Kinetic freeze out from a local anisotropic fluid

Hot Quarks 2016

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Content

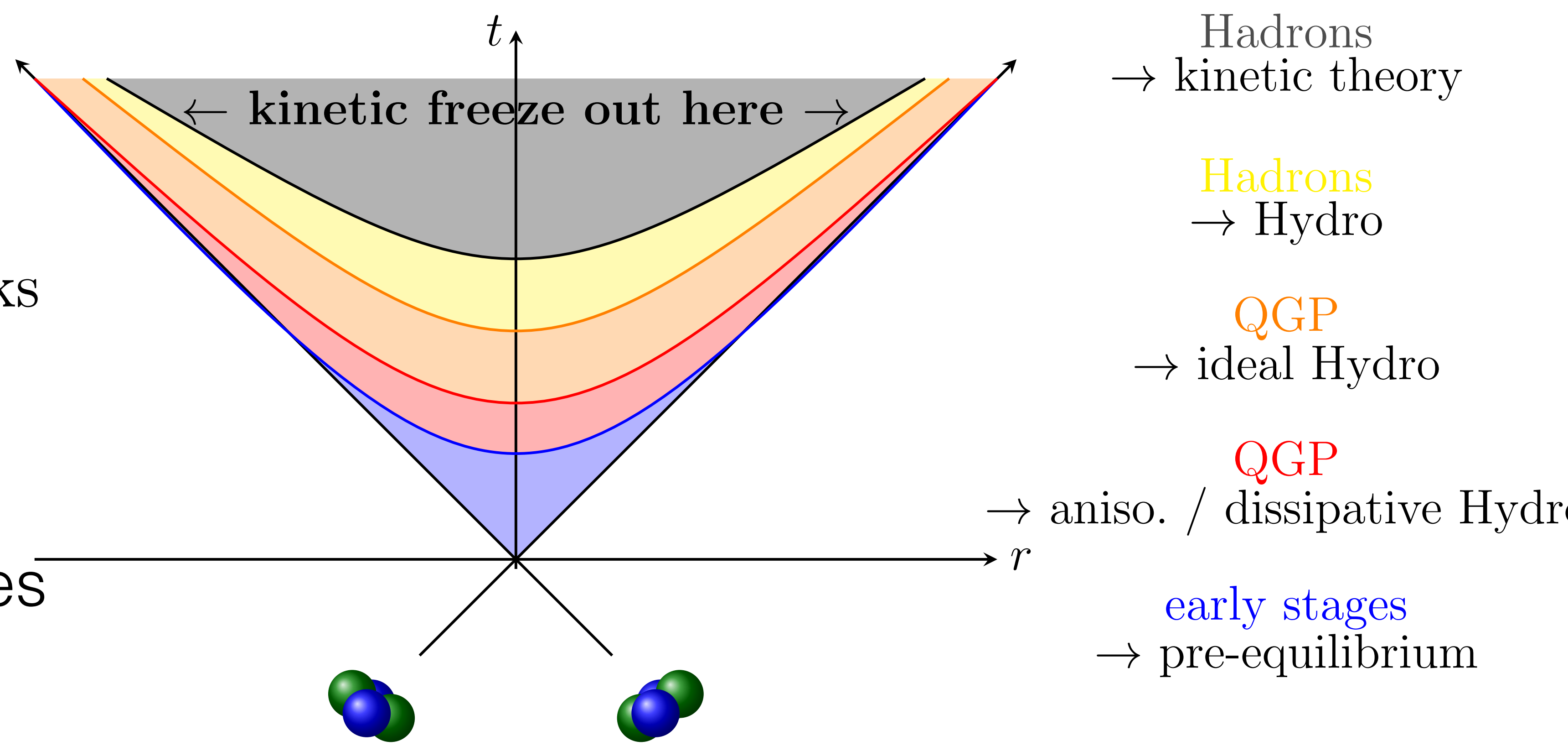
- Reminder on Cooper-Frye freeze out
- Motivation for local anisotropy
- Effects of the local anisotropy on:
    1. transverse particle spectra
    2. flow coefficients
    3. HBT radii (time permitting)
- Conclusion

Need for kinetic freeze out

- Inside QGP fluid-like behavior with small $l_{mfp} \rightarrow$ hydrodynamics works

- Expanding fireball of conserved global quantities

- Particles reaching the detector do not interact with each other, large/infinite $l_{mfp} \rightarrow$ kinetic theory works



