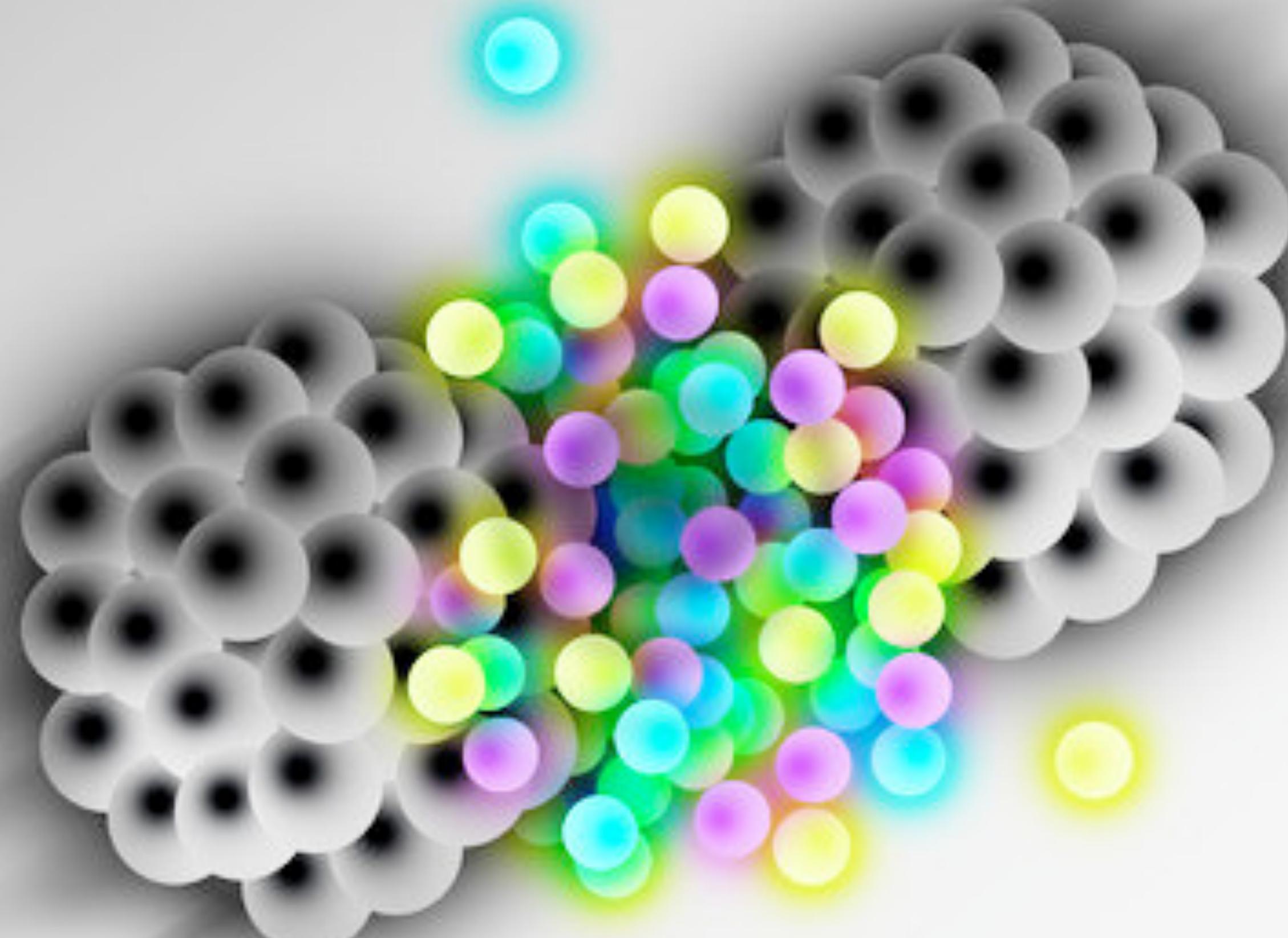


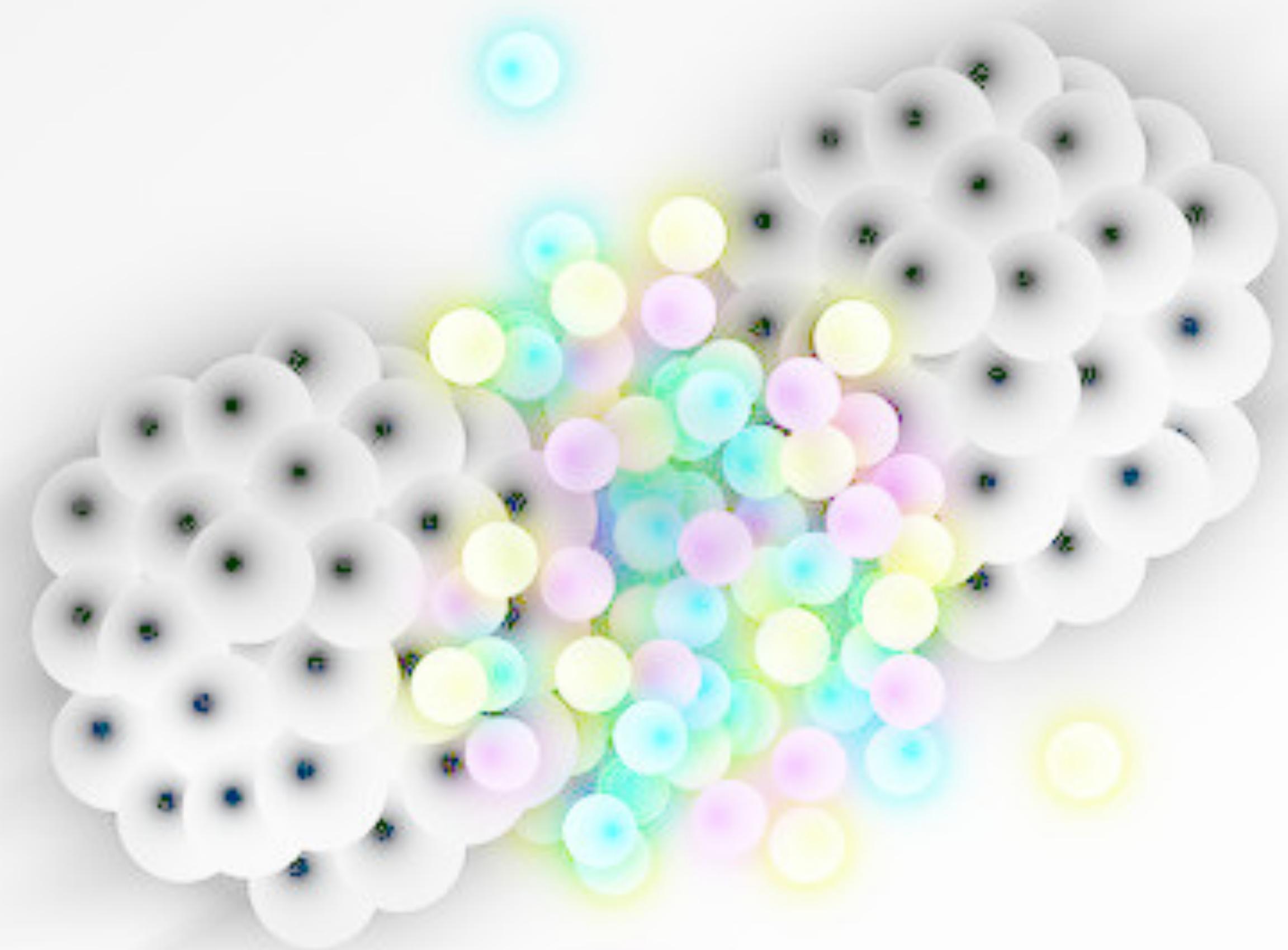
Heavy Ions: theory overview



Liliana Apolinário

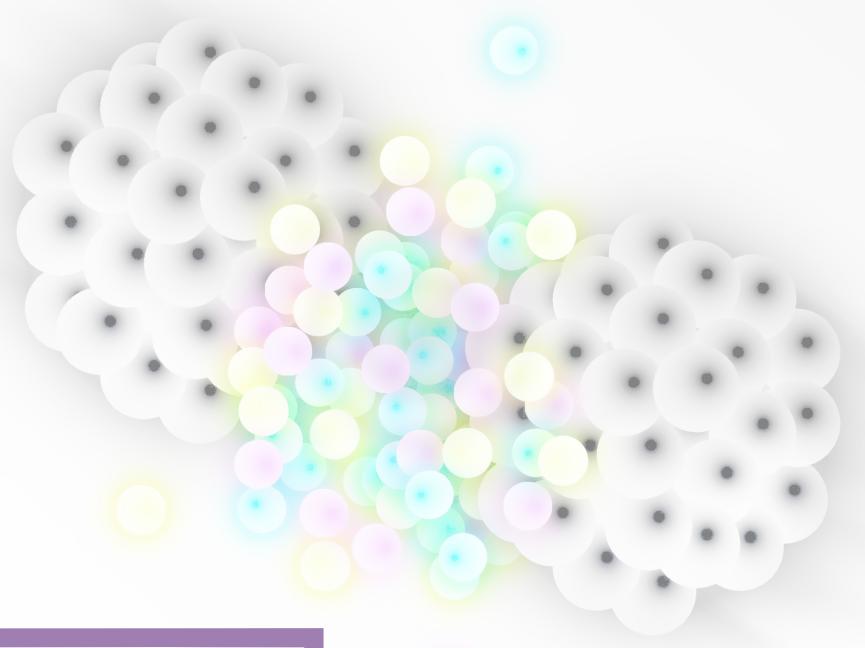


Heavy ions: theory overview



Part II

Outline

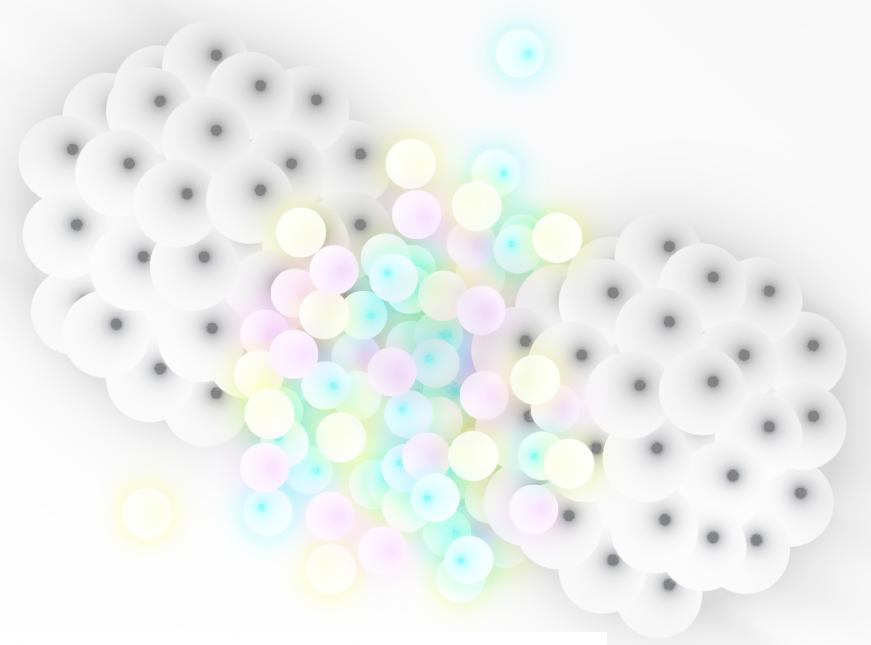
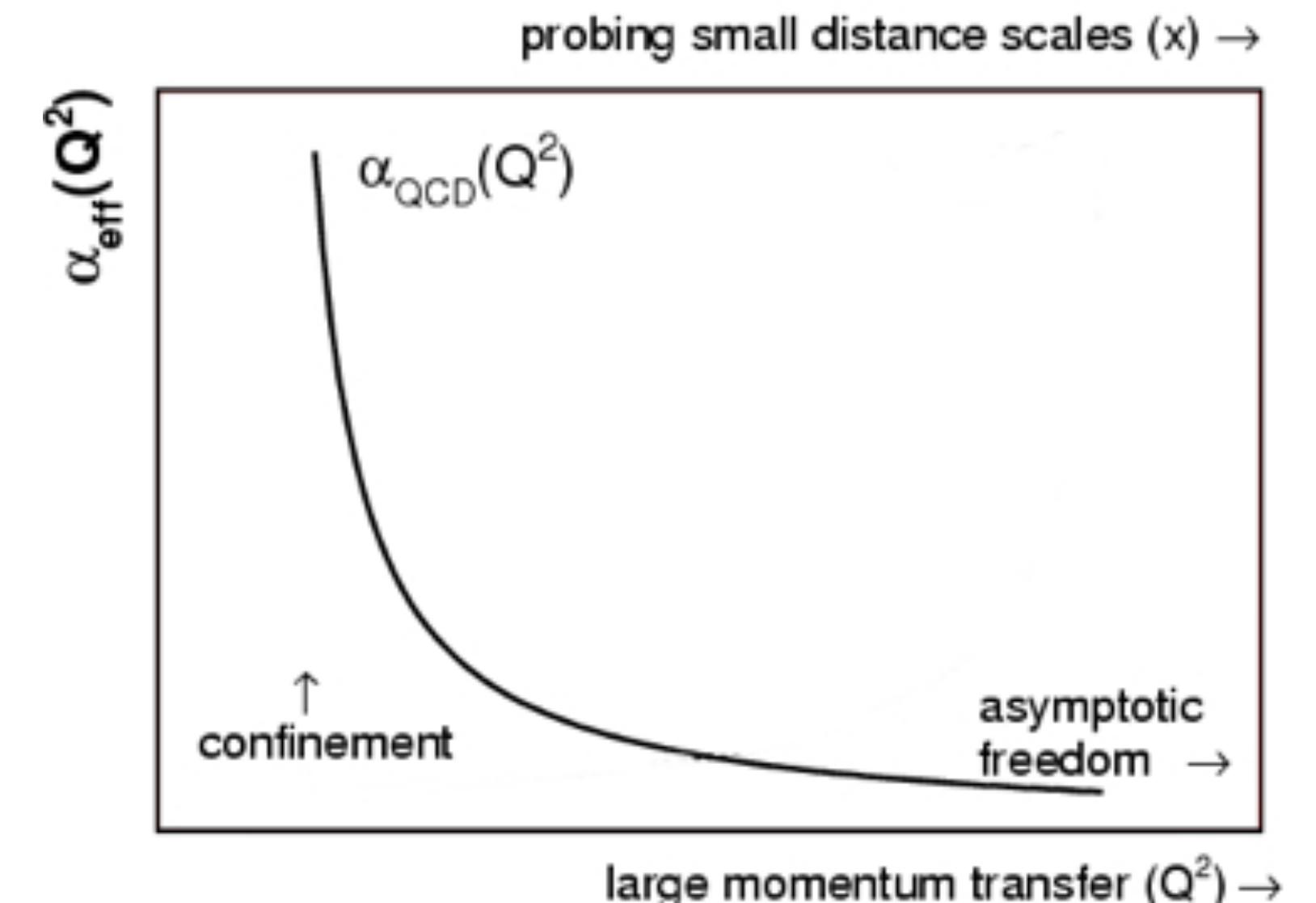
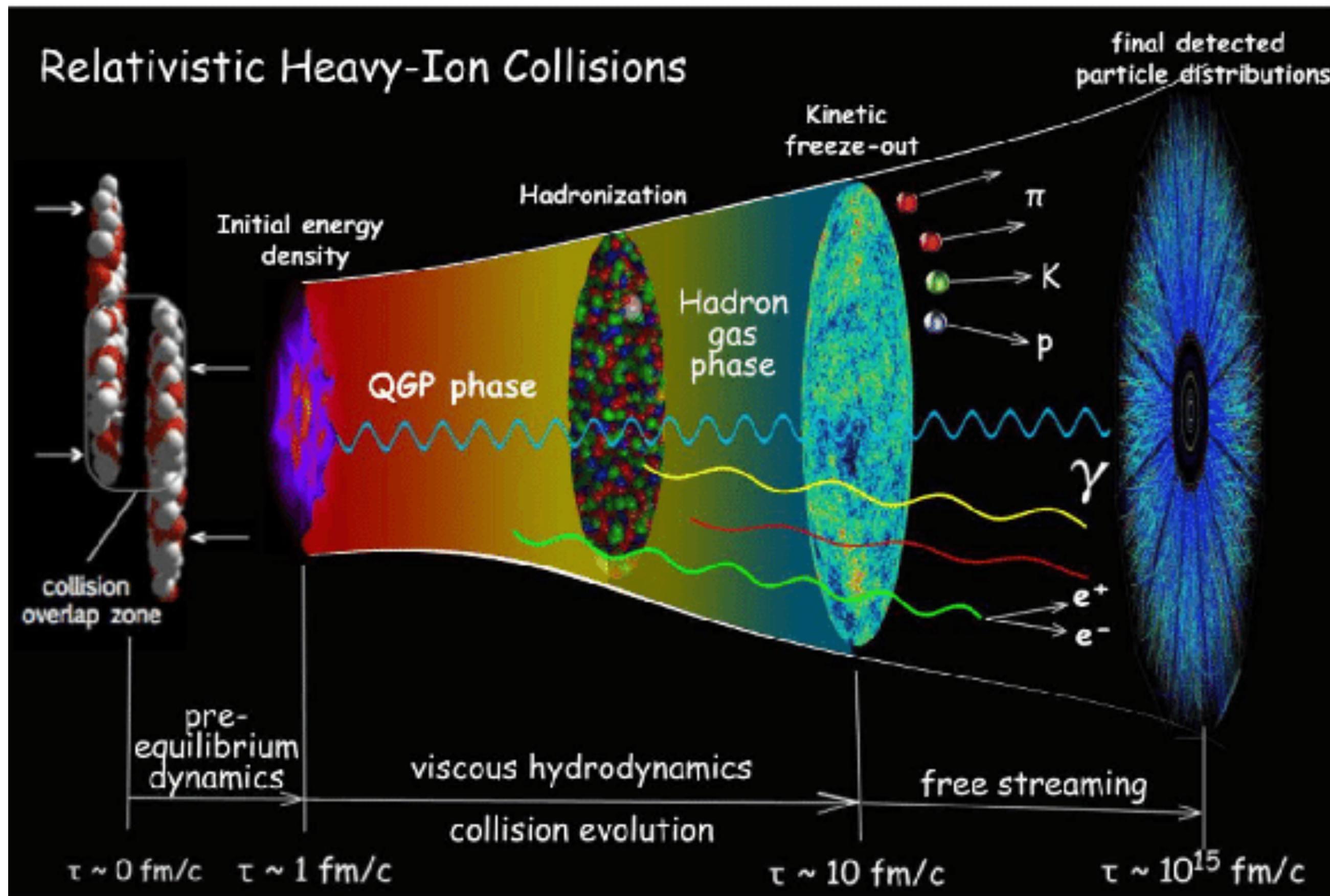


Today's lecture:

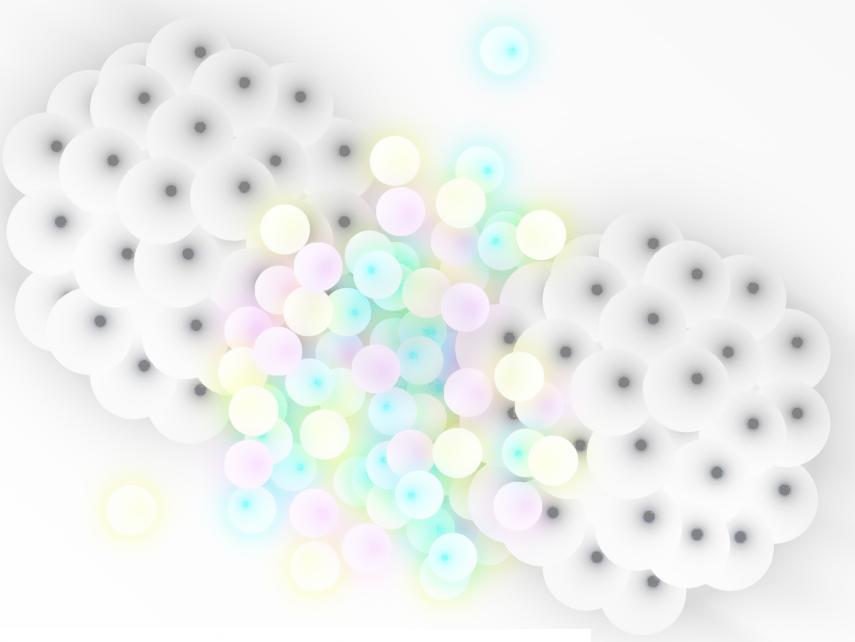
- Part I:
 - Heavy-Ion collisions:
 - What? Why?
 - Quark-Gluon Plasma:
 - What? Why?
 - Hydrodynamics & Flow
 - Initial state
 - Small Systems
- Part II:
 - Probes of QGP short wave-length behaviour:
 - High-momentum particles
 - Jets & Jet substructure
 - See Gian Michele's lectures for quarkonia and heavy-quarks
 - Quark-Gluon Plasma properties:
 - Transport coefficients
 - Timescale evolution

Hard Probes

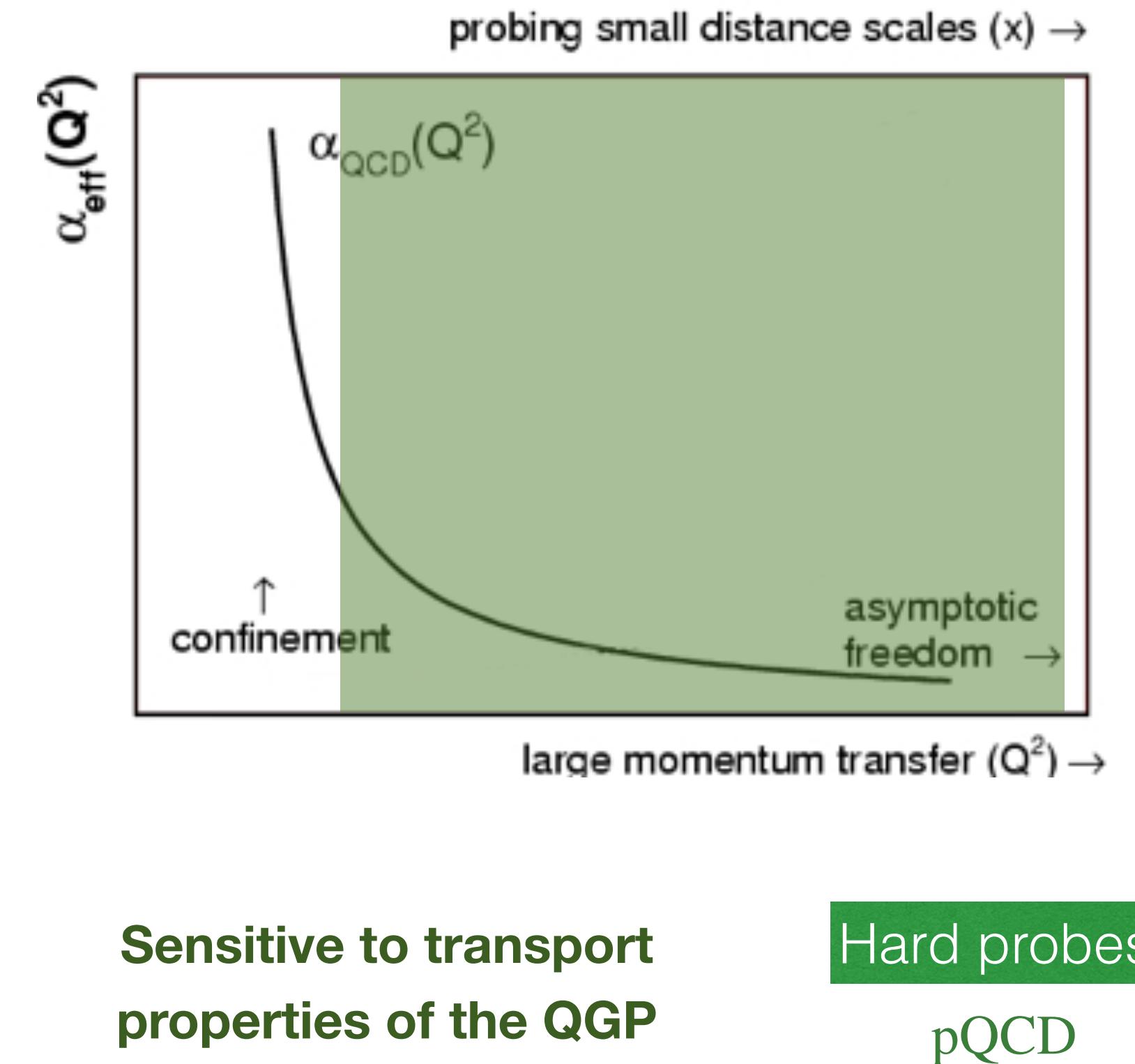
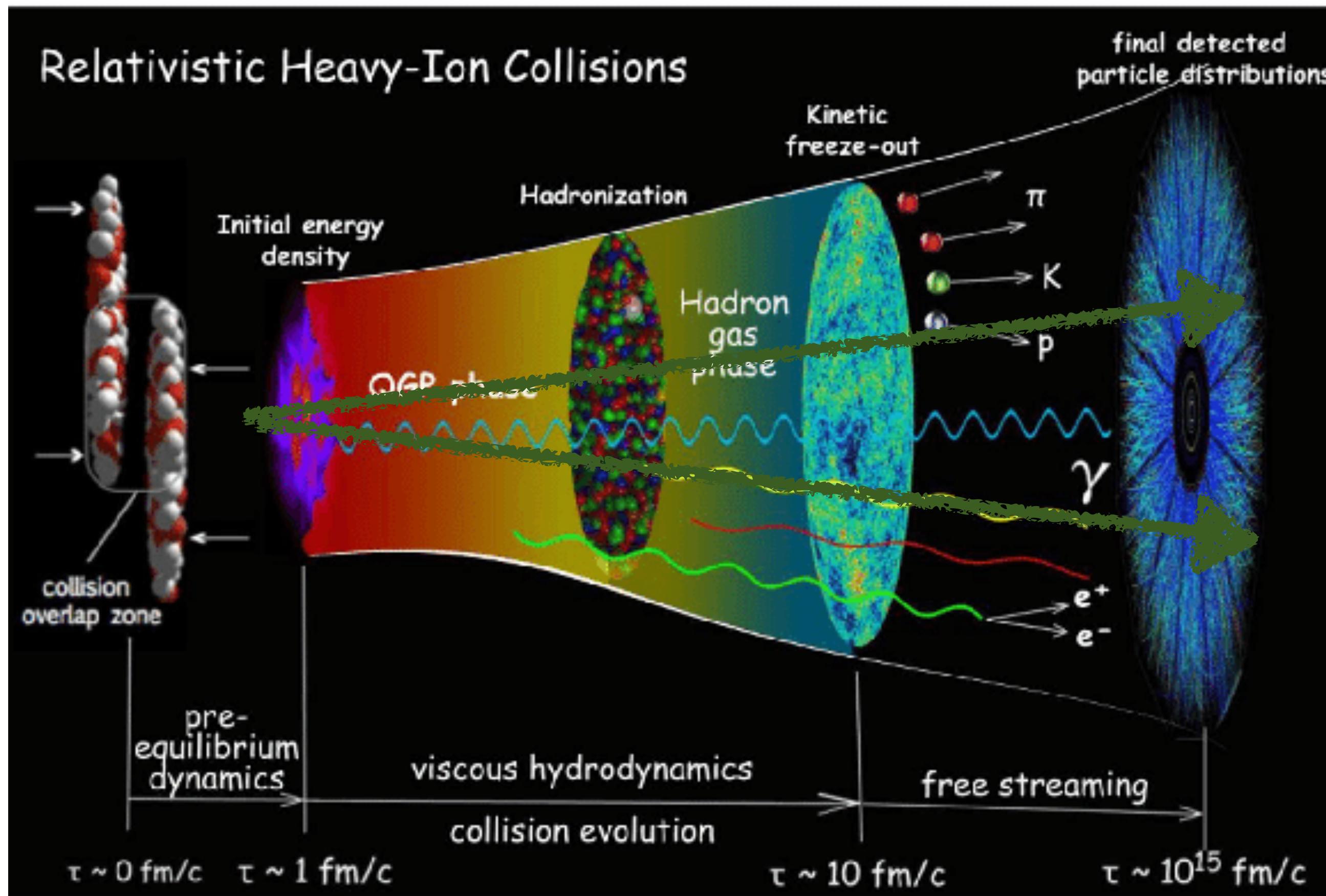
- High-momentum particles produced concurrently with the collision



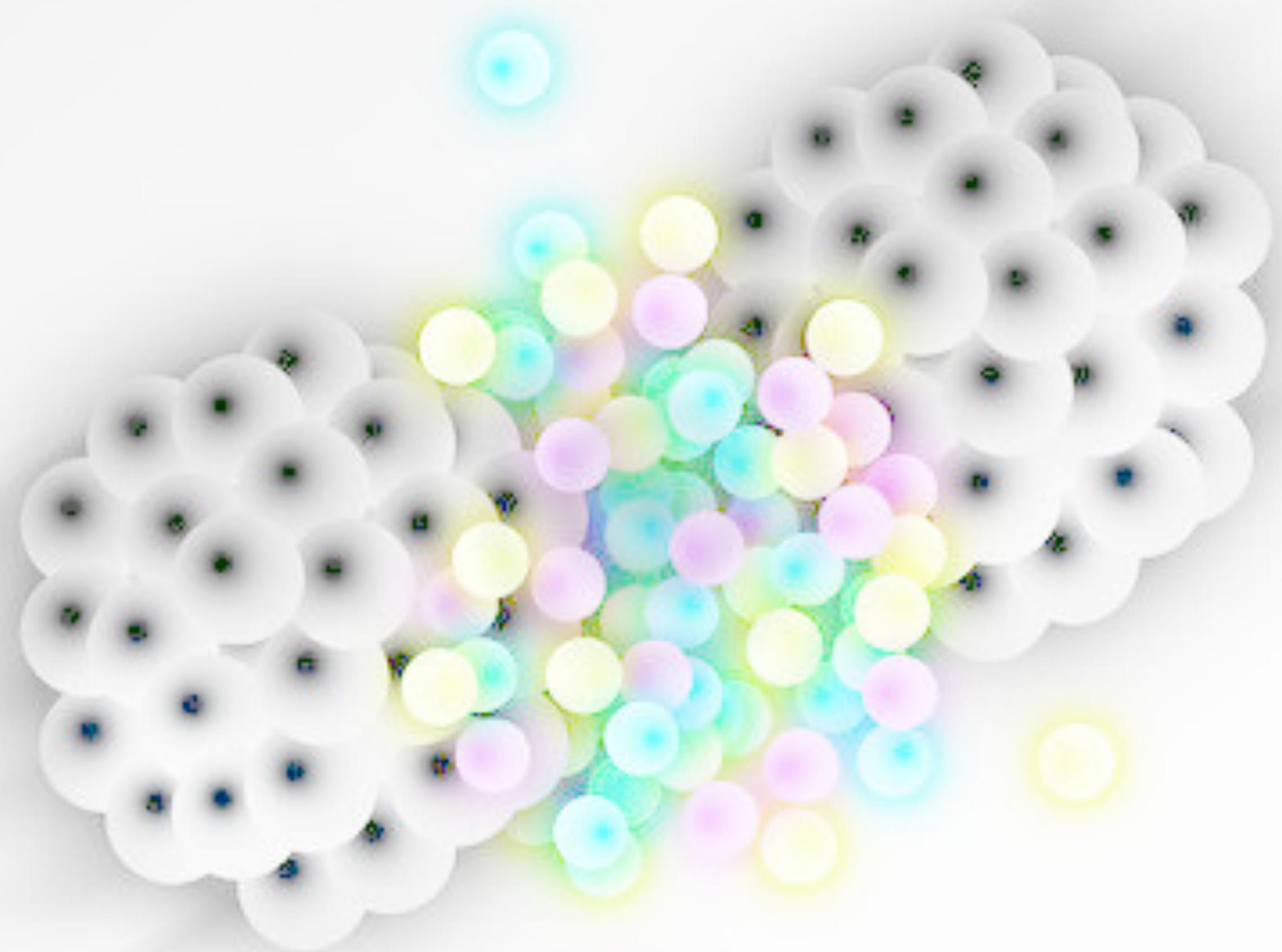
Hard Probes



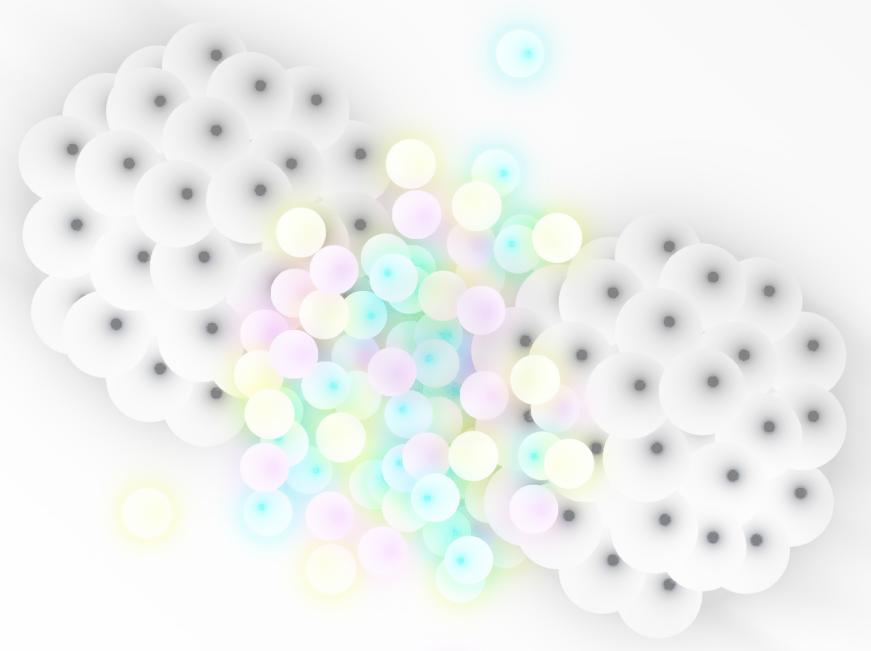
- High-momentum particles produced concurrently with the collision



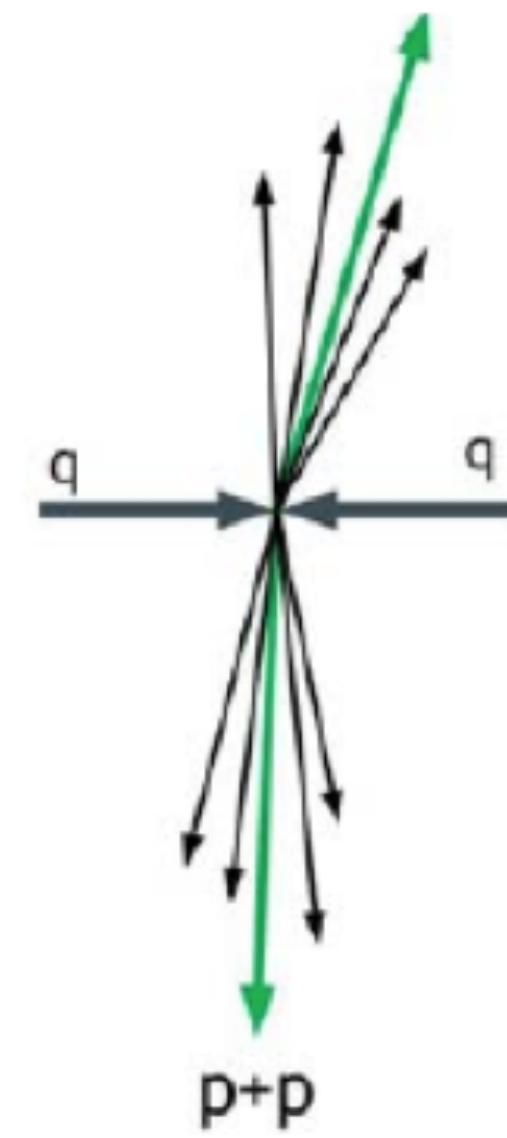
Hard Probes



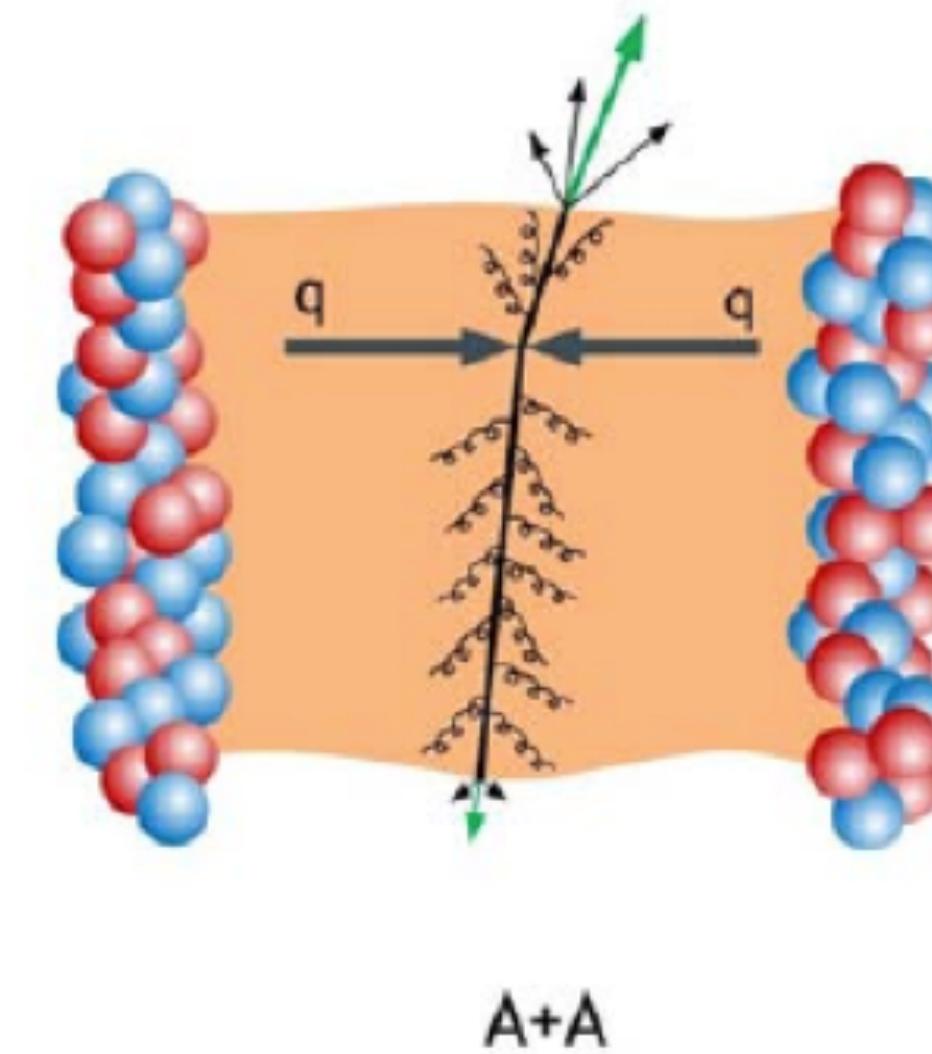
Proton-proton vs AA



- “Shoot” a calibrated probe and see the final modifications with respect to a reference (usually pp)

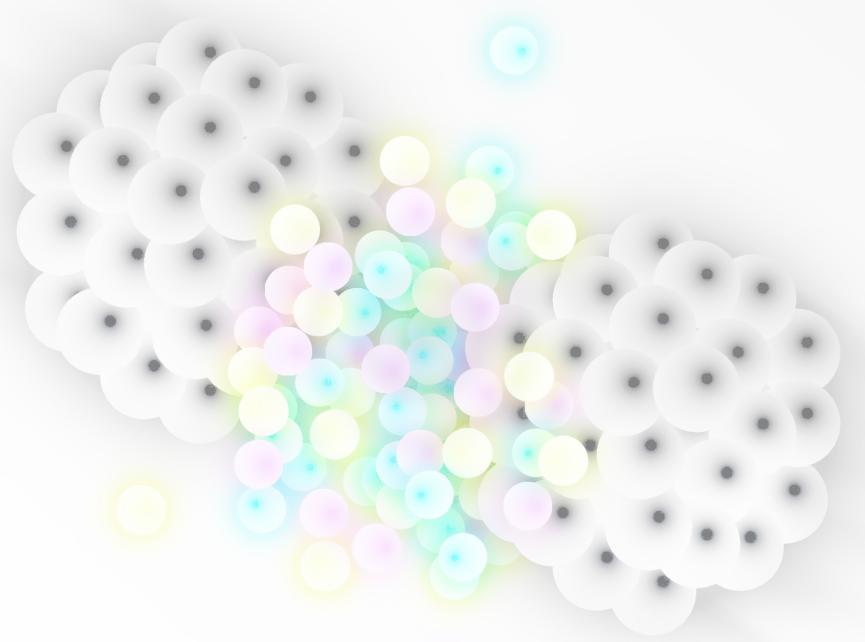


Example: jets in pp
(well known and theoretically
understood)

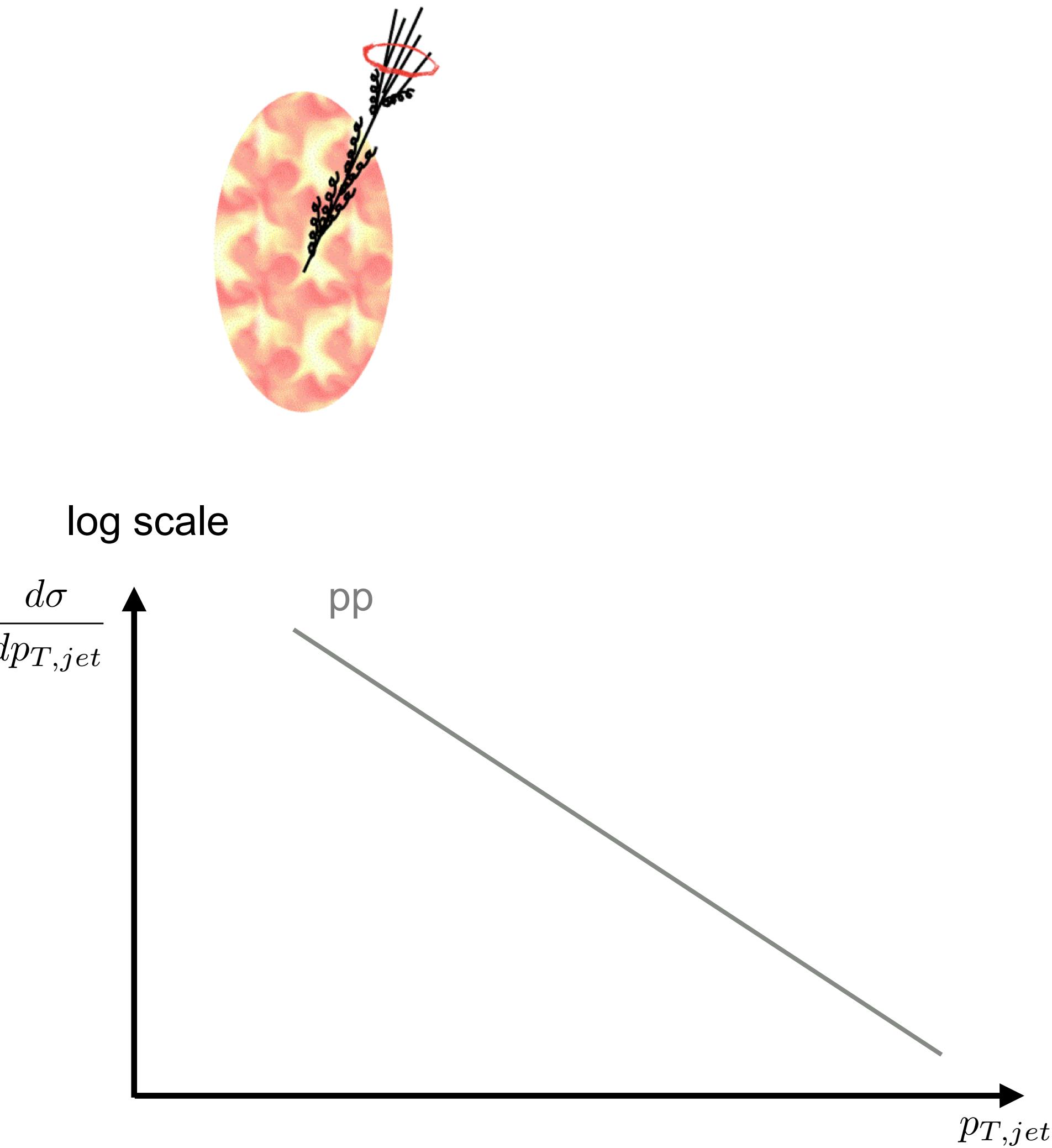
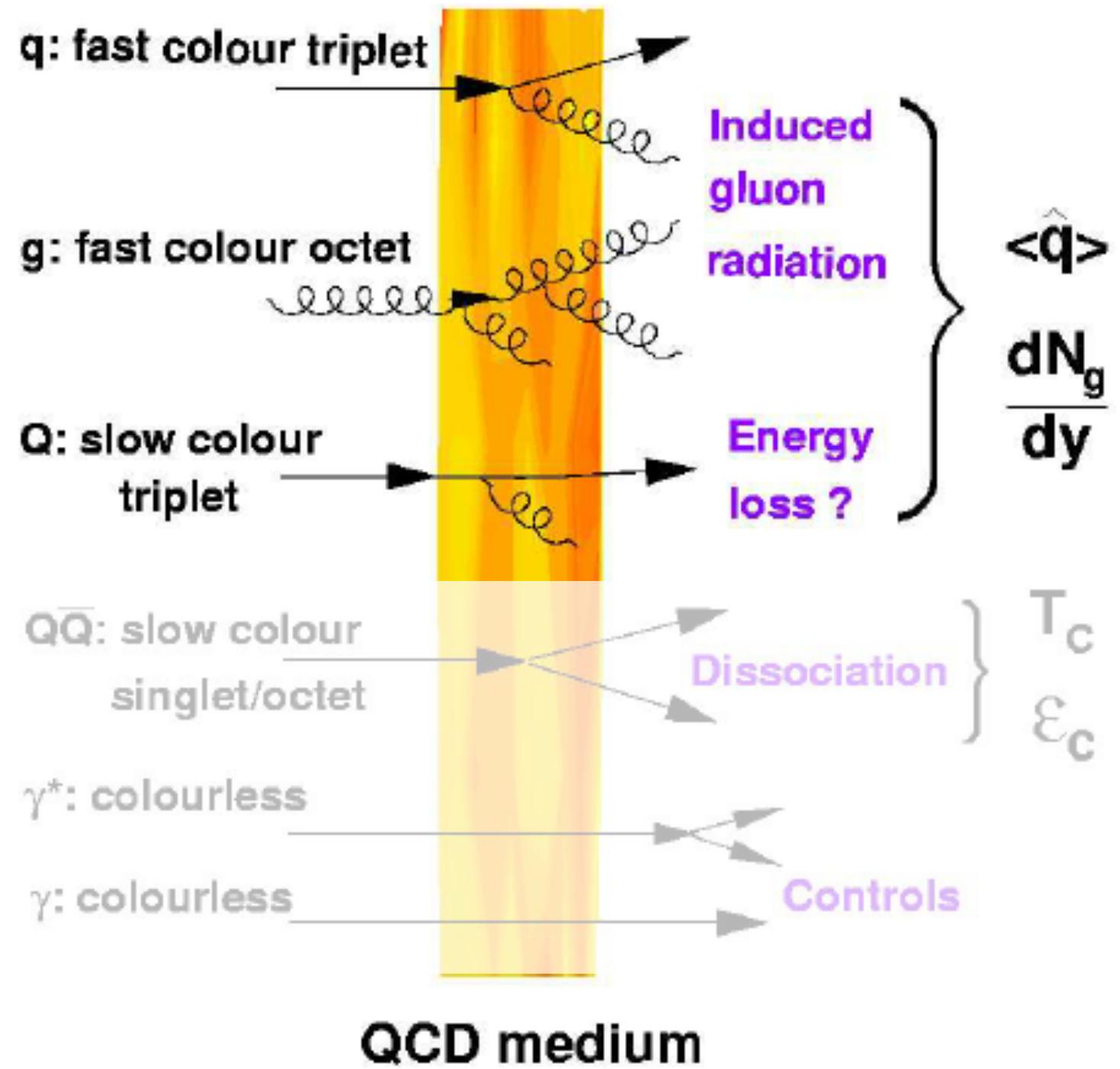


Example: jets in PbPb
(modifications related to the QGP
microscopic properties)

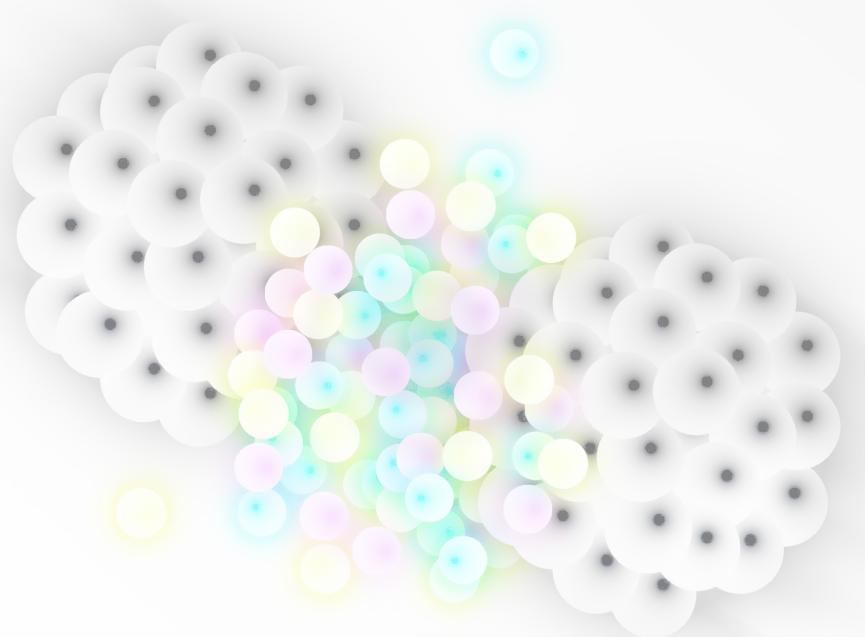
QGP short wavelength behaviour



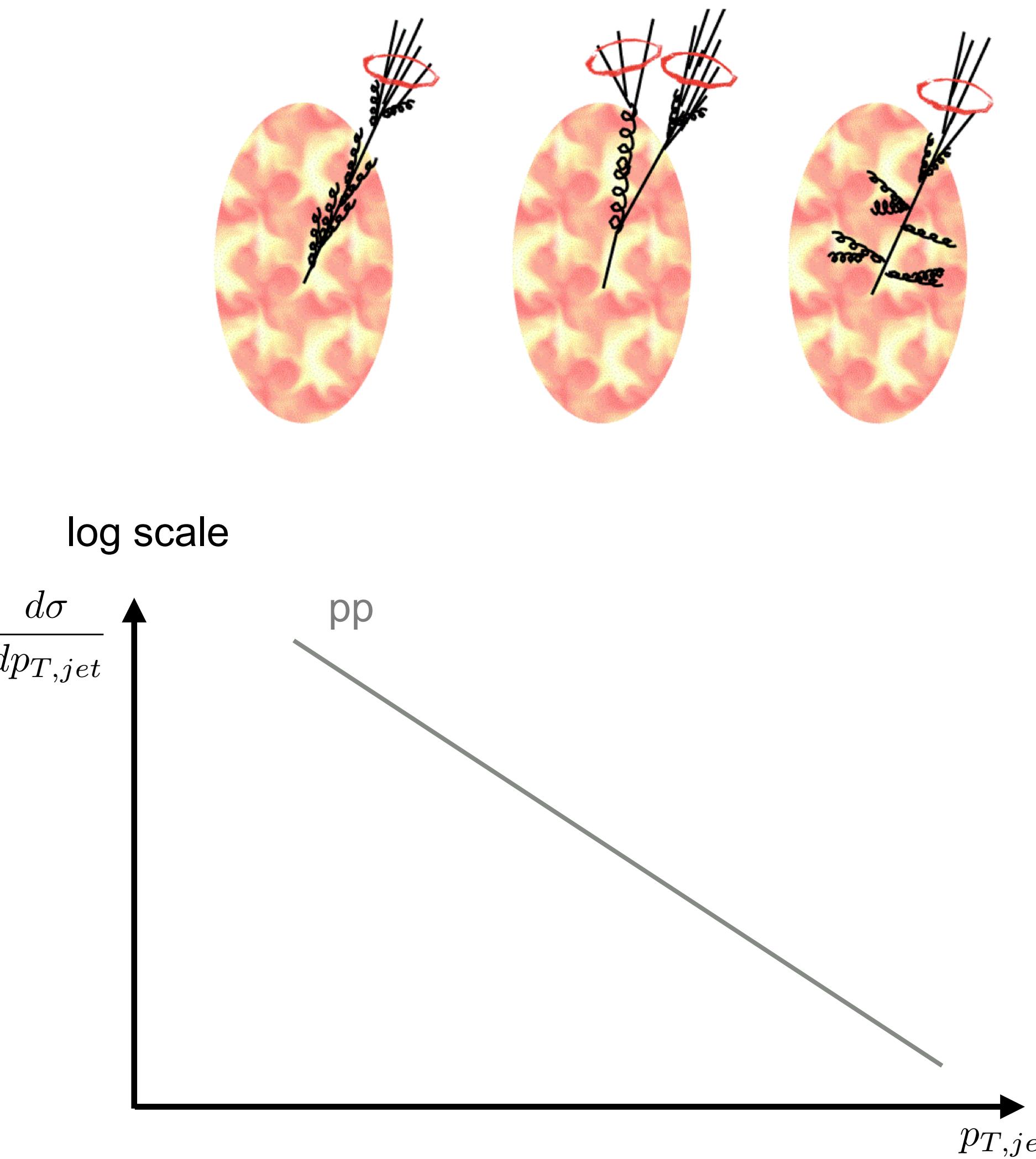
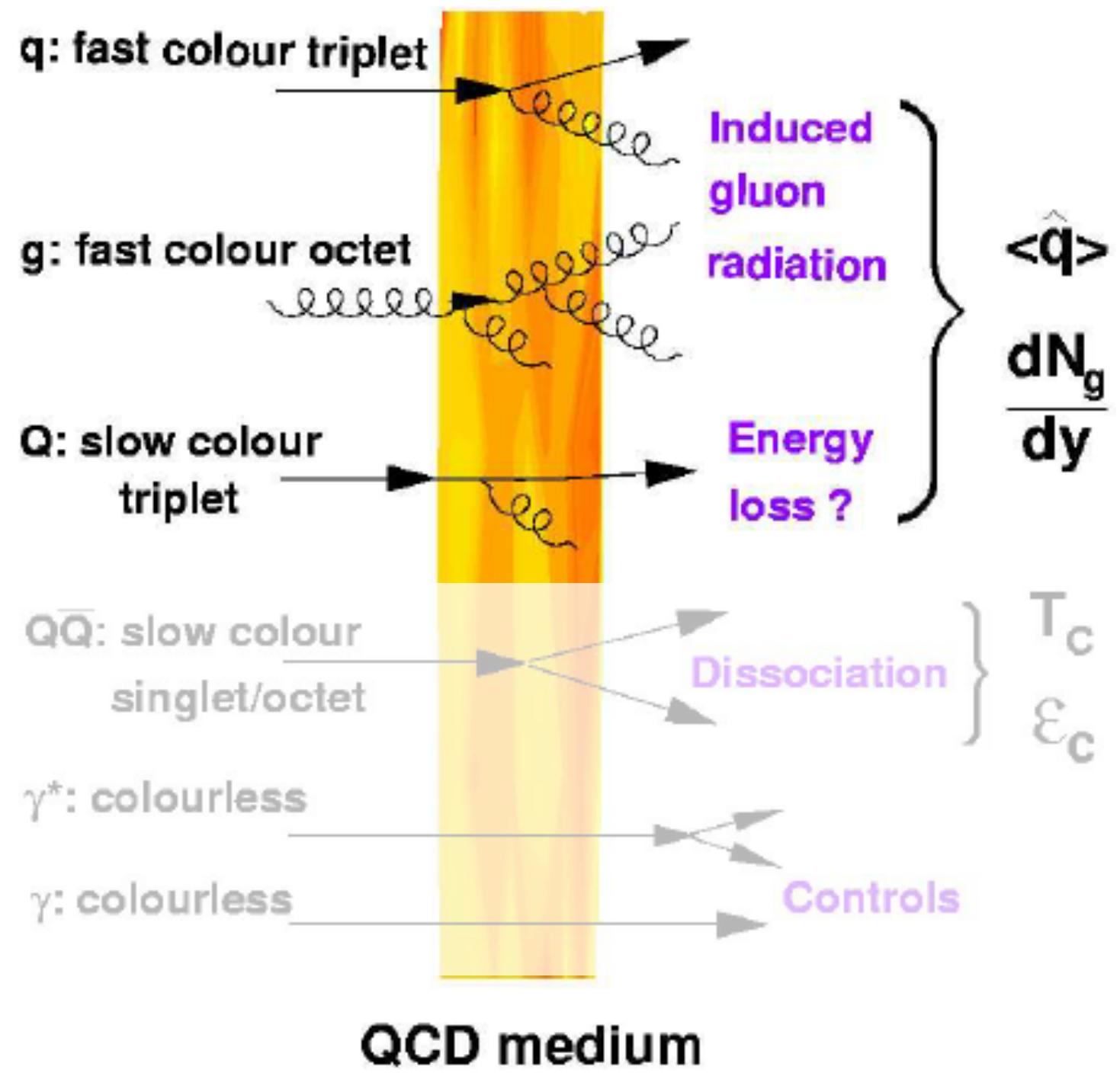
- Probes of the produced medium:



QGP short wavelength behaviour

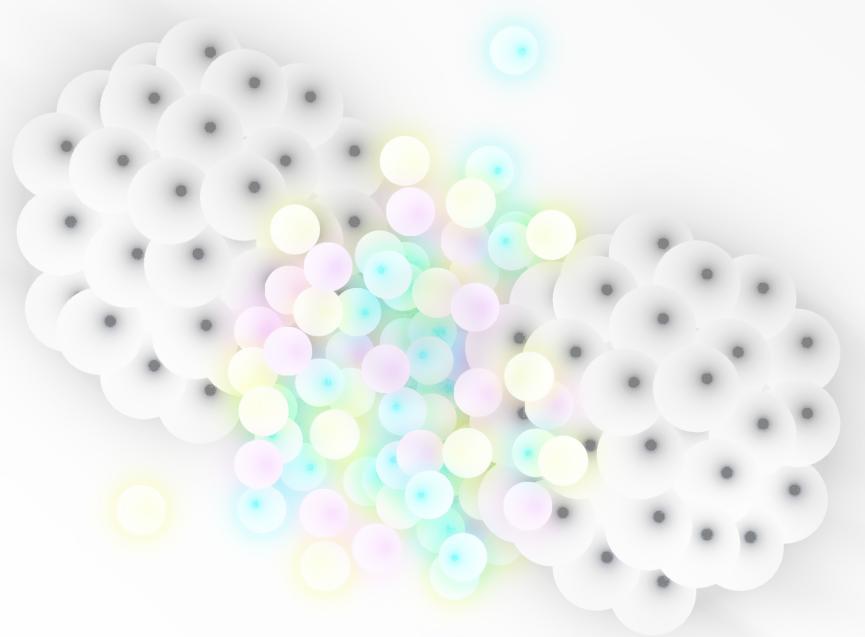


- Probes of the produced medium:

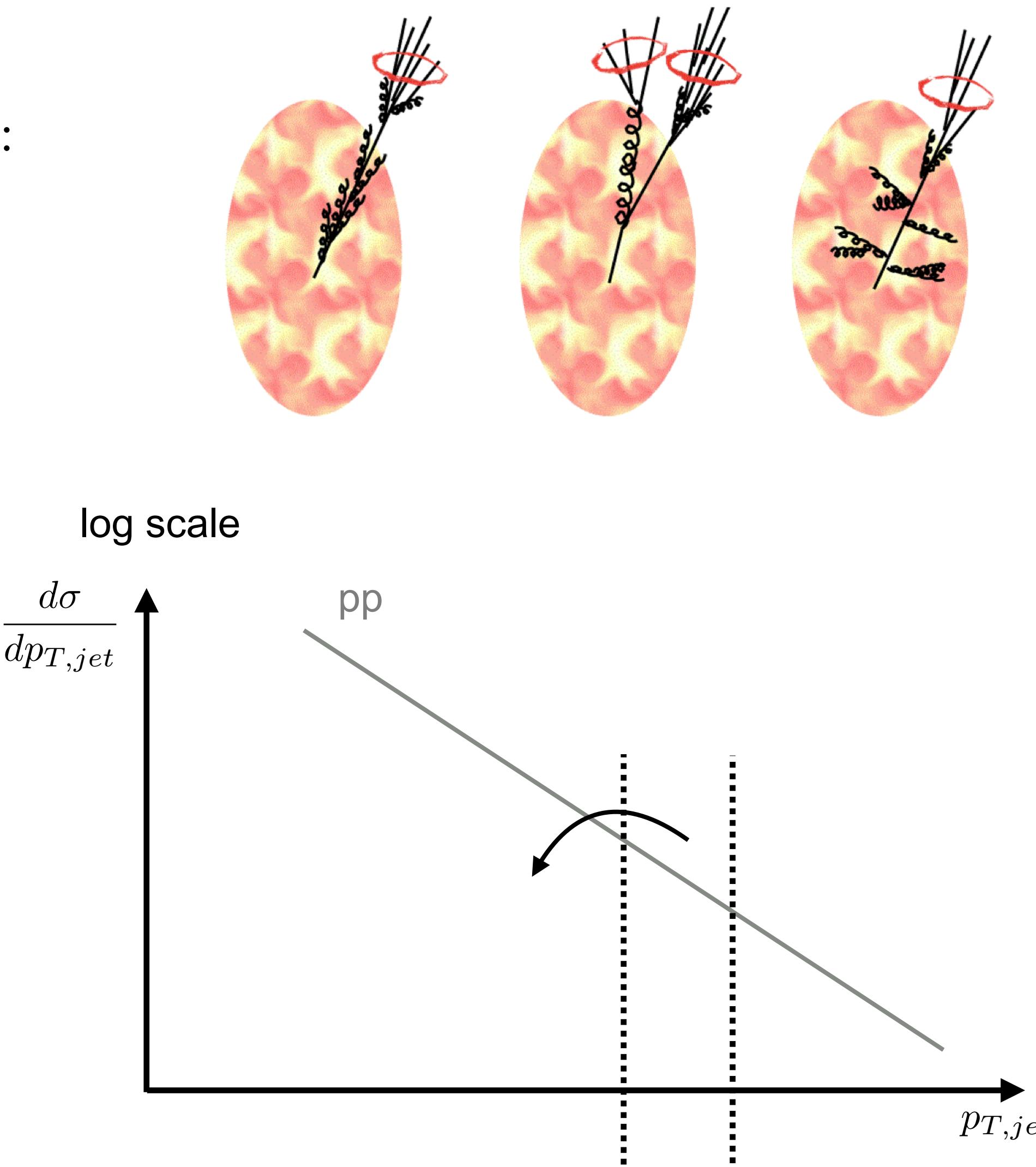
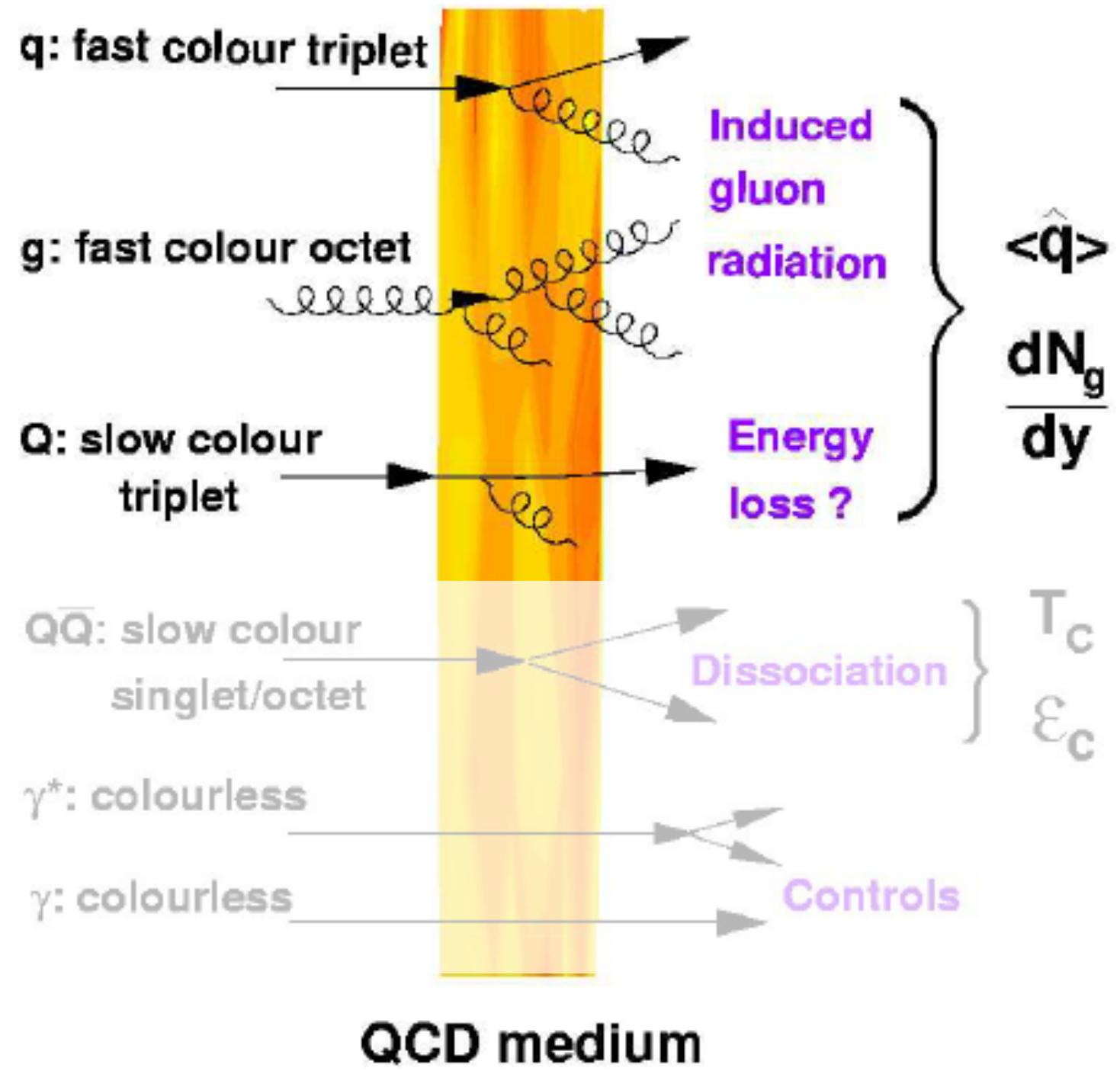


Result into different jet and particle yields

QGP short wavelength behaviour

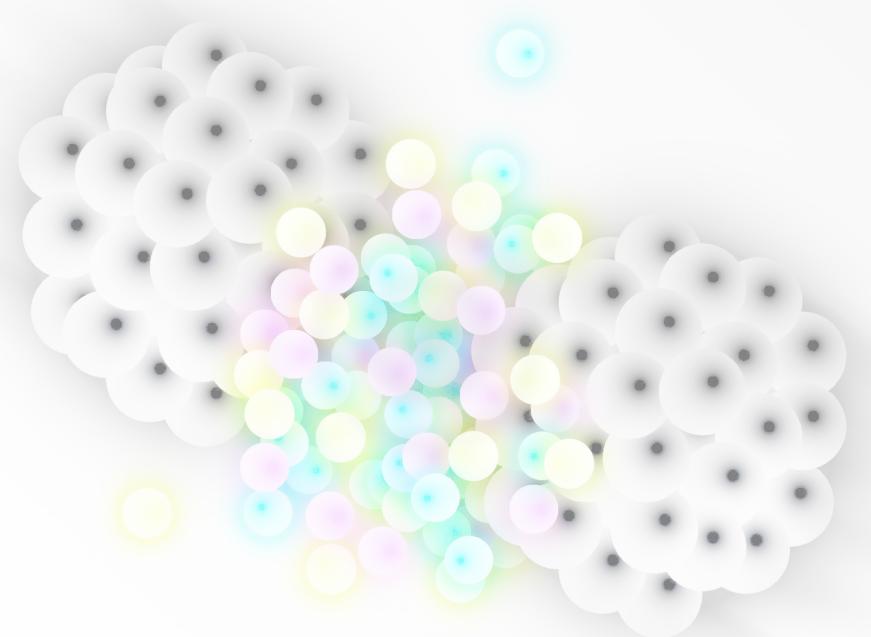


- Probes of the produced medium:

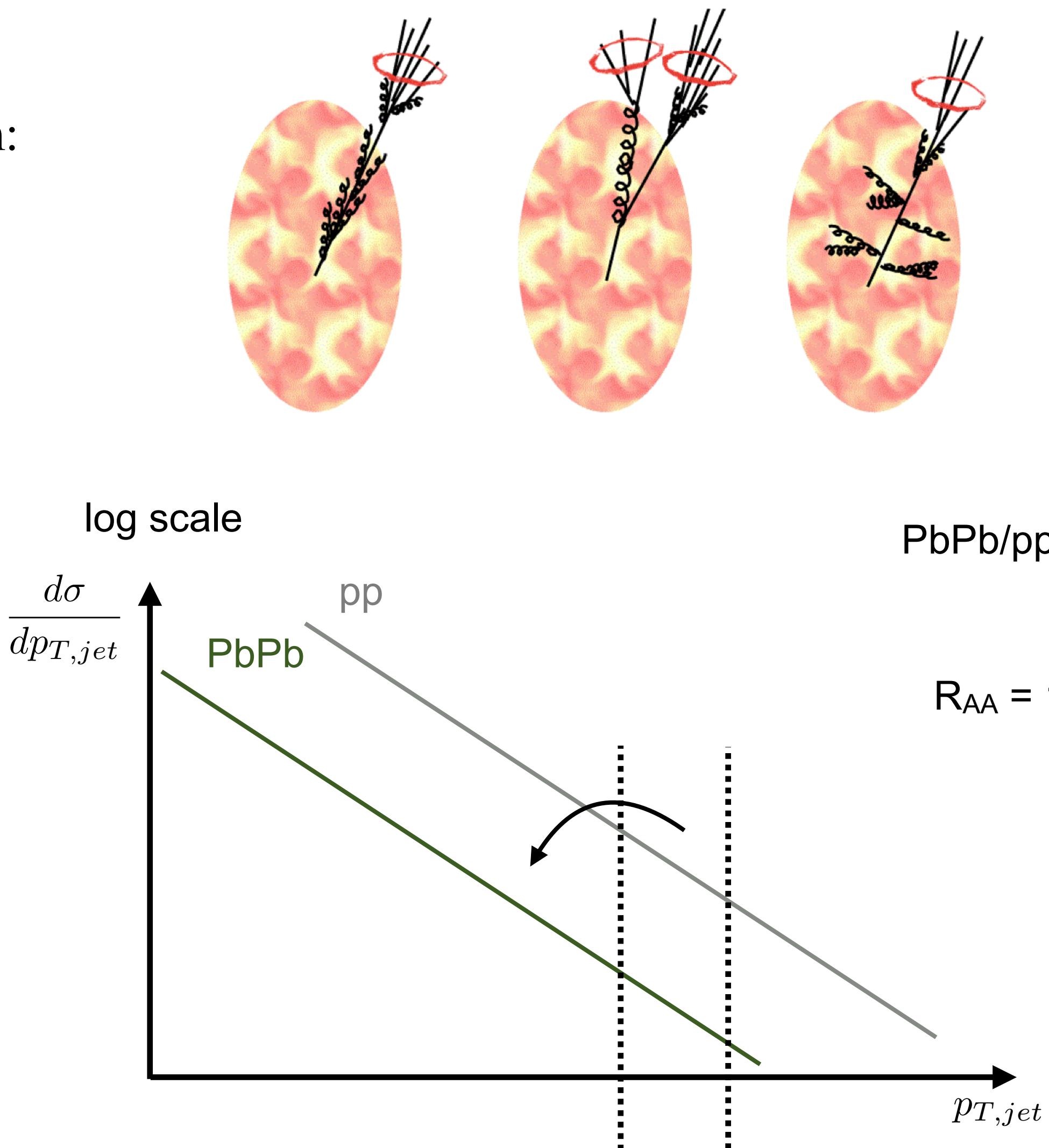
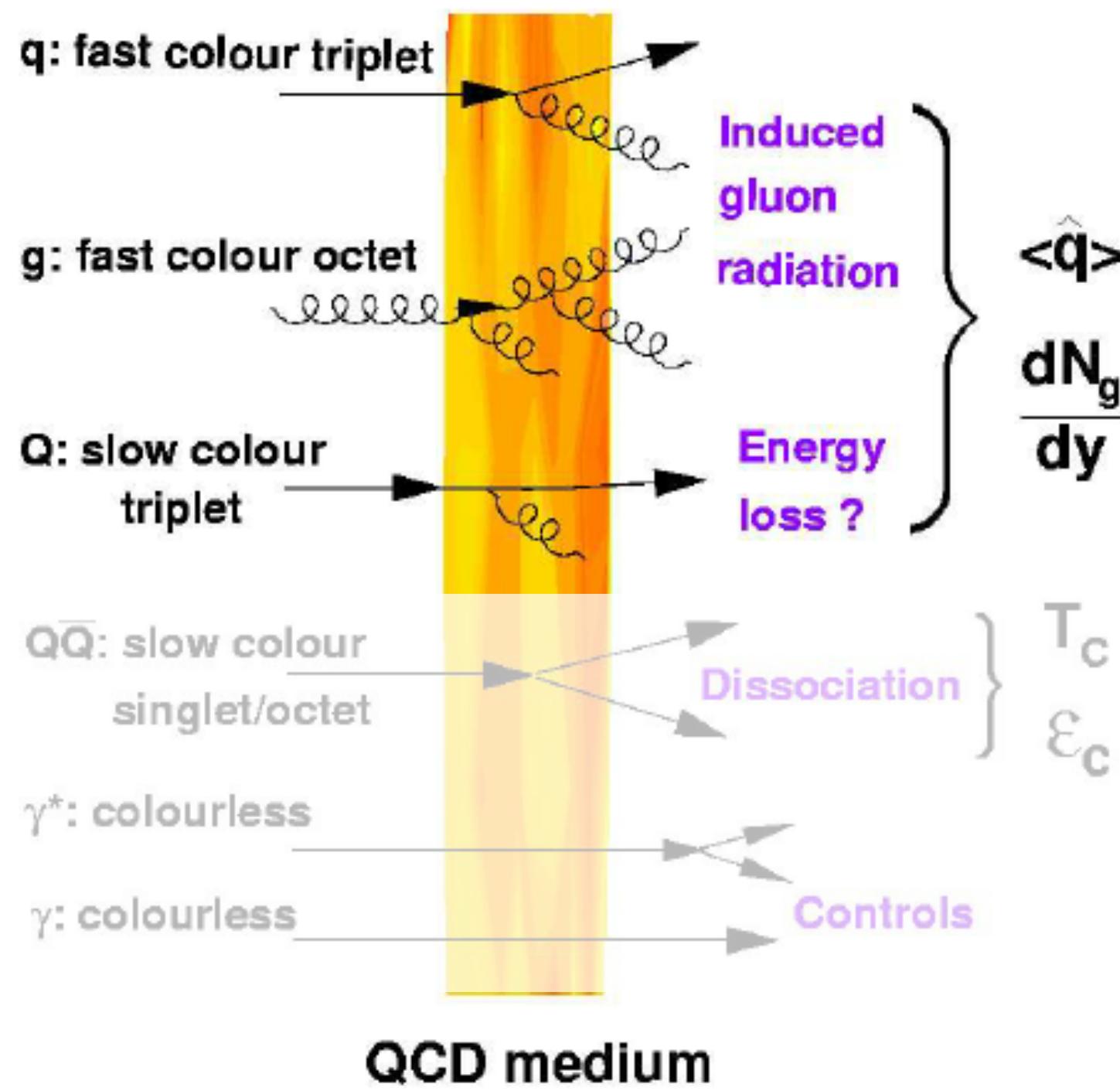


Result into different jet and particle yields

QGP short wavelength behaviour

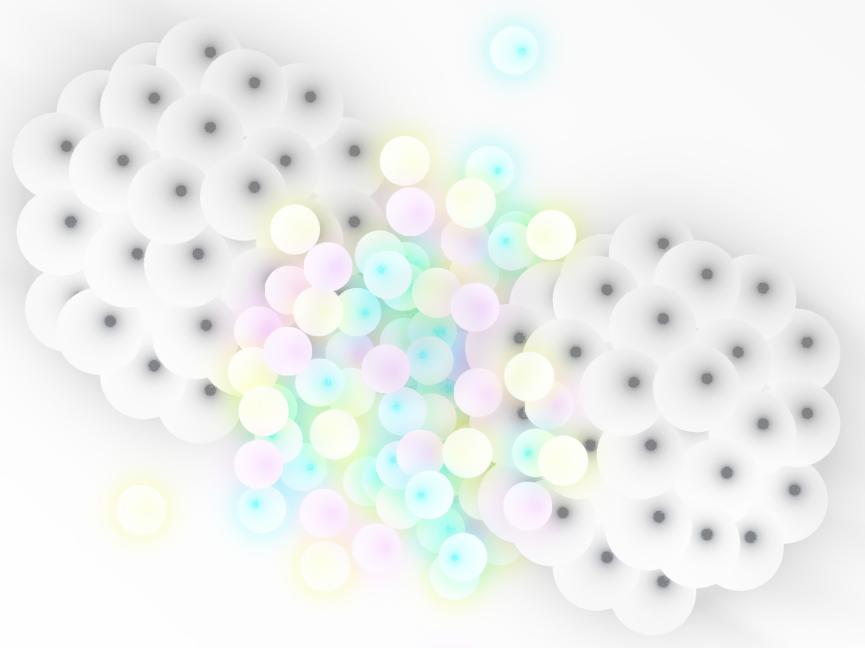


- Probes of the produced medium:

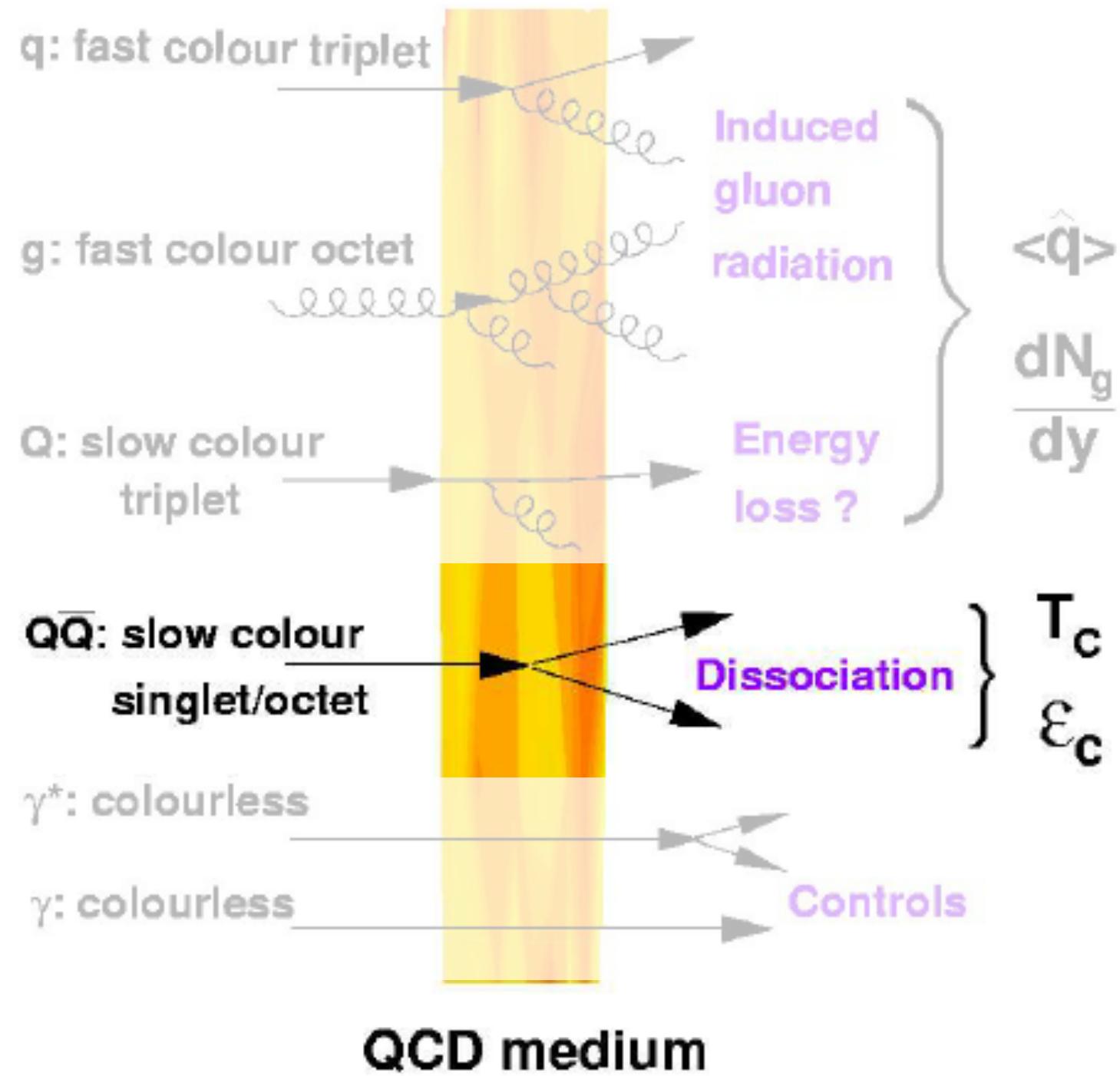


Result into different jet and particle yields

QGP short wavelength behaviour



- Probes of the produced medium:



See Gian Michele's lectures

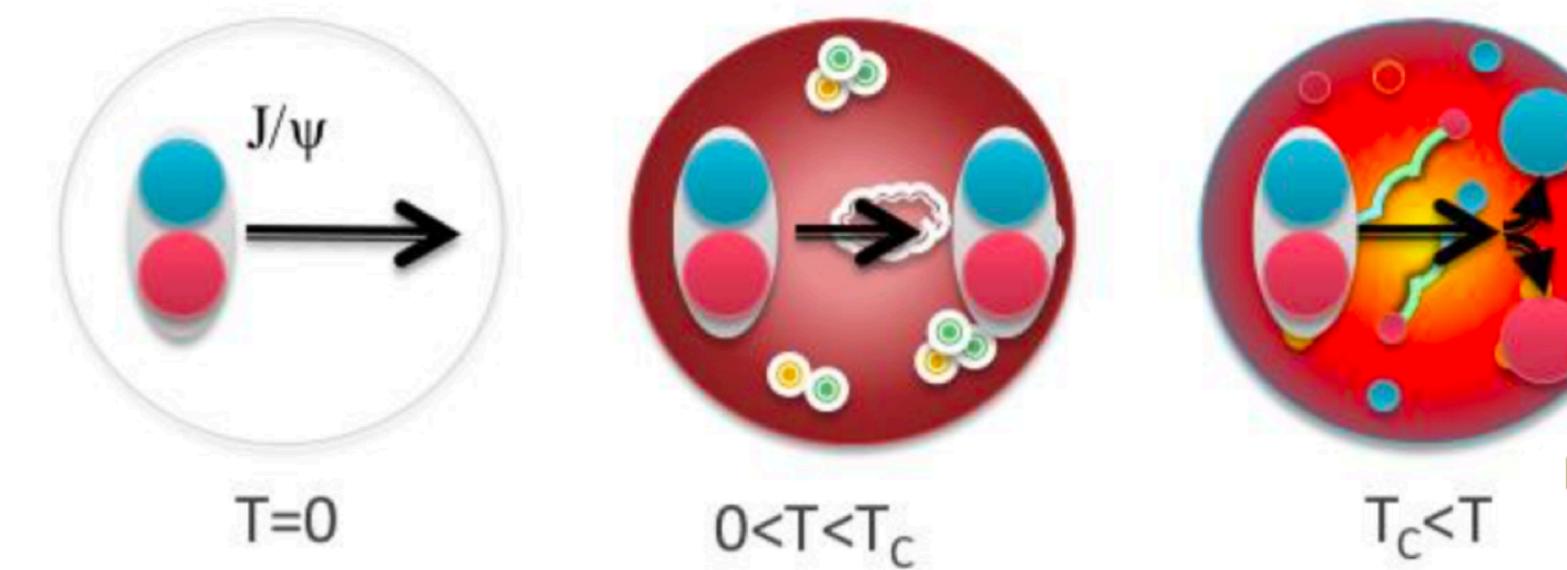
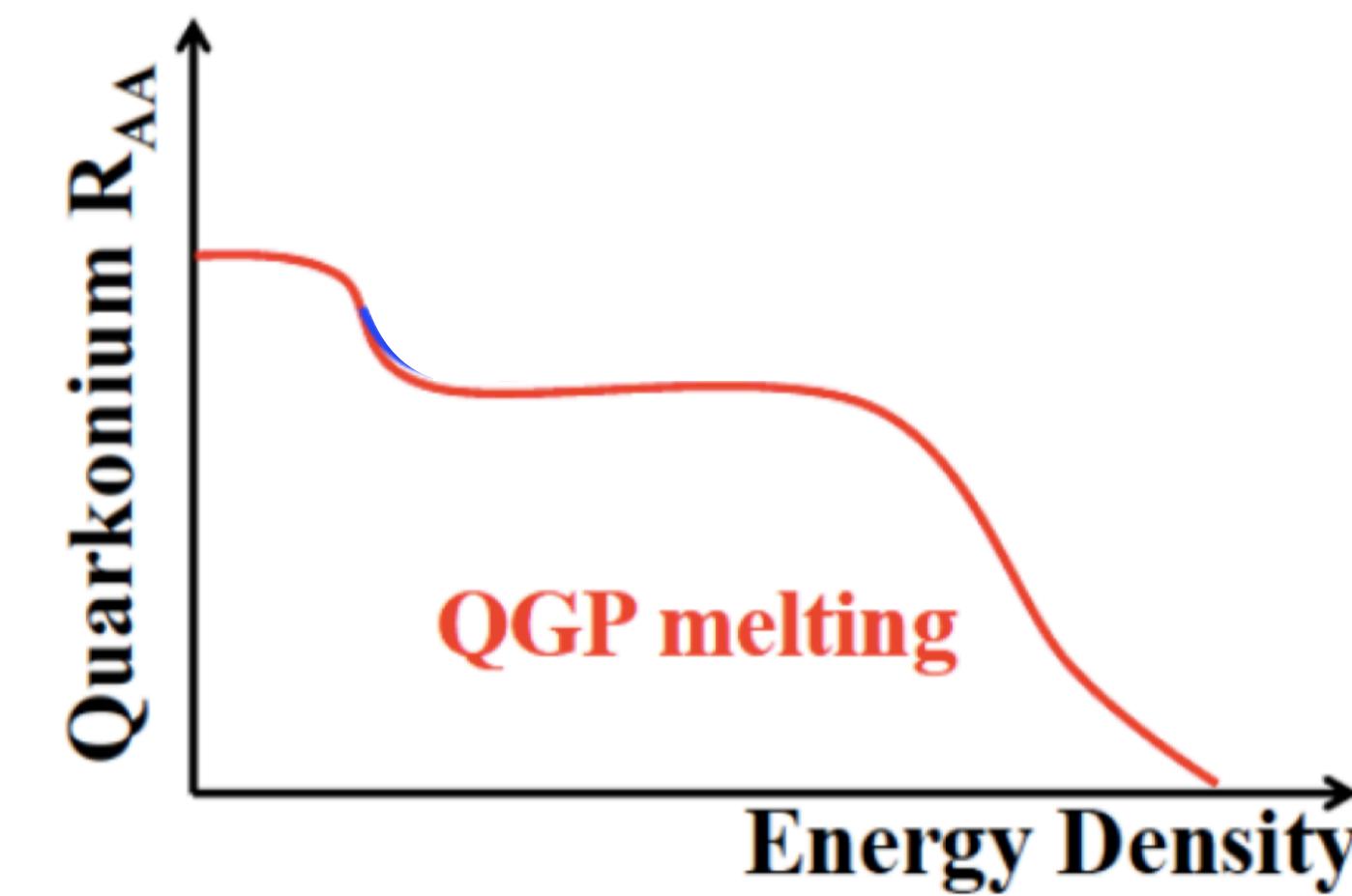
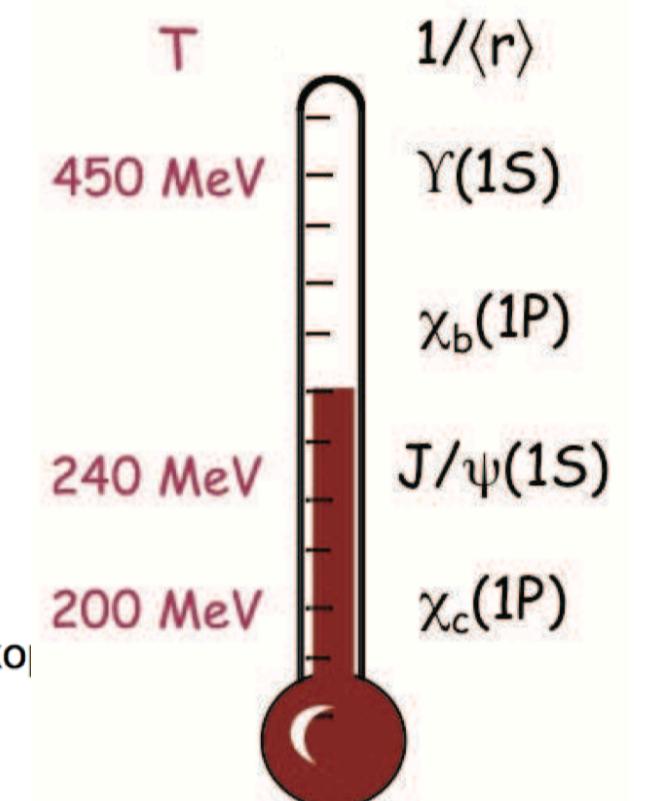
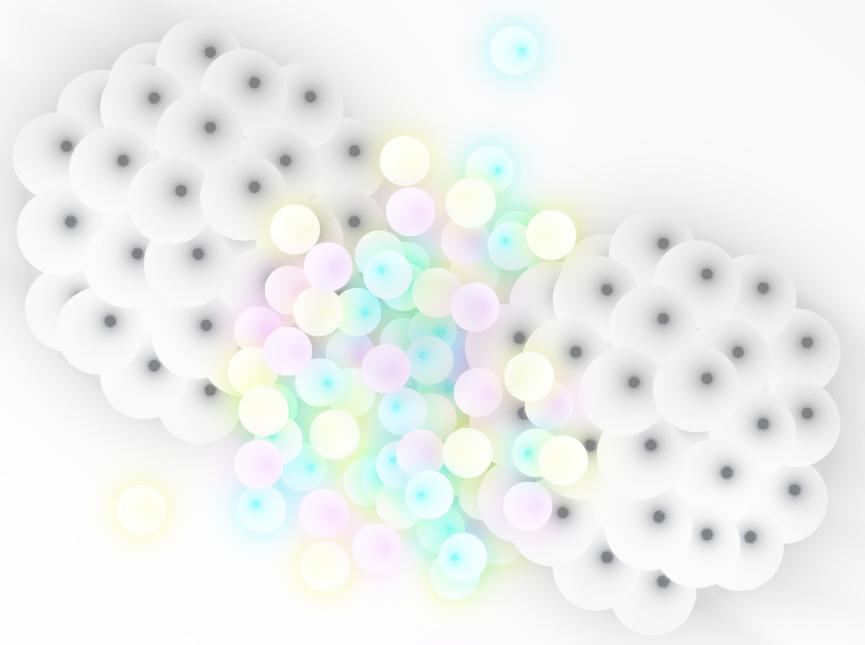


