To scatter or not to scatter: effects of the first re-scattering

Korinna Zapp

Lund University

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Outline

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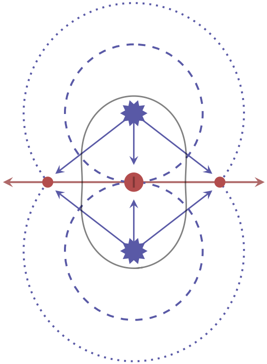
The escape mechanism

Kurkela, Wiedemann, Wu, Phys. Lett. B **783** (2018) 274



- initially isotropic momentum distribution
- particles that interact are anisotropic
- local isotropisation due to scattering induces global anisotropy
- requires only $\mathcal{O}(1)$ scattering per particle
- also observed in transport code AMPT

He, Edmonds, Lin, Liu, Molnar, Wang, Phys. Lett. B **753** (2016) 506

- single hit calculation in AMY EKT finds sizeable v_2 in small systems

Kurkela, Mazeliauskas, Törnkvist, JHEP 11 (2021), 216

- produces a positive v_2

Simulating the Boltzmann equation: parton cascades

Parton cascades

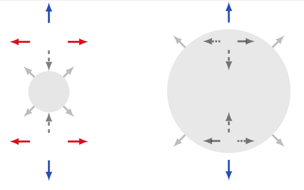
- solve Boltzmann equation by simulating evolution of ensembles sampled from $f(x, p, t_0)$
- explicitly simulate time evolution including interactions
  - geometric interpretation of scattering cross section as area
  - $\rightarrow$ scattering when distance between particles smaller than $\sqrt{\sigma/\pi}$
- ALPACA: parton cascade implementation of AMY EKT of QCD at high T

Kurkela, Törnkvist, Zapp, Eur. Phys. J. C **84** (2024) no.1, 74

Escape mechanism in parton cascades

- finite interaction range
- averaging over volume reduces momentum anisotropy
- eventually particle moving horizontally interact

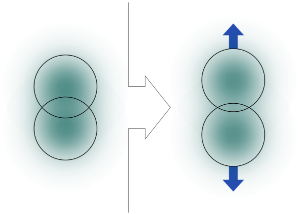
$\rightarrow$ negative v_2

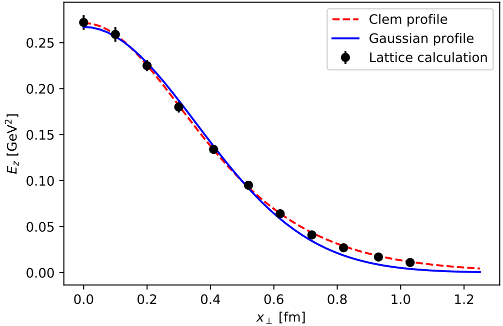


The string shoving model

- strings have a finite transverse size
- overlapping strings repel each other

  analogous to vortex lines in superconductor
- momentum anisotropy in dense systems
- negative v_2 in small systems



