Summary: Jets and High-\(p_T\)

Jana Bielcikova
(Nuclear Physics Institute of the CAS)
Models for medium response in a nutshell

Recoil
JEWEL
LBT
MARTINI
MATTER
JETSCAPE Framework
[MATTER + LBT/MARTINI]

Recoil + Hydro Res.
CoLBT-hydro
JETSCAPE Framework
[MATTER + LBT/MARTINI + CausalDiff + MUSIC]

Hydro Response
Coupled Jet-Fluid
EPOS3-HQ

Weakly-coupled ($> E_{med}$) ~ $E_{med}$ Strongly-coupled ($\leq E_{med}$)

Slide courtesy Y. Tachibana, Plenary Wed 9:00
The $R_{AA}$ ...
Hadron $R_{AA}$ at RHIC: U+U collisions

• $R_{AA}(p_T, N_{\text{part}})$ dependence qualitatively consistent between U+U and Au+Au
• Rich spectrum of meson species measured
• $K^*$, $\phi$ less suppressed than $\pi^0$, $\eta$ at lower $p_T$

Universal high $p_T$ suppression with $N_{\text{part}}$ for light and strange quark mesons → Jet fragmentation not modified (or modified equally).
Jet $R_{AA}$ measurements at LHC: going to large $R$

**ALICE:**
- low $p_T$ jets, moderate $R$

**ATLAS, CMS:**
- high $p_T$ jets, larger $R$

**CMS measured jet $R_{AA}$ in Pb+Pb at 5.02 TeV for large $R > 0.6$ in large background. Only modest increase, $R_{AA}$ never reaches 1.**

*ALICE, PRC 101, 034911 (2020)*
*ATLAS, PLB 790 (2019) 108*
Jet $R_{AA}$ calculations: there are many... not all listed here...

What new have we seen at HP2020?
Predictions for large R jets and di-jets

- Competition of effects results in a very mild evolution of $R_{AA}$ from small to large R
- QGP trough effect more pronounced at RHIC
- Jet suppression due to QGP trough is from the wake of the recoiling jet → new observable

**LHC**

- non-eq. + QPG ridge
- non-eq. + QPG trough

**RHIC**

- Hybrid strong/weak coupling

![Graphs showing predictions for LHC and RHIC](image-url)
Analytical calculation in collinear factorization (LO+LL with nPDF) with medium effects on resummation

Recovery of energy at large angles is non-perturbative and strongly affected by choice of phase space for quenching

$q_{\text{hat}}$: measure of energy lost + resolution parameter of the medium
Machine learning: lower jet $p_T$ and larger $R$?

**charged jets**

| ALICE Pb-Pb 5.02 TeV, 0-10% Charged jets, anti-$k_T$, $|\eta| < 0.9 - R$ |
| ML estimator trained on PYTHIA |
| $R = 0.4$ |
| $R = 0.6$ |

**full jets**

ML estimator trained on PYTHIA

**Aim of ML:** Improved precision and extended reach in $p_T$ and $R$ should help to constrain model predictions and allow for comparison with RHIC.

**ML method:** Haake, Loizides, PRC 99, 064904 (2019)

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**Caution:** Although jet-by-jet fluctuations are significantly narrowed, ML training affected by assumed fragmentation model (~10-40%). Need to include quenched MCs …

**Models:**
- JEWEL: JHEP 1707 (2017) 141
- SCET$_G$: PRD 80 (2009) 054022
- Hybrid Model: PRL 124 (2020) 052301
- LBT: PRC 99 (2019) 054911
Jet yield suppression consistent with inclusive hadron suppression in Au+Au and Cu+Au collisions at RHIC, behavior similar to the LHC.
The correlations … \( \pi^0/\gamma \)-hadron, \( h/\gamma \)+jet
New observable: $I_{AA}(\Delta \phi)$
look for modification of associated particle yields on away-side of pion trigger ("jet substructure level")

$p_T$ and angular dependent modification of away-side hadron yields measured

- high $p_T^{assoc}$: overall suppression
- mid $p_T^{assoc}$: suppression at jet core and enhancement at jet skirt
- low $p_T^{assoc}$: enhancement primarily at jet skirt

