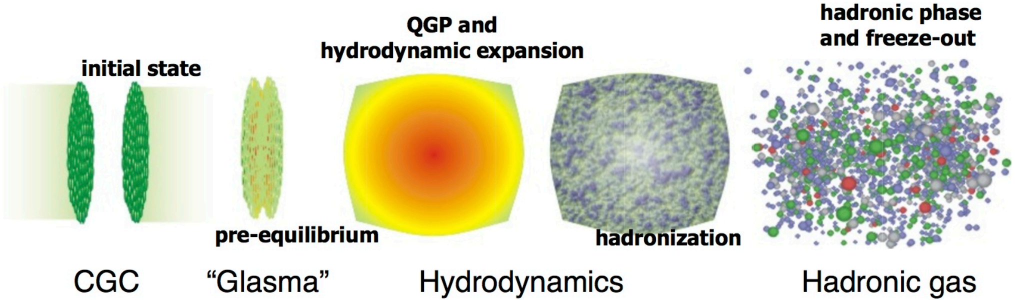
Jakub Cimerman, IK, Boris Tomasik, Pasi Huovinen, Phys.Rev. C **107** (2023) 4, 044902 [2301.11894 [nucl-th]]
plus some new results I've generated last week

Status quo at high energies

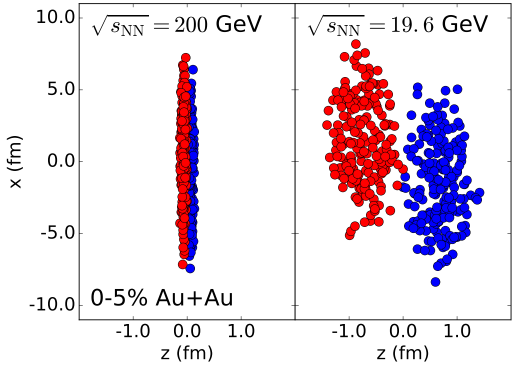
There is a clear time separation between the initial state and the fluid stage



When foraging into lower energies using the same tools:

The paradigm of "thin pancakes" gradually loses its applicability.

- There is no boost invariance
- Baryon and electric charge densities are significant
- **Nuclei pass through each other slowly** (the passage can last as long as subsequent fluid stage)
- There is no clear separation of the initial state and the fluid stage.

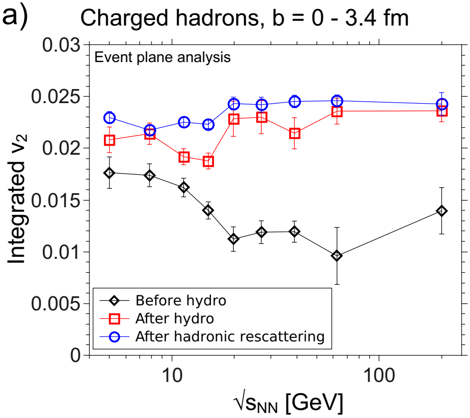


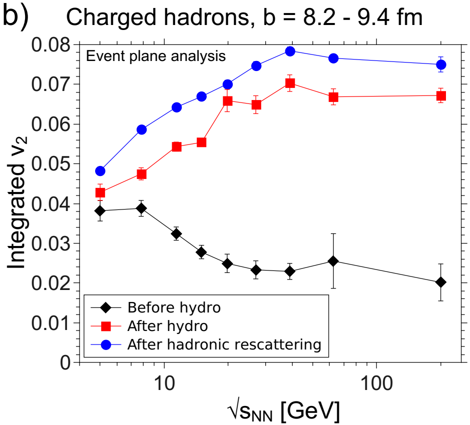
picture credit: C. Shen, B. Schenke, Phys. Rev. C 97, 024907 (2018)

From the last two bullet points:

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 (2013), 064908





In order to see the effects of the EoS at high densities,

One must start hydro description early!

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 dynamics

Hydrodynamic description starts from the very beginning of the collision.

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

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.

Why to reincarnate?