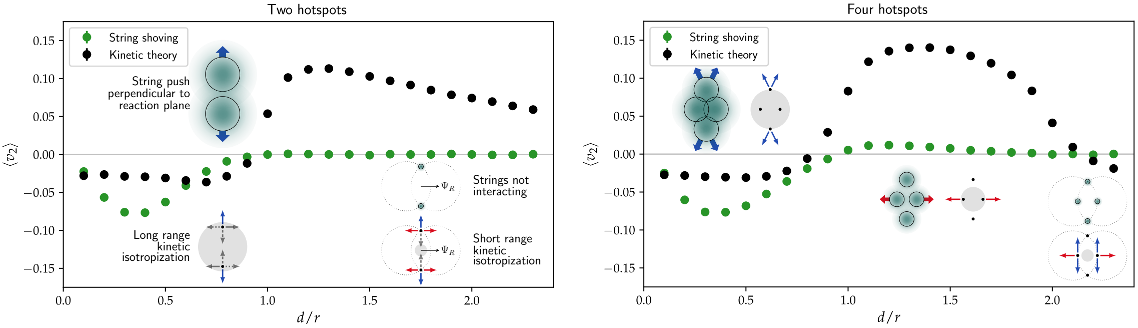


Gaussian profile → force per length

$$f(d_\perp) = \frac{g\kappa d_\perp}{R^2}\exp(-d_\perp^2/4R^2)$$

Bierlich, Chakraborty, Gustafson, Lönnblad, JHEP 03 (2021), 270

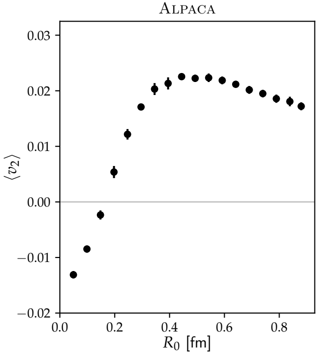
Toy systems: 2 and 4 hot spots



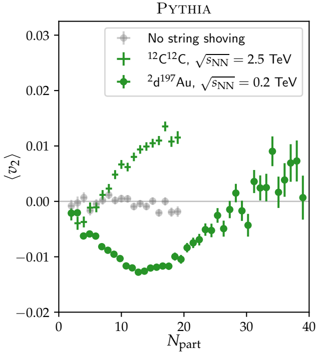
- clear negative v_2 signal when interaction range < system size

Bierlich, Christiansen, Gustafson, Lönnblad, Törnkvist, Zapp, Phys. Lett. B **874** (2026), 140216

More realistic systems



CGC inspired initial condition



nuclear collisions modeled with Angantyr

Bierlich, Christiansen, Gustafson, Lönnblad, Törnkvist, Zapp, Phys. Lett. B **874** (2026), 140216

Concluding remarks

Kinetic theory – do I have to worry?

- sign of v_2 depends on how you solve the Boltzmann equation
- Boltzmann equation applicable when interaction time $\ll$ mean free path
- interaction time $\Delta t_{\text{scat}} \sim 1/\langle\sqrt{-t}\rangle \sim 1/\mu$
- interaction range $d \sim \sqrt{\sigma} \sim 1/\mu$
- $v_2 < 0$ when
  1. $d \gtrsim R$
  2. $N_{\text{scat}} = \mathcal{O}(1) \quad \Rightarrow \quad \lambda \sim R$

  $\Rightarrow$ $\Delta t_{\text{scat}} \gtrsim \lambda$

R: system size

λ: mean free path

$\rightarrow$ outside range of applicability of Boltzmann transport

- AMY requires separation of scales between screening mass and typical momentum

$\rightarrow$ not satisfied for CGC initial condition and small R_0

Final concluding remarks

Measuring the sign of v_2 in small systems is hard

- 2-particle correlations measure v_2^2 — look for a dip in $|v_2|$ vs. N_{ch}
- determining the reaction plane requires measuring v_1, which is very small in small systems

String shoving model

- negative v_2 very solid prediction of the model

→ measuring positive v_2 in small systems would rule out the model

Kinetic theory

- applicability of Boltzmann transport not guaranteed in small systems
- could potentially produce negative v_2

Outline

Introduction

Motivation

- small systems puzzle: why is there high $p_\perp$ v_2 but no jet quenching?
- possible answer: perhaps R_{AA} is not sensitive enough

Le Roux, Milhano, Zapp, Eur. Phys. J. C **85** (2025) no.9, 1065

- kinematic effects have smooth onset & require many interactions to build up
- but changes in colour flow are binary

Our scenario

- consider a single soft early re-scattering
- only effect: changes colour flow $\rightarrow$ loss of colour coherence

$\rightarrow$ loss of angular ordering in first and/or second splitting

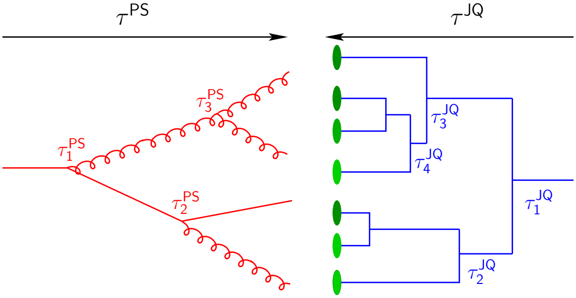
- detect this via change in formation time

The τ algorithm

Apolinário, Cordeiro, Zapp, Eur. Phys. J. C 81 (2021) no.6, 561
Apolinário, Guerrero-Rodríguez, Zapp, Eur. Phys. J. C 84 (2024) no.7, 672

sequential recombination algorithm with $d_{ij} \approx p_{\perp,i}\theta^2 \approx \frac{k_\perp^2}{p_{\perp,i}} \approx \frac{1}{\tau_{\text{form}}}$

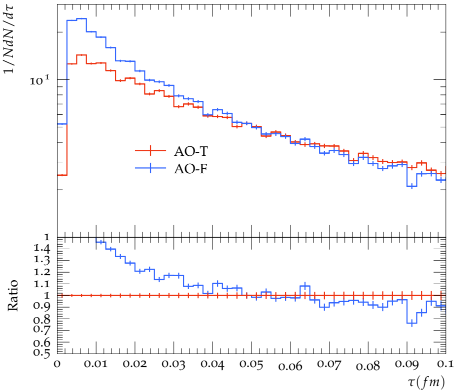
generalised $k_\perp$-algorithm with $p = 1/2$



