Jet energy loss and equilibration

Korinna Zapp

LIP (Lisbon) & CERN

Quark Matter 2017, Chicago 6.–11. 02. 2017

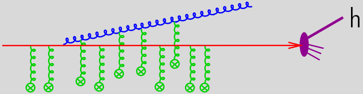
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

Outline

1. Introduction
2. Jet sub-structure in heavy ions
3. Implications for heavy ion community
4. Conclusions

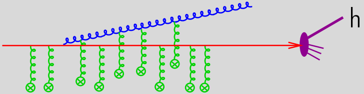
Introduction

jet quenching in 2000

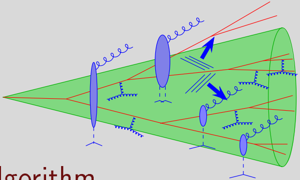


Introduction

jet quenching in 2000



jet quenching in 2017

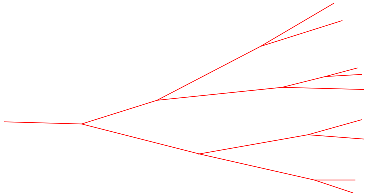


- jets defined by jet algorithm
- requires theory tools capable of dealing with multi-particle final states
- jets reduce the complexity of events → study global event properties

  similar to leading hadron analyses
- jet sub-structure contains information about medium

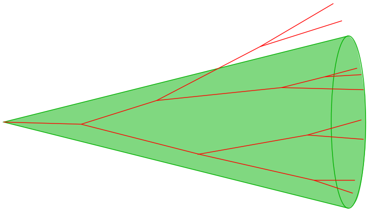
Jets in vacuum and medium

jets in vacuum: well understood in fixed order + resummation



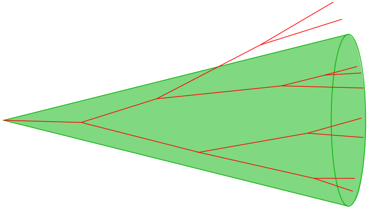
Jets in vacuum and medium

jets in vacuum: well understood in fixed order + resummation



Jets in vacuum and medium

jets in vacuum: well understood in fixed order + resummation

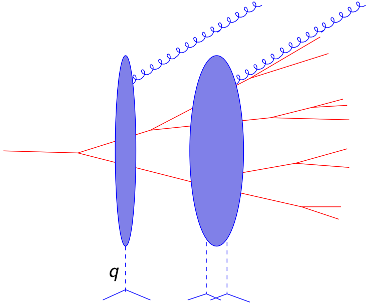


jets in medium:

- Do jets resolve partonic structure of medium?
- momentum transfer q from medium defines resolution
- jets resolve medium & medium resolves jets

Jets in vacuum and medium

jets in vacuum: well understood in fixed order + resummation



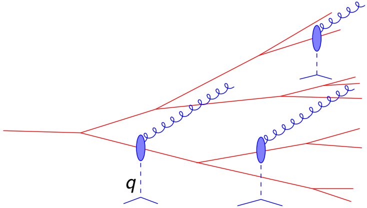
jets in medium:

- Do jets resolve partonic structure of medium?
- momentum transfer q from medium defines resolution
- jets resolve medium & medium resolves jets
  - low q: jet sub-structure not resolved $\rightarrow$ unmodified jet core

Jets in vacuum and medium

jets in vacuum: well understood in fixed order + resummation

jets in medium:

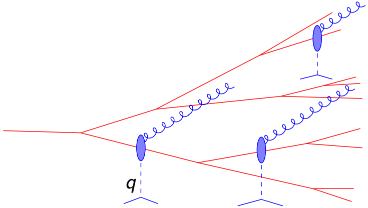


- Do jets resolve partonic structure of medium?
- momentum transfer q from medium defines resolution
- jets resolve medium & medium resolves jets
  - low q: jet sub-structure not resolved → unmodified jet core
  - high q: jet structure resolved → can modify jet core

Jets in vacuum and medium

jets in vacuum: well understood in fixed order + resummation

jets in medium:



- Do jets resolve partonic structure of medium?
- momentum transfer q from medium defines resolution
- jets resolve medium & medium resolves jets
  - low q: jet sub-structure not resolved $\rightarrow$ unmodified jet core
  - high q: jet structure resolved $\rightarrow$ can modify jet core
- jet sub-structure observables should be able to distinguish them

