Jet medium interactions & Jet thermalisation

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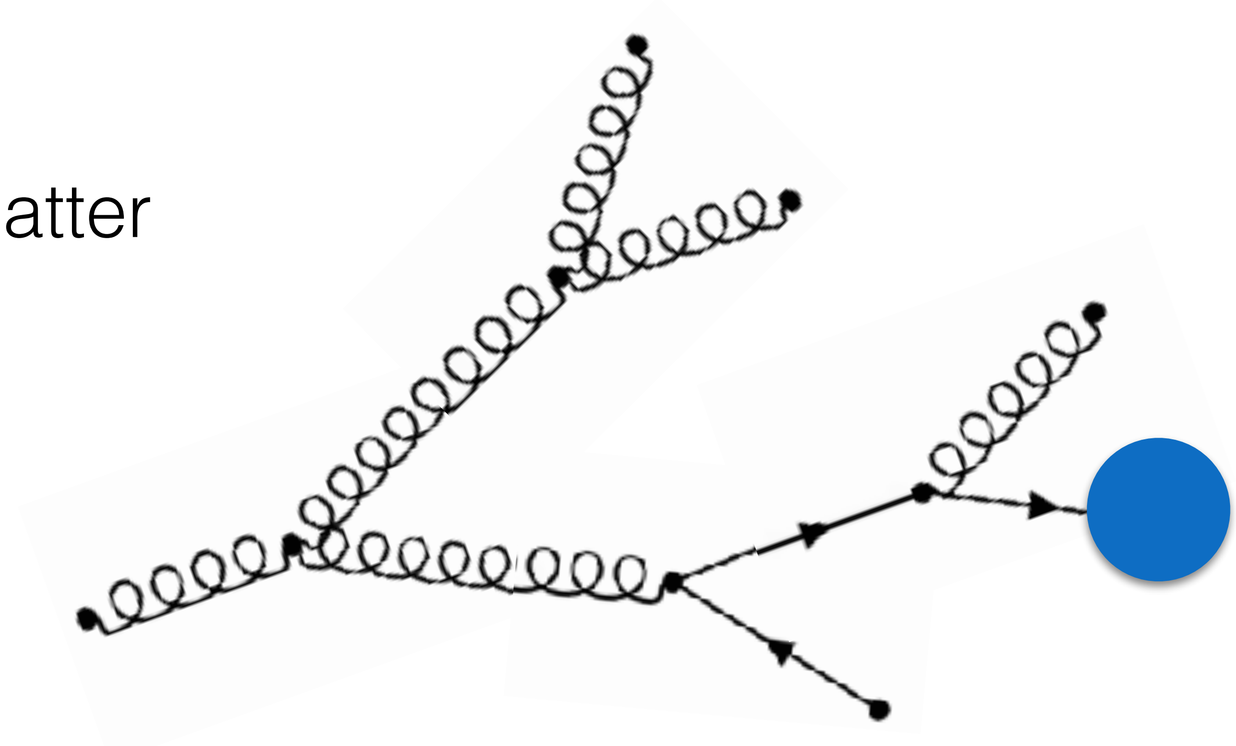
Hard probes in non-equilibrium QCD matter
ICTS-TIFR
Mar 2026



CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

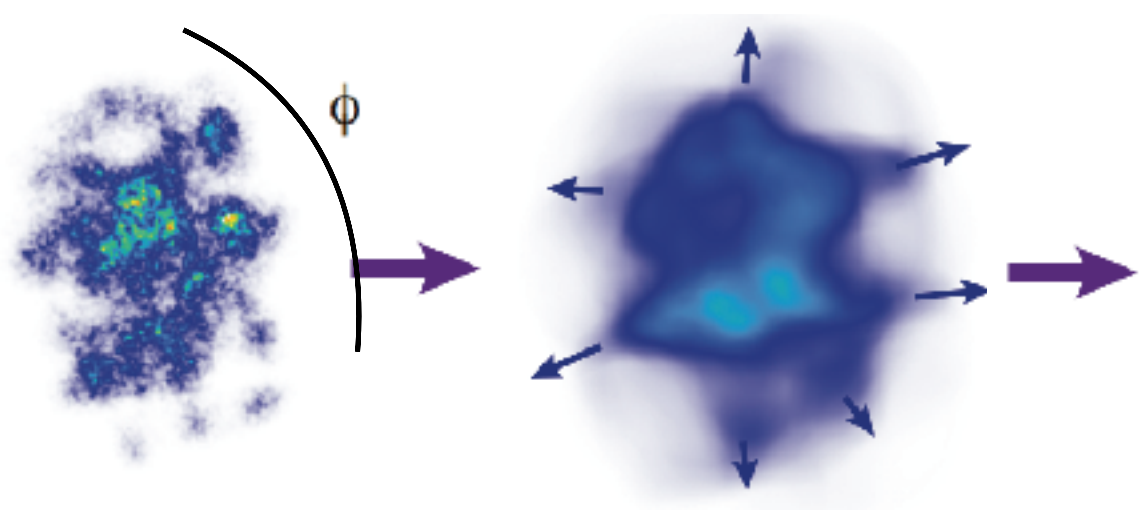
Probes of the QGP

High-energy heavy-ion collisions at RHIC,LHC produce a deconfined QGP

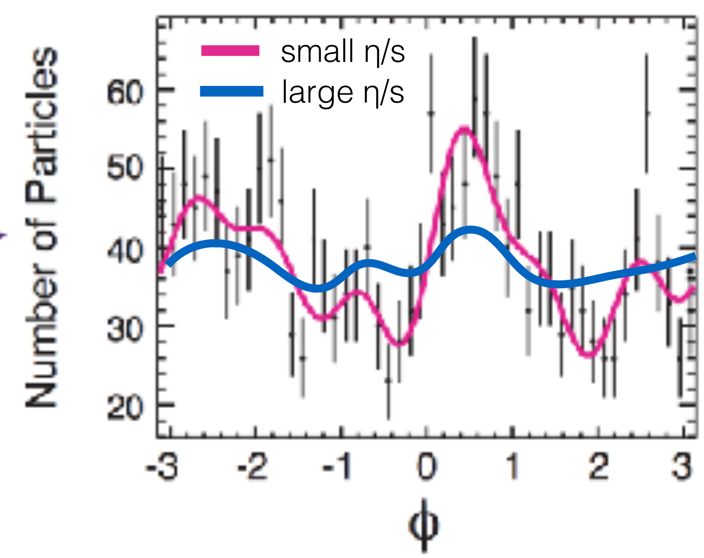
Goal: Characterize & understand properties of deconfined QCD matter

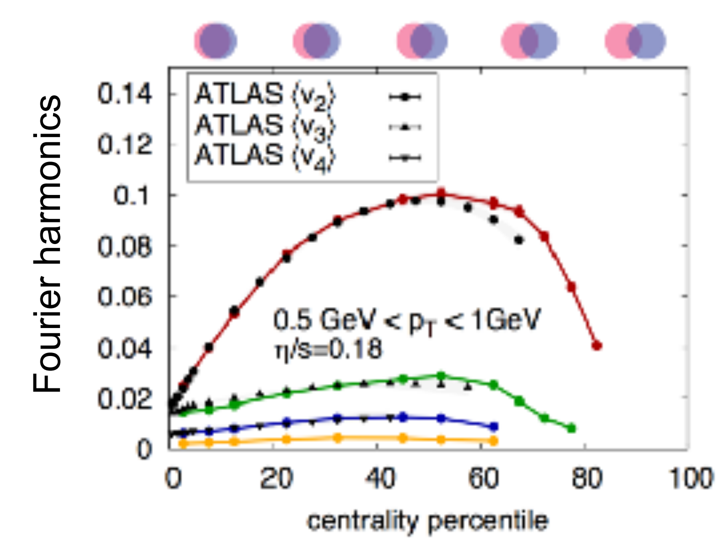
Experiments provide various ways to probe the QGP at different scales

Typical degrees of freedom (p~T) $\lesssim 1\mathrm{GeV}$



B.Schenke, R.Venugopalan, PRL 113 (2014) 102301



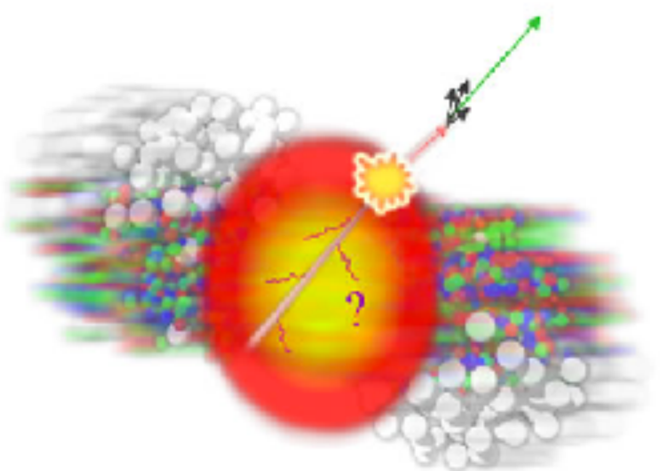


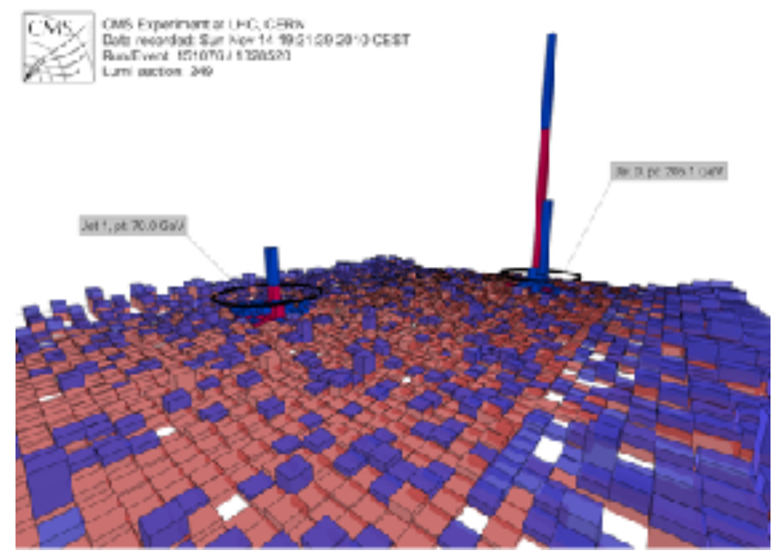
Phenomena: Elliptic flow, close to ideal fluidity (η/s << 1)

=> Extraction of near equilibrium/transport properties of QGP

Probes of the QGP

Hard probes (p>>T) $\sim 100\mathrm{GeV}$





Hard scale in the problem allows for (at least) some level of perturbative control => Calibrated probes of QGP

