Jets: Hard-Soft Correlation

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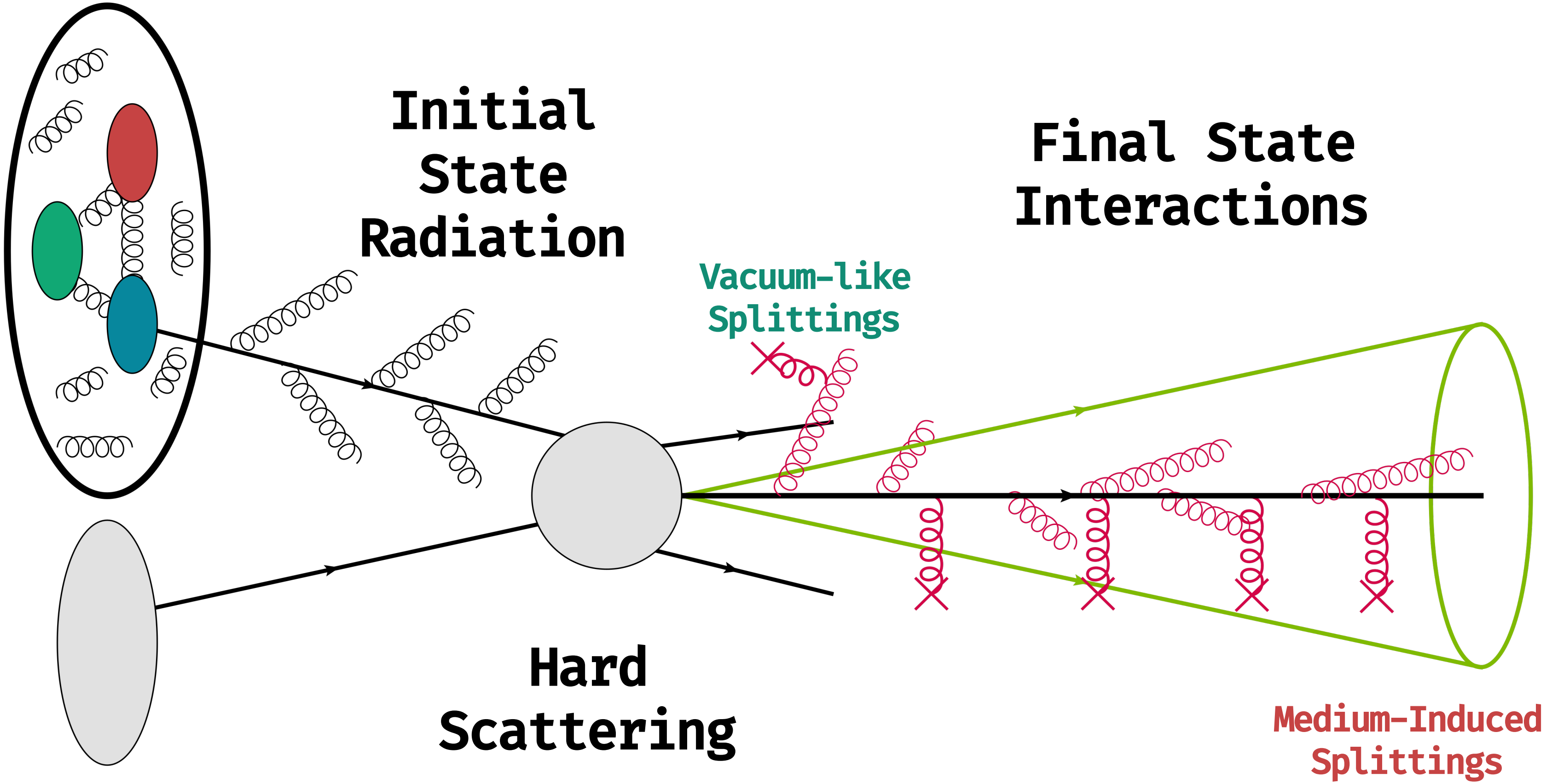
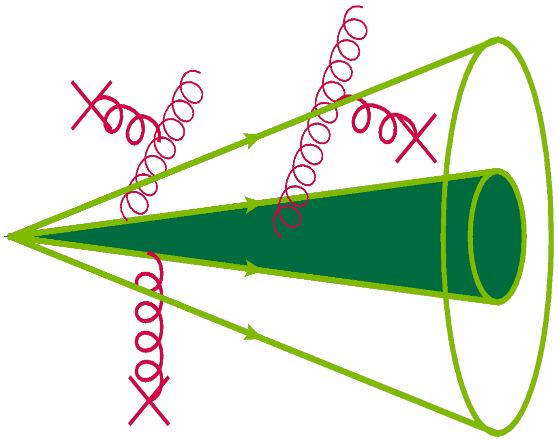
Hard Probes 2024, Nagasaki, Japan

26/09/2024

Hard-Soft Correlations



Vacuum-Like Physics

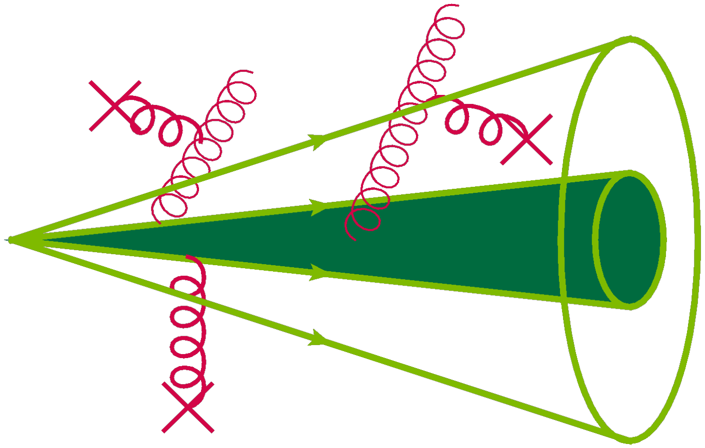


- Initial Coherent Scatterings
  - » Factorization: Coherent Radiation Not Resolved By QGP [Caucal, Iancu, Mueller, Soyez PRL(2018)]
  - » Delayed Energy Loss (τ=0.6 fm/c) [Andres, Armesto, Niemi, Paatelainen, Salgado PLB(2020)]
  - » Modified Vacuum Shower [Kumar, Majumder, Shen(2020)]
  - » Coherent Energy Loss ⇒ Jet v_2 and R_{AA} [Mehtar-Tani, Pablos, Tywoniuk PRD(2024)]
  - » ...

See also: A. Takacs Mon 15:00

Decoherence

- Individual Antennas Resolved By QGP



Decoherence

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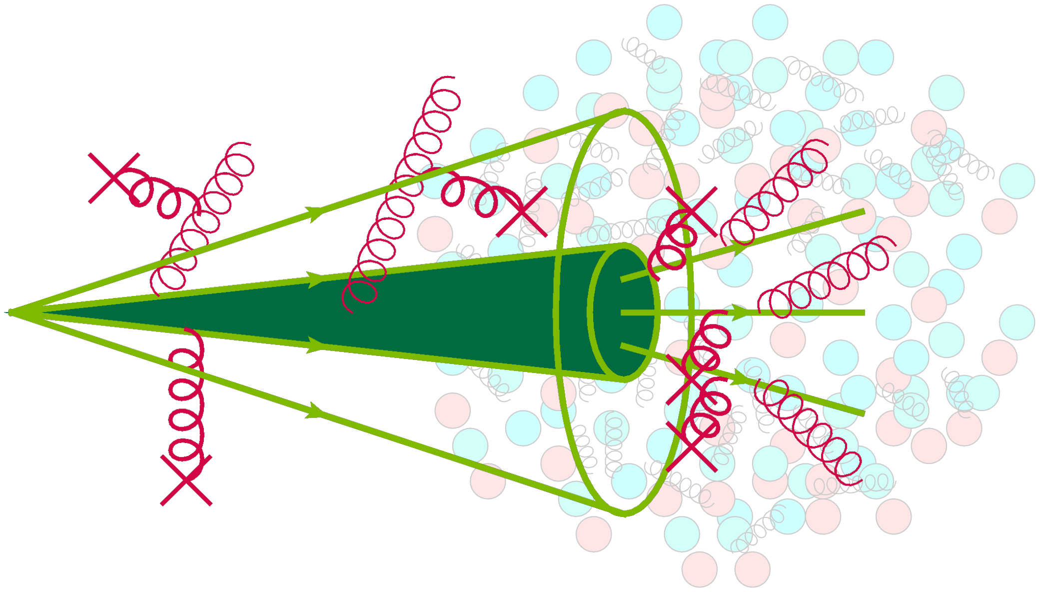
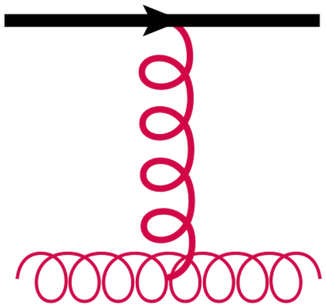
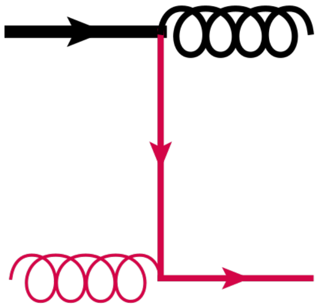


