Do we need viscosity to suppress v_2?

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Emberi Erőforrások Minisztériuma
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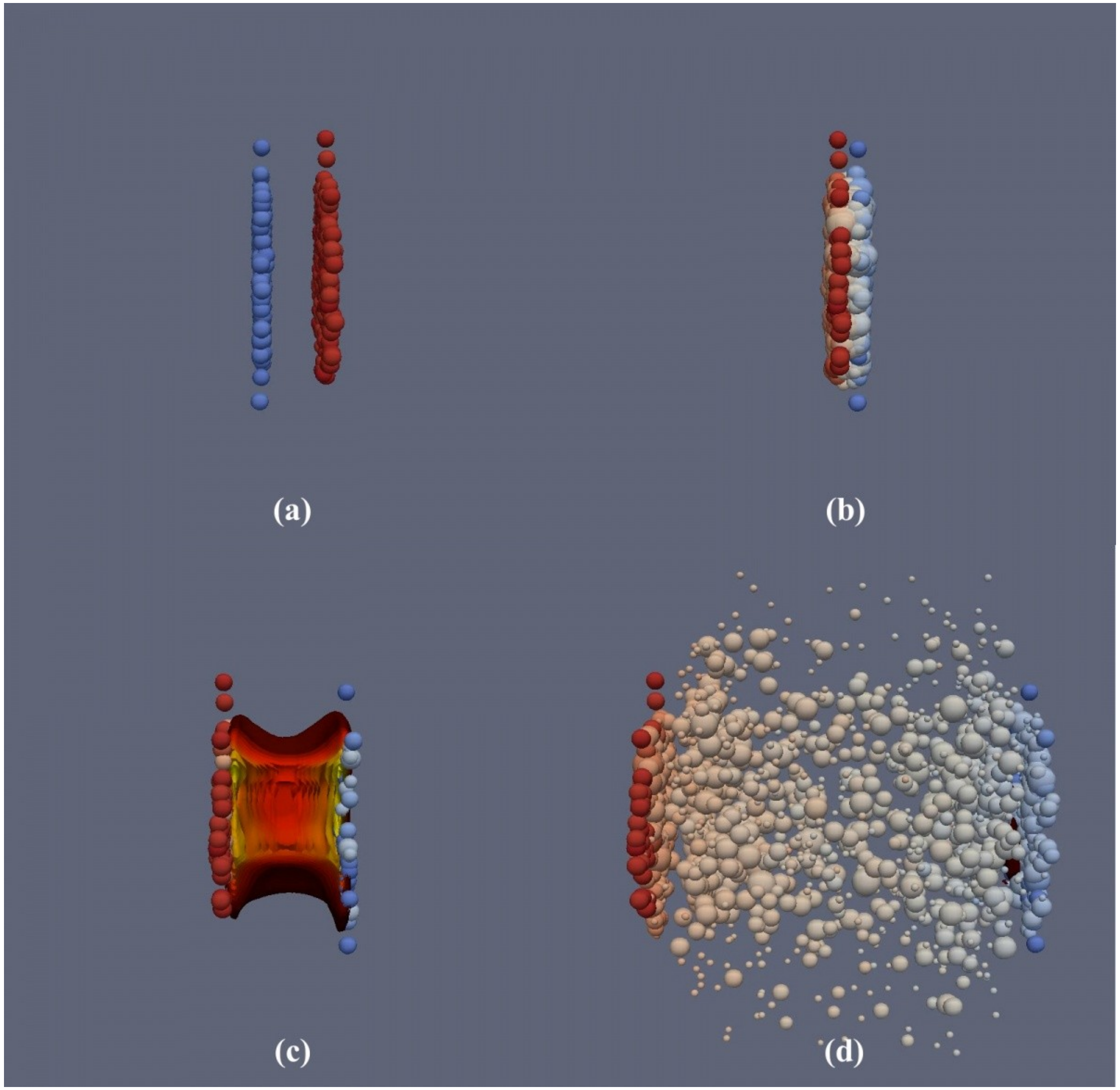
Outline

1. Motivation:
   relativistic hydrodynamics to understand heavy ion collisions
2. Particlization:
   basics, shortcomings, influence on observables
3. How much does f matter?
4. Results
5. Conclusion and outlook

Motivation



MADAI Collaboration

For students: see Gabriel Denicol's talk from Hot Quarks 2018 https://indico.cern.ch/event/703015/contributions/3095199/

Particlization

How is it done?

Particlization: particles from hydro

P. Houven et al Phys. Lett. B **503**, 58 (2001)
K.Dusling, G.D.Moore, D.Teaney, Phys. Rev. C81, 034907 (2010)
D.Molnar & Z.Wolf,f Phys. Rev. C95, 024903 (2017)

Relativistic hydrodynamics [$u^\mu(x^\mu)$, $\varepsilon(x^\mu)$, $n(x^\mu)$]

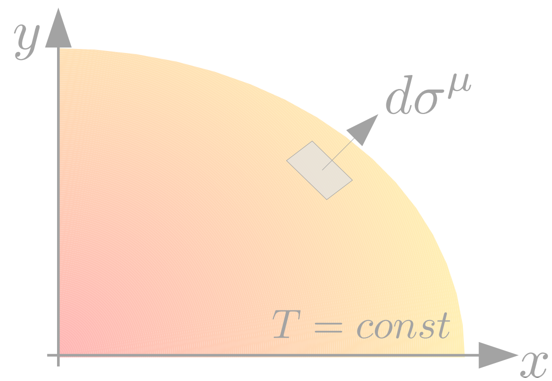
→ conversion fluid → particles (*particlization*)

→ 1. phase space density (particle specie *i*):

$$\left.\begin{aligned} T^{\mu\nu}(x^\lambda) &= \sum_i \int \frac{d^3p}{E} p^\mu p^\nu f_i(x^\lambda, \boldsymbol{p}) \\ N_c^\mu(x^\lambda) &= \sum_i q_{c,i} \int \frac{d^3p}{E} p^\mu f_i(x^\lambda, \boldsymbol{p}) \end{aligned}\right\} \quad f_i(x^\mu, \boldsymbol{p}) = \frac{dN_i(t, \boldsymbol{r}, \boldsymbol{p})}{d^3r d^3p}$$

