



# Multi-fluid description of heavy-ion collisions

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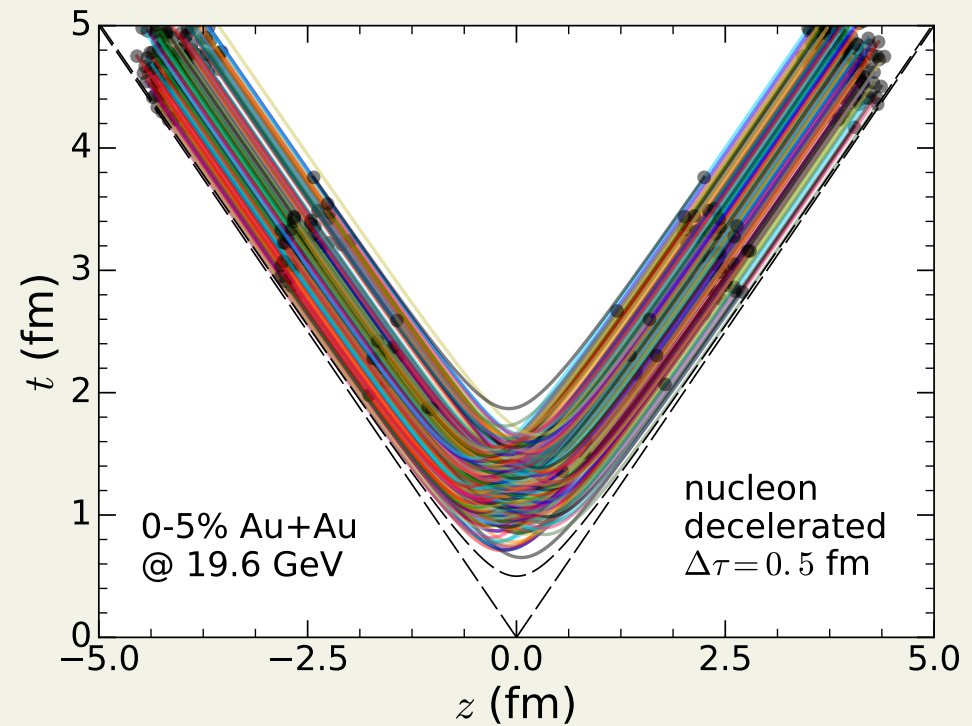
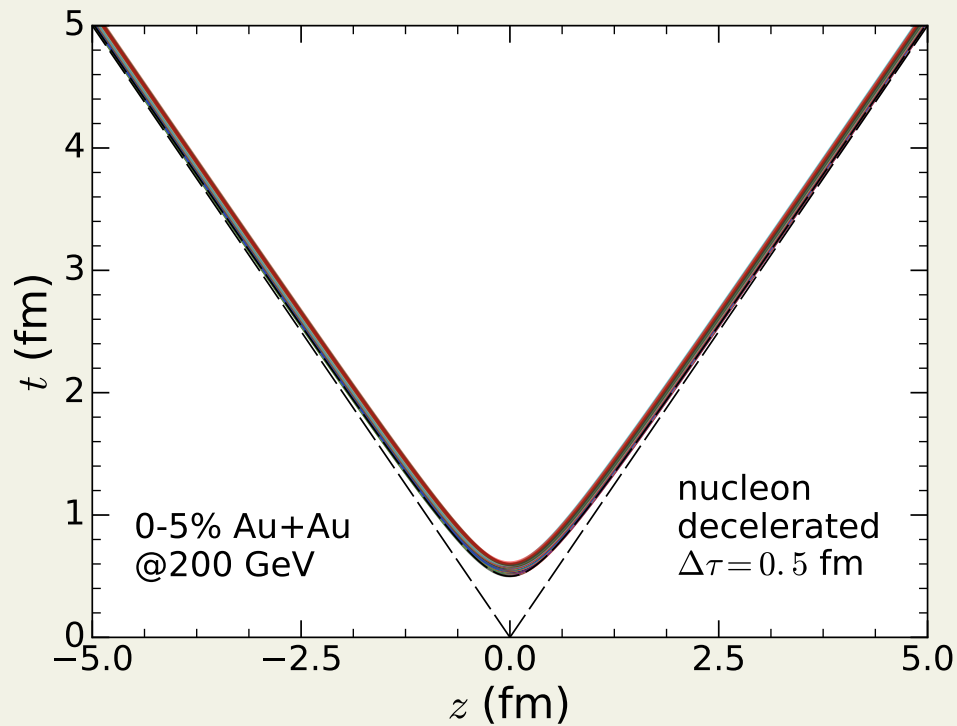
**XVIII Polish Workshop on Relativistic Heavy-Ion Collisions**