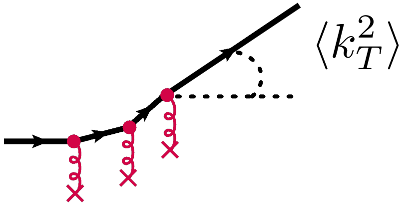
Jet-Medium Scattering



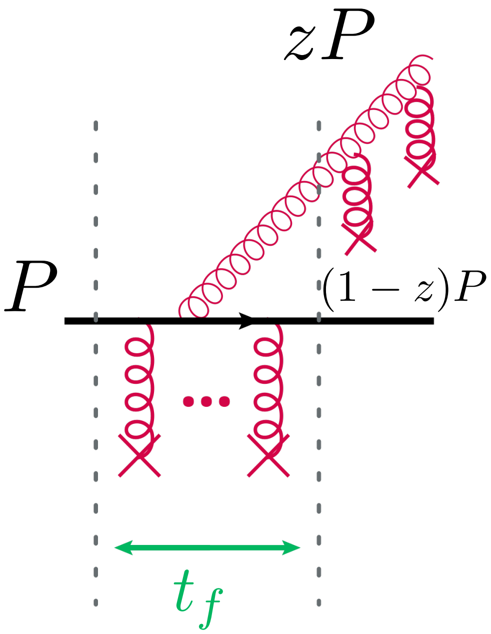


- Multiple Scattering:
  - Momentum Broadening
  - Drag
  - Conversion

$\Big\} \propto \hat{q} = \frac{\langle k_T^2 \rangle}{L}$



Medium-Induced Radiation



- Multiple Scattering ⇒ Induce Radiation
- Interplay form-time $\Longleftrightarrow$ λ_{mfp}

$$\boldsymbol{t_{form}} \sim \frac{z(1-z)P}{k_T^2}\,, \quad \langle k_T^2 \rangle \simeq \hat{q}\, t_{form} \quad \Rightarrow \quad \boldsymbol{t_{form}} \sim \sqrt{\frac{z(1-z)P}{\hat{q}}}$$

[Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Gyulassy, Levai, Vitev, Wiedemann, Arnold, Moore, Yaffe, Caron-Huot, Gale..]

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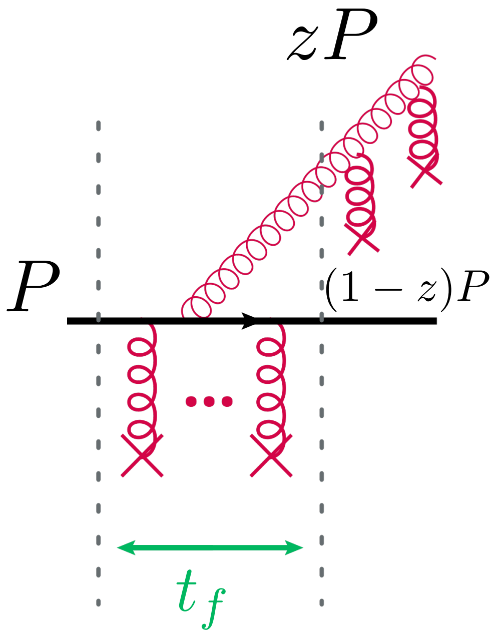

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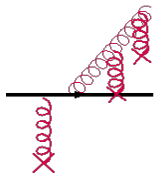
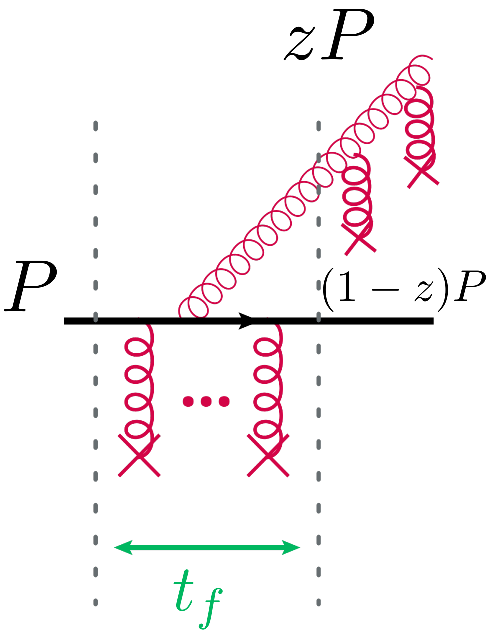


» $t_{form} \ll \lambda_{mfp}$: Finite Number Of Scatterings

[Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Gyulassy, Levai, Vitev, Wiedemann, Arnold, Moore, Yaffe, Caron-Huot, Gale..]

Medium-Induced Radiation



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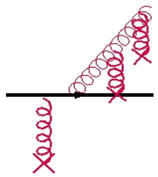
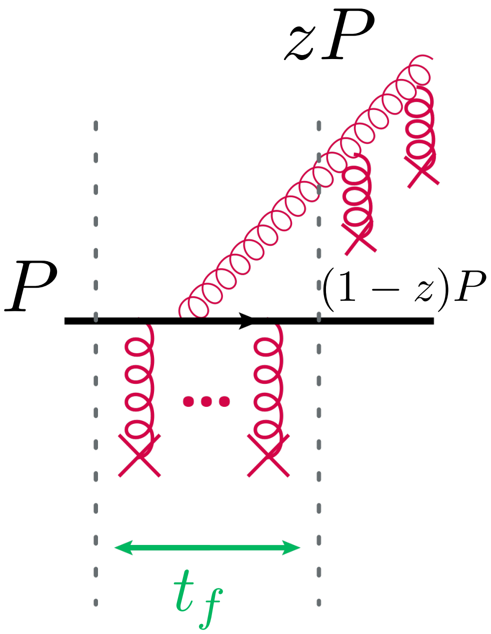


» $t_{form} \ll \lambda_{mfp}$: Finite Number Of Scatterings

» $t_{form} \gg \lambda_{mfp}$: Interference b/w Multiple Scatterings

[Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Gyulassy, Levai, Vitev, Wiedemann, Arnold, Moore, Yaffe, Caron-Huot, Gale..]

Medium-Induced Radiation



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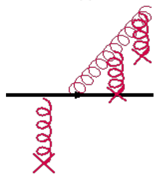


» $t_{form} \ll \lambda_{mfp}$: Finite Number Of Scatterings

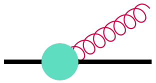
» $t_{form} \gg \lambda_{mfp}$: Interference b/w Multiple Scatterings

- Interference Effects ⇒ LPM Suppression for $zP \gg T$

[Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Gyulassy, Levai, Vitev, Wiedemann, Arnold, Moore, Yaffe, Caron-Huot, Gale..]

Medium-Induced Radiation

» BDMPS-Z Formalism: Resum Multiple-Scattering diagram



$$\underbrace{\frac{d\Gamma^a_{bc}}{dz}(P,z,t)}_{\text{Rate}} = \frac{\mathbf{d}}{\mathbf{dt}}\underbrace{\frac{dI^a_{bc}}{dz}(P,z,t)}_{\text{Spectrum}} = \frac{g^2 P^a_{bc}(z)}{4\pi P^2 z^2(1-z)^2}\,\mathrm{Re}\int_0^t dt_1 \int_{\boldsymbol{p},\boldsymbol{q}} \frac{i\boldsymbol{q}.\boldsymbol{p}}{\delta E(\boldsymbol{q})}\underbrace{\Gamma_3(t)}_{\text{Medium}} \circ G(t,\boldsymbol{q};t_1,\boldsymbol{p})\,.$$

$$\hat{q}(t) = \int d^2k_T\; k_T^2\; \Gamma(t)$$

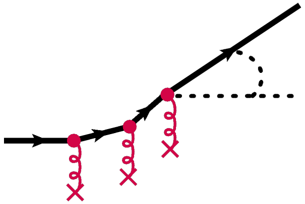
$\Gamma(t) \propto \frac{1}{q^2(q^2+m_D^2)}$ » HTL Potential

$\Gamma(t) \propto \frac{1}{(q^2+m_D^2)^2}$ » Static Screening

$\Gamma(t) \propto \hat{q}b^2$ » Harmonic Oscillator (HO)

$\Gamma(t) \propto C_{NP-QCD}(q)$ » Non-perturbative

$\Gamma(t) \propto C_{Non-Eq}(q)$ » Non-Eq Extracted



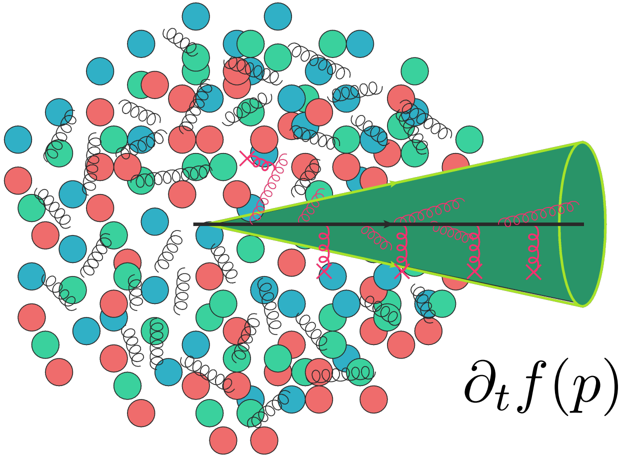
S. Shi Mon. 15:40

[Moore, Schlusser, Schlichting IS JHEP(2020)]

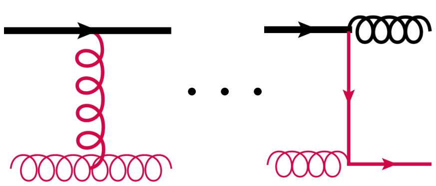
F. Lindenbauer Mon 17:30

[Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Gyulassy, Levai, Vitev, Wiedemann, Arnold, Moore, Yaffe, Caron-Huot, Gale..]

