Jets and jet quenching: from p–p to A–A

LECTURES 1 AND 2: JETS IN VACUUM

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what is a jet?

- experimentally observed collimated spray of hadrons
  - simplifies event structure
    - [many hadrons → few jets]
  - complexity encoded into jet structure
    - [many jet observables]
  - somewhat ambiguous
    - [what does belong to a jet?]

**experimental jet**

**theory jet**

QCD branching of an energetic parton
- perturbatively calculable
- a manifestation of the IR and collinear divergences of pQCD
what is a jet?

usefulness of jets as physical objects requires explicit connection between what is calculated/calculable and what is measured/measurable

:: resolve ambiguity on what jet is by defining it ::
what is a jet?

usefulness of jets as physical objects requires explicit connection between what is calculated/calculable and what is measured/measurable

:: resolve ambiguity on what jet is by defining it ::

let’s start with a theory jet and worry about the rest later…
factorization

for the production of a final state $X$ (parton, jet, hadron) in a hadronic collision

$$\sigma^{h_1 h_2 \to X}(p_1, p_2) = f_i^{h_1}(x_1, Q^2) \otimes f_j^{h_2}(x_2, Q^2) \otimes \sigma^{ij \to k}(x_1 p_1, x_2 p_2, Q^2) \otimes D_{k \to X}(z, Q^2)$$

**PDFs**
[probability of finding parton of species $i$ ($j$) within proton $h_1$ ($h_2$) carrying fraction $x_1$ ($x_2$) of the proton’s longitudinal momentum at relevant scale for partonic process $Q^2$]

**hard partonic cross section**
[scattering of partons $i$ and $j$ to produce partonic system containing parton $k$]

**fragmentation function**
[probability of obtaining state $X$ from parton $k$ carrying a fraction $z$ of its longitudinal momentum]
for the production of a final state $X$ (parton, jet, hadron) in a hadronic collision

$$
\sigma_{h_1 h_2 \rightarrow X}(p_1, p_2) = f_i^{h_1}(x_1, Q^2) \otimes f_j^{h_2}(x_2, Q^2) \otimes \sigma_{ij \rightarrow k}(x_1 p_1, x_2 p_2, Q^2) \otimes D_{k \rightarrow X}(z, Q^2)
$$

try to build this step by step in simple case to understand why QCD events are jetty
soft gluon amplitude

start with $\gamma^* \rightarrow q\bar{q}$

$$M_{q\bar{q}} = \bar{u}_a(p_1)ie_q\gamma_\mu\delta_{ab}v_b(p_2)$$

and then radiate a gluon

$$M_{q\bar{q}g} = -\bar{u}(p_1)ig_A\gamma_\mu v(p_2) + \bar{u}(p_1)ie_q\gamma_\mu \frac{i(p_2 + k)}{(p_2 + k)^2}g_A\gamma_\mu v(p_2)$$

and simplify using $k_\mu \ll p_\mu$ [soft approximation], and massless quarks
soft gluon amplitude

start with $\gamma^* \rightarrow q\bar{q}$

$$\mathcal{M}_{q\bar{q}} = \bar{u}_a(p_1)ie_q\gamma_\mu\delta_{ab}v_b(p_2)$$

and then radiate a soft gluon $k_\mu \ll p_\mu$

$$\mathcal{M}_{q\bar{q}g} \simeq \bar{u}(p_1)ie_q\gamma_\mu t^A v(p_2) \cdot g_s \left( \frac{p_1.\epsilon}{p_1.k} - \frac{p_2.\epsilon}{p_2.k} \right)$$

just an additional colour matrix wrt no-gluon amplitude
Let's concentrate on the first term, collecting the factors proportional to \( qg \) again. To obtain the second line we have made use of the result that the factorizes. We actually need the squared amplitude, summed over one term for emission from the quark and the other for emission from the anti-quark and use of propagator parts later if we need to — which we won’t): where to obtain the second line we have made use of the fact that

\[
\left| \mathcal{M}_{qg} \right|^2 \approx \sum_{A,a,b,\text{pol}} \bar{u}(p_1) i e q \gamma_\mu t^A v(p_2) g_s \left( \frac{p_1.\epsilon}{p_1.k} - \frac{p_2.\epsilon}{p_2.k} \right)^2
\]

\[
= \left| M_{qg}^2 \right|^2 C_F g_s^2 \frac{2p_1.p_2}{(p_1.k)(p_2.k)}
\]

soft gluon radiation factorizes from hard splitting
soft gluon squared amplitude

[summed over colour states and polarizations]

\[ |\mathcal{M}_{q\bar{q}g}|^2 \simeq \sum_{A,a,b,\text{pol}} |\bar{u}_a(p_1) i e_q \gamma_\mu t^A v_b(p_2) g_s \left( \frac{p_1.\epsilon}{p_1.k} - \frac{p_2.\epsilon}{p_2.k} \right)|^2 \]

\[ = |M_{q\bar{q}}^2| C_F g_s^2 \frac{2p_1.p_2}{(p_1.k)(p_2.k)} \]

soft gluon radiation factorizes from hard splitting

include phase space

\[ d\Phi_{q\bar{q}g} \simeq d\Phi_{q\bar{q}} \frac{d^3 k}{2E(2\pi)^3} \]

phase space also factorizes

\[ |\mathcal{M}_{q\bar{q}g}|^2 d\Phi_{q\bar{q}g} \simeq |\mathcal{M}_{q\bar{q}}|^2 d\Phi_{q\bar{q}} d\mathcal{S} \]

\[ d\mathcal{S} = E dE d\cos \theta \frac{d\phi}{2\pi} \cdot \frac{2\alpha_s C_F}{\pi} \frac{2p_1.p_2}{(2p_1.k)(2p_2.k)} \]

\( \theta \) is angle between \( k \) and \( p_1 \)

\( \phi \) is azimuth
soft and collinear divergences

The total cross section for the production of hadrons must be finite. The integral over the gluon-phase space, 

\[ \sigma = \int d^4p_\parallel d^4p_\perp \delta(p_{\text{total}}) \delta^4(p_\parallel - p_\perp) \]

where we have used \( \delta(p_{\text{total}}) \delta^4(p_\parallel - p_\perp) \) is the requirement of QCD and appears whenever a gluon is radiated. Though derived here in the specific context of \( q \to qg \) emission from the quark (or antiquark) direction, such as \( \bar{q} \to qg \) back-to-back with the antiquark, since the quark (or antiquark) remains polarized. The gluon becomes collinear with \( p_\perp \), i.e., the gluon becomes collinear with \( \vec{k} \) and the other, a collinear divergence, when \( E_\parallel \approx E_\perp \). This result has two types of non-integrable divergence: one logarithmic divergence when the gluon is collinear, and the third term is the loop correction. Since we work in the centre-of-mass frame and there is negligible rapidity, the quark direction does not change. Though derived here in the specific context of \( q \to qg \) emission from the quark (or antiquark) direction, such as \( \bar{q} \to qg \) back-to-back with the antiquark, since the quark (or antiquark) remains polarized.

