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Deep learning jet modifications in heavy-ion collisions

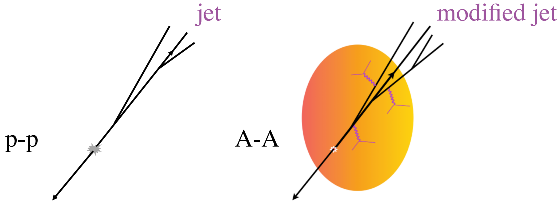
JHEP03(2021)206, PRL 128, 012301 (2022) & arXiv: 2112.00681

with Daniel Pablos and Konrad Tywoniuk

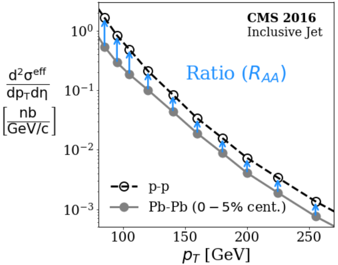
Yi-Lun Du

Outline

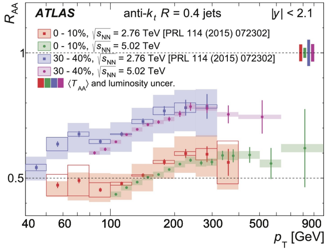
Jets in the medium



J. Brewer, HP’20



$$R_{AA} = \frac{\text{Spectrum in AA}}{\text{Spectrum in pp}}$$

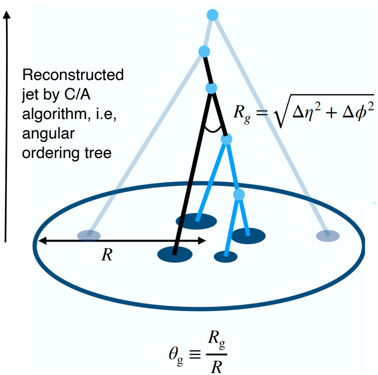


ATLAS collaboration PLB 790 (2019) 108

- Quark-gluon plasma (QGP) in heavy-ion collisions: deconfined quarks & gluons, strongly-coupled medium
- Jets, collimated sprays of energetic particles, serving as hard probe to medium properties
- Jets are quenched in the medium via parton energy loss
- Jet modifications: ratio of jet observables distr. between medium and vacuum, with $p_T^{\text{jet}} > p_T^{\text{cut}}$