→ 2. Cooper–Frye formula at *T(or ε)=const*

$$E\frac{d^3N_i}{d^3\boldsymbol{p}} = \frac{g_i}{(2\pi)^3} \int d\sigma^\mu p_\mu f_i(x^\nu, p)$$



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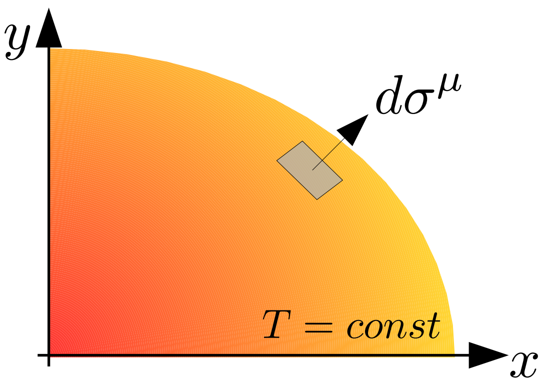

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Assumption 1.: local equilibrium → thermal and chemical equilibrium

$$f_i^{eq}(x,\boldsymbol{p}) = \frac{g_i}{(2\pi)^3} e^{\frac{\mu_i(x) - p_\alpha u^\alpha(x)}{T(x)}} \qquad \mu_i = \sum_c q_{c,i}\mu_c(x)$$

Local rest frame [u^μ_{LR}=(1, **0**)] + Equation of state

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Assumption 2.: near to the local equilibrium

$$f_i(x^\mu,\boldsymbol{p}) = f_i^{eq}(x^\mu,\boldsymbol{p}) + \delta f_i(x^\mu,\boldsymbol{p}) \longrightarrow \begin{aligned} T^{\mu\nu} &= T_{id}^{\mu\nu} + \delta T^{\mu\nu} \\ N_c^\mu &= N_{c,id}^\mu + N_c^\mu \end{aligned} \longrightarrow \begin{aligned} &T(x^\nu), \mu_i(x^\nu) \\ &\delta f_i(x^\mu,\boldsymbol{p}) \end{aligned}$$

Problem: finite set of conditions, can be satisfied with infinitely many different δf_i!

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Problem: finite set of conditions can be satisfied with infinitely many different δf_i!

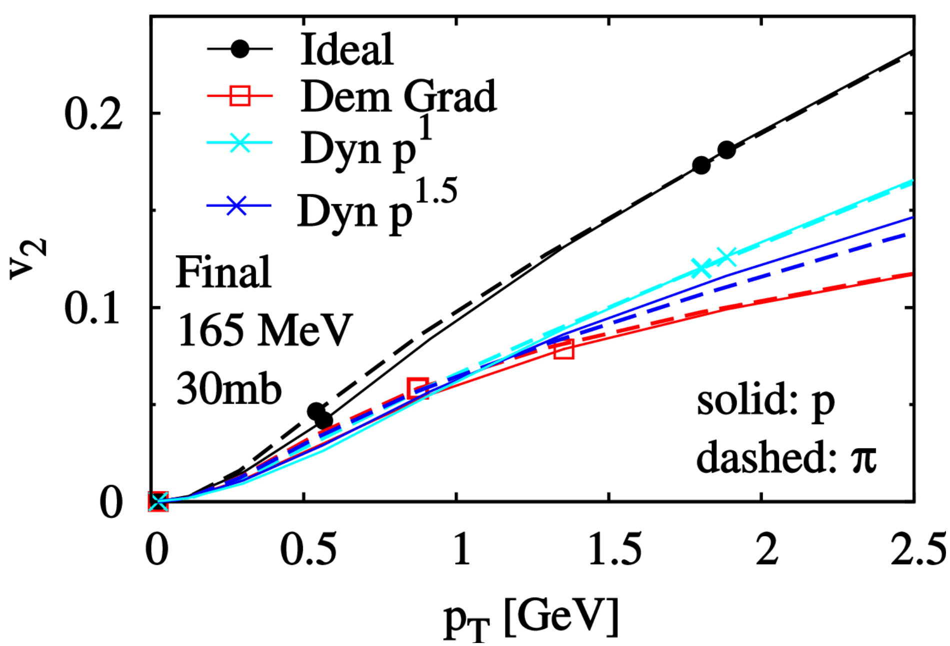
Particlization: particles from hydro

Assumptions for δf_i (for dissipative fluids):

- Democratic Grad (scalar theory and momentum diffusion): $\delta f_i \sim p^2$ all i

  M.Luzum & P.Romatschke, Phys.Rev. C78, 034915 (2008)
- Power law dependence: $\delta f_i \sim p^\alpha$ all i or multicomponent gas

  K.Dusling, G.D.Moore, D.Teaney, Phys.Rev. C81, 034907 (2010)
- Dynamic (linearized kinetic transport)



D.Molnar & Z.Wolff, Phys.Rev. C95, 024903 (2017)

Z.Wolff & D.Molnar, Phys.Rev. C96, 044909 (2017)

Reprint from: Phys.Rev. C95, 024903 (2017)

Problem: theoretical uncertainty in viscosity!

Particlization

Do we know f_{eq}?

(What if it is NOT Botzmann?)