The existing 3-fluid dynamic model
[Ivanov, Russkikh, Toneev, Phys.Rev.C 73 (2006) 044904; Ivanov, Phys.Rev.C 87 (2013), 064904]
does not suit our needs:

- EoS is not swappable
- Evolution in Cartesian coordinates $\rightarrow$ unreliable at $\sqrt{s_{\rm NN}} \geq 20$ GeV
- no viscosity
- no initial state fluctuations
- no hadronic afterburner

Equations of motion in multi-fluid dynamics

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.

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

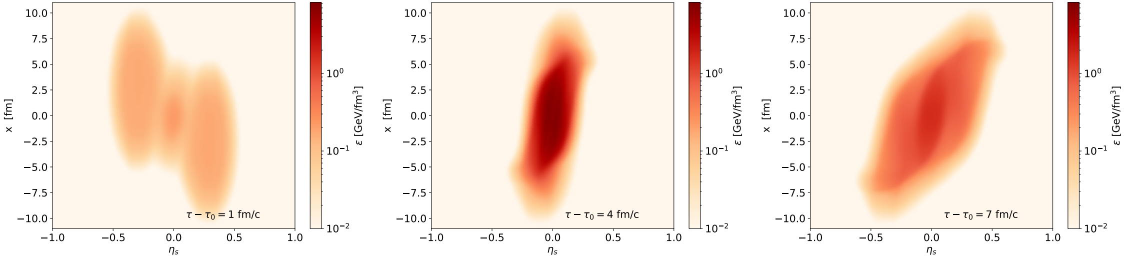
The total energy of all 3 fluids is conserved:

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

the friction terms are F^μ_{p} and F^μ_{t} for projectile-target friction acting on p- and t-fuids, respectively, and F^μ_{fp}, F^μ_{ft} 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**.

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



Friction terms

that we are *currently* using

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)]

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

where:

- ϑ^2 is a unification factor - which suppresses the friction further when the fluids slow down with respect to each other,
- ρ_p^ξ, ρ_t^ξ are generalised densities of constituents in the projectile and target fluids,
- $V_{\rm rel}^{pt}$ is a relative velocity of the $p-$ and $t-$ fluid cells,
- m_N is nucleon mass,
- u_α , $\alpha = p,t$, $\bar\alpha = t,p$ are 4-velocities of the fluid cells,
- $\sigma_{\rm P}, \sigma_{\rm E}$ are cross-sections for momentum and energy transfer, respectively.

Friction terms (2)

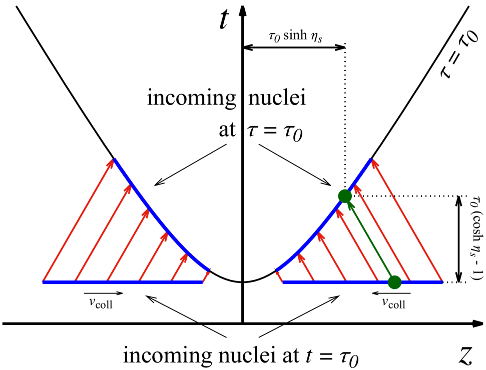
Fireball-projectile/target friction [same reference]:

$$F^{\nu}_{f\alpha} = \rho^{b}_{\alpha}\xi_{f\alpha}(s_{f\alpha})V^{f\alpha}_{\rm rel}\frac{T^{0\nu}_{f(eq)}}{u^{0}_{f}}\sigma^{N\pi\to R}_{\rm tot}(s_{f\alpha}),$$

where:

- ρ^b_p, ρ^b_t are baryon densities of of the projectile and target fluids,
- $V^{f\alpha}_{\rm rel}$ is a relative velocity of the fireball and baryon-rich fluid cells,
- $T^{0\nu}_{f(eq)}$ is energy-momentum tensor of the fireball fluid,
- $\sigma^{N\pi\to R}_{\rm tot}$ is a pion-nucleon cross-section.
- $\xi_{f\alpha}$ is a “K-factor” (a fitting factor) for the friction term, which is intended to compensate for all the missing/incorrect physics therein, and to lead to better agreement with the data

