Often stated goal of jet quenching studies is to use jets to probe the structure of the QGP. Temptation is often to proceed in strict analogy with QED. In QED in the radiative regime, interaction characterized by single scale (radiation length). Passage of particles through matter, such as muons, is characterized by stopping power. Without radiation losses, βγ ≈ 0.1 at 100 GeV. At energies of order 100 GeV, the maximum 4-momentum transfer is greater than 1 GeV/c, where hadronic effects significantly modify the cross sections. This problem has been investigated by J.D. Jackson, who concluded that for hadrons (but not for large nuclei) corrections to dE/dx are negligible below energies where radiative effects dominate. While the cross section for hard collisions is modified, the average stopping power, dominated by many softer collisions, is almost unchanged. In QED in the radiative regime, interaction characterized by single scale (radiation length).
Jet Tomography

- Know from generations of QCD phenomenology that jets emerge from hard scattering processes with large virtuality and that they radiate copiously as they evolve back on shell
  - Pattern of radiation is known as the parton shower
    - Enhancement of higher order radiation (large logs) arising from separation of scales between initial and final jet virtuality
    - Evolution of parton is virtuality ordered
  - Jet is a coherent object and emissions are angular ordered
    - E-loss not obviously characterized by single scale, probe has hierarchy of scales...
    - What is the relationship between these scales and those set by the medium?
      - To what extent does medium resolve jet?
    - Need to understand this well before phenomenon can be used to "measure" the medium scales
Flavor Dependence of Jet Energy Loss

- Properties of jets, final momentum distribution of hadrons within jet, sensitive to whether initial parton is a quark or gluon
  - “Gluon jets” wider, less likely to have high z leading fragment and have larger multiplicity
  - Distinction is only strict in LO picture (or LO+PS)
- May expect gluons to receive 9/4 enhancement in E-loss due to color factor

- But if medium resolves jet how much does initial flavor matter?

- Can study this by varying mixture of of q/g initiated jets

Detailed analysis of this in the context of PYTHIA Cole and Spousta,1504.05169 [hep-ph]
Coherence Approach to Quenched Jets

- Recent theoretical advances in coherence based approach
  - Combined effects of vacuum (virtuality and angular ordered) and in-medium (time ordered, angular anti-ordered) cascades

- Medium resolves jets to some scale ($\Lambda_{\text{med}}$)

- Does not see jet substructure on smaller length scales, only total color charge, i.e. coherent substructures

- Depending on details of parton shower medium resolves jet into number of effective emitters

- Jets with different parton showers (categorizable by their substructures) are quenched differently

Casalderrey-Solana, Mehtar-Tani, Salgado, and Tywoniuk
# Overview of ATLAS Jet Measurements

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Gluon Fractions: Single Jets

- Flavor of jet defined to be highest $p_T$ parton w/in $R$ of jet

- Note that PDFs and flavor fractions are only indirectly related

- Fractions extracted from generator which has initial and final state parton showers that may change flavor/kinematics of parton-level jets

- Two generators (e.g. PYTHIA and HERWIG) that have different PS implementations will not necessarily give the same flavor fractions even if they use the same input PDFs

- Also the *tune* of the generator matters, e.g. $\alpha_s$ used in ISR
Naive expectation, Quark-Gluon configuration expected to show largest asymmetry on average
Partonic Fragmentation Functions

- At fixed hadron $p_T$, expect different mixture of $q/g$ than for inclusive jets
Single Jet Observables: $p_T$ Dependence

- $R_{AA}$ for charged hadrons
- Can see more of flattening trend in latest ATLAS measurement
- Qualitatively similar to flatness observed in jet $R_{AA}$
Increasing rapidity results in a steeper production spectrum (lower $R_{AA}$ at fixed energy loss)

But higher fraction of quark jets (lower energy loss, higher RAA for fixed spectral slope)
Single Jet Observables: Rapidity Dependence

- Neither shows large variation with rapidity suggesting effects mostly cancel

\[ \sqrt{s}, \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
\[ L_{\text{int}}^{\text{PbPb}} = 0.15 \text{ nb}^{-1} \]
\[ L_{\text{int}}^{\text{pp}} = 4.2 \text{ pb}^{-1} \]

\[ 0-5\% \]

\[ \text{ATLAS} \]

\[ JHEP09 (2015) 050 \]

