Theory of jets in dense matter

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Outline

Intro, pQCD and scale dependence

From one theory to multiple theories,

Role of scale in jets and jet observables,

Analytic calculations and Monte Carlo simulations

Results of simulations, and extracted information

Outlook!
QCD is all about scale!

\[ \alpha_s(Q) \]

\[ \text{QCD } \alpha_s(M_Z) = 0.1185 \pm 0.0006 \]
Well known from DIS
What the electron sees, depends on $E, Q^2$

Increasing energy $Q^2 = \text{getting closer to proton}$
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What the electron sees, depends on $E, Q^2$

Increasing energy $Q^2 = $ getting closer to proton
Jets are complicated,
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Many things happen to a jet and the energy deposited by the jet
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Many things happen to a jet and the energy deposited by the jet.

Everything other than leading hadrons is strongly affected by the medium.
From the talk I gave at CIPANP 2009
The different types of Jet modification

Jet weakly coupled to weakly coupled medium
A.M.Y
W.H.D.G.

Jet weakly coupled to arbitrary medium
Higher Twist
A.S.W.

Jet weakly coupled to strongly coupled medium
L.R.W, C-S.T

Jet strongly coupled to strongly coupled medium
Trailing String
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Factorized approaches
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Factorized approaches

\[
\frac{d\sigma^h}{dydp_T} \sim \int dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} \tilde{D}^h_q(z_1)
\]
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N-hadron data
Life was good!

if you only work on a few observables

\[ \hat{q}(\vec{r}, t) = \hat{q}_0 \frac{s(\vec{r}, t)}{s_0} \]

\[ s_0 = s(T_0) \]
A complete change of paradigm!

How jets interact with the medium and evolve depends on

- Temperature of the medium
- Energy of the jet
- scale of the parton in the jet \( (E, \mu^2) \)
- other scale of the medium \( (q \tau) \)

Different approaches to E-loss are valid in different epochs of the jet

A complete description requires all of these approaches

Discussion moves to boundaries between approaches
High energy and high virtuality part of shower

- Radiation dominated regime
High energy and high virtuality part of shower

• Radiation dominated regime
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Theory: Higher Twist
MC: MATTER, YaJEM
Low virtuality, high energy part

Scattering dominated regime
Few, time separated emissions
Low virtuality, high energy part

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Theory: BDMPS, AMY
MC: LBT*, MARTINI, JEWEL*
Low virtuality, high energy part

Scattering dominated regime
Few, time separated emissions

\[ Q^2 = q \tau \]
\[ \tau: \text{lifetime of a parton} \]

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Low virtuality low energy part
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• Many of these partons are absorbed by the medium
Low virtuality low energy part

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• Cannot be described by pQCD
Low virtuality low energy part

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• Modeled! (LBNL-CCNU, YaJEM, JEWEL)
Low virtuality low energy part

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- Scale of parton same as scale of medium
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- Scale of parton same as scale of medium
- AdS/CFT
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P. Chesler, W. Horowitz J. Casalderrey-Solana, G. Milhano, D. Pablos, K. Rajagopal
Grand picture (leading hadrons)

In a static brick
Grand picture (leading hadrons)

In a static brick
Grand picture (leading hadrons)

In a static brick
Grand picture (leading hadrons)

In a static brick

Strong coupling, AdS-CFT

HT

Strong coupling, AdS-CFT

BDMPS-AMY
Grand picture (leading hadrons)

In an expanding QGP
Grand picture (leading hadrons)

In an expanding QGP
Energy deposition-thermalization

Strong coupling, AdS-CFT

Energy thermalization

Soft wide angle radiation

HD

Strong coupling, AdS-CFT

Energy thermalization

BDMPS-AMY
Everything changes with scale in jet quenching
Everything changes with scale in jet quenching

**Strong coupling, AdS-CFT**

**Energy thermalization**

**Soft wide angle radiation**

**Strong coupling, AdS-CFT**
Hadronization

Strong coupling, AdS-CFT

Energy thermalization

Soft wide angle radiation

Strong coupling, AdS-CFT

Everything changes with scale in jet quenching
Transport coefficients for partons in a dense medium

\[ p_z^2 \approx E^2 - p_\perp^2 \]

\[ p^+ \approx p_\perp^2 / 2p^- \]