Origin of $f_{eqi}(x,p)$

1) Microscopic theory (kinetic transport) with *simple* interaction → interaction termalizes

2) Microscopic theory with long-range interaction or fluctuation + relaxation → non-Boltzmann f_{eq} (e.g., Tsallis)

3) Conformal hydro ($\varepsilon=3P$) doesn't require equilibrium. Any isotropic $f_{eq}(p)$ would do

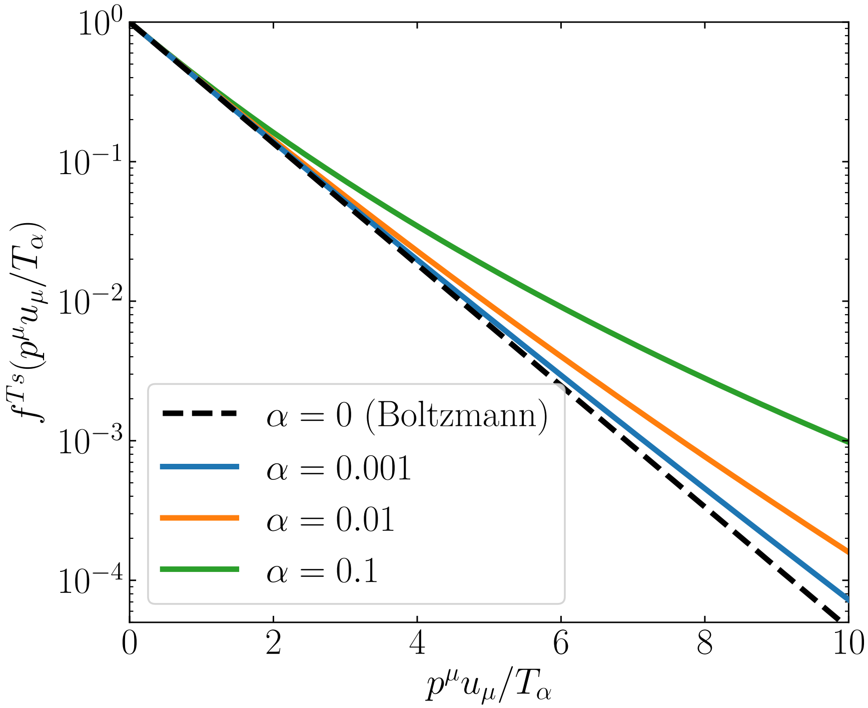
P.Arnold, J.Lenaghan, G.D.Moore, L.G. Yaffe, Phys. Rev. Lett. 94, 072302 (2005)

Isortopic Tsallis phase space density

Ideal hydro with Tsallis distribution:

$$f^{Ts}(x,\boldsymbol{p}) = N\left(1+\frac{\alpha}{T_\alpha}p^\mu u_\mu(x)\right)^{-1/\alpha}$$

$$\lim_{\alpha\to 0} T_\alpha = T \quad \text{(Boltzmann limit)}$$

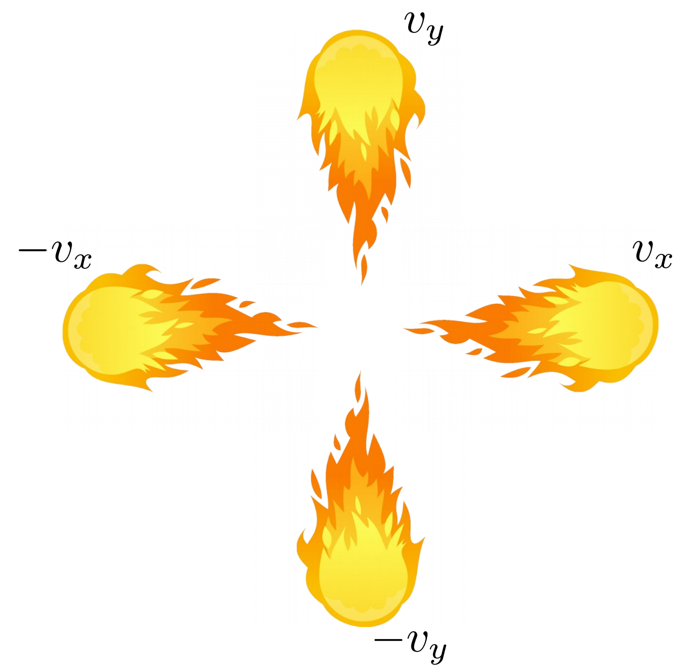


To set (N,α,T_α):

Fix to partial ε and P (T_α changes): simplest assumption.

Results: 4-Source Fireball Model

P. Houven et al Phys. Lett. B **503**, 58 (2001)



- Simple way to model $v_2(p_T)$
- 4-uniform fireballs (same V and T), no longitud. Expansion boosted symmetrically ($\pm v_x$, $\pm v_y$) and t=*const* *freezes-out*

$$f_4(p_T,\phi) = f_{(+v_x)} + f_{(-v_x)} + f_{(+v_y)} + f_{(-v_y)}$$

$$p^\mu_{v_x} = (\gamma_x(m_T x - v_x p_T \cos\phi), \gamma_x(p_T\cos\phi - v_x m_T \cosh y), p_T \sin\phi, m_T \sinh y)$$

$$v_n(p_T) = \frac{\int_0^{2\pi} d\phi f_4(p_T,\phi)\cos(n\phi)}{\int_0^{2\pi} d\phi f_4(p_T,\phi)}$$

Similar setup to:
D.Molnar & Z.Wolff, Phys.Rev. C95, 024903 (2017)
Z.Wolff & D.Molnar, Phys.Rev. C96, 044909 (2017)

