Lecture 3: Results of jet measurements in p-p and heavy ion collisions

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Hard Scattering in p-p Collisions

From Collins, Soper, Sterman

\[
\sigma_{AB} = \sum_{ab} \int dx_a dx_b \, \phi_{a/A}(x_a, \mu^2) \, \phi_{b/B}(x_b, \mu^2) \, \hat{\sigma}_{ab} \left( \frac{Q^2}{x_a x_b s}, \frac{Q}{\mu}, \alpha_s(\mu) \right) \left( 1 + \mathcal{O} \left( \frac{1}{Q^P} \right) \right)
\]

- **Factorization**: separation of \( \sigma \) into
  - Short-distance physics: \( \sigma_{ab} \)
  - Long-distance physics: \( \varphi \)’s
• **Initial and final state parton showers**
  – Angular ordered (initial and) final state showers as by-product of virtuality evolution.
“Baseline”: jets in p-p

→ Leading jet: $p_T = 670$ GeV, $\eta = 1.9$, $\varphi = -0.5$

→ Sub-leading jet: $p_T = 610$ GeV, $\eta = -1.6$, $\varphi = 2.8$
Jet probes of the quark gluon plasma

- Use jets from hard scattering processes to directly probe the quark gluon plasma (QGP)

- Key experimental question:
  \[ \Rightarrow \text{How do parton showers in quark gluon plasma differ from those in vacuum?} \]

- Use vector bosons -- for which the QGP is transparent -- to calibrate hard scattering rates in Pb+Pb collisions.
Jet probes of the quark gluon plasma

- Use γ-jet pairs to directly probe the quark gluon plasma (QGP)

- Key experimental question:
  ⇒ How do parton showers in quark gluon plasma differ from those in vacuum?
  » Where the photon provides a reference energy scale for the jet.
The early days of jet quenching

A-A Hard Scattering Rates

- For “partonic” scattering or production processes, rates are determined by $T_{AB}$
  
  $$T_{AB}(b) = \int d\vec{r} T_A(|\vec{r}|) T_B(|\vec{b} - \vec{r}|)$$

  - $t$-integrated A-A parton luminosity
  - Normalized relative to p-p

- If factorization holds, then
  
  $$\frac{dn_{hard}^{AB}}{dp_\perp^2} = \frac{d\sigma_{hard}^{NN}}{dp_\perp^2} T_{AB}(b)$$

  - Define ratio $R_{AA}$
  - Note: $N_{coll} = \sigma_{NN} T_{AB}$
PHENIX: “jet” quenching @ 130, 200 GeV

- Limited reach in $p_T$ compared to what we are used to in the LHC era.
  - Qualitative features of single hadron suppression already established in 2003.

⇒ In particular, apparent weak $p_T$ variation
"State of the art" in single hadron suppression measurements @ RHIC.
Hadron suppression @ LHC

• At high $p_T$, see factor of 2 suppression in charged hadron yield.
  – photons, $W$’s, $Z$ rates show no suppression
• $p_T$ dependence matches RHIC measurements
Heavy quark suppression

- Heavy quarks provide a valuable test of our understanding of energy loss
  - Large mass changes contribution of collisional and radiative energy loss
  ⇒ But RHIC semi-leptonic decay data proved challenging to describe theoretically.
Recent calculations by Aichelin et al. are able to describe RHIC results—but only by scaling up the collisional interaction rates by a factor of 1.5-2.
Jet tomography

• How to probe geometry of the initial state?
  – Use spatial asymmetry of medium at non-zero impact parameter
  – Measure orientation \( \psi \) event-by-event

• Measure \( R_{AA} \) vs \( \Delta \phi = \phi - \psi \)

• Characterize by amplitude of \( \Delta \phi \) modulation:

\[
\frac{dN}{d\phi} = C \left[ 1 + 2v_2 \cos (2\Delta \phi) \right]
\]
Two calculations: weak, strong coupling

