Suppression of anisotropic flow without viscosity

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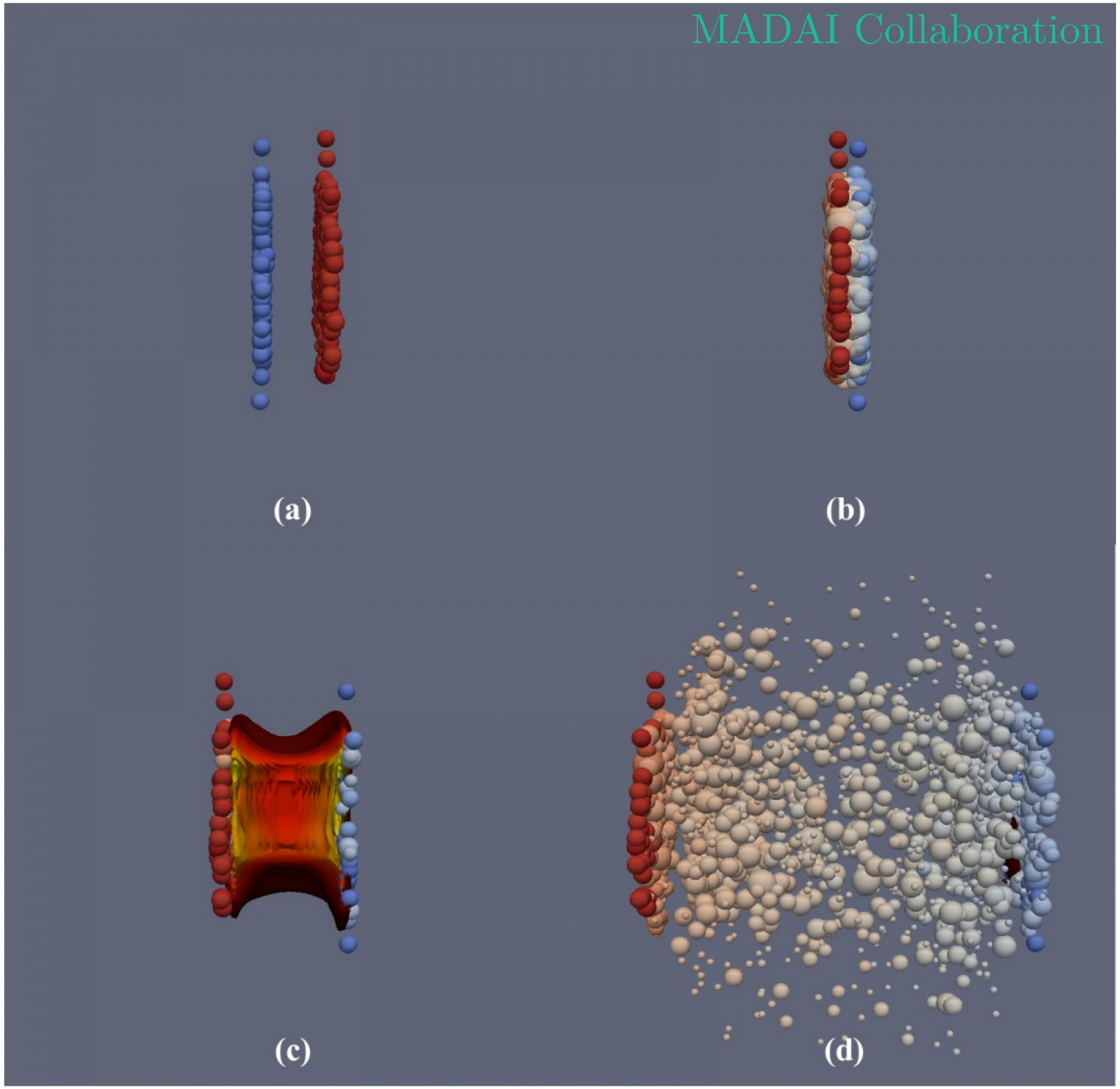
Outline

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

Motivation



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

Motivation

D. Molnar & P. Huovien, J.Phys. G**35** 104125 (2008)
K. Dusling, G.D. Moore, D. Teaney, Phys. Rev. C**81**, 034907 (2010)
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- Shear viscosity is sensitive to the way of particlization
- There is no unique way to do the particlization
- Thermal equilibrium is an assumption

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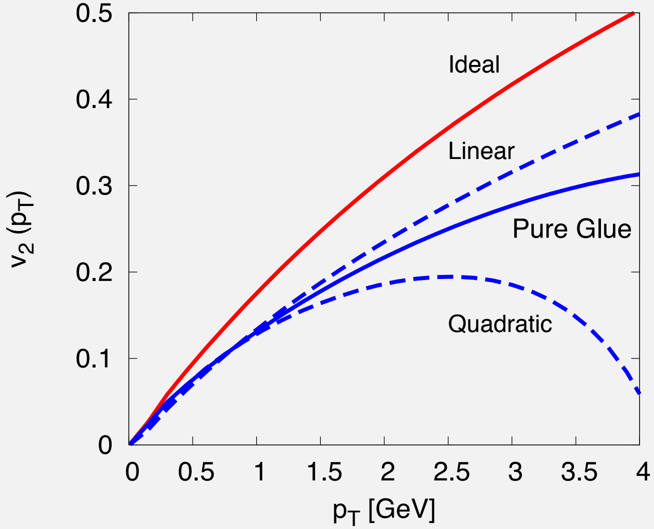

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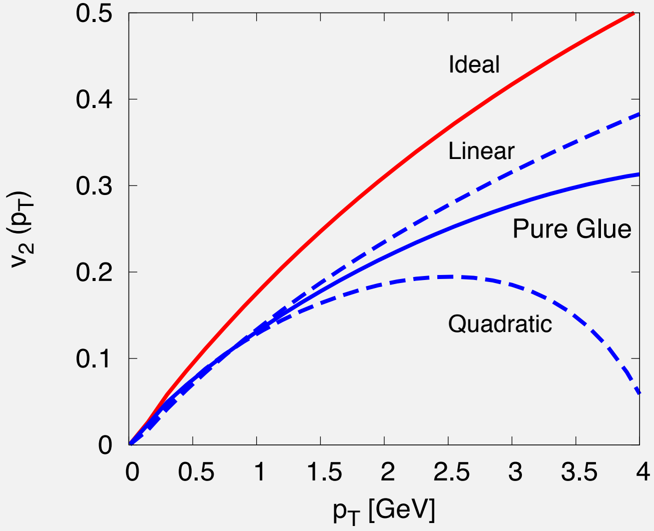


