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Open quantum system approach to medium-induced gluon radiation in a dense QCD medium

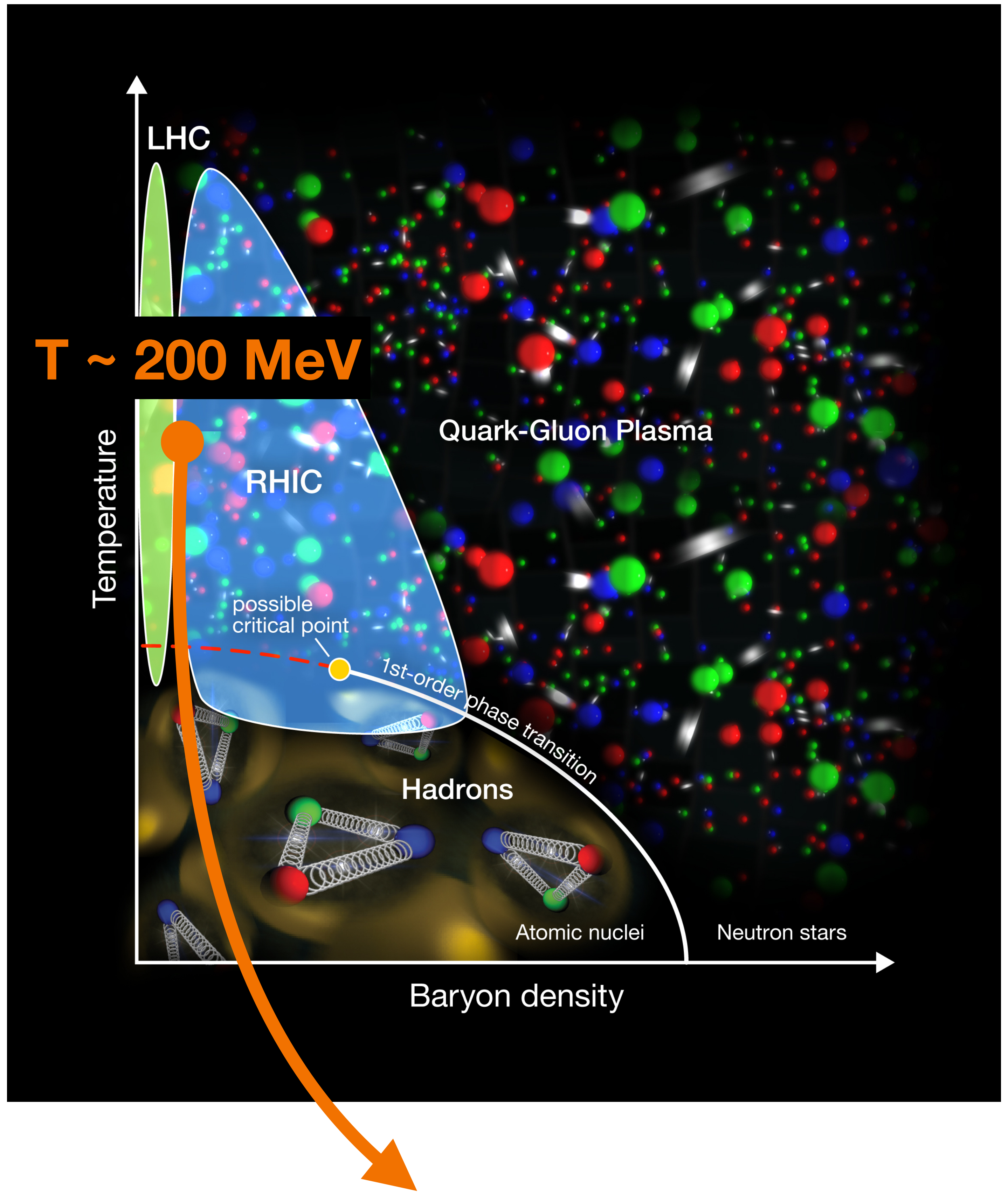
PhD hours

Pietro Benzoni (Theorie)

François Arleo
Paul Caucal
Pol-Bernard Gossiaux

5th March 2026

A dense QCD medium: Quark-Gluon Plasma

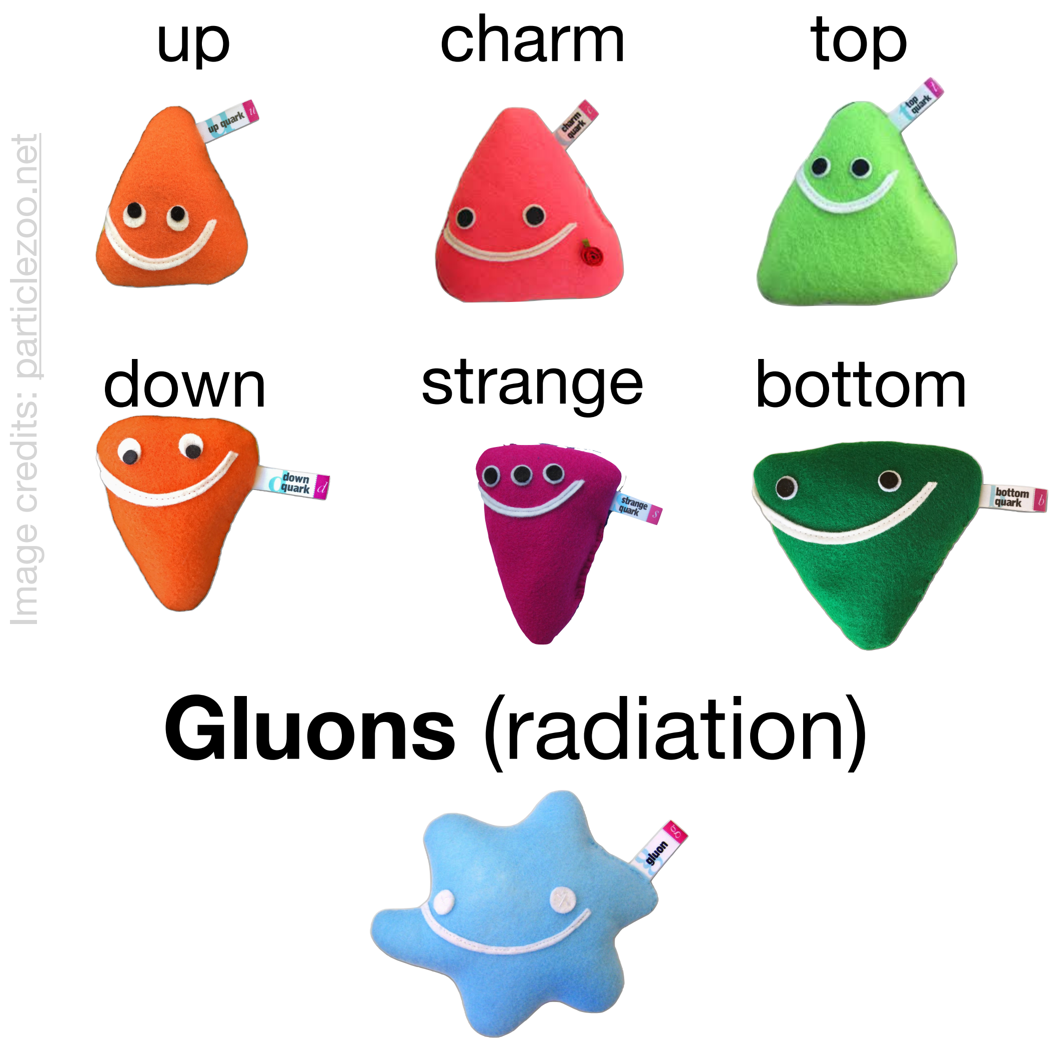


- **Heavy-ion collisions:**

  e.g. Large Hadron Collider (CERN): Pb+Pb collisions at 5 TeV!

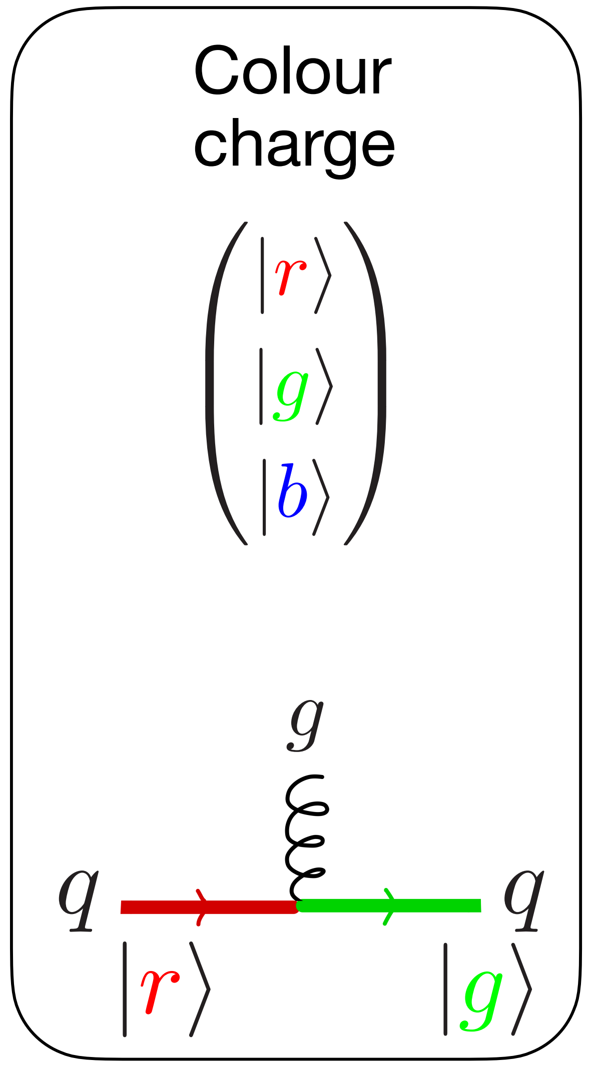
- **Degrees of Freedom:**

Quarks (matter)



Gluons (radiation)

Image credits: particlezoo.net



- **Interactions:**

  Quantum ChromoDynamics (QCD)

