TECHNISCHE UNIVERSITÄT WIEN

FWF Österreichischer Wissenschaftsfonds

Doktoratskolleg Particles and Interactions

Pre-hydrodynamic jet momentum broadening beyond the jet quenching parameter

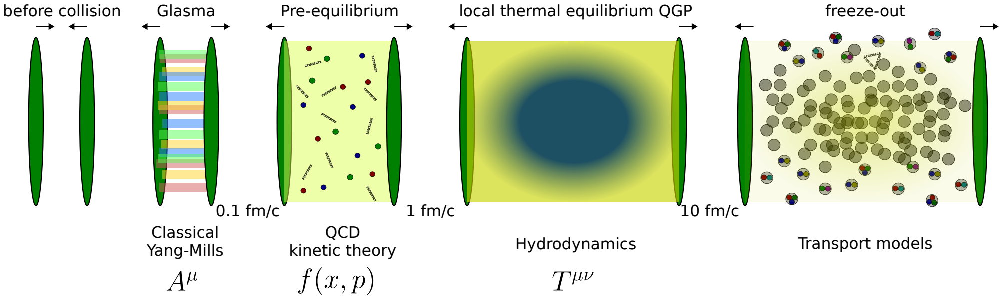
2303.12595 & 2312.00447 with K. Boguslavski, A. Kurkela, T. Lappi, J. Peuron and based on work in preparation with Alois Altenburger & Kirill Boguslavski,

Florian Lindenbauer

TU Wien

15.11.2024, Light ion collisions at the LHC, CERN

Time-evolution of the QGP in heavy-ion collisions

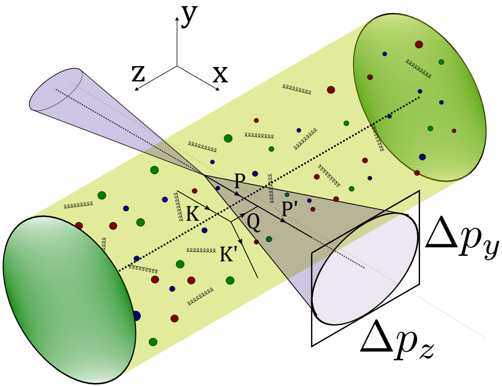


- Different stages in time evolution[1]
- Light-ion collisions
  $\rightarrow$ **Pre-equilibrium/pre-hydrodynamic stages more important**

[1] [Rev.Mod.Phys. 93 (2021) [Berges, Heller, Mazeliauskas, Venugopalan]]

Hard probes to study pre-hydrodynamic evolution

- Study pre-hydrodynamic evolution
  → very **energetic** or **heavy** probes
- Here depicted: **jets**



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    → then measured in the detectors
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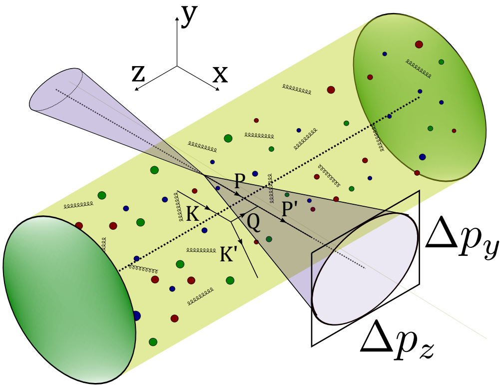

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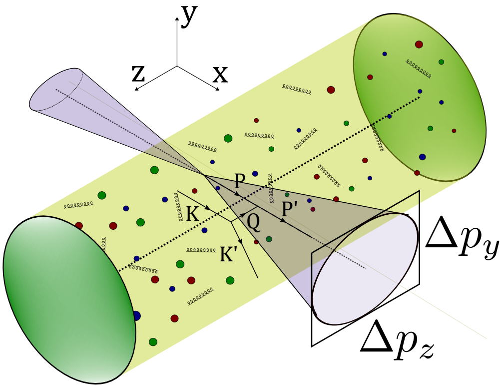
- Probe physics of
  nonequilibrium QCD



Motivation summary

Light ions

- System initially very out of equilibrium
- Smaller medium → **shorter hydrodynamic stage**
- Opportunity for studying **QCD out of equilibrium**

Why jets?