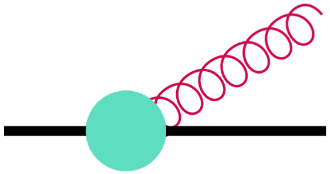
Effective Kinetic Theory



» Elastic Scattering



» Effective $1 \longleftrightarrow 2$ Rate



$$\partial_t f(p) = C^{2\leftrightarrow 2}[f] + C^{1\leftrightarrow 2}[f]$$

Static/Evolving

$$f(p) = f^{QGP}(p) + \delta f^{jet}(p)$$

Includes Medium Recoil/Response

$$\delta f^{jet}(p) = f(p) - f^{QGP}(p) \lessgtr 0$$

Energy Distribution

$$D(x) = \delta(xE_0 - p)p^3 \delta f^{jet}(p)$$

AMY Kinetic Theory

» Integrate Out Time-Dependence $t_{form} \sim \sqrt{\frac{z(1-z)P}{\hat{q}}} \ll L$

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$$\frac{d\Gamma^a_{bc}}{dz}(P, z, \infty) = \frac{g^2 P^a_{bc}(z)}{4\pi P^2 z^2 (1-z)^2} \mathrm{Re} \int_0^\infty dt_1 \int_{\boldsymbol{p},\boldsymbol{q}} \frac{i\boldsymbol{q}.\boldsymbol{p}}{\delta E(\boldsymbol{q})} \Gamma_3(t) \circ G(\infty, \boldsymbol{q}; t_1, \boldsymbol{p}) \ .$$

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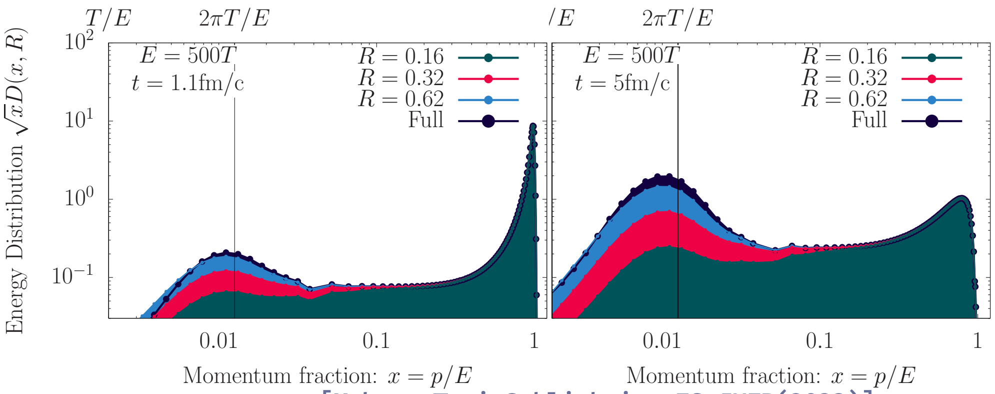

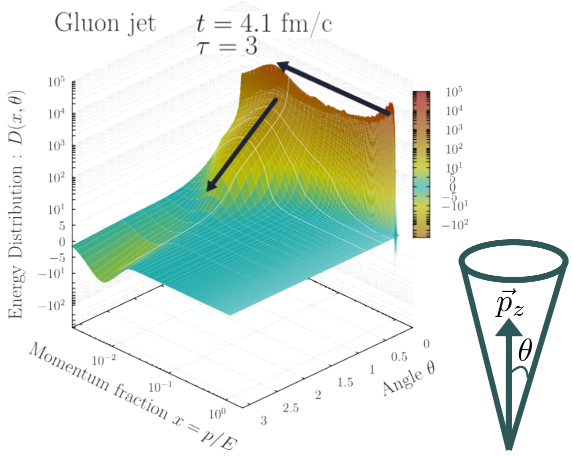

[Mehtar-Tani Schlichting IS JHEP(2023)]

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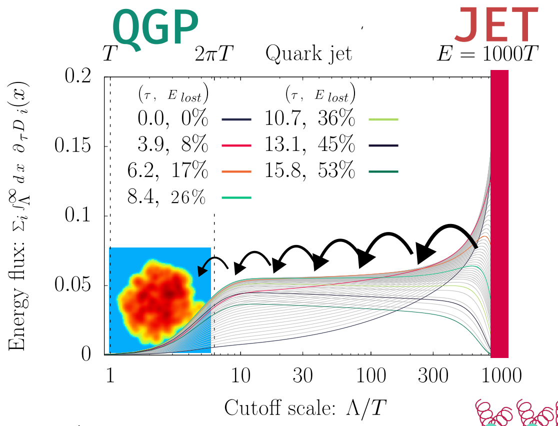
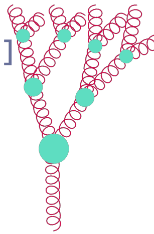
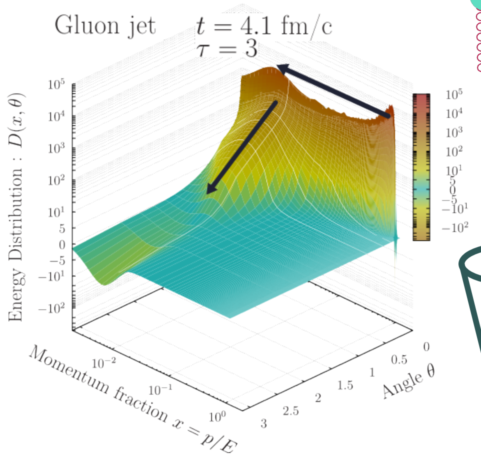
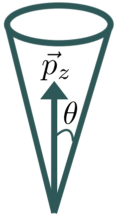
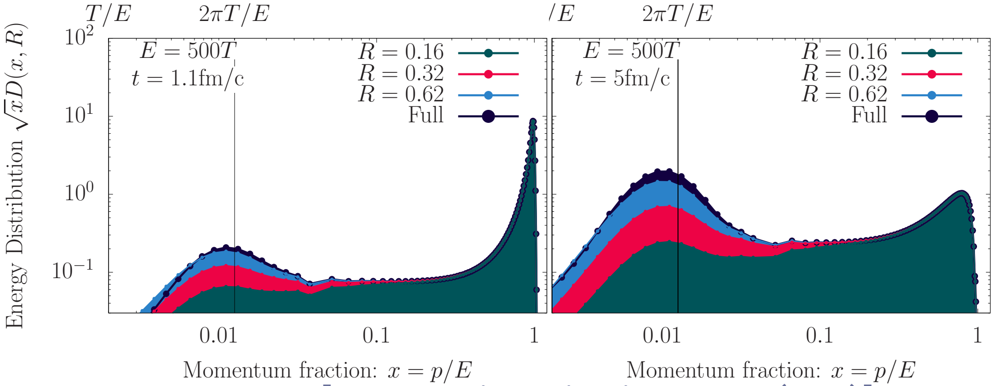
» K-Z Turbulent Cascade ⇒ Stationary Solution $D(x) \propto \frac{1}{\sqrt{x}}$ [Schlichting IS JHEP(2021)]











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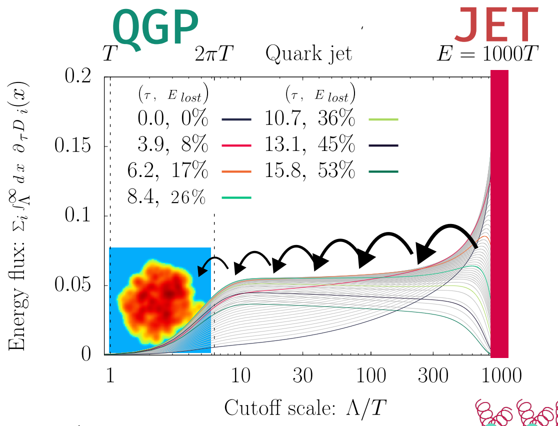

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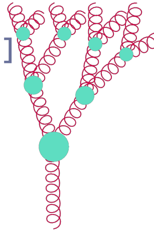
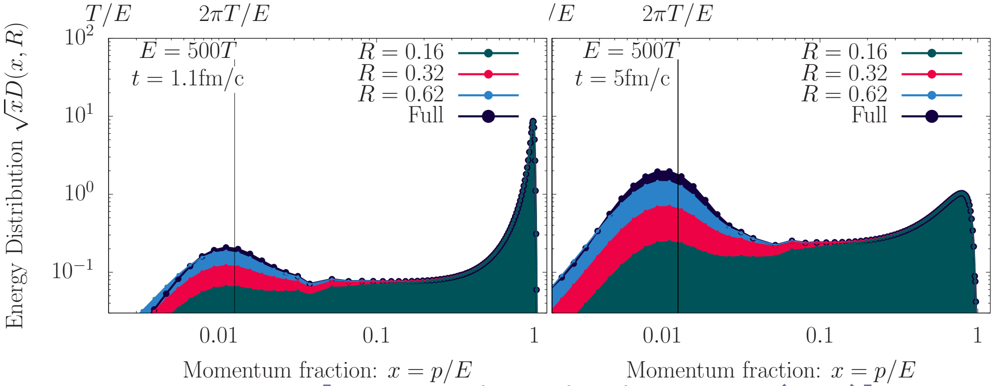
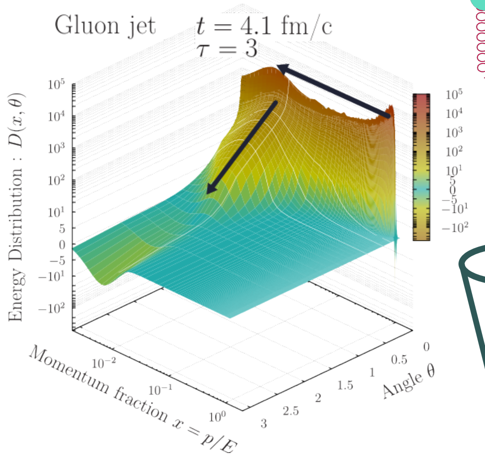