Jet quenching at strong coupling

D. Pablos, Fr 10.30

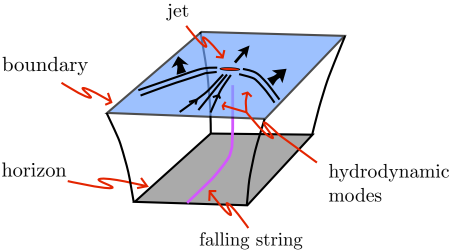
Advantages:

1. exact solution of gauge theory at strong coupling
2. no uncertainty in jet-medium interaction

Fundamental problems:

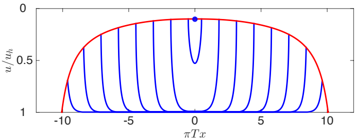
1. jets are a weak-coupling phenomenon
2. QCD is not $\mathcal{N} = 4$ SYM

"holographic jet":
$q\bar{q}$ pair in QGP dual to classical string in black hole geometry



Chesler, Jensen, Karch, Yaffe, Phys. Rev. D 79 (2009) 125015
Chesler & Rajagopal, JHEP 1605 (2016) 098

Jet quenching at strong coupling II



Connection to equilibration

blobs of supersymmetric energy density used to study **jets** and **thermalisation**

Chesler, van der Schee, Int. J. Mod. Phys. E 24 (2015) no.10, 1530011

Is it possible to go beyond energy packets?

- 3-jet configurations from 2 connected strings

  Casalderrey-Solana, Ficnar, arXiv:1512.00371 [hep-th]

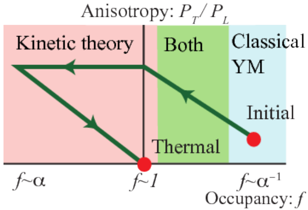
- jets with shapes, opening angles, ...

  J. Brewer, session 2.4, Tue 12.00

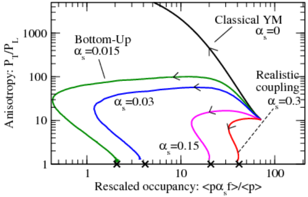
- hybrid: PYTHIA jets + AdS/CFT energy loss + medium response

  K. Rajagopal, session 2.4, Tue 10.40

Jets and thermalisation at weak coupling



A. Kurkela, Nucl. Phys. A 956 (2016) 136



A. Kurkela, Y. Zhu, Phys. Rev. Lett. 115 (2015) no.18, 182301

- early stages of HIC and jets are far-from-equilibrium systems
- region $f \ll 1/\alpha_s$ described by effective kinetic theory

P. B. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0301 (2003) 030

$$-\frac{\mathrm{d}f_{\mathbf{p}}}{\mathrm{d}\tau} = \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}_{\mathrm{exp}}[f_{\mathbf{p}}]$$

- $\mathcal{C}_{1\leftrightarrow 2}$: splitting/merging rate in presence of multiple scattering including LPM effect
- $\mathcal{C}_{2\leftrightarrow 2}$: elastic scattering rate
- both also responsible for parton energy loss

Jet sub-structure observables

- observables built from jet constituents

  particles, partons, calorimeter cells, . . .
- characterise distribution of momentum & find structures inside jet

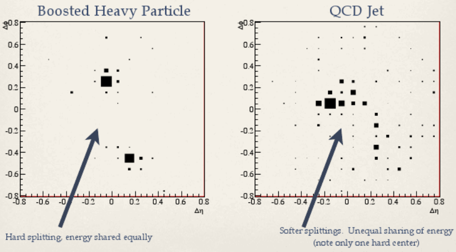


image from David Krohn

- various grooming techniques studied in p+p to separate hard structure from soft contaminations

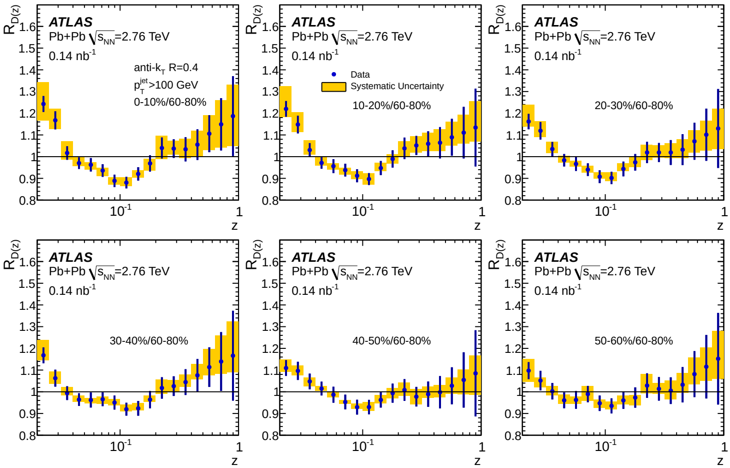
  filtering, trimming, pruning, . . .
- interesting for heavy ions, but requires careful studies