- Created early
  → **sensitive to out-of-equilibrium** medium

Jet energy loss through medium-induced radiation

- **Energy loss** dominated by **gluon radiation**

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- Depends on effective propagator
  Input: **dipole cross section**

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$$C(\mathbf{q}_\perp) = (2\pi)^2 \frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}$$

See also JHEP 07 (2020) [Andres, Apolinário, Dominguez], JHEP 10 (2021) [Moore, Schlichting, Schlusser, Soudi], PRD 105 (2022) [Schlichting, Soudi]

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- **Harmonic approximation**: (small b limit)
  Dependence on single medium parameter $\hat{q}$

$$C(\mathbf{b}) \approx \frac{1}{4}\hat{q}\mathbf{b}^2 + \dots$$

"Jet quenching parameter"

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- Quantifies **momentum broadening**

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2\rangle}{\mathrm{d}L} = \frac{\mathrm{d}\langle p_\perp^2\rangle}{\mathrm{d}t} = \int \mathrm{d}^2 q_\perp\, q_\perp^2 \frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}$$

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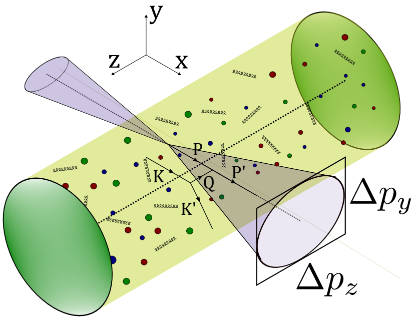

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Motivation

- Most jet implementations:
  based on static media.
- Recent generalization to non-static systems[2]

[2] Phys.Rev.D 104 (2021) [Sadofyev, Sievert, Vitev], Phys.Rev.D 108 (2023) [Barata, Mayo López, Sadofyev, Salgado]

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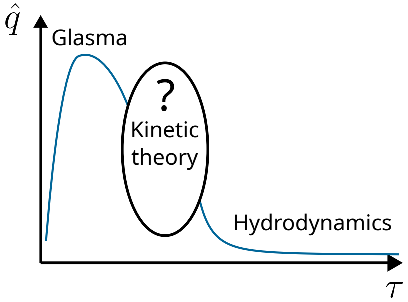
Motivation

- Most jet implementations:
  based on static media.
- Recent generalization to non-static systems[2]
- **Medium input:** $\hat{q}$ (or $C(\mathbf{b})$)
- Recent studies in the initial Glasma stage: $\hat{q}$ very large[3]
- **Goal: $\hat{q}$ during hydrodynamization**
  $\rightarrow$ between Glasma and hydro

Schematic $\hat{q}$ evolution



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Effective kinetic theory description of the QGP

- Gluons with **distribution function** $f(t, \mathbf{p})$

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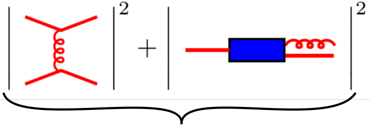
Effective kinetic theory description of the QGP

- Gluons with **distribution function** $f(t, \mathbf{p})$
- Time evolution described by **Boltzmann equation** at leading-order[4]

$$(\partial_t + \boldsymbol{v} \cdot \boldsymbol{\nabla}) f =$$



Collision term

- Azimuthal symmetry around beam axis $\hat{z}$,
  Bjorken expansion, homogeneous in transverse plane

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Bottom-up thermalization in heavy-ion collisions

- Initial condition[5], with $\lambda = g^2 N_C$

$$f(p_\perp, p_z) = \frac{2A}{\lambda} \frac{\langle p_T \rangle}{\sqrt{p_\perp^2 + \xi_0^2 p_z^2}} \times \exp\left(\frac{-2}{3\langle p_T \rangle^2} \left(p_\perp^2 + \xi_0^2 p_z^2 \right) \right)$$