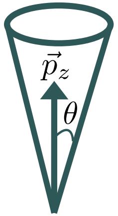
» Due to the Rate Momentum Dependence

$$\partial_t D(x) = \int_0^1 dz \; \mathcal{K}(z) \frac{1}{\sqrt{x}} \left[\sqrt{z} D\left(\frac{x}{z}\right) - z D(x) \right]$$



[Mehtar-Tani Schlichting IS JHEP(2023)]



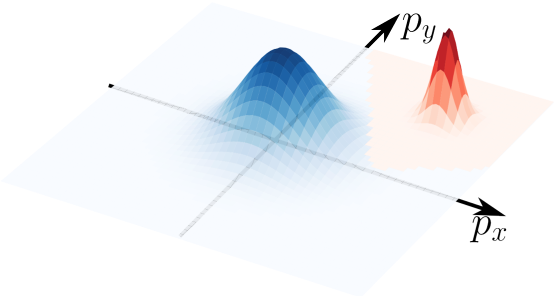


c.f. [Blaizot, Iancu, Mehtar-Tani PRL(2013)]
[Blaizot, Mehtar-Tani AOP(2016)]

Evolving Background

L. F. Zhou Poster
S. B. Cabodevila Mon 18:10

[Zhou, Brewer, Mazeliauskas JHEP(2024)]



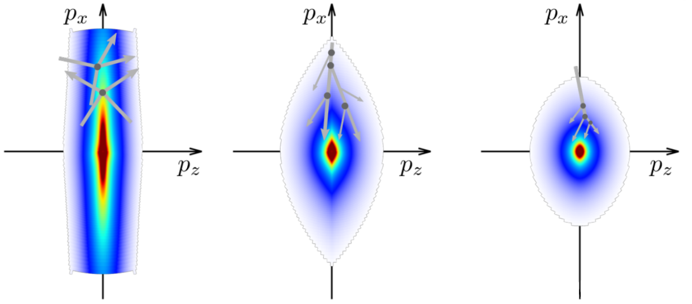
- Evolving Medium

$$\left(\partial_\tau + \frac{p_z}{\tau}\partial_{p_z}\right) f^{QGP}(p,t) = C[f^{QGP}]$$

$$\left(\partial_\tau + \frac{p_z}{\tau}\partial_{p_z}\right) \delta f^{jet}(p,t) = C[f^{QGP}, \delta f^{jet}]$$

- CGC Initial Condition:

$$f^{QGP}(p,t=0) = \frac{2A}{\lambda}\frac{Q_0 \exp[-\frac{2}{3}(p_T^2+\xi^2 p_z^2)/Q_0^2]}{\sqrt{p_T^2+\xi^2 p_z^2}}$$

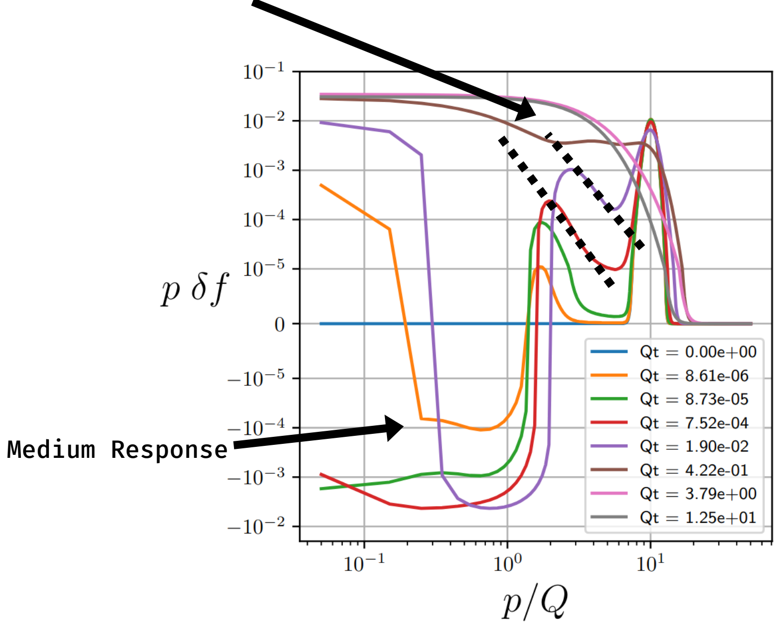


Evolving

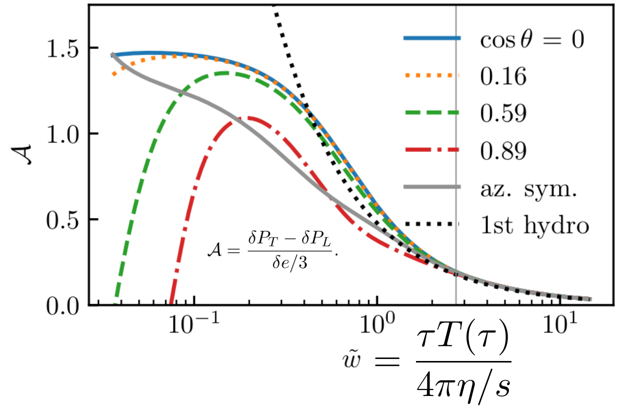
$$f(p,t) = f^{QGP}(p,t) + \delta f^{jet}(p,t)$$

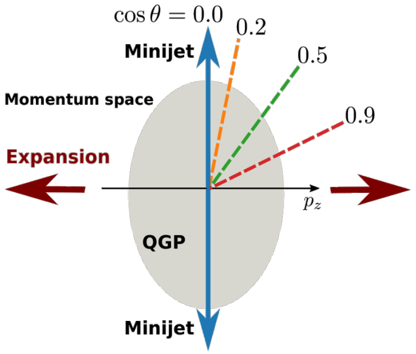
AMY Kinetic Theory

» K-Z Spectrum Recovered



» “Hydrodynamisation” Of Jets: Indistinguishable From Soft Background Perturbations $\tilde{\omega}_{mjh} = 2.7$





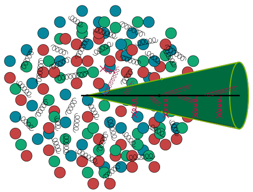
[Zhou, Brewer, Mazeliauskas JHEP(2024)]

S. B. Cabodevila Mon 18:10

L. F. Zhou Poster

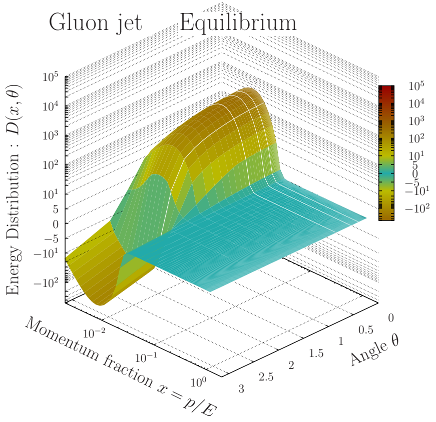
Medium Response

- Thermalized Jet Distribution



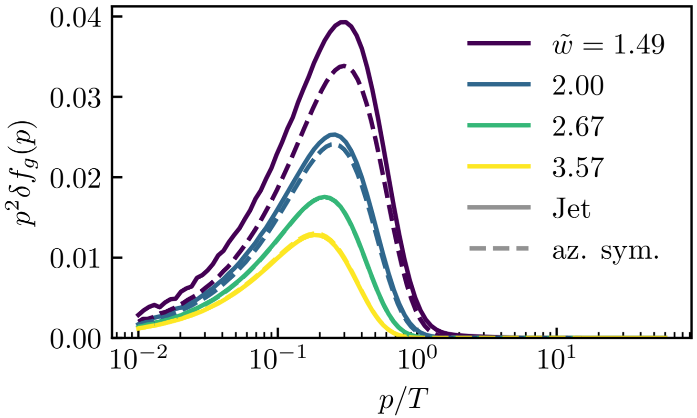
»Static Medium:

$$\delta \bar{f}_a^{(eq)}(\mathbf{p}) = V\left[\boldsymbol{\delta T}\partial_T + \boldsymbol{\delta u^z}\partial_{u^z} + \boldsymbol{\delta \mu_f}\partial_{\mu_f}\right] n_a(\mathbf{p})$$



»Evolving Medium:

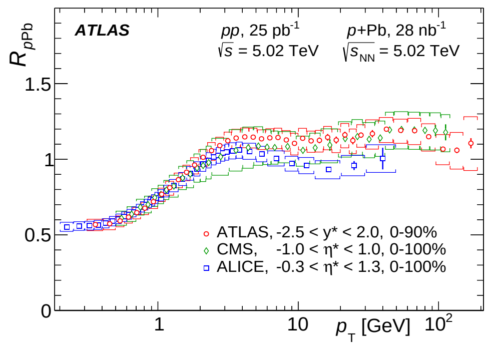
$$\delta f_{\text{visc}} = \frac{\eta/s}{\tau \overline{T}(\tau)}(1 - 3\cos^2\theta) F\left(p/\overline{T}(\tau)\right)$$

