

In-medium parton energy loss in small and large collision systems

Carlota Andrés

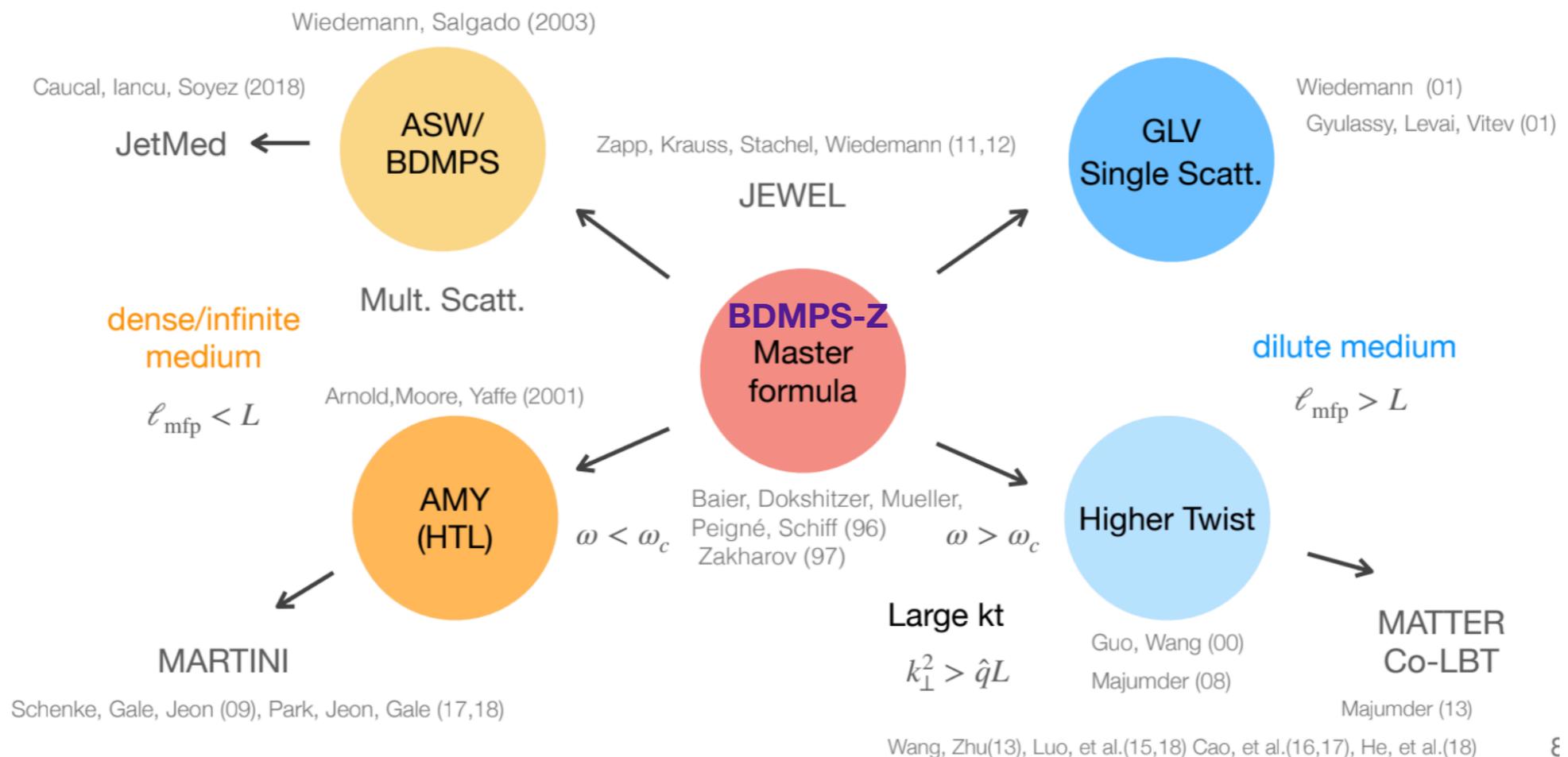
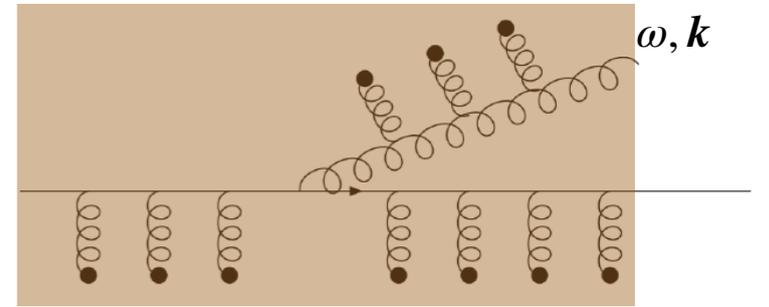
CPhT, École polytechnique
QCD challenges from pp to AA collisions
February 13-17 2023, Padova



Energy loss in AA

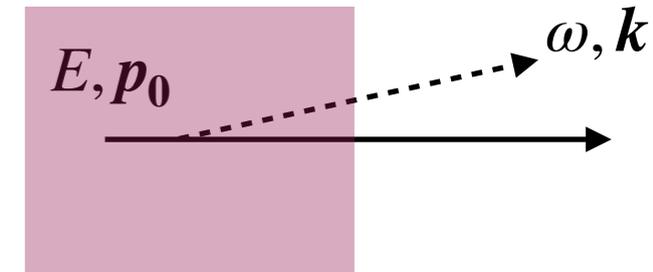
Energy loss

- How does a parton lose energy in a QCD medium?
- Collisions - Important for heavy particles
- **Radiation** - **Extra gluon radiation** induced by multiple scatterings with the medium
Dominant for light quarks and gluons



from Yacine Mehtar-Tani's talk at the HTE seminar series

Recent developments



- The in-medium spectrum is given by ($\omega \ll E$):

$$\omega \frac{dI^{\text{med}}}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\mathbf{p}\mathbf{q}} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) \mathcal{P}(\infty, \mathbf{k}; t', \mathbf{q})$$

BDMPS-Z

- Several new approaches that **evaluate the master formula beyond the usual approximations**

Finite length rates: Caron-Huot and Gale, [1006.2379](#)

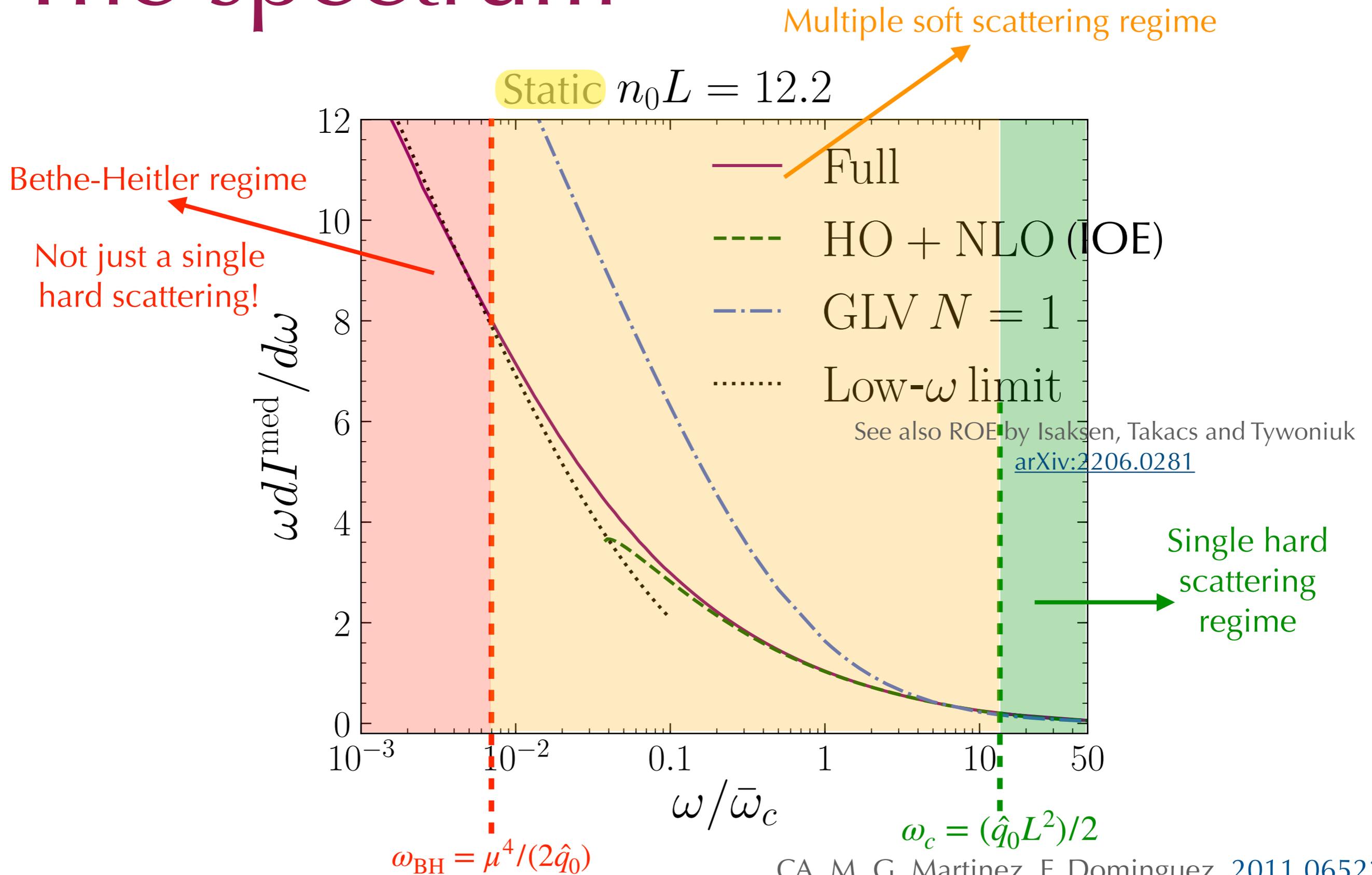
IOE (expansion around the HO): Mehtar-Tani, Barata, Soto-Ontoso, Tywoniuk, [1903.00506](#), [2106.07402](#)

Fully resummed spectrum: CA, Apolinario, Dominguez, Martinez [2002.01517](#), [2011.06522](#)

Finite length rates + non-perturbative potential: Schlichting, Soudi, [2111.13731](#)

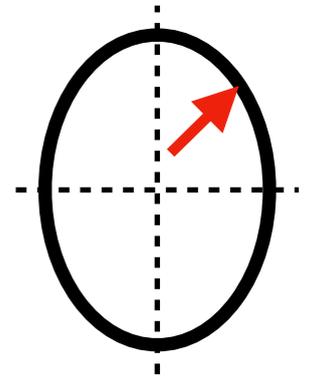
IOE & Resummed opacity expansion (ROE) Isaksen, Takacs and Tywoniuk [arXiv:2206.0281](#)

The spectrum



CA, M. G. Martinez, F. Dominguez, [2011.06522](https://arxiv.org/abs/2011.06522)

R_{AA}



- Single-inclusive cross section:

$$\frac{d\sigma^{AA \rightarrow h+X}}{dp_T dy} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \frac{dz}{z} \sum_{i,j,k} x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/A}(x_2, Q^2) \frac{d\hat{\sigma}^{ij \rightarrow k}}{d\hat{t}} D_{k \rightarrow h}^{(med)}(z, \mu_F^2)$$

nPDFs

- Fragmentation functions:

$$D_{k \rightarrow h}^{(med)}(z, \mu_F^2) = \int_0^1 d\epsilon P_E(\epsilon) \frac{1}{1-\epsilon} D_{k \rightarrow h}^{(vac)}\left(\frac{z}{1-\epsilon}, \mu_F^2\right)$$

FFs

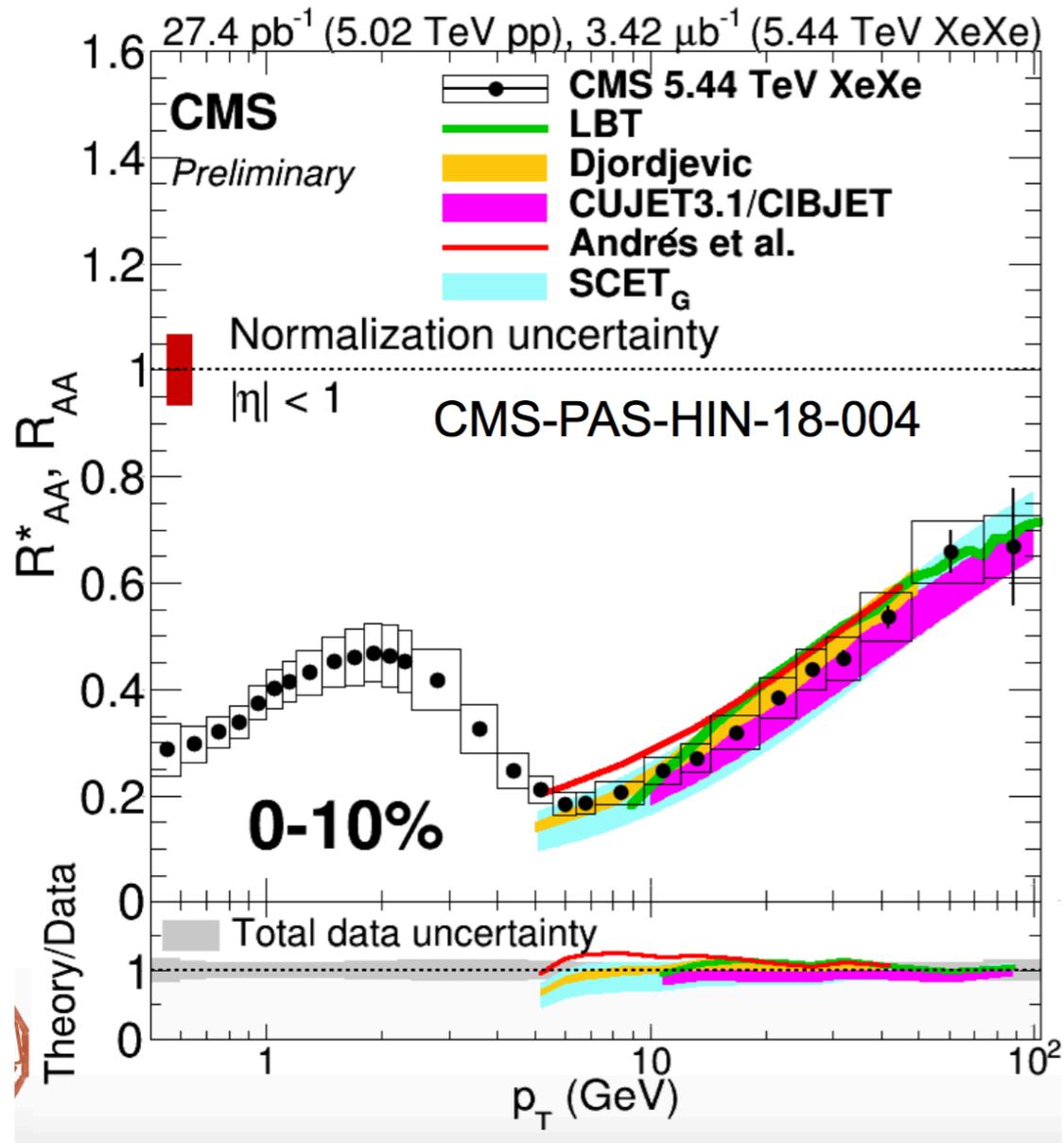
Local medium energy density

ENERGY LOSS: Quenching Weights (QWs)