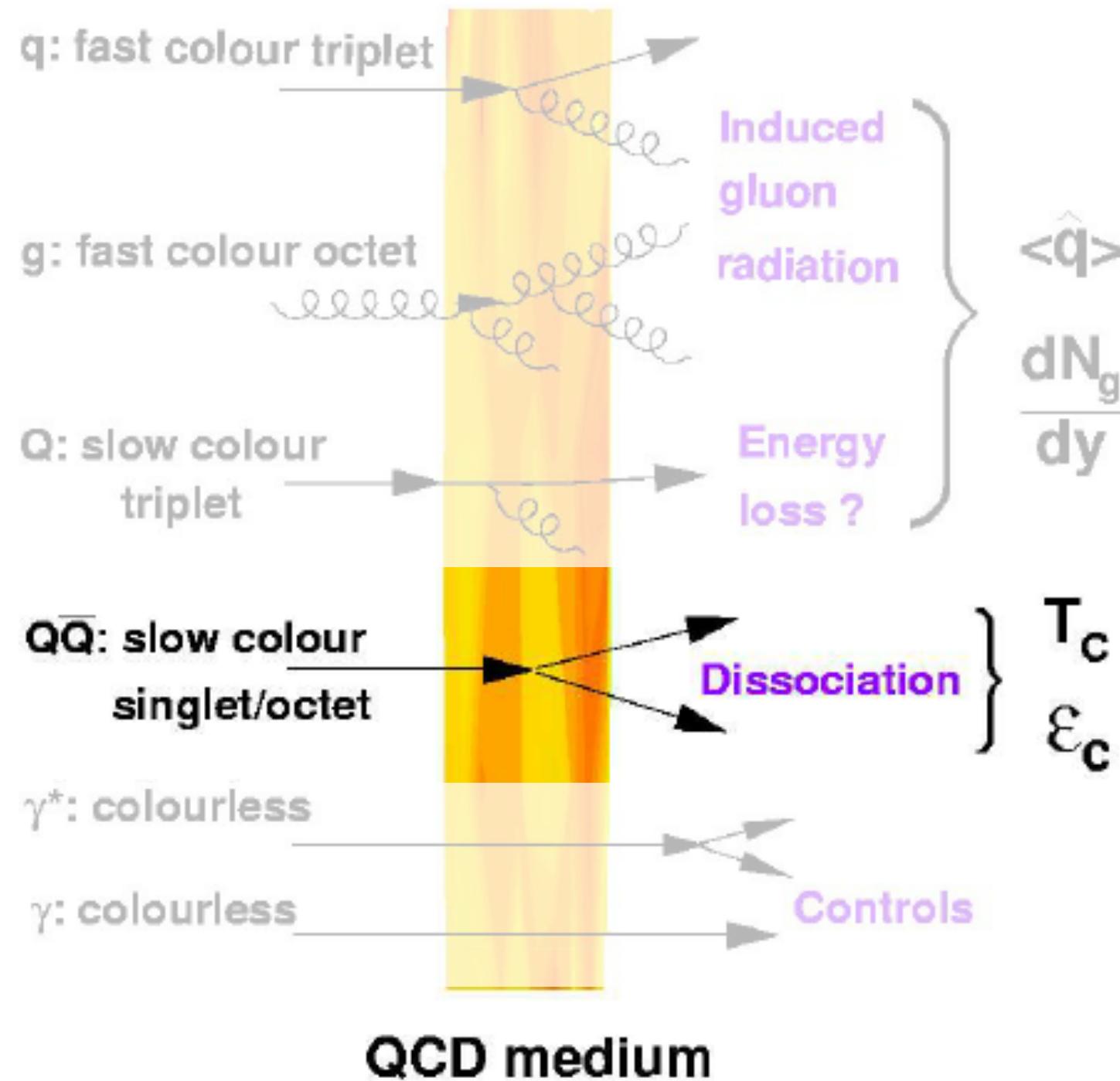
Illustration: A.Rothko



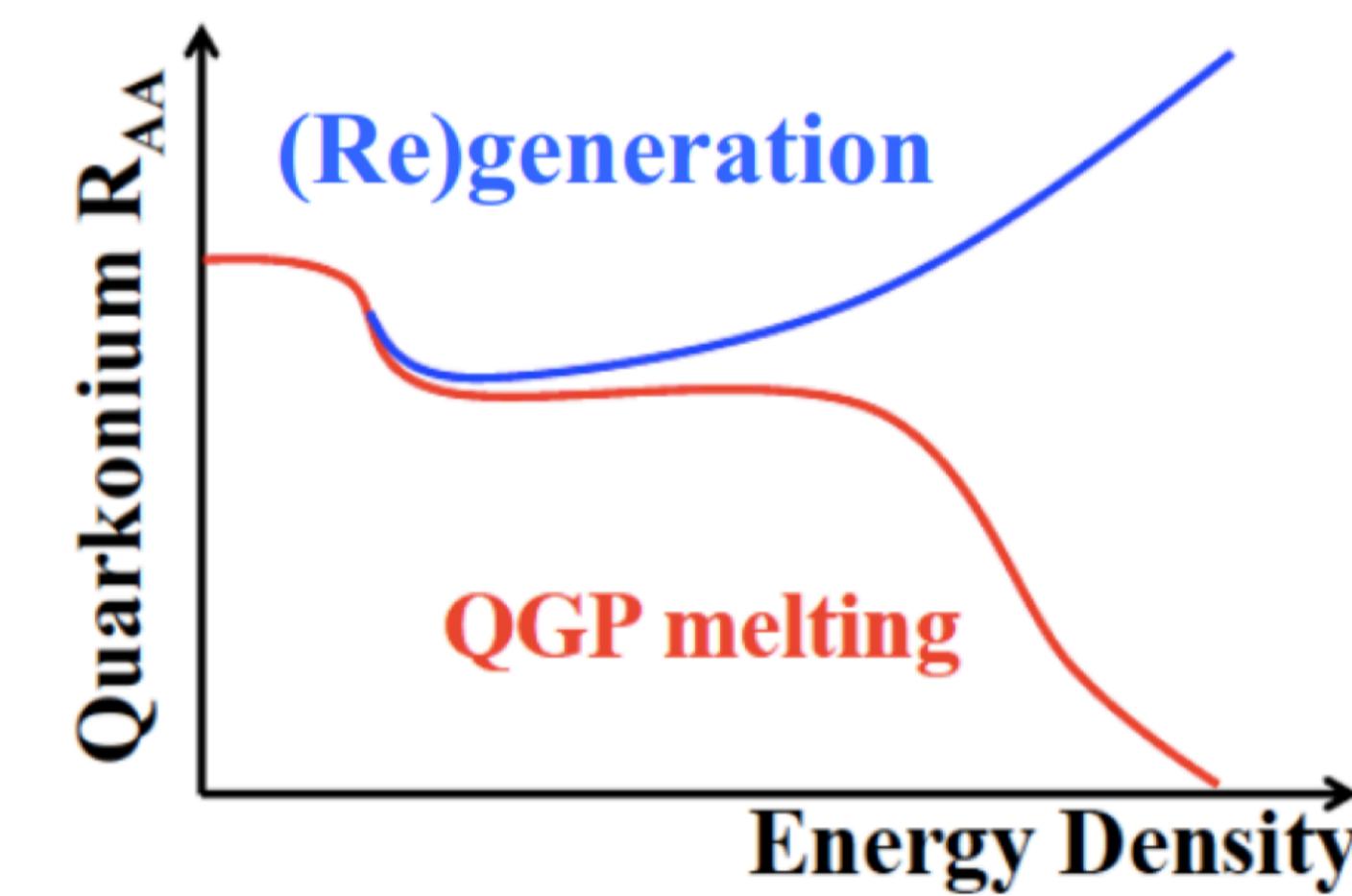
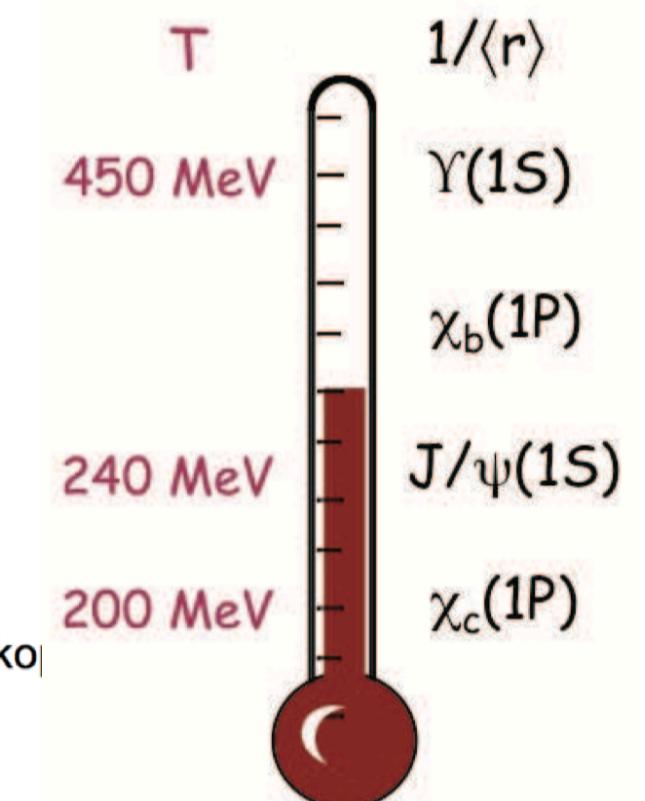
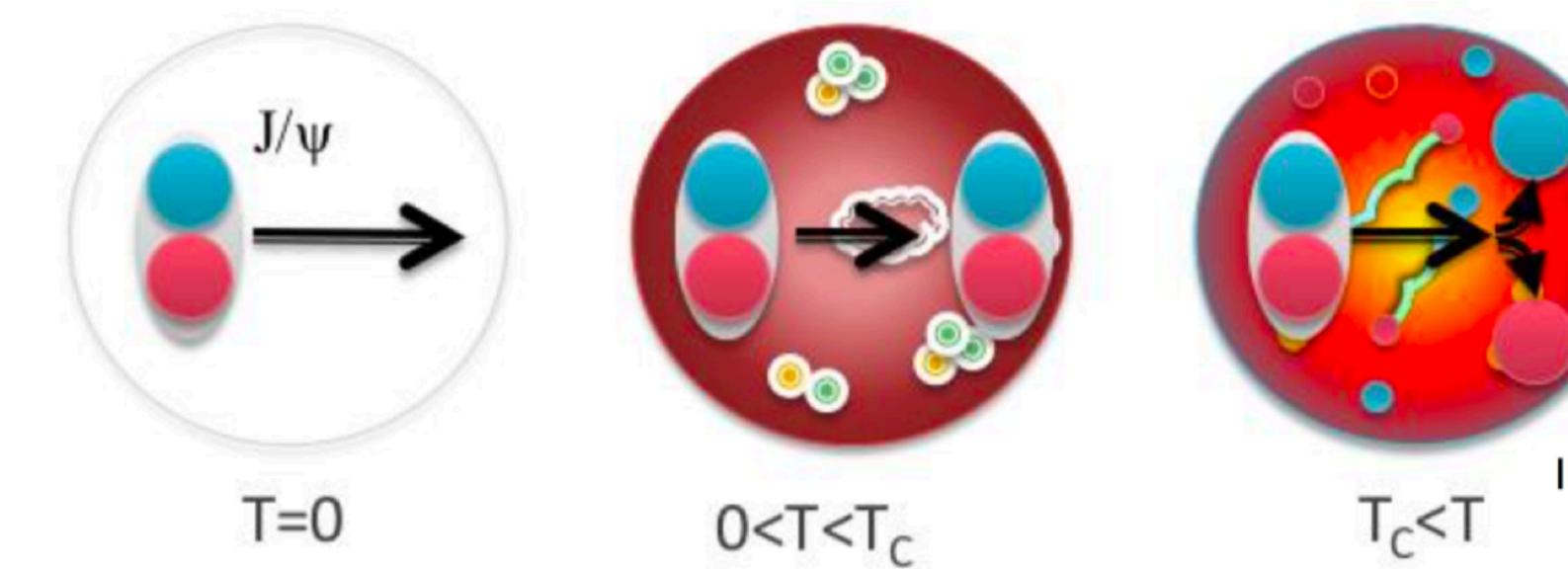
QGP short wavelength behaviour



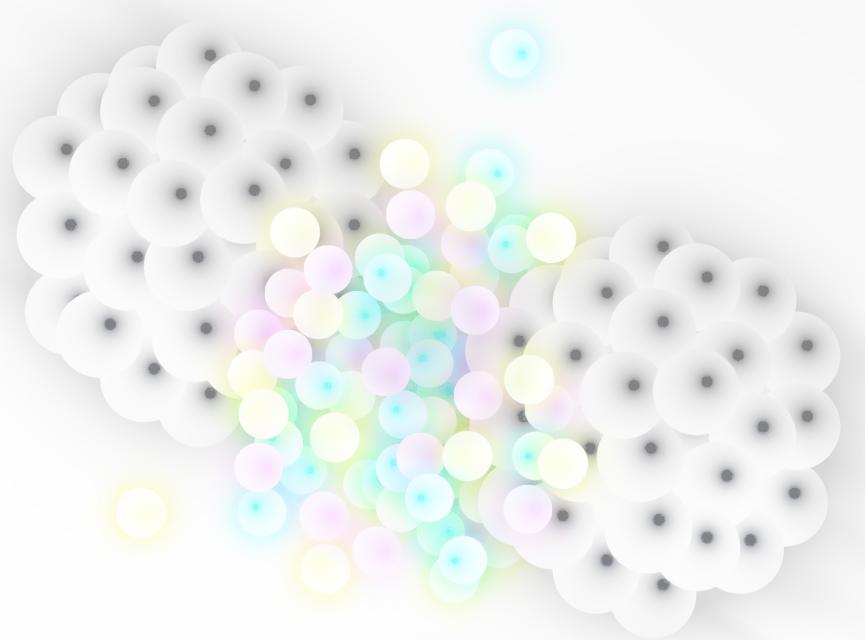
- Probes of the produced medium:



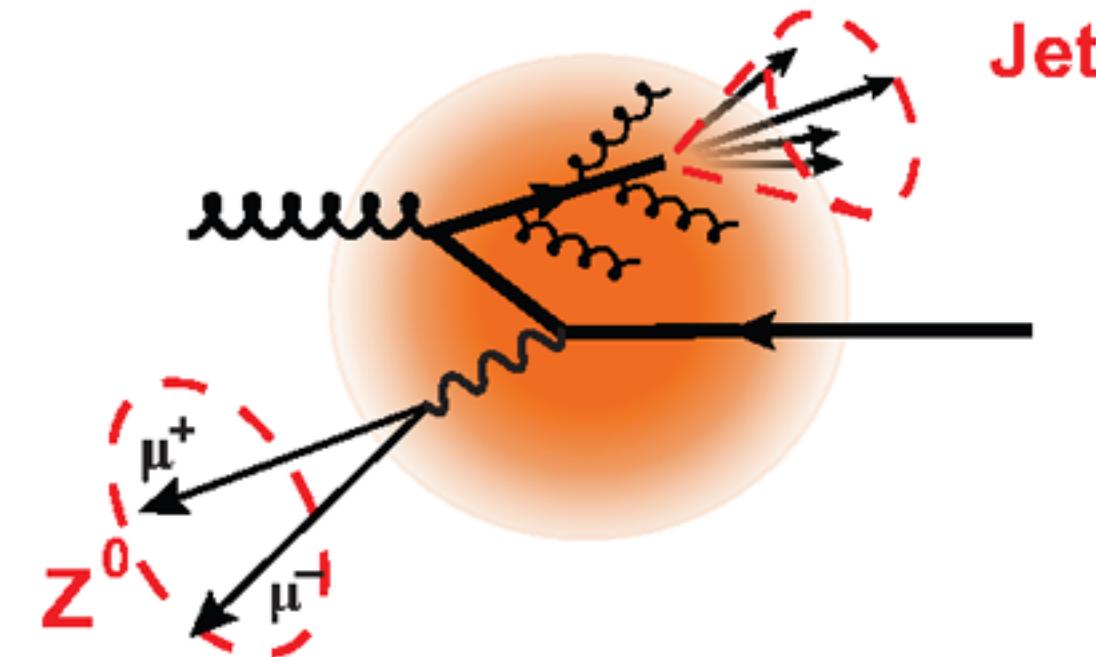
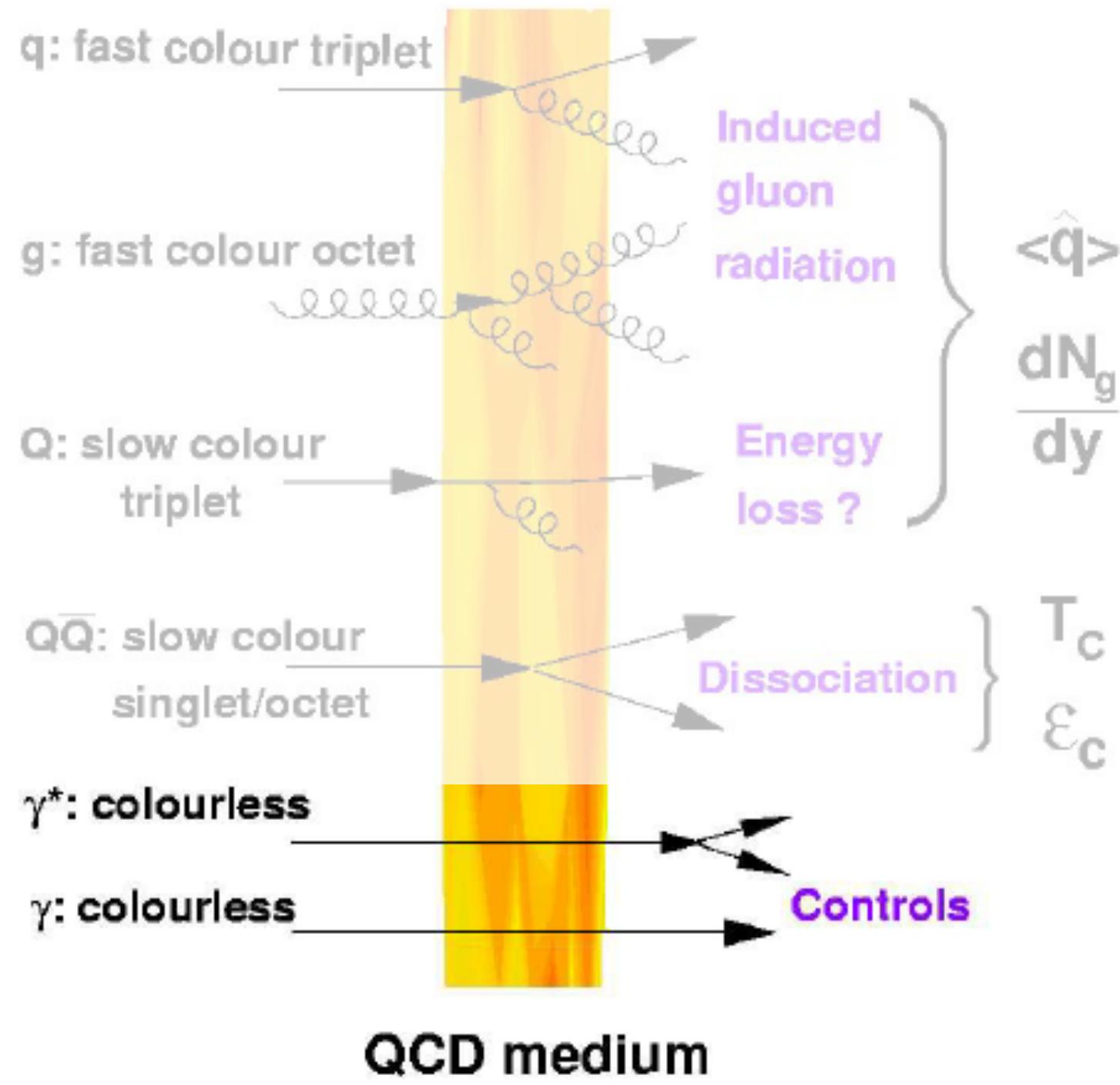
See Gian Michele's lectures



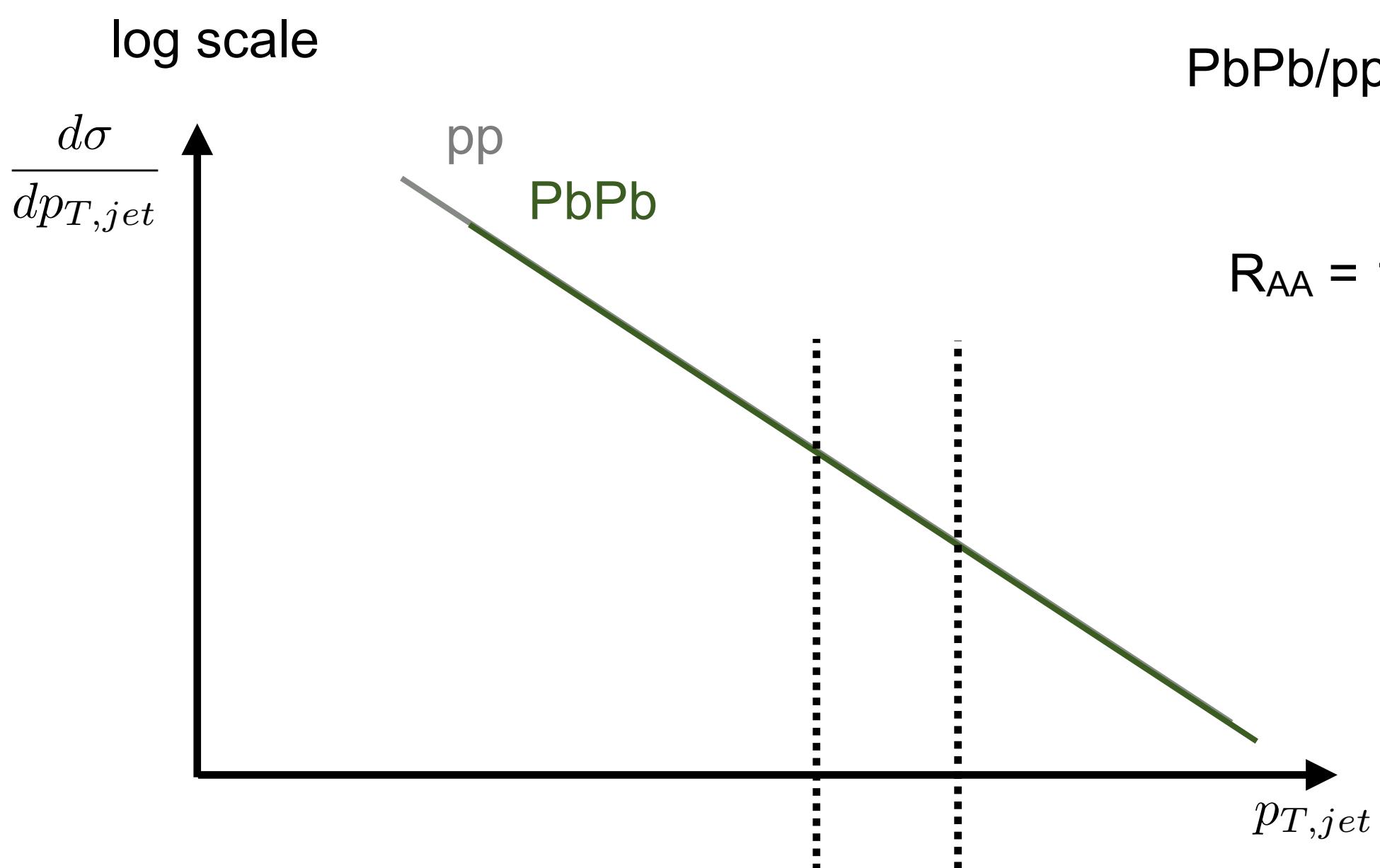
QGP short wavelength behaviour



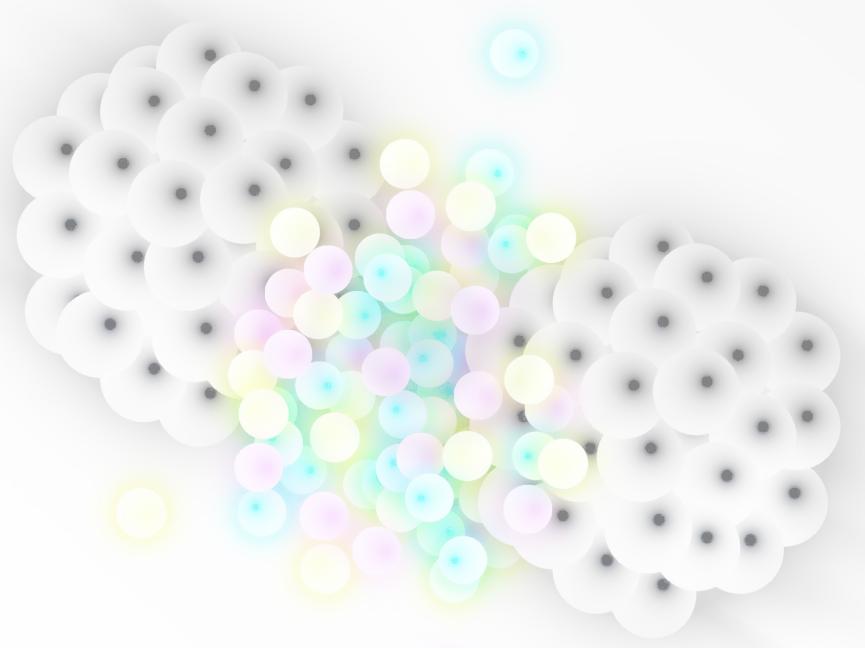
- Probes of the produced medium:



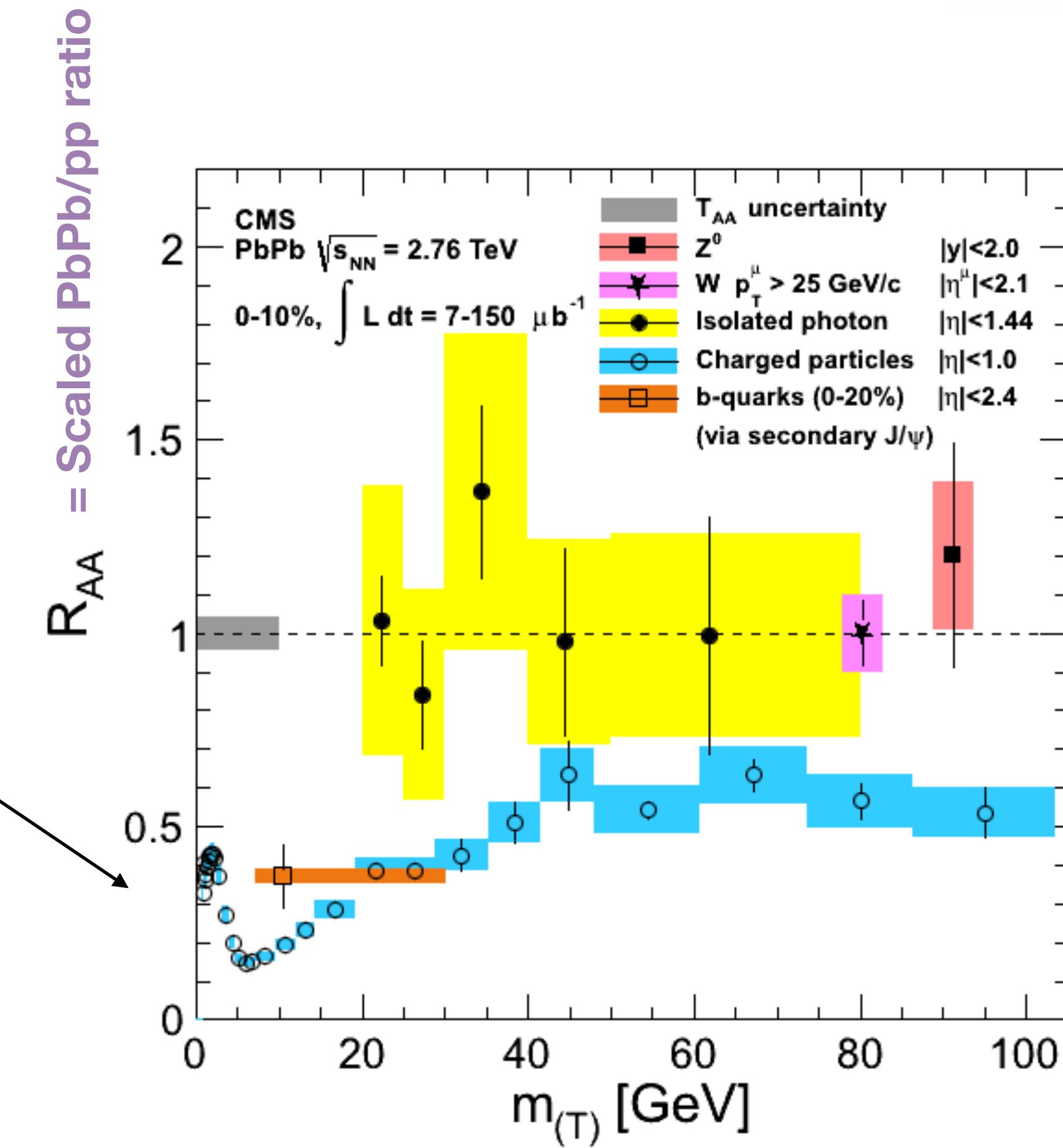
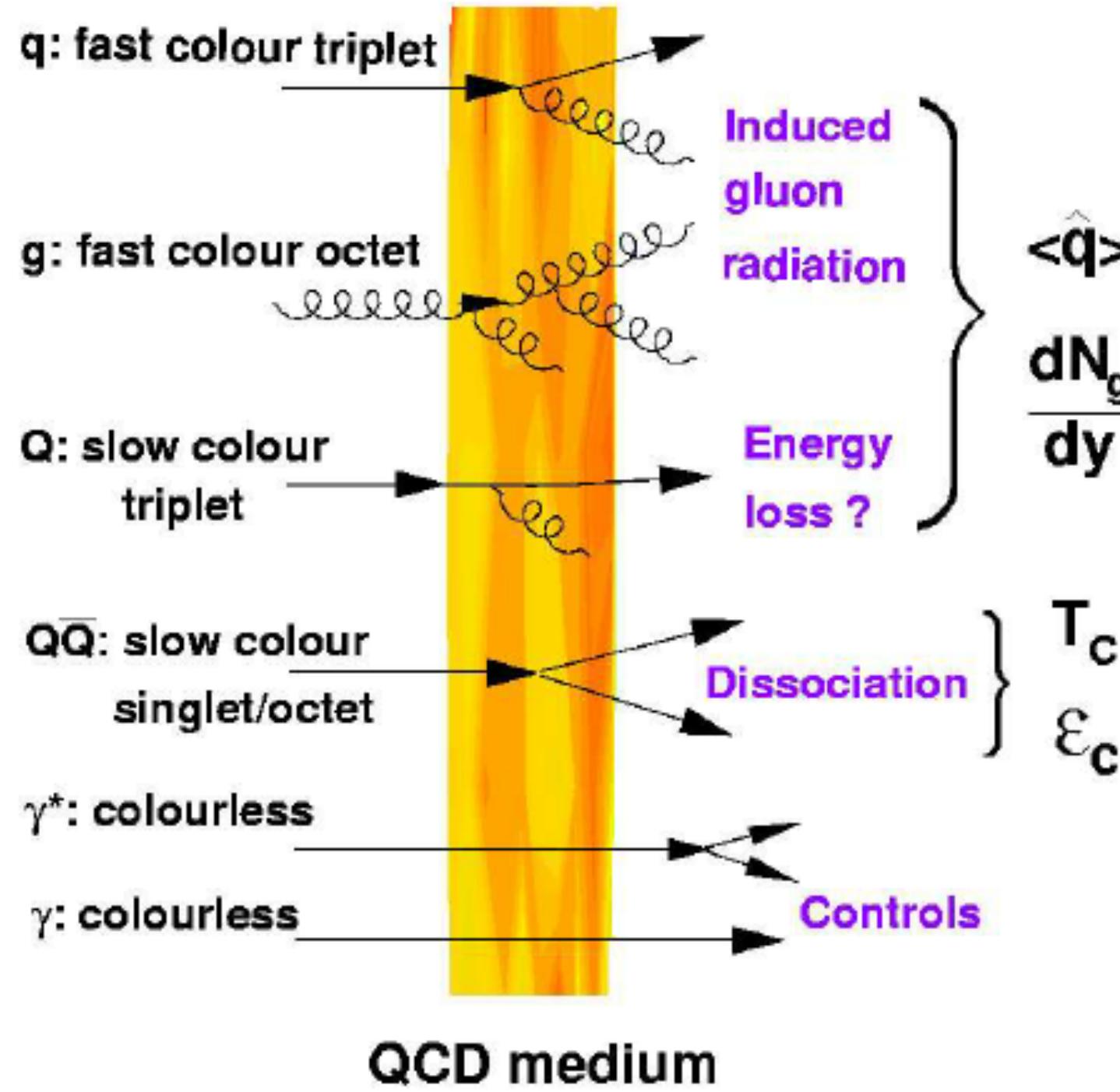
Colourless particles will not interact strongly with the QGP



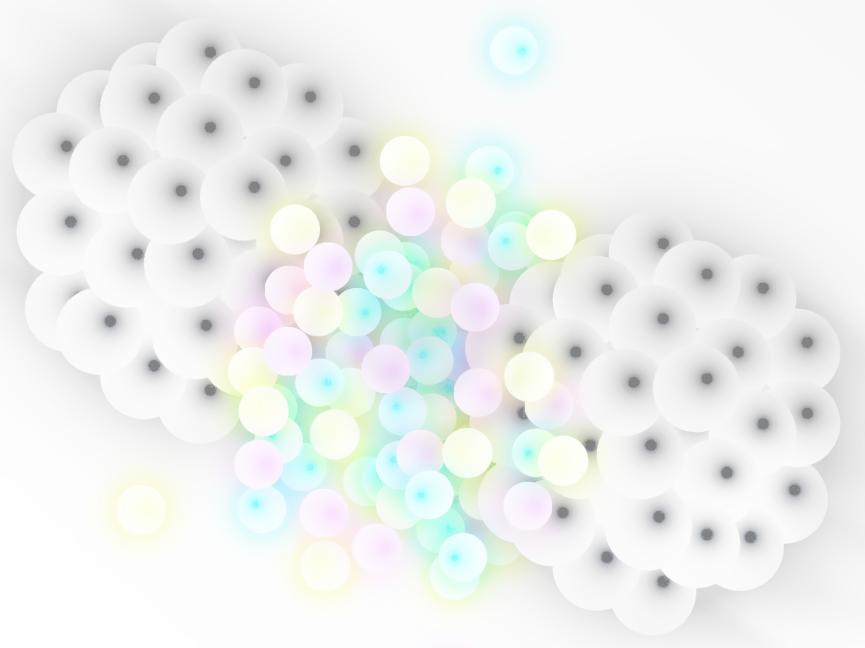
QGP short wavelength behaviour



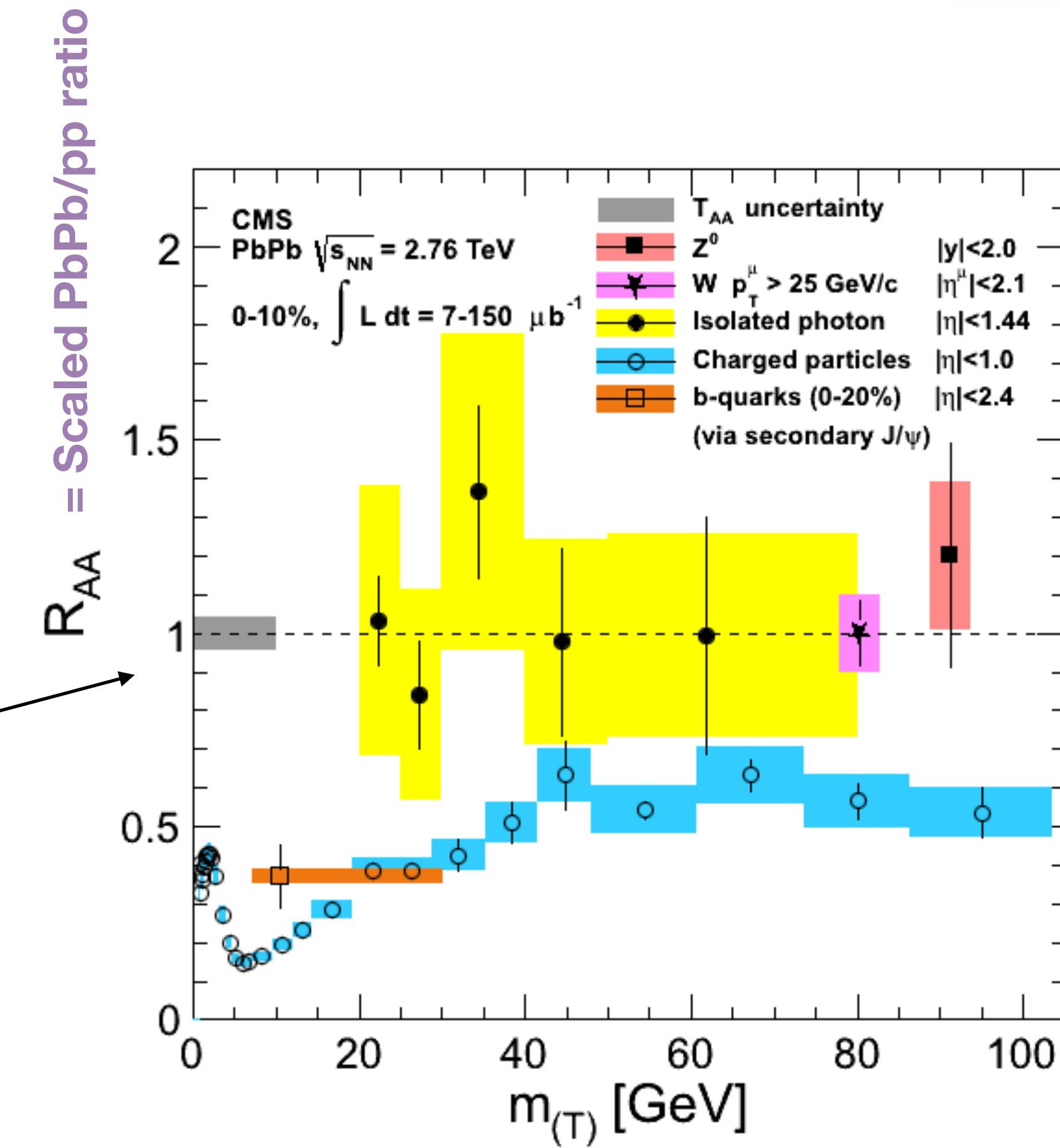
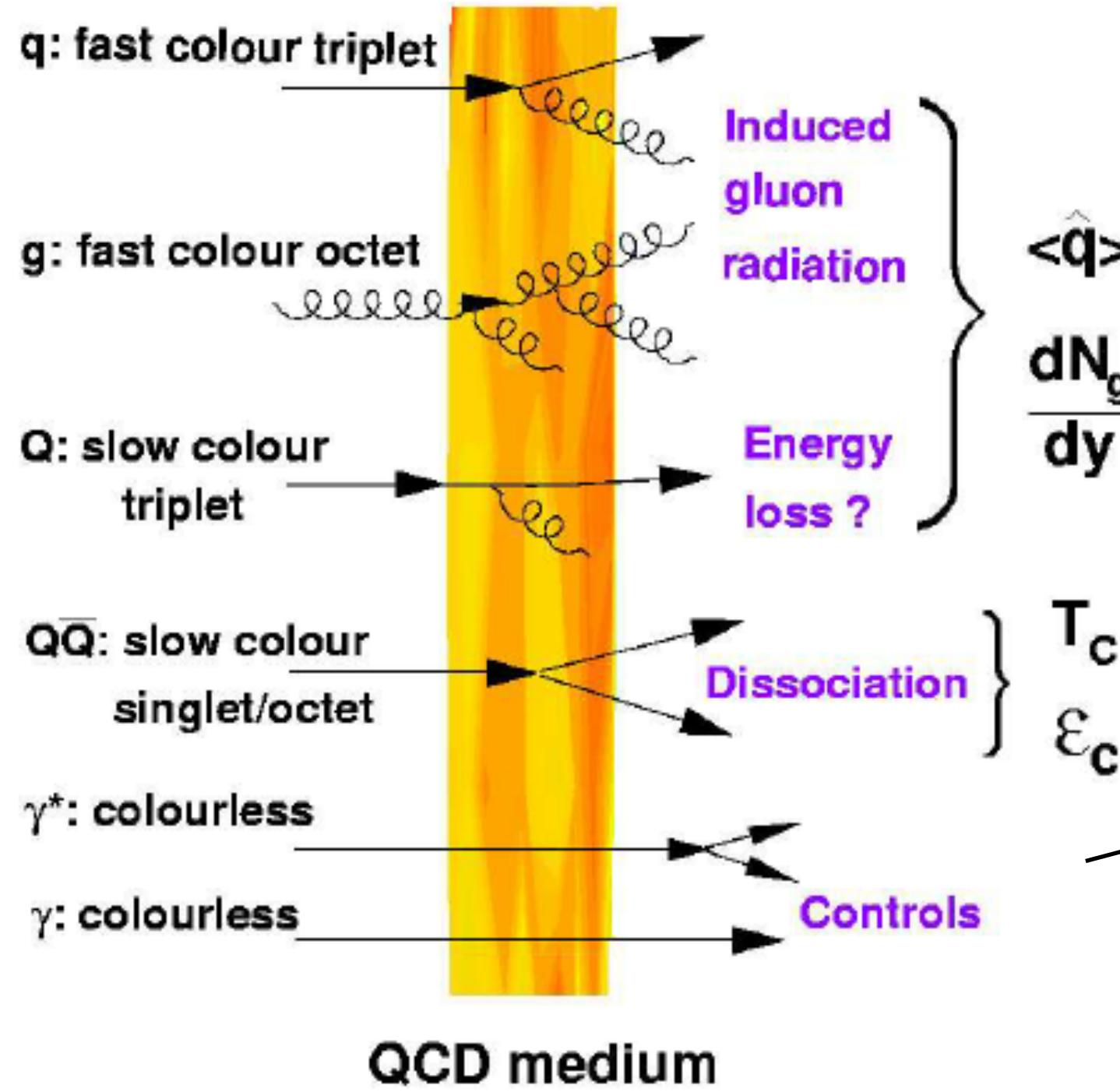
- Probes of the produced medium:



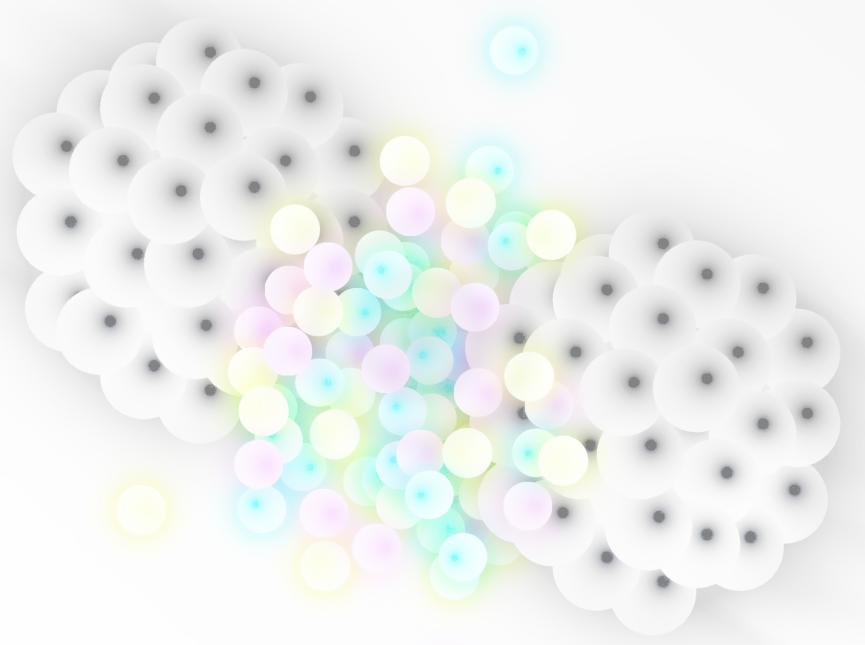
QGP short wavelength behaviour



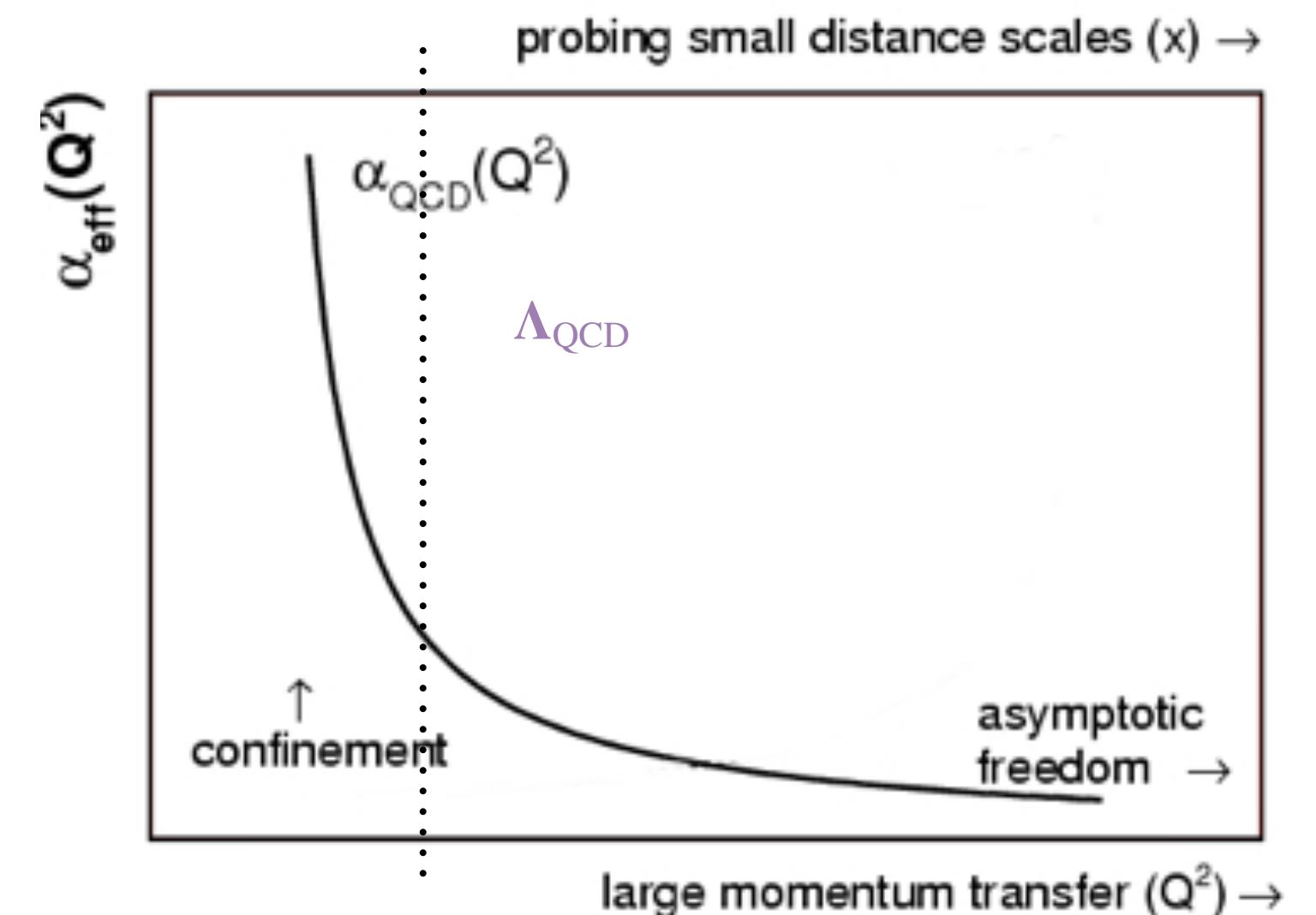
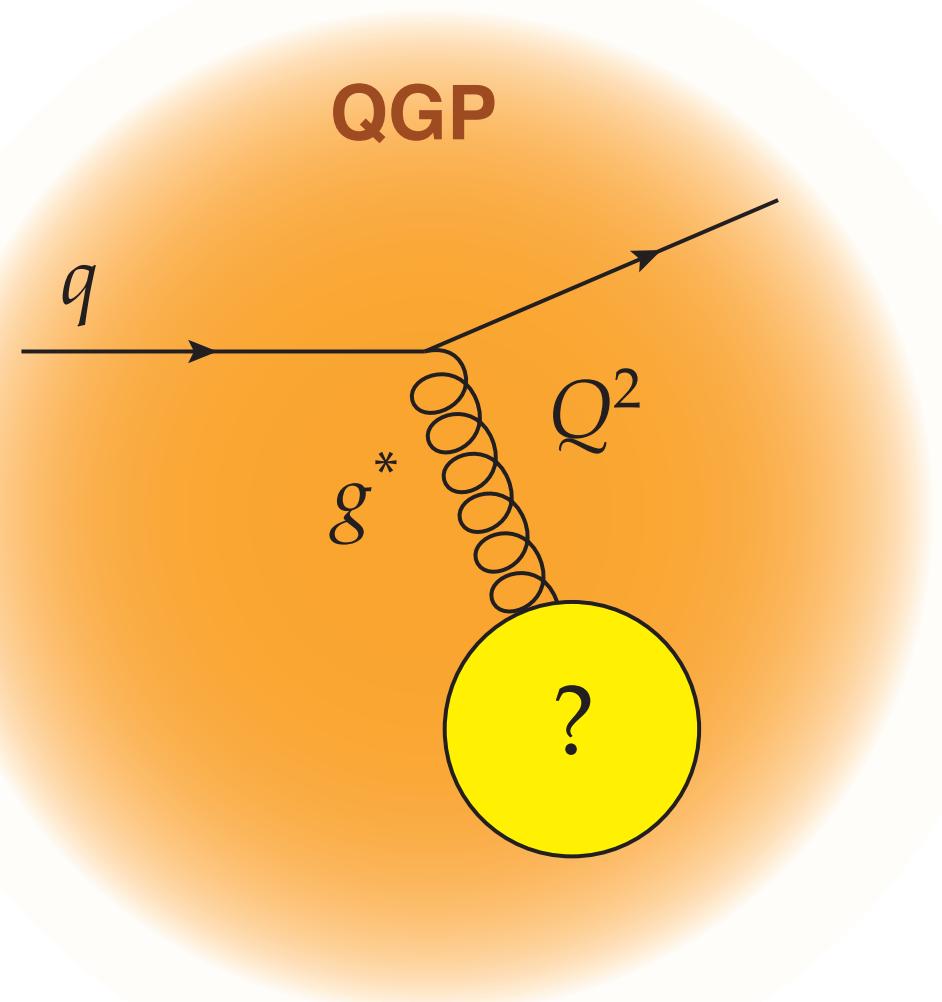
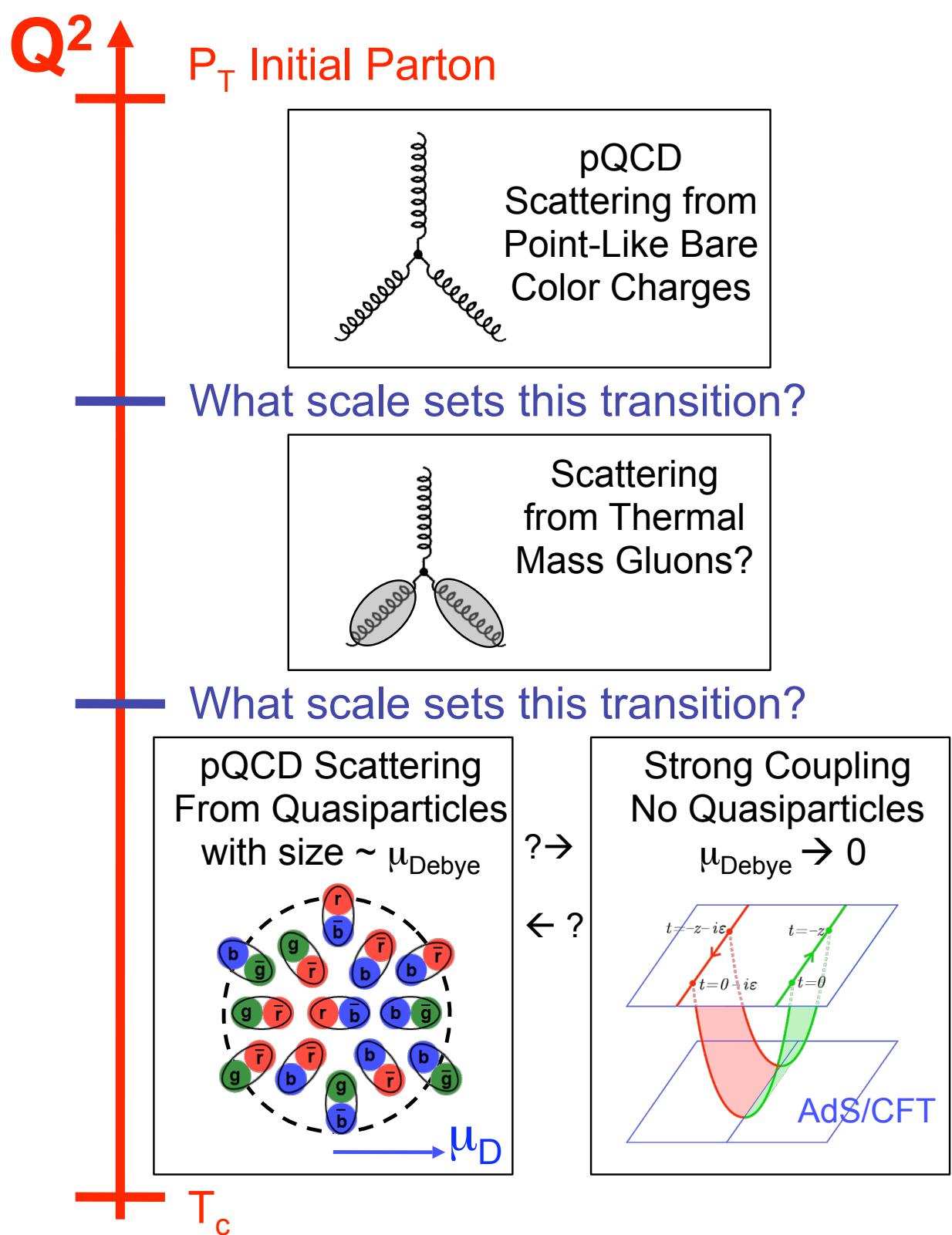
- Probes of the produced medium:



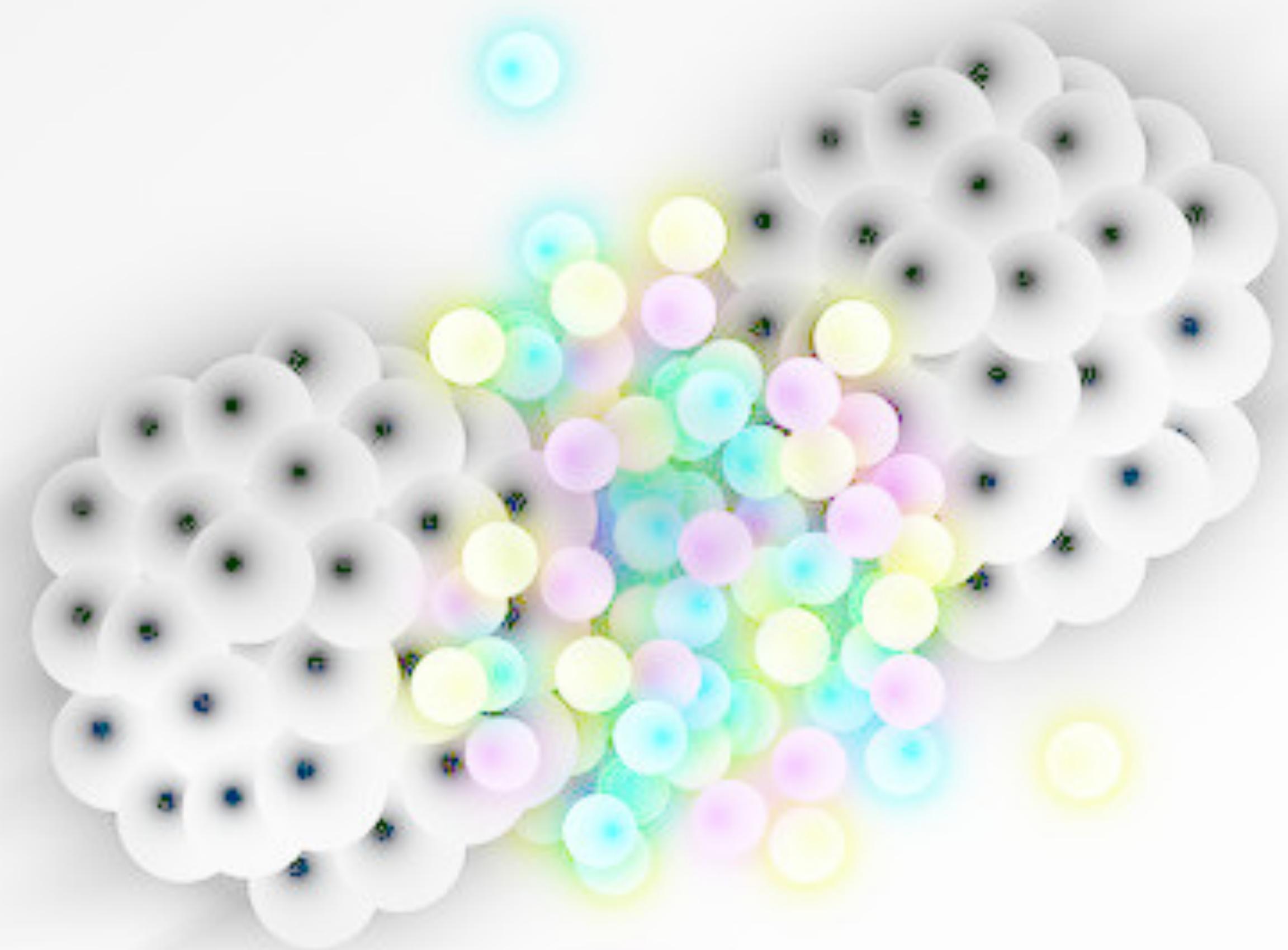
QGP short wavelength behaviour



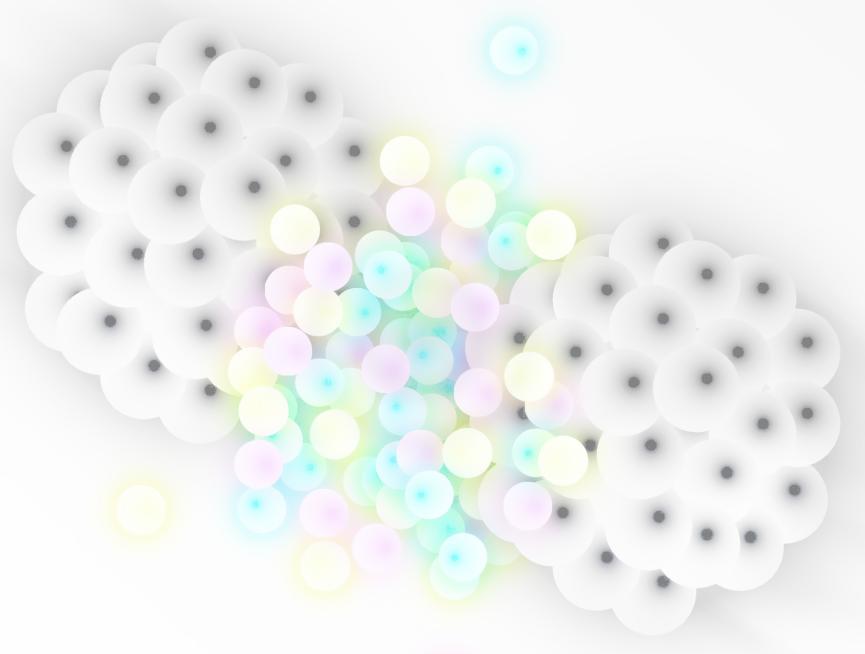
- What is the QGP?



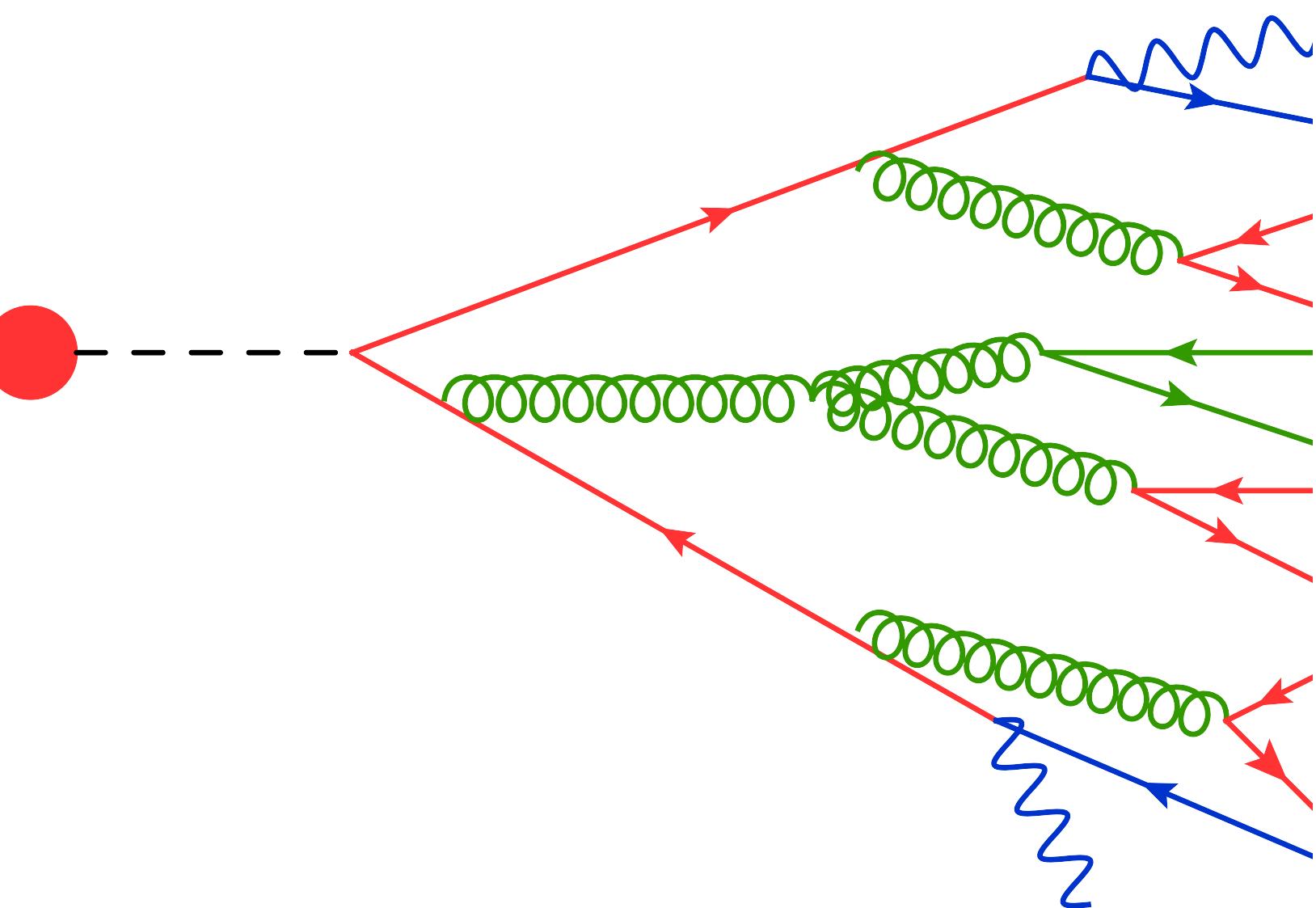
Jet Quenching



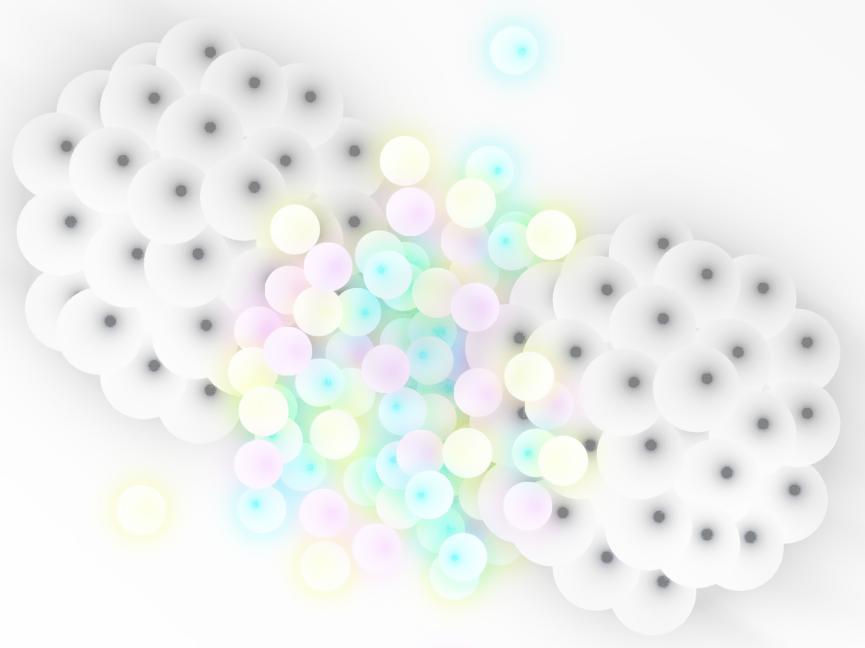
Jet Quenching



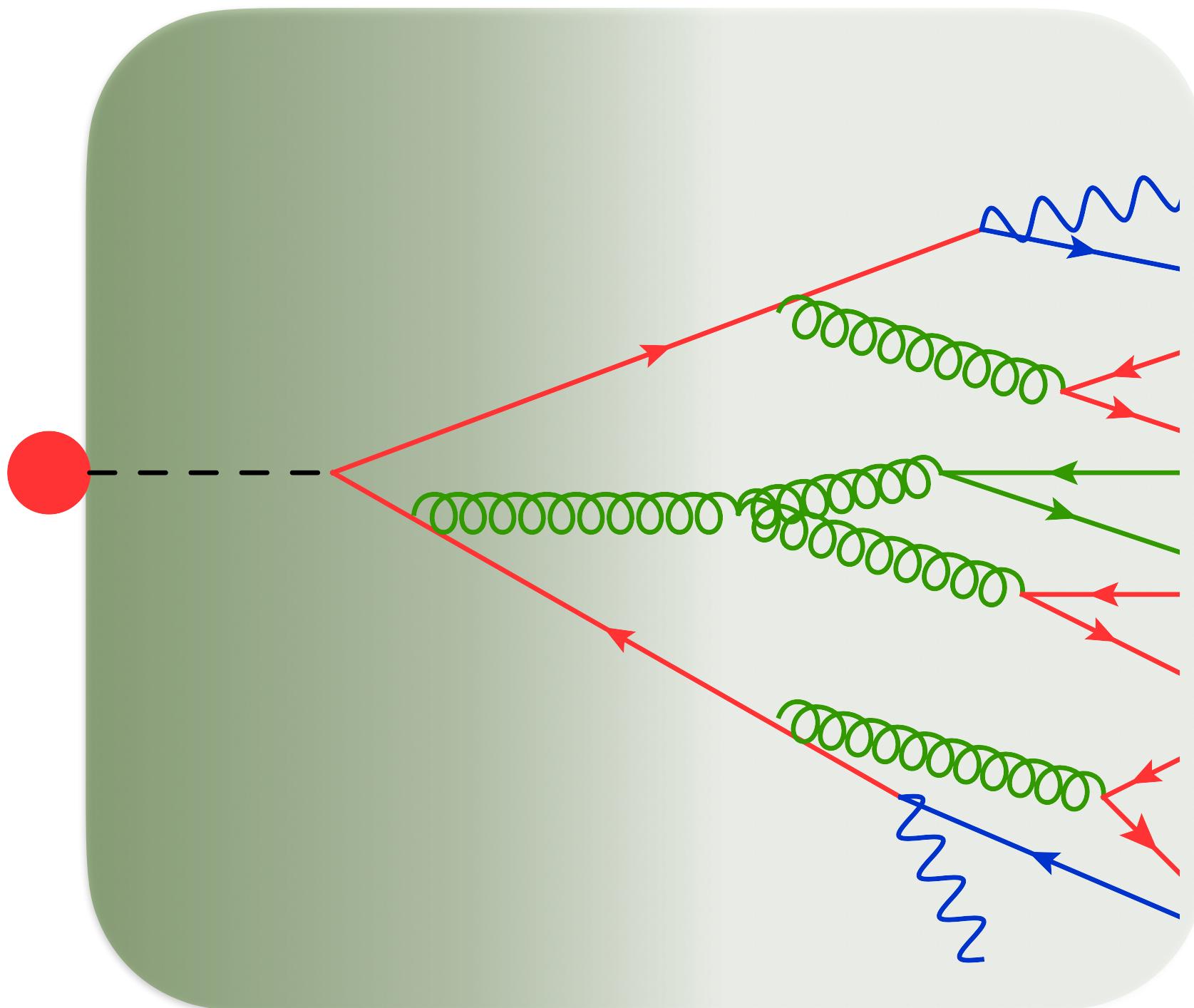
- What happens to a jet inside of a hot and dense QCD matter?



Jet Quenching

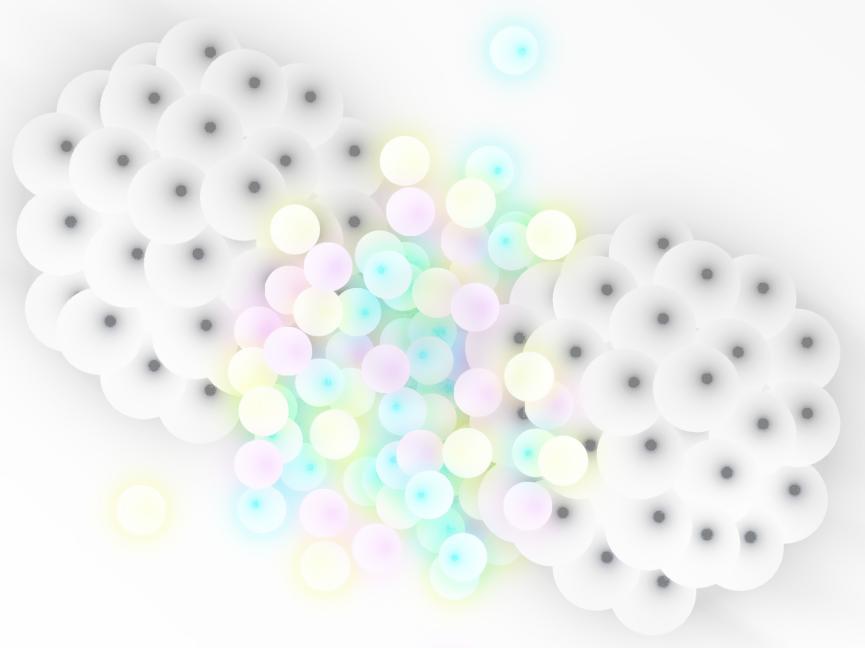


- What happens to a jet inside of a hot and dense QCD matter?

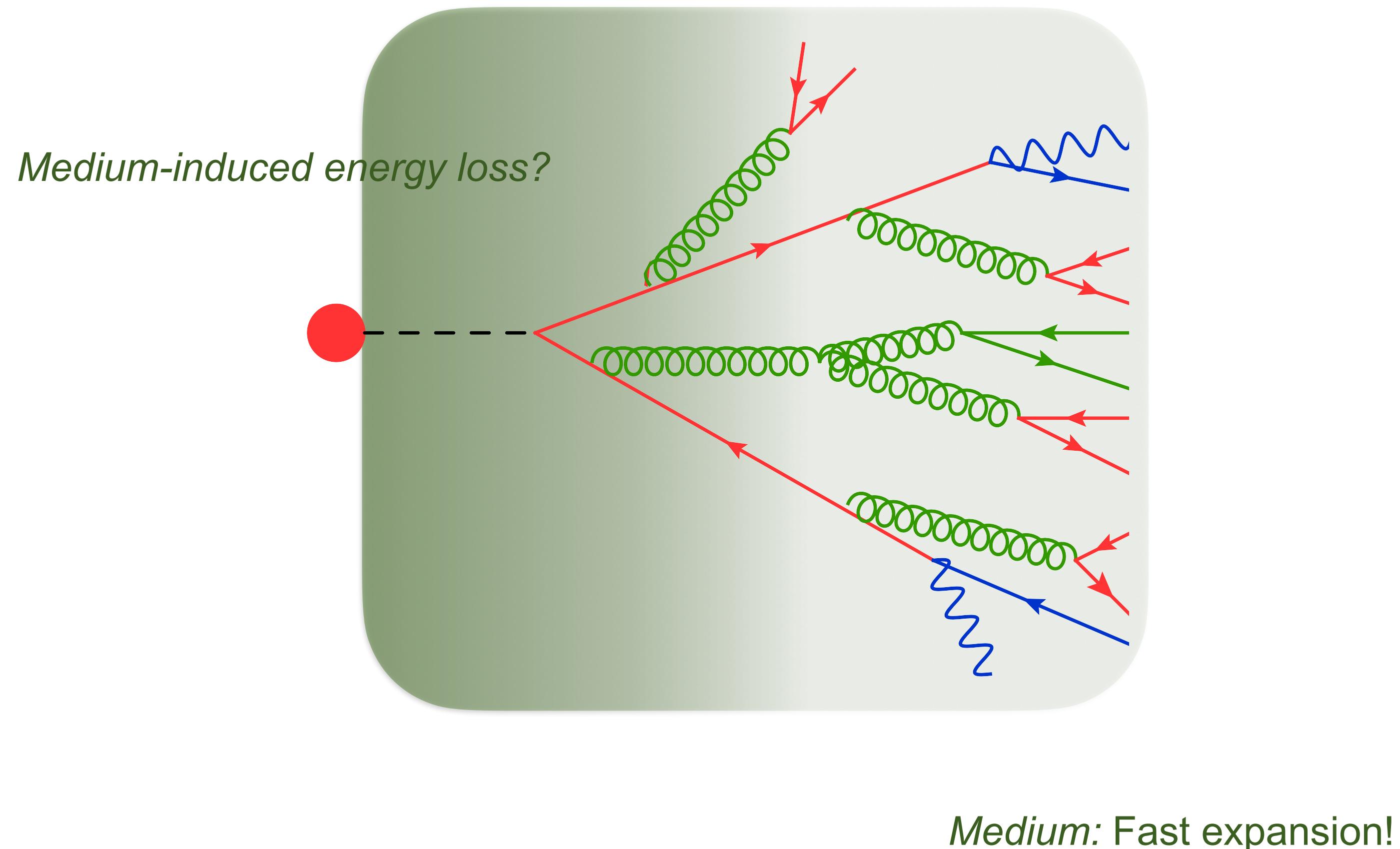


Medium: Fast expansion!

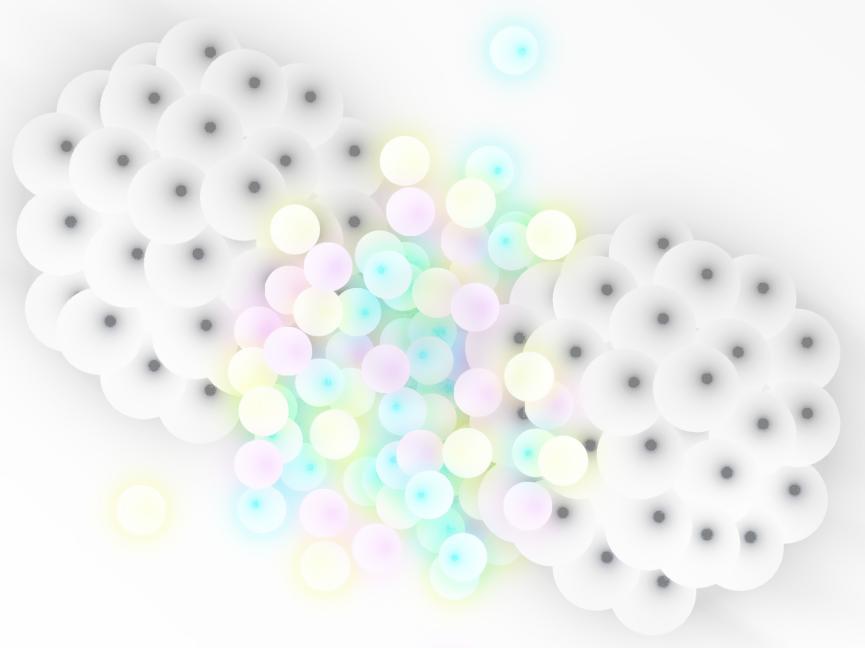
Jet Quenching



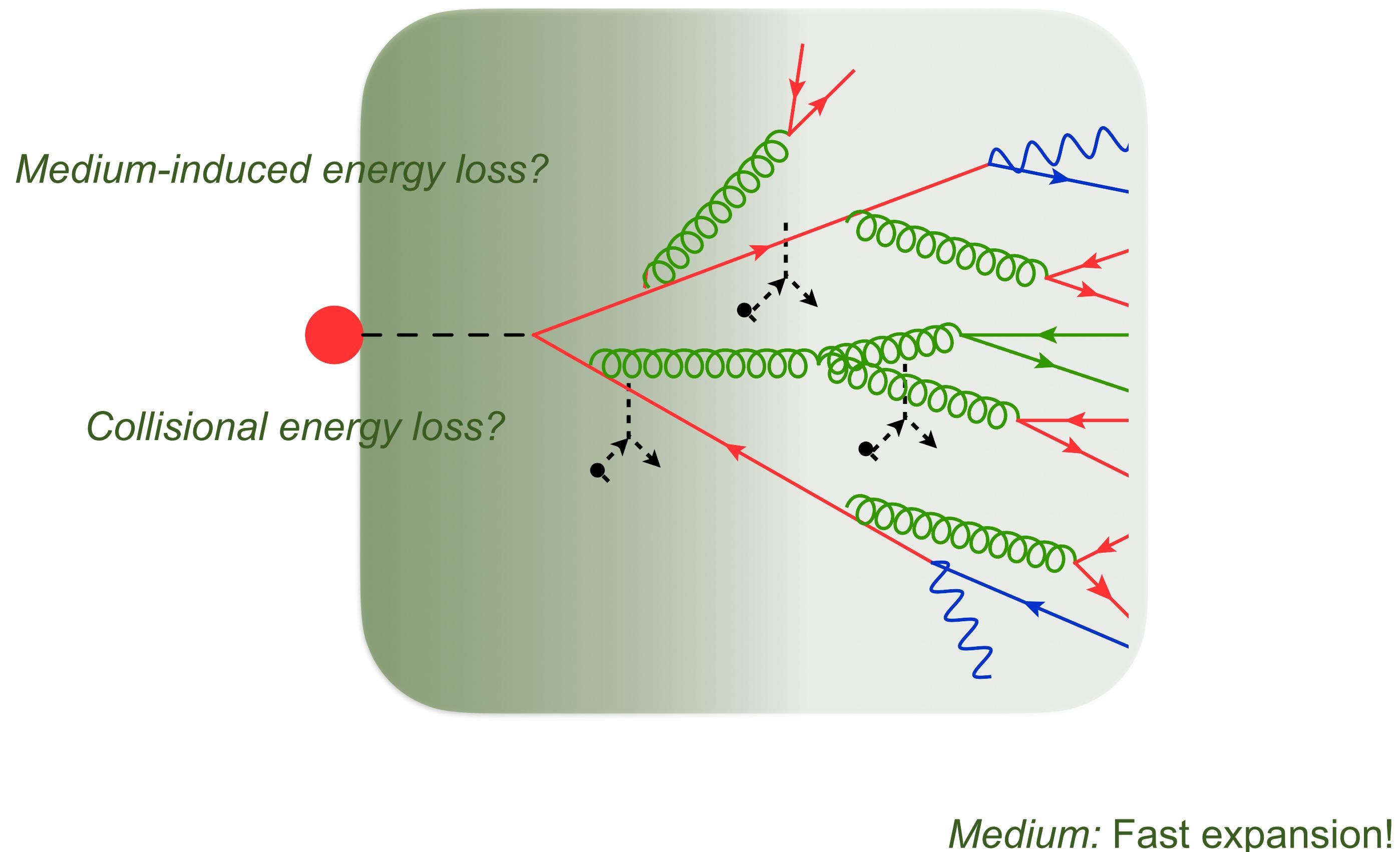
- What happens to a jet inside of a hot and dense QCD matter?



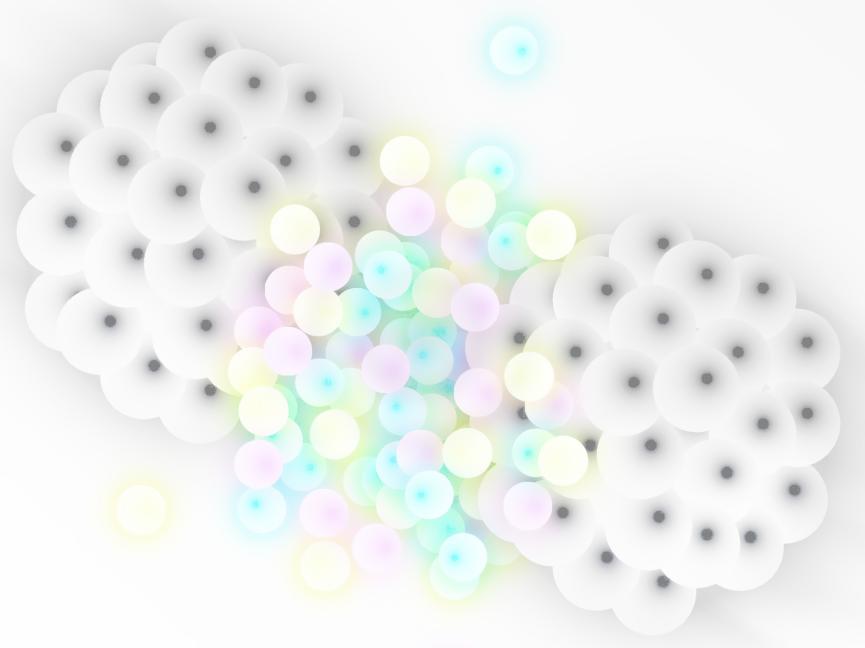
Jet Quenching



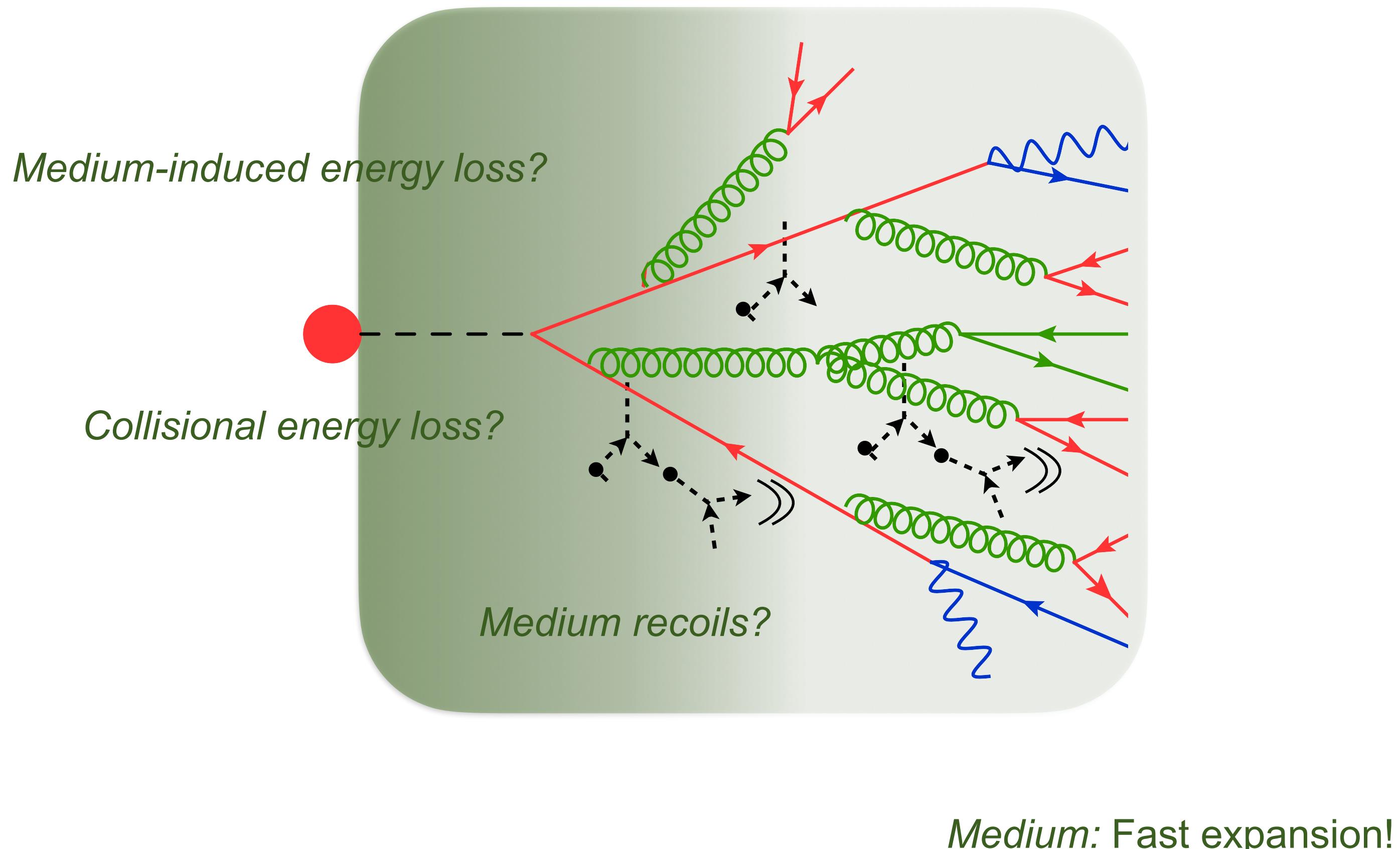
- What happens to a jet inside of a hot and dense QCD matter?



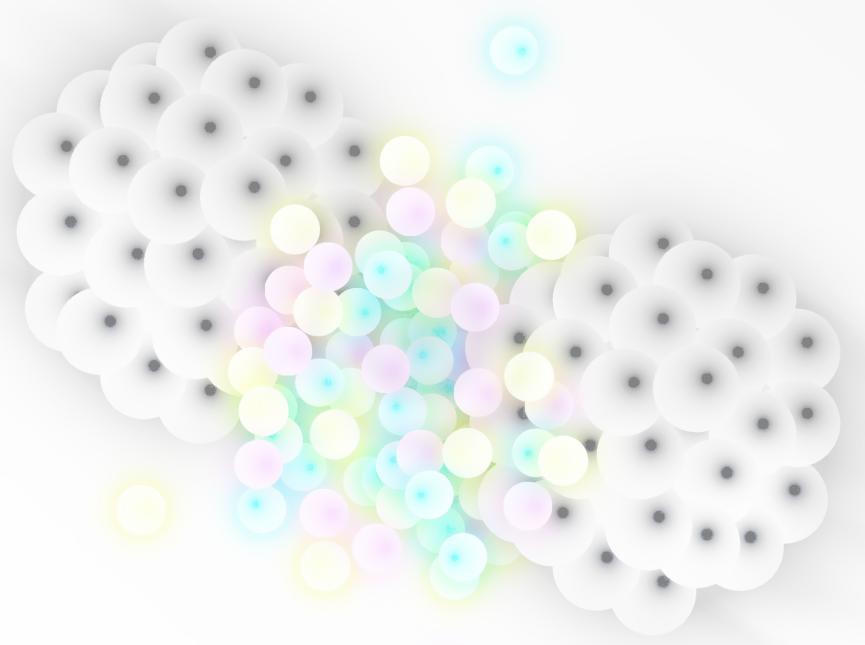
Jet Quenching



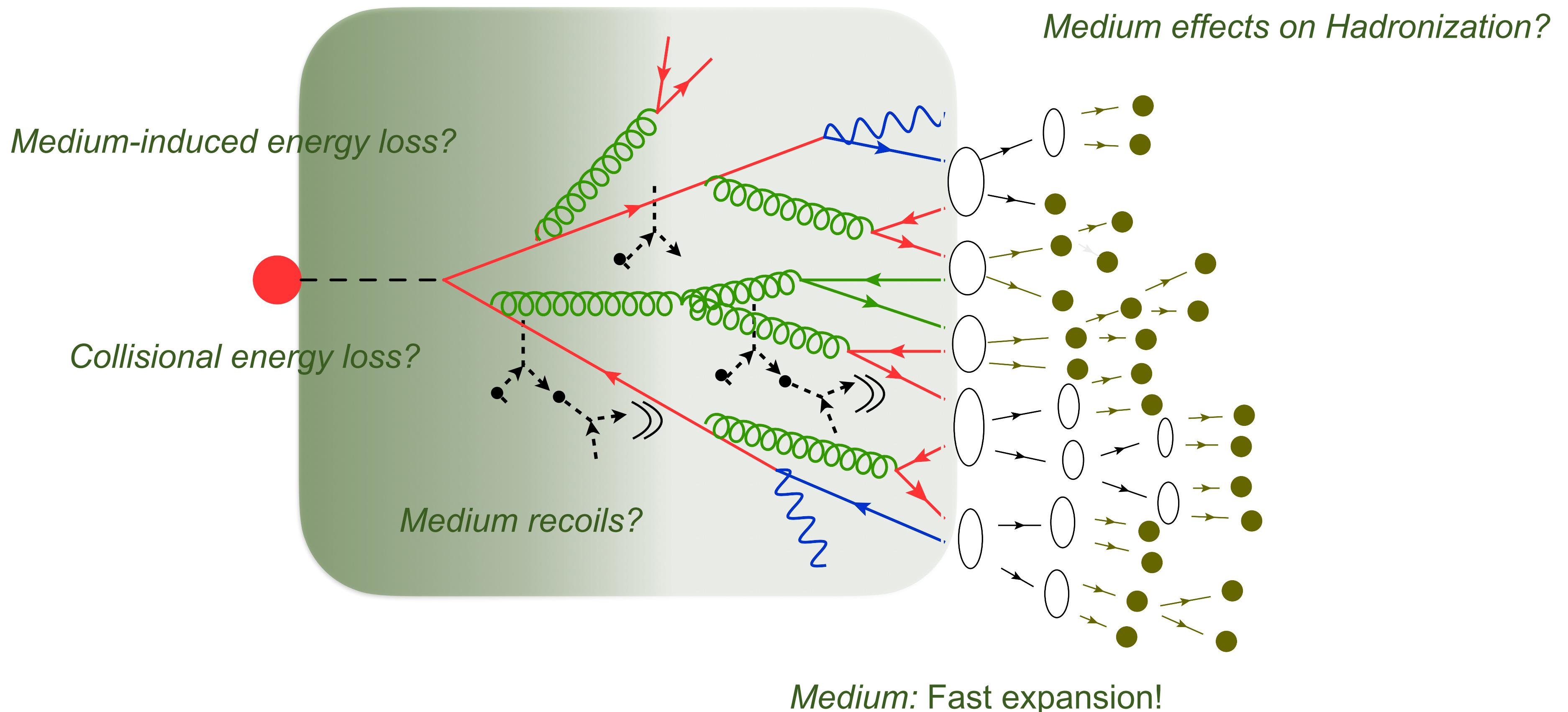
- What happens to a jet inside of a hot and dense QCD matter?



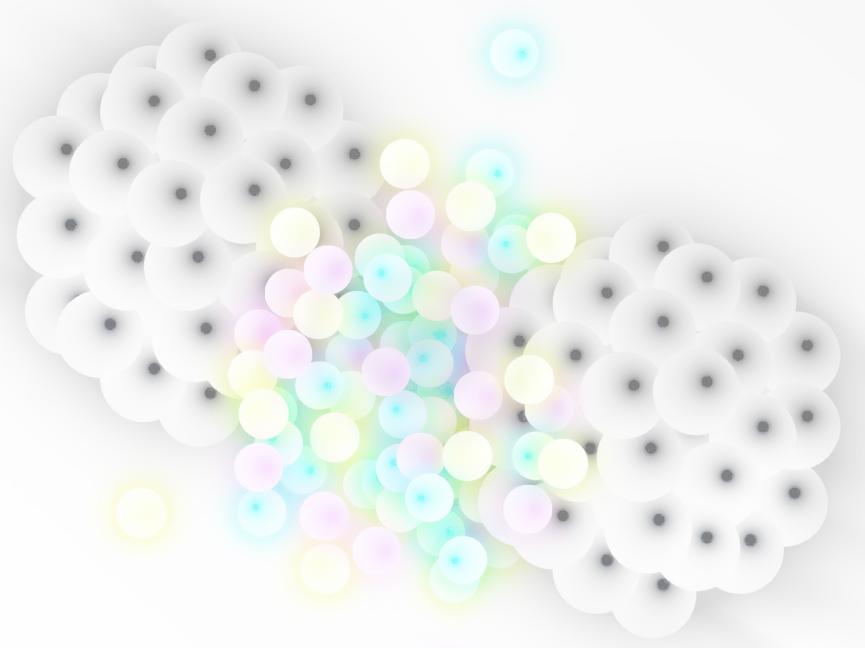
Jet Quenching



- What happens to a jet inside of a hot and dense QCD matter?

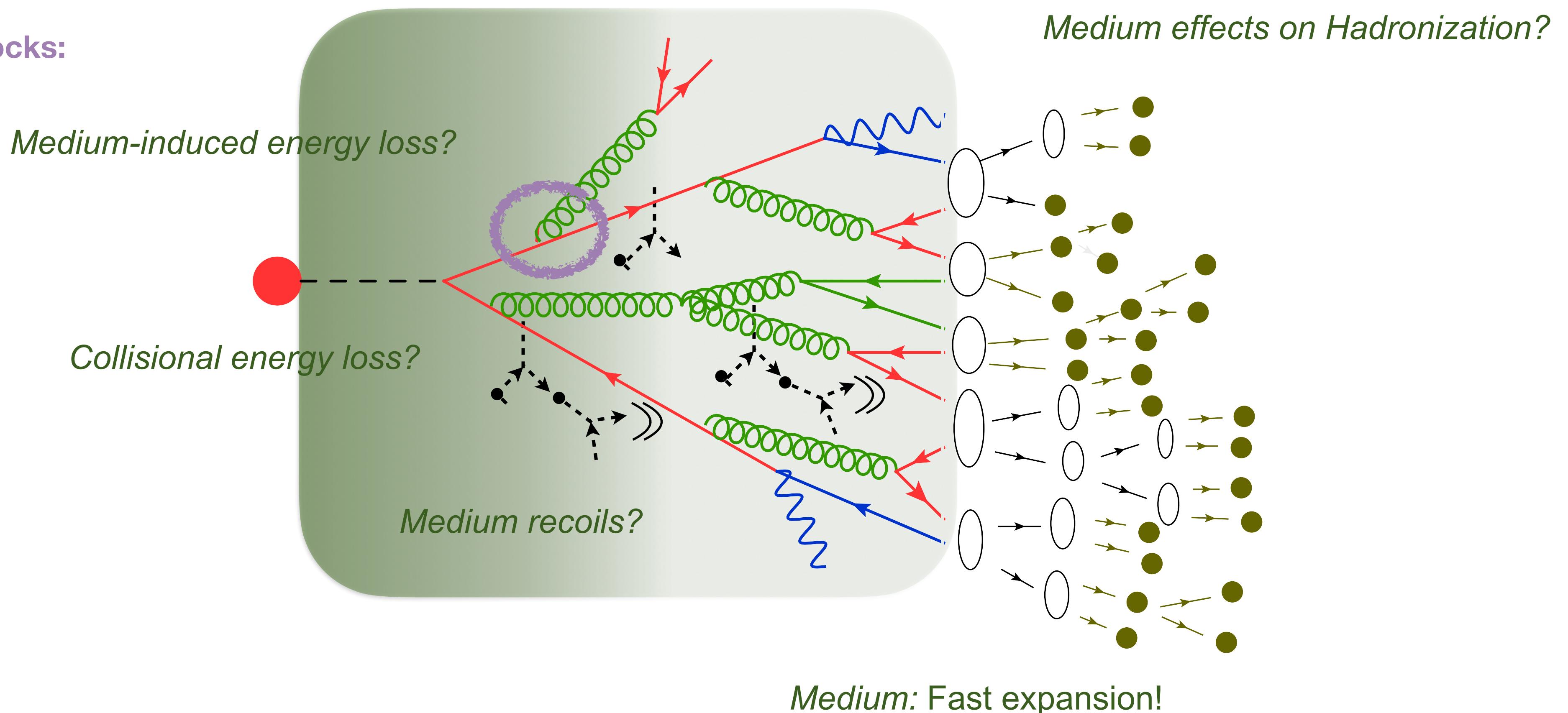


Jet Quenching

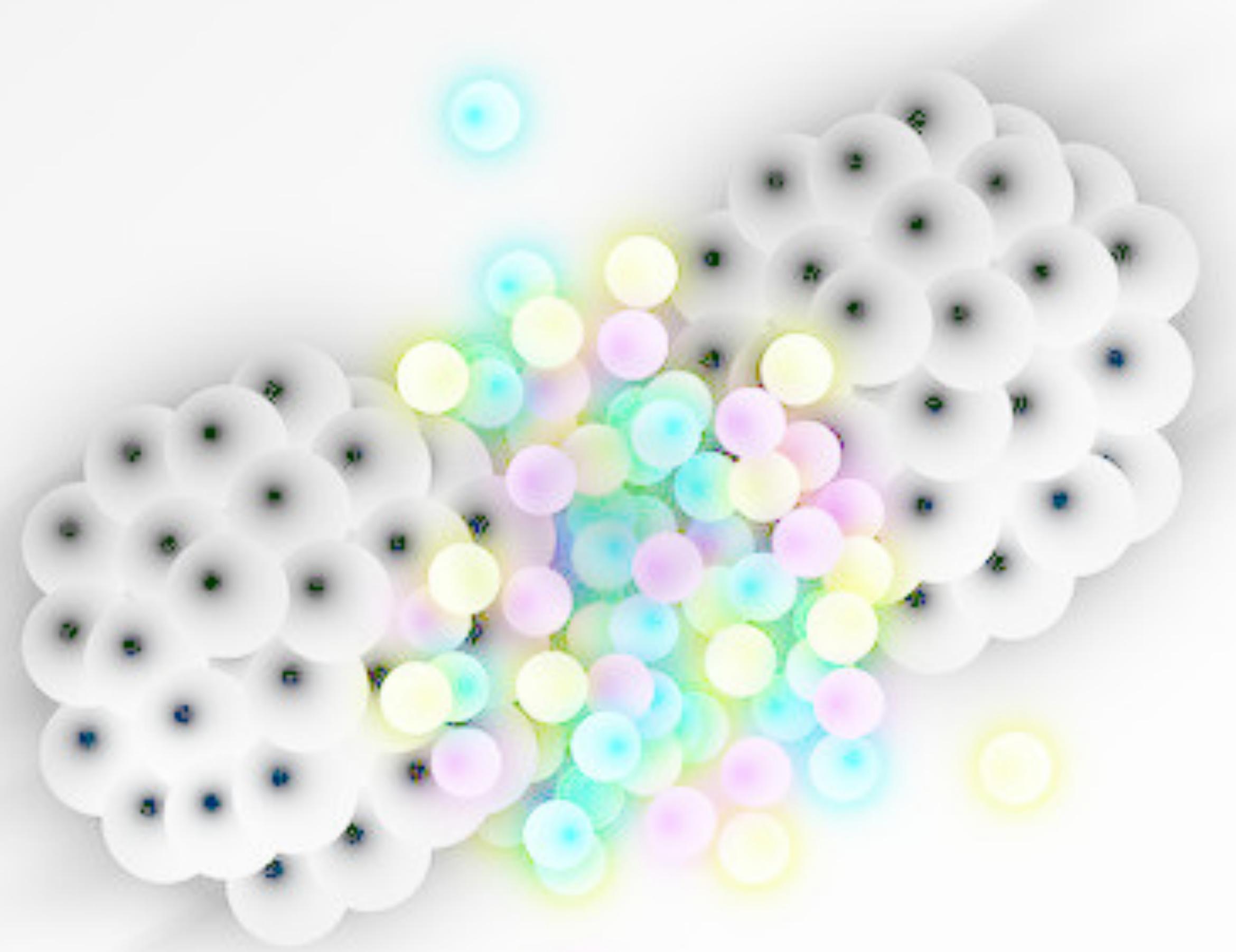


- What happens to a jet inside of a hot and dense QCD matter?