→ *Need to glue two very different types of theoretical models*

Cooper-Frye freeze out

- Description of the medium turns suddenly from fluid to a kinetic one, while passing through a hypersurface $\boldsymbol{\Sigma}$
- On-shell phase space distribution $f(x^\mu, \vec{p})$
- Particles inside a fluid element: $dN = dV \int_{-\infty}^{\infty} d^3\vec{p}\, f(E_p)$
- Lorentz invariant particle spectrum:

$$E_p \frac{d^3N}{d^3\vec{p}} = \frac{1}{(2\pi)^3} \int_\Sigma f(x^\mu, \vec{p})\, p^\mu d^3\sigma_\mu(x^\mu)$$

Problems of (naive) Cooper-Frye freeze out

- Negative contributions to the particle spectrum due to $\boldsymbol{\Sigma}$ regions where $d\sigma_\mu d\sigma^\mu < 0$ (see talk by Oliinychenko)

- Computed observables depend on choice of freeze out parameter

→ Not physical, Nature performs a "smooth" transition between the two asymptotic models

→ *But Cooper-Frye recipe is much too attractive to be discarded*

$$E_p \frac{d^3N}{d^3\vec{p}} = \frac{1}{(2\pi)^3} \int_\Sigma f(x^\mu, \vec{p})\, p^\mu d^3\sigma_\mu(x^\mu)$$

Motivation for an anisotropic distribution function

- Nonrelativistic studies show:
    - Hypersonic flow through a nozzle into vacuum will end in an anisotropic distribution function
    - Characterized by two effective temperatures $T_{||}$ and $T_{\perp}$
- Anisotropic hydrodynamics can improve transition from pre-equilibrium to hydrodynamics (see talk by Bazow)
- Generalization to relativistic HIC case …

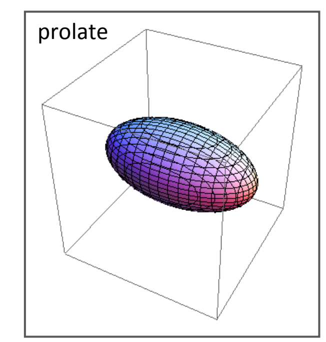
→ technical details coming soon

Anisotropic freeze out

- Idea: implement an anisotropy along the radial direction in the phase space distribution

- Tool: Romatschke-Strickland distribution

$$f_{aniso}^{LRF}(x^\mu, \vec{p}, \Lambda, \xi) \propto exp\left(-\frac{\sqrt{(p\cdot u)^2 + \xi(x^\mu)(p^r)^2}}{\Lambda(x^\mu)}\right)$$



$-1 < \xi < 0$

Taken from: Michael Strickland's Quark Matter 2015 Talk

- Boost into lab-frame

- Consequence: additional parameter ξ

- In order to generate higher effective temperature/pressure in radial direction, need to choose $\xi < 0$

- Next step: insert into Cooper-Frye Integral

Technical details

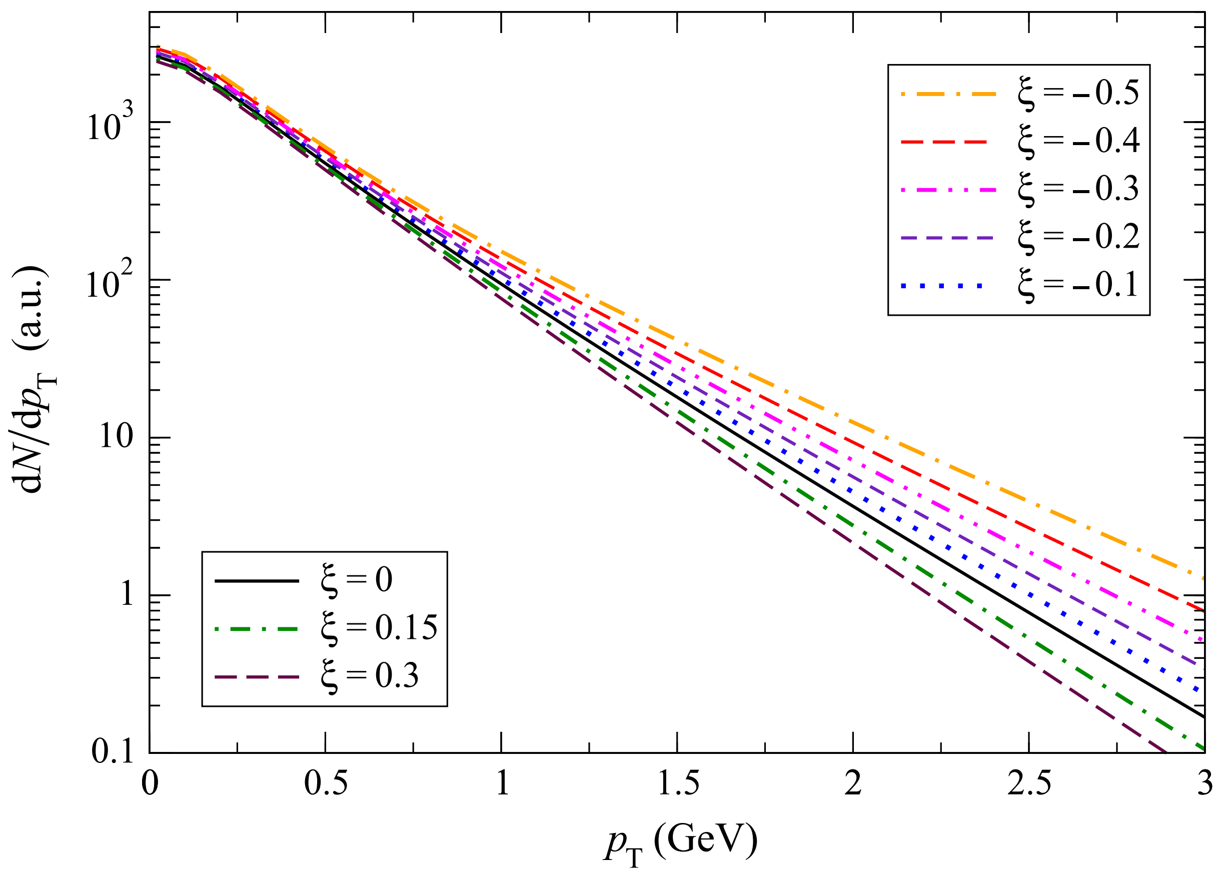
- Cylindrical lab-frame coordinates
- Blast-wave like fluid velocity profile:

$$u^\phi = u^\eta = 0 \quad ; u^r = \bar{u}_{max} \frac{r}{R} \left(1 + 2 \sum_n V_n \cos(n\phi) \right)$$

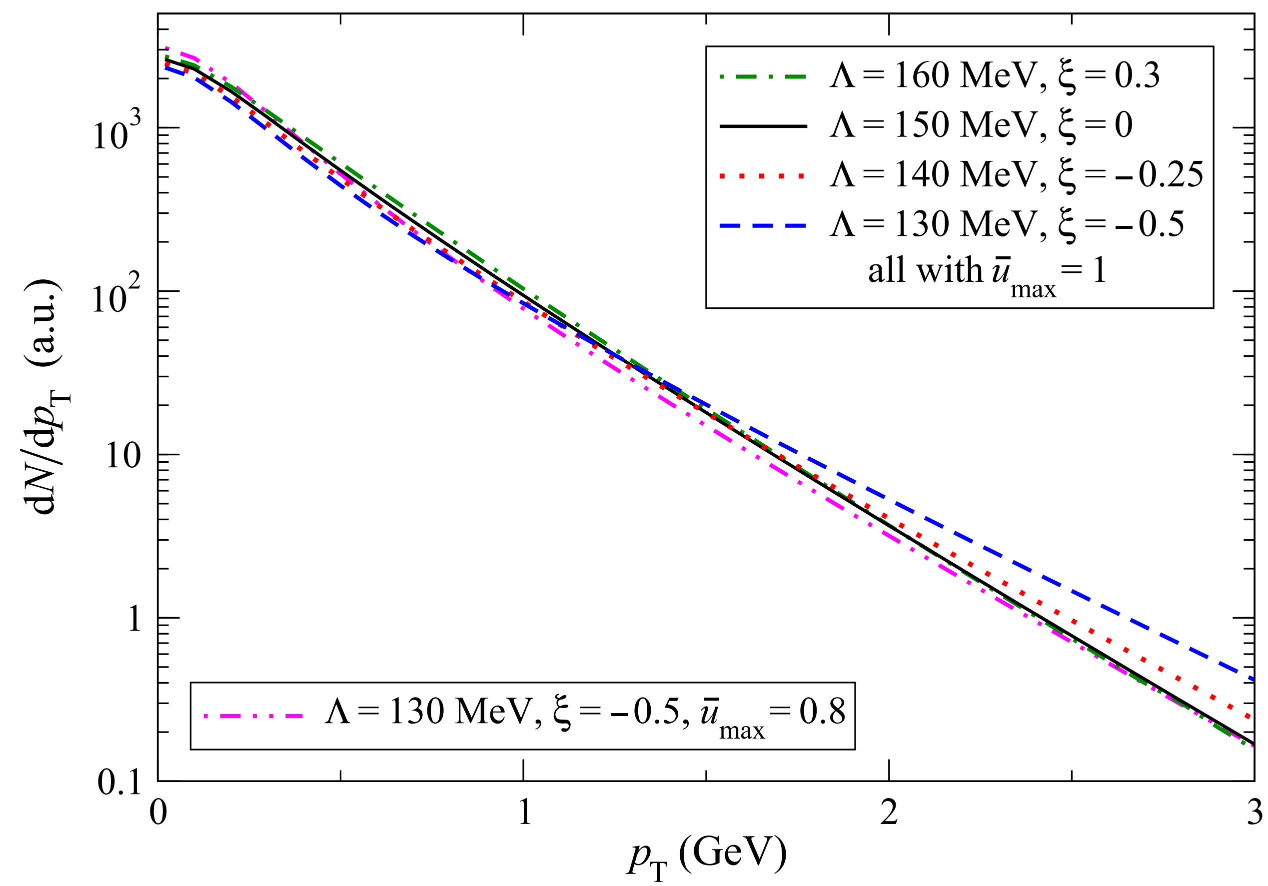
- $R = 10 fm, \quad \tau_{fo} = 7.5 \frac{fm}{c}, \quad V_2 = V_3 = 0.05$
- Particle mass: 140 MeV
- Anisotropic temperature $\Lambda(x^\mu)$, anisotropy parameter $\xi(x^\mu)$