Coordinate frame and setup for multi-fluid evolution



- Nucleons from the incoming nuclei are sampled at $t = t_0$ surface (fixed Cartesian time).
- The nucleons are then propagated according to free-flying trajectories onto $\tau = \tau_0$ hypersurface.
- The nucleons are then melted into the fluids: their energies and momenta are distributed to nearby fluid cells using a smearing kernel:

$$T^{0\mu}(x_{\rm cell}, y_{\rm cell}, \eta_{\rm cell}) = \sum_{i \in \rm nucleons} p_i^\mu K(\Delta x, \Delta y, \Delta \eta_s)$$

$$N^0_{b,q}(x_{\rm cell}, y_{\rm cell}, \eta_{\rm cell}) = \sum_{i \in \rm nucleons} \{B_i, Q_i\} K(\Delta x, \Delta y, \Delta \eta_s)$$

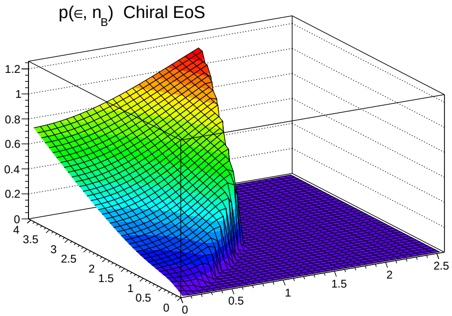
with a smearing kernel: $K(\Delta x, \Delta y, \Delta \eta_s) = A \exp\left(-\frac{\Delta x^2 + \Delta y^2 + \Delta \eta_s^2 \tau^2 \cosh^2 \eta_s \cosh^2 y}{2\sigma^2}\right)$

Equations of state in the fluid stage

Chiral model

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

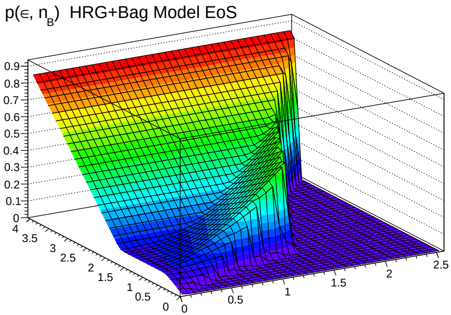
- good agreement with lattice QCD at $\mu_B = 0$
- crossover type PT between confined and deconfined phases at all μ_B



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



Hydrodynamic algorithm: 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

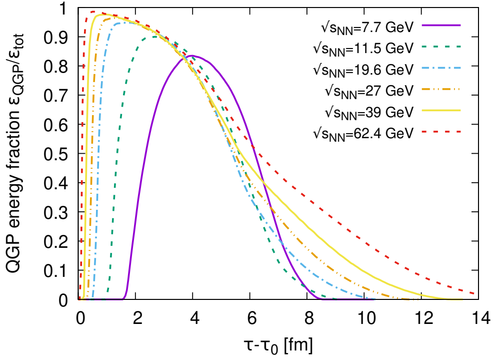
✓ several initial state, EoS modules. All realized via classes ⇒ easy to plug in new IS/EoS

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

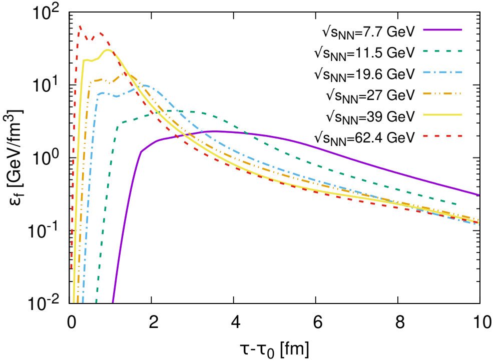
✓ using vHLLE as a library: possible (WIP)

When do we witness QGP creation in MUFFIN?