High-p_T objects provide non-equilibrium probes

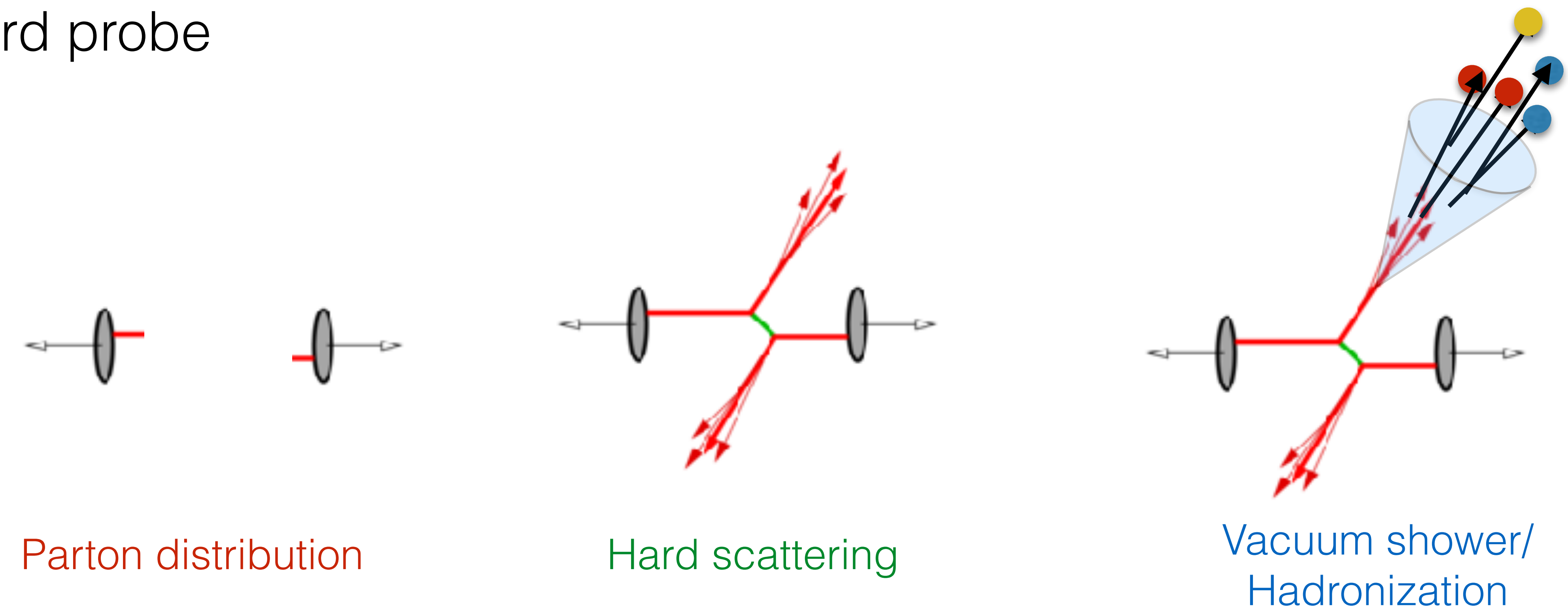
=> Interesting in its own right to study their properties

Distinction between out-of-equilibrium excitations at high p_T and equilibrium excitations at low p_T is dynamical

=> connection to non-equilibrium physics at intermediate scales

Jets/High-p_T probes in p+p

Description based on perturbative QCD (collinear factorization) exploits clear separation of time scales in the production of hard probe



e.g. inclusive hadron production

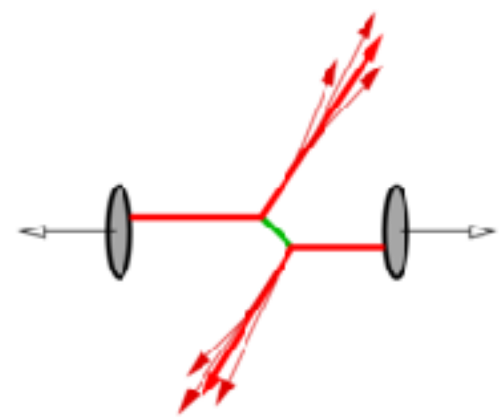
$$\sigma^{AB\to h} = f_A(x_1, Q^2) \otimes f_B(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{i\to h}(z, Q^2)\,,$$

Jets are infrared and collinear safe objects, defined through a clustering algorithm (e.g. anti-kT algorithm and cone-size R)
-> precision physics

