A new era for jet studies in ultra-relativistic heavy-ion collisions

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from nuclei to QGP :: a heavy ion collision

- Colliding [cold] nuclei [initial condition]
- Pre-equilibrium [collision]
- Quark Gluon Plasma [hot, dense and coloured] [equilibrated/thermalized] hydrodynamic expansion
- Hadronization
- Hadrons [back to cold nuclear matter]
quark gluon plasma

• an almost perfect liquid [the most perfect ever observed] of fundamental degrees of freedom [quarks and gluons] :: direct manifestation of collective behaviour in a fundamental non-abelian Quantum Field Theory [QCD]

• a unique, experimentally accessible and theoretically tractable, opportunity to further the understanding of nuclear matter in a novel regime [deconfined, yet strongly interacting, quarks and gluons] also of critical importance in the early history of the Universe
**quark gluon plasma**

- ‘discovered’ and confirmed at the SPS, RHIC and LHC
- current focus on understanding of dynamics and precise measurement of properties :: must rely on self-generated probes [short-lived QGP]

- broadly two sets of handles
  - bulk [collective] observables :: flows, correlations, ...
  - hard probes [detailed microscopic probes]
    - EW [non-interacting benchmark]
    - quarkonia/heavy flavour
    - jets

**focus here on few key theoretical ideas**
**jet definition**

collimated spray of hadrons resulting from the QCD branching of a hard [high-$p_t$] parton and subsequent hadronization of fragments and grouped according to given infra-red and collinear safe procedure [jet algorithm] and for given defining parameters [eg, jet radius]
• major accomplished experimental challenge
  • jets can be systematically reconstructed above large [100 GeV in jet catchment area] and fluctuating [up to 20 GeV] background
• jets are very well understood in vacuum and modified [jet quenching] by the QGP they traverse
• jets are multi-scale probes [wealth of observables/properties sensitive to different QGP scales]
in-medium jet dynamics
jets in vacuum

vacuum jets under overall excellent theoretical control
• reliable baseline and template for inclusion of medium effects
• factorization of initial and final state

\[
\sigma^{h_1 h_2 \to X}(p_1, p_2) = f^h_1(x_1, Q^2) \otimes f^h_2(x_2, Q^2) \otimes \sigma^{j \to k}(x_1 p_1, x_2 p_2, Q^2) \otimes D_k \to X(z, Q^2)
\]

• branching pattern dictated by Altarelli-Parisi splitting functions

\[
dw^{k \to i+m} = \frac{\alpha_s}{4\pi} \frac{d^2 k_+}{k_+^2} \frac{dz P_{ik}(z)}{d z P_{ik}(z)}
\]

• AND coherence [interference] between emitters :: angular ordering [MLLA]

\[
\frac{\partial}{\partial \log Q} D_i(x, Q) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s(k_+^2)}{2\pi} \hat{P}_{ji}(z) D_j(x/z, zQ)
\]
jets in heavy ion collisions

in HIC jets traverse sizable in-medium pathlength
jets in heavy ion collisions

same factorizable structure [challengeable working hypothesis]
jets in heavy ion collisions

sufficiently constrained in relevant kinematical domain
jets in heavy ion collisions

sufficiently constrained in relevant kinematical domain

localized on point like scale oblivious to surrounding matter [calculable to arbitrary pQCD order]
jets in heavy ion collisions

factorized initial state
[insensitive to produced medium]

nPDF $i \otimes \text{hard scattering}$

nPDF $j$
jets in heavy ion collisions

very well [and perturbatively] understood in vacuum

- coherence between successive splittings leads to angular ordering
- faithfully implemented in MC generators

medium modified

- induced radiation
- broadening of all partons traversing medium
- energy/momentum transfer to medium [elastic energy loss]
- strong modification of coherence properties
- modification of colour correlations
jets in heavy ion collisions

- Factorized initial state
  - [Insensitive to produced medium]

\[
\begin{align*}
\text{nPDF}_i & \quad \otimes \quad \text{nPDF}_j \\
\otimes & \quad \text{hard scattering} \\
\end{align*}
\]

- QCD branching
- Hadronization

**In vacuum**
- Effective description in MC [Lund strings, clusters, ...]
- FF for specific final state [jet, hadron class/species, ...]