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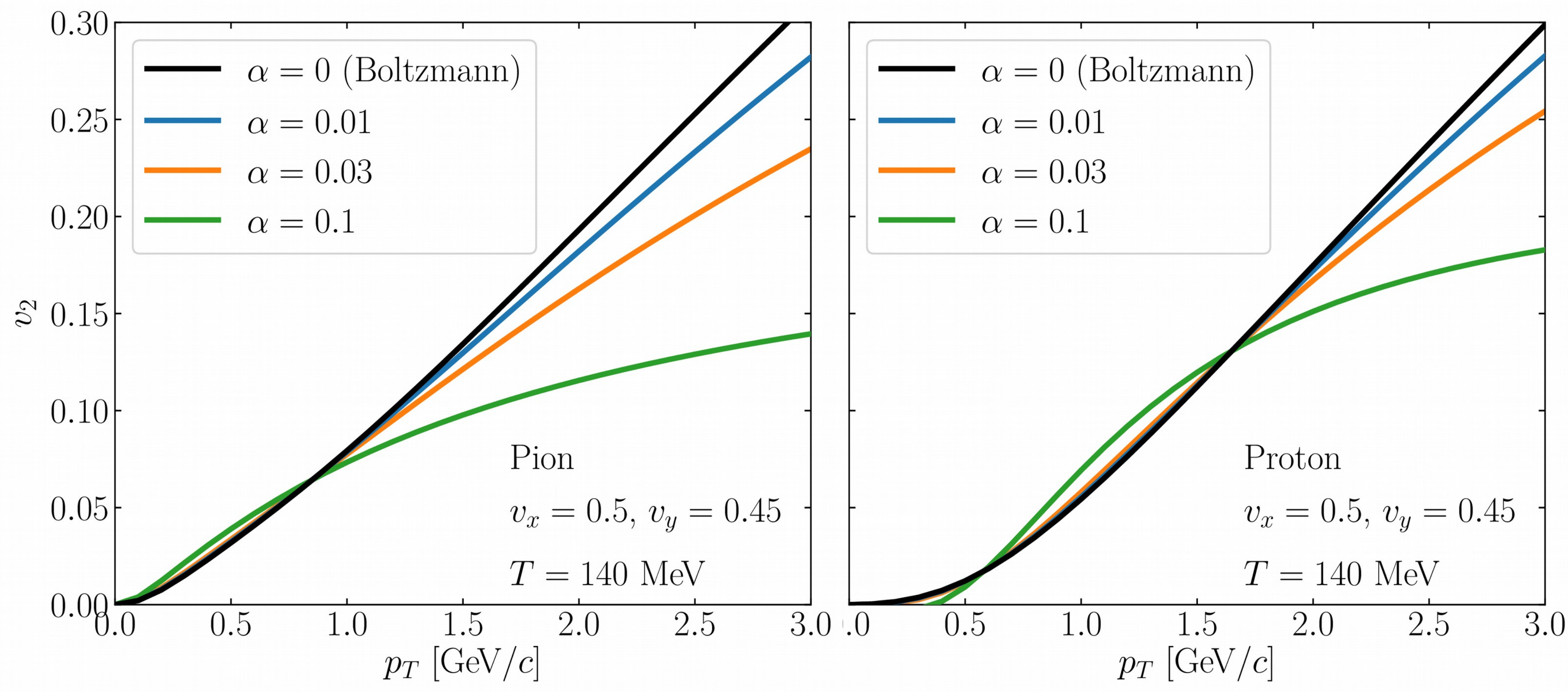