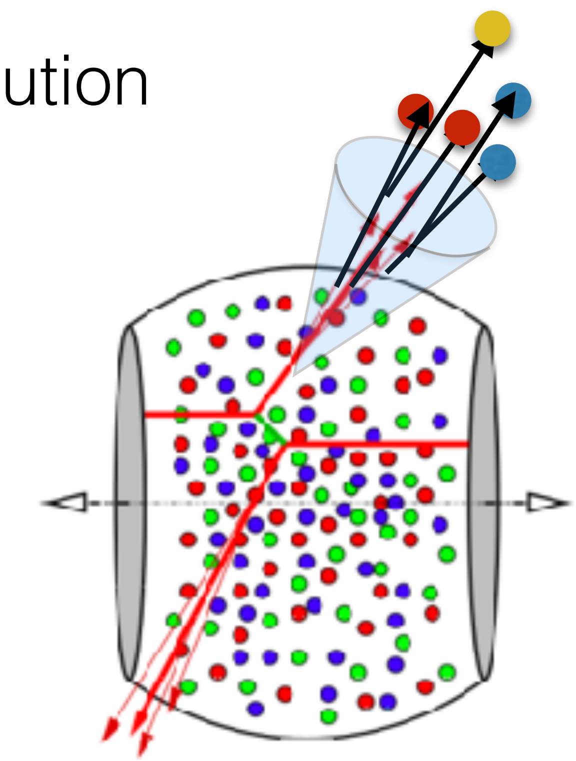
Jets/High-p_T probes in A+A

Presence of QCD medium affects the final state evolution of hard probes

Nuclear
parton distribution



Hard scattering



Vacuum shower/
Medium-Interaction
Hadronization

Different "jet" observables are sensitive to different aspects of the jet-medium interaction, e.g.

- in-medium modifications of vacuum shower (sub-structure)
- energy deposition in the QGP (Jet R_{AA})

more jet phenomenology in lectures by P. Jacobs next week

Outline of lectures

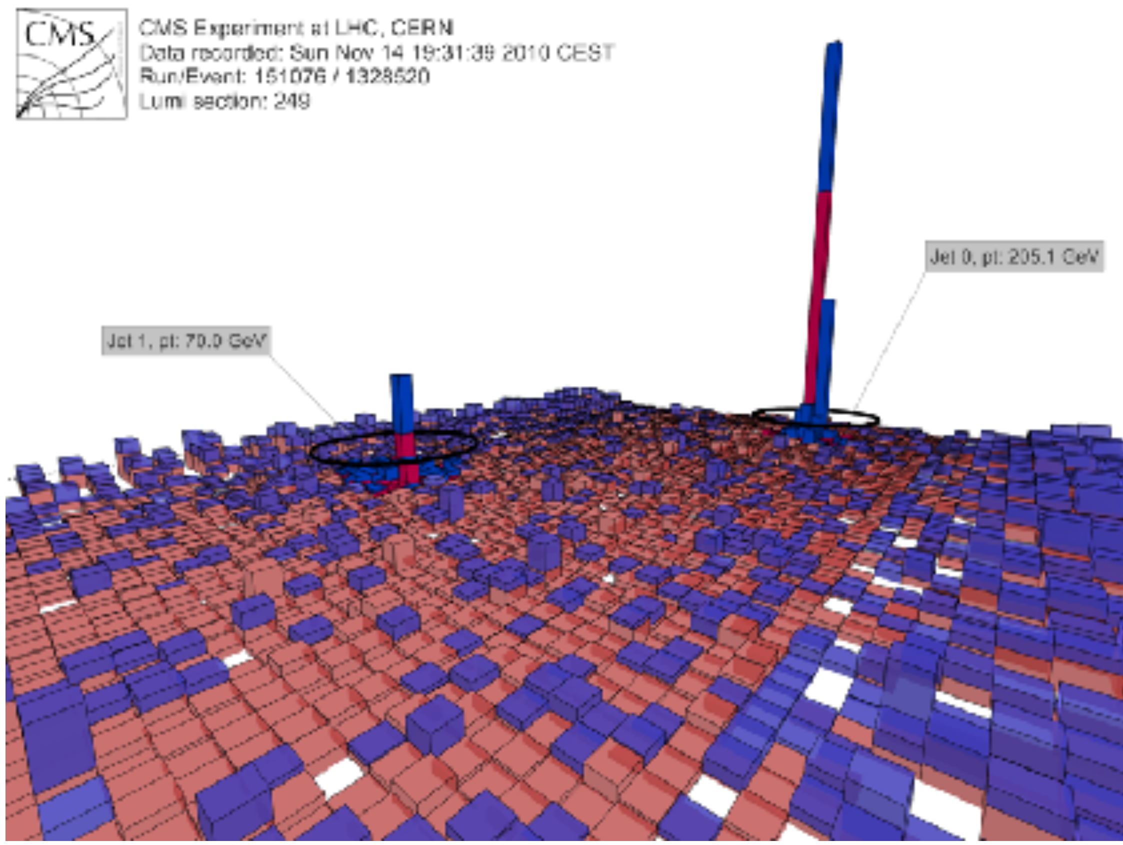
Since modifications can be extreme, up to the point where jet has thermalized inside the medium and is effectively lost, I will adopt a very loose definition of jet as any kind of highly energetic excitations

