jet quenching: towards medium probing

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http://www.qcdlhc.ist.utl.pt
the study of jets
[reconstructed jets and their high-\(p_T\) hadronic content]
in heavy ion collisions aims at their use as probes of
the properties of the hot, dense and coloured matter
created in the collisions
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#1 establishing the probe

#2 probing the medium

not covered in this talk:
• mass effects [heavy quarks]
• strongly coupled approaches
#1 establishing the probe
jets in heavy ion collisions

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

jet :: 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 procedure [jet algorithm] and for given defining parameters [eg, jet radius]
jets in heavy ion collisions

in HIC jets traverse sizable in-medium pathlength

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jets in heavy ion collisions

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

Sufficiently constrained in relevant kinematical domain [further improvement from future pA data]

\[ nPDF_i \otimes nPDF_j \]
jets in heavy ion collisions

- Sufficiently constrained in relevant kinematical domain (future improvement from pA data)
- Localized on point-like scale oblivious to surrounding matter (calculable to arbitrary pQCD order)

\[ nPDF_i \otimes nPDF_j \otimes \text{hard scattering} \]
jets in heavy ion collisions
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 [radiative energy loss]
- 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]

\[ nPDF_i \times nPDF_j \rightarrow \text{hard scattering} \]

QCD branching

hadronization

\[ h_1 \times h_2 \times h_3 \]

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 ???
jets in heavy ion collisions

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

**fragmentation function**
- QCD branching
- hadronization

**jet reconstruction**

**factorized initial state**
- [insensitive to produced medium]
to establish quenched jets [their hadron ‘jet-like’ and full jet observables] as medium probes requires a full theoretical account of

- QCD branching
- effect on hadronization [if any]

in the presence of a generic medium

and

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

:: probe ::
physical object/process under strict theoretical control for which a definite relationship between its observable properties and those of the probed system can be established
observation of jet quenching
hadron spectra

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

- clear and strong suppression of all hadronic yields
- persistent to high-\(p_T\)
- no apparent strong rising trend
- photons/\(Z^0\) unsuppressed
- centrality dependence
- jet suppression
Correlations

Very clear effect: spectra and correlations

- Azimuthal distribution of particles with $2 < p_T < 6 \text{ GeV}/c$

Trigger particle with $4 < p_T < 6 \text{ GeV}/c$

$\pi^0$ AuAu and scaled pp

$1/N_{\text{trigger}} \, dN/d(\phi)$

$\Delta \phi (\text{radians})$

- suppression of back-to-back hadrons in AA
- but not in dA
Very clear effect: spectra and correlations

• Azimuthal distribution of particles with $2<p_{T}<p_{T}^{\text{trigger}}$

- Trigger particle with $4<p_{T}^{\text{trigger}}<6$ GeV

- $\pi^0$ AuAu and scaled pp

$\frac{1}{N_{\text{trigger}}} \frac{dN}{d\phi}$

$\Delta \phi$ (radians)

- suppression of back-to-back hadrons in AA

- but not in dA

hadronic observables intrinsically sensitive to hadronization and oblivious to broadening effects on radiation
dijet asymmetry

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

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

- 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**
dijet asymmetry

- energy lost from jet cone recovered in soft fragments at large angles
dijet asymmetry

\[ p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Leading Jet}}) \]

- energy lost from jet cone recovered in soft fragments at large angles

direct sensitivity to broadening
analagous to dijet case

\[ x_{J\gamma} = \frac{p_{T\gamma}}{p_{T\text{jet}}} \]

\[ \Delta\phi_{\gamma\text{jet}} > \frac{7\pi}{8} \]

knowledge of initial parton energy [obvious advantage]

energy lever-arm [very] limited by statistics
FF modified by loss of intermediate $p_t$ fragment reconverted into several low $p_t$ fragments

© [personal view] major caveat for phenomenological interpretation: jets with same final energy are compared

→ very wide binning: all jets above 100 GeV
most salient: excess for larger radii [of soft fragments]

consistent with FF results

same caveats as FF
medium induced radiation

- single gluon emission understood in 4 classes of pQCD-based formalisms
  - Baier-Dokshitzer-Mueller-Peigné-Schiff–Zakharov
  - Gyulassy-Levai-Vitev
  - Arnold-Moore-Yaffe
  - Higher-Twist [Guo and Wang]
medium induced radiation

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- all build multiple gluon emission from [ad hoc] iteration of single gluon kernel
  - 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]
**medium induced radiation [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
  \[ N_{coh} \sim \frac{t_{coh}}{\lambda} \quad t_{coh} \sim \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \]

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

- Average energy loss
  \[ \Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2 \]
medium induced radiation

- medium modification of quark fragmentation function

  - systematic comparison in a simple common model medium [the BRICK]
  - large discrepancies [mostly due to necessary extension of formalism beyond strict applicability domain]
medium induced radiation

**Figure 10:** Comparison of quark fragmentation function ratios using different formalisms for a uniform medium with $L = 2$ fm (upper panels) and $L = 5$ fm (lower panels). For both upper and lower panels the left plot is at $T = 250$ MeV and the right plot is at $T = 350$ MeV. For details, see text.