Questions:

1. How sensitive is ideal hydro?
2. Is thermal equilibrium a legitimate assumption?

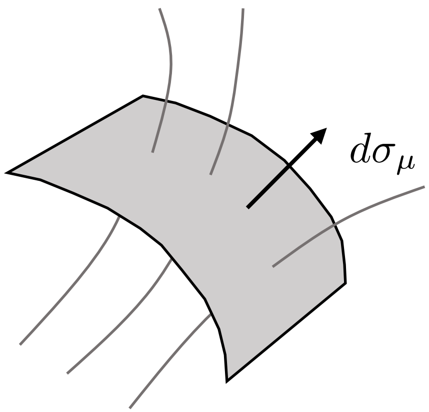
Particlization

How is it done?

Particlization: from hydro to particles

L. Csernai, *Introduction Relativistic Heavy Ion Collisions (1994)*

Conversion of fluid → particles on a 3D hypersurface: $d\sigma^\mu$



Inside: fluid $(u^\mu(x), \varepsilon(x), P(x), n(x))$

$$N^\mu(x) = (n(x), \vec{j}(x))$$

$$T^{\mu\nu}(x) = [\varepsilon(x) + P(x)]u^\mu u^\nu - P(x)g^{\mu\nu}$$

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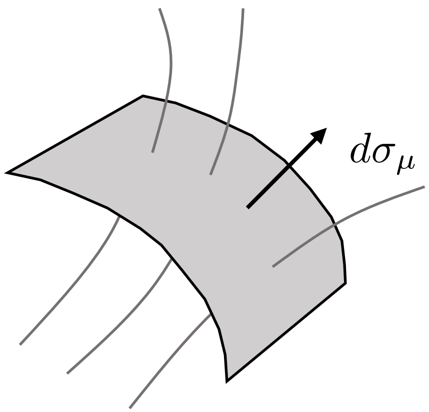

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Outside: particle $f(x,p)$

$$N^\mu(x) = \int \frac{d^3p}{p^0} p^\mu f(x,p)$$
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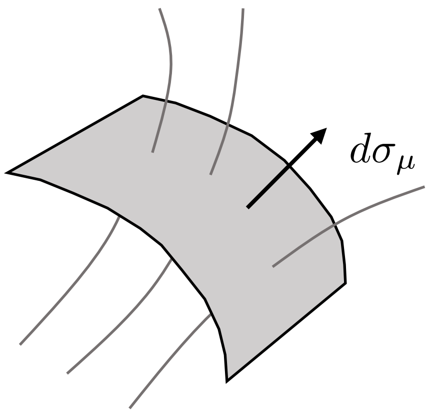

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Boundary: conservation laws

$$[N^\mu d\sigma_\mu]_{\text{in}-\text{out}} = 0$$
$$[T^{\mu\nu} d\sigma_\mu]_{\text{in}-\text{out}} = 0$$

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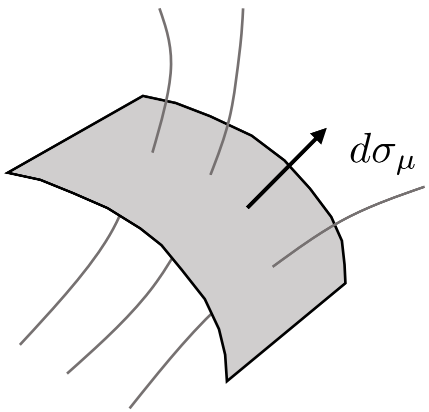

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Cooper-Frye formula: momentum spectrum (measurable)

$$E\frac{d^3N}{d^3p} = \int d\sigma_\mu p^\mu f(x,p)$$

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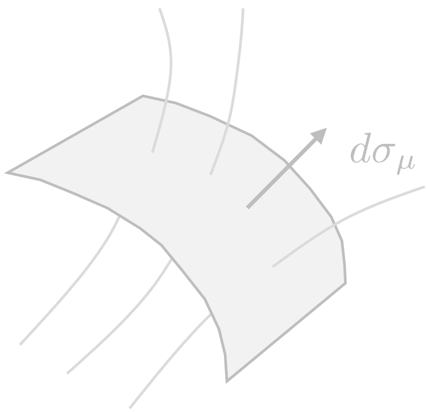

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What is $f(x,p)$?

Cooper-Frye formula: momentum spectrum (measurable)

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Particlization: what is $f(x, p)$?

$f(x, p)$ - single-particle distribution

- We don't know.

Particlization: what is $f(x,p)$?

$f(x,p)$ - single-particle distribution

- Described by some kinetic transport theory (assumption)

Particlization: what is $f(x,p)$?

$f(x,p)$ - single-particle distribution

- Described by the <u>B</u>oltzman <u>T</u>ransport <u>E</u>quation
  (assumption of assumption)

Particlization: what is $f(x,p)$?

$f(x,p)$ - single-particle distribution

- 0^{th} solution of the BTE
  (assumption of assumption of assumption)
  Relativistic Boltzmann (thermal) distribution:
  $$f_0(x,p) = \frac{g}{(2\pi)^3} \mathrm{e}^{-\frac{p^\mu u_\mu(x)}{T(x)}}$$
  One field describes everything: $T(x)$ temperature.

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- Change a little to „non-extensive“: corrections
  $$f(x,p) = A\left[1 + \frac{\alpha}{T_\alpha(x)} p^\mu u_\mu(x)\right]^{-\frac{1}{\alpha}}$$
  One field $T_\alpha(x)$ „temperature“ + non-ext. parameter α.
  If $\alpha \to 0$ we get back Boltzmann!
  Starts in exponential, end in power law!