Focus on jet medium-interaction

1) Color exchange & momentum broadening

2) Medium induced radiation

3) Jet thermalization



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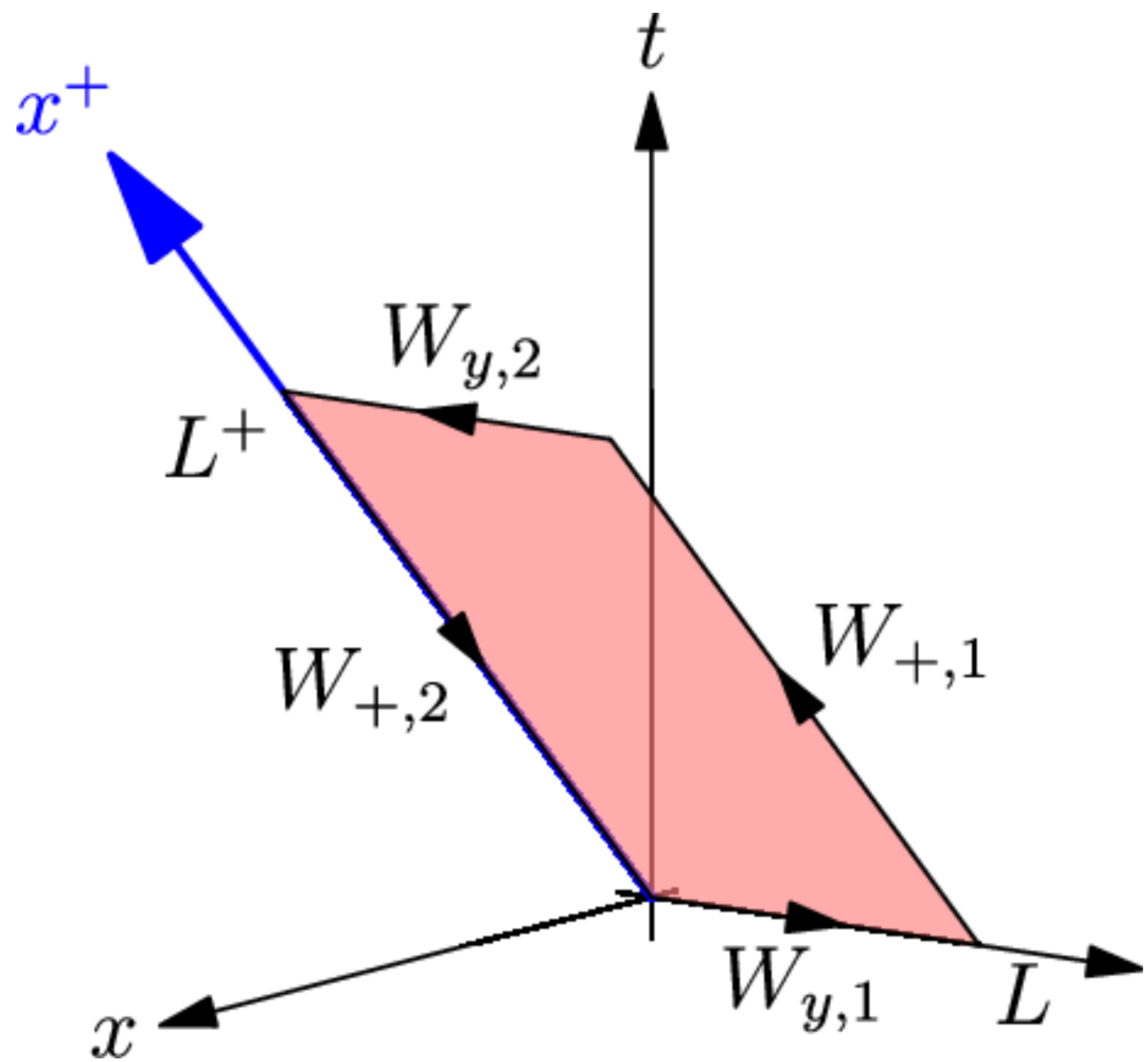


Collisional broadening kernel

Perturbative results

Leading order

Arnold, Xiao PRD 78 (2008) 125008

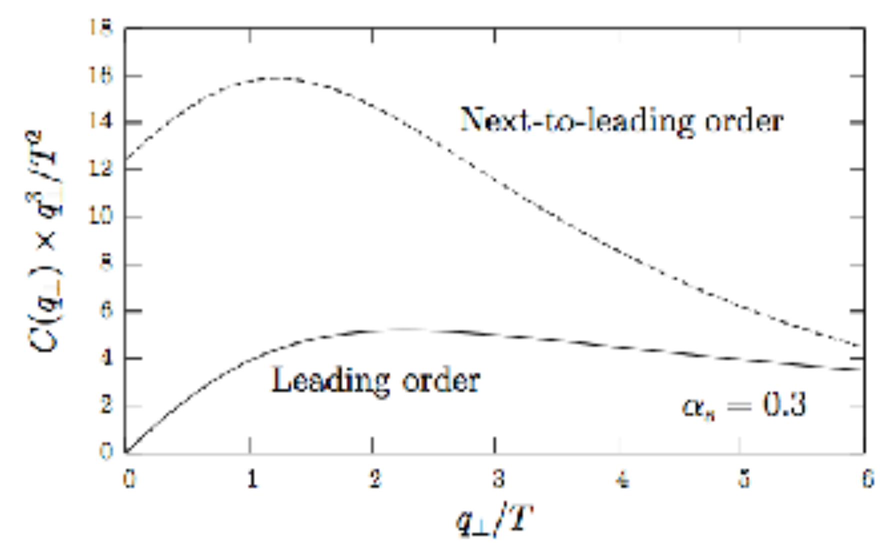
$$C^{\rm LO}_{\rm QCD}(q_\perp) = \frac{g^4 C_{\rm R}}{q_\perp^2\,(q_\perp^2 + m_{\rm D}^2)} \int \frac{{\rm d}^3p}{(2\pi)^3}\,\frac{p-p_z}{p}\,\left[2C_{\rm A} n_{\rm B}(p)(1+n_{\rm B}(p')) + 4N_{\rm f} T_{\rm f} n_{\rm F}(p)(1-n_{\rm F}(p'))\right],$$

Next-to-leading order O(g) corrections due to contributions from soft ~gT modes with large phase-space occupancies ~T/ω