\[ dS = \frac{2\alpha_s C_F}{\pi} \frac{dE}{E} \frac{d\theta}{\sin \theta} \frac{d\phi}{2\pi} \]

\( dS \) is the squared matrix element and phase space, where we have used 

\[ \frac{d^4p_\parallel d^4p_\perp}{\delta(p_{\text{total}}) \delta^4(p_\parallel - p_\perp)} \]

\( dS \) is the squared matrix element as a function of \( E \) and \( \theta \). These divergences are general, they occur whenever a gluon is radiated.

logarithmic divergence when the gluon has zero energy [soft/IR]

logarithmic divergence when the gluon is collinear

these divergences are general, they occur whenever a gluon is radiated
total cross section

total cross section must be finite [unitarity]

divergences in real part [emission of real gluon] must be cancelled by virtual part [interference between emission and no-emission]

\[
\sigma_{tot} = \sigma_{q\bar{q}} \left( 1 + \frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\sin \theta} R \left( \frac{E}{Q}, \theta \right) - \frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\sin \theta} V \left( \frac{E}{Q}, \theta \right) \right)
\]

\[
\lim_{E \to 0} (R - V) = 0, \quad \lim_{\theta \to 0,\pi} (R - V) = 0
\]
The total cross section must be finite [unitarity]

Divergences in real part [emission of real gluon] must be cancelled by virtual part [interference between emission and no-emission]

\[
\sigma_{tot} = \sigma_{q\bar{q}} \left( 1 + \frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\sin \theta} R \left( \frac{E}{Q} , \theta \right) - \frac{2\alpha_s C_F}{\pi} \int \frac{dE}{E} \int \frac{d\theta}{\sin \theta} V \left( \frac{E}{Q} , \theta \right) \right)
\]

\(\lim_{E \to 0} (R - V) = 0\), \(\lim_{\theta \to 0, \pi} (R - V) = 0\)
total cross section

• corrections to total cross section due to emission of hard, large angle gluons

• soft gluons don’t change total cross section
  [they are produced late]

• hadronization should also not change total cross section
  [happens also on a long time-scale]

• logarithmic divergences will appear whenever we are not inclusive

  [eg, the requirement of having an extra gluon in the final state spoils the real-virtual cancellation]

  [the ‘probability’ of emitting one gluon is not well defined :: it diverges]
total cross section

- corrections to total cross section due to emission of hard, large angle gluons
- soft gluons don’t change total cross section
  [they are produced late]
- hadronization should also not change total cross section
  [happens also on a long time-scale]
- logarithmic divergences will appear whenever we are not inclusive
  [eg, the requirement of having an extra gluon in the final state spoils the real-virtual cancellation]
  [the ‘probability’ of emitting one gluon is not well defined :: it diverges]

to get meaningful answers one needs to ask meaningful questions
meaningful question

By A. Larkoski [arXiv:1709.06195]

rewrite emission probability as  [\(z\) is fraction of energy carried by gluon]

\[
P(z, \theta^2) \, dz \, d\theta^2 = \frac{\alpha_s C_F}{\pi} \frac{dz}{z} \frac{d\theta^2}{\theta^2} = \frac{\alpha_s C_F}{\pi} \left(\log \frac{1}{z}\right) \left(\log \frac{1}{\theta^2}\right)
\]

and ‘plot’ it

emissions uniformly [for fixed coupling] distributed in Lund plane
meaningful question

calculate ratio of invariant mass of quark+gluons to its energy [here called \( E \)]

\[
\tau = \frac{m^2}{E^2} = \sum_{i=\text{gluon}} z_i \theta_i^2
\]

emissions uniformly distributed in Lund plane, therefore exponentially far apart in \((z, \theta^2)\)

fixed \( \tau \) in Lund plane \( \log \tau = \log z + \log \theta^2 \)
meaningful question

\[ \tau = z\theta^2 \]

fixed \( \tau \) in Lund plane \( \log \tau = \log z + \log \theta^2 \)

emissions here lead to different value of \( \tau \)

probability of measuring \( \tau \) = probability of no emission in forbidden region
probability of emission in a cell in forbidden region

\[ P(\text{emit in region } i) = \frac{\alpha_s C_F}{\pi} \cdot (\text{Area of region } i) \]

probability of no emission in a cell in forbidden region

\[ P(\text{no emit in region } i) = 1 - \frac{\alpha_s C_F}{\pi} \cdot (\text{Area of region } i) \]

probability of no emission in forbidden region

\[ P(\text{no emissions}) = \left( 1 - \frac{\alpha_s C_F}{\pi} \frac{\log^2 \tau}{N} \right)^N \]

probability of no emission in forbidden region \( N \to \infty \)

\[ P(\text{no emissions}) = \exp \left[ -\frac{\alpha_s C_F}{\pi} \frac{\log^2 \tau}{2} \right] \]
probability of emission below scale $\tau$

$$P(x < \tau) = \exp \left[ -\frac{\alpha_s}{\pi} \frac{C_F}{2} \log^2 \tau \right]$$

Sudakov form factor

probability distribution

$$p(\tau) = \frac{d}{d\tau} \exp \left[ -\frac{\alpha_s}{\pi} \frac{C_F}{2} \log^2 \tau \right] = -\frac{\alpha_s C_F}{\pi} \frac{\log \tau}{\tau} \exp \left[ -\frac{\alpha_s}{\pi} \frac{C_F}{2} \log^2 \tau \right]$$
meaningful question gives meaningful answer

probability of emission below scale $\tau$

\[ P(x < \tau) = \exp \left[ -\frac{\alpha_s}{\pi} \frac{C_F}{2} \log^2 \tau \right] \]  
Sudakov form factor

probability distribution

\[ p(\tau) = \frac{d}{d\tau} \exp \left[ -\frac{\alpha_s}{\pi} \frac{C_F}{2} \log^2 \tau \right] = -\frac{\alpha_s C_F}{\pi} \frac{\log \tau}{\tau} \exp \left[ -\frac{\alpha_s}{\pi} \frac{C_F}{2} \log^2 \tau \right] \]

to get meaningful answers one needs to ask meaningful questions

we did that and all divergences disappeared

we accounted for [resummed] any number of gluon emissions
IRC-safe observables

For an observable’s distribution to be calculable in [fixed-order] perturbation theory, the observable should be infra-red safe, i.e. insensitive to the emission of soft or collinear gluons. In particular if \( \vec{p}_i \) is any momentum occurring in its definition, it must be invariant under the branching

\[
\vec{p}_i \rightarrow \vec{p}_j + \vec{p}_k
\]

whenever \( \vec{p}_j \) and \( \vec{p}_k \) are parallel [collinear] or one of them is small [infrared].