Hydrodynamic Simulation

1. Initial condition: 20-30% Au+Au @ 200 GeV analytic Glauber Model
   S_0=110 fm^{-3}, b=7 fm ~ 20-30% centrality

2. Ideal hydro 2+1D with AZHYDRO package $\mu=0$

3. Cooper–Frye freeze-out with Tsalis phase space density
   $\varepsilon(x)$ and $P(x)$ are fixed, T_f=165 MeV

4. Resonance decay is included with RESO

Similar setup to:
D.Molnar & Z.Wolff, Phys.Rev. C95, 024903 (2017)
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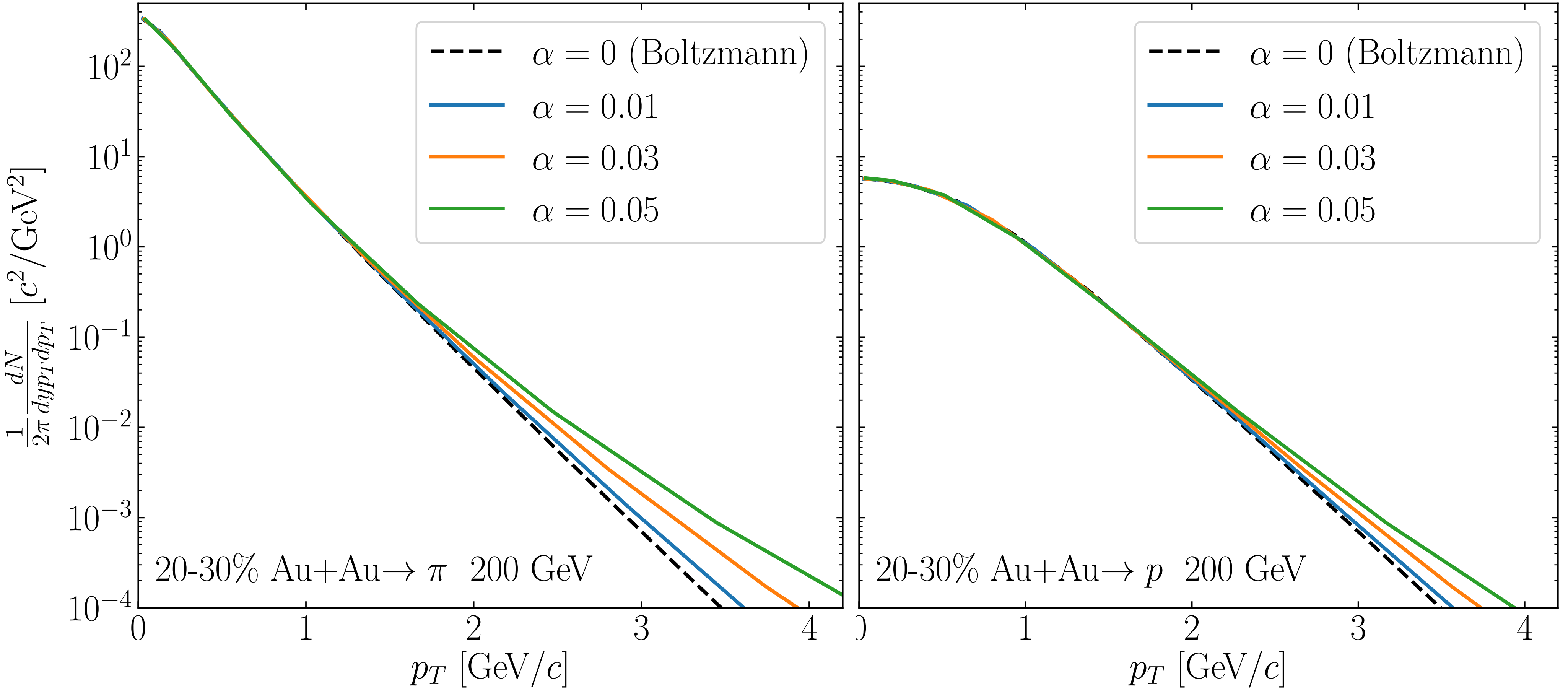
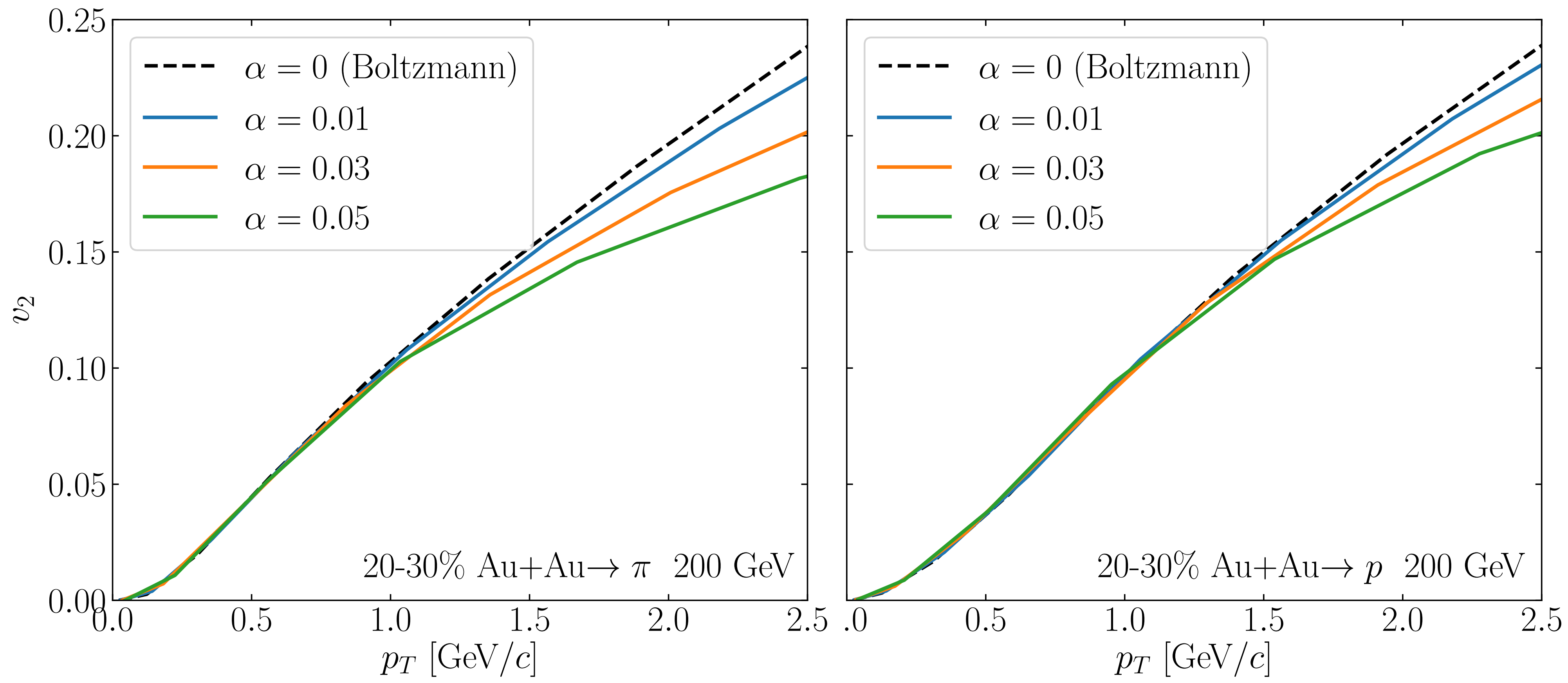


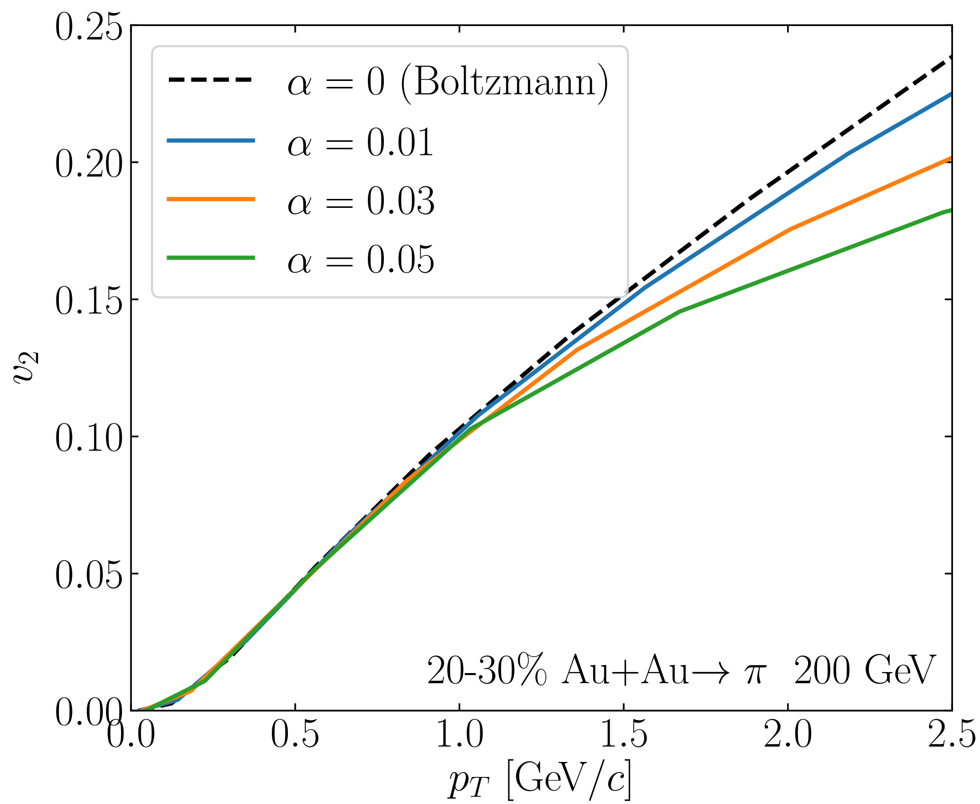
- The α→ 0 limit gives back the Boltzmann case
- Beginning doesn‘t change, α describes the tail
- More suitable shape for experimental data