Experimental results

- intra-jet fragmentation function (ATLAS)

ATLAS, Phys. Lett. B 739 (2014) 320

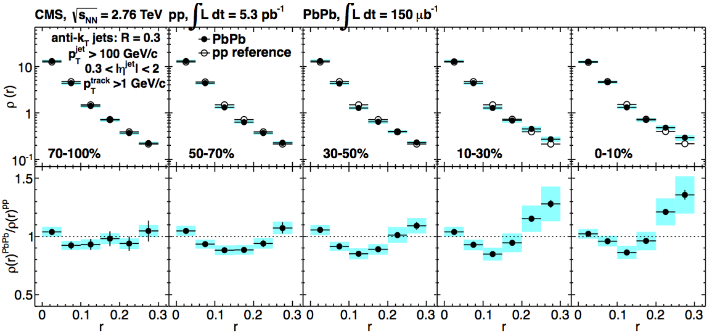
ALICE, arXiv:1702.00804



Experimental results

- intra-jet fragmentation function (ATLAS) — ATLAS, Phys. Lett. B 739 (2014) 320
- jet profile (CMS) — CMS, Phys. Lett. B 730 (2014) 243

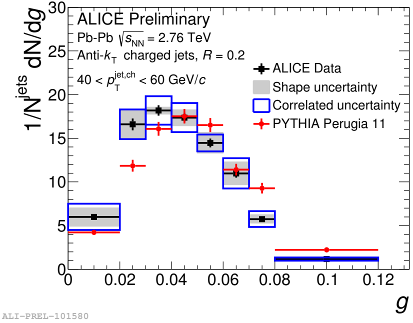
ALICE, arXiv:1702.00804



Experimental results

- intra-jet fragmentation function (ATLAS) — ATLAS, Phys. Lett. B 739 (2014) 320
- jet profile (CMS) — CMS, Phys. Lett. B 730 (2014) 243
- girth/radial moment (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593

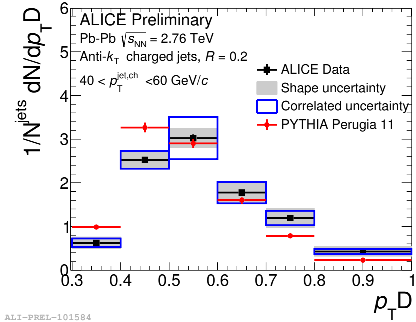
ALICE, arXiv:1702.00804



Experimental results

- intra-jet fragmentation function (ATLAS) — ATLAS, Phys. Lett. B 739 (2014) 320
- jet profile (CMS) — CMS, Phys. Lett. B 730 (2014) 243
- girth/radial moment (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593
- momentum dispersion $p_\perp D$ (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593

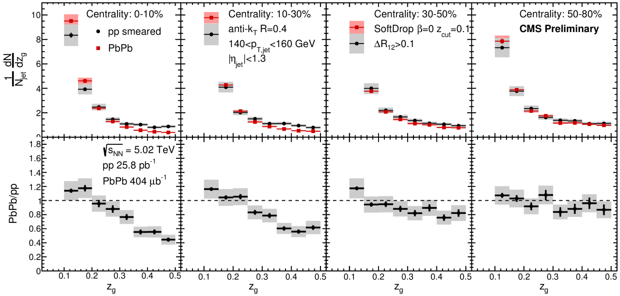
ALICE, arXiv:1702.00804



Experimental results

- intra-jet fragmentation function (ATLAS) — ATLAS, Phys. Lett. B 739 (2014) 320
- jet profile (CMS) — CMS, Phys. Lett. B 730 (2014) 243
- girth/radial moment (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593
- momentum dispersion $p_\perp D$ (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593
- groomed shared momentum fraction z_g (CMS, STAR) — CMS-HIN-16-006

