Heavy quark jets in evolving anisotropic matter

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[Work in collaboration with João Barata, Xoan Mayo and Andrey Sadofyev]

 $\sum_{i=1}^n a_i$

Hard Probes 2004

International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions

$(A\text{ possible})$ Time evolution of a HIC

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In contrast to usual HEP, **time and distance are relevant variables** in heavy-ion collisions **Measure time evolution - in equilibrium and out of equilibrium**

Hard Probes 2024. Heavy quarks in anisotropic media 4 medium evolution. For that we studied the hadronically-decaying W bosons, in particular in events with a p*s*NN = 2.76 TeV Pb-Pb collisions at the LHC $\frac{1}{\sqrt{2}}$ top-antitop quark pair. The corresponding chain of decays () provide the unique feature of a $\frac{1}{\sqrt{2}}$

Can we access the initial stages with jet quenching?

 T_c

different energies but these results are nearly independent of T

with the medium

First ~3ys… *ϵ K*

dotted green and green and develop the correspondered purple of the corresponding to the correspondence of the second purple, and α

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Is there an interplay between time evolution properties (velocity fields, gradients…) and jets developping in the medium?

[So that we can measure these properties with jet observables for different times]

\mathbf{S} \mathcal{Y}) \mathcal{Y} is \mathcal{Y} in \mathcal{Y} is the second to control experimentally important to control experimental in \mathcal{Y} 20 yrs ago… [rather ad-hoc implementation] **Strategic**

 $\frac{1}{\sqrt{2}}$ does with $\frac{1}{\sqrt{2}}$ does with p. This suggests that $\frac{1}{\sqrt{2}}$ does with p. This suggests that $\frac{1}{\sqrt{2}}$

two classes of applications for α applications for α our calculations: α

In the absence of a medium, the parton fragments ac-

 $d = 0$

 $\frac{1}{\sqrt{1-\frac{1$ $\begin{bmatrix} \text{Tauu ruoves} \\ \end{bmatrix}$ \mathbf{d} lective flow. Lower part: calculated distortion of the jet en-

 \blacksquare a) If the (density/temperature) gradients in jet $\sum_{0.1}^{\text{1}}$ $\sum_{0.1}^{\text{1}}$ $\sum_{0.2}^{\text{1}}$ $\sum_{0.1}^{\text{1}}$ $\sum_{0.2}^{\text{1}}$ $\sum_{0.1}^{\text{1}}$ $\sum_{0.2}^{\text{1}}$ $\sum_{0.1}^{\text{1}}$ $\sum_{0.2}^{\text{1}}$ $\sum_{0.1}^{\text{1}}$ $\sum_{0.2}^{\text{1}}$ $\sum_{0.1}^{\text{1}}$ $\sum_{0.2}^{\text{1}}$ $\sum_{0.1}^{\text{1$ quenching observables?

function of the production point r⁰ of the hard parton for different orientations

4 qnf α ⁺₁, α ⁻ **W**

pocket formula ∆E ≈ αsuc [29]. This motivates to investigate was assuced with the second with the second with t
This motivates to investigate with the second with the second with the second with the second with the secon

Fig. 3. Fig. 3. Fig. 2. Fig. in during media media media media di sensibele in terme di sensibele la model di
Teatry quarks in anisotropic media Hard Probes 2024. Heavy quarks in anisotropic media 9

In-medium parton propagation

$$
W(x_{\perp}) = \mathcal{P} \exp \left\{ ig \int d\xi \, n \cdot A(\xi, x_{\perp}) \right\}
$$

$$
G(x_{\perp}; y_{\perp}) = \mathcal{P} \int \mathcal{D} \mathbf{r} \exp \left\{ i \frac{E}{2} \int d\xi \left[\frac{d\mathbf{r}}{d\xi} \right]^2 + ig \int d\xi \, n \cdot A(\xi, \mathbf{r}) \right\}
$$

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✗ \overline{J} Yt Scattering amplitudes

ale - The simple **COLORED ROTATION** $S-Markix$ I ✗ ' \mathbf{P} > = $S_{\alpha'\beta'\alpha\beta}(\alpha\beta) = W_{\alpha'\alpha}(x_1)W_{\beta'\beta}^{\dagger}(y_+) |\alpha\beta\rangle$ Survival Robability $S(x_{1}, y_{1}) =$ $\frac{1}{N}$ tr $\left[W(x_1)W^{\dagger}(y_2)\right]$ Average over Configurations **Color dipole** - The simplest configuration