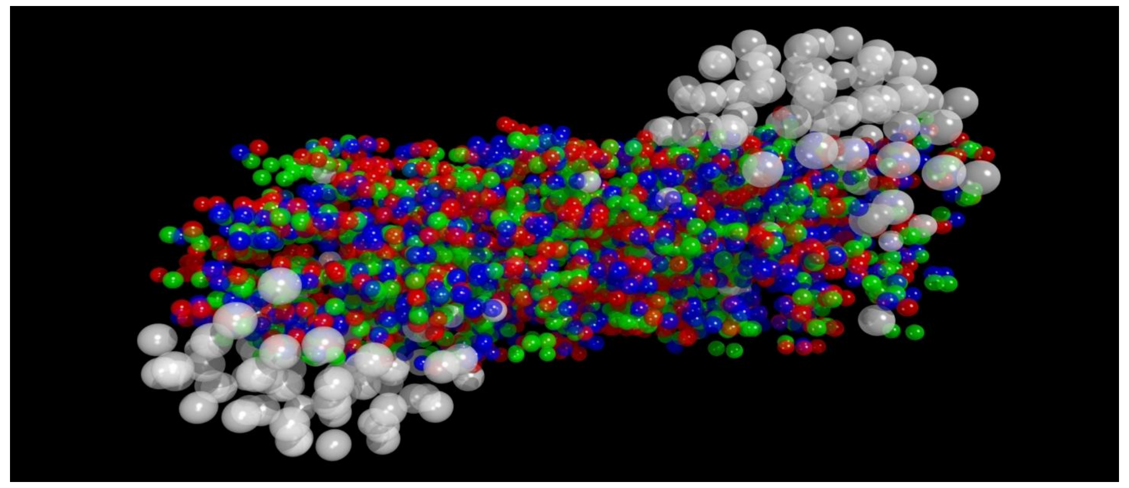
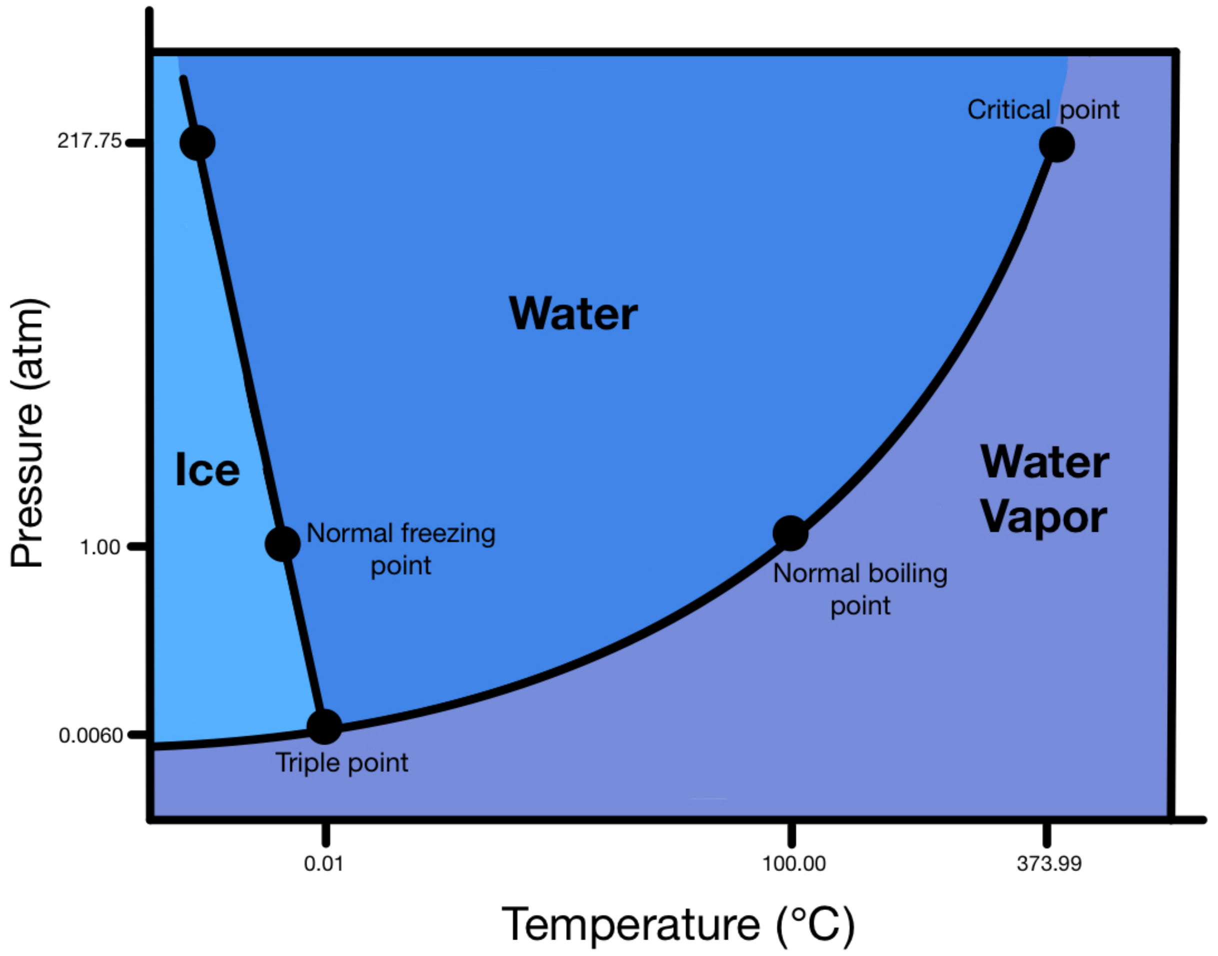


Image credits: https://www.eurekalert.org/multimedia/906348

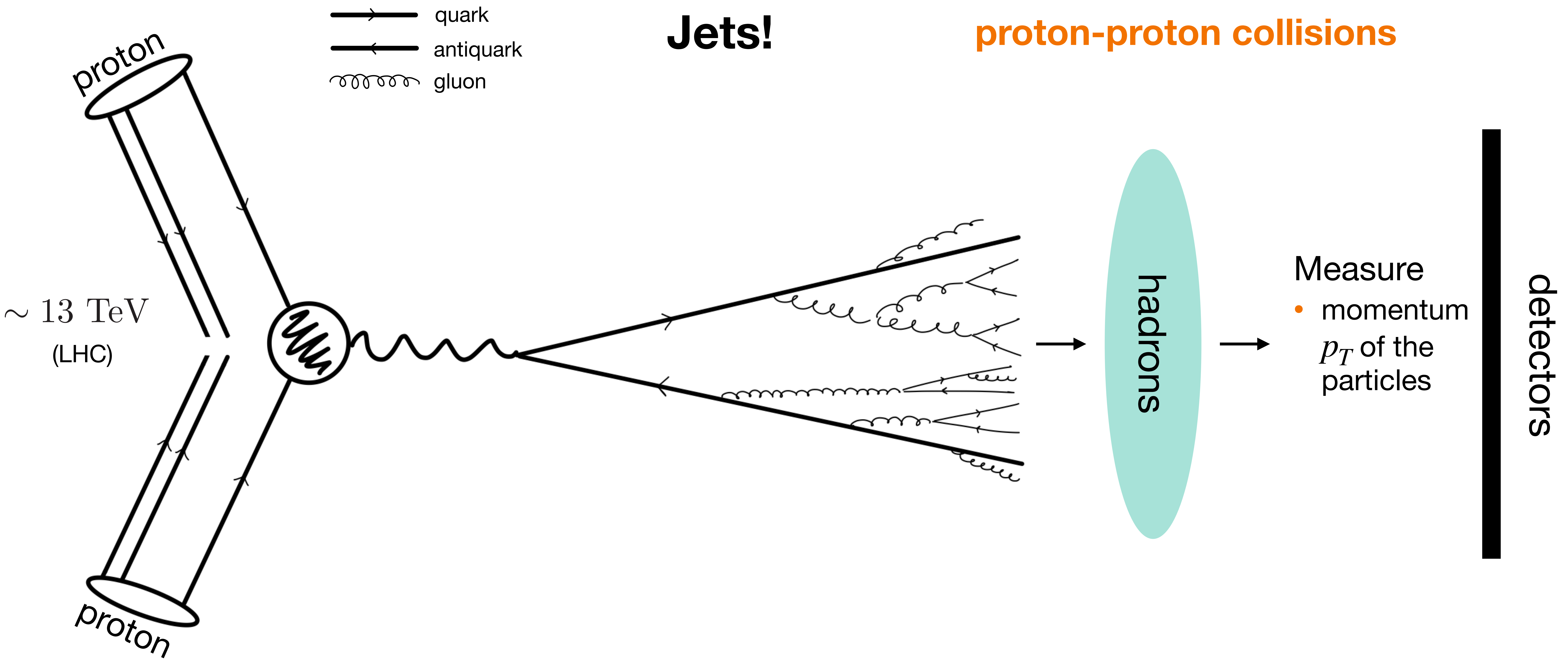


- **DoF:** H_2O molecules
- **Interactions:** electro-magnetic forces *(Lennard-Jones, Hydrogen bonds)*

problem: the QGP has a life of ~10 fm/c (10^{-23} s) before cooling down to hadrons!

Jets as QGP probes

- **Idea:** use **high-energetic (hard)** particles which are produced in the **early-stages** of heavy-ion collisions and which leave an **identifiable mark in the measurements**



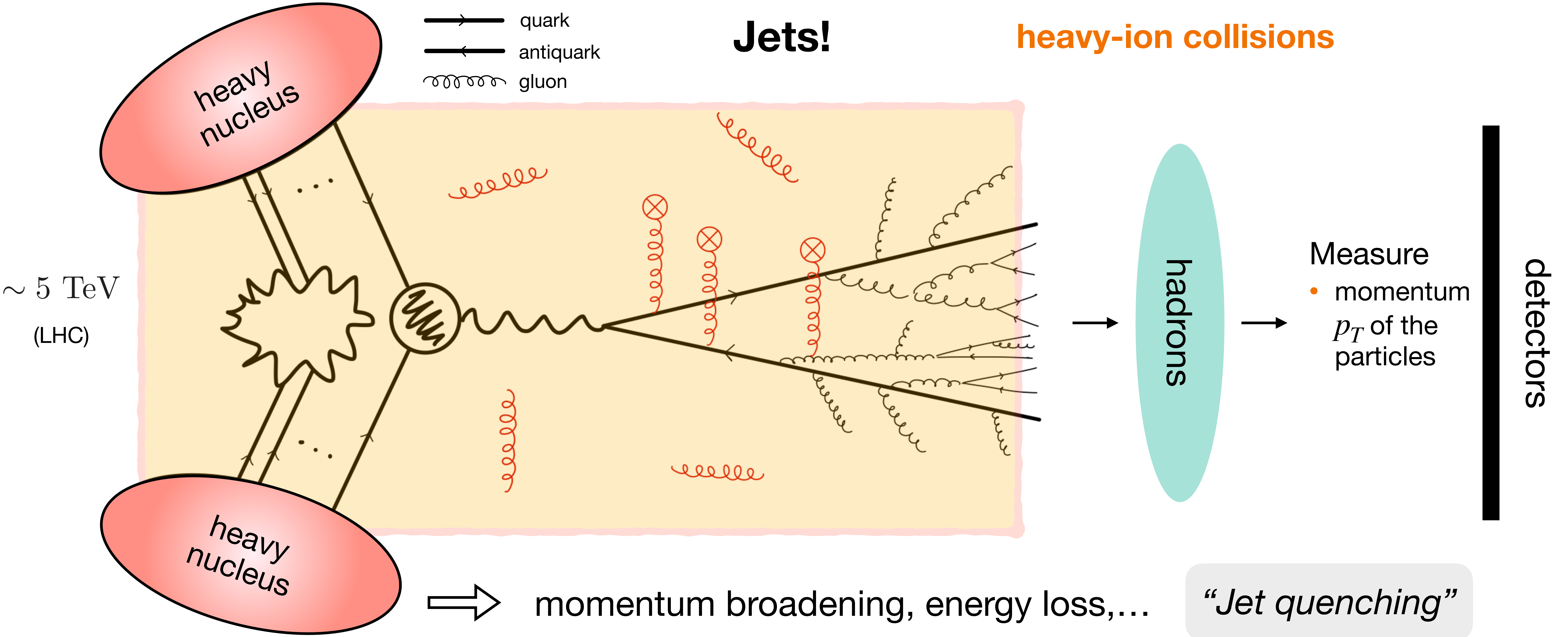
Jets!

proton-proton collisions

Measure
- momentum p_T of the particles

Jets as QGP probes

- **Idea:** use **high-energetic (hard)** particles which are produced in the **early-stages** of heavy-ion collisions and which leave an **identifiable mark in the measurements**



Jets!

heavy-ion collisions

Measure
- momentum p_T of the particles

⇨ momentum broadening, energy loss,…

“Jet quenching”