$\xi_0 \sim$ anisotropy, $\langle p_T \rangle = 1.8 Q_s$,
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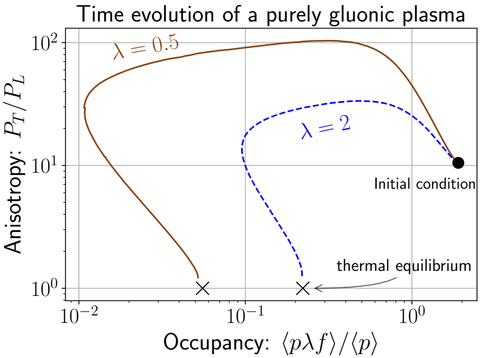

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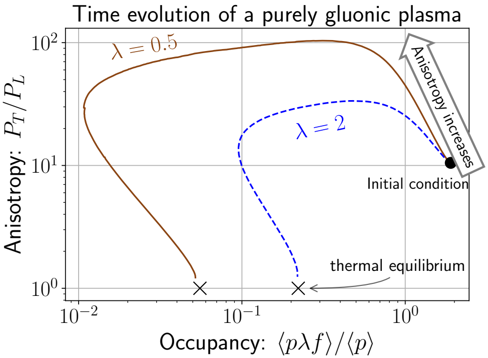

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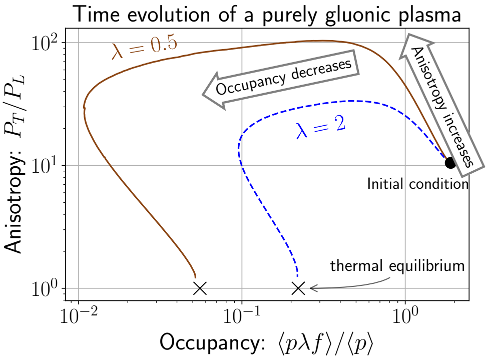

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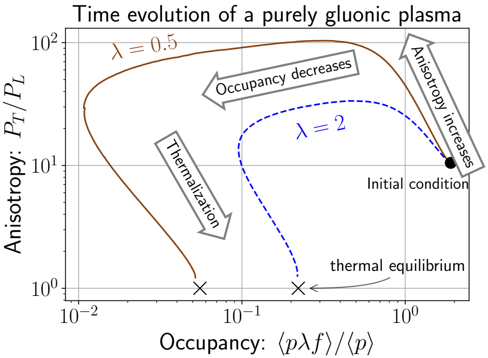

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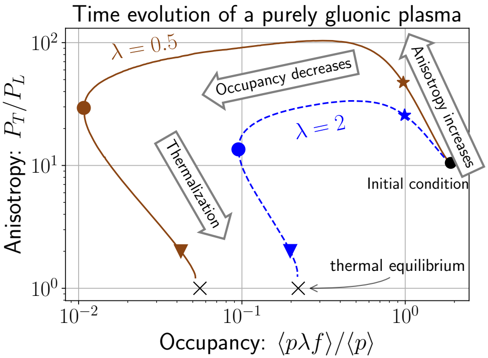
Markers represent **different stages**



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Jet momentum broadening in kinetic theory

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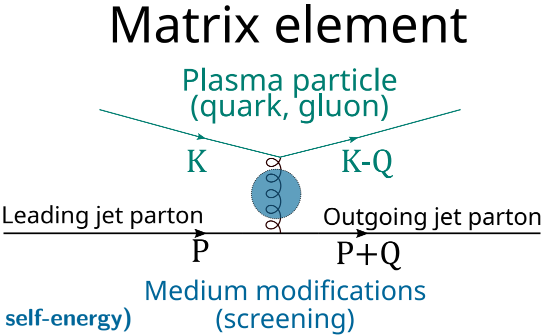
Outgoing plasma particle

$$\hat{q}^{ij} = \int_{\substack{q_\perp < \Lambda_\perp \\ p \to \infty}} \mathrm{d}\Gamma_{\mathrm{PS}}\, q^i q^j \, |\mathcal{M}|^2 f(k)\,(1 + f(k'))$$

