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Deep learning jet modifications in heavy-ion collisions

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with Daniel Pablos and Konrad Tywoniuk

Yi-Lun Du



UNIVERSITY OF BERGEN

Outline

1 Motivation

2 Deep learning jet energy loss

3 Application

- Sensitivity of jet observables to in-medium modification
- Jet tomography

4 Conclusion and outlook



Jets in the medium



J. Brewer, HP'20

- Quark-gluon plasma (QGP) created in heavy ion collision: deconfined phase, hot dense medium
- Jets, collimated sprays of energetic particles, serving as hard probe to medium properties
- Jets are quenched and modified in the medium via parton energy loss



Jet substructures

 Detector as camera: positions, energies of particles

- All jet constituents are reclustered in angular ordering.
- SoftDrop: find the first *hard* splitting between two subjets satisfying $z_g > z_{cut}\theta^{\beta}$ with momentum sharing z_g and angle of branching R_g .



Jet modifications: ambiguous interpretations



Ratio of jet observables distr. between medium and vacuum, BOTH with $p_T^{jet} > p_T^{cut}$ ■ Interplay: jet substructures, e.g., *R_g*, could

- be modified during the passage through the medium and/or
- affect the amount of jet energy loss and then this jet doesn't pass the p_T cut in the selection, i.e., selection bias.
- Jets produce emissions with smaller R_g in medium than in vacuum: presumes medium scale dominates
- Jets with larger R_g in vacuum are more suppressed in medium: presumes vacuum scale dominates
- Can we disentangle these two effects with knowledge of the degree of quenching for eac individual measured jets?

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Energy loss ratio



Hybrid model



- PYTHIA8 down to hadronization scale
- Strongly coupled energy loss at every stage
- Hadrons from the hydro. wake (medium response)

Casalderrey-Solana, Gulhan, Milhano, Daniel Pablos, Rajagopal JHEP '15,'16,'17

- Vacuum jets using $\hat{p}_{T,\min} = 50$ GeV, with oversampling power p_T^4 .
- PbPb collisions in 0-5% centrality at $\sqrt{s} = 5.02$ ATeV.
- Reconstructed jets with anti- k_T , R = 0.4, required to be $|\eta| < 2$ and $p_T^{\text{jet}} > 100 \,\text{GeV}$.
- ~ 250,000 jets. 80% for training and 20% for validation.



CNN Prediction & Interpretability



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Jet selections

Study jet observables for jets that belong to 2 different quenching classes:

- Unquenched class: $\chi_{jh} > 0.9$.
- Quenched class: $\chi_{jh} < 0.9$.
- pp jets: p_T > 200 GeV
- PbPb jets:
 - − Final Energy Selection (FES): impose p_T cut on final energy $p_T > 200 \text{ GeV} \rightarrow \text{Steeply falling energy}$ loss dist. Biased by little quenched samples!
 - − Initial Energy Selection (IES): impose p_T cut on initial energy via χ_{jh} , $p_T/\chi_{jh} > 200$ GeV & $p_T > 100$ GeV → More support of fairly quenched jets in the quenched class. More distinguishable!





Jet radius, R_g

 R_g ratio between PbPb and pp jets

■ FES: Selection bias towards jets with smaller *R_g*, originated by *p_T* cut.

IES:

- Unquenched class: still biased due to χ_{jh} cut: to belong to this class, a jet had better to be with smaller R_g , compared with all pp jets.
- Quenched class presents features related to energy loss, compared with unquenched class: jet quenching leads to enhancement of large R_g - creation of a new, semi-hard branch.





Y.-L. Du, D. Pablos, K. Tywoniuk, JHEP03(2021)206

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Applications: creation points & orientation





10/17

- IES "removes" final state interactions (selection bias), since we record "all" jets.
- IES provides access to the genuine jet creation point (path length) distribution and possible initial-state jet anisotropy.

Y.-L. Du, D. Pablos, K. Tywoniuk, arXiv: 2106.11271

 $V_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

Applications: Jet tomography, length VS χ_{jh}





Conclusion and outlook

- CNN can extract energy loss jet-by-jet from jet image with good performance
- Procedure generalisable to many jet quenching models
- Jet shape contains significant predictive power: angular distribution of soft particles
- Mitigate selection bias and reveal medium effects on various jet observables
- Open opportunity to make tomographic study

- Generalizability to other MC quenching models?
- Applicability to more realistic environment: fluctuating background?
- Better performance from other state-of-the-art neural networks?
- Extract traversed length with better precision?
- Unfold jet *initial* properties apart from jet energy?



Backup: Prediction performance with FCNN

Input (size)	Output	Network	Loss
FF (10)	Xjh	FCNN	0.0058
Jet shape (8)	Xjh	FCNN	0.0033
FF, jet shape (18)	Xjh	FCNN	0.0032
FF, jet shape, features (25)	Xjh	FCNN	0.0028
Jet image & FF, jet shape, features (25)	Xjh	API: CNN&FCNN	0.0028

- Jet shape outperforms jet FF.
- Motivates construction from jet shape by 17-parameter fitting:
 - Still a bit worse than CNN
- Jet observables recover the performance by jet image with equivalent predictive power: interpretability!



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Backup: Groomed momentum sharing fraction, z_g

 z_g ratio between PbPb and pp jets

 FES: No selection bias observed. Scale of emission isn't strongly dependent on splitting fraction z_g.

IES.

 Quenched class presents features related to energy loss, compared with unquenched class: jet quenching leads to enhancement of smaller z_g subjets.





Backup: Soft Drop multiplicity, n_{SD}

 n_{SD} ratio between PbPb and pp jets

■ FES: Selection bias towards jets with fewer *n_{SD}*, originated by *p_T* cut.

IES:

- Unquenched class: still biased due to χ_{jh} cut: to belong to this class, a jet had better to be with fewer n_{SD} , compared with all pp jets.
- Quenched class presents features related to energy loss, compared with unquenched class: jet quenching leads to enhancement of large n_{SD}.





Backup: Jet shape & FF with FES & IES



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Backup: Jet tomography with χ_{jh} & v_2

- $v_2 = \frac{\rho_x^2 \rho_y^2}{\rho_x^2 + \rho_y^2}$
- Top row: In-plane jets ($v_2 > 0$) going left ($p_x < 0$) and right ($p_x > 0$)
- Bottom row: Out-of-plane jets ($v_2 < 0$) going up ($p_y > 0$) and down ($p_y < 0$)
- To get very quenched, jets have to travel longer in medium. So v₂ & p_{x,y} are helpful for jet tomography.



Creation points density for centrality 30-40%, $R = 0.4 \odot \sqrt{s_{HN}} = 5.02$ TeV, FES, $p_T > 100$ GeV