December 13, 2025, Jagiellonian University, Cracow

with **Clemens Werthmann** and **Iurii Karpenko**  
arXiv:2511.10487

# Conventional initialisation

- primary collisions overlap with secondary collisions



Shen & Schenke, PRC97, 024907 (2018)

# 3-fluid dynamics

$$0 = \partial_\mu T^{\mu\nu}$$

# 3-fluid dynamics

$$\begin{aligned} 0 &= \partial_\mu T^{\mu\nu} \\ &= \partial_\mu T_t^{\mu\nu} \end{aligned}$$

$$T_t^{\mu\nu} = \text{target fluid}$$

# 3-fluid dynamics

$$\begin{aligned} 0 &= \partial_\mu T^{\mu\nu} \\ &= \partial_\mu T_t^{\mu\nu} + \partial_\mu T_p^{\mu\nu} \end{aligned}$$

$T_t^{\mu\nu}$  = target fluid

$T_p^{\mu\nu}$  = projectile fluid

# 3-fluid dynamics

$$\begin{aligned} 0 &= \partial_\mu T^{\mu\nu} \\ &= \partial_\mu T_t^{\mu\nu} + \partial_\mu T_p^{\mu\nu} + \partial_\mu T_{\text{fb}}^{\mu\nu} \end{aligned}$$

$T_t^{\mu\nu}$  = target fluid

$T_p^{\mu\nu}$  = projectile fluid

$T_{\text{fb}}^{\mu\nu}$  = fireball fluid

- target and projectile represent colliding nucleons
- fireball (loosely) represents produced particles
- three fluids, each with temperature and flow velocity of its own

# 3-fluid dynamics

$$\partial_\mu T_t^{\mu\nu}(x) = -F_t^\nu(x) + F_{ft}^\nu(x)$$

$$\partial_\mu T_p^{\mu\nu}(x) = -F_p^\nu(x) + F_{fp}^\nu(x)$$

$$\partial_\mu T_{fb}^{\mu\nu}(x) = F_p^\nu(x) + F_t^\nu(x) - F_{fp}^\nu(x) - F_{ft}^\nu(x)$$

- interaction between **target** and **projectile**:  
friction terms  $-F_t^\nu(x)$  and  $-F_p^\nu(x)$
- interaction between fireball and **target/projectile**:  
friction terms  $F_{fp}^\nu(x)$  and  $F_{ft}^\nu(x)$

# Friction from kinetic theory

## Boltzmann equation for three fluids

$$p^\mu \partial_\mu f_i = C_i[f_p, f_t, f_f] = \sum_{j,k} C_i^{jk}[f_j, f_k], \quad i, j, k \in \{p, t, f\}$$

$C_i^{jk}$ : change in distribution/fluid  $i$  due to interactions of particles in  $j$  and  $k$