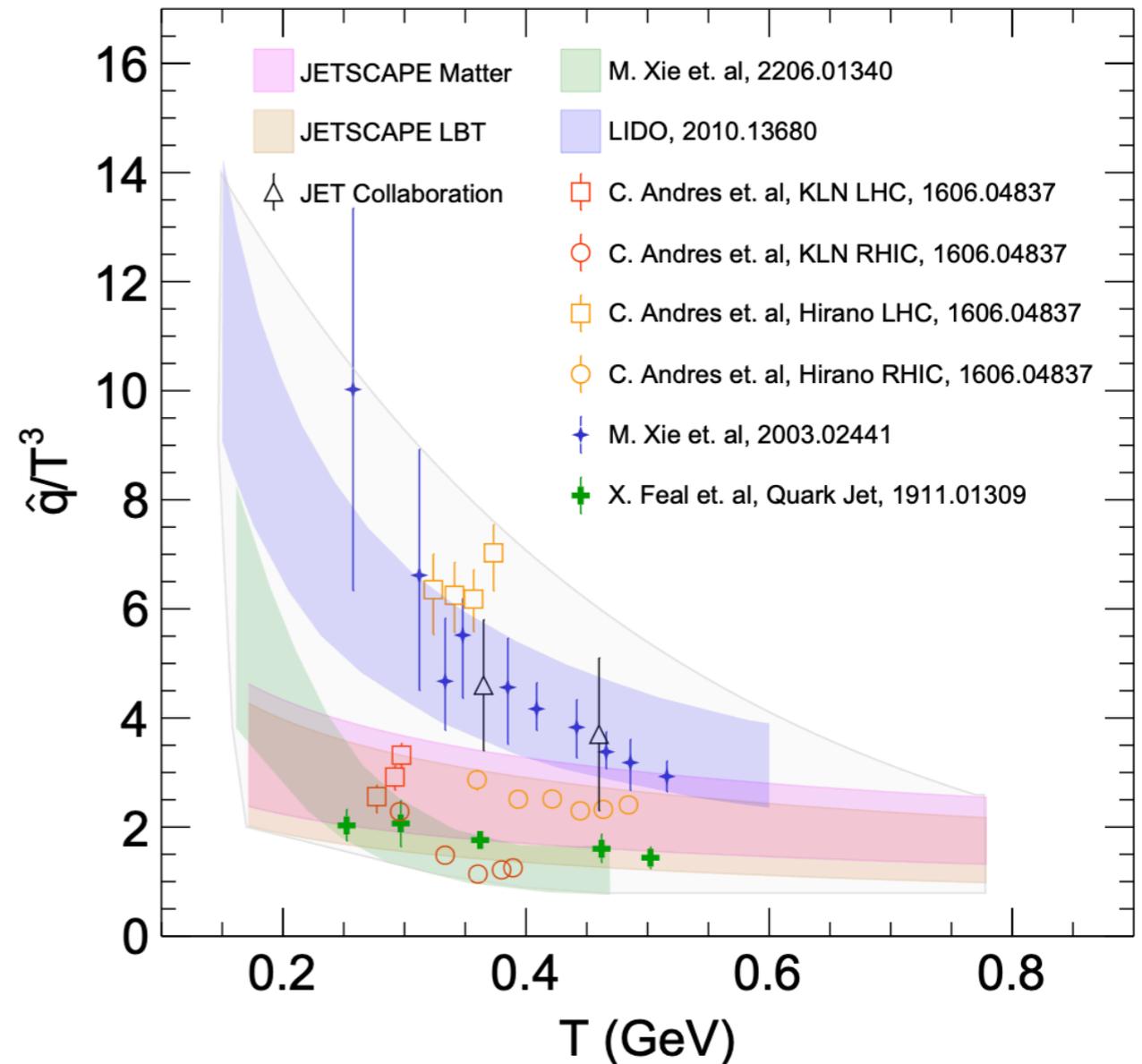
$$\hat{q}(\xi) = K \cdot 2\epsilon^{3/4}(\xi)$$

Probability distribution of a fractional energy loss $\epsilon = \Delta E / E$ of the hard parton in the medium

R_{AA} and \hat{q}



Austin Baty, QM2018



Apolinario, Lee, Winn, [arXiv: 2203.16352](https://arxiv.org/abs/2203.16352)

Small systems

Small systems

Jet quenching is the only QGP signature **not observed** in small systems

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra (“radial flow”)	yes	yes	yes	[47, 71, 317, 318, 654, 657, 663, 664, 667, 668]
Intermediate p_T (“recombination”)	yes	yes	yes	[317, 657–663]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[318, 638, 664, 665]
Statistical model	$\gamma_s^{\text{GC}} = 1, 10\text{--}30\%$	$\gamma_s^{\text{GC}} \approx 1, 20\text{--}40\%$	MB: $\gamma_s^{\text{C}} < 1, 20\text{--}40\%$	[318, 638, 669]
HBT radii ($R(k_T), R(\sqrt[3]{N_{\text{ch}}})$)	$R_{\text{out}}/R_{\text{side}} \approx 1$	$R_{\text{out}}/R_{\text{side}} \lesssim 1$	$R_{\text{out}}/R_{\text{side}} \lesssim 1$	[670–677]
Azimuthal anisotropy (v_n) (from two particle correlations)	$v_1\text{--}v_7$	$v_1\text{--}v_5$	$v_2\text{--}v_4$	[48, 312–314, 632, 633, 652, 678–688]
Characteristic mass dependence	$v_2\text{--}v_5$	v_2, v_3	v_2	[48, 315, 326, 683, 686, 689–691]
Directed flow (from spectators)	yes	no	no	[692]
Charge-dependent correlations	yes	yes	yes	[249, 253, 254, 693–696]
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	“4 \approx 6 \approx 8 \approx LYZ” +higher harmonics	“4 \approx 6 \approx 8 \approx LYZ” +higher harmonics	“4 \approx 6”	[316, 683, 688, 697–708]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[227, 687, 709–712]
Non-linear flow modes	up to v_6	not measured	not measured	[713]
Weak η dependence	yes	yes	not measured	[685, 707, 714–719]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[682, 684, 720–722]
Event-by-event v_n distributions	$n = 2\text{--}4$	not measured	not measured	[723–725]
Direct photons at low p_T	yes	not measured	not observed	[544, 726]
Jet quenching through dijet asymmetry	yes	not observed	not observed	[348, 360, 374, 727–729]
Jet quenching through R_{AA}	yes	not observed	not observed	[323, 344, 346, 347, 352, 730–737]
Jet quenching through correlations	yes (Z–jet, γ –jet, h–jet)	not observed (h–jet)	not measured	[354, 357, 375, 376, 380, 388, 733, 738–740]
Heavy flavor anisotropy	yes	yes	not measured	[262, 326, 460–464, 497, 741–745]
Quarkonia production	suppressed [†]	suppressed	not measured	[262, 454, 456, 459, 478, 479, 491, 492, 494, 495, 497, 579, 746–755]

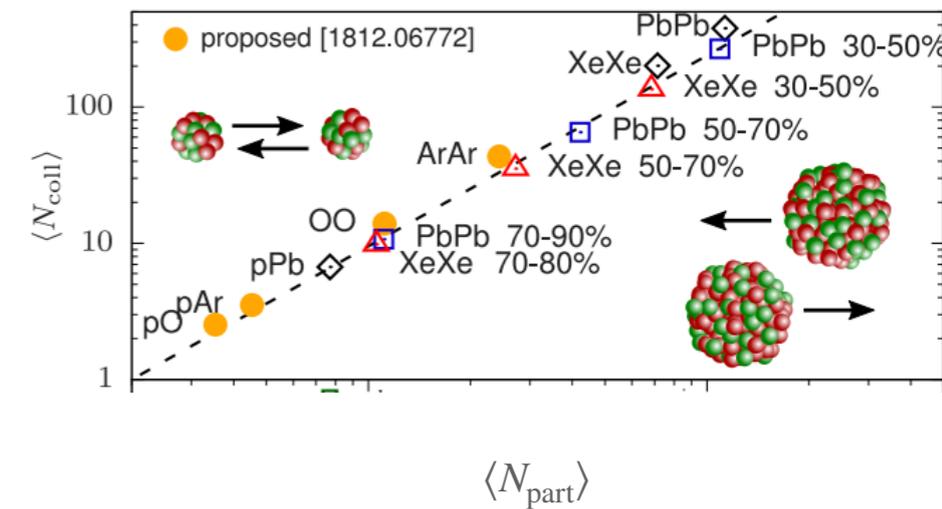
[†] J/ψ \uparrow , $Y(\downarrow)$ w.r.t. RHIC energies.

No signal of jet quenching!

[arXiv:1812.06772](https://arxiv.org/abs/1812.06772)

Energy loss in small systems

- Expected to be **small**
 - Difficult to select pPb collisions with small b
- Why don't we go for **peripheral PbPb** instead?
 - Event selection and geometry biases

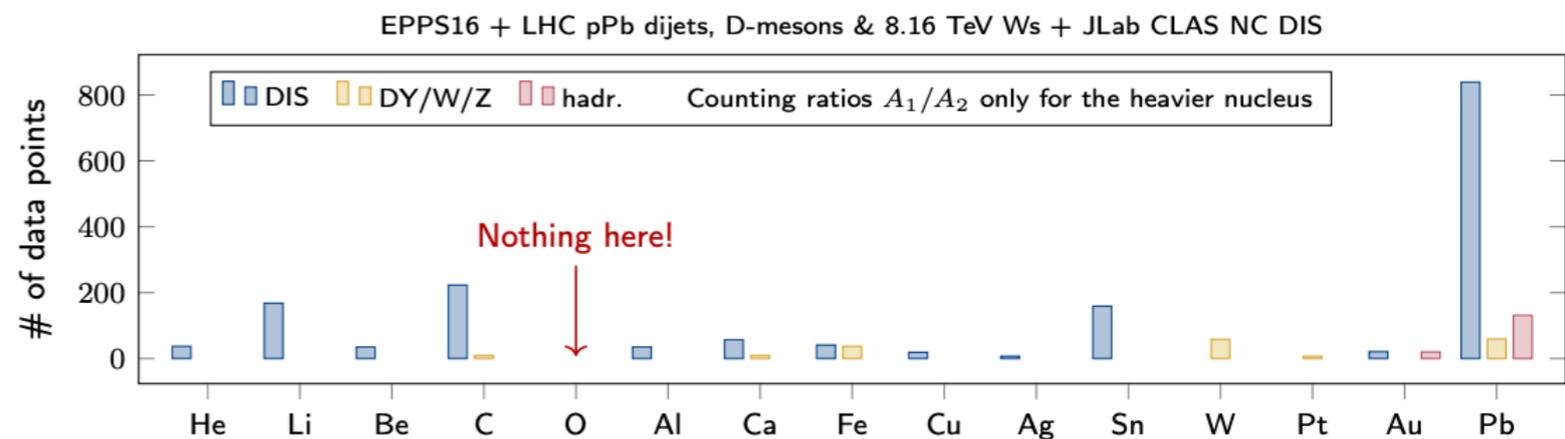
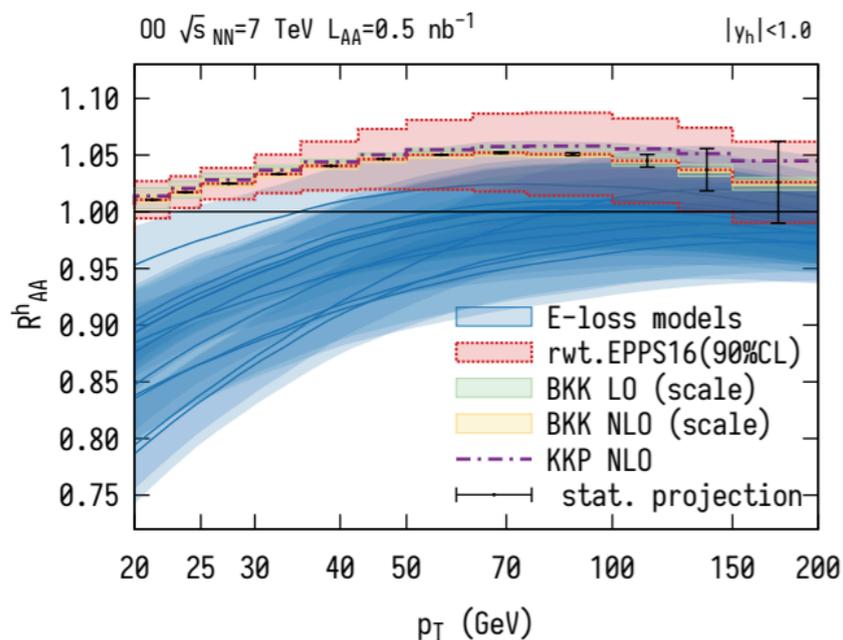


Morsch and Loizides, [arxiv: 1705.08856](https://arxiv.org/abs/1705.08856)

• Oxygen-Oxygen?

Huss, Kurkela, Mazeliauskas, Paatelainen, Van der Schee, Wiedemann [arxiv:2007.13754](https://arxiv.org/abs/2007.13754), [arxiv:2007.13754](https://arxiv.org/abs/2007.13754)

From Petja Paakkinen's [talk](#) at the [Opportunities of OO and pO collisions at the LHC workshop](#)



Glucos poorly constrained for light nuclei

Significant **parametrization biases**

$$R_{AA, \text{min bias}}^{h,j}(p_T, y) = \frac{1}{A^2} \frac{d\sigma_{AA}^{h,j}/dp_T dy}{d\sigma_{pp}^{h,j}/dp_T dy}$$

Jets pheno

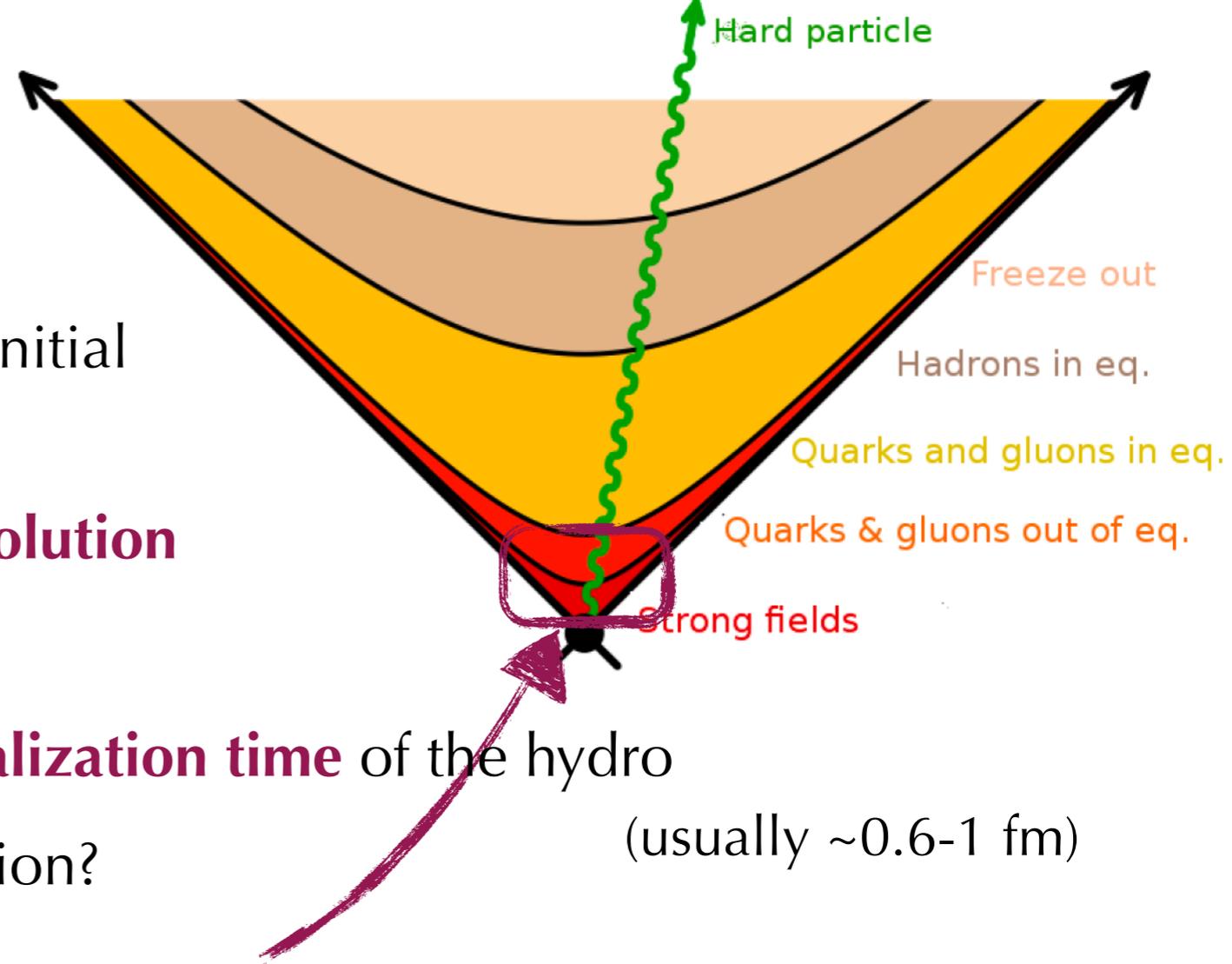
- Hard probes/jets are produced in the initial hard scattering