**In medium**
- Time delayed [high enough p_t] thus outside medium
- Colour correlations of hadronizing system changed

Fragmentation outside medium = vacuum FFs ???
[however, many jet observables largely insensitive to hadronization]
jets in heavy ion collisions

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jets in heavy ion collisions

factorized initial state [insensitive to produced medium]

jet quenching ::
observable consequences [in jet and jet-like hadronic observables] of the effect of the medium

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in medium
- time delayed [high enough $p_t$] thus outside medium
- colour correlations of hadronizing system changed
to establish quenched jets as medium probes requires a full theoretical account of

- QCD branching
- effect on hadronization [for hadrons]

in the presence of a generic medium and

a detailed assessment of the sensitivity of observables to specific medium properties

:: probe ::
physical object/process/observable under strict theoretical control for which a definite relationship between its properties and those of the probed system can be established
interaction with QGP leads to enhanced splitting probability \([\text{more emissions}]\) for each jet component \([\text{parton}]\)

classical \([\text{Brownian}]\) broadening of all partons

understood within several perturbative approaches

\[
R^\text{med}_q \approx 4\omega \int_0^L dt' \int \frac{d^2 k'}{(2\pi)^2} \mathcal{P}(k - k', L - t') \sin \left( \frac{k'^2}{2k_f^2} \right) e^{-\frac{k'^2}{2k_f^2}}
\]

\[
\hat{q} \approx \frac{\mu^2}{\lambda} \quad \text{:: transport coefficient}
\]

\[
\tau_f = \sqrt{\omega/\hat{q}}
\]

\[
Q_s^2 = \hat{q}L
\]

\[
k_f^2 = \sqrt{\hat{q}\omega}
\]
large broadening

- In-medium formation time for small angle and soft gluons in vacuum is very short.
- Democratic broadening is a large effect for soft partons:
  - Soft radiation decorrelated from jet direction/transported to large angles without disturbing back-to-back correlation.
  - Enhancement of soft fragments outside the jet.
  - Jet energy depletion driven by away transport of soft fragments NOT by rare out-of-cone semi-hard splitting.

\[
\tau \sim \frac{\omega}{k_{\perp}^2} \quad \rightarrow \quad \langle \tau \rangle \sim \sqrt{\frac{\omega}{q}}
\]

\[
\langle k_{\perp} \rangle \sim \sqrt{qL}
\]

\[
\omega \leq \sqrt{qL}
\]

**an important lesson learnt from dijet asymmetry data**
multiple emissions :: vacuum antennas

bona fide description of multiple gluon radiation requires understanding of emitters interference pattern
multiple emissions :: vacuum antennas

- bona fide description of multiple gluon radiation requires understanding of emitters' interference pattern

→ qqbar antenna [radiation much softer than both emitters] as a TH lab
multiple emissions :: vacuum antennas

- bona fide description of multiple gluon radiation requires understanding of emitters interference pattern

- qqbar antenna [radiation much softer than both emitters] as a TH lab

\[ r_{\perp} \sim \theta_{q\bar{q}} \tau_f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega} \]
multiple emissions :: vacuum antennas

- A bona fide description of multiple gluon radiation requires understanding of emitters' interference pattern.

- \( \text{qqbar antenna} \) [radiation much softer than both emitters] as a TH lab.

::vacuum::

- Transverse separation at formation time:
  \[ r_\perp \sim \theta_{q\bar{q}} T_f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega} \]

- Wavelength of emitted gluon:
  \[ \lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega \theta} \]
multiple emissions :: vacuum antennas

- bona fide description of multiple gluon radiation requires understanding of emitters interference pattern

→ qqbar antenna [radiation much softer than both emitters] as a TH lab

\[ k_{\perp}, \omega \]

::vacuum::

