Jet momentum broadening during initial stages of heavy-ion collisions from effective kinetic theory

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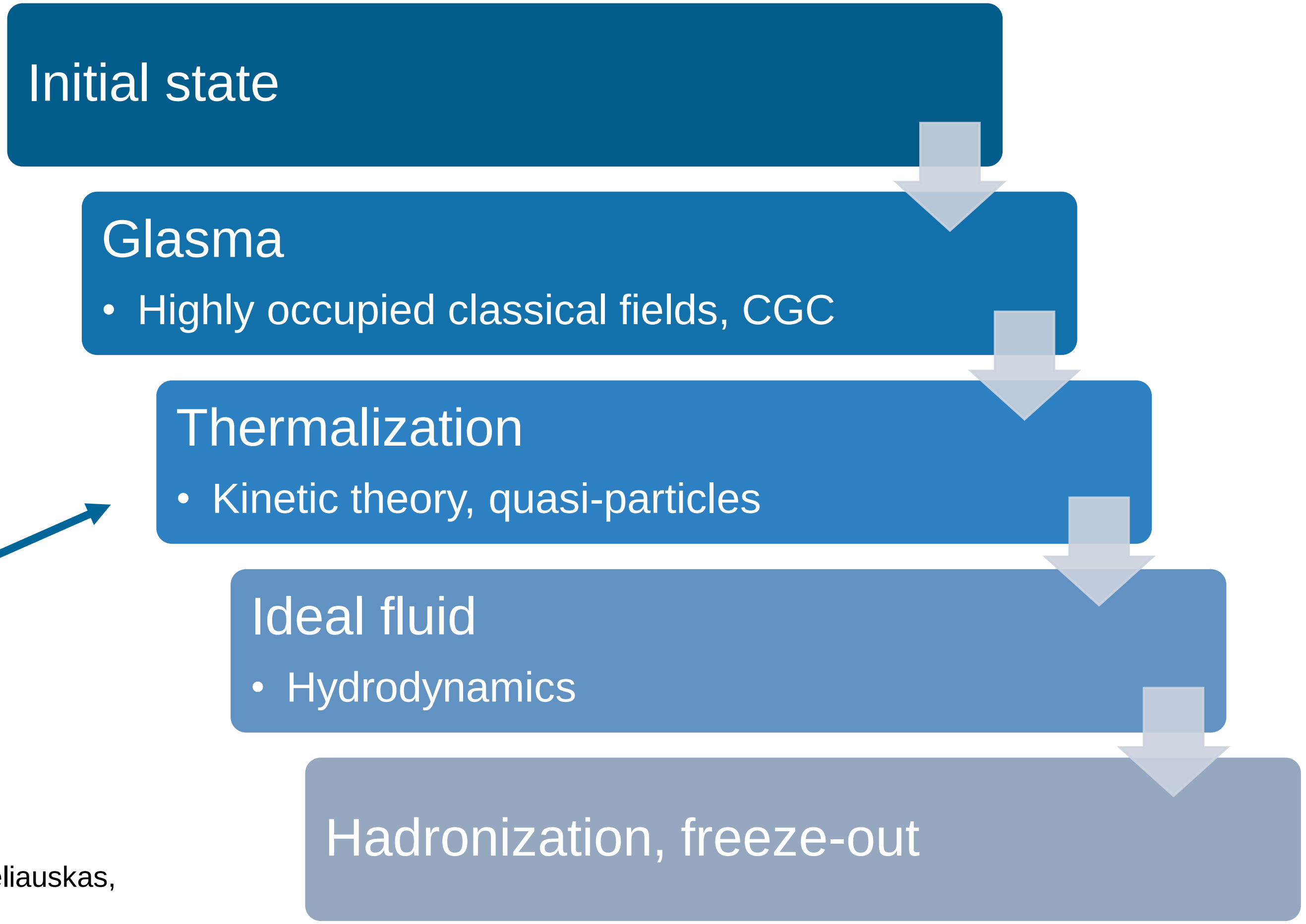
Time-evolution of the Quark-Gluon plasma

- Quark-Gluon plasma is created in heavy-ion collisions
- Several stages with different descriptions
- Consider **Thermalization**



Rev.Mod.Phys. 93 (2021) 3, 035003 [Berges, Heller, Mazeliauskas, Venugopalan]

arXiv:2210.12056 [Elfner, Müller]

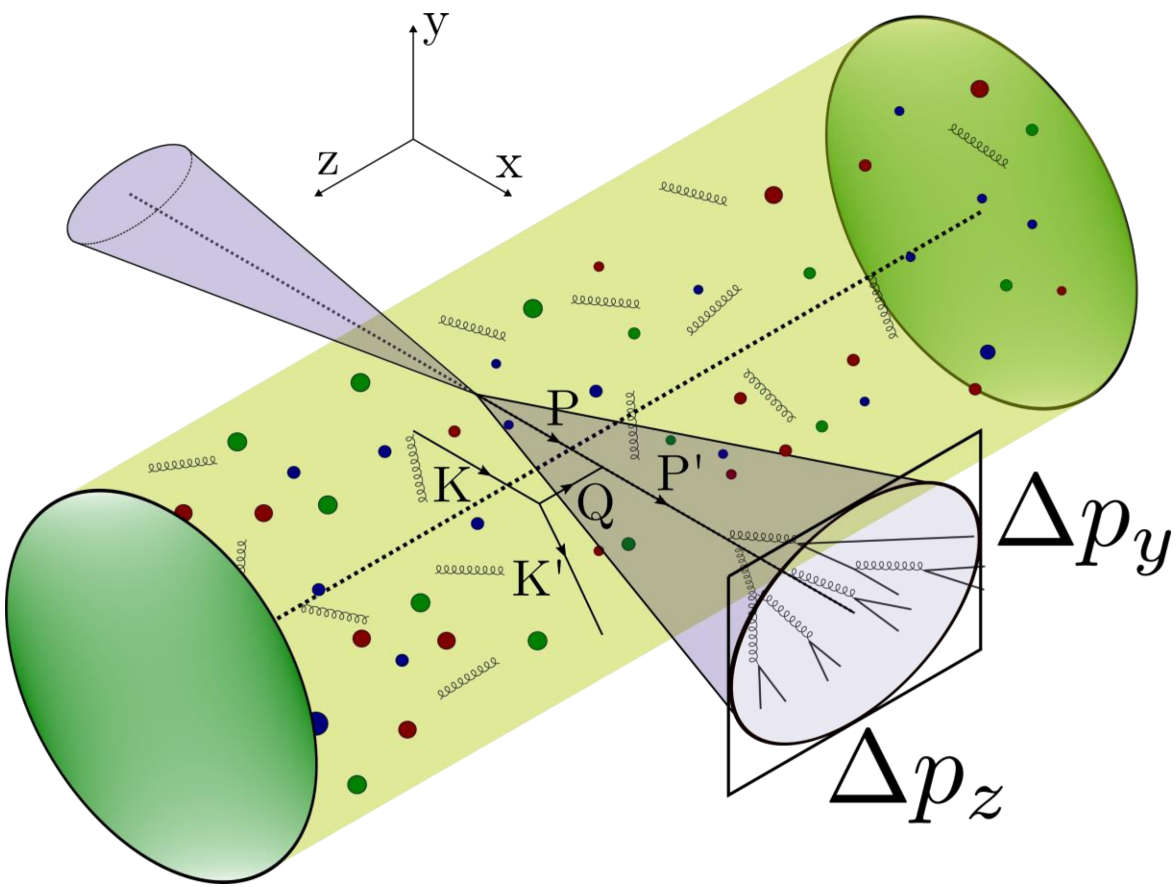
Jet quenching parameter

- During initial collision, highly energetic particles are created
  - Move through Quark-Gluon plasma
  - Interact with it
  - Split into many particles
  - Measured as “jets” in the detector

- $\hat{q}$ is defined via

$$\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}L} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{\mathrm{d}t}.$$

- Quantifies momentum broadening

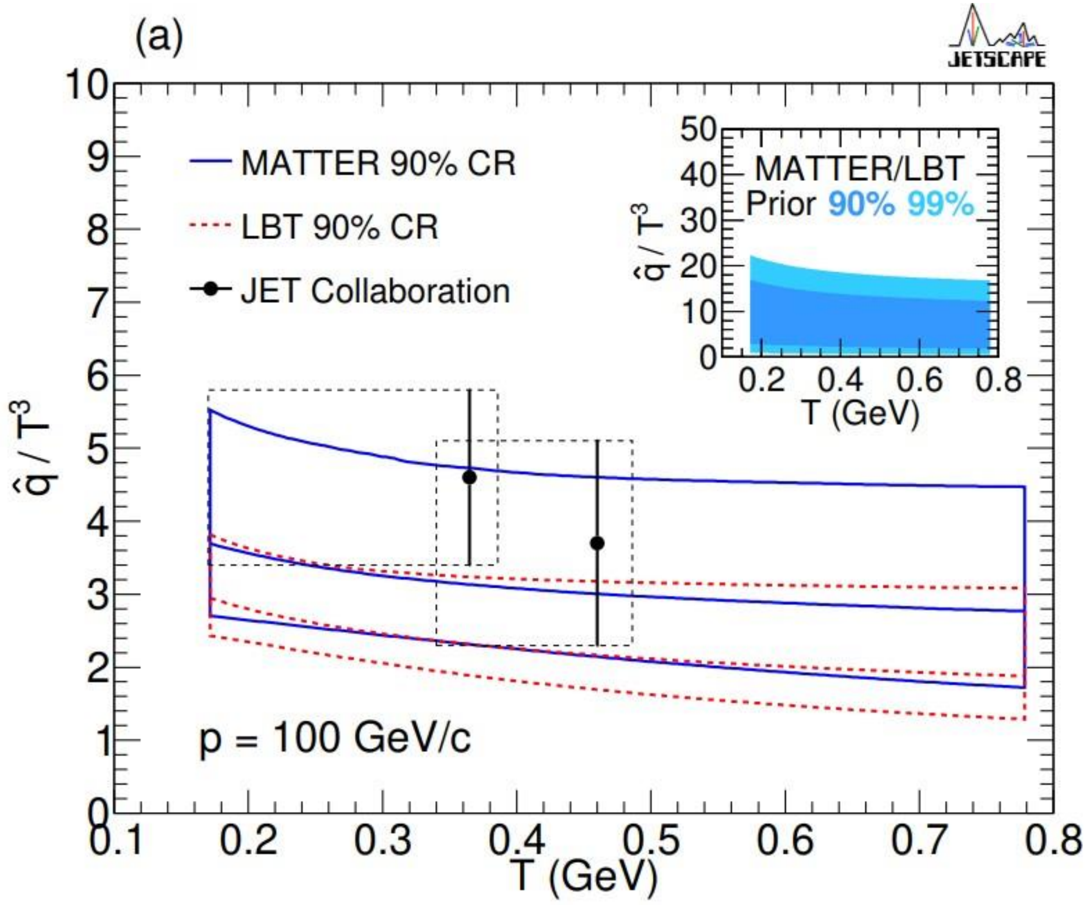


Estimates of the jet quenching parameter

- Mostly evaluated at later stages (hydrodynamics) or in thermal equilibrium

- Recently also considered in Glasma
  Phys.Lett.B 810 (2020) 135810 [Ipp, Müller, Schuh]
  arXiv 2202.00357 [Carrington, Czajka, Mrowczynski]

- Want to consider $\hat{q}$ during thermalization
  → between Glasma and hydro



Phys.Rev.C 104 (2021) 2, 024905 [JETSCAPE Collaboration]