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---

none necessarily right or wrong, all incomplete
relaxing approximations

- Energy of radiated gluon assumed [not in AMY] much smaller than that of emitter \( x = \omega / E \ll 1 \) but emission spectrum computed for all allowed phase space with violation of energy-momentum conservation cured by explicit cut-offs
relaxing approximations

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\[ \frac{dE}{dI} \]

- large-x limit computed in path-integral formalism, explicitly in the multiple soft scattering approximation, and small-large x interpolating ansatz

Apolinário, Armesto, Salgado [1204.2929]
relaxing approximations

- energy of radiated gluon assumed [not in AMY] much smaller than that of emitter \( \chi = \omega/E \ll 1 \) but emission spectrum computed for all allowed phase space with violation of energy-momentum conservation cured by explicit cut-offs

→ general case computed in SCET

application for jet quenching pioneered by Adilbi & Majumder [0808.1087]

d’Eramo, Liu, Rajagopal [1006.1367]
Ovanesyan & Vitev [1103.1074, 1109.5619]

- promising powerful framework
  - elastic and inelastic [+broadening] energy loss within same formalism
    - same aim in different approach [Zapp, Krauss, Wiedemann [1111.6838]]
  - recoils
  - based on scale hierarchy
    - hard scale \( \sim \sqrt{s} \sim \lambda^0 \) \( \gg \) jet scale \( \sim p_t \sim \lambda^1 \) \( \gg \) soft radiation scale \( \sim \lambda^2 \)

- degrees of freedom
  - collinear modes: \( p_c \sim [\lambda^0, \lambda^2, \lambda] \)
  - soft modes: \( p_s \sim [\lambda^2, \lambda^2, \lambda^2] \)
  - Glauber modes [jet-medium interaction]: \( q \sim [\lambda^2, \lambda^2, \lambda] \)
[de]coherence of multiple emissions

- A bona fide description of multiple gluon radiation requires understanding of emitters' interference pattern.
[de]coherence of multiple emissions

- 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

MAJOR EFFORT
Mehtar-Tani, Salgado, Tywoniuk [1009.2965 ... 1205.5739]
Casalderrey-Solana & Iancu [1105.1760]
[de]coherence of multiple emissions

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Also for initial/final state

MAJOR EFFORT
Mehtar-Tani, Salgado, Tywoniuk [1009.2965 ... 1205.5739]
Casalderrey-Solana & Iancu [1105.1760]

Armesto, Ma, Martínez, Mehtar-Tani, Salgado[1207.0984]

a challenge for factorization ???
[de]coherence of multiple emissions

- 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

- qqbar colour coherence survival probability
  \[ \Delta_{\text{med}} = 1 - \exp \left\{ -\frac{1}{12} \hat{q} \theta_{\bar{q}q}^2 t^3 \right\} \]

- time scale for decoherence
  \[ \tau_d \sim \left( \frac{1}{\hat{q} \theta_{\bar{q}q}^2} \right)^{1/3} \]

- total decoherence when \( L > \tau_d \)
[de]coherence of multiple emissions

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

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

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\[ \hat{q} \]

- colour decoherence open up phase space for emission
  - large angle radiation [anti-angular ordering]
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- large angle radiation [anti-angular ordering]
- geometrical separation

\[
\frac{dN_{\text{tot}}^{q,\gamma^*}}{d\omega} = \frac{\alpha_s}{\pi} \frac{d\omega}{\omega} \frac{\sin \theta}{1 - \cos \theta} \frac{d\theta}{\theta} \left[ \Theta(\cos \theta - \cos \theta_{qq}) - \Delta_{\text{med}} \Theta(\cos \theta_{q\bar{q}} - \cos \theta) \right]
\]
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\bar{\alpha}^{-1} \frac{dN_{q,g}}{d\omega d\omega' d\theta} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin \theta}{1 - \cos \theta} \left[ \Theta(\cos \theta - \cos \theta_q\bar{q}) - \Delta_{med} \Theta(\cos \theta_{q\bar{q}} - \cos \theta) \right]
\]

\[
\Delta_{med} \to 0 \quad \text{coherence}
\]

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- \[ \Delta_{med} \rightarrow 0 \] coherence
- \[ \Delta_{med} \rightarrow 1 \] decoherence
scales

- physics driven by characteristic transverse scales
  - antenna separation: $r_t = \theta_{qq} L$
  - medium colour correlation length: $1/Q_s = (qhat L)^{-1/2}$
scales