Transverse momentum spectrum for different:

ξ values



(Λ,ξ)-pairs



- ξ decreasing → more fast particles, due to higher effective pressure
- Varying "temperatures" Λ at freeze out, but nearly same spectrum

Anisotropic flow coefficients

Fourier series in azimuthal angle ϕ_p

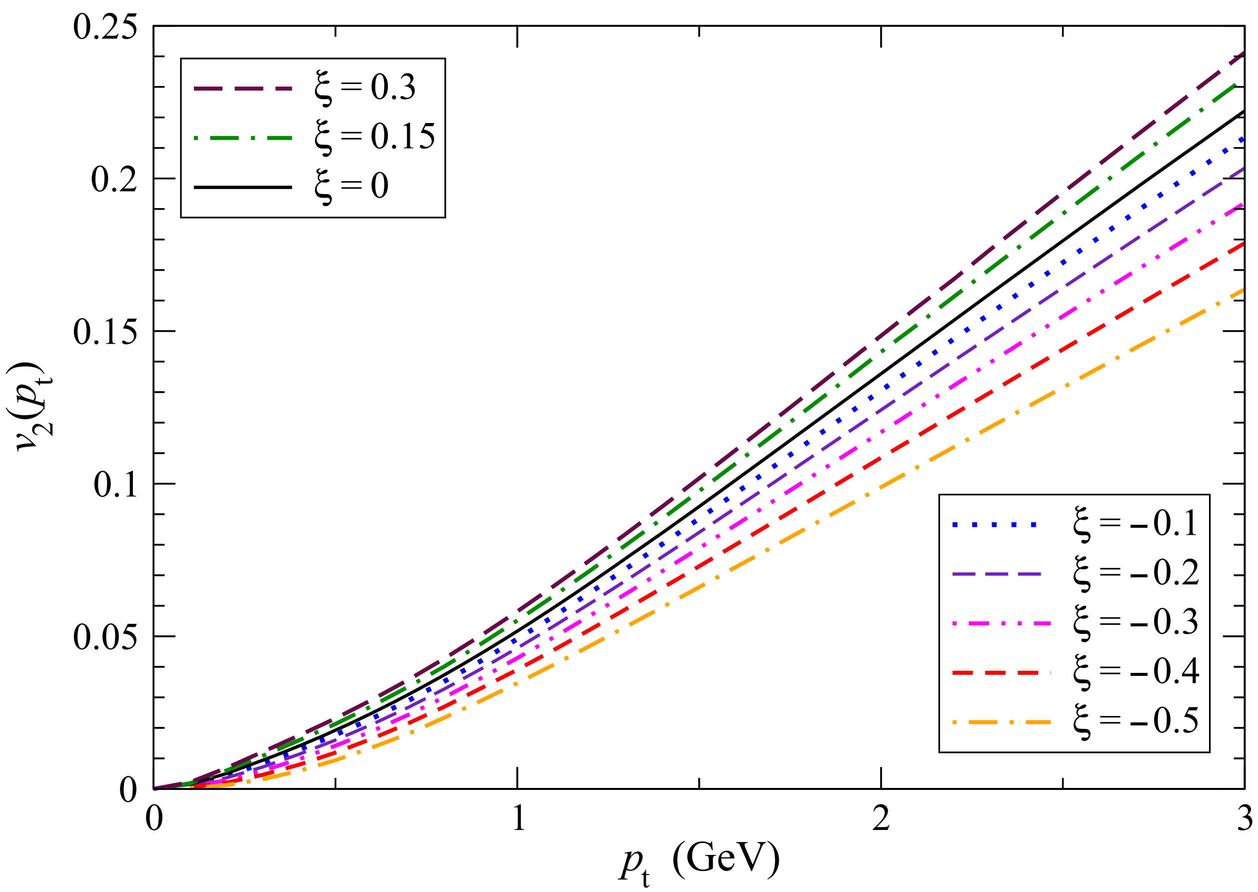
$$\frac{d^2N}{d^2\vec{p}_t} = \frac{1}{2\pi}\frac{dN}{p_t dp_t}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi_p - \psi_n))\right]$$