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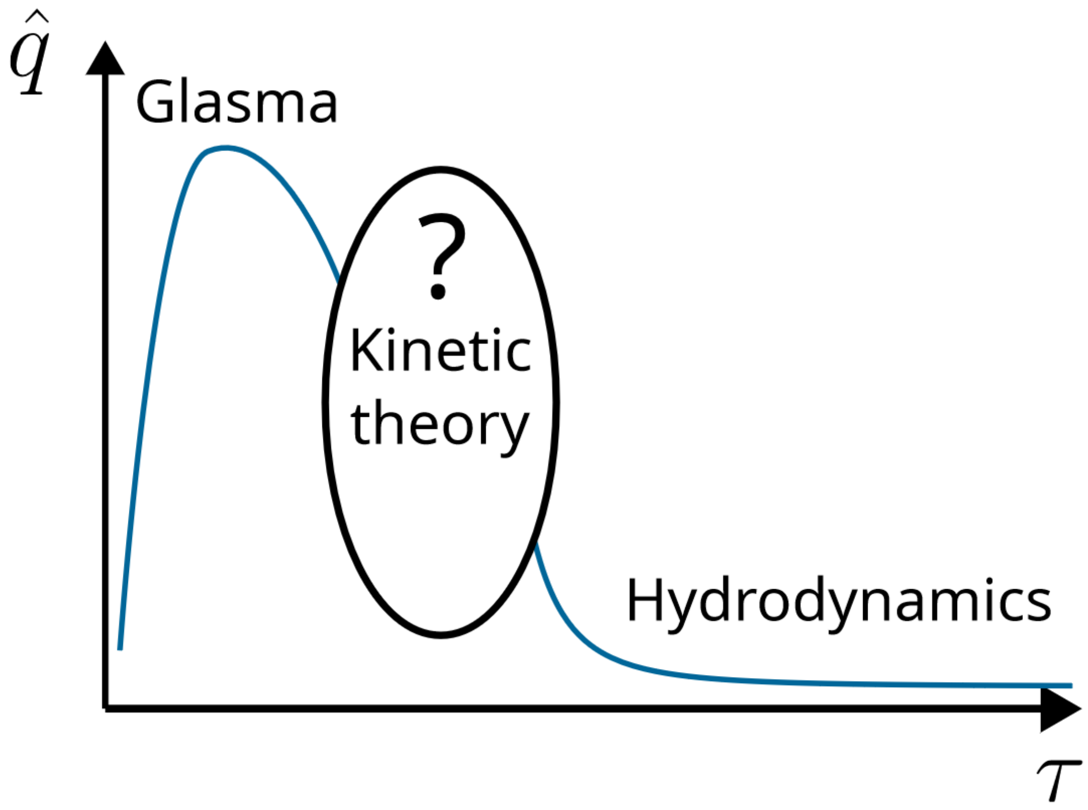
Schematic overview of $\hat{q}$ evolution

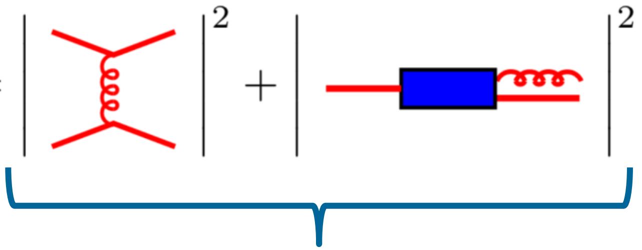


Effective kinetic theory description of the QGP

- Quasi-particles with distribution function $f(t,\vec{p})$

- Time evolution described by Boltzmann equation at LO

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



Collision term

JHEP01(2003)030 [Arnold, Moore, Yaffe]
Int.J.Mod.Phys.E 16 (2007) 2555-2594 [Arnold]

- Solved numerically using Monte Carlo techniques

Phys.Rev.Lett. 115 (2015) 18, 182301 [Kurkela, Zhu]

Jet quenching parameter in kinetic theory

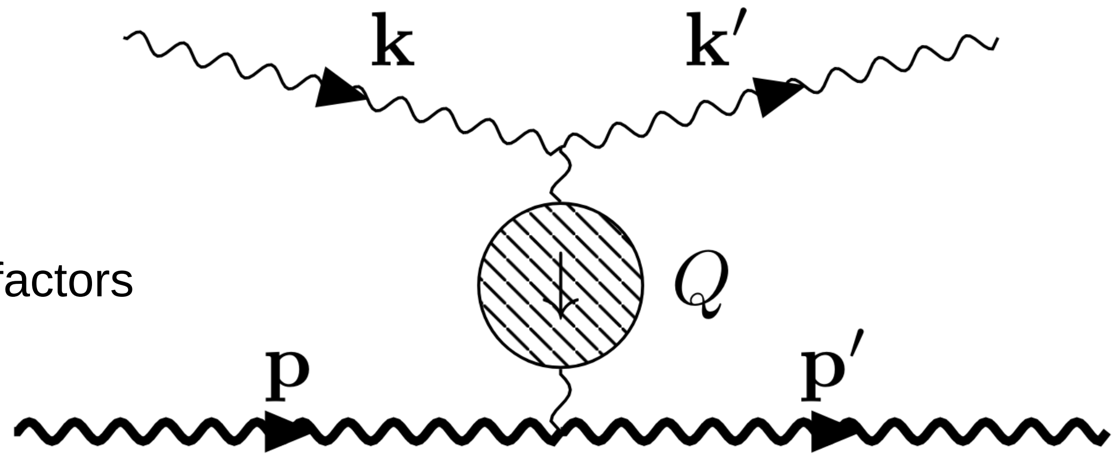
- Provided we know $f(\mathbf{k})$:

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

Ingoing/outgoing state factors

Appropriate phase-space measure

With momentum cutoff $q_\perp < \Lambda_\perp$

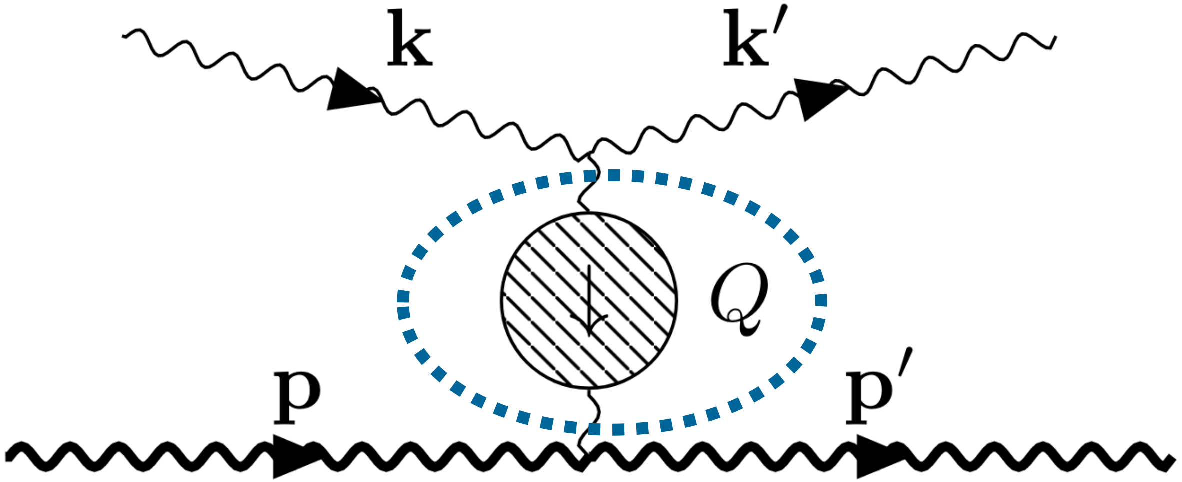


Matrix element with medium corrections (self-energy)

$$\hat{q} = \hat{q}^{yy} + \hat{q}^{zz}$$

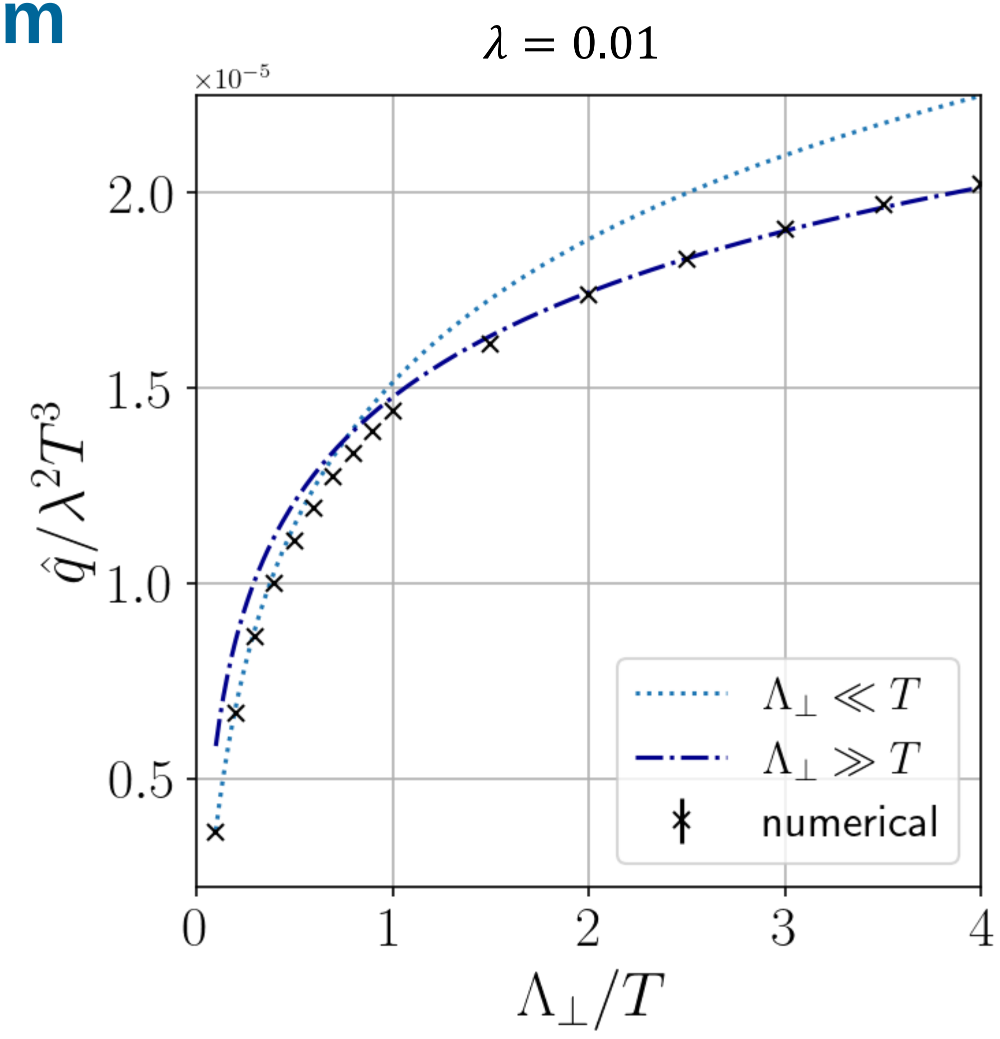
Screening in the matrix element

- Scattering matrix element includes in-medium propagator
- Receives self-energy corrections
- Anisotropic Hard thermal loop (HTL) self-energy $\rightarrow$ Unstable modes
- Approximation: Use isotropic HTL matrix element



Comparison in thermal equilibrium

- Formula reproduces known results in thermal equilibrium:
  - Previously $\hat{q}$ has been known for $\Lambda_\perp \ll \mathrm{T}$, and $\Lambda_\perp \gg \mathrm{T}$
- Now also region $\Lambda_\perp \approx \mathrm{T}$



Physical meaning of the momentum cutoff

- Momentum cutoff $\Lambda_\perp$ grows for larger jet energy

- Thermalization: Plasma gluon as “jet”, splitting rates calculated using $\Lambda_\perp \ll T$

  Phys.Rev.D 78 (2008) 065008 [Arnold, Dogan]
  Ann.Rev.Nucl.Part.Sci. 69 (2019) 447-476 [Schlichting, Teaney]

- For highly energetic jets we need to use $\Lambda_\perp \gg T$
- *Phys.Rev.D 78 (2008) 125008 [Arnold, Xiao]*

Fix at some E, T

- LPM cutoff $\Lambda_\perp^{\mathrm{LPM}}(E,T) = \zeta^{\mathrm{LPM}} g(ET^3)^{1/4}$
- Kinematic cutoff $\Lambda_\perp^{\mathrm{kin}}(E,T) = \zeta^{\mathrm{kin}} g(ET)^{1/2}$