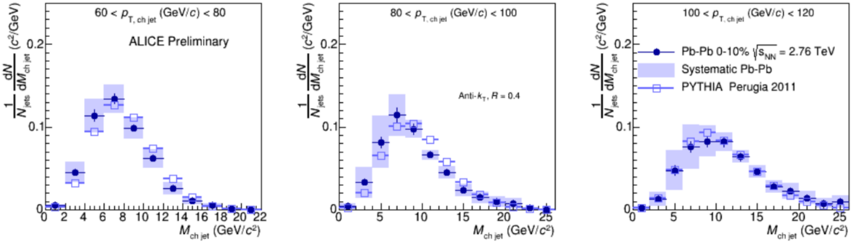
ALICE, arXiv:1702.00804



Experimental results

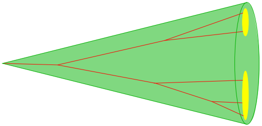
- intra-jet fragmentation function (ATLAS) — ATLAS, Phys. Lett. B 739 (2014) 320
- jet profile (CMS) — CMS, Phys. Lett. B 730 (2014) 243
- girth/radial moment (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593
- momentum dispersion $p_\perp D$ (ALICE) — ALICE, Nucl. Phys. A 956 (2016) 593
- groomed shared momentum fraction z_g (CMS, STAR) — CMS-HIN-16-006
- jet mass (ALICE) not strictly a jet shape observable, but shares some similarities

ALICE, arXiv:1702.00804



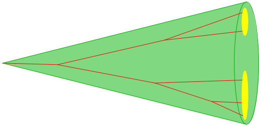
Soft Drop: measuring the splitting function?

M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146



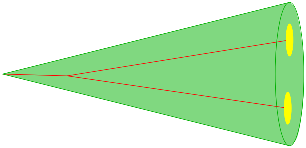
- Soft Drop procedure: identifies hardest 2-prong structure in a jet
- groomed shared momentum fraction $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_\text{cut}}^{1/2} \mathrm{d}z\, P(z) + P(1 - z)} \Theta(z_g - z_\text{cut})$

Soft Drop: measuring the splitting function?



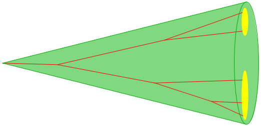
M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146

- Soft Drop procedure: identifies hardest 2-prong structure in a jet
- groomed shared momentum fraction $z_g = \dfrac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \dfrac{P(z_g) + P(1-z_g)}{\int_{z_{\text{cut}}}^{1/2} \mathrm{d}z\, P(z) + P(1-z)} \Theta(z_g - z_{\text{cut}})$



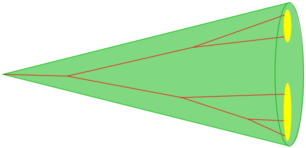
Soft Drop: measuring the splitting function?

M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146

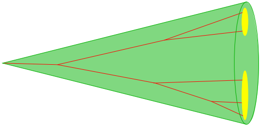


- Soft Drop procedure: identifies hardest 2-prong structure in a jet

- groomed shared momentum fraction $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \frac{P(z_g) + P(1-z_g)}{\int_{z_\mathrm{cut}}^{1/2} \mathrm{d}z\, P(z) + P(1-z)} \Theta(z_g - z_\mathrm{cut})$

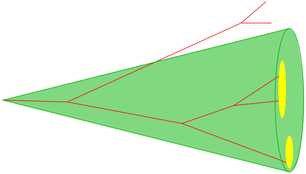


Soft Drop: measuring the splitting function?

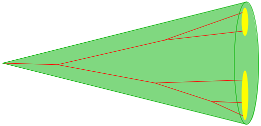


M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146

- Soft Drop procedure: identifies hardest 2-prong structure in a jet
- groomed shared momentum fraction $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} \mathrm{d}z\, P(z) + P(1 - z)} \Theta(z_g - z_{\mathrm{cut}})$



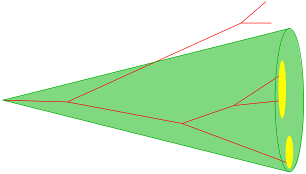
Soft Drop: measuring the splitting function?