Increasing associated $p_T$
γ+jet and $\pi^0$+jet studies at RHIC

- γ does not interact strongly → a calibrated probe
- γ+jet data consistent with $\pi^0$+jet

Radius dependent $I_{AA}$ suppression observed:
→ $p_T$ behavior differs from models.
Jet radial profile: no significant in-medium broadening

PYTHIA 6 and PYTHIA 8 give different pictures
→ pp data needed (analysis ongoing)

Models:
**Jet-fluid**: Chang, Qin, *PRC* 94 (2016) 024902
**Vitev et. al**: Sievert, Vitev, Yoon, *PLB* 795 (2019) 502
Jet acoplanarity in Pb+Pb collisions

First measurement of fully corrected acoplanarity down to low $p_T$ recoil jets.

Recoil jet yield suppressed with respect to PYTHIA + indication of $\Delta \phi$ narrowing.

$\Delta \phi \sim \pi$: vacuum: broadening (Sudakov radiation) medium: interplay of multiple soft scattering (↑) and radiative corrections (↓)

$\Delta \phi \ll \pi$: large-angle deflection of hard partons off quasiparticles

Chen et al, PLB 773 (2017) 672
Gyulassy et al., arxiv:1808.03238
Zakharov, arxiv:2003.10182

D’Eramo, Rajagopal, Yin, JHEP 01 (2019) 172
Jet acoplanarity in small systems: jet quenching?

How to explore it?
Traditional $R_{AA}$: no, Glauber scaling undefined! → study acoplanarity instead

- High vs. low event activity spectra in p+Au suppressed, but acoplanarity minimally modified.
- Qualitatively reproduced by PYTHIA

High-multiplicity trigger suppresses events with one hard recoil jet and enhances multi-jet events …
Out-of-cone energy loss: RHIC vs LHC

PHENIX, PRC 87, 034911 (2013)

Inclusive $\pi^0$
$\Delta p_T = 2-3$ GeV/$c$

RHIC: various channels consistent ($\pi^0$, jet, trigger+jet)

In-medium energy loss smaller at RHIC than at the LHC.
Path-length dependence of energy loss:

- Positive jet $v_2(p_T) \sim 2-3\%$
- Increased asymmetry of dijet pairs vs pp collisions persists even at leading jet $p_T \sim 0.5\text{ TeV}$

**Observables studied:**
- Jet $v_2$
- Dijet momentum imbalance $x_J = p_{T1}/p_{T2}$

Jet $v_2$: tension with ALICE; higher precision data needed
Let us look closer at jets

jet shapes
jet fragmentation
jet substructure
jet charge …
Jet shapes at RHIC

Radial distribution of momentum of jet constituents

Low-$p_T$ (< 2 GeV) particles pushed toward larger radii in the out-of-plane direction relative to the in-plane direction.

Larger yields of low-$p_T$ particles observed in the out-of-plane direction → inline with in-medium path length dependence.
Almost no modification of the jet core in Pb+Pb relative to p+p, enhancement of particles at larger radii.

Coupled jet-fluid model captures features observed in data.

Jet shape ratio Pb+Pb/pp:
- Inclusive jets: non-monotonic function of radius
- \(\gamma\)-jets ratio increases monotonically with radius

Chang, Tachibana, Qin, PLB 801 (2020) 135181
Jet fragmentation …
Semi-inclusive jet fragmentation function at RHIC

First fully corrected results of semi-inclusive jet fragmentation functions at RHIC. Data agree well with PYTHIA8.

Possible tangential bias on jet selection by requiring high-$p_T$ trigger particle? → pp data measurement and analysis in more central events ongoing.
Jet fragmentation and substructure … the ATLAS way

A. Sickles, Wed 10:30
W. Zou, poster

ATLAS - CONF-2019-056

Significant modification of structure of jet fragments:
• qualitative change happens at $p_T \sim 4$ GeV
• most of the “extra” particles within the jet cone

Direct probe of the ability of medium to resolve parton fragments.
Jets with 1 subjet less quenched than multiple subjets.

$D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r dr} \frac{dN_{\text{ch}}(p_T, r)}{dp_T}$

$\Delta D(p_T, r) = D(p_T, r)_{\text{Pb+Pb}} - D(p_T, r)_{pp}$

$R_{D(p_T, r)} = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{pp}}$
Hybrid model: back reaction needed, but not sufficient. SCET$_G$ and CoLBT-hydro qualitatively describe the trend.