**PRL 114 (2015) 072302**
**Single Jet Observables: Rapidity Dependence**

- $p_T$, centrality and $y$ dependence of $R_{AA}$ well described by recent calculations

- $R_{AA}$ larger at forward rapidity $\Rightarrow$ increasing quark fraction wins out over increasing steepness of spectrum
Jet Structure: Rapidity Dependence

$|\eta| < 2.1$  $|\eta| < 0.3$  $0.3 < |\eta| < 0.8$  $1.2 < |\eta| < 2.1$

**ATLAS Preliminary**

- **Pb+Pb 0-10%**
  - $|\eta| < 2.1$
  - $|\eta| < 0.3$

- **Pb+Pb 20-30%**
  - $|\eta| < 2.1$
  - $|\eta| < 0.3$
  - $0.3 < |\eta| < 0.8$

- **Pb+Pb 30-40%**
  - $|\eta| < 2.1$
  - $|\eta| < 0.3$
  - $0.3 < |\eta| < 0.8$

- **Pb+Pb 60-80%**
  - $|\eta| < 2.1$
  - $|\eta| < 0.3$
  - $0.3 < |\eta| < 0.8$

2011 Pb+Pb data, 0.14 nb
2013 pp data, 4.0 pb
$S_{NN} = 2.76$ TeV
anti-$k_t$, $R = 0.4$ jets

**Pb+Pb 0-10%**

- $1.2 < |\eta| < 2.1$

**Pb+Pb 20-30%**

- $1.2 < |\eta| < 2.1$

**Pb+Pb 30-40%**

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**Pb+Pb 60-80%**

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New fragmentation measurement
- Includes $pp$ reference using high stat. 2013 run
- Significant improvement in ratios at high $z$

- Higher quark fraction?
Jet Structure: Rapidity Dependence

New fragmentation measurement
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$S_{NN} = 2.76$ TeV
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$1.2 < |\eta| < 2.1$

Preliminary ATLAS

Jet Structure: Rapidity Dependence

- Includes $pp$ reference using high stat. 2013 run
- Significant improvement in ratios at high $z$
- Modifications at high $z$ observed to be significant for first time

ATLAS-CONF-2015-055
Jet Structure: Rapidity Dependence

New fragmentation measurement
- Includes pp reference using high stat. 2013 run
- Significant improvement in ratios at high $z$
- Modifications at high $z$ observed to be significant for first time
- Jet $p_T$ and $\eta$ dependence
  - Unmodified distributions for quark and gluon jets very different
- Modifications at high $z$ weaker at larger $\eta$
- Higher quark fraction?

ATLAS-CONF-2015-055
Jet structure: $p_T$ dependence

- Modifications at high $z$ are less strong at larger $p_T$
Jet Energy loss: Dijet asymmetry

100 < $p_{T1}$ < 126 GeV, $x_J = p_{T2} / p_{T1}$

- Fully unfolded in two-dimensional $p_{T2}$ - $p_{T1}$ space and projected onto $x_J$
  - Can be directly compared to theory

- In $pp$ collisions, most probable dijet configuration is $x_J$~1, balanced dijets

- In central Pb+Pb collisions most probable configuration for dijets is for one jet to have HALF as much energy as the other

⇒ Qualitative change in dijet behavior
general feature of central HI collisions

ATLAS-CONF-2015-052
Dijets: $\rho_{T1}$ and Possible Flavor Dependence

For dijets, $qq/gg/qg$ composition of pairs changes with $\rho_{T1}$

$\rho_{T1}$ evolution more abrupt than for single jets, e.g. $R_{AA}$ shows very weak $p_T$ dependence

Much less modification at higher $p_T$

PRL 114 (2015) 072302
Single Jets: Geometry Dependence

- Jet yields observed to depend on angle wrt second order event plane: $\Delta \phi = \phi - \psi_2$

- In/out-of-plane differences consistent with second harmonic modulation which is consistent w/ simple assumptions of $L^2$ E-loss and expanding medium

\[ \int_{L} dt = 0.14 \text{ nb}^{-1} \]
\[ \text{Pb+Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
\[ N_{\text{part}} = 100 \]

\[ 50-60 \% \]
\[ 45 < p_T < 60 \text{ GeV} \]

\[ 40-50 \% \]
\[ 60 < p_T < 80 \text{ GeV} \]

\[ 30-40 \% \]
\[ 80 < p_T < 110 \text{ GeV} \]

\[ 20-30 \% \]
\[ 110 < p_T < 160 \text{ GeV} \]
Dijets: Geometry Dependence

\[ A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \text{ (not unfolded)} \]