- $N_{\text{part}}$ dependence same for both
- But data prefer strong coupling

Calculations:
- Wicks et al., NPA784, 426
- Marquet, Renk, PLB685, 270
- Drees, Feng, Jia, PRC71, 034909
- Jia, Wei, arXiv: 1005.0645
In Au-Au collisions we see one “jet” at a time

- Strong jet quenching
- Enhanced by surface bias

**STAR Experiment: “Jet” Observations**

Proton-proton jet event

Analyze by measuring (azimuthal) angle between pairs of particles

Graph showing number of pairs vs. angle between high energy particles.
Two-particle correlations

Through very detailed measurements from STAR and PHENIX we've learned that most of this has little to do with high-p\textsubscript{T} physics, though it is very interesting.
First step towards jets: $\gamma$-hadron

Measure jet fragmentation using $\gamma$-jet events but measuring “jet” via single hadrons

- Compare to measurements from TASSO

$\Rightarrow$ Good agreement

First step towards jets: $\gamma$-hadron (2)

- Observe suppression in yield of large $z$ (small $\xi$) fragments in (central) Au+Au collisions
Jet measurements at the LHC

Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET

Heavy Ion Collision Event with 2 Jets
Jet probes of the quark gluon plasma (2)

Jet - QGP interactions schematically

From Quark Matter 2011 talk by B. Muller

**QGP can modify jets in multiple ways:**

1. Collisional energy loss (analog of Bethe-Bloch)
2. Radiative energy loss (enhanced splitting)
3. Broadening of parton shower

\[ \Rightarrow 2 \text{ & } 3 \text{ will depend on jet radius} \]
Successive recombination algorithms

• Start with “proto-jets”
  – Particles, towers, clusters, ...

• Define angular distance measure:
  – $D_{ij} = \min \left( p_{T_i}^{2p}, p_{T_j}^{2p} \right) \frac{\Delta R_{ij}^2}{R^2}$, $p = -1, 0, 1$.

  – $\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$

• Also, define single-jet “cutoff”, $D_i = p_{T_i}^{2p}$

• From all pairs select minimum of $\{D_{ij}, D_i\}$
  – If $D_i$ is minimum, jet $i$ is final
  – Otherwise combine $i$ and $j$ (below)

• Iterate until all jets are final
**k_T algorithm**

- **k_T algorithm, p = 1**
  - k_T of pair measured with respect to the higher energy parton
  
  \[ D_{ij} = \min \left( p_T^{2p_i}, p_T^{2p_j} \right) \frac{\Delta R_{ij}^2}{R^2} \rightarrow \min(k_T^2) \]

  \[ \Rightarrow k_T \approx p_T \Delta R \]

- **designed to reverse pQCD splitting**
  - tends to make large, lumpy jets

From 2009 talk by P.A. Delsart
anti-$k_T$ algorithm

- $k_T$ algorithm, $p = -1$
  - High $p_T$ proto-jets provide minimum $1/p_T^2$
  - Define stable points around which $D_{ij}$ is measured
  - Proto-jets get clustered to the local maximum proto-jet out to a radius $R$.

- anti-$k_T$ algorithm behaves like an IR and collinear safe cone algorithm.
  - Most commonly used algorithm.

From 2009 talk by P.A. Delsart
Cambridge-Aachen, SIScone

• Cambridge-Aachen algorithm, $p = 0$
  – Clusters proto-jets that are closest in angle
    $\Rightarrow D_{ij} \rightarrow \frac{\Delta R_{ij}^2}{R^2}$
  – Similar in behavior to $k_T$ algorithm

• SISCone
  – Seedless, infrared safe cone algorithm by Soyez

From 2009 talk by P.A. Delsart
Comparison of jet algorithms

- Four algorithms, one event.
  - $k_t$, anti-$k_t$, and SIScone are collinear, IR safe
Jet reconstruction: reality