Excess of low $p_T$ particles, depletion at high $p_T$ in central collisions observed at the LHC. Similar trends observed at RHIC in $\gamma$-hadron correlations as well.
**γ-tagged jet fragmentation function**

**Comparison with CMS**

**Comparison with ATLAS**

Measured centrality dependent enhancement of soft hadrons (large $\xi$) mainly due to medium response.

The lost energy is redistributed into soft hadrons by multiple scattering, gluon radiation and medium excitation from jet.

*Note: In T. Luo’s talk are shown further jet substructure observables confirming importance of medium response to describe data at the LHC.*
Z-tagged fragmentation

- **SCET** with $g=2.0$ reasonable description of data
- Hybrid model with medium wake undershoots intermediate $p_T = 3-5$ GeV, discrepancy even more pronounced in $\Delta \phi$ distributions

Similarly as for $\gamma$-tagged correlations excess (depletion) of low (high) momentum particles measured

Need to improve medium response

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K. Tatar, Thu 11:55
J. Ouellette, Thu 13:30

SCET G PRD 93 (2016) 074030,
PRD 101 (2020) 076020
Hybrid JHEP 1410 (2014) 019
Wake of jets in linearized hydrodynamics

Linearized hydro provides improved description of medium back-reaction

→ harder $p_T$ spectrum of back-reaction particles
→ beaming of spectrum along jet azimuthal direction
→ wider rapidity distribution
→ larger fraction of semi-hard particles recovered around the jet
→ slower recovery of jet energy with $R$
Medium modification of jet and subjet fragmentation

pQCD based on factorized picture: vacuum-like and medium-induced emissions (BDMPS-Z)

medium: fixed brick of size L
Jet $R_{AA}$ data described reasonably well.

Modification of jet fragmentation function, qualitatively agrees with the LHC data, but it is not IRC safe observable.

New observable:
Study modification of subjet FF which is IRC safe

$D_{\text{sub}}(z) = 1/N_{\text{jets}} \frac{dN_{\text{sub}}}{dz}$
Let us groom the jets …

removing soft, wide-angle radiation from jets
SoftDrop grooming in Pb+Pb collisions

$z_g$ : sensitive to modification of QCD splitting function, (in)coherent $E_{\text{loss}}$

$\theta_g$ : medium-induced gluon radiation broadens jets, but $E_{\text{loss}}$ narrows them, q-g fractions, path-length effects …

First fully corrected measurement of $\theta_g$ and $z_g$ in A+A collisions:
- no significant modification of $z_g$ distribution
- modification of $\theta_g \rightarrow$ hint of collimation

Alternative groomers? Which limitations they have?
Jet grooming at RHIC

What is origin of the $R_{d+Au}$ enhancement? Jet quenching in $d+Au$? Explore jet mass ...

First inclusive p+p and p+Au (groomed) jet mass measurements at RHIC:
- No CNM effects on (groomed) jet mass ...

Other groomed observables explored:
$z_g$ and $R_g$ p+p 200 GeV  \( \text{STAR: arXiv: 2003.02114} \)
Au+Au 200 GeV  \( \text{poster D. Nemes} \)
Jet substructure: dynamical grooming

SoftDrop has flexibility to select splittings from different kinematic regions, but how to choose the parameters?

More aggressive grooming with decreasing $a$

- Removal of soft radiation sensitive to total color charge
- Auto-generated grooming condition on a jet-by-jet basis
- $k_T$Drop is remarkably robust to hadronization.

$\theta_2 > \theta_1 > \theta_0$

Physical interpretation:
- $a=2$: TimeDrop
- $a=1$: $k_T$Drop
- $a=0$: zDrop


Mehtar-Tani, Soto-Ontoso, Tywoniuk:
PRD 101 (2020) 034004

Jet substructure in p+p from ALICE

First measurement of jet angularities and dynamically groomed distributions $\theta_g, z_g$

PyTHIA provides reasonable description of measured distributions.