Jet substructures

$$z_g \equiv \frac{p_{\rm T,sublead}}{p_{\rm T,lead} + p_{\rm T,sublead}}$$

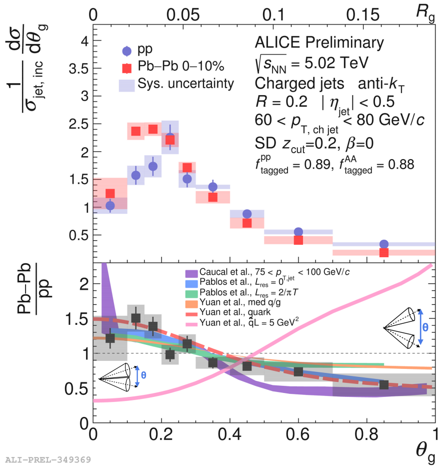


Soft Drop condition: $z_g > z_{\rm cut}(\frac{R_g}{R})^\beta$

J. Mulligan, HP'20

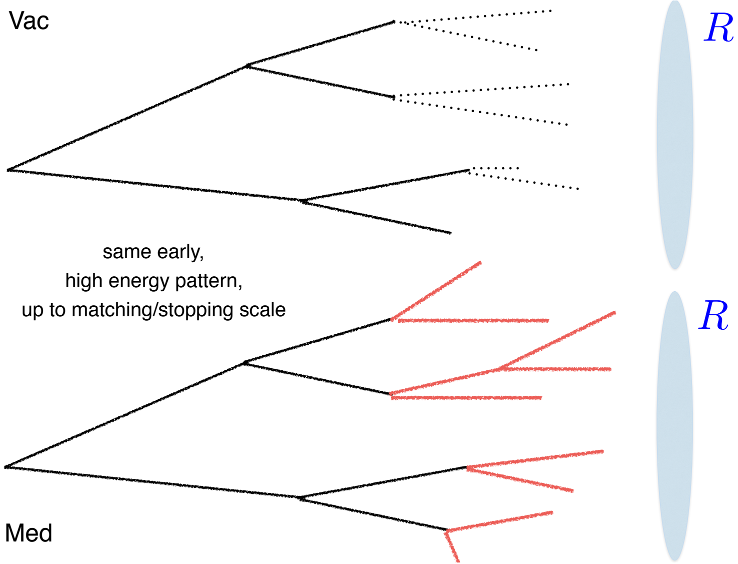
- Detector as camera: positions, energies of particles
- All jet constituents are reclustered with Cambridge/Aachen (C/A) algorithm in angular ordering.
- SoftDrop: find the first *hard* splitting between two subjets satisfying $z_g > z_{\rm cut}\theta^\beta$ with momentum sharing z_g and angle of branching R_g.

Jet modifications: ambiguous interpretations



- 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 don't pass the p_T cut of the distribution, i.e., selection bias.
- Jets in medium produce emissions with smaller R_g 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 each individual measured jets?

Define the generalizable energy loss ratio



$$E_i$$

$$\chi_{jh} \equiv \frac{E_f^h}{E_i^h}$$

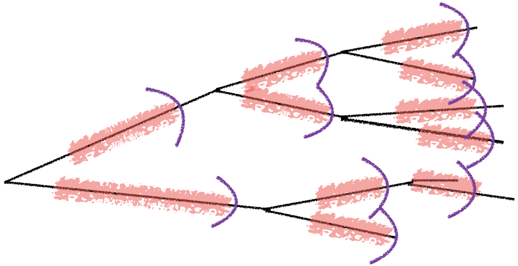
$$E_f$$

Vacuum-like emission

Hypothetical vacuum-like emission

Medium induced emission

Strong/weak hybrid model

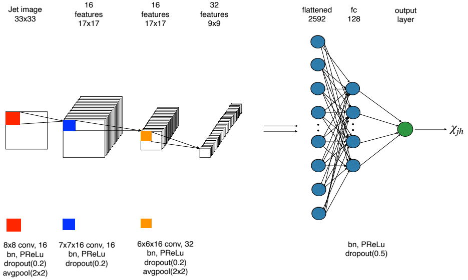


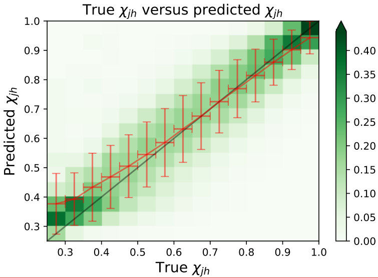
- PYTHIA8 down to hadronization scale
- Strongly coupled energy loss at every stage
- Hadrons from the hydro. wake (medium response)

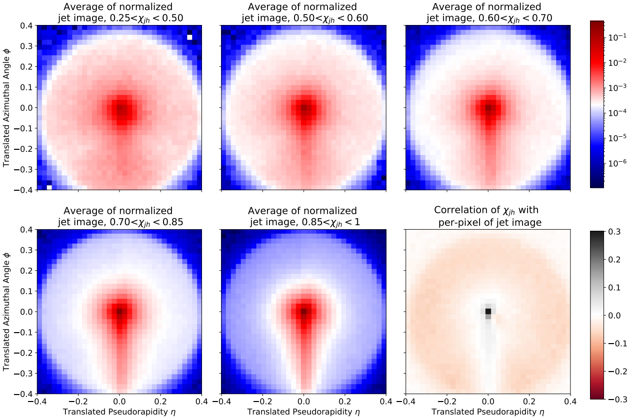
Casalderrey-Solana, Gulhan, Milhano, Daniel Pablos, Rajagopal JHEP '15,'16,'17

- 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 $p_T^{\rm jet} > 100\,\mathrm{GeV}$.
- $\sim$ 250,000 jets. 80% for training and 20% for validation.