Results: hydrodynamic simulation



- The α→ 0 limit gives back the Boltzmann case
- Beginning doesn't change
- The α present a suppression in flow
- Less suppression for proton than pion
  Just like shear viscosity

Results: hydrodynamic simulation



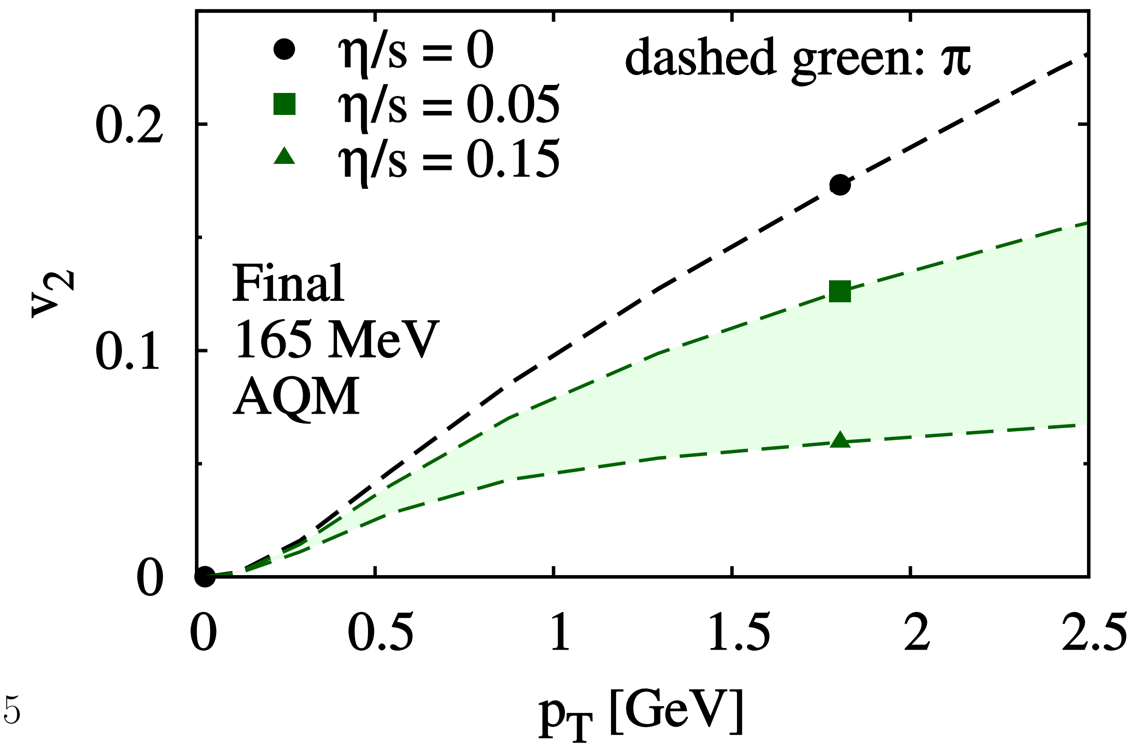


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Figure from:
D.Molnar & Z.Wolff, Phys.Rev. C95, 024903 (2017)

Summary

- The choice of δf_i is arbitrary → uncertainty in observables (known)
- The choice of f_{eq} is arbitrary too → additional uncertainty
- Keeping the full ideal hydro, but using Tsallis as a phase space density
  - Better shape for the spectra!
  - Suppression of flow without dissipation but similar to shear viscosity η_s/s~0.05 for α~0.05. From previous spectrum studies: α~0-0.07

K.Urmossy, G.G.Barnafoldi, T.S.Biro, J. of Phys. Conf.Ser. 612 012048 (2015)

- Why does hydrodynamics work?
  - Can isotropization occur for heavy ions?
  - If it does, can the system be stuck in that state?

} Conformal theory

Thank you for your attention!

Dissipative fluid

M.Luzum & P.Romatschke, Phys.Rev. C78, 034915 (2008)
D.Molnar & P.Houvinen, J.Phys. G35, 104125 (2008)
K.Dusling, G.D.Moore, D.Teaney, Phys.Rev. C81, 034907 (2010)
D.Molnar & Z.Wolff, Phys.Rev. C95, 024903 (2017)