Jets **witness the space-time system evolution** (including the initial stages)

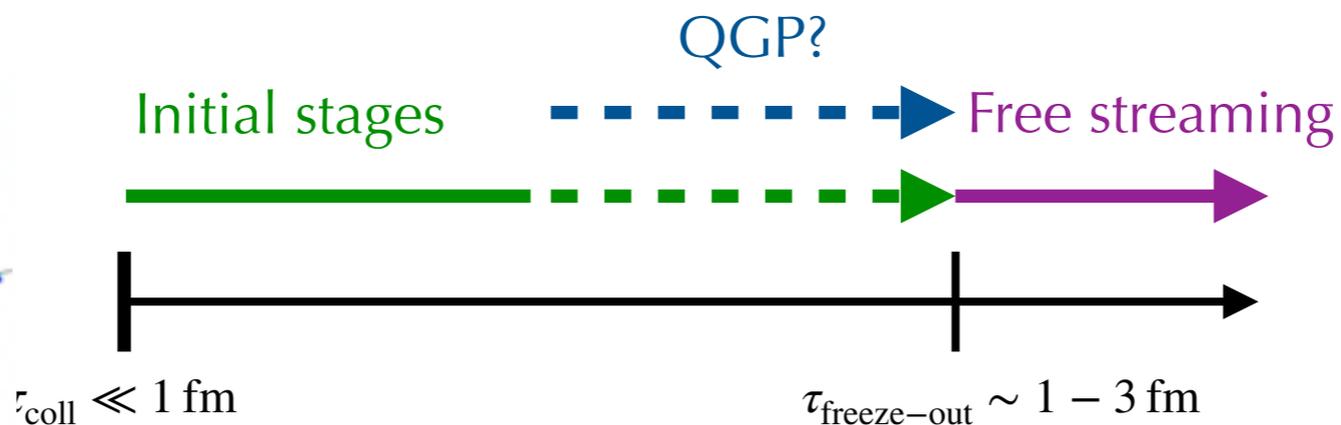
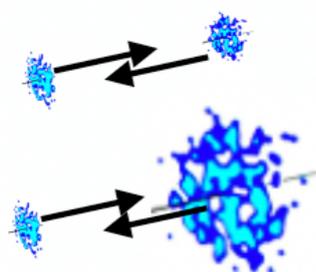
- The **quenching set to start at the initialization time** of the hydro (usually $\sim 0.6-1$ fm)
No energy loss before thermalization?

- How **sensitive are jet observables in AA to the initial stages?**
Crucial to understand the apparent lack of energy loss in small systems

- The initial stages represent a larger fraction of the system's evolution in small systems



pA & pp



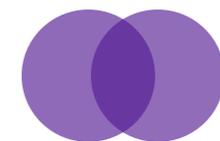
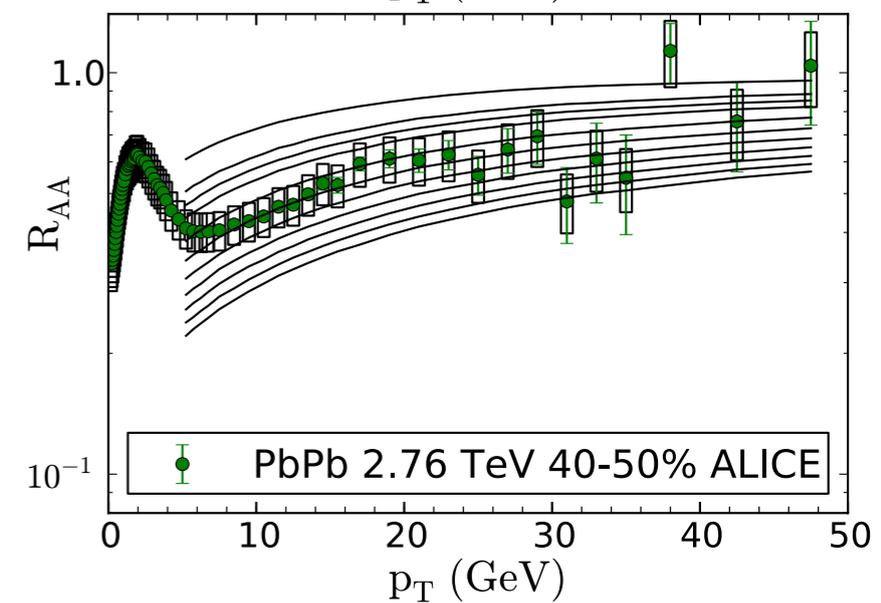
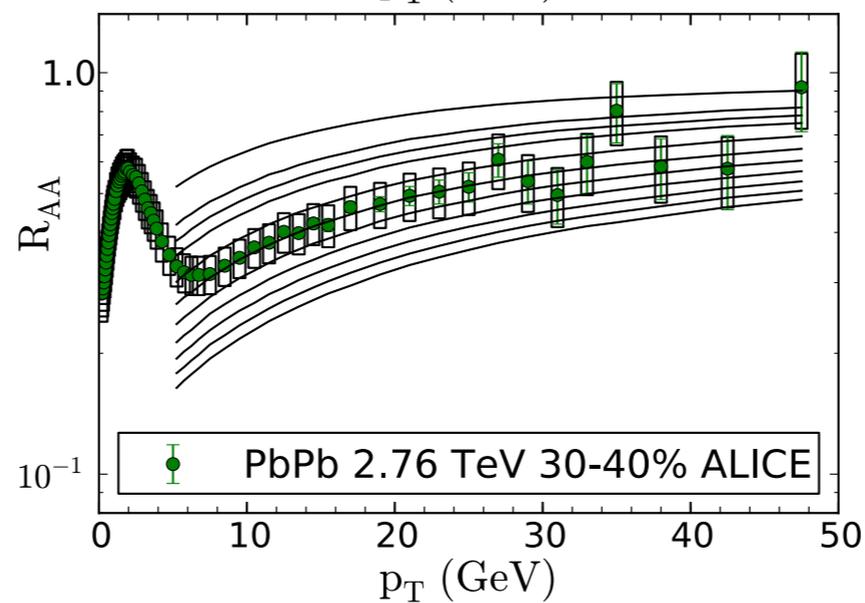
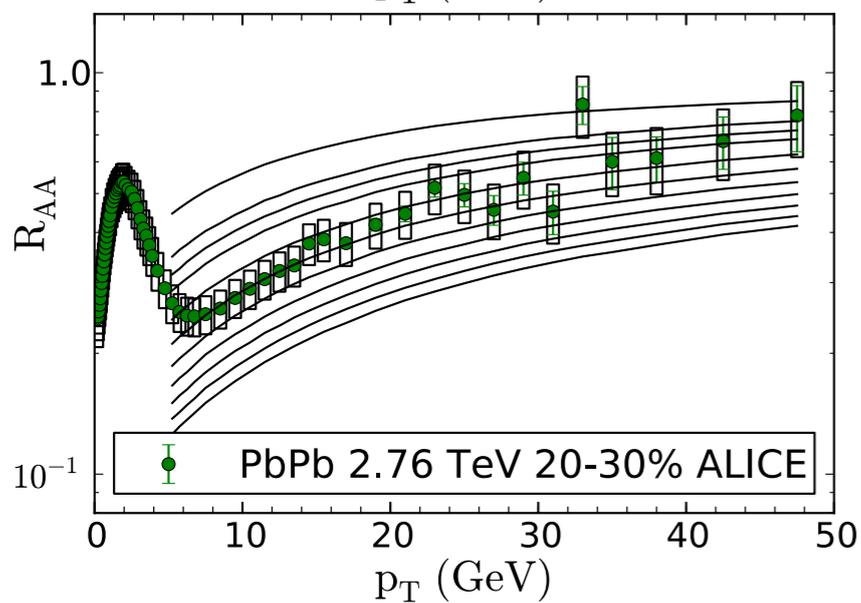
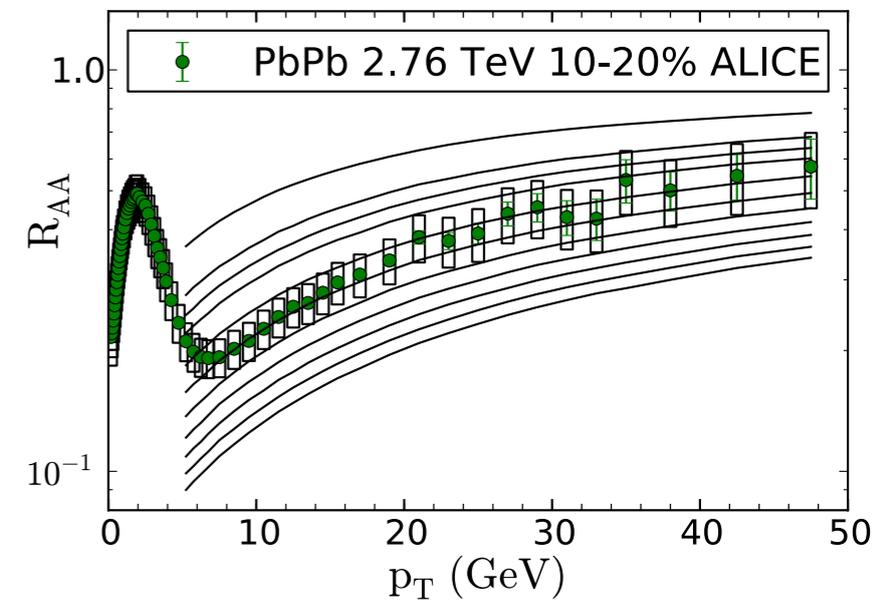
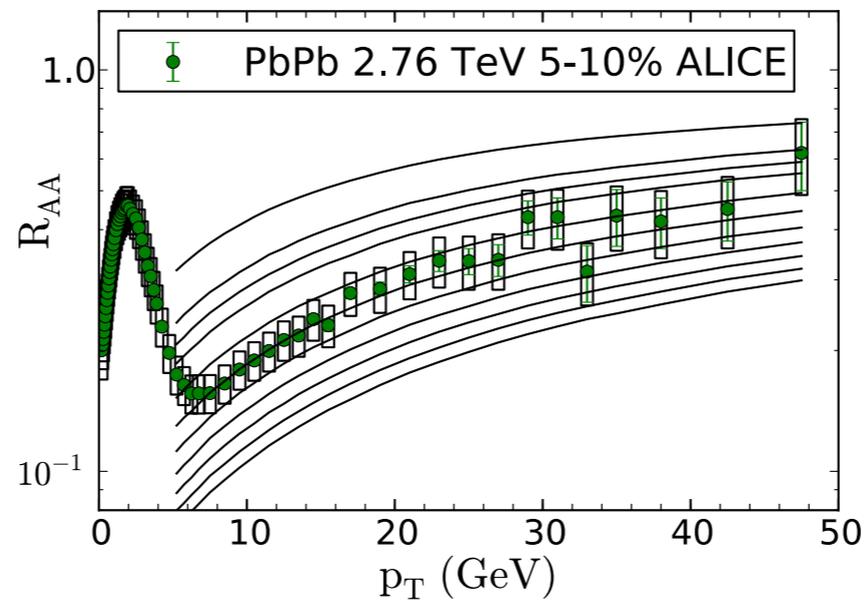
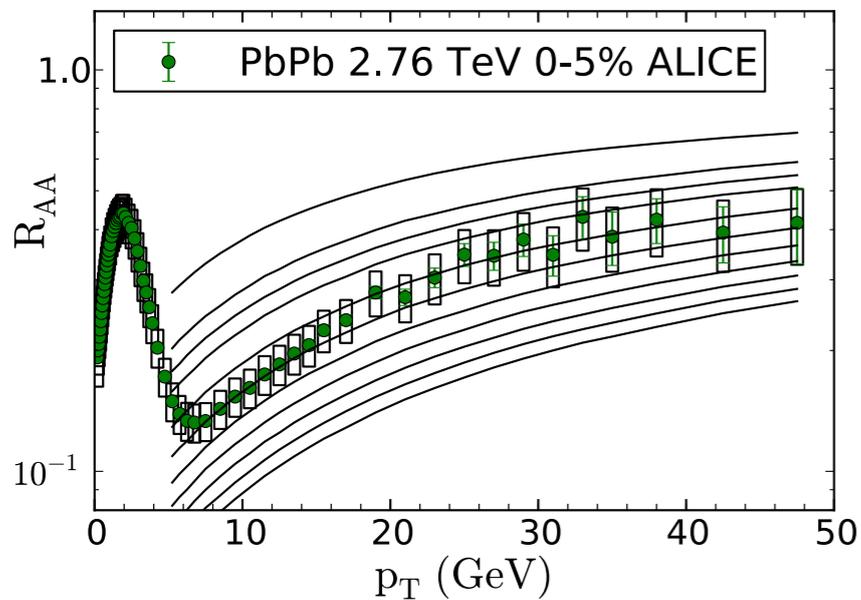
Energy loss & initial stages in AA

R_{AA} at 2.76 TeV



QWs in the Harmonic oscillator
2+1 viscous hydro

$$\hat{q}(\xi) = K \cdot 2e^{3/4}(\xi)$$



Formalism

- Energy density taken from the hydro

Viscous 2+1 hydrodynamics

$$\eta/s = 0.16$$

Luzum and Romatschke [arXiv:0804.4015](https://arxiv.org/abs/0804.4015)
[arXiv:0901.4588](https://arxiv.org/abs/0901.4588)

$$\tau_{\text{hydro}} = 1 \text{ fm}$$

fKLN model for the initial condition

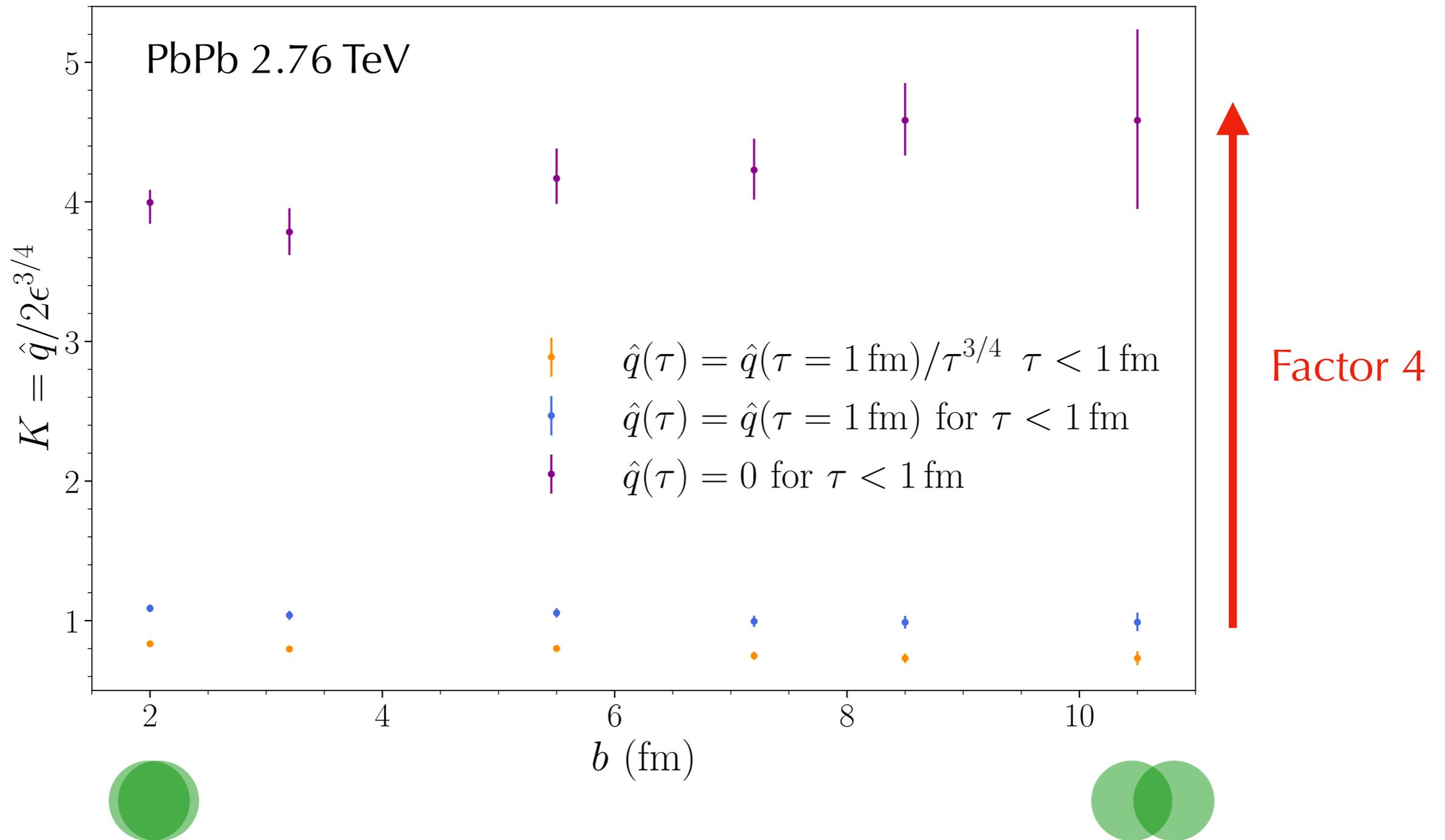
- Before τ_{hydro} ?