- gluon multiplicity is not IRC safe
- energy of hardest particle is not IRC safe
- mass/energy is IRC safe after resummation
- energy flow onto a cone is IRC safe
  - a possible definition of a jet
what is a jet?

experimental jet

theory jet
jet definition [Sterman and Weinberg (1977)]

$e^+e^-$ has $n$ jets if at least a fraction $(1-\varepsilon)$ of the event’s energy is contained within $n$ cones of half-angle $\delta$
what happens when?

time it takes for parton to split [radiate] = lifetime of virtual mother parton

\[ t_s \sim \frac{1}{M} \frac{E}{M} = \frac{E}{(p + k)^2} \]

assume daughters to be on-shell and massless

\[(p + k)^2 = 2E_p E_k (1 - \cos \theta)\]

and small angle emission \((\theta \ll 1)\)

\[(p + k)^2 = z(1 - z)E^2 \theta^2\]

and soft emission \((z \ll 1)\)

\[(p + k)^2 = zE^2 \theta^2\]
what happens when?

\[ t_s \sim \frac{E}{zE^2\theta^2} = \frac{1}{zE\theta^2} = \frac{1}{\omega\theta^2} \]

\[ \omega \equiv E_k = zE \]

- emissions are **ordered in decreasing angle** [angular ordering] for fixed energy
  - this is why QCD radiation is confined to a ‘cone’
- emissions are **ordered in increasing softness** for fixed angle
  - soft emissions happen late

Can also write \[ k_\perp = \omega \sin \theta \simeq \omega \theta \]

\[ t_s \sim \frac{\omega}{k^2} \]

- emissions also ordered in relative transverse momentum

These observations are at the core of what is called a parton shower
resummation vs. parton showers

- resummation allows to calculate one observable at a time
- parton showers use the same ‘Sudakov form factor’ to generate emissions
  - from probability of not emitting gluon above some $p_\perp$ (Sudakov) deduce $p_\perp$
    - solve for $p_\perp$ by randomly $(r)$ sampling Sudakov
  - repeat for subsequent emission(s) until $p_\perp$ falls below some NP cut-off

$r = \exp\left\{- \frac{2\alpha_s C_A}{\pi} \ln^2 \frac{p_{\perp,\text{max}}^2}{p_\perp^2}\right\}$

here radiated gluons do not radiate themselves [a simplification]

see https://github.com/gavinsalam/zuoz2016-toyshower for such barebones shower
Jet definition revisited

A jet is defined by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop.

Jet algorithm

Robust and efficient
IR and collinear safe

Theoretically calculable
Fragmentation of energetic parton

Experimentally measurable
collimated spray of hadrons
jet definition revisited

A jet is defined by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop.

- **Experimental jet**: Experimentally measurable collimated spray of hadrons
- **Jet algorithm**: Robust and efficient, IR and collinear safe
- **Theory jet**: Theoretically calculable fragmentation of energetic parton

A jet is a jet is a jet is a jet
jet algorithms [IRC safe]

e.g., generalized $k_T$ family of sequential recombination jet algorithms

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

$$d_{iB} = p_{ti}^{2p},$$

1. compute all distances $d_{ij}$ and $d_{iB}$
2. find the minimum of the $d_{ij}$ and $d_{iB}$
3. if it is a $d_{ij}$, recombine $i$ and $j$ into a single new particle and return to 1
4. otherwise, if it is a $d_{iB}$, declare $i$ to be a jet, and remove it from the list of particles. return to 1
5. stop when no particles left

follows transverse momentum ordering of splittings $\quad p = 1 :: k_T$ algorithm

follows angular ordering of splittings $\quad p = 0 ::$ Cambridge/Aachen algorithm

very robust experimentally $\quad p = -1 ::$ anti-$k_T$ algorithm

If one takes $p \to -\infty$ then energy is privileged at the expense of angle and the algorithm then becomes collinear unsafe, and somewhat like an IC-PR algorithm.
jet diversity

• $k_T$ R=0.4 jets are **different** from anti-$k_T$ R=0.4, 

![jet diversity diagram](image)

• also, anti-$k_T$ R=0.2 are **not** the inner R=0.2 core of anti-$k_T$ R=0.4 jets, etc.

• jets reconstructed with a given algorithm can be reinterpreted [reclustered] with a different algorithm to benefit simultaneously from experimental robustness and direct theoretical interpretation

• however, C/A reclustering of anti-kt R=0.4 jet is not C/A R=0.4 jet

• **jet diversity is a tool** rather than a hindrance :: grooming/substructure methods
Jets and jet quenching: from p–p to A–A

LECTURES 3 AND 4: JETS IN AA

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FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

\[ \sim 0.1 \text{ fm/c} \]
\[ [\sim 10^{-25} \text{ s}] \]
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

~ 0.1 fm/c
[~10^{-25} s]

colliding nuclei

collision [out-of-equilibrium process]

many soft [small momentum exchange] collisions
  • responsible for bulk low-momentum particle production
  • will quickly hydrodynamize
very few hard [large momentum exchange] collisions
  • offspring will slowly relax towards hydrodynamization,
    yet remain out-of-equilibrium, while propagating
    through soft soup
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

~ 0.1 fm/c
~ 1 fm/c
[~10^{-24} s]

colliding nuclei
[nuclear structure encoded in nPDFs]

Quark Gluon Plasma
[hot, dense and coloured nuclear matter]
[quarks and gluons are the relevant dof]

collision
[out-of-equilibrium process]
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

\begin{itemize}
  \item \textbf{colliding nuclei} \hspace{1cm} [nuclear structure encoded in nPDFs]
  \item \textbf{collision} \hspace{1cm} [out-of-equilibrium process]
  \item \textbf{Quark Gluon Plasma} \hspace{1cm} [hot, dense and coloured nuclear matter] \hspace{1cm} [quarks and gluons are the relevant dof]
  \item \textbf{hadronization} \hspace{1cm} [the QGP expands and thus cools down] \hspace{1cm} [once T \sim 150 \text{ MeV} back to hadronic matter]
\end{itemize}

\begin{align*}
  \text{time} & \approx 0.1 \text{ fm/c} \\
  & \approx 1 \text{ fm/c} \hspace{1cm} [\sim 10^{-24} \text{ s}] \\
  & \approx 10 \text{ fm/c}
\end{align*}

\begin{align*}
  \text{s} & = 200 \text{ GeV} \\
  \text{s} & = 5.5 \text{ TeV}
\end{align*}
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

colliding nuclei
[nuclear structure encoded in nPDFs]

