theoretical overview of jet quenching

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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
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

#1 establishing the probe
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.

#1 establishing the probe

#2 probing the medium
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

#1 establishing the probe

#2 probing the medium

not covered in this talk:
• heavy quark [mass effects] W Horowitz today 12.15
• strongly coupled phenomena H-U Yee friday 12.15
#1 establishing the probe
jets in heavy ion collisions

vacuum jets under overall excellent theoretical control
  • 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

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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
[further improvement from future pA data]
jets in heavy ion collisions

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

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]
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]

\[ nPDF_i \otimes nPDF_j \otimes \text{hard scattering} \]

QCD branching

hadronization

\[ h_1 \]

\[ h_2 \]

\[ h_3 \]

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

jet reconstruction

[Diagram with factors initial state and fragmentation function]
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
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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  - Poissonian ansatz [BDPMS and GLV]; rate equations [AMY]; medium-modified DGLAP [HT]
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- Monte Carlo implementations [HIJING, Q-PYTHIA/Q-HERWIG, JEWELL, YaJEM, MARTINI]
medium induced radiation

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- 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]

---

Majumder & van Leeuwen [1002.2206]
medium induced radiation

systematic comparison in a simple common model medium [the BRICK]

large discrepancies [mostly due to necessary extension of formalism beyond strict applicability domain]

none necessarily right or wrong, all incomplete
relaxing approximations
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

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

- 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

\[ x = \frac{\omega}{E} \ll 1 \]

- general case computed in SCET

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

d’Eramo, Liu, Rajagopal [1010.0890]
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]: \( q \sim [\lambda^2, \lambda^2, \lambda] \)

Ovanesyan fri 16.50 [parallel 7E]
[de]coherence of multiple emissions

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

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→ 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]
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→ also for initial/final state

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

Mehtar-Tani thu 15.20 [parallel 5D]

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
  \[ \Delta_{\text{med}} = 1 - \exp \left\{ - \frac{1}{12} \hat{q} \theta_{qq}^2 t^3 \right\} \]

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

- total decoherence when \( L > \tau_d \)
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- large angle radiation [anti-angular ordering]
- geometrical separation

\[
\frac{dN_{q,\gamma}^{\text{tot}}}{\omega d\omega d\sin\theta d\theta} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{\sin\theta}{1 - \cos\theta} \left[ \Theta(\cos\theta - \cos\theta_{qq}) - \Delta_{\text{med}} \Theta(\cos\theta_{\bar{q}q} - \cos\theta) \right]
\]
coherence of multiple emissions

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

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\[ \Delta_{\text{med}} \to 0 \quad \text{coherence} \]
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- qqbar antenna [radiation much softer than both emitters] as a TH lab

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\]

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

\[
\Delta_{\text{med}} \rightarrow 1 \quad \text{decoherence}
\]

- qqbar colour coherence survival probability

\[
\Delta_{\text{med}} = 1 - \exp \left\{ -\frac{1}{12} \hat{q}_\theta^2 t^3 \right\}
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[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

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

\[
k^2_{br} = \sqrt{z(1 - z)p^+ \hat{q}_{eff}}
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[de]coherence of multiple emissions

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

emerging full account of medium effect on QCD coherence
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

\[ Q_{s}^{2} = \hat{q}L \]

\[ k_{f}^{2} = \sqrt{\hat{q}\omega} \]

\[ \tau_{f} = \sqrt{\omega/\hat{q}} \]

AN IMPORTANT LESSON FROM DATA

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

**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]
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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no medium interaction after radiation

- colour properties of hadronizing system vacuum-like
- radiated gluon belongs to system
interplay of branching and hadronization

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medium interaction after radiation
- colour properties of hadronizing system modified
- radiated gluon LOST

Beraudo, Milhano, Wiedemann [1109.5025, 1204.4342]
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first steps towards fully colour differential framework
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 \( \phi = 0 \).

- Left 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

- colour correlations modified with respect to vacuum case

essential input for realistic hadronization schemes

![Graph showing distribution of pT and Nv]

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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

• prior to medium formation \([T_{\text{med}} \sim 0.1 \text{ fm}]\)
  • hard skeleton defined \([3\text{-jet rates, hard frag, ...}]\)
  • effect of Glasma ?

• 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
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  • hadronization of colour modified system
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soft components at large angles
[double counting?]
life story of an in-medium jet

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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 loss on all jet ‘propagators’ and ‘vertices’ remain pQCD like ???

most [all?] questions asked, many [most?] being answered
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 and sensitivities to dynamical mechanisms

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

Renk [1110.2313,1112.2503,1202.4579]
the truth is in data [and data is out there]

- theory validation [constraining dynamics] requires

→ RHIC to LHC description
the truth is in data [and data is out there]

- 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
realistic medium

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

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

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

- 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
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...

• outstanding tasks require structured efforts
  • JET collaboration [US based]; Europe [??]; Asia [??]
many thanks

to the program committee and IAC
for the privilege of giving this talk

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P Skands, and U Wiedemann
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