<u>P produce de la production de la productio</u>
Production de la production de la product

al of the medium **Medium averages needed - model of the medium**

Medium averages

A recoil-less medium ∼ **a collection of static scattering centers**

nls)5(r) [≈] f- § r2 In the harmonic approximation $S(\mathbf{x}_{\perp}, \mathbf{y}_{\perp}) \simeq \exp$

sca Hering centers

$$
\sum_{\mathbf{y}} \sum_{N^2 - 1}^{1} \text{Tr} \left\langle W_A(\mathbf{x}) W_A(\mathbf{y}) \right\rangle = \exp \left\{ -\frac{1}{2} \int_{t_0}^{t} ds \, n(s) \, \sigma(\mathbf{x} - \mathbf{y}) \right\}
$$
\nDipole cross section

\n
$$
\sigma(\mathbf{r}) = \int_{\mathbf{q}} |v(\mathbf{q})|^2 (1 - e^{i\mathbf{q}\mathbf{r}})
$$
\n
$$
S(\mathbf{x}_{\perp}, \mathbf{y}_{\perp}) \simeq \exp \left\{ -\frac{1}{4} \hat{q} L(\mathbf{x}_{\perp} - \mathbf{y}_{\perp}) \right\}
$$

G

$$
\frac{\partial}{\partial L} \int_{\mathbf{q}} \mathbf{q}^2 S(\mathbf{q})
$$

Where the second moment of the distribution defines the jet quenching parameter

 $\hat{q}=$

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Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

Heavy quark radiation

 $(\mathbf{p},\mathbf{q};t,\mathbf{p})\mathcal{P}(L,\mathbf{k};t',\mathbf{q})\times\exp\left(-\mathbf{p}\right)$ $\sqrt{ }$ *i M*² $\frac{d^2L}{2E}x(t'-t)$ \bigcap $W_M(\mathbf{x}_\perp, E) = W(\mathbf{x}_\perp) \times \exp$ $\sqrt{ }$ *i* M^2 $\frac{d^{12}}{2E}$ $(s-t)$ \mathcal{L}

$$
\omega \frac{dN}{d\omega d^2 \mathbf{k}} \sim \frac{\alpha_s C_R}{\omega^2} \text{Re} \int_{t',t} \int_{\mathbf{p},\mathbf{q}} \mathbf{p} \cdot \mathbf{q} \, \tilde{\mathcal{K}}(t)
$$

Leading mass correction to Wilson line

$$
\omega \frac{dN}{d\omega d^2 \mathbf{k}} \sim \frac{\alpha_s C_R}{\omega^2} \text{Re} \int_{t',t} \int_{\mathbf{p},\mathbf{q}} \mathbf{p} \cdot \mathbf{q} \tilde{\mathcal{K}}(t)
$$

Heavy quark radiation **The massive case**

Leading mass correction to Wilson line

Taking
$$
t_{\text{form}} \sim \frac{1}{\theta^2 x E}
$$

$$
\exp\left\{i\frac{M^2}{2E}t_{\text{form}}\right\} \simeq \exp\left\{i\left(\frac{\theta_{\text{DC}}}{\theta}\right)^2\right\}
$$

Radiation suppressed for $\theta < \theta_{DC}$

For the medium, interplay with LPM radiation angle - competing effects

 $T_{\rm eff}$ stochastic field can be written as $T_{\rm eff}$ as $T_{\rm eff}$ as $T_{\rm eff}$ as $T_{\rm eff}$ With gradients and velocity fields

$$
gA^{a\mu}(q) = \sum_{i} u_i^{\mu} e^{-iq \cdot x_i} t_i^a v_i(q) (2\pi) \delta(q_0 - \mathbf{q} \cdot \mathbf{q})
$$

[Stolen from Xoan Mayo - previous talk]

NOW WITH VELOCITY FIELDS

"Directional broadening" where *v*(*q, x, z*) ⌘ *v* medium interactions in the \mathbf{r} *^E*2*m*² *^u·p ^p*² (*Lz*0) $G \cap G$ ⁺ G ⁺ G </sub> G G ^{H} G G *^E*2*m*² *^u·p ^p*² 2 ^p*E*2*m*² *.* (9) $S_{\rm eff}$ introducing the results and introducing amplitude and introducing a two-point function of the effect-point function of the effect-point function of the effect-point function of the effect-point function of the ef

