Jets & particle correlations in heavy-ion collisions

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Jet quenching @ RHIC

High $p_T$ hadron spectra in central AA suppressed by 5x
No comparable suppression in peripheral AA or pA

Interpreted as parton energy loss in quark-gluon plasma
Collective flow @ RHIC

- Collectivity measured with particle correlations
- Elliptic flow ($v_2$) measures how well initial asymmetry in non-central AA collisions propagates to final-state particles

Heinz & Snellings
STAR, PRC 72 (2005) 014904

- Flow measurements successfully described by hydrodynamics
- Surprisingly close to the ideal case, i.e., viscous corrections are small
- Shear viscosity / entropy density close to lower bound of $1/4\pi$ from AdS / CFT
Jets @ the LHC
ca. 2010

The large collision energy and hermetic detectors of the LHC enabled full reconstruction of jets in heavy-ion collisions for the first time:

- Removes sensitivity to non-perturbative hadronization effects
- Enables new observables, e.g., internal structure of jets
Charged particle $R_{AA}$

- Extended to $p_T > 100$ GeV → adding discrimination power btwn models
- Whereas flat @ RHIC, now seen to slowly rise, nearly to unity
Jet $R_{AA}$ for jets rises slowly, then remarkably flat out to $\approx 1$ TeV!

- Quenching independent of cone size, up to $R=0.4$ (except @ low $p_T$) 
  $\rightarrow$ quenched energy transferred to large angle (see also missing $p_T$)
- How to reconcile with charged hadrons? Is there an interplay between the jet fragmentation pattern and the parton energy loss?
Dijet imbalance

- Additional imbalance expected based on path-length difference between leading dijets
- Imbalance persists to largest $p_T$ measured

![Graph showing dijet imbalance](image-url)
Origin of dijet imbalance

- Surprisingly, in JEWEL*, imbalance not generated by path-length difference
- Rather, driven by dependence of quenching on jet fragmentation pattern
  → For showers w/ more soft partons, more energy is pushed outside of the jet

\[ A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

“Origins of the dijet asymmetry in heavy ion collisions”, Milhano & Zapp, EPJC 76 (2016) 288

*JEWEL: PYTHIA-based generator that incorporates energy loss into parton shower model
Unfolded dijet $p_T$ imbalance

- Dijet results recently unfolded for experimental effects
- Show a pronounced feature that diminishes with increasing $p_T$
- Not yet clear whether models will be able to reproduce this trend
Jet $R_{AA}$ vs. rapidity

- $R_{AA}$ flat vs. rapidity, except at largest $p_T$

- With increasing $y$ expect:
  - Steeper spectral slope
  - Larger quark/gluon ratio

... which should push $R_{AA}$ in opposite directions
Jet fragmentation

- Intra-jet fragmentation function: hadron w.r.t. reconstructed jet
- Ratio of central PbPb to pp shows
  - Excess at low $z$
  - Depletion at intermediate $z$
  - Excess again at large $z$

$ATLAS$, arXiv:1702.00674

$R_{Q/\pi} = \frac{p_T^{\text{hadron}}}{p_T^{\text{jet}}}$

$z = \frac{p_T^{\text{hadron}}}{p_T^{\text{jet}}}$
Quark vs. gluon energy loss

- Naively, gluon/quark radiative energy loss: $9/4$
- One model explains both high & medium $z$ fragmentation & jet $R_{AA}$ vs. $y$, w/ only flavor dependence of energy loss
- In this picture, fragmentation dependent quenching related to the initiating parton, rather than subleading shower partons
Jet mass

- Jet mass sensitive to the virtuality of the initiating parton
- Quenching expected to induce additional radiation, increasing mass

Results consistent w/ PYTHIA… a model with no quenching!
→ Core of jet with R=0.4, may simply not be significantly modified
- Q-PYTHIA: quenching modeled as enhanced parton splitting, overestimates effect (update expected soon)
- JEWEL shows a strong sensitivity to how medium recoil is modeled
Substructure: a new frontier