- transverse separation at formation time
  \[ r_{\perp} \sim \theta_{q\bar{q}} f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega} \]
- wavelength of emitted gluon
  \[ \lambda_{\perp} \sim \frac{1}{k_{\perp}} \sim \frac{1}{\omega \theta} \]

for \( \lambda_{\perp} > r_{\perp} \) emitted gluon cannot resolve emitters, thus emitted coherently from total colour charge

large angle radiation suppressed :: angular ordering
new medium induced colour decorrelation scale

\[ \Lambda_{med} \sim \frac{1}{k_{\perp}} \sim \frac{1}{\sqrt{\hat{q} L}} \]

such that decorrelation driven by timescale

\[ \tau_d \sim \left( \frac{1}{\hat{q} \theta_{q\bar{q}}^2} \right)^{1/3} \]
[de]coherence of multiple emissions

- qqbar colour coherence survival probability
  \[ \Delta_{med} = 1 - \exp \left\{ - \frac{1}{12} \hat{q} \theta^2_{qq} t^3 \right\} = 1 - \exp \left\{ - \frac{1}{12} \frac{r^2}{\Lambda^2_{med}} \right\} \]
- time scale for decoherence
  \[ \tau_d \sim \left( \frac{1}{\hat{q} \theta^2_{qq}} \right)^{1/3} \]
- total decoherence when \( L > \tau_d \)

→ colour decoherence opens up phase space for emission
**[de]coherence of multiple emissions**

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→ colour decoherence opens up phase space for emission

- large angle radiation [anti-angular ordering]
  - *geometrical separation [in soft limit]*

\[
dN_{q,\gamma^*}^{\text{tot}} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin \theta}{1 - \cos \theta} \left[ \Theta(\cos \theta - \cos \theta_{qq}) - \Delta_{med} \Theta(\cos \theta_{q\bar{q}} - \cos \theta) \right]
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colour decoherence opens up phase space for emission

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\]

\[
\Delta_{\text{med}} \to 0 \quad \text{coherence}
\]
[de]coherence of multiple emissions

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\]

\( \Delta_{\text{med}} \to 0 \) coherence
\( \Delta_{\text{med}} \to 1 \) decoherence

\( \omega \to 0 \)
from antennas to jets

- $r_t < \Lambda_{\text{med}}$ :: antenna unresolved by medium :: vacuum like
- $r_t > \Lambda_{\text{med}}$ :: medium probes antenna :: strong suppression of interference :: independent radiation from each constituent

- in-medium jet dynamics driven by number of resolved charges
from antennas to jets

Medium-induced radiation (not collinear)

Collinear A

Collinear A-O

Collinear A-O

Here \( \Theta_{gq\mu} \sim \frac{1}{\sqrt{q_{T\mu}}} \)

Medium-induced radiation

\[ \Theta_{gq\mu} \sim \frac{1}{\sqrt{q_{T\mu}}} \]

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beyond antennas [full in-medium jet calculus]

compute in-medium splitting vertices for arbitrary momentum fraction of radiation
compute in-medium splitting vertices for arbitrary momentum fraction of radiation

- general decoherence features survive [just more complicated]

- in short formation time limit [equivalently infinite medium] full evolution equation derived :: not valid close to medium edge
life story of an in-medium jet
life story of an in-medium jet

• prior to medium formation [$T^{\text{med}} \sim 0.1 \text{ fm}$]
  • hard skeleton defined [3-jet rates, hard frag, ...]
  • effect of Glasma ?
life story of an in-medium jet

• prior to medium formation \( [\tau_{\text{med}} \sim 0.1 \text{ fm}] \)
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• during medium traversal \([\sim \text{ few fm}] \) :: modification of formation times
  • enhanced \([\text{mostly soft}]\) radiation
  • broadening \([\text{large for very soft}]\)
  • breakdown of colour coherence
  • modification of colour correlations
  • E-p transfer to medium
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• after medium escape
  • vacuum branching
  • hadronization of colour modified system
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soft components at large angles
life story of an in-medium jet

very appealing pQCD based overall picture

BUT

the QGP is strongly coupled and its collective behaviour [flows] suggestive of the non-existence of scattering centres [quasi-particles]

still, parton branching is a perturbative process
are there quasi-particles?
are there quasi-particles?

- do hard probes have finite mean free paths?