Fourier coefficients:

$$v_n = \frac{\int_0^{2\pi} d\phi_p \cos(n\phi_p)\frac{d^2N^{aniso}}{d\vec{p_t}}}{\int_0^{2\pi} d\phi_p \frac{d^2N^{aniso}}{d\vec{p_t}}}$$

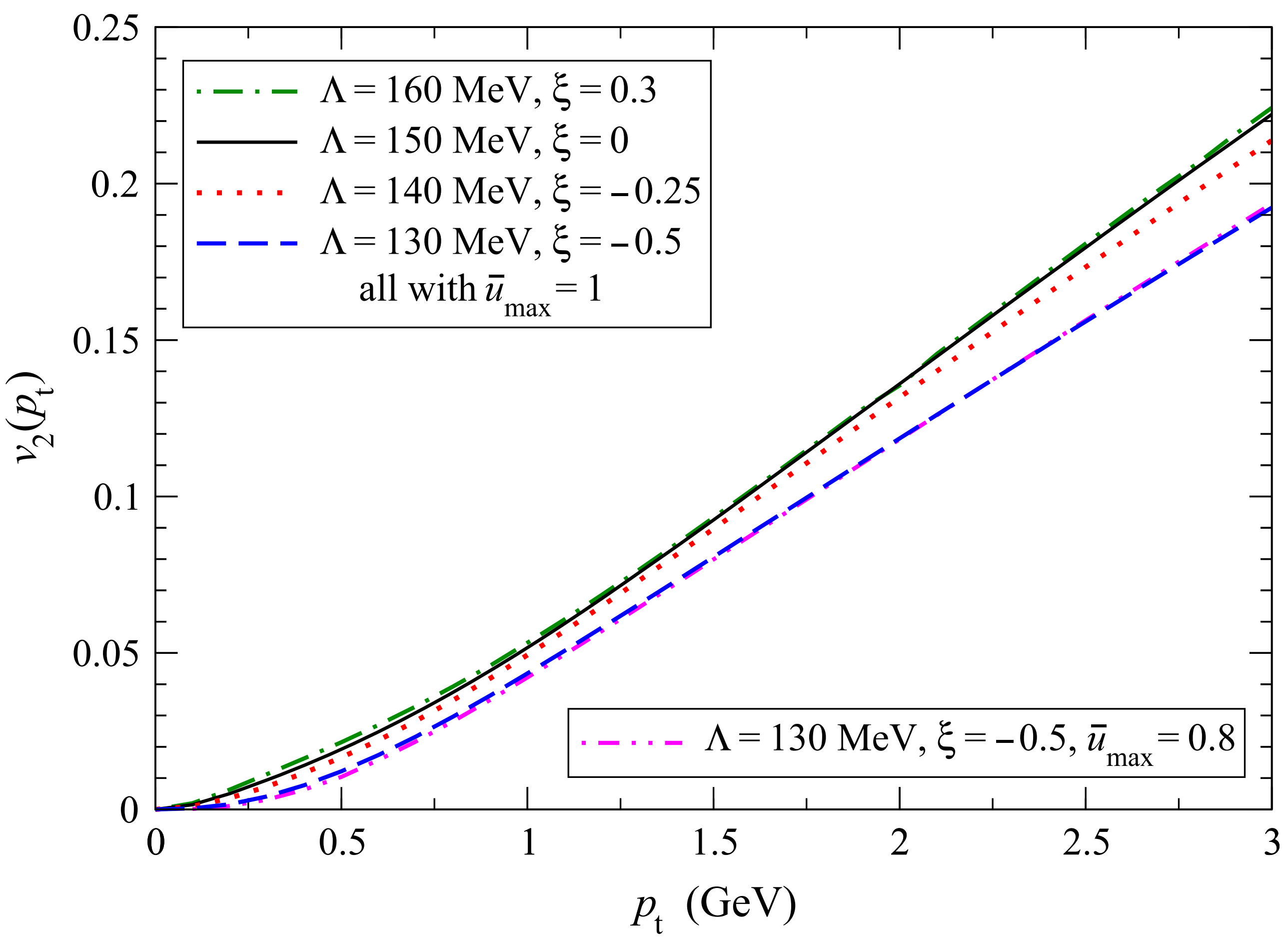
Elliptic flow v_2 for different

ξ values



- Higher anisotropy leads to smaller anisotropic flow
- v_3 and v_4 follow same trend