Caron-Huot PRD 79 (2009) 065039

$$C^{\rm NLO}_{\rm EQCD}(q_\perp) = g^4 T^2 C_R C_A \frac{7}{32 q_\perp^3} + \cdots \quad \text{for } q_T << T$$

Discrepancies between LO and NLO due to qualitative change of the IR behavior $1/q_T^2$ vs $1/q_T^3$



Caron-Huot PRD 79 (2009) 065039

Non-perturbative determination

Large contributions from soft modes can be calculated within dimensionally reduced theory of EQCD (3D QCD with adj. scalar A_0)

Soft classical contributions to $C(q_T)$ can be computed from space-like Wilson lines, which can be calculated non-perturbatively in lattice EQCD

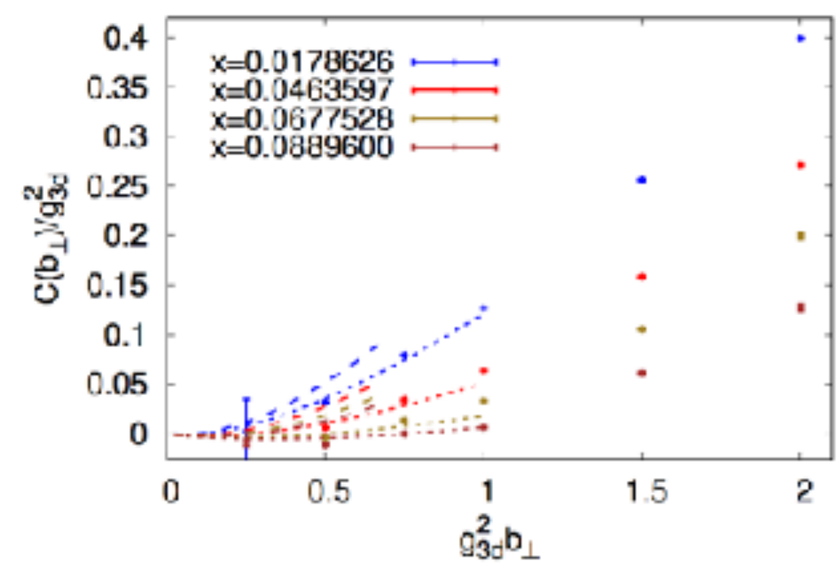
Caron-Huot PRD 79 (2009) 065039

Continuum extrapolated results EQCD results obtained for $C(b_T)$ in EQCD

Moore, Schlusser PRD 101 (2020) 1, 014505

Still require matching to QCD to restore correct UV behavior

Casalderrey-Solana, Teaney JHEP 04 (2007) 039
Moore, SS, Schlusser, Soudi JHEP 10 (2021) 059



Moore, Schlusser PRD 101 (2020) 1, 014505

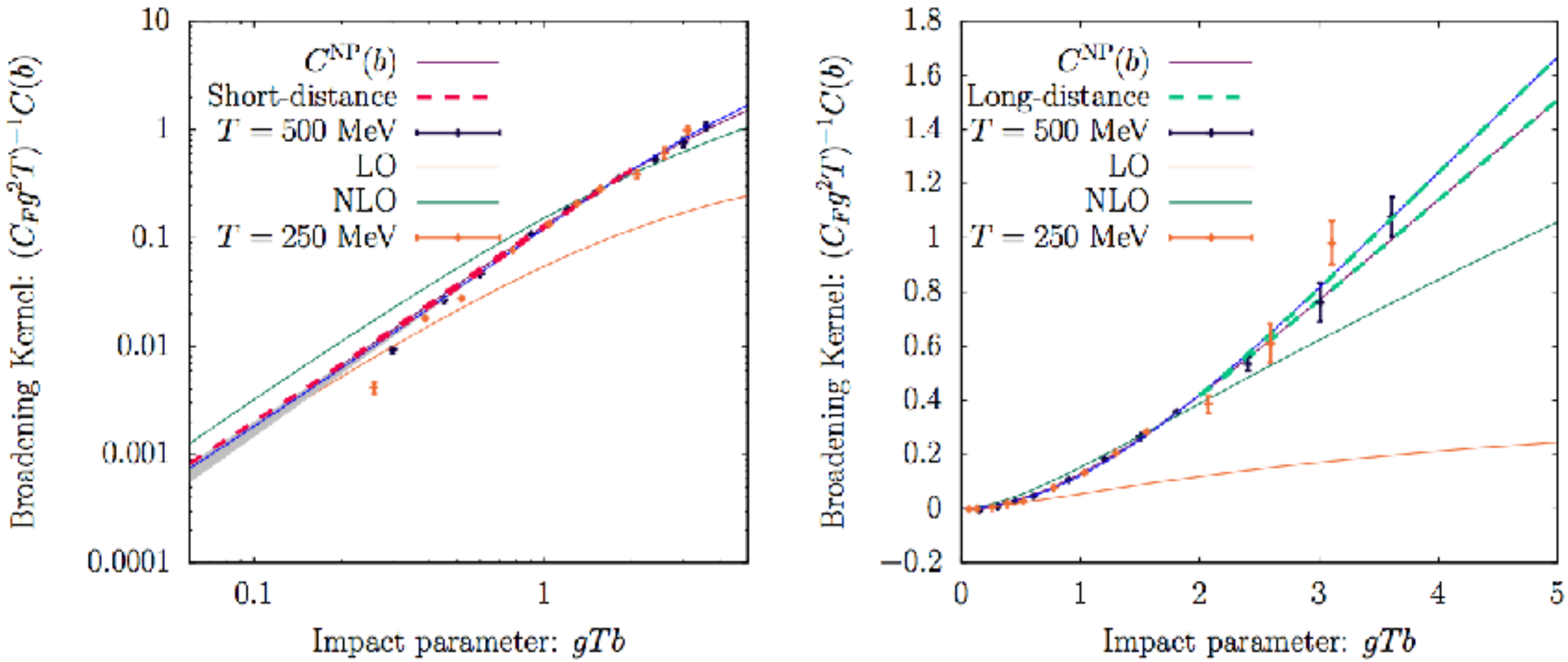
$$C_{\rm QCD}(b_\perp) \approx \left(C^{\rm pert}_{\rm QCD}(b_\perp) - C^{\rm pert}_{\rm EQCD}(b_\perp) \right) + C^{\rm latt}_{\rm EQCD}(b_\perp)$$