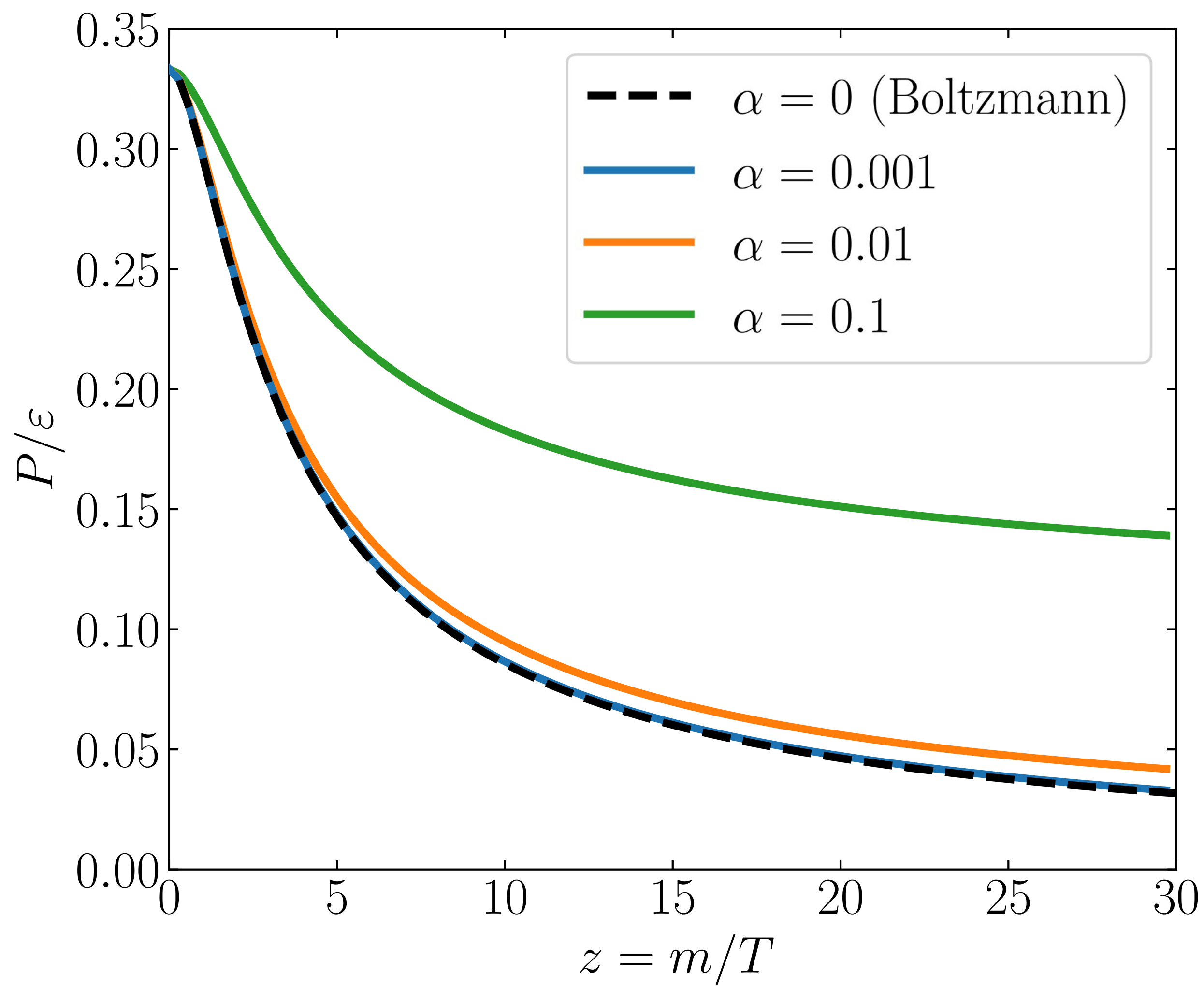
Close to local equilibrium: $f_i(x,\boldsymbol{p}) = f_i^{eq}(x,\boldsymbol{p}) + \delta f_i(x,\boldsymbol{p})$

$$T^{\mu\nu} = T^{\mu\nu}_{id} + \delta T^{\mu\nu} \qquad N^{\mu}_{c} = N^{\mu}_{c,id} + N^{\mu}_{c}$$

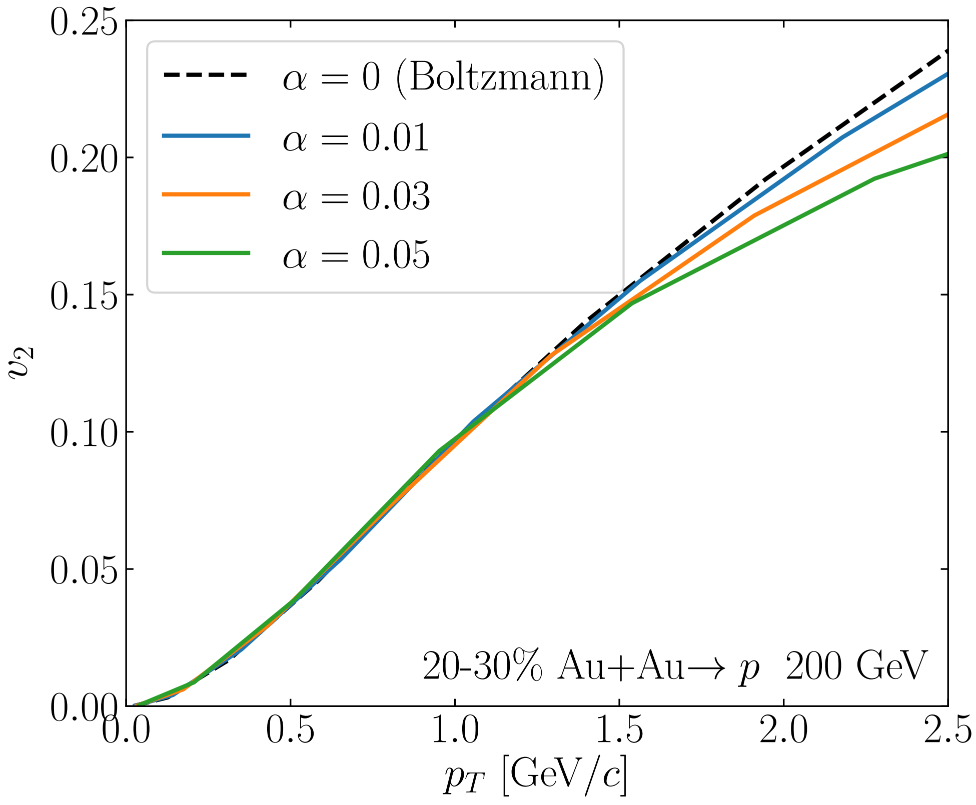
$$\left.\begin{aligned} \delta T^{\mu\nu} &= \sum_i \int \frac{d^3p}{E} p^{\mu} p^{\nu} \delta f_i(x,\boldsymbol{p}) \\ \delta N^{\mu}_{c}(x) &= \sum_i q_{c,i} \int \frac{d^3p}{E} p^{\mu} \delta f_i(x,\boldsymbol{p}) \end{aligned}\right\} \quad \delta f_i(x,\boldsymbol{p})$$