(Λ,ξ)-pairs



- Variation of parameters gives nearly the same observables

Hanbury-Brown Twiss radii

- Computation of HBT radii:

$$\begin{aligned} R^2_{out} &= \langle (\tilde{x} - v_{out}\ \tilde{t})^2 \rangle \\ R^2_{side} &= \langle (\tilde{y})^2 \rangle \\ R^2_{long} &= \langle (\tilde{z})^2 \rangle \end{aligned}$$

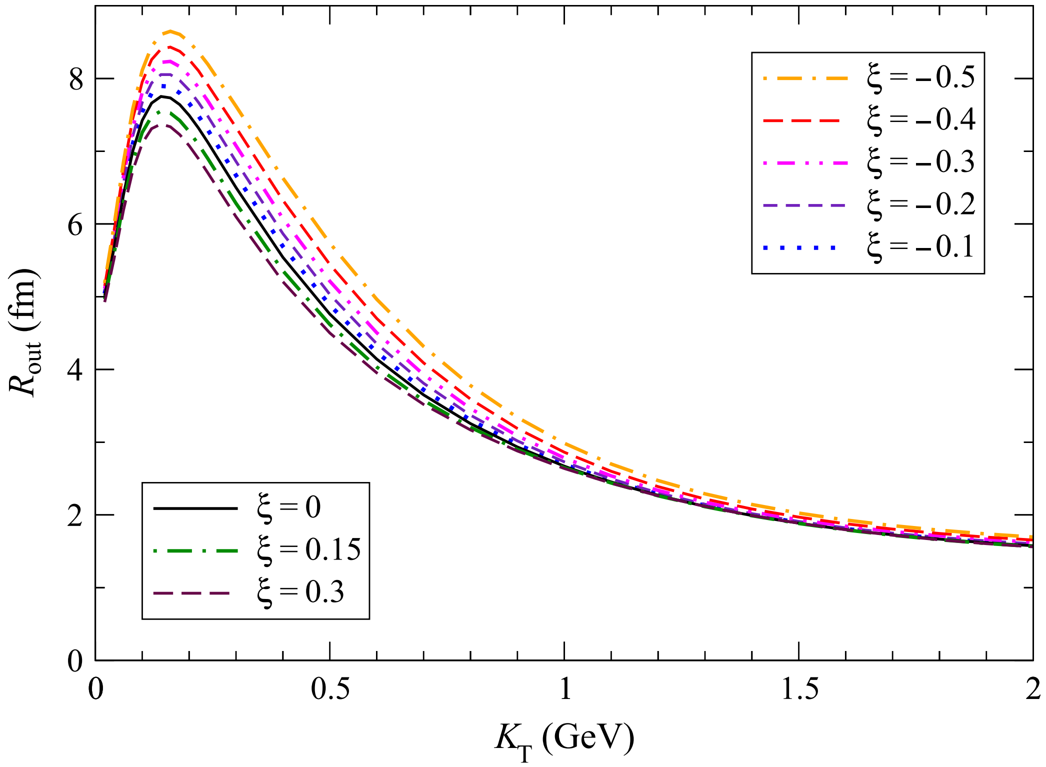
- Averaging:

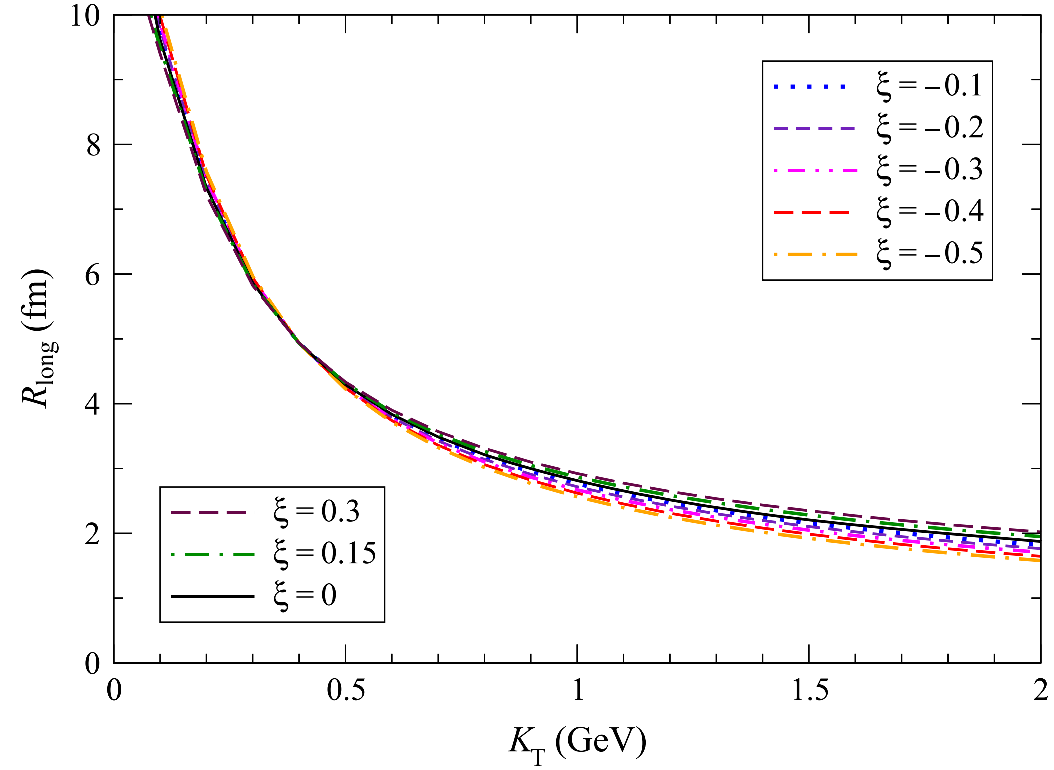
$$\langle X \rangle = \frac{\int d^4x\ X\ S(x^\mu, \vec{k})}{\int d^4x\ S(x^\mu, \vec{k})}$$