Start with the building blocks:

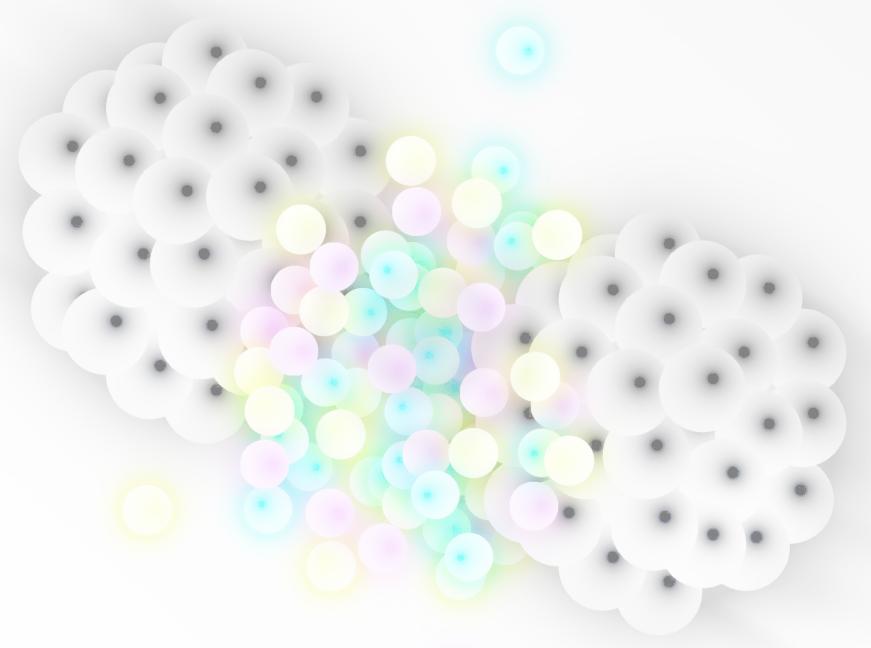


Jet Quenching

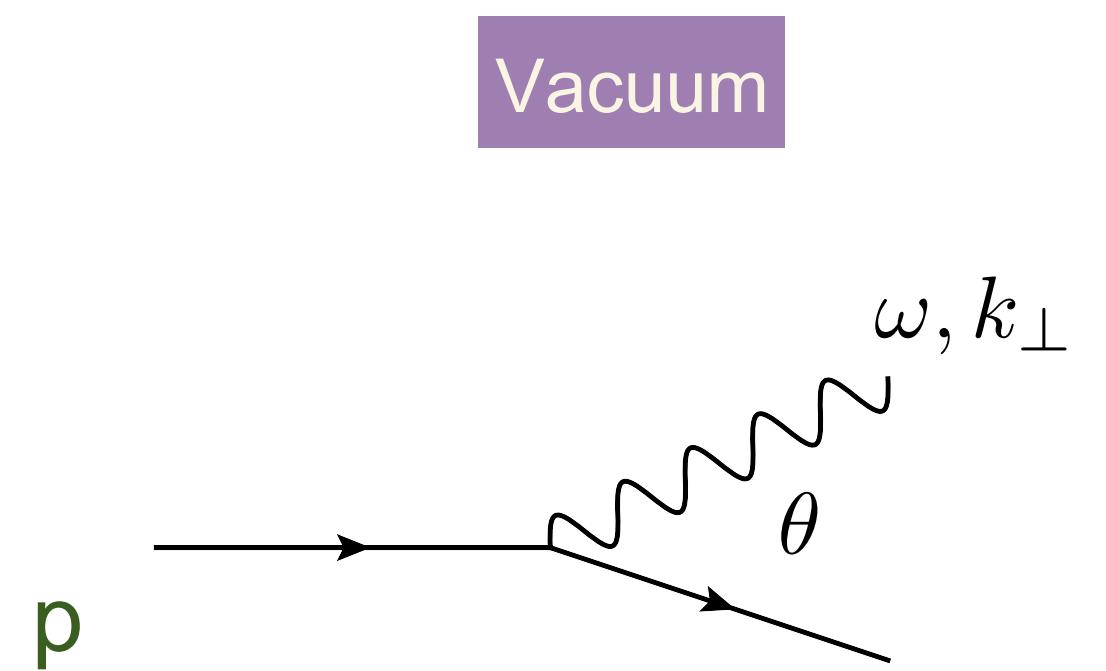


**Single-gluon
emission**

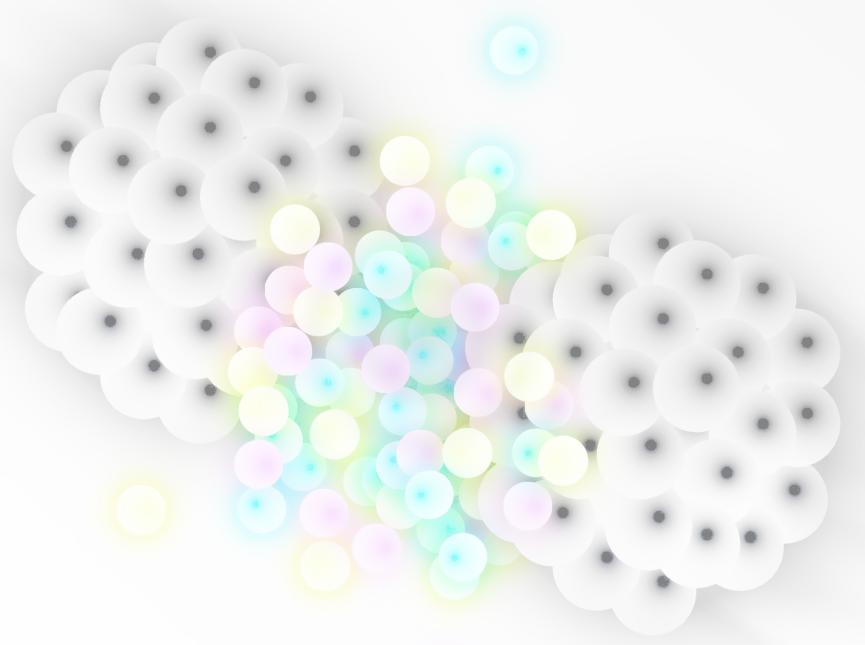
Medium-induced radiation



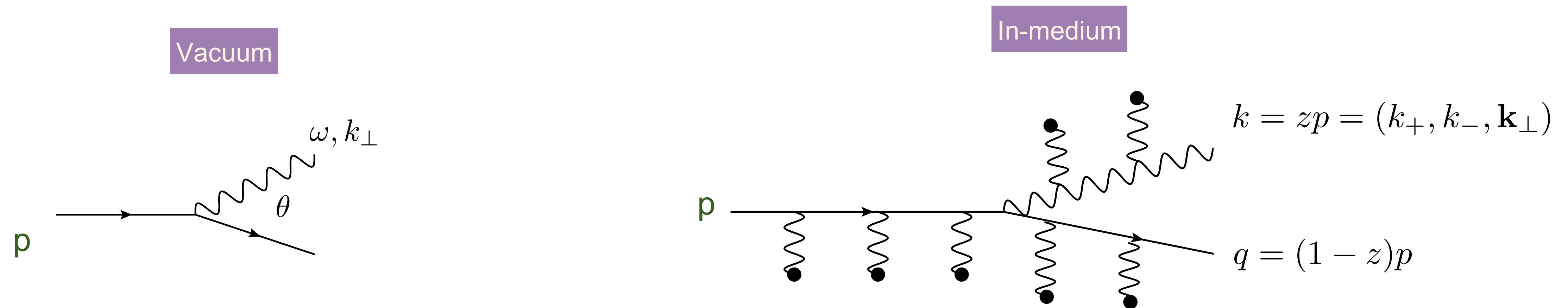
- Within a perturbative QCD perspective, the incoming quark will undergo multiple scatterings with the medium (QGP):



Medium-induced radiation



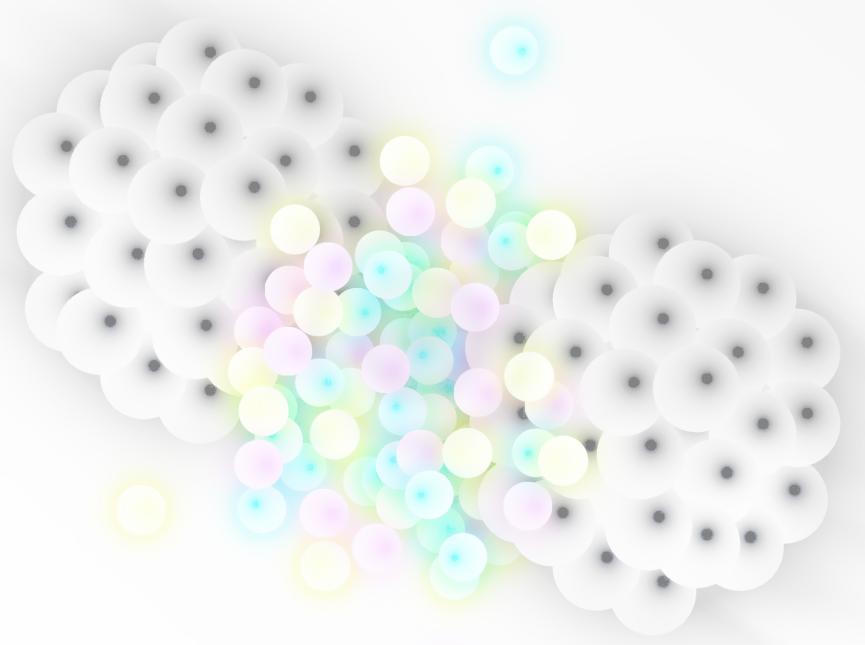
- Within a perturbative QCD perspective, the incoming quark will undergo multiple scatterings with the medium (QGP):



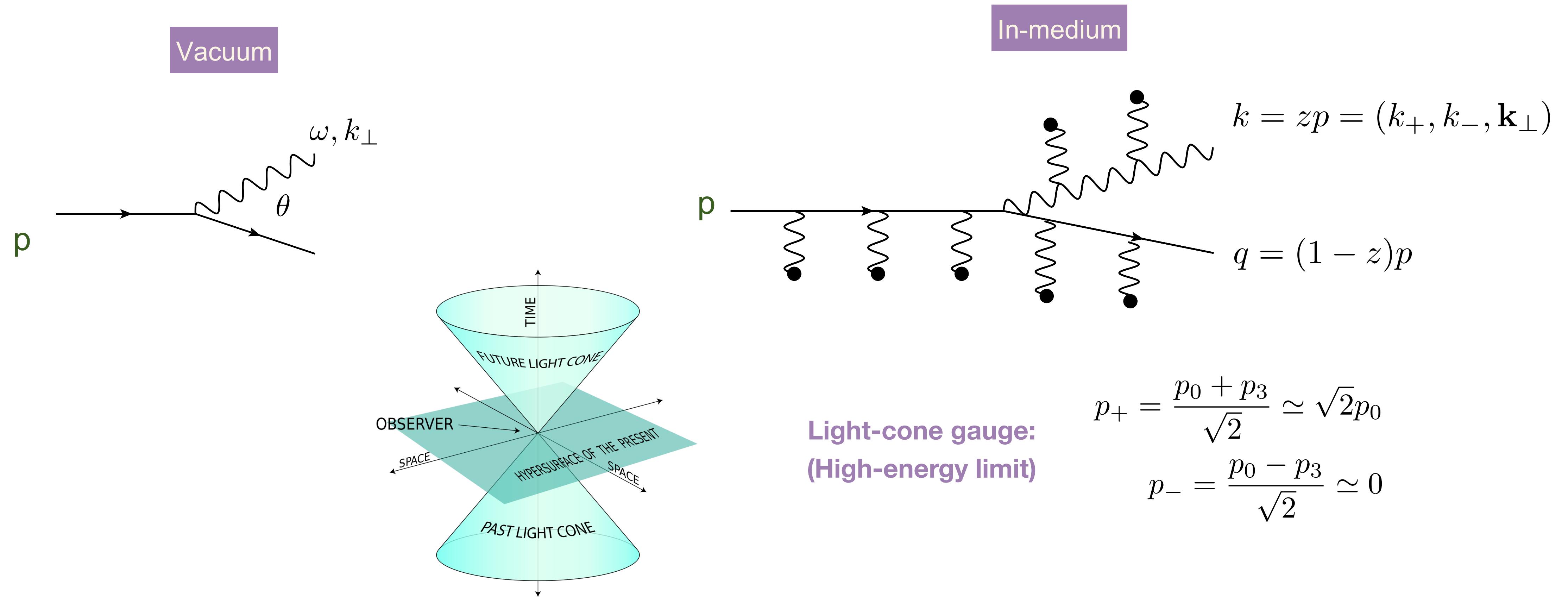
Light-cone gauge:
(High-energy limit)

$$p_+ = \frac{p_0 + p_3}{\sqrt{2}} \simeq \sqrt{2}p_0$$
$$p_- = \frac{p_0 - p_3}{\sqrt{2}} \simeq 0$$

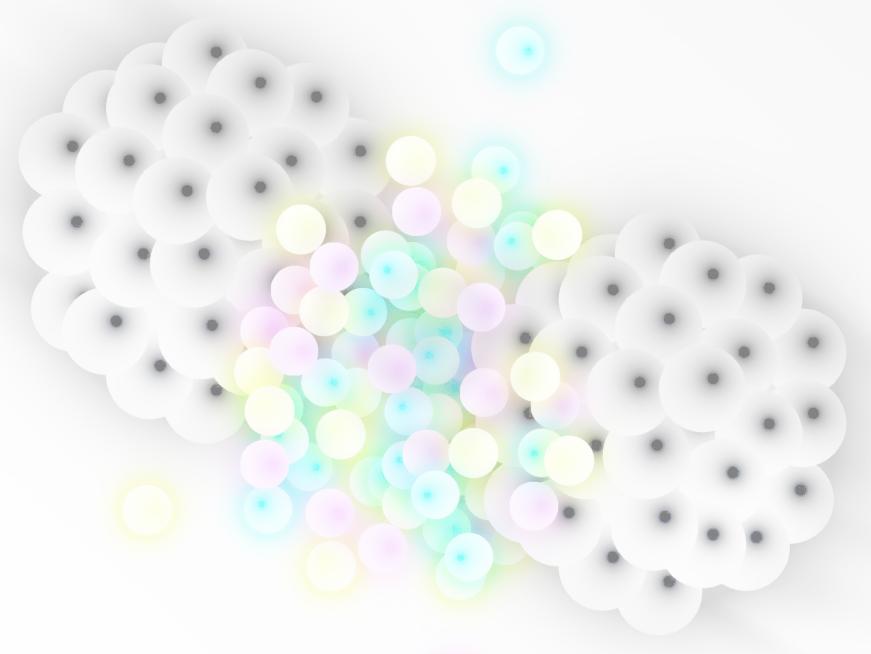
Medium-induced radiation



- Within a perturbative QCD perspective, the incoming quark will undergo multiple scatterings with the medium (QGP):



In-medium propagators



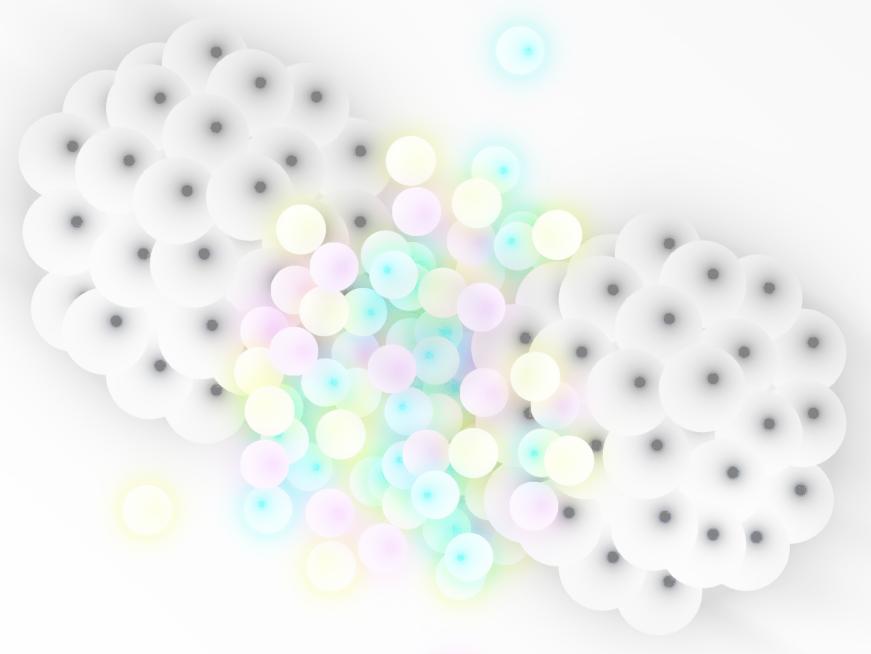
- Adapt Feynman rules to account for a hot and dense QCD medium:

Vacuum QCD
Feynman rules

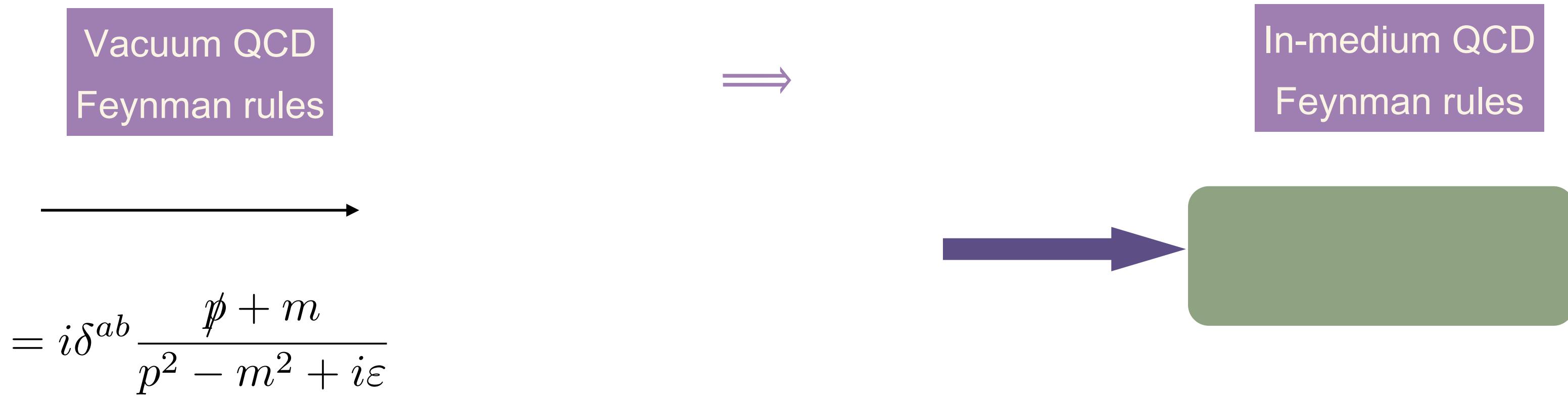


$$= i\delta^{ab} \frac{\not{p} + m}{p^2 - m^2 + i\varepsilon}$$

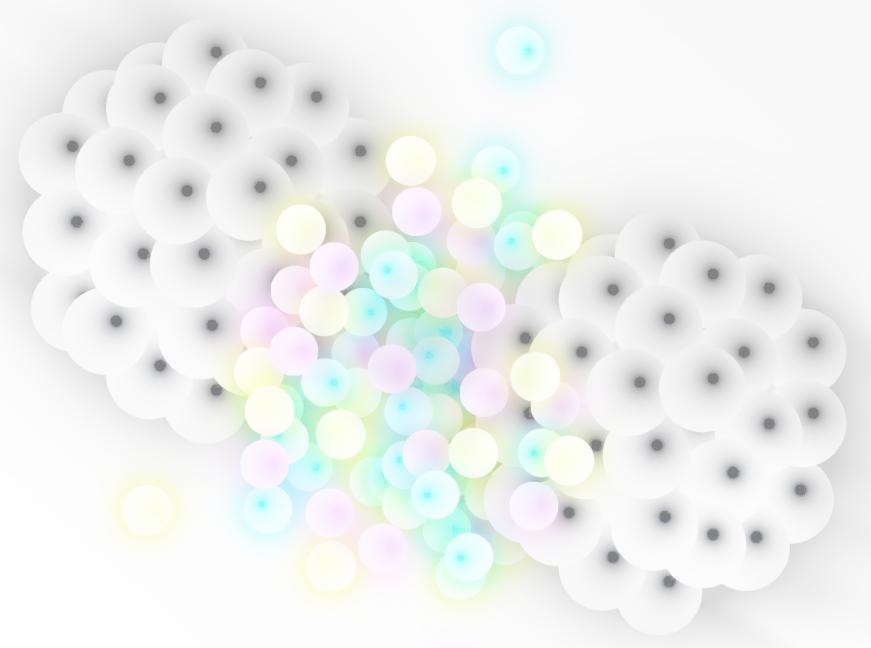
In-medium propagators



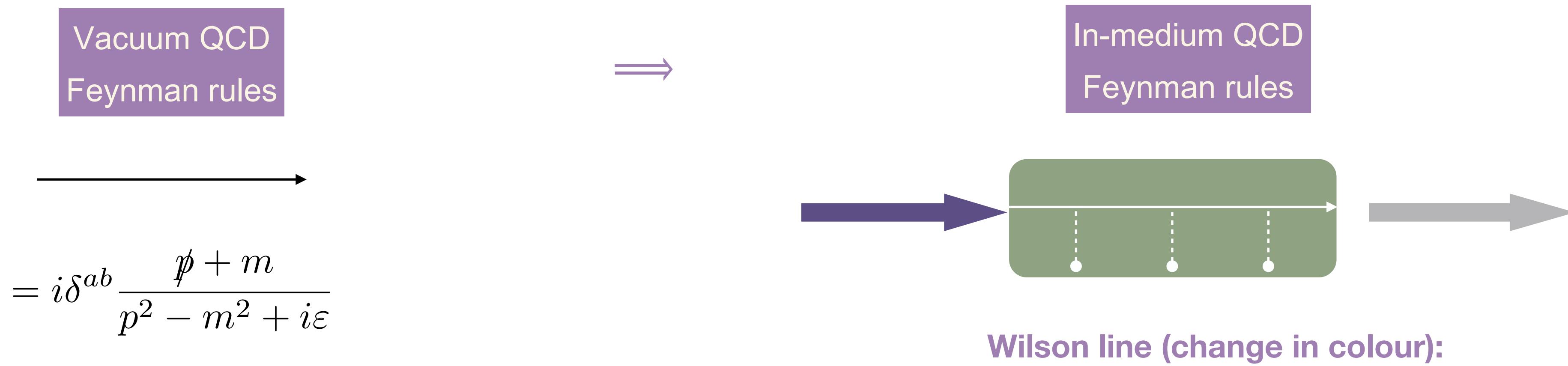
- Adapt Feynman rules to account for a hot and dense QCD medium:



In-medium propagators

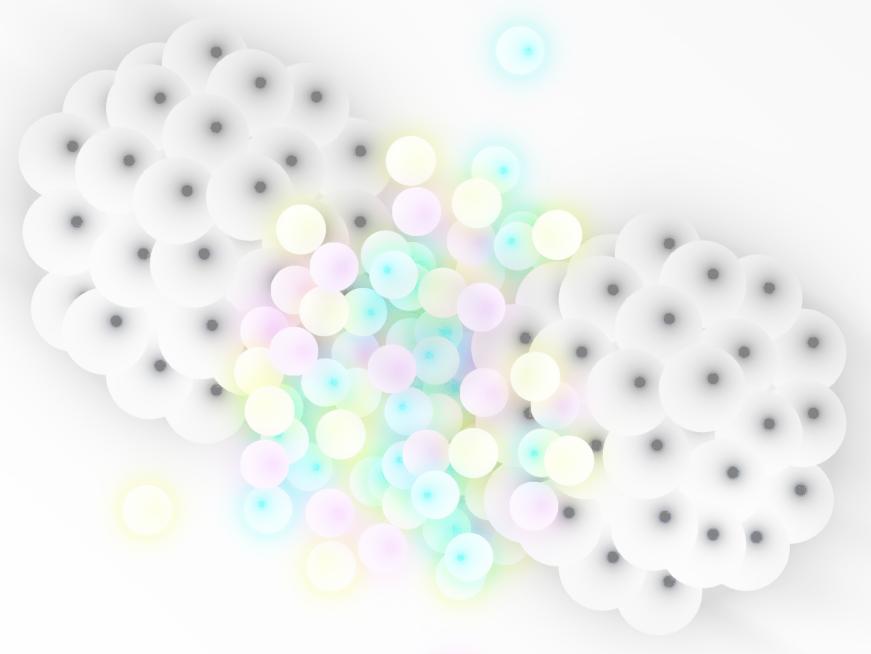


- Adapt Feynman rules to account for a hot and dense QCD medium:

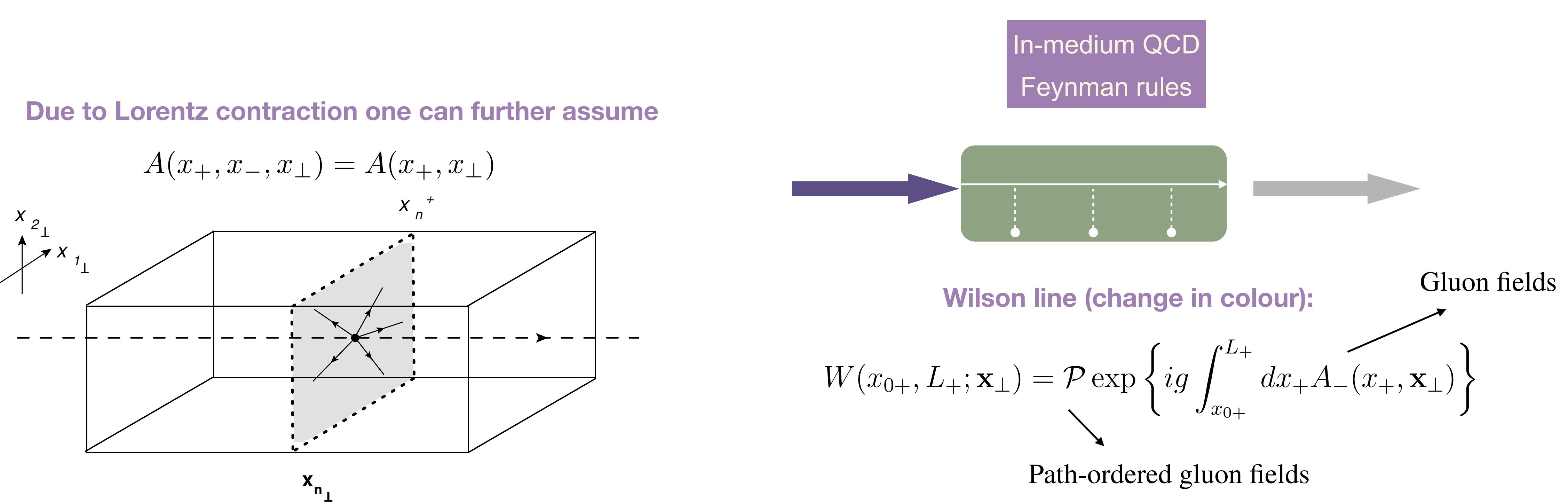


$$W(x_{0+}, L_+; \mathbf{x}_\perp) = \mathcal{P} \exp \left\{ ig \int_{x_{0+}}^{L_+} dx_+ A_-(x_+, \mathbf{x}_\perp) \right\}$$

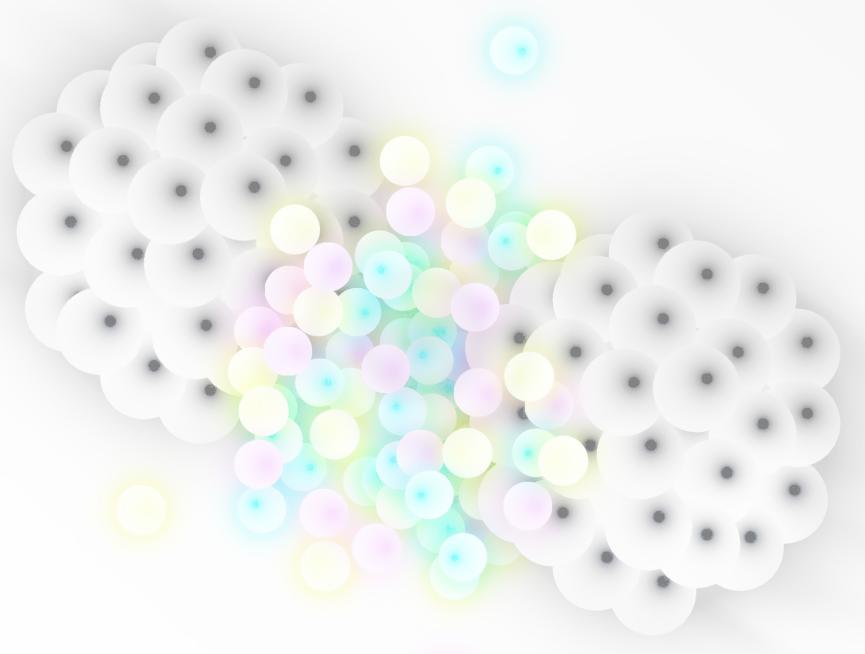
In-medium propagators



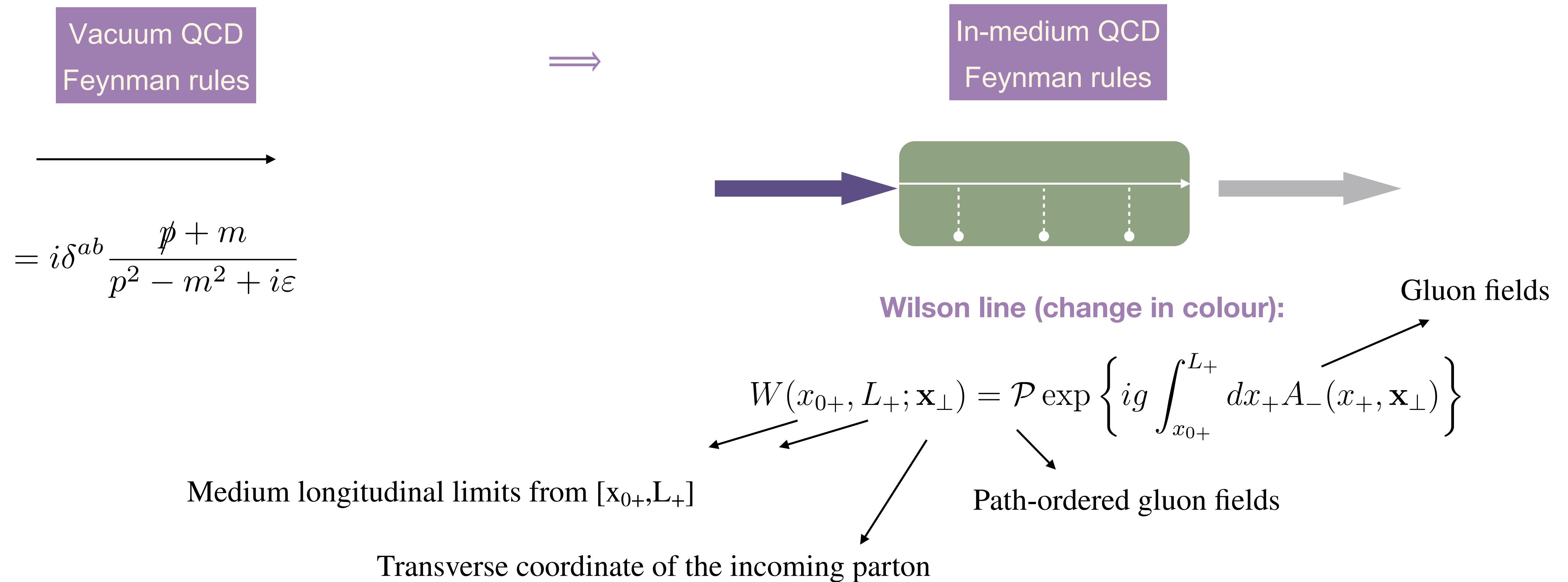
- Adapt Feynman rules to account for a hot and dense QCD medium:



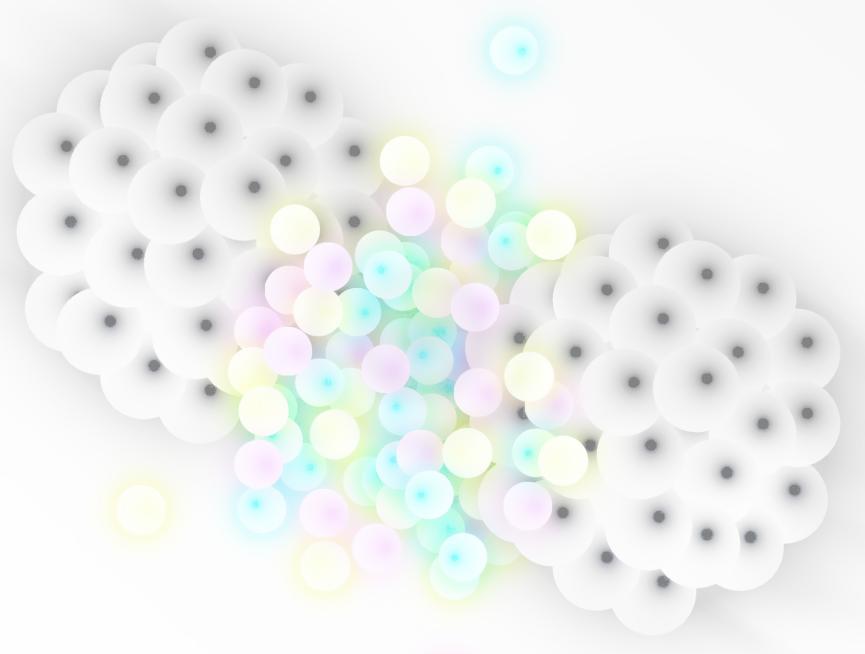
In-medium propagators



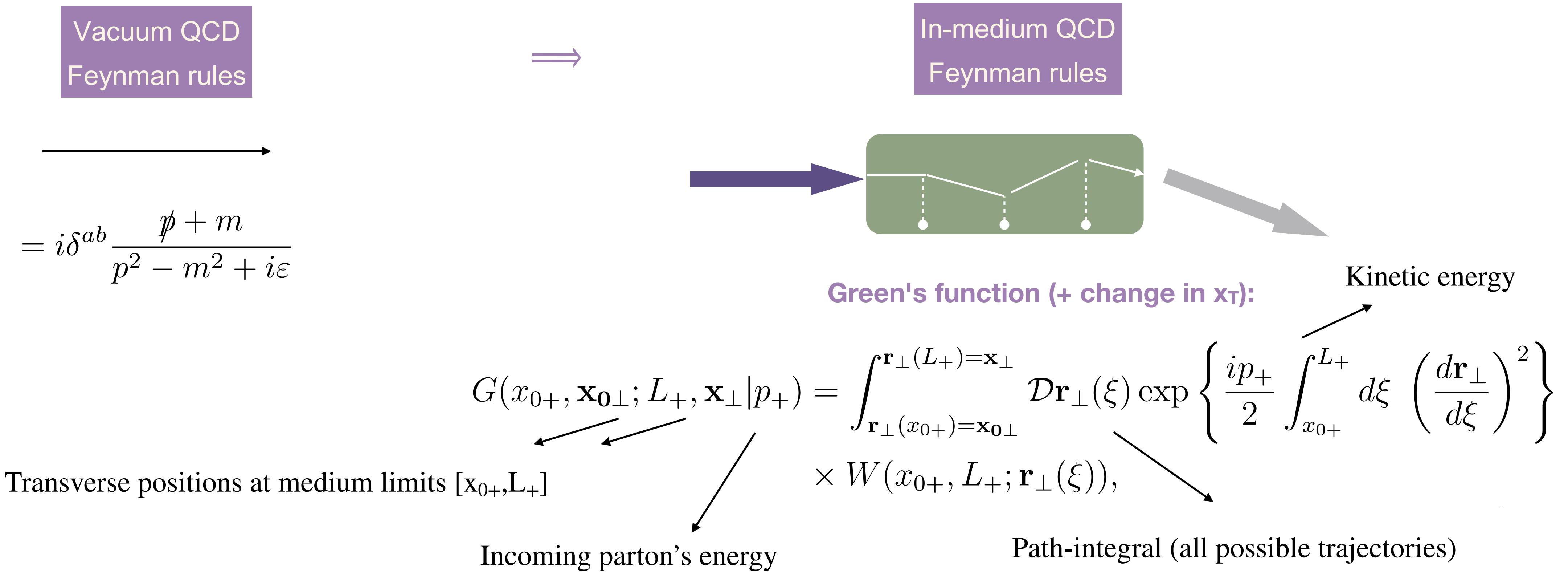
- Adapt Feynman rules to account for a hot and dense QCD medium:



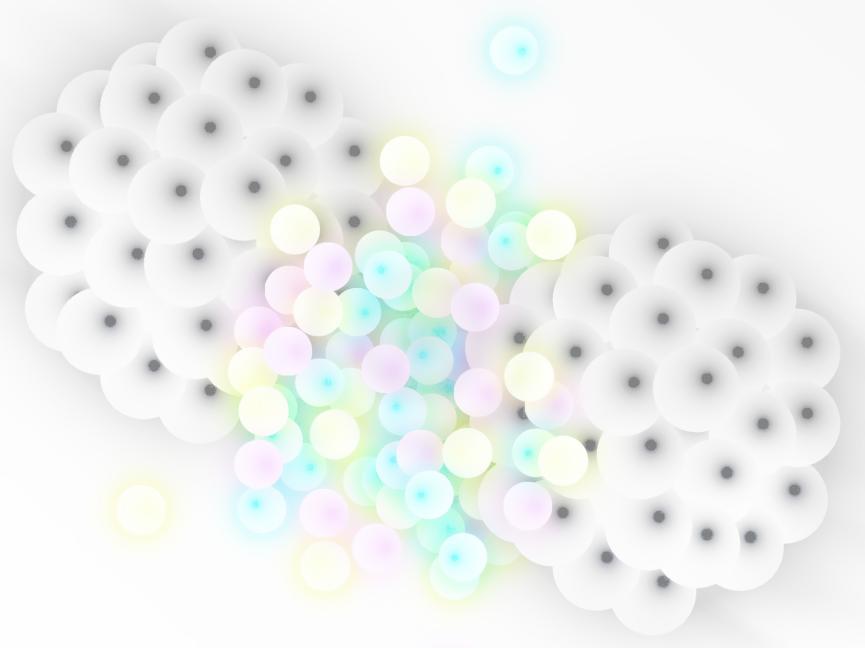
In-medium propagators



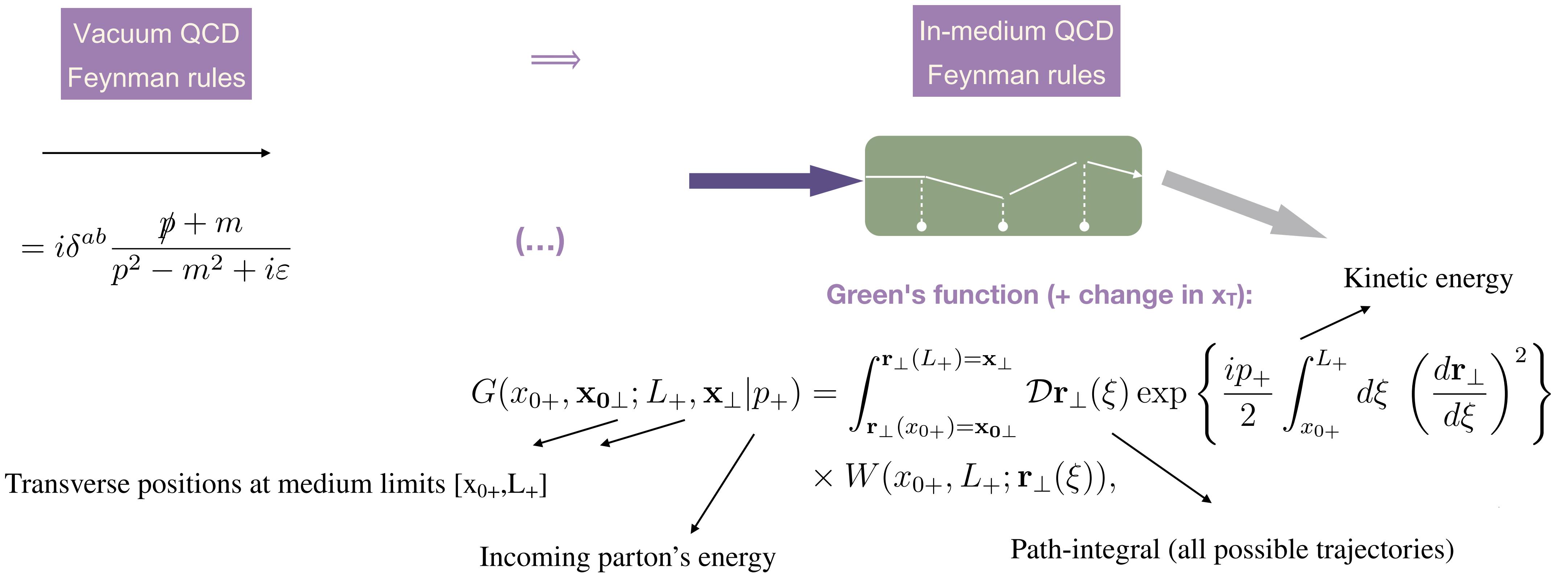
- Adapt Feynman rules to account for a hot and dense QCD medium:



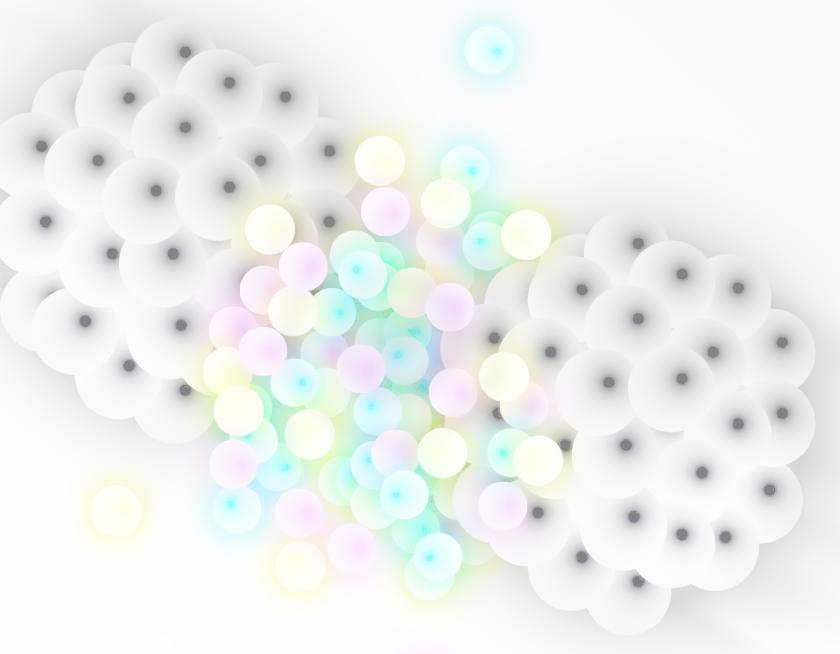
In-medium propagators



- Adapt Feynman rules to account for a hot and dense QCD medium:

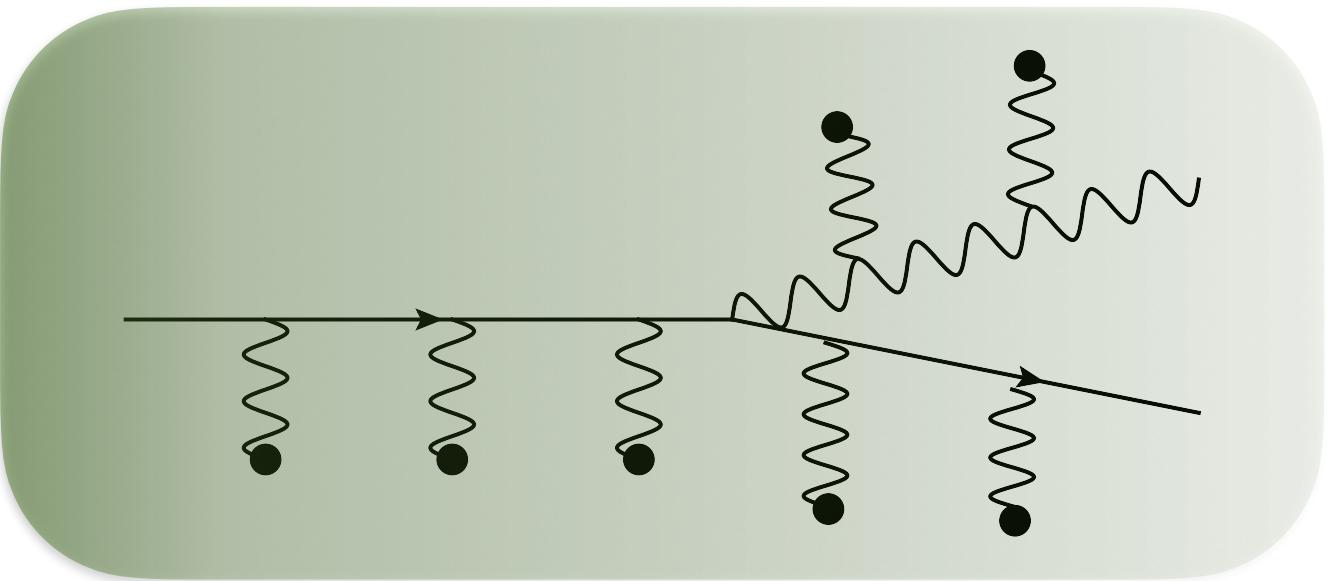


Medium-induced radiation

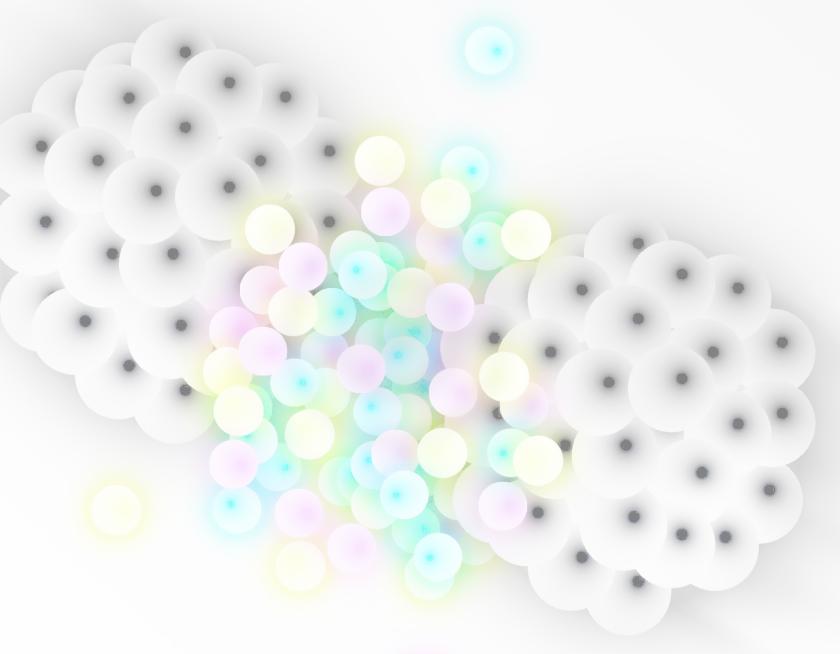


- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

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

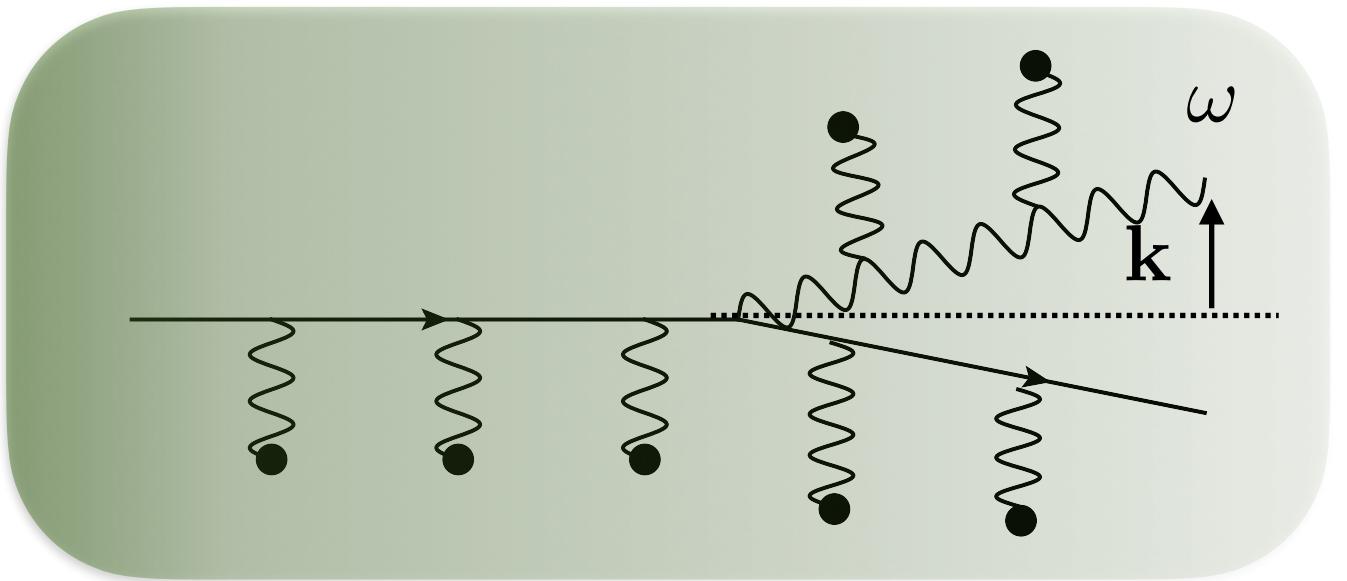


Medium-induced radiation

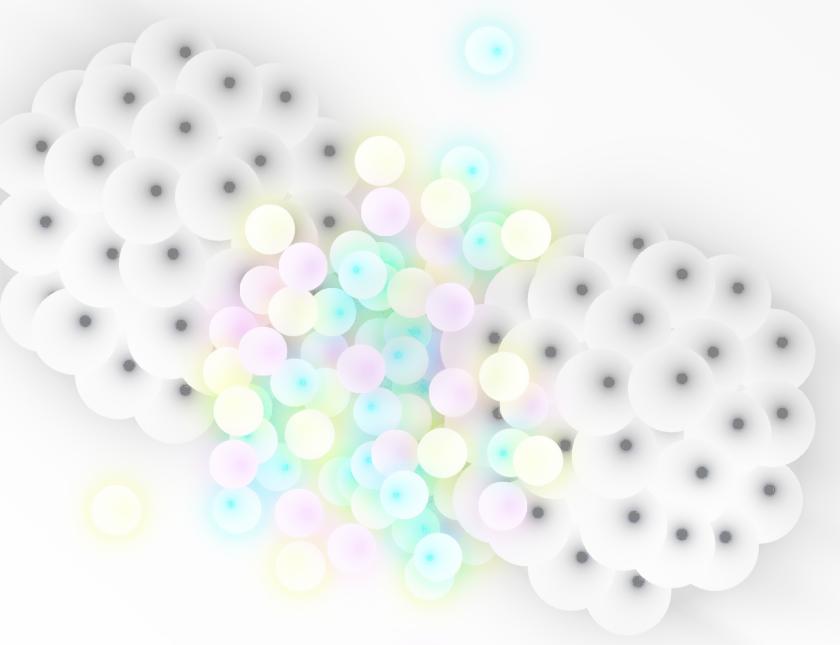


- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

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

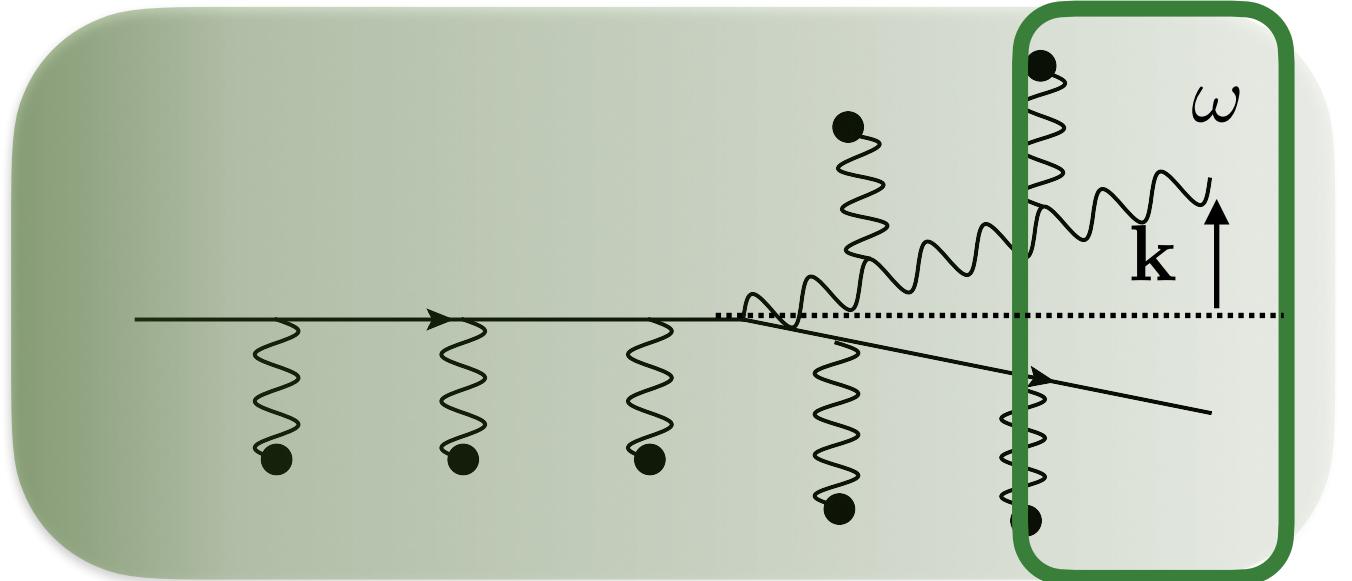


Medium-induced radiation



- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

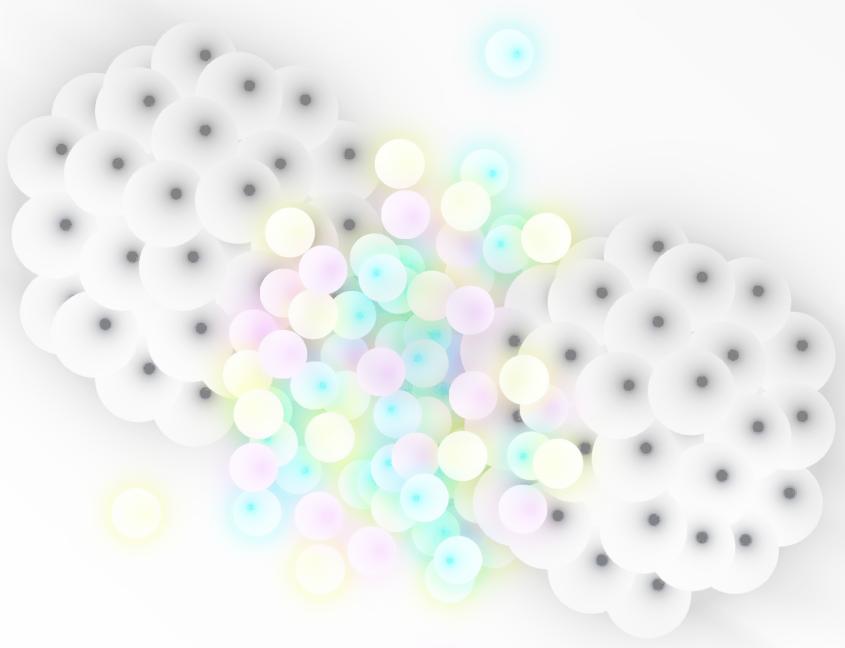
$$\omega \frac{dI}{d\omega d^2\mathbf{k}} = \frac{2\alpha_s C_R}{(2\pi)^2 \omega^2} \text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\mathbf{p}, \mathbf{q}} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t', \mathbf{q}; t, \mathbf{p}) P(\infty, \mathbf{k}; t', \mathbf{q})$$



Momentum Broadening:

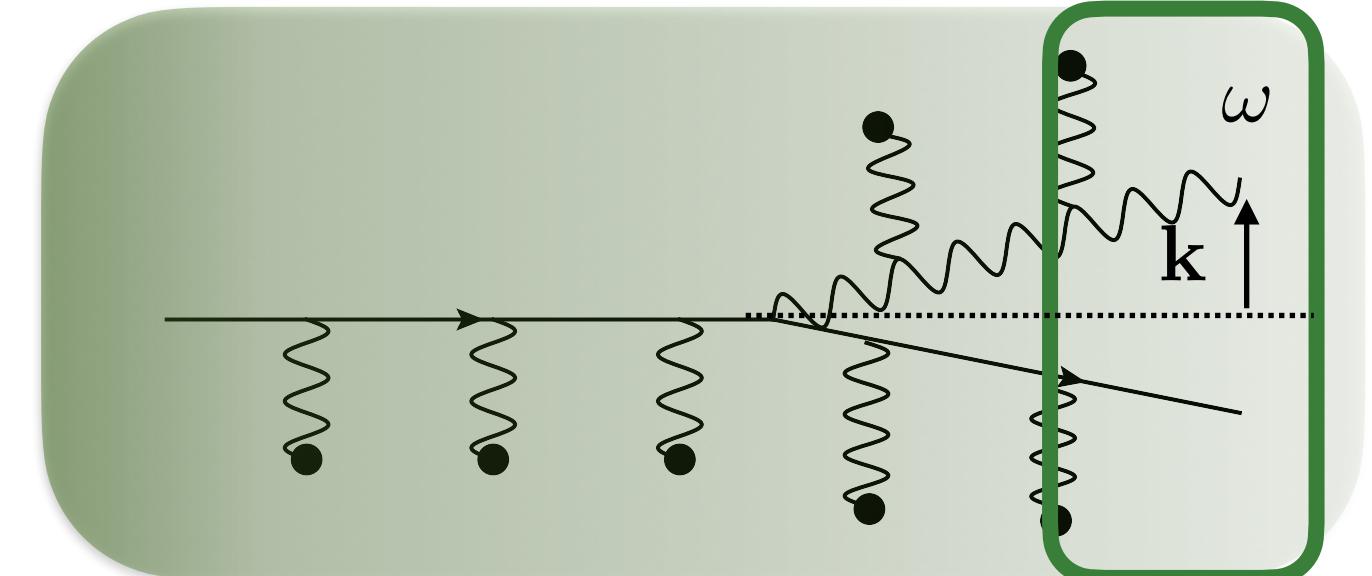
$$\mathcal{P}(t'', \mathbf{k}; t', \mathbf{q}) \equiv \int d^2 z e^{-i(\mathbf{k}-\mathbf{q}) \cdot z} \exp \left\{ -\frac{1}{2} \int_{t'}^{t''} ds n(s) \sigma(z) \right\}$$

Medium-induced radiation



- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

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



Density of scattering centres:

$$n(x_+) = \int dx_{i+} \delta(x_+ - x_{i+}).$$

Momentum Broadening:

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

Dipole cross-section (collision rate):

$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q}) (1 - e^{i\mathbf{q}\mathbf{r}})$$

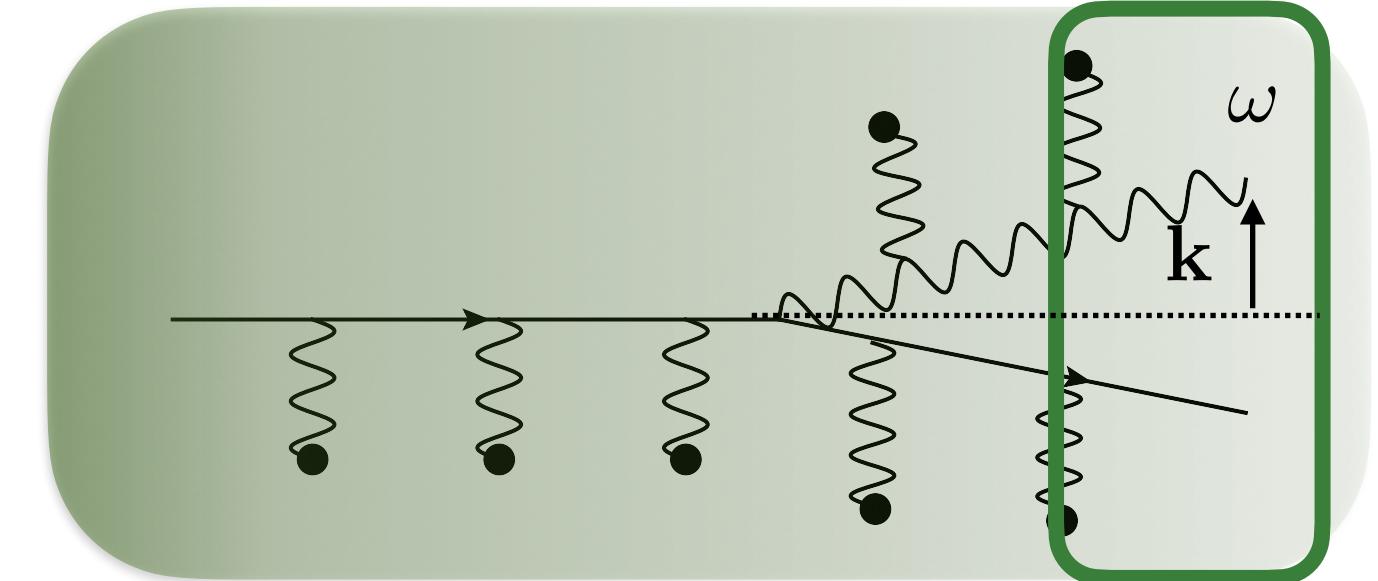
Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

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

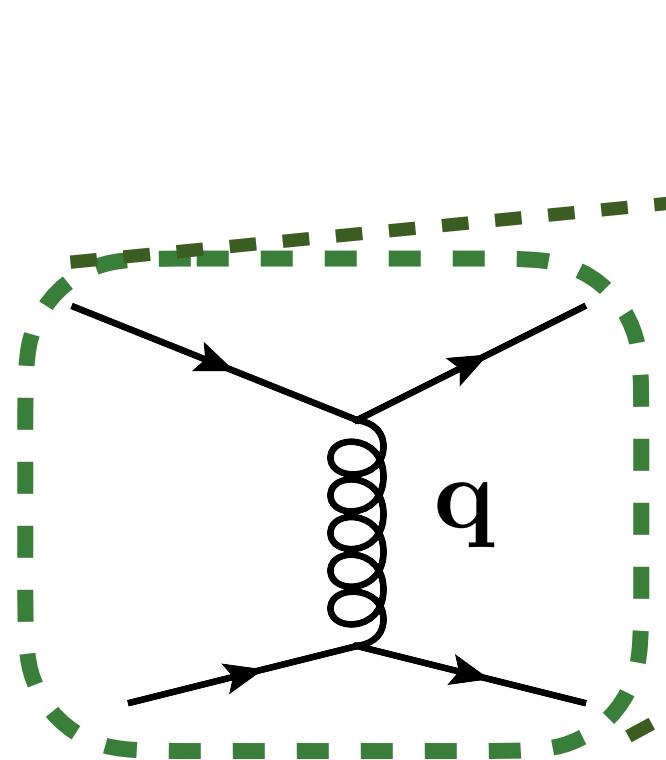
Momentum Broadening:

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



Density of scattering centres:

$$n(x_+) = \int dx_{i+} \delta(x_+ - x_{i+}).$$



Dipole cross-section (collision rate):

$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q}) (1 - e^{i\mathbf{q}\mathbf{r}})$$

Parton-medium
interaction

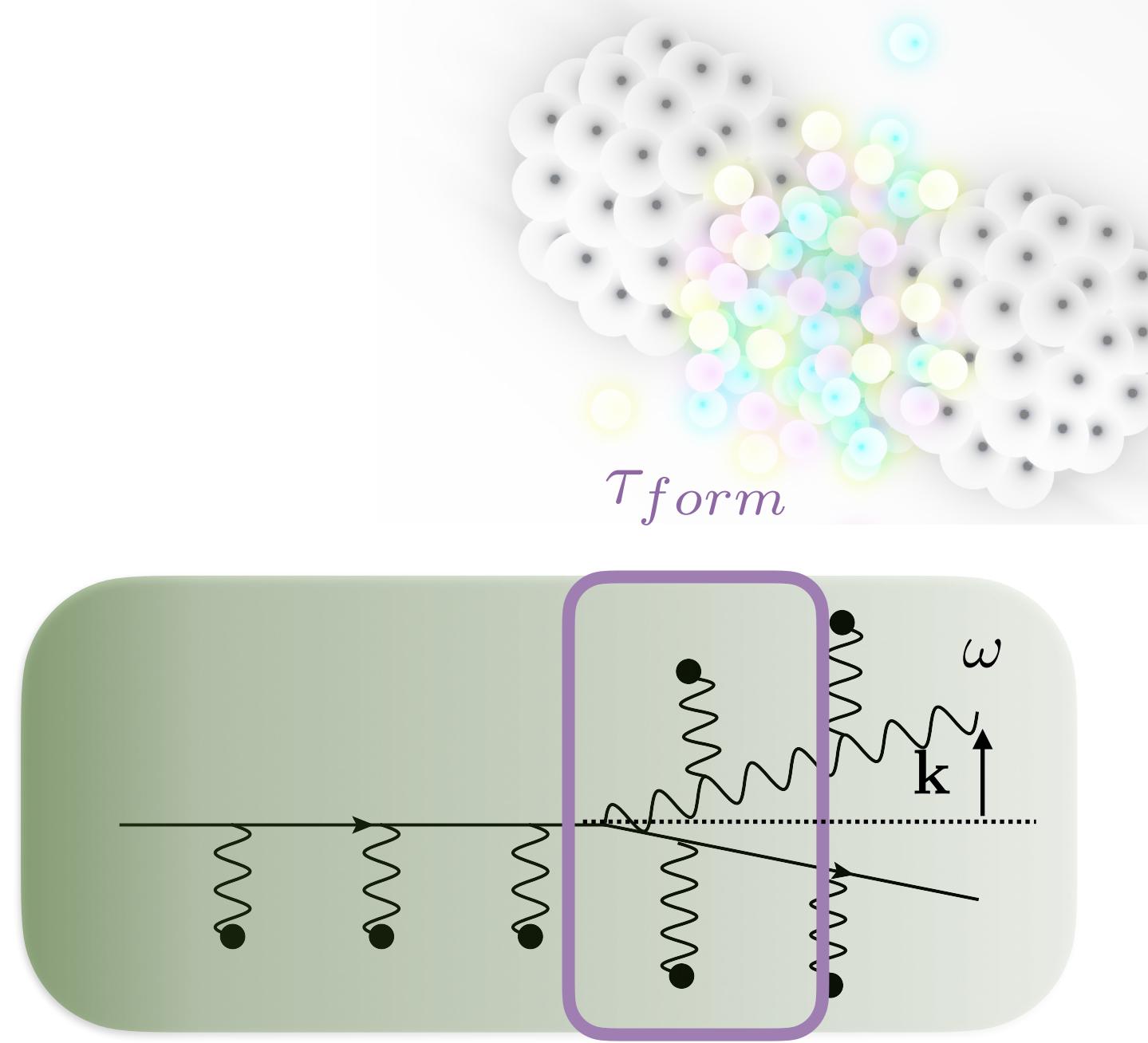
Medium-induced radiation

- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

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

Emission Kernel:

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



Density of scattering centres:

$$n(x_+) = \int dx_{i+} \delta(x_+ - x_{i+}).$$

Dipole cross-section (collision rate):

$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q}) (1 - e^{i\mathbf{q}\mathbf{r}})$$

Medium-induced radiation

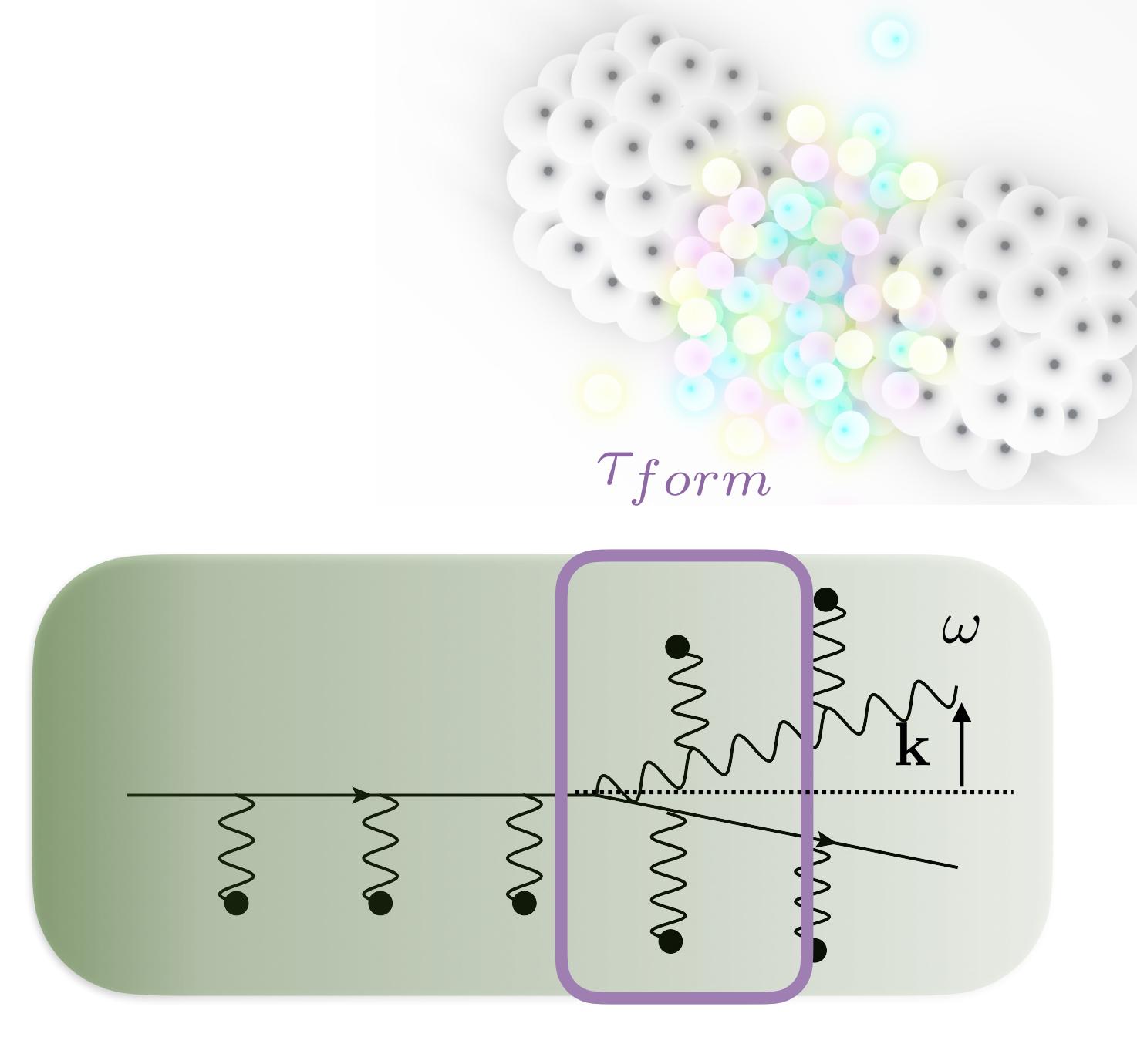
- Accumulation of momenta enhances gluon radiation:
 - Single-gluon emission spectrum:

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

Emission Kernel:

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

Solution to the path integral (for an arbitrary potential) poses significant technical challenges...



Density of scattering centres:

$$n(x_+) = \int dx_{i+} \delta(x_+ - x_{i+}).$$

Dipole cross-section (collision rate):

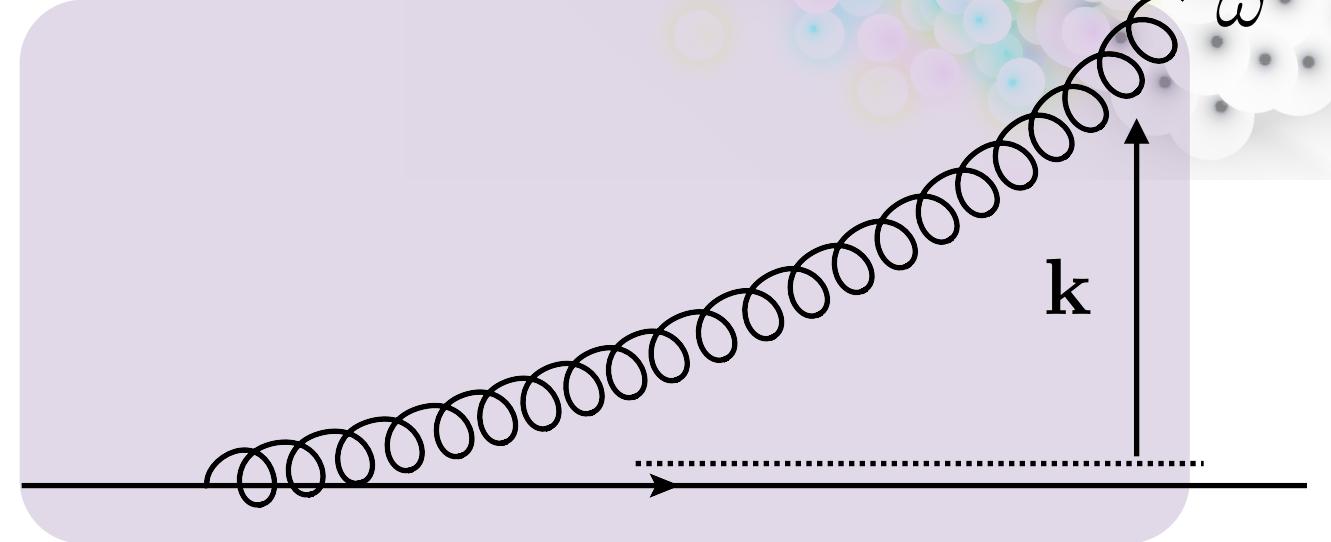
$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q}) (1 - e^{i\mathbf{q}\mathbf{r}})$$

Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Physical picture



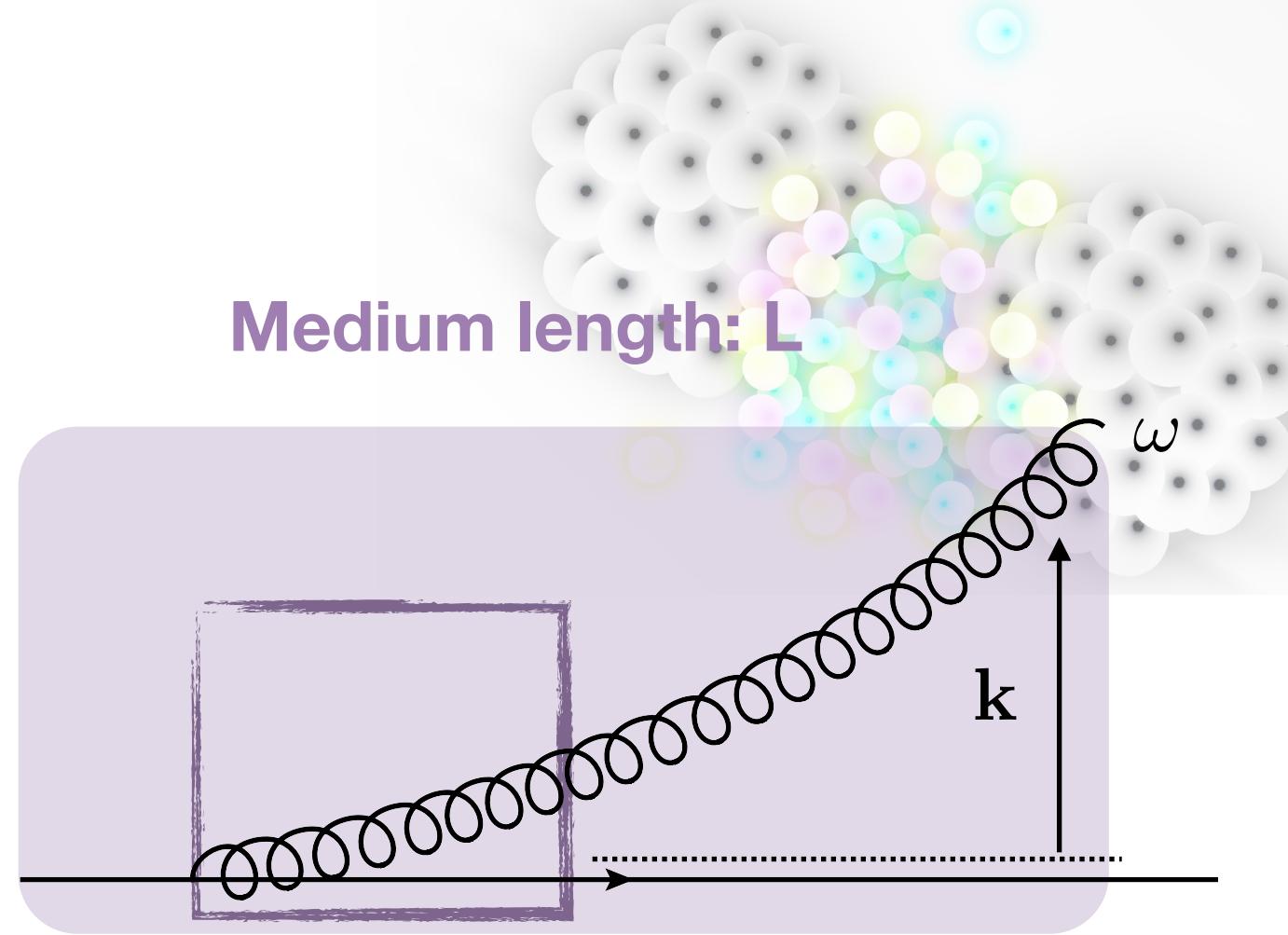
Medium length: L

Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Physical picture

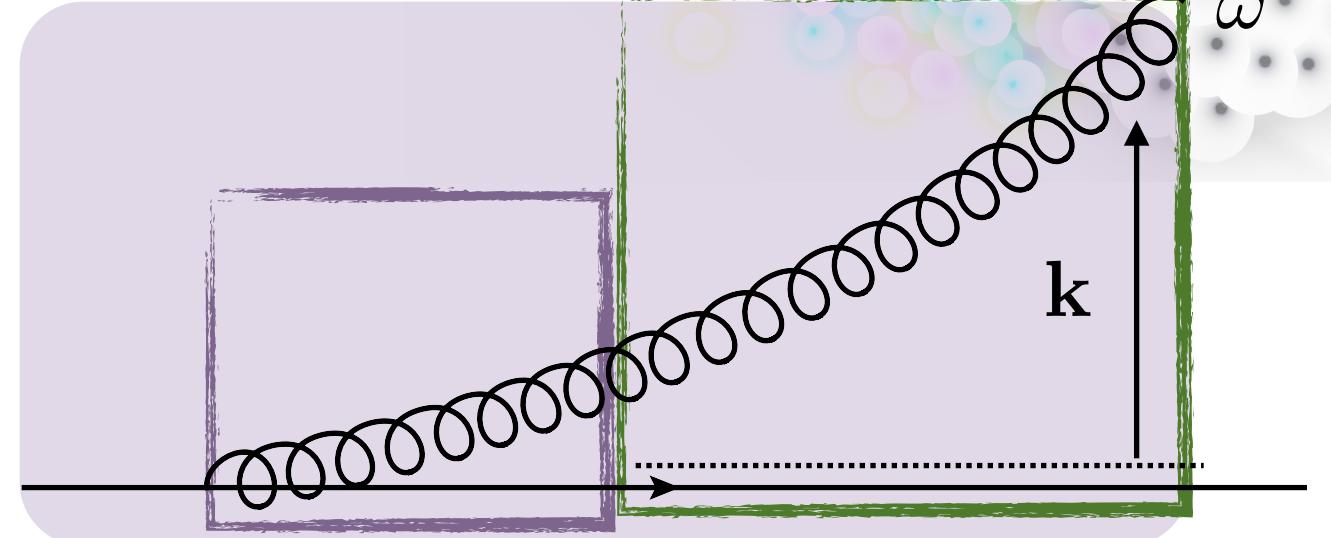


Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Physical picture



Medium length: L

Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

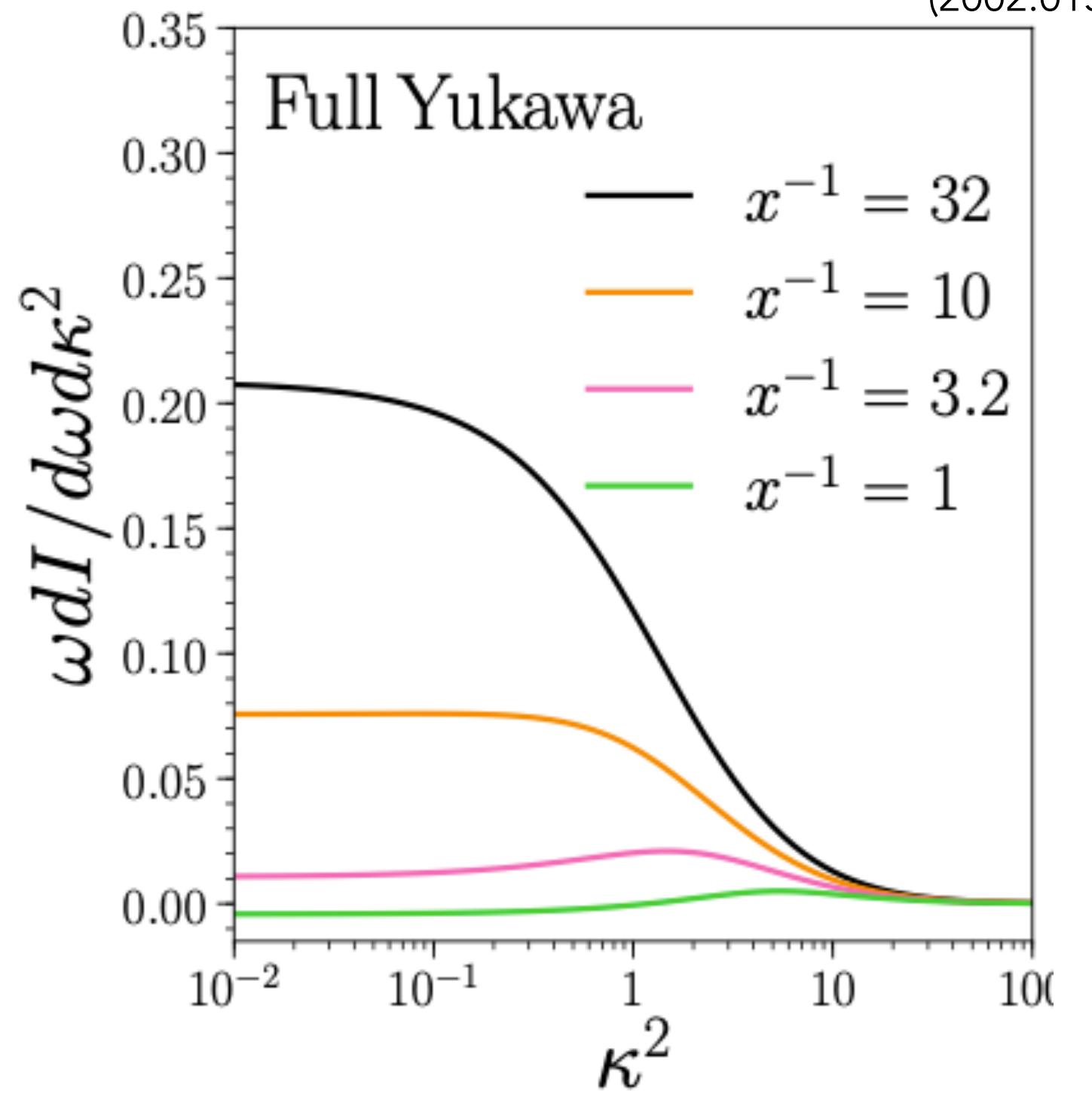
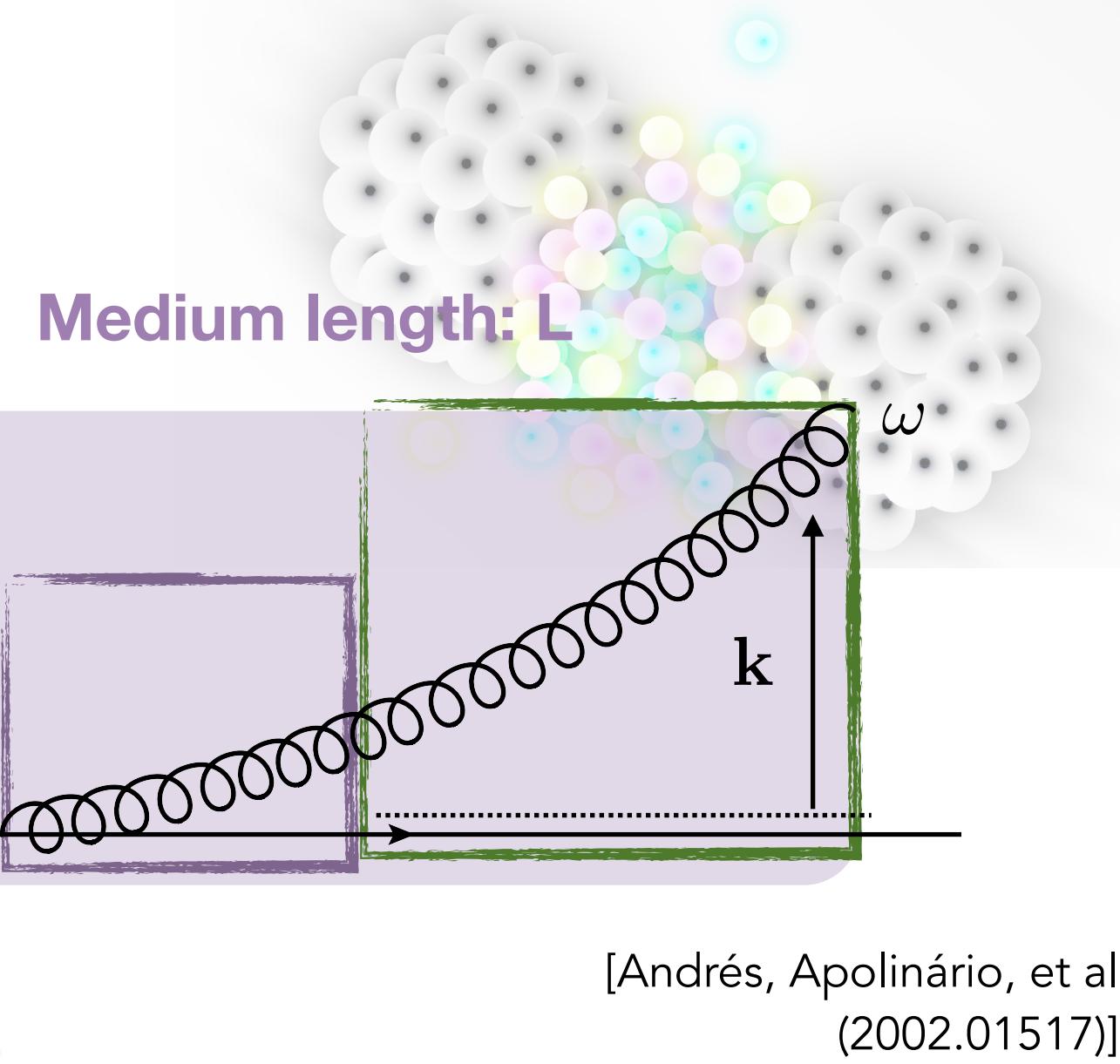
Scattering rate
(interaction potential)

$$\sigma(r) \propto V(q) = \frac{8\pi\mu^2}{(q^2 + \mu^2)^2}$$

Scaled energy: $x = \frac{\omega}{\bar{\omega}_c} = \frac{2\omega}{\mu^2 L}$

Scaled transverse momentum: $\kappa^2 = \frac{k^2}{\mu^2}$

Physical picture



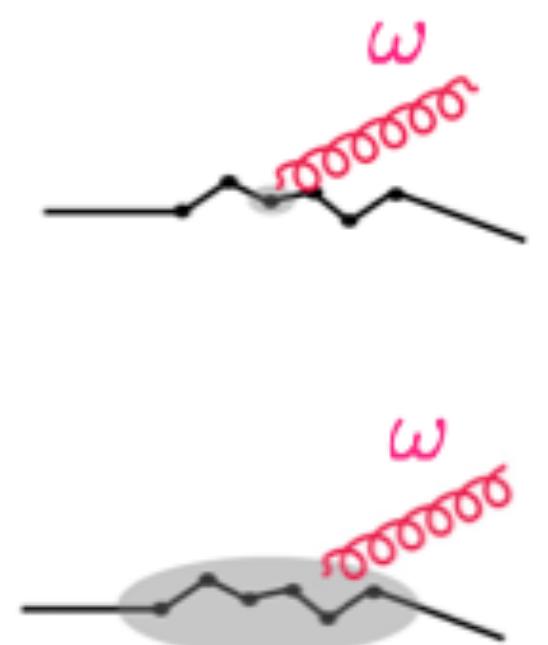
Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Scattering rate
(interaction potential)

$$\sigma(r) \propto V(q) = \frac{8\pi\mu^2}{(q^2 + \mu^2)^2}$$



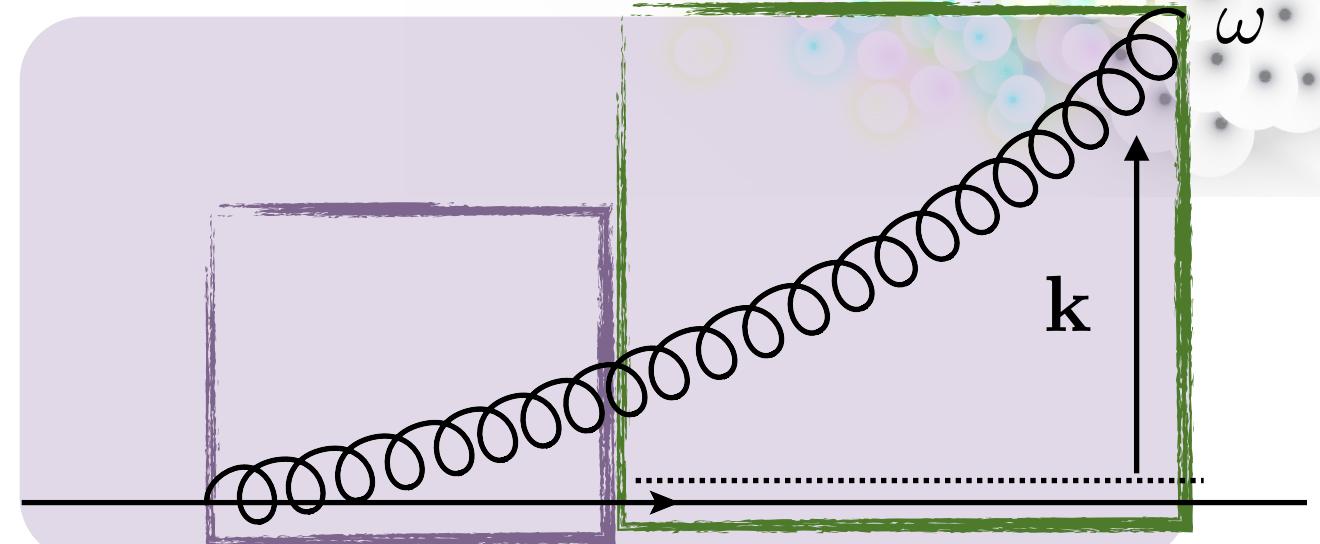
Scaled energy: $x = \frac{\omega}{\bar{\omega}_c} = \frac{2\omega}{\mu^2 L}$