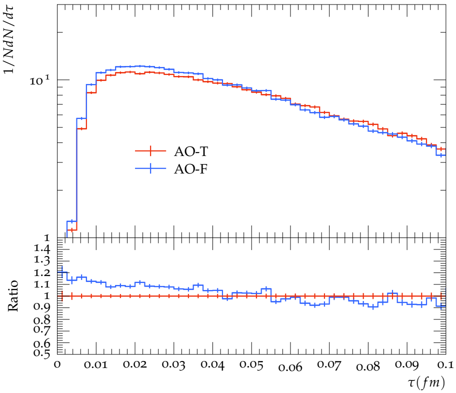
- find jets with anti-$k_\perp$ algorithm
- cluster particles in jets again with τ algorithm
- undo clustering steps and calculate formation times
- extract time information from reconstructed jets

Effect of (loss of) angular ordering on formation time

generated formation times first splitting



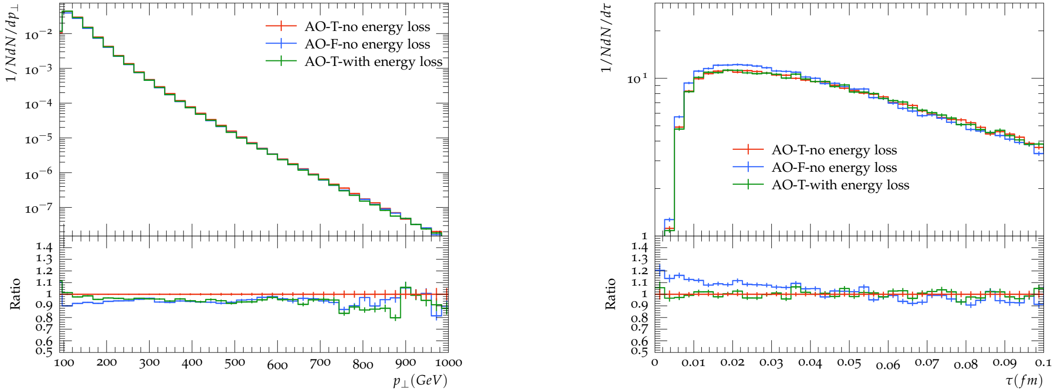
reconstructed formation times



- clear effect due to loss of angular ordering
- suffers from imperfect reconstruction

Apolinário, Le Roux, Zapp, arXiv:2510.11914

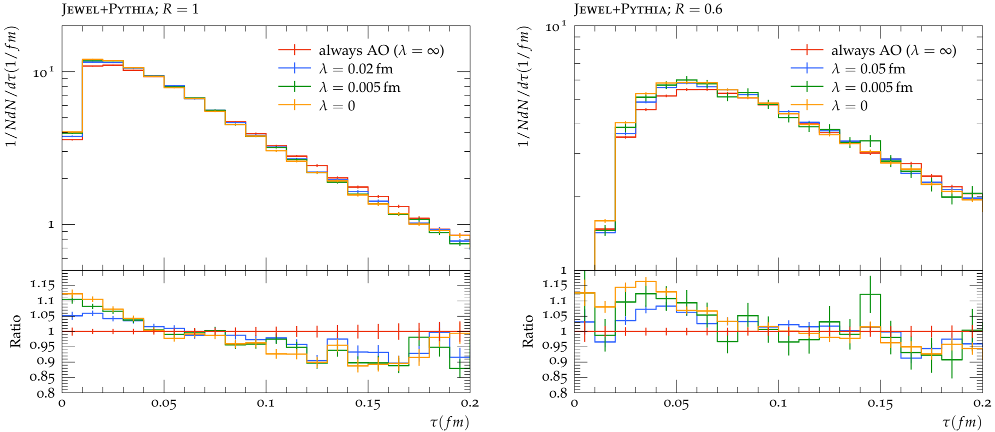
Loss of angular ordering vs. energy loss



- compare to 1% energy loss
- energy loss does not affect formation time

Apolinário, Le Roux, Zapp, arXiv:2510.11914

What scattering rates is this sensitive to?



- can steer sensitivity to different mean free paths with jet radius

Apolinário, Le Roux, Zapp, arXiv:2510.11914

Conclusions

- even single soft(ish) scattering can change colour flow
- leads to loss of angular ordering due to breaking of colour coherence

$\rightarrow$ formation times become shorter

- can be accessed with τ-algorithm
- can distinguish between energy loss and loss of coherence
- different jet radii sensitive to different formation times

$\rightarrow$ can tune sensitivity to different mean free paths

Outline

Conclusions

What do you conclude?