- $\hat{q}(\tau) = \hat{q}(\tau_{\text{hydro}})/\tau^{3/4}$ for $\tau < \tau_{\text{hydro}}$

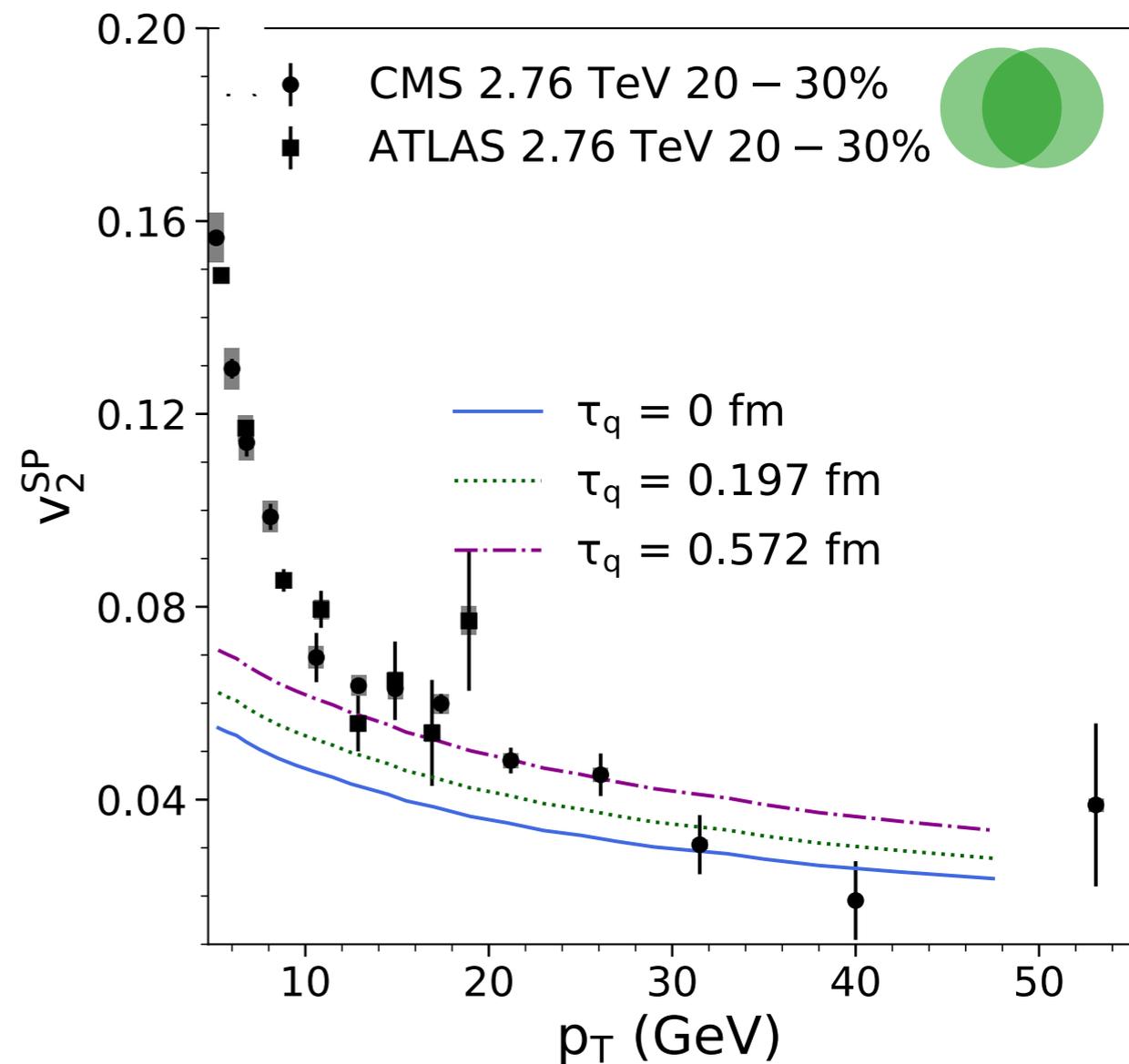
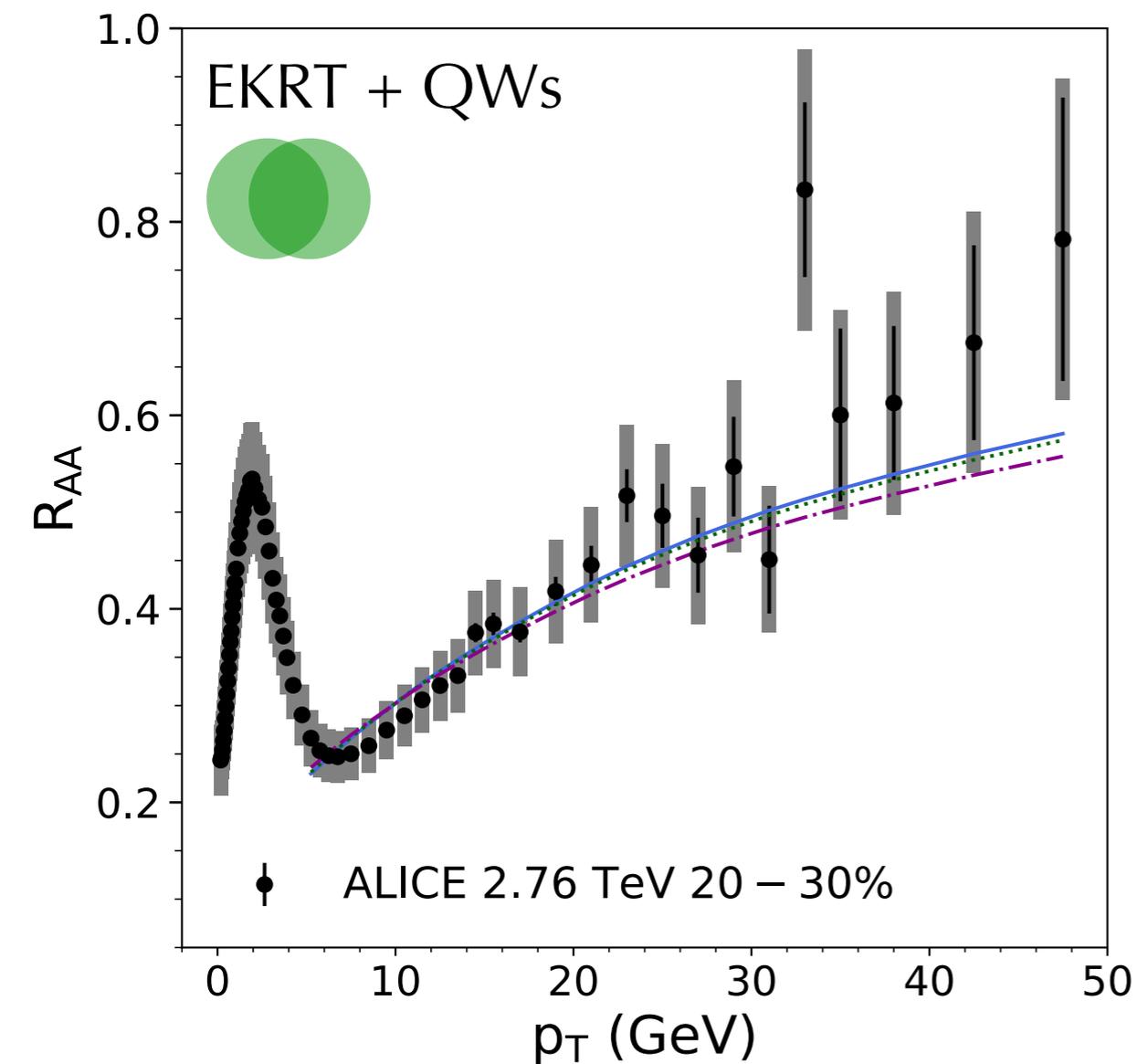
- $\hat{q}(\tau) = \hat{q}(\tau_{\text{hydro}})$ for $\tau < \tau_{\text{hydro}}$

- $\hat{q}(\tau) = 0$ for $\tau < \tau_{\text{hydro}}$ \longrightarrow Energy loss delayed 1 fm

Jet quenching parameter



R_{AA} and high- p_T v_2 as a probe of IS



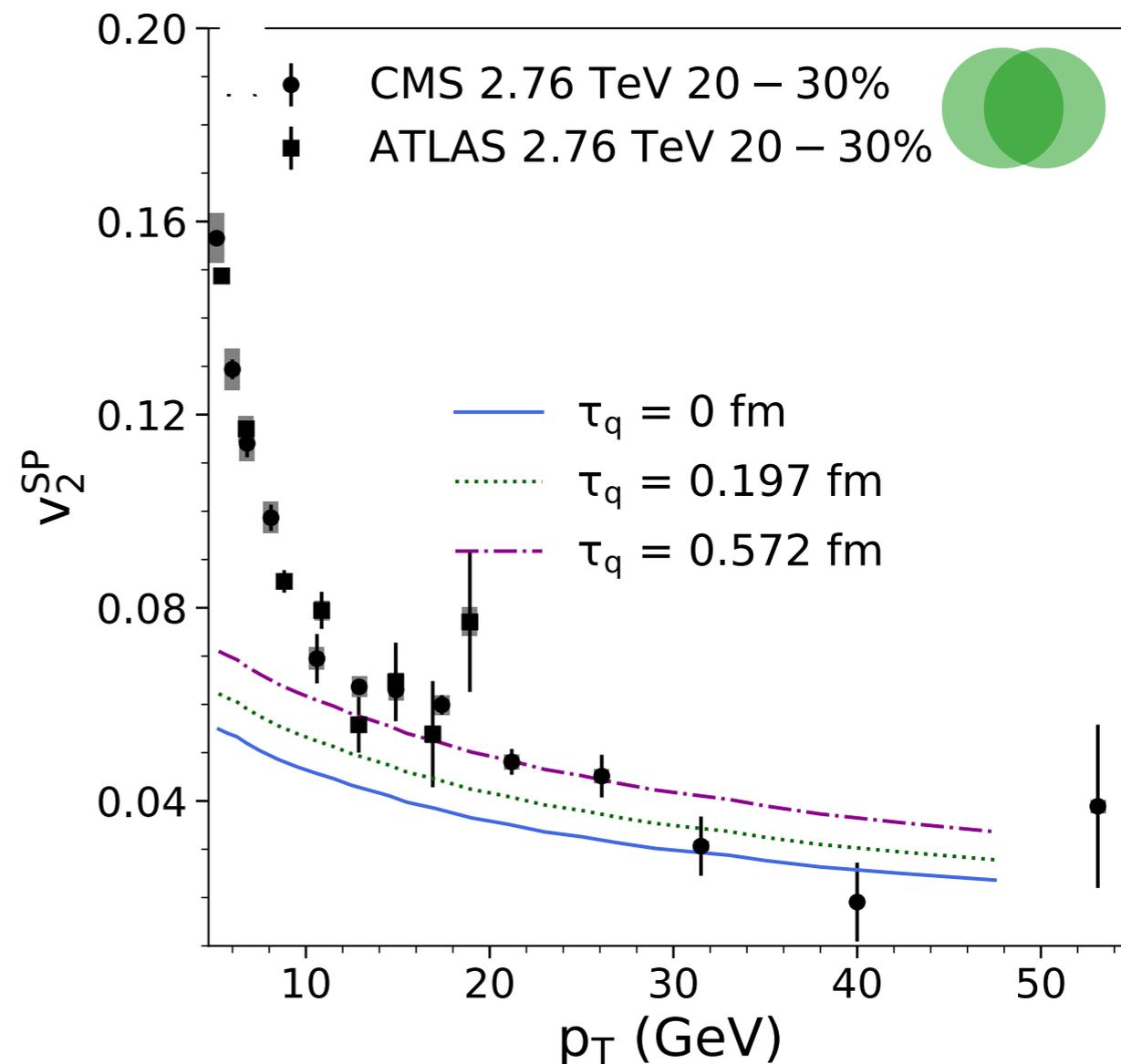
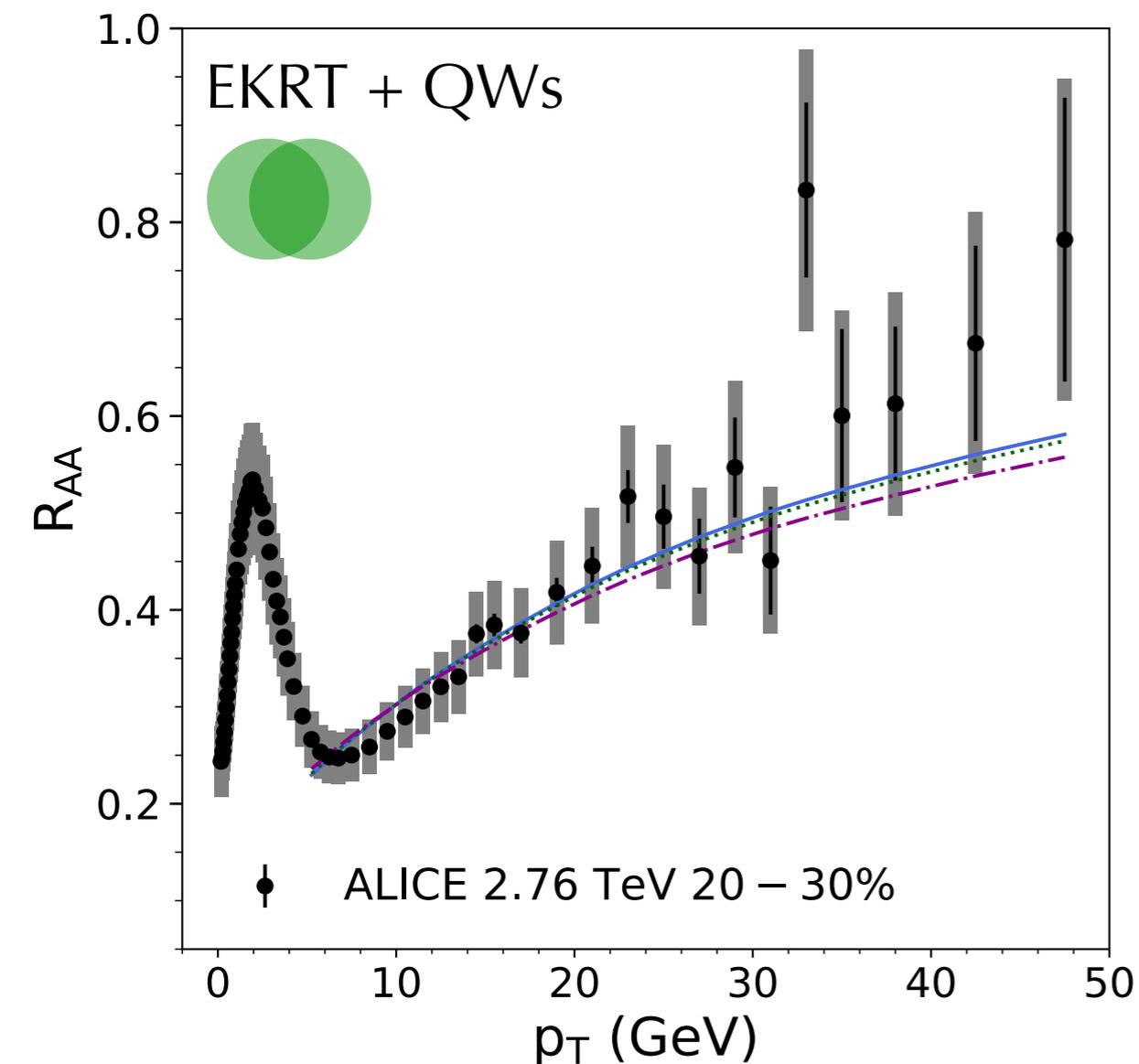
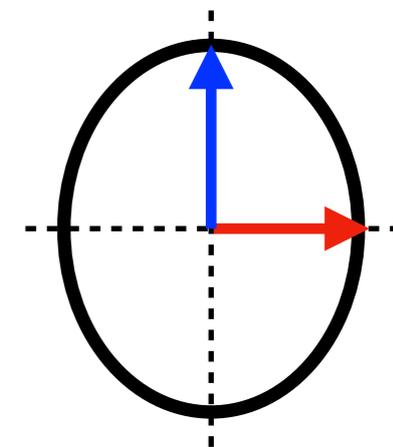
Very sensitive to the initial stages!