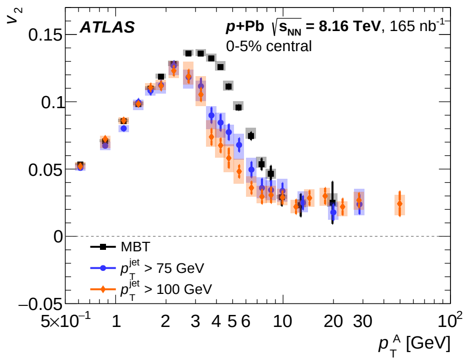


[Zhou, Brewer, Mazeliauskas JHEP(2024)]

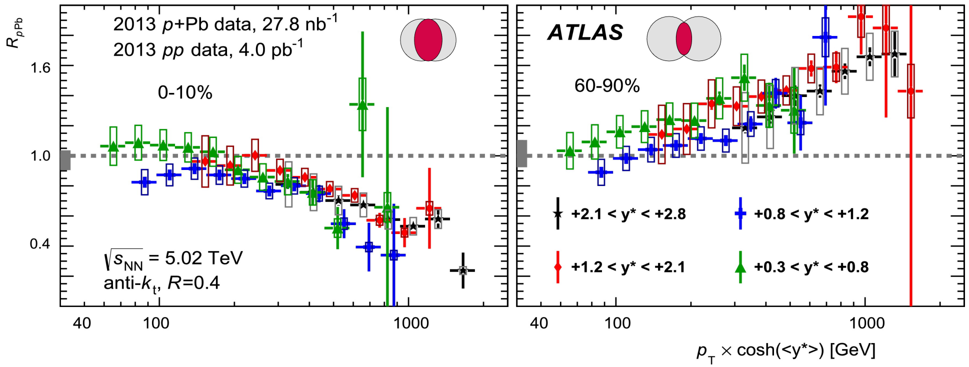
Small Systems: v_2 vs R_{AA}

[ATLAS JHEP. 07, 074 (2023)]
[CMS JHEP. 04, 039 (2017)]
[ALICE JHEP. 11, 013 (2018)]





- High-p_T v_2 in pp and pPb
- Centrality Dependence R_{pPb}
  - » Initial State Correlations?
  - » Initial State Energy loss?
- Exciting Lab For Hard/Soft Correlations



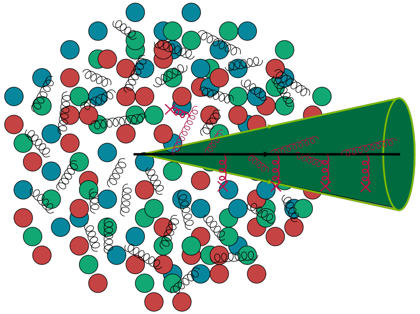
[ATLAS Phys. Lett. B. 748, 392–413 (2015)]

Jet No Longer A Perturbation

- Jets No Longer A Perturbation On Top Of Bulk
  - » Jet Carry Substantial Amount Of Energy
  - » Jet Modifies The Bulk
  - » Bulk Extent is Small $\Rightarrow$ Finite Size Effects Important
  - » Energy Loss Negligible?
  - » Vacuum-like Physics Important: Higher-Twist, GLV...

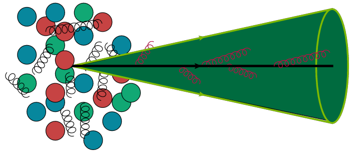
Heavy-Ion

$$f(p) = f^{QGP}(p) + \delta f^{jet}(p)$$

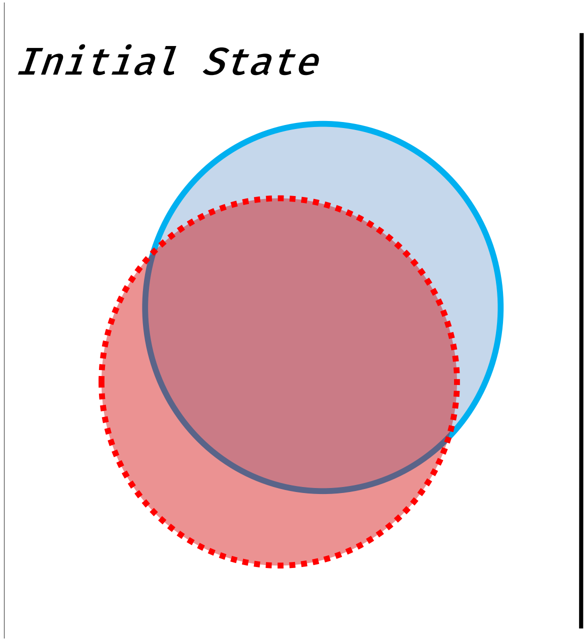


Small Systems

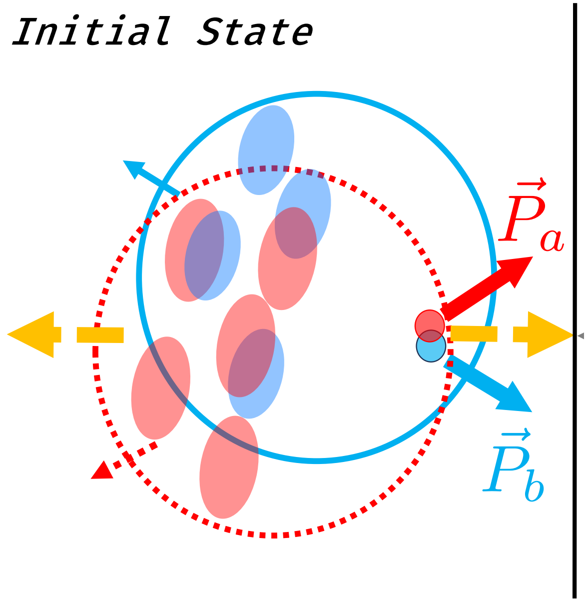
$$f(p) = f^{jet}(p) + \delta f^{Bulk}(p)$$



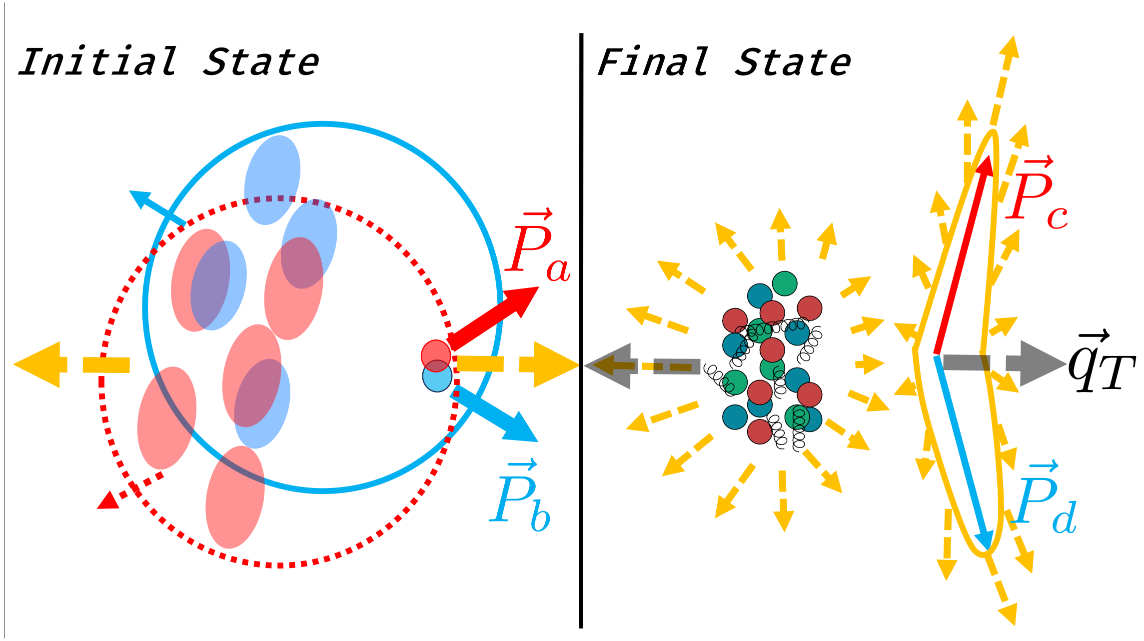
Transverse Correlation



Transverse Correlation



Transverse Correlation

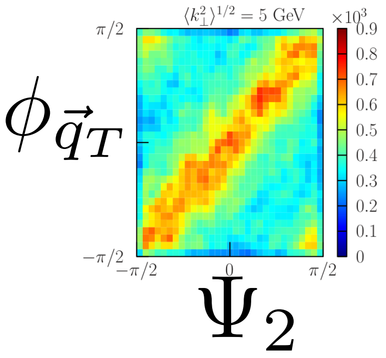


- Balanced Transverse Momentum $\vec{q}_T = \vec{p}_{aT} + \vec{p}_{bT}$ b/w Hard/Soft Particles