~ 0.1 fm/c

Quark Gluon Plasma
[hot, dense and colored nuclear matter]
[quarks and gluons are the relevant dof]

~ 1 fm/c

[~10^{-24} s]

hadronization
[the QGP expands and thus cools down]
[once T ~ 150 MeV back to hadronic matter]

~ 10 fm/c

hadrons
[what is seen by experiments]
what we can ideally determine/constrain elsewhere

- electron-nucleus EIC/LHeC/FCC-eA
- proton-nucleus [to a lesser extent] LHC/RHIC—sPHENIX
what we can ideally determine/constrain elsewhere
• electron-nucleus EIC/LHeC/FCC-eA
• proton-nucleus [to a lesser extent] LHC/RHIC—sPHENIX

all we have
WHAT WE WANT TO UNDERSTAND

• how we get here?
• what it is?
• how it stops being?

WHAT WE CAN IDEALLY DETERMINE/CONSTRAIN ELSEWHERE

• electron-nucleus EIC/LHeC/FCC-eA
• proton-nucleus [to a lesser extent] LHC/RHIC—sPHENIX

ALL WE HAVE
HOW TO PROBE ANYTHING [INCLUDING QGP]

scatter something off it
HOW TO PROBE ANYTHING [INCLUDING QGP]

scatter something off it

*RIBBIT*

*CLICK*

KA-POW

FUN FACT: Ex-particle physicists make the worst biologists.
HOW TO PROBE ANYTHING [INCLUDING QGP]

scatter something off it

cannot [easily] understand a frog from scattering it off another frog

Abstruse Goose
scatter something you understand off it

deep inelastic scattering is the golden process for proton/nucleus structure determination

dial $Q^2 = -q^2 = -(k' - k)^2$ to probe distances $\lambda = \hbar/Q$

QGP too short-lived for external probes to be of any use
to mimic DIS paradigm need multi-scale probes produced in the same collision as the QGP
WHAT IS A JET?

UNIQUE AMONGST QGP PROBES

• multi-scale
  :: broad range of spatial and momentum scales involved in jet evolution in QGP

• multi-observable
  :: different observable jet properties sensitive to different QGP scales and properties

• very well understood in vacuum
  :: fully controlled benchmark

• feasible close relative of a standard scattering experiment
what are the microscopic dynamical properties of QGP?
what are the microscopic dynamical properties of QGP?

how does QGP interact with jets?
What are the microscopic dynamical properties of QGP?

How does QGP interact with jets?

How can we access specific microscopic dynamical properties of QGP using jets?
robust arguments for non-modification wrt vacuum :: familiar physics

nuclear structure sufficiently constrained in relevant kinematical domain

hard scattering localized on point like scale oblivious to surrounding matter [calculable to arbitrary pQCD order]

all will be easy [denial]
shower constituents exchange [soft] 4-momentum and colour with QGP:: shower modified into interleaved vacuum+induced shower:: modified coherence properties:: single parton intuition and results do not carry through trivially:: multi-scale problem:: some shower constituents de-correlate:: some QGP becomes correlated

Mehtar-Tani, Tywoniuk, Salgado :: many
Blaizot, Dominguez, Iancu, Mehtar-Tani :: JHEP 1406 (2014)
Apolinário, Armesto, Milhano, Salgado :: JHEP 1502 (2015)

this is tough [anger]
LEADING PERTURBATIVE MECHANISMS

➤ interaction with QGP leads to enhanced splitting probability [more emissions] for each jet component [parton]

➤ classical [Brownian] broadening of all partons

➤ understood within several perturbative approaches

\[ R_{q}^{\text{med}} \approx 4\omega \int_{0}^{L} dt' \int \frac{d^{2}k'}{(2\pi)^{2}} \mathcal{P}(k - k', L - t') \sin \left( \frac{k'^{2}}{2k_{f}^{2}} \right) e^{-\frac{k'^{2}}{2k_{f}^{2}}} \]

\[ \hat{q} \approx \frac{\mu^{2}}{\lambda} \text{ :: transport coefficient} \]

\[ \tau_{f} = \sqrt{\omega/\hat{q}} \]

\[ Q_{s}^{2} = \hat{q}L \]

\[ k_{f}^{2} = \sqrt{\hat{q}\omega} \]
bona fide description of multiple gluon radiation requires understanding of emitters interference pattern

qqbar antenna [radiation much softer than both emitters] as a TH lab

::vacuum::

- transverse separation at formation time
  \[ r_{\perp} \sim \theta_{q\bar{q}} \tau_f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega} \]

- wavelength of emitted gluon
  \[ \lambda_{\perp} \sim \frac{1}{k_{\perp}} \sim \frac{1}{\omega \theta} \]

for \( \lambda_{\perp} > r_{\perp} \) emitted gluon cannot resolve emitters, thus emitted coherently from total colour charge

large angle radiation suppressed :: angular ordering
Medium Antennas

\( k_{\perp}, \omega \)

\[ \Lambda_{med} \sim \frac{1}{k_{\perp}} \sim \frac{1}{\sqrt{\hat{q}L}} \]

- new medium induced colour decorrelation scale

\[ \tau_d \sim \left( \frac{1}{\hat{q} \theta_{q\bar{q}}^2} \right)^{1/3} \]

- such that decorrelation driven by timescale

**Major Effort**

Mehtar-Tani, Salgado, Tywoniuk
Casalderrey-Solana & Iancu
Blaizot, Dominguez, Iancu, Mehtar-Tani
Mehtar-Tani, Milhano, Tywoniuk [review]
[DE] COHERENCE OF MULTIPLE EMISSIONS

\[ \Delta_{med} = 1 - \exp \left\{ -\frac{1}{12} \hat{q} \theta_{qq}^2 t^3 \right\} = 1 - \exp \left\{ -\frac{1}{12} \Lambda_{med}^2 \right\} \]

- q\overline{q}bar colour coherence survival probability
- time scale for decoherence
- total decoherence when \( L > \tau_d \)

- colour decoherence opens up phase space for emission
- large angle radiation [anti-angular ordering]
  - geometrical separation [in soft limit]

\[
dN_{q,\gamma*}^{tot} = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \sin \theta \frac{d\theta}{1 - \cos \theta} \left[ \Theta(\cos \theta - \cos \theta_{qq}) - \Delta_{med} \Theta(\cos \theta_{q\overline{q}} - \cos \theta) \right]
\]