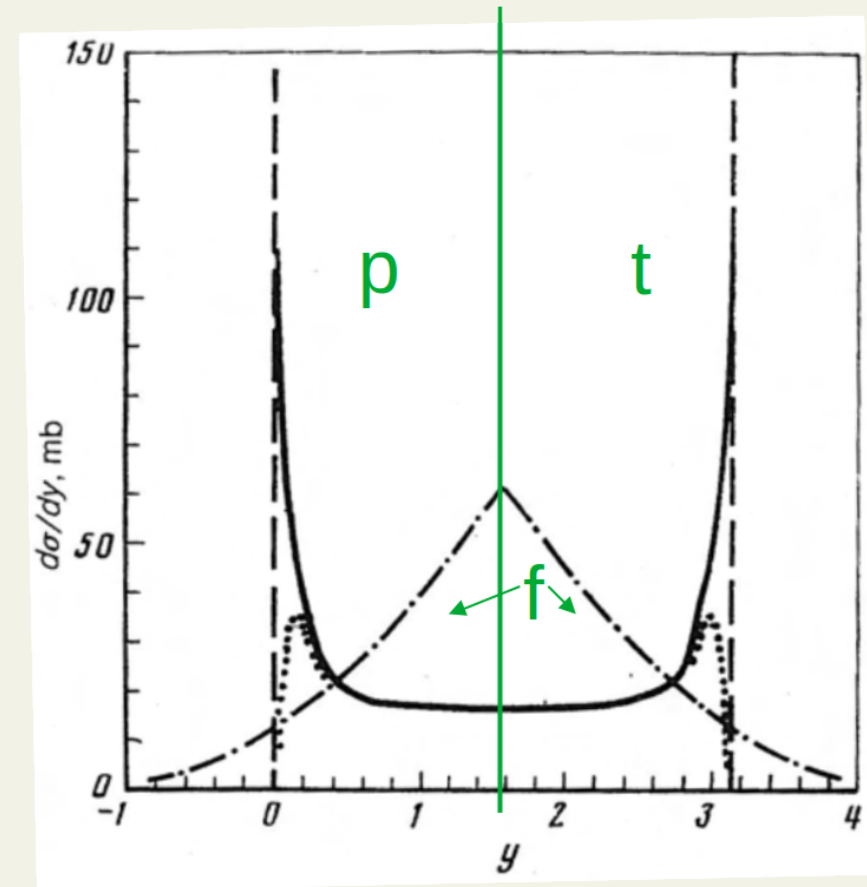
for given  $C_i^{jk}$ , friction obtained as

$$\partial_\mu T_i^{\mu\nu} = \int \frac{d^3p}{p^0} p^\nu C_i = F_i^\nu, \quad \partial_\mu J_{B,i}^\mu = B_i \int \frac{d^3p}{p^0} C_i = R_{B,i}$$

# Ivanov/Mishustin/Satarov (IMS)

Ivanov, Russkikh, Toneev PRC 73, 044904 (2006)

- $N+N$  scattering:  $N$  strongly peaked at ingoing rapidities,  $\pi$  at midrapidity  
 $\Rightarrow$  in p-t friction:  $N$  stay in p/t,  $\pi$  go to f
- $\pi + N$  mostly resonance formation  
 $\Rightarrow$  all outgoing particles from p-f friction go to p
- $\mu_B = 0$  in fireball