*G*0(*p, L*; *p*1*, z*0) = (2⇡)

2

(2)(*^p ^p*1) *^e*

2

^p*E*2*m*²

$$
\boldsymbol{p}-\boldsymbol{\bar{p}})-\frac{\boldsymbol{p}^2-\boldsymbol{\bar{p}}^2}{2E}\bigg)\,W_L(\boldsymbol{p};\boldsymbol{\bar{p}})-\int_{\boldsymbol{l}\boldsymbol{\bar{l}}}\mathcal{K}(\boldsymbol{l},\boldsymbol{\bar{l}})W_L(\boldsymbol{l};\boldsymbol{\bar{l}})
$$

. (9)

3

$$
\left\langle \mathcal{G}(\boldsymbol{p},L;\boldsymbol{p}_{in},0)\,\mathcal{G}^{\dagger}(\bar{\boldsymbol{p}},L;\bar{\boldsymbol{p}}_{in},0)\right\rangle
$$

Square the results introduced and introduced and introducing a two-point function of the effective control to the effect of $W_L(\boldsymbol{p},\boldsymbol{p}_{in};\bar{\boldsymbol{p}},\bar{\boldsymbol{p}}_{in}) = \langle$ $\mathcal{G}(\boldsymbol{p},L;\boldsymbol{p}_{in},0)$ \mathcal{G}^{\dagger} $\langle \bar{\boldsymbol{p}}, L; \bar{\boldsymbol{p}}_{in}, 0) \rangle$ *|M*(*p*)*|* $\frac{1}{2}$ $\sqrt{ }$ *pin,p*¯*in* $\frac{\partial}{\partial x}W_{I}(\bm{n}\cdot\vec{\bm{n}})=i\left(\begin{array}{cc}E&-n\bm{n}\cdot(\bm{n}-\vec{\bm{n}})-\frac{\bm{p}^{2}-\vec{\bm{p}}}{2} \end{array}\right)$ \int_{-}^{2} $\int W_{I}(\mathbf{n}\cdot\vec{\mathbf{n}}) = \int K(I,\vec{I})W_{I}$ where the interaction can be convenient interaction can be convenient in the interaction equation equatio \overline{I} ¹ $p = -\frac{1}{E^2 - 1}$ $\frac{2}{m^2} \int_{\bm{a}\bar{\bm{c}}\bm{x}} \Bigg| v(\bm{q},\bm{x},L) v(\bar{\bm{q}},L)$ 2*E* $L)\rho(\boldsymbol{x},L)e^{-\gamma}$ \boldsymbol{x} $(\vec{p} - \vec{q}) \delta^{(2)}(\vec{p} - \vec{q} - \vec{l}) \delta^{(2)}(\vec{p} - \vec{q} - \vec{l})$ The broadening is given by the average of two path integrals $\mu(\bm{p},\bm{p}_{in})$ \cdot ? \bm{b}, \bm{j} \overline{a} $\langle \mathcal{G}(\boldsymbol{p},L;\boldsymbol{p}_{in},0) \, \mathcal{G}^{\dagger}(\bar{\boldsymbol{p}},L;\bar{\boldsymbol{p}}_{in}) \rangle$ $, 0)$ In turn, the turn, the turns of the two-point function can be conveniently defined the two- $\frac{\partial}{\partial L}W_L(\bm{p};\bar{\bm{p}})=i$ ✓ *E* $\sqrt{E^2 - m^2}$ $\boldsymbol{u} \cdot (\boldsymbol{p}-\boldsymbol{\bar{p}}) - \frac{\boldsymbol{p}^2-\boldsymbol{\bar{p}}^2}{2E}$ 2*E* ◆ $W_L(\bm{p};\bar{\bm{p}})$ z
Z $l\bar{l}$ $\mathcal{K}(\bm{l},\overline{\bm{l}})W_L(\bm{l};\overline{\bm{l}})$ $\frac{1}{2}$ $\mathcal{K}(\bm{l},\overline{\bm{l}}) = -\, \frac{\mathcal{C}\,E^2}{E^2-\tau}$ $E^2 - m^2$ z
Z $\bm{q\bar{q}}\bm{x}$ $\sqrt{ }$ $v(\boldsymbol{q},\boldsymbol{x},L)v(\bar{\boldsymbol{q}},\boldsymbol{x},L)\rho(\boldsymbol{x},L)e^{-i\boldsymbol{x}\cdot(\boldsymbol{q}-\bar{\boldsymbol{q}})}$ $-\frac{1}{2}$ 2 $v(\boldsymbol{q},\boldsymbol{x},L)v(\bar{\boldsymbol{q}},\boldsymbol{x},L)\rho(\boldsymbol{x},L)e^{-i\boldsymbol{x}\cdot(\boldsymbol{q}+\bar{\boldsymbol{q}})}$ $\delta^{(2)}(\bm{p}-\bm{l})\delta^{(2)}(\bar{\bm{p}}-\bm{q}-\bar{\bm{q}}-\bar{\bm{l}})$ $-\frac{1}{2}$ 2 $v(\boldsymbol{q},\boldsymbol{x},L)v(\bar{\boldsymbol{q}},\boldsymbol{x},L)\rho(\boldsymbol{x},L)e^{i\boldsymbol{x}\cdot(\boldsymbol{q}+\bar{\boldsymbol{q}})}$ $\delta^{(2)}(\bm{p}-\bm{q}-\bar{\bm{q}}-\bm{l})\delta^{(2)}(\bar{\bm{p}}-\bar{\bm{l}})$ $\overline{}$ The resummation of multiple scatterings can be done with