Get T from energy density ϵ

Thermalization in heavy-ion collisions

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

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

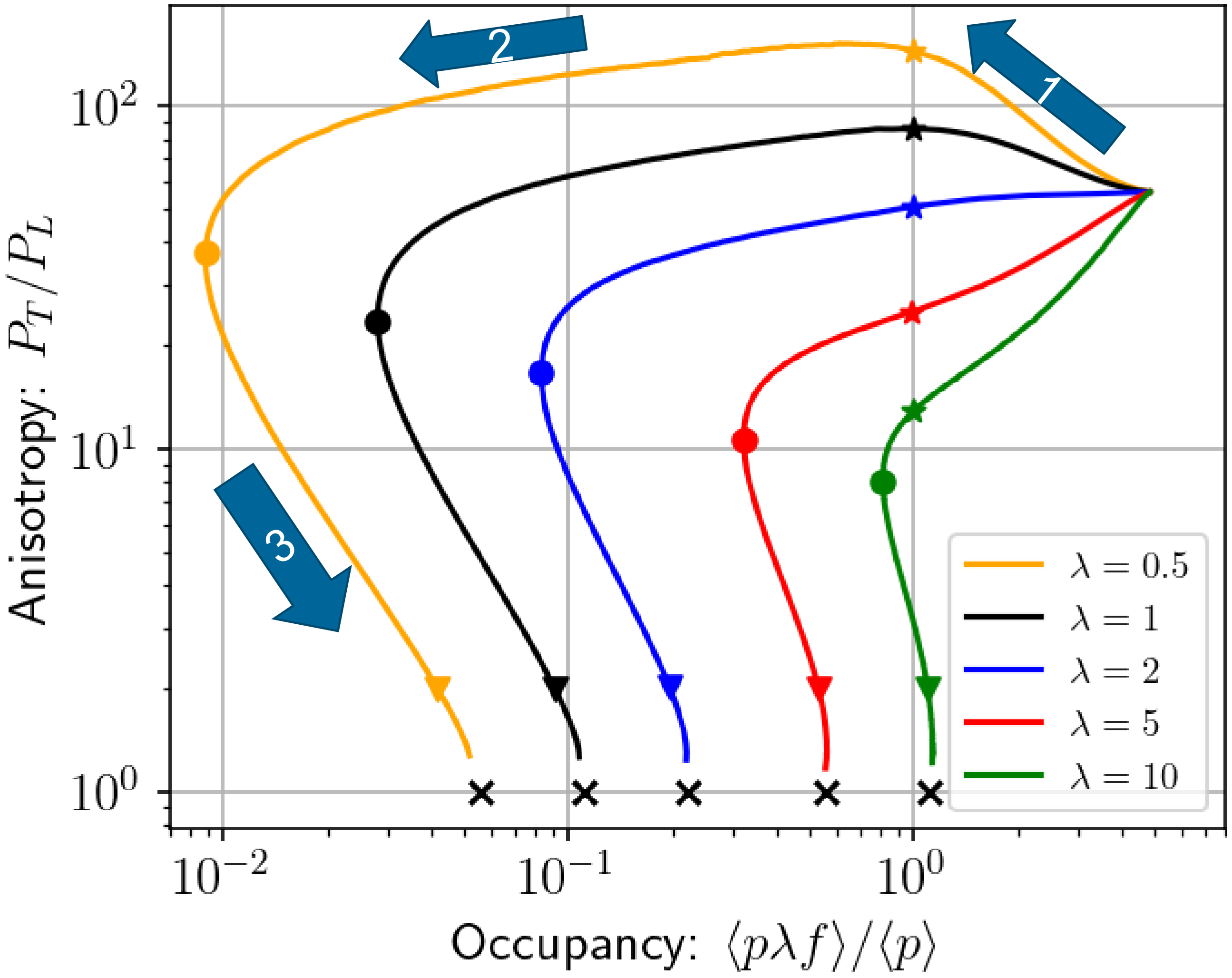
Phys.Rev.Lett. 115 (2015) 18, 182301 [Kurkela, Zhu]

- Phase 1: Anisotropy increases
- Phase 2: Occupancy decreases
- Phase 3: System thermalizes at time $\tau_{BMSS} = \left(\frac{\lambda}{12\pi}\right)^{-\frac{13}{5}} / Q_s$

Phys.Lett.B502:51-58,2001 [Bayer, Mueller, Schiff, Son]

Markers represent different stages

Time evolution of a purely gluonic plasma

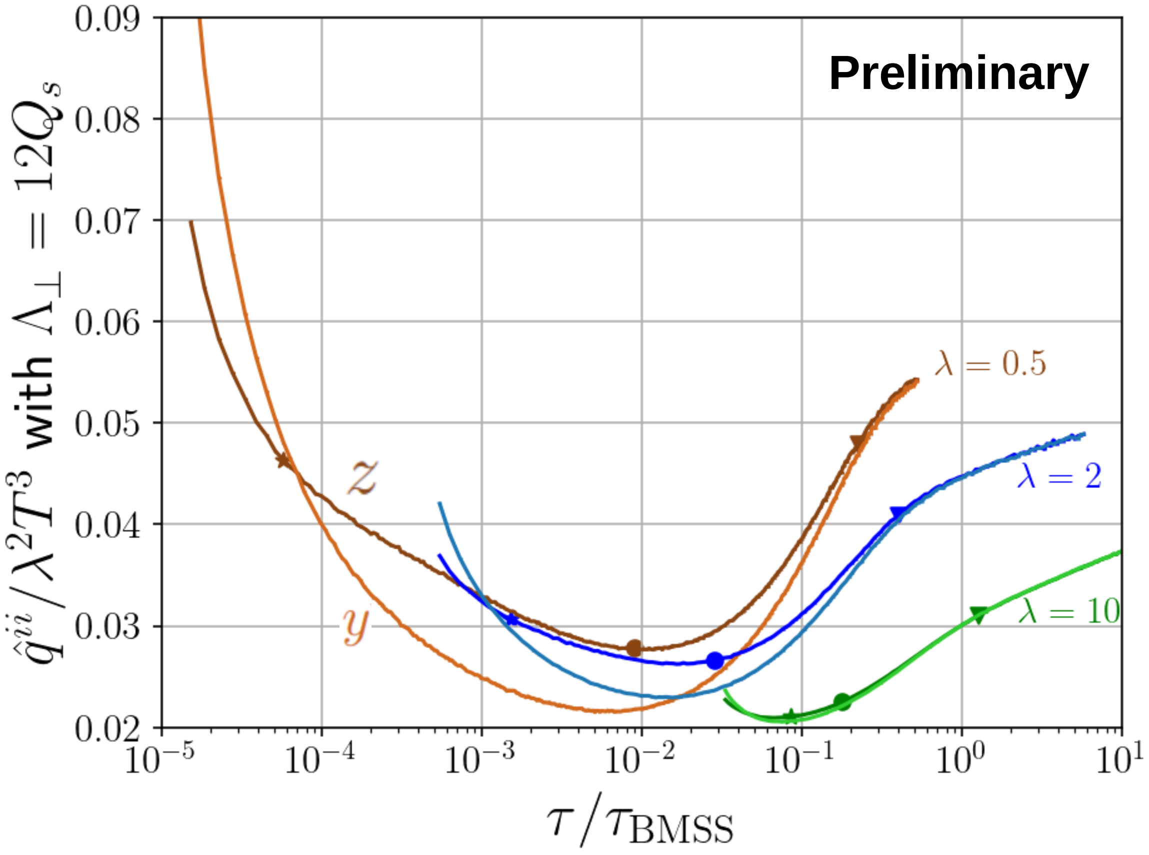


Time evolution

- Qualitative behavior depends strongly on coupling
- Mostly $\hat{q}^{zz} > \hat{q}^{yy}$
- Here for a fixed large cutoff, but in this region