\( \Delta_{med} \to 0 \) coherence
\( \Delta_{med} \to 1 \) decoherence

\( \omega \to 0 \)

medium-induced radiation vacuum radiation geometrical separation
FROM ANTENNAS TO JETS

- $r_t < \Lambda_{\text{med}}$ :: antenna unresolved by medium :: vacuum like
- $r_t > \Lambda_{\text{med}}$ :: medium probes antenna :: strong suppression of interference :: independent radiation from each constituent

- In-medium jet dynamics driven by number of resolved charges
Medium-induced radiation (not collinear)

Collinear A0

Collinear A-0

Here \( \Theta_{gg} \sim \frac{1}{\sqrt{q_t m}} \)

Medium-induced radiation
very little known about QGP induced modifications of already ill-understood hadronization in vacuum

jet-QGP interaction modifies color connections in the jet and thus hadronization pattern
[in any reasonable effective model]
can learn about hadronization modifications at an EIC

if you let me do away with this, I will produce some results  [bargaining]
A JET IN QGP :: JET RECONSTRUCTION

uncorrelated QGP background needs to be subtracted :: jet-correlated QGP should not :: do experimental and phenomenological procedures do the same [and the right] thing? :: how can I know?

this is probably hopeless [depression]
A JET IN QGP :: OBSERVABLES

keeping in mind all the caveats compute something that has been/you want to be measured and understand what it might be sensitive to and how it can help removing the caveats

work with what you have to eventually have more  [acceptance]
THE FIVE STAGES OF HEAVY ION JET PHENOMENOLOGY

denial :: anger :: bargaining :: depression :: acceptance

the theoretical, phenomenological, and experimental challenges posed by the complexity of jets in heavy ion collisions are the best shot we have at furthering our understanding of the QGP
CANONICAL QUENCHING OBSERVABLES

- the standard approach to assess QGP effects on jets [quenching] is to compare a given observable in AA and pp collisions for jets with the same reconstructed $p_T$

- the nuclear modification factor $R_{AA}$

\[ R_{AA} = \left. \frac{\sigma_{AA}^{\text{eff}}}{\sigma_{pp}^{\text{eff}}} \right|_{p_T} \]

\[ \sigma_{pp}^{\text{eff}} = \sigma_{pp} \]

\[ \sigma_{AA}^{\text{eff}} = \sigma_{AA}/\langle N_{\text{coll}} \rangle \]
CANONICAL QUENCHING OBSERVABLES

- the standard approach to assess QGP effects on jets [quenching] is to compare a given observable in AA and pp collisions for jets with the same reconstructed $p_T$
- the nuclear modification factor $R_{AA}$

$$R_{AA} = \left. \frac{\sigma_{AA}^{\text{eff}}}{\sigma_{pp}^{\text{eff}}} \right|_{p_T} \sigma_{pp}^{\text{eff}} = \sigma_{pp} \sigma_{AA}^{\text{eff}} = \sigma_{AA} / \langle N_{\text{coll}} \rangle$$

essentially measures fraction of jets that lost little or no energy
- in steeply falling spectrum large energy losses translate into very small effects
- $R_{AA}$ provides quantitative handle on energy loss only within some model framework
CANONICAL QUENCHING OBSERVABLES

- the standard approach to assess QGP effects on jets [quenching] is to compare a given observable in AA and pp collisions for jets with the same reconstructed \( p_T \)

- e.g., a jet shape

\[
\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0 < r < r_f} (p_T^{\text{trk}} / p_T^{\text{jet}})}
\]
CANONICAL QUENCHING OBSERVABLES

- the standard approach to assess QGP effects on jets [quenching] is to compare a given observable in AA and pp collisions for jets with the same reconstructed $p_T$

- e.g., a jet shape

\[
\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} \left( \frac{p_{\text{trk}}}{p_{\text{jet}}} \right)}{\sum_{\text{jets}} \sum_{0 < r < r_f} \left( \frac{p_{\text{trk}}}{p_{\text{jet}}} \right)},
\]

comparison between AA and pp at same reconstructed jet $p_T$ confounds QGP-induced shape modification with bin-migration effects

- here the comparison is between jets that were born different

- again, some model framework that must be invoked for assessment of what was modified in a jet
A COMPLEMENTARY PROCEDURE

- divide jet samples sorted in $p_T$ [from highest] in quantiles of equal probability
- compare the $p_T$ of jets in AA and pp in the same quantile

$$Q_{AA} = \left. \frac{p_{T_{AA}}}{p_{T_{pp}}} \right|_{\Sigma_{\text{eff}}}$$

$\Sigma_{\text{eff}}(p_{T_{\text{min}}}) = \int_{p_{T_{\text{min}}}}^{\infty} dp_T \frac{d\sigma_{\text{eff}}}{dp_T}$

$(1-Q_{AA})$ is a proxy for the average energy loss :: would be exact if energy loss was strictly monotonic
ion jet with reconstructed momentum also provides a natural proxy for the unmodified jet the jet energy before medium e effects cannot be measured. In general jet events, however, modified boson energy approximates the initial energy of or Z boson is produced back-to-back with a jet, the un-

For completeness, we also show the pseudo-quantile picture in the context of a realistic event generator where significant non-monotonicities are present. The pseudo-quantile picture is defined on the cumulative cross-section, though we will not use these in the present study.

A key result of this work is that the quantile picture is consistent with the parameters used to fit data at 76 TeV and re-

Due to the steeply-falling jet production spectrum in more realistic hydrodynamic simulations, we can define the jet-medium interaction influence its energy loss and reconstruction. The default heavy-ion background in JEWEL is a di-jet, and for di-jet events we consider the two highest-

For proton-proton jets in the same quantile, of Z+jet and di-jet samples from JEWEL, we fit data at 2.1.0, based on vacuum

Using these Z+jet and di-jet samples from JEWEL, we fit data at 2.1.0, based on vacuum

CMS 2016

Inclusive Jet

p-p Pb-Pb (0-10% cent.)

0.8 0.9
e e

p quant 100 150 200 250 [GeV]

Ratio (...2016

Pseudo-Quantile

Pseudo-Ratio

Quantile

JEWEL Di-Jet

Pseudo-Ratio

Quantile

JEWEL Di-Jet

p-p Pb-Pb (0-10% cent.)

0.8 0.9

p quant 100 150 200 250 [GeV]

Ratio (R AA)

CMS 2016

Inclusive Jet

p-p Pb-Pb (0-10% cent.)

0.8 0.9

p quant 100 150 200 250 [GeV]

Pseudo-Quantile (Q AA)

Pseudo-Ratio ( R AA)

Quantile ( Q AA)

p quant 100 150 200 250 [GeV]

Ratio (R AA)

CMS 2016

Inclusive Jet

p-p Pb-Pb (0-10% cent.)