Confirmed later by: Stojku et al.

CA, Armesto, Niemi, Paatelainen, Salgado, [arXiv:1902.03231](https://arxiv.org/abs/1902.03231)

[arXiv:2008.08987](https://arxiv.org/abs/2008.08987)

R_{AA} and high- p_T v_2 as a probe of IS



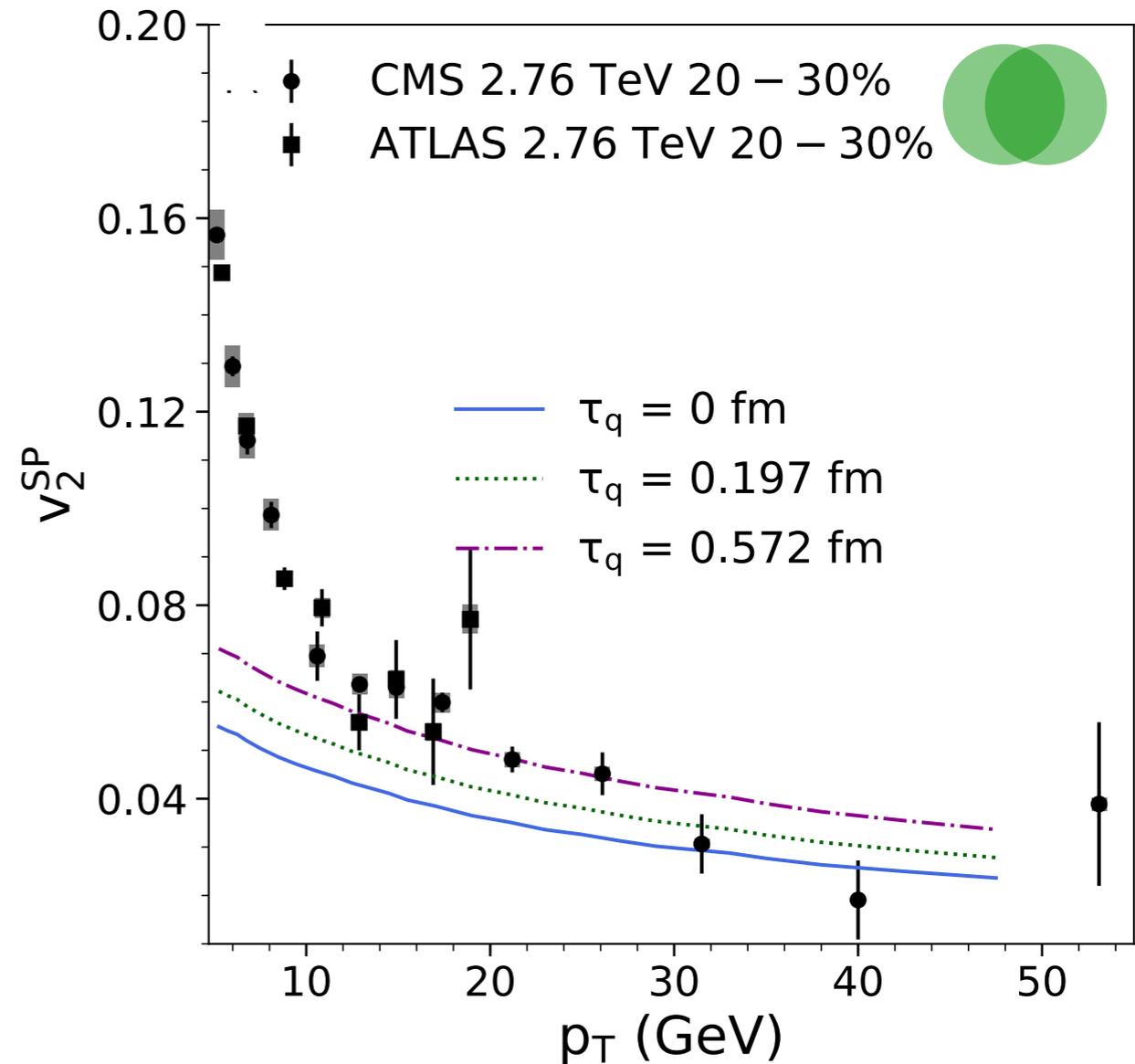
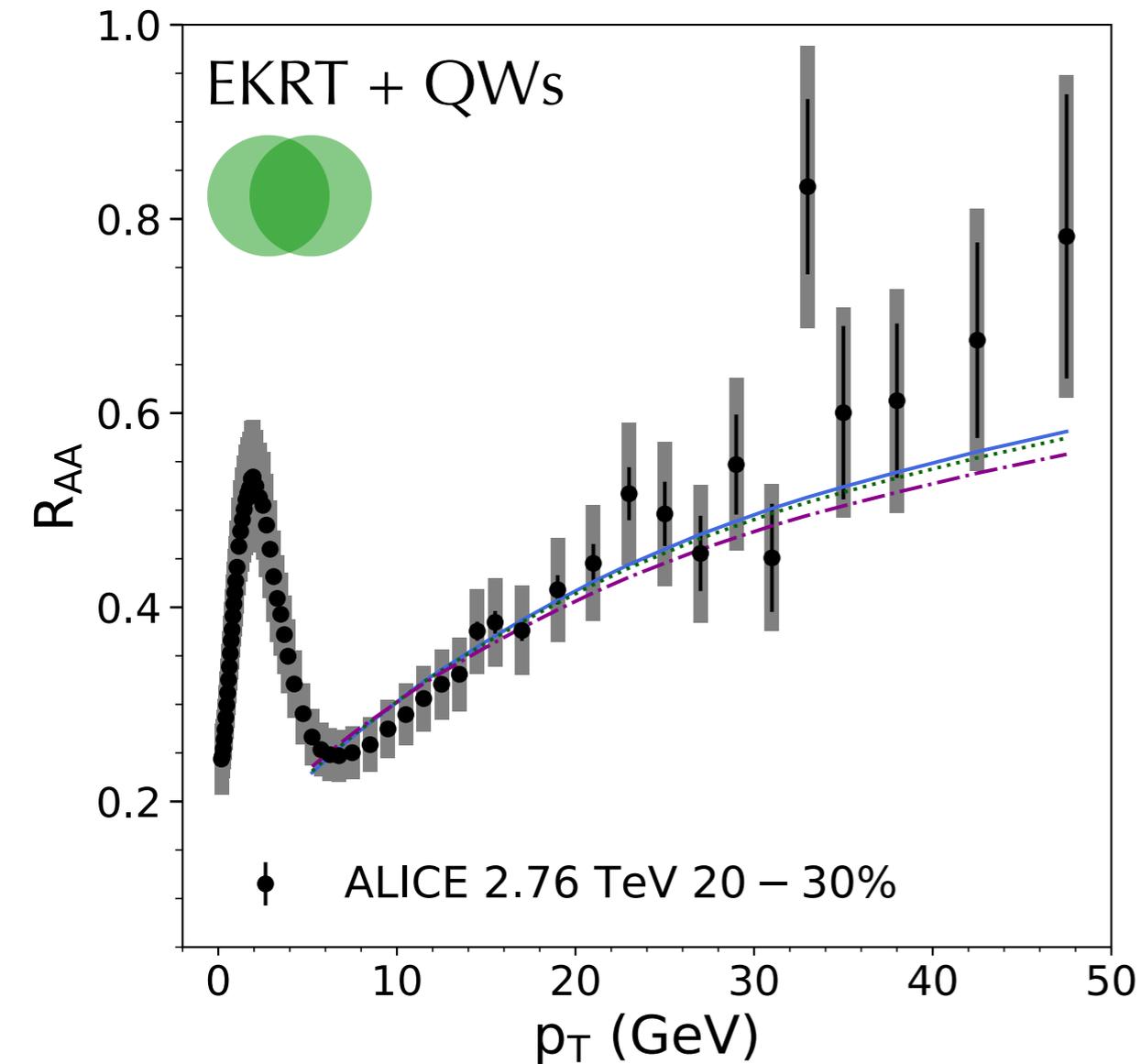
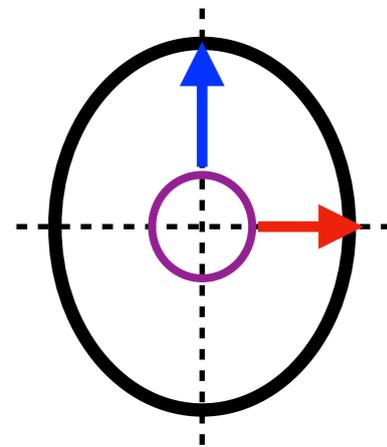
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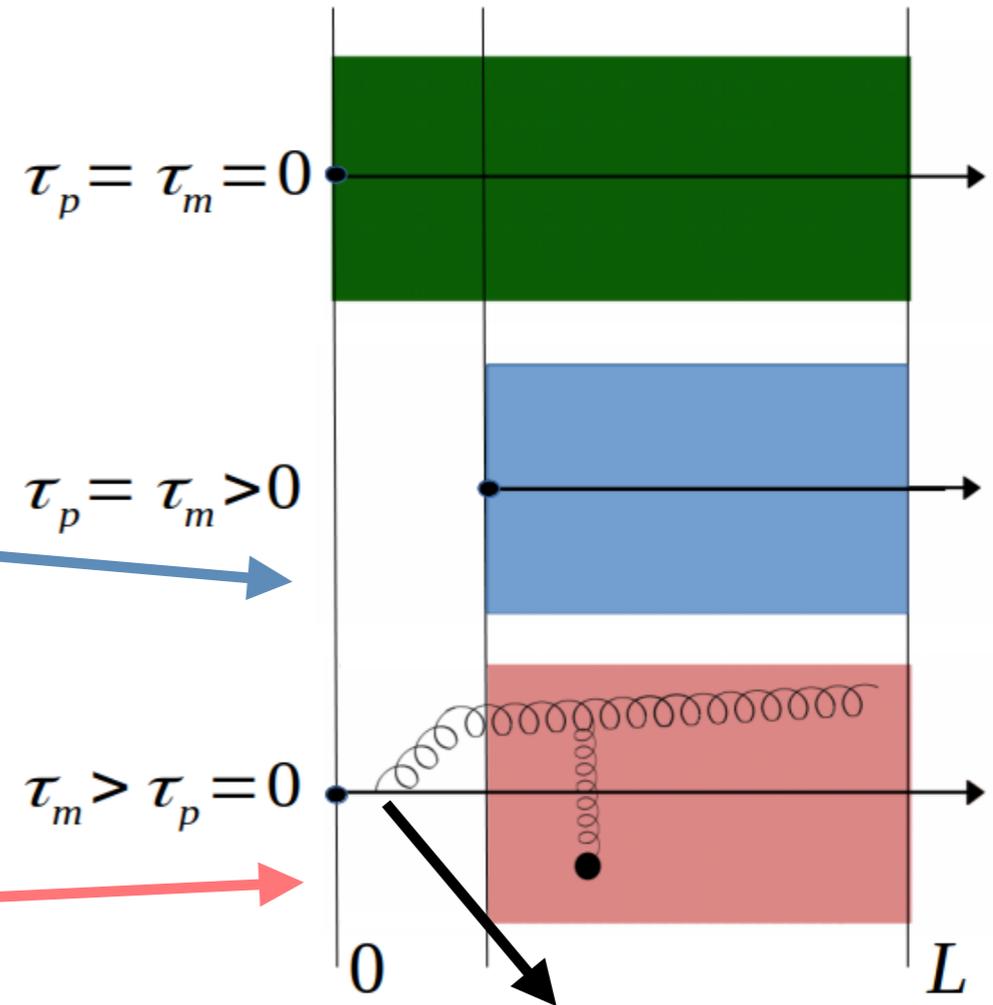
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Radiation in the IS

- Up to here: parton set to be produced *inside* the QGP
- We **were ignoring** (medium-induced) radiation emitted before the formation of the QGP
- How to isolate the effects due to this initial radiation?
 - Emitter produced at $\tau_p \sim 0$
 - Propagates in vacuum from τ_p to $\tau_m = \tau_{\text{hydro}}$
 - In-medium propagation from τ_m to L



Extra medium-induced radiation included

CA, Apolinário, Dominguez, M. G. Martinez, Salgado, [arXiv: 2112.04593](https://arxiv.org/abs/2112.04593)

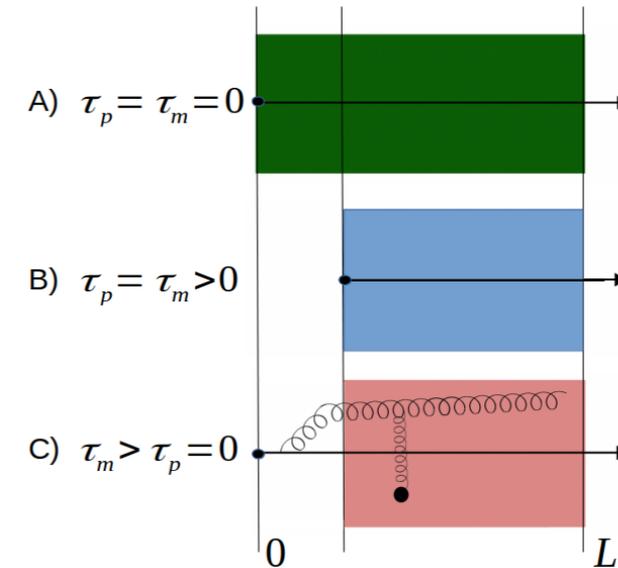
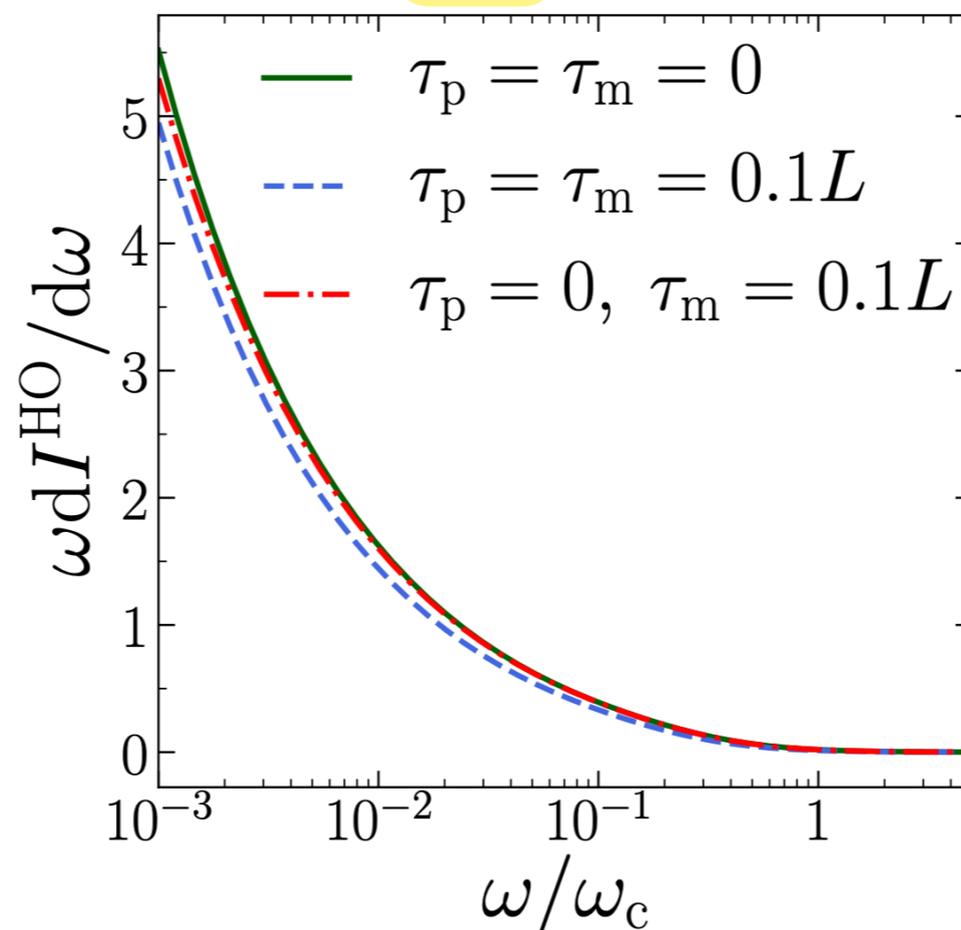
Radiation in the IS