tive single-particle propagators *WL*(*p, pin*; *p*¯*, p*¯*in*) = ⌦

G(*p, L*; *pin,* 0) *G†*

(*p*¯*, L*; *p*¯*in,* 0)↵

, we can expect the set of \mathbb{R}^n

express it as @ \mathcal{L} ^{*u*} **PRELIMINARY**

$$
\bar{\bm{q}},\bm{x},L)\rho(\bm{x},L)e^{-i\bm{x}\cdot(\bm{q}-\bar{\bm{q}})}\delta^{(2)}(\bm{p}-\bm{q}-\bm{l})\delta^{(2)}(\bar{\bm{p}}-\bar{\bm{q}}-\bar{\bm{l}})
$$

$$
L)e^{-i\boldsymbol{x}\cdot(\boldsymbol{q}+\bar{\boldsymbol{q}})}\delta^{(2)}(\boldsymbol{p}-\boldsymbol{l})\delta^{(2)}(\bar{\boldsymbol{p}}-\boldsymbol{q}-\bar{\boldsymbol{q}}-\bar{\boldsymbol{l}})
$$

$$
L)e^{i\boldsymbol{x}\cdot(\boldsymbol{q}+\bar{\boldsymbol{q}})}\delta^{(2)}(\boldsymbol{p}-\boldsymbol{q}-\bar{\boldsymbol{q}}-\boldsymbol{l})\delta^{(2)}(\bar{\boldsymbol{p}}-\bar{\boldsymbol{l}}).
$$
 (12)

The information from these expressions can be encoded computing the (generalized) jet quenching parameter $\frac{1}{2}$ state momentum distribution. For instance, the tensorial generalization of $\frac{1}{2}$ parameter reads to the control of t
In the control of th

PRELIMINARY

\hat{q} is a tensor q is a tensor

$$
\begin{split} \frac{\hat{q}_{ij}}{\partial L} &= \frac{\partial}{\partial L} \langle \boldsymbol{p}_i \boldsymbol{p}_j \rangle = -\frac{1}{\mathcal{N}} \int_{\boldsymbol{p}} \boldsymbol{p}_i \boldsymbol{p}_j \int_{l\bar{l}} \mathcal{K}(\boldsymbol{l},\bar{\boldsymbol{l}}) \big|_{\bar{\boldsymbol{p}}=\boldsymbol{p}} W_L(\boldsymbol{l};\bar{\boldsymbol{l}}) \\ &\simeq \left(1 - \frac{EL}{\sqrt{E^2 - m^2}} \, \boldsymbol{u} \cdot \boldsymbol{\nabla} g \frac{\delta}{\delta g}\right) \frac{\mathcal{C} \rho(L) \, E^2}{E^2 - m^2} \int_{\boldsymbol{q}} \boldsymbol{q}_i \boldsymbol{q}_j [v(\boldsymbol{q},L)]^2 \\ &\simeq \frac{1}{2} \left(1 - \frac{EL}{\sqrt{E^2 - m^2}} \, \boldsymbol{u} \cdot \boldsymbol{\nabla} g \frac{\delta}{\delta g}\right) \hat{q}_0 \left[\left(1 - \frac{m^2 \boldsymbol{u}^2}{2E^2}\right) \delta_{ij} - \boldsymbol{u}_i \boldsymbol{u}_j \frac{m^2}{E^2}\right] \end{split}
$$

explicit the subset of the [Also considered in Hauksson, Iancu (2023) and Barata, Salgado, Silva (2024) - see next talk!]