Jets as QGP probes

- Observe these effects and compare with pp collisions

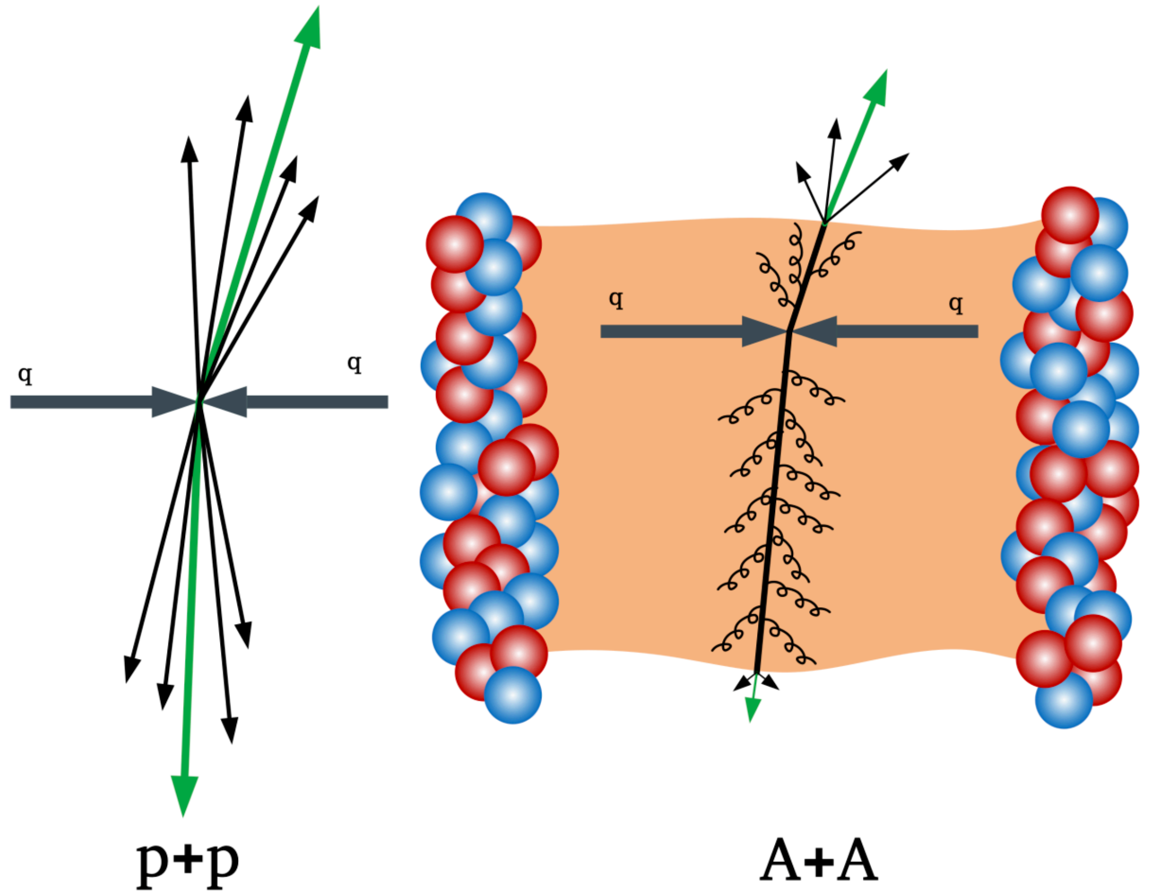
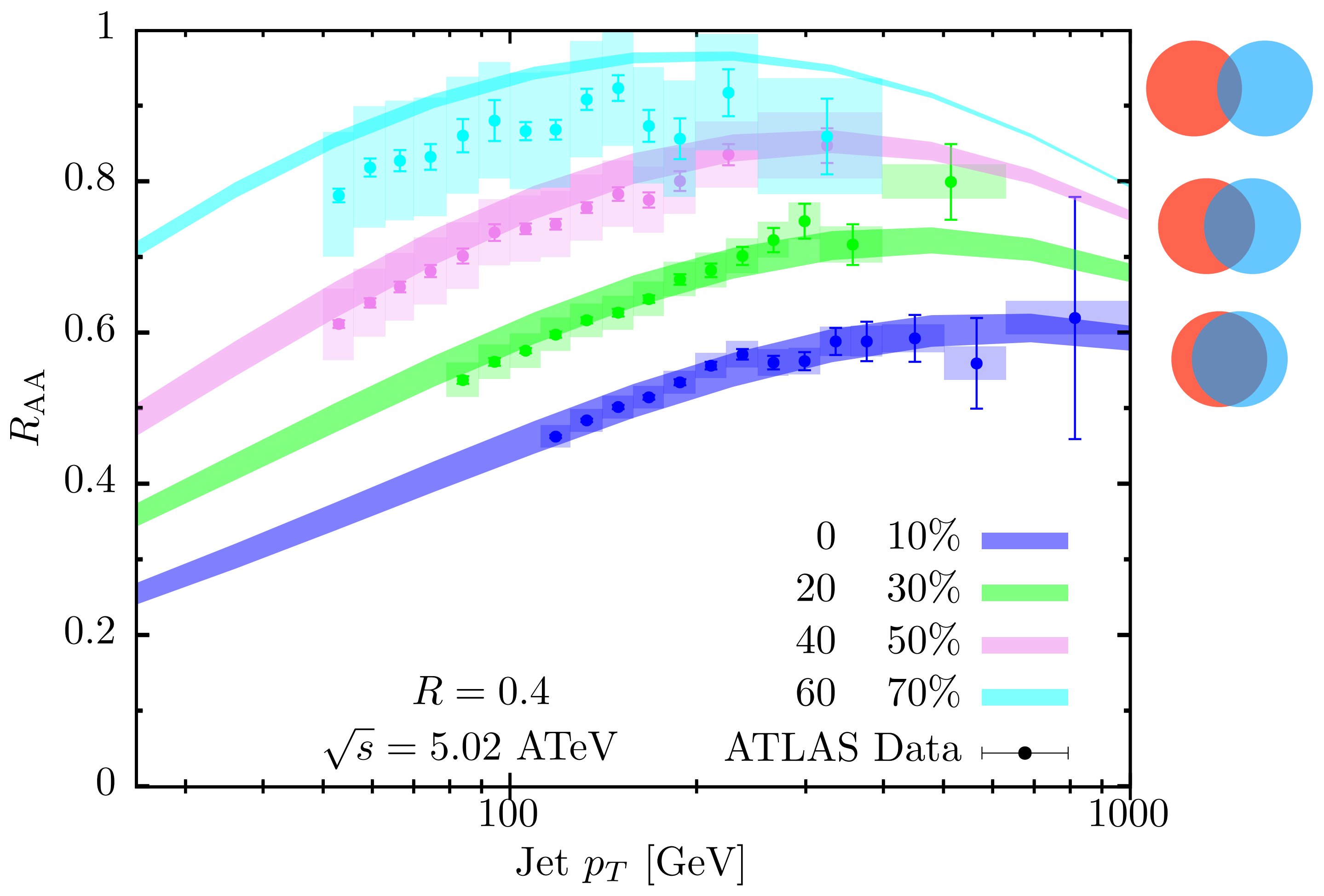


Image credits: Atlas Collaboration/CERN

Ratio between **protons** and **heavy-ion** collisions:

Mehtar-Tani (2025)



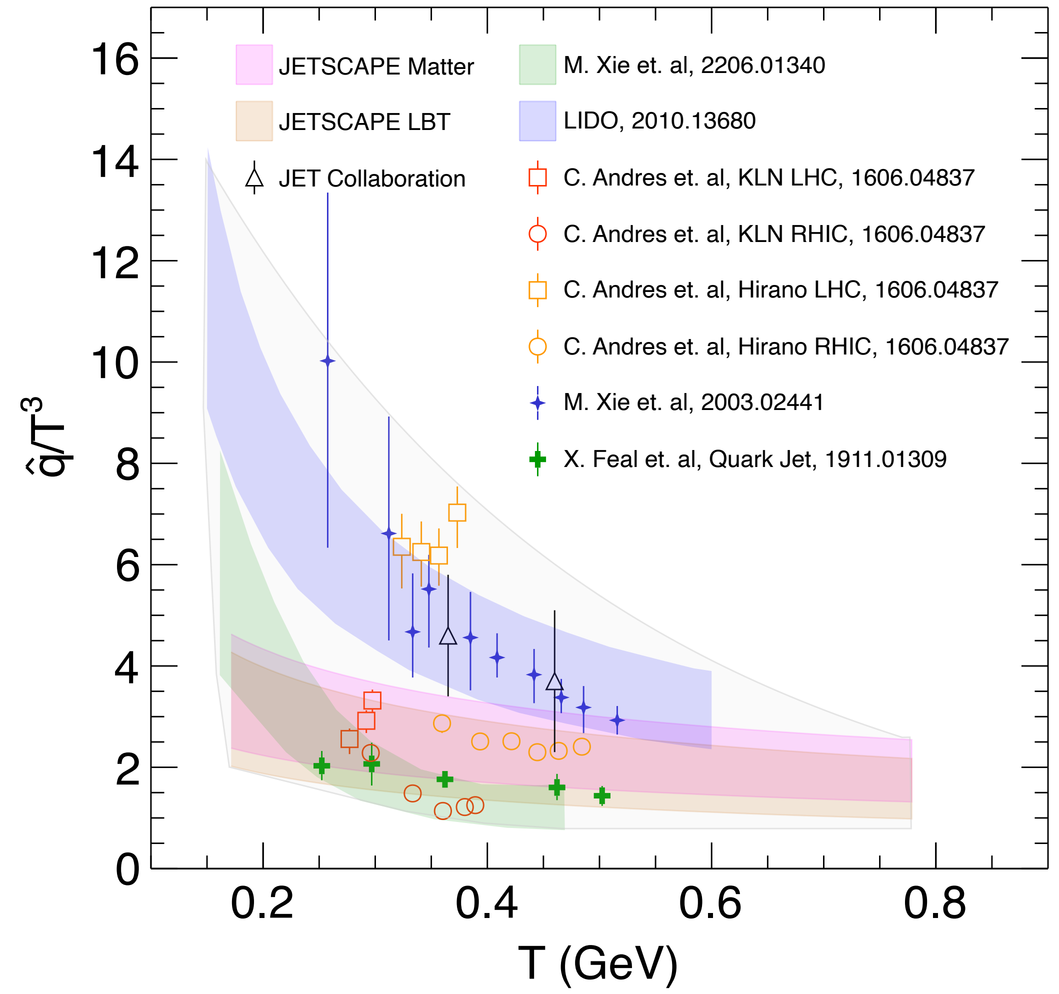
- Extract quantities of the QGP:

e.g. **jet quenching parameter $\hat{q}$**

- transverse momentum (squared) per unit length
- relation with the QGP viscosity η/s

→ **theoretical uncertainties**: depending on

- initial state modelling
- QGP modelling
- jet-medium interaction modelling
- …



Apolinário et al. (2022)

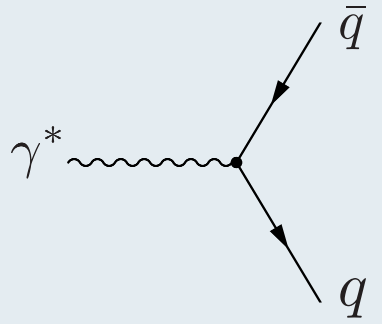
Jets as QGP probes

- We focus on the problem of **jet interaction with the QCD medium (QGP)**

Strong force **colour** representations:

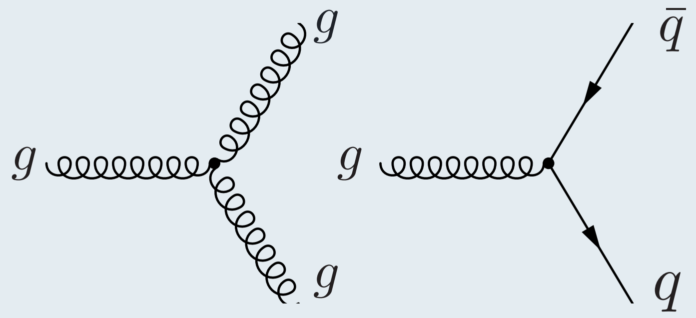
singlet
colourless (non-interacting)

e.g.
photon



octet
interacting

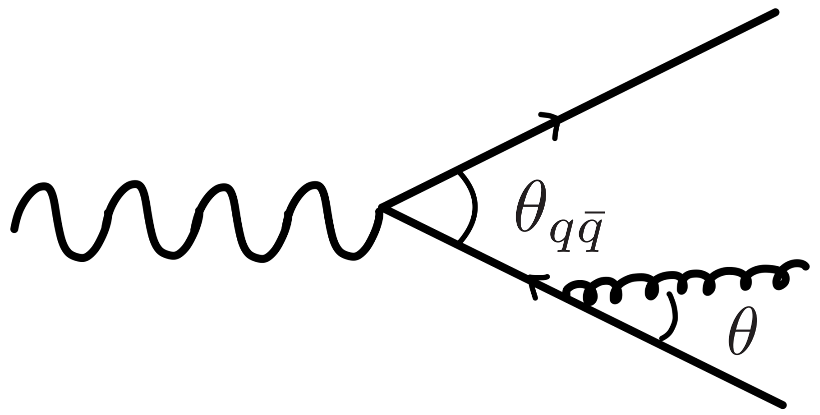
e.g.
gluon



Colour coherence (vacuum)

Colour decoherence (in-medium)

Soft (low energy) gluon radiation:

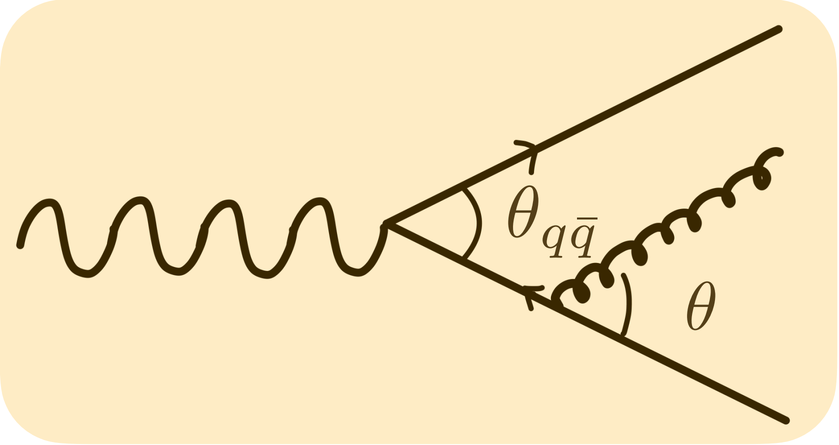


$\theta < \theta_{q\bar{q}}$

otherwise, the gluon **resolves** the full $q\bar{q}$ dipole

⟶ **suppressed**

Dokshitzer, Khoze, Mueller, Troyan (1991)



radiation **also** for $\theta > \theta_{q\bar{q}}$

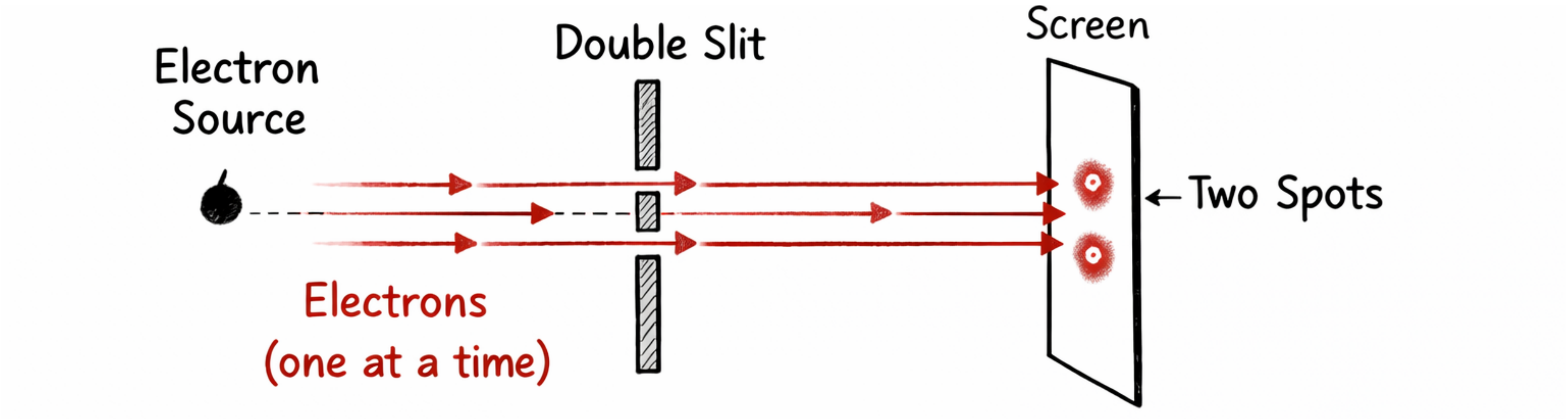
⟶ **enhancement** of large angle radiation

Mehtar-Tani, Salgado, Tywoniuk (2011-2013)
Casalderrey-Solana, Iancu (2011)

A step back: what is decoherence?

Quantum mechanics has a *uncommon* behaviour

e.g. **double slit experiment**



classical mechanics **expected** outcome

real outcome

- **Quantum mechanics:**

describes electrons as **clouds of probability** of where to find a moving particle → well-described through the **Schrödinger's equation** as propagating waves

- Different from our daily experience: classical mechanics

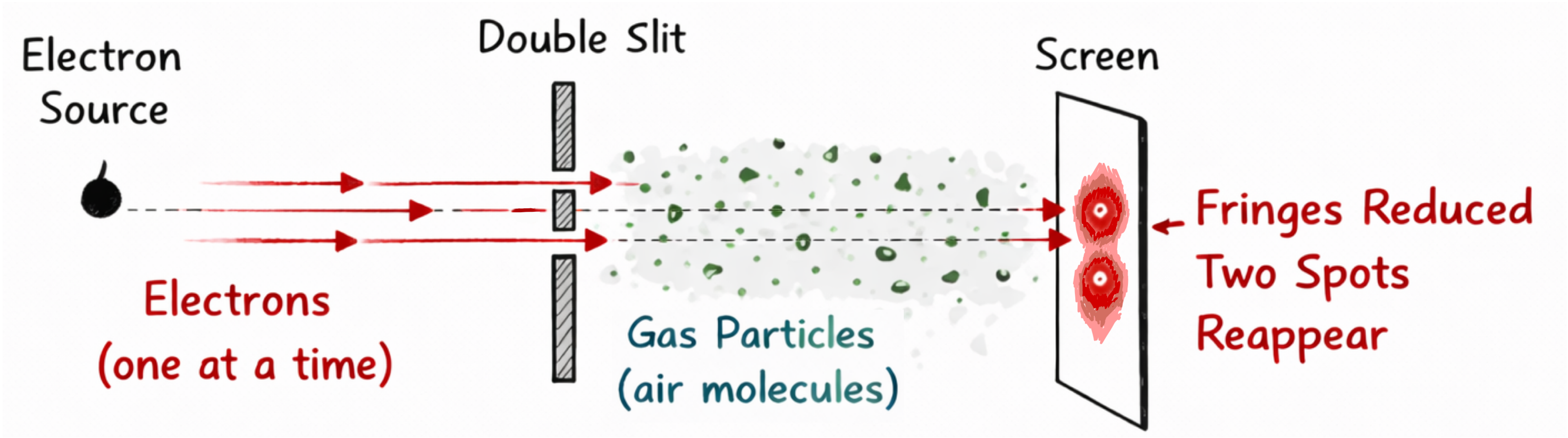
e.g. a goalkeeper would have a tough life…

→ Why do we experience this? **Decoherence!**

A step back: what is decoherence?

- **Decoherence** is the consequence of studying a physical system in a **non-isolated (open) environment**

- If we look again at the double slit experiment, but we forget to pump the vacuum out of (i.e. **isolate**) our system:



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Quantum dynamics gets **modified** when a system is put inside an environment!

~~Schrödinger's equation~~

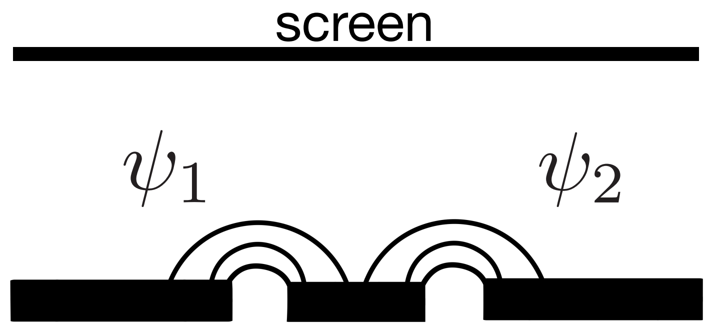
New master equation

Open quantum systems (OQSs) !

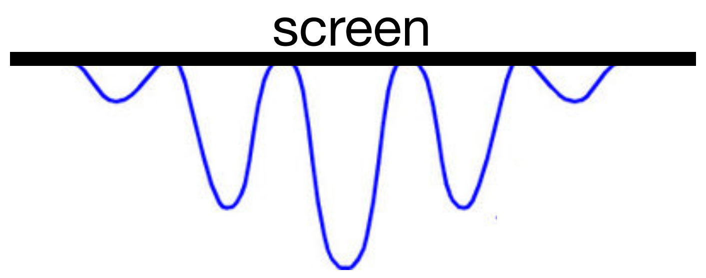
A step back: what is decoherence?

- Just a bit more precisely, what's happening?

- The **interactions with the medium** are destroying the **quantum interferences**



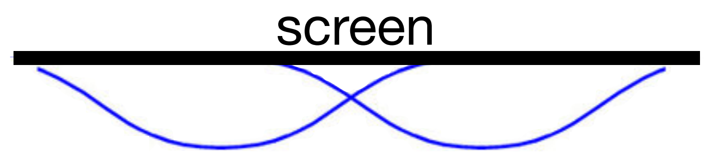
$$\Psi = \psi_1 + \psi_2$$



$$|\Psi|^2 \neq |\psi_1|^2 + |\psi_2|^2$$

without
medium
(vacuum)

→



$$|\Psi|^2 = |\psi_1|^2 + |\psi_2|^2$$

with
medium
(air)

In the language of OQSs: **off-diagonal** terms of the density matrix get **suppressed**!