QGP fraction as a function of time at different $\sqrt{s_{\rm NN}}$:



Energy density in central cell of fireball fluid as a function of time at different $\sqrt{s_{\rm NN}}$:

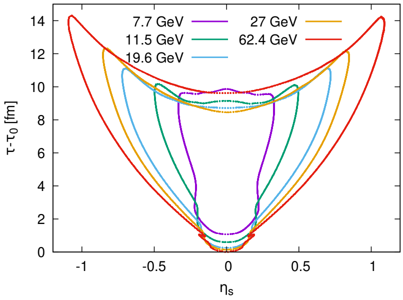


Significant fraction of medium in QGP phase exists down to $\sqrt{s_{\rm NN}} = 7.7$ GeV.

Fluid-to-particle transition (particlization) part 1

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

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



- On such hypersurface, $\int d\Sigma_\mu T^{0\mu}=0$ (Gauss theorem)

  $\Rightarrow$ we use it to check the accuracy of the simulations

Particlization part 2

- 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`:

$$N = \int \frac{d^3p}{E_p} \int d\Sigma_\mu(x) p^\mu f(p, T(x), \mu_i(x))$$

(grand canonical sampling with $T(x)$, $\mu_i(x)$)

- Sampled hadrons +spectator nucleons

$\Downarrow$

`SMASH` for rescatterings and resonance decays

Centrality determination in MUFFIN vs. “Monte Carlo Glauber”

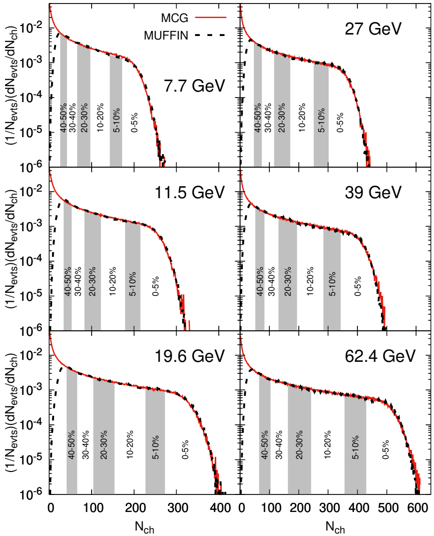
We make a comparison between:

- a semi-minimum-bias MUFFIN simulation $(0 < b < 12$ fm$)$ and
- a two-component model for particle production, where $N_{\rm part}$ and $N_{\rm coll}$ come from a Monte Carlo Glauber sampling:

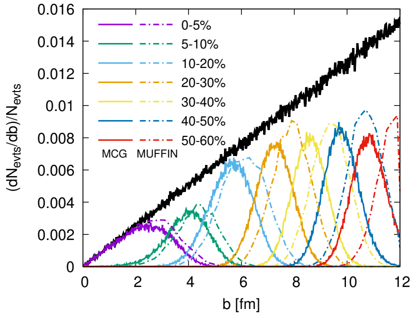
$$\frac{dN_{\rm ch}}{d\eta} = n_{pp}\left[(1-x)\frac{\langle N_{\rm part}\rangle}{2} + x\langle N_{\rm coll}\rangle\right]$$

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

- “MCG” fits the $N_{\rm ch}$ distribution from a semi-minbias MUFFIN simulation with $b = 0 - 12$ fm



- we bin the generated events in centrality classes based on $dN_{\mathrm{ch}}/d\eta$ at mid-rapidity:



- For each centrality class, the mean impact parameter in MUFFIN has a larger value as compared to the “Monte Carlo Glauber”

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

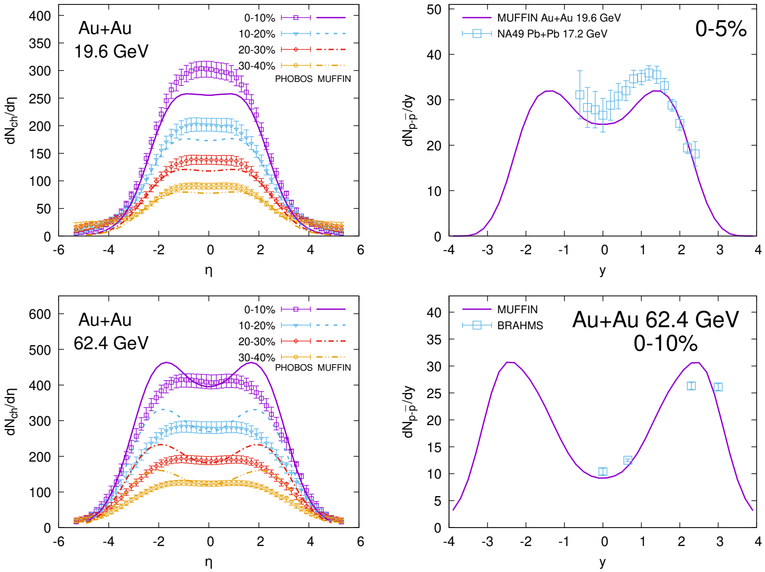
Basic observables vs. the data: $dN/d\eta$, net protons