  - all pQCD based approaches assume so

  - in AdS/CFT [strong coupling] constructions

    - heavy quarks propagate without mean free path :: lost energy goes into Mach cone and wake

    - light quarks/jets propagate towards thermalization :: no collinear structure [hedgehog jets]
are there quasi-particles?

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    - heavy quarks propagate without mean free path :: lost energy goes into Mach cone and wake
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- probability of large broadening larger for pQCD [\(\sim 1/k_t^4\)] than for strong coupled [gaussian]
  - rare, yet unmeasured, but measurable events

![Graph showing probability as a function of transverse momentum](image-url)
Multiple soft exchanges may lead to additional in-medium radiation even if the plasma is out and re-interact, potentially departing from the jet area. While it is conceivable that away from the propagating patrons reducing the overall energy of the jet. In a perturbative dynamics play a role. From the point of view of the jet shower, the medium takes energy transition, the relevant coupling is not small. It is at this stage when strong coupling medium temperature, and therefore, for plasma temperatures not far from the deconfining transition, the form explicitly in terms of the 't Hooft coupling.

In order to have some other benchmarks against which to compare the success of our hybrid model, we explore the consequences of an energy loss rate. In our model, we explore the consequences of an energy loss rate

\[
\frac{dE}{dx}\bigg|_{\text{strongly coupled}} = -\frac{4}{\pi} \frac{E_{\text{in}} x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}, \quad x_{\text{stop}} = \frac{1}{2 \kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}
\]

single free parameter [accounts for QCD/N=4 SYM differences]
hybrid strong/weak coupling model

- vacuum jets [no medium induced radiation] where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]

\[
\frac{dE}{dx}\bigg|_{\text{strongly coupled}} = -4 \frac{E_{\text{in}}}{\pi} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}, \quad x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}
\]

[accounts for QCD/N=4 SYM differences]
hybrid strong/weak coupling model

5 observables and centrality dependence all described with single parameter

Bands in all plots correspond to $0.32 < \kappa_{sc} < 0.41$

$O(1)$ as expected.

$x_{stop}^{QCD} \sim (2 - 3)x_{stop}^{N=4}$
understanding sensitivity
[a non-trivial example towards a new era]
dijet asymmetry

imbalance of jet energy within a cone of radius R for ‘back-to-back’ di-jets
dijet asymmetry

Most naive guess: medium-induced asymmetry is sensitive to difference in traversed QGP by leading and recoiling jets.

Imbalance of jet energy within a cone of radius $R$ for ‘back-to-back’ di-jets.

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$
a sanity check

di-jet production points
a sanity check

![Diagram showing di-jet production points with color-coded density.](image)
a sanity check

![di-jet production points](image1)

![di-jet production points](image2)

![di-jet asymmetry in PbPb](image3)
a sanity check

di-jet production points

asymmetry is not driven by path-length differences
asymmetry is driven by fragmentation fluctuations [how many constituents in a jet] which are mostly due to vacuum-like fragmentation

direct sensitivity to ‘number of emitters’

much more interesting than the naive guess
outlook

• in just over ten years jet studies in heavy ion collisions have gone from ‘an idea’ to a robust experimental reality
• recent efforts have established a clear pathway to reliably compute jet dynamics in QGP

• detailed probing programme in its beginnings
  • time to think hard about ‘new’ observables [measurable and calculable]
  • direct sensitivity to formation times
  • sensitivity to different time and spacial scales
  • isolation of ‘pure’ sample of strongly modified jets where
jets in vacuum [recombination algorithms]

\[ d_{ij} = \min \left( p_{ti}^2, p_{tj}^2 \right) \frac{\Delta R_{ij}^2}{R^2} \]
\[ \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

\[ p = 1 \]
:: \( k_t \) [from soft to hard] ::
:: preserves information on shower structure ::

\[ p = -1 \]
:: \( \text{anti-}k_t \) [from hard to soft] ::
:: robustness in large background situations ::

additional handle [yet to be explored in heavy ions]
:: different jet definitions [recombination sequence] yield different jet populations
Jet physics in heavy-ion collisions

Fig. 1. Diagrams contributing to the dipole scattering rate in Eq. (10) (one must also add the complex conjugate diagrams).