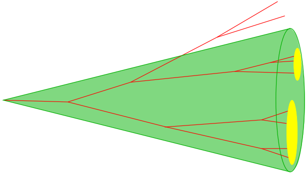


M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146

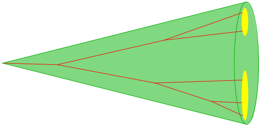
- Soft Drop procedure: identifies hardest 2-prong structure in a jet

- groomed shared momentum fraction $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_\text{cut}}^{1/2} \mathrm{d}z\, P(z) + P(1 - z)} \Theta(z_g - z_\text{cut})$



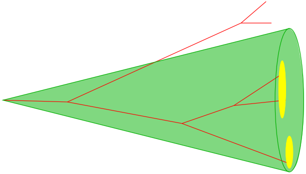


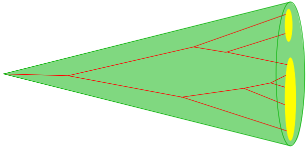
Soft Drop: measuring the splitting function?



M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146

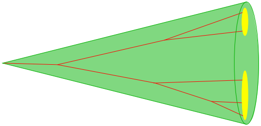
- Soft Drop procedure: identifies hardest 2-prong structure in a jet
- groomed shared momentum fraction $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} \mathrm{d}z\, P(z) + P(1-z)} \Theta(z_g - z_{\mathrm{cut}})$



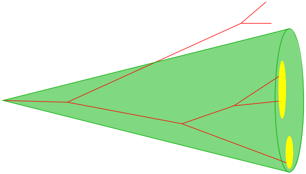


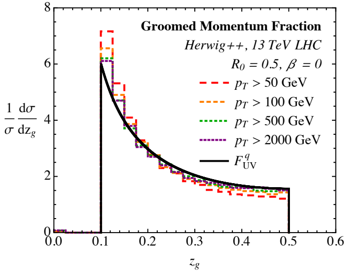
Soft Drop: measuring the splitting function?

M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP 1309 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146



- Soft Drop procedure: identifies hardest 2-prong structure in a jet
- groomed shared momentum fraction $z_g = \dfrac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$
- LO order calculation: $p(z_g) = \dfrac{P(z_g) + P(1-z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} \mathrm{d}z\, P(z) + P(1-z)} \Theta(z_g - z_{\mathrm{cut}})$





A. J. Larkoski, S. Marzani, J. Thaler, Phys. Rev. D 91 (2015) no.11, 111501

Theory Challenges I: What is needed to make sense of z_g?

Can z_g help to extract the in-medium splitting function?

- grooming and medium-induced splitting

K. Tywoniuk, session 3.4, Tue 15.00

- in-medium splitting functions from SCET_G H. Xing, session 5.4, We 9.30

How can we understand coherence of jets?

- z_g and coherence Y. Mehtar-Tani, session 6.4, We 11.40
- 2-gluon calculations P. Arnold, session 5.3, We 9.10

J. Casalderrey-Solana, D. Pablos, K. Tywoniuk, JHEP 1611 (2016) 174

- radiation off a non-eikonal antenna

L. Apolinário, N. Armesto, J. G. Milhano and C. A. Salgado, JHEP 1502 (2015) 119

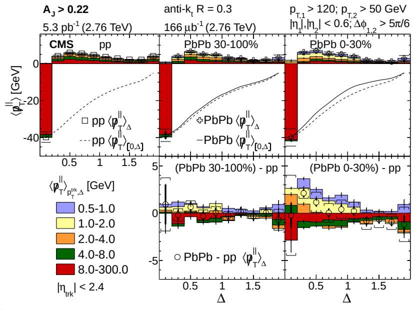
How do vacuum like and medium induced emissions interplay?

- studied in JEWEL, needs further work

J. G. Milhano, K. C. Zapp, Eur. Phys. J. C 76 (2016) no.5, 288

Soft Drop: sensitivity to medium response

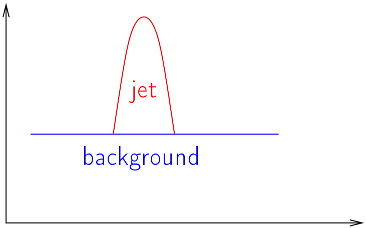
- Soft Drop in A+A is more complicated than that
- sensitivity to medium response
  - energy lost by jet is transferred to medium
  - theoretical ideas: Mach cone, wake, . . .
  - observed: additional soft activity