Fitting parameters in the model:

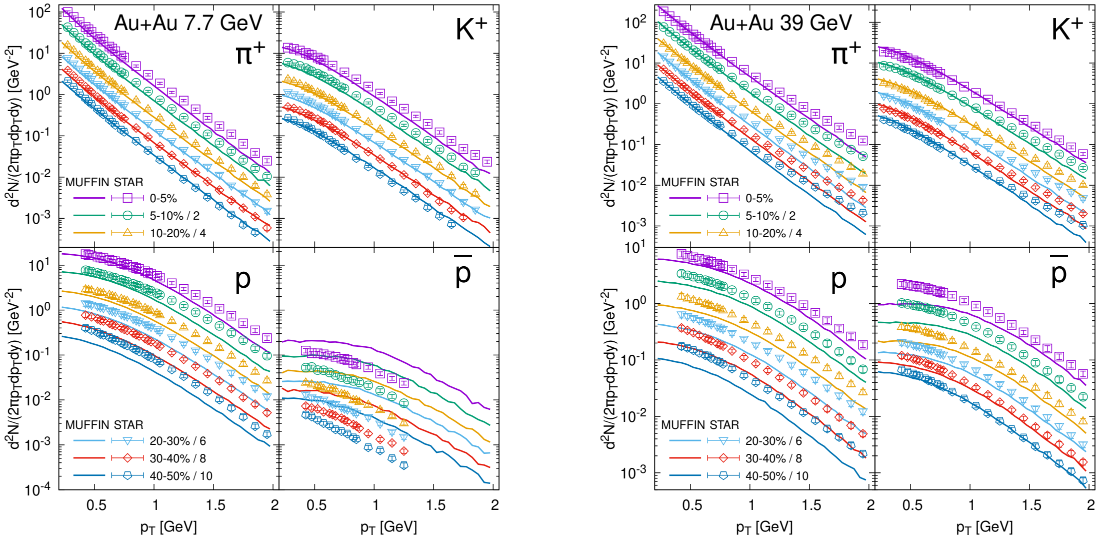
Friction Terms

(both their functional form and the amplitudes)

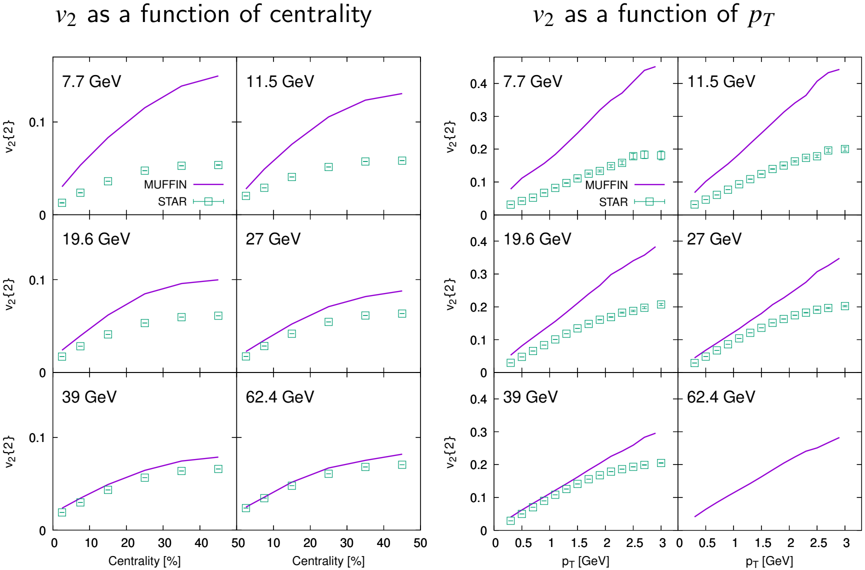
We fix the functional form and vary the $\xi_{pt}(\sqrt{s_{\rm NN}})$, $\xi_{f\alpha}(\sqrt{s_{\rm NN}})$ to get overall agreement with the data $\Rightarrow$