- To illustrate this, let's consider the case of **spin**:

e.g. spin state decoherence

$$|\psi\rangle = \frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}}$$

$$\rho = |\psi\rangle\langle\psi|$$

probabilities

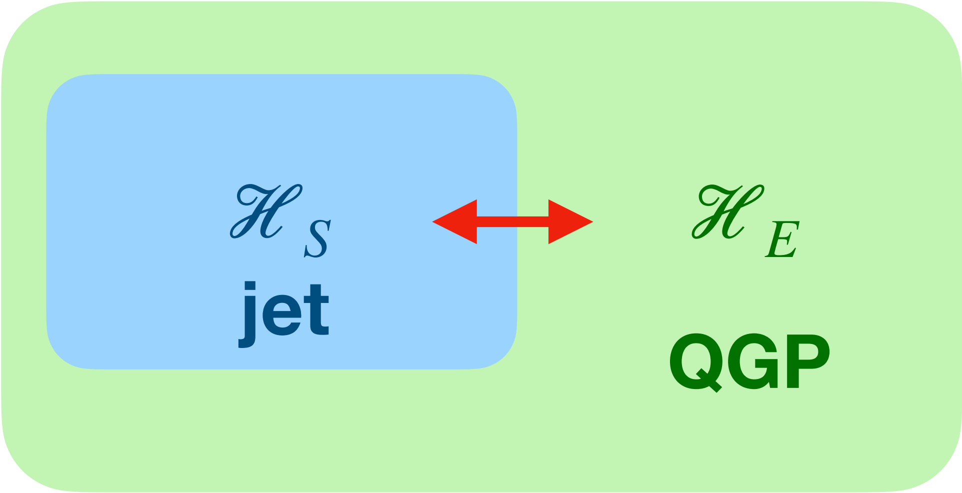
coherences

$$\rho(t=0) = \frac{1}{2}\begin{array}{cc} |\uparrow\rangle & |\downarrow\rangle \\ \end{array}\begin{pmatrix} \bigcirc\!\!\!\!1 & \bigcirc\!\!\!\!1 \\ \bigcirc\!\!\!\!1 & \bigcirc\!\!\!\!1 \end{pmatrix}\begin{array}{c} \langle\uparrow| \\ \langle\downarrow| \end{array} \xrightarrow[\text{magnetic field}]{\text{stochastic}} \rho(t\to\infty) = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

A “more sophisticated double slit”: jets as OQSs

- We are interested in describing the way radiation of several energetic particles (quarks and gluons) behave **in the QGP**

  ⟶ quantify **decoherence** and **momentum broadening**



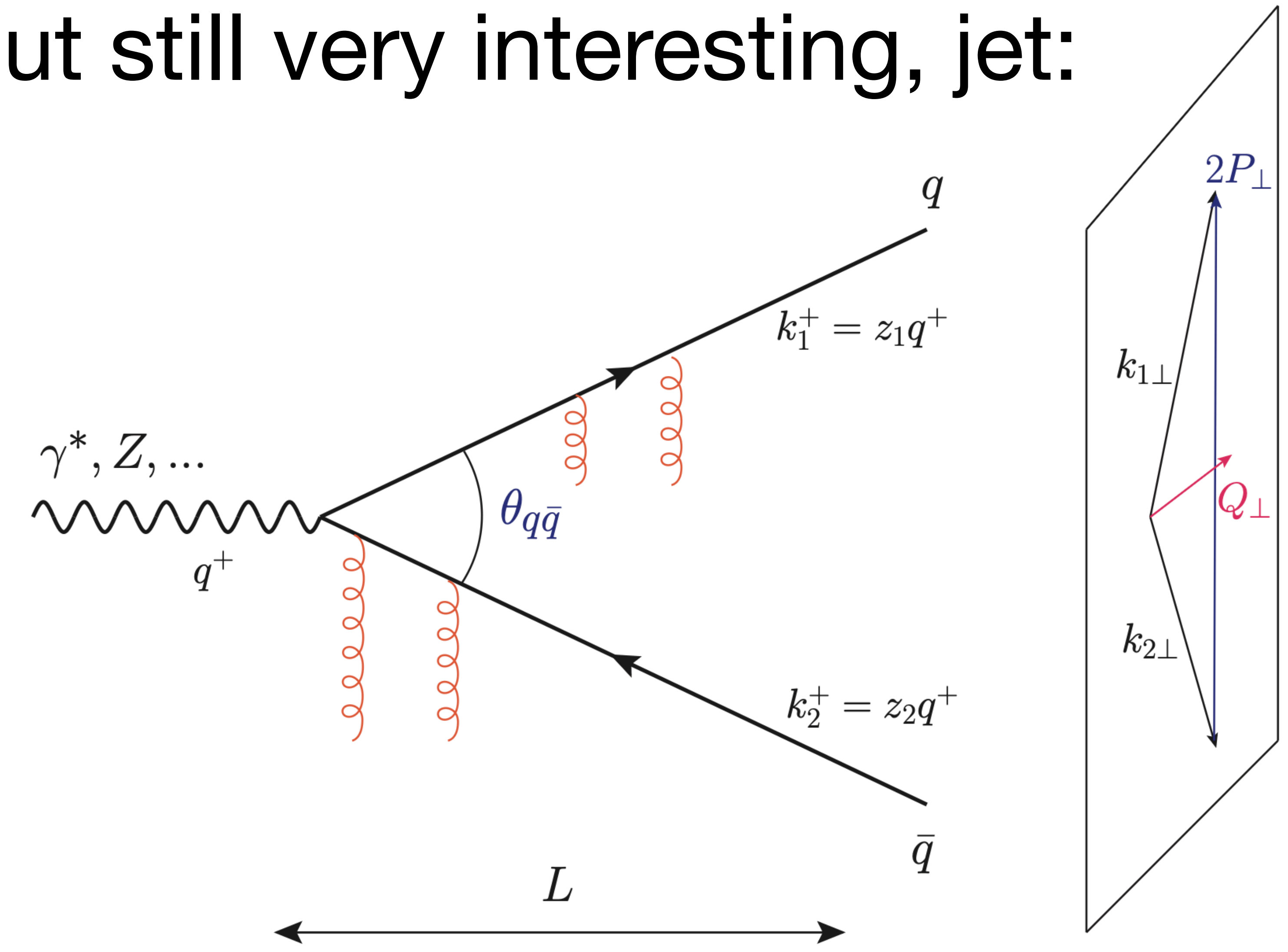
$\rho = \rho_S \otimes \rho_E$

- As a **first step** we have studied the (almost) simplest, but still very interesting, jet:

High energy $q\bar{q}$ dipole

$$E \sim q^+ \gg P_\perp \gg Q_\perp$$

longitudinal mom. — relative transv. mom. — center-of-mass transv. mom.



- Why starting from here?
  - **Heavy quark-antiquark** (quarkonium) OQS

    Blaizot, Escobedo (2018)
  - **Single quark jet** OQS

    Barata, Blaizot, Mehtar-Tani (2023)

heavy mass → **non-relativistic** description → in 3+1 dimensions

high energy → **non-relativistic** description → **in 2+1 dimensions**

Derivation of the master equation

- **Hamiltonian** in 2D transverse space:

$$H = \overbrace{\left(\frac{\hat{p}^2_{\perp,q}}{2k_1^+} + \frac{\hat{p}^2_{\perp,\bar{q}}}{2k_2^+}\right) \otimes \mathbb{1}_E}^{\text{kinetic term}} \overbrace{- g \int \mathrm{d}^2\boldsymbol{x}_\perp \, \hat{n}^a(\boldsymbol{x}_\perp) \otimes A_a^-(t, \boldsymbol{x}_\perp)}^{\text{interaction}} + \overbrace{\mathbb{1}_S \otimes H_{\mathrm{pl}}}^{\text{QGP}}$$

number density: $\hat{n}^a(\boldsymbol{x}_\perp) = \underbrace{\delta(\boldsymbol{x}_\perp - \hat{x}_{\perp,q}) t^a \otimes \mathbb{1}_{\bar{q}}}_{\text{quark}} - \underbrace{\mathbb{1}_q \otimes \delta(\boldsymbol{x}_\perp - \hat{x}_{\perp,\bar{q}}) \tilde{t}^a}_{\text{antiquark}}$

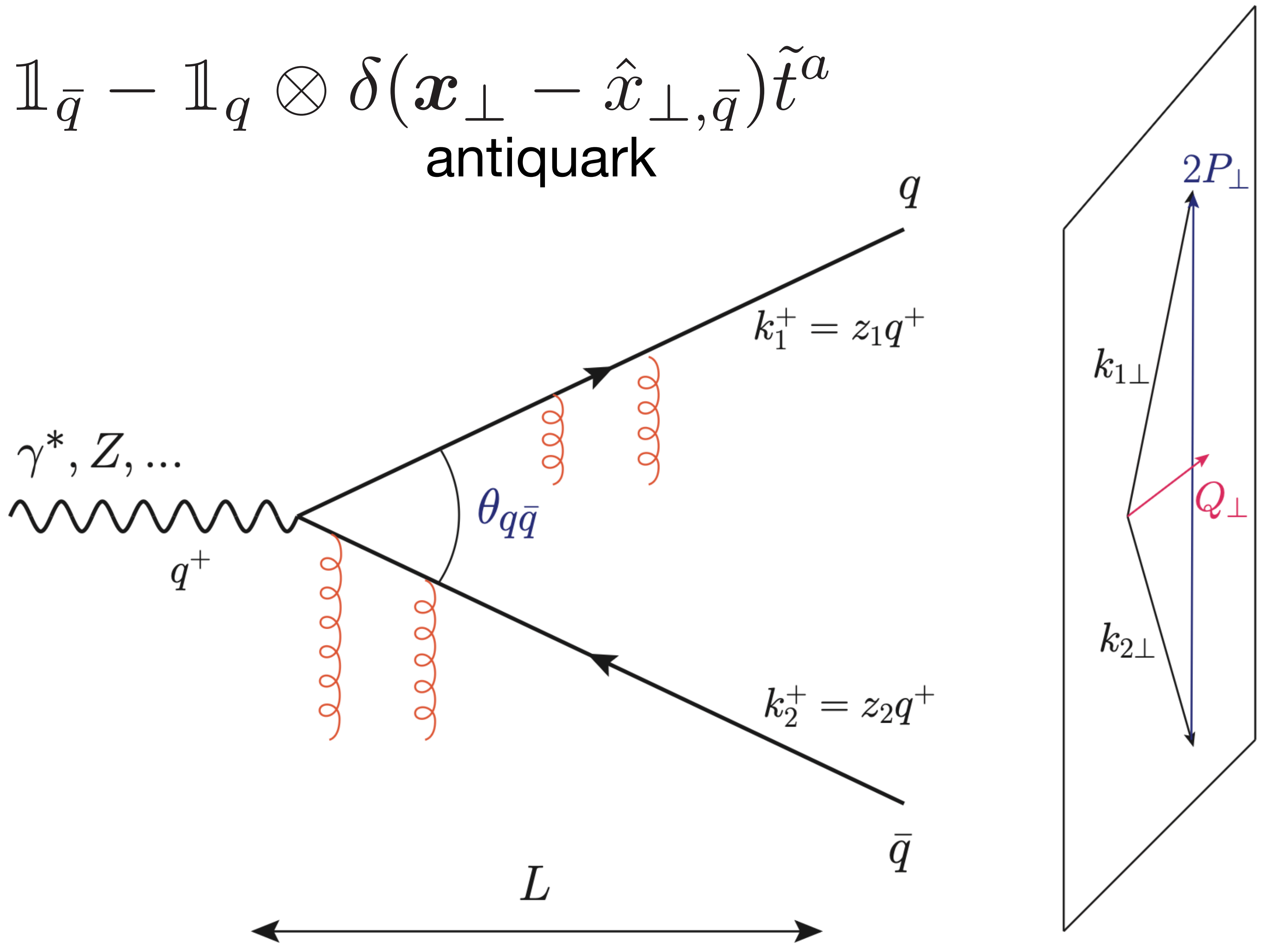
$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -i\,[H, \rho]$$

Von Neumann's equation

Partial trace over environment

$$\mathrm{Tr}_E\,(\cdot)$$

$$\rho = \underset{\text{system}}{\rho_S} \otimes \underset{\text{environment}}{\cancel{\rho_E}}$$



$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} = -i\,[H_0, \rho_S] + \mathcal{D}(\rho_S)$$

Linblad's equation

contains the **potential** $W(\boldsymbol{x}_\perp - \boldsymbol{x}'_\perp)$ which describes the interactions with the medium

⟶ in the **high-energy limit**: mainly **collisions**

Master equation

$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} = -i\,[H_0, \rho_S] + \mathcal{D}(\rho_S)$$

$\boldsymbol{r}_\perp$ relative position

$\boldsymbol{p}_\perp$ relative

$\boldsymbol{q}_\perp$ center-of-mass

transv. momentum

- **Harmonic approximation** of the potential: $W \propto \hat{q}\,\hat{\mathcal{O}}\left[\boldsymbol{r}_\perp^2, \nabla^2_{\boldsymbol{p}_\perp}, \nabla^2_{\boldsymbol{q}_\perp}\right]$

- We have a **master equation**!