This gives rise to the so-called Landau-Pomeranchuk-Migdal (LPM) effect: the formation time of induced radiation can exceed the mean free path giving rise to interference effects between subsequent rescatterings, see Sec. 4.1 for a comprehensive discussion. Since the radiative processes scale with a larger power of the in-medium path length, see Eq. (29) and discussion below, compared to elastic ones, one usually neglects the latter effects for highly energetic probes and large media. While elastic rescattering effects should be incorporated consistently for low-p_T observables, see also Ref. 78 and comment below, we will not currently examine them in more detail.

Then, for soft momentum transfers from the medium, \(|q| \ll T\), the potential (squared) at leading order in the coupling becomes

\[ \text{HTL}(q^2) = g^2 q^2 (q^2 + m^2 D), \]

and scales as \( \text{HTL} \sim N g^4 q^4 \) for \(|q| \ll T\), where the constant is e.g. given in Ref. 84.

Comparing to the static potential, Eq. (7), one observes a divergent behavior for small \(|q|\). Higher-order corrections in \( g \) to Eq. (8) are also known, and lead to an even bigger enhancement of the soft sector. Thermal effects are included in several theoretical calculations 45–47, 86–88 of radiative processes in medium, recently also in the presence of a finite chemical potential.

From our discussion so far, the probe will be sensitive to medium characteristics through interactions which induce dependence on parameters. The second moment of the correlator in Eq. (6), historically called \( \hat{q} \), is a measure of the transverse momentum (squared) acquired by the probe per unit length in the elastic scattering and, as we will see below, is a highly important quantity for the study of jets in medium. We will define it stripped of its relevant color factor, as

\[ \hat{q}(t) \equiv \alpha_s n(t) \int_{|q| < q^*} dq^2 \, q^2 \gamma(q^2), \]

and

\[ \hat{q} \approx \frac{\mu^2}{\lambda}. \]
medium induced radiation
medium induced radiation

- single gluon emission understood in 4 classes of pQCD-based formalisms

  - \textbf{Baier-Dokshitzer-Mueller-Peigné-Schiff–Zakharov}
  - \textbf{Gyulassy-Levai-Vitev}
  - \textbf{Arnold-Moore-Yaffe}
  - \textbf{Higher-Twist [Guo and Wang]}


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- differ in modeling of the medium and some kinematic assumptions [most shared]
medium induced radiation

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  - Poissonian ansatz [BDPMS and GLV]; rate equations [AMY]; medium-modified DGLAP [HT]
medium induced radiation

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- Monte Carlo implementations [HIJING, Q-PYTHIA/Q-HERWIG, JEWELL, YaJEM, MARTINI]
single emission [BDMPS-Z]

\[ \hat{q} \approx \frac{\mu^2}{\lambda} \]
single emission [BDMPS-Z]

Brownian motion

\[ \langle k_\perp^2 \rangle \sim \hat{q}L \]

\[ \hat{q} \sim \frac{\mu^2}{\lambda} \]
single emission [BDMPS-Z]

- Brownian motion
  \[ \langle k_{\perp}^2 \rangle \sim \hat{q} L \]

- Accumulated phase
  \[ \langle \frac{k_{\perp}^2 L}{\omega} \rangle \sim \frac{\hat{q} L^2}{\omega} \sim \frac{\omega_c}{\omega} \sim \text{characteristic gluon energy} \]

\[ \hat{q} \sim \frac{\mu^2}{\lambda} \]
single emission [BDMPS-Z]

- Brownian motion
  \[ \langle k_{\perp}^2 \rangle \sim \hat{q}L \]

- Accumulated phase
  \[ \left\langle \frac{k_{\perp}^2 L}{\omega} \right\rangle \sim \frac{\hat{q}L^2}{\omega} \sim \frac{\omega_c}{\omega} \]