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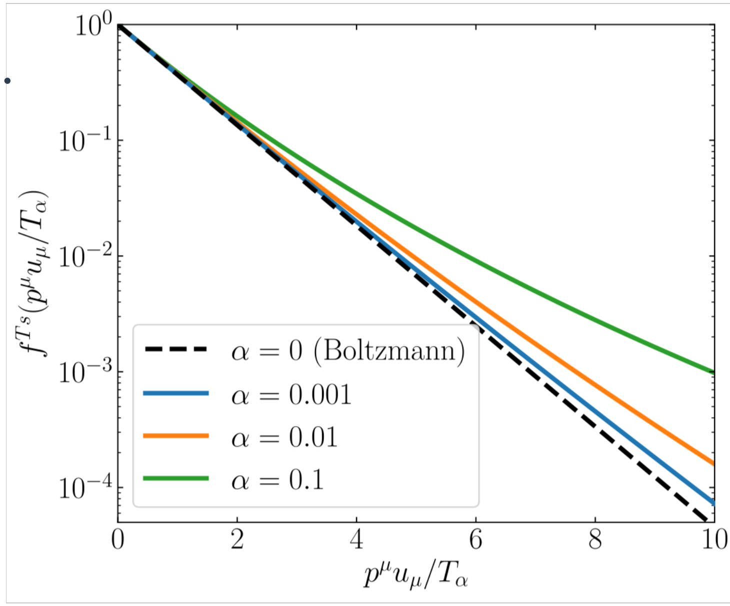

How does spectrum and flow change?

- Spectrum: exponential like $\rightarrow$ power-law tail (sounds good)

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- Flow:

$$v_n(p) = \frac{\int d\phi \cos(n\phi) E \frac{d^3N}{d^3p}}{\int d\phi E \frac{d^3N}{d^3p}}$$

Boltzmann:

$$v_n(p) \sim \frac{\mathrm{e}^{-ap}}{\mathrm{e}^{-bp}} = \mathrm{e}^{-(a-b)p} \to 1$$

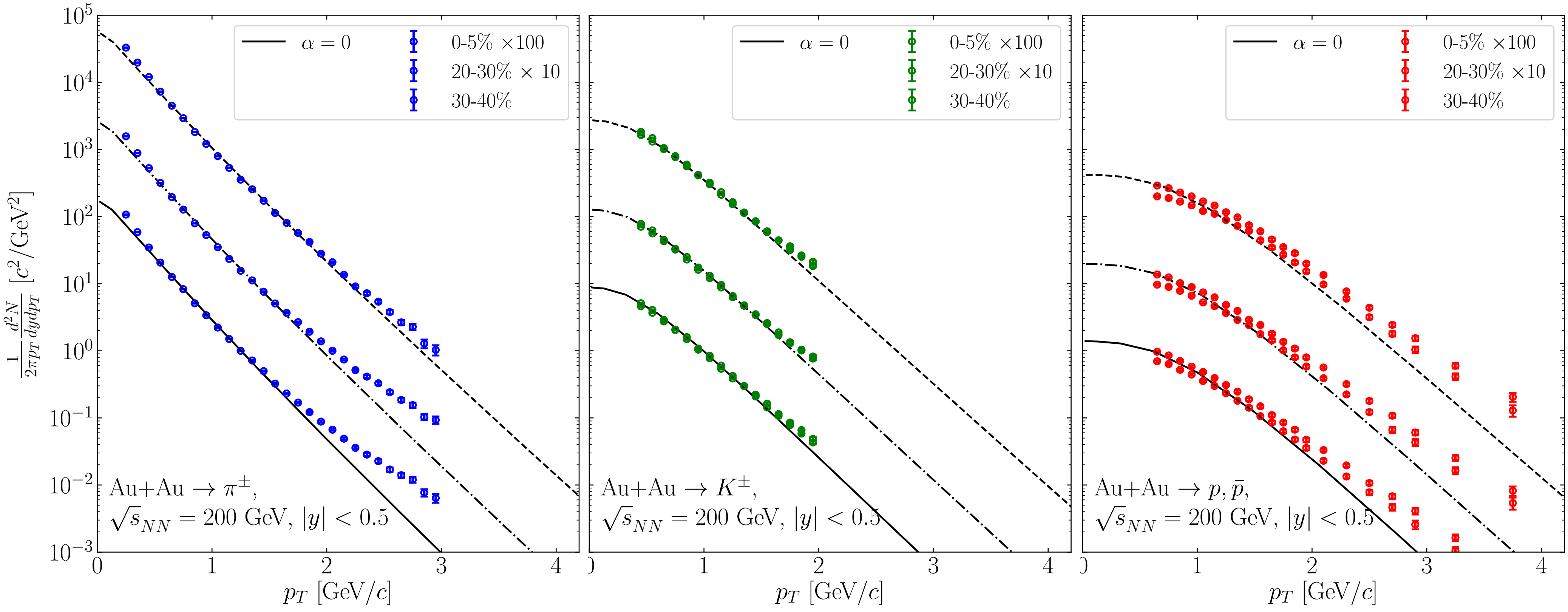
Tsallis:

$$v_n(p) \sim \frac{(ap)^{-1/\alpha}}{(bp)^{-1/\alpha}} \to \left(\frac{a}{b}\right)^{-\frac{1}{\alpha}} \leq 1$$ (looks interesting!)

Hydrodynamic Simulation

1. Initial condition: Au+Au @ 200 GeV optical Glauber model S_0=110 fm^{-3}.
2. 2+1D numerical ideal hydro with Azhydro.
3. Cooper–Frye freeze-out with Tsallis
   $\varepsilon(x), P(x)$ and q are fixed, $T_f = 140$ MeV
4. Resonance decays are included.