supplies correct QCD UV behavior

subtracts incorrect EQCD UV and pert. QCD IR behavior

should exhibit standard g^2 power counting

Broadening kernel $C(b_T)$



Short distance behavior matched to pQCD $C(b_T) \sim b_T^2 \log(b_T) + \hat{q}\, b_T^2$

Non-pert. long distance behavior $C(b_T) \sim \sigma_{EQCD}\, b_T$

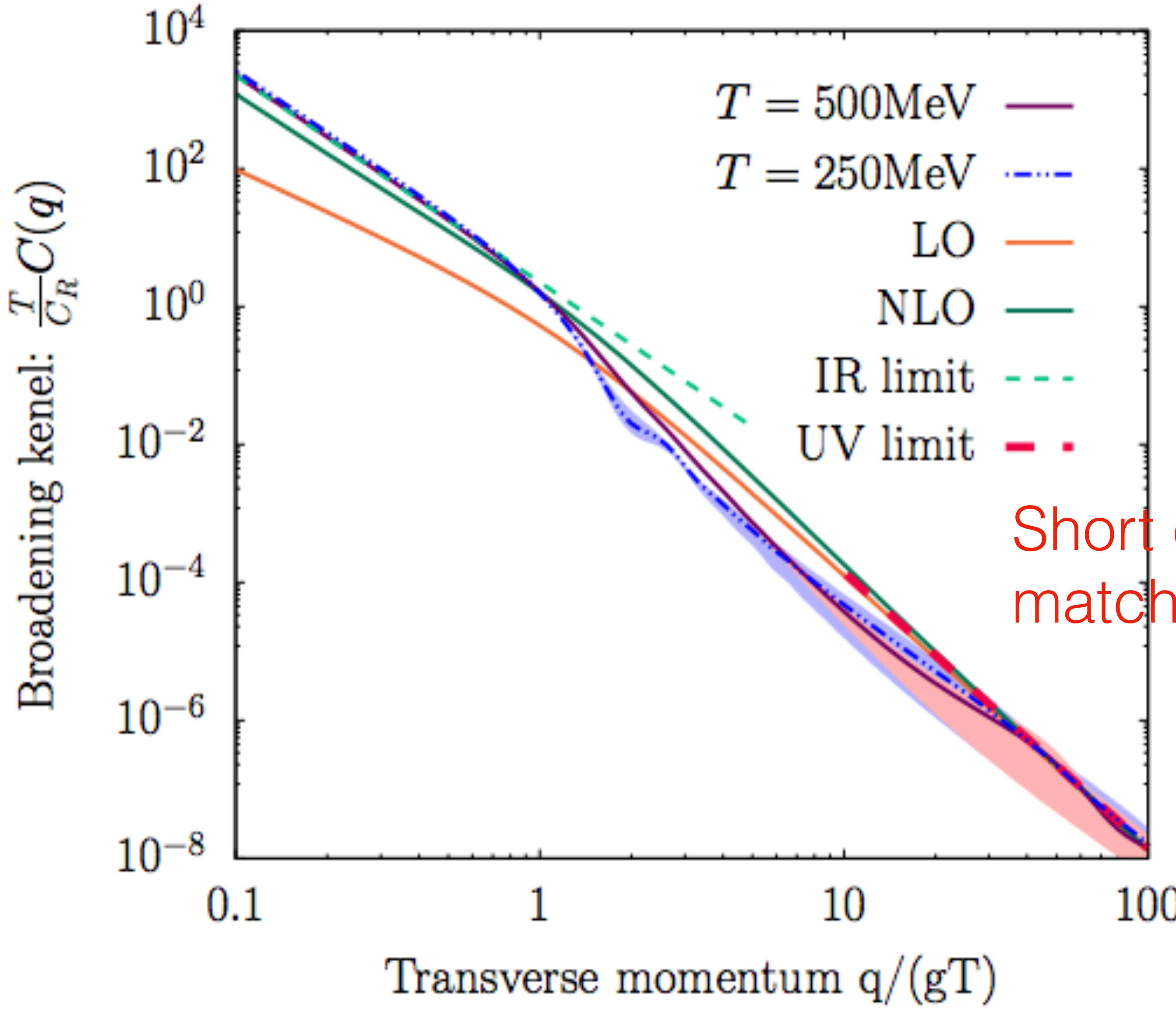
Scaling with g^2T and gT removes dominant T dependence