- Methods developed to distinguish boosted objects from QCD jets
- Idea: Run jet clustering in reverse to isolate the hardest splittings

\[ p_T \text{ fraction of subleading branch:} \]

\[ z_g \equiv \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \]

- For vacuum case (e.g., pp): directly related to Altarelli-Parisi splitting
- For quenching jets: sensitive to coherence between nearby partons
- CMS measures down to minimum opening angle of \( \theta_g = 0.1 \)
- Requires grooming*, a procedure to remove soft radiation and uncorrelated background

* CMS using “Soft-drop” Larkowski et al., JHEP 1405 (2014) 146
Groomed momentum fraction

- Relatively fewer symmetric subjets w/ increasing centrality
- Effect disappears in peripheral & at high $p_T$ (not shown)
- Several explanations on the market, premature to conclude this is coherence breaking at low $p_T$
Collectivity @ the LHC: small systems

- “Ridge” = long-range rapidity correlation → must arise @ early time
- Shows up even in small systems given high enough multiplicity
(De)composition of the ridge

- Flow coeff’s $v_n$ from Fourier analysis
- At the outset, large $v_2$ expected from almond shape of overlap region
- Later, fluctuations understood to generate higher order $v_n$ terms, e.g., triangular flow ($v_3$)
- Ridge arises from coherent sum of $v_n$, i.e., corresponds to hydrodynamic flow

Alver & Roland, PRC 81 (2010) 054905

ATLAS, PRC 86 (2012) 014907
Mapping initial state fluctuations

Fourier harmonics from long-range correlations reflect fluctuations of the initial state of dense QCD matter before hydrodynamic expansion.

Power spectrum of the cosmic microwave background reflect fluctuations in the density of matter in the early universe before inflation.
Multiparticle correlations

Two-particle correlations suffer from residual “non-flow” effects (e.g., from jets). More robust (but statistically demanding) are correlations among many particles.

Common pattern emerges for all collision systems for multiplicity $>\sim 100$. Collectivity apparently universal, seemingly arising from a fluctuations even at the scale of the proton.
Maniplulating geometry @ RHIC

Helium 3 collided with gold to exploit intrinsic triangular geometry.

Hydrodynamics generally describes $v_2$ and $v_3$ in central He3+Au data.

However, relatively large sensitivity to initial state and pre-equilibrium dynamics.

Nagle et al., PRL 113 (2014), 112301

He3 + Au

PHENIX, PRL 115 (2015), 14230
Flow & non-flow in pp

Flow extraction in pp is highly sensitive to event classification and residual non-flow.

Collective flow signal only if $\nu_2\{4\} = 4\sqrt{-c_2\{4\}} < 0$

- Emerging consensus: High multiplicity pp collisions do exhibit collectivity
- Still debated:
  - Is hydrodynamics a valid description of small systems?
  - Can collectivity arise purely from initial state fluctuations?
- In any case, this is “new physics” emerging from high density QCD
If collective effects are observed in small systems, do jets also show effects from dense QCD?
No suppression as would be expected from jet quenching
Rather, enhancement due to nuclear effects on the parton distributions
How can these nPDF effects be measured with precision at the LHC?
Dijets in pA

- Dijets correlated to parton kinematics, for leading order $2 \rightarrow 2$ scattering
  \[ \eta_{\text{dijet}} = (\eta_1 + \eta_2)/2 \propto \log(x_p / x_A) \]
  \[ p_{T,\text{dijet}} = (p_{T,1} + p_{T,2})/2 \propto Q \]

- Nuclear effects result in (tiny!) shift in $\eta$, but measurable w/ self-normalization

- Dijets @ LHC sample gluon shadowing, anti-shadowing and EMC regimes
Despite percent level deviations, significant nuclear effects observed
Moreover, discrimination between various global fit analysis
Inclusion into nPDF fit

“EPPS16: Nuclear parton distributions with LHC data”
Eskola et al., EPJC 77 (2017) 163

Gluon nuclear modification similar to quarks (from ν-nucleus DIS)

→ Supports collinear factorization and process independent nPDFs
→ Best constraints so far on the high-x nuclear gluon distribution
Collectivity only clearly pronounced in light systems in high multiplicity events

What about jets in high activity events?