Incoming plasma particles with momentum k

Matrix element **with medium corrections (HTL self-energy)**

appropriate phase-space measure



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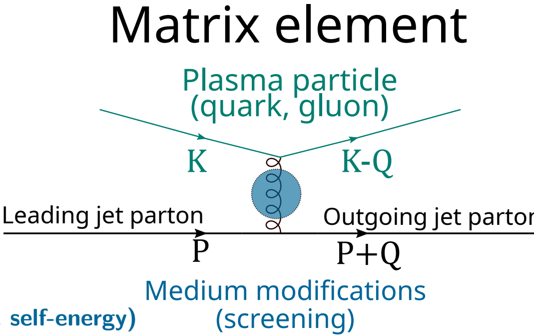

Results for $\hat{q}$

- Logarithmic cutoff $\Lambda_\perp$ dependence[7]

  $$\hat{q}^{xx}(\Lambda_\perp \gg T_\varepsilon) \simeq a_x \ln \frac{\Lambda_\perp}{Q_s} + b_x$$

  (and similar for $\hat{q}^{yy}$)

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  - $\Lambda_\perp^{\mathrm{LPM}}(E, T_\varepsilon) = \zeta^{\mathrm{LPM}} g \times (E T_\varepsilon^3)^{1/4}$
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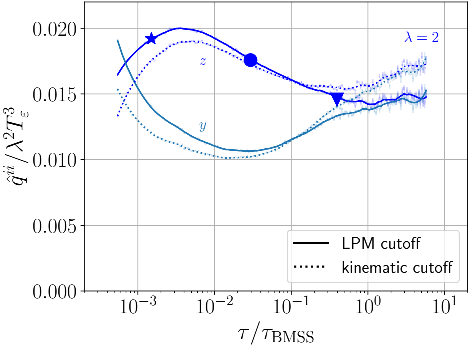

[Phys.Lett.B 850 (2024) [Boguslavski, Kurkela, Lappi, FL, Peuron]]

Plot for $E = 100\,\mathrm{GeV}$

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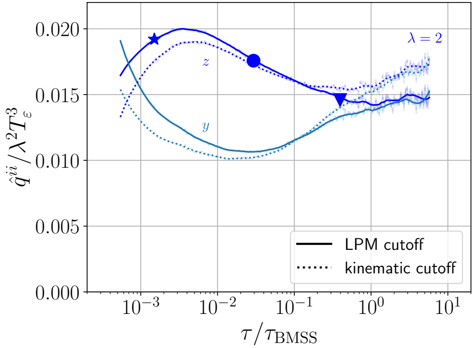
  $\rightarrow$ **Enhanced broadening along beam axis**
- Similar results for both cutoffs



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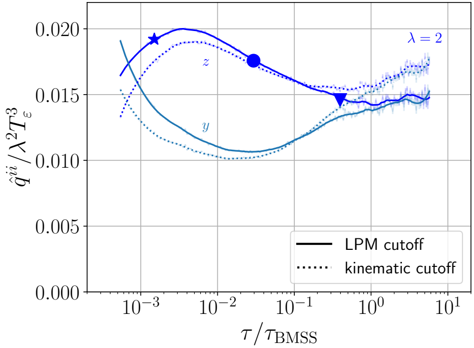

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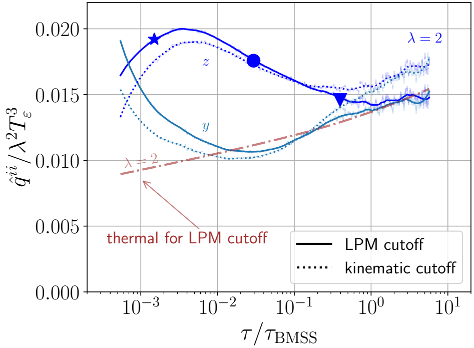