Transverse Correlation

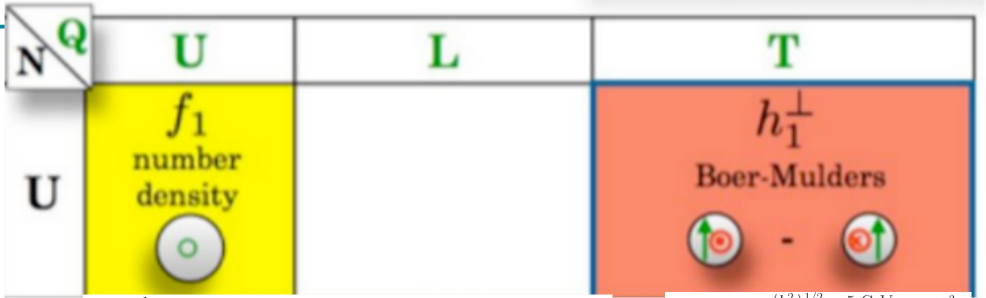
Transverse Correlation

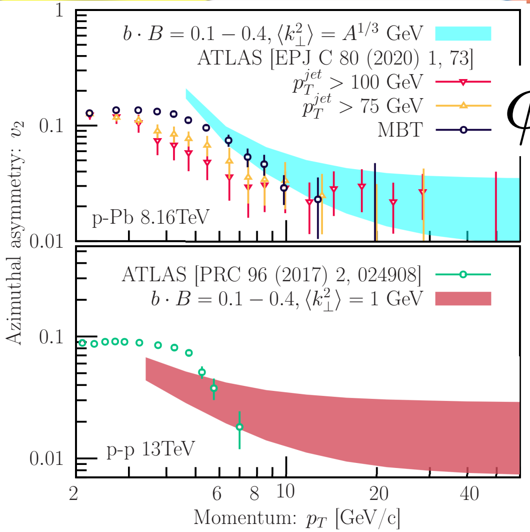
- Conservation Of Momentum ⇒ Hard/Soft Correlation
  - » Corroborated By Simple PYTHIA simulation

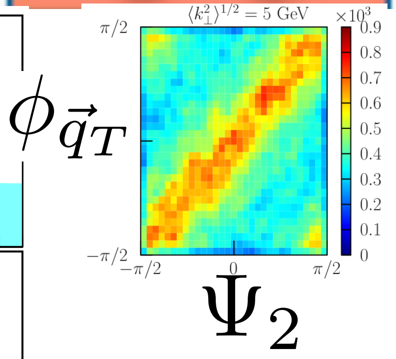


Transverse Correlation

- Conservation Of Momentum ⇒ Hard/Soft Correlation
  - » Corroborated By Simple PYTHIA simulation
- TMD-PDFs and FFs:
  - » Azimuthal Correlations Due Initial k_T
  - » Boer-Mulders'/Collins Effects





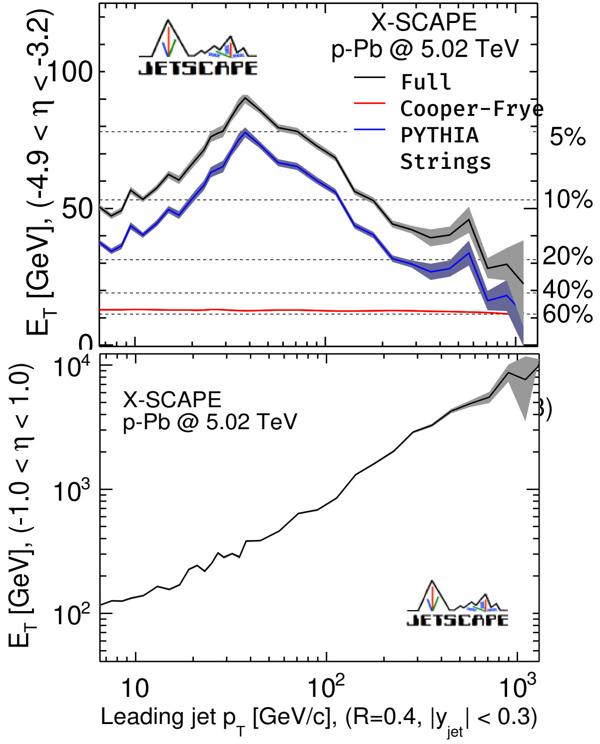


[IS, Majumder ArXiv:2404.05287]
[IS, Majumder ArXiv:2308.14702]

Energy Conservation

S. Jeon Tue. 16:15

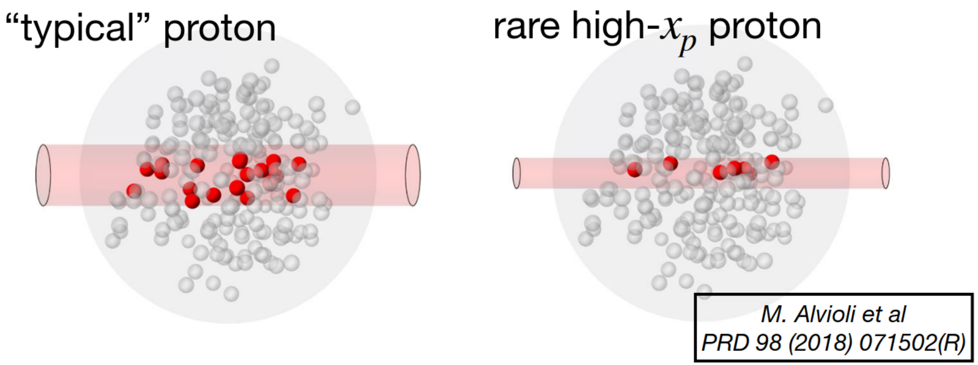
- Multi-stage Framework For Small Systems
  - » Correlations b/w Soft/Hard Particle Production
  - » Competition b/w Jet p_T and Partonic remnants
  - » Hard Scattering Increasing E_T until Momentum Conservation Limits

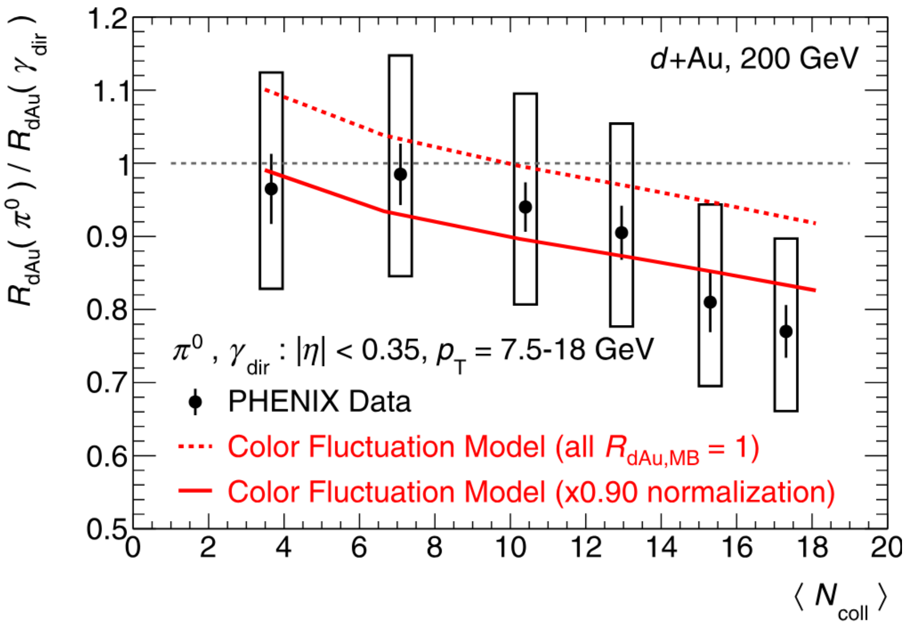


[JETSCAPE ArXiv:2407.17443]

Bjorken-x

D. Perepelitsa Mon 14:40





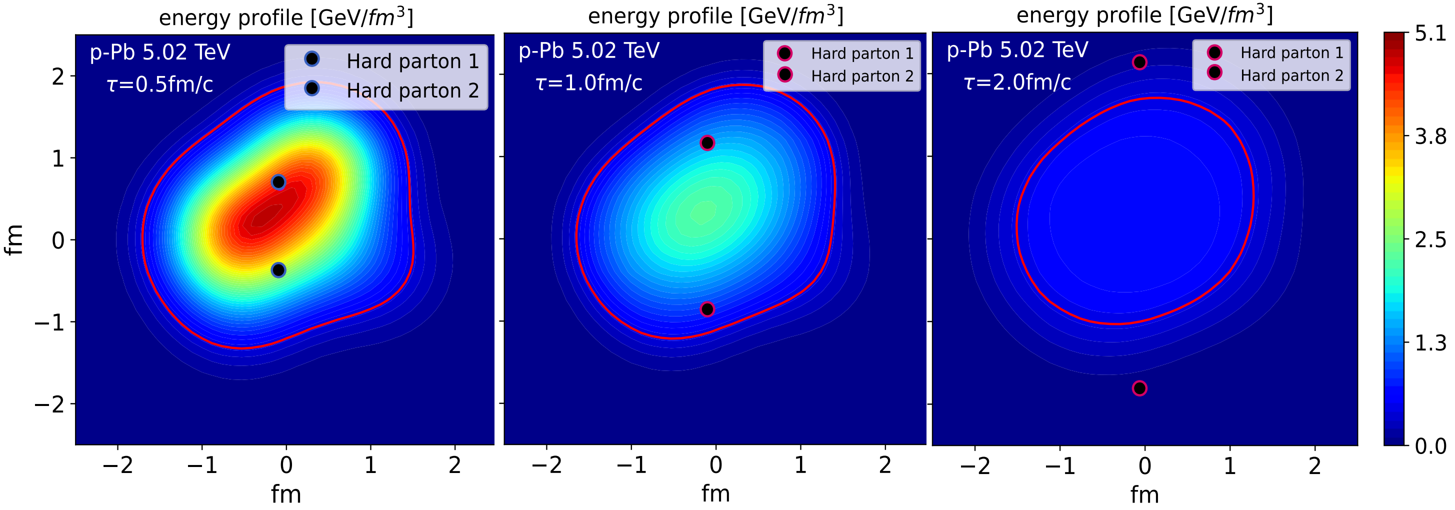
- Presence of Hard Partons ⇒ Significant Difference Bjorken-x Distribution Than Average Protons