$$\hat{q} \sim a \, \log \Lambda_\perp + b$$

- Use this coefficients a and b to get $\hat{q}$ for any large cutoff

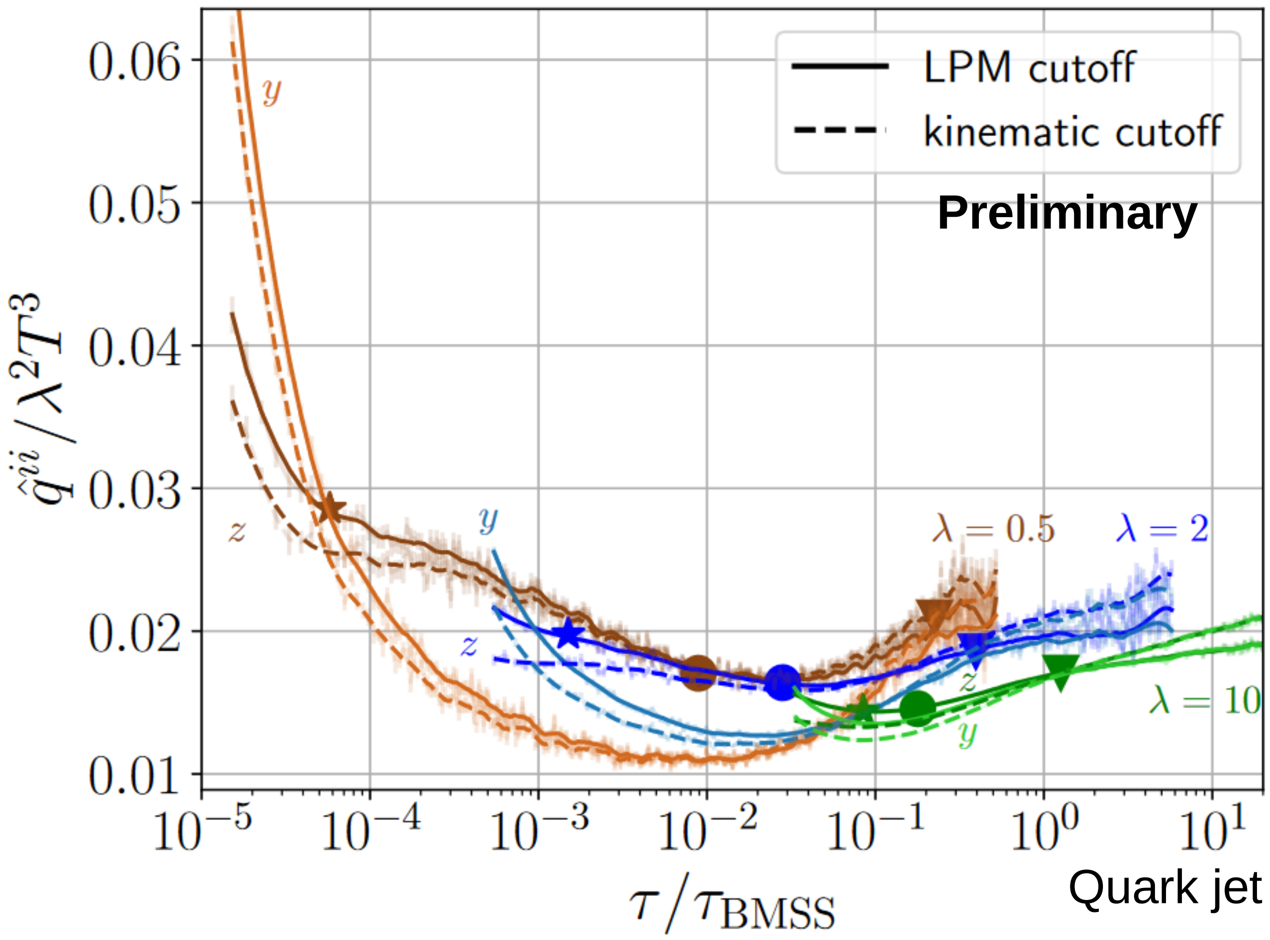


Quark jet

Jet quenching parameter with varying cutoff

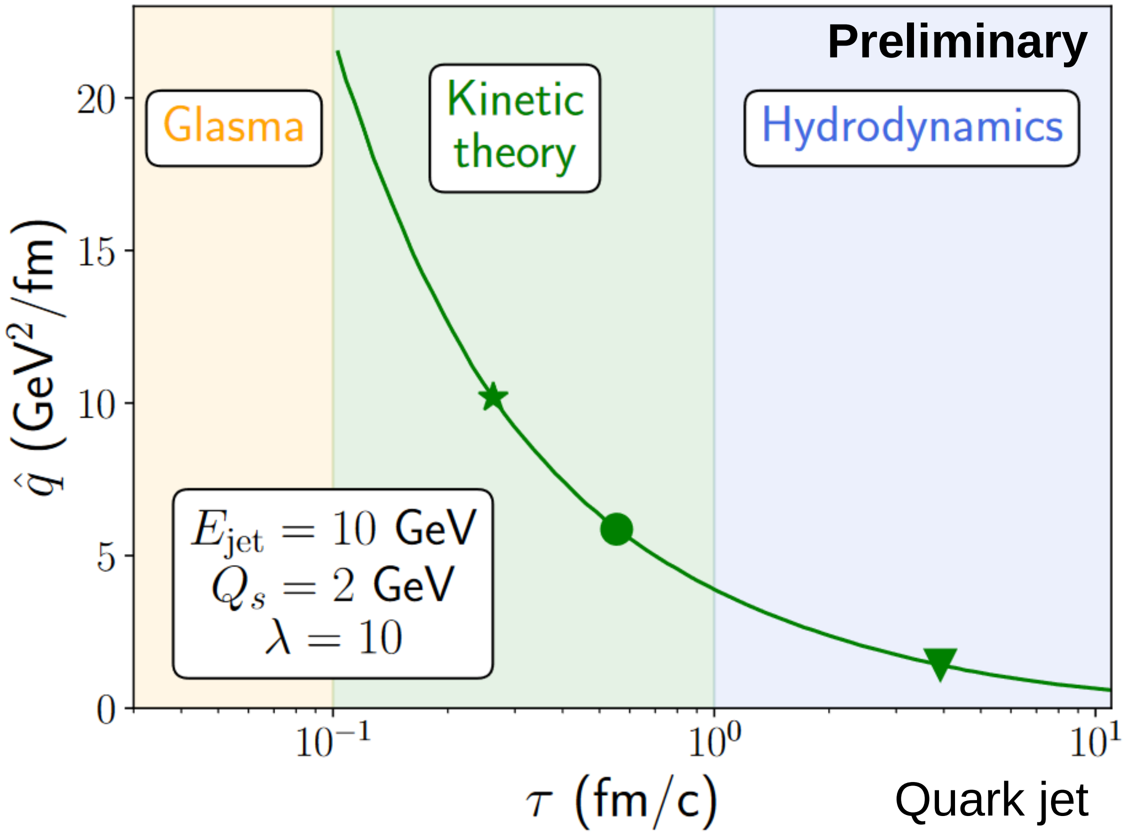
- Fix cutoff at „triangle“ marker for $\lambda = 10$
- Jet energy $E_{jet} = 10\ Q_s$
- Kinematic and LPM cutoff similar

$$\Lambda_\perp^{\mathrm{LPM}}(E,T) = \zeta^{\mathrm{LPM}} g(ET^3)^{1/4}$$
$$\Lambda_\perp^{\mathrm{kin}}(E,T) = \zeta^{\mathrm{kin}} g(ET)^{1/2}$$



Time evolution of jet quenching parameter

- Model jet evolution
- Connects **large values** from **Glasma** and lower values in hydrodynamic stage
- Dependence on initial conditions and cutoff



Conclusion and outlook

- Derived formula for $\hat{q}$ in kinetic theory for anisotropic systems
- Comparison with analytic results in thermal equilibrium
- Model cutoff dependence
- During time evolution: $\hat{q}$ decreases, initially of the order of magnitude of the Glasma value
- $\hat{q}^{zz} > \hat{q}^{yy}$ during most of the evolution

Outlook:

- Different initial conditions, dependence on jet angle and momentum
- Relax isotropic screening approximation
- Experimental signature of $\hat{q}$ from thermalization stages, impact

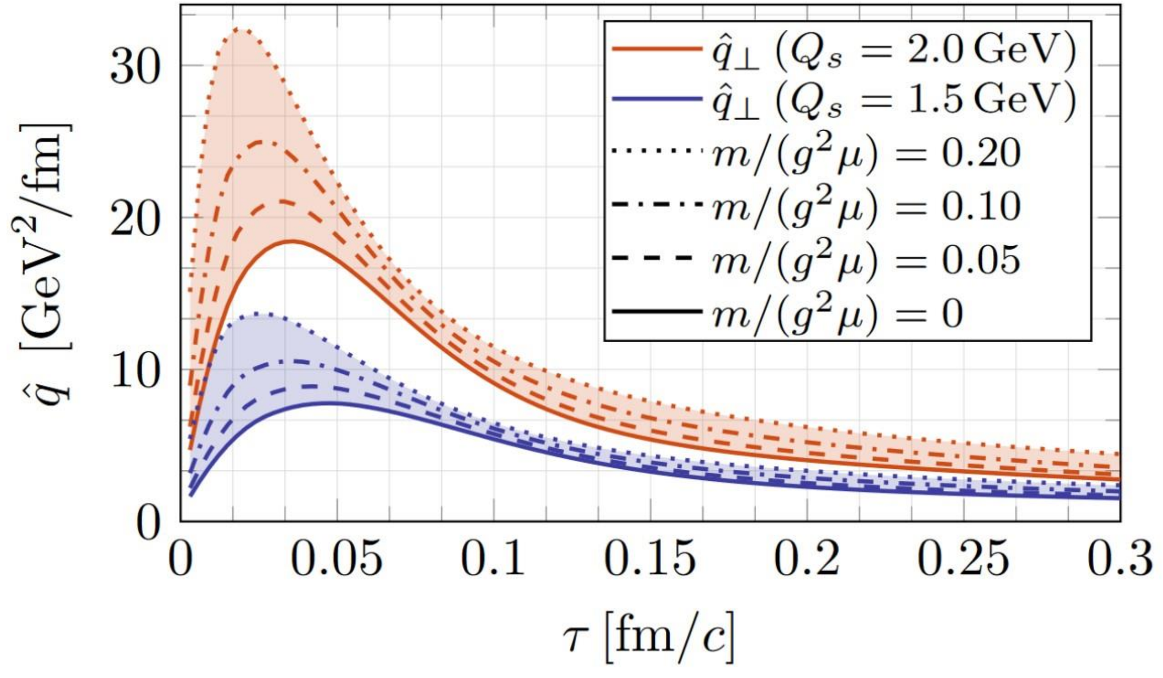
Backup slides

Comparison with the glasma

- Consistent with value for $\hat{q}$ extracted from glasma
  Phys.Lett.B 810 (2020) 135810 [Ipp, Müller, Schuh]
  arXiv 2112.06812 [Carrington, Czajka, Mrowczynski]

- We obtain for $Q_s \sim \mathcal{O}(1)\ \mathrm{GeV}$ a value of $\hat{q} \sim \mathcal{O}(10)\, \frac{\mathrm{GeV}^2}{\mathrm{fm}}$ at beginning

(e.g. $\lambda = 10, \Lambda_\perp = 10\ Q_s$ and our initial conditions:
$T \approx 0.5\ Q_s, \hat{q} \approx 9\ T^3 \approx Q_s^3$ at beginning)



Phys.Lett.B 810 (2020) 135810 [Ipp, Müller, Schuh]

Screening in the matrix element II

- Use isotropic HTL matrix element

- Another approximation using single screening constant ξ

$$\frac{su}{t^2} \to \frac{su}{t^2} \frac{q^4}{(q^2 + \xi^2 m_D^2)^2}$$

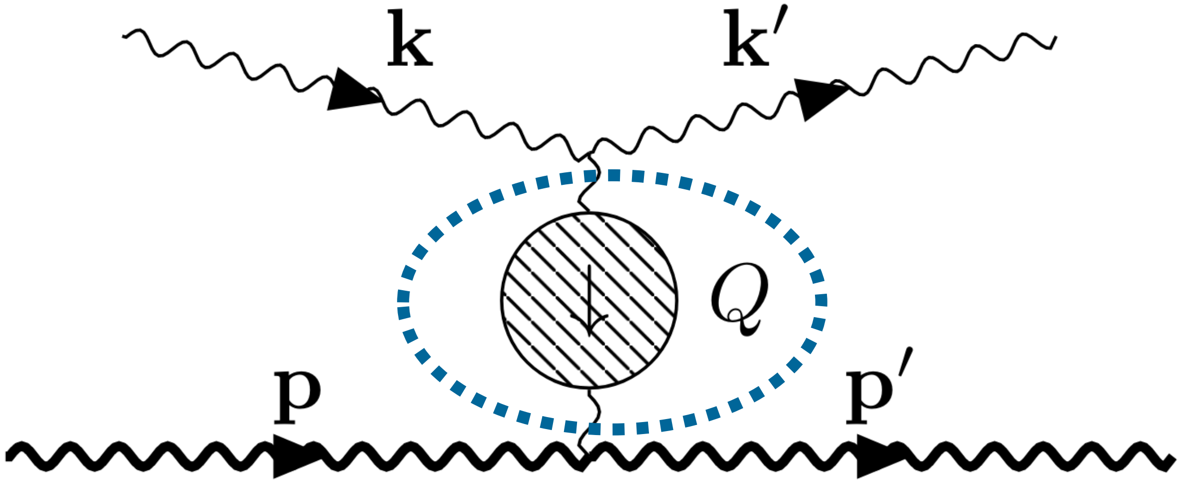
- Different for longitudinal

$$\xi_L = e^{5/6}/\sqrt{8}$$

Phys.Rev.D 89 (2014) 7, 074036 [York, Kurkela, Lu, Moore]