By definition, describe how the medium modifies the jet parton!
In general, 2 kinds of transport coefficients

Type 1: which quantify how the medium changes the jet

\[ \hat{q}(E, Q^2) \quad \hat{q}_4(E, Q^2) = \frac{\langle p_T^4 \rangle - \langle p_T^2 \rangle^2}{L} \ldots \]

\[ \hat{e}(E, Q^2) \quad \hat{e}_2(E, Q^2) = \frac{\langle \delta E^2 \rangle}{L} \quad \hat{e}_4(E, Q^2) = \frac{\langle \delta E^4 \rangle - \langle \delta E^2 \rangle^2}{L} \ldots \]

Type 2: which quantify the space-time structure of the deposited energy momentum at the hydro scale

\[ \delta T^{\mu \nu} \]
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Type 2: which quantify the space-time structure of the deposited energy momentum at the hydro scale

\[\delta T^{\mu \nu}\]
Observables: more type 2, more MC
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1. Observables that only depend on type 1
   1. Strong dependence on hard $\sigma$:
      1. Hadron $R_{AA}$, high $p_T v_2$!
      2. Dihadron, $I_{AA}$, $\gamma$-Hadron
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         (clear dependence on $q$, but also require fragmentation functions)
   2. Weaker dependence on hard $\sigma$ :
      1. Near side $I_{AA}$ ! (badly surface biased)
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2. Observables that depend on type 1 and some type 2
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      1. Jet $R_{AA}$, high $p_T v_2$!
      2. DiJets ($X_j$), $\gamma$-Jet
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(reduce dependence on type 2 by increasing $E$, lose sensitivity, reduce $R$, requires resummation)

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   1. $z_g$
   2. Jet Mass, Jet shape
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3. Observables that depend strongly on type 2
   Jet medium correlations
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3. Observables that depend strongly on type 2
   Jet medium correlations
Need a Monte-Carlo event generator based approach

Need to have a framework

• That can modularly incorporate a variety of theoretical approaches

• Which can allow you to model medium response, and entire range of transport coefficients

• Can address all observables simultaneously
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Such a framework now exists: JETSCAPE

https://github.com/JETSCAPE
Applying Multi-scale models

It's the right thing to do.
Pushing limited approaches past limits creates tension!

LBT
fixed $\alpha_s = 0.15$

mean $\alpha_s = 0.2$

S. Cao, LBT
Evidence of multiple scales from multiple-stage Monte Carlos

Switching between one event-generator and the next in a brick @JETSCAPE Phys.Rev. C96 (2017) no.2, 024909
Repeat with hadronization and fluid medium being calculated
Evidence of multiple scales from multiple-stage Monte Carlos.

- For $Q_0 = 1$ GeV:
  - LBT is more effective than MAT in showing energy distribution into larger angles since elastic scattering is included in LBT.
  - Interests non-monotonic behavior at $Q_0 = 1$ GeV — enhanced Sudakov type splitting at very small $r$ and LBT scattering at large $r$.

- Partly understand the jet shape measurement even with a brick.

Switching between one event-generator and the next in a brick @JETSCAPE Phys.Rev. C96 (2017) no.2, 024909.

Repeat with hadronization and fluid medium being calculated.

$E_{\text{init}} = 50$ GeV

$Q_0 = 1$ GeV

$Q_0 = 2$ GeV

$Q_0 = 3$ GeV

$\rho(r)$ of daughter partons (jet shape)

In-medium evolution changes the jet shape — depletes energy in small cone and enhances energy in large cone.
How would this work?