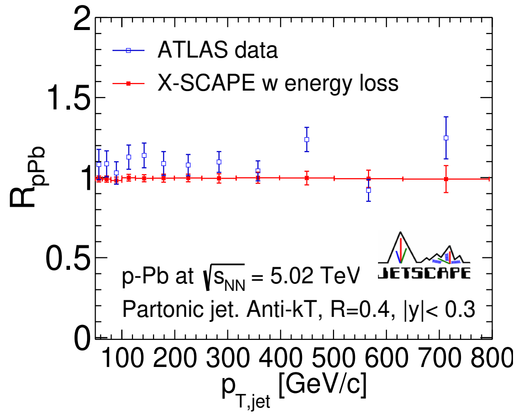
[Perepelitsa PRC(2024)]

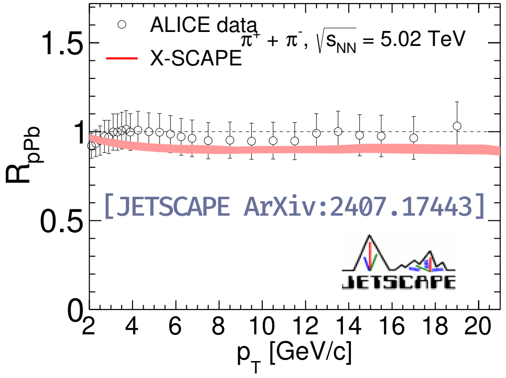
Energy Loss?

S. Jeon Tue. 16:15

- Short Bulk Extent
  - » Energy Loss Negligible







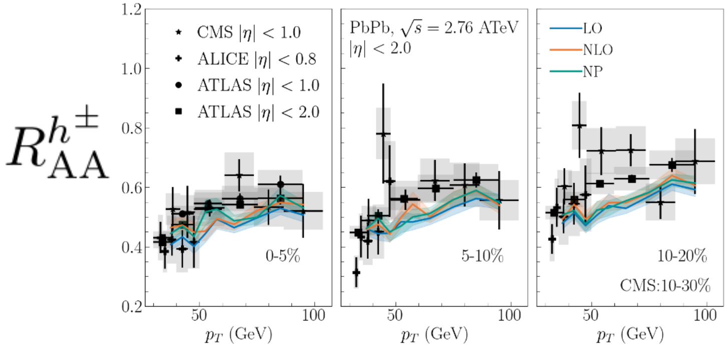
Formation Time

Shuzhe Mon. 15:40

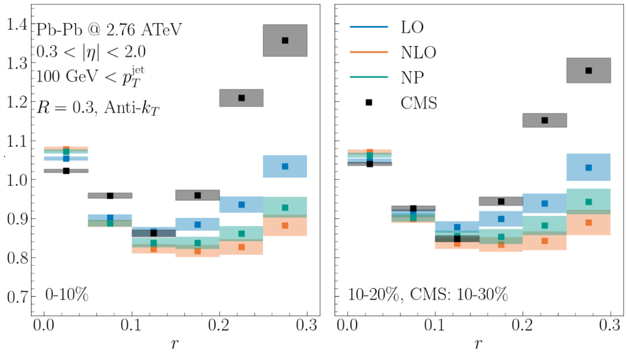
»Formation Time ⇒ Simultaneous Desc. Charged Hadron And Jet R_{AA}

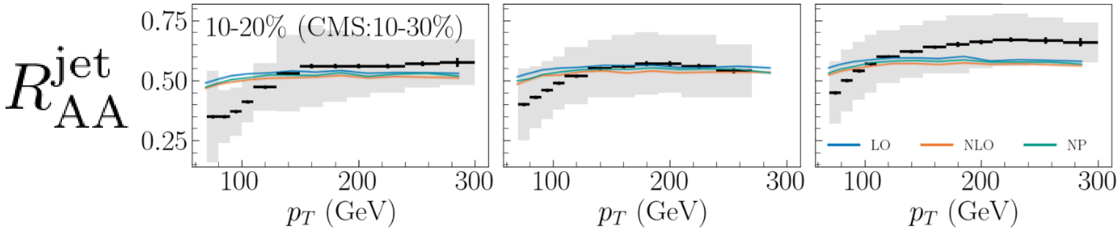
»Limitation: Jet Substructure Observables

»LO/NLO/NP Potential ⇒ Similar Ratios, ≠ Substructure



$$R^{\rho}_{\rm AA} = \frac{\rho_{\rm AA}(r)}{\rho_{\rm pp}(r)}$$





[Modarresi-Yazdi, Shi, Gale, Jeon ArXiv:2407.19966]

Early Stages

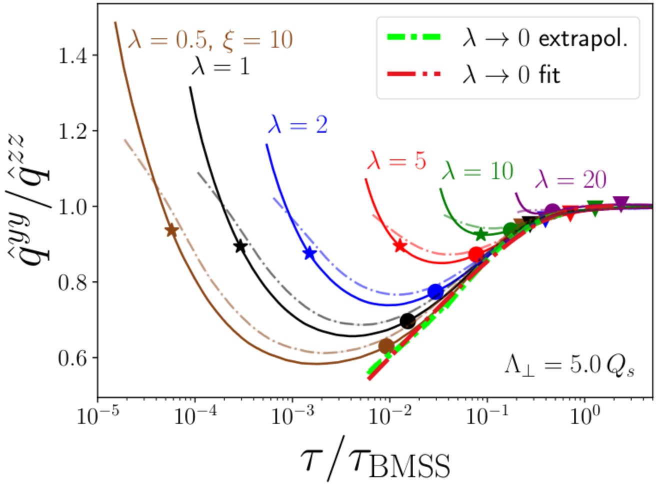
F. Lindenbauer Mon. 17:30

- Broadening In Non-Eq EKT

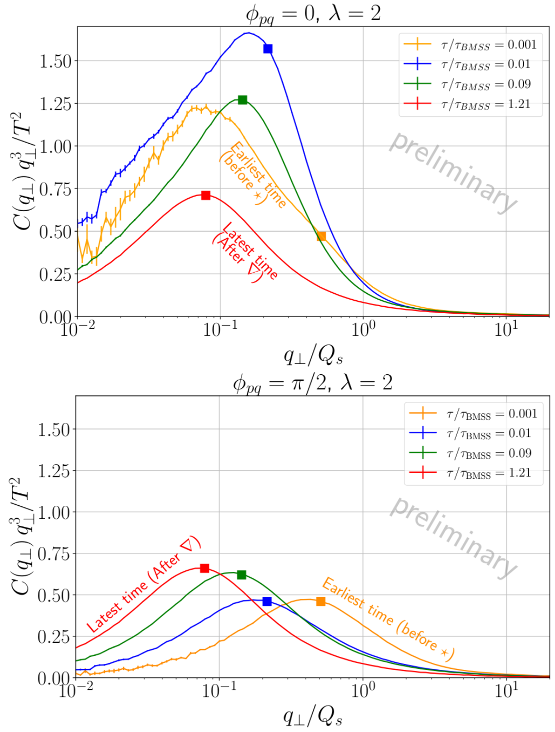
»Momentum Broadening Affected By Anisotropy⇒Scaling Behavior

»Broadening Kernel Extraction ⇒ Markedly Different Throughout The Equilibration

$\hat{q}$



$C(q_T)$



[K. Boguslavski, A. Kurkela, T. Lappi, F. Lindenbauer, J. Peuron PLB (2024) PhysRevD (2024)]

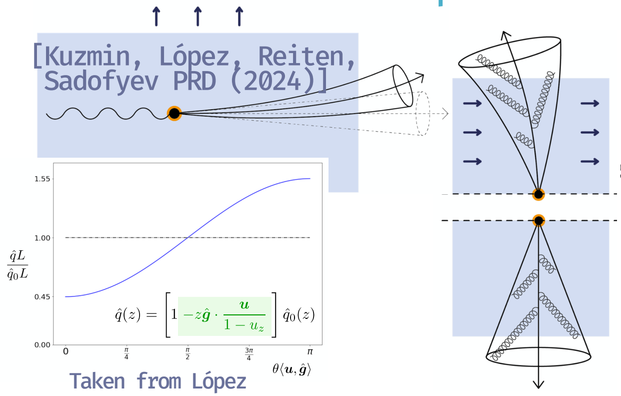
Gradient effects

Medium Gradients

Broadening

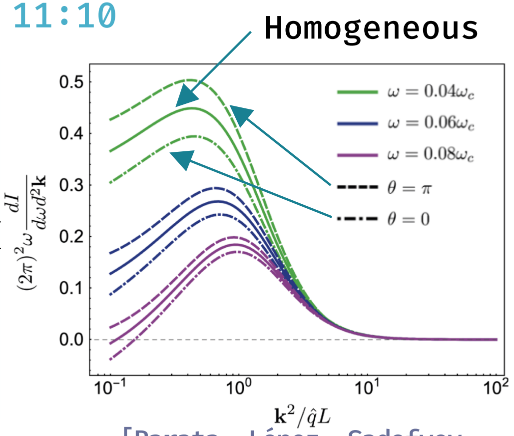
X. Lopez Wed. 11:10

[Kuzmin, López, Reiten, Sadofyev PRD (2024)]