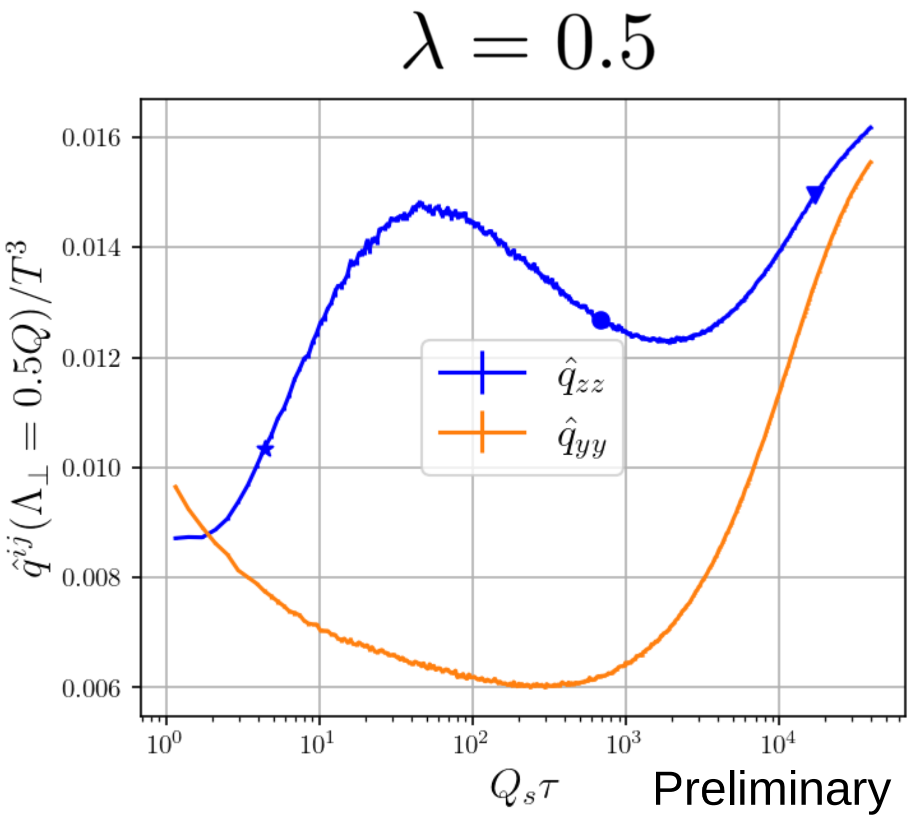
- and transverse momentum broadening

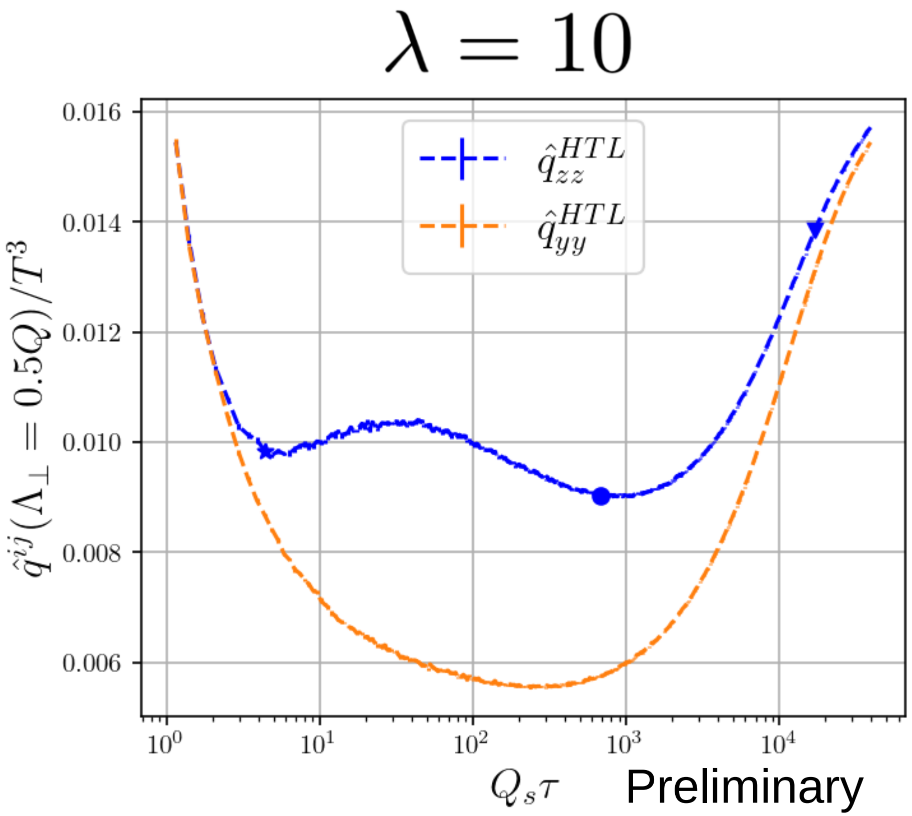
$$\xi_T = e^{1/3}/2$$



m_D is the Debye mass,
s, u and t are the Mandelstam variables

Time evolution – small cutoff





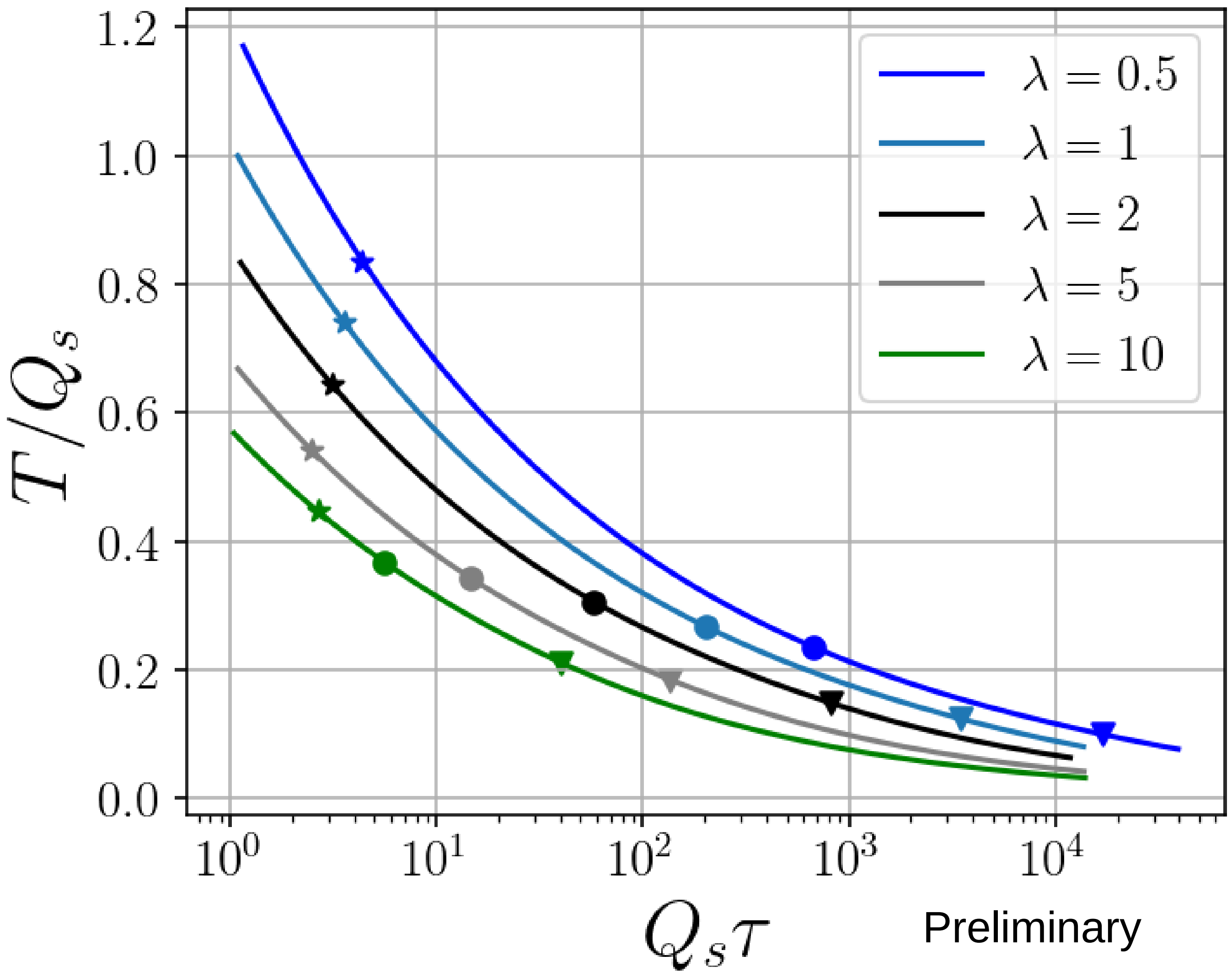
- For small cutoff: Qualitative behavior depends strongly on coupling
- Mostly $\hat{q}^{zz} > \hat{q}^{yy}$, anisotropy up to factor 2

Temperature evolution

- We have used a constant cutoff $\Lambda_\perp$
- Comparison with temperature T, as extracted from the energy density via

$$\epsilon = \int \frac{d^3p}{(2\pi)^3} p\, f(\vec{p}) =: \frac{\pi^2 T^4}{30}$$

- T decreases throughout evolution: factor 3 for $\lambda = 10$ (realistic coupling)

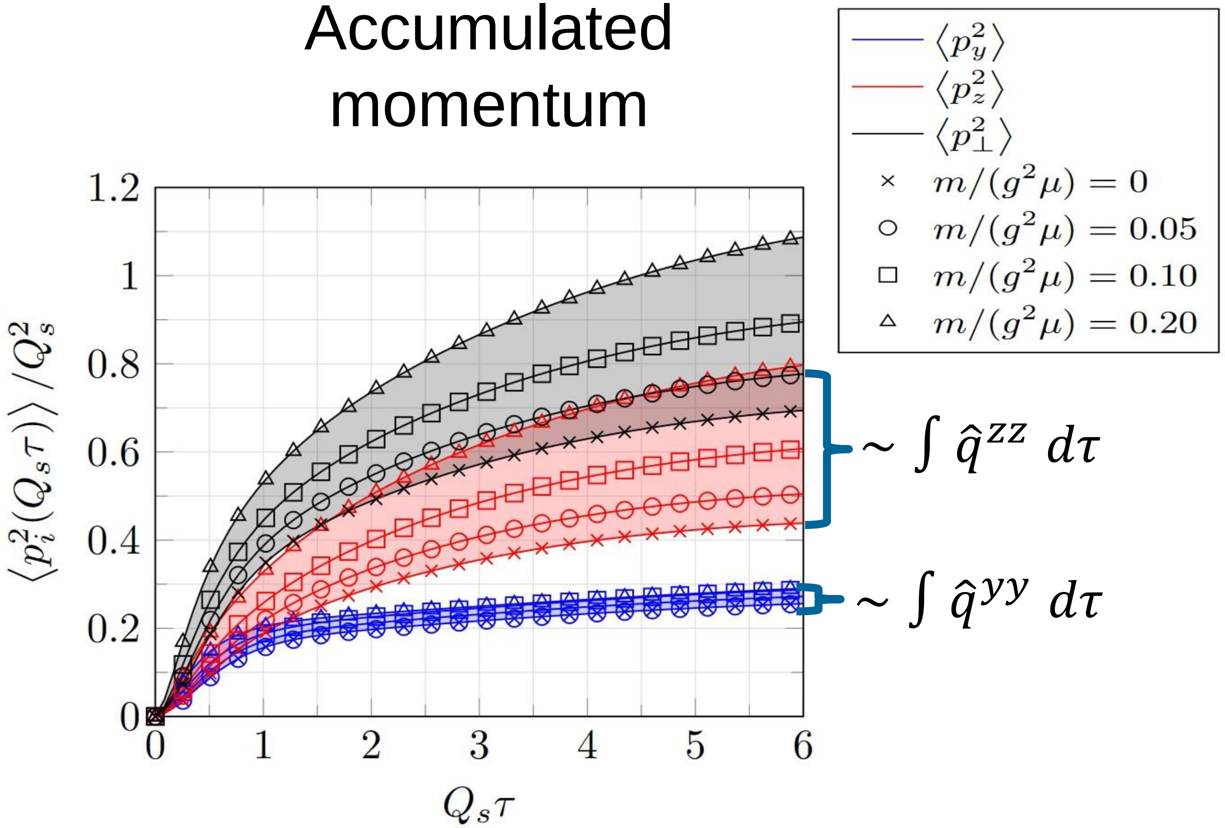


Preliminary

Comparison with the glasma

- Different ordering at beginning
- Same ordering (after overoccupied phase)

Accumulated momentum



Phys.Rev.D 102 (2020) 7, 074001 [Ipp, Müller, Schuh]

Individual components

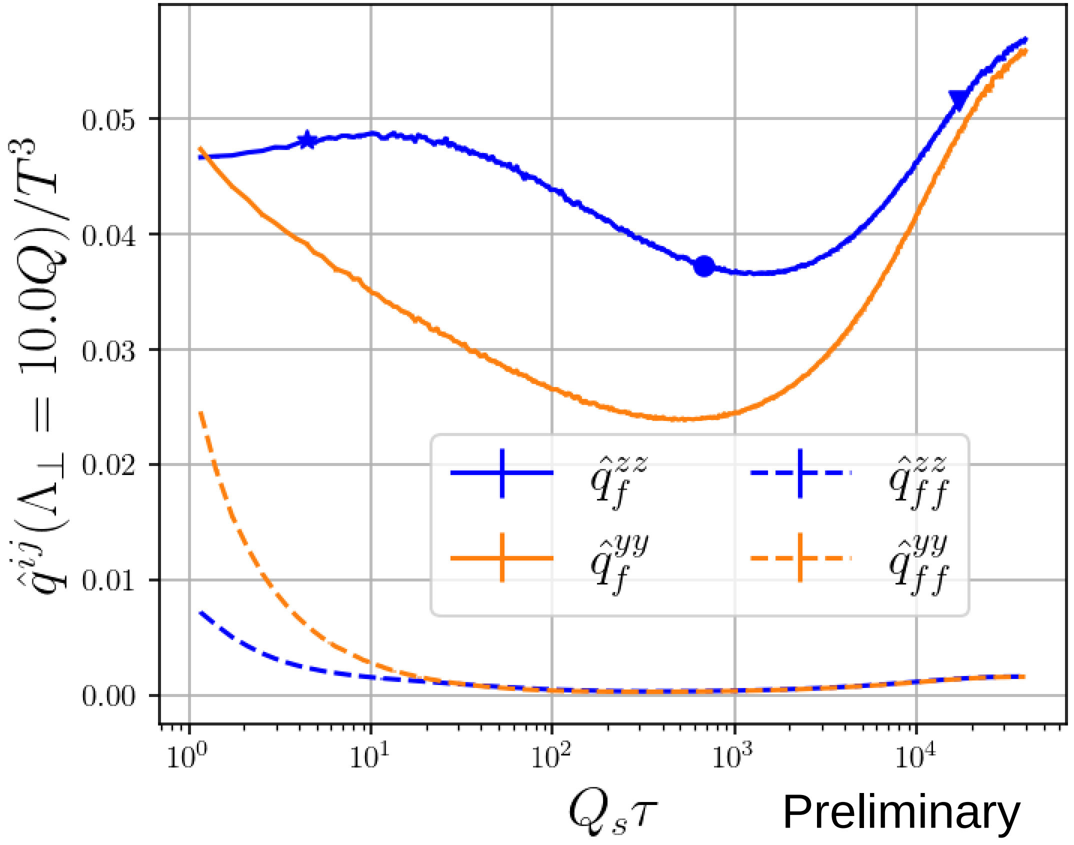
$$\hat{q}^{ij}(\Lambda_\perp) = \int_{q_\perp < \Lambda_\perp} \mathrm{d}\Gamma_{PS}\, q^i q^j \left|\mathcal{M}\right|^2 f(\mathbf{k})(1 + f(\mathbf{k}'))$$