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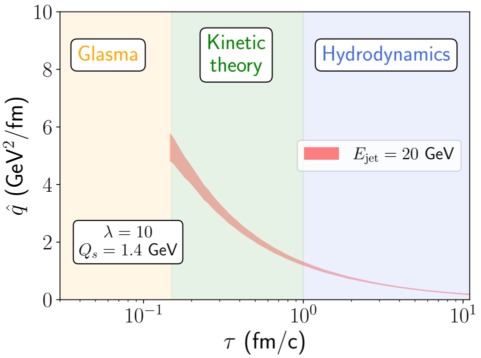
Time evolution of jet quenching parameter

- Model cutoff variation for fixed jet energy
- Dependence on initial conditions and cutoff (bands)



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Time evolution of jet quenching parameter

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- Dependence on initial conditions and cutoff (bands)
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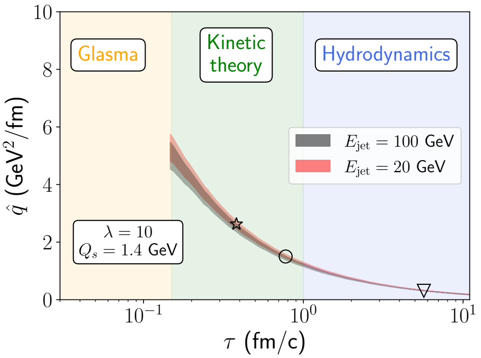

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Time evolution of jet quenching parameter

- Model cutoff variation for fixed jet energy
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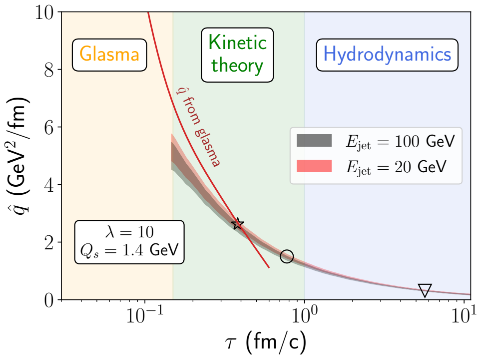
- Little jet energy dependence
- Supports **large values** from **Glasma**[7] and lower values in hydrodynamic stage



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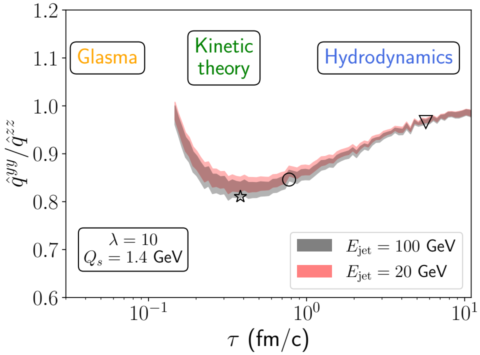
Time evolution of jet quenching parameter

- Model cutoff variation for fixed jet energy
- Dependence on initial conditions and cutoff (bands)
- Little jet energy dependence
- Broadening **anisotropy** up to 15 %
- Possible impact on polarization[7], azimuthal and spin observables[8]



[Phys.Lett.B 850 (2024) [Boguslavski, Kurkela, Lappi, FL, Peuron]]

[7] [JHEP 08 (2023) [Hauksson, Iancu]]

[8] [arXiv:2407.04774 [Barata, Salgado, Silva]]

Momentum broadening kernel

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[9] [JHEP 05 (2002) [Aurenche, Gelis, Zaraket]]

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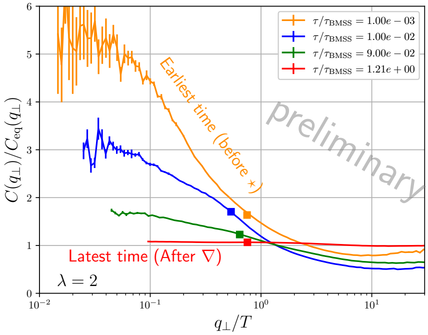
Normalize using (Landau-matched) thermal kernel, with small $q_\perp$ form[9]

$$C_{\mathrm{equ}}(q_\perp \ll T) = \frac{C_R g^2 T m_D^2}{q_\perp^2 (q_\perp^2 + m_D^2)}$$



9 [JHEP 05 (2002) [Aurenche, Gelis, Zaraket]]