0.8 0.9

p quant 100 150 200 250 [GeV]

Pseudo-Quantile (Q AA)

Pseudo-Ratio ( R AA)

Quantile ( Q AA)

p quant 100 150 200 250 [GeV]
COMPLEMENTARY INFORMATION

- $Q_{AA}$ and $R_{AA}$ provide very different information
  - $R_{AA}$ depends on different spectral shape for quark and gluon initiated jets :: $Q_{AA}$ does not
• provides a proxy for the initial $p_t$ of a quenched [prior to QGP-induced energy loss]

$$\Sigma_{pp}^{\text{quant}}(p_T) \equiv \Sigma_{AA}^{\text{eff}}(p_T^{AA})$$
• quantile procedure closely reconstructs unquenched [initial] $p_T$ :: in this case measurable

• quantile procedure cannot undo fluctuations
PERFORMANCE IN DI-JET EVENTS

- similar performance to Z+jet
- access to unmeasurable quantity :: allows for comparison of large statistics samples of jets that were born fairly equal
MITIGATION OF MIGRATION EFFECTS :: AN EXAMPLE

- part of observable modification due to bin migration [comparison of jets with different initial energy]
- quantile procedure isolates ‘true’ modification
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

- A_J distribution shifted to larger asymmetries
- no modification of acoplanarity distribution

\[ A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}} \]
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution
measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

peeling-off of soft gluons is driving mechanism of jet energy loss
measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

NOT out of cone semi-hard rare emissions as previously thought

peeling-off of soft gluons is driving mechanism of jet energy loss
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

paradigm change triggering experimental analyses and theoretical developments

NOT out of cone semi-hard rare emissions as previously thought

peeling-off of soft gluons is driving mechanism of jet energy loss

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT
cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
cartoon implicitly suggests importance of path-length difference in di-jet asymmetry

follows naive intuition and introduces cognitive bias that can compromise your conclusions
➤ cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
➤ follows naive intuition and introduces cognitive bias that can compromise your conclusions
➤ it should not have in this case as peeling-off of soft jet components is the key mechanism for jet energy loss [in whatever language you choose to address it]
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

- cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
- follows naive intuition and introduces cognitive bias that can compromise your conclusions
- it should not have in this case as peeling-off of soft jet components is the key mechanism for jet energy loss [in whatever language you choose to address it]
- however there is much more to it
A TOOL :: MONTE-CARLO EVENT GENERATOR

➤ JEWEL implements most known jet quenching physics as modification of parton shower from scattering of constituents with QGP partons

➤ JEWEL tackles jet evolution and jet-QGP interaction within a common framework solidly based on perturbative QCD

➤ JEWEL has been validated for a wide set of observables

➤ JEWEL can be used as an exploration tool
KEY LESSON :: ALWAYS CHECK

density weighted path-length
[accounts for medium expansion, rapidity independent for boost invariant medium]

\[ L_n = 2 \int d\tau \frac{\tau n(\mathbf{r}(\tau), \tau)}{\int d\tau n(\mathbf{r}(\tau), \tau)} \]

- small bias towards smaller path-length for leading jets
  - however, significant fraction [34%] of events have longer path-length for leading jet
  - consequence of fast medium expansion
A\textsubscript{J} CAN BE GENERATED FOR EQUAL PATH LENGTHS

$A_J$ CAN BE GENERATED FOR EQUAL PATH LENGTHS

The di-jet asymmetry — the measure of the momentum imbalance in a di-jet system — is a key jet observable. Using the event generator models, we attempt to observe a di-jet asymmetry at RHIC. We find that the di-jet asymmetry in PbPb collisions is larger than in proton-proton collisions, indicating the presence of a medium. This is in contrast with the predictions of perturbation theory, which fail to describe the data. The di-jet asymmetry can be calculated for equal path lengths, allowing for a systematic reconstruction of jets above the hadronization scale. We discuss how in proton-proton collisions the di-jet asymmetry is generated through recoil and out-of-cone fluctuations both in proton-proton and in heavy ion collisions. The ability to systematically reconstruct jets above the hadronization scale is shown to be a sub-leading effect. We apply our results to the interpretation of the jet data, and demonstrate that the di-jet asymmetry can be used as a probe of the medium in heavy ion collisions.
**A_J CAN BE GENERATED FOR EQUAL PATH LENGTHS**


- **di-jet event sample with no difference in path-length have A_J distribution compatible with realistic [full-geometry] sample**
  - ‘typical’ event has rather similar path-lengths
  - difference in path-length DOES NOT play a significant role in the observed modification of A_J distribution
JET ENERGY LOSS DOMINATED BY FLUCTUATIONS

➤ not all same-energy jets are equal
➤ number of constituents driven by initial mass-to-\( p_t \) ratio
➤ more populated jets have larger number of energy loss candidates

Mass distribution of partons in the initial configuration in \( p+p \)

\[
\frac{1}{N_{ijet}} \frac{dN}{d(m^{(in)}/p_{T}^{(in)})}
\]

\[
\begin{array}{lllllll}
0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\
0 & 0.6 & 1 & 1.2 & 1.4 & 1.6
\end{array}
\]

Escobedo, Iancu 1609.06104 [hep-ph] for related work
JET ENERGY LOSS DOMINATED BY FLUCTUATIONS

➤ transverse momentum loss largely determined by mass-to-\(p_t\) ratio of initial configuration in both pp and AA

➤ strong dependence for bulk of distribution

➤ saturation at high ratio result from reconstruction cone radius [large angle structure beyond R] :: will shift to higher values for higher R

➤ effect of medium induced fluctuations seen in flattening for low \(p_t\) jets

\[
p_{\perp} \text{ loss of quark jets in pp } \gamma\text{-jet events in JEWEL+PYTHIA}
\]

\[
\frac{\Delta p_{\perp}}{p_{\perp}^{(in)}} \quad \text{vs} \quad \frac{m^{(in)}}{p_{\perp}^{(in)}}
\]

\[
p_{\perp} \text{ loss of quark jets in PbPb } \gamma\text{-jet events in JEWEL+PYTHIA}
\]

\[
\frac{\Delta p_{\perp}}{p_{\perp}^{(in)}} \quad \text{vs} \quad \frac{m^{(in)}}{p_{\perp}^{(in)}}
\]
what is hot nuclear matter?
what is hot nuclear matter?

what do jets interact with?
what is hot nuclear matter?

what do jets interact with?

Is it a gas of quarks and gluons?