Results: hydrodynamic simulation



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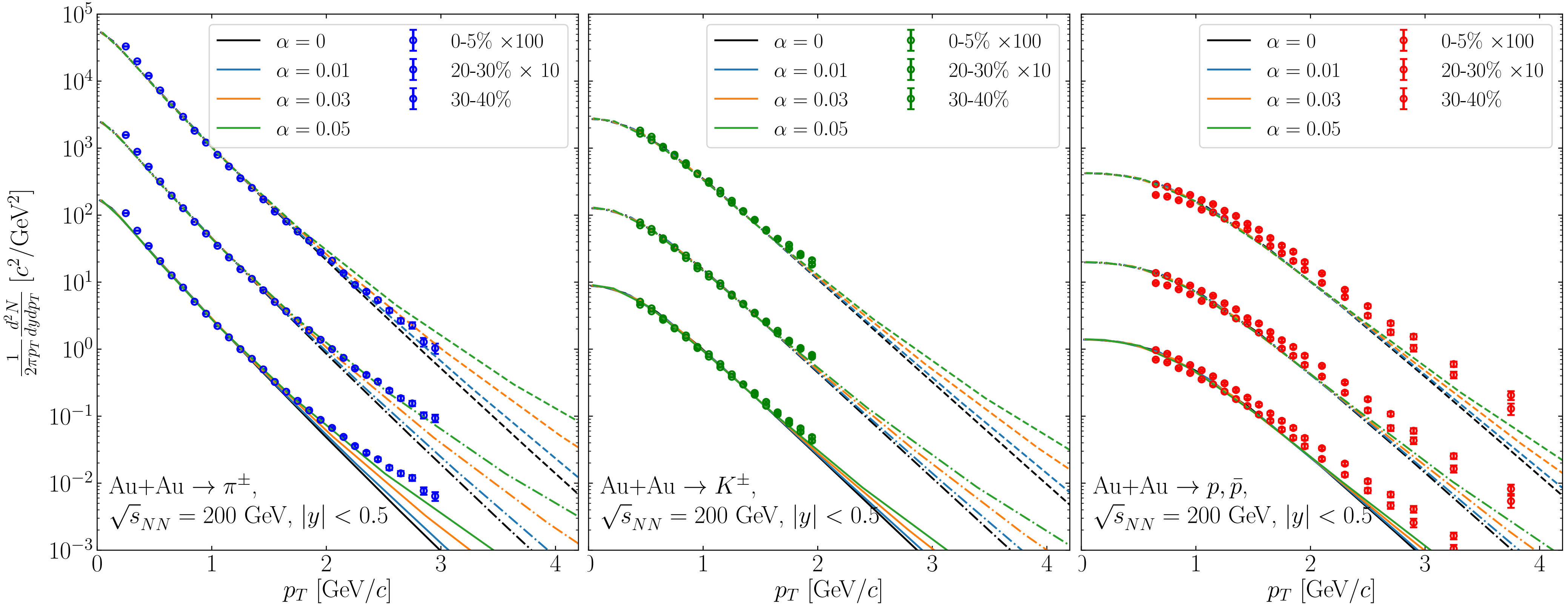
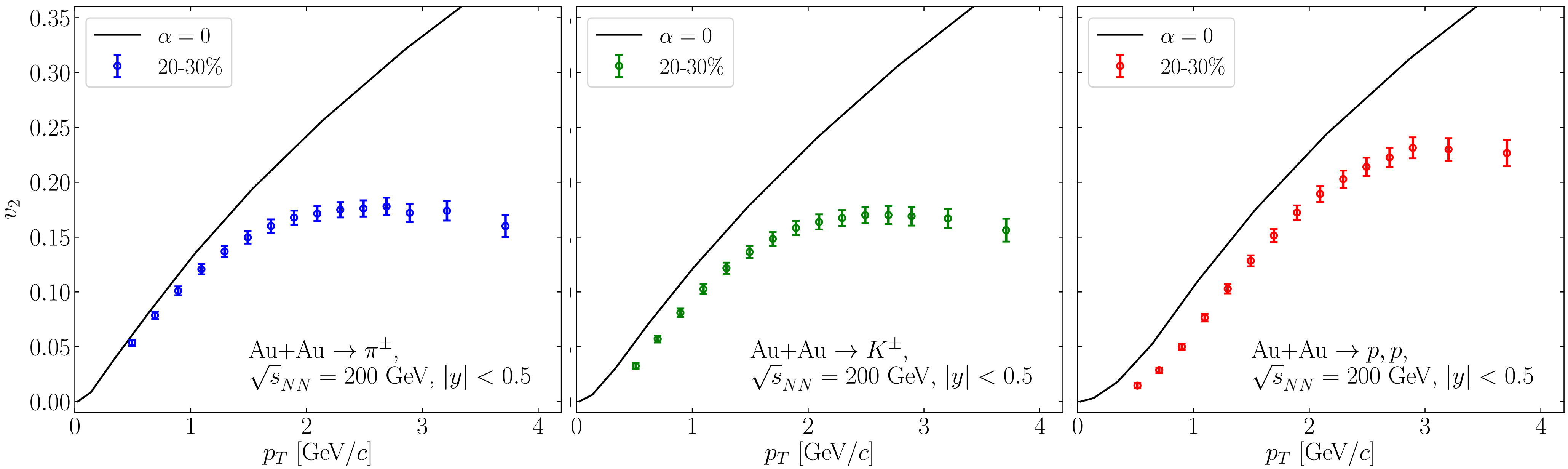


- Power-law tail appears
- Better agreement with data!