**Diagram:**
- **Nuclear Monte-Carlo (Nuclear Parton Distribution Function)**
  - Initial hard N-parton distribution
  - Lattice QCD Input
- **High E, High Q shower**
- **High E, low Q shower**
  - Phenomenological input: Transport coefficients, Energy deposition
- **Low E, low Q shower**
- **Viscous Fluid dynamics of QGP**
- **Hadronic cascade**
- **Hard & semi-hard hadronization**
- **AdS/CFT**
- **Detector simulation**
- **Statistical emulation**
- **Corrected data**
- **Statistical fit test**
  - Yes: **Success!**
  - No: **Modify, input parameters e.g., , .**

**Input:**
- **Transport coefficients**
- **Energy deposition**

**Success criteria:** Yes! No!

**ETSCAPE Event Generator**
How would this work?

Nuclear (Monte Carlo) + Parton Distribution Function → High E, High Q shower → Viscous Fluid dynamics of QGP

Lattice QCD + Initial hard N-parton distribution → High E, low Q shower

Phenomenological input: Transport coefficients, Energy deposition

AdS/CFT

Low E, low Q shower → Hard & semi-hard hadronization

Modify, input parameters e.g., \( q \), \( \hat{e} \).

Detector simulation → Statistical emulation

JETSCAPE Event Generator

Initial soft density distribution → Success! Yes! No!

Modify, input parameters e.g., \( q \), \( \hat{e} \).
How would this work?

Modify, input parameters e.g., $q$, $e$.

Nuclear Parton Distribution Function → Initial hard N-parton distribution → High E, High Q shower

Lattice QCD Input → Phenomenological input: Transport coefficients, Energy deposition

Viscous Fluid dynamics of QGP

Hadronic cascade

Hard & semi-hard hadronization

AdS/CFT

Input

Success! Yes! No!
Using the full event generator

• Any good event generator needs a good p-p baseline

PYTHIA for initial state
MATTER for all final state partons > 1GeV
PYTHIA based hadronization of final partons
Preliminary results from JETSCAPE

Initial state with TRENTO for both hydro and jets
TRENTO $\rightarrow$ PreEquib $\rightarrow$ MUSIC $\rightarrow$ Soft Hadronization
TRENTO $\rightarrow$ PYTHIA init
$\rightarrow$ (MATTER/LBT/MARTINI/AdS) + MUSIC profile
$\rightarrow$ PYTHIA based hadronization

[Graphs showing data points and comparisons]
What did we learn from all this?
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$\hat{q}/T^3 \sim 4$ at 0.2 TeV, $\sim 3$ at 2.76 TeV
What did we learn from all this?

\[ \hat{q}/T^3 \sim 4 \text{ at } 0.2 \text{TeV}, \sim 3 \text{ at } 2.76 \text{TeV} \]

Personal opinion: its not this \( \rightarrow \) rather an energy or scale dependence in \( \hat{q} \)

Non-Monotonic behavior
what you may think this means!

If this is true, must effect the centrality dependence of \( R_{AA}, v_2 \) and its centrality dependence at a given collision energy...
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Jets have multiple scales, with different interactions with medium
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Qualitatively similar but quantitatively different picture for heavy Q (see Shanshan’s talk)

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Limits on \( \hat{e} \) from jets and leading hadrons
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Limits on \( \hat{e} \) from jets and leading hadrons

Medium recoil needed to get jet physics

Deposited energy seems to thermalize very rapidly into fluid
What do you want to learn
What do you want to learn

How does the parton in the jet see the medium?
What do you want to learn

How does the parton in the jet see the medium?
What do you want to learn

How does the parton in the jet see the medium?
Jet medium interactions, allow for a needle like probe of the hydro medium
Allow us to shatter quasi-particles and see them reconstitute, and equilibrate
Outlook

Jets provide multi-scale probes of the evolving QGP

Multi-scale dynamics, growing number of T.Cs, and observables require a modular, modifiable, event generator —> JETSCAPE

Established values of q, e,

(Heavy-quarks provide a slightly shifted view of this)

Need for medium response for jets studies.

