Jets in QCD matter: Theory summary

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Apologies. . .

▶ . . . to all speakers whose talks I should have attended but didn’t, because I was in the other session.

▶ . . . to all speakers whose work I misunderstand or misrepresent.
Jet shapes/sub-structure  Agnostic approaches  Comprehensive models  Systematic improvements  New ideas

HP18 jet talk topology

- theory: understanding specific aspects
- phenomenology: modeling of all relevant aspects

allows for comparison to experimental data

What is needed to model jet shapes/sub-structure

- **vacuum baseline**: jet production + evolution
  - extra emissions give rise to jet sub-structure
- **radiative energy loss**
  - out-of-cone: jet energy loss
  - in-cone: redistribution of energy inside jet
    → modification of sub-structure
- **collisional energy loss + medium response**
  - partial recovery of lost energy
  - medium response distribution wider
    → modification of jet sub-structure

important mostly at large $r$
Approaches presented at Hard Probes 2018

- LBT/coLBT
  - Wei Chen (Tue)
  - Xin-Nian Wang (Wed)

- \( \text{SCET}_G \)
  - Hai Tao Li (Tue)
  - Yang-Ting Chien (Wed)

- AdS/CFT
  - Wilke van der Schee (Tue)
  - Daniel Pablos (Thu)

- hybrid model
  - Yasuki Tachibana (Wed)

- JETSCAPE
  - Ning-Bo Chang (Tue)
  - Guang-You Qin (Wed)

- Pythia + Boltzmann + higher twist + hydro
- vacuum + higher twist + LBT + hydro
Jet profile

**Pb-Pb @ 2.76 TeV (0-10%)**

- Anti-$k_T$, $R=0.3$
- $p_T^{jet}>100 \text{ GeV}/c$, $p_T^{trk}>1 \text{ GeV}/c$
- $|\eta^{jet}|<2.0$

**Inclusive, PbPb (2.76 TeV)**

- $p_T^{jet}>100 \text{ GeV}/c$, $R=0.3$
- $q_{q,0}=1.7 \text{ GeV}^2/\text{fm}$, $\omega_{\text{cut}}=1.0 \text{ GeV}/c$
- $p_T^{trk,byd}>1 \text{ GeV}/c$

**JEWEL+PYTHIA (0−10%), Pb+Pb $\sqrt{s}=2.76 \text{ TeV}$**

- Without recoil
- With recoil ($p_{\text{cut}}=4T$)

**Tachibana, Chang, Qin,** *Phys. Rev. C* **95** (2017) no. 4, 044909

**Kumarwalkam Elayavalli, Zapp,** *JHEP* **1707** (2017) 141

**Park, Jeon, Gale,** arXiv:1807.06550

**Park, Chang, Qin,** *Phys. Rev. C* **95** (2017) no. 4, 044909

**Korinna Zapp (LIP & CERN)**

Jets in QCD matter: Theory summary
Jet profile continued

- unclear, whether increase due to medium response or induced radiation
Agnostic approaches

Goal

extract energy loss characteristics or medium properties from data as model independently as possible

 Talks at Hard Probes 2018

▶ systematically scan radiation phase space (Lund diagram)

↔ jet sub-structure

Marta Verwej (Wed)
Yi Chen (Wed)

▶ machine learning

Yue Shi Lai (Tue)
Yang-Ting Chien (Wed)

▶ generic models

François Arleo (Tue)
Martin Rohrmoser (Tue)
Xin-Nian Wang (Wed)

▶ quantile matching

Jasmine Brewer (Tue)
**Lund and grooming**

Grooming selects on momentum fraction and angle of branches in angular ordered tree

- **$(z, \beta) = (0.1, 0)$**
  - $Z_{\text{cut}} = 0.1$
  - $\beta = 0$
  - Cuts only on the energy sharing fraction

- **$(z, \beta) = (0.5, 1.5)$**
  - $Z_{\text{cut}} = 0.5$
  - $\beta = 1.5$
  - Stronger grooming at large angle

- **$(z, \beta) = (0.1, -1.0)$**
  - $Z_{\text{cut}} = 0.1$
  - $\beta = -1$
  - Only hard radiation remains

Varying the grooming condition allows to select different regions of radiation phase space

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**Scanning the Lund diagram (slide from Marta Verweij)**

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Quantile matching (slide from Jasmine Brewer)

Key question: compare A-A jets to which p-p jets?