Moore, SS, Schlusser, Soudi JHEP 10 (2021) 059

Broadening kernel $C(q_T)$

Non-pert. long distance behavior

$C(q_T) \sim \sigma_{EQCD}/q_T^3$



Short distance behavior matched to pQCD

$C(q_T) \sim 1/q_T^4$

Scaling with T and gT removes dominant T dependence

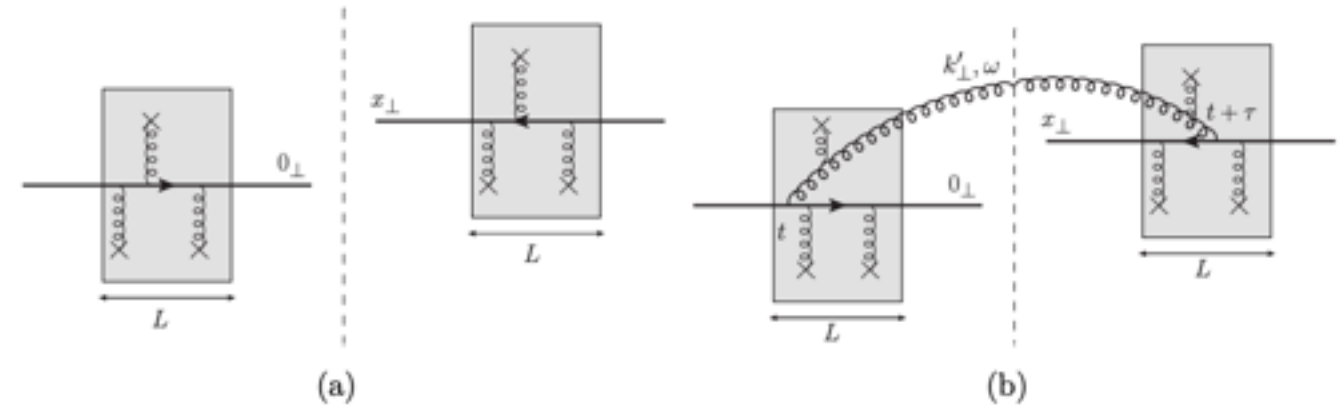
Bands represent uncertainties stat. errors and spline interpolation of EQCD data

SS, Soudi PRD 105 (2022) 7, 076002

Broadening kernel $C(q_T)$

Beyond leading order there are also potentially large $O(g^2)$ radiative corrections, with logarithmic phase-space enhancement that may require resummation

Liou, Mueller, Wu, NPA 916, 102 (2013)
Blaizot, Dominguez, Iancu, Mehtar-Tani, JHEP 06, 075 (2014),;
Caucal, Mehtar-Tani arXiv:2109.12041, 2203.09407

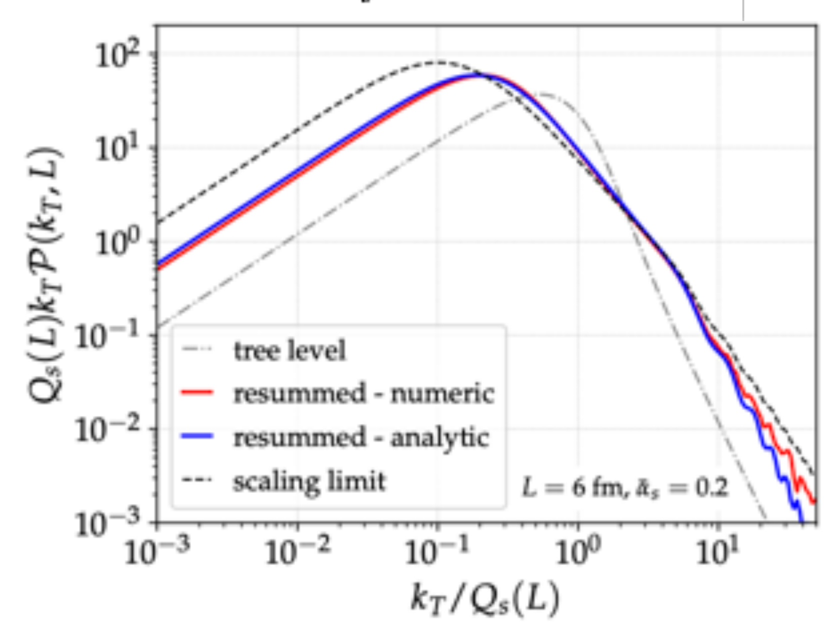


Double log resummation for jet-quenching for hard gluons (kT>Qs) with short formation time

$$\hat{q}(\tau, \boldsymbol{k}_\perp^2) = \hat{q}^{(0)}(\tau_0, \boldsymbol{k}_\perp^2) + \int_{\tau_0}^{\tau} \frac{\mathrm{d}\tau'}{\tau'} \int_{Q_s^2(\tau')}^{\boldsymbol{k}_\perp^2} \frac{\mathrm{d}\boldsymbol{k}_\perp'^2}{\boldsymbol{k}_\perp'^2}\, \bar{\alpha}_s(\boldsymbol{k}_\perp'^2)\, \hat{q}(\tau', \boldsymbol{k}_\perp'^2)\,,$$

$$Q_s^2(\tau) = \hat{q}(\tau, Q_s^2(\tau))\tau\,,$$

$$\mathcal{P}(\boldsymbol{k}_\perp) = \int \mathrm{d}^2\boldsymbol{x}_\perp \mathrm{e}^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp - \mathcal{S}(\boldsymbol{x}_\perp)}\,.$$



introduces an anomalous dimension for the perturbative kT >> Qs tail

Caucal, Mehtar-Tani arXiv:2109.12041,