- Separate $\hat{q}$ into

$$\hat{q} = \hat{q}_{ff} + \lambda \hat{q}_f$$

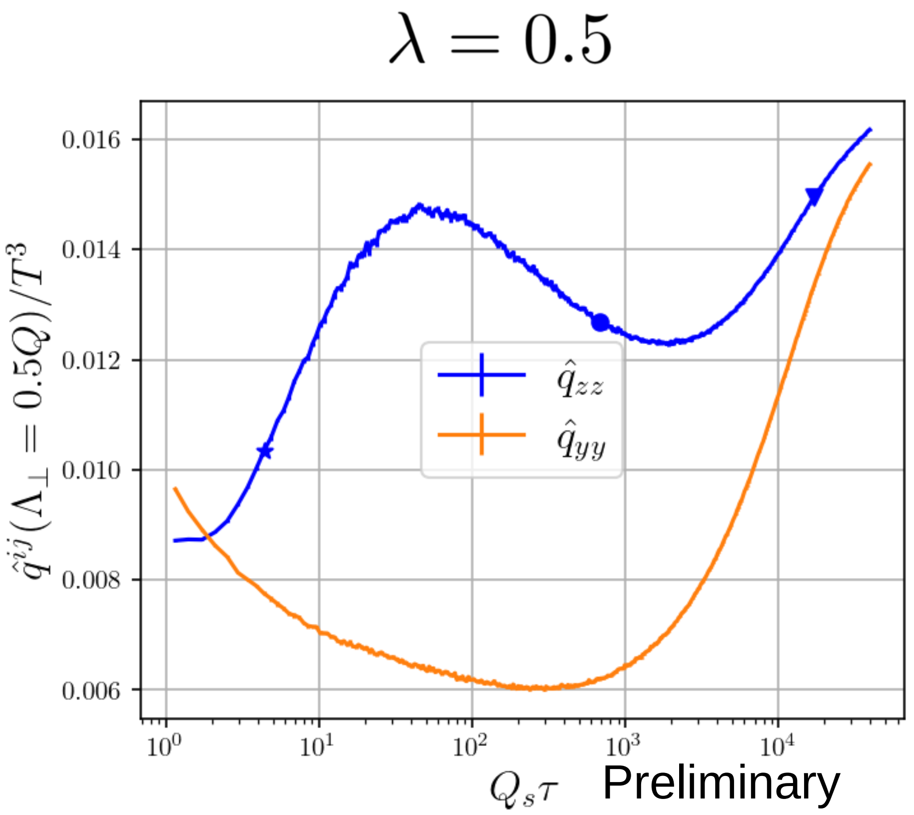
- In overoccupied phase:
  Large contribution from $\hat{q}_{ff}$,
  especially $\hat{q}_{ff}^{yy}$

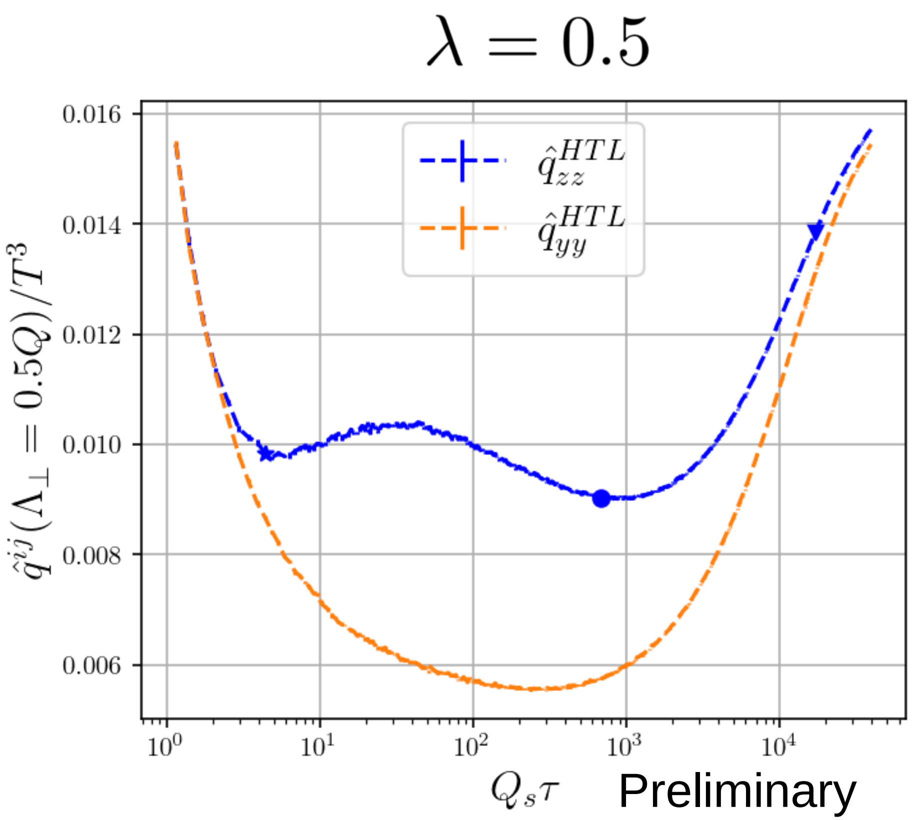
$\lambda = 0.5$



Preliminary

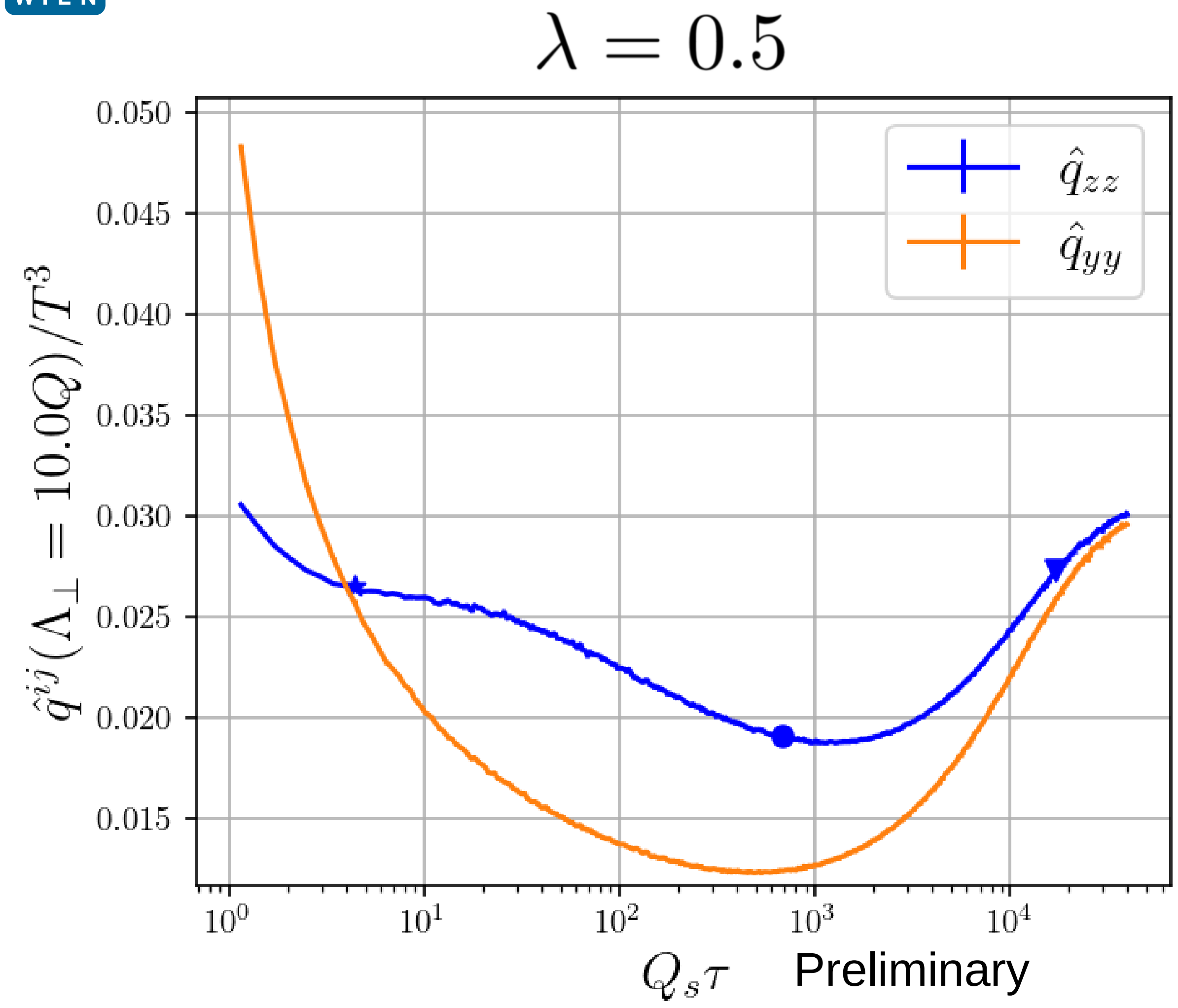
Comparison with isotropic HTL matrix element

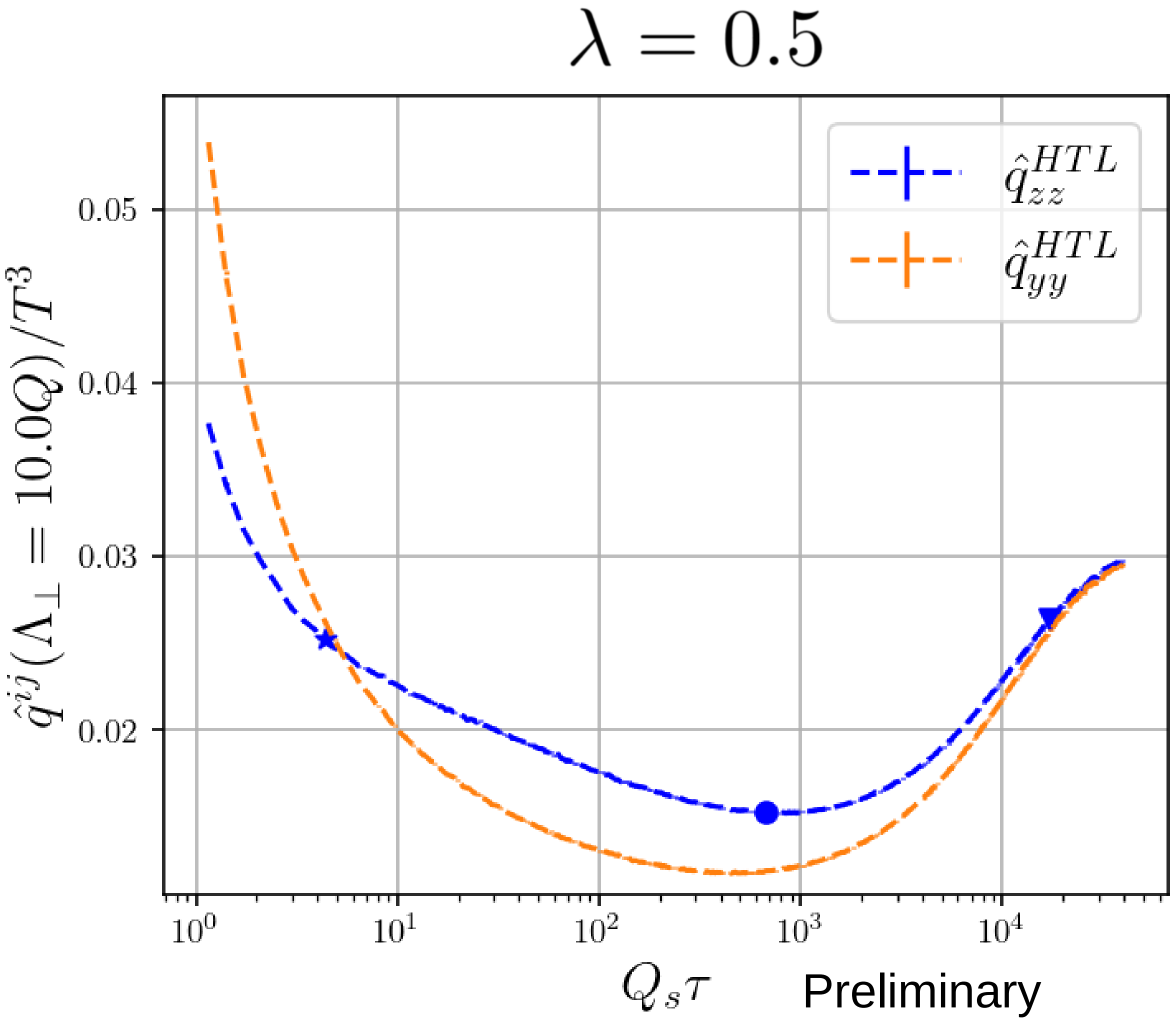




- Largest effects for small coupling and small cutoff
- Others: Qualitatively similar