CMS, JHEP 1601 (2016) 006

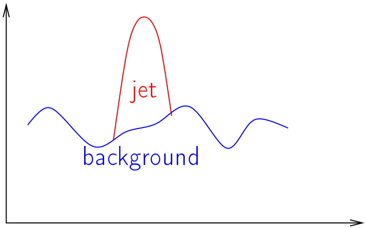
- chance to observe medium's reaction to perturbation

Theorist's view of background



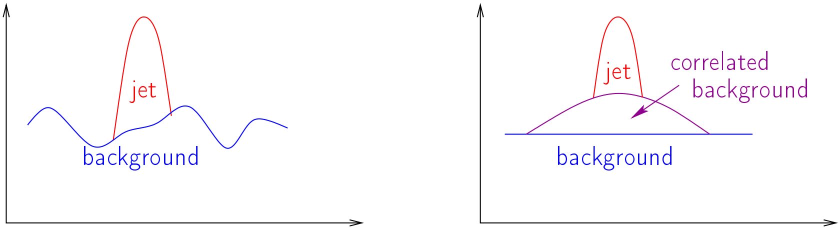
- ideal situation: flat background – can be subtracted

Theorist's view of background



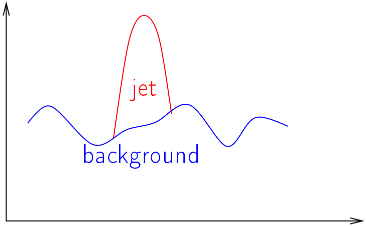
- ideal situation: flat background – can be subtracted
- more realistic: fluctuating background – can be subtracted on average, have to unfold

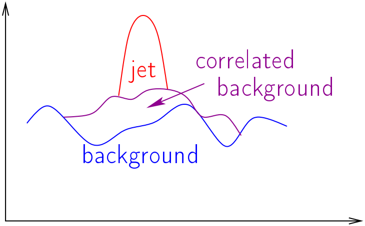
Theorist's view of background



- ideal situation: flat background – can be subtracted
- more realistic: fluctuating background – can be subtracted on average, have to unfold
- even more realistic: correlated background
  - part of the background is correlated with jet → medium response
  - activity above background
  - correlated background cannot and should not be subtracted

Theorist's view of background





- ideal situation: flat background – can be subtracted
- more realistic: fluctuating background – can be subtracted on average, have to unfold
- even more realistic: correlated background
  - part of the background is correlated with jet → medium response
  - activity above background
  - correlated background cannot and should not be subtracted
- finally: also fluctuations in correlated part of background matter

Theory Challenges II: Adding the soft component to z_g

How can we model medium response to jets?

- transport equations for jets combined with hydro for medium

  W. Chen, session 1.4, Tue 9.30

  Y. Tachibana, We 12.00
- fast thermalisation of soft jet fragments E. Iancu, B. Wu, JHEP 1510 (2015) 155
- effect of medium response on z_g G. Milhano, session 3.4, Tue 14.40
- recoil momentum in JEWEL and JEWEL+hydro

  S. Floerchinger, K. C. Zapp, Eur. Phys. J. C 74 (2014) no.12, 3189
  R. Kunnawalkam Elayavalli, K. C. Zapp, in preparation

What is the role of fluctuations?

- fluctuations and correlations in in-medium gluon cascade

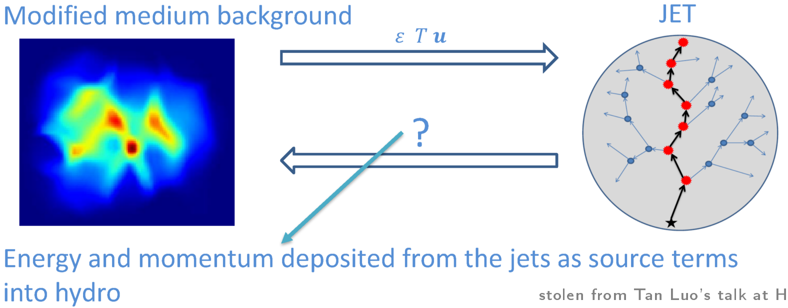
  M. Á. Escobedo Espinosa, session 6.2, We 12.00
- fluctuations in vaccum like radiation pattern & energy loss in JEWEL

  J. G. Milhano, K. C. Zapp, Eur. Phys. J. C 76 (2016) no.5, 288

CoLBT-Hydro model

Y. He, T. Luo, X. N. Wang, Y. Zhu, Phys. Rev. C 91 (2015) 054908
L. Pang, Q. Wang, X. N. Wang, Phys. Rev. C 86 (2012) 024911