- Number of coherent scatterings
  \[ N_{coh} \sim \frac{t_{coh}}{\lambda} \]
  \[ t_{coh} \sim \frac{\omega}{k_{\perp}^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \]

\[ k_{\perp}^2 \sim \hat{q} t_{coh} \]

\[ \omega = xE \]

\[ \hat{q} \sim \frac{\mu^2}{\lambda} \]

characteristic gluon energy

Brownian motion

\[ k_{\perp}^2 \sim N_{coh} \mu^2 \]
Brownian motion
\[ \langle k_{\perp}^2 \rangle \sim \hat{q}L \]

accumulated phase
\[ \left\langle \frac{k_{\perp}^2 L}{\omega} \right\rangle \sim \frac{\hat{q}L^2}{\omega} \sim \frac{\omega}{\omega} \]
characteristic gluon energy
\[ \hat{q} \sim \frac{\mu^2}{\lambda} \]

number of coherent scatterings
\[ N_{coh} \sim \frac{t_{coh}}{\lambda} \quad t_{coh} \sim \frac{\omega}{k_{\perp}^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \]

 gluon energy distribution
\[ \omega \frac{dI_{med}}{d\omega dz} \sim \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega dz} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \]
single emission [BDMPS-Z]

- Brownian motion
  \[ \langle k_{\perp}^2 \rangle \sim \hat{q} L \]

- Accumulated phase
  \[ \left\langle \frac{k_{\perp}^2 L}{\omega} \right\rangle \sim \frac{\hat{q} L^2}{\omega} \sim \frac{\omega_c}{\omega} \]
  \[ k_{\perp}^2 \sim \hat{q} t_{coh} \]

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- Gluon energy distribution
  \[ \omega \frac{dI_{med}}{d\omega dz} \sim \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega dz} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \]

- Average energy loss
  \[ \Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2 \]
Beyond back the envelope [path-integral]

- Eikonal trajectory of parton propagating in medium

\[ W_{\alpha_f \alpha_i}(x_f^+, x_i^+; r(\xi)) = \mathcal{P} \exp \left\{ ig \int_{x_i^+}^{x_f^+} d\xi A_-(\xi, r(\xi)) \right\} \]

- Off[but close to]-eikonal trajectory

\[ G_{\alpha_f \alpha_i}(x_f^+, x_f; x_i^+, x_i | p_+) = \int_{r(x_i^+)=x_i}^{r(x_f^+)=x_f} D\!r(\xi) \exp \left\{ \frac{ip_+}{2} \int_{x_i^+}^{x_f^+} d\xi \left( \frac{dr}{d\xi} \right)^2 \right\} W_{\alpha_f \alpha_i}(x_f^+, x_i^+; r(\xi)) \]

- Observables computed from medium averages of Gs [from medium field 2-pt correlators]

- BDMPS: quark eikonal, gluon soft and [slightly] off-eikonal
large broadening [a lesson from data]
large broadening [a lesson from data]

imbalance of jet energy within a cone of radius R for ‘back-to-back’ di-jets

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]
large broadening [a lesson from data]

significant enhancement of asymmetry

imbalance of jet energy within a cone of radius R for ‘back-to-back’ di-jets
large broadening [a lesson from data]

- significant enhancement of asymmetry
- no disturbance of azimuthal distribution

imbalance of jet energy within a cone of radius $R$ for 'back-to-back' di-jets
large broadening [a lesson from data]

- energy lost from jet cone recovered in soft fragments at large angles
medium induced radiation off a single quark in a dense medium

\( \mathcal{R}_{\text{med}}^q \approx 4\omega \int_0^L dt' \int \frac{d^2 k'}{(2\pi)^2} \mathcal{P}(k - k', L - t') \sin \left( \frac{k'^2}{2k_f^2} \right) e^{-\frac{k'^2}{2k_f^2}} \)

quantum emission/broadening during formation time

\( \tau_f = \sqrt{\frac{\omega}{\hat{q}}} \)

classical broadening

\( Q_s^2 = \hat{q}L \)

AN IMPORTANT LESSON FROM DATA

large broadening [beyond quasi-eikonal] is a prominent dynamical mechanism for jet energy loss [dijet asymmetry]
very reasonable phenomenological approach that remains unsubstantiated by a first principle calculation
large broadening

very reasonable phenomenological approach that remains unsubstantiated by a first principle calculation
interplay of branching and hadronization