CNN Prediction & Interpretability







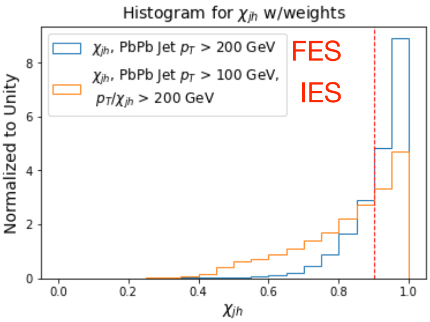
- Jet quenching increases the number of soft particles at large angles
- Jet shape can capture the main feature

Jet selections

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

- Unquenched class: $\chi_{jh} > 0.9$.
- Quenched class: $\chi_{jh} < 0.9$.

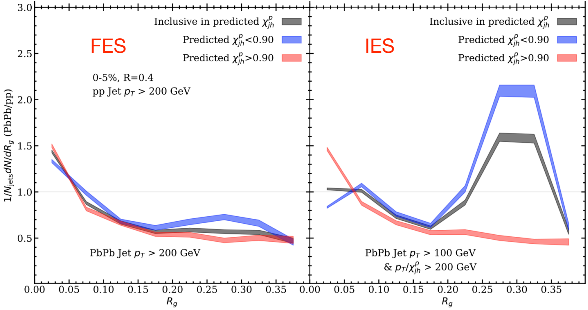
- pp jets: $p_T > 200$ GeV
- PbPb jets:
  - Final Energy Selection (FES): impose p_T cut on final energy $p_T > 200$ GeV $\rightarrow$ Steeply falling energy loss dist. Biased by little quenched samples!
  - Initial Energy Selection (IES): impose p_T cut on *initial energy* via χ_{jh}, $p_T/\chi_{jh}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



Jet radius, R_g

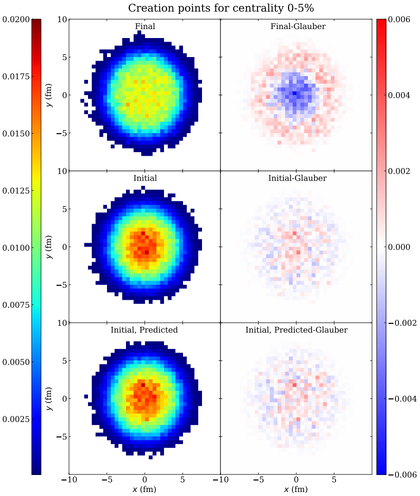
R_g ratio between PbPb and pp jets

- 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.

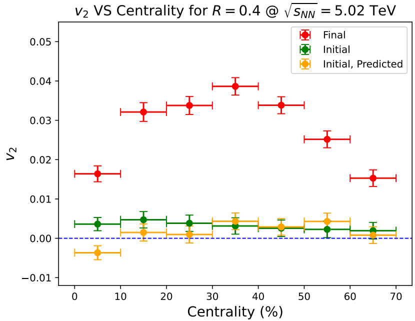


Y.-L. Du, D. Pablos, K. Tywoniuk, JHEP03(2021)206

Applications: creation points & orientation



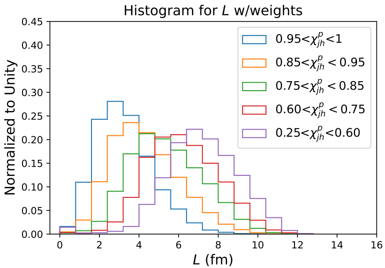
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

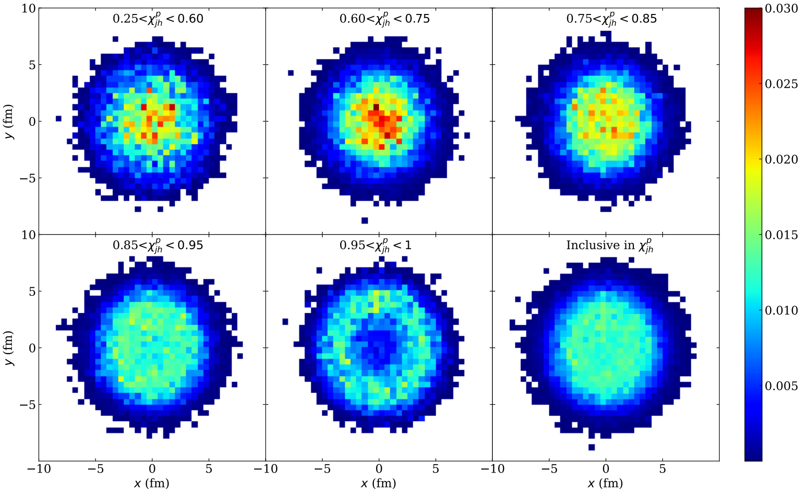


- IES "removes" final state interactions (selection bias), since we record "all" jets.
- IES provides access to the genuine jet creation point (path length) distribution and possible initial-state jet anisotropy.