Basic observables vs. the data: dN/dp_T



Basic observables vs. the data: v_2



Here a probable culprit is ideal fluid evolution: we haven't switched the viscosity on yet.

Directed flow: origins

Rischke, Puersuen, Maruhn, Stoecker, Greiner,

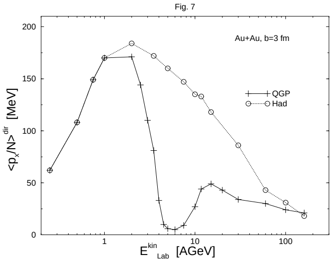
Acta Physica Hungarica: 1, 309–322 (1995)

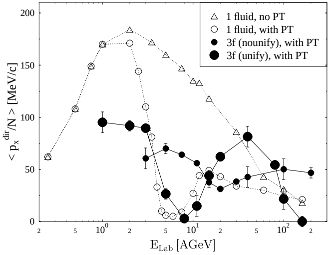
[nucl-th/9505014]

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

Phys. Rev. C61 (2000) 024909

[nucl-th/9908010]



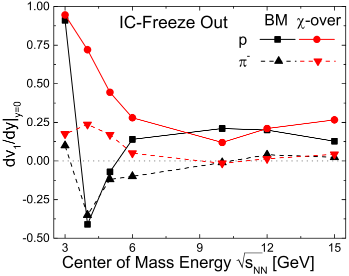


The conclusion was clear: non-monotonic dependence of v_1 $\rightarrow$ phase transition.

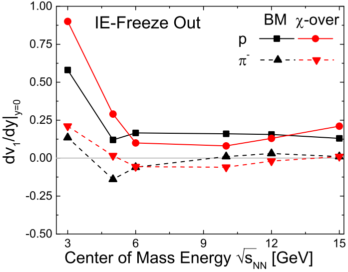
Directed flow: further developments circa 2014

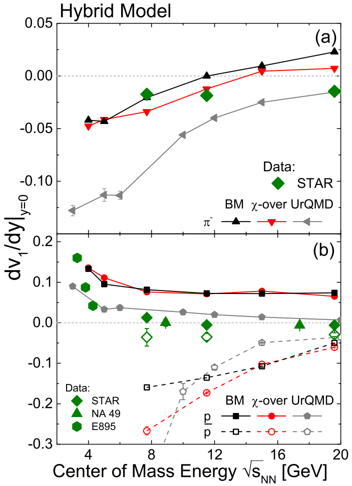
J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, Phys. Rev. C 89 (2014) 054913, arXiv:1402.7236

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



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



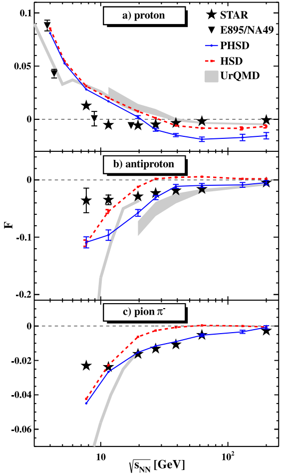


- Full hybrid model: no sign change of dv_1/dy, weak EoS dependence and no agreement with the data

Full-fledged models generally struggle to reproduce the v_1

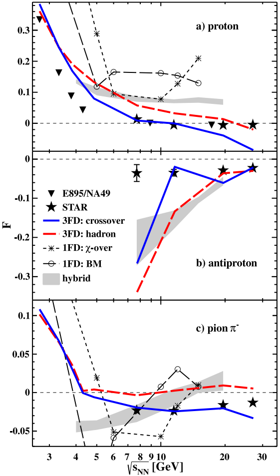
PHSD/HSD/UrQMD models:

Konchakovski, Cassing, Ivanov, Toneev,



3-fluid/1-fluid models:

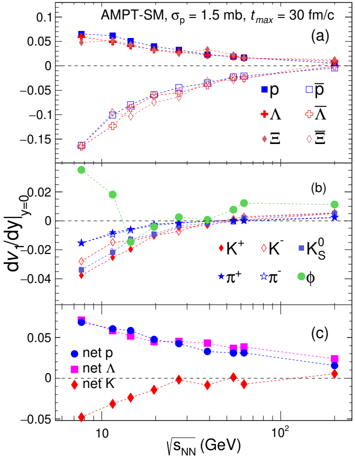
Phys. Rev. C 90, 014903 (2014)



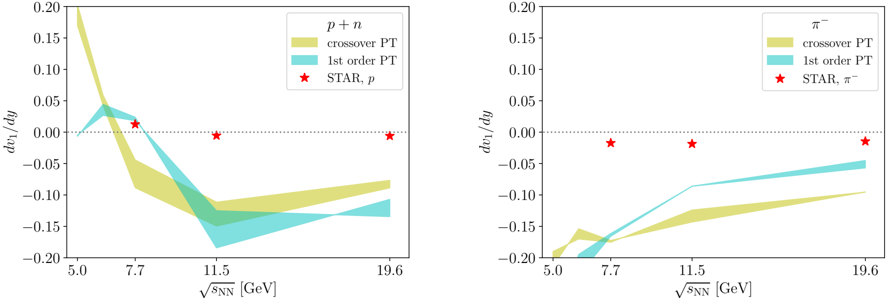
AMPT model:

K. Nayak, S. Shi, Nu Xu, Zi-Wei Lin,

Phys. Rev. C 100, 054903 (2019)