- Source-function:

$$S(x^\mu, \vec{p}) = \int p^\mu\ d\Sigma_\mu\ f(\vec{p}, x'^\mu)\ \delta^{(4)}(x'^\mu - x^\mu)$$

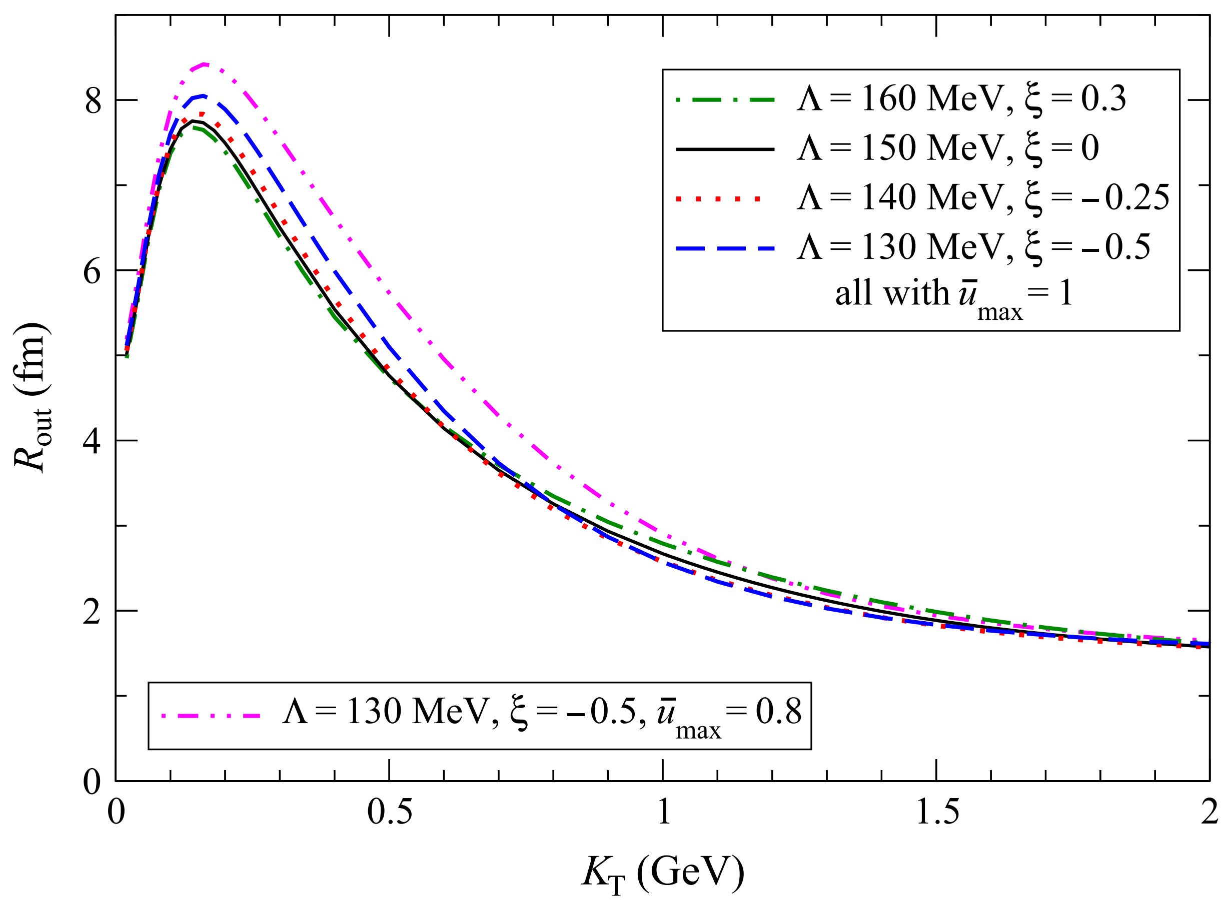
HBT radii for different anisotropy parameter values