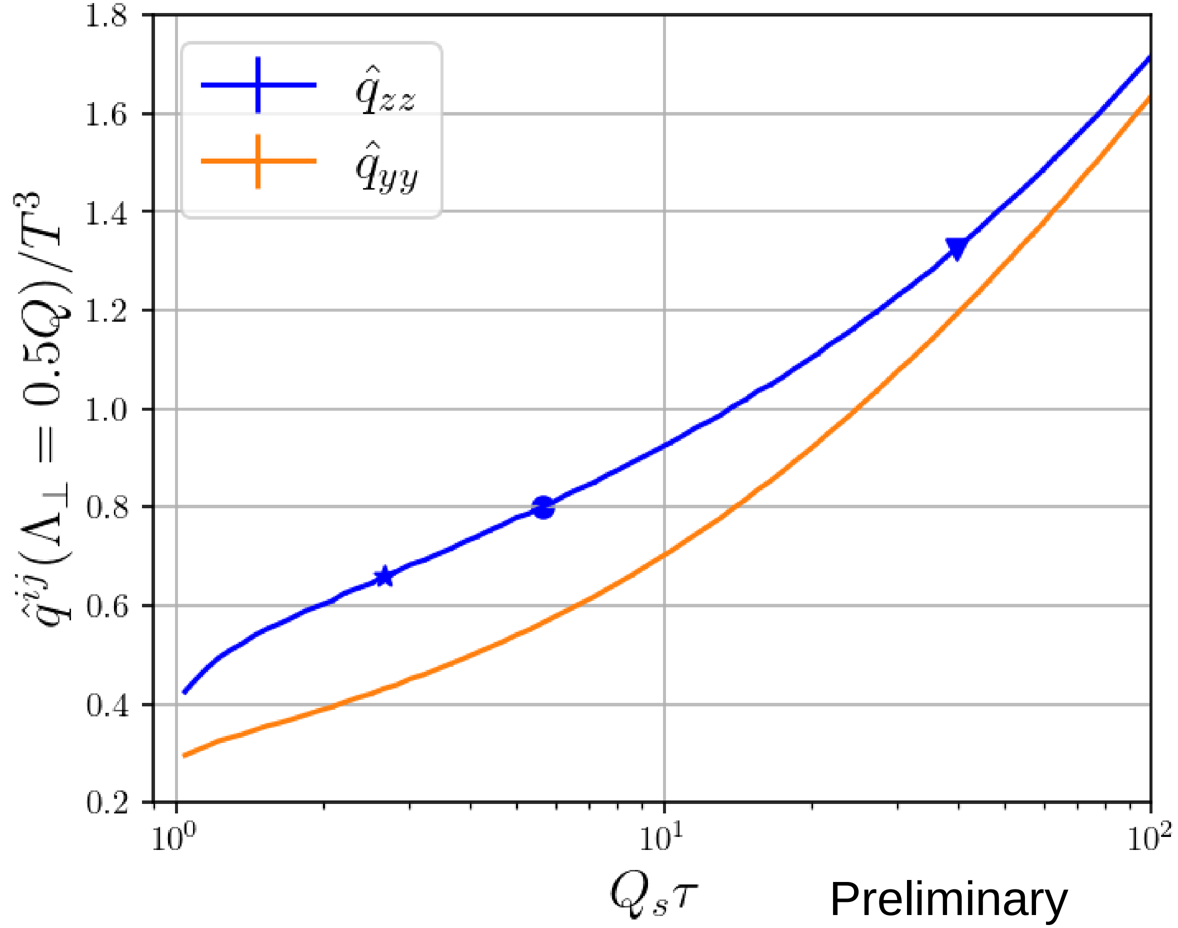
Comparison with isotropic HTL matrix element





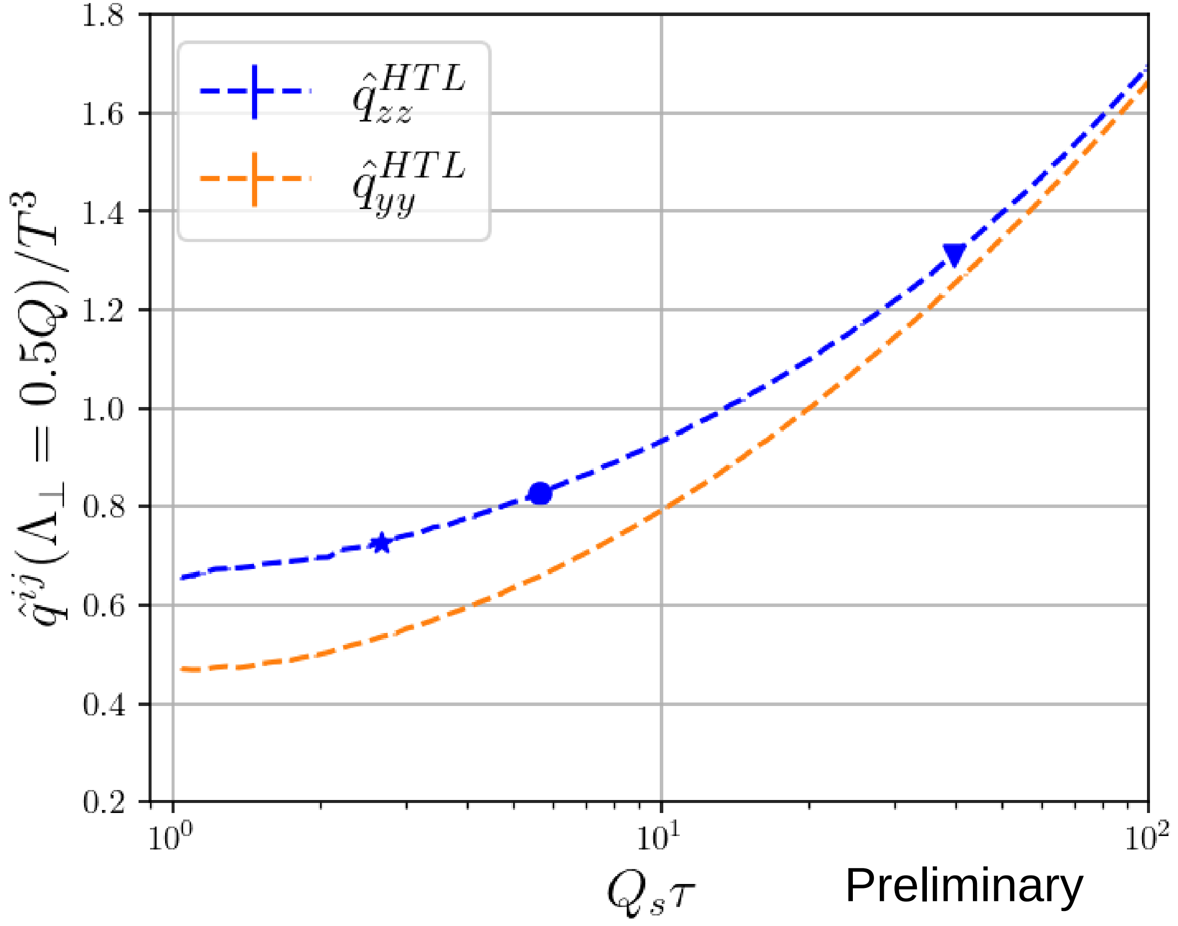
Comparison with isotropic HTL matrix element