- Details that matter for all calorimeters:
  - Technology
  - Longitudinal, transverse segmentation
  - Hadronic vs electromagnetic response
  - Electronic noise
  - Dead material
Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET

ATLAS EXPERIMENT

Heavy Ion Collision Event with 2 Jets
Reconstruct (unsubtracted) Pb+Pb event

Here, for demonstration, with $k_t$ algorithm

⇒ But the $k_t$ algorithm is problematic because the background jets “eat” edges of real jets
The underlying event

• ~ universal starting point for UE subtraction
  \[ E_T^{\text{subtr}} = E_T^{\text{unsubtr}} - \rho A \]

  But the details are critical

• Important considerations:
  - What kind of objects is subtraction applied to?
    - Towers, topoclusters, cells, ...
  - How to estimate UE energy density, \( \rho \) ?
  - With what granularity?
  - Event -by-event or event-averaged?
    - But if averaged, need separate measure of \( \mu \)
  - How to exclude jets, photons, ... from \( \rho \) ?
The underlying event (ATLAS)

\[
\rho(\eta) = \left\langle \frac{E^i_T}{\Delta \eta^i \Delta \phi^i} \right\rangle \quad \text{for each calorimeter layer:}
\]

\- Calculate an AVERAGE (not median!) cell \( E_T \) density in \( \Delta \eta = 0.1 \) intervals
\- Excluding cells that lie within \( \Delta R = 0.4 \) of seeds

\- Then, apply \( E^\text{subtr}_T = E^\text{unsubtr}_T - \rho A \) to each cell within tower constituents of reconstructed jets
The underlying event (ATLAS)

- Pb+Pb collisions present additional complications
  - collective flow in the UE
    - as large as ± 20%
    - fluctuates event to event
- Accounted for in subtraction
  \[ \rho^{Pb+Pb}(\eta, \phi) = \rho(\eta)(1 + 2v_2^{UE} \cos[2(\phi - \Psi_2)]) \]
- With amplitude of modulation \( (v_2) \) determined event-by-event
  \[ v_2^{UE} = \langle E_T^i \cos[2(\phi^i - \Psi_2)] \rangle_{i \notin \text{jet}} \]
  - excluding any \( \eta \) interval containing a seed

A single Pb+Pb data event, \( dE_T/d\phi \) integrated over \( |\eta| < 5 \)
ATLAS jet performance

- Three metrics
  - Jet energy resolution
  - Jet energy scale
  - Jet reconstruction efficiency
    - with ($\varepsilon'$) and without ($\varepsilon$) fake rejection

- Of these, we only have control over JES
  - Sensitive test of background subtraction
An example Pb+Pb jet event

Even more central collision, more asymmetric dijet
ATLAS dijet asymmetry measurement

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \]

\[ E_{T1} > 100 \text{ GeV} \]

\[ E_{T2} > 25 \text{ GeV} \]

1st indication of medium modifications of jets @ LHC
Clear demonstration that the effects of differential quenching extend to high $p_T$ - what is role of jet flavor (quark, gluon, heavy)?

⇒ In particular, gg vs qg.
AMY energy loss with 1 free parameter ($\alpha_s$)

- Good description of modified asymmetry distribution

⇒ Decisive test of energy loss calculations

⇒ 1st step towards quantitative probe of jet + sQGP interactions using jets
Hard scattering rate control: Z

$Z \rightarrow e^+e^-$ event display

$Z \rightarrow \mu^+\mu^-$ event display
• Compare Pb+Pb Z rapidity distributions (minimum-bias) and $p_T$ spectra to PYTHIA scaled to NNLO calculations
  – Pb+Pb Z production rates consistent with MC
⇒ hard scattering rates under control
• For these results, no absolute normalization
  – awaiting absolute jet energy scale uncertainty
Jet yields: centrality dependence