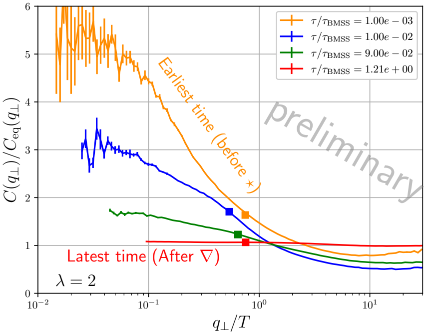
Momentum broadening kernel

$$C(\mathbf{q}_\perp) = \int \mathrm{d}\Gamma_{\mathrm{PS}} \, |\mathcal{M}|^2 f(\mathbf{k})(1 + f(\mathbf{k} - \mathbf{q}))$$

Normalize using (Landau-matched) thermal kernel, with small $q_\perp$ form[9]

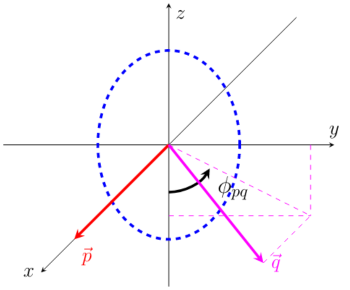
$$C_{\mathrm{equ}}(q_\perp \ll T) = \frac{C_R g^2 T m_D^2}{q_\perp^2 (q_\perp^2 + m_D^2)}$$

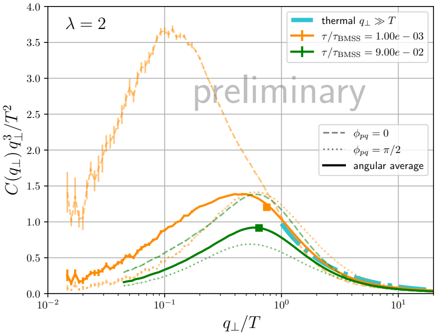
- **Momentum transfer of soft momenta enhanced**
- Late times (red curve):Thermal



[9] [JHEP 05 (2002) [Aurenche, Gelis, Zaraket]]

Angular dependence and contribution to $\hat{q}$





- Contribution to $\hat{q} = \int \mathrm{d}^2\mathbf{q}_\perp\, q_\perp^2\, C(\mathbf{q}_\perp)/(2\pi)$
- **Peaked at Debye mass** ■ for later times
- Along beam ($\phi_{pq} = 0$): Much larger and different form at early times

Conclusions and outlook

- Out-of-equilibrium plasma described by kinetic theory
  $\rightarrow$ important for light-ion collisions
- Studied **momentum broadening of jets**
  $\rightarrow$ $\hat{q}$ and $C(\mathbf{q}_\perp)$ during initial stages in heavy-ion collisions
  $\rightarrow$ input for jet quenching simulations
- Values of $\hat{q}$ within $\sim 20\%$ of thermal estimate
- More momentum broadening along the beam axis ($\hat{q}^{zz} > \hat{q}^{yy}$)
- $C(\mathbf{q}_\perp)$ at small $\mathbf{q}_\perp$ is enhanced compared to thermal (especially along beam)

Outlook

- Obtain gluon emission spectrum from pre-equilibrium $\hat{q}$ (with Barata, Sadofyev)
- Inclusion of quarks in plasma background (with Mazeliauskas, Takacs, Zhou)

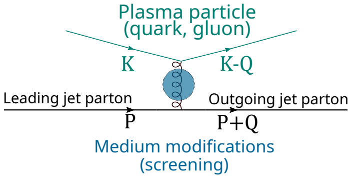
Thank you very much for your attention!