- HO spectrum

$$\omega \frac{dI^{\text{HO}}}{d\omega} = \frac{2\alpha_s C_R}{\pi} \ln \left| \cos \left[\Omega L \left(1 - \frac{\tau_m}{L} \right) \right] - \Omega L \frac{\tau_m - \tau_p}{L} \sin \left[\Omega L \left(1 - \frac{\tau_m}{L} \right) \right] \right|$$

Extra medium-induced radiation

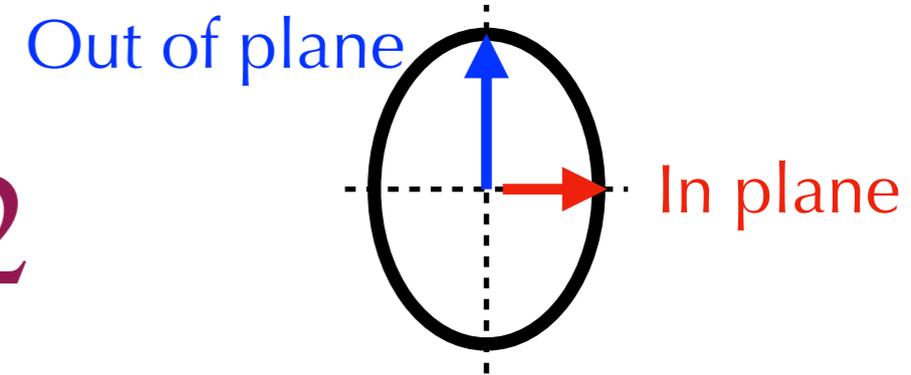
Static HO



$$\Omega L \equiv (1 - i) \sqrt{\frac{\omega_c}{2\omega}}$$

$$\omega_c \equiv \frac{1}{2} \hat{q} L^2$$

R_{AA} and high- p_T v_2



- Compute the HO spectrum for a power-law expanding medium

$$\hat{q}(\tau) = K_1 T^3(\tau) \quad T(\tau) = T_0 \left(\frac{\tau_0}{\tau + \tau_0} \right)^c$$

Parameters fixed to
Luzum and Romatschke's hydro

- Compute the QWs (using the spectrum)

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^n \int d\omega_i \frac{dI^{(med)}(\omega_i)}{d\omega} \right] \delta \left(\Delta E - \sum_{i=1}^n \omega_i \right) \exp \left[- \int_0^{\infty} d\omega \frac{dI^{(med)}}{d\omega} \right]$$

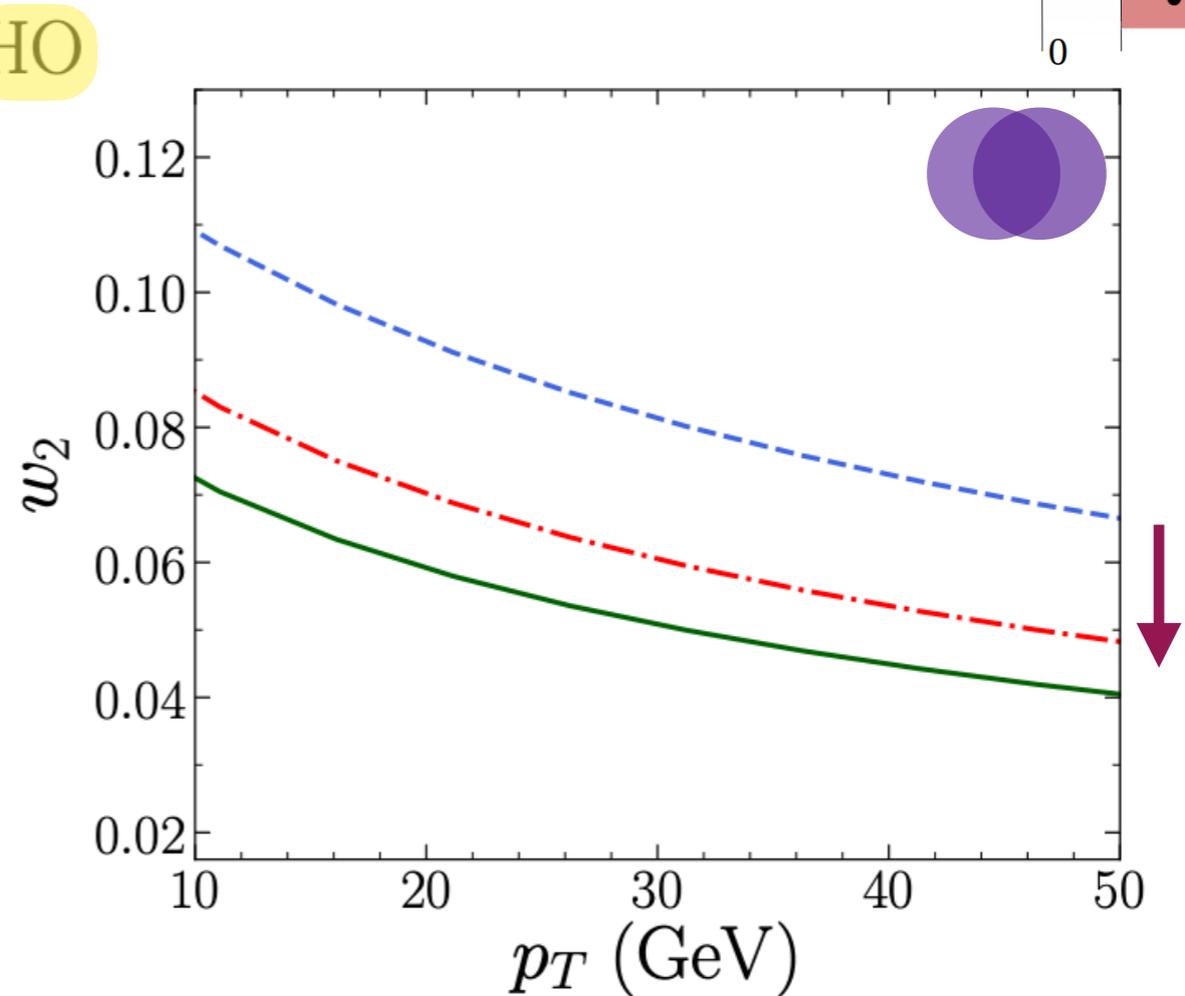
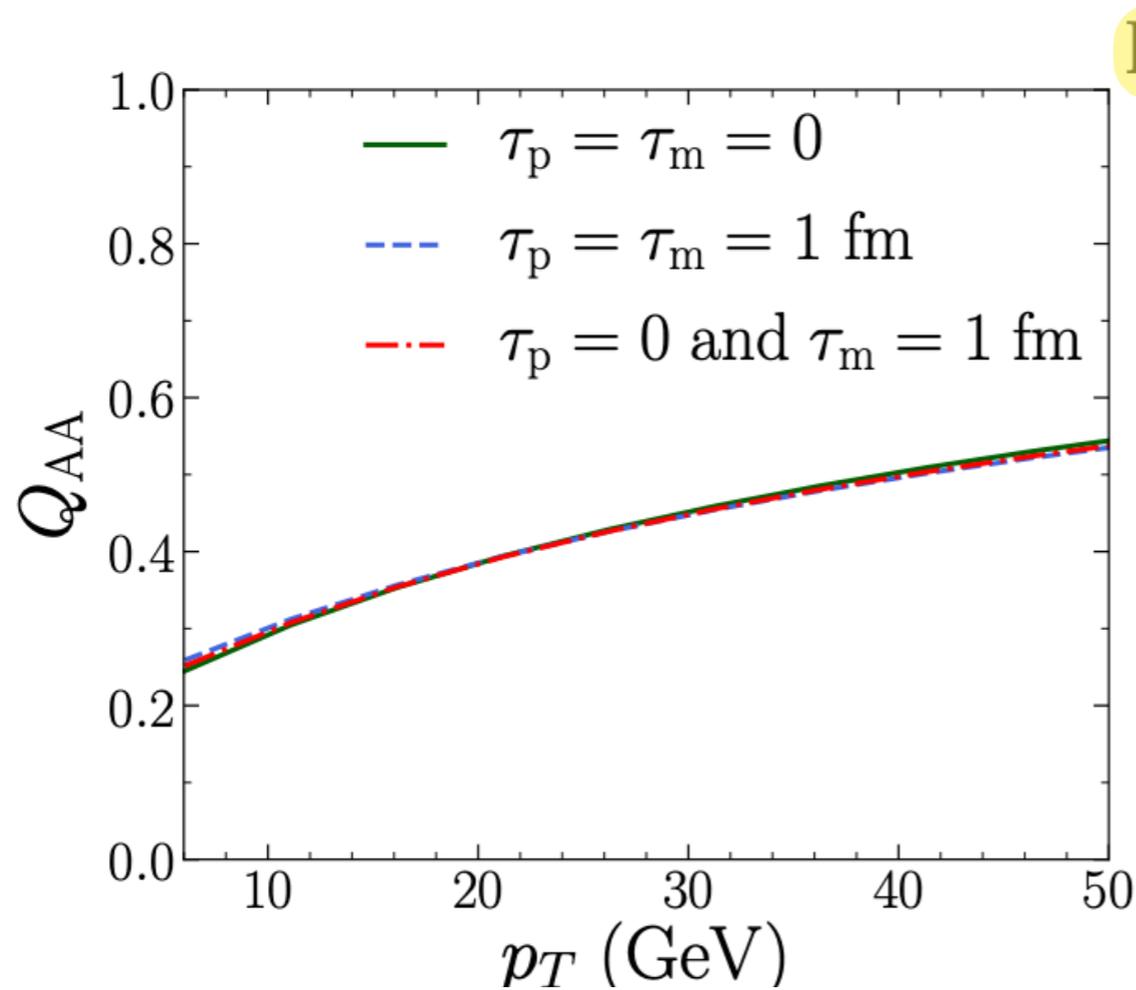
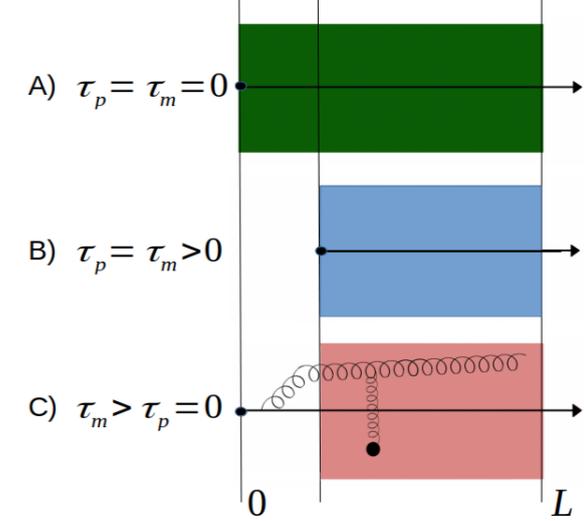
- Compute the hadron suppression factor

$$Q_f(p_T) = \frac{d\sigma^{med}(p_T)/dp_T}{d\sigma^{vac}(p_T)/dp_T} \sim \int d\Delta E P(\Delta E) \left(\frac{p_T}{p_T + \Delta E} \right)^n$$

- Compute the high- p_T v_2

$$w_2 = \frac{1}{2} \frac{Q_i^{\text{in}}(p_T) - Q_i^{\text{out}}(p_T)}{Q_i^{\text{in}}(p_T) + Q_i^{\text{out}}(p_T)}$$

