











Abhijit Majumder Wayne State University

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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!

















Many things happen to a jet and the energy deposited by the jet

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Everything other than leading hadrons is strongly affected by the medium

This is not how things were done traditionally







PRC 90 014909 2014



Applied different formalism to the entire history of the jet.



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, μ^2)
- other scale of the medium ($\mathbf{\hat{q}} \tau$)

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







Radiation dominated regime



Theory: Higher Twist, GLV MC: MATTER, YaJEM







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 τ : lifetime of a parton

Scattering dominated regime Few, time separated emissions

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Theory: BDMPS, AMY MC: LBT*, MARTINI, JEWEL*

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P. Chesler, W. Horowitz J. Casalderrey-Solana, G. Milhano, D. Pablos, K. Rajagopal



In a static brick



BDMPS-AMY



In a static brick



In a static brick



In an expanding QGP



In an expanding QGP

Energy deposition-thermalization

Strong coupling, AdS-CFT Energy thermalization

DMPS-AM

Strong coupling, AdS-CFT

Soft wide angle

Energy thermalization

Energy deposition-thermalization

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APS-A

Strong coupling, AdS-CFT

Soft wide angle

Energy thermalization

Transport coefficients for partons in a dense medium $p^+ \simeq p_\perp^2 / 2p^$ $p_z^2 \simeq E^2 - p_\perp^2$ $D\left(\frac{\vec{p}_{h}}{\left|\vec{p}+\vec{k}_{\perp}\right|}, m_{J}^{2}\right) \qquad \hat{q} = \frac{\langle p_{\perp}^{2} \rangle L}{L} \qquad \text{Transverse momentum} \\ \text{diffusion rate}$ Elastic energy loss $D\left(\frac{p_h}{p-k}, m_J^2\right)$ $\hat{e} = \frac{\langle \Delta E \rangle_L}{L}$ rate also diffusion rate e2

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 $\hat{q}_4(E,Q^2) = \frac{\langle p_T^4 \rangle - \langle p_T^2 \rangle^2}{L} \dots$ $\hat{q}(E,Q^2)$ $\hat{e}(E,Q^2) \quad \hat{e}_2(E,Q^2) = \frac{\langle \delta E^2 \rangle}{L} \quad \hat{e}_4(E,Q^2) = \frac{\langle \delta E^4 \rangle - \langle \delta E^2 \rangle^2}{L} \dots$

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 $\delta T^{\mu
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How this done currently



Full jet carries recoil particles sampled from a Boltzmann distribution. as regular jet partons, and negative parsons or holes

Other methods

Constant Broadening





AdS/CFT drag

- 1. Observables that only depend on type 1
 - 1. Strong dependence on hard σ :
 - 1. Hadron R_{AA} , high $p_T v_2!$
 - 2. Dihadron, I_{AA} , γ -Hadron

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δT^{μ}	ν					

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Such a framework now exists: JETSCAPE <u>https://github.com/JETSCAPE</u>





Applying Multi-scale models Its the right thing to do.

Pushing limited approaches past limits creates tension!











How would this work?



JETSCAPE Manual e-Print: arXiv:1903.07706 [nucl-th]
How would this work?



JETSCI

PF

JETSCAPE Manual e-Print: arXiv:1903.07706 [nucl-th]

How would this work?

JETS



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Using the full event generator



Any good event generator needs a good p-p baseline

anti-kT with R=0.2, |n|<2.0 **PYTHIA** for initial state 1.5 MATTER for all final state partons > 1GeV PYTHIA based hadronization of final partons 0.5 $\sqrt{s} = 2.76$ ATeV, Jets anti- k_t R=0.4 JETSCAPE Preliminary ATLAS Data $126 < p_T < 158 \text{ GeV}$ 3 Colorless Had 100 150 200 IETSCAPE Preliminar JETSCAPE Preliminary

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Preliminary results from JETSCAPE



Initial state with TRENTO for both hydro and jets TRENTO —> PreEquib—> MUSIC —> Soft Hadronization TRENTO —> PYTHIA init

- —> (MATTER/LBT/MARTINI/AdS) + MUSIC profile
- —> PYTHIA based hadronization



A jet hadronization mechanism that generalizes from p-p to A-A



Have separate strings for each shower initiating parton (colored)
Connect all the showers with one string to one fake (colorless) 23

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Jet and leading hadron v₂



Need event-by-event hydro and initial state to hydro adjustments

Jet shape

Energy in angle away from jet axis





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Fragmentation function



fraction of energy carried by hadrons in jet

 $\hat{q}/T^3 \sim 4$ at 0.2TeV, ~ 3 at 2.76TeV



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Personal opinion: its not this —> rather an energy or scale dependence in \hat{q}





If this is true, must effect the centrality dependence of $R_{\rm AA,}$ $v_{\rm 2}$ and its centrality dependence at a given collision energy

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Jets have multiple scales, with different interactions with medium

- Qualitatively similar but quantitatively different picture for heavy Q
- Limits on **ê** from jets and leading hadrons
- Medium recoil needed to get jet physics

How does the parton in the jet see the medium?

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Does the interaction with medium change with scale



Consistent with the the idea of Coherence!

Casalderrey-Solana et al. PLB 725 (2013) 357

Jet medium correlations !

Jet medium interactions, allow for a needle like probe of the hydro medium

Allow us to shatter quasi-particles and see them reconstitute



Outlook

- Jets provide multi-scale probes of the evolving QGP
- Multi-scale dynamics, growing number of T.Cs, and observables Requires a modular, modifiable, event generator —> JETSCAPE Established values of \hat{q} , \hat{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

Everything changes with scale in jet quenching

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Strong coupling, AdS-CFT Energy thermalization

BDMPS-AMY

Soft wide angle radiation

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Energy thermalization

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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



In all calculations presented bulk medium described by viscous fluid dynamics

Medium evolves hydro-dynamically as the jet moves through it Fit the q for the initial T in the hydro in central coll.





From RHIC to LHC circa 2012



Reasonable agreement with data, no separate normalization at LHC W/O any non-trivial x-dependence (E dependence)