Test pQCD by systematic measurements for multiple $R, \beta$. 
Jet charge …
Different flavor jet charges remain distinct in HI collisions.

\[ Q_{\kappa, \text{jet}} = \frac{1}{(p_T^{\text{jet}})^{\kappa}} \sum_{h \text{ in jet}} Q_h (p_T^h)^{\kappa} \]

- \( Q_{\kappa, \text{jet}} \) is the jet charge with the parameter \( \kappa \).
- \( p_T^{\text{jet}} \) is the transverse momentum of the jet.
- \( Q_h (p_T^h)^{\kappa} \) is the charge of the \( h \) flavor parton with transverse momentum \( p_T^h \).

R. Field et al. (1978)

- in-medium modification jet flavor dependent
- separation important to advance understanding of medium effects

large \( p_T \): isospin effects dominate
\( p_T < 200 \text{ GeV} \): effects of in-medium parton showers

Proposed measurement:
charge of individual jet flavors
First jet charge measurements in HI collisions:
- no significant modification observed in the jet charge width (contrary to PYQUEN)
- quark and gluon-like fractions from template fitting centrality independent and in agreement with pp data

BUT: current analysis relies on PYTHIA template fitting

Going beyond templates → toward data driven measurement of q and g jet modification

pp: Metodiev, Thaler, PRL 120 (2018) 24, 241602
Komiske, Metodiev, Thaler, JHEP 11 (2018) 059
Heavy-flavor jet substructure in p+p at the LHC

V. Kucera: Wed 13:05  
X. Wang: Wed 13:45

**c-jets:**  
D⁰-tagged jets grooming via iterative declustering

**n<sub>SD</sub>:** number of hard splittings in jet fragmentation

Less hard splittings for D⁰-tagged jets than for inclusive  
→ harder c-quark fragmentation

First direct measurement of the dead cone!  
→ Suppression of radiation toward small angles

**b-jet shape measurements:**  
data provide excellent opportunity to improve modeling of b-jet production and fragmentation

*CMS, arXiv: 2005.14219*

More on heavy-flavor in Roberta Arnaldi’s talk
Jet quenching in the hadron gas

For reshuffling jet shapes the full hadron gas can be approximated with a pion gas and constant $\sigma = 100\text{ mb}$.

Reasonable to neglect $E_{\text{loss}}$ in the hadronic stage for single-particle or even jet $R_{AA}$, but for substructure observables and disentangling medium effects, the hadronic phase might be important (up to particle $p_T = 8-10\text{ GeV}$)!

Dorau, Rose, Pablos, Elfner, PRC 101 (2020) 3, 035208
• Modular framework, allows for study of different physics concepts in a consistent environment.
• Applicable to full range of HI phenomenology.
• Bayesian analysis enables systematic model-to-data comparison

**Hydrodynamics**
- Event-by-event VISHNew Hydro (2+1D)
- TRENTO (2+1D) initial conditions with free streaming

**Jet evolution**
- MATTER + LBT
- Switching virtuality between MATTER and LBT shower, $Q_0 = 1, 2, 3$ GeV
- $\hat{q} \propto \alpha_s^2 T^3 \ln \left( \frac{cE}{\alpha_s T} \right)$ based on HTL where $\alpha_s = 0.25$

**Medium response**
- Recoils: Kinetic theory based approach
- Medium constituents kicked out by jet propagate in jet shower
- Energy/momentum from medium subtracted from jet signals

*slide courtesy C. Park*

Double ratio of jet $R_{AA}$ relative to $R=0.2$ close to unity well reproduced, as well as jet structure, $v_2$ ...
Instead of summarizing the summary …

Summary and Outlook

Partonic energy loss in nuclear collisions at RHIC is firmly established

• broadly consistent with pQCD-based energy loss models
• present measurements supply significant lower bound to initial color charge density

But it promises much more: detailed study of interplay between fragmentation and thermalization may supply new and unique probes of the dynamics

• This is hard, we are only at the beginning
• Intermediate $p_T \sim 5$-10 GeV/c appears to provide a laboratory in which we can isolate the various physics
Instead of summarizing the summary …

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  - Intermediate $p_T \sim 5-10$ GeV/c appears to provide a laboratory in which we can isolate the various physics

Yes, still true. But we made a great progress!

We have a large reach in $p_T$ now, but the “intermediate” $p_T$ will probably teach us most …

1st Hard Probes conference (2004) "Status and perspectives of jets and high-$p_T$ physics" (given by P. Jacobs)

Thank you for your attention