Let's discuss!

Acknowledgment

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Bonus material

The AMY effective kinetic theory

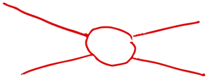
- effective kinetic theory of QCD at high temperature $\rightarrow g(T) \ll 1$

Arnold, Moore, Yaffe, JHEP **0301** (2003) 030

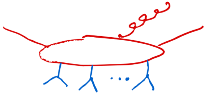
- partons are quasi-free and quasi-massless particles
- correctly describes dynamics of hard modes $\mathcal{O}(T) \rightarrow$ typical momenta in thermal system
- Boltzmann equation: $(\partial_t + \mathrm{v} \cdot \nabla_x) f(\mathrm{x}, \mathrm{p}, t) = -C[f]$

dynamics contained in collision kernel $C[f]$

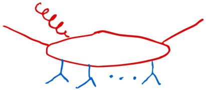
- 2 types of processes:



$2 \leftrightarrow 2$



"$1 \rightarrow 2$"



"$2 \rightarrow 1$"

- interaction rates depend on effective masses m_{eff} and temperature T_*

ALPACA

Kurkela, Törnkvist, K. Zapp, Eur. Phys. J. C 84 (2024) no.1, 74

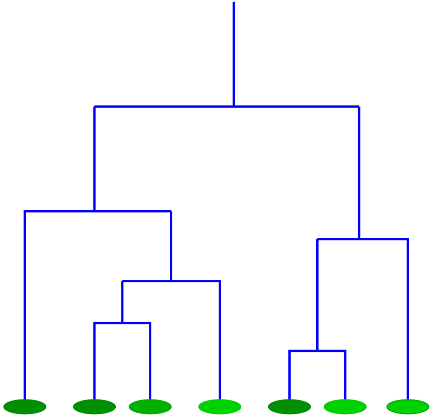
- evolves parton ensemble according to AMY collision kernels
- Lorentz-invariant implementation
- elastic scattering: interaction when invariant distance $d_{ij} < \sqrt{\sigma/\pi}$ black disk approximation
- merging: similar to scattering
- splitting: analoguous to radioactive decay standard MC solution available: veto algorithm
- effective masses and temperature: obtained by summing over nearby partons

$$m_{\text{eff}}^2 \propto \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{f(\mathrm{p})}{|\mathrm{p}|} \quad \text{and} \quad T_* \propto \frac{1}{m_{\text{eff}}^2} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} f(p)[1+f(p)]$$

- infra-red momentum cut-off p_{min}: have to regularise divergent splitting/merging rates

cancellation not automatic as in Boltzmann equation

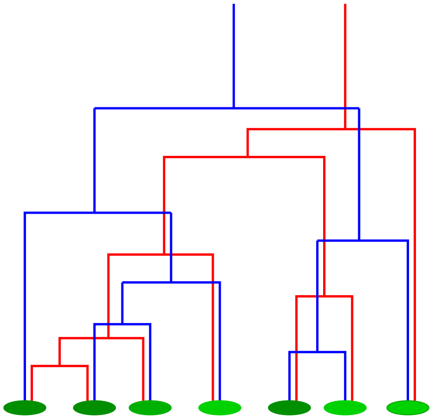
Jet clustering



Sequential recombination algorithms:

- define pair-wise distance d_{ij}
- iteratively recombine pair with smallest d_{ij}
- $\rightarrow$ hierarchical structure

Jet clustering



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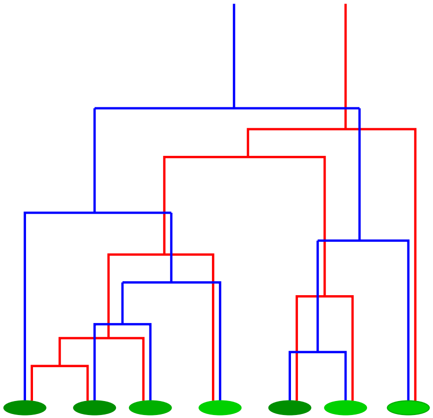

The $k_\perp$-family:

$$d_{ij} = \min\left(p_{\perp,i}^{2p}, p_{\perp,j}^{2p}\right)\frac{R_{ij}^2}{R^2}$$

- $p = 1$: $k_\perp$ algorithm

  similar to parton shower

- $p = 0$: Cambridge/Aachen

  → angular ordering

- $p = -1$: anti-$k_\perp$ algorithm

  convenient in busy environments, no physical interpretation

- $p = 0.5$: τ algorithm

  → formation time

Formation times and jet radii