- Another answer: match in (effective) cumulative jet cross-section
  \[ \sigma^{\text{eff}} = \sigma^{\text{pp}} \frac{\sigma^{\text{HI}}}{\langle T_{\text{AA}} \rangle} \]

- "Quantile" matching

(see backup for technicalities)
Constructing comprehensive models

- consistency of single-inclusive hadron observables
  Carlota Andrés (Tue)
- AMY kinetic energy loss in JETSCAPE
  Tianyu Dai (Tue)
- modeling of $b$-jets
  Sa Wang (Tue)
- LPM effect in BAMPS
  Florian Senzel (Tue)
- jet $R_{AA}$ and $v_2$ in LBT
  Yayun He (Thu)
- integrate jets in EPOS-HQ
  Iurii Karpenko (Thu)
- hadron & jet suppression and $v_2$ in JETSCAPE
  Chanwook Park (Thu)
The JETSCAPE philosophy

Multi-stage jet evolution in JETSCAPE

- Jet energy loss modules and their transition in JETSCAPE

Virtuality separation scale: $Q_0$

Switching between modules for parton by parton

Large- $Q (> Q_0)$

MATTER
Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)

Radiation dominated
Virtuality ordered splitting

Higher Twist Formalism

Large- $E$

LBT
Wang, Zhu(13), Luo, et al.(15,18)
Cao, et al.(16,17), He, et al.(18)

Scattering dominated
On-shell parton transport

Higher Twist Formalism

Small- $Q (< Q_0)$

MARTINI
Schenke, Gale, Jeon(09),
Park, Jeon, Gale(17, 18)

On-shell parton transport

AMY Formalism

Small- $E$

AdS/CFT
Chesler, Rajagopal(14, 15)
Pablos, et al.(15, 16, 17)

Diffusion into medium

$\mathcal{N} = 4$ super Yang-Mills
Systematic improvements of existing approaches

### Moving to higher precision

- Cancellation of IR singularities in medium: Yacine Mehtar-Tani (Tue)
- Definition of $\hat{q}$: Bin Wu (Tue)
- Baseline for $p_\perp$ imbalances: pQCD expansion + resummation: Shu-yi Wei (Tue)

### Others

- In-medium antenna with finite formation time: Víctor Vila (Tue)
- BDMPS quenching weights in expanding medium: Souvik Priyam Adhya (Tue)
- DGLV beyond soft gluon approximation: Bojana Balgojevic (Tue)
- Generalised higher twist approach: Yuang-Yuanyang Zhang (Thu)
- Distribution of partons scattering off pointlike objects: Yi Yin (Thu)
- $\hat{q}$ from lattice simulations: Amit Kumar (Thu)
Modified cancellation of IR divergences (slide from Yacine Mehtar-Tani)

NLO correction to the jet spectrum

Mismatch between real and virtual

$Q^{(1)}(p_T) = \bar{\alpha} \int_{\theta_c}^{R} \frac{d\theta}{\theta} \int_{(\hat{q}/\theta^4)^{1/3}}^{p_T} \frac{d\omega}{\omega} [Q^2_q(p_T) - 1] Q_{tot}(p_T)$

Gluon + quark energy loss $\gg$ Quark energy loss
Generalised Higher Twist (slide from Yuang-Yuang Zhang)

Radiative energy loss: assumptions

Approaches to radiative energy loss: BDMPS-Z, GLV, AMY, SCET, High Twist

- Scattering Center: Static or Dynamic?
  - Static: no energy transfer (BDMPS-Z, GLV)
  - Dynamic: both momentum and energy transfer

- Radiated Gluon: Soft or hard?
  - $z \rightarrow 0$ (BDMPS-Z, GLV, SCET)
  - $z$ finite

- Transverse momentum transfer: smaller or same order $l_\perp$?
  - $k_\perp \ll l_\perp$ (High Twist)
  - $k_\perp \sim l_\perp$
(Mostly) new ideas & approaches

- parton energy loss in unstable plasma  
  Sigtryggur Hauksson (Tue)
- vacuum like emissions in medium  
  Paul Caucal (Thu)
- calculate spectral function on lattice  
  Kirill Boguslavski (Thu)
- new jet function for small $R$ jets  
  Chathuranga Sirimanna (Thu)
Quark vs. gluon jet energy loss

Jet evolution (vacuum & medium)

- parton energy loss:
  - QCD: \( \frac{\Delta E^{(q)}}{\Delta E^{(g)}} = \frac{C_F}{C_A} = \frac{4}{9} \)
  - AdS/CFT: \( \frac{\Delta E^{(q)}}{\Delta E^{(g)}} = \left( \frac{C_F}{C_A} \right)^{1/3} \)

- jet energy loss: only out-of-cone radiation contributes
- MC study: energy loss ratio much closer to 1

Turbulent in-medium cascade

- chemistry of in-medium cascade
- at large \( x \) and strong quenching: most energy carried by quarks
Some personal thoughts

- jet quenching many-faceted and interesting
- but do we learn anything about the medium?
- something that can only be learned from jets:
  
  At which scale are quasi-particles resolved?
- scattering off quasi-particles: power-law tail to large angles
- is this observable?
- in jets/leading partons: difficult due to large fluctuations in vacuum part of fragmentation pattern
- medium response: additional source of fluctuations
Conclusions
See you at Hard Probes 2020!