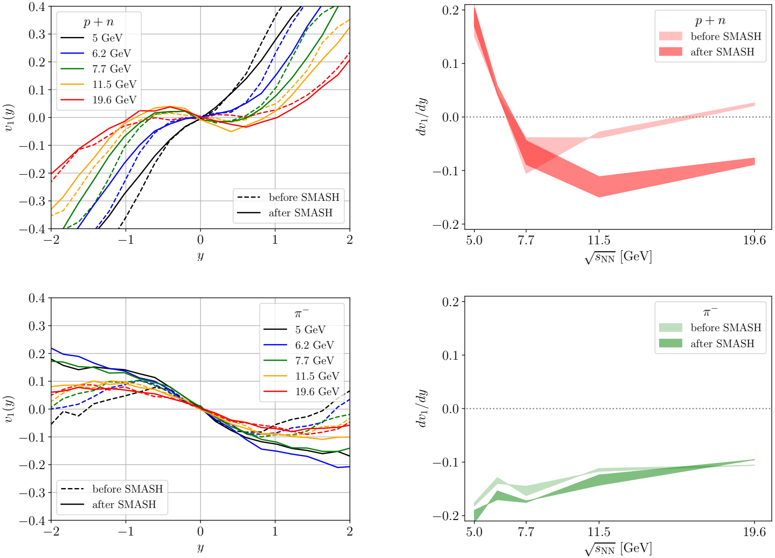
Where do se stand with MUFFIN



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

Directed flow in MUFFIN

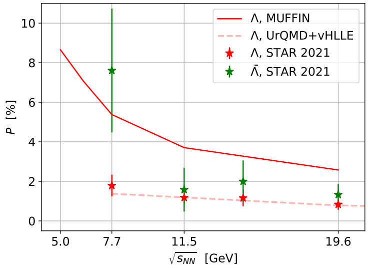
effects of hadronic cascade



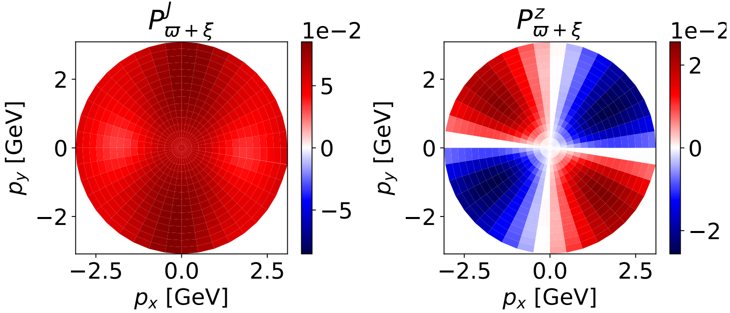
Final-state hadronic cascade drives the directed flow further away from the data.

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

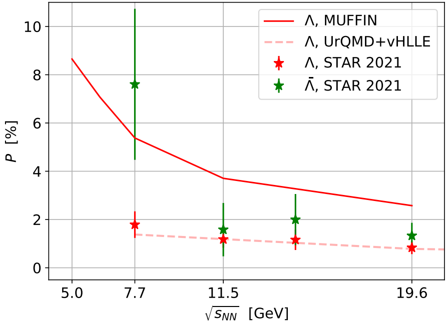


Mean hyperon polarization is much stronger in MUFFIN as compared to STAR data

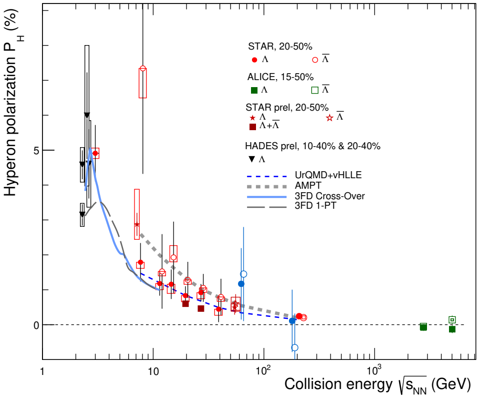
Local polarization: same patterns as observed at high energies

Hyperon polarization

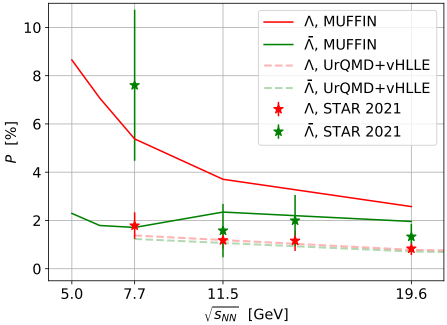
MUFFIN compared to other models



Compilation by Subhash Singha @ SQM 2022

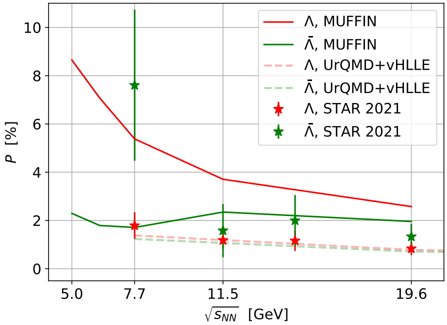


Polarization of $\bar{\Lambda}$ vs. Λ



- 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]

Polarization of $\bar{\Lambda}$ vs. Λ



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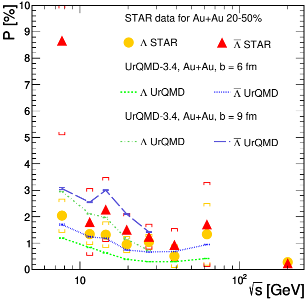
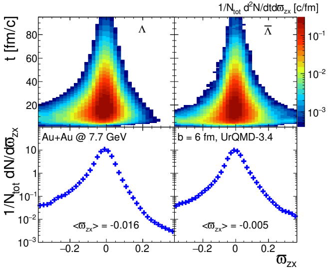
- There was a similar but much weaker trend with UrQMD+vHLLE
- Same trend in AMPT+MUSIC, Baochi Fu et al, Phys. Rev. C 103, 024903 (2021) [arXiv:2011.03740]

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 Λ 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 Λ is strong but has a wrong sign.
- **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).