What is the correct picture of the QGP?

gas of quarks and gluons [weakly coupled]
what is hot nuclear matter?

what do jets interact with?

gas of quarks and gluons
[weakly coupled]

no quasi-particles
[strongly coupled]
what in a jet interacts with QGP

- only structures that are resolvable by the QGP can interact with it independently
- for interaction with QGP, a developing jet is a set of resolved structures
- a delicate interplay between an evolving QGP scale and distances within jet
energy loss of a 2-prong object :: building up a jet

- energy loss probability [quenching weight] for 2-prong object is convolution of energy loss of total charge with resolved colour singlet dipole

\[ t_d \sim (\hat{q}\theta_{12})^{-1/3} \]

\[ \mathcal{P}_{qg} = \mathcal{P}_q \otimes \mathcal{P}_{\text{sing}} \]
what in a jet interacts with QGP

- only structures that are resolvable by the QGP can interact with it independently
- for interaction with QGP, a developing jet is a set of resolved structures
- a delicate interplay between an evolving QGP scale and distances within jet

at present, only MC implementation is that of weak/strong coupling Hybrid
what is hot nuclear matter?

what do jets interact with?

can jet–QGP interaction be consistently described for a strongly coupled QGP?
HYBRID STRONG/WEAK COUPLING MODEL

- physics at different scales merit different treatments
- vacuum jets where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]
- lost energy becomes a wake [QGP response], part of which will belong to the jet

$$\left. \frac{dE}{dx} \right|_{\text{strongly coupled}} = -\frac{4}{\pi} \frac{E_{\text{in}}}{x_{\text{stop}}^2} \frac{x^2}{x_{\text{stop}}^2 - x^2}, \quad x_{\text{stop}} = \frac{1}{2r_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

single free parameter
[accounts for QCD/N=4 SYM differences]
HYBRID STRONG/WEAK COUPLING MODEL :: POSTDICTIONS

5 observables and centrality dependence all described with single parameter

0.32 < κ_{sc} < 0.41

O(1) as expected.

x_{stop}^{QCD} \sim (2 - 3)x_{stop}^{N=4}
HYBRID STRONG/WEAK COUPLING MODEL :: PREDICTIONS

Theory Comparison: Central PbPb $x_{J\gamma}$

- In general, models appear to describe $x_{J\gamma}$
- LBT has normalization issue relative to other curves
  - To be fixed in conjunction with analyzers
- JEWEL and HYBRID comparable through all bins

Preliminary

CMS Preliminary

$\sqrt{s_{_{NN}}}$ = 5.02 TeV

$0 - 30\%$

$40 < p_T^\gamma < 50$ GeV/c

$50 < p_T^\gamma < 60$

$60 < p_T^\gamma < 80$

$80 < p_T^\gamma < 100$

$p_T^\gamma > 100$

LBT (CCNU-LBNL)

PYTHIA + HYDJET

PbPb

PbPb 404 µb$^{-1}$, pp 25.8 pb$^{-1}$

Christopher McGinn
Theory Comparison: $x_{J\gamma}$ in PbPb

- CMS Preliminary
- $\sqrt{s_{NN}} = 5.02$ TeV
- $p_T^{\gamma} > 60$ GeV/c
- $50 - 100%$
- $p_T^{\gamma} > 60$ GeV/c
- $30 - 50%$
- $p_T^{\gamma} > 60$ GeV/c
- $10 - 30%$
- $p_T^{\gamma} > 60$ GeV/c
- $0 - 10%$
- $p_T^{\gamma} > 60$ GeV/c
- PbPb 404 $\mu b^{-1}$, pp 25.8 pb$^{-1}$

PAS-HIN-16-002
Theory Comparison: Distribution of $x_{J\gamma}$ vs. $\gamma p_T$

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model
Theory Comparison: $R_{J\gamma}$ in PbPb

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$\Delta \phi_{J\gamma} > \frac{7\pi}{8}$

PbPb 404 $\mu$b$^{-1}$, pp 25.8 pb$^{-1}$

$0 - 30\%$

anti-$k_T$ Jet $R = 0.3$

$p_T^{\text{Jet}} > 30$ GeV/c

$|\eta^{\text{Jet}}| < 1.6$

$30 - 100\%$

CMS

Christopher McGinn
Theory Comparison: $x_{J\gamma}$ in PbPb

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$\Delta \phi_{J\gamma} > \frac{7\pi}{8}$

PbPb 404 $\mu$b$^{-1}$, pp 25.8 pb$^{-1}$

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PAS-HIN-16-002
Theory Comparison: $x_{J\gamma}$ in PbPb

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$\Delta \phi_{J\gamma} > \frac{7\pi}{8}$

PbPb 404 $\mu$b$^{-1}$, pp 25.8 pb$^{-1}$

$p_T^\gamma > 60$ GeV/c

anti-$k_T$ Jet R = 0.3

$p_T^{\text{Jet}} > 30$ GeV/c

$|\eta^{\text{Jet}}| < 1.6$

$\gamma_{pp} = 5.02$ TeV

$\gamma_{\text{PbPb}} > 80$ GeV/c

$N_{\text{coll}}$-weighted $<N_{\text{part}}>$

Theory Comparison: $x_{J\gamma}$ in PbPb

PAS-HIN-16-002
Photon-Jet Correlations in $pp$ and $PbPb$ collisions at 5.02 TeV with CMS

Hard Probes 2016
Wuhan, China

On behalf of the CMS experiment at the LHC

Overlaid PYTHIA+HYDJET, JEWEL, LBT and Hybrid Model
\[
\sqrt{s_{NN}} = 5.02 \text{ TeV}
\]

**CMS Preliminary**

- PbPb + PYTHIA
- LBT (CCNU-LBNL)
- Hybrid Model
- pQCD jet E-loss

**PbPb 404 \(\mu\)b\(^{-1}\), pp 25.8 pb\(^{-1}\)**

**Anti-k**. Jet \(R = 0.3\), \(p_T^{\text{jet}} > 30\) GeV/c, \(|\eta^{\text{jet}}| < 1.6\)

- 0 - 30%\(\gamma_T\)
- < 50 GeV/c

- 30 - 100%\(\gamma_T\)
- < 50 GeV/c

- 30 - 100%\(\gamma_T\)
- < 60 GeV/c

- 30 - 100%\(\gamma_T\)
- < 80 GeV/c

- 30 - 100%\(\gamma_T\)
- < 100 GeV/c

- > 100 GeV/c

- 0 - 30%\(p_T\)
jet–QGP interaction can be described in strong coupling

however, effective models are most informative when and where they fail
The Failures of the Hybrid Strong/Weak Coupling Model

➤ an example of generic failure to describe edge structure of jets
➤ what Physics is missing?
    ➤ possibly not all lost energy hydrodynamizes…
    ➤ need improved treatment for conclusive check
    ➤ fate of lost energy best handle on thermalization [how QGP came into being]

Figure 10: Ratio of the jet shape in PbPb collisions with $p_s=2.76$ ATeV with 0-10% centrality (left) and 10-30% centrality (right) to the jet shape in proton-proton collisions. The two colored bands show the results of our hybrid model calculation with no broadening, with both jets and background hadronized, and with our background subtraction procedure for high-$p_T$ jets applied.