Y.-L. Du, D. Pablos, K. Tywoniuk, *Phys. Rev. Lett. 128, 012301 (2022)*

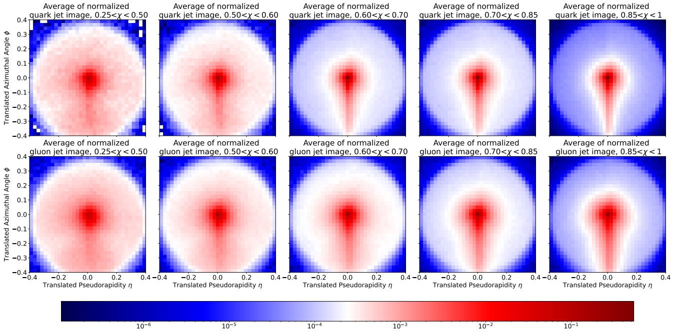
Applications: Jet tomography, length VS χ_{jh}

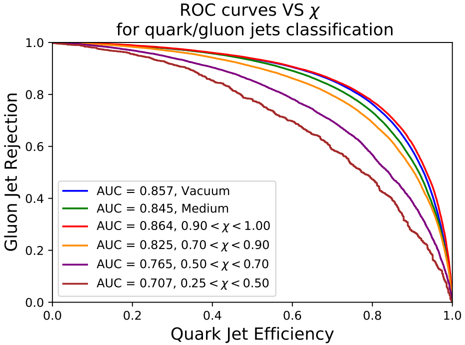




Due to the strong correlation between L and χ_{jh}, selecting jets with different χ_{jh} will naturally select jets that traversed different L.
$\rightarrow$ Great potential to make tomographic application!

Classification of quark and gluon jets





- Same qualitative characteristics: more soft particles at large angles within the jet cone
- The quenching smears the difference of substructures of quark/gluon jets
- The greater the energy loss is, the more difficult the classification becomes

Yi-Lun Du, D. Pablos, K. Tywoniuk, arXiv: 2112.00681

Conclusion and outlook

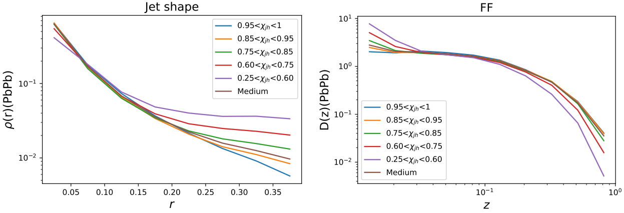
- CNN can extract energy loss jet-by-jet from jet image with good performance
- Procedure generalisable to many jet quenching models
- Jet shape contains significant predictive power: angular distribution of soft particles
- Mitigate selection bias and reveal medium effects on various jet observables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

- 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?

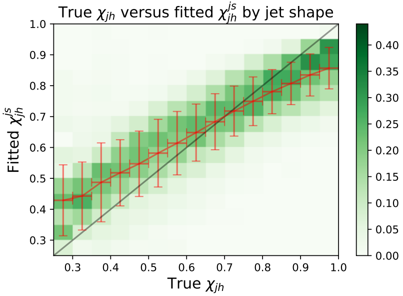
Thanks for your attention!

Backup: Prediction performance with FCNN

Input (size)	Output	Network	Loss
FF (10)	χ_{jh}	FCNN	0.0058
Jet shape (8)	χ_{jh}	FCNN	0.0033
FF, jet shape (18)	χ_{jh}	FCNN	0.0032
FF, jet shape, features (25)	χ_{jh}	FCNN	0.0028
Jet image & FF, jet shape, features (25)	χ_{jh}	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!