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- [dipole regime] $r_t < Q_s^{-1}$
  - pair unresolved by medium: single emitter
  - vacuum-like radiation at angles larger than $\theta_{qq}$
scales

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- [Decoherence] $r_t > Q_s^{-1}$
  - Medium probes antenna structure
  - Strong suppression of interferences
  - Independent radiation from each constituent
scales

- physics driven by characteristic transverse scales

  - antenna separation: \( r_t = \theta_{qq} L \)
  
  - medium colour correlation length: \( 1/Q_s = (\hat{q} \lambda L)^{-1/2} \)

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  - vacuum-like radiation at angles larger than \( \Delta \)

- [decoherence] \( r_t > Q_s^{-1} \)

  - medium probes antenna structure
  
  - strong suppression of interferences
  
  - independent radiation from each constituent

- \( Q_{\text{hard}} = \max(r_t^{-1}, Q_s) \): maximum transverse momentum of induced gluon

  - vacuum coherence recovered for \( k_t > Q_{\text{hard}} \)
[de]coherence of multiple emissions

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

interferences suppressed by $\tau_f / L$

- only relevant for emissions during formation time of previous gluon

in the small formation times limit

- probabilistic decohered branching process via master equation for generating functional

- in-medium splitting function

\[
K_{BC}^A(q - zp, z) = \frac{2}{p^+} P_{AB}(z) \sin \left[ \frac{(q - zp)^2}{2k_{br}^2} \right] \exp \left[ -\frac{(q - zp)^2}{2k_{br}^2} \right]
\]

\[
k_{br}^2 = \sqrt{z(1-z)p^+ \hat{q}_{eff}}
\]

Blaizot, Dominguez, Iancu, Mehtar-Tani [soon]
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emerging full account of medium effect on QCD coherence
broadening

medium induced radiation off a single quark in a dense medium

BDMPS-Z revisited

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

quantum emission/broadening during formation time

classical broadening

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

AN IMPORTANT LESSON FROM DATA

large broadening [beyond quasi-eikonal] is a prominent dynamical mechanism for jet energy loss [dijet asymmetry]
AN IMPORTANT LESSON FROM DATA

large broadening [beyond quasi-eikonal] is a prominent dynamical mechanism for jet energy loss [dijet asymmetry]

• in-medium formation time for small angle and soft gluons [vacuum] is very short

• democratic broadening is a large effect for soft partons
  • soft radiation decorrelated from jet direction/transported to large angles
  • enhancement of soft fragments outside the jet

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

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

\[
\omega \leq \sqrt{\hat{q}L}
\]

Casalderrey-Solana, Milhano, Wiedemann [1105.1760]
Qin & Muller [1012.5280]
AN IMPORTANT LESSON FROM DATA

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Casalderrey-Solana, Milhano, Wiedemann [1105.1760]
Qin & Muller [1012.5280]
jet collimation

- sufficiently soft modes decorrelated [lost] from jet

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

- sufficiently soft modes decorrelated from jet

$$\omega \leq \sqrt{qL}$$

- does not disturb azimuthal correlation

![Diagram showing event fraction vs. Delta Phi and dD/dxi distribution](image)
jet collimation

- sufficiently soft modes decorrelated [lost] from jet

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

- good qualitative description of average medium induced asymmetry

- does not disturb azimuthal correlation
jet collimation

- geometry
  - path length fluctuations with realistic nuclear profile
  - all distances density weighed and account for $1/\tau$ expansion
jet collimation

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- energy loss fluctuations
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  - average number of vacuum gluons from MLLA [spectrum at $Q_0 = 1$ GeV]
jet collimation

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  - event-by-event number of gluons with Poissonian assumption
  - additional medium induced gluons from Gaussian distributed ‘BDMPS’ formula
    - path length dependent
    - event-by-event with [independent] Poissonian assumption

\[ \omega \cdot \frac{dI}{d\omega} = \frac{C_R}{\pi} \alpha_s \sqrt{\frac{qL^2}{\omega}} \]

[= 0.3]
jet collimation

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  - event-by-event number of gluons with Poissonian assumption
  - additional medium induced gluons from Gaussian distributed ‘BDMPS’ formula
    - path length dependent
    - event-by-event with [independent] Poissonian assumption
    - $q^\text{hat}$ is the ONLY variable parameter
  - vacuum baseline from data [CMS]

$$\omega \frac{dI}{d\omega} = \frac{C_R}{\pi} \alpha_s \sqrt{\frac{\hat{q}L^2}{\omega}}$$

[= 0.3]
energy dependence of dijet imbalance

- q_t^2 = 17 GeV^2/fm
- PbPb [CMS]
- PYTHIA+HYDJET [CMS]

Centrality 0-20%

- 120 < p_T,1 < 150 GeV
- 220 < p_T,1 < 260 GeV
- 150 < p_T,1 < 180 GeV
- 260 < p_T,1 < 300 GeV
- 180 < p_T,1 < 220 GeV
- 300 < p_T,1 < 500 GeV

R=0.3
p_T,2 > 30 GeV

\[ x = \frac{p_{t,2}}{p_{t,1}} \]
broadening [jet collimation]

Intriguing [given its naivety and caveats] excellent overall account of data
need first principle calculation to support
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]
interplay of branching and hadronization

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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 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 exceeds 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 momentum.