Very small, but significant anti-correlation between EP angle and \( <A_J> \)

\( <A_J> \) smaller for dijets in the direction of EP which see shorter path lengths

Shows second harmonic modulation

Constrains extent to which asymmetry determined by geometry

ATLAS-CONF-2015-021
Radiative Corrections to $q_{\perp}$

- Resummation of radiative corrections yields *anomalous dimension for $q_{\perp}$*

- Implies anomalous dimension for path length dependence

\[ q_{\perp} \sim m_{D} \ll k_{\perp 1} \ll ... \ll p_{\perp} \sim Q_{s} = \hat{q}L \]

\[ \hat{q}(p_{\perp}) \]

\[ DL \]

\[ \hat{q}(q_{\perp}) \]

\[ \Delta E \sim L^{2+\gamma} \quad \text{with} \quad \gamma \equiv \sqrt{\frac{4\alpha_{s}N_{c}}{\pi}} \]

- Analysis predicts a path length dependence between pQCD radiative energy loss ($L^{2}$) and AdS strong coupling ($L^{3}$)

  ➤ Tantalizing possibility to connect strong and weak coupling limits

- Can we observe effect of anomalous dimension through

  - More precise measurements?
  - Selection on kinematics to enhance contribution?

Diagram from Y. Mehtar-Tani’s talk at QM15
Geometry and Jet Quenching: Next Steps

LHC Run 1 results showed improvements in determination of event-by-event geometry

Classify events both by centrality and ellipticity: $|q_2|$

Running out of statistics for this in run 1...

$\langle A_J \rangle$ also has very small signal ...

ATLAS-CONF-2015-021
Multi-jets in Heavy Ion Collisions

- LHC run 2 should benefit much higher rates of complicated radiation patterns
  - Nearby jets see similar path lengths and density fluctuations
  - Have correlated color structure
  - $k_t$ / opening angle of splitting sets scale to probe medium

First measurement of conditional yields of nearby jets performed by ATLAS could benefit hugely/be expanded

Conditional yields are suppressed in central collisions
Observing Coherence Effects with Jet Pull?

- Observable sensitive to color flow: jet pull vector

\[ \vec{u}_p^J = \sum_{i \in J} \frac{p_T^i |r_i^J|}{p_T^J} \hat{r}_i. \]

- Example here is for distinguishing b b̅ final states

\[ pp \rightarrow H \rightarrow b\bar{b} \]

Signal

\[ pp \rightarrow g \rightarrow b\bar{b} \]

Background

Particle production on axis connecting jets

Color connection between jet and beam remnants

\[ \Delta \phi = \phi - \phi_{J_1} \]

\[ \Delta y = y - y_{J_1} \]

Fig. from PLB (2015) 475-493

See stronger quenching effects in kinematic regions where they are expected from underlying flavor fractions

- Aspects of this puzzle (e.g. $R_{AA}$) already well described by theoretical calculations

- Needs full theoretical treatment to sort this out
  - Can be improved using new experimental results
    - Updated NPDF input from LHC measurements
    - Comparisons to unfolded $x_J$ distributions $\Rightarrow$ additional benchmark

- Flavor just one way of selecting jets with different parton showers
  - Measuring quenching observables for jets tagged by substructure properties could also address this
  - Multi-jets and observables sensitive to color flow also promising
  - Both get at role of decoherence in energy loss

- See geometric dependence consistent with $L^2$ path length dependence
  - Can we see deviations in Run 2?
Extras
Key Experimental Challenge: Jet Response

Jet energy scale (JES): shift in mean response

Jet energy resolution (JER): width of response distribution

Receive contributions both from UE and from detector

JES/JER convenient measures of response

How well known they are often dominant systematic

In ATLAS use “data overlay” generator jets embedded in real HI events

UE contributions to jets described ~exactly
Key Experimental Challenge: Jet Response

Determine JES uncertainty on MC response through data-driven studies (in situ contribution)

Residual contributions from fact that response is different for quark and gluon jets and may be different for quenched jets

“Data period” uncertainty arises from fact that pp and Pb+Pb data taken in different years and calorimeter response may have changed

Will not be present in run 2 since pp reference run was taken ~concurrently!

Residual contributions from fact that response is different for quark and gluon jets and may be different for quenched jets