R_{AA} and high- p_T v_2



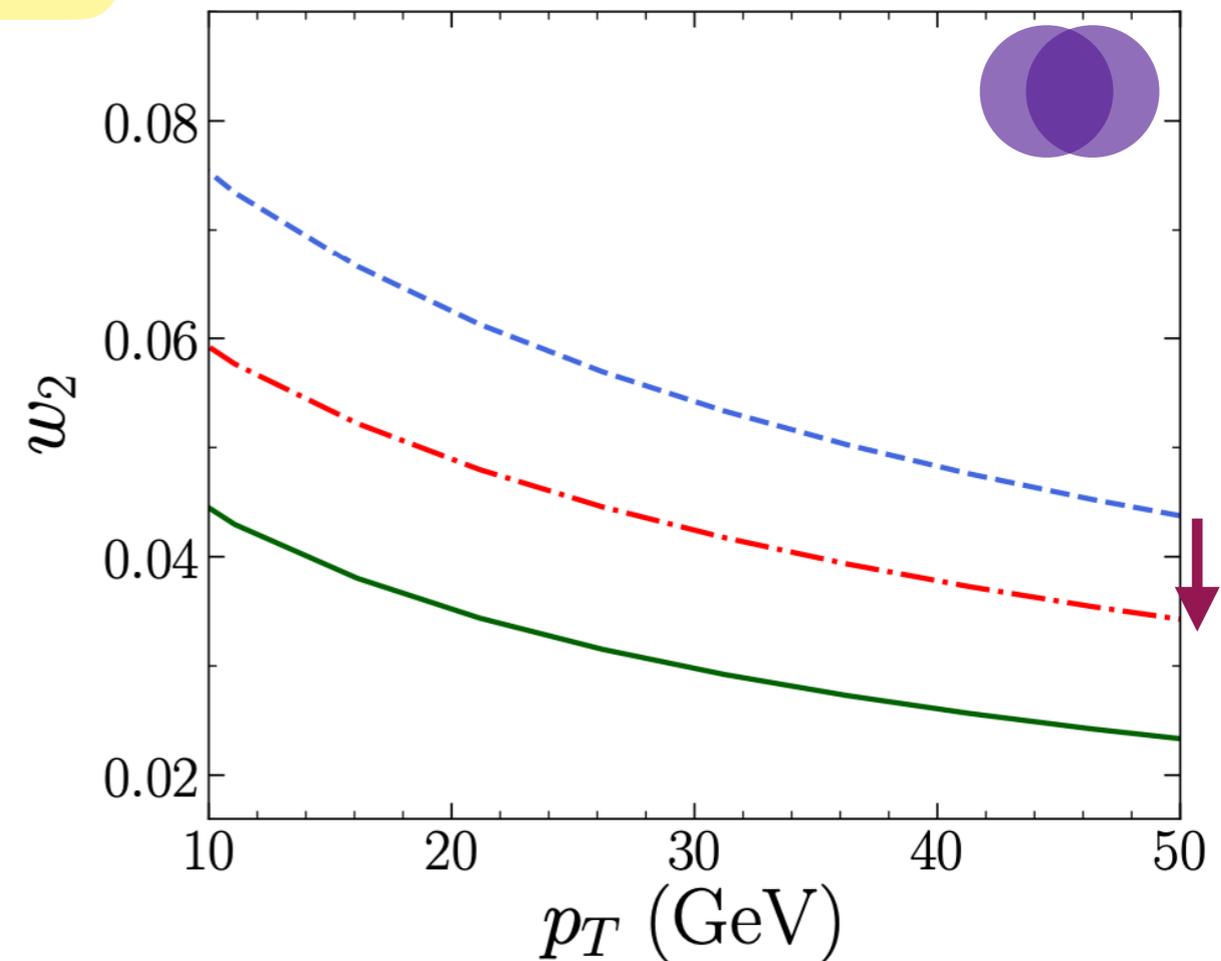
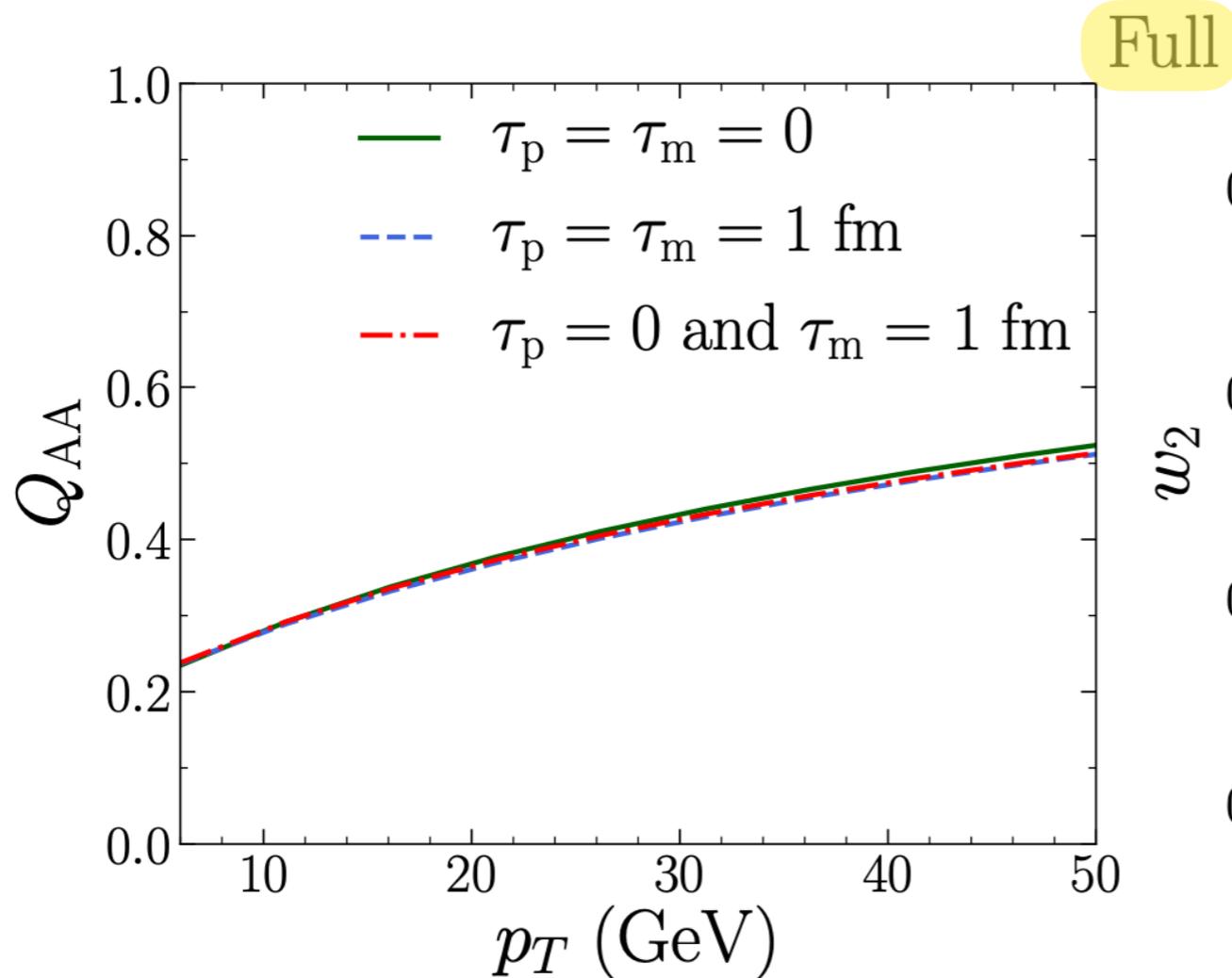
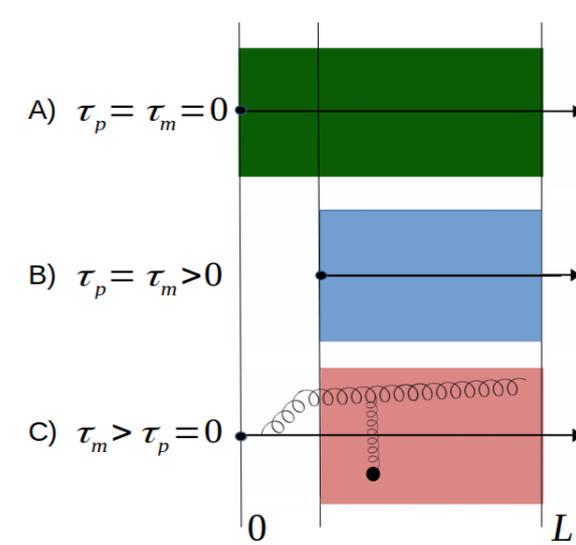
Case	K_1
A) $\tau_p = \tau_m = 0 \text{ fm}$	1.5
B) $\tau_p = \tau_m = 1 \text{ fm}$	16
C) $\tau_p = 0 \text{ and } \tau_m = 1 \text{ fm}$	8

$$\hat{q}(t) = K_1 T^3(t)$$

Including the initial radiation makes the high- p_T v_2 decrease

CA, Apolinário, Dominguez, M. G. Martinez, Salgado
[arXiv: 2211.10161](https://arxiv.org/abs/2211.10161)

R_{AA} and high- p_T v_2



Case	C_1
A) $\tau_p = \tau_m = 0 \text{ fm}$	2.2
B) $\tau_p = \tau_m = 1 \text{ fm}$	4.5
C) $\tau_p = 0 \text{ and } \tau_m = 1 \text{ fm}$	2.5

$$n(t) = C_1 T(t) \quad \mu^2(t) = 6\pi\alpha_s T^2(t)/e$$

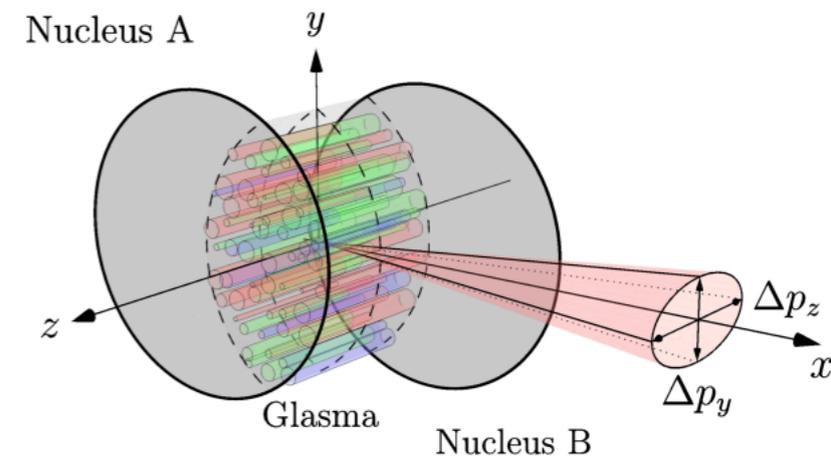
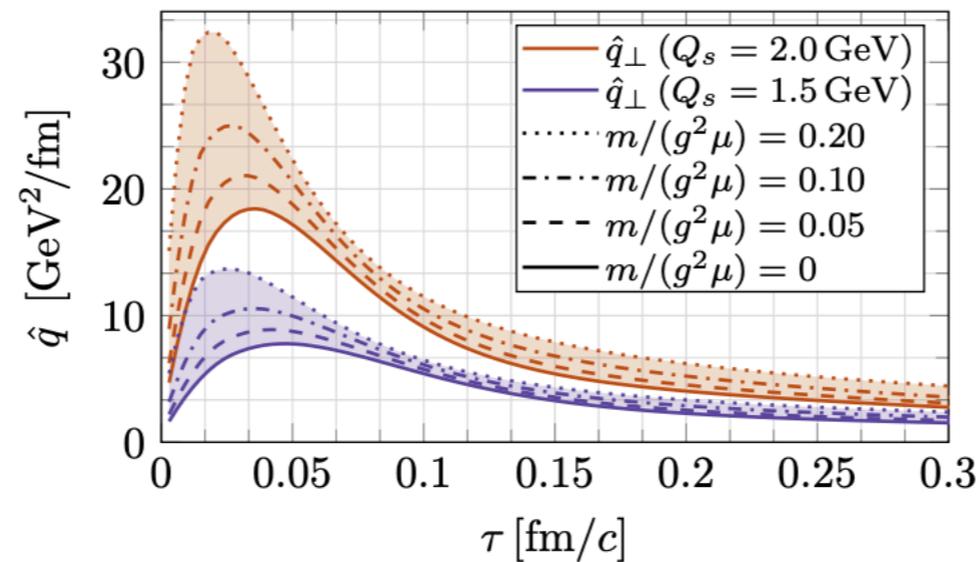
Using the *Full* formalism yields to more robust results

CA, Apolinário, Dominguez, M. G. Martinez, Salgado
[arXiv: 2211.10161](https://arxiv.org/abs/2211.10161)

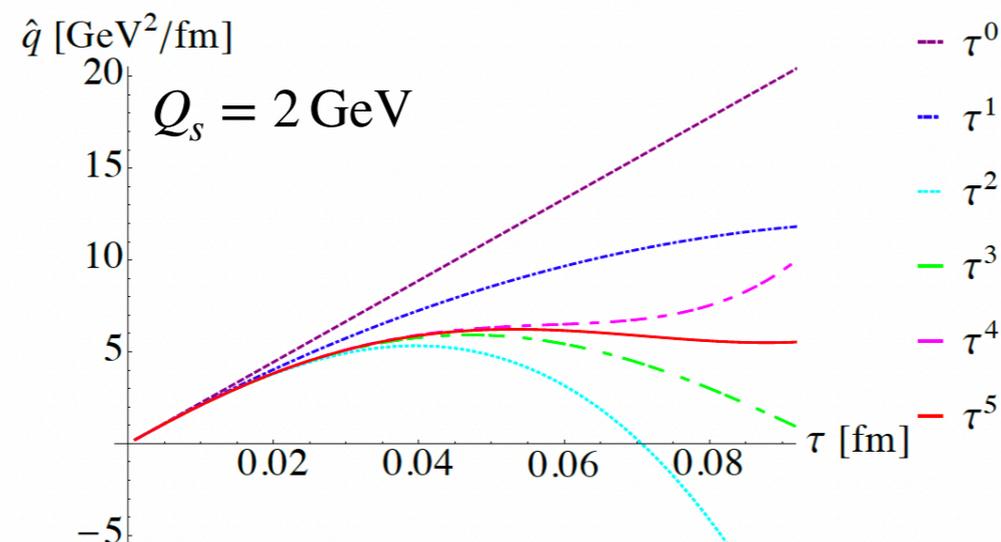
Jet broadening in the glasma

- Hard partons deflected by the chromomagnetic and chromoelectric forces in the Glasma phase

Ipp, Müller, Schuh
[arXiv:2001.10001](https://arxiv.org/abs/2001.10001)
[arXiv:2009.14206](https://arxiv.org/abs/2009.14206)



Carrington, Czajka,
 Mrówczyński
[arXiv:2112.06812](https://arxiv.org/abs/2112.06812)
[arXiv:2202.00357](https://arxiv.org/abs/2202.00357)



\hat{q} relatively large!

Conclusions

- Many recent theoretical developments in the calculation of the in-medium spectrum
- Energy loss has not been observed in small systems
- In small systems the initial stages are specially important
- Jet quenching studies in AA usually neglect energy loss in the initial stages
 - Extraction of \hat{q} in A-A sensitive to the IS
 - Simultaneous description of R_{AA} and high- p_T v_2 in A-A sensitive to the IS

Understanding jet quenching in the initial stages is crucial to understand the apparent lack of energy loss in small systems

Thanks

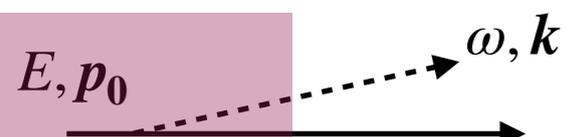
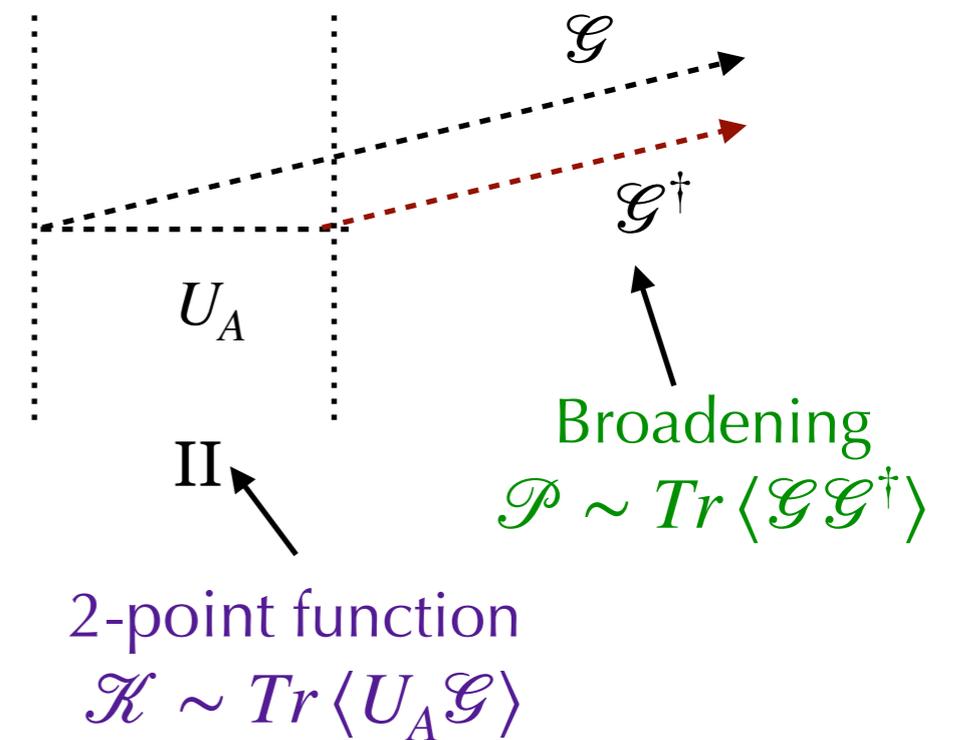
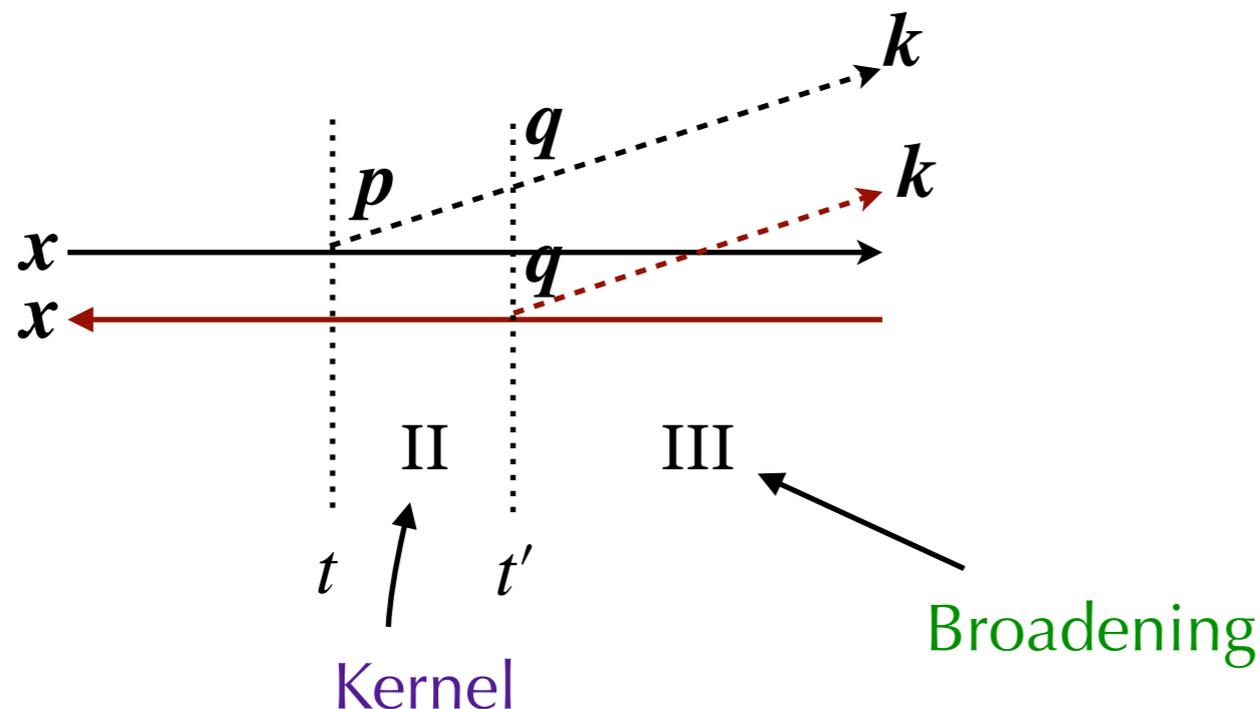
Medium-induced gluon spectrum