Results: hydrodynamic simulation



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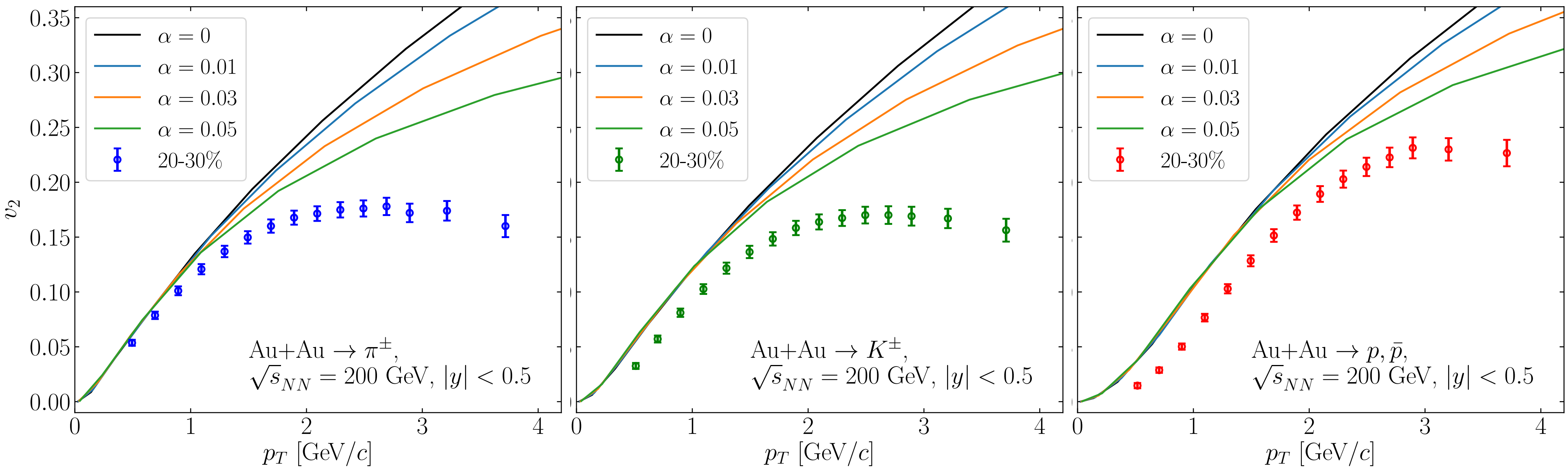
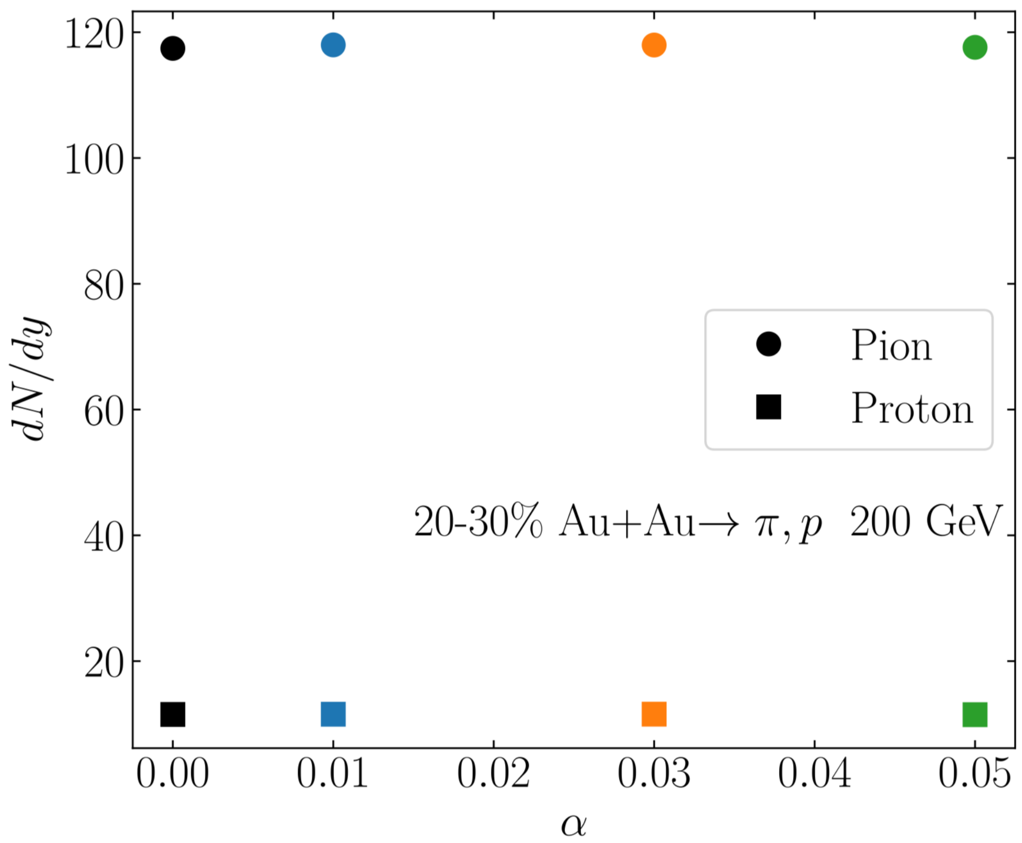
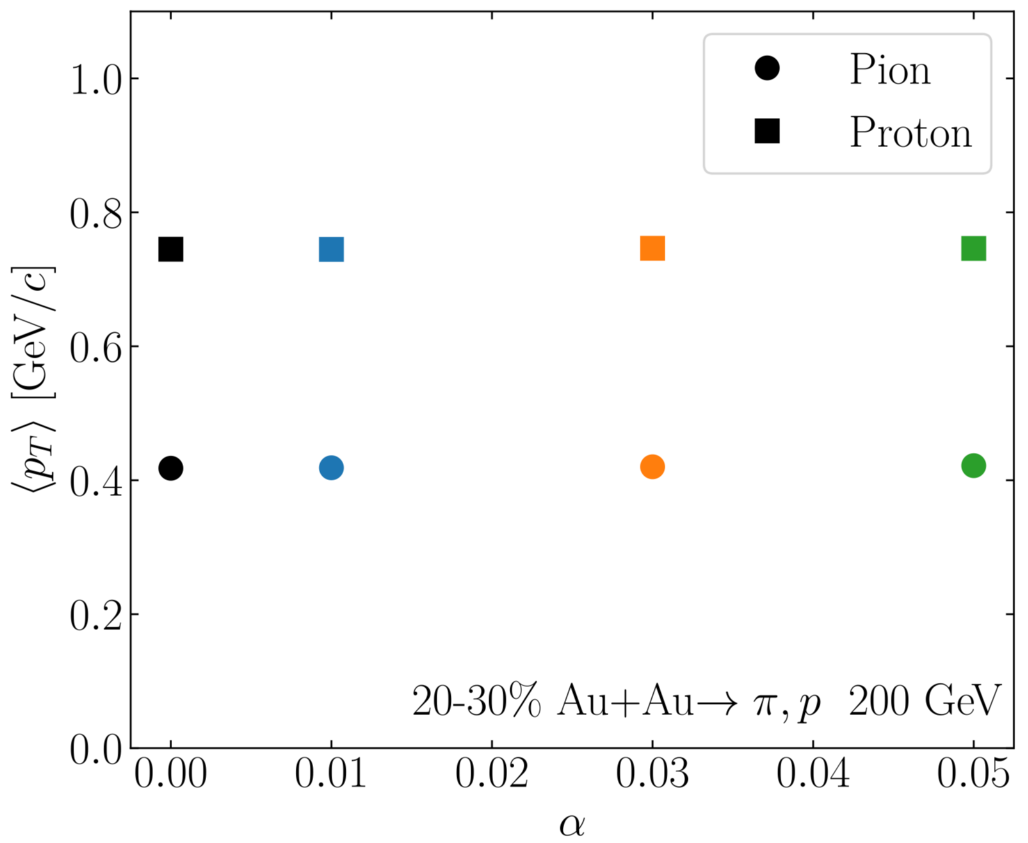


- Suppression in flow!
- Better agreement with data!
- Mass ordering in the suppression, like shear viscosity!