- Colour of all jet components rotated by interaction with medium
  - Colour correlations modified with respect to vacuum case
    - Theoretically controllable within a standard framework [opacity expansion]
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**no medium interaction after radiation**
- colour properties of hadronizing system vacuum-like
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Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]
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**First steps towards fully colour differential framework**

Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]
interplay of branching and hadronization

- Colour correlations modified with respect to vacuum case
- Essential input for realistic hadronization schemes

**Figure 13.** The $p_T$ and $\eta$ distributions of the hadrons from the fragmentation of the Lund strings shown in Fig. 12. Both the quark and the gluon are emitted at mid rapidity at a relative angle $\phi = 0$.

- Panel: fragmentation pattern in the FSR (in red) and ISR (in green) color channels. Right panel: rapidity distribution of the hadrons in the ISR channel. The sharpest peak around $\eta = 0$ (continuous line) comes from the fragmentation of the leading string. The pattern "broad peak + plateau" (dashed line) arises from the fragmentation of the subleading string, connected to the beam remnant (hence the long plateau). Also shown (dot-dashed line) is the case in which both endpoints of the subleading string are attached to a medium particle. There is hadronic yield in a transverse momentum range that exceed the $p_T$ of the leading quark.

In the Lund model, this accounts for the fact that QCD is a finite resolution theory in which a perturbatively radiated gluon does not automatically increase the hadronic multiplicity by order unity or more: it is not necessarily 'lost' but, remaining color-connected with the other daughter of the branching, may still contribute to the formation of the leading hadron. In contrast, the ISR case (green curve) clearly shows that medium modification of color connections between the radiated gluon and the projectile fragment results in a softening of the hadron distribution: all hadronic yield above $p_T$ is suppressed and an additional contribution arises at soft momenta below $k_T$. The reason is that, for the ISR contribution, the color-decohered gluon and quark belong to different strings and thus cannot contribute to the same leading hadronic fragment. Therefore, hadronic multiplicity increases by construction with each color-decohered gluon by order unity or more, and the additional multiplicity is found in soft fragments of transverse momentum lower than $k_T$, which is much smaller than $p_T$.

These differences in the color flow of the ISR and FSR contribution have consequences for the distribution of hadronic fragments. In particular, the fragmentation of the Lund string of a vacuum-like (FSR) contribution results mainly in semi-hard and hard hadrons. For instance, fragmentation of the FSR string of total energy $\sim 55$ GeV in Fig. 13 yields on average $\langle N_h \rangle = 5.4$ hadrons, of which 3.9 carry $p_T > 2$ GeV transverse momentum. Since the multiplicity of Lund strings grows only mildly with the total length and with the number of small kinks, the string -2 7–

**generic [robust] effects:**
- Softening of hadronic spectra
- Lost hardness recovered as soft multiplicity
- At work even if radiative energy loss kinematically unviable
- Survives branching after medium escape

Modification of jet hadrochemistry
Aurenche & Zakharov [1109.6819]
interplay of branching and hadronization

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fragmentation in vacuum NOT the same as using vacuum FFs
sensitivity :: hadron spectra

\[ R_{AA}(p_T) = \frac{\langle 1/N_{cvt}^{AA} \rangle d^2N_{cvt}^{AA} / d\eta dp_T}{\langle N_{coll} \rangle (1/N_{cvt}^{pp}) d^2N_{ch}^{pp} / d\eta dp_T} \]

- clear and strong suppression of all hadronic yields
- photons/Z⁰ unsuppressed
- centrality [path-length] dependence

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- sensitive to induced radiation, also to hadronization modifications, but NOT to broadening
sensitivity :: jet $R_{AA}$

- just counts fraction of unmodified jets [steeply falling jet spectrum]
- [recall] dijet asymmetry sensitive to broadening, same for photon jet [advantage of known initial energy, but statically limited]
sensitivity :: fragmentation functions

- sensitivity to medium-induced radiation, broadening, hadronization

→ remarkably similar to vacuum jets [most branching occurs after medium escape; branching within unresolved systems also vacuum like]