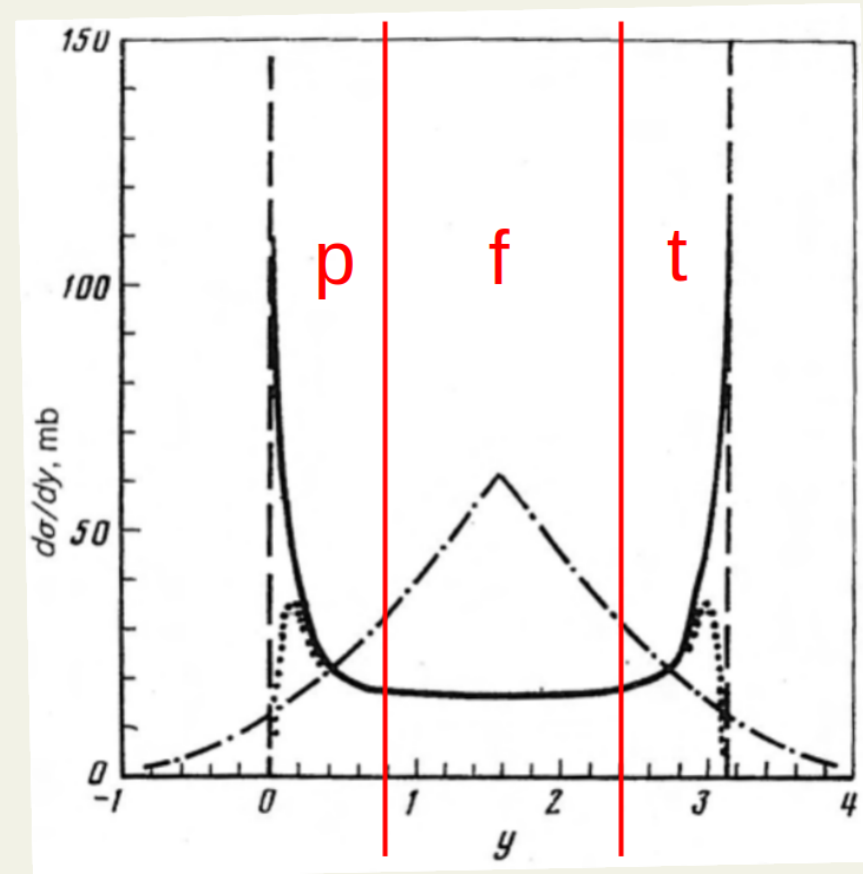


# Charge Transfer (CT) friction

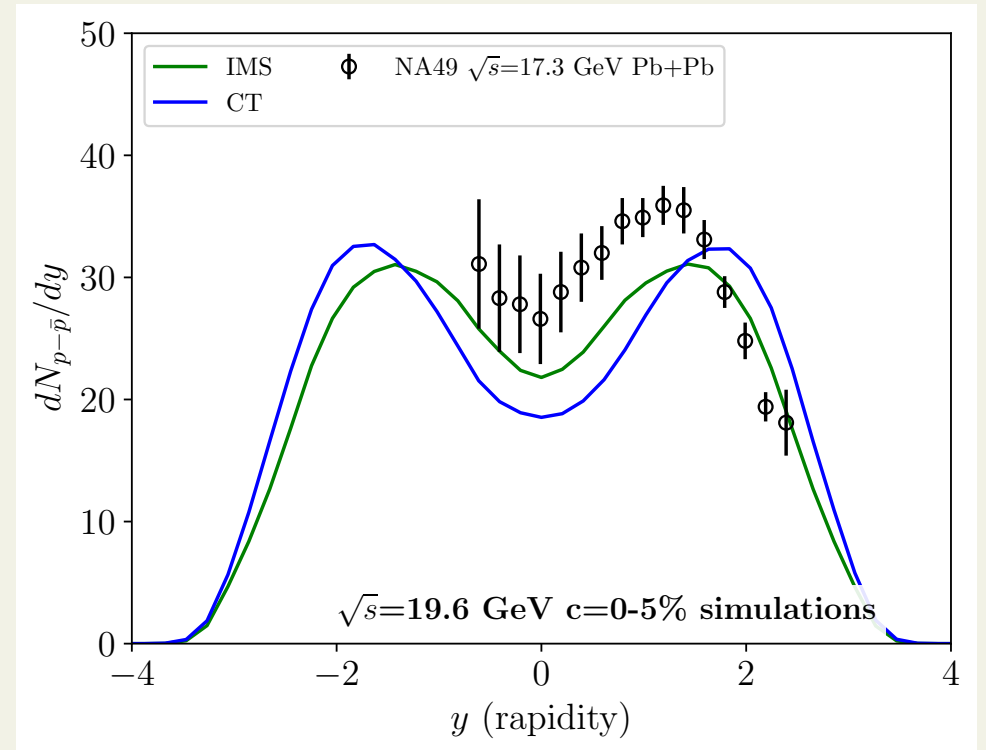
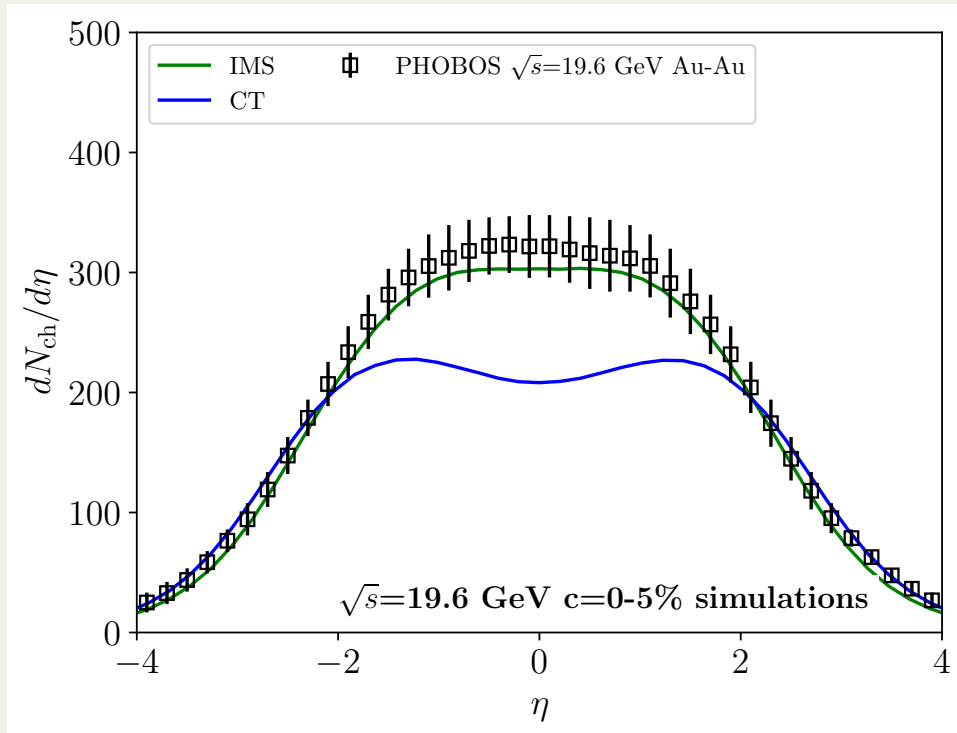
- for our purposes:  
need high  $\mu_B$  also in fireball!
- idea: divide outgoing N from N+N  
into **3** regions  
 $\Rightarrow$  p+t friction moves B to fireball