Backup: changes in other observables





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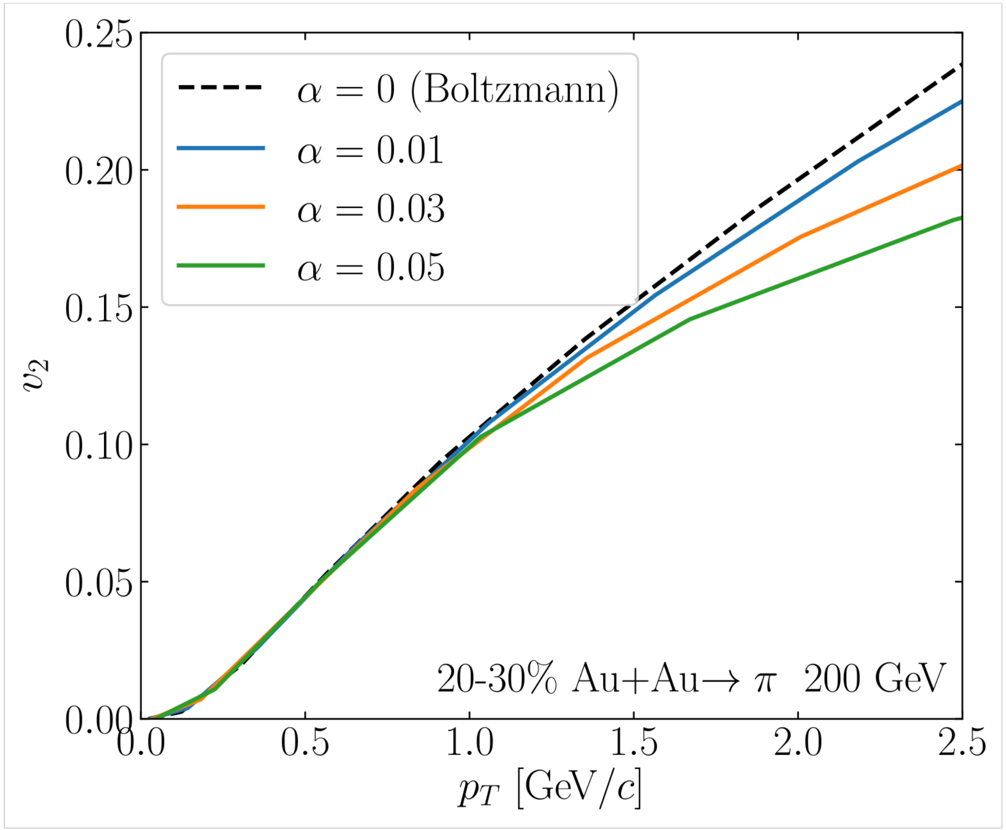
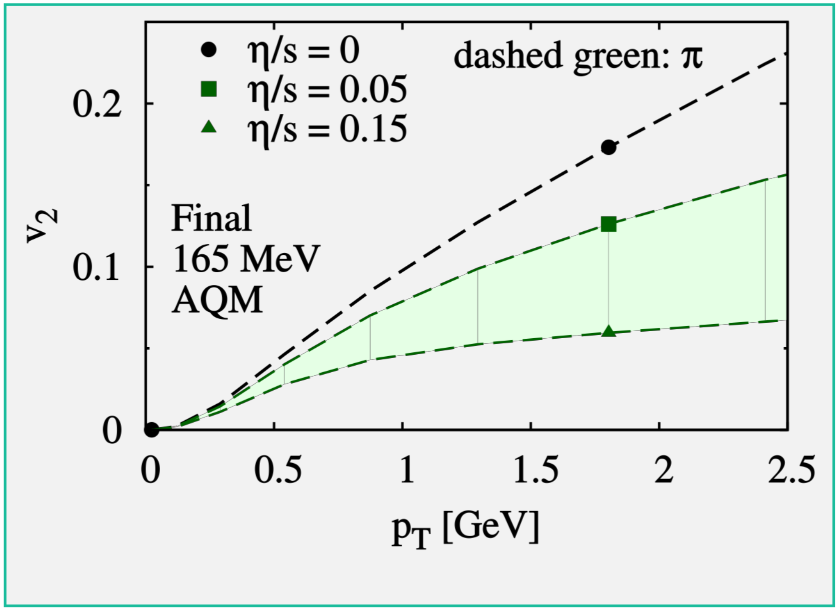


Viscous calculation:



Reprint: D.Molnar & Z.Wolff, Phys.Rev. C**95**, 024903 (2017)

- Non-ext. behaves like shear viscosity (no viscosity in the model)!
- Comparison to viscous calculation: $\alpha \approx 0.05 \leftrightarrow \eta/s = 0.05$
- From fits to spectra: $\alpha = 0 - 0.07$ K.Urmossy, G.G.Barnafoldi, T.S.Biro, J.Phys. Conf.Ser. 612 012048 (2015)

Summary

- Relativistic Boltzmann distribution (thermal equilibrium) is an approximation.
- To study a specific type of correction (using Tsallis distribution):
  1. Finite size effects and correlations.
  2. More suitable for the spectrum (power law tail) and the flow ($v_n < 1$).
  3. Isotropization? Conformal theories do not require equilibrium.
- The correction has important effects:
  - Better spectra.
  - Suppressed flow
  - Mimic shear viscosity: $\alpha \approx 0.05 \leftrightarrow \eta/s = 0.05$
- Future:
  - Extend to viscous calculation.
  - Study kinetic transport for an exact correction. Better understand α

P.Arnold, J.Lenaghan, G.D.Moore, L.G. Yaffe, Phys. Rev. Lett. **94**, 072302 (2005)
M.Luzum & P.Romatschke. Phys.Rev. C**78** 034915 (2008)

Thank you for your attention!