- 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 below $k_T$. The $p_T$ of the leading quark.

- 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.

**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]
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**modification of jet hadrochemistry**
Aurenche & Zakharov [1109.6819]

fragmentation in vacuum NOT the same as using vacuum FFs
life story of an in-medium jet
life story of an in-medium jet

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

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- during medium traversal [$\sim \text{ few fm}$] :: modification of formation times
  - enhanced [mostly soft] radiation
  - broadening [large for very soft]
  - breakdown of colour coherence
  - modification of colour correlations
  - E-p transfer to medium
life story of an in-medium jet

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• after medium escape
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  • hadronization of colour modified system
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[soft components at large angles [double counting ?]]
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most [all?] questions asked, many [most?] being answered
life story of an in-medium jet

very appealing pQCD based overall picture

BUT

can we confidently exclude a conceptually different scenario in which strong jet-medium coupling effects drag energy from all jet ‘propagators’ and ‘vertices’ remain pQCD like ???

most [all?] questions asked, many [most?] being answered

Can Gulhan, Casalderrey-Solana, Milhano, Pablos, Rajagopal
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]
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- probability of large broadening larger for pQCD [~1/k_t^4] than for strong coupled [gaussian]
  → rare but measurable events

Eramo, Lekaveckas, Liu, Rajagopal [1211.1922]
the truth is in data [and data is out there]

- theory validation [constraining dynamics] requires

  - multi-observable description [\(R_{AA}, I_{AA}\) (jets, hadrons), jet asym, shapes, FFs, ...]
  - understand specific biases [pathlength, etc.] and sensitivities to dynamical mechanisms

![Graph showing sensitivity of \(I_{AA}\) to weight of elastic energy loss](image)

Renk [1110.2313,1112.2503,1202.4579,1212.0646]
In terms of the Glauber nuclear thickness profile initial state parton energy loss and broadening effects from first principles. While the magnetic modification factor of partons is less than 3 and the bulk reaction plane determined from low-rapidity particles relative to the beam energy dependence of light quark and gluon jet quenching theory in a sQGP phase of matter.

The main challenge to pQCD multiple collision theory validation [constraining dynamics] requires RHIC to LHC description.

Consistency

- theory validation [constraining dynamics] requires RHIC to LHC description
theory validation [constraining dynamics] requires

... 

assessment of importance of NLO corrections

jet reconstruction [as in exp]

response of calculables to background

detector response [exp unfold/ph fold :: we need to decide]
#2 probing the medium
meaningful determination of medium properties requires embedding of faithful jet dynamics in realistic medium description [partly constrained elsewhere]
realistic medium

- establish relationship between properties of realistic medium and parameters effecting jet quenching

→ first principle [SU(2) lattice] computation of

\[ \hat{q} = \frac{4\pi^2\alpha_s}{N_c} \int \frac{dy^-d^2y_\perp d^2k_\perp}{(2\pi)^3} e^{\frac{k^2+y^2}{2\mu^2}} \langle P | \text{Tr} \left[ F^{a+\mu}_\perp(y^-, y_\perp)U^\dagger(\infty^-, y_\perp; 0^-, y_\perp) \right. \\
T^\dagger(\infty^-, \infty_\perp; \infty^-, y_\perp)T(\infty^-, \infty_\perp; \infty^-, 0_\perp) \left. U(\infty^-, 0_\perp; 0^-) F^{b+}_\perp,\mu \right] | P \rangle \]

→ for a weakly coupled medium

→ full embedding of probe in dynamical hydro medium [Monte Carlo]

→ most complete effort :: MARTINI + MUSIC
  - hard partons from Pythia
  - McGill-AMY for radiative and elastic
  - 3+1 hydro medium

\[ \text{MC efforts reviewed by} \]
K Zapp [QM2011]
outlook

• in just over ten years jet quenching has gone from ‘an idea’ to a robust experimental reality
• recent efforts have established a clear pathway to conclude [soon] the ‘establish the probe’ programme
• recent efforts have readied the necessary [embedding] tools for realistic medium probing

• pA as complementary baseline [CNM]

• time to think hard about ‘new’ observables
  • direct sensitivity to formation times
  • sensitivity to different time and spacial scales
  • isolation of ‘pure’ sample of strongly modified jets