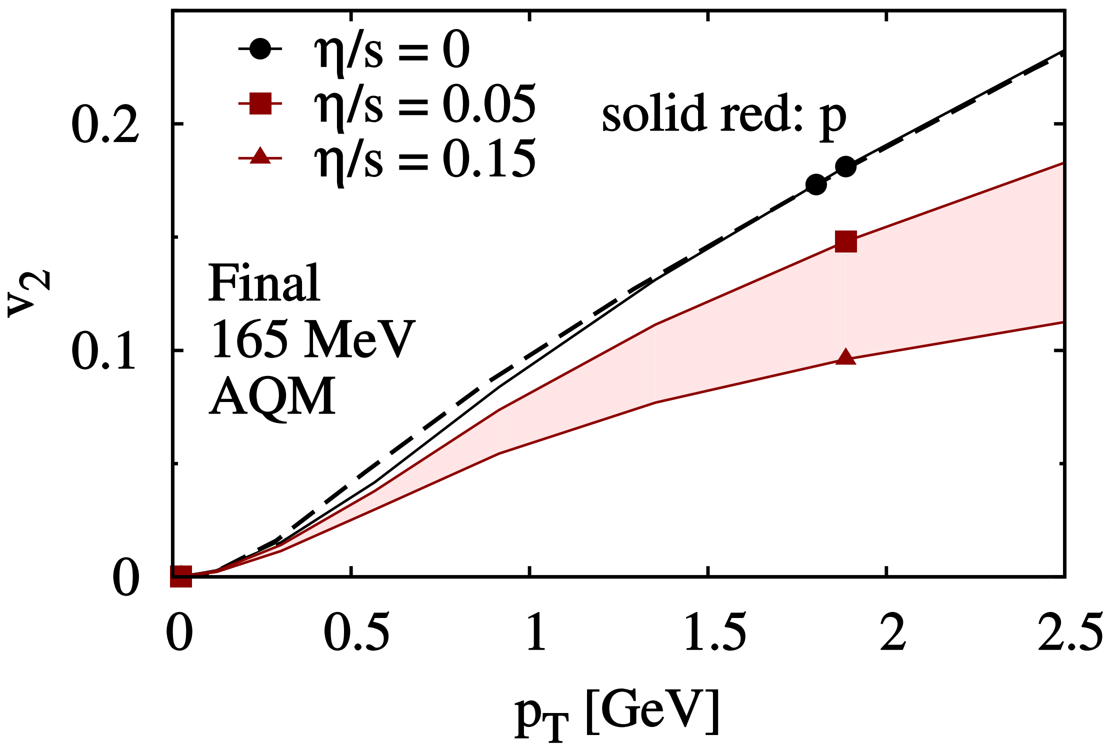
Problem: finite set of conditions can be satisfied with infinitely many different δf_i!

Backup: 4-Fireball Source Model



Results: hydrodynamic simulation





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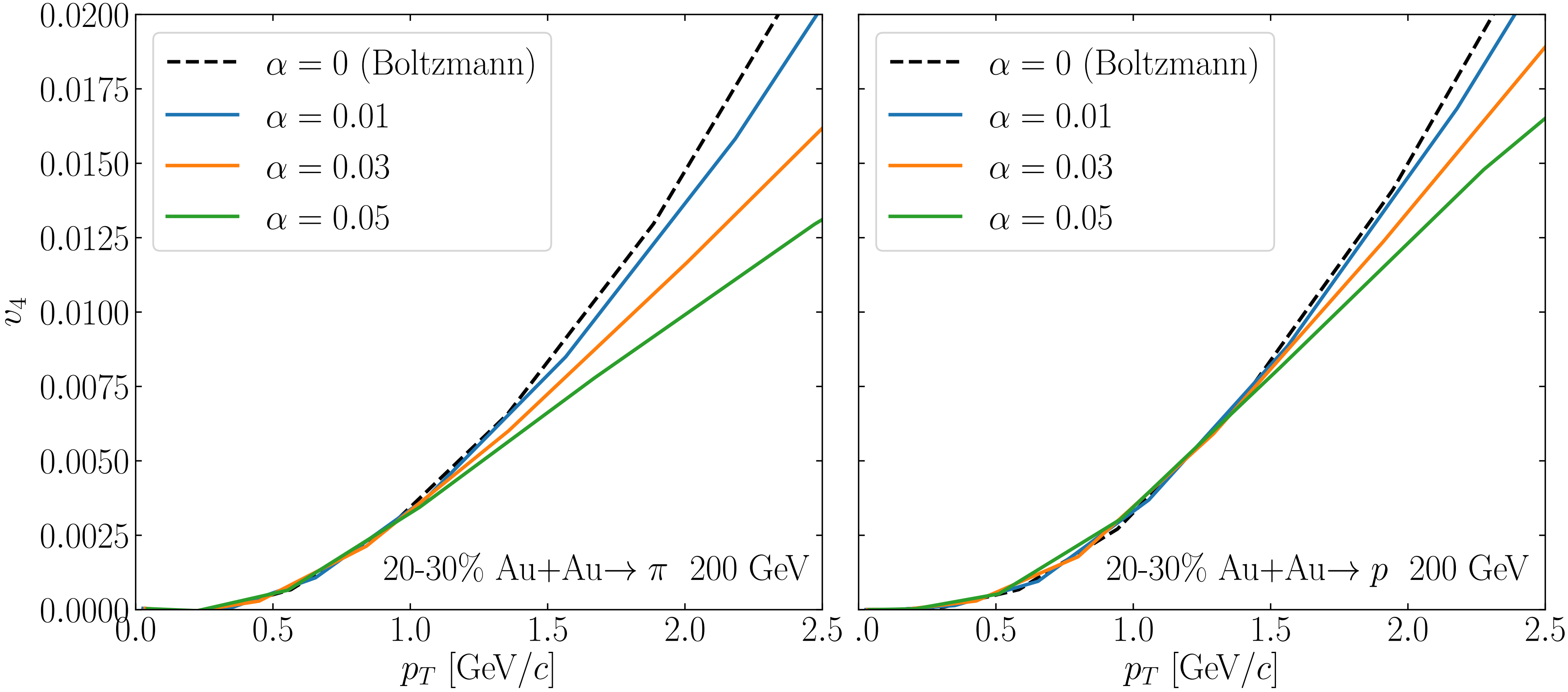

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