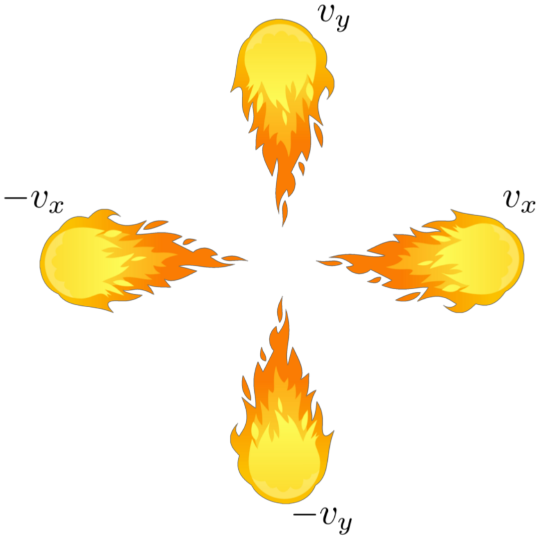
How does spectrum and flow change?

- Spectrum: exponential like → power law tail
- Flow:

$$v_n(p) = \frac{\int d\phi \cos(n\phi) E \frac{d^3N}{d^3p}}{\int d\phi E \frac{d^3N}{d^3p}}$$

- Simple 4-source model:
  4-uniform fireballs, no long. expansion, boosted sym. $(\pm v_x, \pm v_y)$ and $T{=}const$ freeze-out

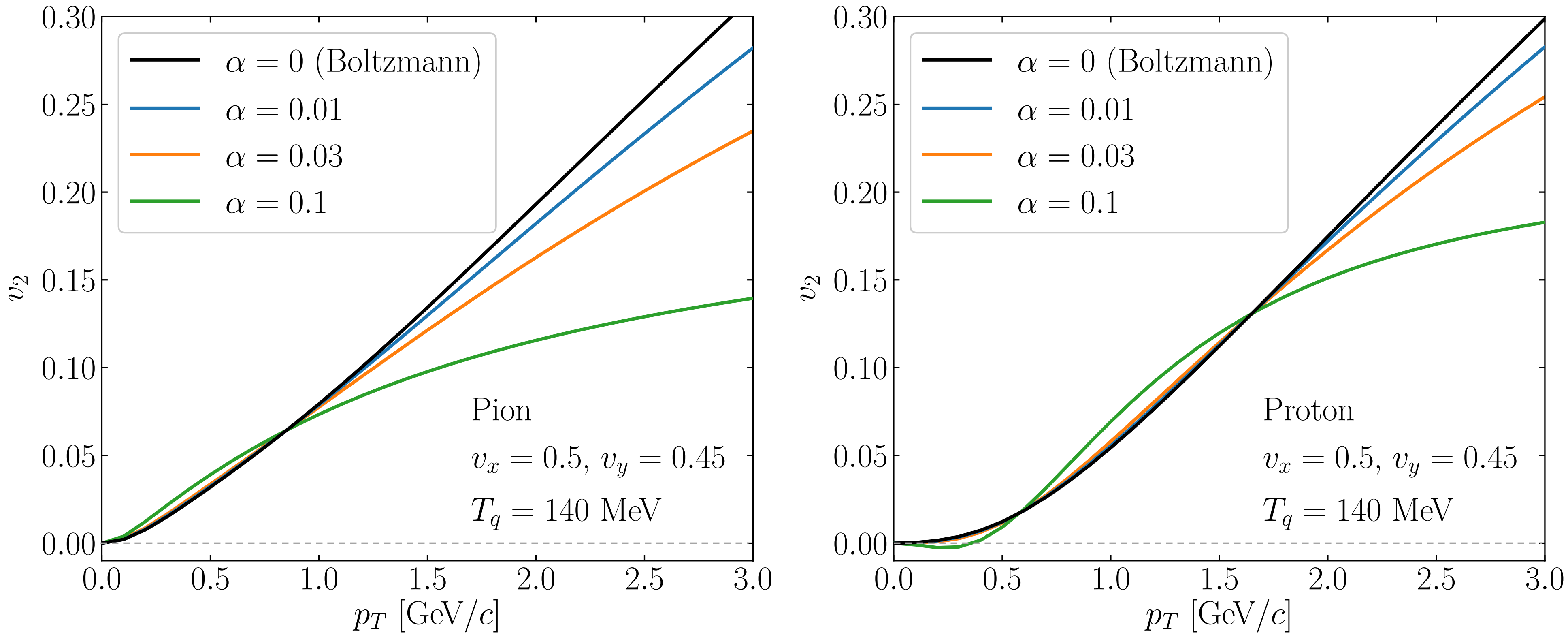
$$f^{4s}(p) = f|_{v_x} + f|_{-v_x} + f|_{v_y} + f|_{-v_y}$$



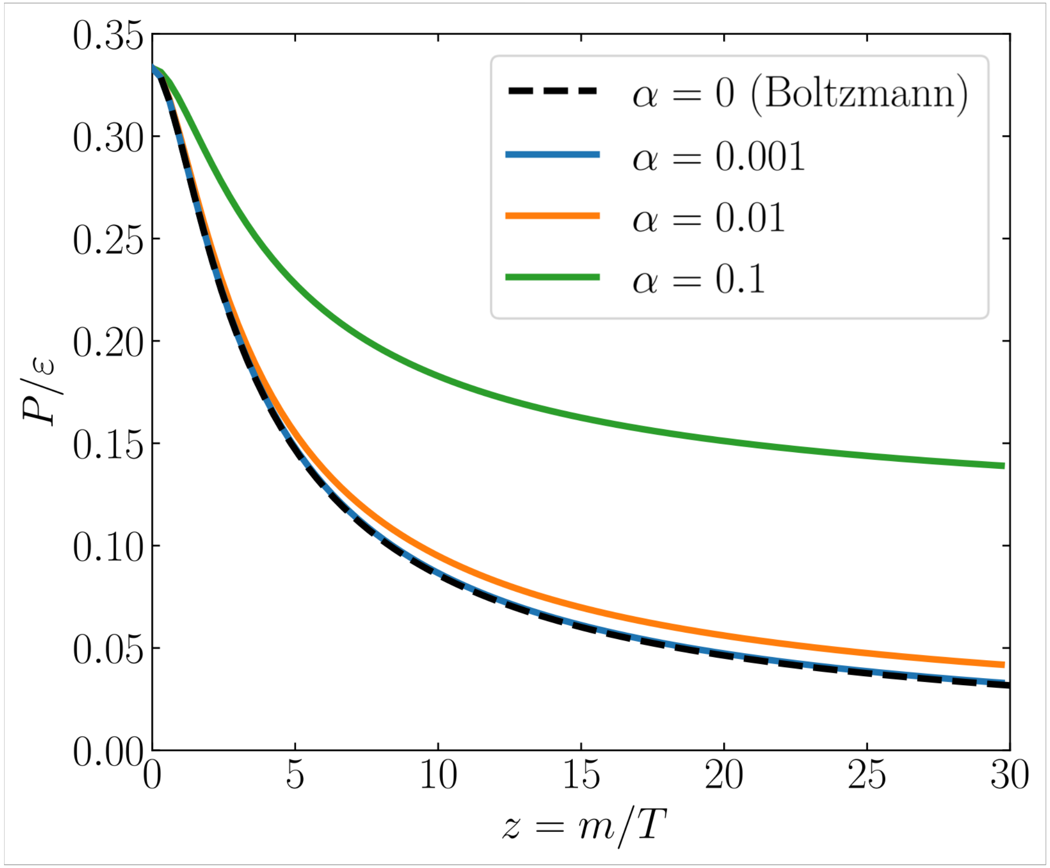
P. Houven et al Phys. Lett. B **503**, 58 (2001)