Colour factors:

N_c # of colours

$$C_F = \frac{N_c^2 - 1}{2N_c}$$

jet quenching parameter

kinetic term

colour transitions

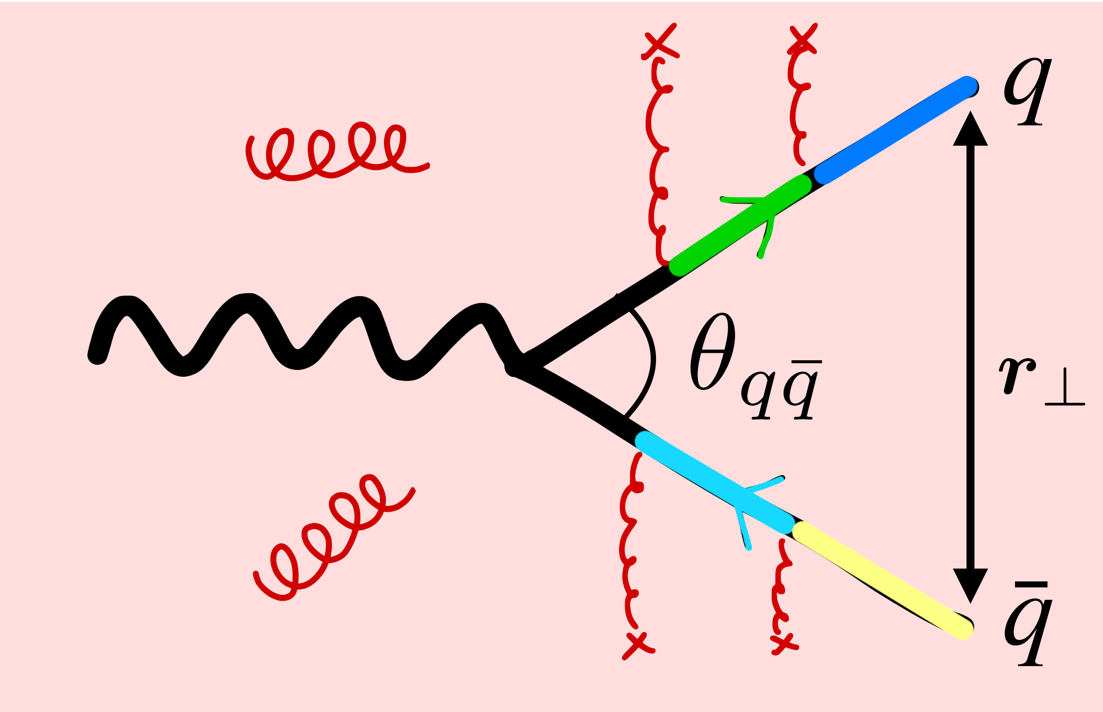
$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_s \\ \rho_o\end{pmatrix} + \frac{1}{E}\boldsymbol{p}_\perp \cdot \nabla_{\boldsymbol{r}_\perp}\begin{pmatrix}\rho_s \\ \rho_o\end{pmatrix} = \frac{\hat{q}\boldsymbol{r}_\perp^2}{4C_F}\begin{pmatrix}-2C_F & 2C_F \\ \frac{1}{N_c} & -\frac{1}{N_c}\end{pmatrix}\begin{pmatrix}\rho_s \\ \rho_o\end{pmatrix}$$

$$\frac{1}{E} = \frac{1}{k_1^+} + \frac{1}{k_2^+}$$

effective longitudinal momentum

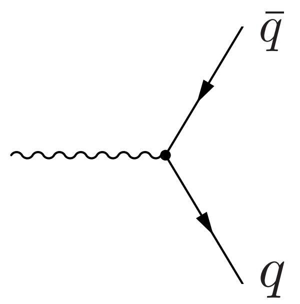
We have separated the evolution of the

- **singlet component** ρ_s (colourless/ non-interacting)
- **octet component** ρ_o (colourful/ interacting)



Solutions: colour decoherence

- We want to investigate the **quantum** behaviour of **colour decoherence**:
  → do you remember the interferences in the *double slit experiment* and the *spin state*?
  - Initial colour **singlet** state: $|\psi(0)\rangle = \frac{|r\bar{r}\rangle + |b\bar{b}\rangle + |g\bar{g}\rangle}{\sqrt{3}}$

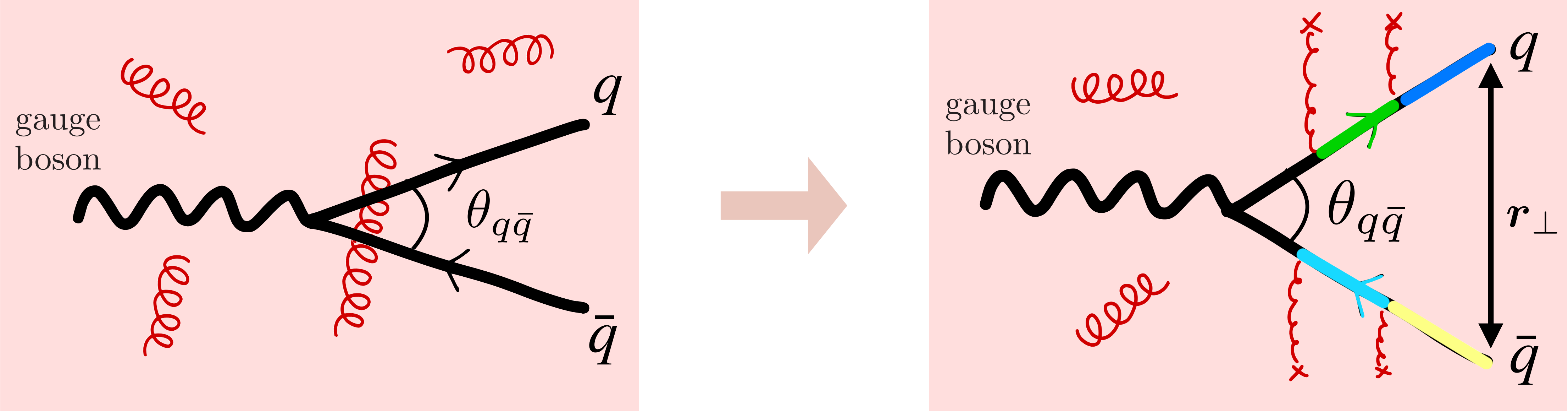


$$q \in \{|r\rangle, |g\rangle, |b\rangle\}$$
$$\bar{q} \in \{|\bar{r}\rangle, |\bar{g}\rangle, |\bar{b}\rangle\}$$

$$\rightarrow \hat{\rho}(0) = \begin{pmatrix} |r\bar{r}\rangle\langle r\bar{r}| & & |r\bar{r}\rangle\langle b\bar{b}| & & |r\bar{r}\rangle\langle g\bar{g}| \\ & 0 & & 0 & \\ |b\bar{b}\rangle\langle r\bar{r}| & & |b\bar{b}\rangle\langle b\bar{b}| & & |b\bar{b}\rangle\langle g\bar{g}| \\ & 0 & & 0 & \\ |g\bar{g}\rangle\langle r\bar{r}| & & |g\bar{g}\rangle\langle b\bar{b}| & & |g\bar{g}\rangle\langle g\bar{g}| \end{pmatrix} \xrightarrow[\substack{\text{time} \\ \text{evolution} \\ t \to \infty}]{t_c = \left(\frac{4}{\hat{q}\theta^2_{q\bar{q}}}\right)^{\frac{1}{3}}} \begin{pmatrix} |r\bar{r}\rangle\langle r\bar{r}| & & & 0 & & \\ & |r\bar{g}\rangle\langle r\bar{g}| & & & & \\ & & |r\bar{b}\rangle\langle r\bar{b}| & & & \\ & & & |b\bar{r}\rangle\langle b\bar{r}| & & \\ & 0 & & & \ddots & \\ & & & & & \ddots \end{pmatrix}$$

  - Colour **decoherence**: suppression of the off-diagonal elements (coherences)
  - Colour **equilibration**: total randomization of the colour of the dipole

- Physical picture:



Solutions: kinematical decoherence

$$\frac{1}{E} = \frac{1}{k_1^+} + \frac{1}{k_1^+}\,;\quad q^+ = k_1^+ + k_2^+$$

- Let’s now consider the **motion of the center-of-mass** too:

kinetic term **CoM diffusion** **colour transitions**

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix} + \left(\frac{1}{E}\boldsymbol{p}_\perp\cdot\nabla_{\boldsymbol{r}_\perp} + \frac{1}{q^+}\boldsymbol{q}_\perp\cdot\nabla_{\boldsymbol{b}_\perp}\right)\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix} = \frac{\hat{q}}{4C_F}\left\{\begin{pmatrix}0 & 0\\ 0 & N_c\end{pmatrix}\nabla^2_{\boldsymbol{q}_\perp} + \begin{pmatrix}-2C_F & 2C_F\\ \frac{1}{N_c} & -\frac{1}{N_c}\end{pmatrix}\boldsymbol{r}^2_\perp\right\}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix}$$

- Initial colour **singlet** state

$$\rho_T(\boldsymbol{q}_\perp, \boldsymbol{b}_\perp; 0) = \frac{1}{\pi^2}e^{-\boldsymbol{q}_\perp^2/\Lambda^2 - \Lambda^2\boldsymbol{b}_\perp^2}$$

(Gaussian with width Λ)