Scaled transverse momentum: $\kappa^2 = \frac{k^2}{\mu^2}$

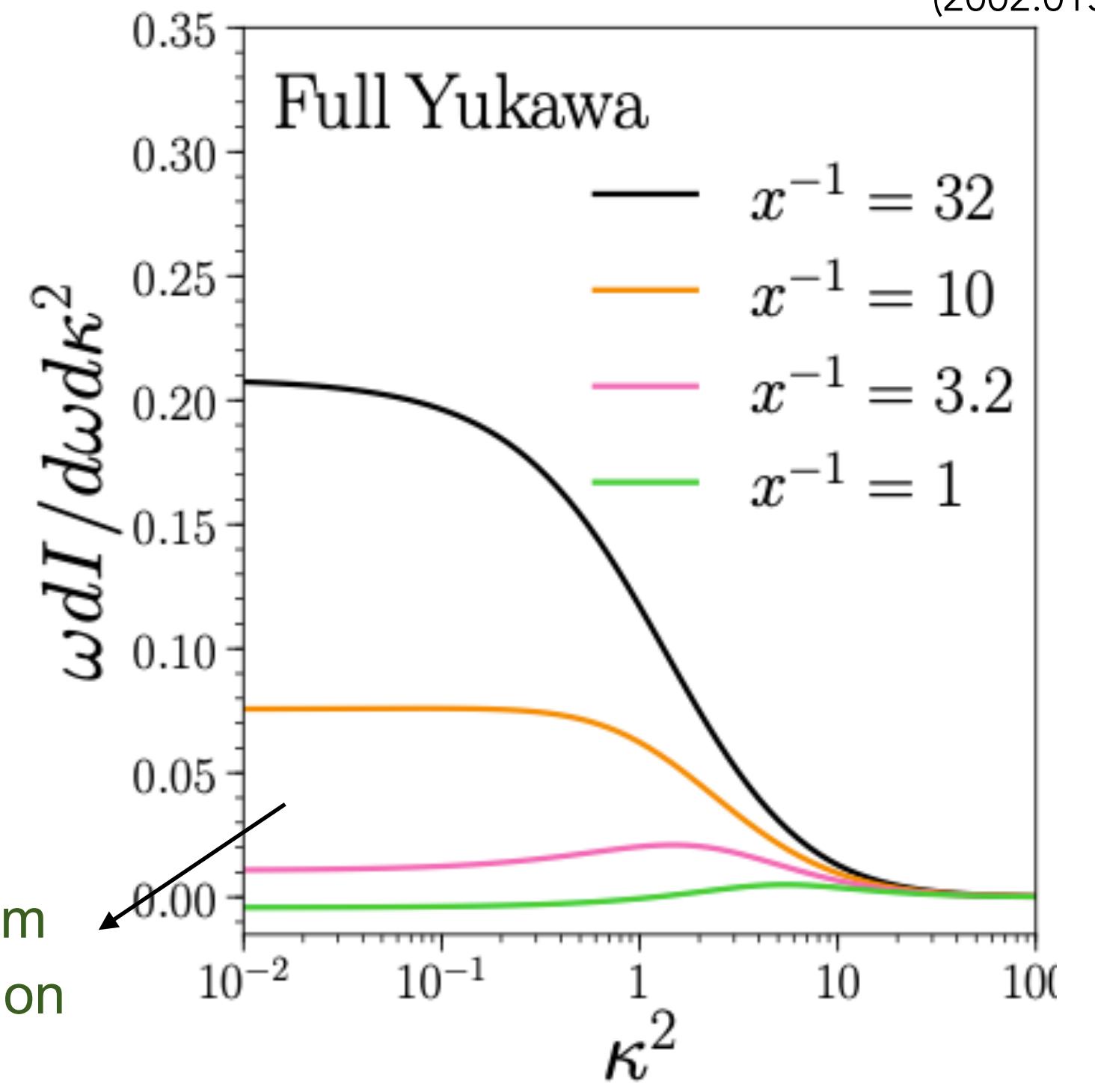
In-medium suppression

Physical picture

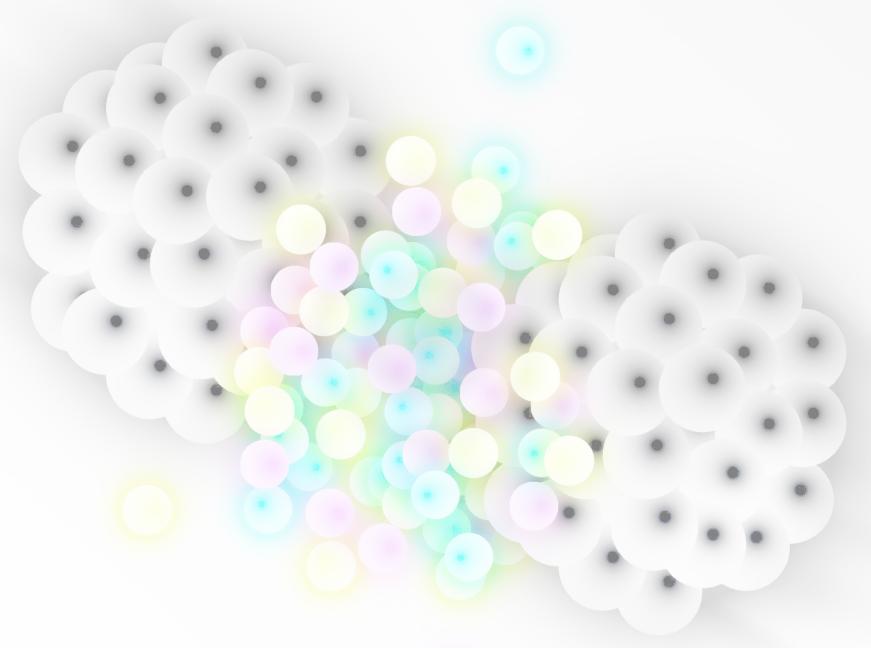
Medium length: L



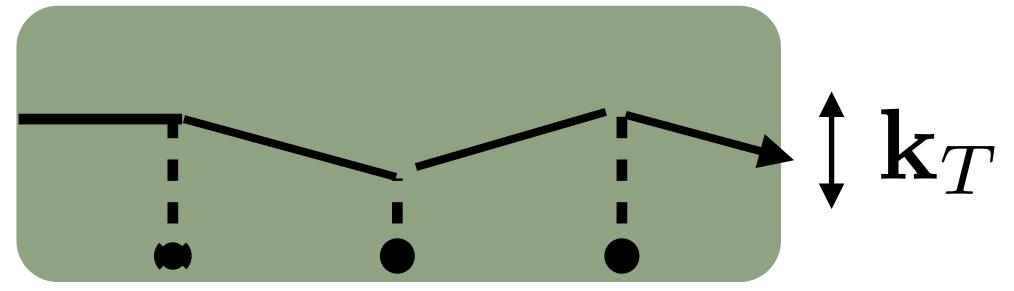
[Andrés, Apolinário, et al
(2002.01517)]



From the probe to the medium



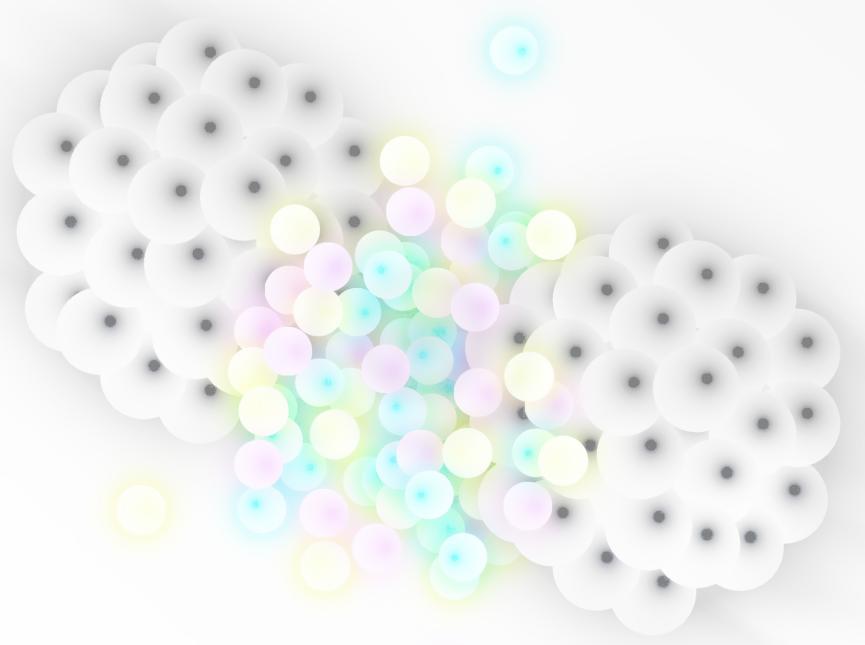
- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)
 - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening



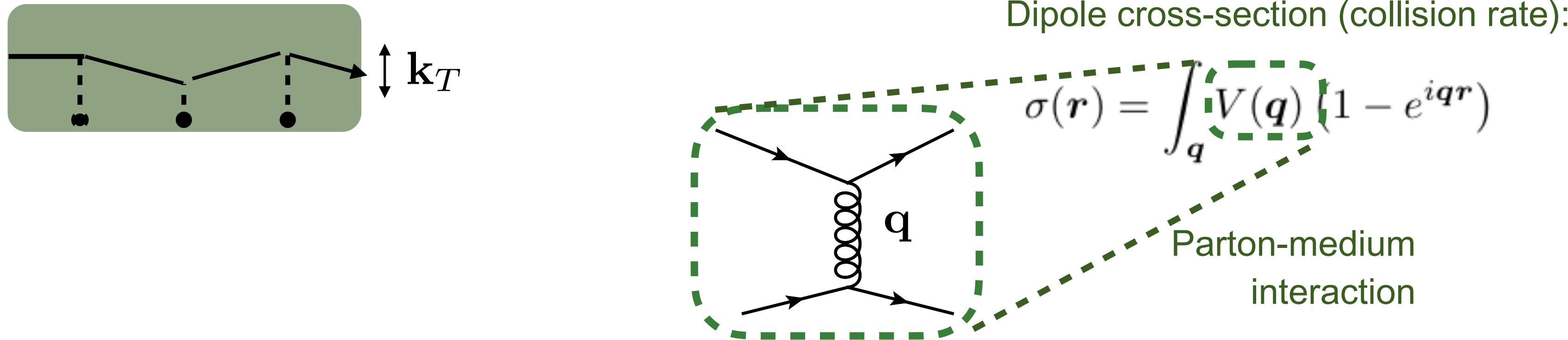
Dipole cross-section (collision rate):

$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q}) (1 - e^{i\mathbf{q}\mathbf{r}})$$

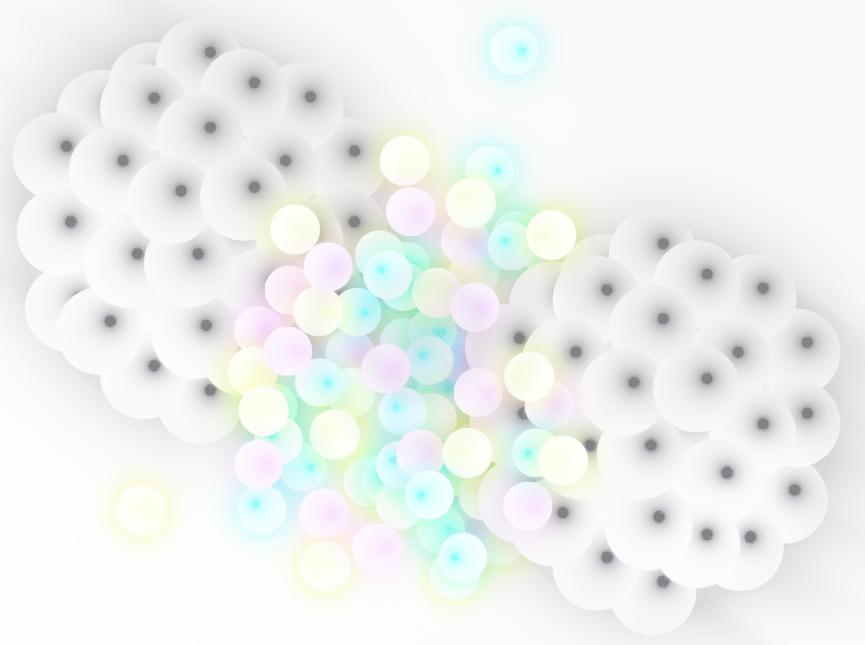
From the probe to the medium



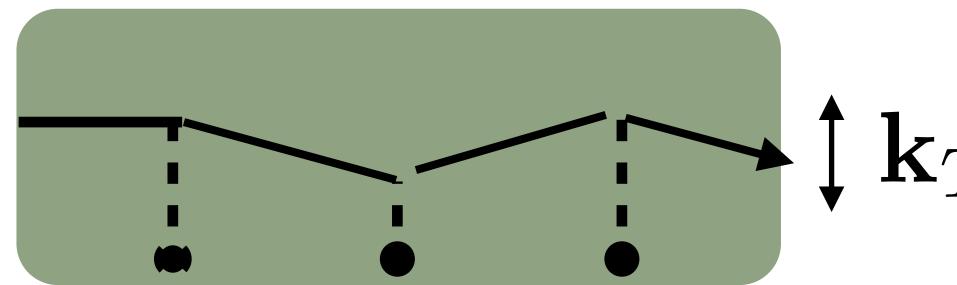
- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)
 - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening



From the probe to the medium



- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)
 - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening



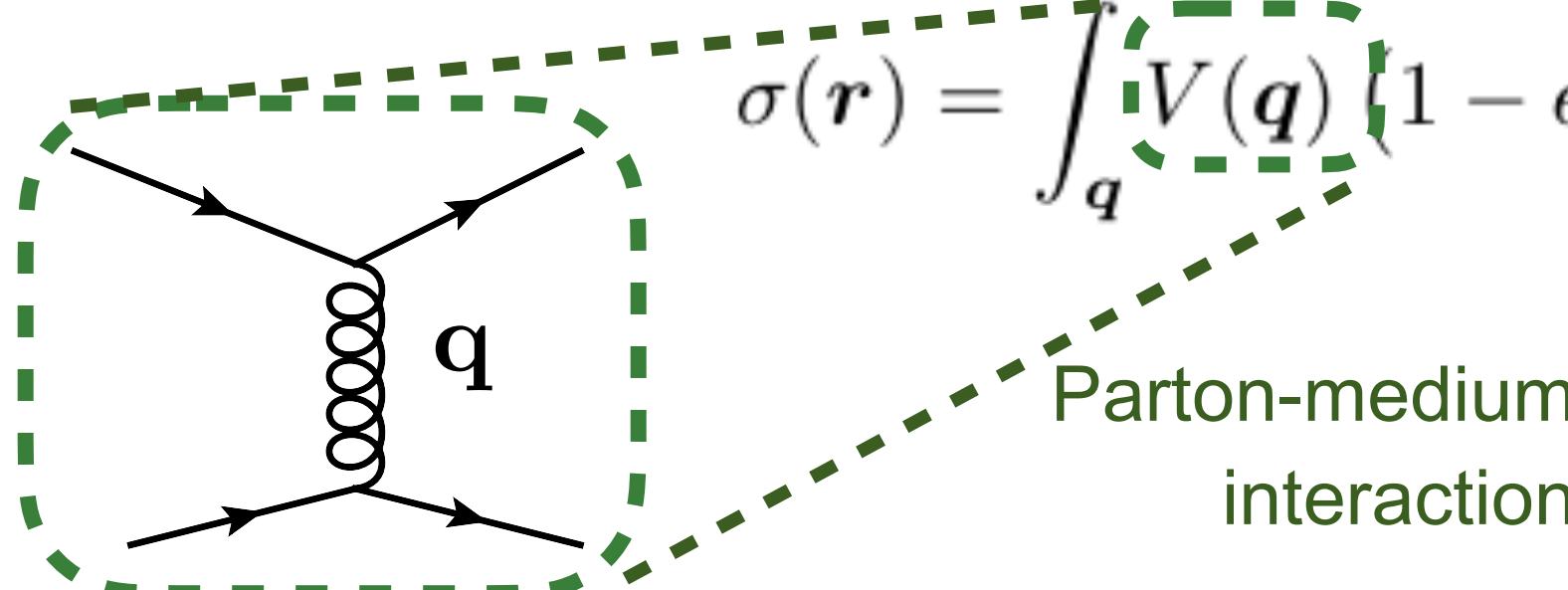
Transport coefficient:

$$\hat{q} = \frac{\langle k_T \rangle}{\lambda}$$

$$\hat{q} \propto \int d^2\mathbf{q}^2 q^2 \frac{d\sigma(\mathbf{q})}{d^2\mathbf{q}}$$

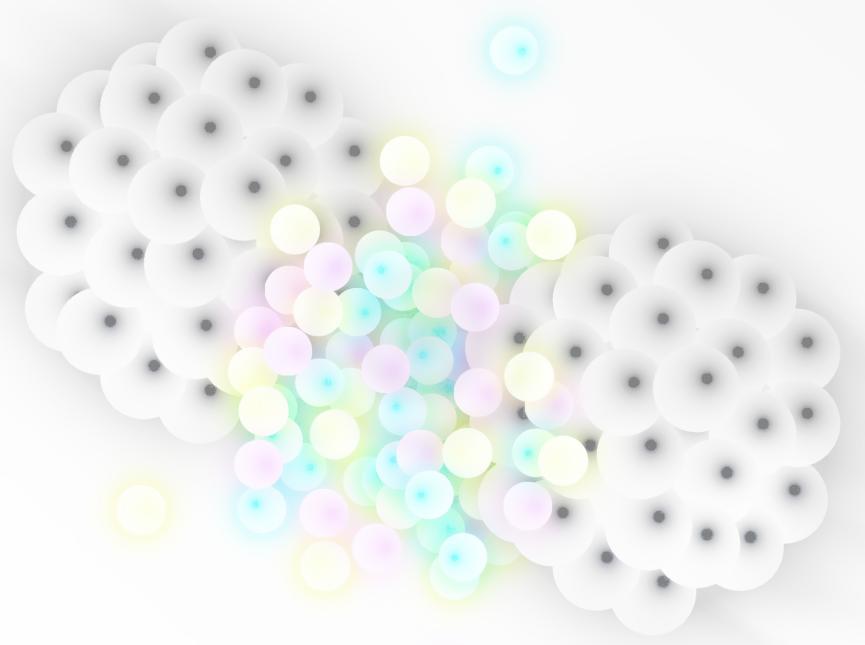
Dipole cross-section (collision rate):

$$\sigma(\mathbf{r}) = \int_{\mathbf{q}} V(\mathbf{q}) (1 - e^{i\mathbf{q}\mathbf{r}})$$

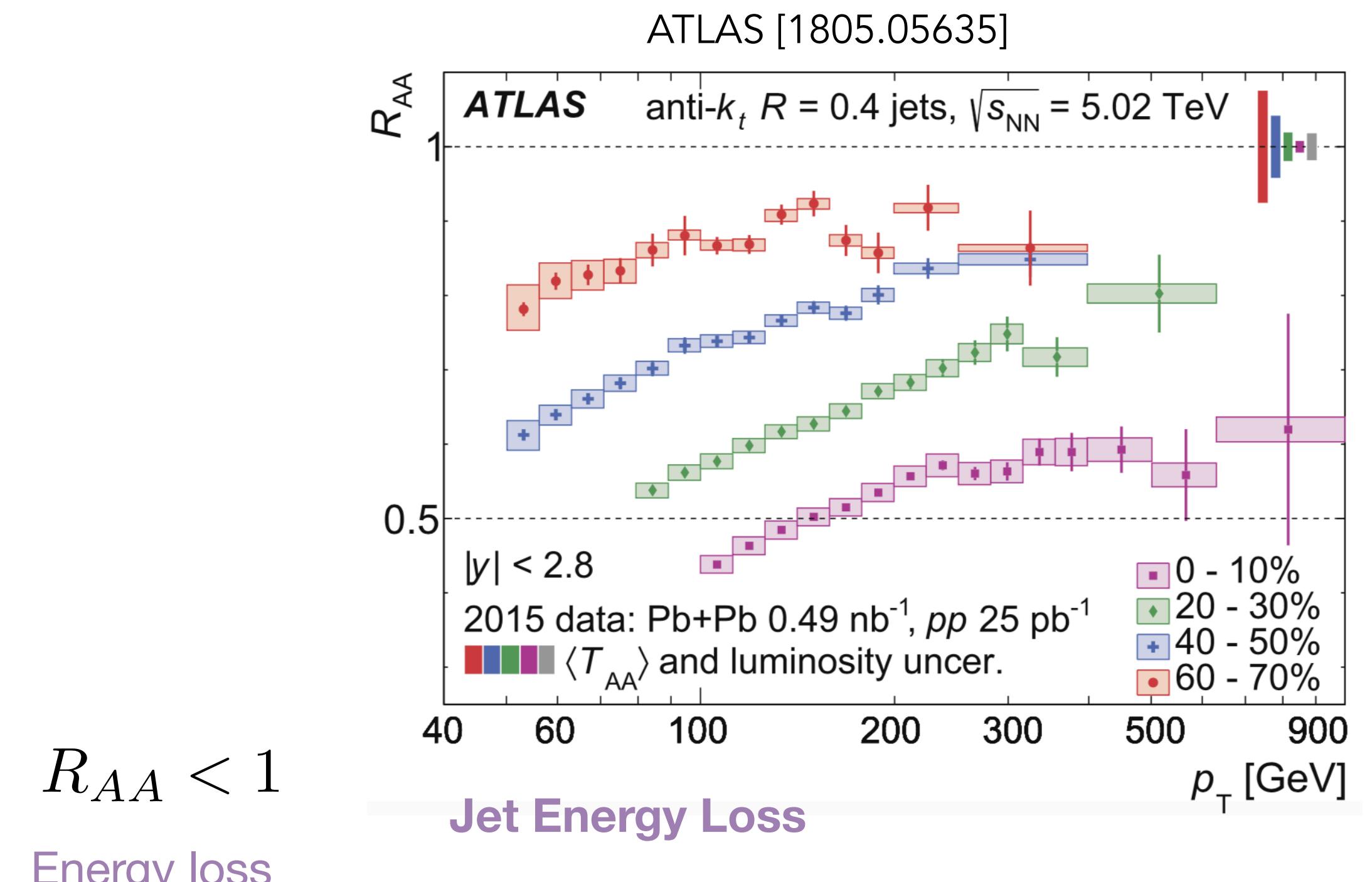
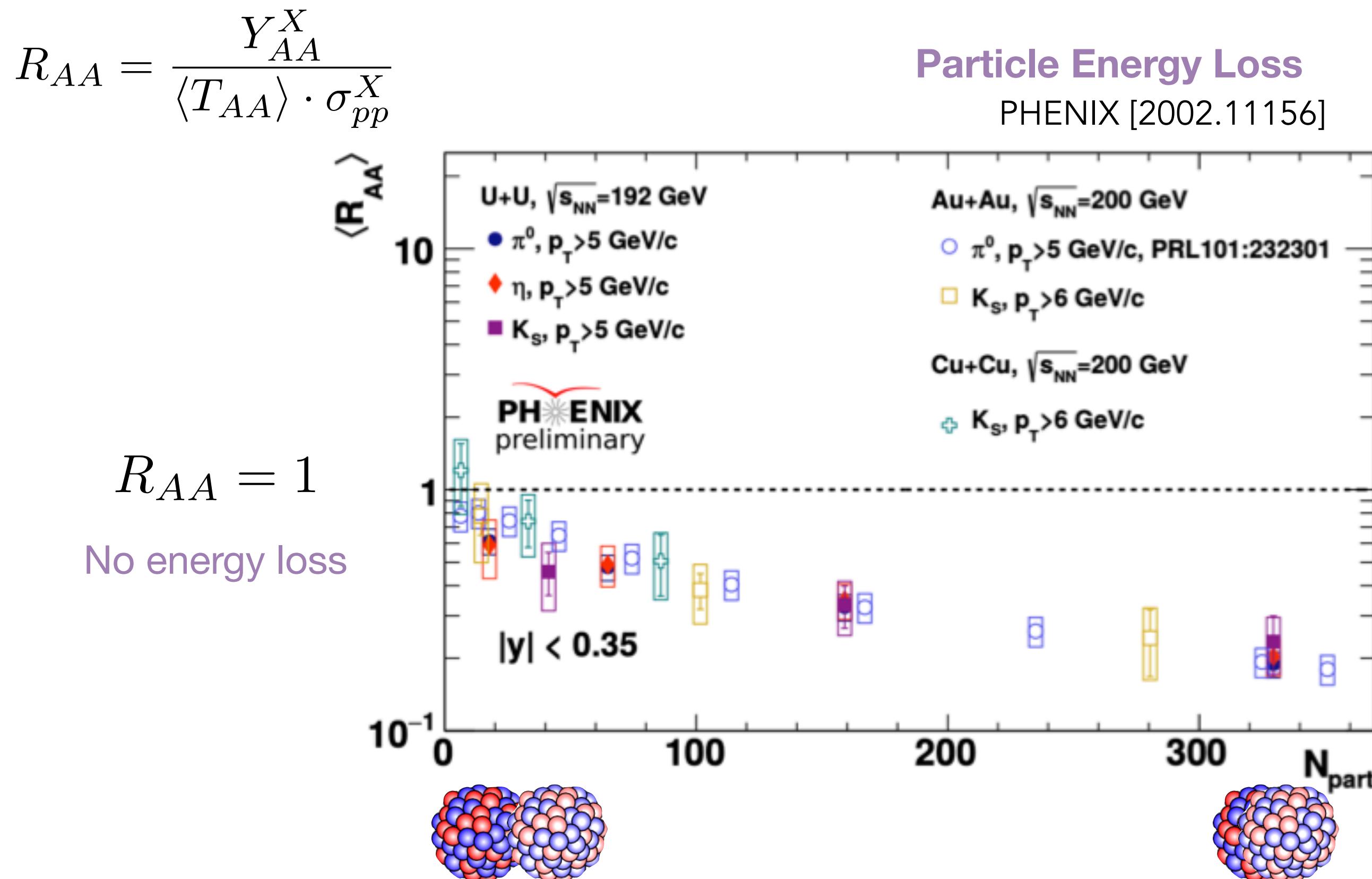


Parton-medium
interaction

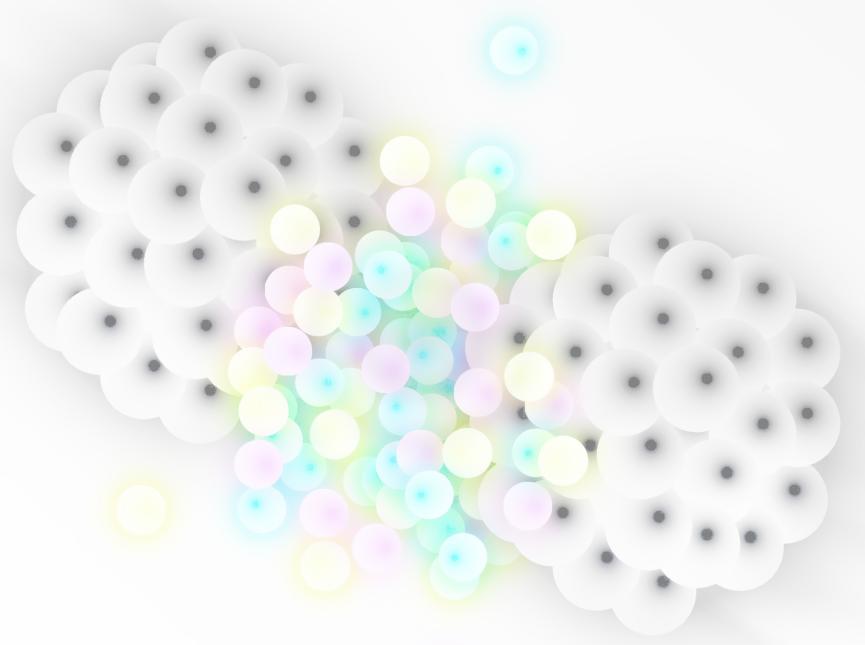
From the probe to the medium



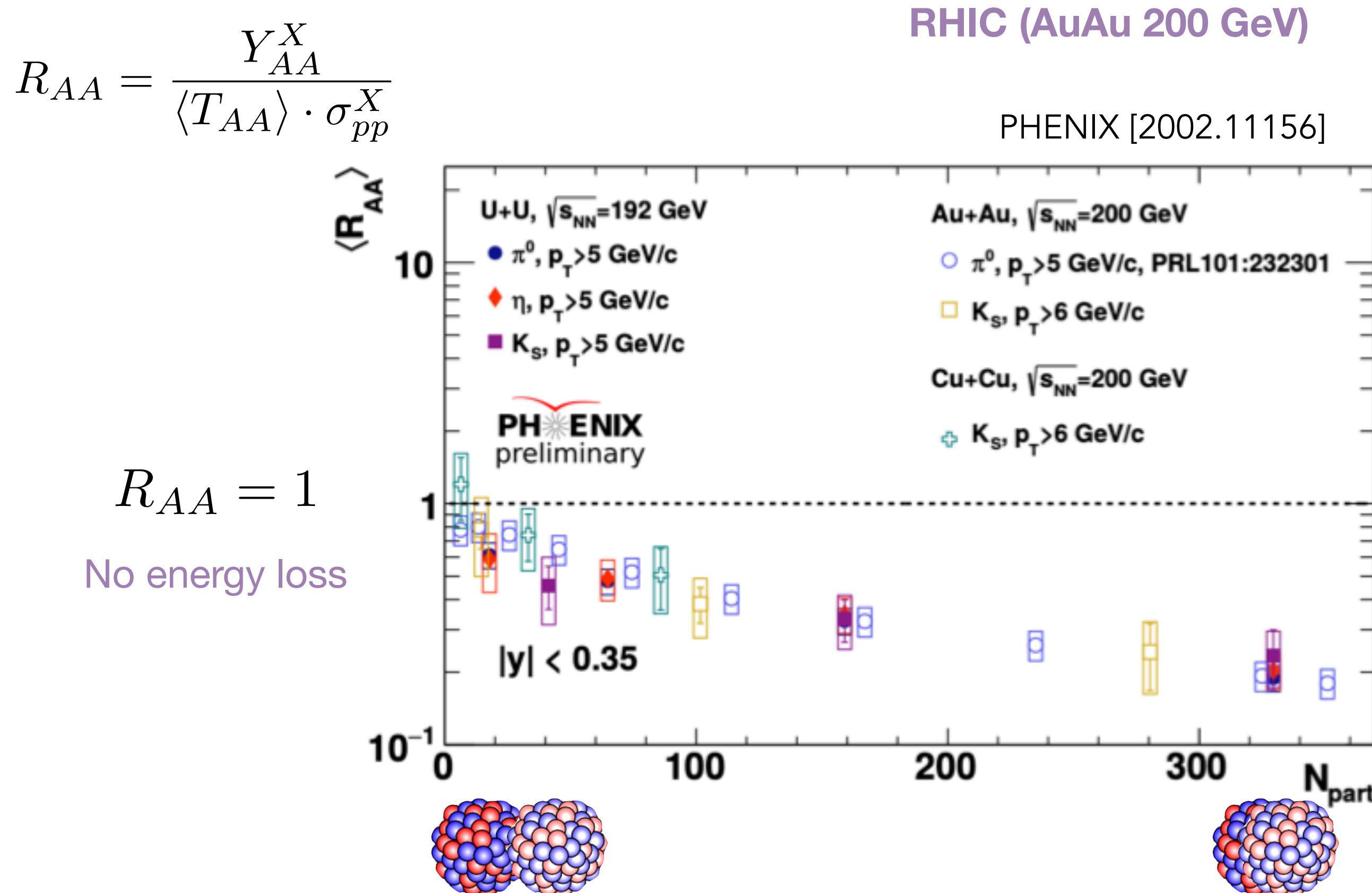
- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)
 - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening



From the probe to the medium

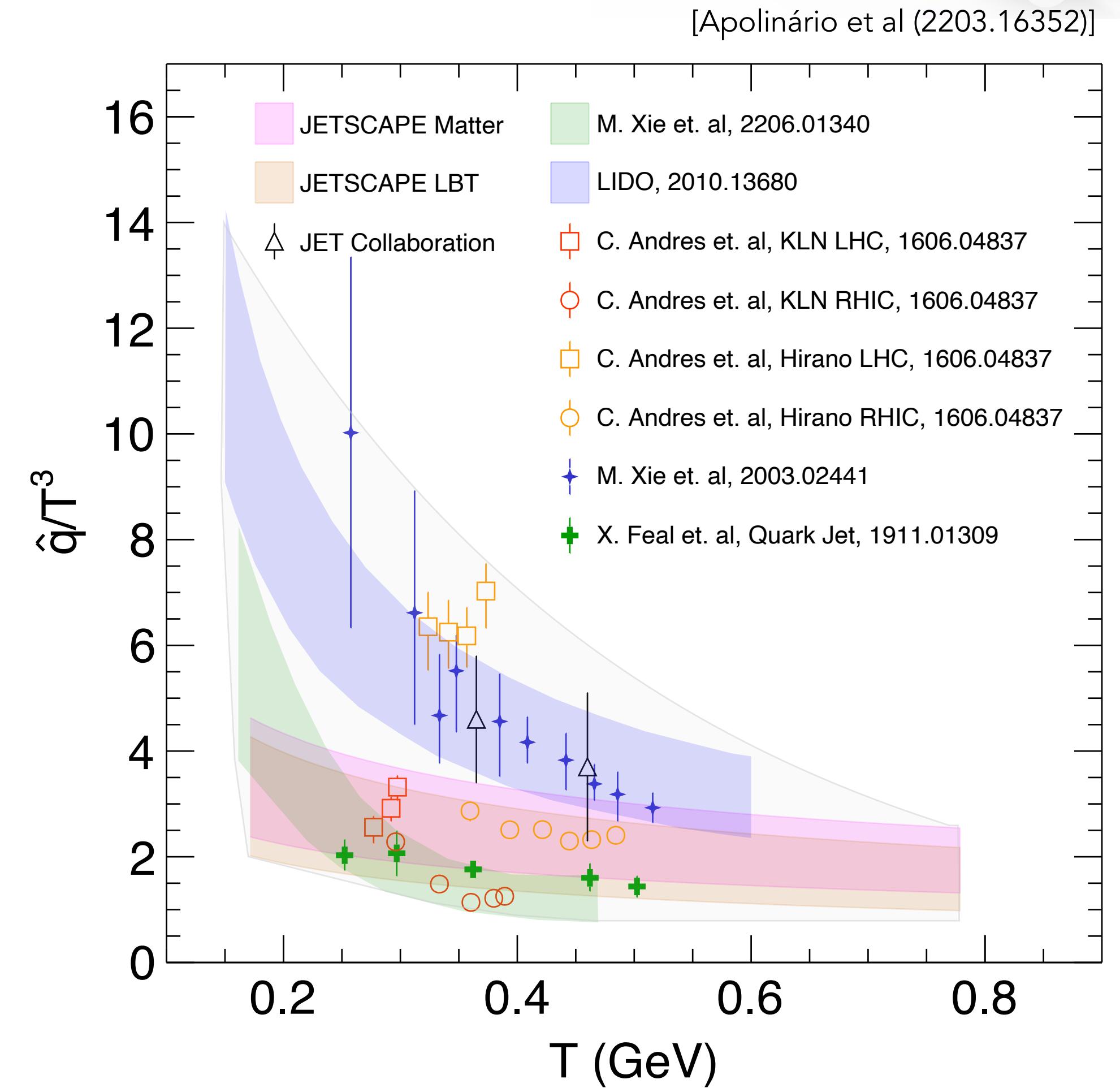
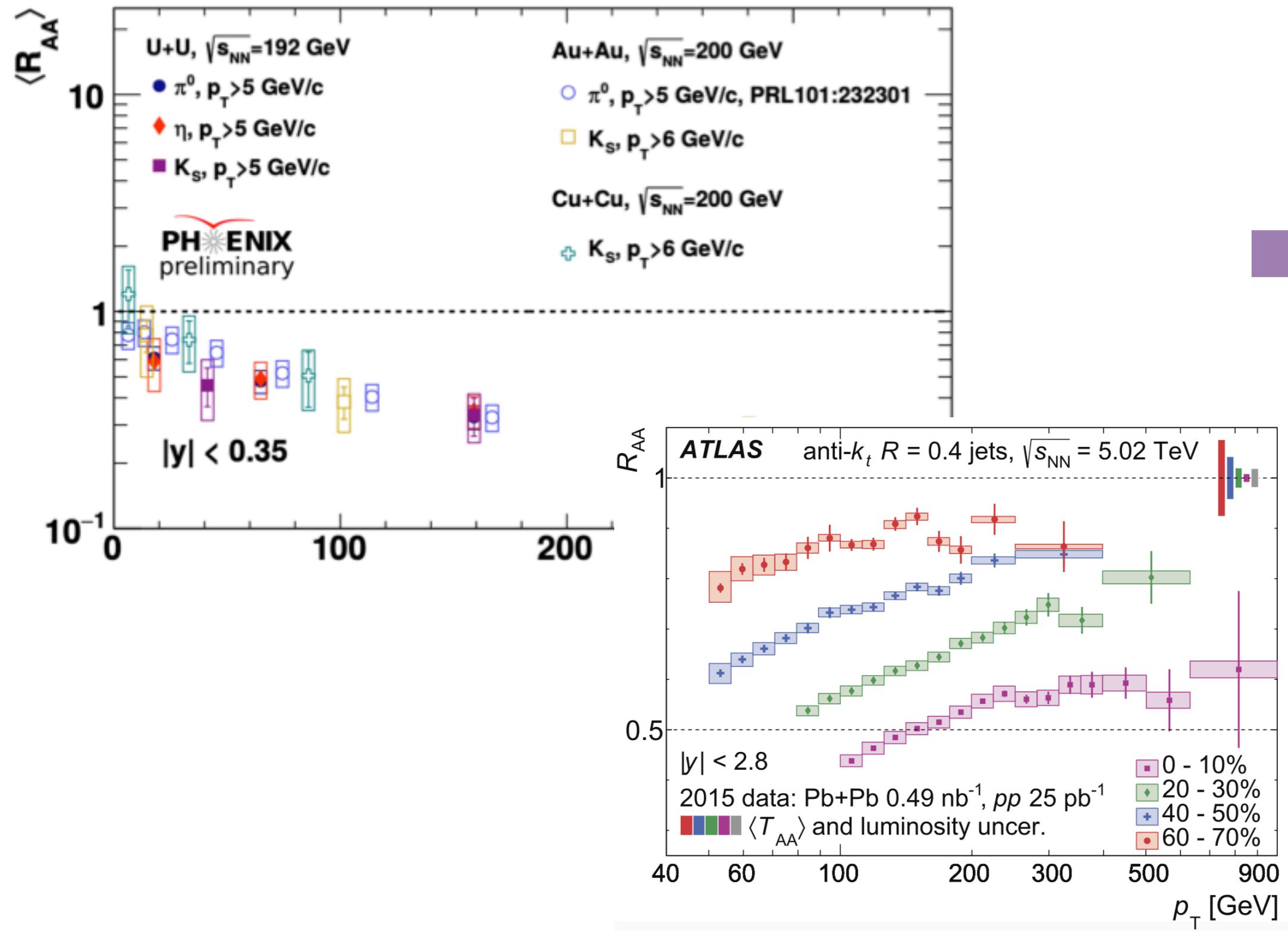


- Medium-induced radiation and momentum broadening closely connected (multiple soft-scattering approximation)
 - Accumulation of momenta enhances gluon radiation and partons undergo transverse momentum broadening

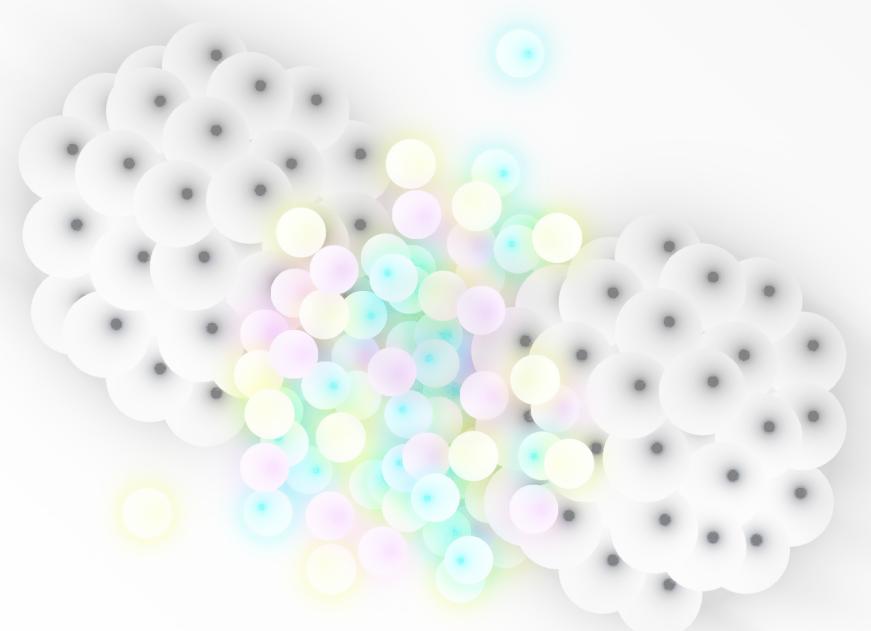


Medium transport coefficients

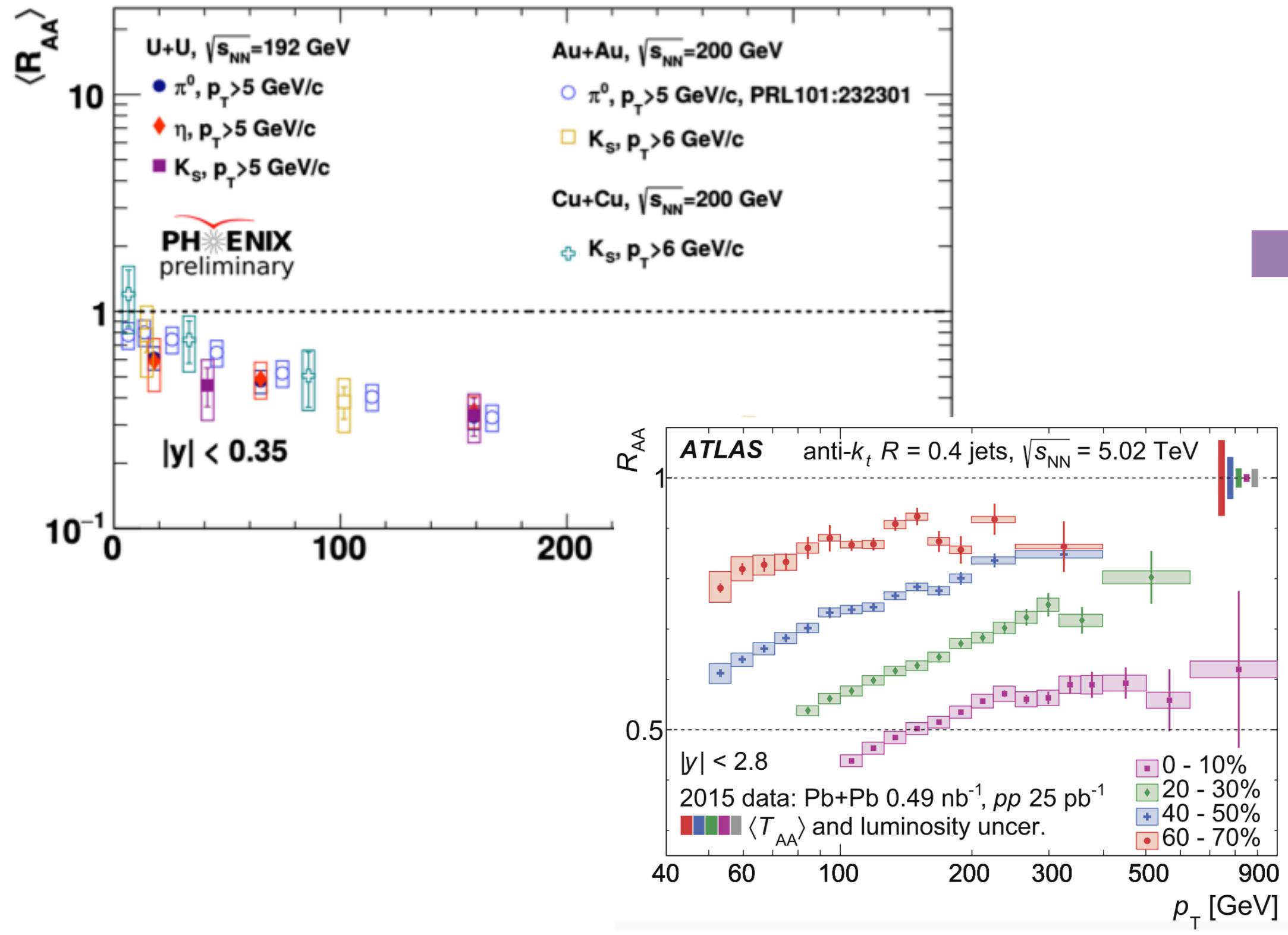
- From single-particle or jet suppression recover \hat{q}



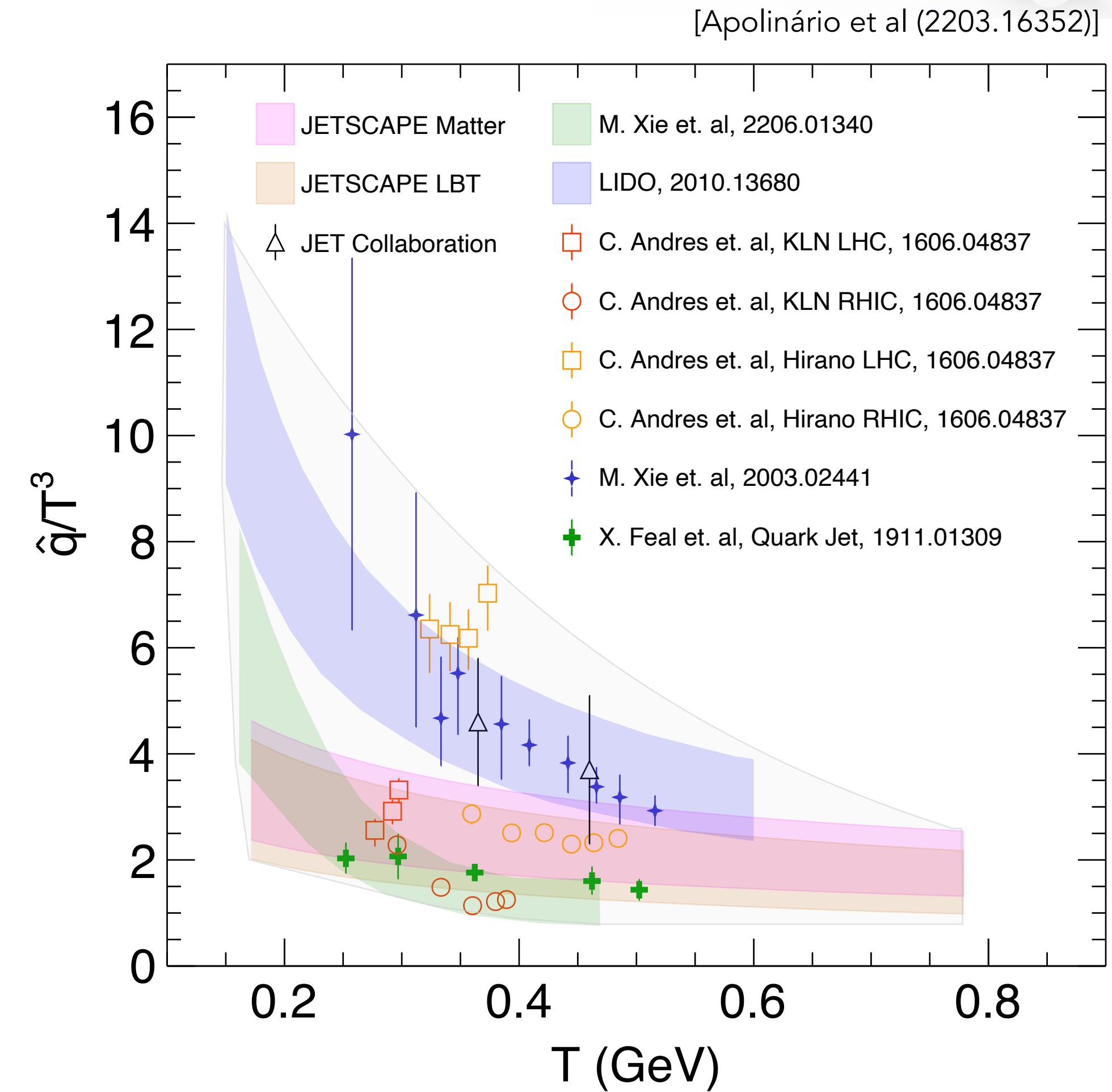
Medium transport coefficients



- From single-particle or jet suppression recover \hat{q}



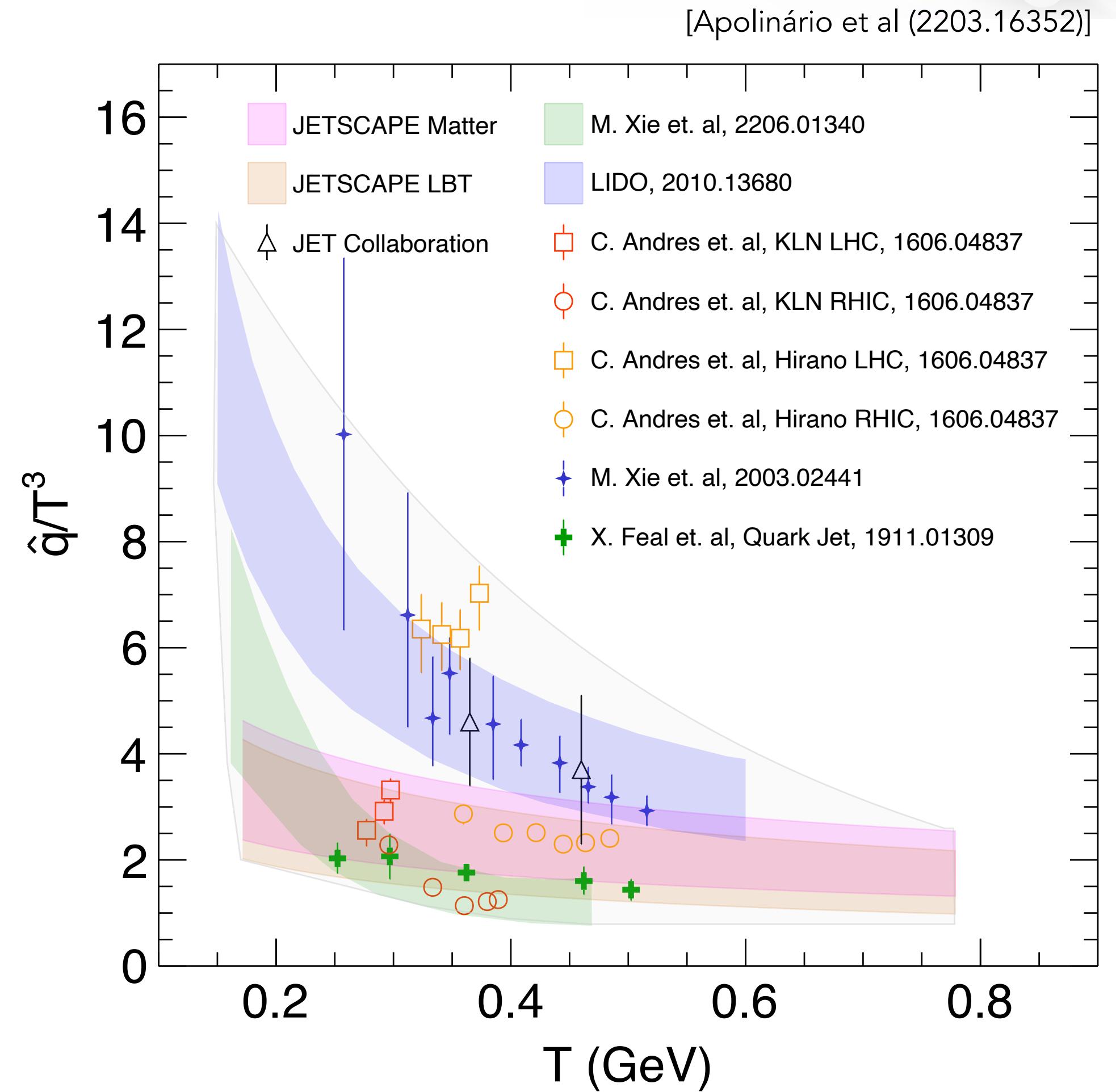
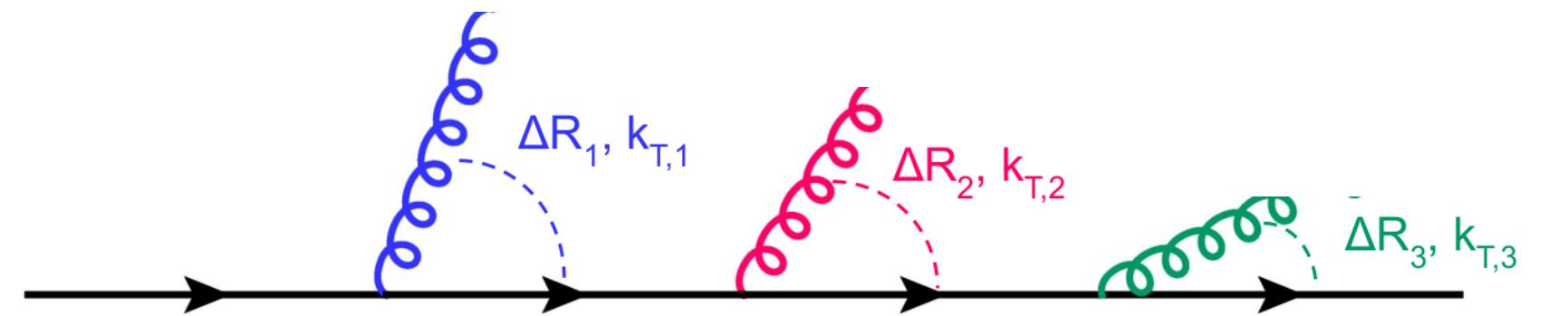
??



Medium transport coefficients

- From single-particle or jet suppression recover \hat{q}

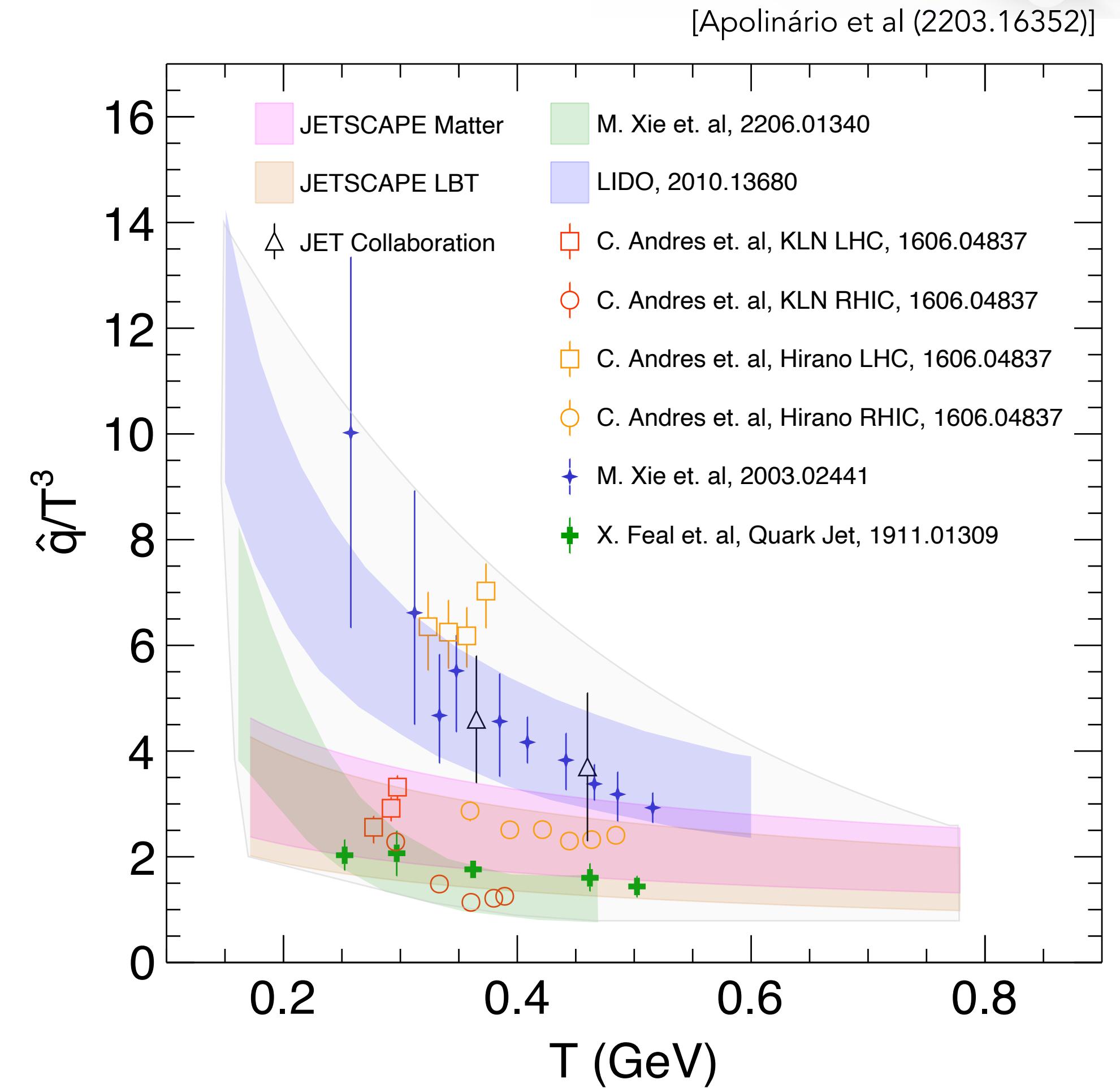
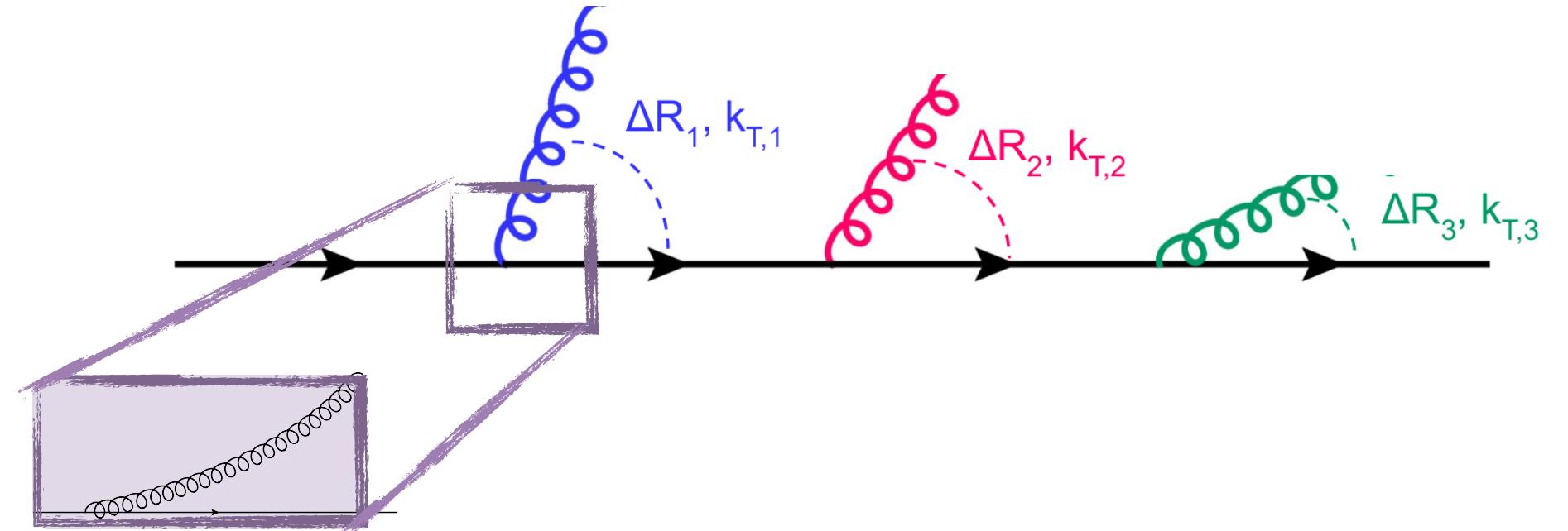
Assume independent gluon emissions:



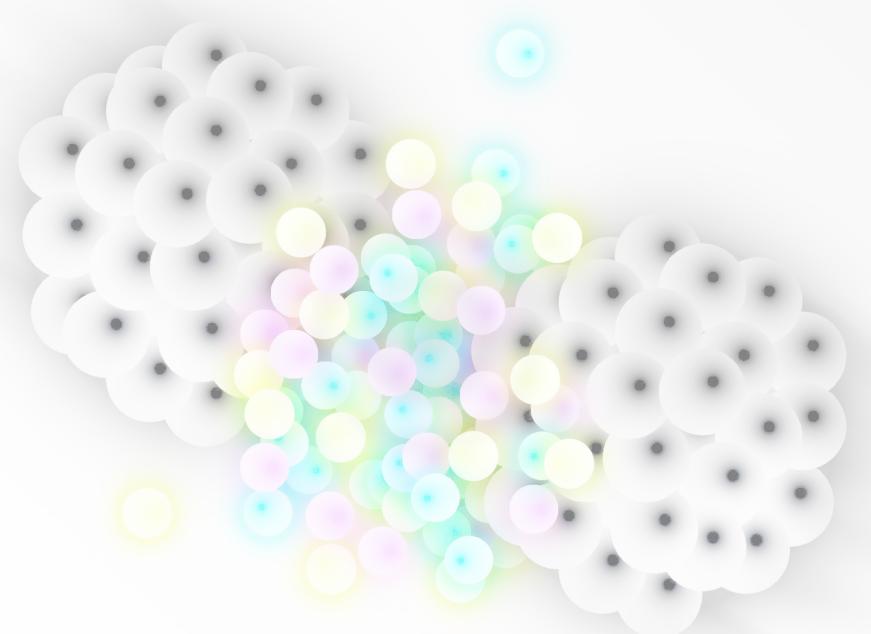
Medium transport coefficients

- From single-particle or jet suppression recover \hat{q}

Assume independent gluon emissions:

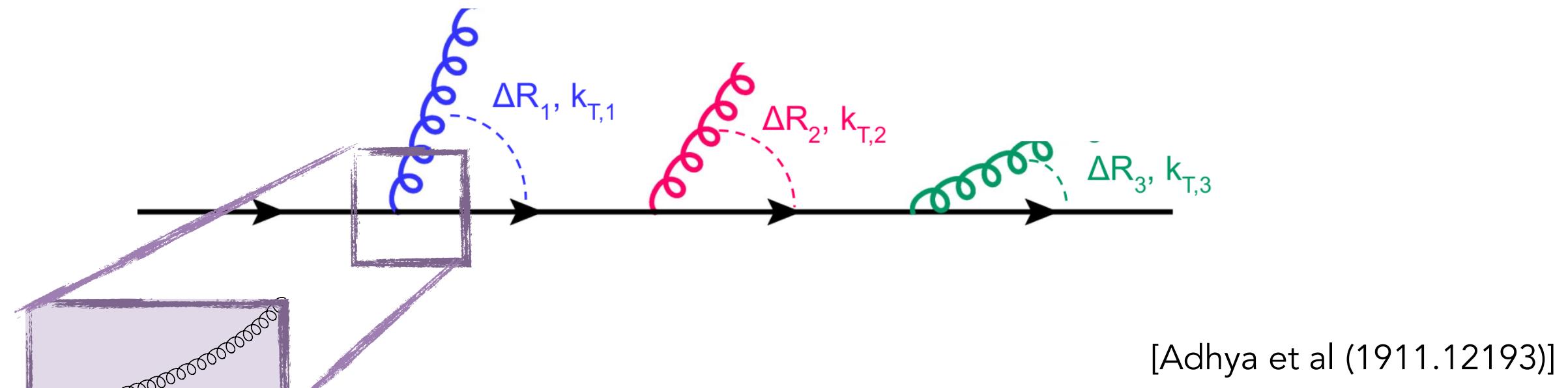


Medium transport coefficients

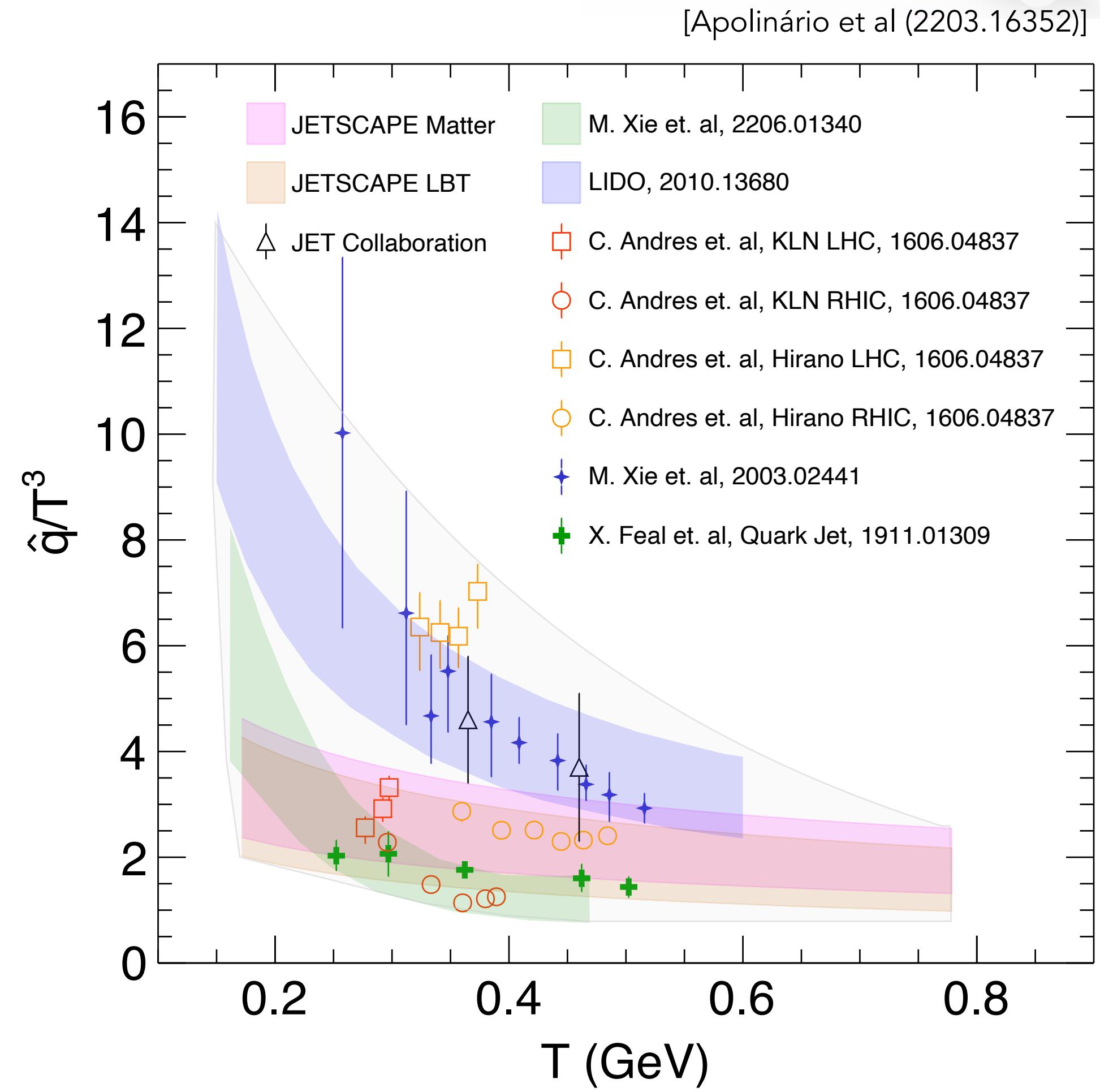
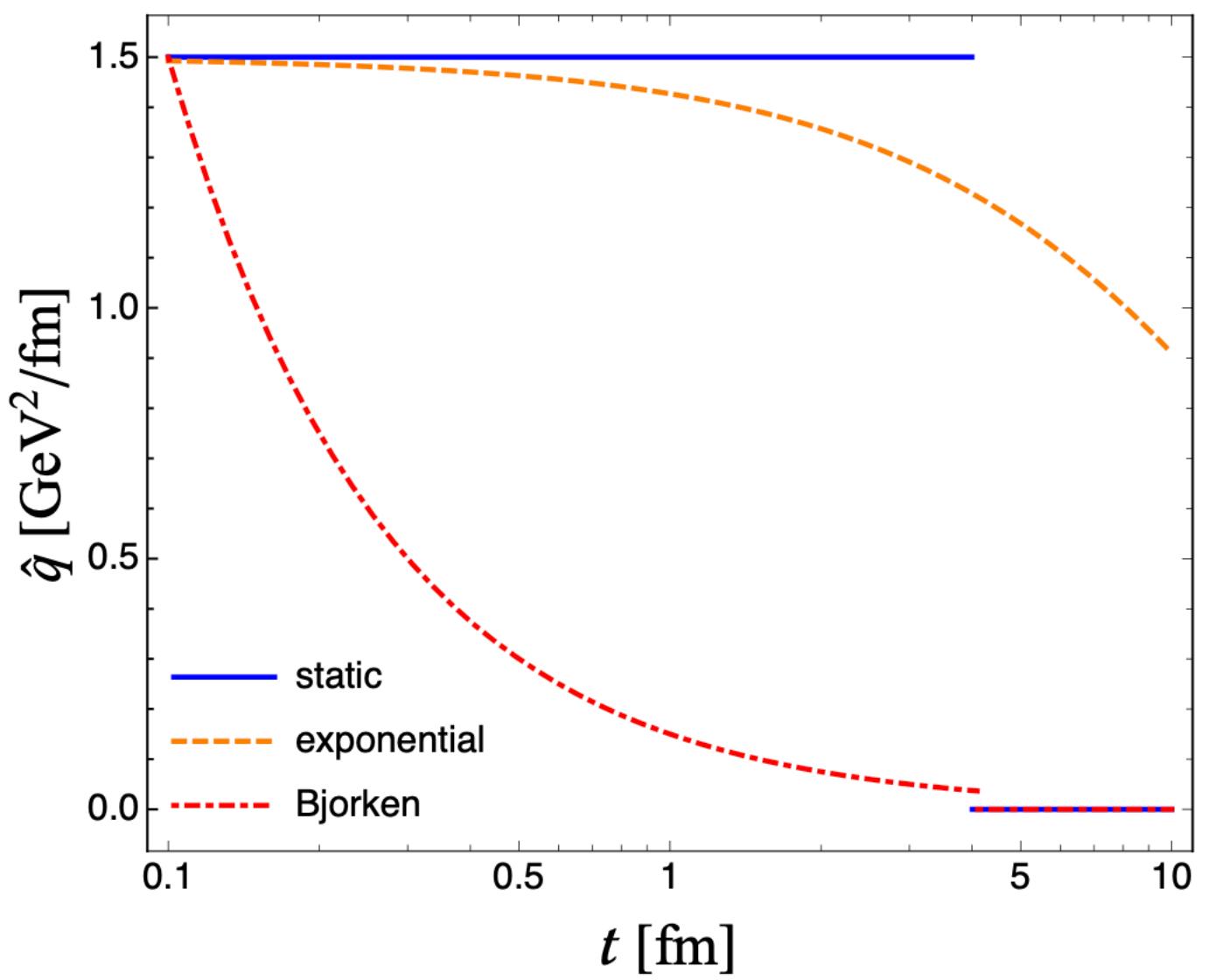


- From single-particle or jet suppression recover \hat{q}

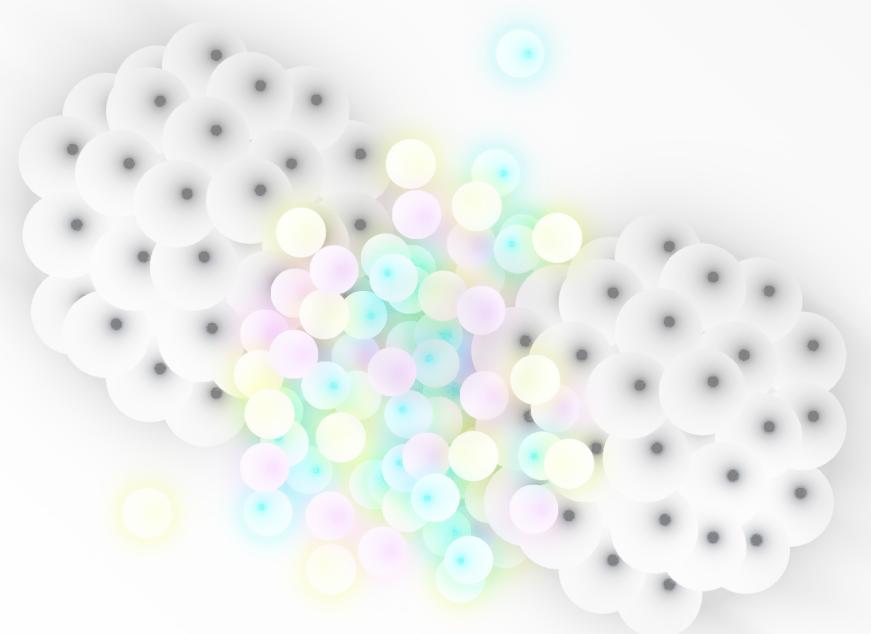
Assume independent gluon emissions:



Consider different medium time-evolution scenarios:

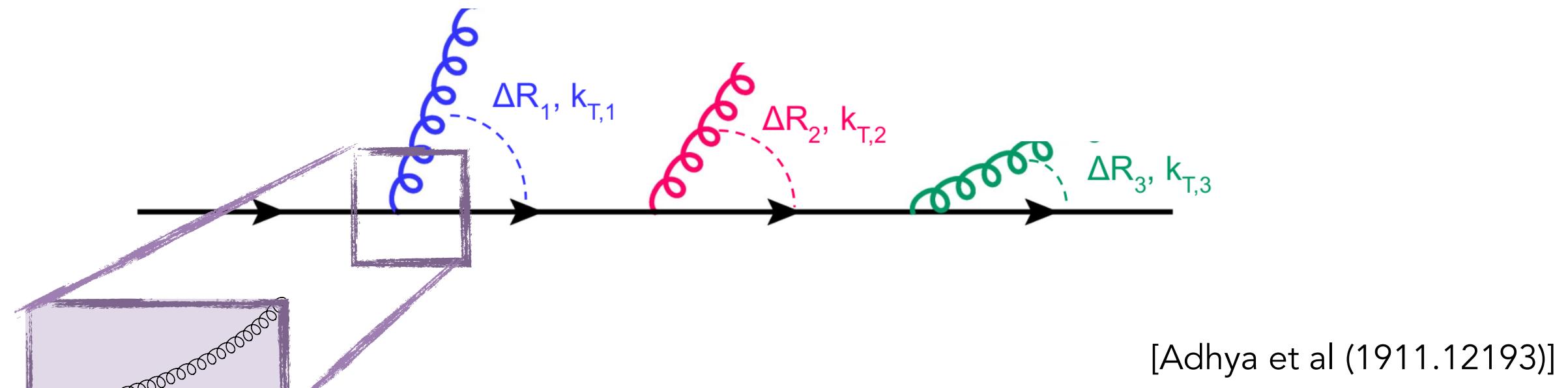


Medium transport coefficients

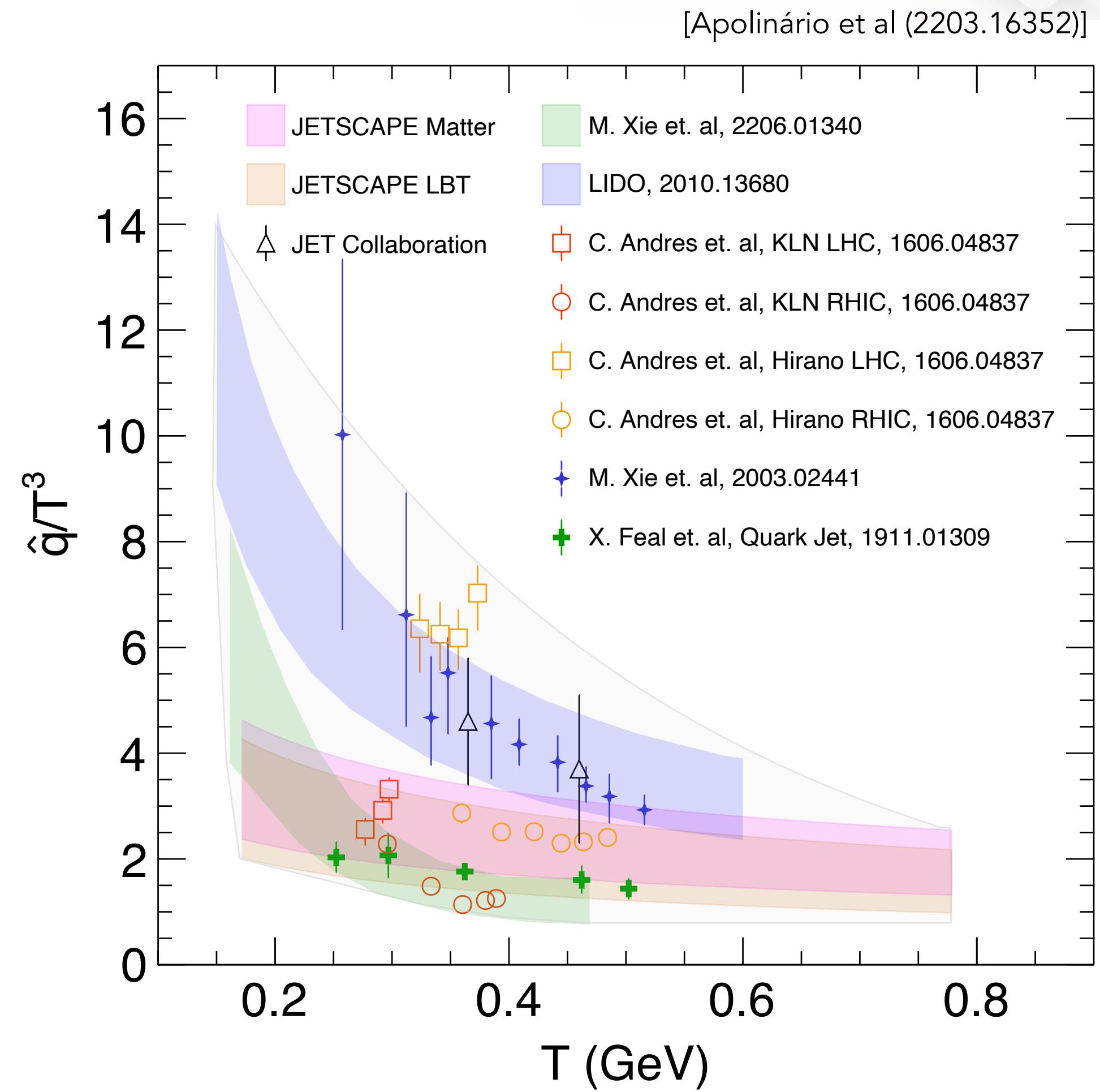
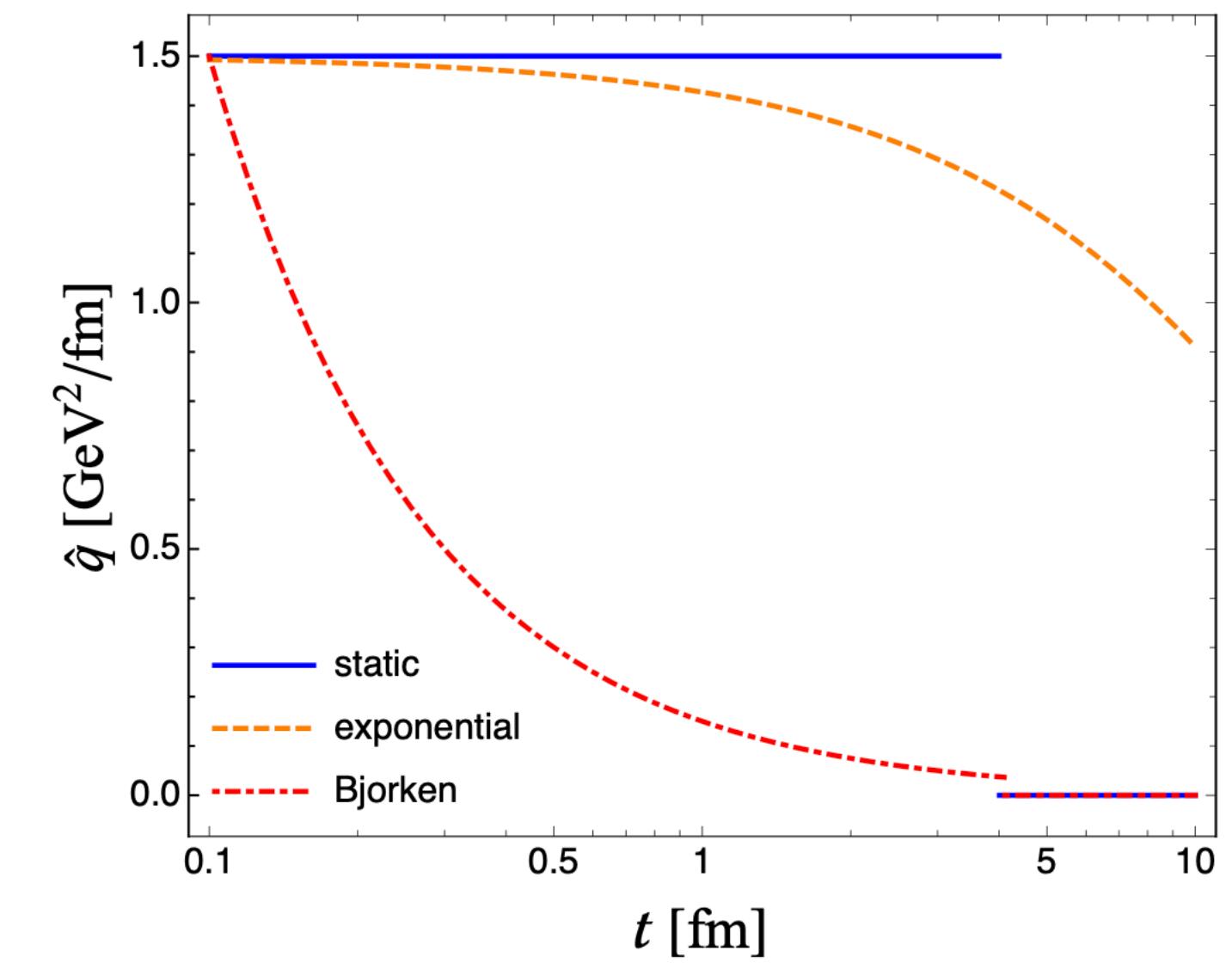


- From single-particle or jet suppression recover \hat{q}

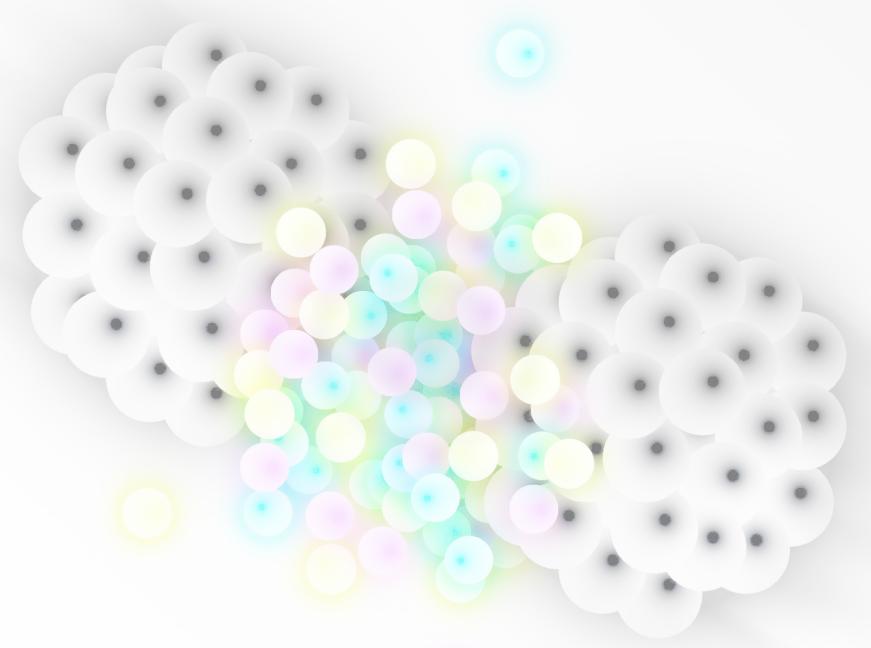
Assume independent gluon emissions:



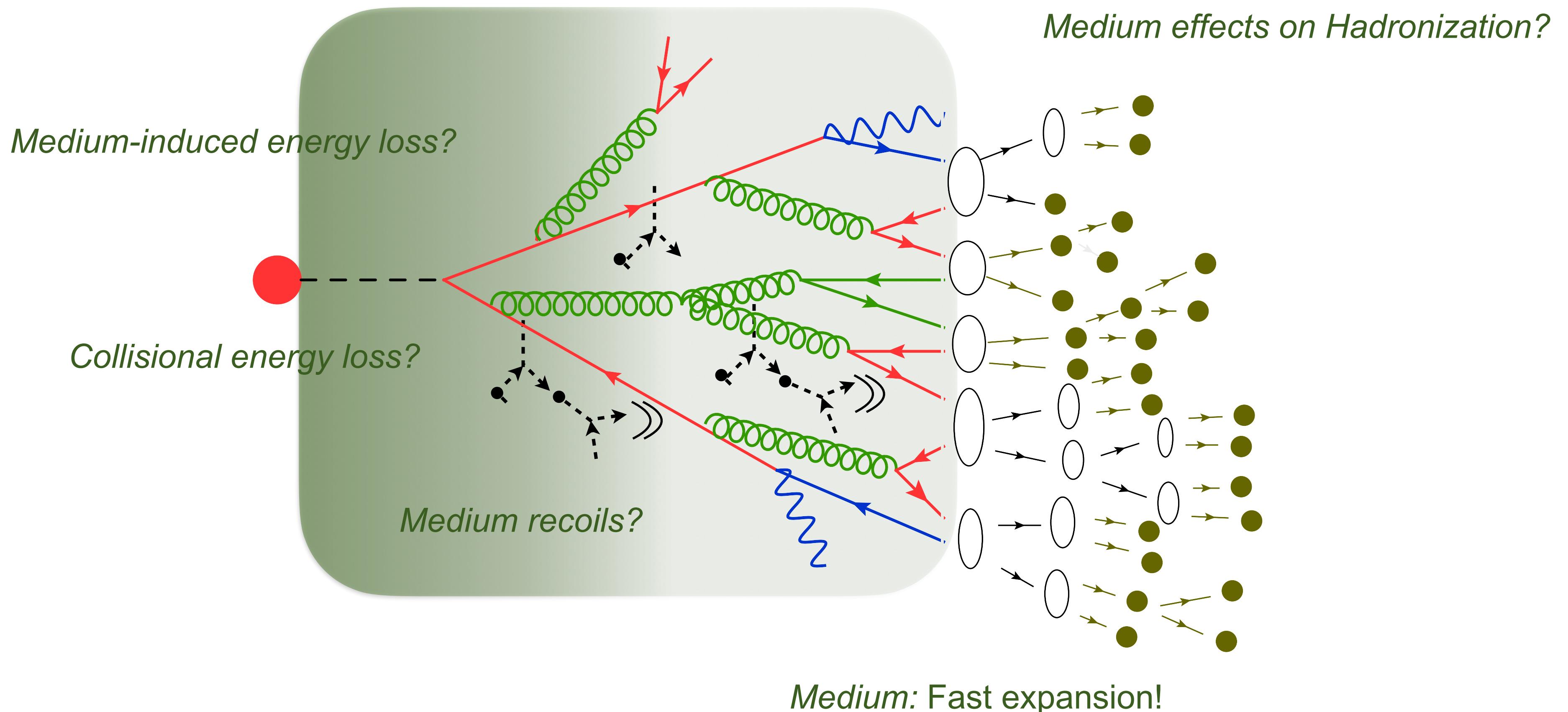
Consider different medium time-evolution scenarios:



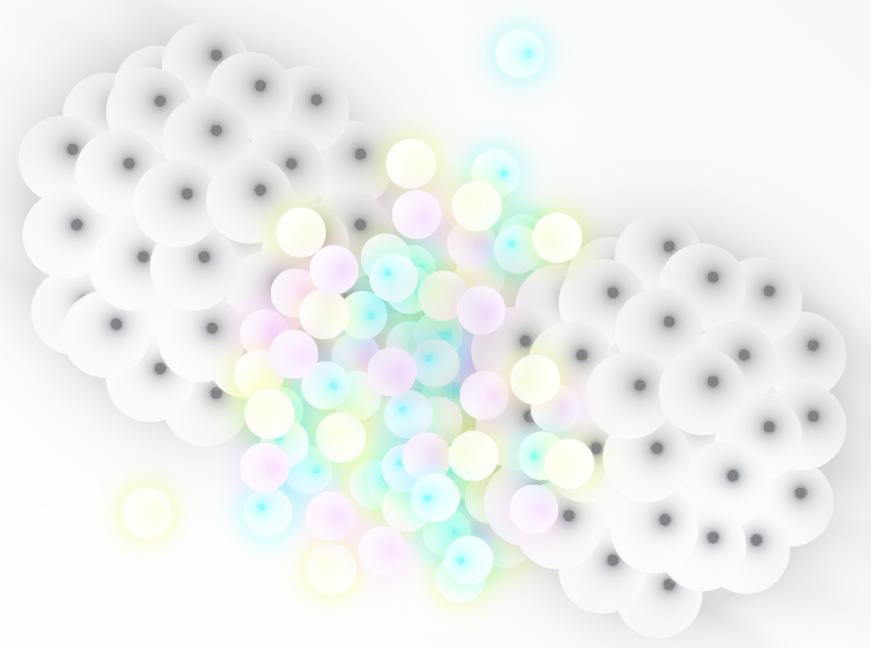
Jet Quenching II



- What happens to a jet inside of a hot and dense QCD matter?

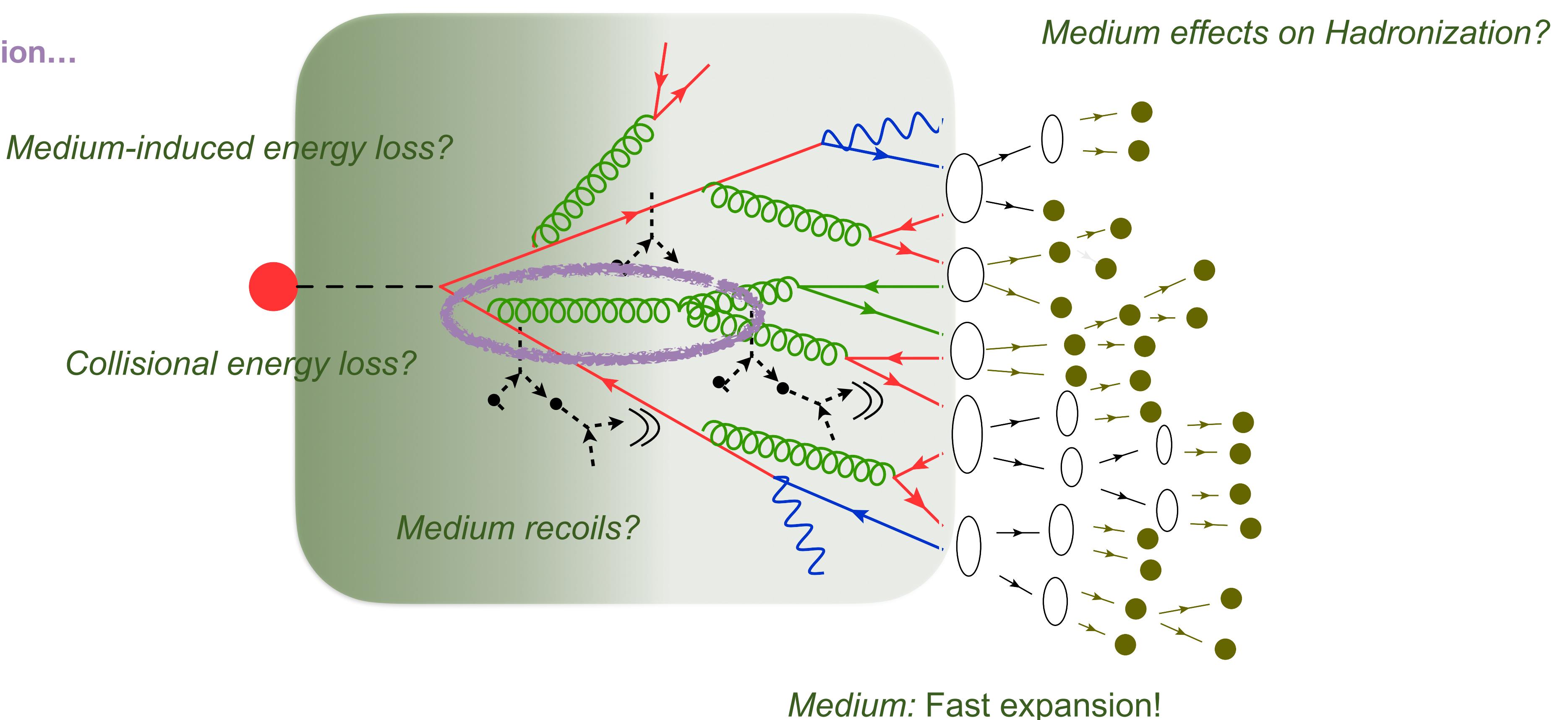


Jet Quenching II

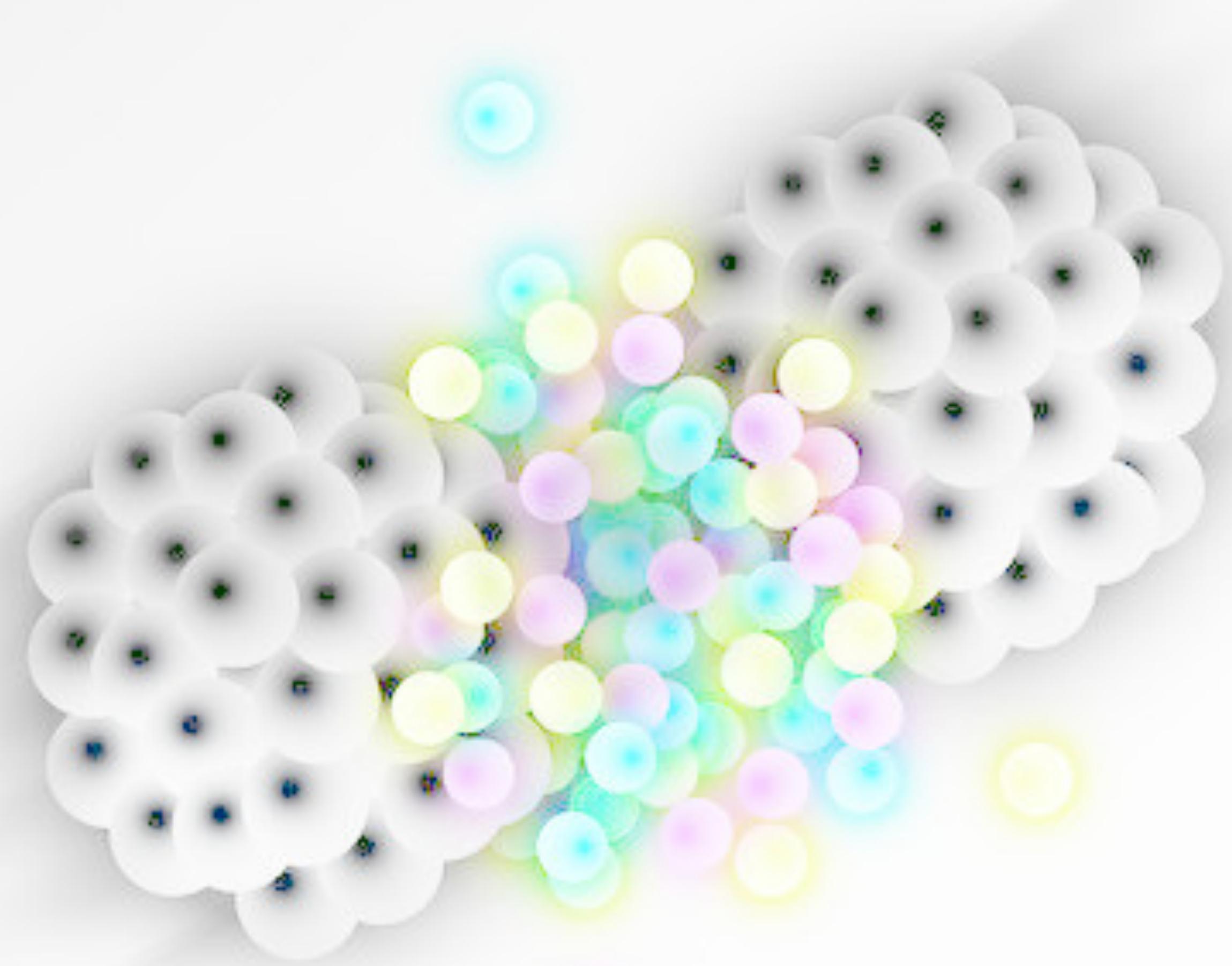


- What happens to a jet inside of a hot and dense QCD matter?

Beyond single gluon emission...