but: need doubly differential cross sections! ( $y, E$ )

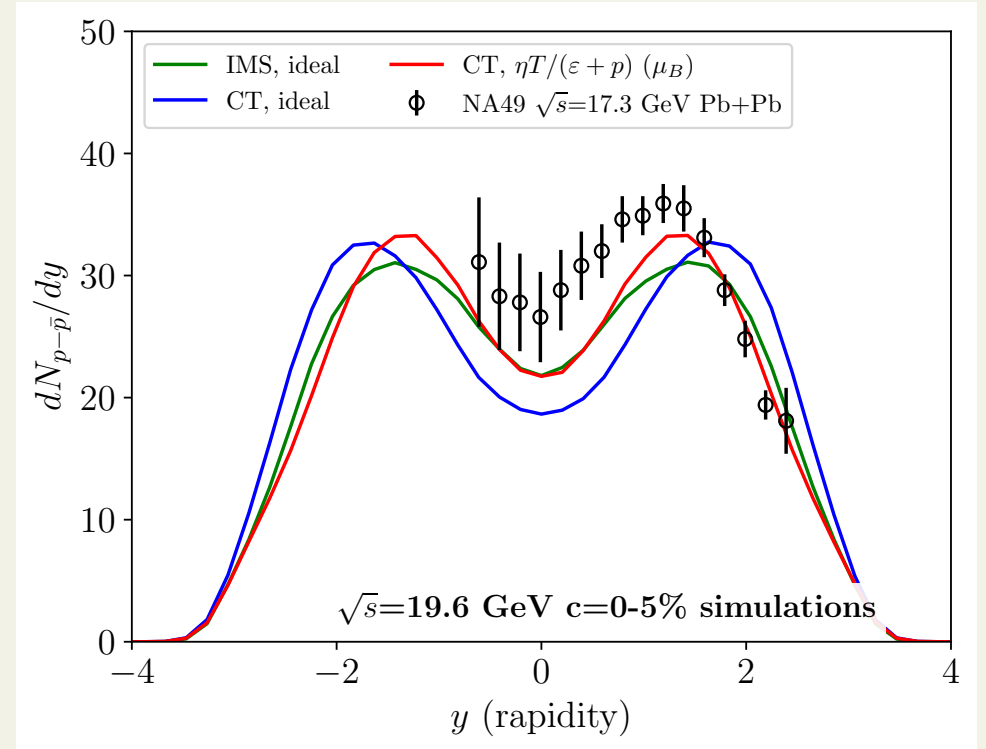
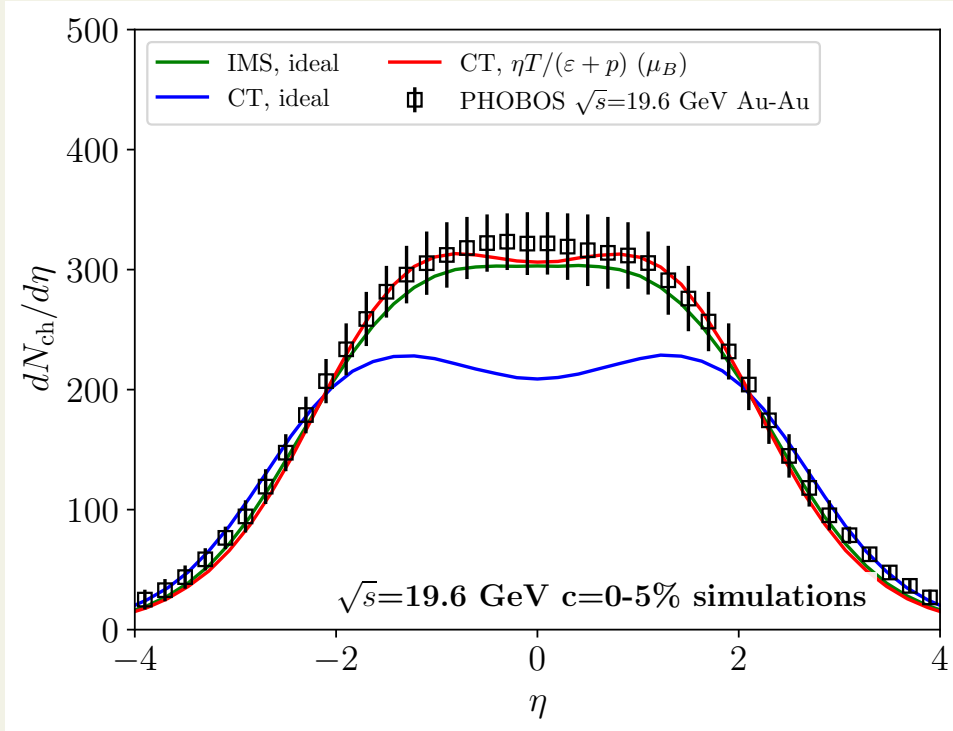
- two more parameters :(