$\lambda = 10$



Preliminary

$\lambda = 10$



Preliminary

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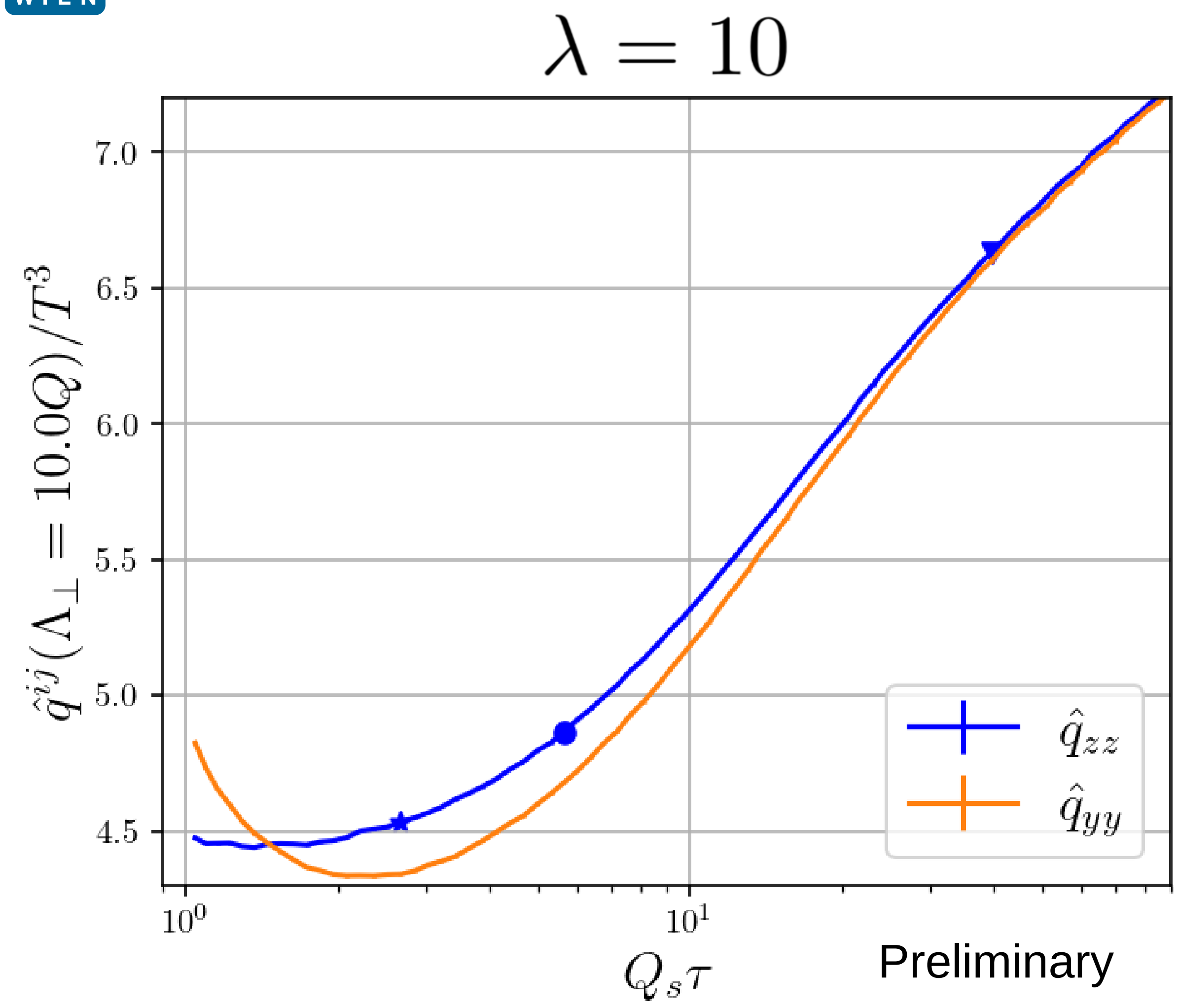
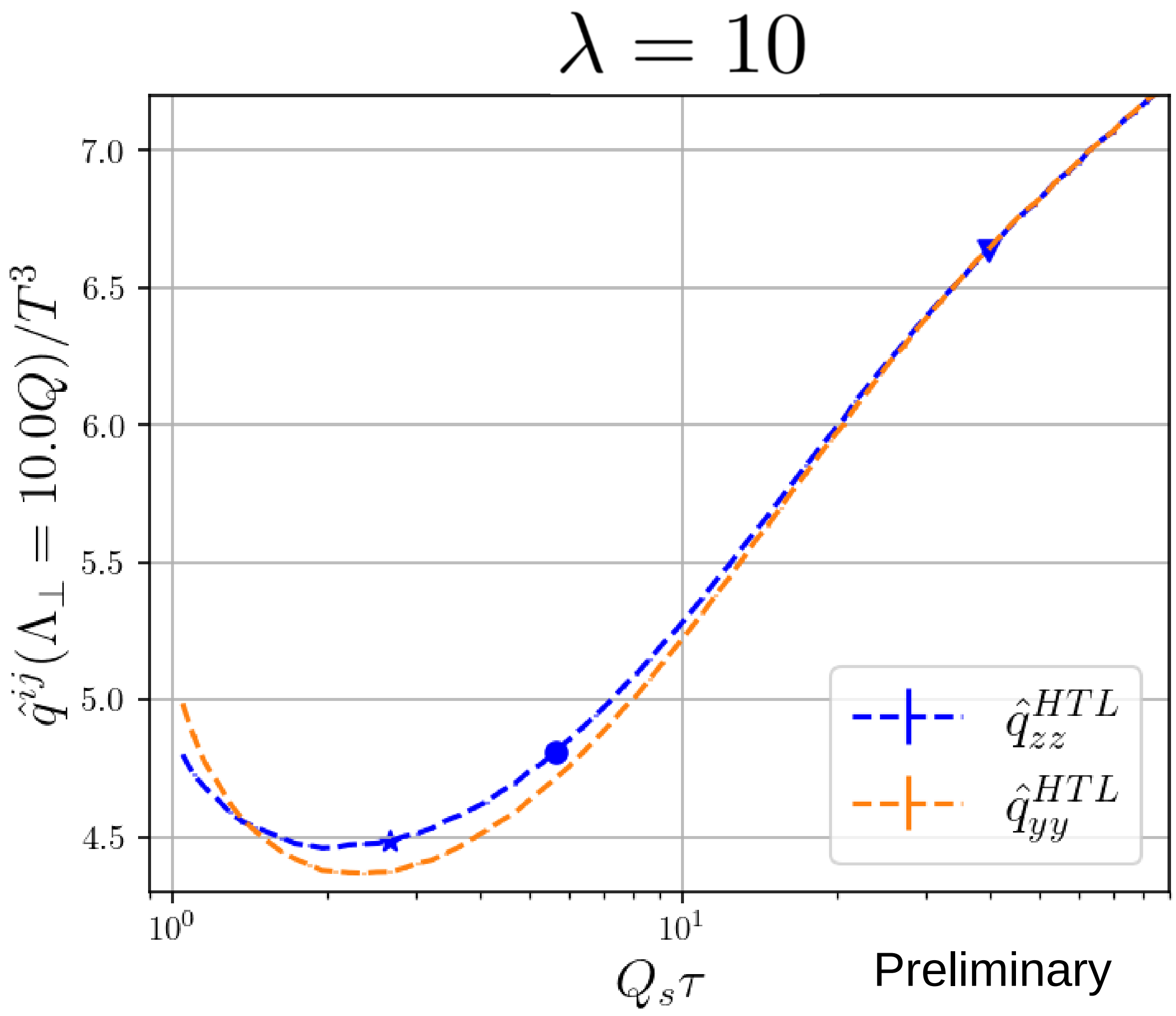


Preliminary



Preliminary

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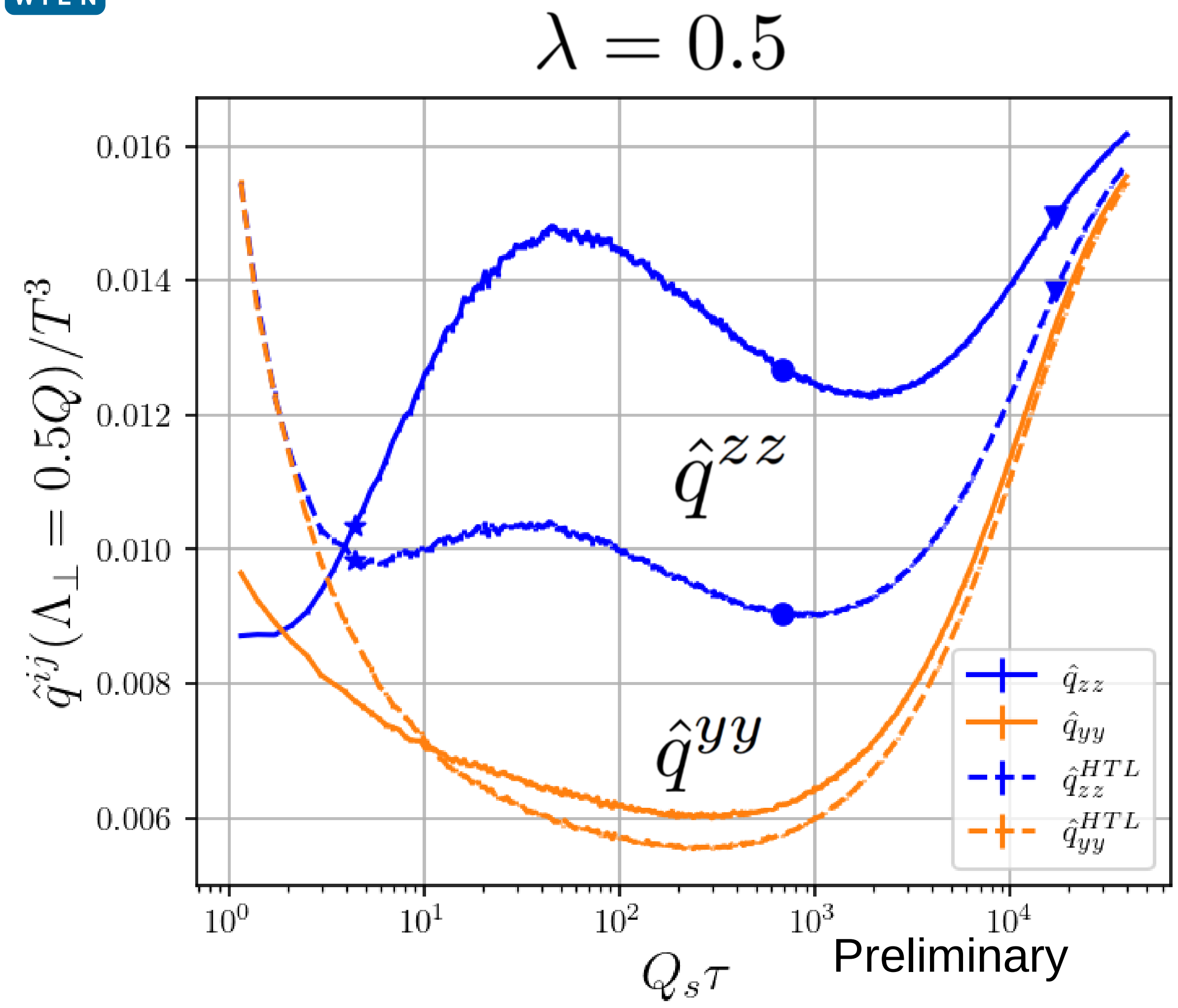

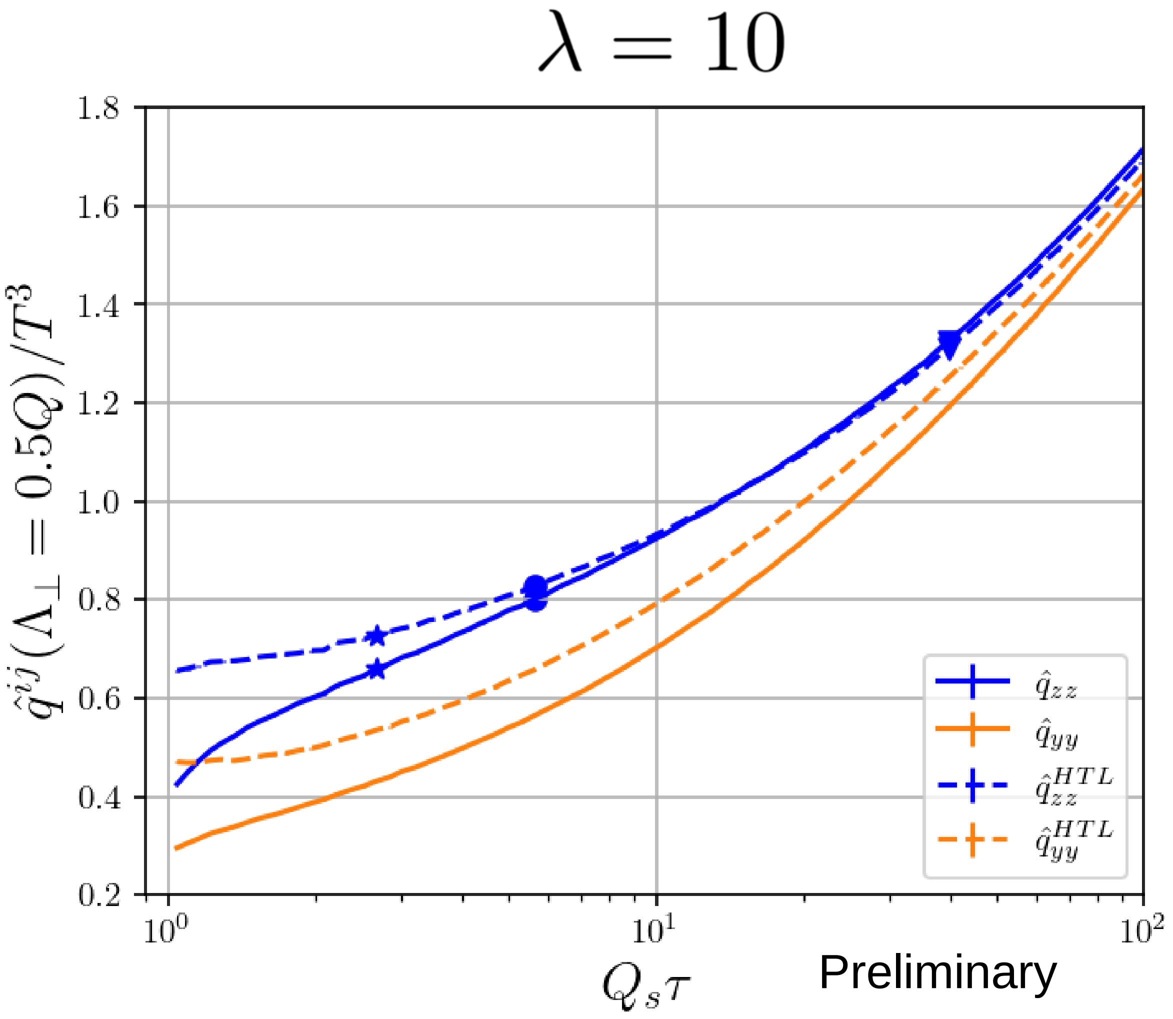

Time evolution – large cutoff