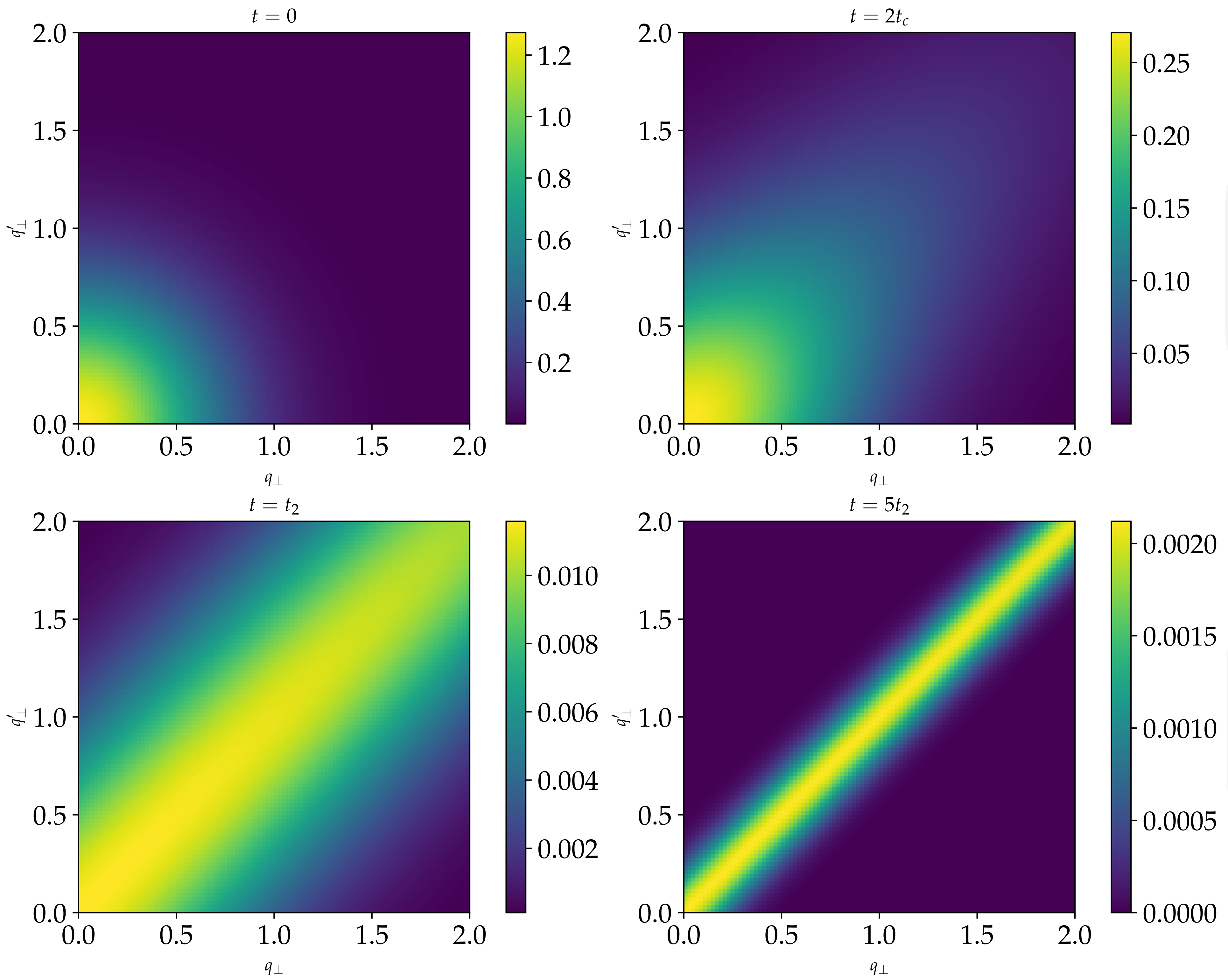
Numbers:

$$\Lambda = 500\ \mathrm{MeV}$$

$$\hat{q} = 1.5\ \mathrm{GeV}^2/\mathrm{fm}$$

$$q^+ = 50\ \mathrm{MeV}$$

$$\theta_{q\bar{q}} = 0.4$$



$$t_c = \left(\frac{4}{\hat{q}\theta^2_{q\bar{q}}}\right)^{\frac{1}{3}} \sim 0.87\ \mathrm{fm}$$

colour decoherence occurs (**inside** the medium)

$L = 4\ \mathrm{fm}$ medium length

$$t_2 = \left(\frac{(q^+)^2}{\hat{q}\Lambda^2}\right)^{1/3} \sim 10\ \mathrm{fm}$$

kinematical decoherence occurs (**outside** the medium)

Summary

- We have derived a **master equation** for the $q\bar{q}$ evolution with the **OQS formalism**
    - The collisions with the medium cause **color decoherence**
        - **colour transitions** (singlet-octet)
        - **diagonalization** of the density matrix in the colour-anticolour basis
        - **color equilibration**
    - and afterwards, **kinematical decoherence** in momentum space (if not already outside the QGP)

- Beyond what has been shown here, we have also studied
    - the **broadening** of the center-of-mass transverse momentum
    - **perturbatively** the **full** master equation equipped of the relative transverse momentum diffusion term

Towards better *open* and *quantum* jets

- We are now working to implement **radiation** within the OQS framework
  - This means generalizing the master equation to a **non-fixed number of particles**

- Interesting **real-time** formalism for quantifying
  - **In-medium** modifications of the radiation spectrum
  - **Color decoherence**

- Possible implementation into **Monte Carlo codes** to simulate jets in a QGP and do phenomenology

Thank you for your attention!

Backups

Derivation of the master equation

- From the Von Neumann equation we have carried out the following approximations:

$$i\frac{d\rho}{dt} = [H, \rho]$$

Von Neumann equation

  - Double iteration of the equation by integrating it and insert the solution back $$\frac{d}{dt}\rho^I(t) = -ig\left[H^I(t), \rho^I(0)\right] - g^2\int_0^t dt'\left[H^I(t), \left[H^I(t'), \rho^I(t')\right]\right]$$

partial trace

  - **Born** approximation: the state remains factorized at all times $\rho(t) = \rho_S(t) \otimes \rho_E$
  - **Markov** approximation: we impose **locality in time** thanks to the weak coupling g → **Redfield** equation: $$\frac{d}{dt}\rho_S^I(t) = -g^2\int_0^t dt'\mathrm{Tr}_E\left[H^I(t), \left[H^I(t'), \rho_S^I(\mathbf{t}) \otimes \rho_E\right]\right]$$
  - Locality is not enough for **Markovianity**: the equation still depends on the initial condition at $t' = 0$

Derivation of the master equation

- If we assume that the **environment correlation time** τ_E is much smaller than the **system relaxation time** τ_R than, the information on the specific initial state at $t' = 0$ becomes irrelevant

  → we extend the integration domain from $t' \in [0,t]$ to $[-\infty, t]$. Then, after a change of variables we obtain

$$\frac{d}{dt}\rho_S^I(t) = -g^2 \int_0^{+\infty} dt' \mathrm{Tr}_E \left[H^I(t), \left[H^I(t-t'), \rho_S^I(t) \otimes \rho_E\right]\right]$$

- Now, one has just to substitute the factorized structure of the Hamiltonian and keep within the partial trace just the environment contributions

  → two-point correlators of the environment part of the interaction

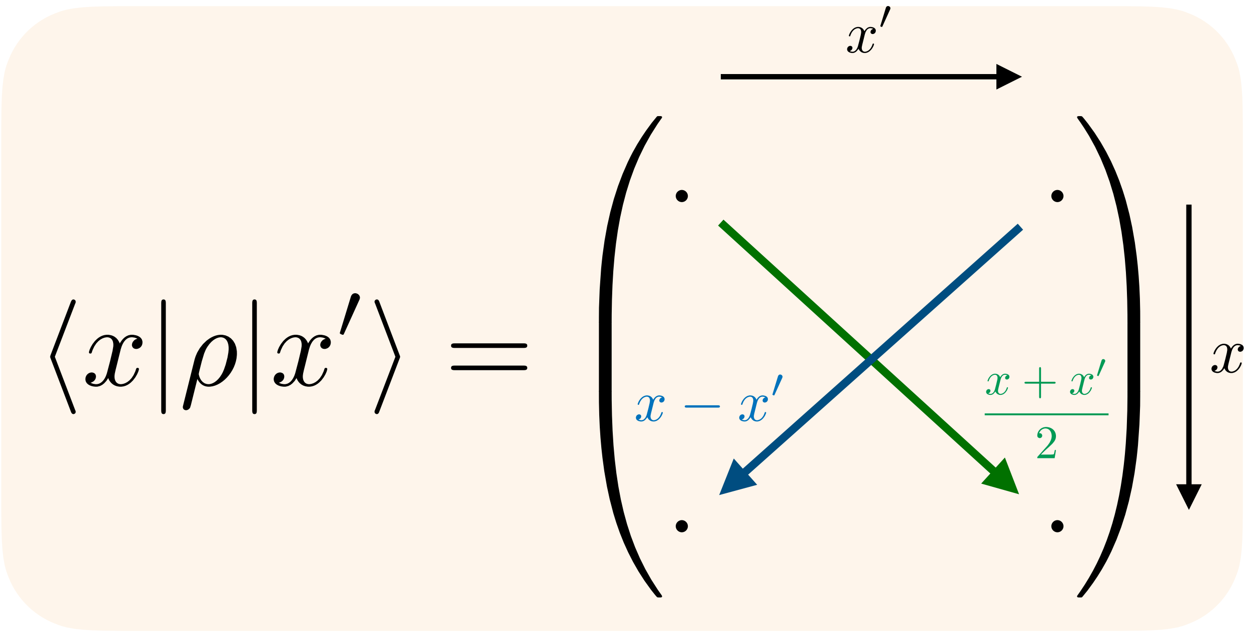
Derivation of the master equation

$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} = -i\left[H_0, \rho_S\right] + \mathcal{D}(\rho_S)$$

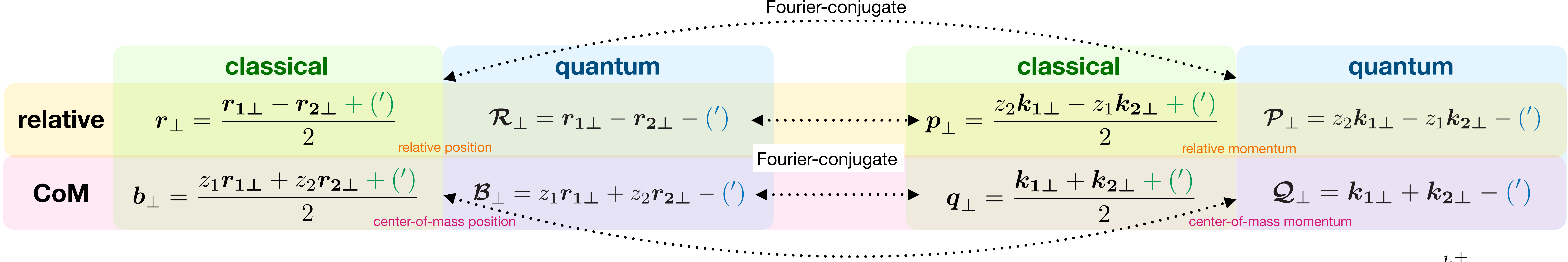
Wigner function and variables

- The equation is still at the **operator** level: we want to study the evolution of the **matrix elements** of the density matrix ρ

$$\langle \boldsymbol{r_{1\perp}} \boldsymbol{r_{2\perp}} | \rho | \boldsymbol{r_{1\perp}}' \boldsymbol{r_{2\perp}}' \rangle = \rho(\boldsymbol{r_{1\perp}} \boldsymbol{r_{2\perp}}; \boldsymbol{r_{1\perp}}' \boldsymbol{r_{2\perp}}')$$