# (pseudo)rapidity distributions



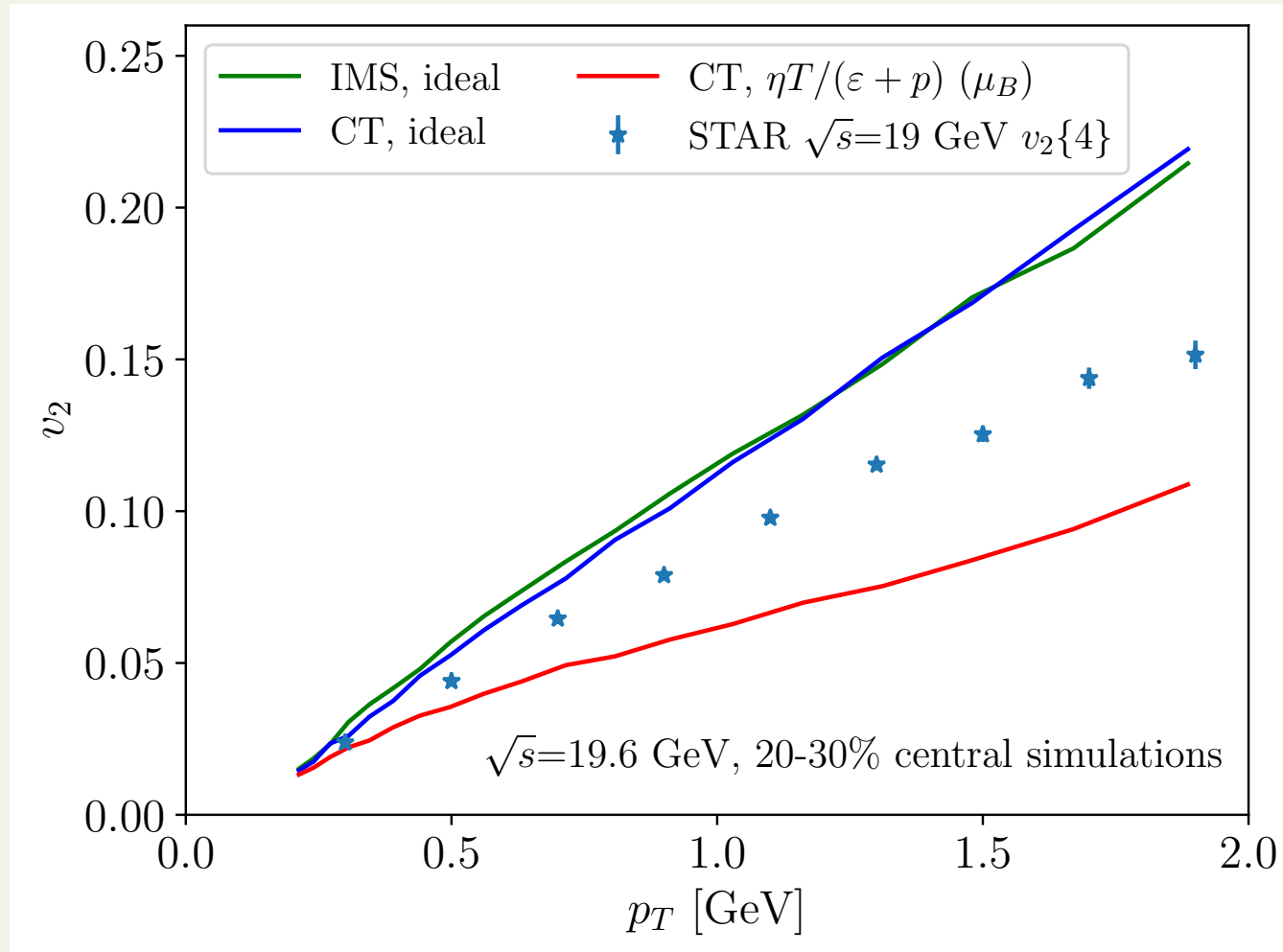
# (pseudo)rapidity distributions with shear



- $\tilde{\eta}(\mu_B) = [\eta T / (\epsilon + P)](\mu_B)$  **from Jahan et al., PRC110, 054905 (2024)**

$$\tilde{\eta}(\mu_B) = \begin{cases} \eta_0 + (\eta_2 - \eta_0) \frac{\mu_B [\text{GeV}]}{0.2}, & 0 < \mu_B \leq 0.2 \text{ GeV} \\ \eta_2 + (\eta_4 - \eta_2) \frac{(\mu_B [\text{GeV}] - 0.2)}{0.2}, & 0.2 < \mu_B < 0.4 \text{ GeV} \\ \eta_4, & \mu_B \geq 0.4 \text{ GeV} \end{cases}$$