Jet medium correlations provide a possible window into degrees of freedom of the QGP, next stage of JETSCAPE.
Back Up
In all calculations presented, bulk medium described by viscous fluid dynamics evokes hydro-dynamically as the jet moves through it. Fit the \( q \) for the initial \( T \) in the hydro in central coll.

\[
\hat{q}(\vec{r}, t) = \hat{q}_0 \frac{s(\vec{r}, t)}{s_0}
\]

\[
s_0 = s(T_0)
\]

\[
R_{AA} \sim \frac{dN_{AA}}{dp_T dy} \frac{N_{bin}}{dN_{pp}}
\]

![Graph showing R_AA as a function of p_T (GeV) with data points and fitted curves for PHENIX (0-5%) and PHENIX (20-30%) as well as 2+1D viscous Hydro, \( \hat{q} = 2.2 \text{ GeV}^2/\text{fm}, \xi_{\text{max}} \text{ fixed} \) and \( \xi_{\text{max}} \text{ calculated} \).]
Reasonable agreement with data,
no separate normalization at LHC
W/O any non-trivial x-dependence (E dependence)
Results from the JET collaboration

Do separate fits to the RHIC and LHC data for maximal $\hat{q}$ without assuming any kink in the $q$ vs $T^3$ curve
Do separate fits to the RHIC and LHC data for maximal $\hat{q}$ without assuming any kink in the $q$ vs $T^3$ curve
A factorized picture

\[ q^- = \frac{q^0 + q^3}{\sqrt{2}} \]

\[ q \sim Q(\lambda^2, 1, \lambda) \]

\[ k \sim Q(\lambda^2, \lambda^2, \lambda) \]

\[ p \sim Q(1, \lambda^2, \lambda) \]

\[ q^- \sim Q \]
A factorized picture

\[ q^- = \frac{q^0 + q^3}{\sqrt{2}} \]

\[ q \sim Q(\lambda^2, 1, \lambda) \]

\[ k \sim Q(\lambda^2, \lambda^2, \lambda) \]

\[ p \sim Q(1, \lambda^2, \lambda) \]

\[ Q \text{ is the hard scale of the jet } \sim E \]

\[ Q\lambda \text{ is a semi-hard scale } \sim (ET)^{1/2}, \]

\[ q \text{ contains all dynamics below } Q\lambda \]

\[ \lambda \rightarrow 0 \]
A factorized picture

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\[ q \sim Q(\lambda^2, 1, \lambda) \]

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\[ \lambda \rightarrow 0 \]
Input PDF at $Q^2 = 1 \text{ GeV}^2$

- Sea like
- Wide Valence
- Narrow Valence
Putting it all together
\[ G(x) = C x^a (1 - x)^b \]

making \( b \) negative increases strength at \( x \sim 1 \)

Seems ruled out by fits..

Mass of d.o.f. less than mass of nucleon.
Going from semi-analytic (event-averaged) to MC event generators

Some parts are done with much greater accuracy at low $p_T$ sensitive to in-medium frag.

Need a prescription at lower $p_T$. Used hard cut for partons at $Q=1$GeV more than a fm inside.
More sensitive to multiple scales for full jet

- jets done partonically
- hard cut for $Q<1\text{GeV}$ more than 1fm in
- Should do the $Q<1\text{GeV}$ more carefully
- Enter JETSCAPE!

![Graph showing $R_{AA}$ versus $p_T$ for Pb-Pb collisions at 2.76 TeV, comparing ATLAS hadron and CMS jet R=0.3 to MATTER pion.](image)
Near side and away side correlations

A wide range of single particle observables can be explained by a weak coupling formalism.
How the jet sees the medium depends on jet scale

Extracted $q$ has a lot or fluctuation included in it. Looks different at different scales.
How the jet sees the medium depends on jet scale

Extracted $q^*$ has a lot or fluctuation included in it. Looks different at different scales.
How the jet sees the medium depends on jet scale

Extracted q has a lot or fluctuation included in it. Looks different at different scales.
How the jet sees the medium depends on jet scale

Extracted $q^*$ has a lot of fluctuation included in it. 
Looks different at different scales

[Graph showing curves labeled Low Q and Mid Q]
How the jet sees the medium depends on jet scale

Extracted $q^*$ has a lot or fluctuation included in it. Looks different at different scales.