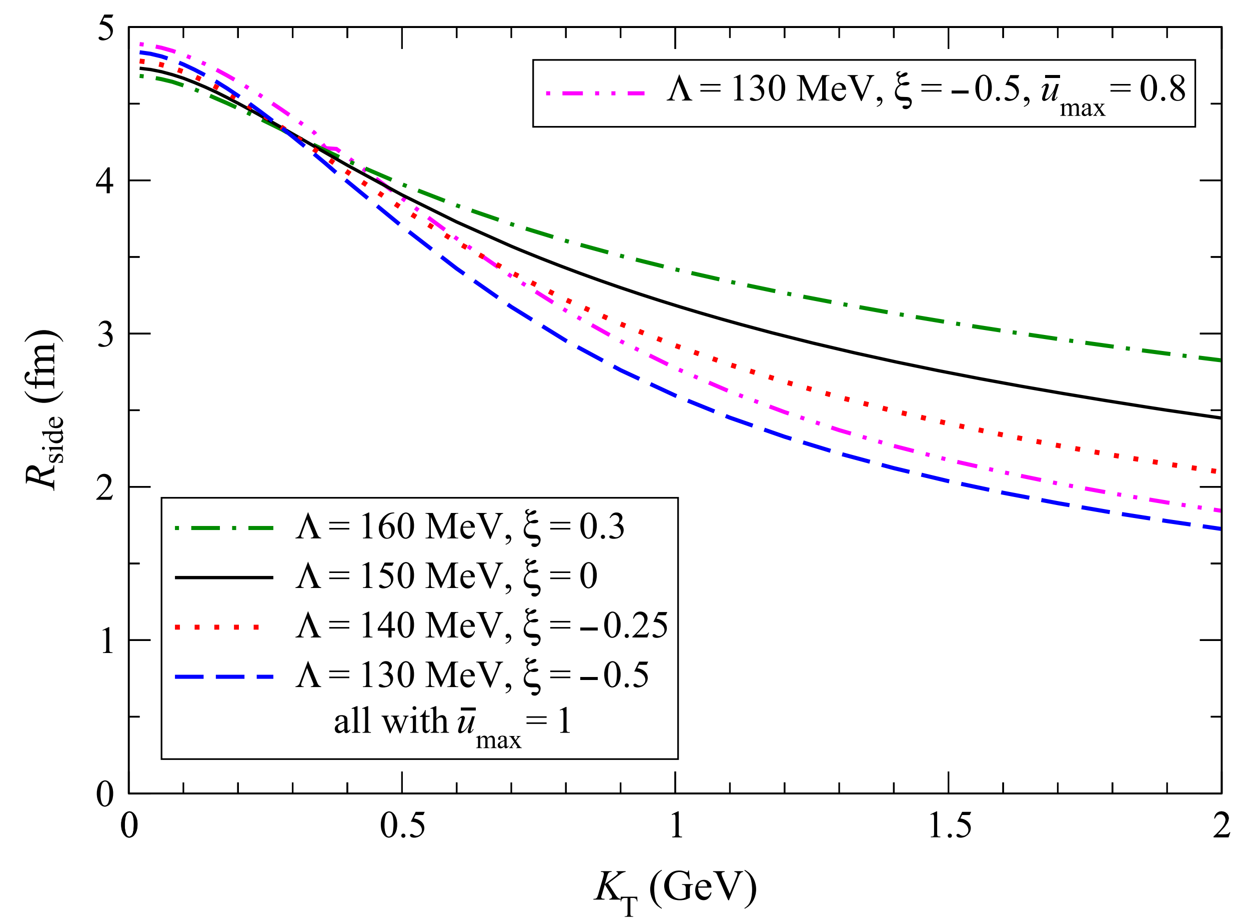




- R_{out} varies due to higher radial thermal motion
- R_{long} nearly constant

HBT radii for different (Λ,ξ)-pairs





- Small variation of R_{out}
- R_{side} very sensitive to parameter pair

Conclusion

- Introduce an anisotropic phase space distribution

  → Get additional parameter ξ

- Lower sensitivity of observables on parameters at freeze out
- Option for a smoother transition from hydro to kinetic theory
- Further reading:

  1. N. Borghini, SF, C. Lang; Eur. Phys. J. C 75 (2015) 275
  2. Work in preparation

Thank you for your attention