Taken from López

Radiation



[Barata, López, Sadofyev, Salgado PRD (2023)]

Jet Drift

$$\langle \vec{q}_{drift}\rangle = \hat{e}_\perp \int d\tau \frac{3}{E(\tau)} \frac{\mu^2(\tau)}{\lambda(\tau)} \ln\frac{E(\tau)}{\mu(\tau)} \frac{u_\perp(\tau)}{1-u_\parallel(\tau)}$$

Flow enhanced and flow direction controlled

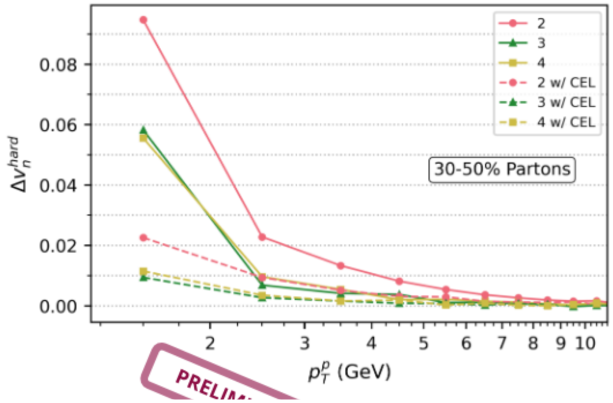
Energy suppressed

Temperature/Density Enhanced

$\frac{1}{\lambda} = \sigma\rho$
$\rho \propto T^3$
$\mu \propto T$

Derivation
A. V. Sadofyev, I. Vitev, & M. D. Sievert
Phys.Rev.D 104 (2021)
(arXiv:2104.09513)

Analytic Pheno.
L. Antiporda, J. Bahder, H. Rahman & M. D. Sievert
Phys.Rev.D 105 (2022)
(arXiv: 2110.03590)



J. Bahder Tue 11:50

» Suppressed Brodening/Radiation Along Gradient

» Enhanced Broadening/Radiation Opposite To Gradient

» Jet-v_2 correlations due to drifts

Conclusion

- Heavy-Ion ⇒ Jet Perturbation On Top Of The QGP
- Small Systems ⇒ Bulk Dynamics Altered By Jets

»Observables ⇒ Jet v_2 vs R_{AA} , Jet-Substructure See Daniel Talk Before

»Small Systems ⇒ A Laboratory to Understand Int. St. Correlations? Int. St. Energy Loss? See Isobel Talk Next

Backup

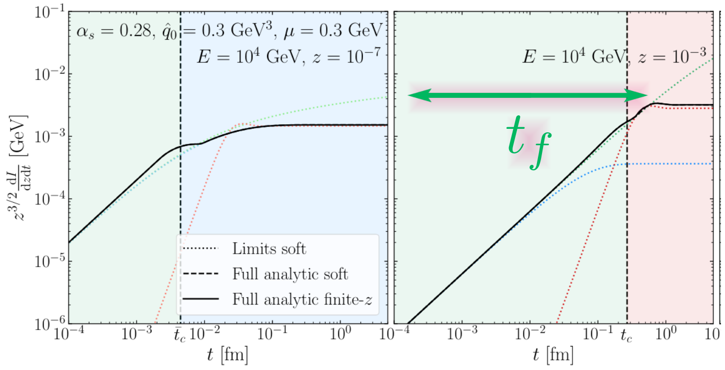
Beyond AMY

» Time Dependent Splitting Rates

[Isaksen, Takacs, Tywoniuk JHEP(2023)]

$$\partial_t D(x) = \int_0^1 dz \left[\frac{d\Gamma^a_{bc}}{dz}\left(\frac{x}{z}, z, t\right) zD\left(\frac{x}{z}\right) - \frac{d\Gamma^a_{bc}}{dz}(x, z, t) zD(x)\right]$$

» Static Medium



Rate

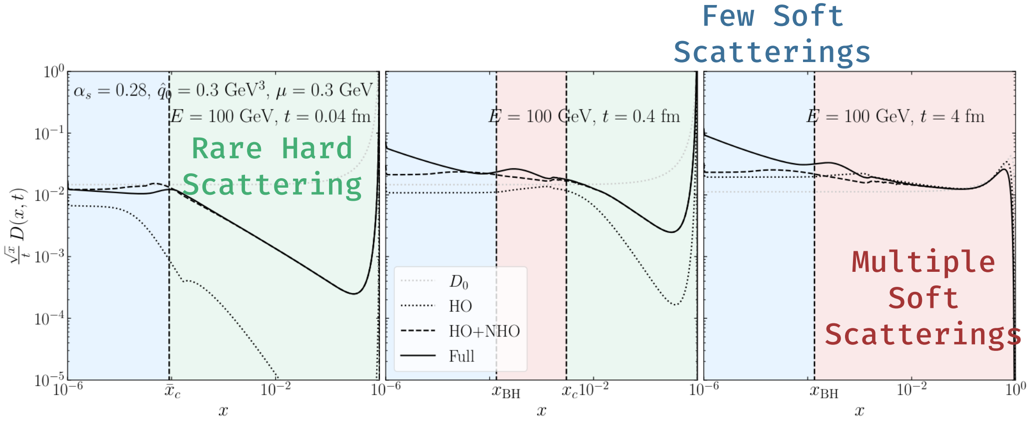
Beyond AMY

» Time Dependent Splitting Rates

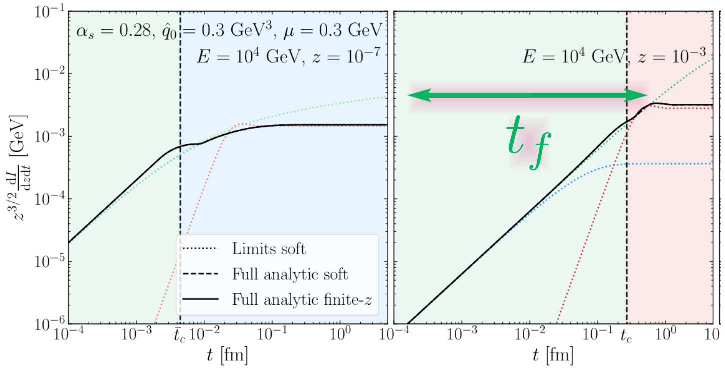
[Isaksen, Takacs, Tywoniuk JHEP(2023)]

$$\partial_t D(x) = \int_0^1 dz \, \left[\frac{d\Gamma^a_{bc}}{dz}\left(\frac{x}{z}, z, t\right) zD\left(\frac{x}{z}\right) - \frac{d\Gamma^a_{bc}}{dz}(x, z, t) zD(x) \right]$$

» Static Medium



Distribution

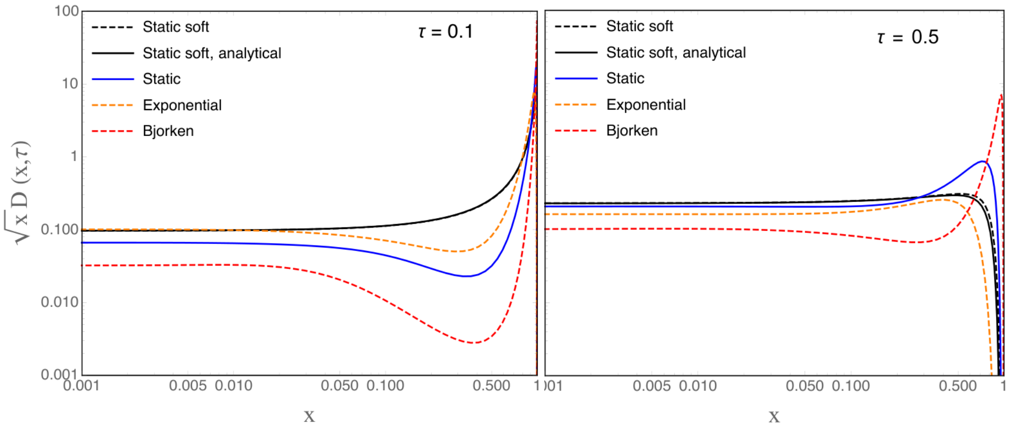


Rate

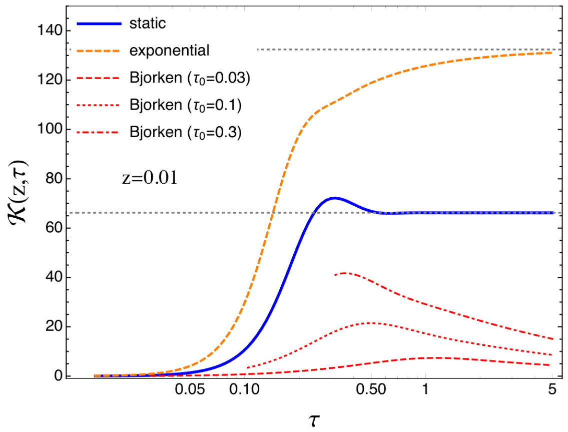
Harmonic Oscillator

[AdhHya, Salgado,Spoustaa, Tywoniuk JHEP (2020)]

- »Rates in Expanding Medium w/ HO Approx.
- »Analytical expressions [BDMPS, Arnold]
- »Temperature decreases $T \ll P \Rightarrow$ Multiple Soft Scattering



Distribution



Rate