- Introduce new variables:



	classical	quantum	classical	quantum
relative	$\boldsymbol{r}_\perp = \frac{\boldsymbol{r_{1\perp}} - \boldsymbol{r_{2\perp}} + (')}{2}$ relative position	$\boldsymbol{\mathcal{R}}_\perp = \boldsymbol{r_{1\perp}} - \boldsymbol{r_{2\perp}} - (')$	$\boldsymbol{p}_\perp = \frac{z_2 \boldsymbol{k_{1\perp}} - z_1 \boldsymbol{k_{2\perp}} + (')}{2}$ relative momentum	$\boldsymbol{\mathcal{P}}_\perp = z_2 \boldsymbol{k_{1\perp}} - z_1 \boldsymbol{k_{2\perp}} - (')$
CoM	$\boldsymbol{b}_\perp = \frac{z_1 \boldsymbol{r_{1\perp}} + z_2 \boldsymbol{r_{2\perp}} + (')}{2}$ center-of-mass position	$\boldsymbol{\mathcal{B}}_\perp = z_1 \boldsymbol{r_{1\perp}} + z_2 \boldsymbol{r_{2\perp}} - (')$	$\boldsymbol{q}_\perp = \frac{\boldsymbol{k_{1\perp}} + \boldsymbol{k_{2\perp}} + (')}{2}$ center-of-mass momentum	$\boldsymbol{\mathcal{Q}}_\perp = \boldsymbol{k_{1\perp}} + \boldsymbol{k_{2\perp}} - (')$

$$z_i = \frac{k_i^+}{k_1^+ + k_2^+}$$

- **Wigner function:**

$$\rho(\boldsymbol{r}_\perp, \boldsymbol{\mathcal{R}}_\perp, \boldsymbol{b}_\perp, \boldsymbol{\mathcal{B}}_\perp) \xrightarrow{\text{partial Fourier transforms}} \boxed{\rho(\boldsymbol{r}_\perp, \boldsymbol{p}_\perp, \boldsymbol{b}_\perp, \boldsymbol{q}_\perp)}$$

Quasi-probability distribution

Master equation

- **Harmonic approximation** of the potential:

$$W = W(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp, \boldsymbol{\mathcal{R}}_\perp, \boldsymbol{\mathcal{B}}_\perp) \longrightarrow \text{harmonic approx.} \xrightarrow{\text{Wigner transform}} \propto \hat{q}\,\hat{\mathcal{O}}\left[\boldsymbol{r}_\perp^2, \nabla^2_{\boldsymbol{p}_\perp}, \nabla^2_{\boldsymbol{q}_\perp}\right]$$

- We have a **master equation**!

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix} + \left(\overbrace{\frac{1}{E}\boldsymbol{p}_\perp\cdot\nabla_{\boldsymbol{r}_\perp} + \frac{1}{q^+}\boldsymbol{q}_\perp\cdot\nabla_{\boldsymbol{b}_\perp}}^{\text{kinetic term}}\right)\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix} = \frac{\hat{q}}{4C_F}\left\{\overbrace{\begin{pmatrix}0 & 0\\ 0 & N_c\end{pmatrix}\nabla^2_{\boldsymbol{q}_\perp}}^{\text{CoM diffusion}} + \overbrace{\begin{pmatrix}-2C_F & 2C_F\\ \frac{1}{N_c} & -\frac{1}{N_c}\end{pmatrix}\boldsymbol{r}_\perp^2}^{\text{colour transitions}} + \underbrace{\begin{pmatrix}\frac{C_F}{2} & \frac{C_F}{2}\\ \frac{1}{4N_c} & \frac{C_F}{2}-\frac{1}{2N_c}\end{pmatrix}\nabla^2_{\boldsymbol{p}_\perp}}_{\text{relative diffusion}}\right\}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix}$$

$$\frac{1}{E} = \frac{1}{k_1^+} + \frac{1}{k_1^+}$$

$$q^+ = k_1^+ + k_2^+$$

quantum diffusion:

It causes *diffusion* in $\boldsymbol{p}_\perp, \boldsymbol{q}_\perp$
and *decoherence* in $\boldsymbol{\mathcal{R}}_\perp, \boldsymbol{\mathcal{B}}_\perp, \boldsymbol{\mathcal{P}}_\perp, \boldsymbol{\mathcal{Q}}_\perp$

rescaling of variables

→ **relative diffusion**
operator **scales** as

$$\kappa^2 \sim \frac{\theta_s^2}{\theta_c^2} \qquad \theta_s = \frac{\sqrt{\hat{q}L}}{E}$$

small in $E \gg \boldsymbol{p}_\perp, \boldsymbol{q}_\perp$
high-energy regime

- A “two species” Fokker-Planck -like equation: any analytical **solutions**?

Solutions: colour transitions

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix}+\underbrace{\left(\frac{1}{E}\boldsymbol{p}_\perp\cdot\nabla_{\boldsymbol{r}_\perp}+\frac{1}{q^+}\boldsymbol{q}_\perp\cdot\nabla_{\boldsymbol{b}_\perp}\right)}_{\text{kinetic term}}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix}=\frac{\hat{q}}{2}\left\{\underbrace{\begin{pmatrix}0&0\\0&1\end{pmatrix}\nabla^2_{\boldsymbol{q}_\perp}}_{\text{CoM diffusion}}+\underbrace{\begin{pmatrix}-1&0\\1&0\end{pmatrix}\boldsymbol{r}^2_\perp}_{\text{colour transitions}}\right\}\begin{pmatrix}\rho_s\\ \rho_o\end{pmatrix}$$

Large-N_c limit

- **Neglect** the diffusion term ⟶ **analytical solution** with the method of characteristics
- **Initial** Wigner function (colour **singlet**): $\rho(\boldsymbol{p}_\perp,\boldsymbol{r}_\perp;\boldsymbol{q}_\perp,\boldsymbol{b}_\perp;0)=\underbrace{\rho_R(\boldsymbol{p}_\perp,\boldsymbol{r}_\perp;0)}_{\text{relative}}\underbrace{\rho_T(\boldsymbol{q}_\perp,\boldsymbol{b}_\perp;0)}_{\text{center-of-mass}}$

$$\rho_R(\boldsymbol{p}_\perp,\boldsymbol{r}_\perp;0)=H(\boldsymbol{p}_\perp)\delta(\boldsymbol{r}_\perp)$$

$$\rho_T(\boldsymbol{q}_\perp,\boldsymbol{b}_\perp;0)=\frac{1}{\pi^2}e^{-\boldsymbol{q}^2_\perp/\Lambda^2-\Lambda^2\boldsymbol{b}^2_\perp}$$

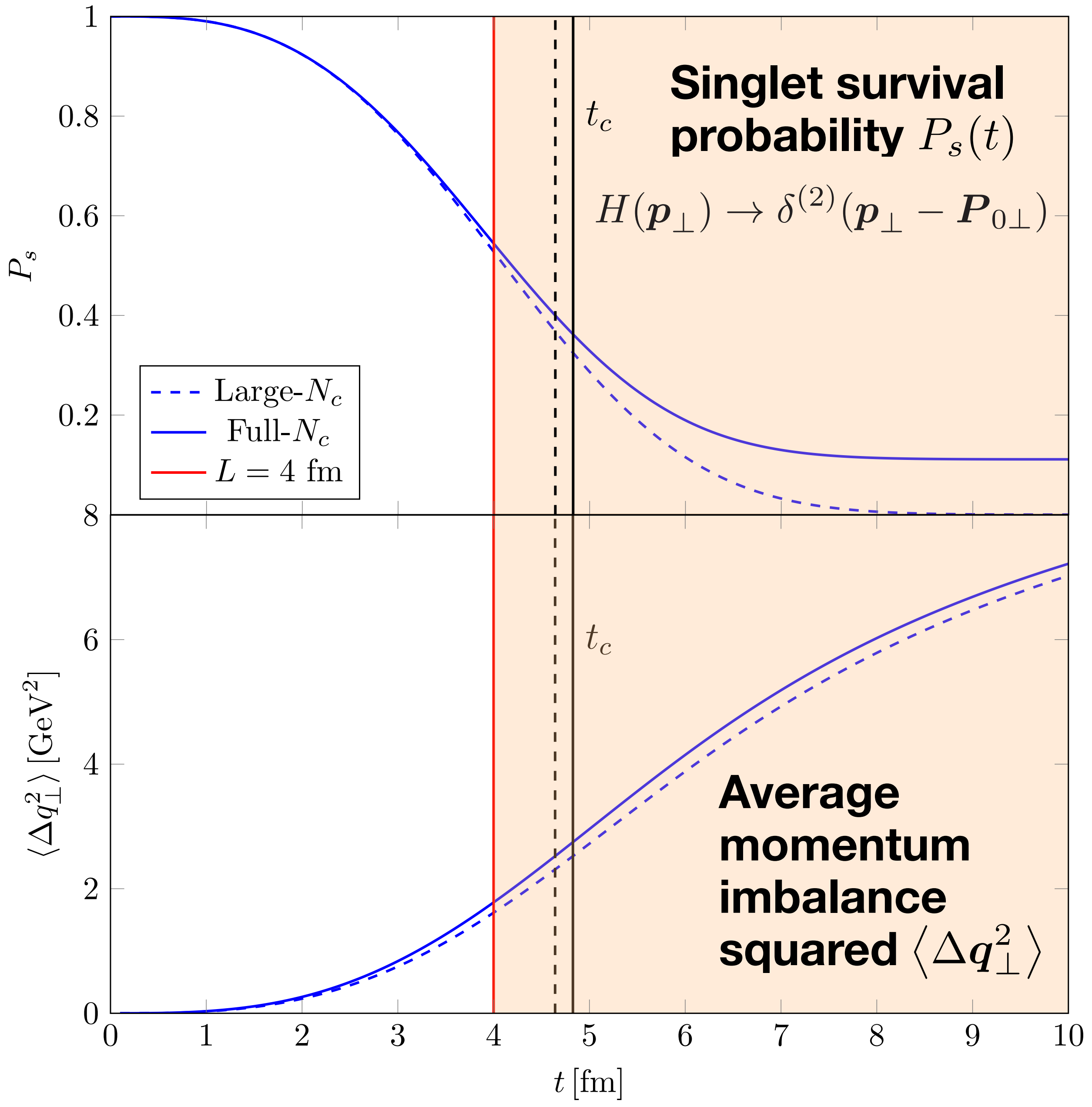
- By integrating over the coordinates $\boldsymbol{r}_\perp$ and $\boldsymbol{b}_\perp$:

$$(\Lambda\to 0)\qquad\frac{\mathrm{d}P}{\mathrm{d}^2\boldsymbol{p}_\perp\mathrm{d}^2\boldsymbol{q}_\perp}=H(\boldsymbol{p}_\perp)\times\frac{1}{\pi}\left\{\underbrace{e^{-\frac{\hat{q}\theta^2_{q\bar{q}}t^3}{12}}\delta(\boldsymbol{q}_\perp)}_{\text{singlet}}+\int_0^t\mathrm{d}s\,\underbrace{\frac{\theta^2_{q\bar{q}}(t-s)^2}{8s}e^{-\frac{\hat{q}\theta^2_{q\bar{q}}(t-s)^3}{12}}e^{-\frac{\boldsymbol{q}^2_\perp}{2\hat{q}s}}}_{\text{octet}}\right\}$$

$$t_c=\left(\frac{4}{\hat{q}\theta^2_{q\bar{q}}}\right)^{\frac{1}{3}}\qquad\theta^2_{q\bar{q}}=\frac{2\boldsymbol{p}^2_\perp}{E^2}$$

- We compute the **CoM transverse momentum distribution**:

$$Q^2_s=\hat{q}L\qquad\langle\Delta Q^2_\perp\rangle=2Q^2_s\left\{1-\int_0^1\mathrm{d}s\exp\left(-\frac{\theta^2_{q\bar{q}}}{\theta^2_c}\frac{s^3}{3}\right)\right\}\qquad\theta^2_c=\frac{4}{\hat{q}t^3}$$



- **Non-trivial check** of known *Wilson lines*-like calculations with OQSs
  Dominguez et al. (2019); Isaksen, Tywoniuk (2023); …
- **Clarify hypothesis** behind the same results
  - initial factorization
  - neglect diffusion term