*Activity measured with forward calorimeter on Pb-going side

Suppression at high $p_T$ in high activity pA
Enhancement at high $p_T$ in low activity pA?
Projectile scaling of jets

- Effect stronger in proton-going direction
- Goes away on nucleus-going side

Scaling observed with $E \approx p_T \times \cosh y$, which is $\propto$ Bjorken $x$ from the proton

A possible explanation:
The more energy taken by jet, the less available at forward rapidity?
Dijet-forward energy correlation

- Dijets in pp: anti-correlation between jets and forward energy, as would be expected from momentum conservation
- Under-predicted by standard event generators

ATLAS, PLB 756 (2016) 10
Dijet-forward energy correlation

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\[ x_{\text{proj}} = \frac{p_T^{\text{avg}}(e^{+\eta_1} + e^{+\eta_2})}{\sqrt{s}}, \]
\[ x_{\text{targ}} = \frac{p_T^{\text{avg}}(e^{-\eta_1} + e^{-\eta_2})}{\sqrt{s}}. \]

However, correlation only between dijets and same-side forward energy
- NOT between “projectile”-side jet and opposite-side “target” energy as in pA
- One possibility: Due to proton size fluctuations, high x protons have a smaller cross-section for interacting with the nucleus (could explain the EMC effect)

Alvioli et al., PRC 93, 011902 (2016)
Conclusions

Jets and correlations in pp, pA & AA are bringing new insight into QCD in the high density regime

- Measurements of jet quenching increasingly precise;
- Internal structure of quenched jets sensitive to e-loss mechanism
- Successful description of collectivity in terms of hydrodynamics

- No sign yet of jet quenching, but best constraints so far on the nuclear gluon distribution & novel effects related to “centrality”
- Evidence indicating collectivity even in systems as small as pp, precise nature of fluctuating initial state still to be elucidated
A parting thought:

In contrast to the high-energy physicist, for the heavy-ion physicist, is the simple case, is more complicated case, and for we are only scratching the surface. Emergent QCD phenomena are a fertile area of progress in systems large & small!
Backup
Dijet imbalance in pA?

- No anomalous imbalance observed in pA
- Independent of event activity at forward rapidity
Centrality in small systems

Activity decorrelated across event \( \rightarrow \) hence also to impact parameter

Observed collective effects in pA & pp tied to mid-rapidity multiplicity
\( \rightarrow \) so far no way to tune multiplicity without biasing jet production
Boson-jet correlations

EW bosons do not interact strongly w/ the QGP
→ proxy for recoiling parton before energy loss

- Precision quenching measurements for upcoming high luminosity data
- Requires advanced generators for vacuum physics (e.g., NLO + parton shower)
as well as for parton energy loss models (exclusive final states, recoil, etc),possibly simultaneously.
The antenna problem

pQCD energy loss calculations consider successive gluon emissions, but not how color coherence of parton shower is modified by QGP

Test configuration: q-qbar antenna

For separation $r_T$ larger than coherence length $\Lambda_{med}$, partons radiate independently

Otherwise acts as single emitter

$\Lambda_{med}$ inversely proportional to $(\text{scattering power} \times \text{pathlength})^2$

How can we access the antenna configuration experimentally?

“A new picture of jet quenching dictated by color coherence”
Casalderry-Solana, et al., PLB 725 (2013) 357
$p_T$ dependence of groomed momentum fraction

CMS-PAS-HIN-16-006
z_g interpretation

A number of models reproduce the general trend observed in data e.g., JEWEL: Nearby splitting promoted over min z_g cut by jet-medium interaction

Complementary information being pursued: jet mass, n-subjettiness, etc.