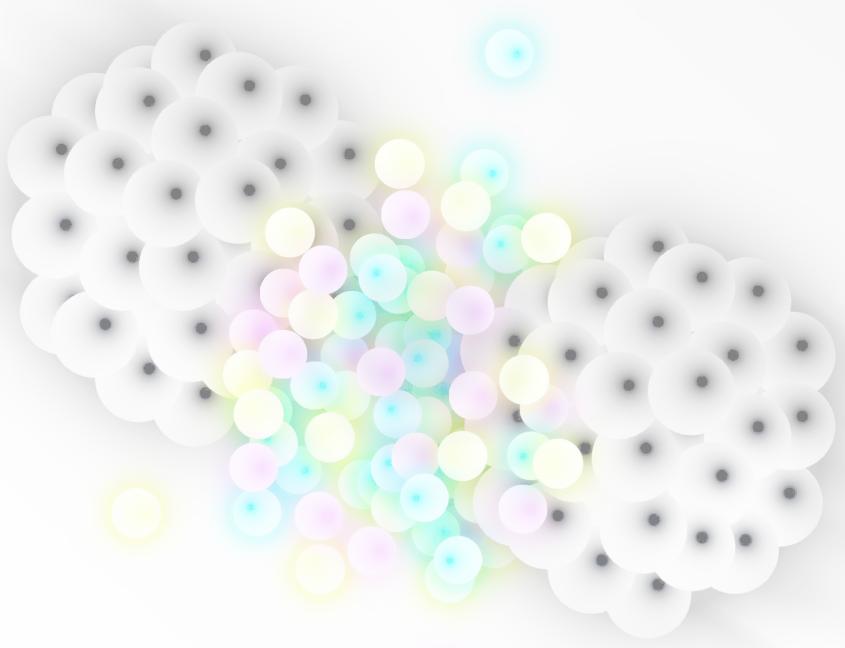


Jet Quenching

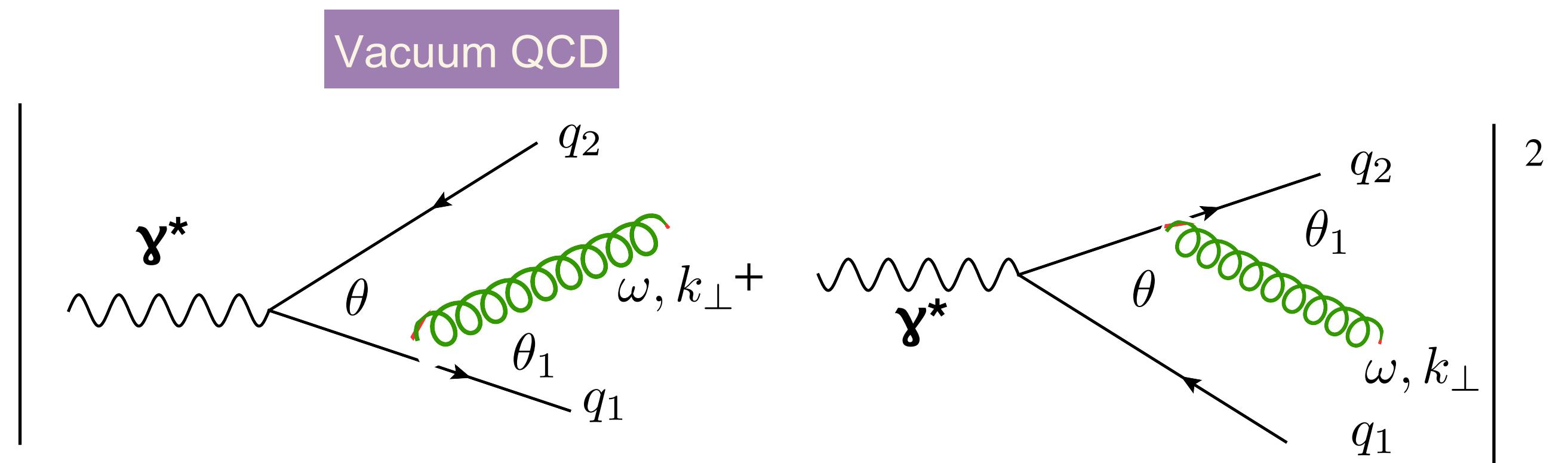


Multiple
emissions

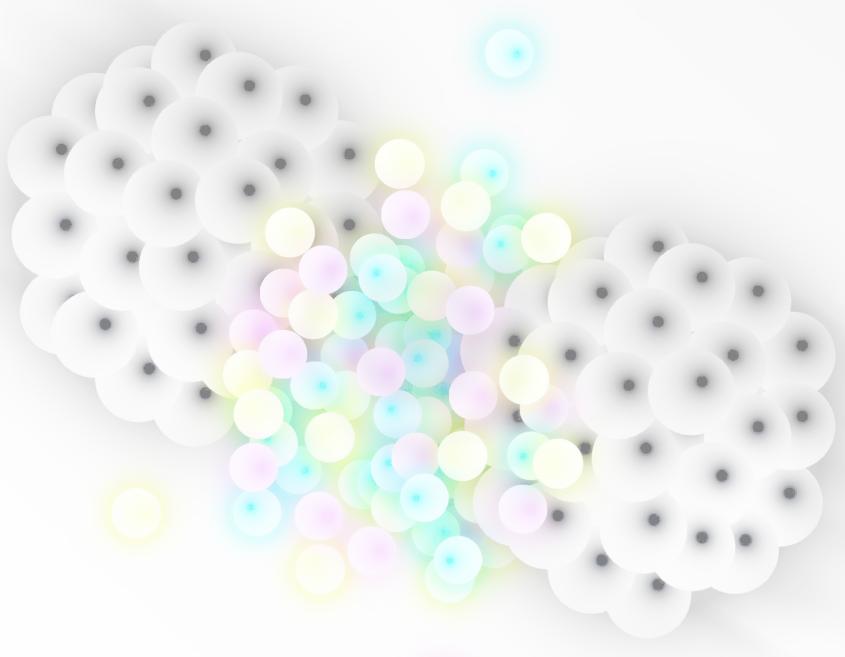
QCD Angular ordering



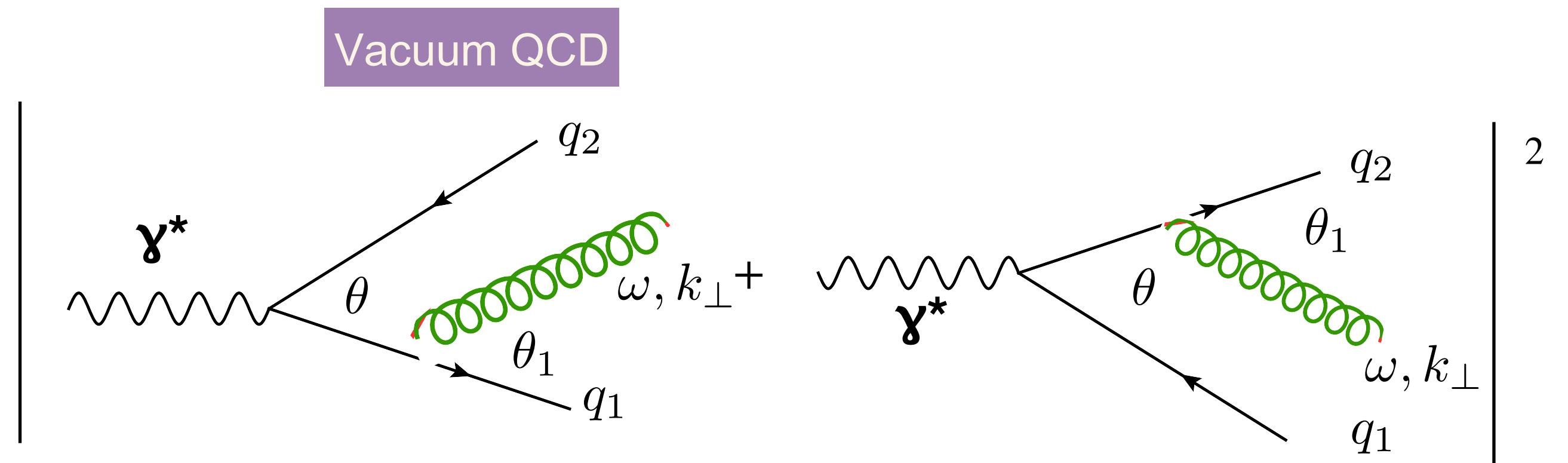
- QCD Antenna setup: emission from a qqbar pair:



QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

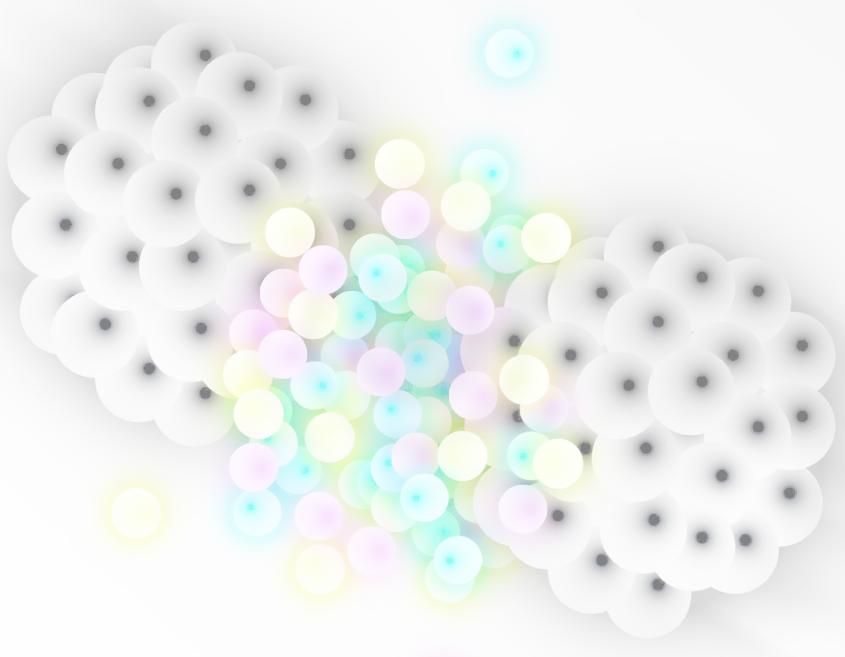


Probability of emitting “soft” (low-energy) gluons:

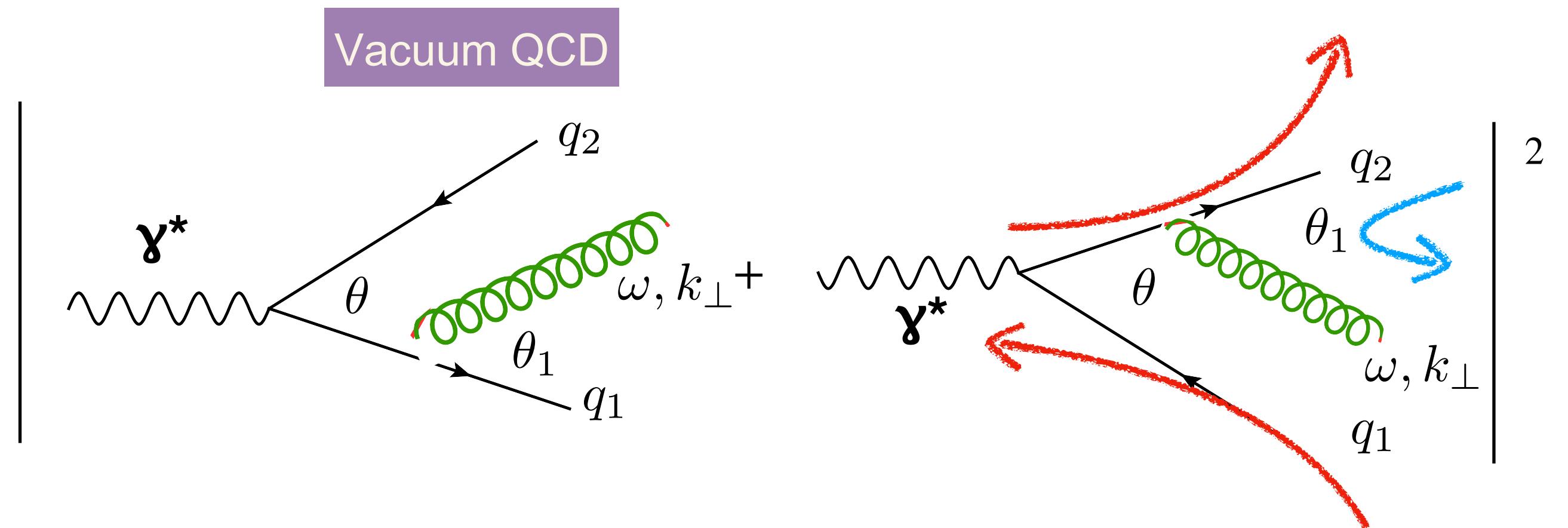
$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1 - \cos\theta} \Theta(\cos\theta_1 - \cos\theta)$$

QCD Angular ordering

QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

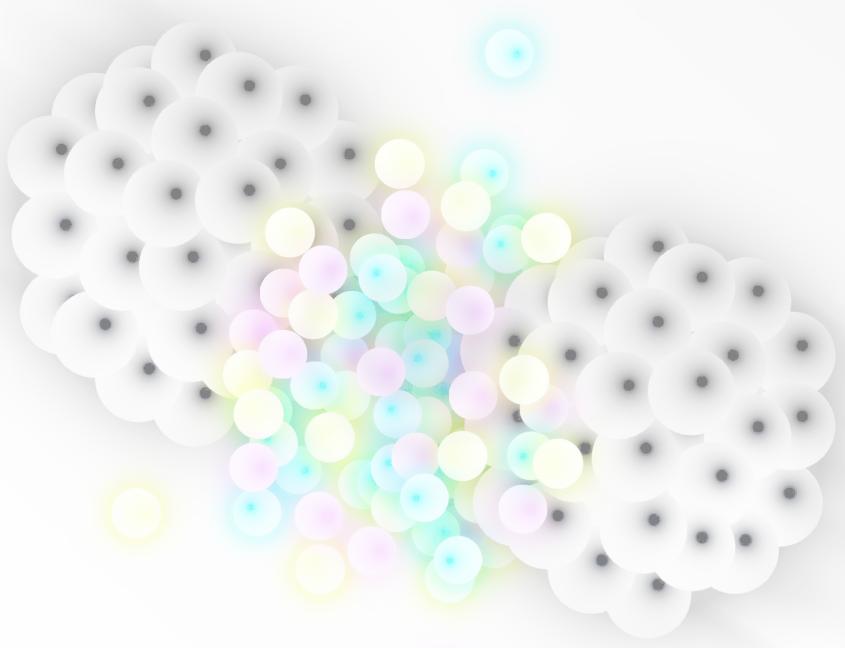


Probability of emitting “soft” (low-energy) gluons:

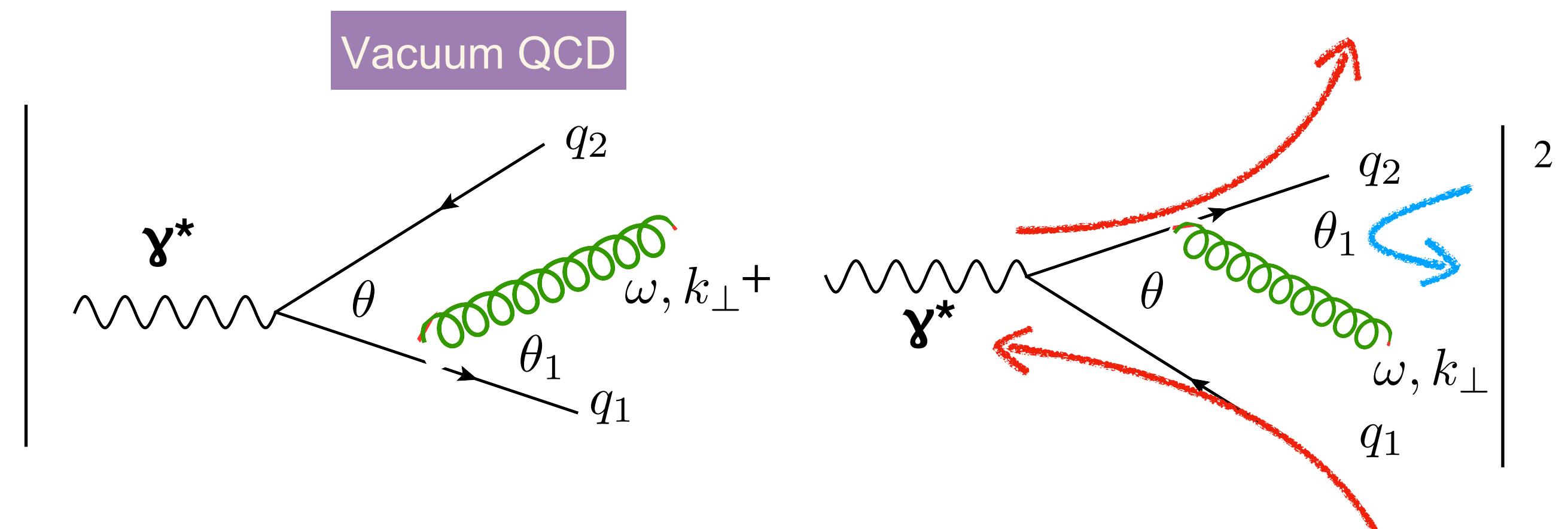
$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1 - \cos\theta} \Theta(\cos\theta_1 - \cos\theta)$$

QCD Angular ordering

QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

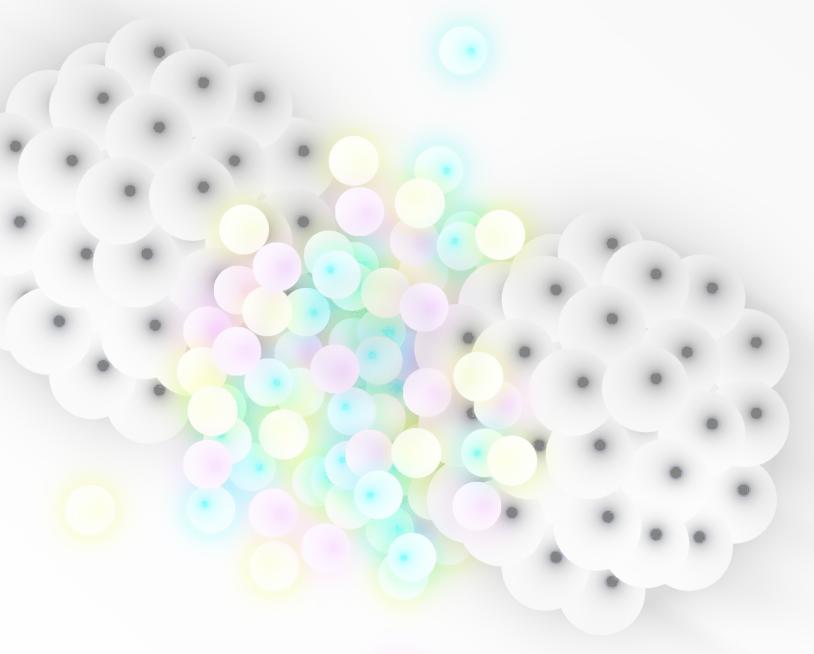


Probability of emitting “soft” (low-energy) gluons:

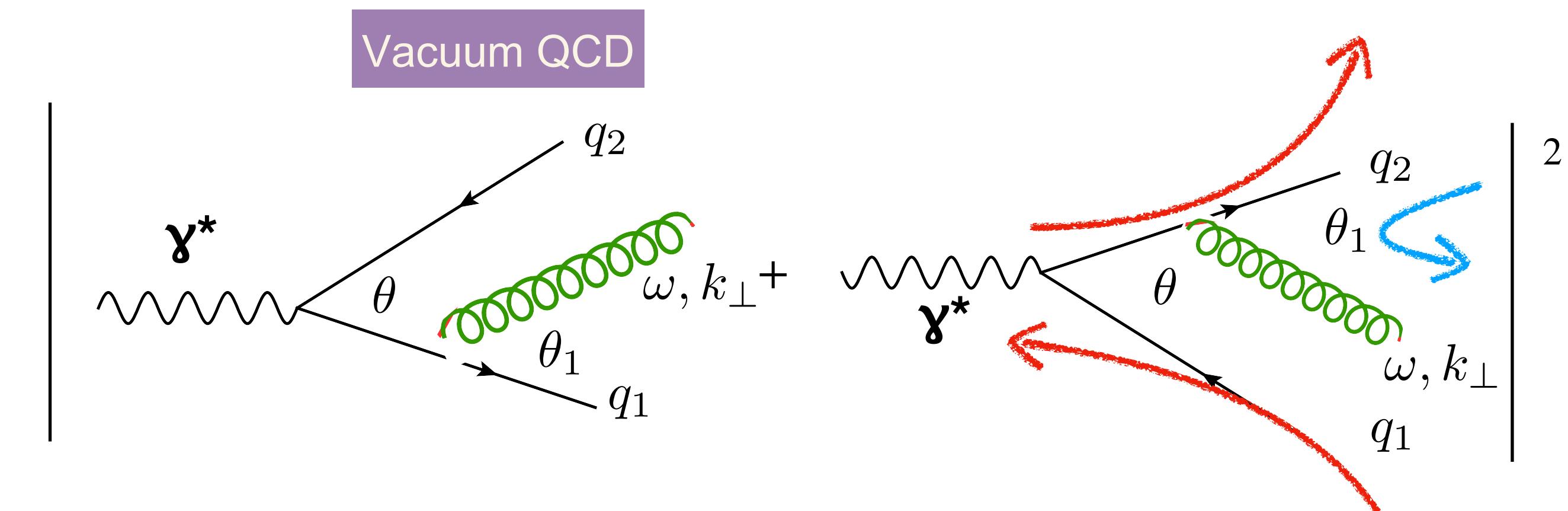
$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1 - \cos\theta} \Theta(\cos\theta_1 - \cos\theta)$$

QCD Angular ordering

QCD Angular ordering

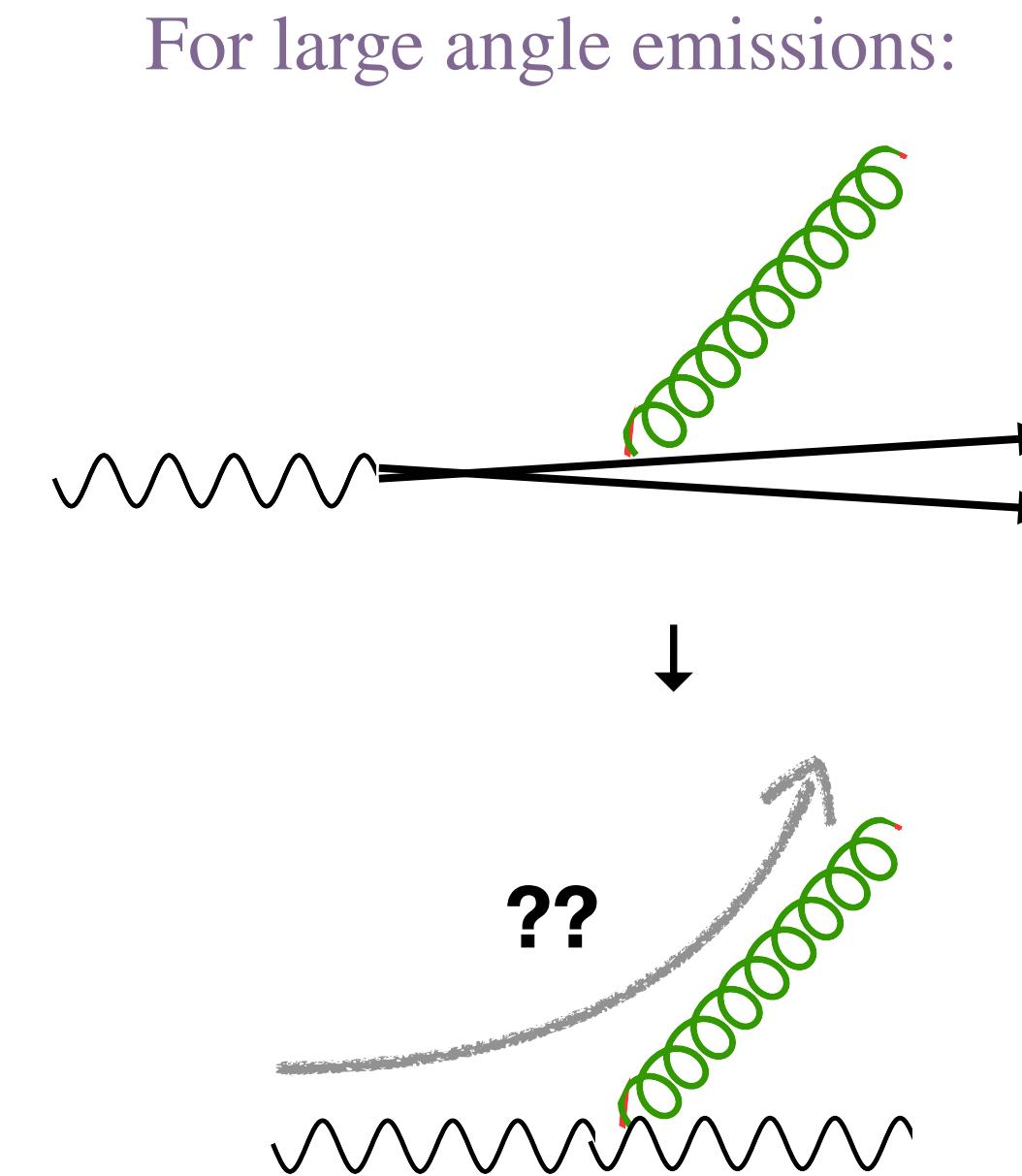


- QCD Antenna setup: emission from a qqbar pair:

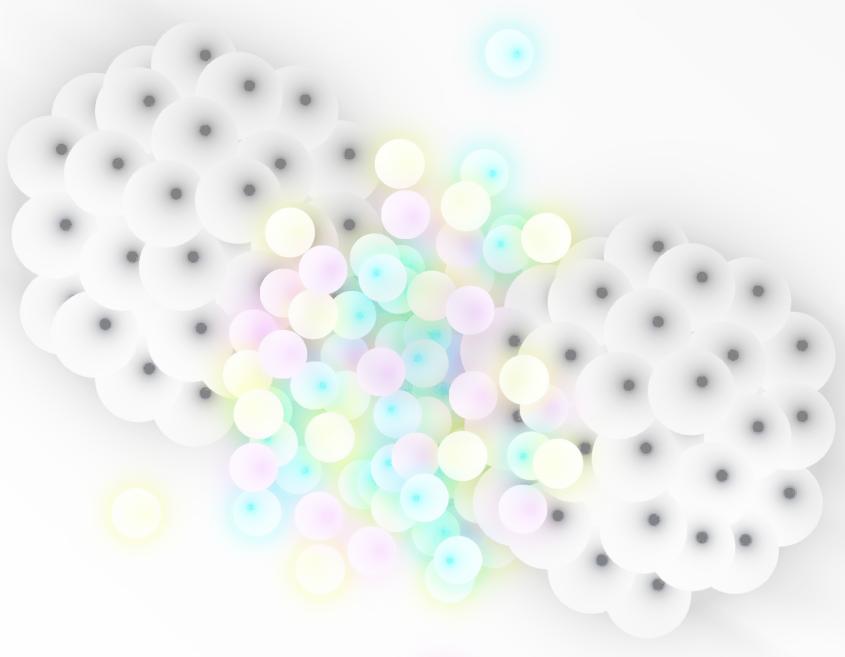


$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} \Theta(\cos \theta_1 - \cos \theta)$$

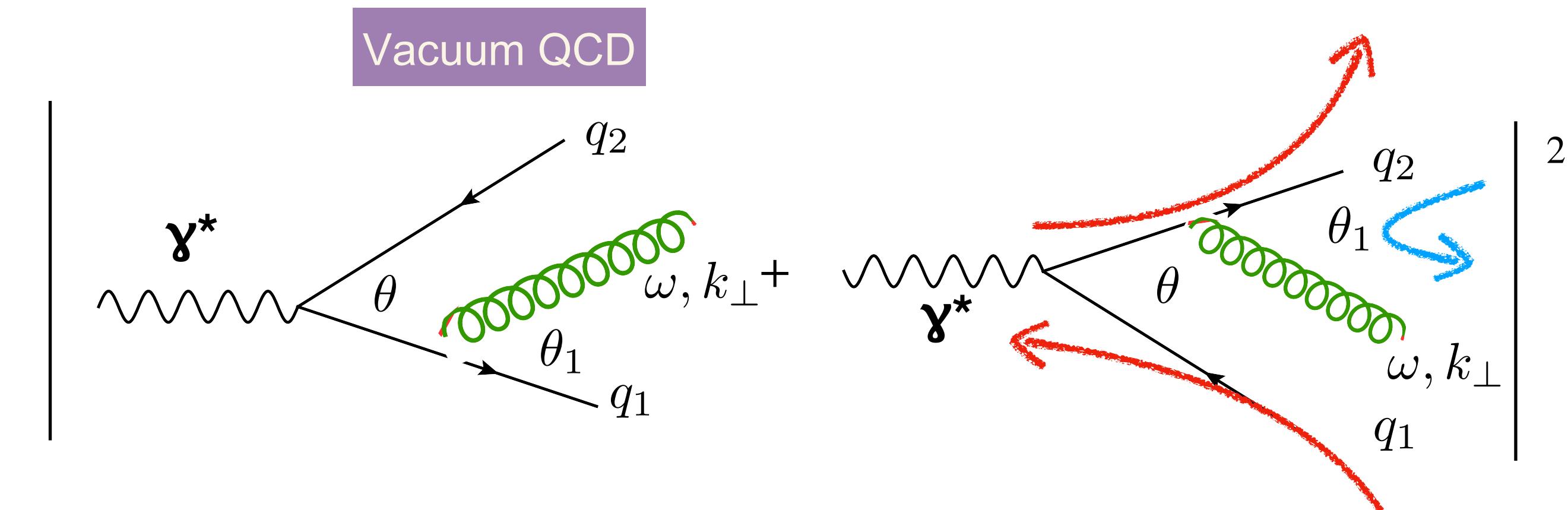
QCD Angular ordering



QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

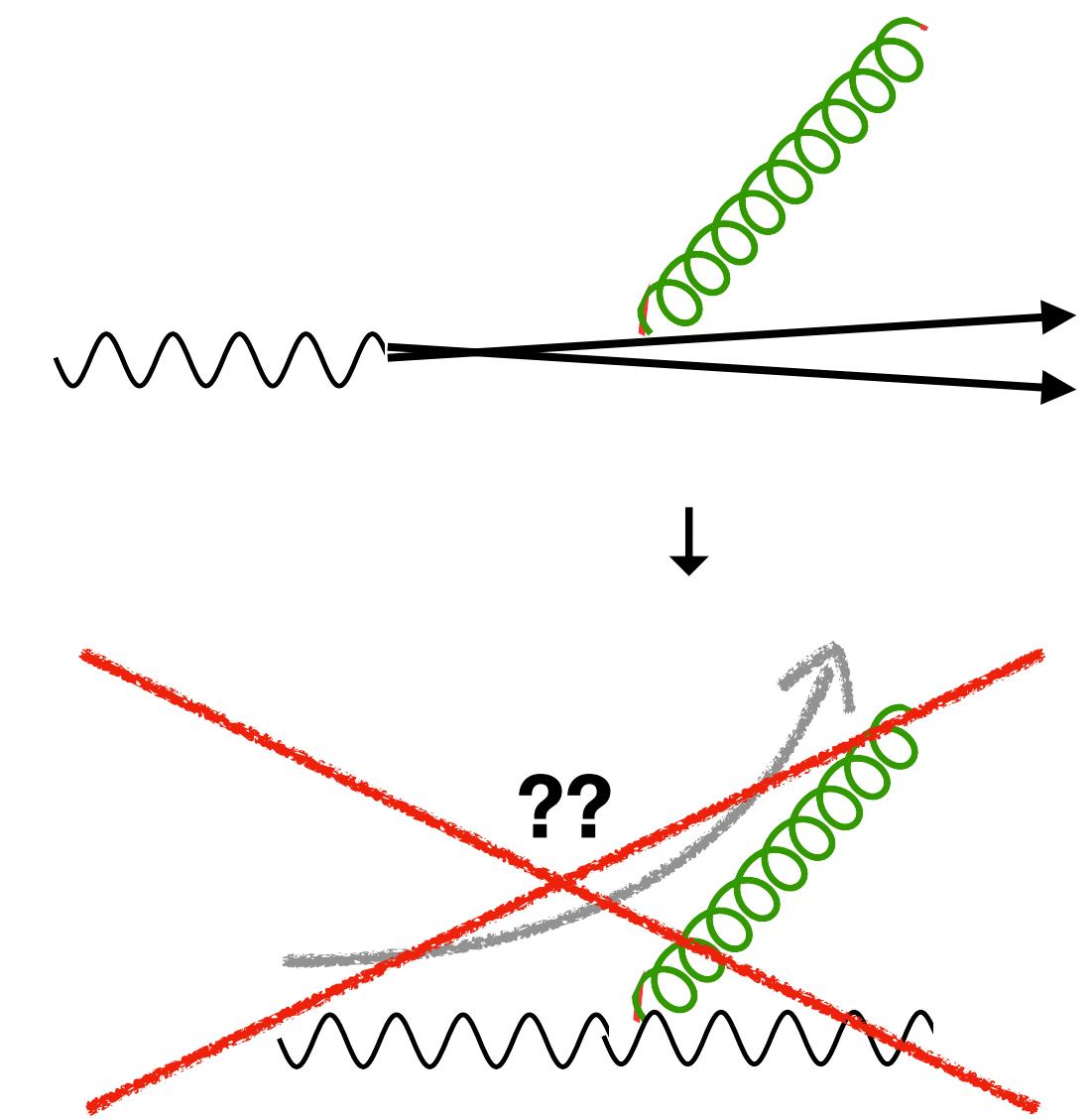


Probability of emitting “soft” (low-energy) gluons:

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1 - \cos\theta} \Theta(\cos\theta_1 - \cos\theta)$$

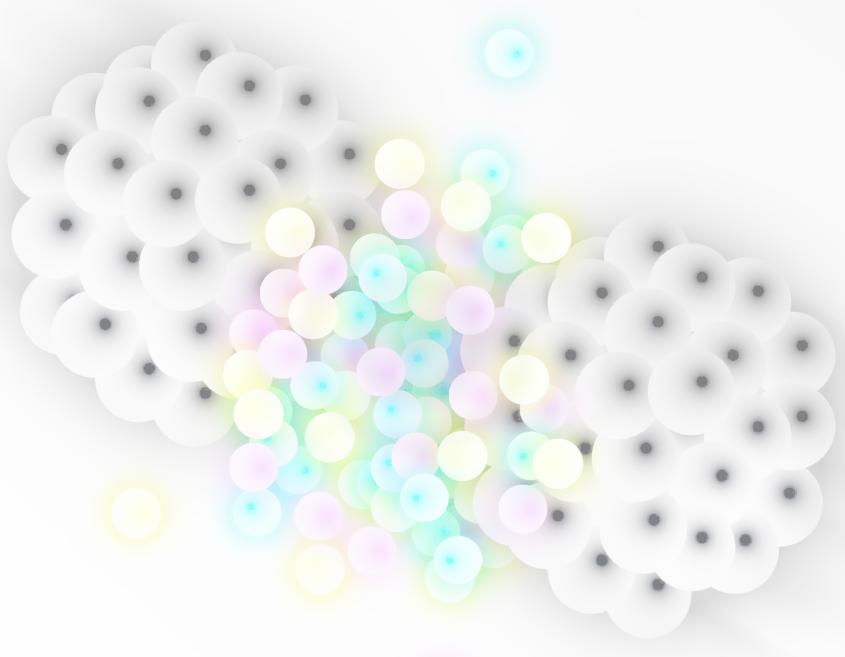
QCD Angular ordering

For large angle emissions:



Photons do not carry colour charge...

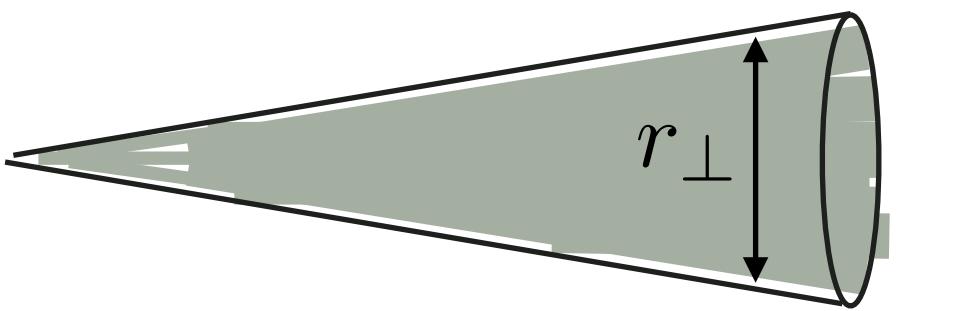
QCD Angular ordering



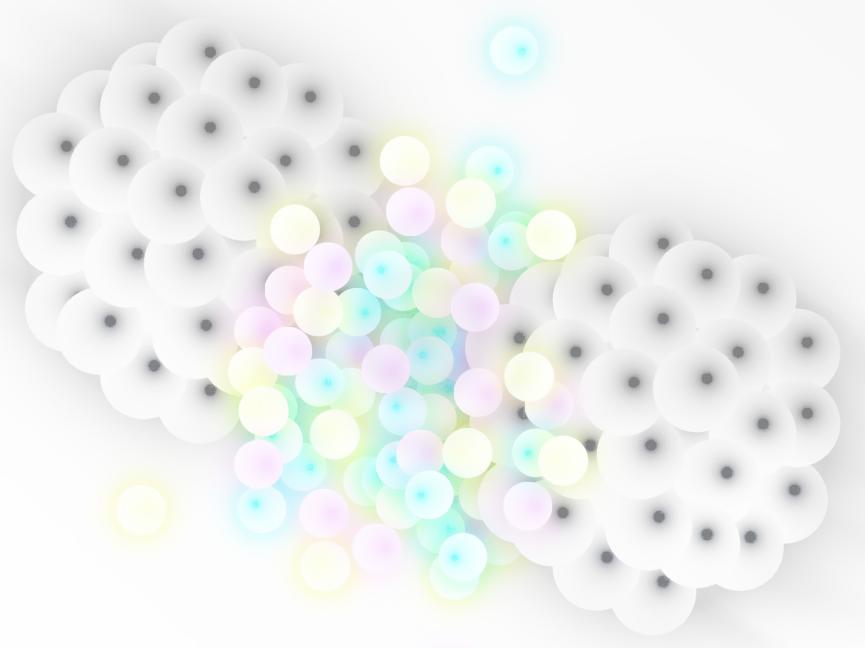
- QCD Antenna setup: emission from a qqbar pair:

Vacuum QCD

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin\theta d\theta}{1 - \cos\theta} \Theta(\cos\theta_1 - \cos\theta)$$



QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

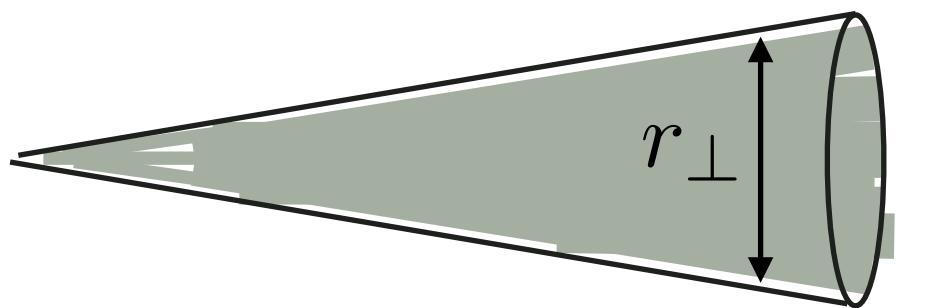
Vacuum QCD

\implies

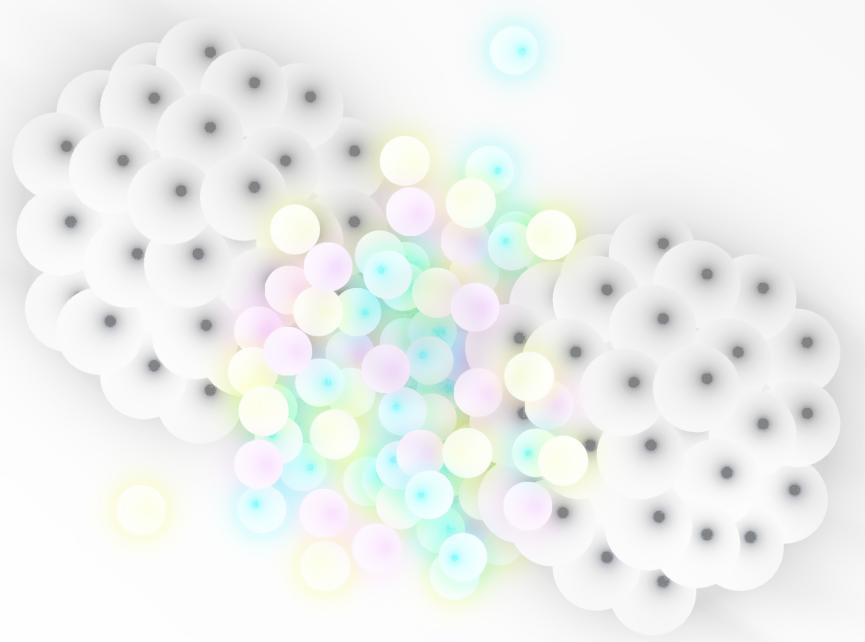
In-medium QCD

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} \Theta(\cos \theta_1 - \cos \theta)$$

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} [\Theta(\cos \theta_1 - \cos \theta) +$$



QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

$$\Delta_{med} \approx 1 - e^{-\frac{1}{12} Q_s^2 r_\perp^2}$$

Vacuum QCD

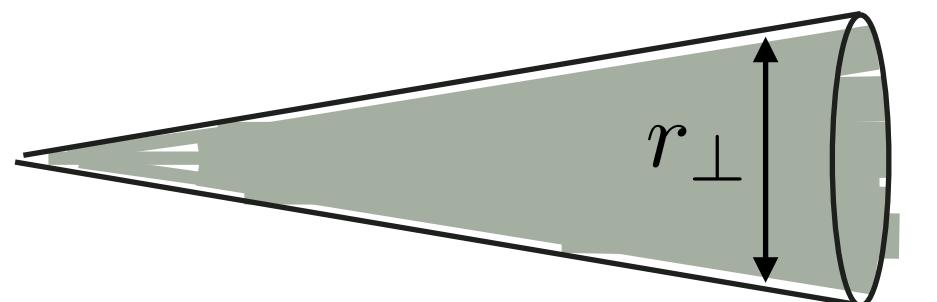
\implies

In-medium QCD

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} \Theta(\cos \theta_1 - \cos \theta)$$

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} [\Theta(\cos \theta_1 - \cos \theta) + \underline{\Delta_{med} \Theta(\cos \theta - \cos \theta_1)}]$$

QCD Anti-Angular ordering



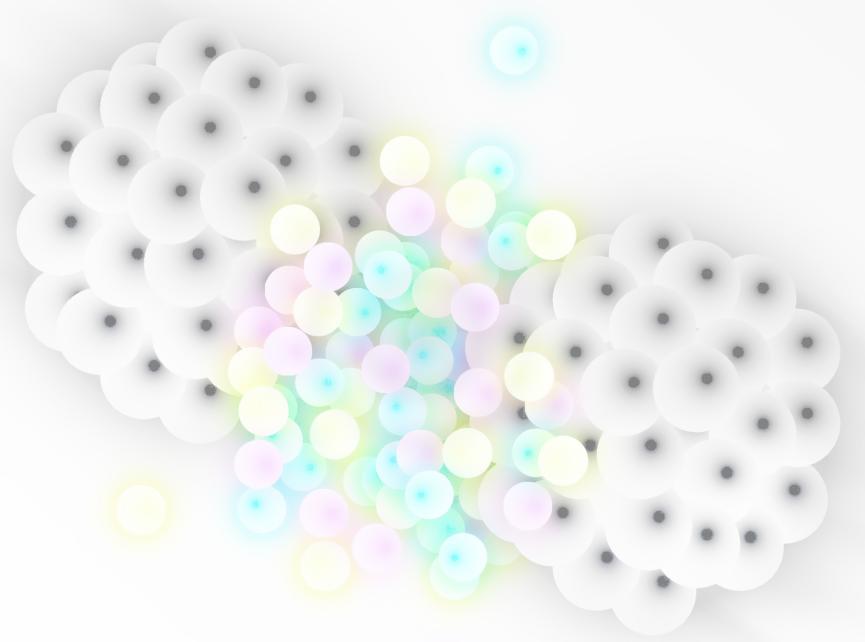
Antenna Transverse resolution:

$$r_\perp = \theta L$$

Medium Transverse Scale:

$$Q_s^{-1} = \sqrt{(\hat{q}^\perp L)^{-1}}$$

QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

$$\Delta_{med} \approx 1 - e^{-\frac{1}{12} Q_s^2 r_\perp^2}$$

Vacuum QCD



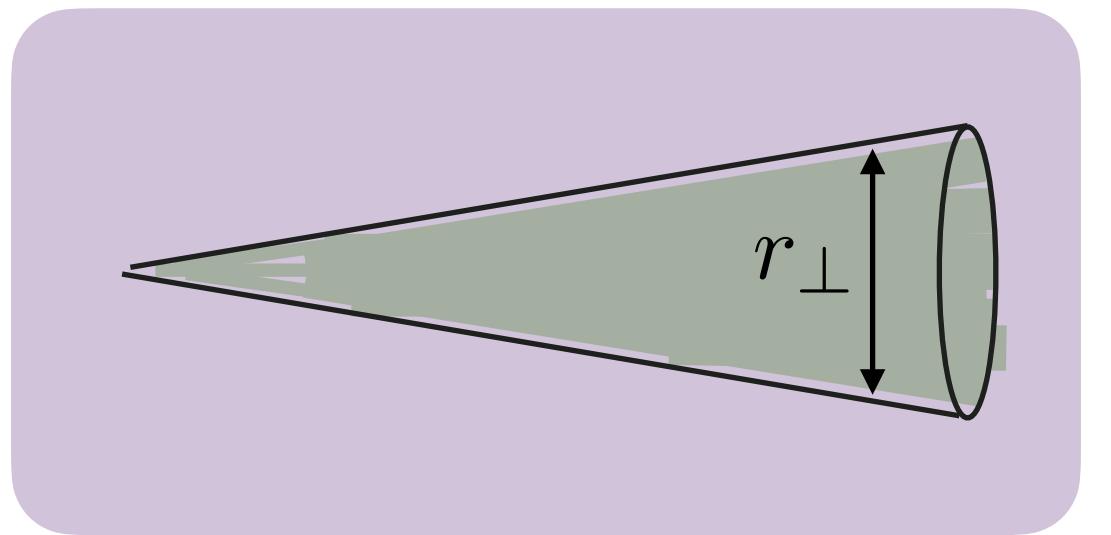
In-medium QCD

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} \Theta(\cos \theta_1 - \cos \theta)$$

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} [\Theta(\cos \theta_1 - \cos \theta) + \underline{\Delta_{med} \Theta(\cos \theta - \cos \theta_1)}]$$

QCD Anti-Angular ordering

Angular ordering



Antenna Transverse resolution:

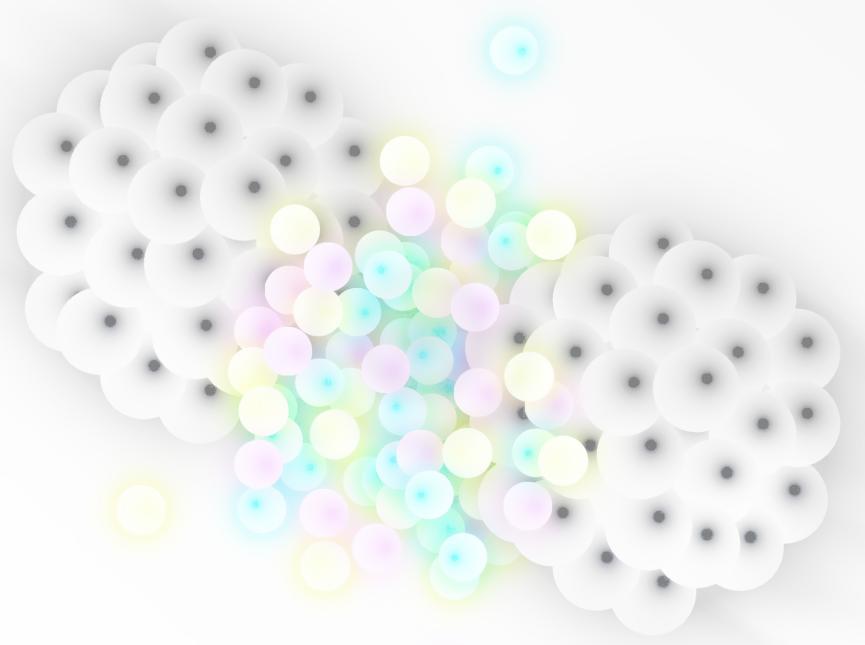
$$r_\perp = \theta L$$

Medium Transverse Scale:

$$Q_s^{-1} = \sqrt{(\hat{q}^\perp L)^{-1}}$$

$$\Delta_{med} \rightarrow 0$$

QCD Angular ordering



- QCD Antenna setup: emission from a qqbar pair:

$$\Delta_{med} \approx 1 - e^{-\frac{1}{12} Q_s^2 r_\perp^2}$$

Vacuum QCD

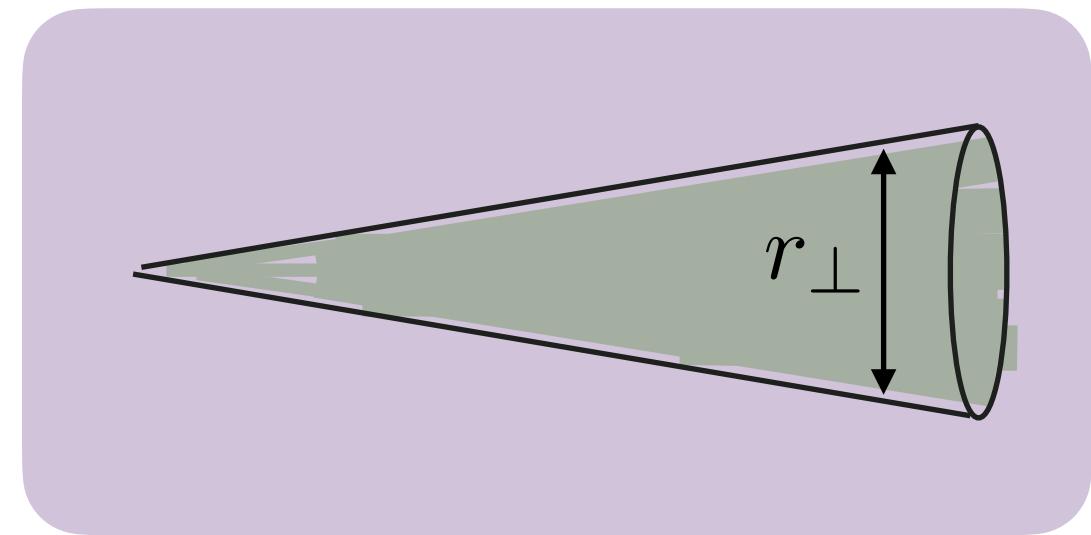


In-medium QCD

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} \Theta(\cos \theta_1 - \cos \theta)$$

$$dN_q^{\omega \rightarrow 0} \sim \alpha_s C_R \frac{d\omega}{\omega} \frac{\sin \theta d\theta}{1 - \cos \theta} [\Theta(\cos \theta_1 - \cos \theta) + \underline{\Delta_{med} \Theta(\cos \theta - \cos \theta_1)}]$$

Angular ordering



$$\Delta_{med} \rightarrow 0$$

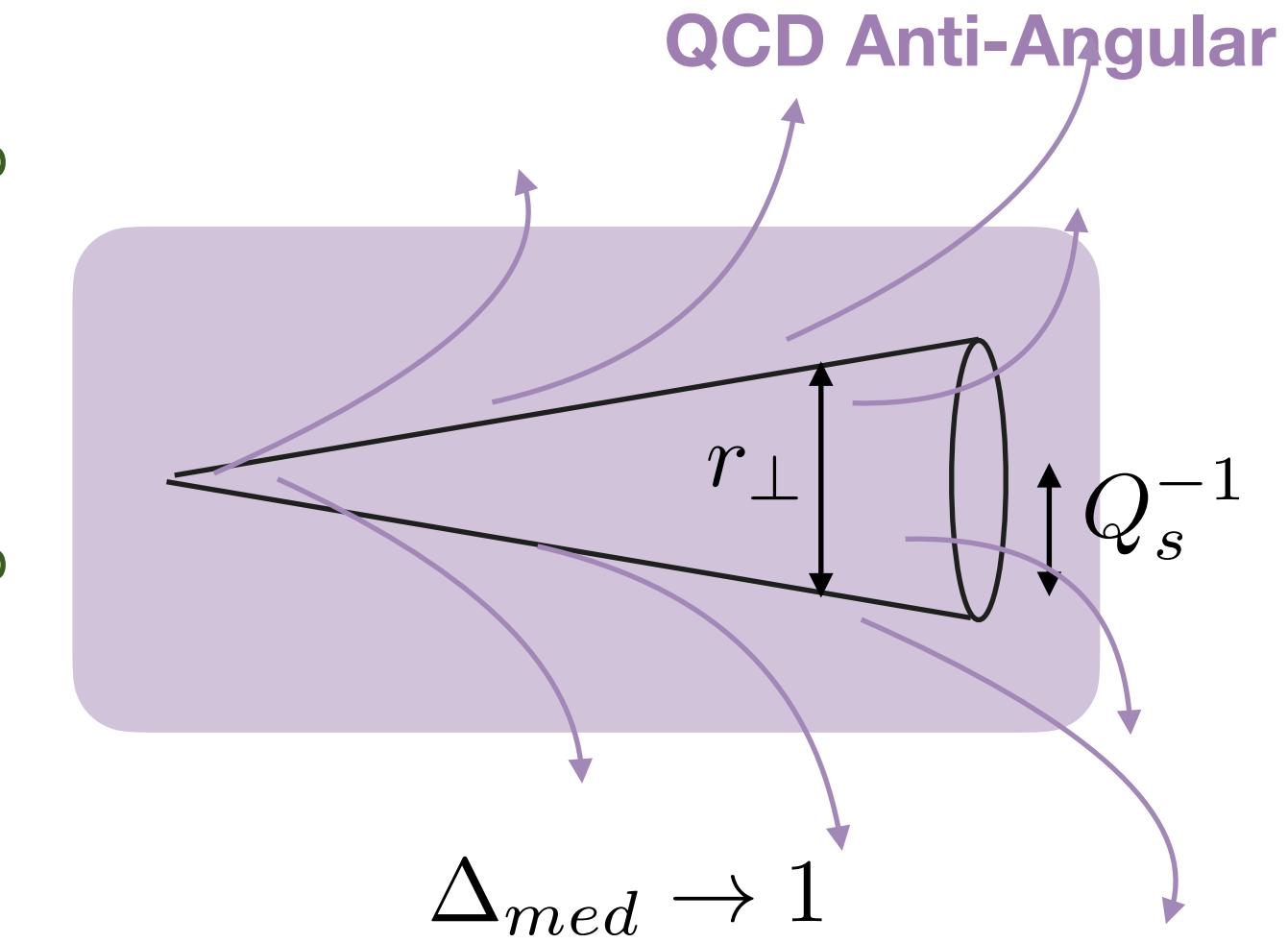
Antenna Transverse resolution:

$$r_\perp = \theta L$$

Medium Transverse Scale:

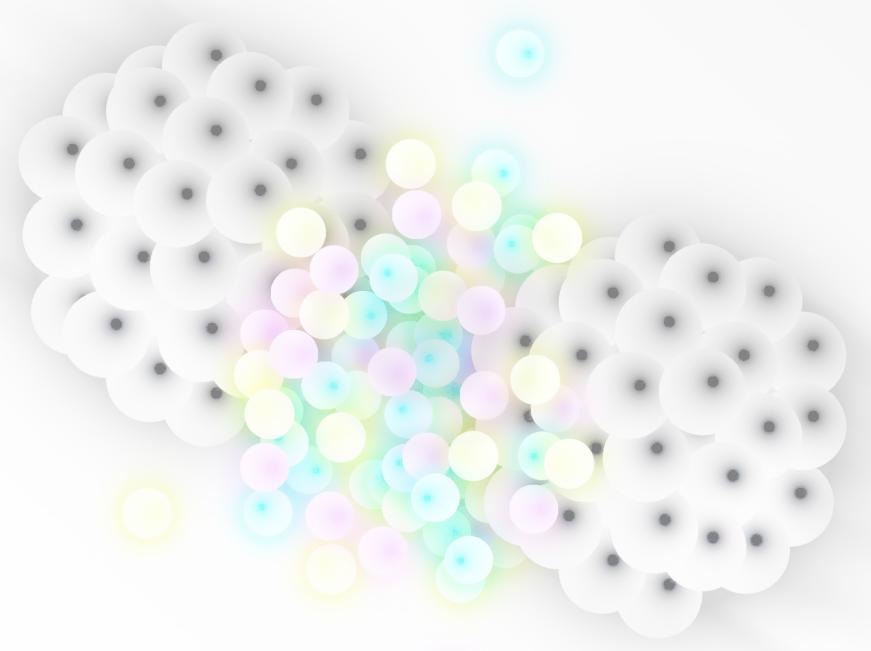
$$Q_s^{-1} = \sqrt{(\vec{q}^\perp L)^{-1}}$$

Anti-Angular ordering



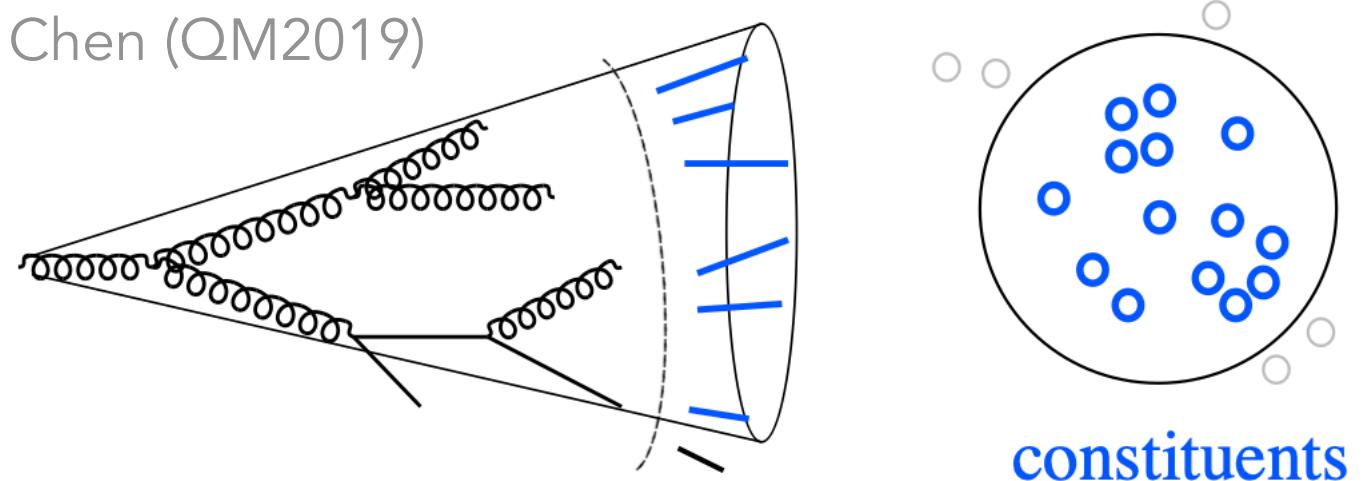
$$\Delta_{med} \rightarrow 1$$

Jet substructure



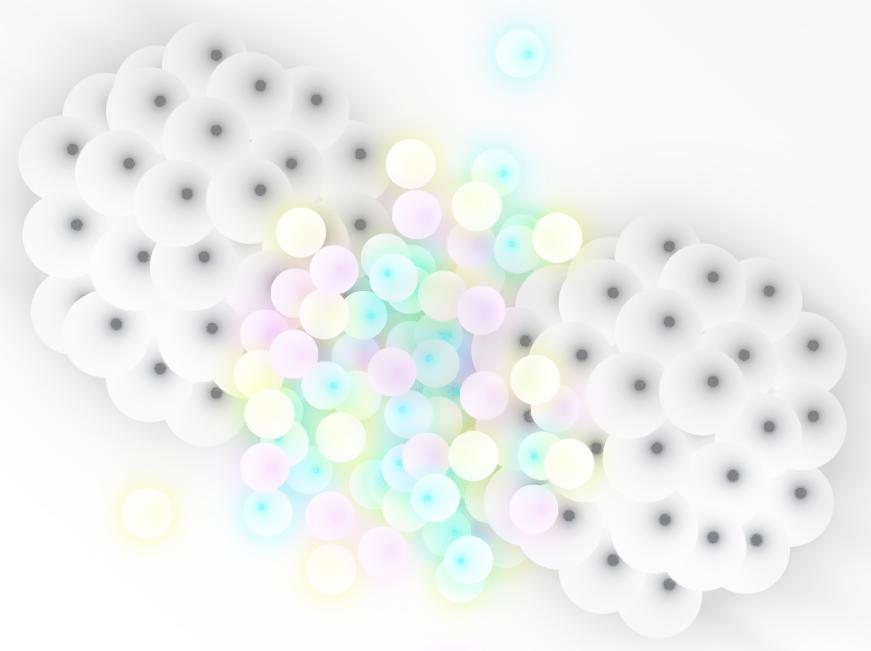
- To look for jet (de)coherence, single particle measurements will not suffice...
 - Need jet substructure!
- What is a jet?

[Adapted from Yi Chen (QM2019)]



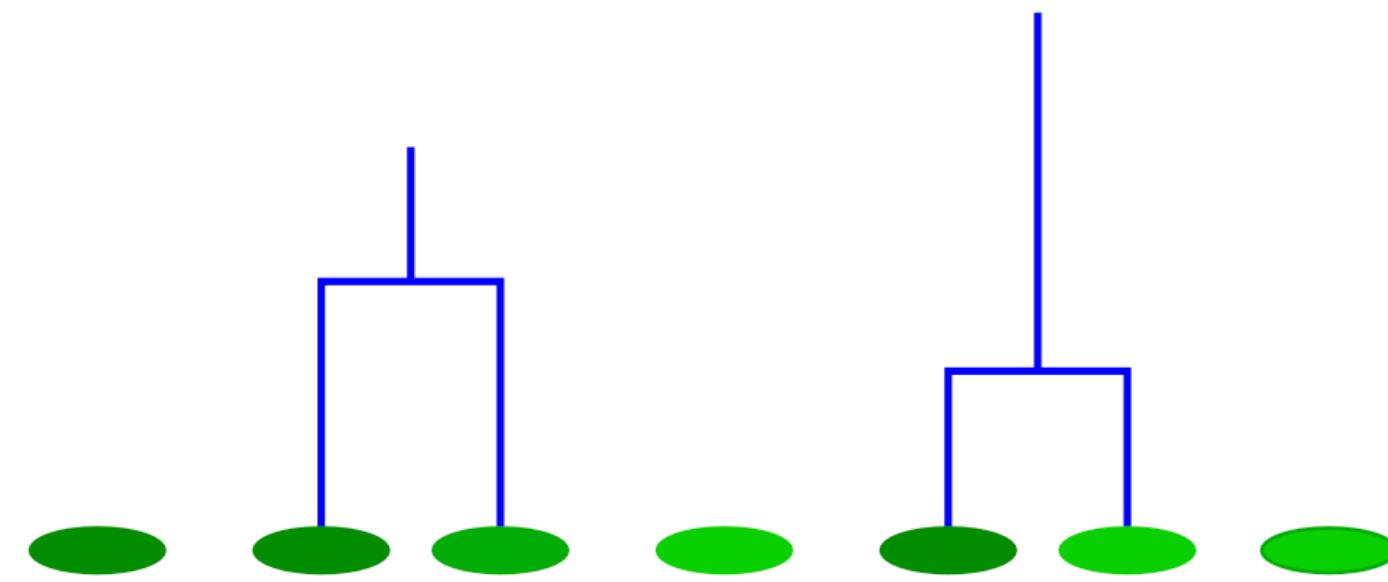
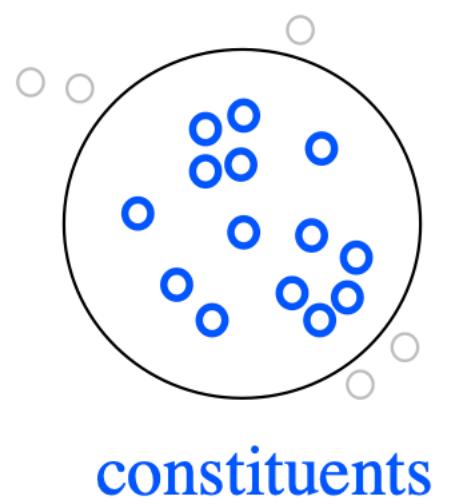
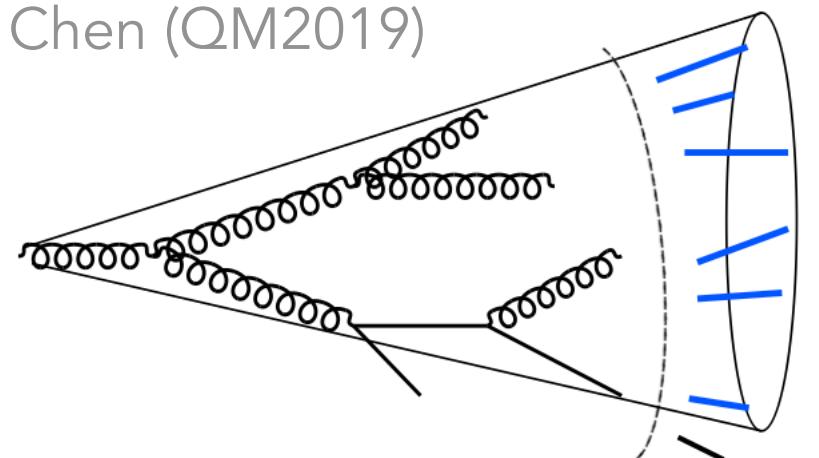
[Adapted from K. Zapp (2021)]

Jet substructure



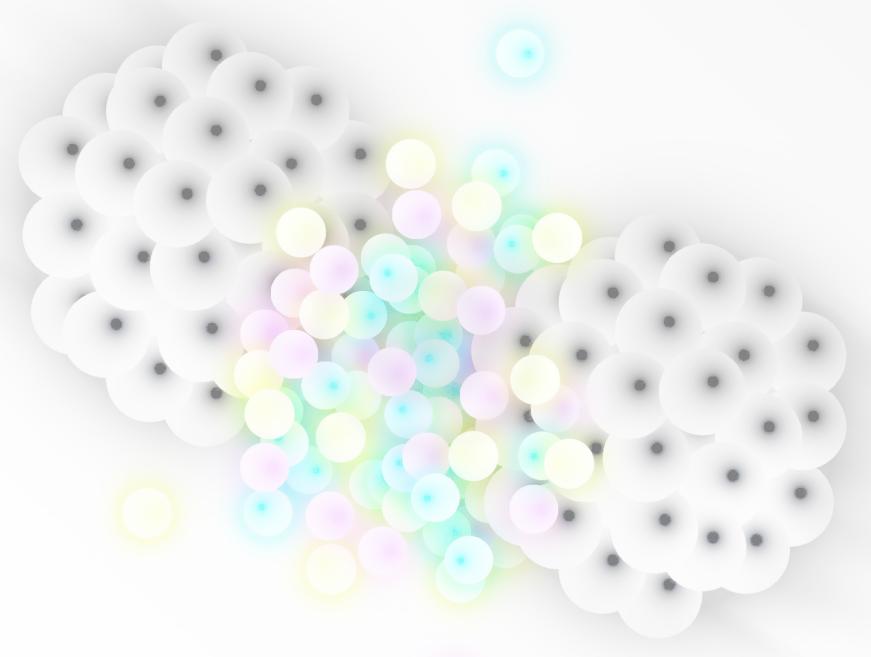
- To look for jet (de)coherence, single particle measurements will not suffice...
 - Need jet substructure!
- What is a jet?

[Adapted from Yi Chen (QM2019)]



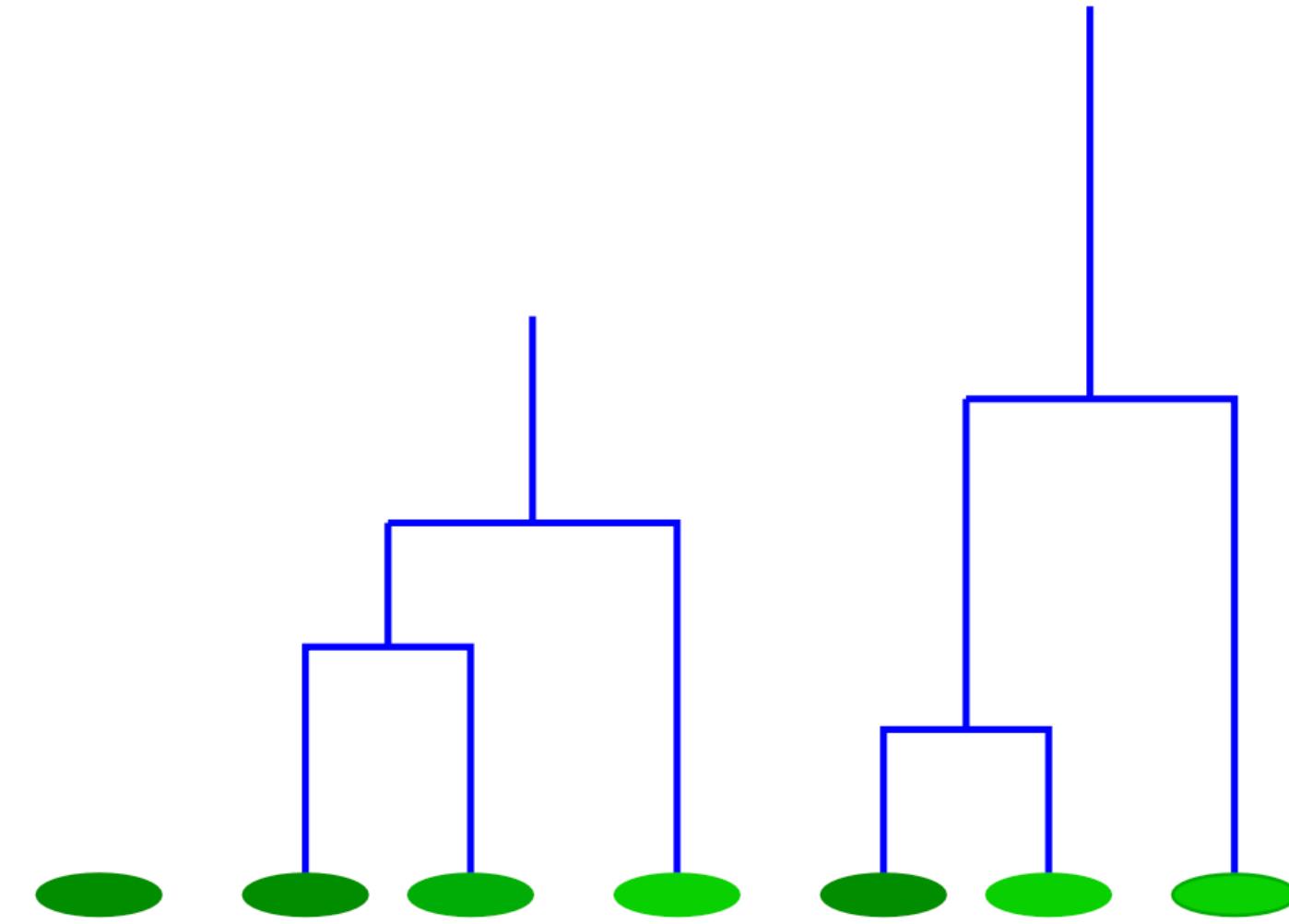
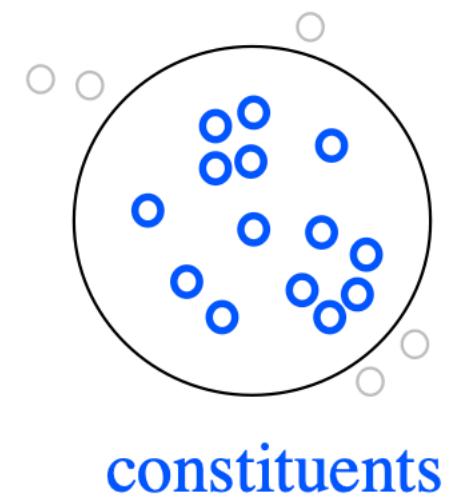
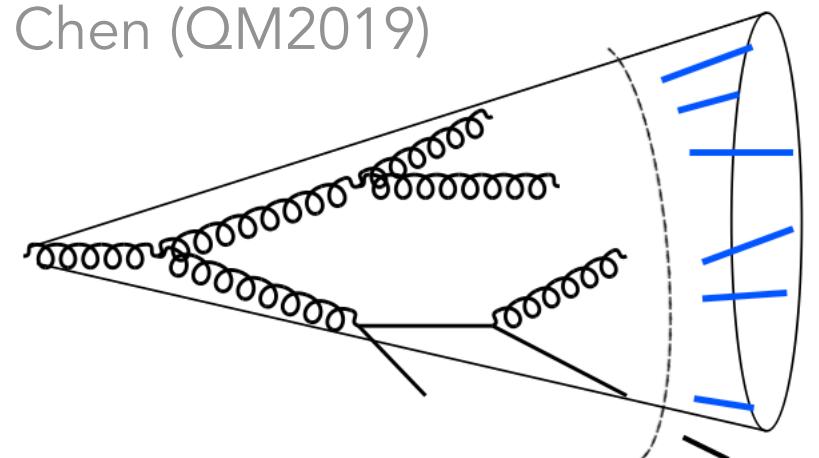
[Adapted from K. Zapp (2021)]

Jet substructure



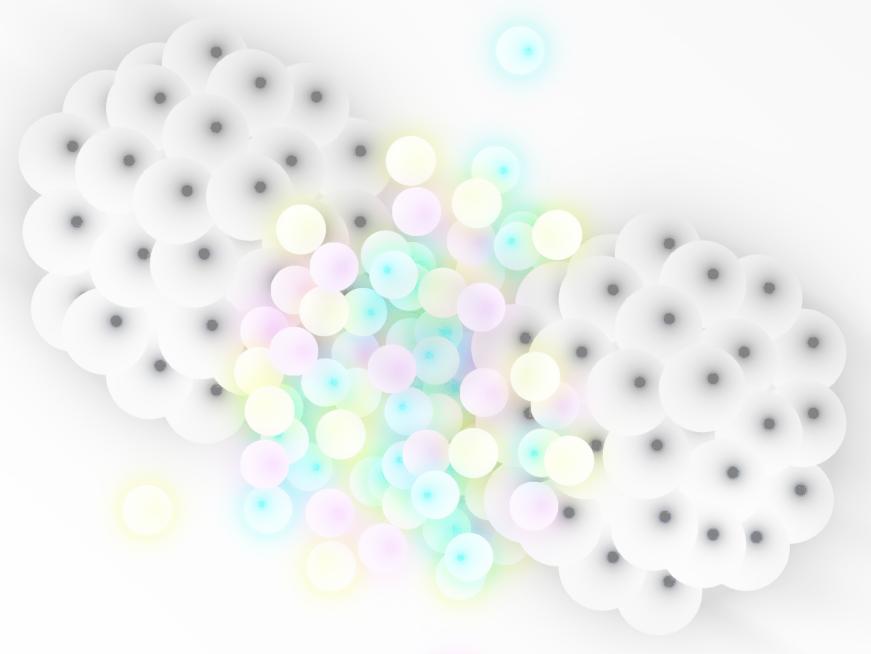
- To look for jet (de)coherence, single particle measurements will not suffice...
 - Need jet substructure!
- What is a jet?

[Adapted from Yi Chen (QM2019)]



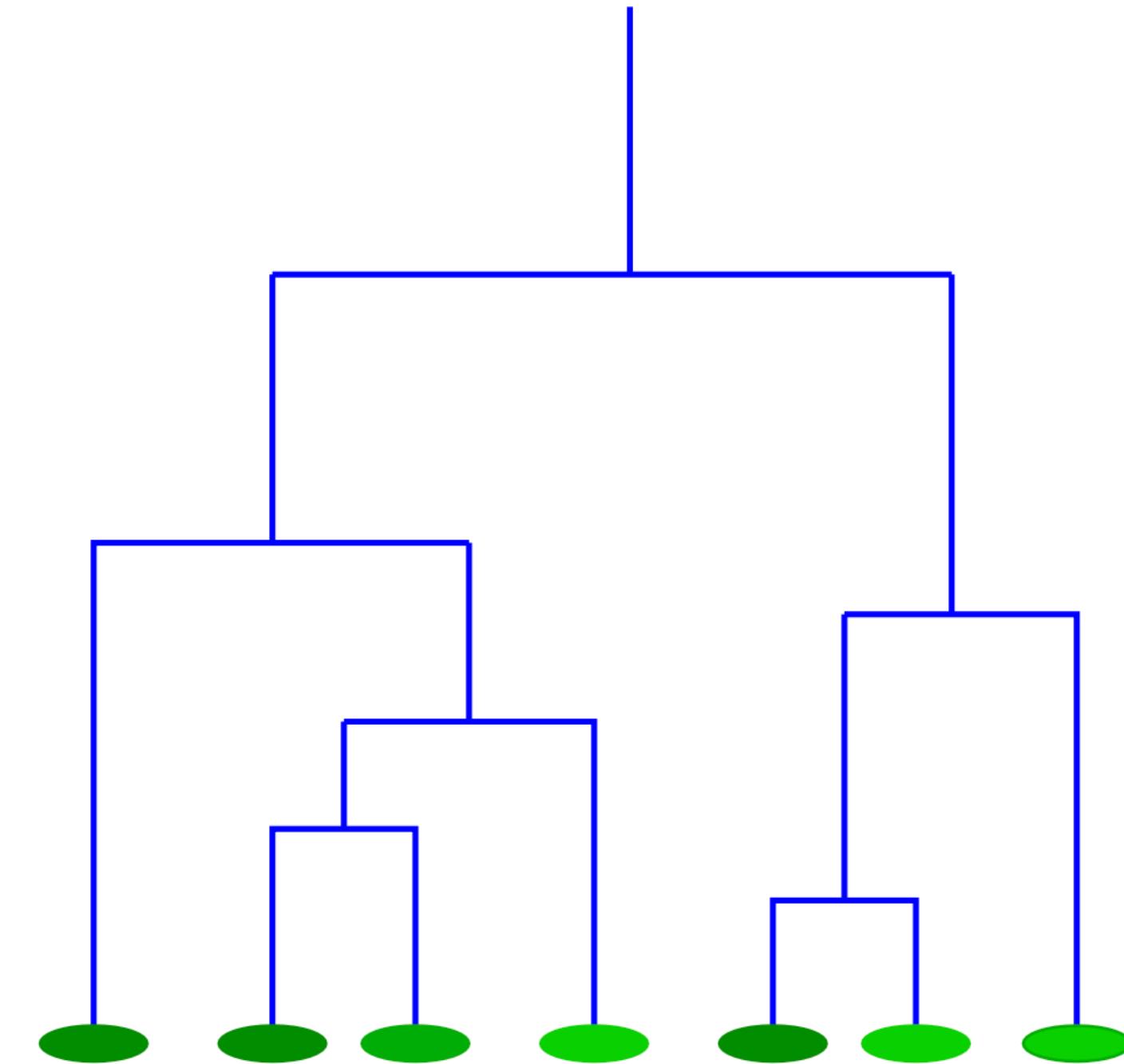
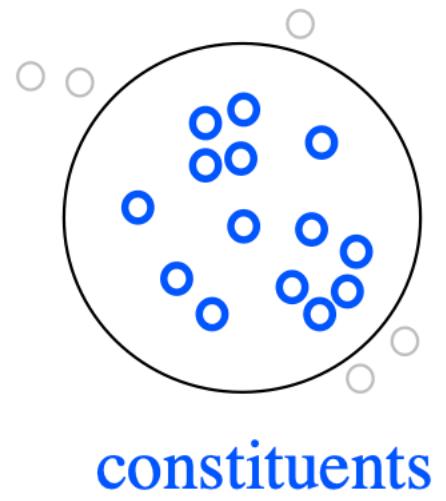
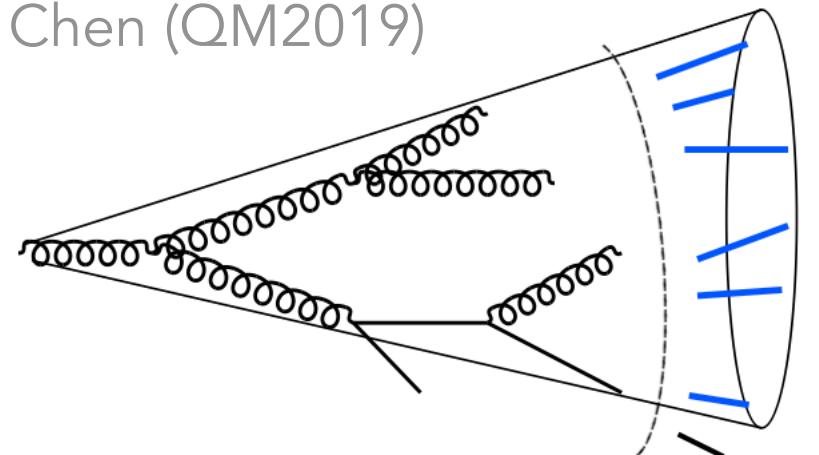
[Adapted from K. Zapp (2021)]

Jet substructure



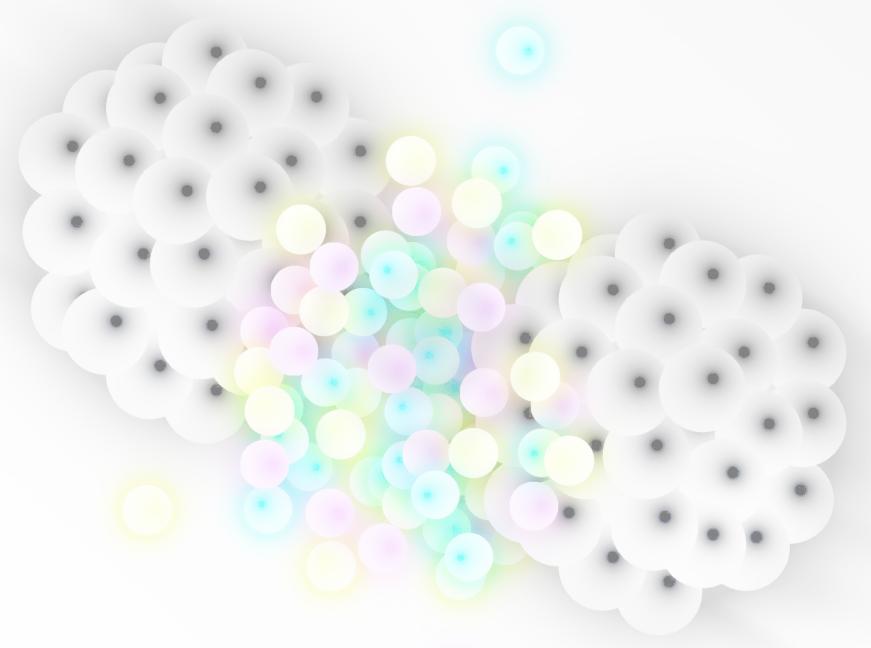
- To look for jet (de)coherence, single particle measurements will not suffice...
 - Need jet substructure!
- What is a jet?

[Adapted from Yi Chen (QM2019)]



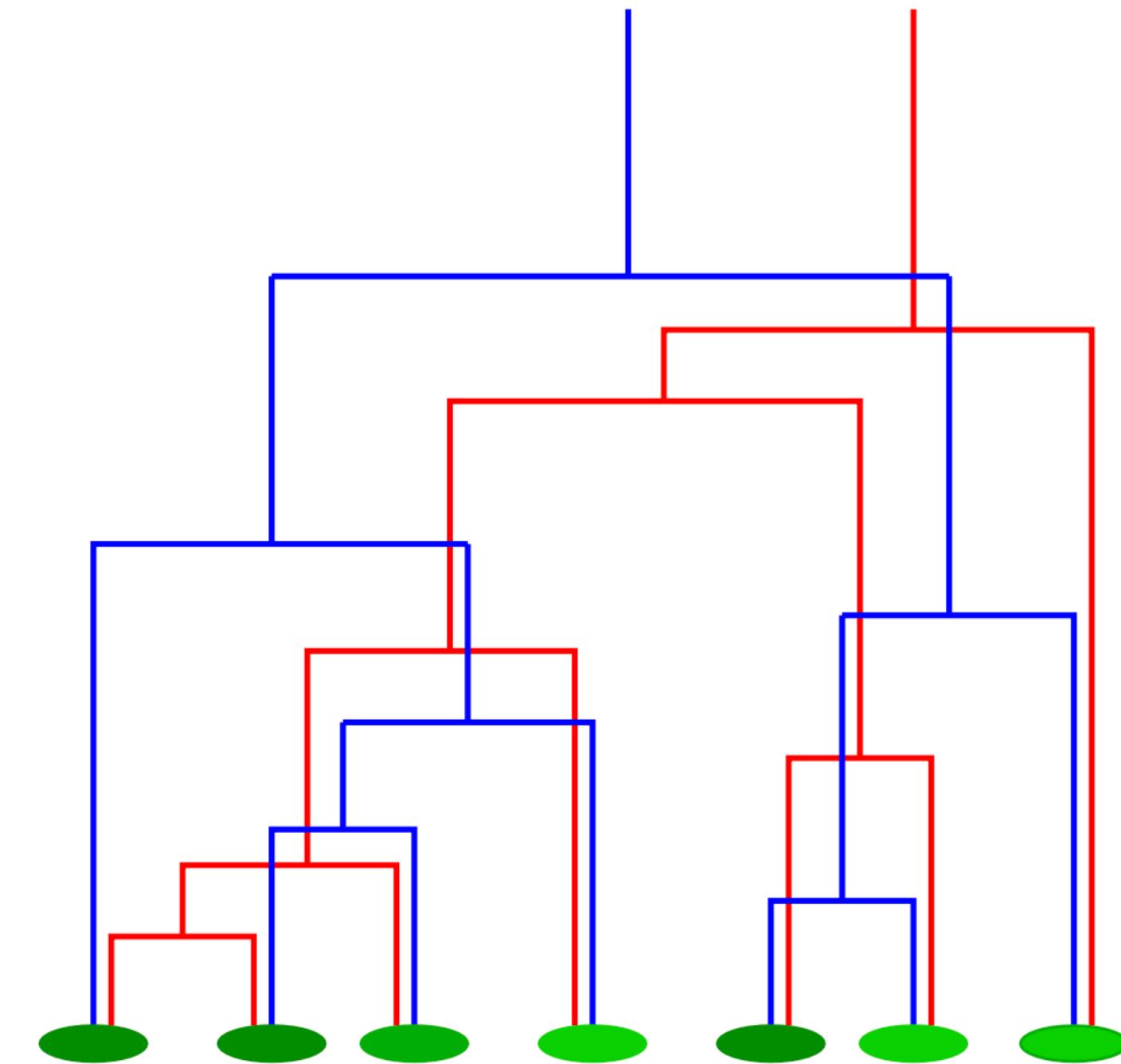
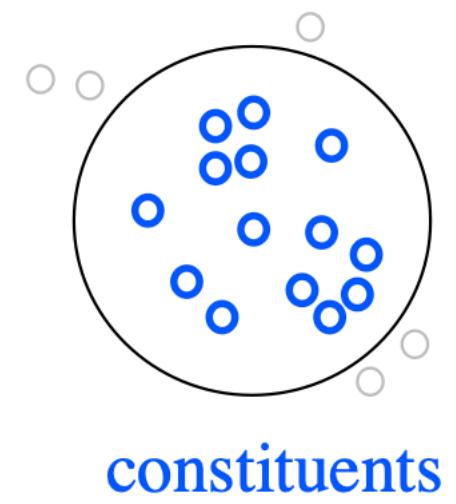
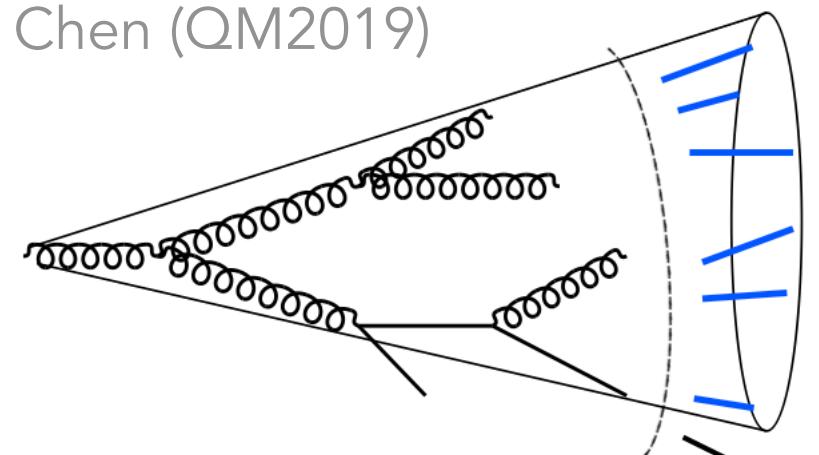
[Adapted from K. Zapp (2021)]

Jet substructure



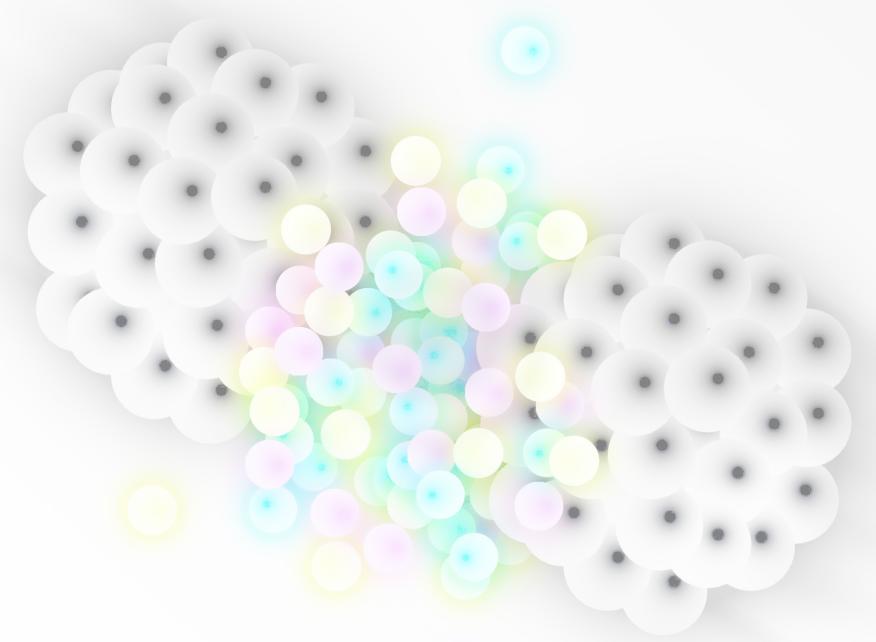
- To look for jet (de)coherence, single particle measurements will not suffice...
 - Need jet substructure!
 - What is a jet?

[Adapted from Yi Chen (QM2019)]



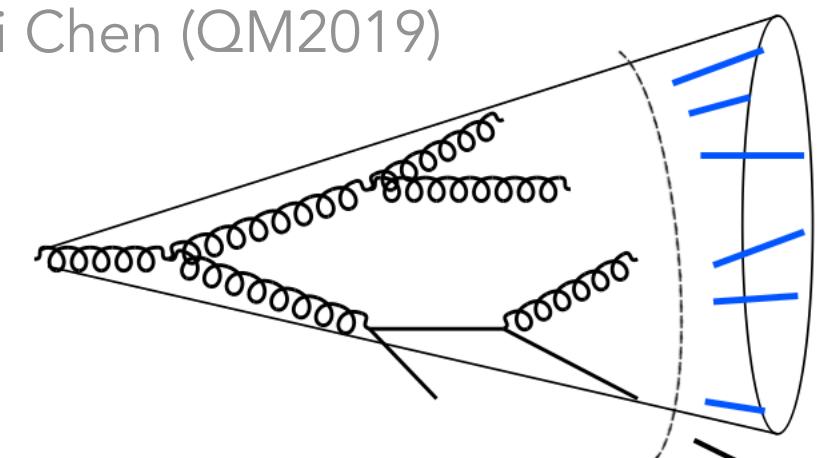
[Adapted from K. Zapp (2021)]

Jet substructure



- To look for jet (de)coherence, single particle measurements will not suffice...
 - Need jet substructure!
- What is a jet?