# elliptic flow



we've got too large  $\eta/s$

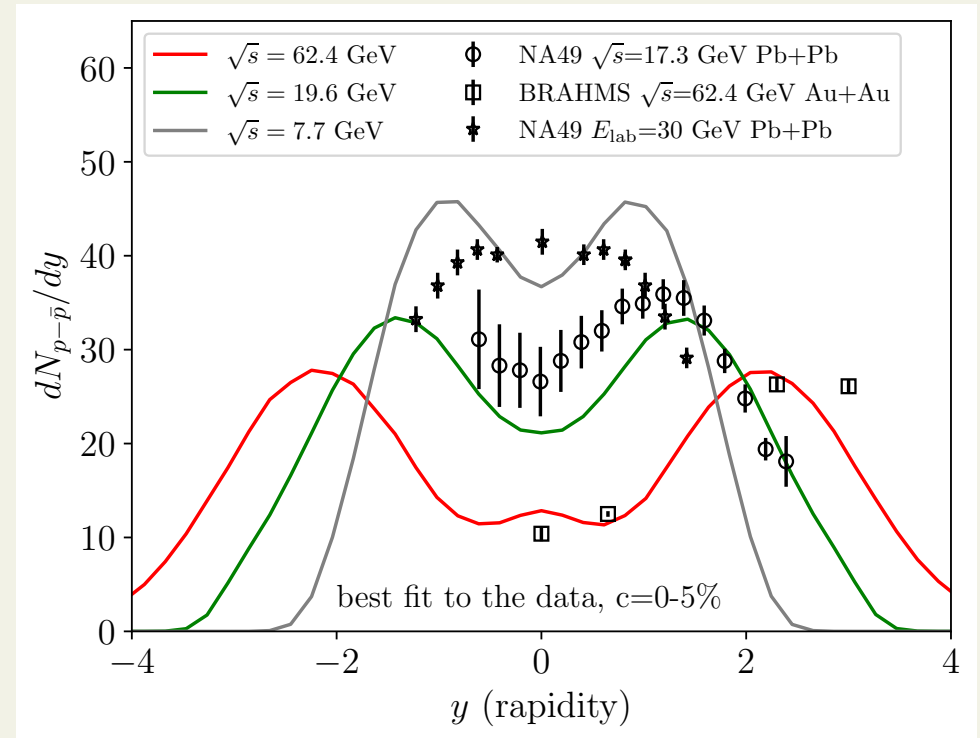
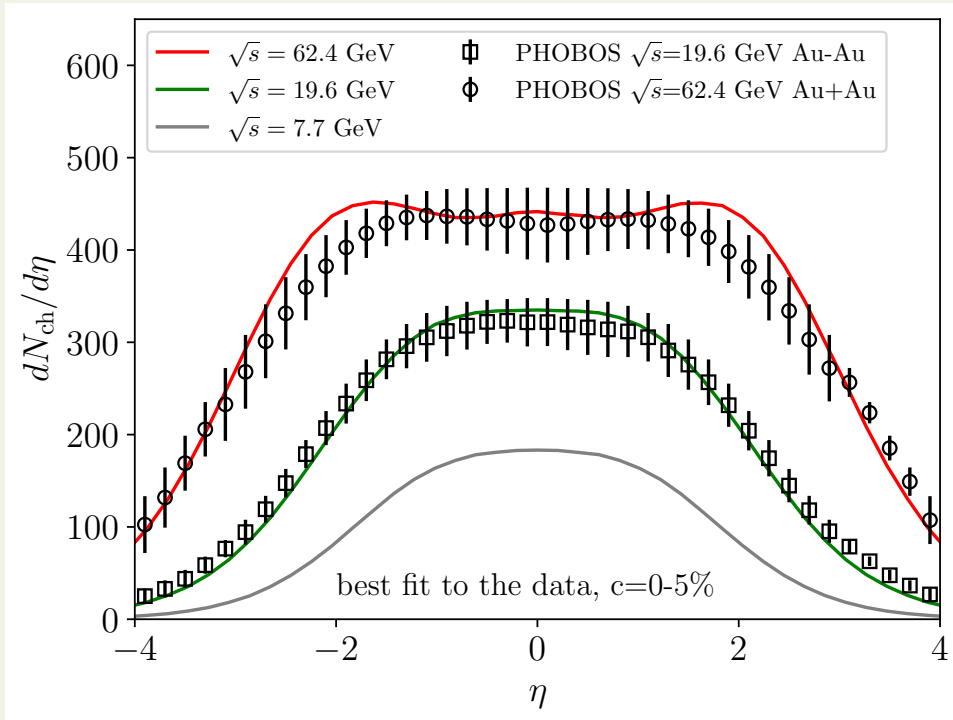
# Summary

- **3-fluid approach to collisions at BES energies**
  - projectile, target, produced particles described as separate fluids
- **improved friction term**
- **finite viscosity required to fit the data**
- **$\sim 50\%$  entropy increase during evolution, at LHC it is small correction**

# We are hiring!

- **The Wrocław multi-fluid project has openings for**
  - a post-doc
  - graduate student**starting in summer 2026**

# other energies



# other energies