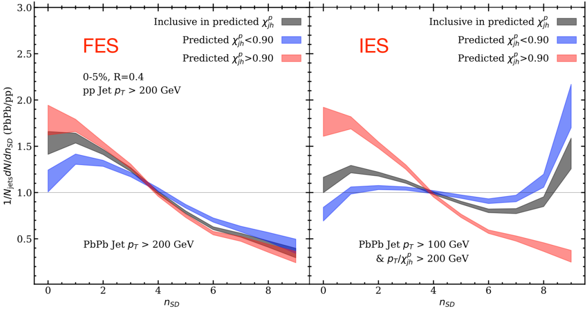


$$\chi_{jh}^{js} = \sum_i \left(\frac{p_{Ti}}{p_T}\right)^{\alpha_i} r_i^{\beta_i} + \gamma$$

Backup: Soft Drop multiplicity, n_{SD}

n_{SD} ratio between PbPb and pp jets

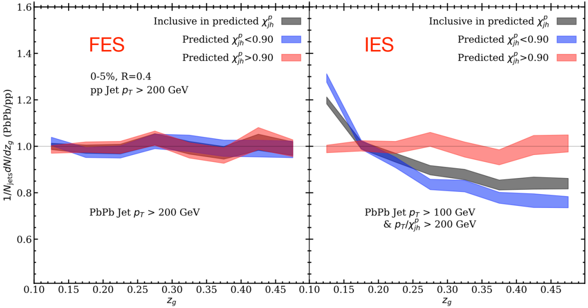
- FES: Selection bias towards jets with fewer n_{SD}, originated by p_T cut.
- IES:
  - Unquenched class: still biased due to χ_{jh} cut: to belong to this class, a jet had better to be with fewer n_{SD}, compared with all pp jets.
  - Quenched class presents features related to energy loss, compared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



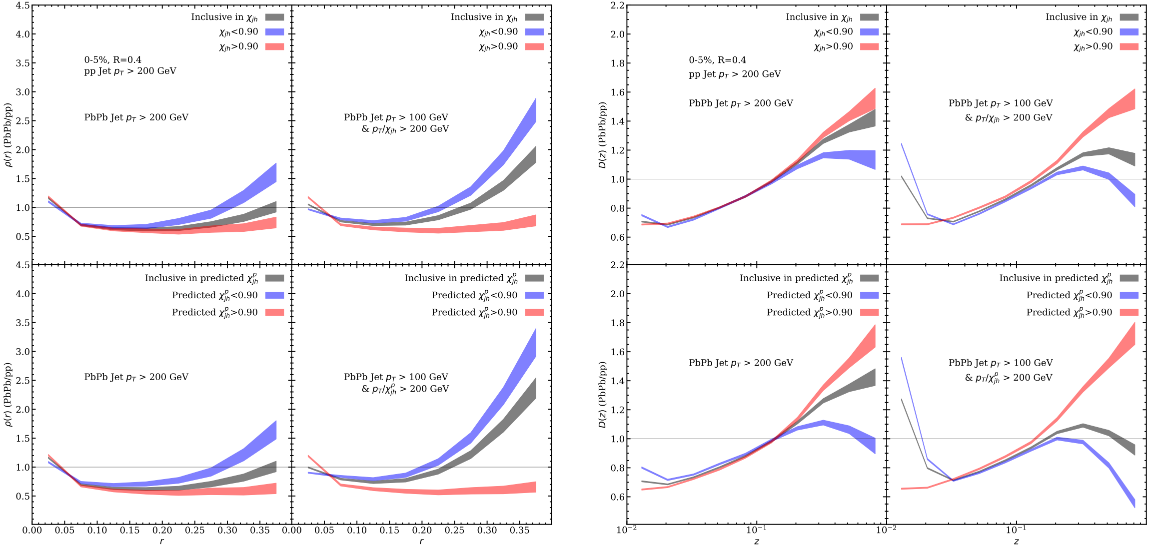
Backup: Groomed momentum sharing fraction, z_g

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: Jet shape & FF with FES & IES



Backup: Jet tomography with χ_{jh} & v_2

- $v_2 = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}$
- 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 v_2 & $p_{x,y}$ are helpful for jet tomography.