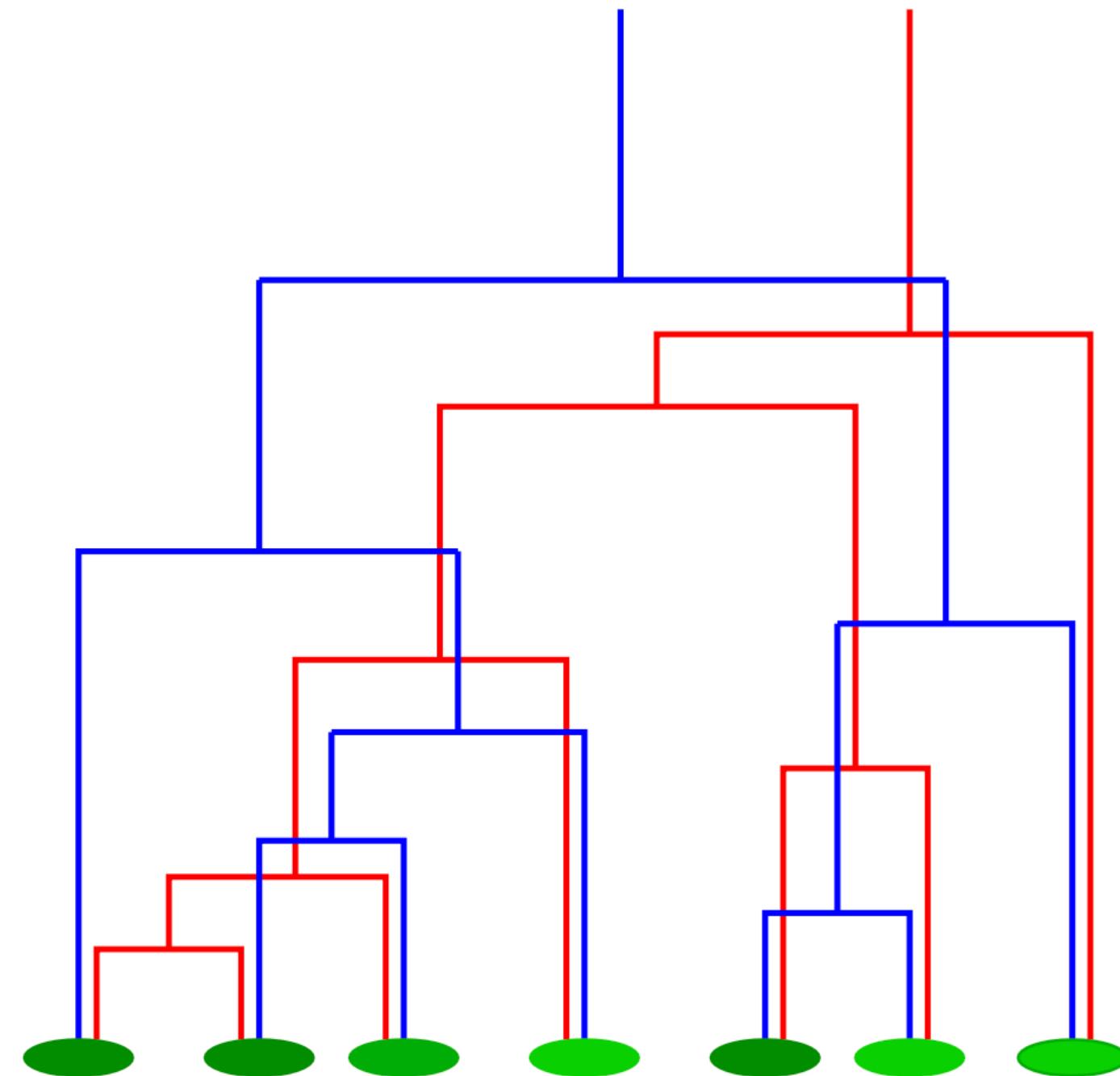
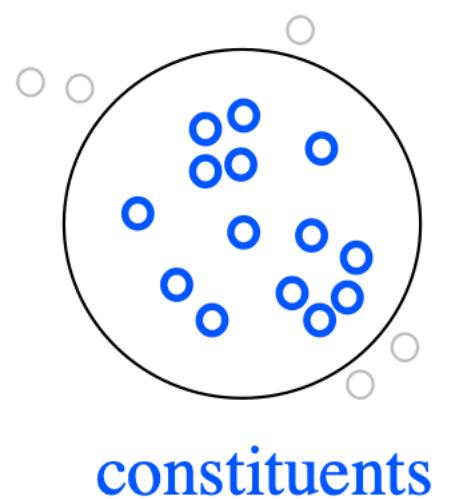
[Adapted from Yi Chen (QM2019)]



Iterative distance between 2 pseudo-jets

Generalized- k_T family:

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{t,i}^{2p}$$



[Adapted from K. Zapp (2021)]

$p = -1: \text{Anti-}k_T \text{ (signal jets)}$

[Cacciari et al (0802.1189)]

**$p = 0: \text{Cambridge/Aachen}$
(Angular ordered tree, QCD)**

[Dokshitzer et al (hep-ph/9707323)]

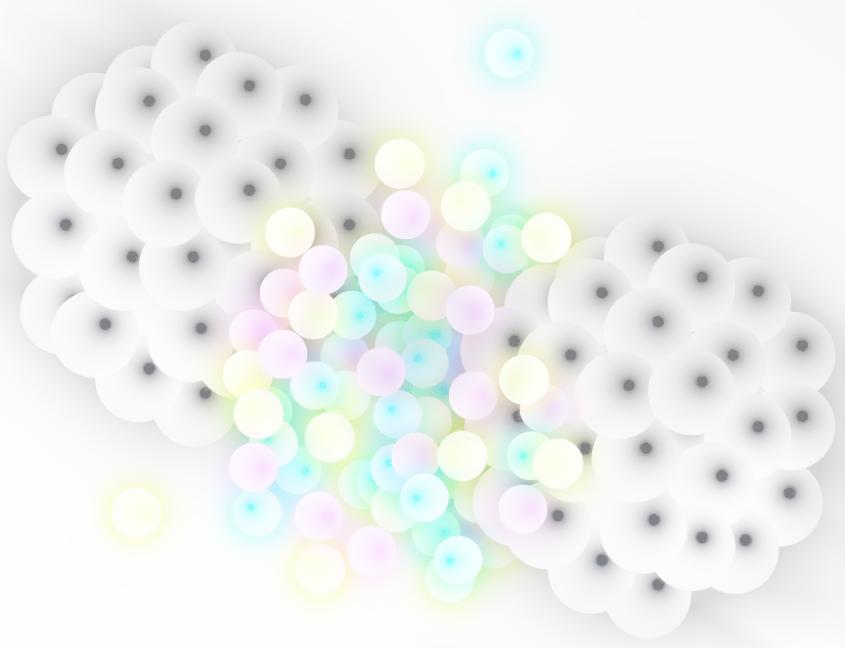
**$p = 1: k_T$
(HI background)**

[Catani et al, Ellis et al (hep-ph/9305266)]

**$p = 0.5: \tau$ (QCD Formation time
ordered tree, jet quenching)**

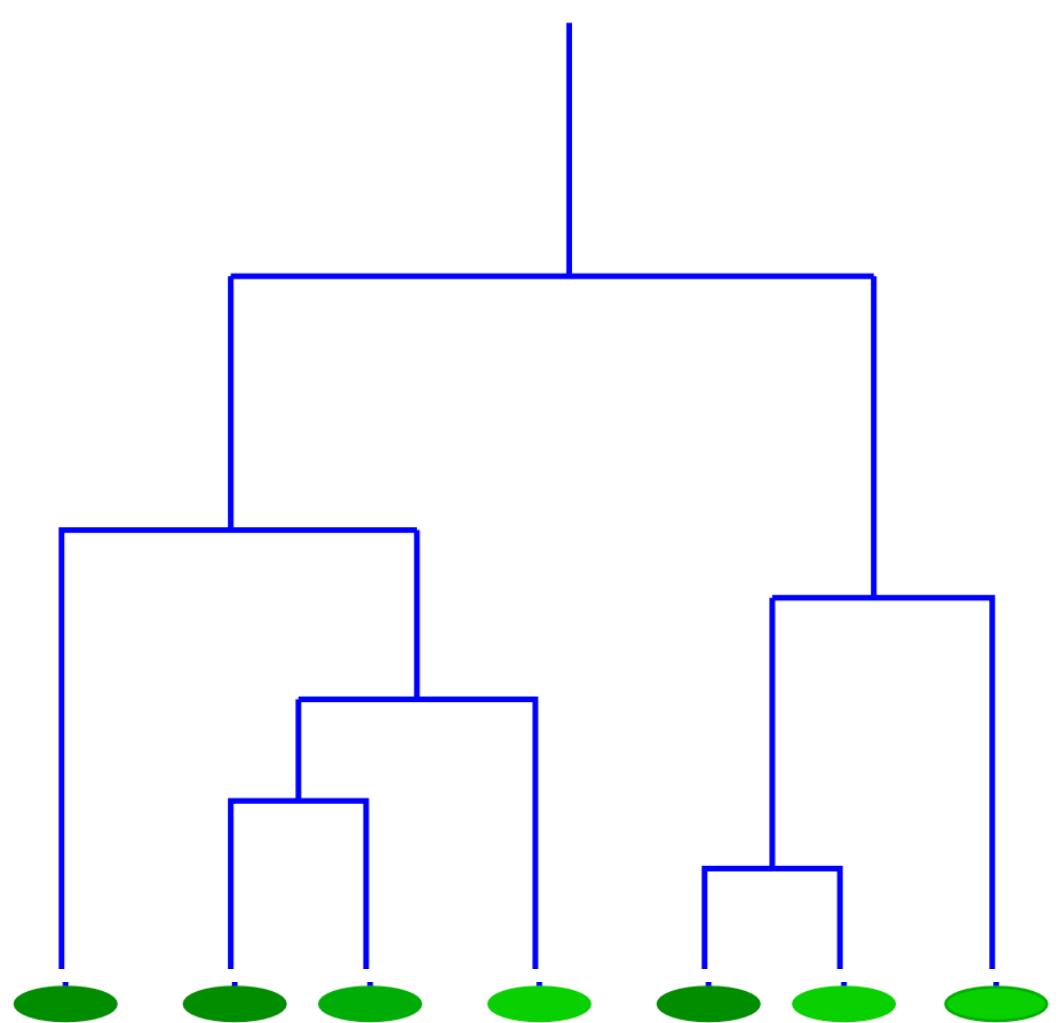
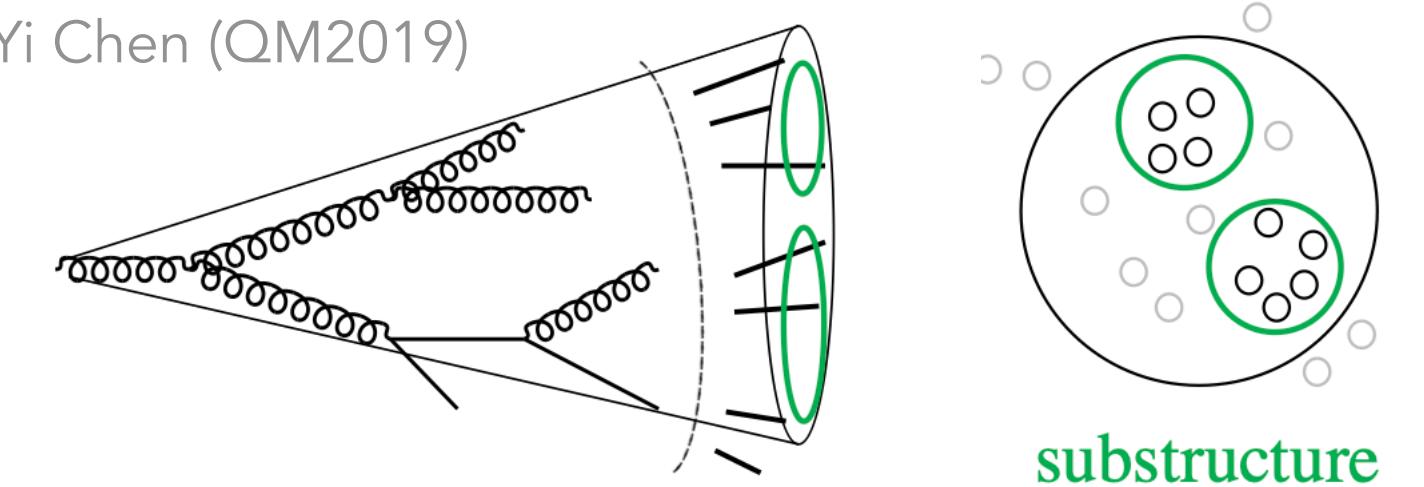
[Apolinário et al (2012.02199)]

Jet substructure

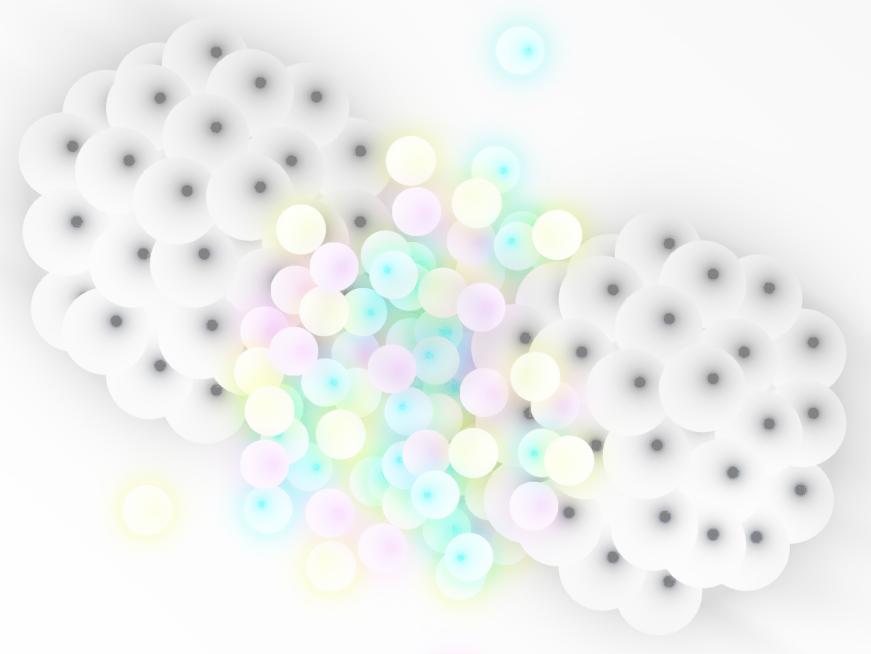


- How can we access QGP-related information with jet substructure?

[Adapted from Yi Chen (QM2019)]

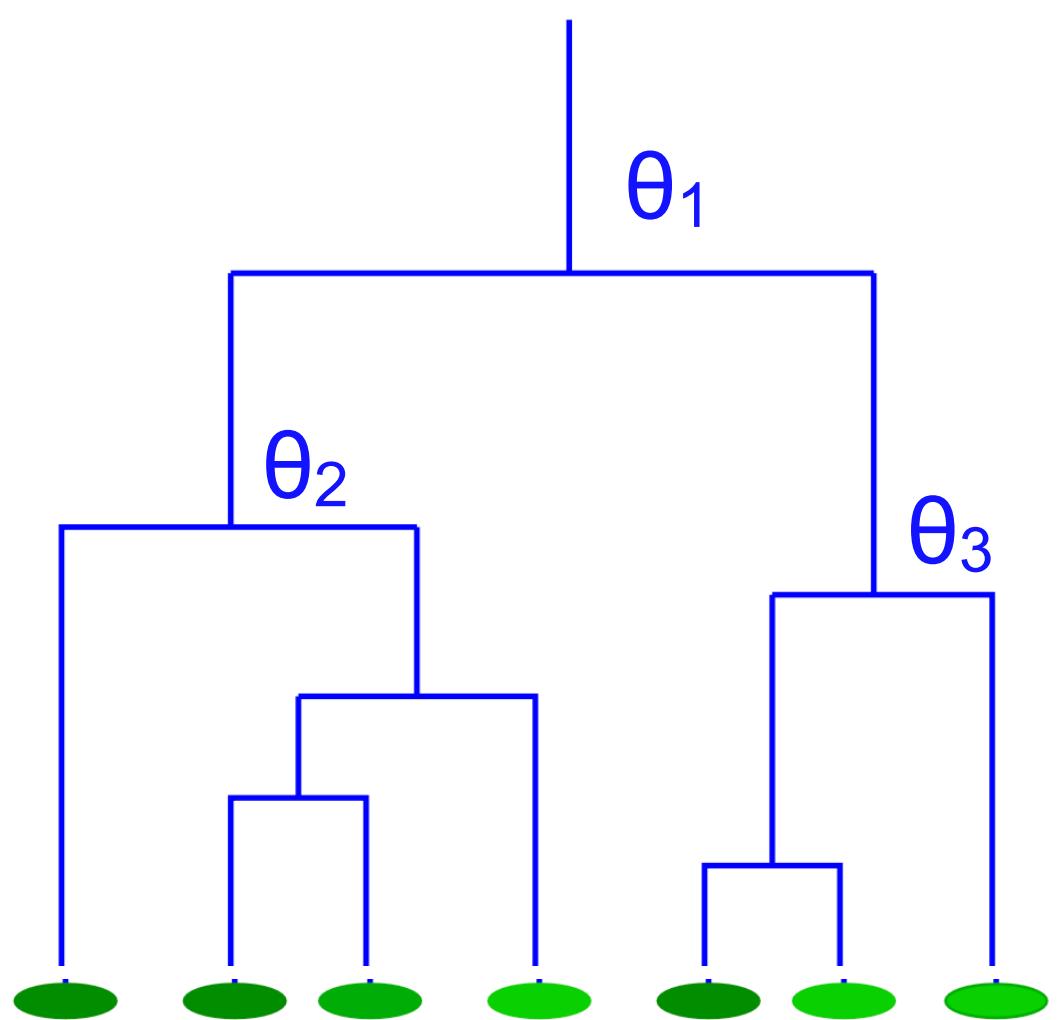
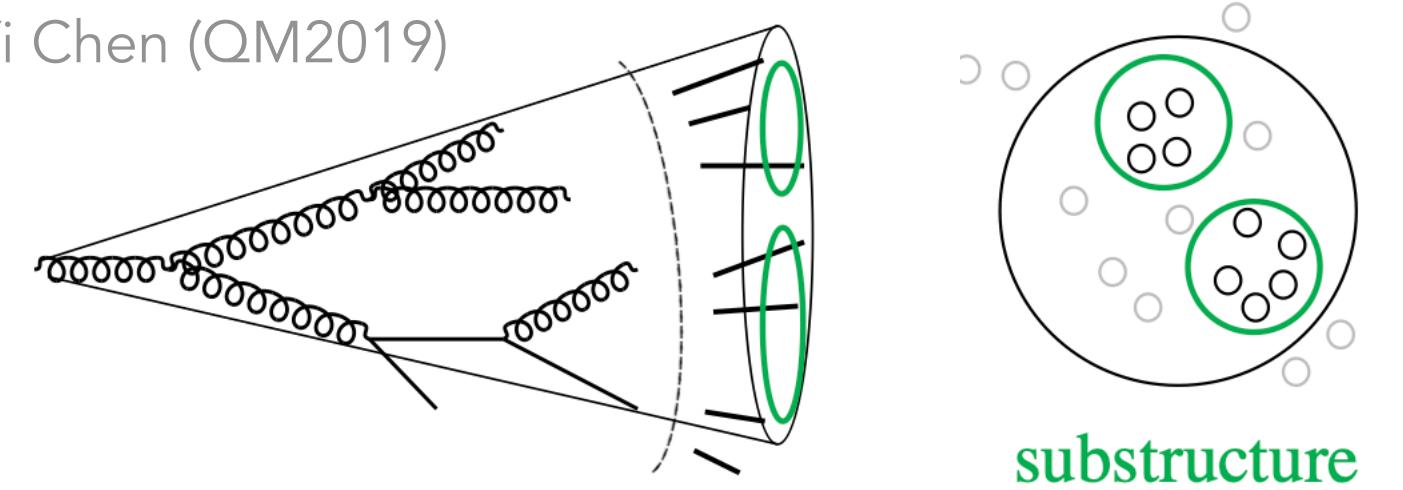


Jet substructure



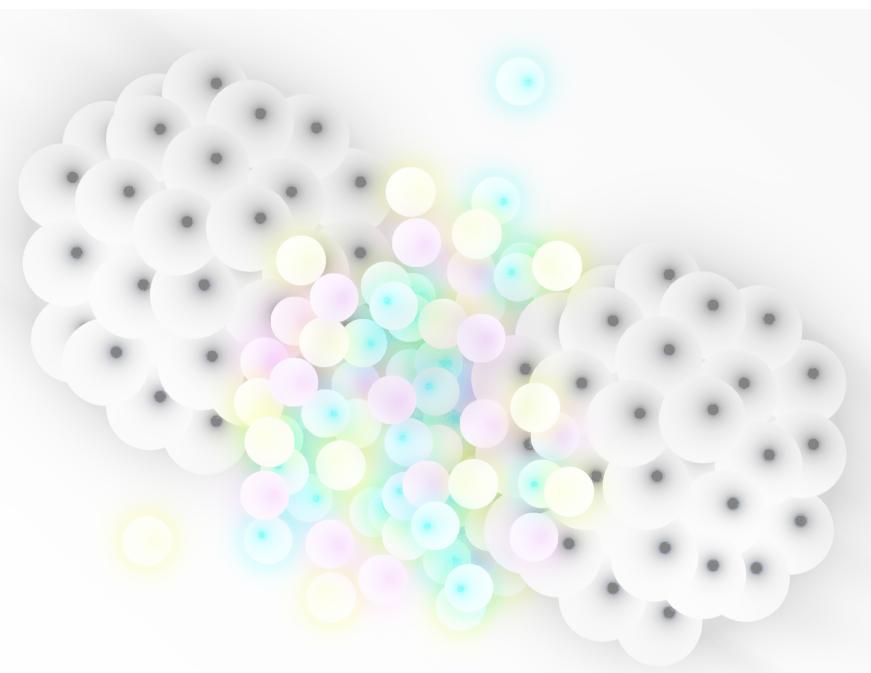
- How can we access QGP-related information with jet substructure?

[Adapted from Yi Chen (QM2019)]



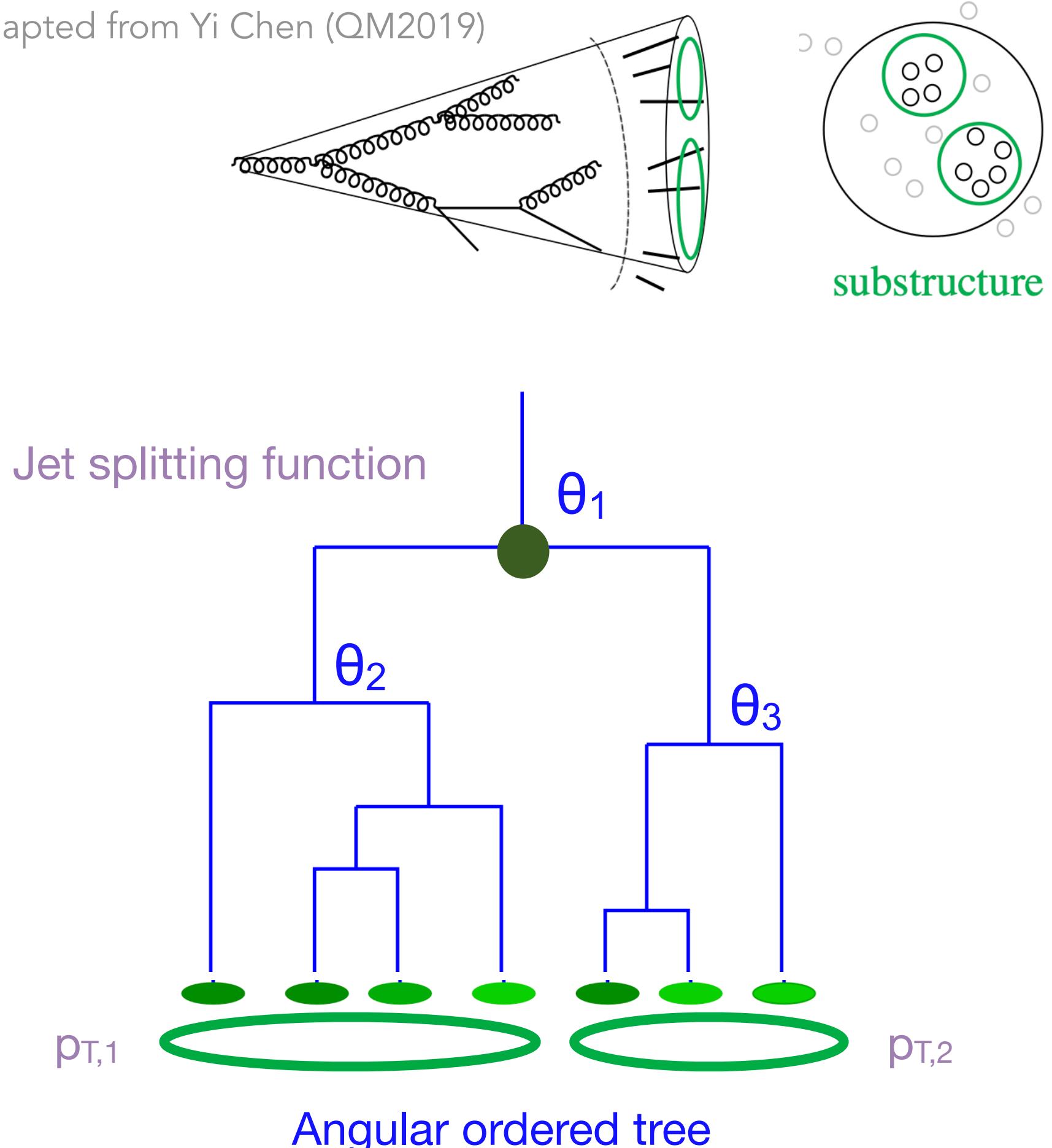
Angular ordered tree

Jet substructure



- How can we access QGP-related information with jet substructure?

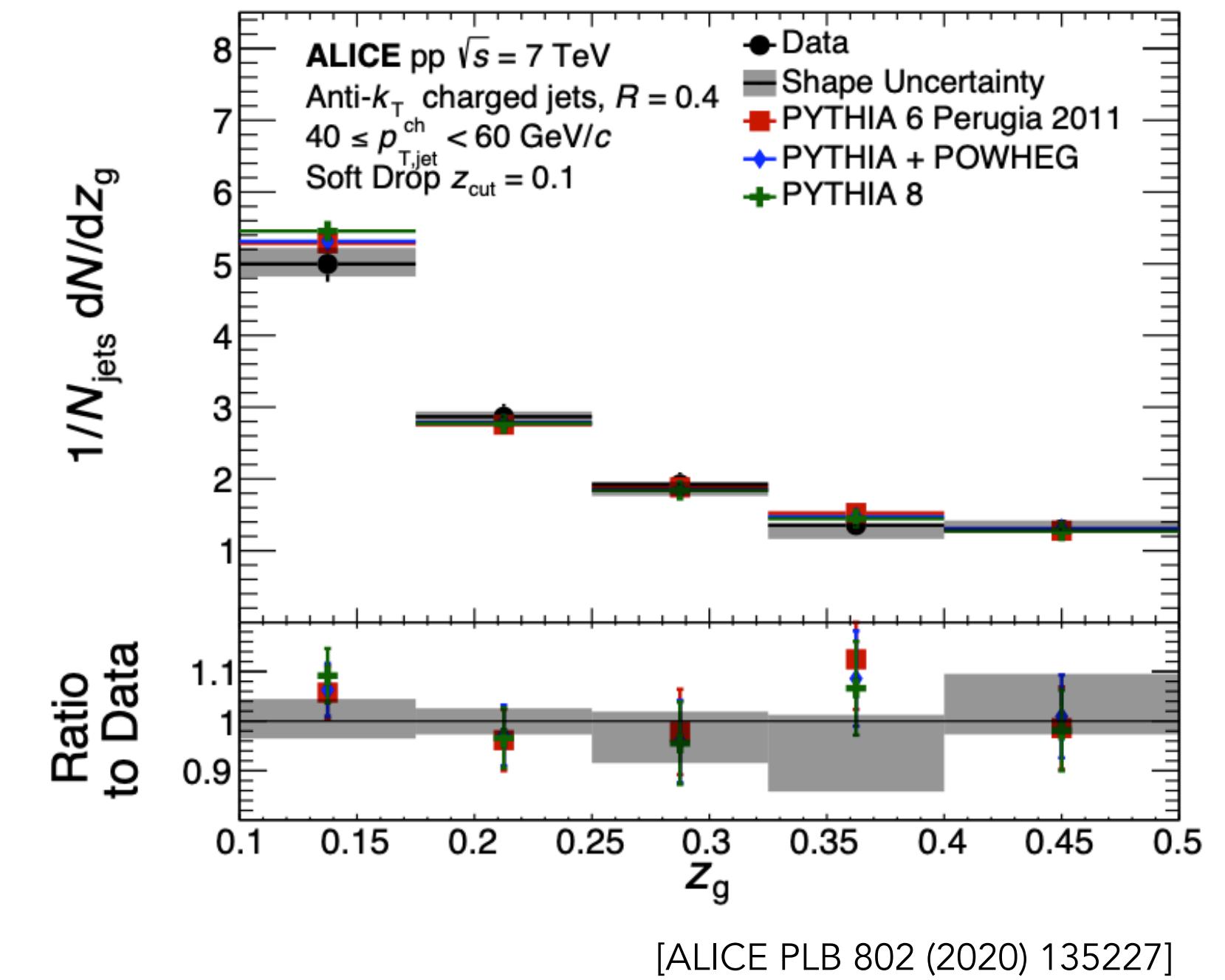
[Adapted from Yi Chen (QM2019)]



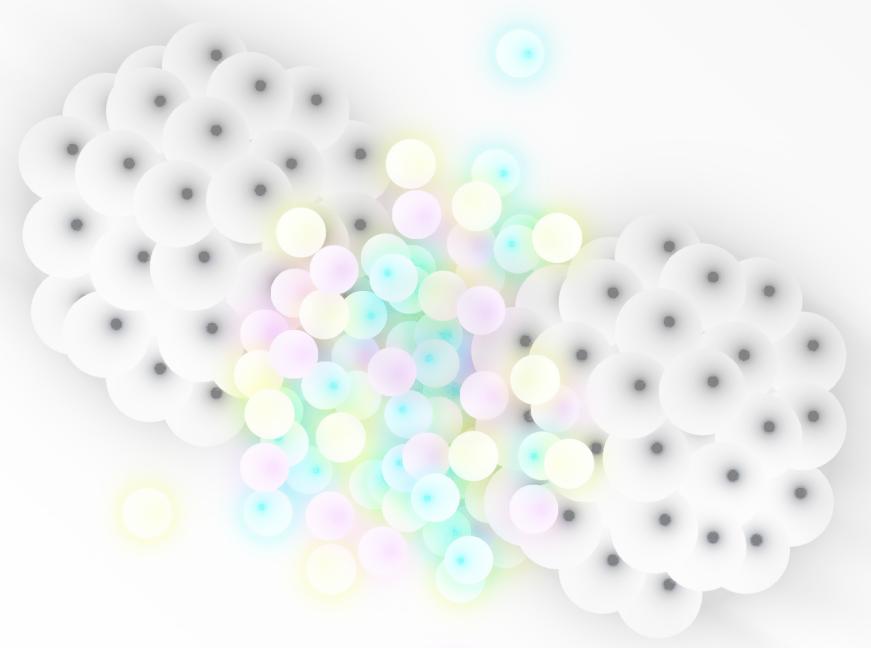
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

when $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{R_{12}}{R_0} \right)^\beta$

[Larkoski, Marzani, Soyez, Thaler (1402.2657)]
 [Dasgupta, Fregoso, Marzani, Salam (1307.0007)]

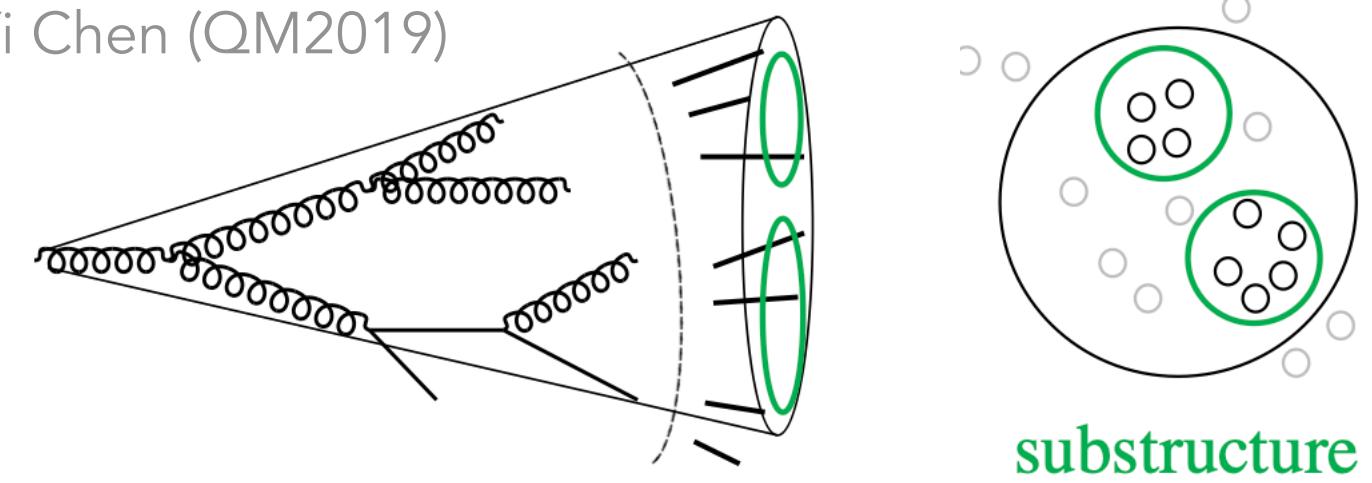


Jet substructure



- How can we access QGP-related information with jet substructure?

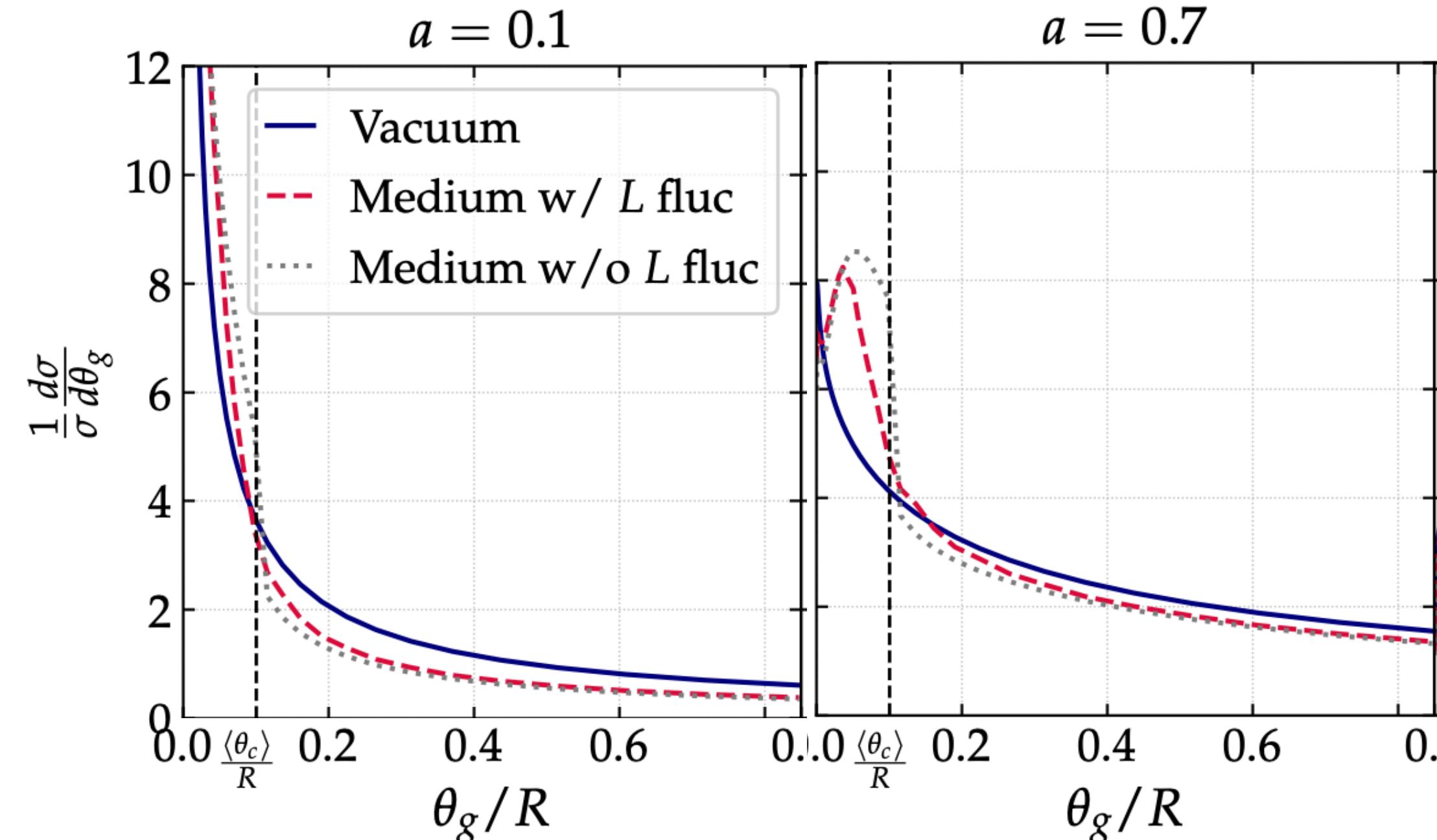
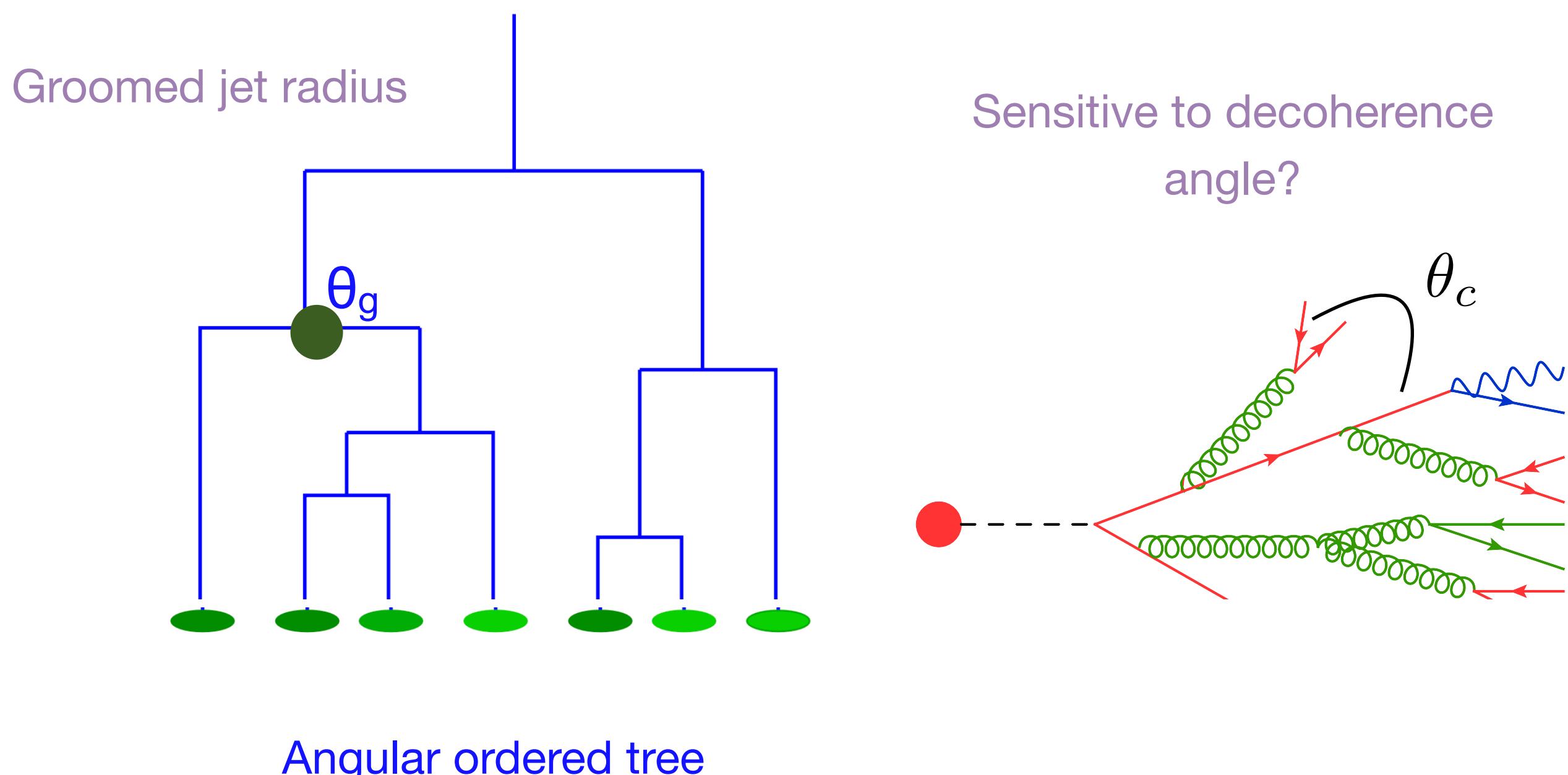
[Adapted from Yi Chen (QM2019)]



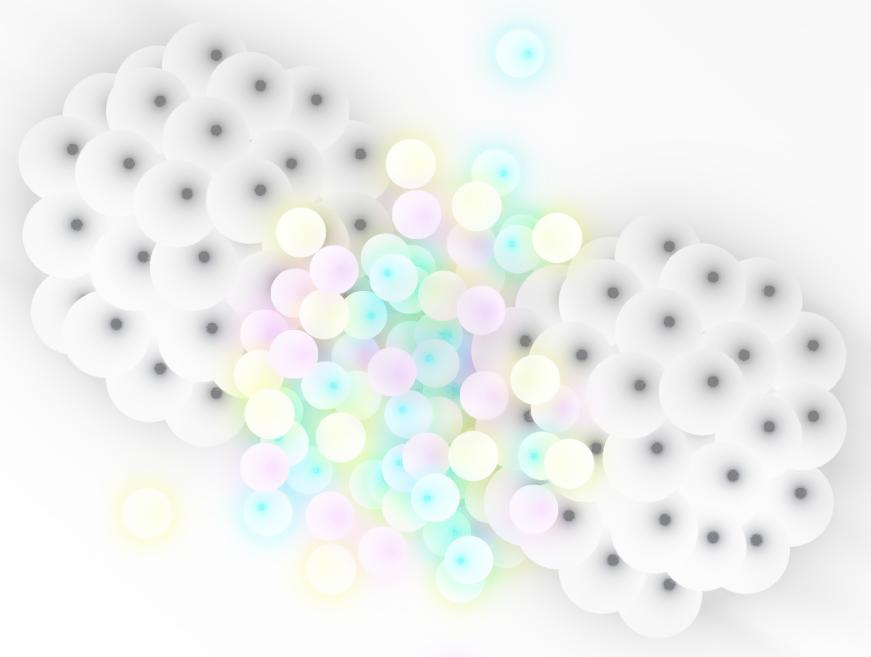
$$\kappa^{(a)} = \frac{1}{p_{t,\text{jet}}} z(1-z)p_t \left(\frac{\theta}{R}\right)^a$$

[Mehtar-Tani, et al (1911.00375)]

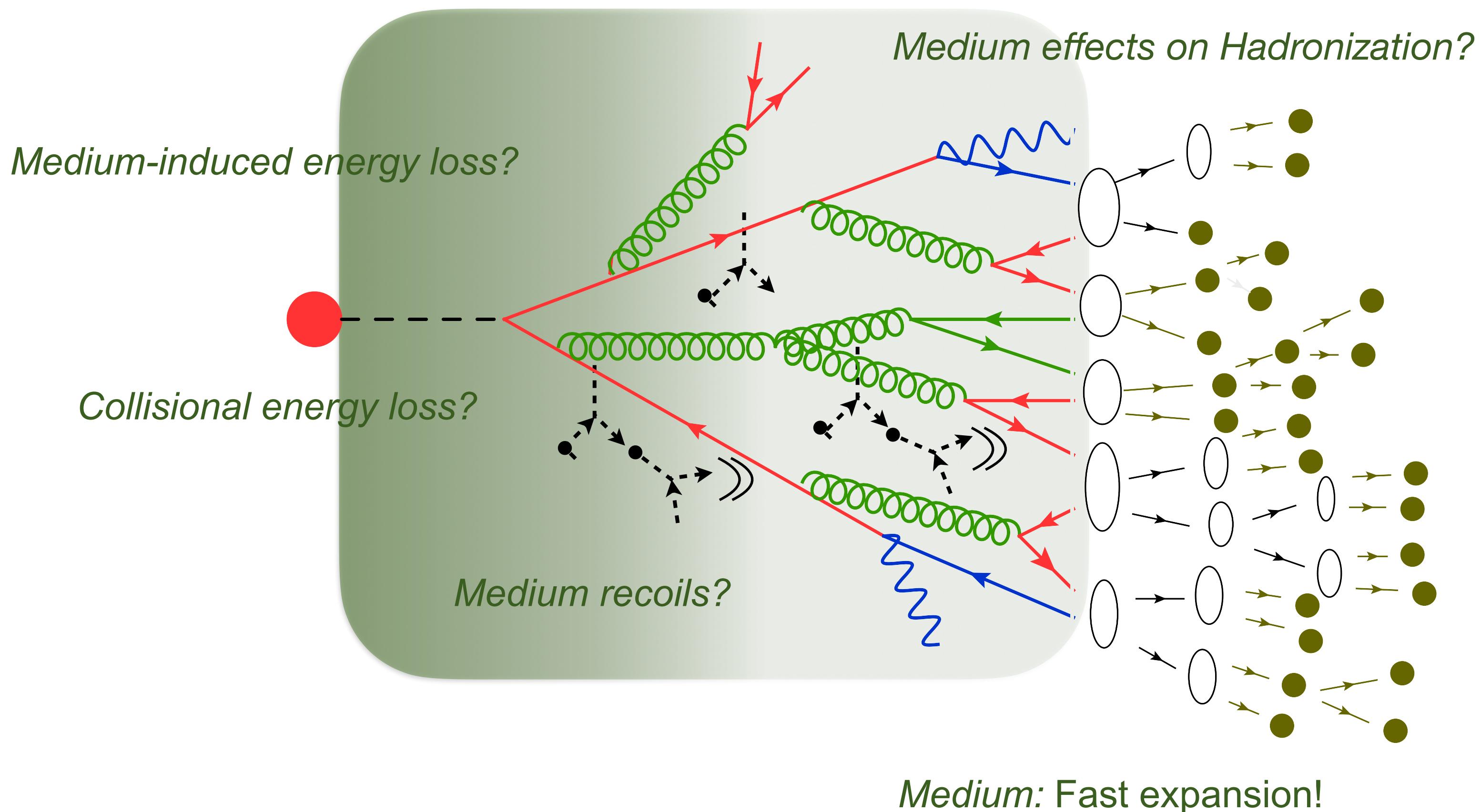
[Caucal et al (2111.14768)]



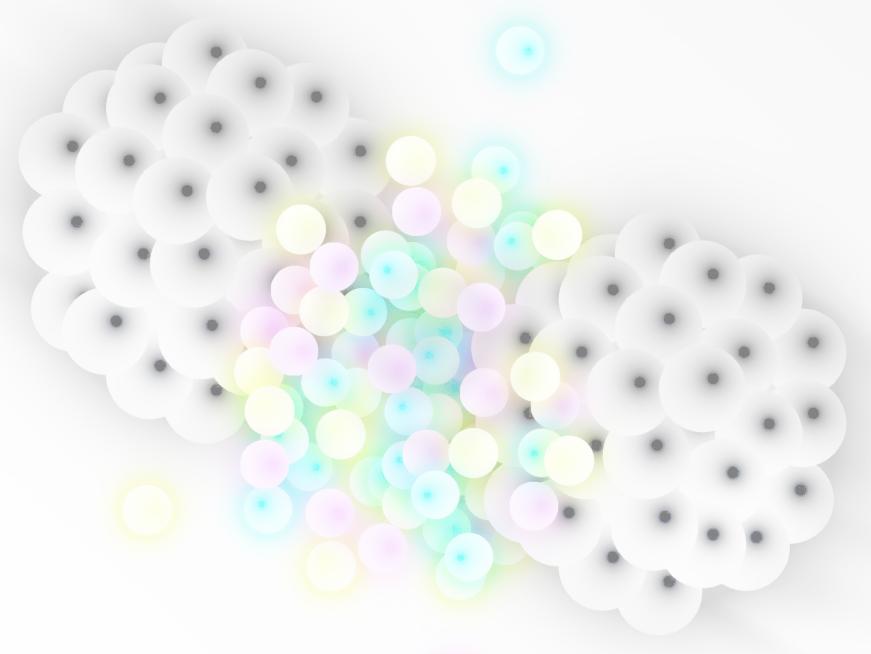
Jet Quenching III



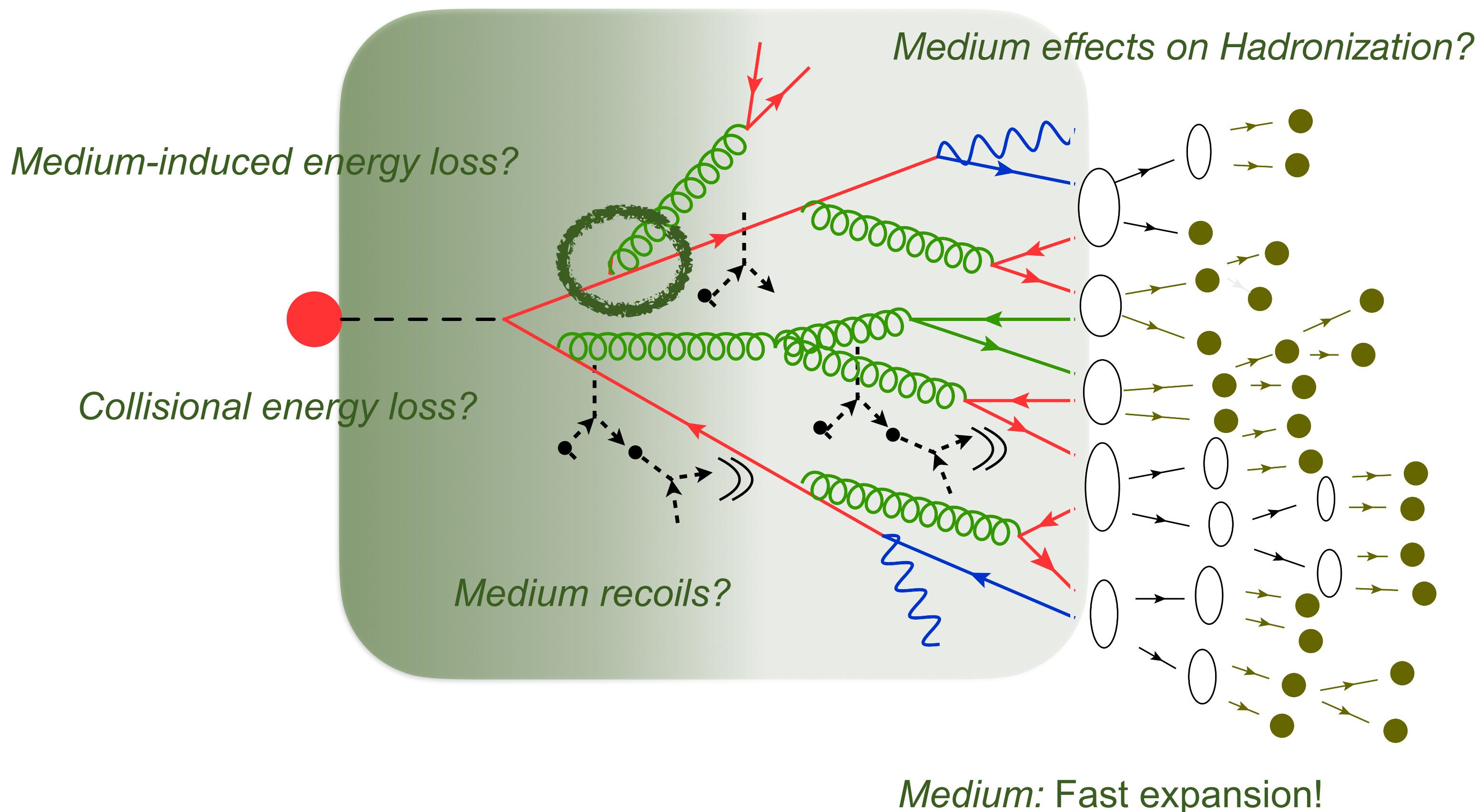
- Medium = Hot gas of quarks and gluons:



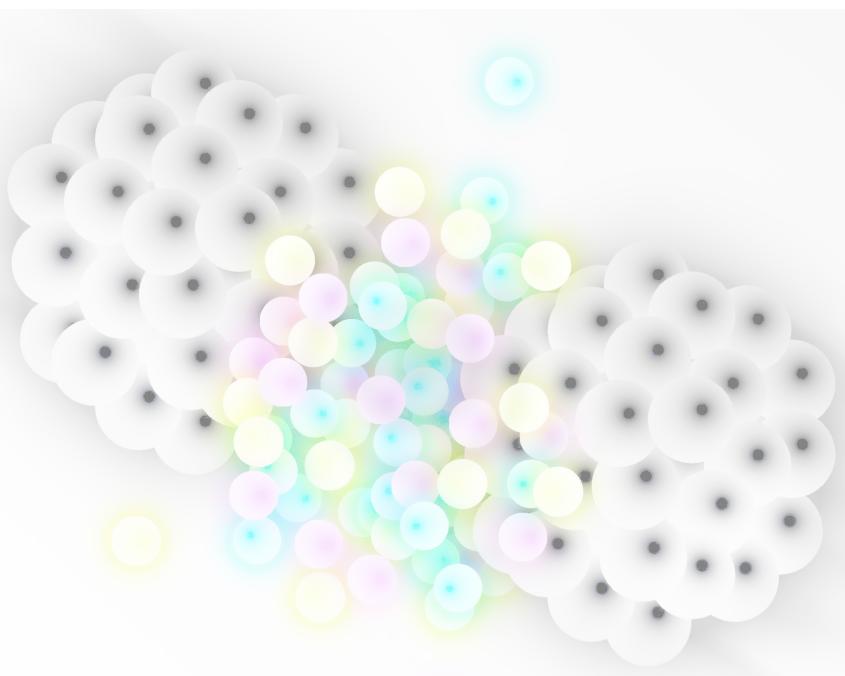
Jet Quenching III



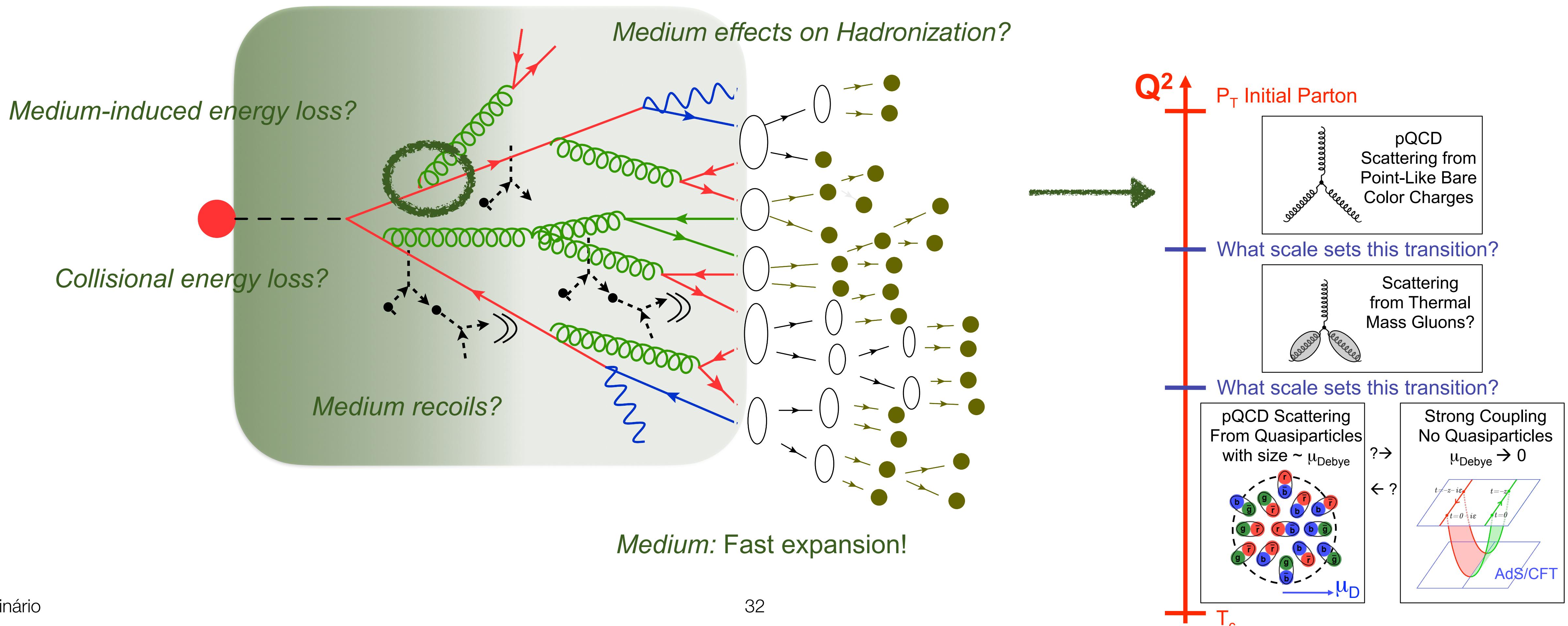
- Medium = Hot gas of quarks and gluons:



Jet Quenching III

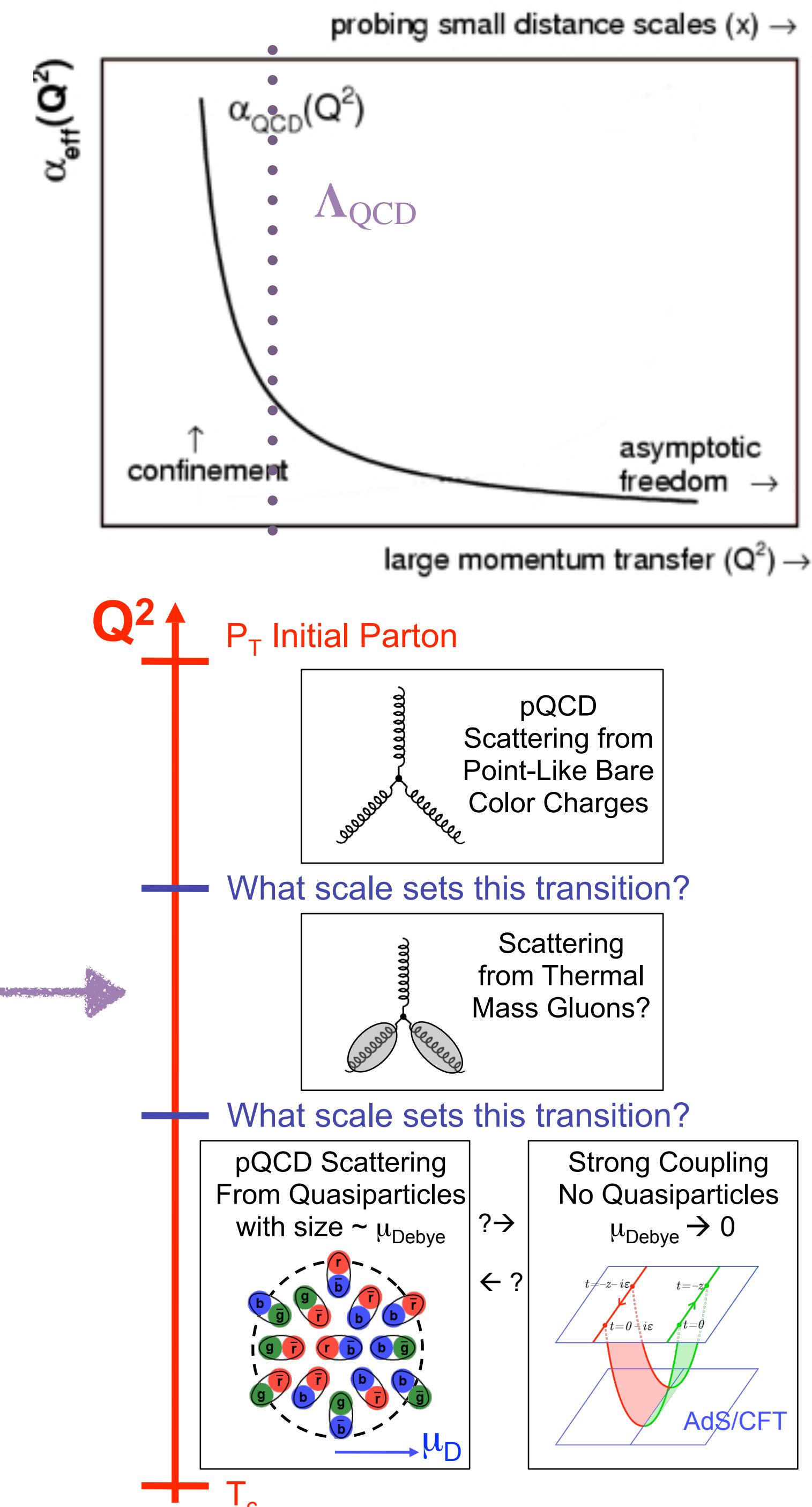
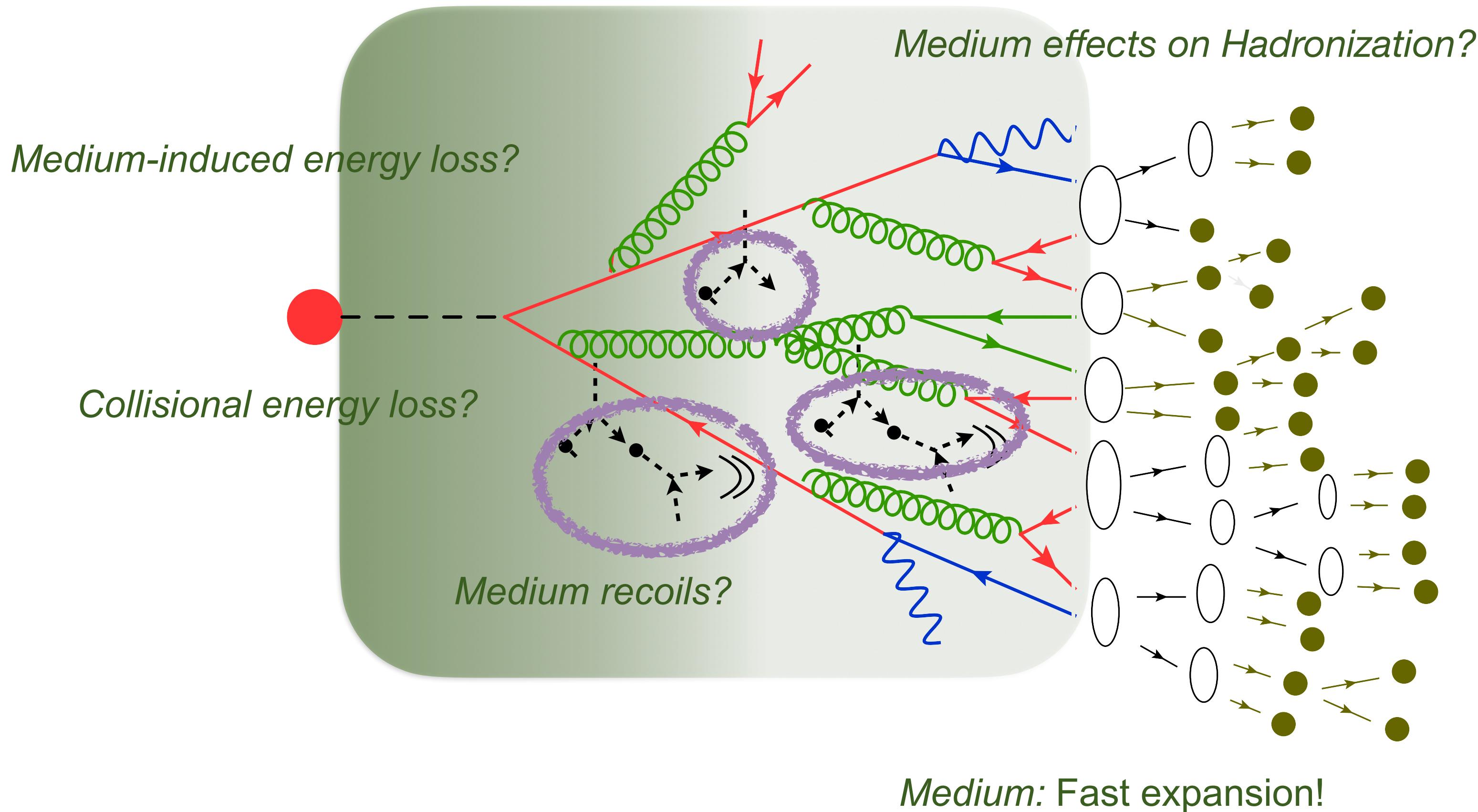


- Medium = Hot gas of quarks and gluons:

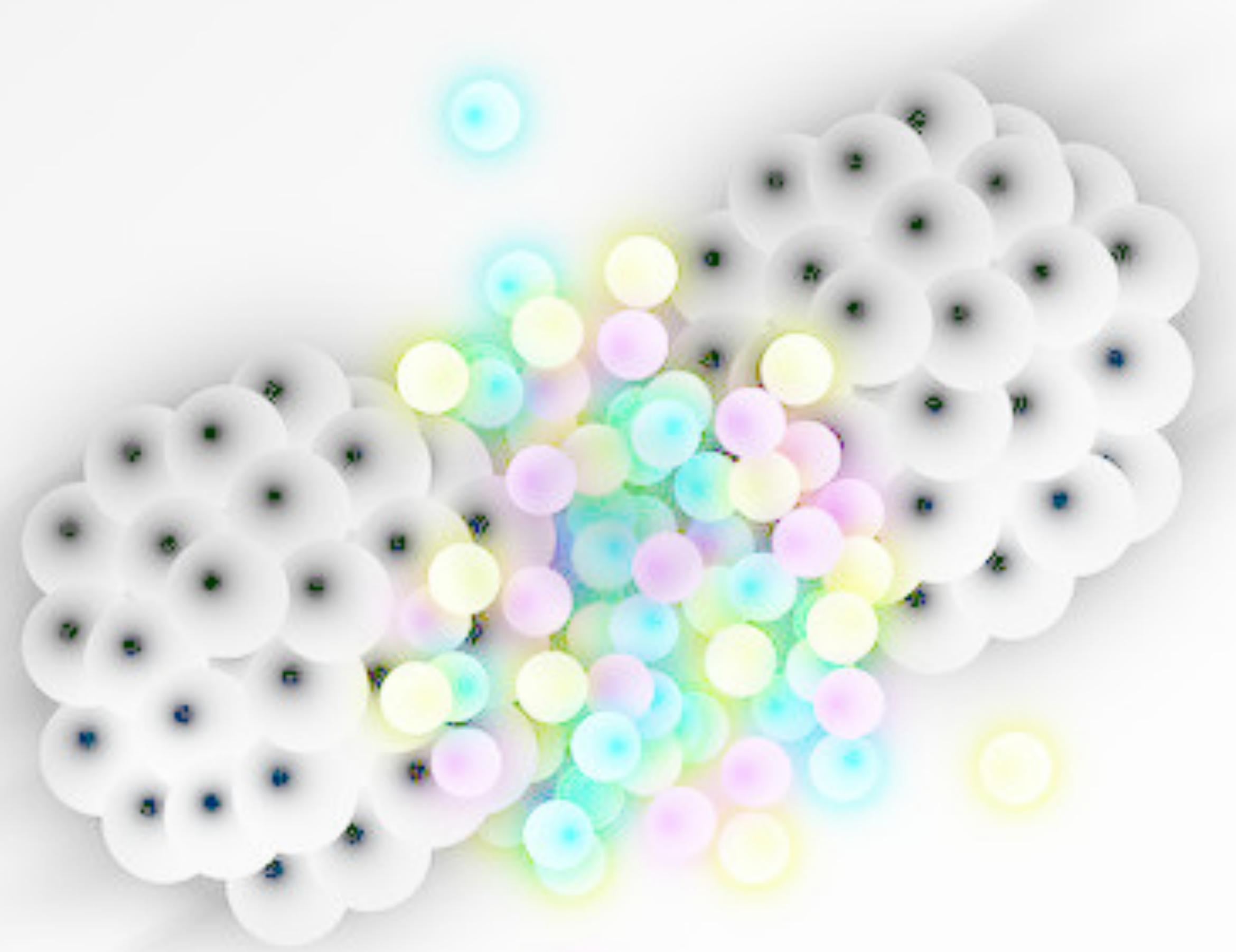


Jet Quenching III

- Medium = Hot gas of quarks and gluons:

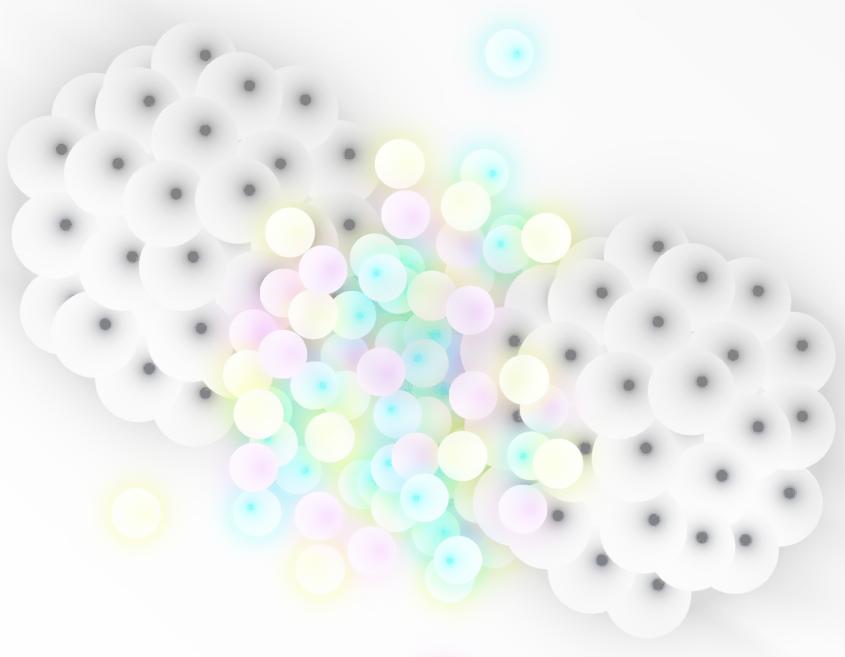


Jet Quenching



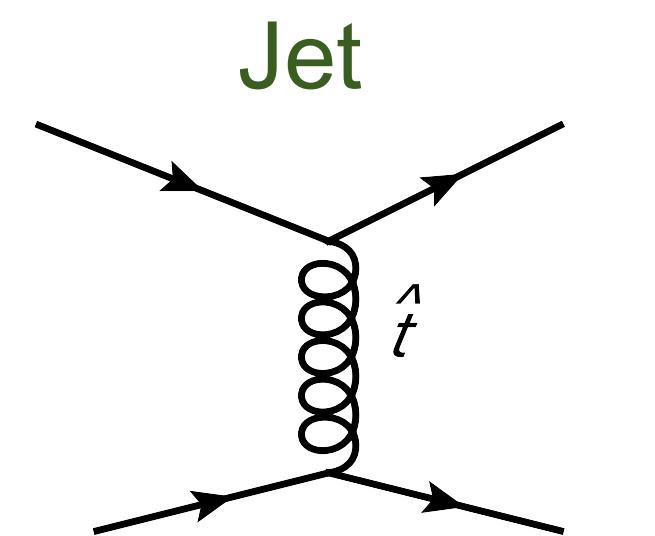
Medium response

Medium response



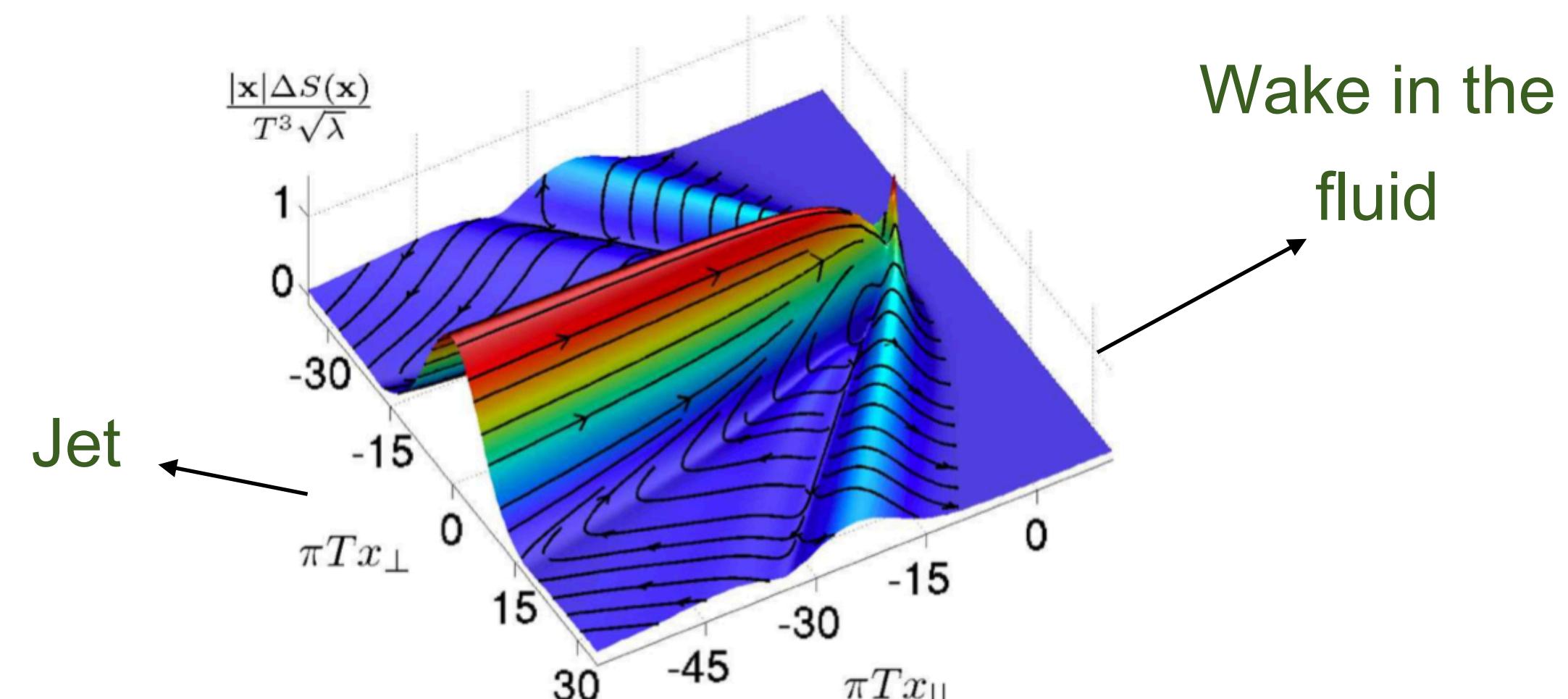
- QGP part that become correlated with the jet:
 - Elastic scatterings with medium constituents or drag effect?

pQCD perspective



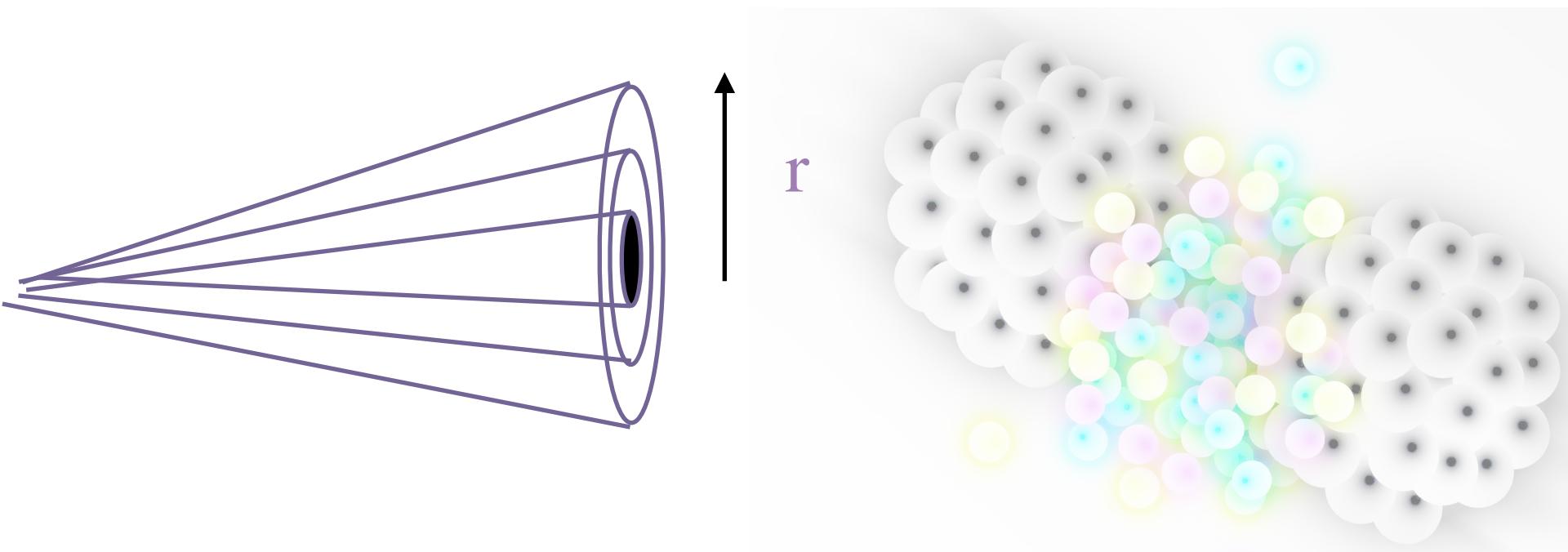
$$\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s}, |\hat{t}|) \simeq \frac{C_R 2\pi \alpha_s^2}{(|\hat{t}| + \mu_D^2)^2}$$

AdS/CFT perspective

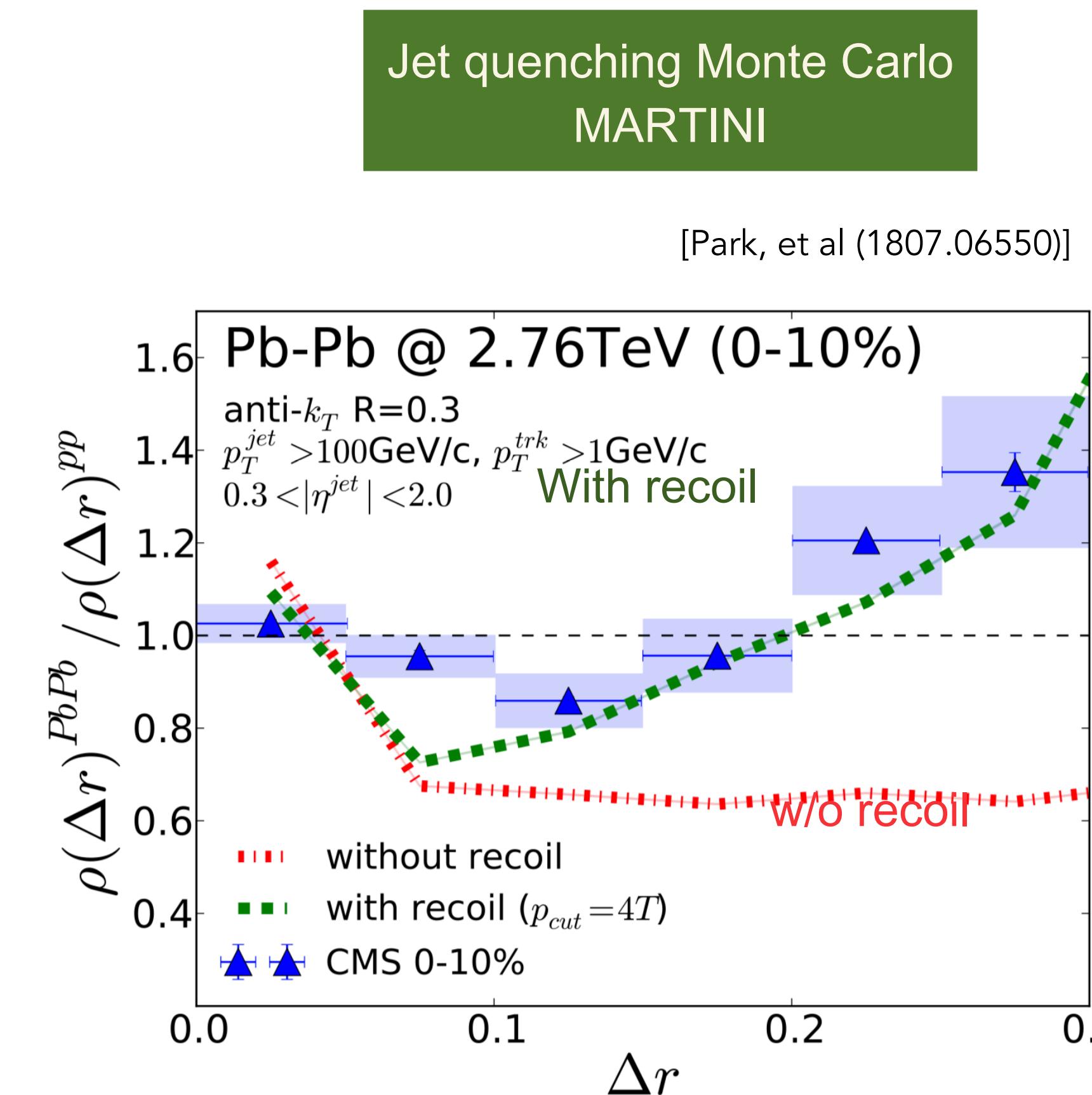
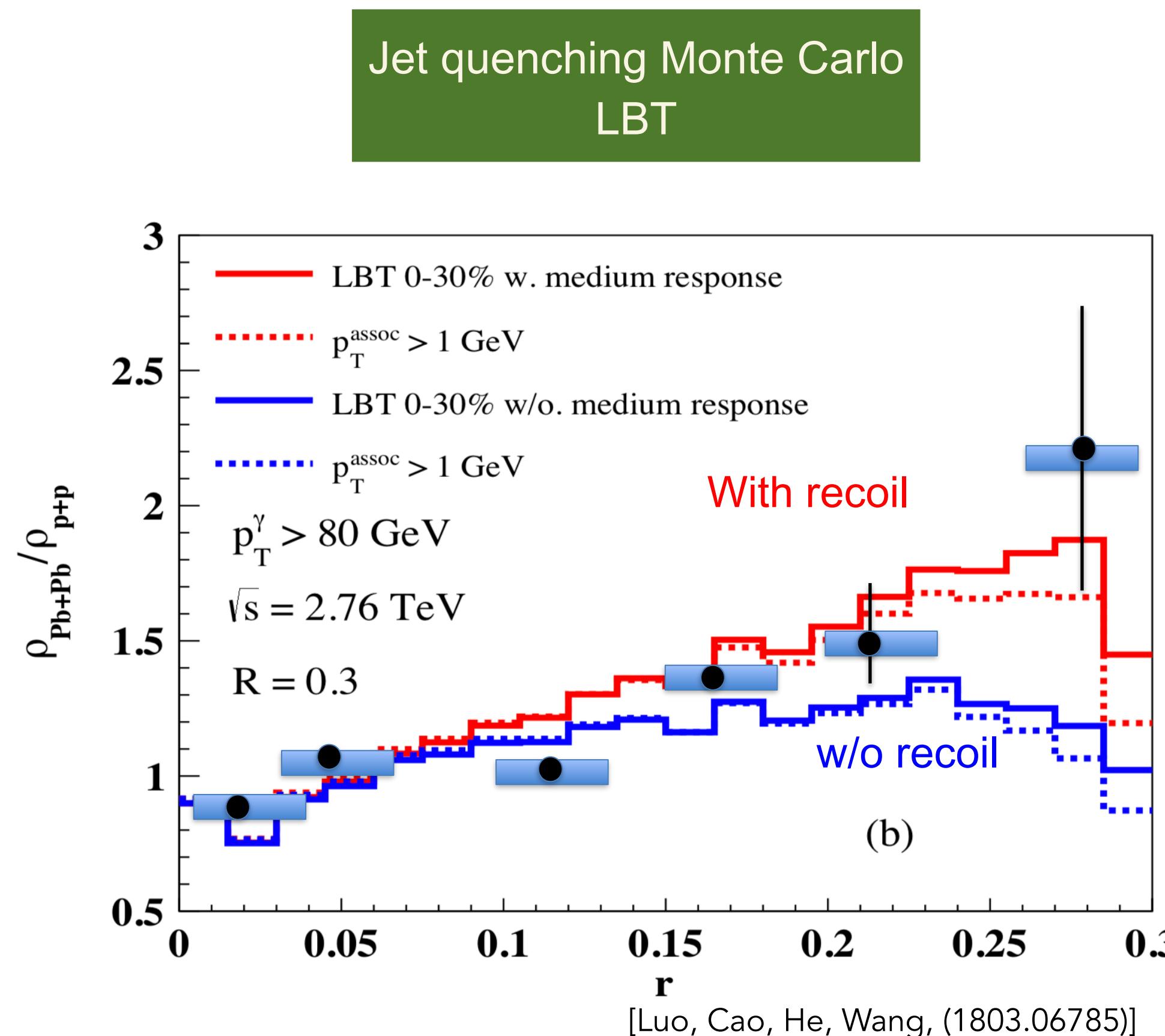


$$\left. \frac{dE}{dx} \right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}$$

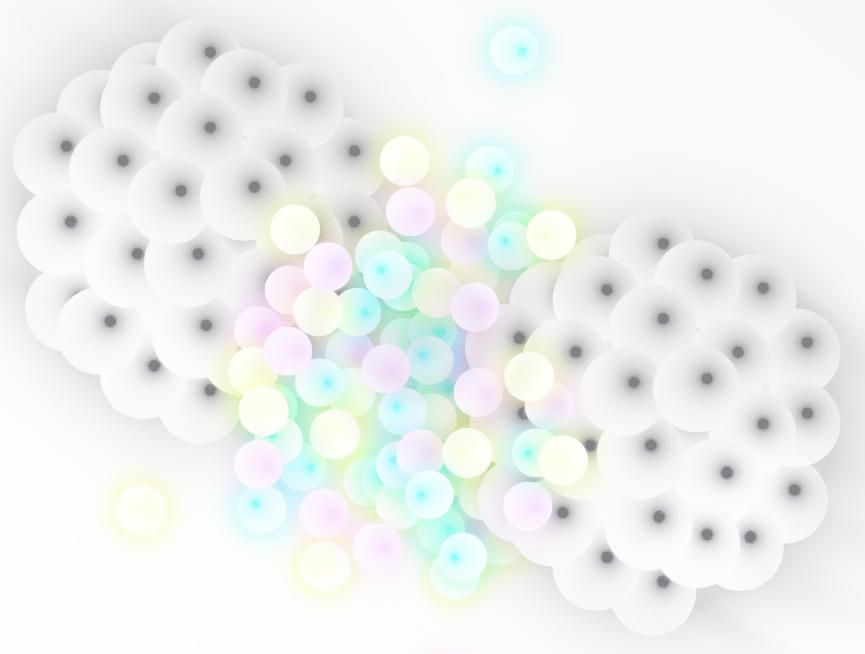
Medium response



- Soft components seem necessary for a better description of the jet radial profile and/or jet mass:

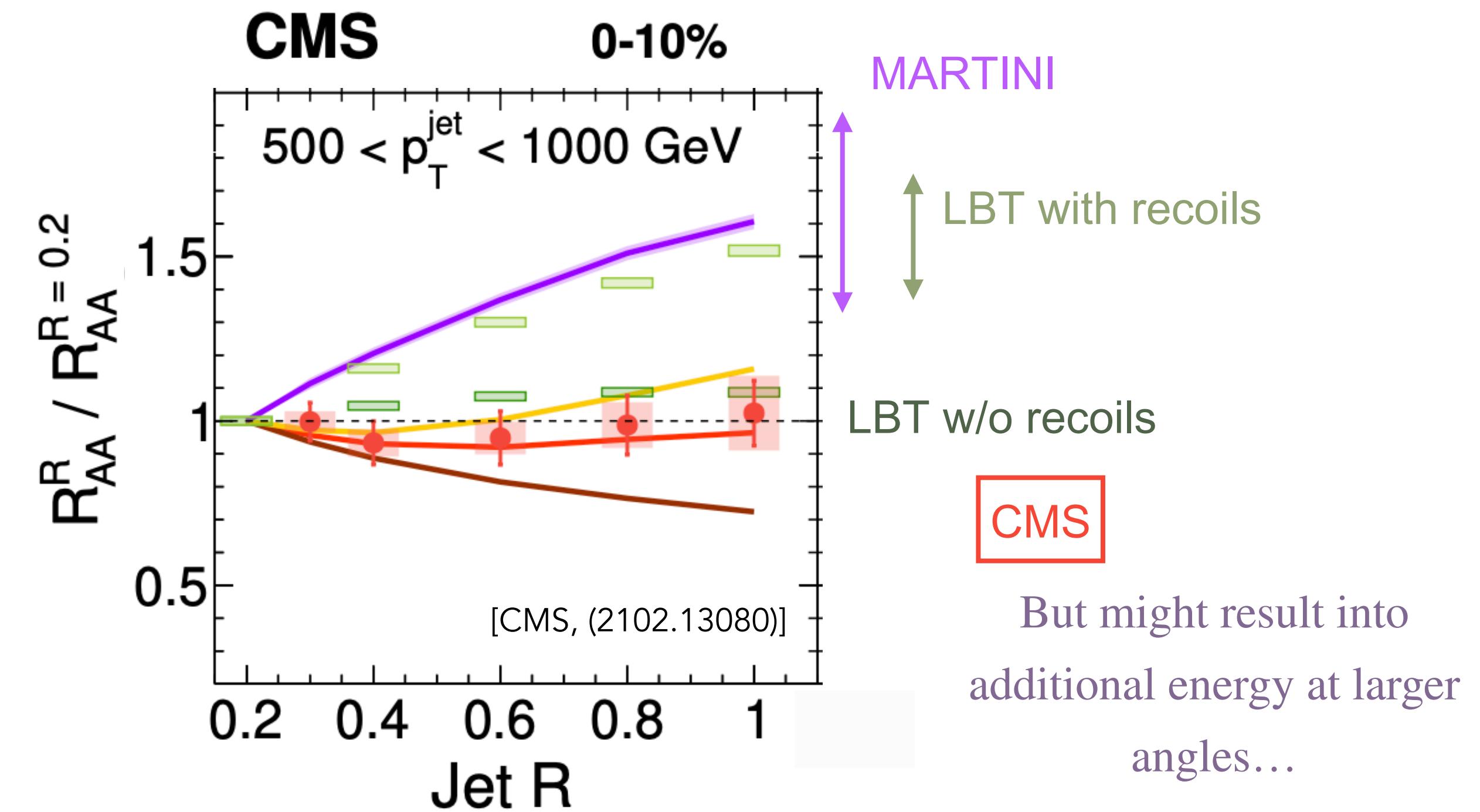
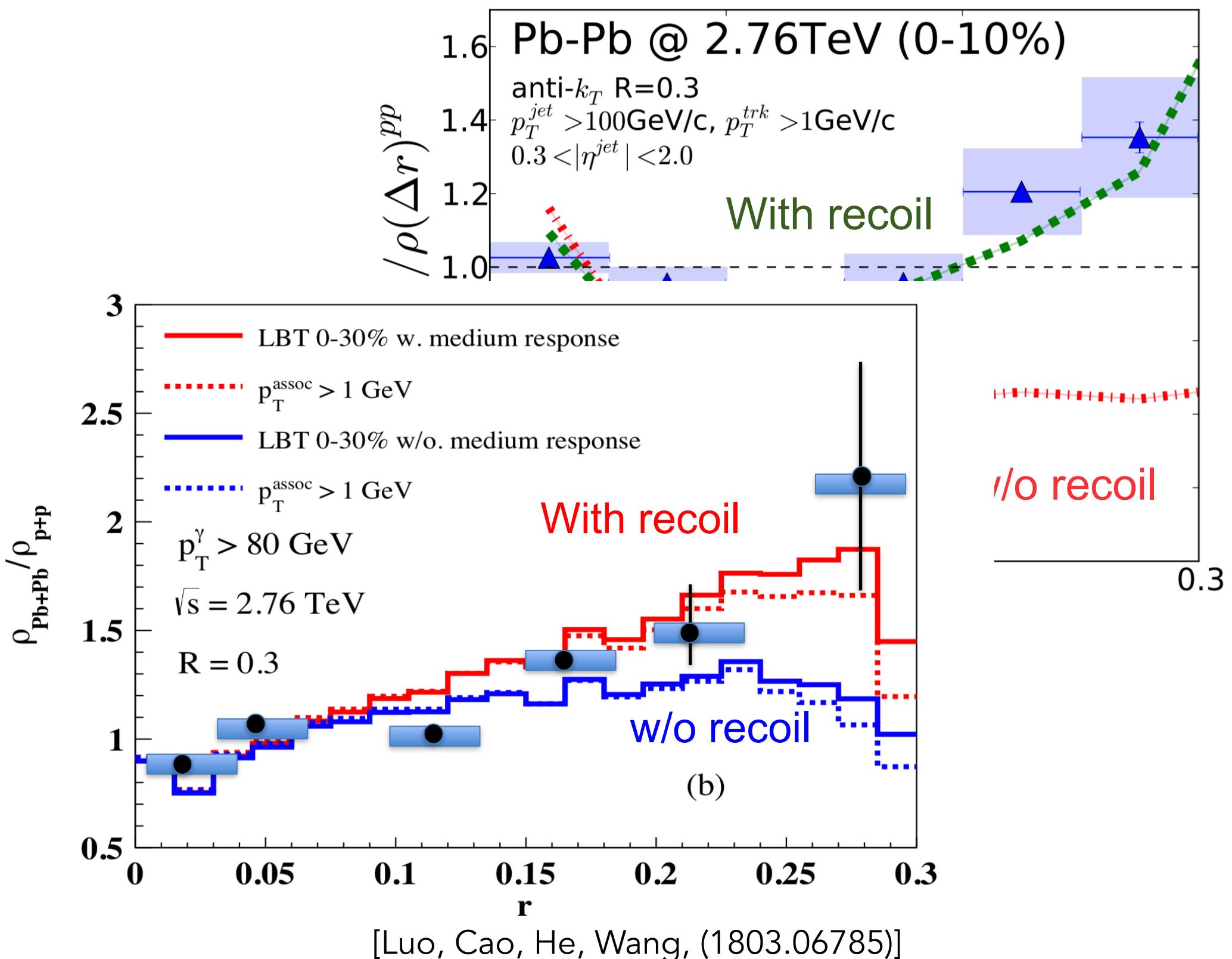


Medium response

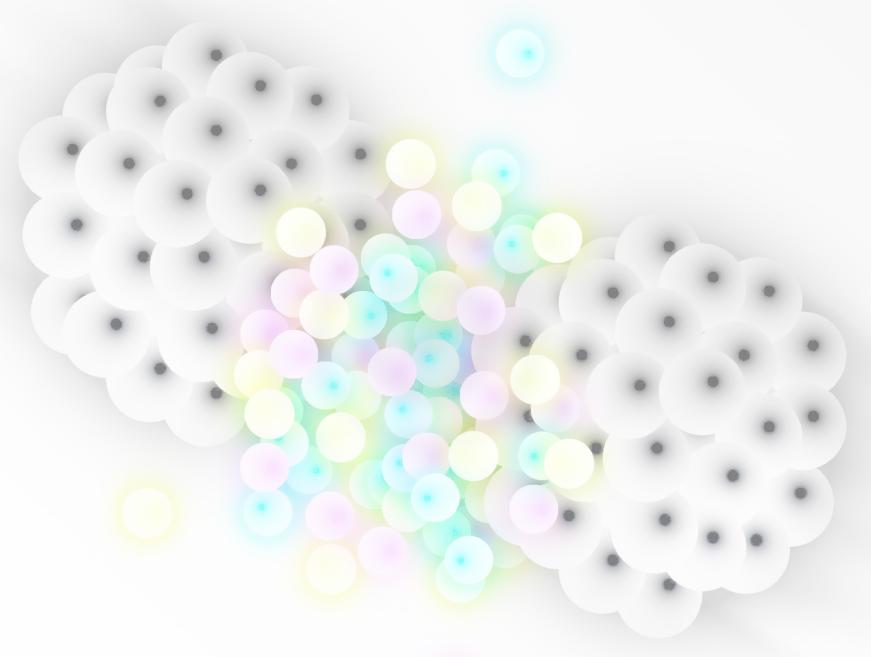


- Soft components seem necessary for a better description of the jet radial profile and/or jet mass:

[Park et al (1807.06550)]