FL is a recipient of a DOC Fellowship of the Austrian Academy of Sciences at the University TU Wien. This work is supported by the Austrian Science Fund (FWF) under project DOI 10.55776/P34455 and 10.55776/W1252

Screening in the matrix element of $\hat{q}$

- Scattering matrix element includes **in-medium propagator**
- Receives **self-energy corrections**
- Anisotropic hard thermal loop (HTL) self-energy $\rightarrow$ unstable modes[10]
- **Approximation: Use isotropic HTL matrix element**
  Similar approximation also in EKT implementations[11]

Matrix element



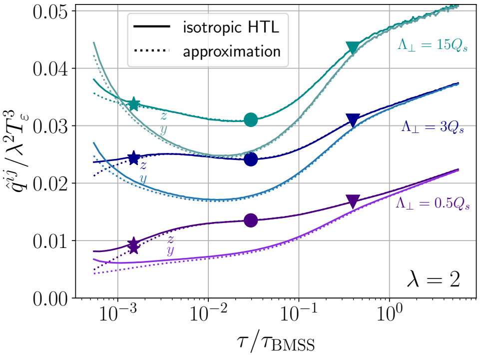
[10] [Phys.Rev.D 68 (2003) [Romatschke, Strickland]]
[11] [Phys.Rev.Lett. 115 (2015) [Kurkela, Zhu]; Phys.Rev.Lett. 122 (2019) [Kurkela, Mazeliauskas]; Phys.Rev.D 104 (2021) [Du, Schlichting]]

Screening approximation to the matrix element

- Compare with simple screening approximation

$$\frac{(s-u)^2}{t^2} \to \frac{(s-u)^2}{t^2} \frac{q^4}{(q^2+\xi_T^2 m_D^2)^2}$$

- Longitudinal[12] $\xi_L = e^{5/6}/\sqrt{8}$
- Transverse broadening: $\xi_T = e^{1/3}/2$
- **Good agreement**

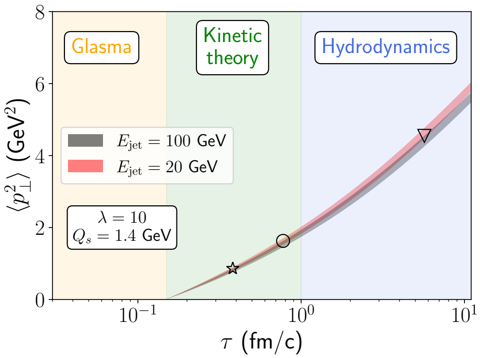


s, u, t: Mandelstam variables

[12][Phys.Rev.D 89 (2014) [York, Kurkela, Lu, Moore]]

What about total momentum broadening?

- Per definition, $\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}\tau}$
- Naïvely $\Delta p_\perp^2 = \int \mathrm{d}\tau \, \hat{q}(\tau)$ over lifetime of jet
- Think of $\hat{q}$ as medium parameter.



Making sense of the cutoff

- Cutoff $\Lambda_\perp$ restricts transverse momentum transfer $q_\perp < \Lambda_\perp$ (needed in eikonal limit $p \to \infty$)

$$\hat{q} \sim \int \mathrm{d}^2 q_\perp \, q_\perp^2 \underbrace{\frac{\mathrm{d}\Gamma^{\mathrm{el}}}{\mathrm{d}^2 q_\perp}}_{1/q_\perp^4 \text{ for large } q_\perp} \sim \int \frac{\mathrm{d}q_\perp}{q_\perp}$$

Making sense of the cutoff

- Cutoff $\Lambda_\perp$ restricts transverse momentum transfer $q_\perp < \Lambda_\perp$ (needed in eikonal limit $p \to \infty$)
- Cutoff should grow with jet energy
- **kinematic cutoff** $\Lambda_\perp^{\mathrm{kin}}(E, T) = \zeta^{\mathrm{kin}} g(ET)^{1/2}$
  obtained from comparing leading log behavior for large p and $\Lambda_\perp$
- **LPM cutoff** $\Lambda_\perp^{\mathrm{LPM}}(E, T) = \zeta^{\mathrm{LPM}} g(ET^3)^{1/4}$
  Estimate for momentum broadening during LPM 'formation time':
  $Q_\perp^2 \sim \hat{q} t^{\mathrm{form}}$, $t^{\mathrm{form}} \sim \sqrt{E/\hat{q}}$, approximately $\hat{q} \sim g^4 T^3$

[arXiv:2312.00447 [Boguslavski, Kurkela, Lappi, FL, Peuron]]