Directional radiation '2*g*²*C^F* ⁴⇡!² Re ✓ *^E* ^p*E*² *^m*² $\mathsf{2}\cap$ *dz*¯*^s* Z *^z^s dz^s* Z *^eⁱ ^m*2*x*² *^S*² (*k, ^k, z^f* ; *^x*¯ *^uz*¯*s, ^y, ^z*¯*s*) = ¹ $|d|$ D f *^K* (*y, ^x*1*, ^z*¯*s*; *^x ^uzs, ^x*1*, zs*) = ¹ D ^p*E*² *^m*² 2 *l ^E*² *^m*² *^v*² *V*/*P*C/*PC/P* \blacksquare diatio

PRELIMINARY *^K*¯ (*y, ^z*¯*s*; *^x, zs*) ' $\overline{}$ *^Gab* (*y, ^z*¯*s*; *^x ^uzs, zs*) *^W†,ba*

^A (*x*1; ¯*zs, zs*)

E

, (110)

'

$$
2(2\pi)^{3}\omega E \frac{d\mathcal{N}}{d\omega dE d^{2}\mathbf{k}} \simeq \frac{2g^{2}C_{F}}{4\pi\omega^{2}} \text{Re}\left(\frac{E}{\sqrt{E^{2}-m^{2}}}\right)^{2} \int_{0}^{\infty} d\bar{z}_{s} \int_{0}^{z_{s}} dz_{s} \int_{y} e^{i\frac{m^{2}x^{2}}{2\omega}(z_{s}-\bar{z}_{s})} \times (\mathbf{\nabla}_{x} \cdot \mathbf{\nabla}_{\bar{x}}) \bar{S}_{2}(\mathbf{k}, \mathbf{k}, z_{f}; \bar{x}, \mathbf{y}, \bar{z}_{s}) \bar{K}(\mathbf{y}, 0, \bar{z}_{s}; \mathbf{x}, 0, z_{s}) \Big|_{\mathbf{x}=\bar{\mathbf{x}}=0}.
$$

Prine a tensorial jet quenching parameters of the set of We can now also define a tensorial jet quenching parameter \overline{M} also *q* ˆ *u*2 *^x*² + (2ˆ*^q ^q* ˆ ⁰)(*u · x*) namic gradients and distribution and distribution and distribution and distribution and distribution and distri

Vgq(*q*) = *C*⇢

$$
\mathcal{V}_{gq}(\boldsymbol{x}) \simeq \frac{1}{4} \hat{q}_{\parallel} x_1^2 + \frac{1}{4} \hat{q}_{\perp} x_2^2
$$

$$
\hat{q}_{\parallel} = \hat{q} \left[1 + \frac{1}{2} \frac{m^2}{E^2} \left(1 - \frac{1}{2} \boldsymbol{u}^2 - \left(1 - \frac{\hat{q}}{2} \right) \right) \right]
$$

$$
\hat{q}_{\perp} = \hat{q} \left[1 + \frac{1}{2} \frac{m^2}{E^2} \left(1 - \frac{1}{2} \boldsymbol{u}^2 \right) \right]
$$

^r*A*?

resulting in *g* ' 2*.*8r*^T*

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^T , and, for simplicity, we will use *g* = 3r*^T*

Conclusions

Gradients (T, density, etc…) and flow velocities modify jet properties —broadening and medium-induced radiation

 \square Softer particles are bent in the gradient / velocity direction - effect is subleading in energy Additional source of energy loss that could be very important phenomenologically (R_{AA} vs v_2)

Jet quenching parameter becomes a **tensor** both for broadening and radiation □ Some observable consequences in the next talk by João Silva

For the massive case

Dead cone effect is then also directional - mass effect in radiation depends on the relative direction of the propagation of the quark and the fluid velocity

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