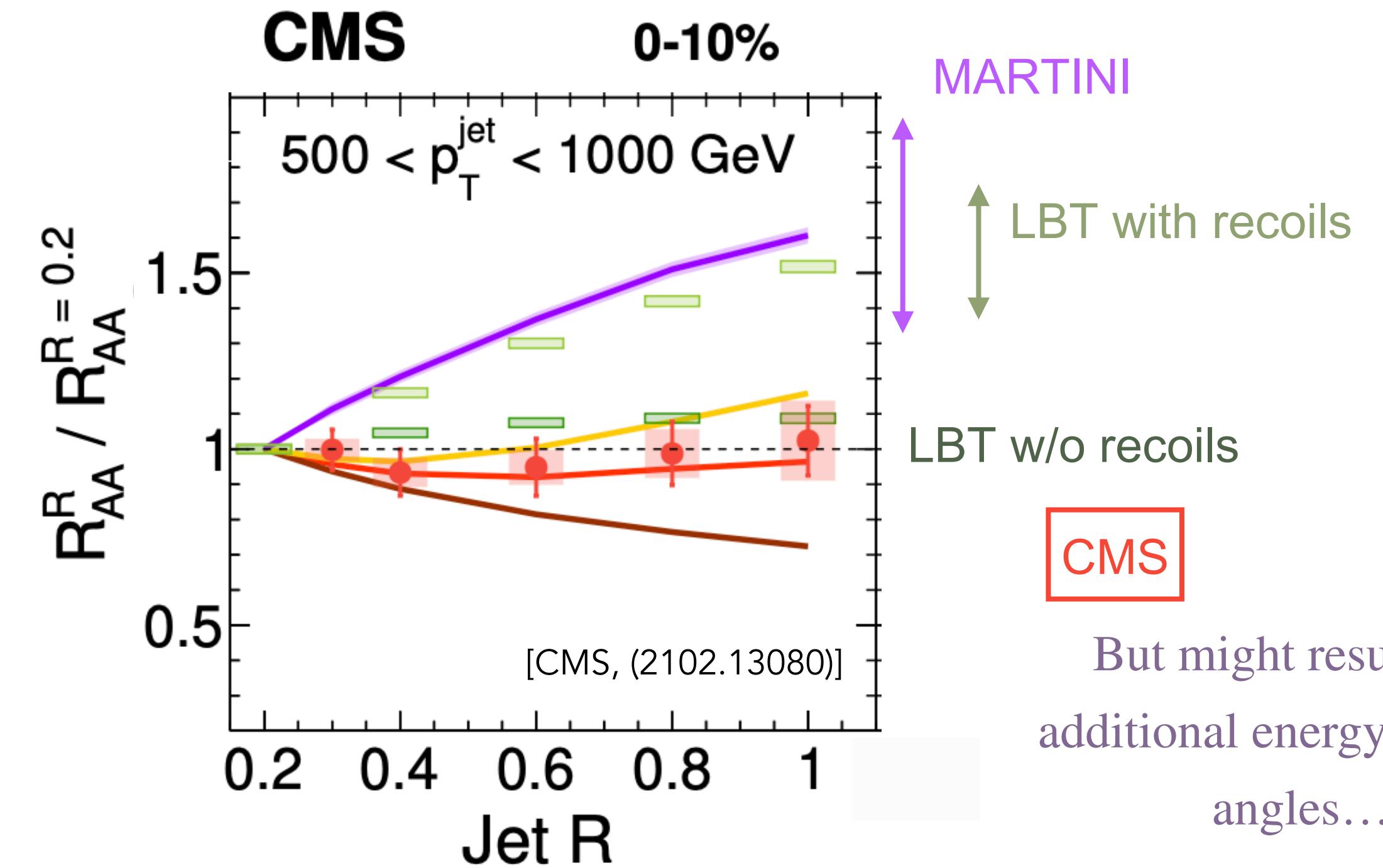
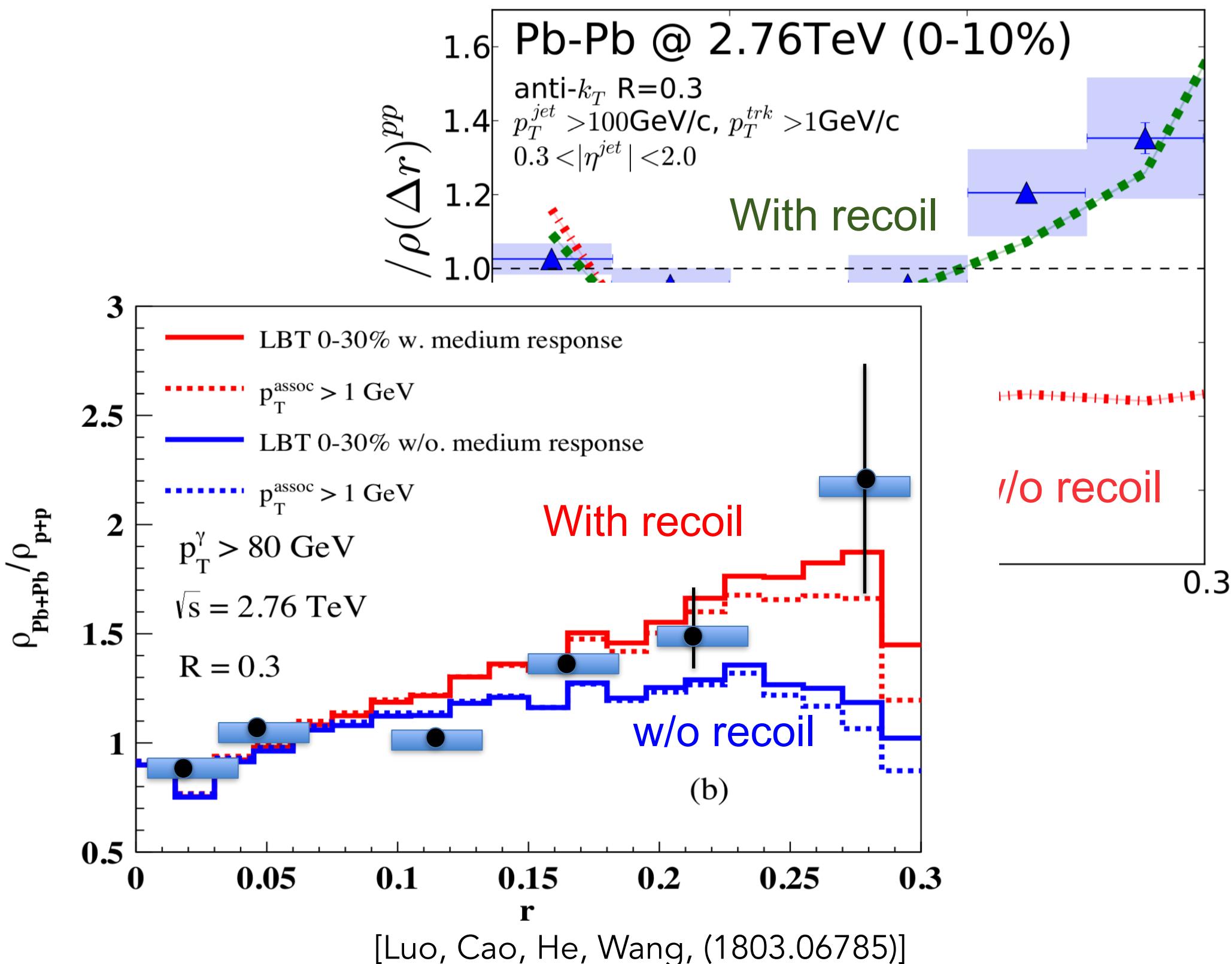


Medium response



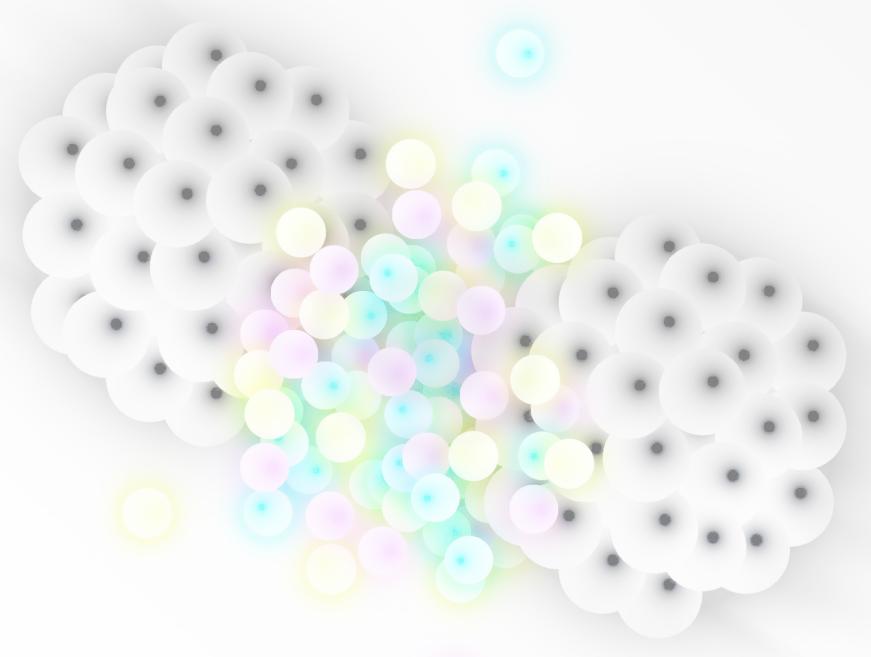
- Soft components seem necessary for a better description of the jet radial profile and/or jet mass:

[Park et al (1807.06550)]

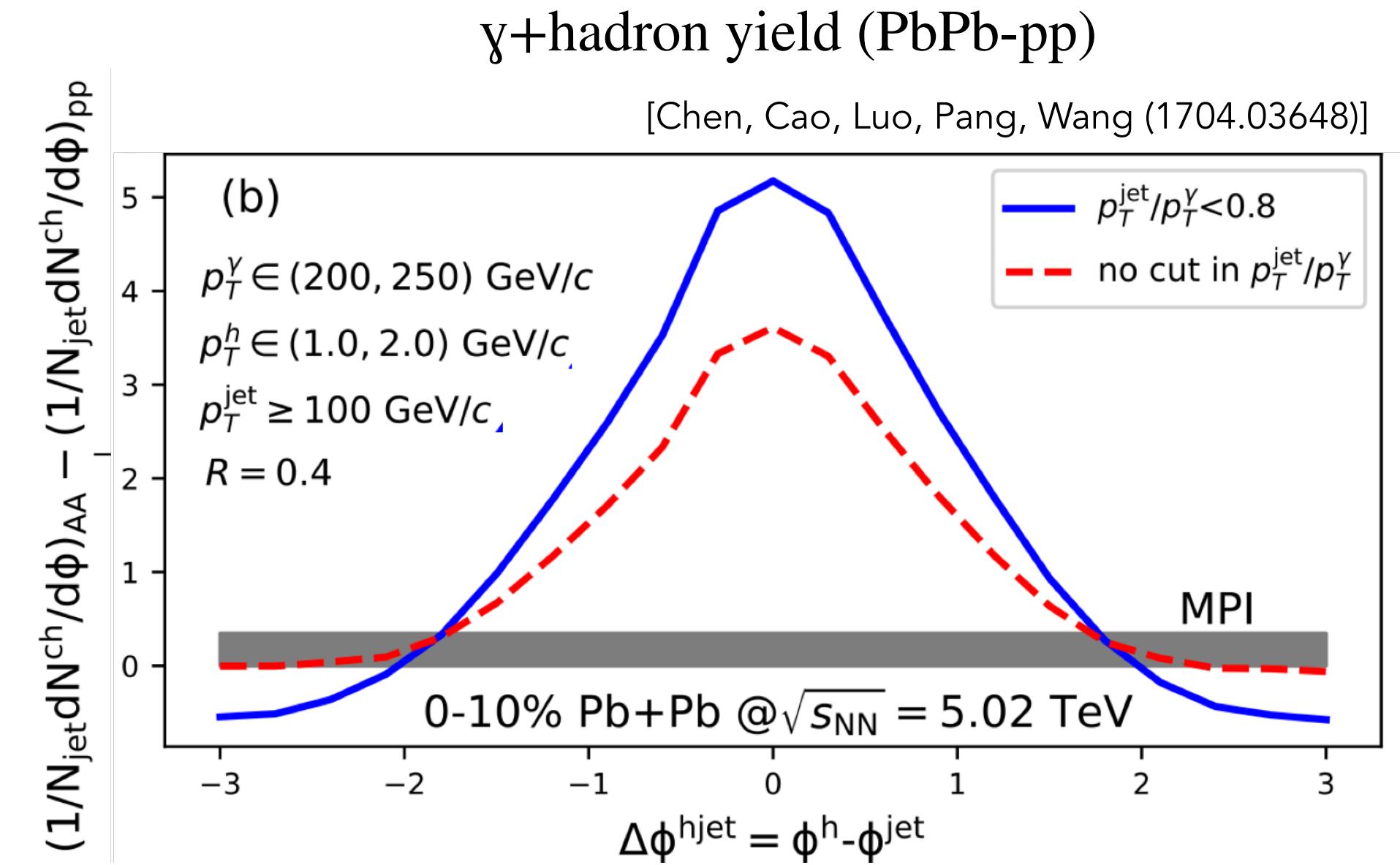
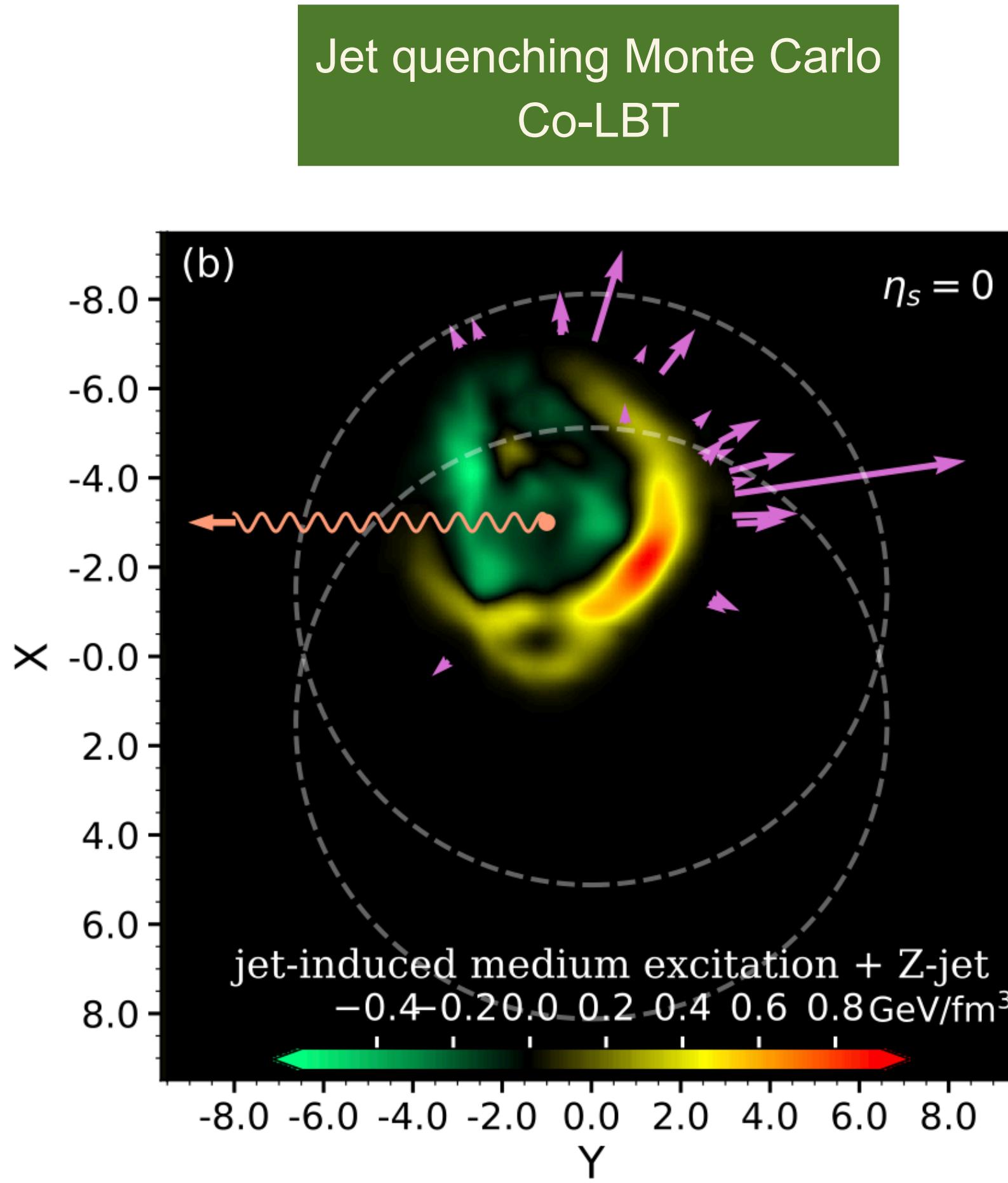


Is the enhancement due to medium-response or to poorly known non-perturbative physics?

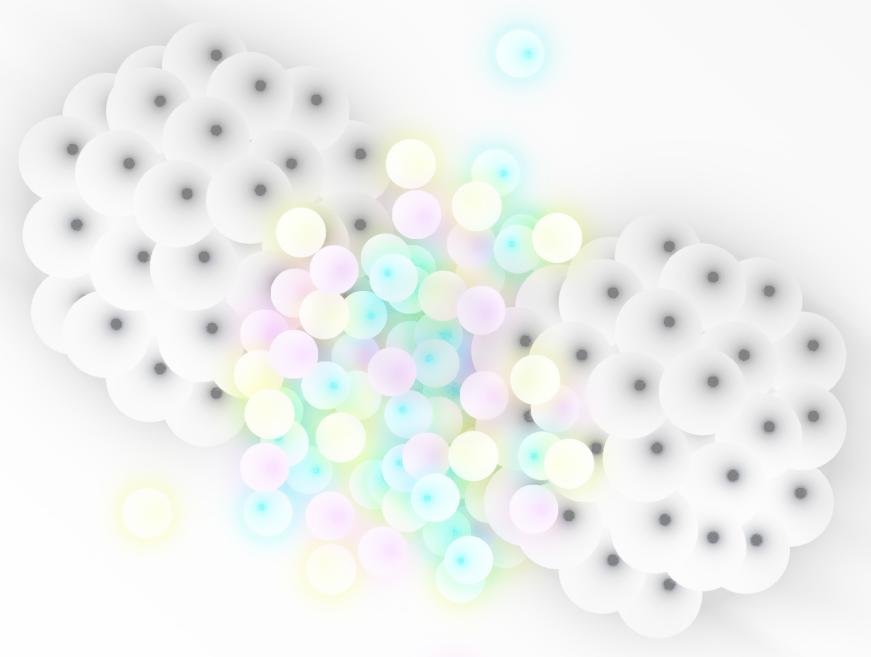
QGP-wake signal



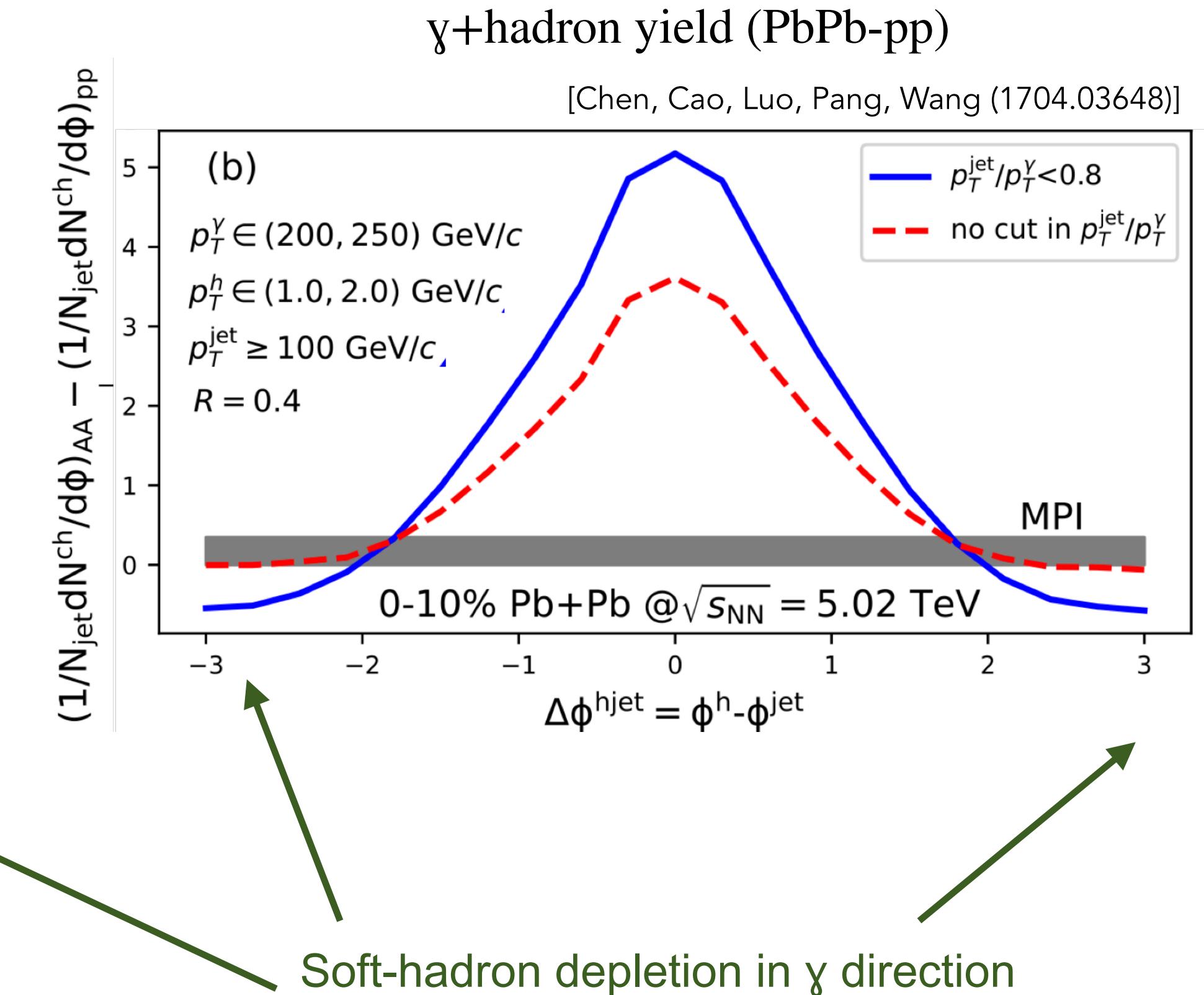
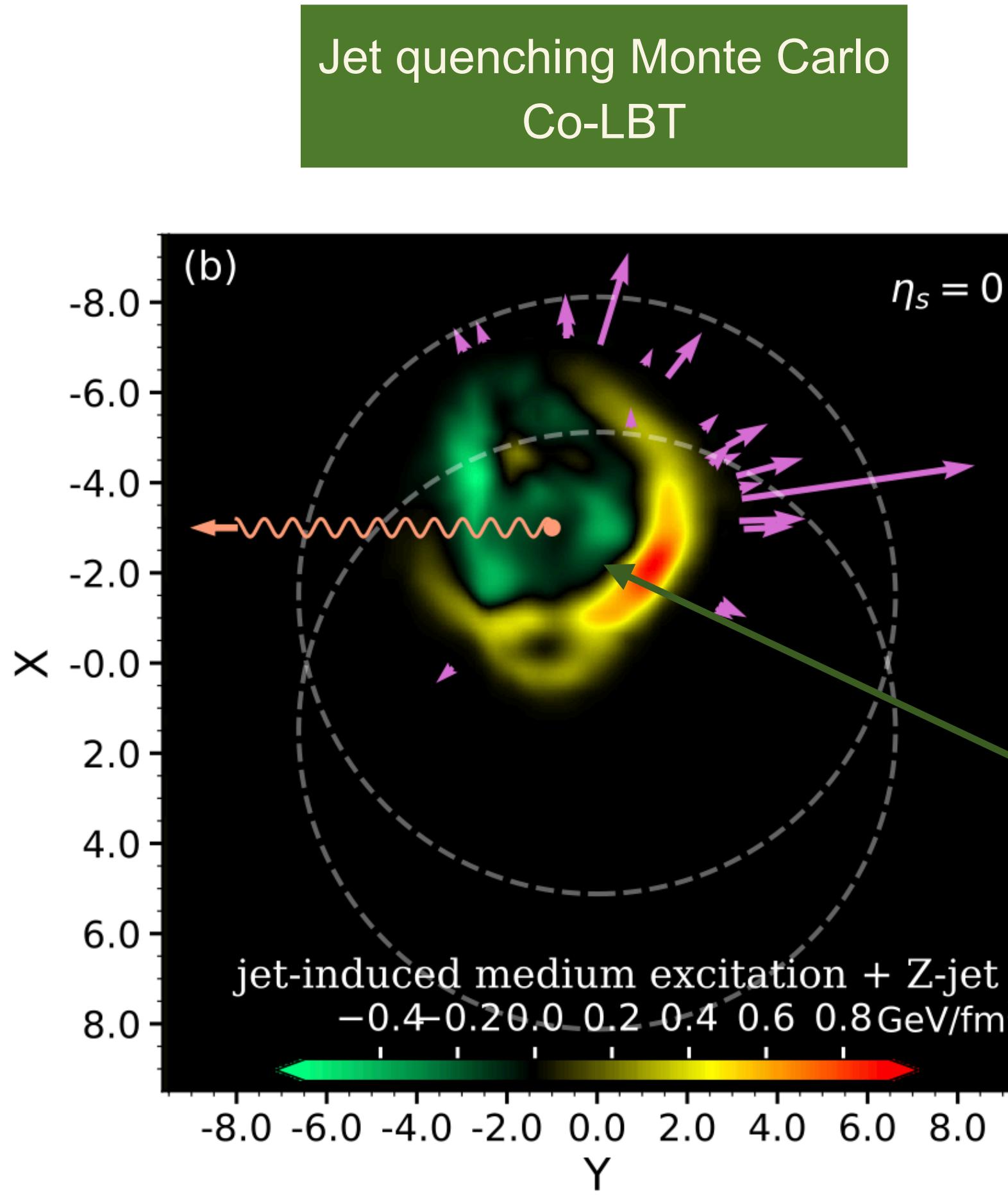
- Jet-induced medium exceptions in Z+jet events:



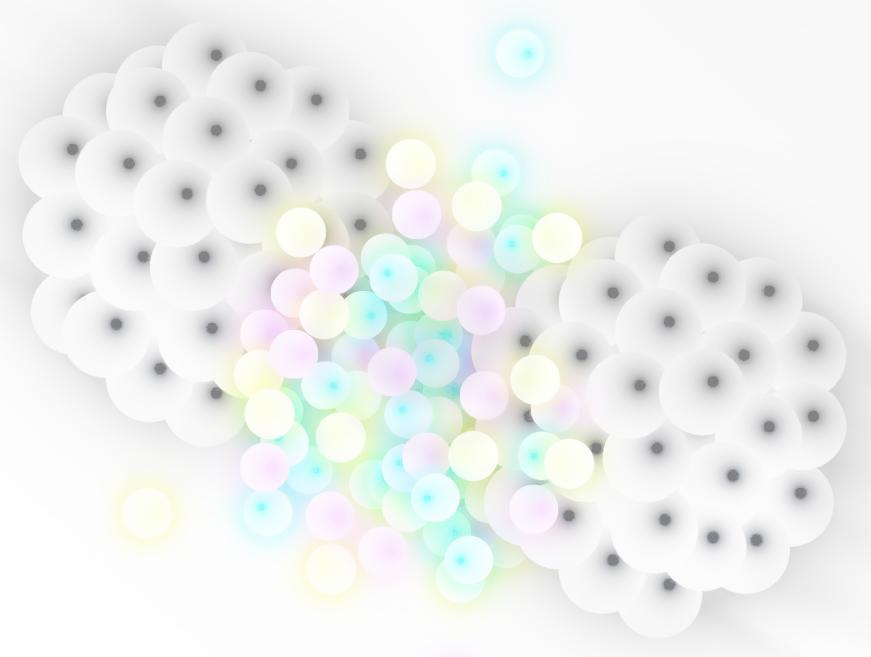
QGP-wake signal



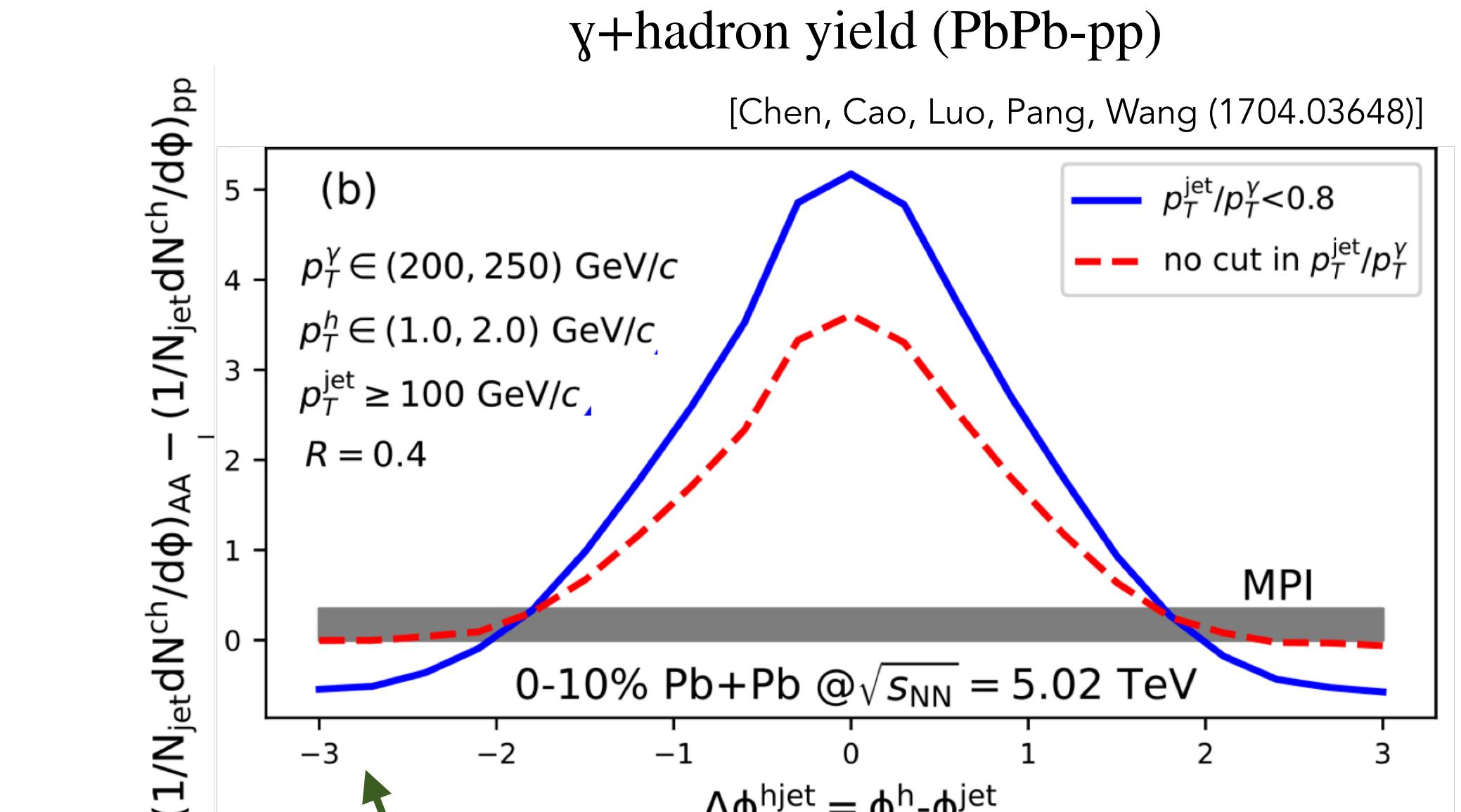
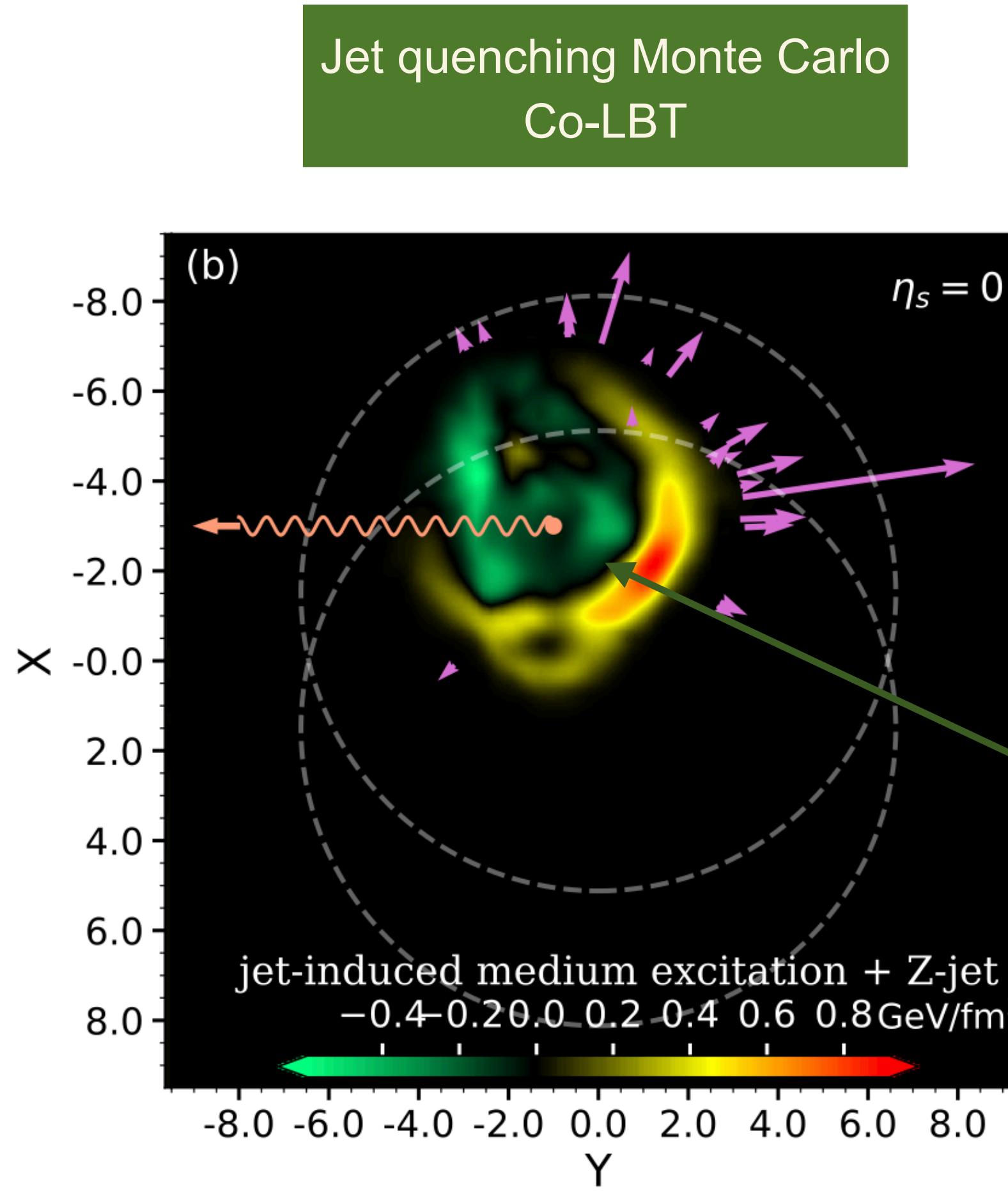
- Jet-induced medium exceptions in Z+jet events:



QGP-wake signal



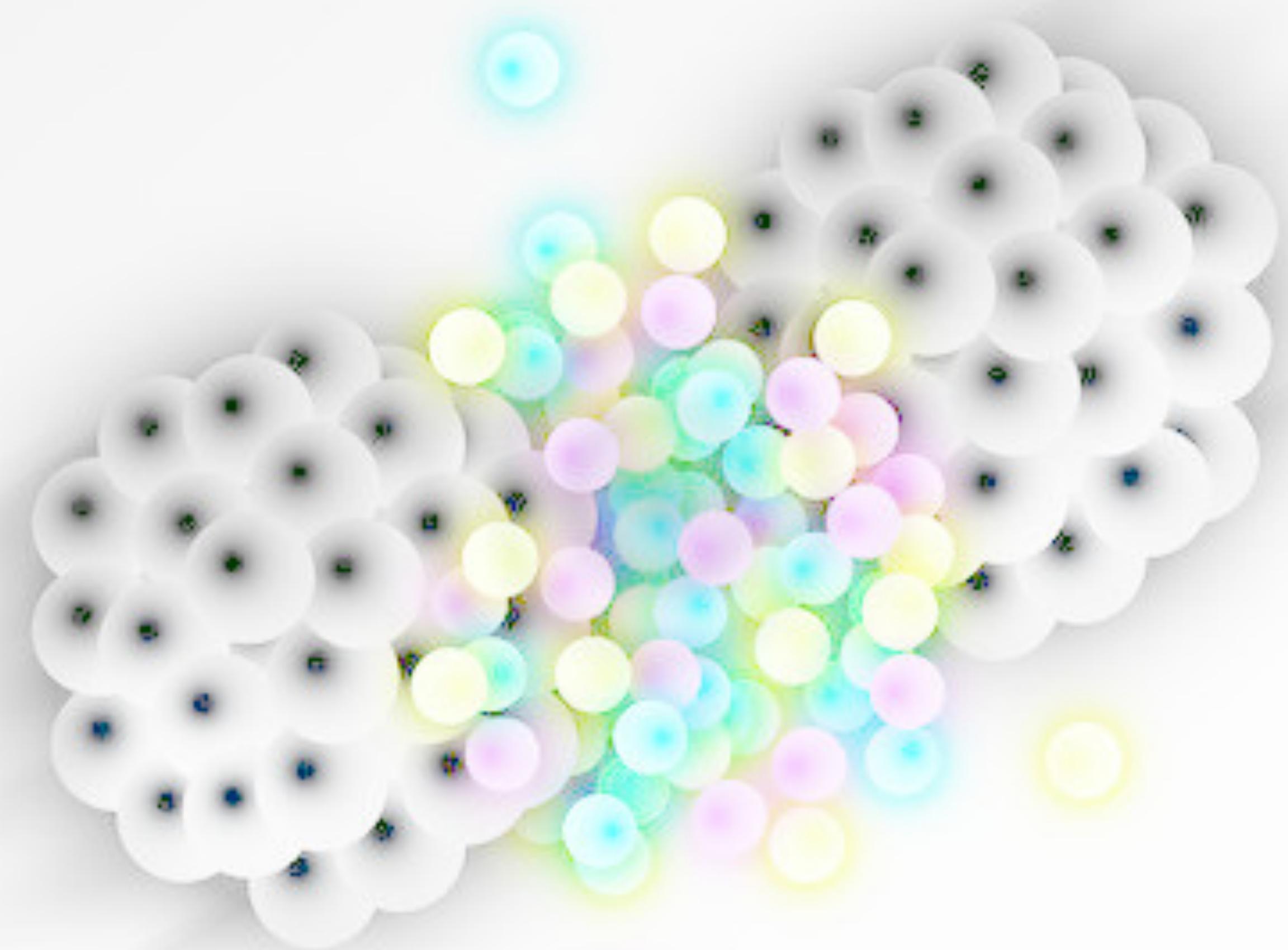
- Jet-induced medium exceptions in Z+jet events:



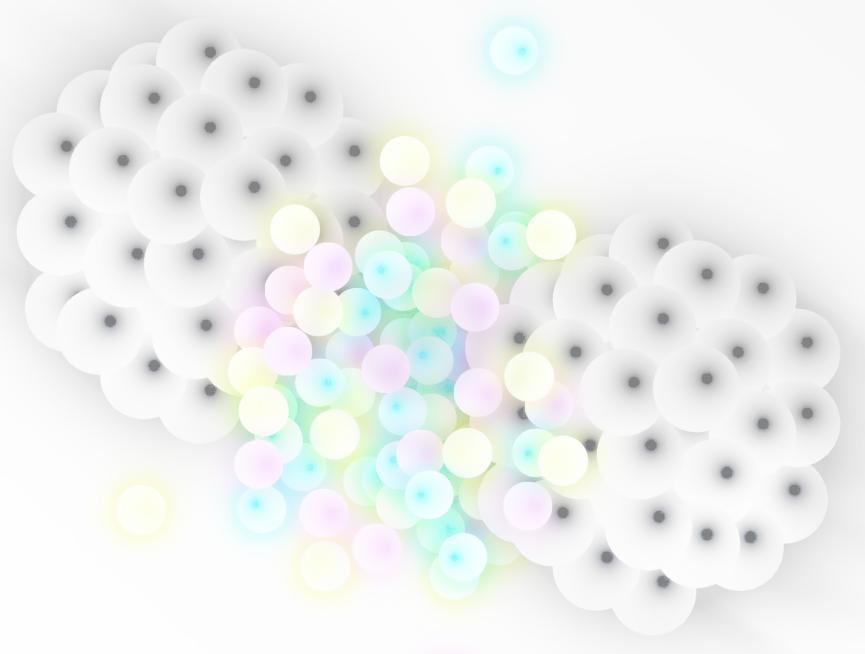
Soft-hadron depletion in γ direction

Introduction of viscous hydro in MC \Rightarrow 3D Wake that depend on EoS

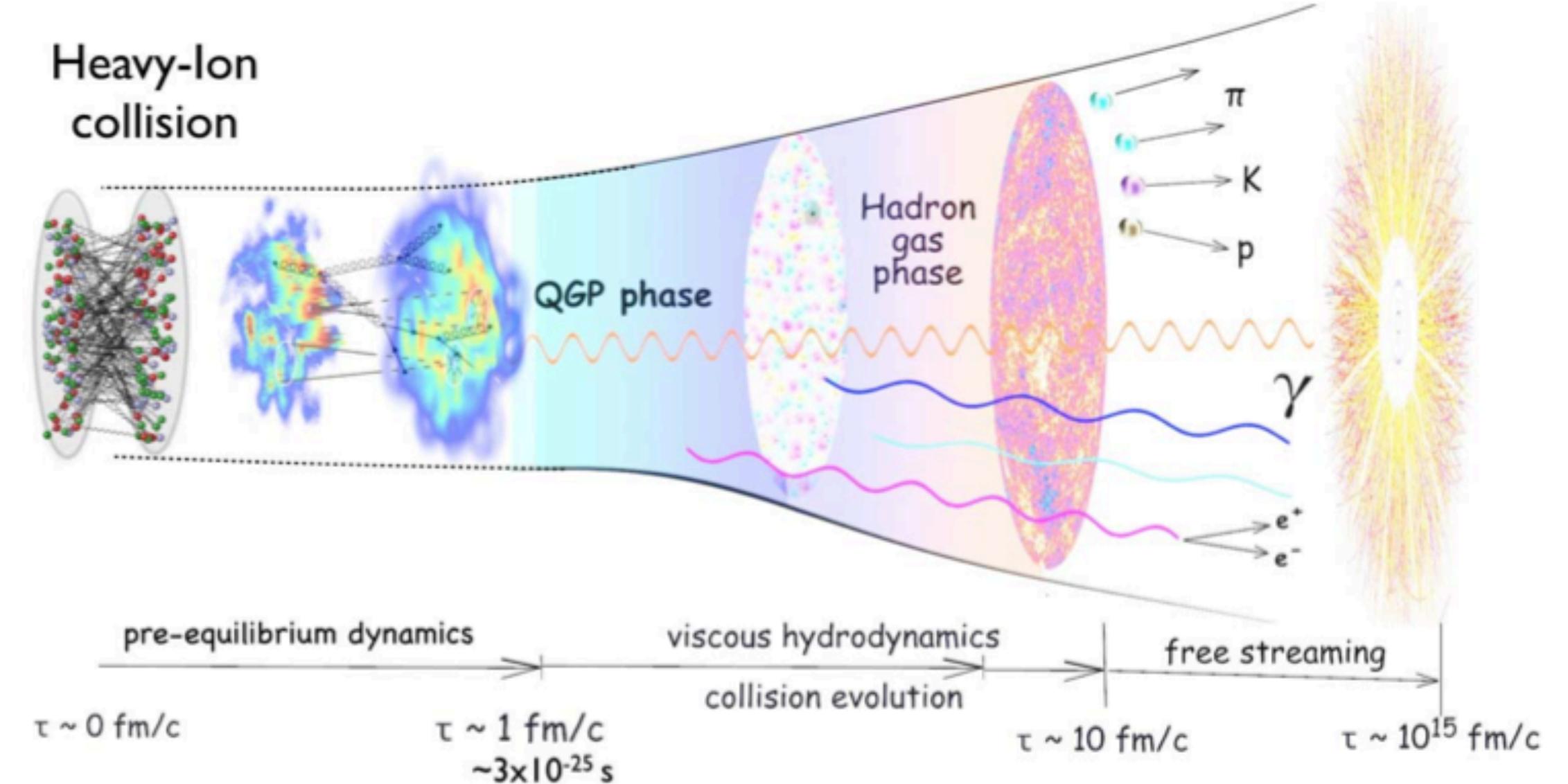
QGP time evolution



QGP: a fast expanding medium



- What is the information that we get?
 - Integrated result of the whole medium (fast) evolution
 - However there is a strong time-dependence of the medium properties (expansion and cooling of the system)

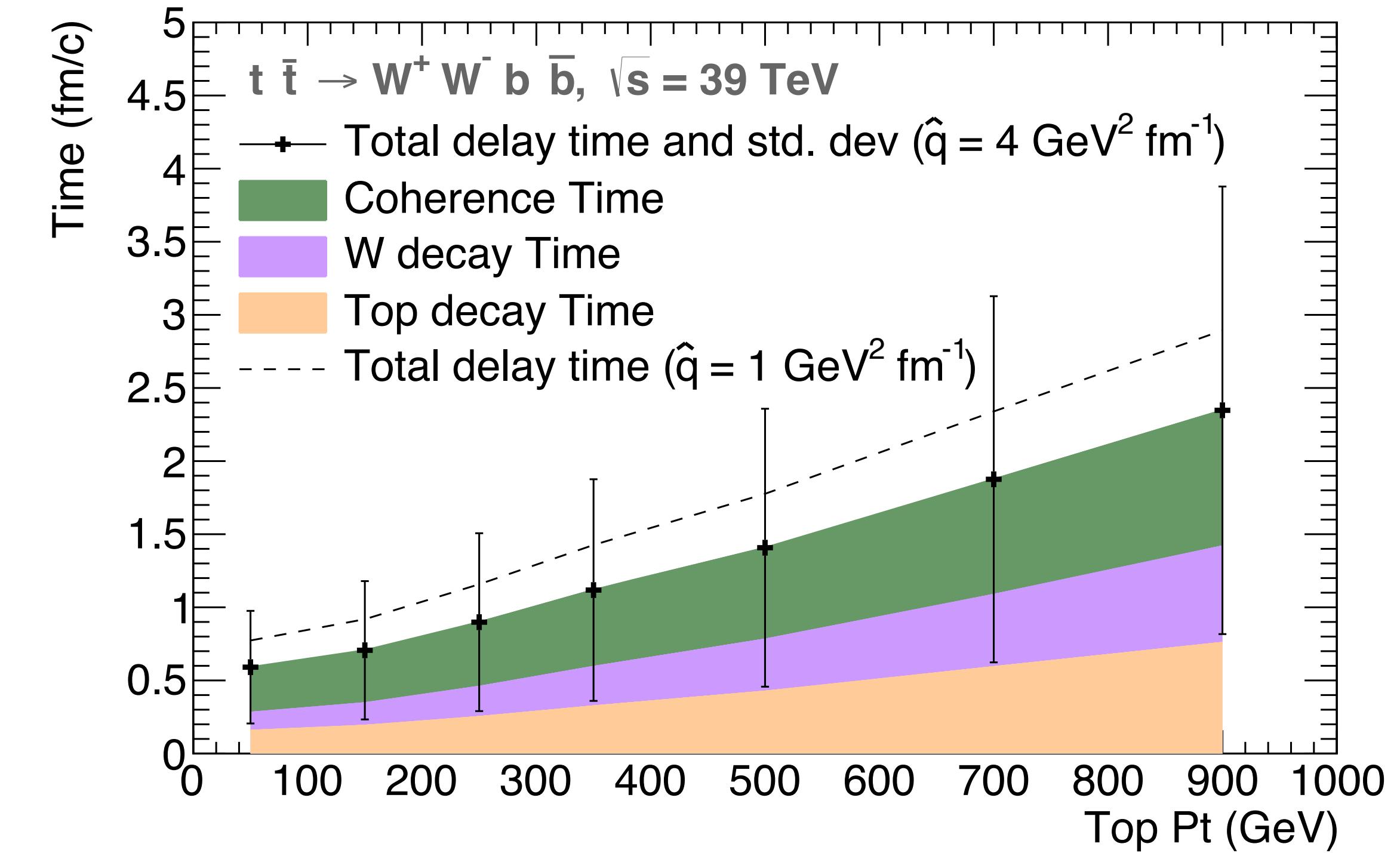
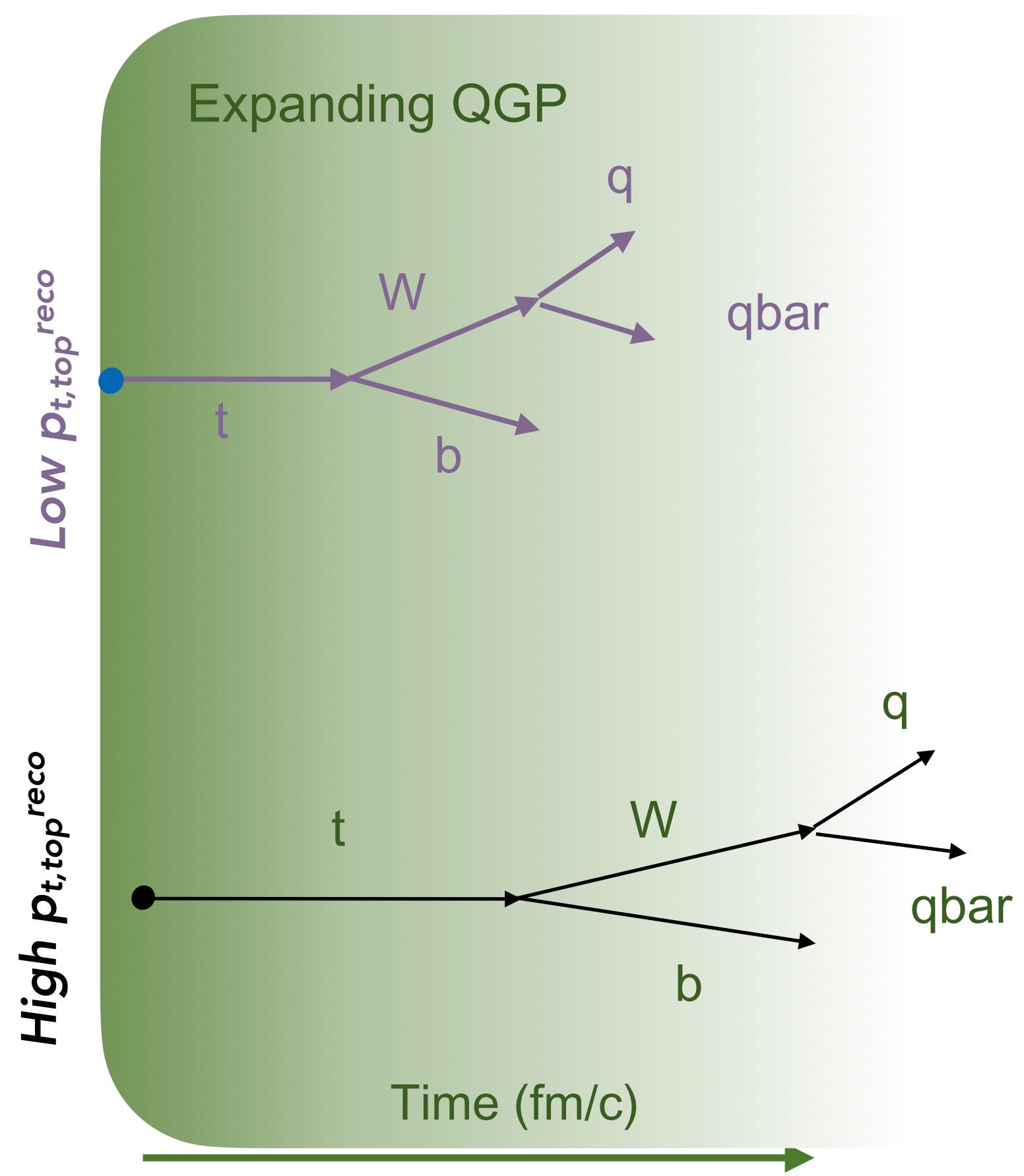


Can hard probes be able to probe different structures of the QGP?

Sensitivity to QGP timescales



- Reconstructed hadronic W boson jet mass:



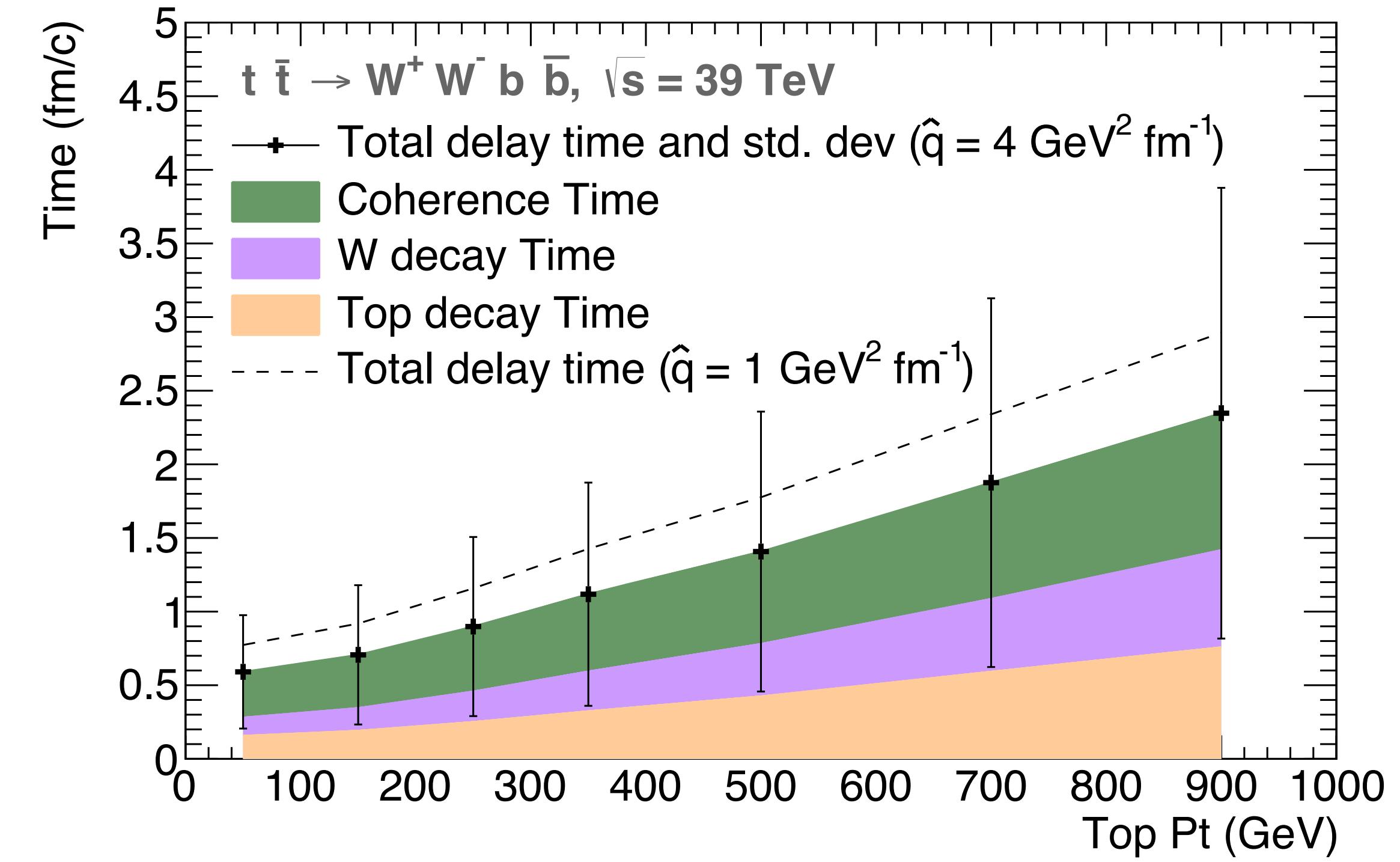
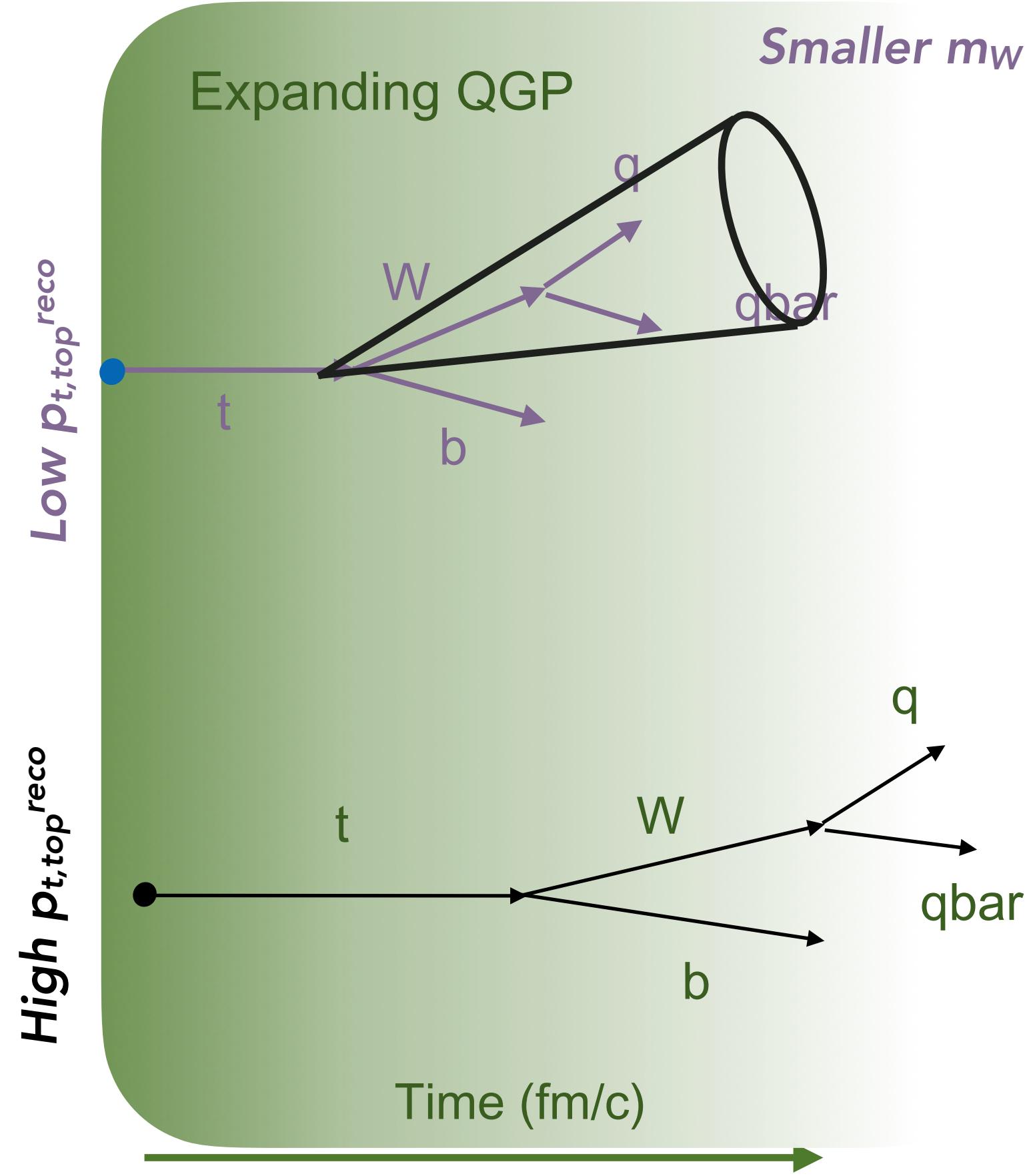
Decay times boosted by: $\gamma_{t,X} = \sqrt{p_{t,X}^2/m_X^2 + 1}$

qqbar remains coherent during: $\tau_d = (12/(\hat{q}\theta_{q\bar{q}}^2))^{1/3}$

Sensitivity to QGP timescales



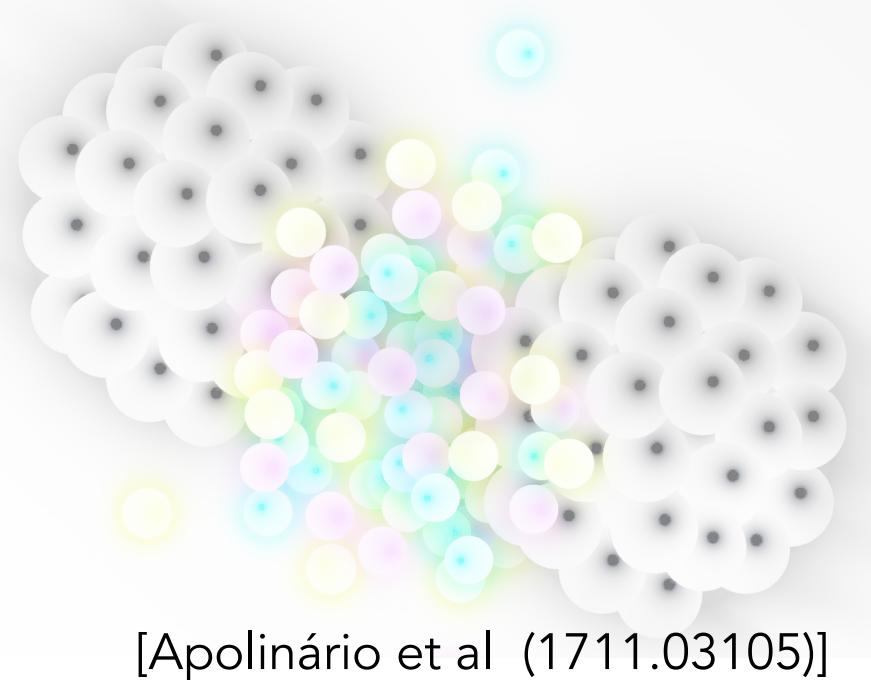
- Reconstructed hadronic W boson jet mass:



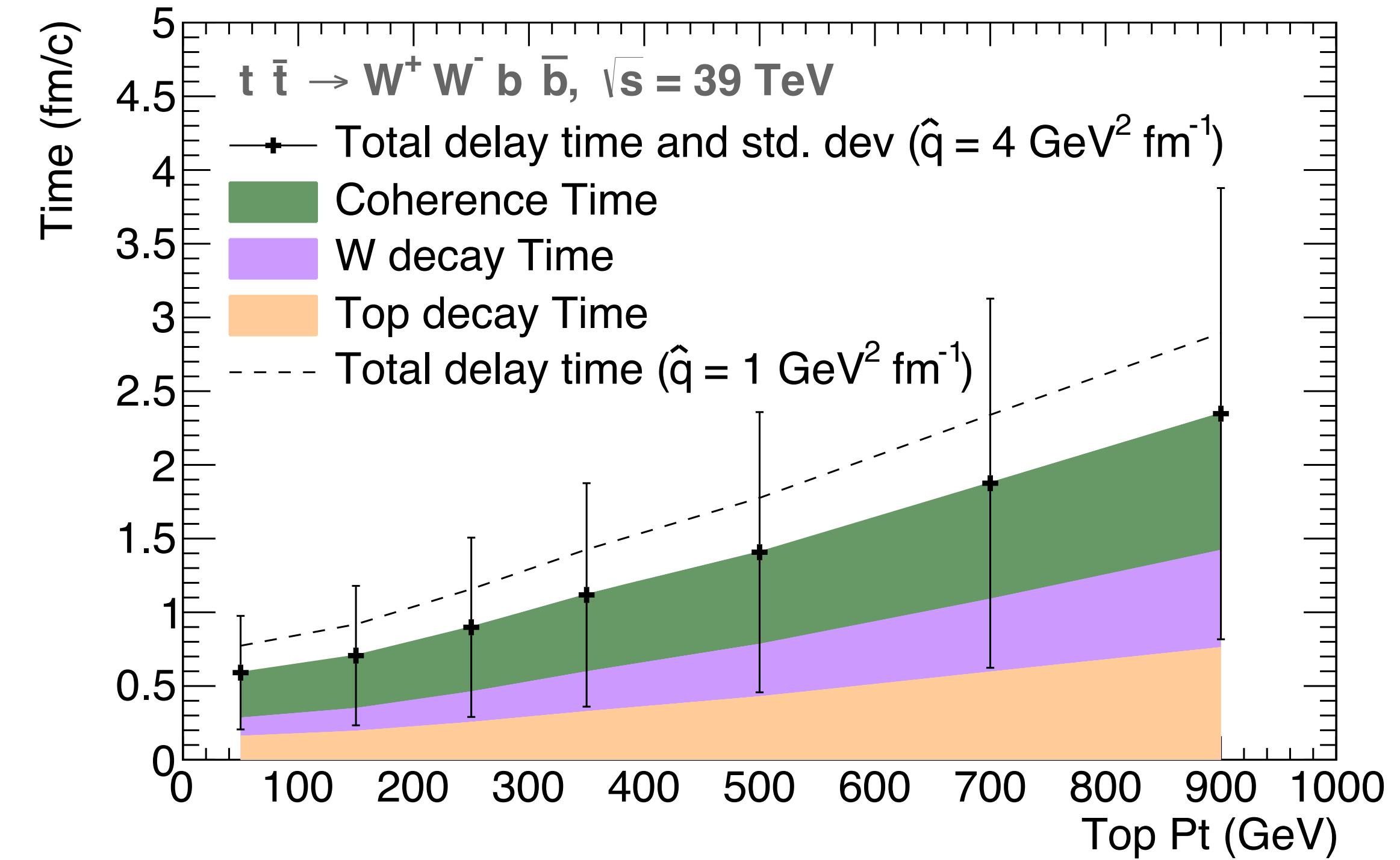
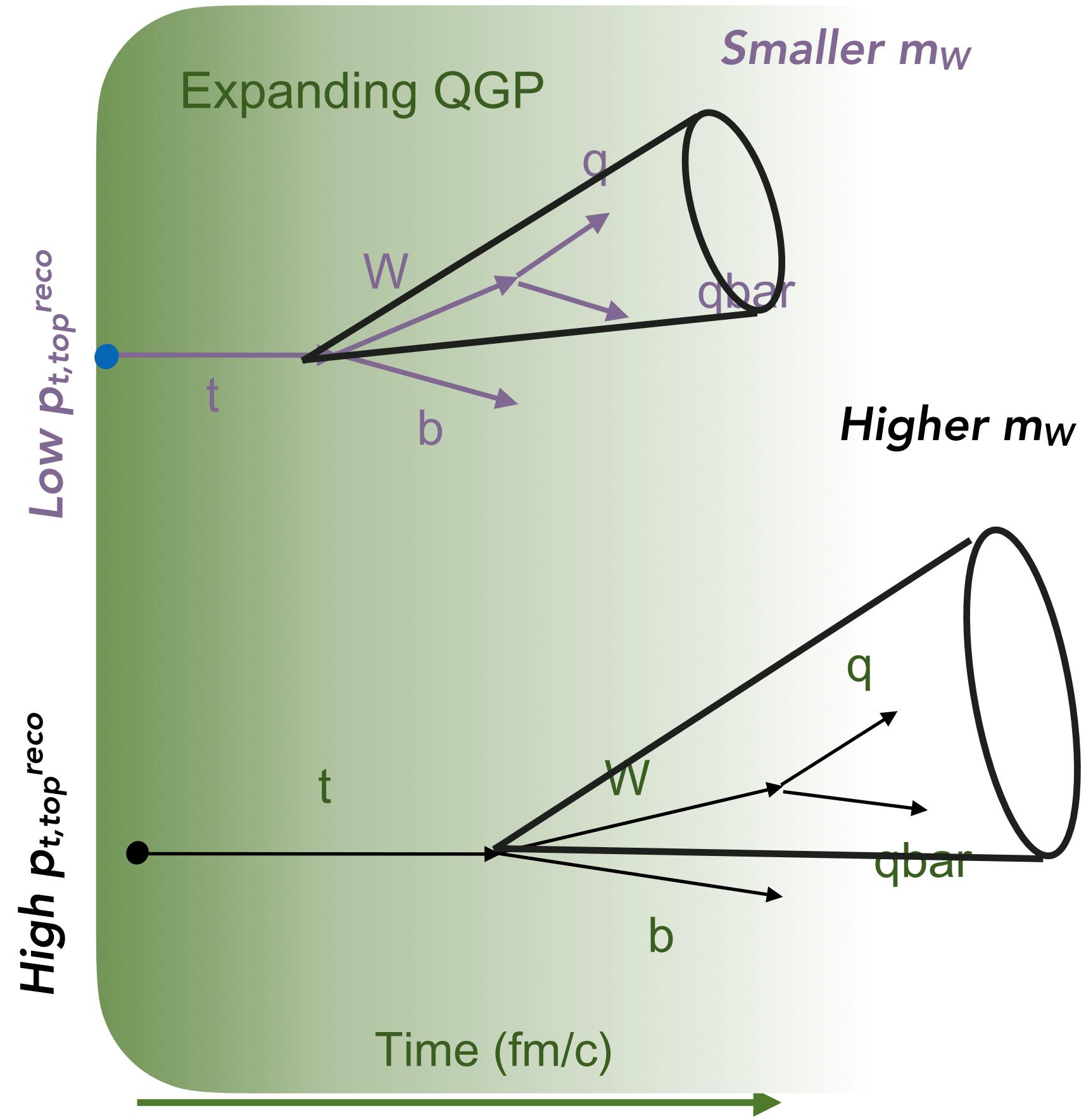
Decay times boosted by: $\gamma_{t,X} = \sqrt{p_{t,X}^2/m_X^2 + 1}$

$q\bar{q}$ remains coherent during: $\tau_d = (12/(\hat{q}\theta_{q\bar{q}}^2))^{1/3}$

Sensitivity to QGP timescales



- Reconstructed hadronic W boson jet mass:

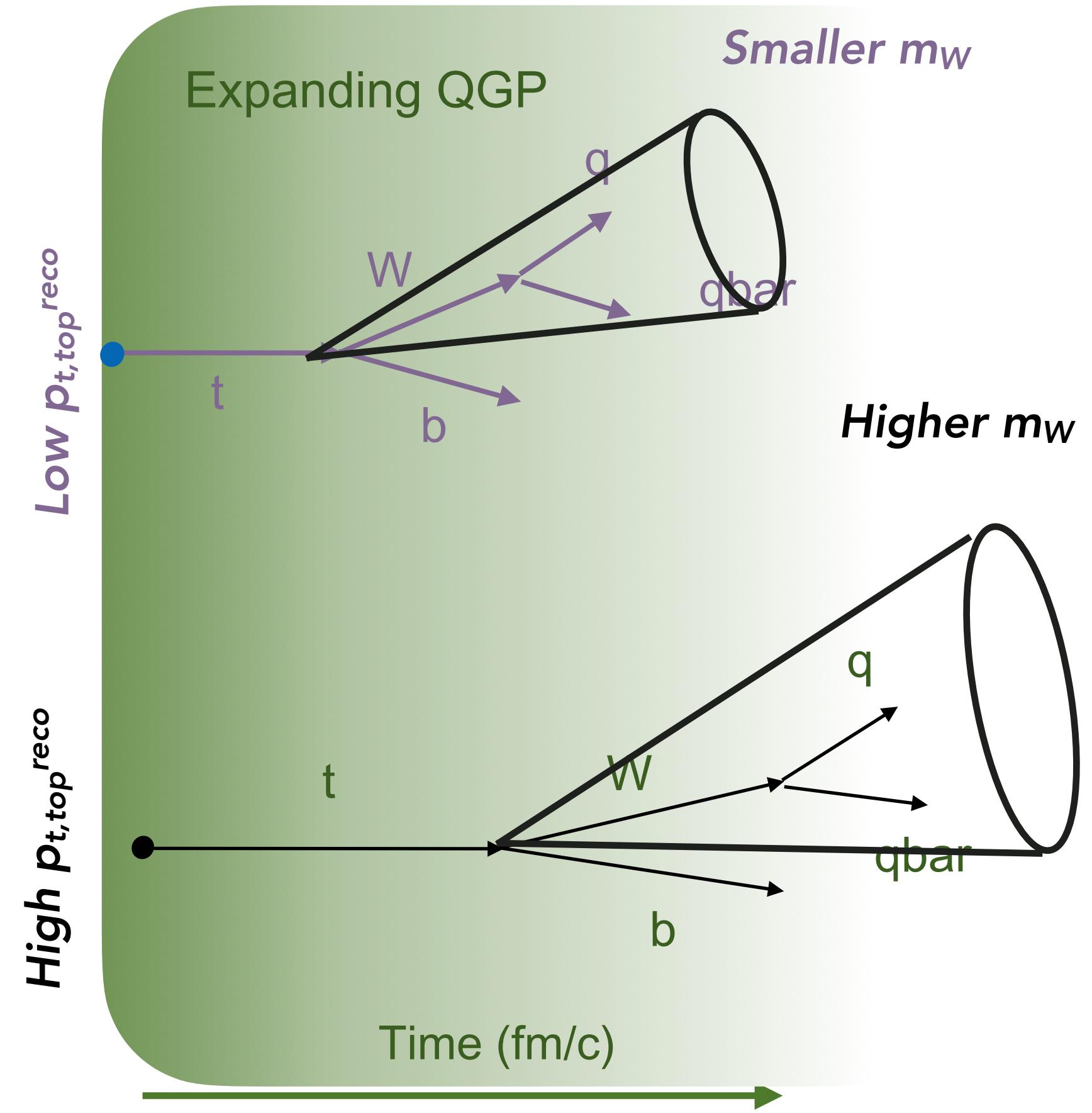


Decay times boosted by: $\gamma_{t,X} = \sqrt{p_{t,X}^2/m_X^2 + 1}$

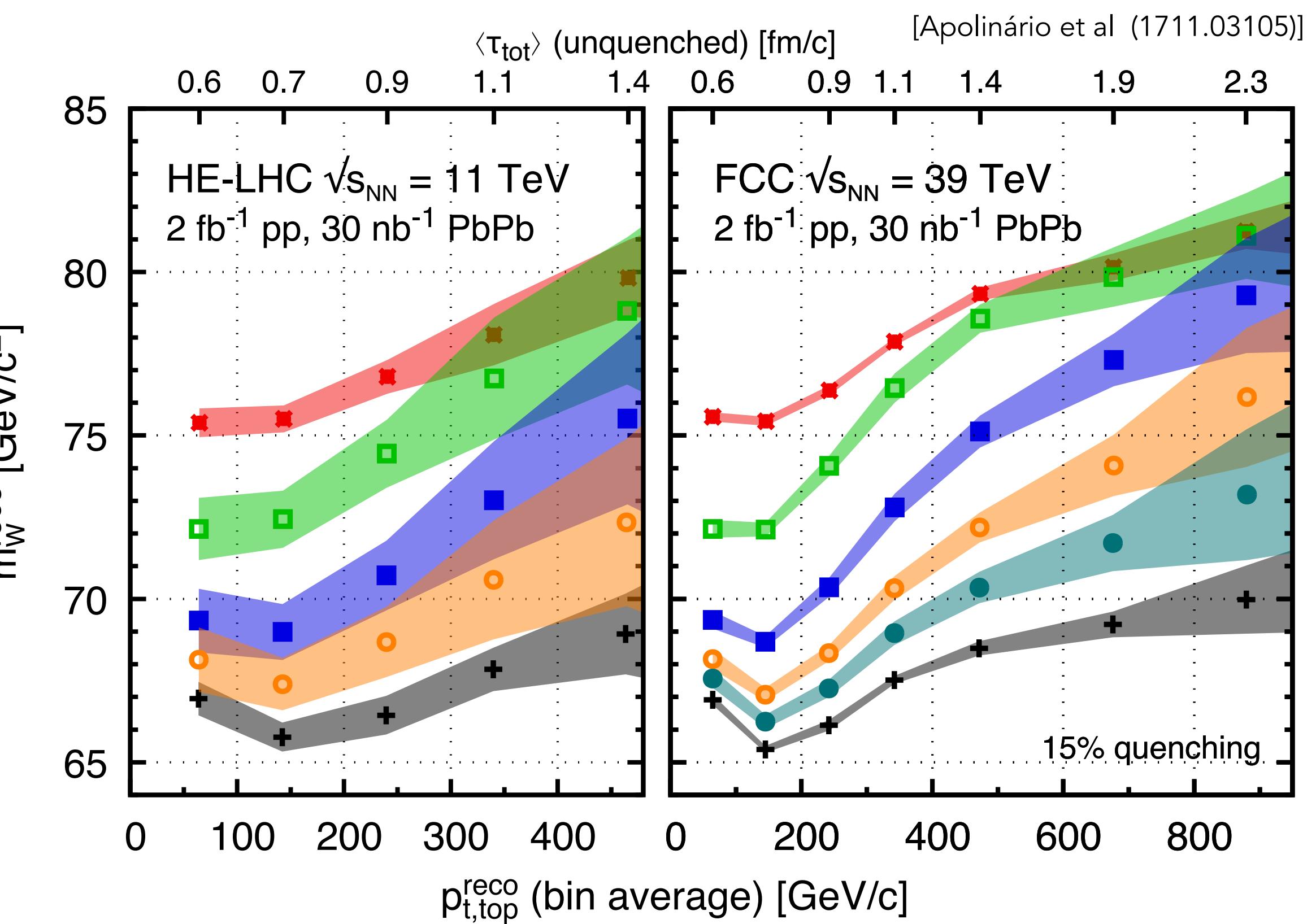
qqbar remains coherent during: $\tau_d = (12/(\hat{q}\theta_{q\bar{q}}^2))^{1/3}$

Sensitivity to QGP timescales

- Reconstructed hadronic W boson jet mass:

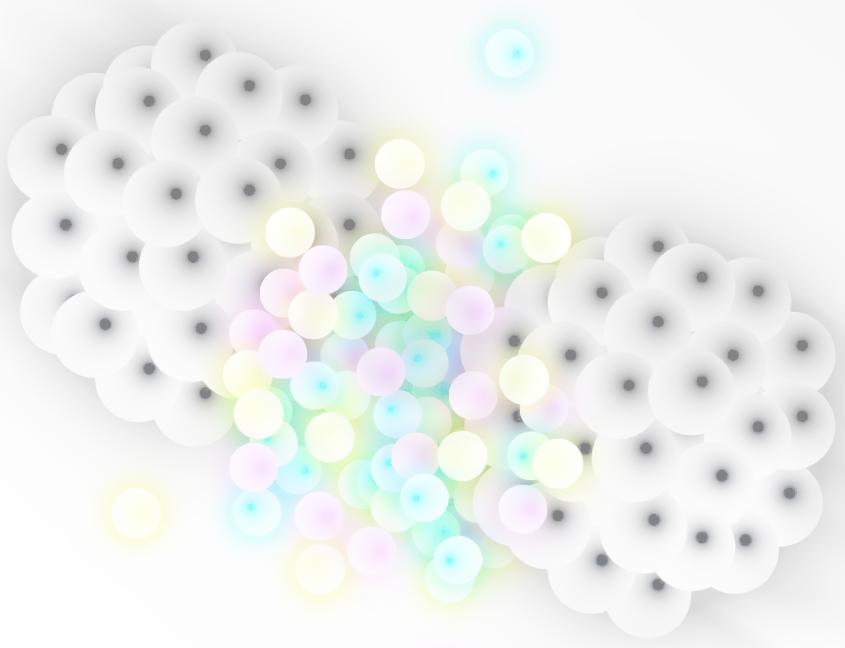


■ unquenched + quenched	□ $\tau_m = 1.0 \text{ fm/c}$ ■ $\tau_m = 2.5 \text{ fm/c}$	○ $\tau_m = 5 \text{ fm/c}$ ● $\tau_m = 10 \text{ fm/c}$
---	---	---



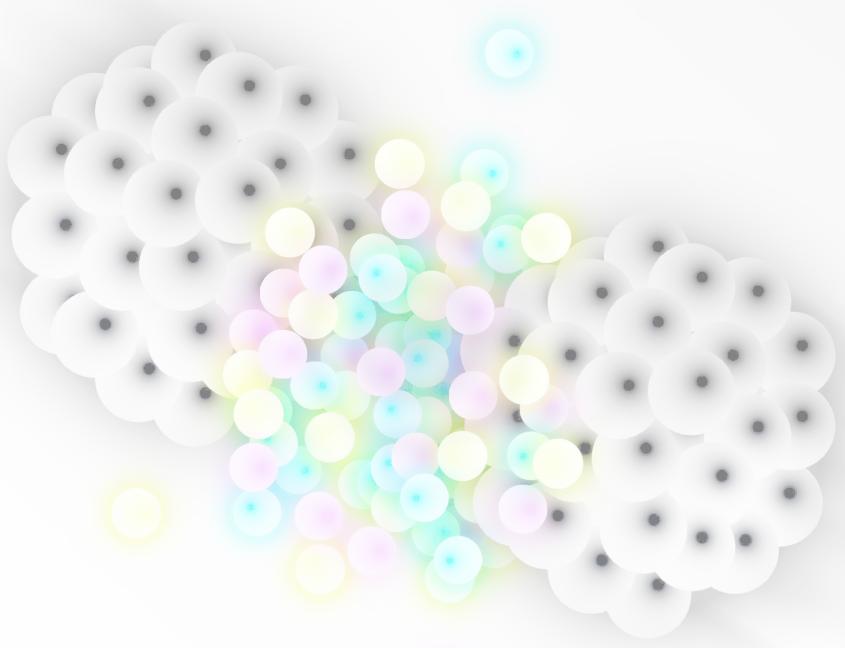
Tops as time-delayed probes of the QGP
(QGP tomography)

Take-home messages



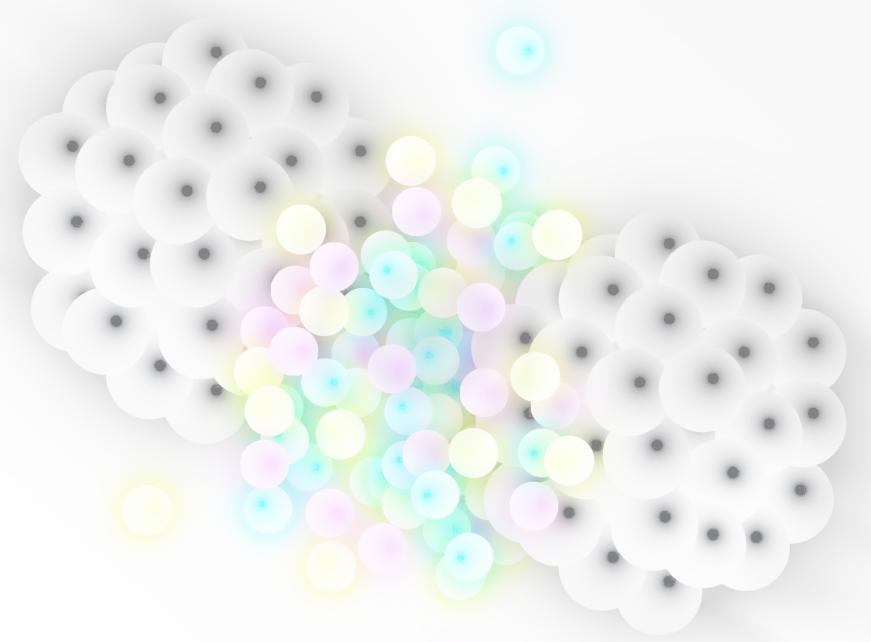
- There isn't a method able to address QCD in-medium processes across all momentum scales...
 - **Success** lies in pQCD accuracy + non-pQCD modelling

Take-home messages



- There isn't a method able to address QCD in-medium processes across all momentum scales...
 - **Success** lies in pQCD accuracy + non-pQCD modelling
- **Hard probes** are a powerful tool to study QCD in different density regimes
 - Access to:
 - QGP transport coefficients, QGP time-evolution,...
 - Novel phenomena w.r.t to “vacuum” (e.g: anti-angular ordering)
 - Push/test pQCD boundaries!

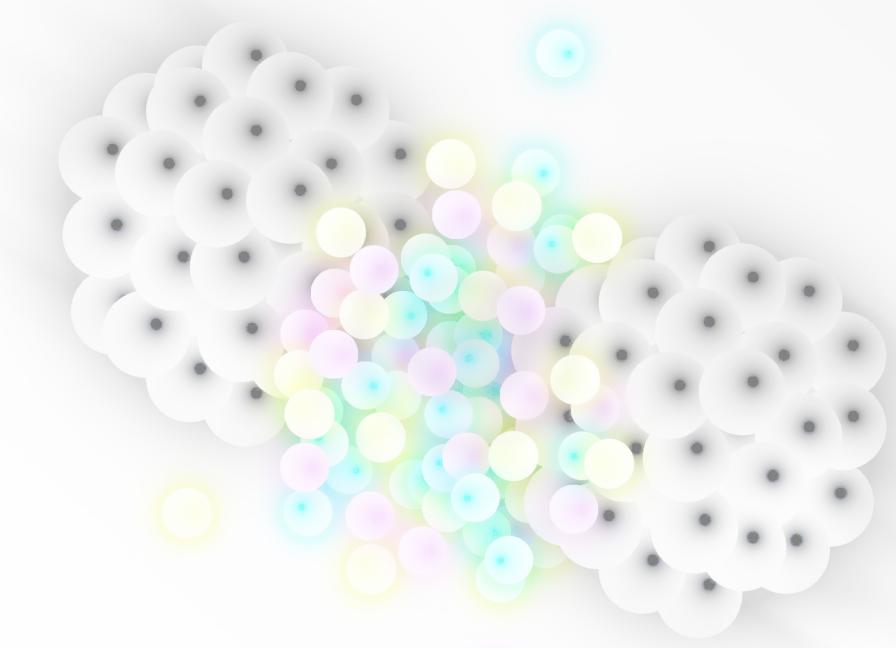
Take-home messages



- There isn't a method able to address QCD in-medium processes across all momentum scales...
 - **Success** lies in pQCD accuracy + non-pQCD modelling
- **Hard probes** are a powerful tool to study QCD in different density regimes
 - Access to:
 - QGP transport coefficients, QGP time-evolution,...
 - Novel phenomena w.r.t to “vacuum” (e.g: anti-angular ordering)
 - Push/test pQCD boundaries!

Thank you!