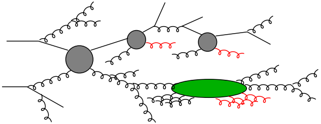
- Boltzmann transport for jet including radiation & elastic scattering
- linearised: treat only interactions of jet partons with background
- background provided by hydro
- soft partons from transport give source term for hydro
- solve both in parallel



stolen from Tan Luo's talk at HP 2016

Medium response in JEWEL

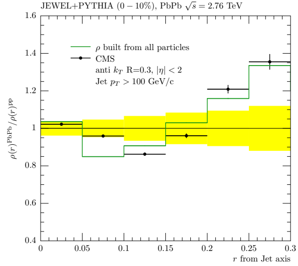
work with Raghav Kunnawalkam Elayavalli & Guilherme Milhano

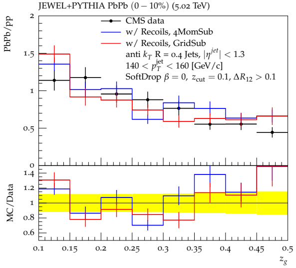


- can hadronise recoiling thermal partons together with jet

recoils are colour connected to jet

- have to subtract thermal 4-momentum at analysis level
- improved description of jet shape observables





Fluctuations & correlations in democratic gluon cascade

M. A. Escobedo, E. Iancu, JHEP 1605 (2016) 008 & JHEP 1612 (2016) 104

- hardest gluon that can be emitted coherently:

$$\omega_c = \alpha_s \hat{q} L^2$$

- emission probability of ω_c gluons $\mathcal{P}(\omega_c) \ll 1$
- hardest gluon that can be emitted with probability $\mathcal{P}(\omega_{br}) = \mathcal{O}(1)$:

$$\omega_{br} = \alpha_s^2 \hat{q} L^2$$

- ω_{br} gluons dominate typical energy loss

$\rightarrow$ large energy loss fluctuations

- semi-hard gluon ($\omega \simeq \omega_{br}$) undergoes fast & democratic branching

$\rightarrow$ energy transferred to soft, large angle gluons

Jet sub-structure requires community effort

What jet sub-structure observables have taught us

- have to understand in detail what a particular observable is sensitive to
- this requires advanced tools
- and close collaboration between theorists & experimentalists
- Lisbon accord: effort involving theorists and experimentalists to
  - agree on how data should be presented

    which corrections, unfolding etc. should be applied
  - agree on what are well defined observables

    theoretically sound

    should not require model dependent processing
  - agree on good practice for comparisons between theory and data
  - introduce standards, formats and tools
  - make standard particle physics tools usable for heavy ions

If you want to contribute, please contact G. Milhano.

JETSCAPE

http://jetscape.wayne.edu/

Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope

- NSF funded project involving experimentalists, theorists, computer scientists, and statisticians
- goal: provide software package for simulation of jets in heavy ion collisions + statistical tools
- tools will be useful insightful mapping out of theory uncertainties
- I hope JETSCAPE will join Lisbon accord

Things I left out

Things I did not have time to talk about

- $\hat{q}$ at RHIC and LHC — C. Andres Casas, session 1.4, Tue 9.50
- $\hat{q}$ from broadening — G.-Y. Qin, seesion 2.4, Tue 11.00
- scale dependence of $\hat{q}$ — A. Kumar, session 5.4, We 8.50
- jets in semi-Quark-Gluon-Monopole Plasma — J. Liao, session 7.4, We 15.40

Conclusions

- Jet shape observables have potential to elucidate thermalisation.
  - → jet shape observables are sensitive to hard and soft physics
  - → chance to observe medium's reaction to perturbations
- They may revolutionise our view of jet-medium interactions.
  - → related to question whether jets resolve quasi-particles in medium
  - → related to (colour) coherence
- Understanding jet shapes requires special theoretical techniques.
  - → need tools able to handle multi-particle final states
  - → have to account for vacuum like radiation & jet-medium interactions
  - → there is no way around coherence
  - → have to quantify medium response
- Jet quenching is becoming a quantitative discipline.
  - → have to agree on standards,
  - → ways of presenting measurements,
  - → how to achieve fair data-theory comparison
  - → theoretically sound observable definitions
  - → requires close collaboration between experimentalists and theorists