How does spectrum and flow change?

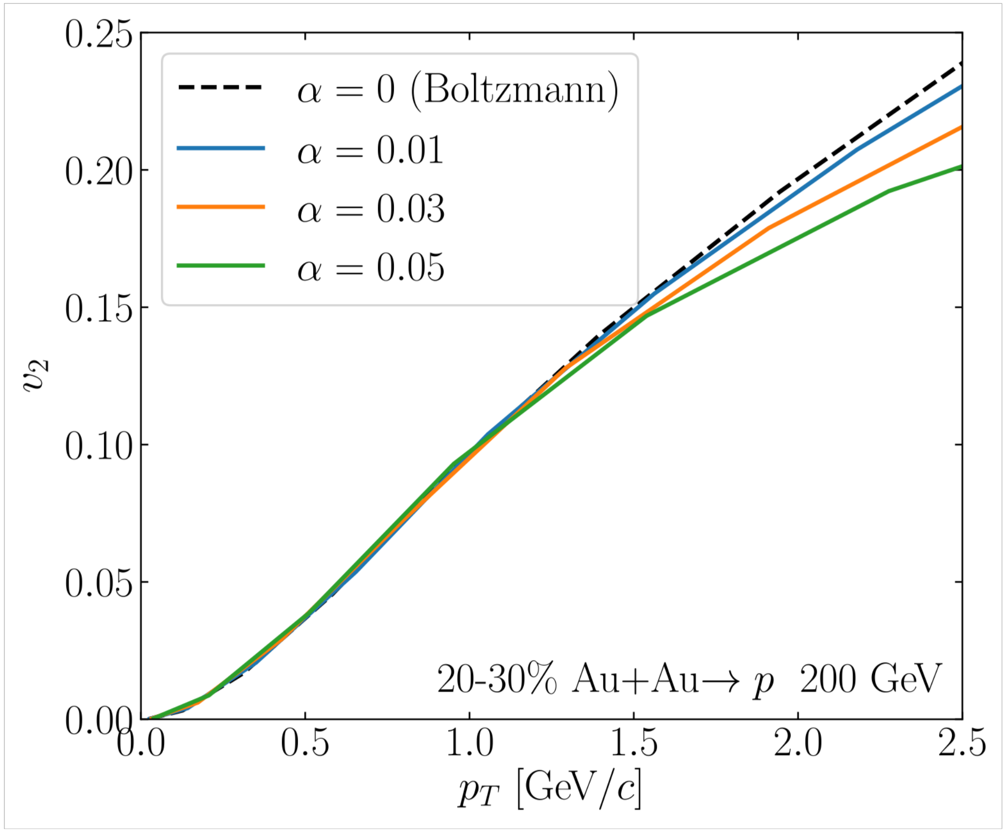
Result from 4-source model: suppression in v_2!

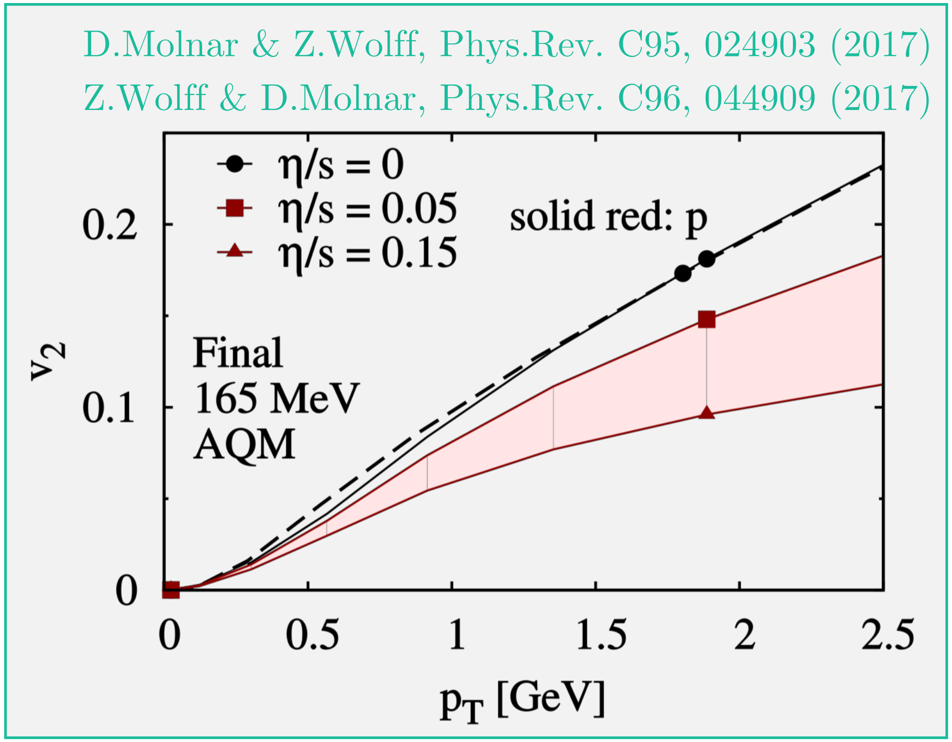


Backup: describing hydro fields with non-ext. distr.



Backup: non-ext. parameter vs. shear viscosity





Backup: v_4 with non-ext. f