- If factorization holds jet yields should vary with centrality $\propto N_{\text{coll}}$
- Compare yields between centrality bins using “$R_{\text{cp}}$”

\[
R_{\text{cp}} = \left. \frac{\frac{1}{N_{\text{coll}}} \frac{1}{N_{\text{evt}}} \frac{dN}{dp_T}}{\frac{1}{N_{\text{coll}}} \frac{1}{N_{\text{evt}}} \frac{dN}{dp_T}} \right|_{\text{cent}} \bigg|_{60-80}
\]

- Overall jet energy scale divides out in ratio
Centrality dependence of jet $R_{cp}$

- Study centrality evolution for fixed jet $p_T$
  - $R_{cp}$ vs $N_{part}$
  - $\Rightarrow$ Smooth turn on of jet suppression between peripheral and central collisions.
Jet radius dependence of $R_{cp}$

- Evaluate jet radius dependence of $R_{cp}$
  - Modest but significant variation of $R_{cp}$
  - Less suppression for larger $R$
  \[ \Rightarrow \text{An indication of jet broadening?} \]
ALICE: jet suppression

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
0-10% Centrality
Charged+Neutral Jets
Anti-$k_T$ $R = 0.2 \ |\eta|<0.5$
Leading charged track $p_T > 5$ GeV/c
$p_{T,\text{const}} > 0.15$ GeV/c

$R_{AA}$

$R_{CP}$

Charged Jets
Anti-$k_T$ $R = 0.3$
$p_{\text{track}} > 0.15$ GeV/c

$R = 0.2$ \( R = 0.3 \)

correlated uncertainty
shape uncertainty

ALICE PRELIMINARY
• First results on jet $R_{AA}$ @ LHC

⇒ Consistent behavior with ATLAS $R_{cp}$
Differential jet suppression

- Measure jet yields in 8 bins of $\Delta \phi$ with respect to the elliptic event plane
  - Here for $R = 0.2$ jets, $60 < p_T < 80$ GeV
  - $\Rightarrow$ UE subtraction corrected for elliptic flow modulation in calorimeter
Differential jet suppression

- Observe non-zero jet $v_2$ for $(R = 0.2) \ p_T$ values $> 100$ GeV

$\Rightarrow$ jet quenching clearly sensitive to initial geometry out to very high $p_T$
• Do rough comparison of jet, charged $v_2$ at high $p_T$
  - plot 0.02 for 0/5-10%
  - plot 0.03 for > 10%
  ⇒ As good as could be expected
Inclusive jet fragmentation

We are well along or started on all of these

Unfolded for jet and charged particle resolution

\[ D(z) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dz}, \ z = \frac{\vec{p}_{chg} \cdot \vec{p}_{jet}}{|\vec{p}_{jet}|} \]

\[ D(p_T) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dp_T} \]
• First observation of modified parton shower in inclusive jets
  ⇒ Not only seeing “left over” unquenched jets.
First direct handle on the $p_T$ dependence of modifications of the parton shower.

- Important to determine whether modification is $p_T$ or $z$ dependent.
- How to determine whether low-$p_T$ enhancement is from PS or from medium?
• Check that the modification is not due to the measurement of jet $p_T \Rightarrow D(p_T)$

$\Rightarrow D(p_T)$ shows similar modifications
CMS gamma-jet

- Analogous to dijet measurement but with “clean” photon
  - See clear shift in fraction of photon energy carried by jet

⇒ But beware, photon is not proxy for unquenched jet (p-p)
Heavy flavor @ moderate $p_T$
Summary

• Extensive set of measurements at RHIC and the LHC showing that high-pT quarks and gluons lose energy in the quark gluon plasma.

• Non-trivial theoretical problem
  – Controlling approximations
  – Role of collisional and radiative energy loss
  – Parton shower not single quark
  – Description of the time-evolving medium

• Data prior to start of the LHC program was not sufficiently discriminating to sufficiently constrain theory
  – More rapid progress with jet measurements

⇒ Stay tuned