- For a **soft** emitted gluon ($\omega \ll E$)

Baier, Dokshitzer, Mueller, Peigné, Schiff (96)
Zaharov (97)

$$\omega \frac{dI}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{pq} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) \mathcal{P}(\infty, \mathbf{k}; t', \mathbf{q})$$

BDMPS-Z



For the spectrum beyond the soft approximation see Dominguez's talk. Today 11:00

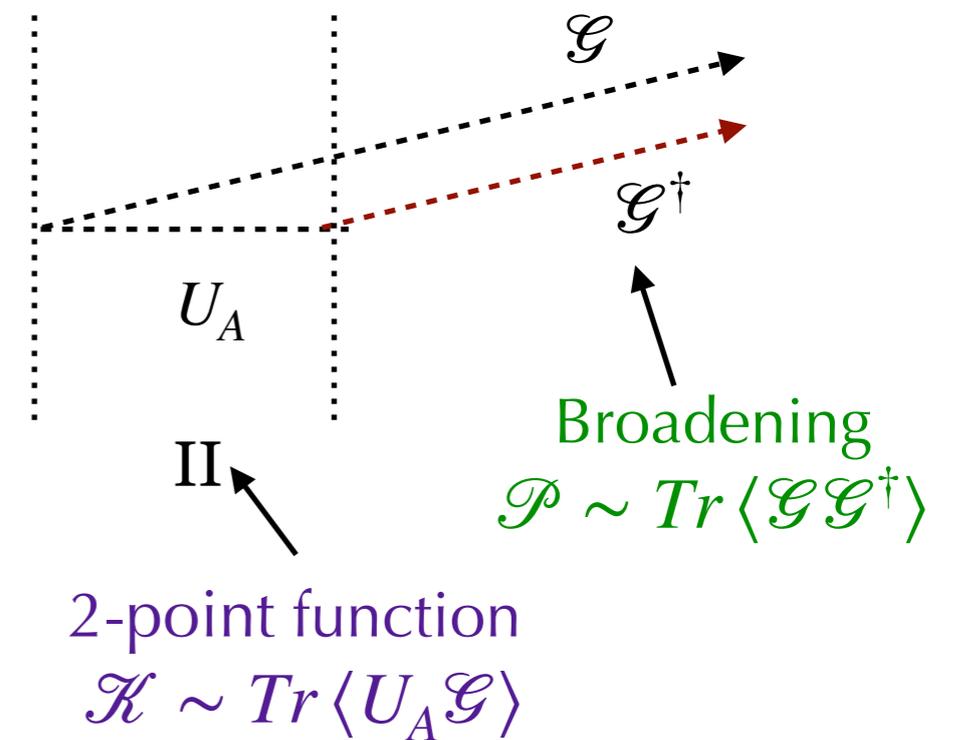
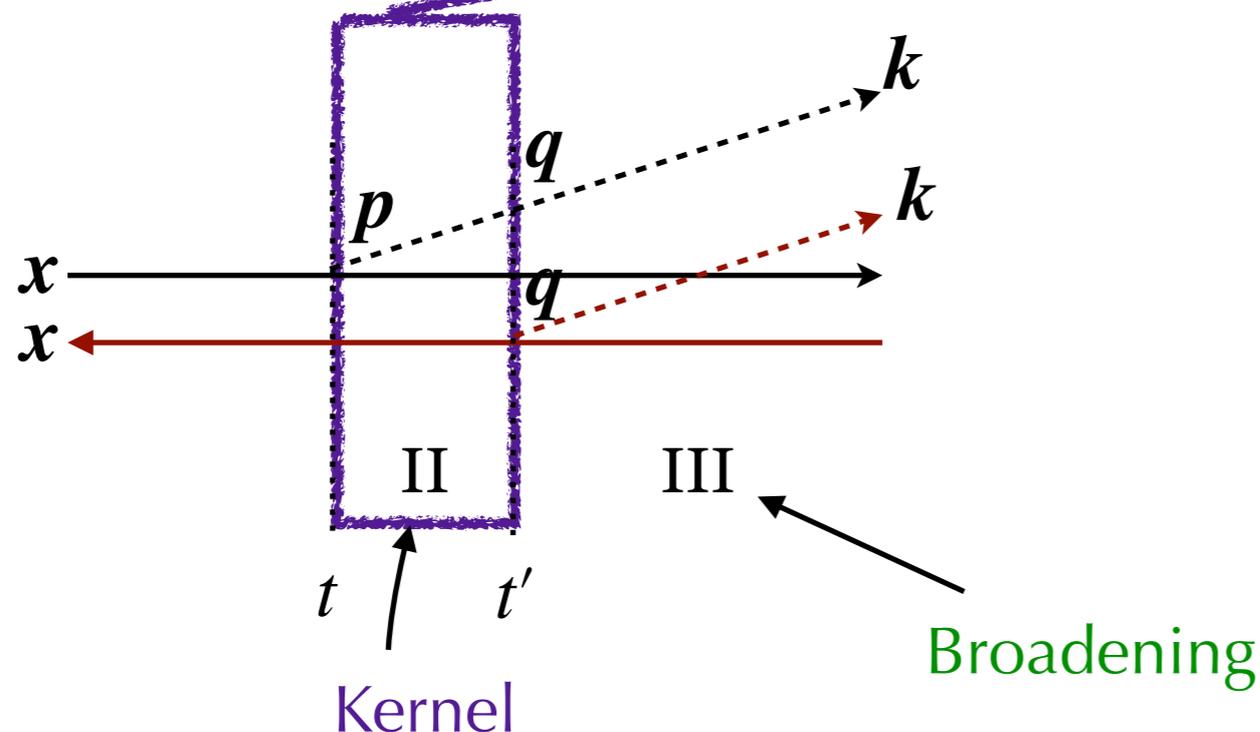
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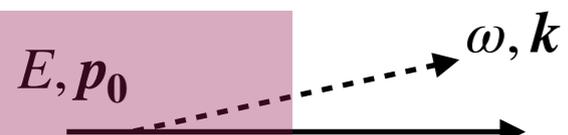
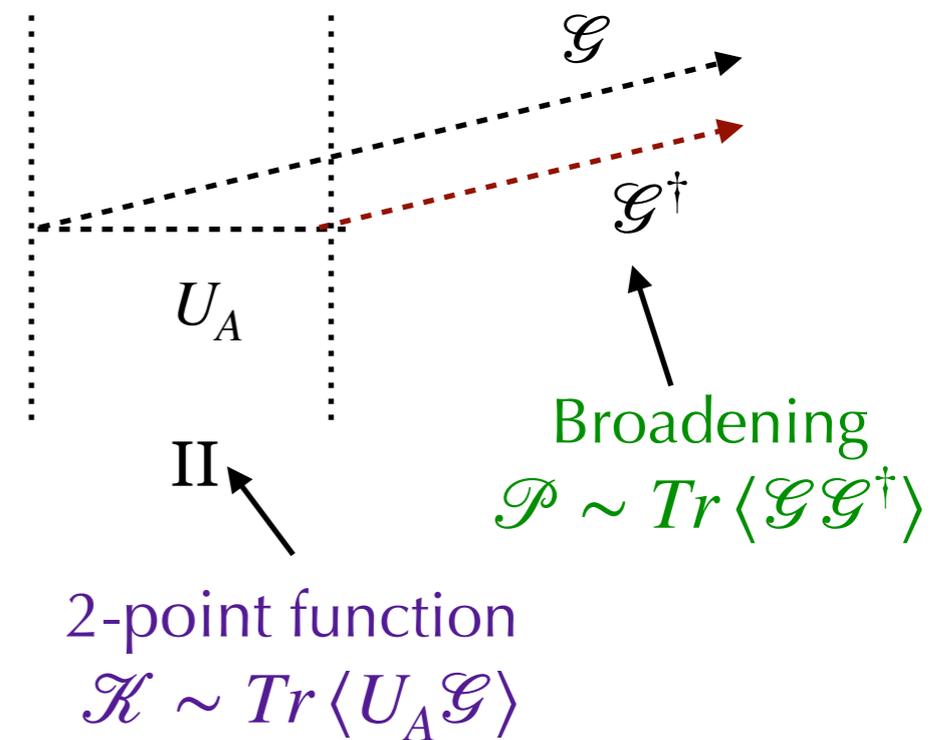
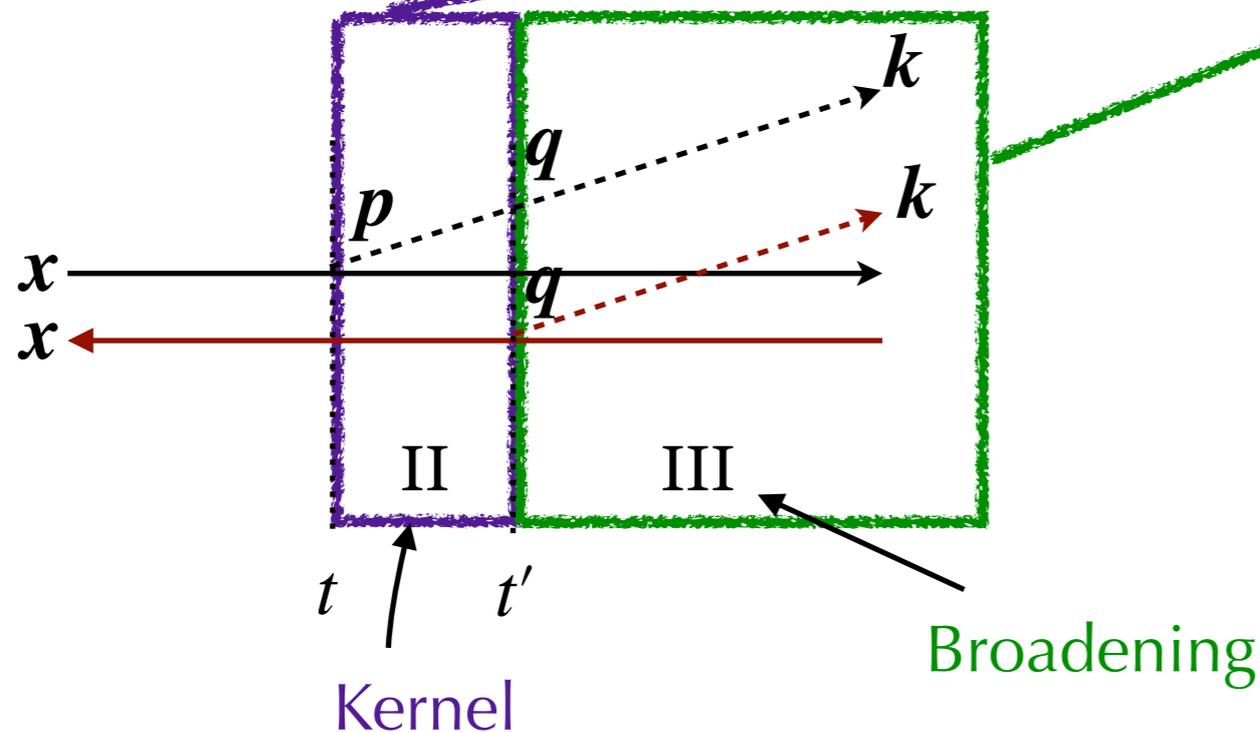
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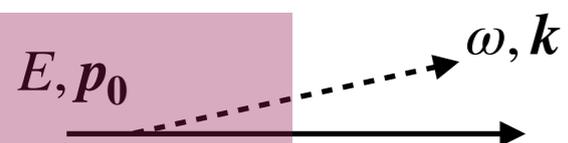
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BDMPS-Z

$$\mathcal{P}(t'', \mathbf{k}; t', \mathbf{q}) \equiv \int d^2\mathbf{z} e^{-i(\mathbf{k}-\mathbf{q})\cdot\mathbf{z}} \exp \left\{ -\frac{1}{2} \int_{t'}^{t''} ds n(s) \sigma(\mathbf{z}) \right\}$$

$$\begin{aligned} \mathcal{K}(t', \mathbf{z}; t, \mathbf{y}) &\equiv \int_{\mathbf{p}\mathbf{q}} e^{i(\mathbf{q}\cdot\mathbf{z}-\mathbf{p}\cdot\mathbf{y})} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) \\ &= \int_{\mathbf{r}(t)=\mathbf{y}}^{\mathbf{r}(t')=\mathbf{z}} \mathcal{D}\mathbf{r} \exp \left[\int_t^{t'} ds \left(\frac{i\omega}{2} \dot{\mathbf{r}}^2 - \frac{1}{2} n(s) \sigma(\mathbf{r}) \right) \right] \end{aligned}$$

Medium information



Difficult to solve numerically for realistic $\sigma(\mathbf{r})$

Analytic approximations: GLV

Opacity expansion

$\sigma(\mathbf{r})$ is taken as the full Yukawa cross-section $\sigma(\mathbf{r}) \equiv \int_{\mathbf{q}} V(\mathbf{q})(1 - e^{i\mathbf{q}\mathbf{r}})$ $V(\mathbf{q}) = \frac{8\pi\mu^2}{(\mathbf{q}^2 + \mu^2)^2}$

The integrand in the Kernel is expanded in powers of $(n(s)\sigma(\mathbf{r}))^N$

$N = 1$: **First opacity** or **GLV** approximation (single hard scattering)

The $N=1$ energy spectrum (no cut-off $\omega \frac{dI}{d\omega} = \int_0^\infty \omega \frac{dI}{d\omega d^2k}$)

Gyulassy, Levai, Vitev (99)

Wiedemann (2001)

DGLV: Djordjevic, Gyulassy (2003)

$$\omega \frac{dI^{\text{GLV}}}{d\omega} = \frac{4\alpha_s C_R}{\pi} n_0 L \int_0^\infty dp \frac{p^2 - \sin p^2}{p^3} \frac{1}{xp^2 + 1}$$

$$x = \frac{\omega}{\bar{\omega}_c} \quad \bar{\omega}_c = \frac{\mu^2 L}{2}$$

Further orders in opacity: Gyulassy, Levai, Vitev, 0006010

Analytic approximations: HO

Harmonic, \hat{q} or Gaussian approximation

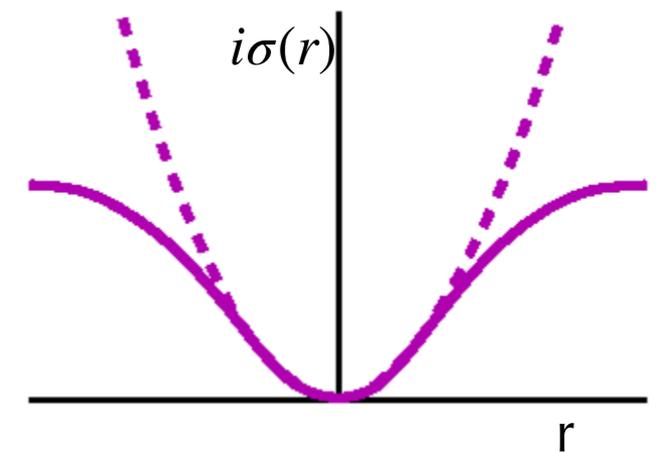
- Small \mathbf{r} approximation of the dipole cross section

$$n(s)\sigma(\mathbf{r}) \approx \frac{1}{2}\hat{q}(s)r^2 + \mathcal{O}(r^2 \ln r^2)$$

Perturbative tails neglected

The **Kernel can be computed analytically** (for a static medium)

Multiple soft scatterings



Note: $\hat{q} = 4iV''(0)$

Stolen from Peter Arnold slides

- The energy spectrum (no cut-off $\omega \frac{dI}{d\omega} = \int_0^\infty \omega \frac{dI}{d\omega d^2k}$)

$$\omega \frac{dI^{\text{HO}}}{d\omega} = \frac{2\alpha_s C_R}{\pi} \ln \left| \cos \left((1-i) \sqrt{\frac{\omega_c}{2\omega}} \right) \right|$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (96)
Zakharov (97)

Parameters: \hat{q} , L

$$\omega_c = \frac{\hat{q}L^2}{2}$$

Wiedemann, Salgado (2003)

Spectrum