Acknowledgments



REPÚBLICA
PORTUGUESA



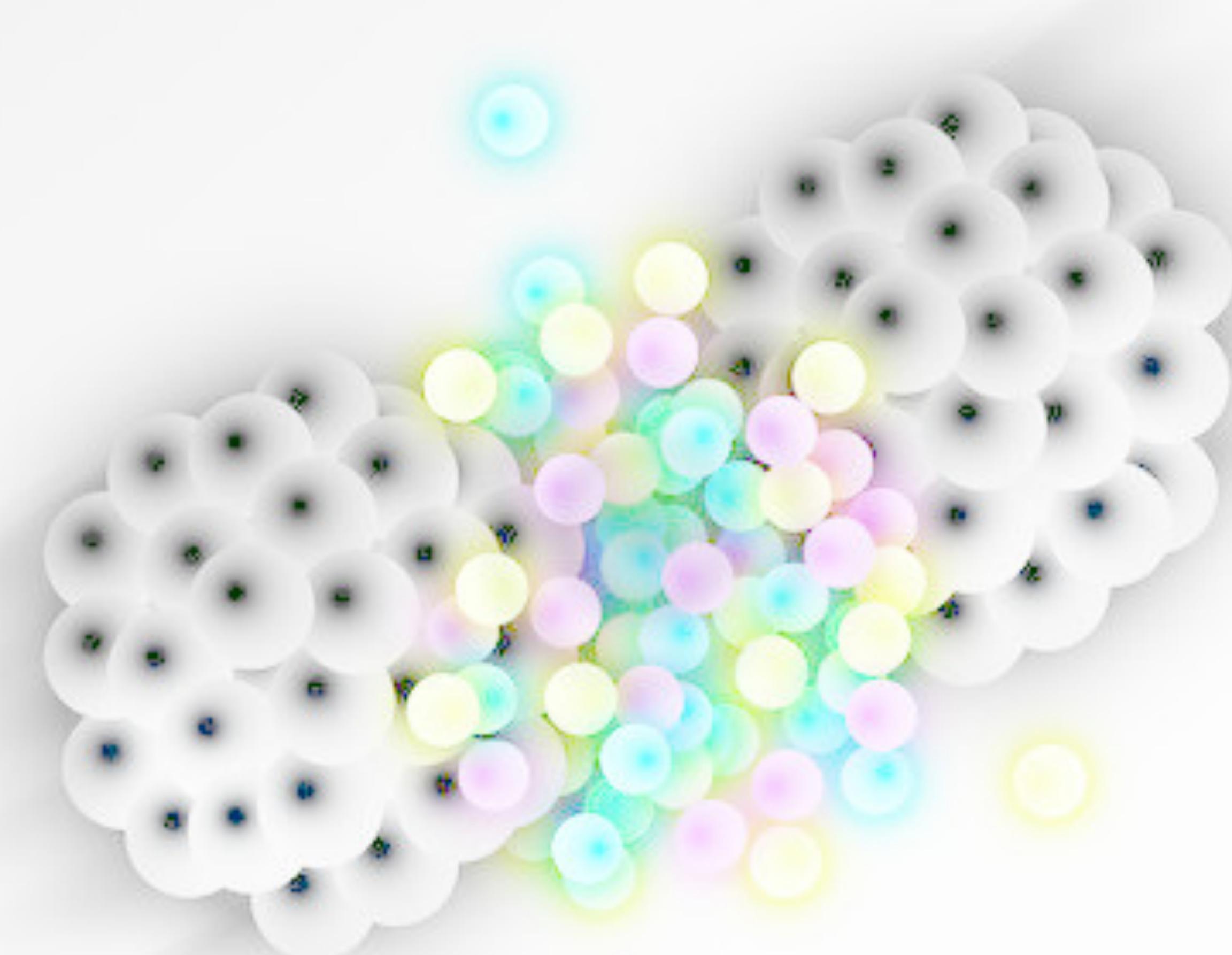
FCT

Fundaçao para a Ciencia e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÉNCIA



TÉCNICO
LISBOA

Backup Slides

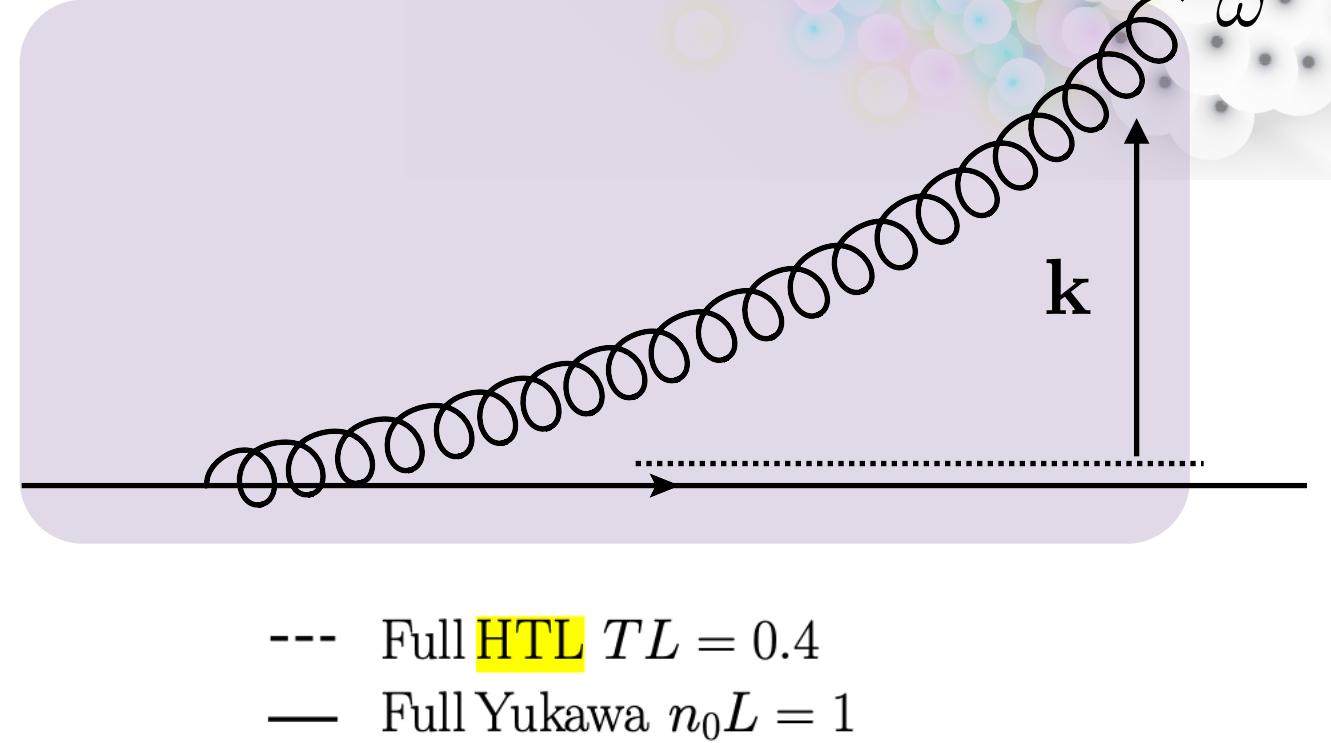


Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Physical picture



Yukawa: $\sigma(r) \propto V(q) = \frac{8\pi\mu^2}{(q^2 + \mu^2)^2}$

Hard Thermal Loop: $\sigma(r) \propto V(q) = \frac{g_s^2 N_c m_D^2 T}{q^2 (q^2 + m_D^2)}$

Scaled energy:

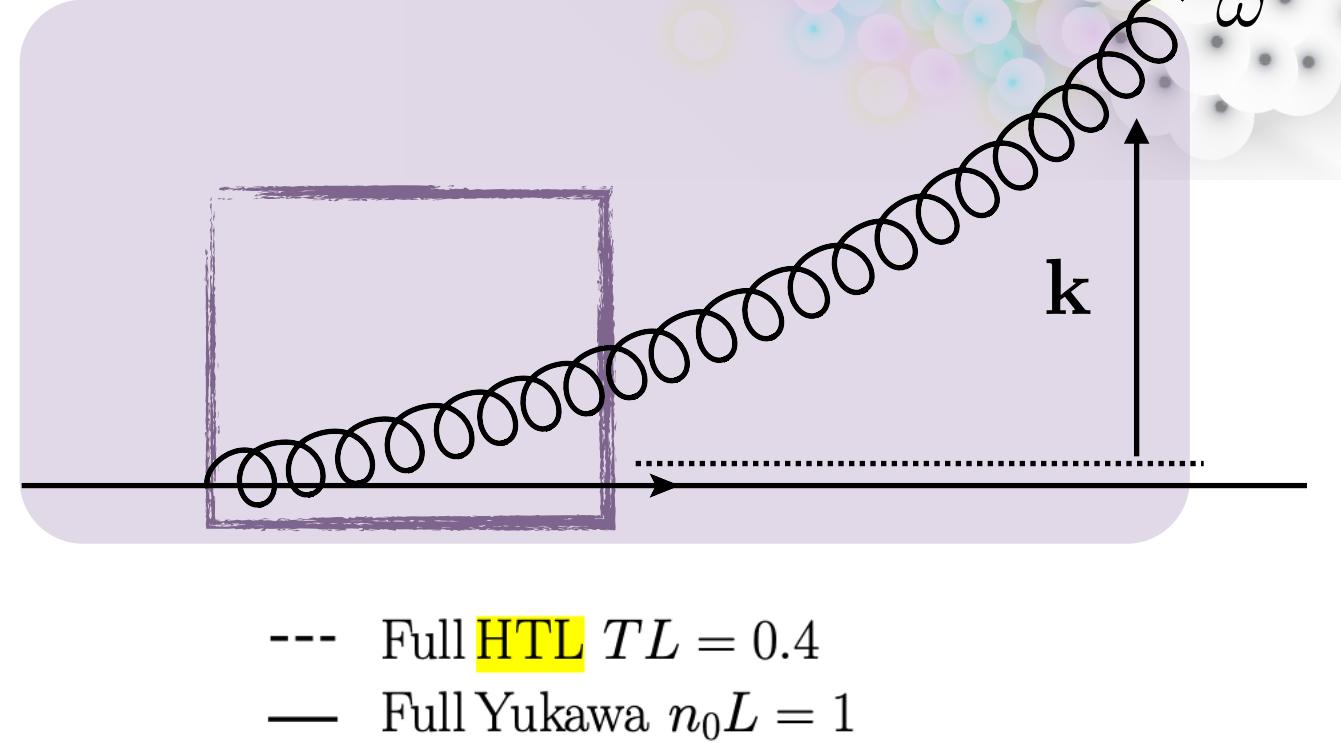
Scaled transverse momentum:

Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Physical picture



Yukawa: $\sigma(r) \propto V(q) = \frac{8\pi\mu^2}{(q^2 + \mu^2)^2}$

Hard Thermal Loop: $\sigma(r) \propto V(q) = \frac{g_s^2 N_c m_D^2 T}{q^2 (q^2 + m_D^2)}$

Scaled energy:

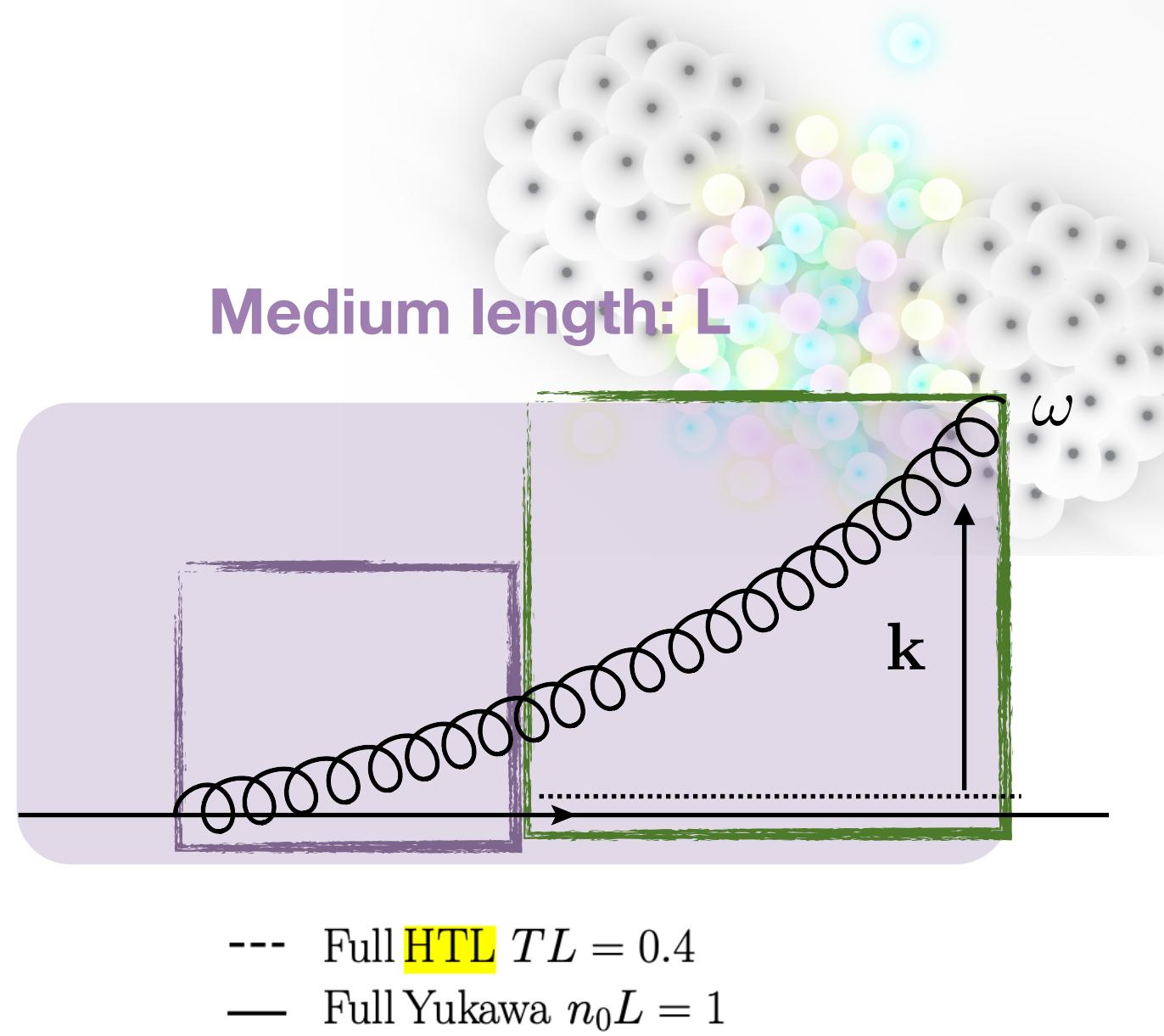
Scaled transverse momentum:

Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

Physical picture



Yukawa: $\sigma(r) \propto V(q) = \frac{8\pi\mu^2}{(q^2 + \mu^2)^2}$

Hard Thermal Loop: $\sigma(r) \propto V(q) = \frac{g_s^2 N_c m_D^2 T}{q^2 (q^2 + m_D^2)}$

Scaled energy:

Scaled transverse momentum:

Medium-induced radiation

- Medium-induced gluon radiation (numerical evaluation)

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

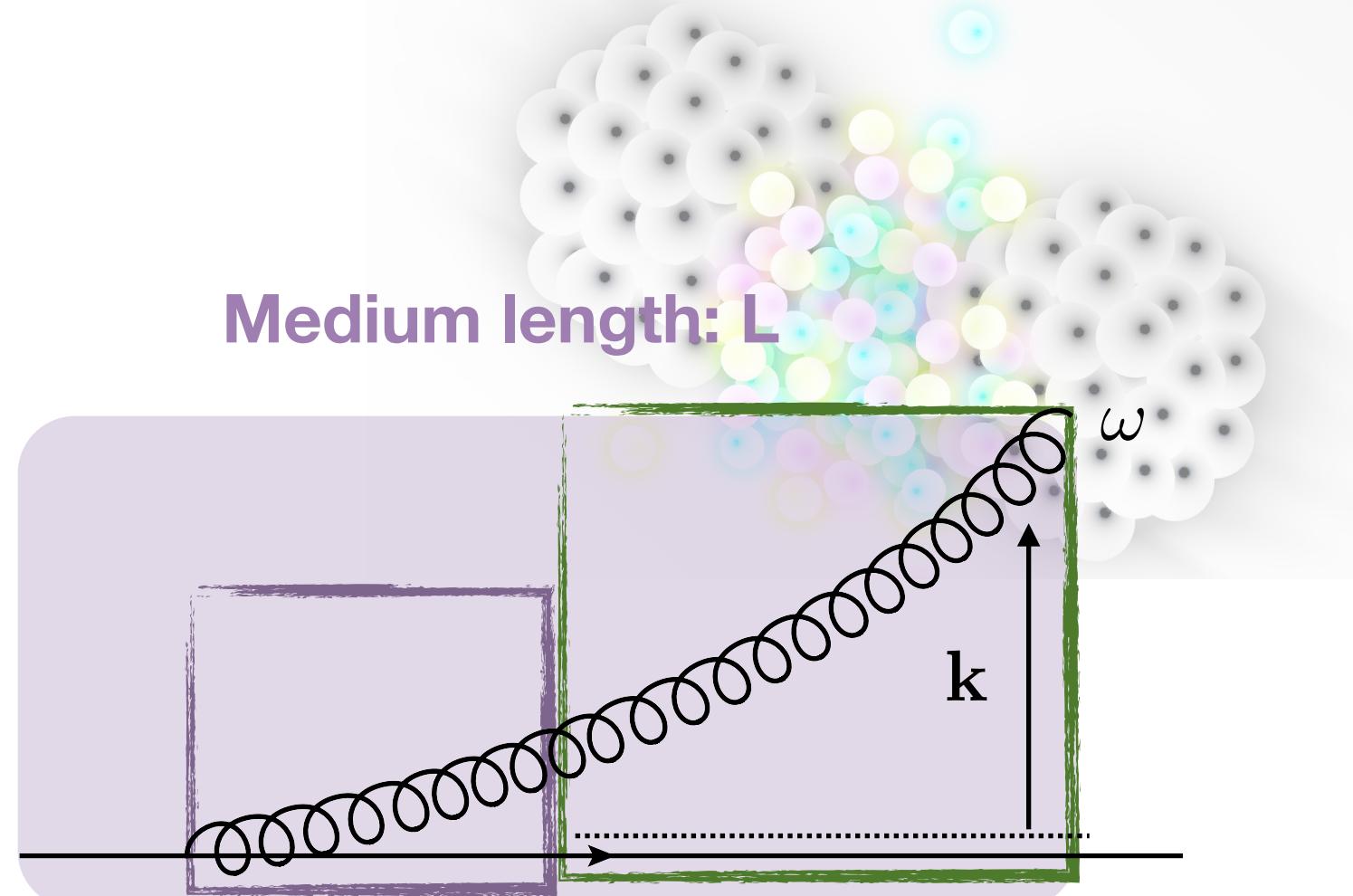
Yukawa: $\sigma(r) \propto V(q) = \frac{8\pi\mu^2}{(q^2 + \mu^2)^2}$

Hard Thermal Loop: $\sigma(r) \propto V(q) = \frac{g_s^2 N_c m_D^2 T}{q^2 (q^2 + m_D^2)}$

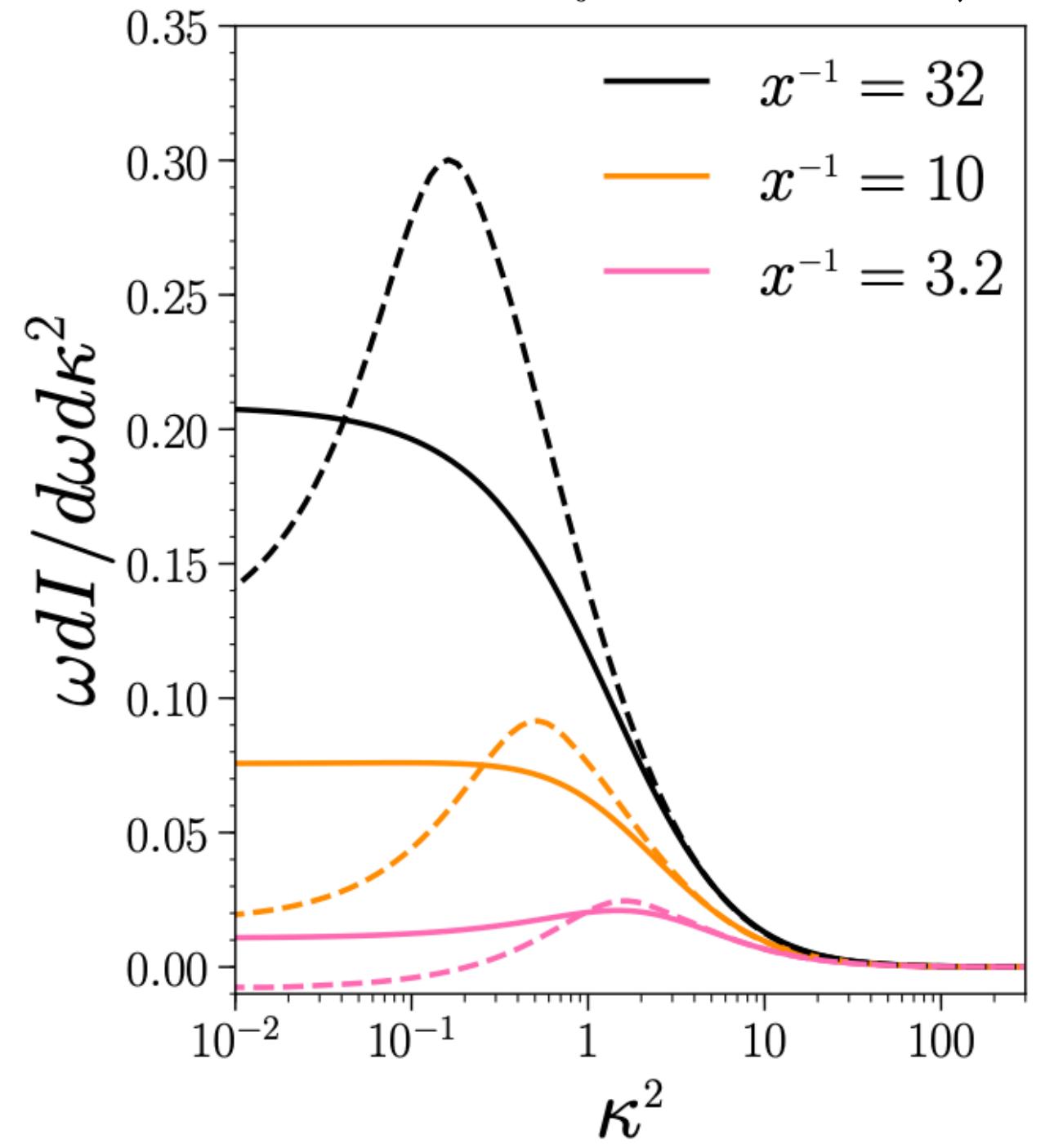
Scaled energy: $x = \frac{\omega}{\bar{\omega}_c} = \frac{2\omega}{\mu^2 L}$

Scaled transverse momentum: $\kappa^2 = \frac{k^2}{\mu^2}$

Physical picture

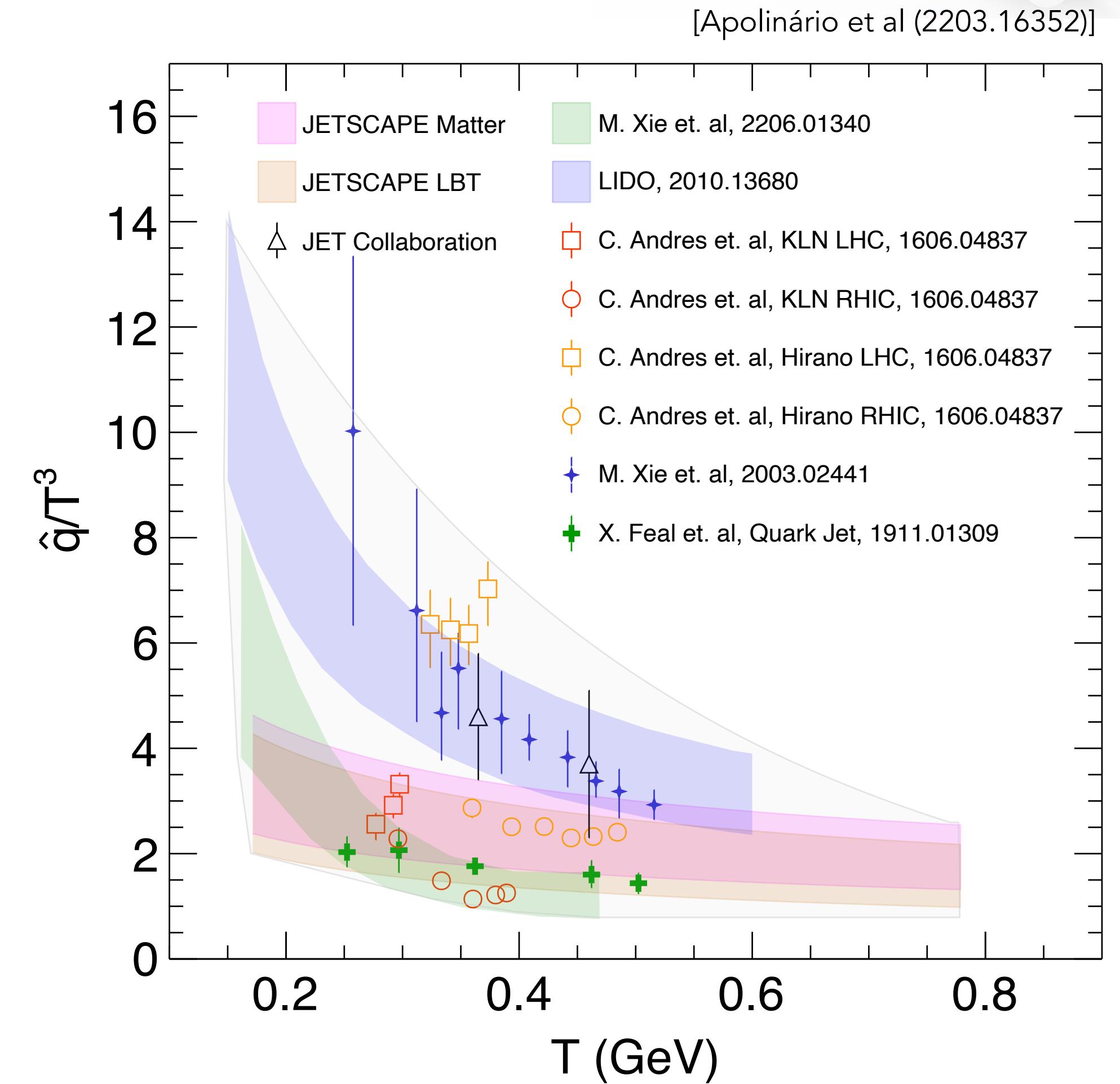


--- Full HTL $TL = 0.4$ [Andrés, Apolinário, et al (2002.01517)]
— Full Yukawa $n_0 L = 1$

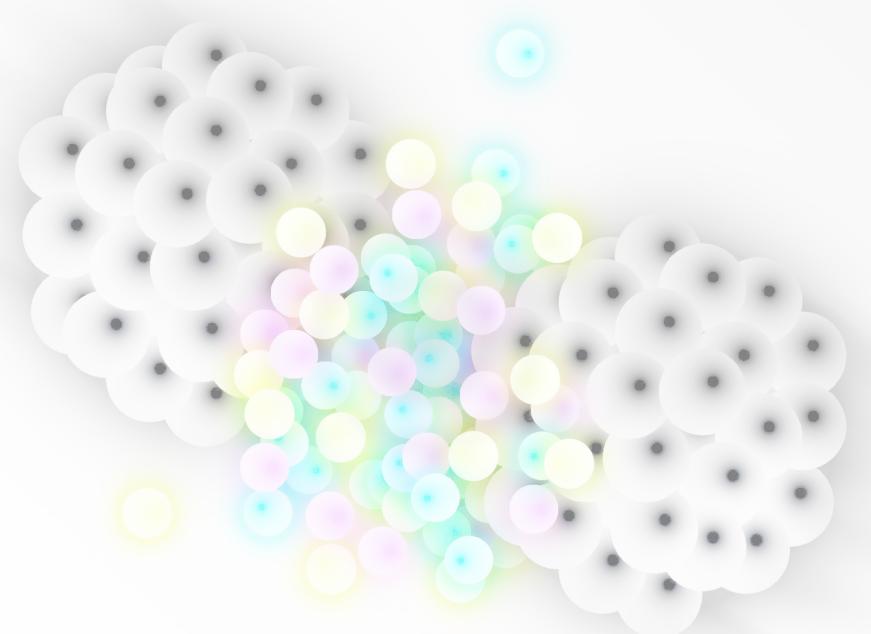


Medium transport coefficients

- From single-particle or jet suppression recover \hat{q}

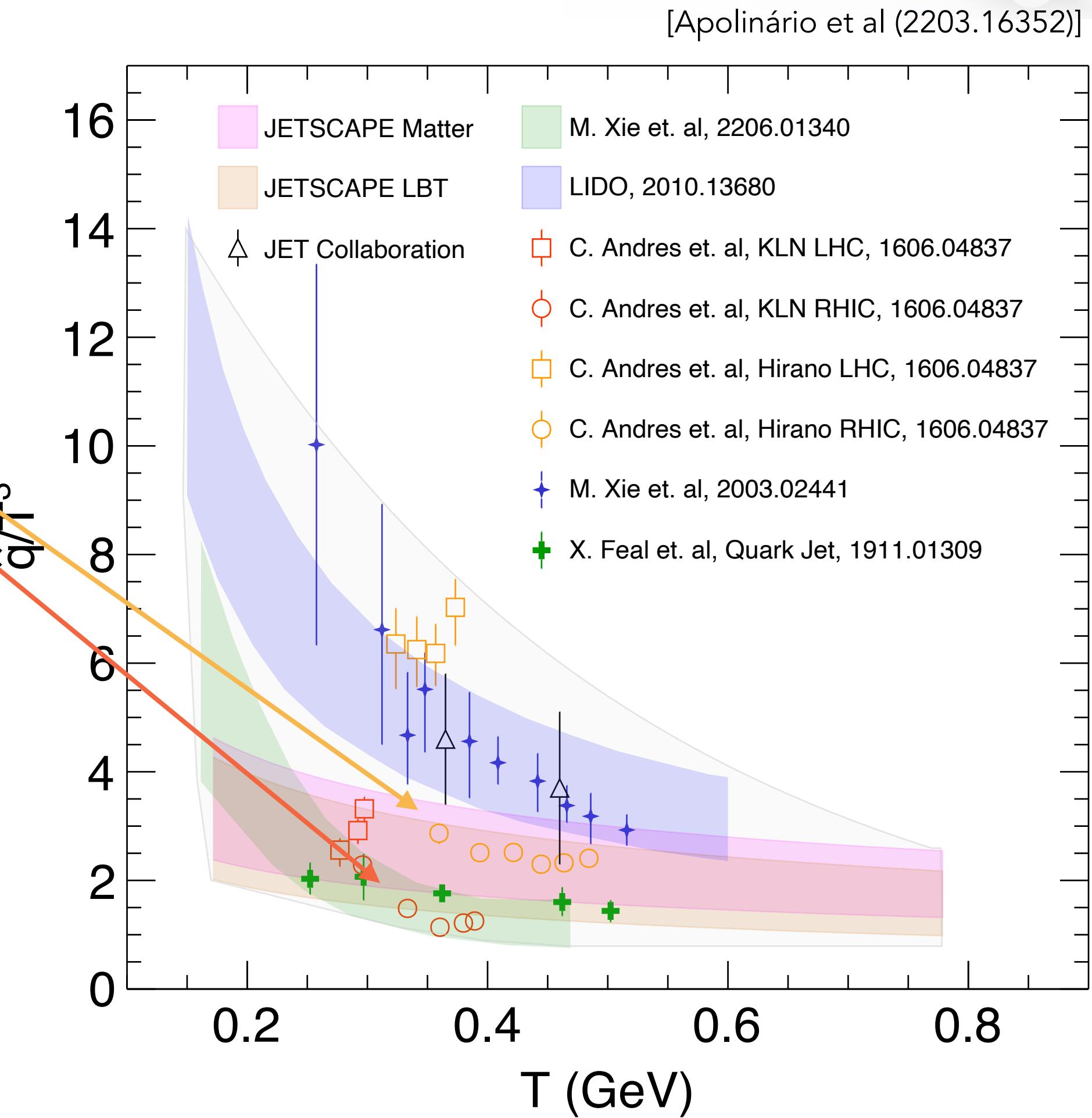
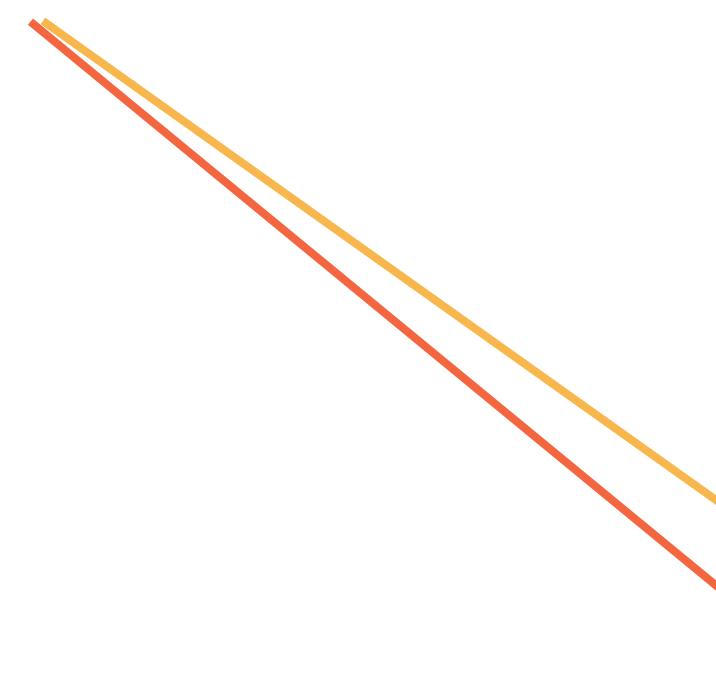


Medium transport coefficients

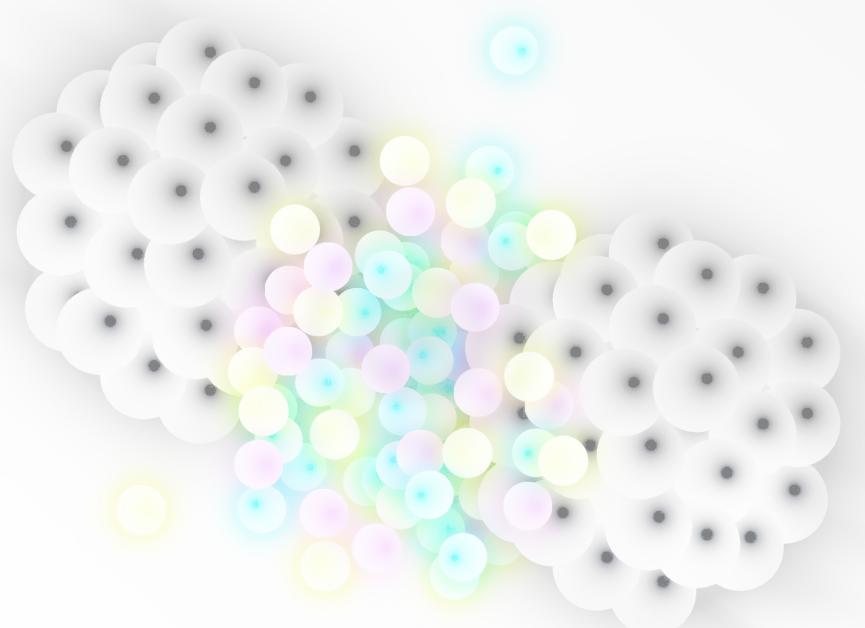


- From single-particle or jet suppression recover \hat{q}

Changing QGP initialisation conditions



Medium transport coefficients



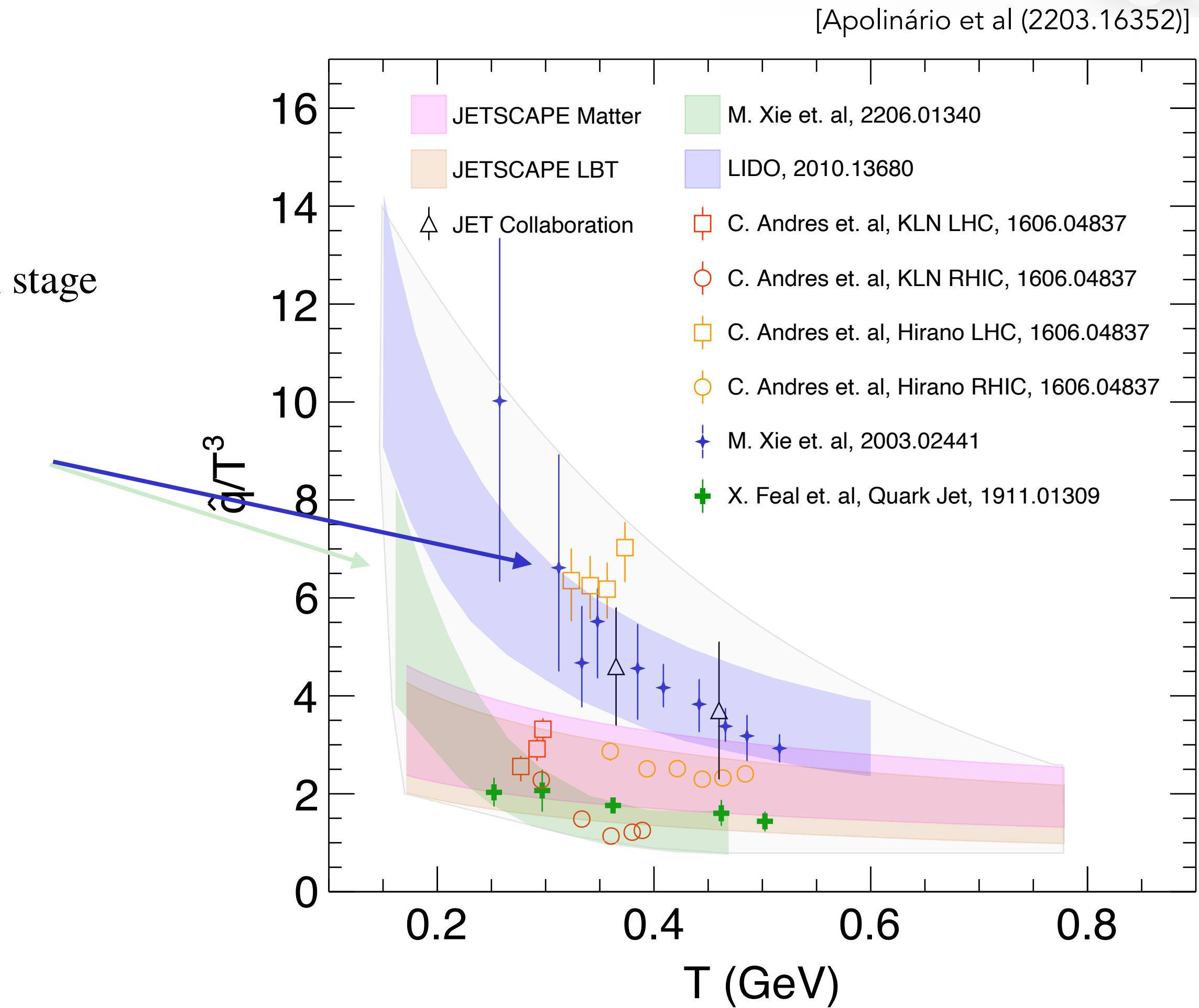
- From single-particle or jet suppression recover \hat{q}

Changing QGP initialisation conditions

Energy loss during all parton shower evolution vs energy loss during final stage

(Compensation of effects with higher transport coefficient)

Improved Bayesian analysis gives a stronger temperature dependence



Medium transport coefficients

- From single-particle or jet suppression recover \hat{q}

Changing QGP initialisation conditions

Energy loss during all parton shower evolution vs energy loss during final stage

(Compensation of effects with higher transport coefficient)

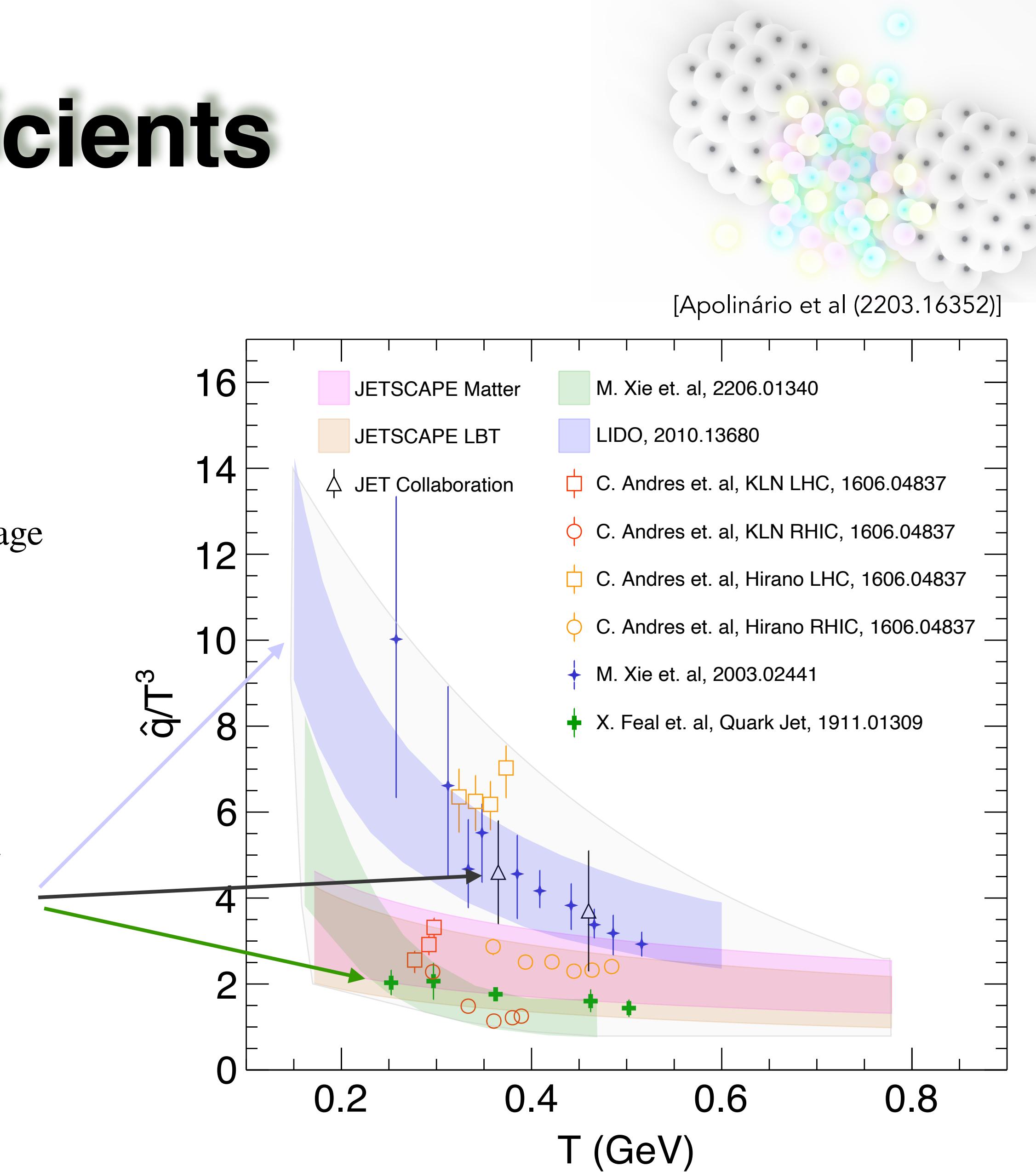
Improved Bayesian analysis gives a stronger temperature dependence

Include different data sets

(boson-hadron correlations dominated by quark, inclusive particle spectra
contains a mixture of the two)

Hadron vs Jet measurements

(model-dependent description of medium response on jets)



Medium transport coefficients

- From single-particle or jet suppression recover \hat{q}

Changing QGP initialisation conditions

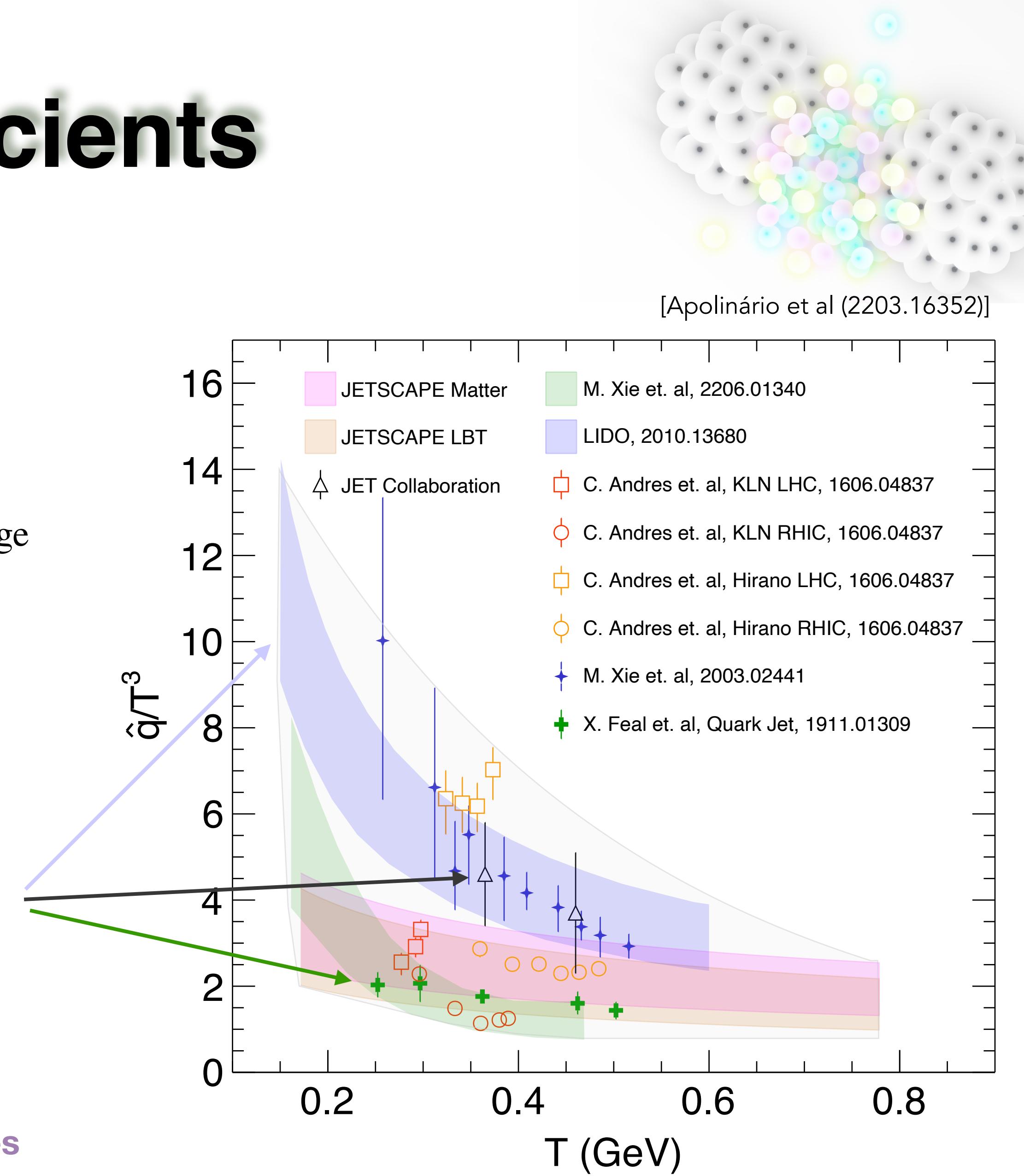
Energy loss during all parton shower evolution vs energy loss during final stage
(Compensation of effects with higher transport coefficient)

Improved Bayesian analysis gives a stronger temperature dependence

Include different data sets
(boson-hadron correlations dominated by quark, inclusive particle spectra
contains a mixture of the two)

Hadron vs Jet measurements
(model-dependent description of medium response on jets)

Quantitative assessment of QGP characteristics using hard probes



Medium response

- QGP part that become correlated with the jet:

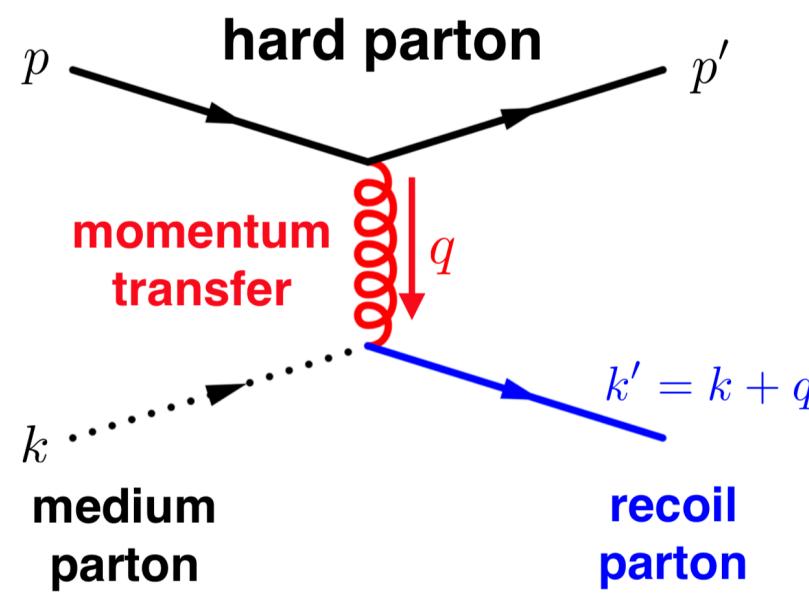
- Seen as (pQCD approach):

- Recoils from jet-medium interactions with a QGP particle distribution

→ Dominated by small momentum transfers (close to non-perturbative region)

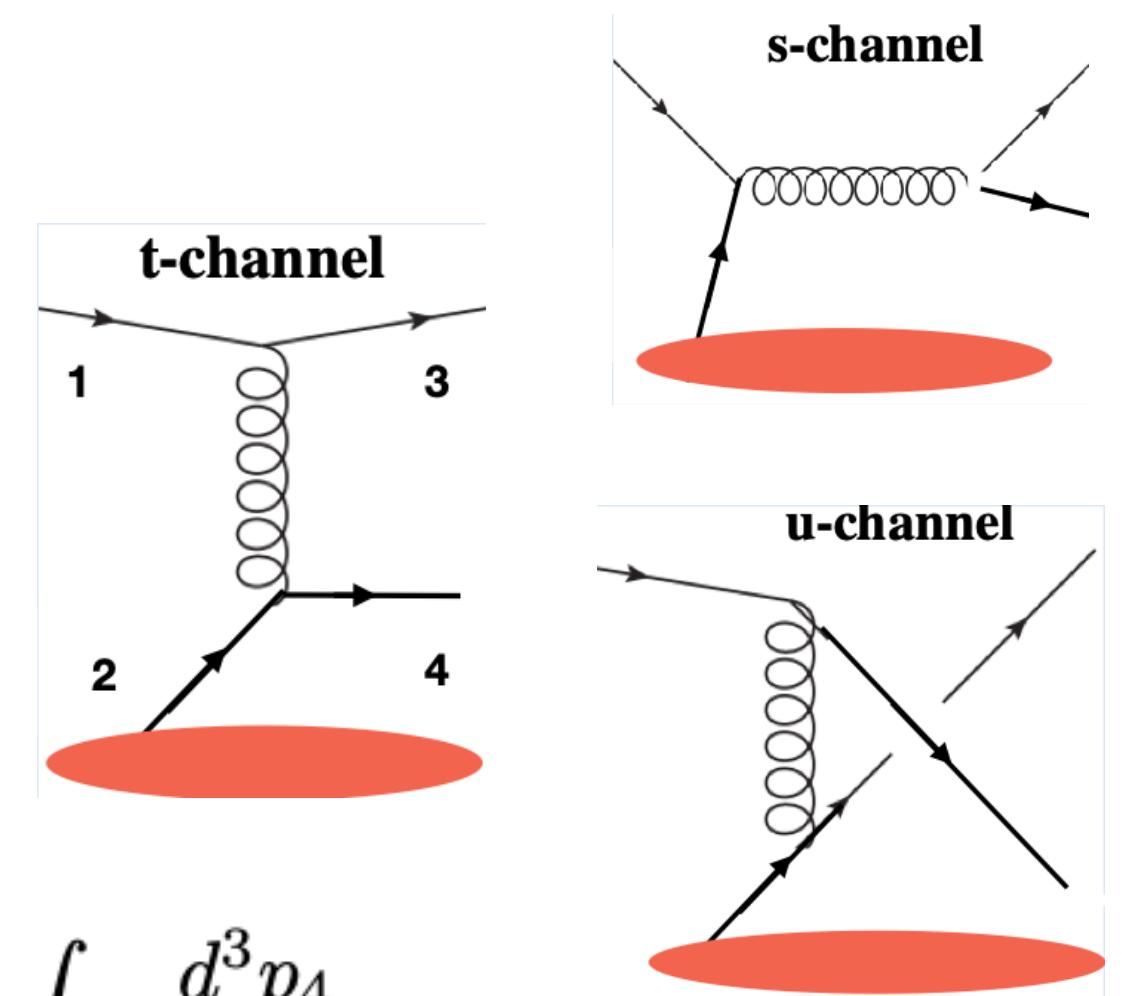
E.g: JEWEL

$$\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s}, |\hat{t}|) \simeq \frac{C_R 2\pi \alpha_s^2}{(|\hat{t}| + \mu_D^2)^2}$$



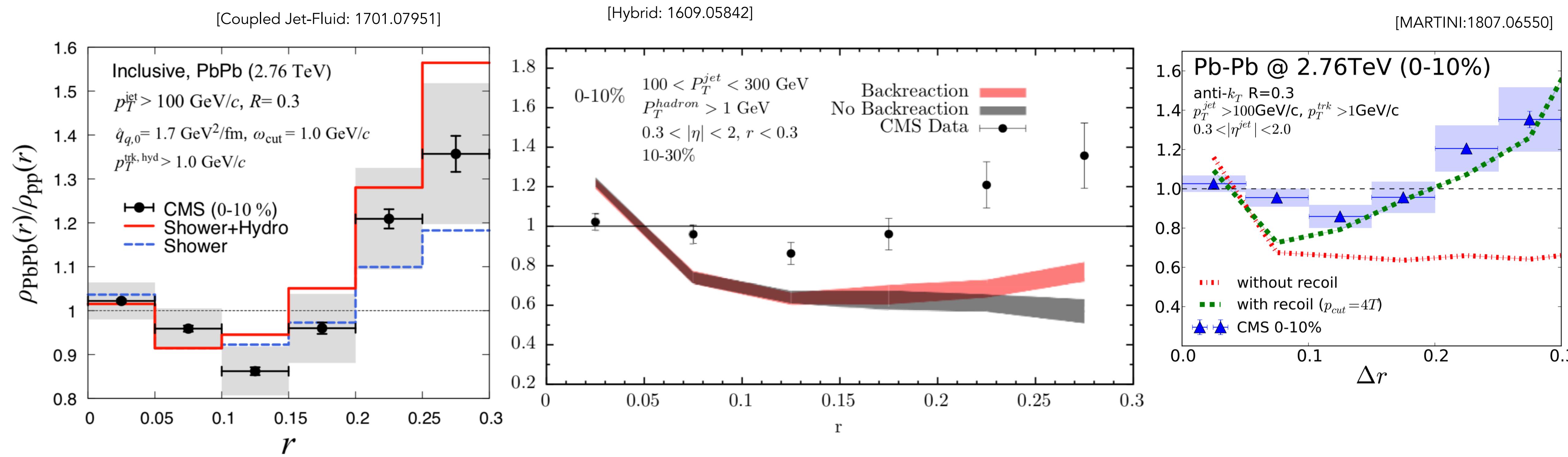
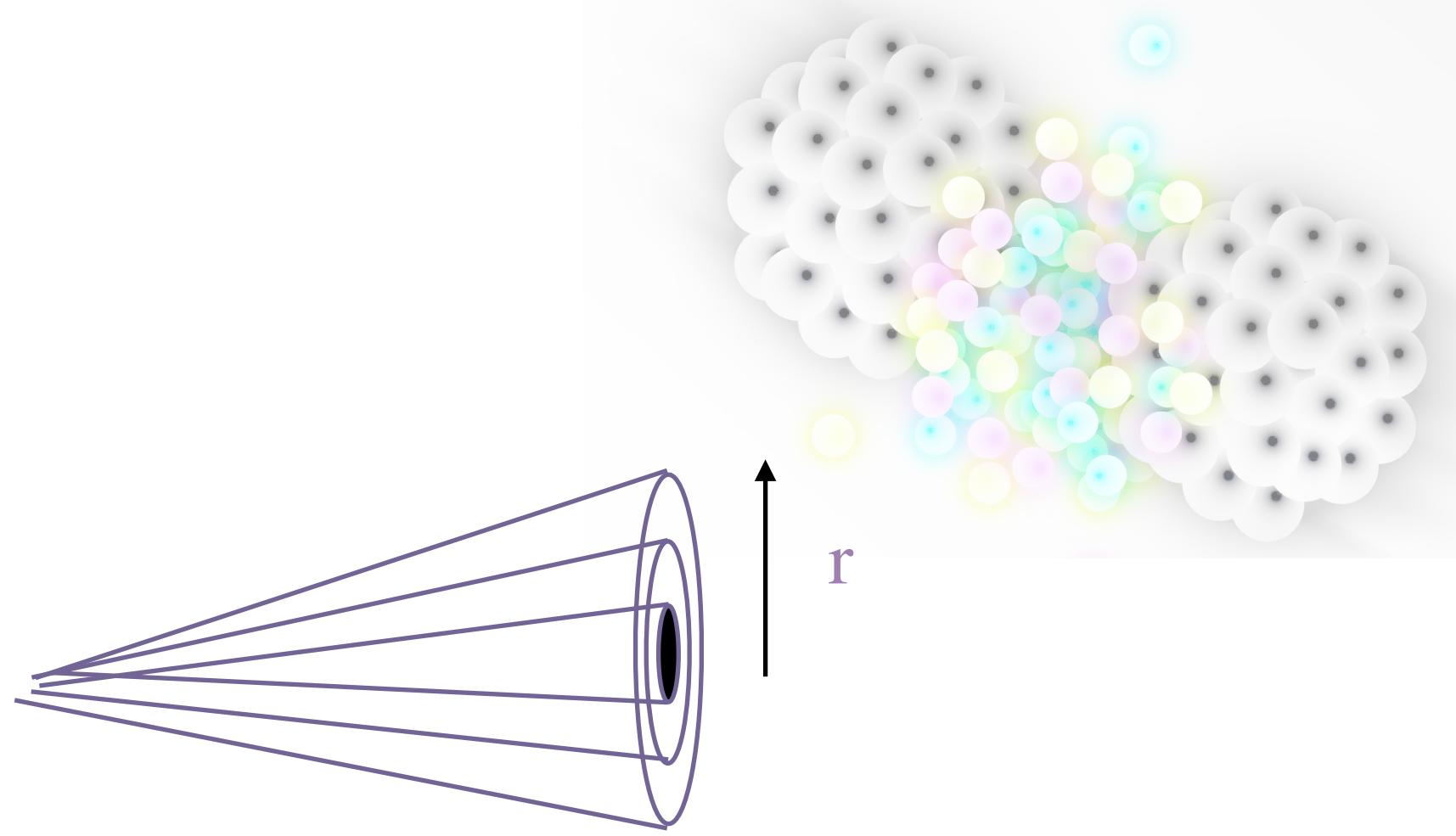
E.g: LBT

$$\begin{aligned} p_1 \cdot \partial f_a(p_1) = & - \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \int \frac{d^3 p_3}{(2\pi)^3 2E_3} \int \frac{d^3 p_4}{(2\pi)^3 2E_4} \\ & \sum_{b(c,d)} \frac{g_b}{2} [f_a(p_1)f_b(p_2) - f_c(p_3)f_d(p_4)] |M_{ab \rightarrow cd}|^2 \\ & \times S_2(s, t, u) (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4), \end{aligned}$$

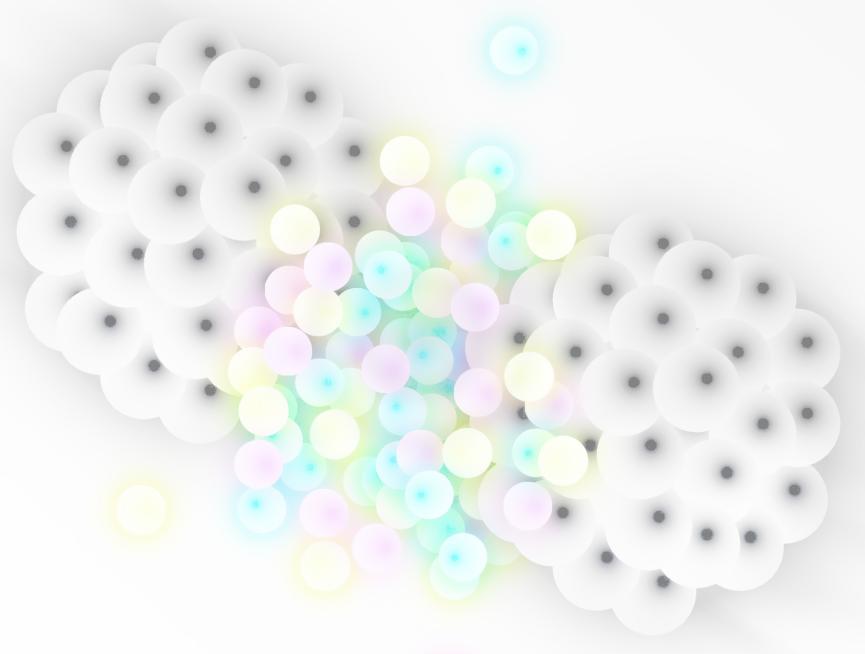


Fast or Slow Thermalisation?

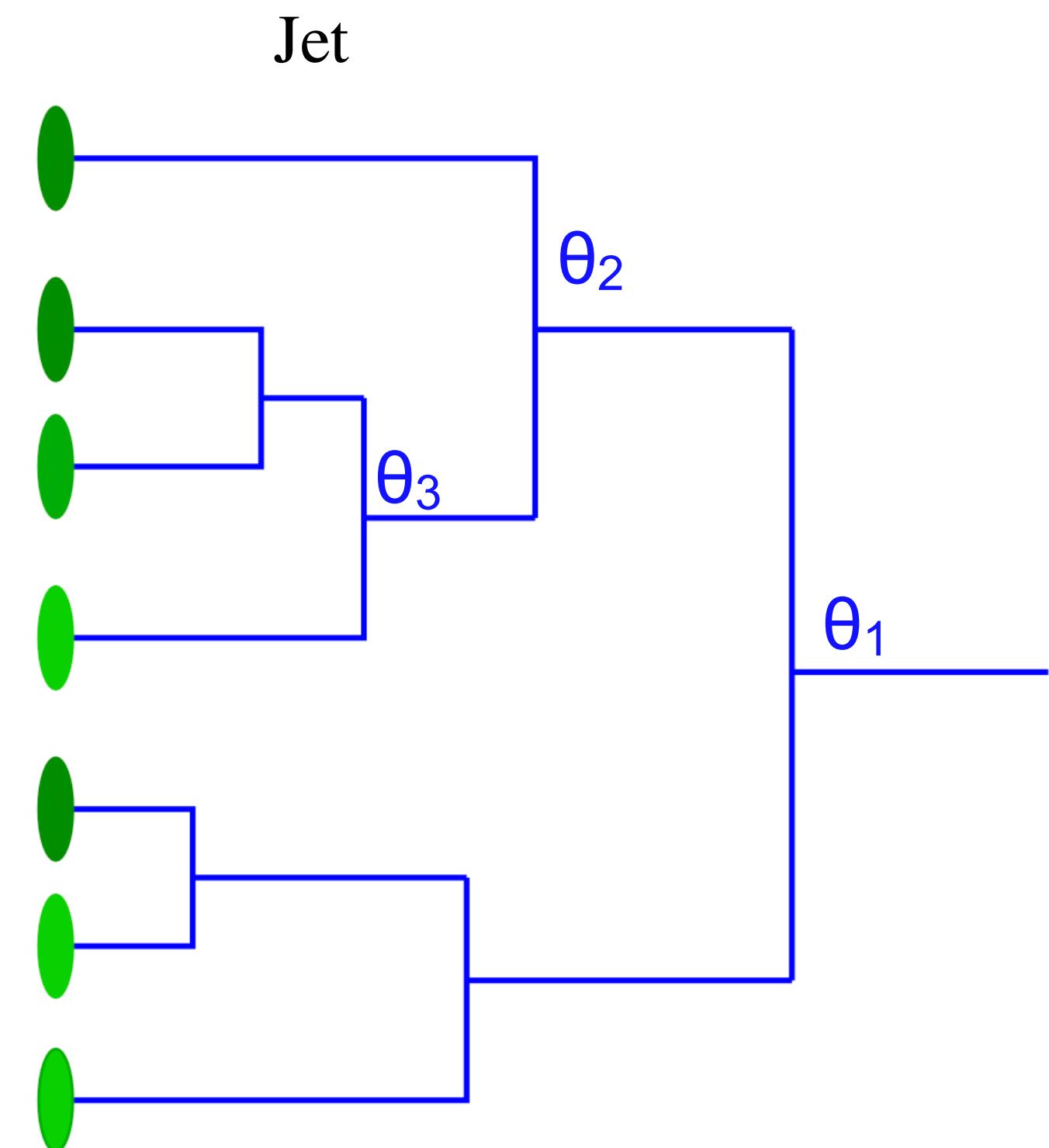
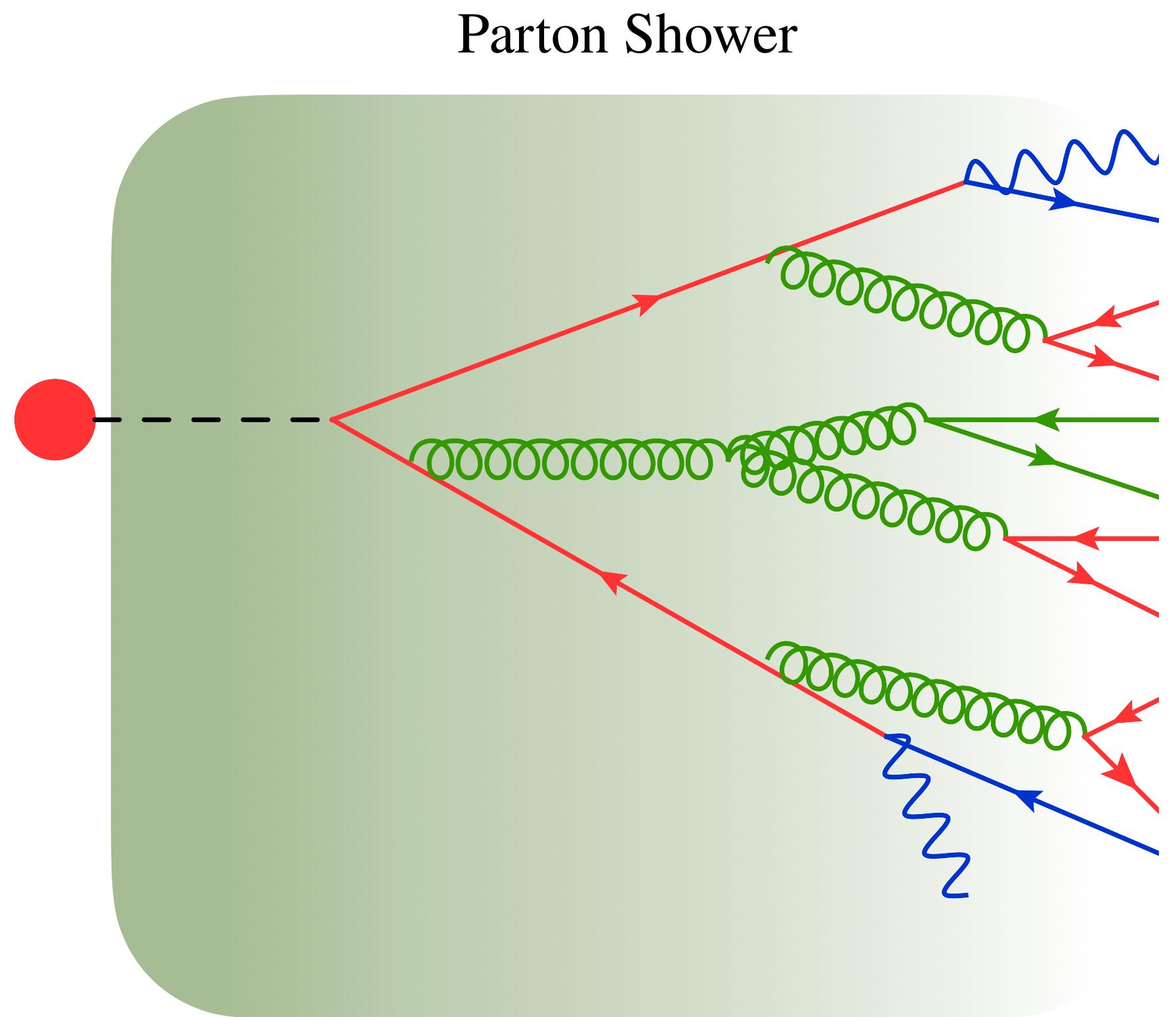
- Medium response:
 - What exactly is the amount of medium response to the jet passage?



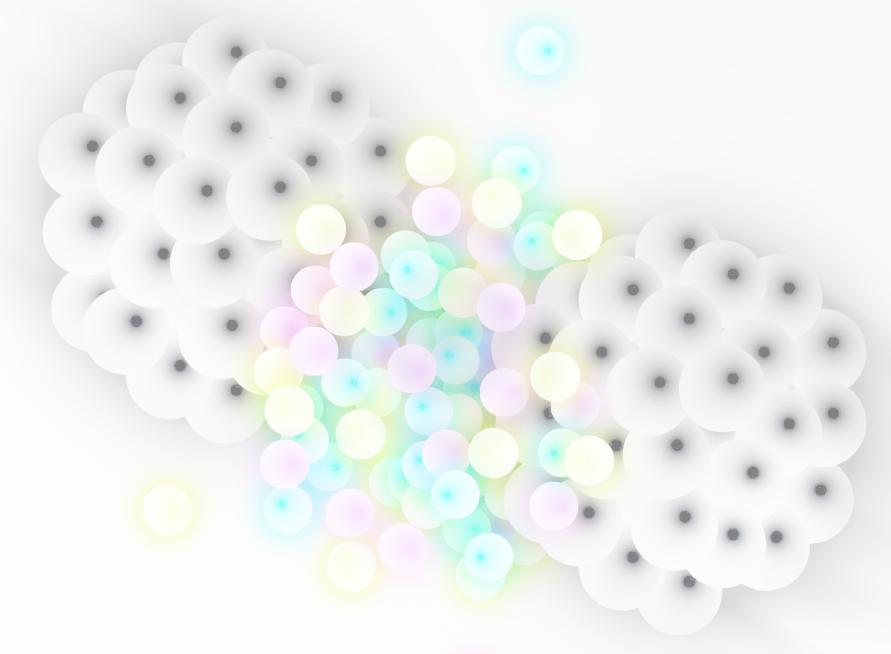
Towards in-medium parton showers



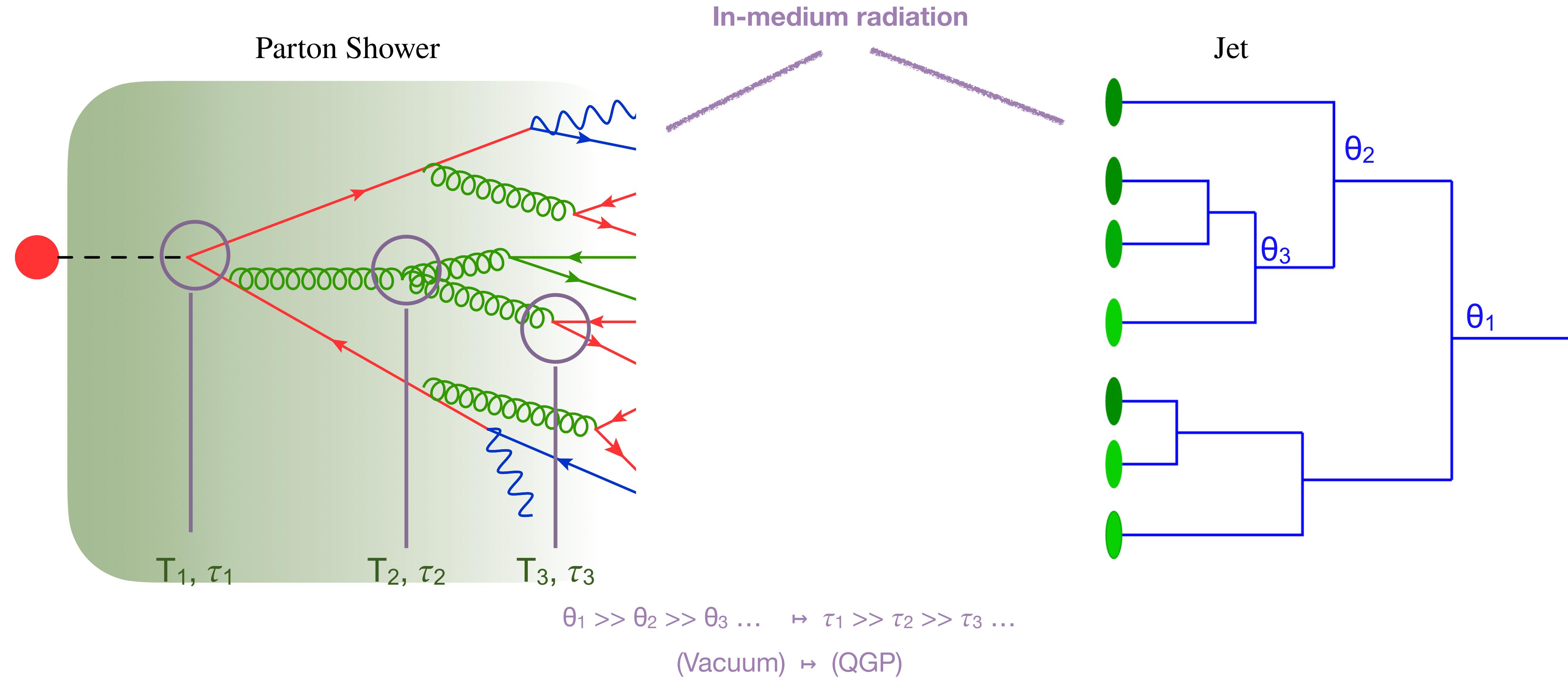
- Jets propagate on a fast evolving medium:



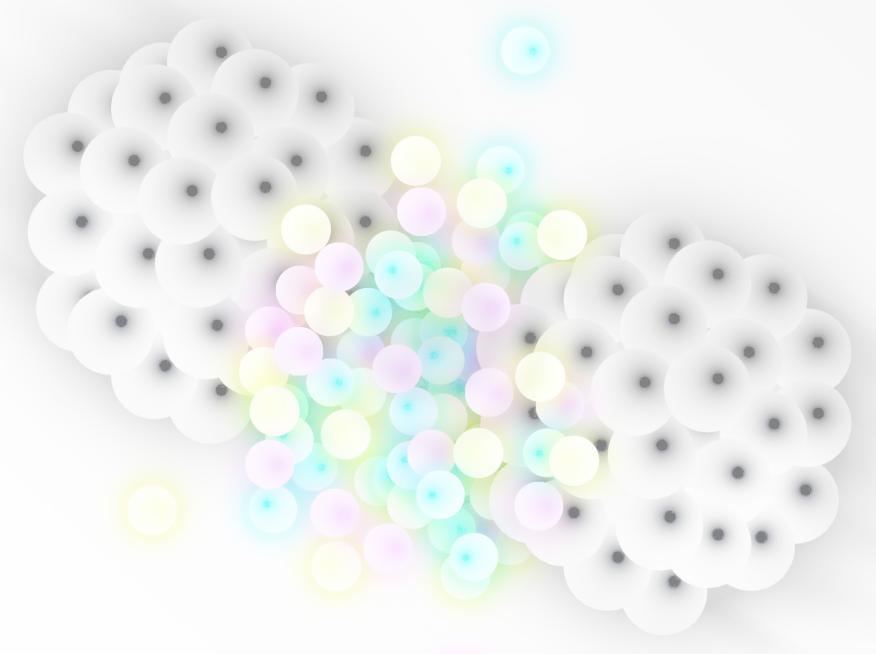
Towards in-medium parton showers



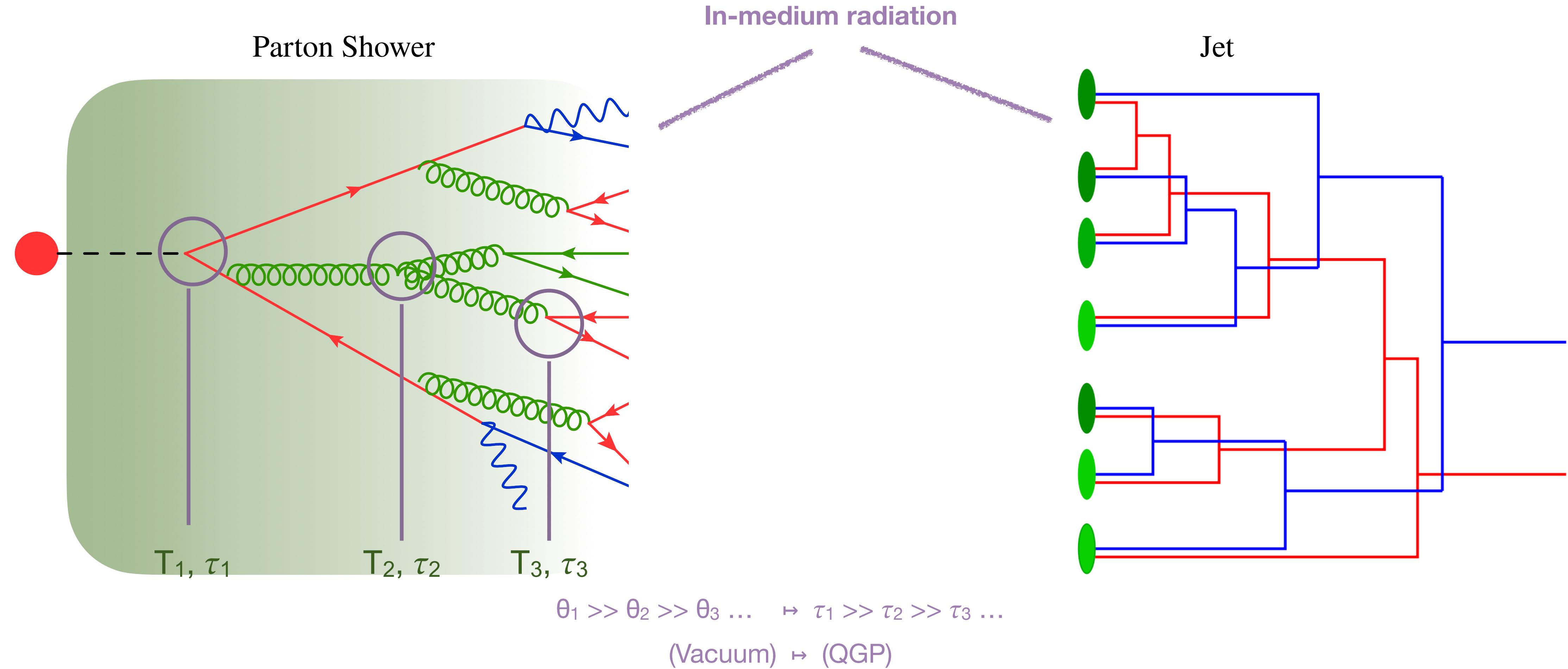
- Jets propagate on a fast evolving medium:



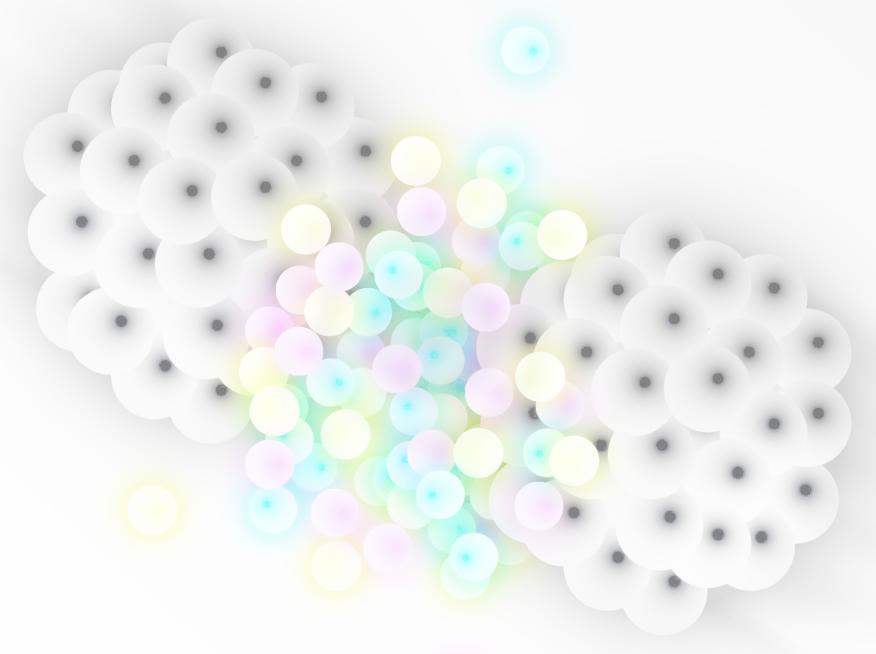
Towards in-medium parton showers



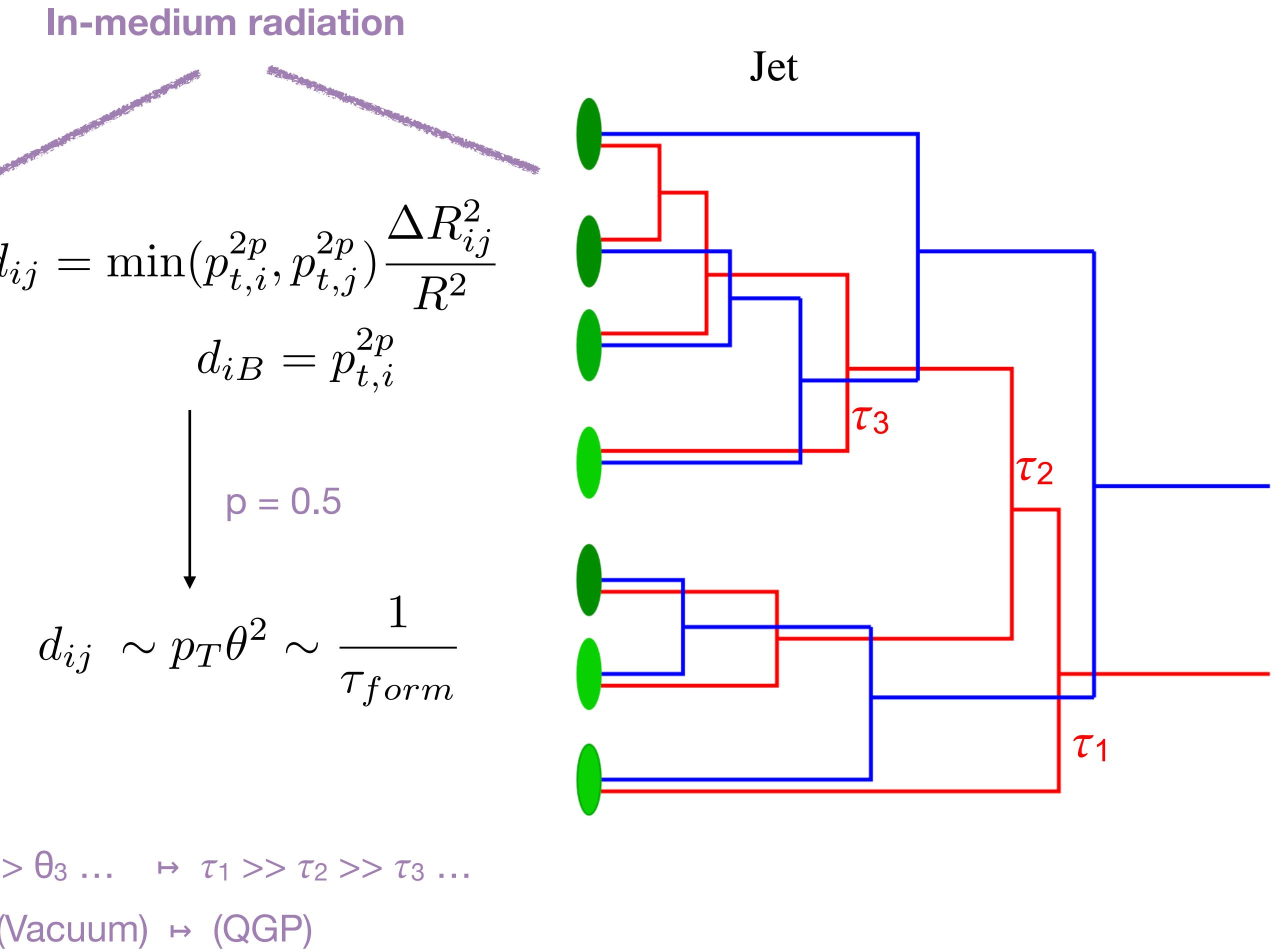
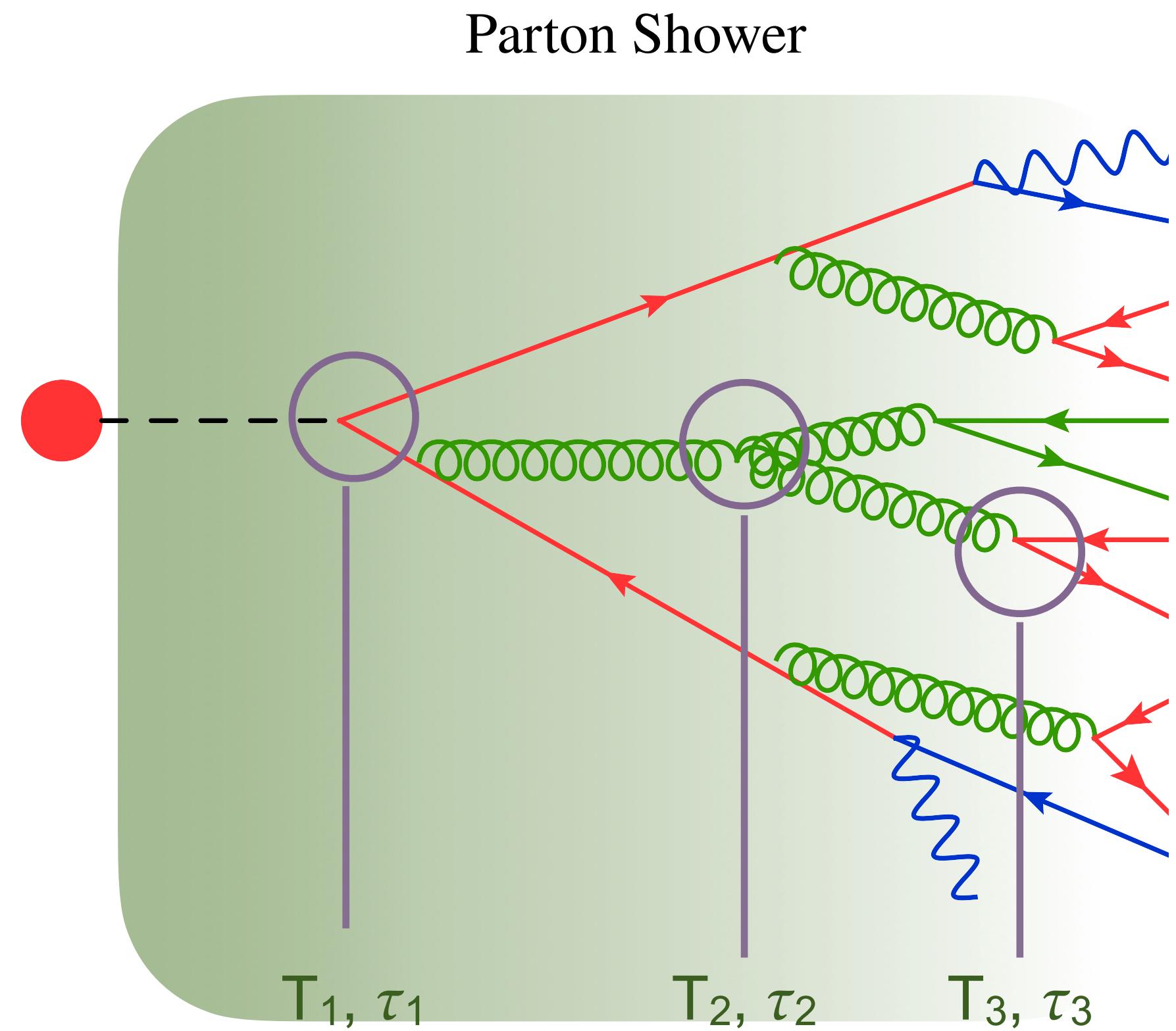
- Jets propagate on a fast evolving medium:



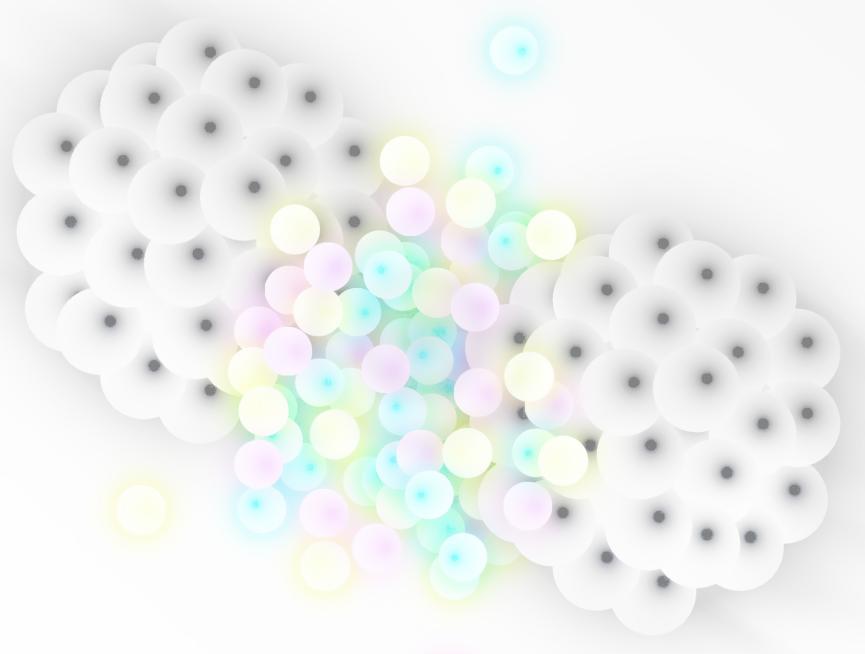
Towards in-medium parton showers



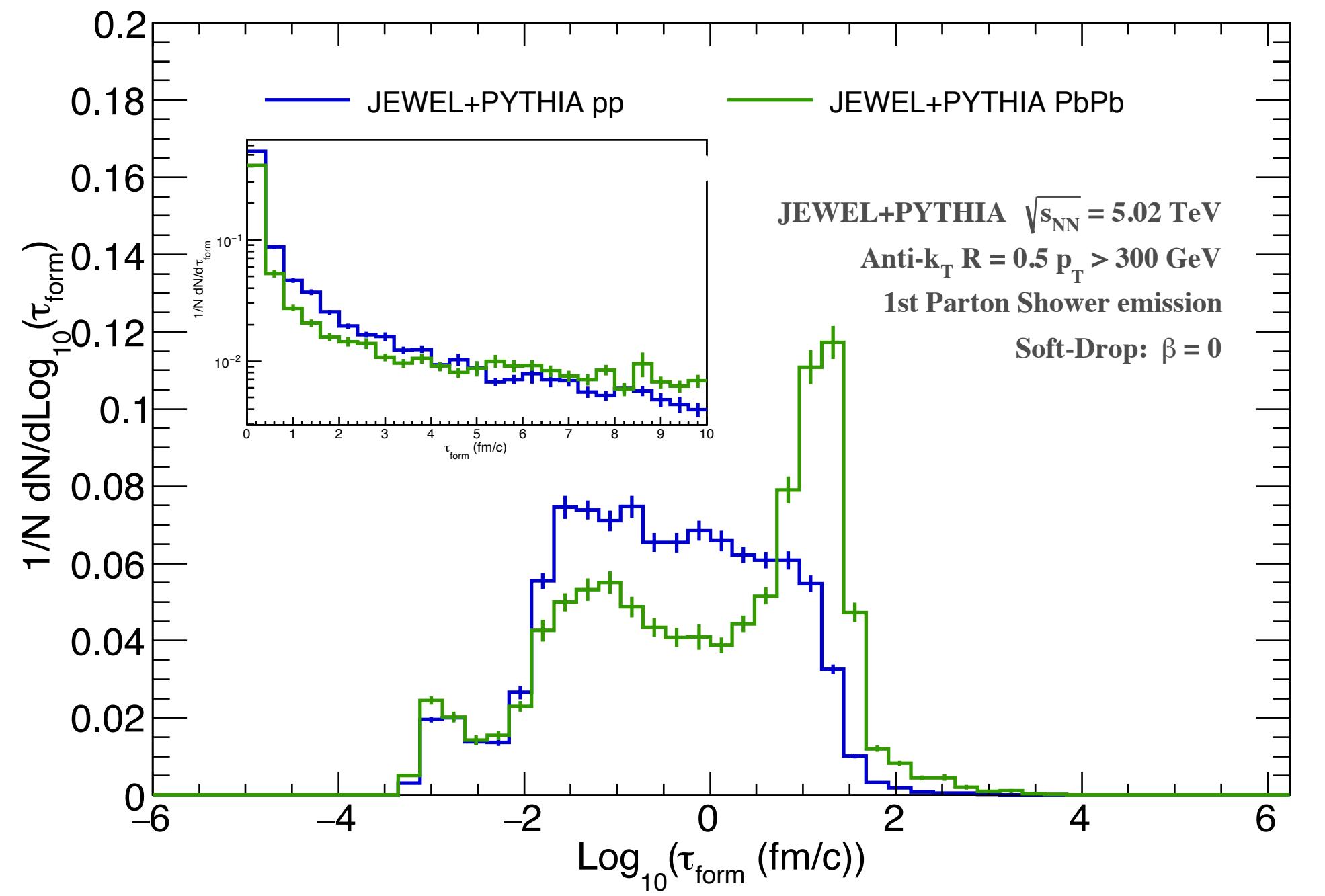
- Jets propagate on a fast evolving medium:



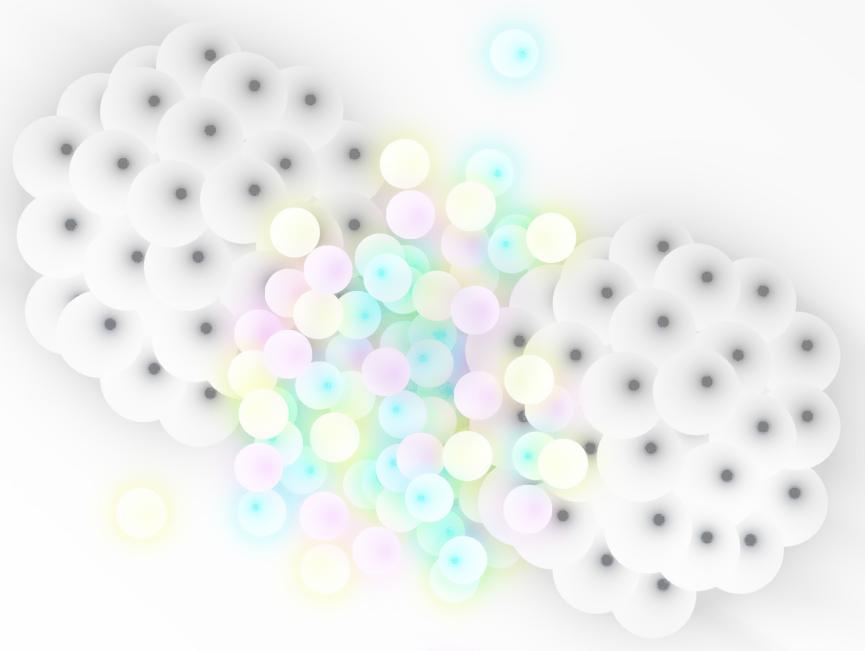
Enhancing quenching effects



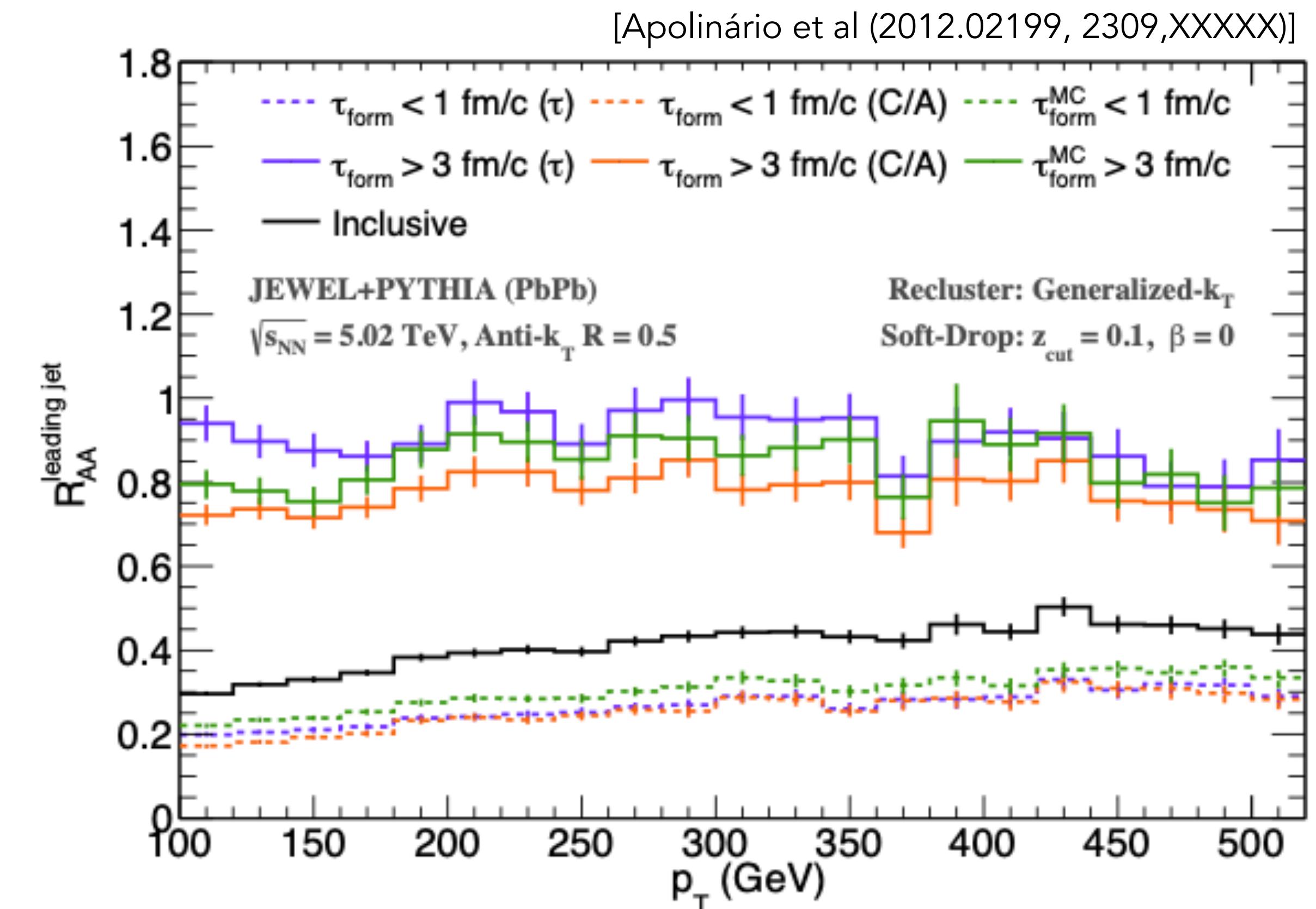
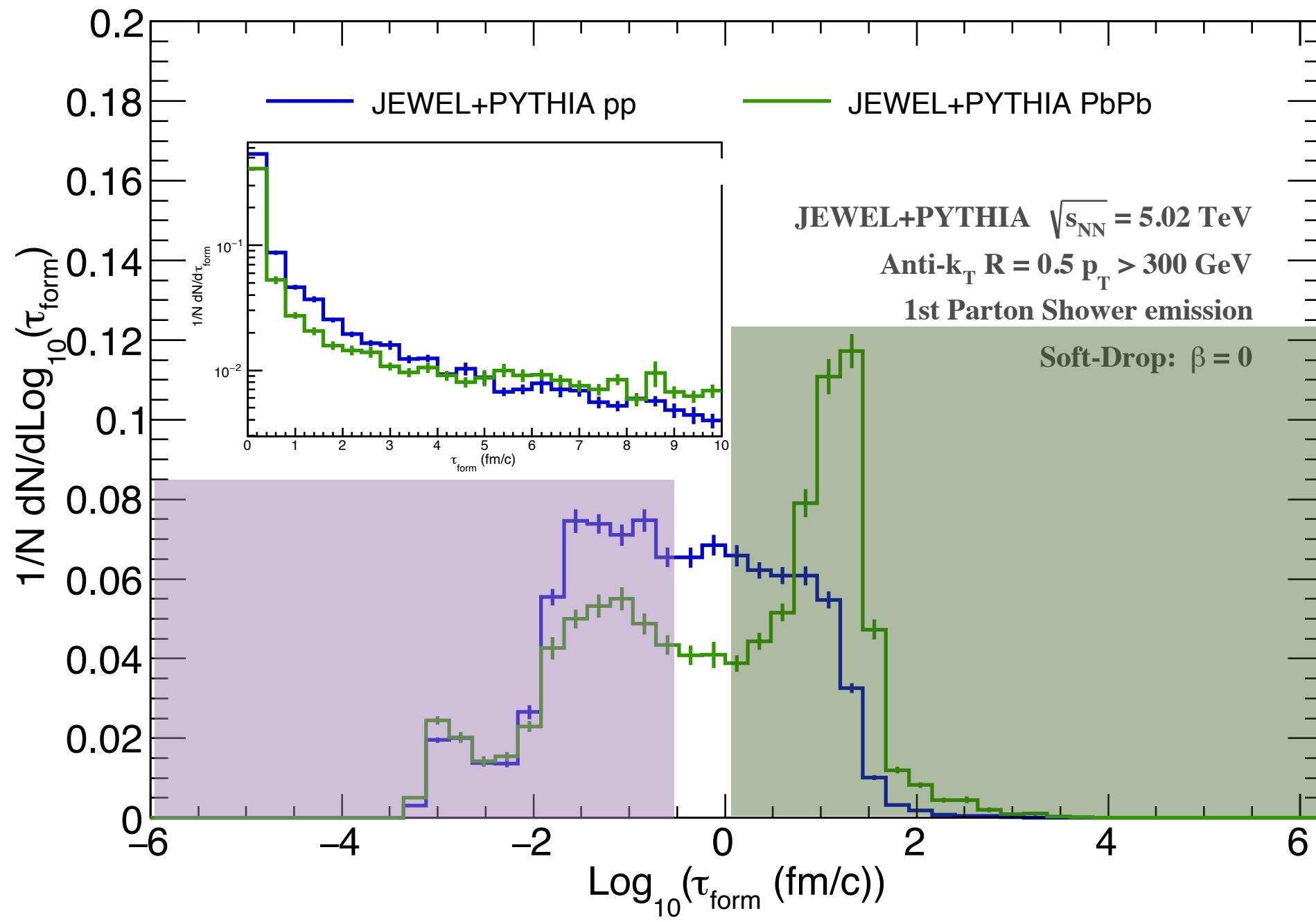
- Easily select two classes of jets:



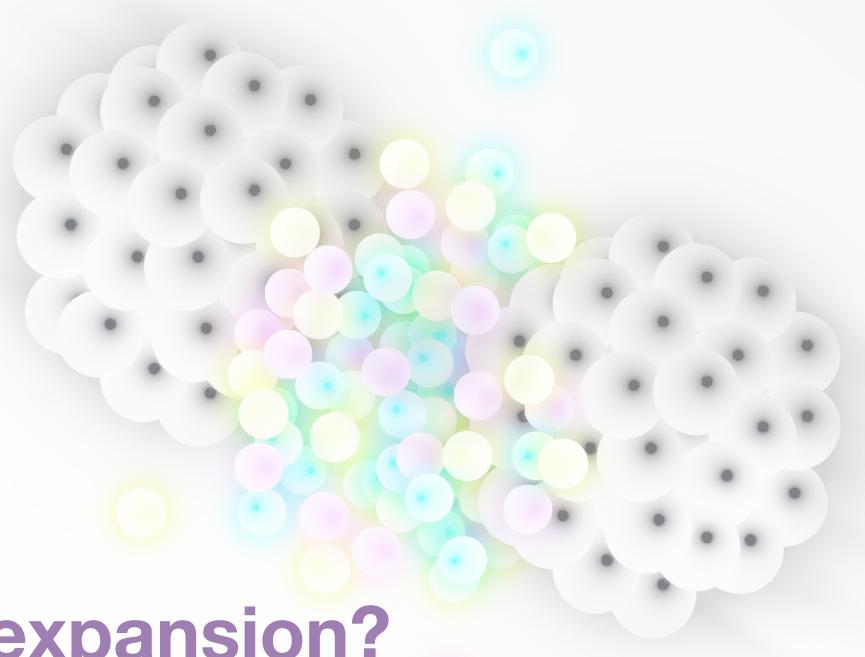
Enhancing quenching effects



- Easily select two classes of jets:
 - “early” jets: $\tau_1 < 1 \text{ fm/c}$ (strongly modified)
 - “late” jets: $\tau_1 > 3 \text{ fm/c}$ (weakly modified)



Enhancing quenching effects



- Easily select two classes of jets:
 - “early” jets: $\tau_1 < 1 \text{ fm/c}$ (strongly modified)
 - “late” jets: $\tau_1 > 3 \text{ fm/c}$ (weakly modified)