In the calculation shown as the red band we include the effects of backreaction, namely the particles coming from a wake in the medium. We compare our calculation with and without backreaction to data from CMS [51].

Jet energies with a Gaussian whose width corresponds to the difference between the jet energy resolution in the presence of our background and the jet energy resolution measured by CMS; we describe the procedure in Appendix B. Last, we subtract background tracks in the jet cone following a simple procedure from Ref. [51] in which we subtract the $\langle \rangle$-reflection of each event from that event. This procedure does not work for jets near $|\langle \rangle|<0.3$ is excluded from both our analysis and the measurement reported in [51].

To gauge the effects of adding our simplified background, performing the background subtraction procedure, and hadronization on one hand, and the effects due to the backreaction of the medium, namely the particles coming from the wake in the plasma, on the other in both panels we show the jet shape ratio computed at the hadronic level with and without backreaction. As we saw in Section 4, energy loss serves to narrow the angular size of jets in a given window of energies in heavy ion collisions relative to that of jets with the same energies in proton-proton collisions. As a consequence, without backreaction the effect of energy loss is to increase the importance of narrow jets in the quenched jet sample, leading to a depletion of the jet shape at large angles. Note that the only differences between the simulations without backreaction in Fig. 10 and the $K=0$ simulations displayed in Fig. 5 are: adding the simplified but fluctuating background that we are employing, performing our background subtraction and jet reconstruction, and adding hadronization. The partonic distributions whose ratio is plotted in Fig. 5 give rise to narrower distributions than the hadronic ones that go into Fig. 10, a natural consequence of the non-trivial angular distribution of the Lund strings connecting the hard partons within the jet which means that hadronization broadens the jet somewhat. (See for example Ref. [185].)

Despite the hadronic uncertainties, the jet shape ratio shows a clear increase at larger values of the angular variable $r$ when we include backreaction, confirming the expectation that some of the particles from the wake in the plasma do end up reconstructed as part of the jet, and confirming the expectation that they are less tightly focused in angle than the jet itself was. That said, it...
medium response

... is an unavoidable component of a jet

- implemented very differently in different approaches where it is essential for description of some observables \([FF, \text{ jet shapes, } z_J, \ldots]\)
  - JEWEL :: recoil partons free-stream :: hadronized jointly with jet
  - LBT/MARTINI :: recoil partons transported :: hadronized separately
  - CoLBT :: sources further hydro evolution :: hadronized separately
  - Hybrid :: fully thermalized wake :: hadronized separately

- links jet quenching to physics of thermalization :: how a QGP converts external perturbations into more QGP

... relative importance is observable dependent
what does jet interact with?

hydro paradigm → QGP is a strongly coupled fluid → no quasiparticles

*jet-fluid interaction*

- full holographic ‘jets’
- strong/weak coupling hybrid
what does jet interact with?

hydro paradigm  \(\rightarrow\) QGP is a strongly coupled fluid  \(\rightarrow\) no quasiparticles

however,

**jet-[quasi]particle interaction**

- underlies pQCD based calculations
  - BDMPS-Z, [D]GLV, AMY, HT, SCET\(_G\)
- and their MC implementations, regardless of sophistication of simulated QGP
  - HIJING, Q-PYTHIA, PYQUEN, CUJET, JEWEL, MARTINI, LBT, CoLBT, JETSCAPE

**jet-fluid interaction**

- full holographic ‘jets’
- strong/weak coupling hybrid

phenomenological success claimed in both cases
what does jet interact with?

- success of approaches reliant on interaction with QGP quasiparticles is conceptually challenging

- account of $v_n$ coefficients in kinetic theory [which implies a larger $\eta/s$ than that extracted from hydro] may provide a solid theoretical underpinning to quasiparticle structure of QGP

- ... and incidentally challenge the hydro paradigm...
finding quasi-particles in QGP

- compare Gaussian distribution of kicks [no quasiparticles] with perturbative tail [quasiparticles]
  - large kicks [Molière scattering] are rare but not exponentially so
- where to look?
  - energy distribution within and around jet [medium response depends on nature of QGP]
- change of acoplanarity distribution [in di-jet, γ/Z-jet, hadron-jet]
  - multiple effects may make it very hard to see [a lesson from the Hybrid model]
modelling

**spritz approaches**
- all included mechanisms are concurrent
- dynamical decision on what happens when
  - Q-PYTHIA, JEWEL, Hybrid, and [by construction] analytical calculations

**prosecco bitter soda ice garnish approaches**
- sequential deployment of included mechanisms [shower then transport, etc.]
- requires matching scales [added uncertainty?]
  - MARTINI, LBT, CoLBT, JETSCAPE [in principle allows for concurrency]
- can it be justified? do different mechanism factorize?
robust conclusions from agreement with data

\[ z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \quad z_g > 0.1 \]

modified splitting kernel [SCETg]
Chien, Vitev 1608.07283

coherent+decoherent induced-radiation [BDMPS]
Mehtar-Tani, Tywoniuk 1610.08930

coherent+decoherent induced-radiation [HT]
Chang, Cao, Qin 1707.03767

inelastic and elastic eloss + medium response
Milhano, Wiedemann, Zapp 1707.04142

• no presently available model or calculation includes all known and potentially relevant mechanism underlying in-QGP jet modification

• successful data description leads to diverse conclusions in different models

• need to justify observable lack of sensitivity to missing ingredients for robust conclusion
**Z_g**: GROOMED SHARED MOMENTUM FRACTION

**modified Mass Drop Tagger / Soft Drop [β=0]**

1. cluster jets with anti-\(k_t\)
2. re-cluster with Cambridge/Aachen [from closest to furthest in angle]
3. undo last clustering [jet as 2-prong object] step and compute \(z_g\)
4. if \(z_g > z_{cut}\) stop,
   else discard softer prong and go back to 3

at LO

\[
p(z_g) = \frac{P(z_g) + P(1-z_g)}{\int_{z_{cut}}^{0.5} dz \left( P(z) + P(1-z) \right)} \Theta(z_g - z_{cut})
\]

- in vacuum, the procedure measures the LO Altarelli-Parisi splitting function
➤ mMDT/Soft Drop in pp is sensitive to UE

➤ worse for the lower $p_\perp$ in CMS [and STAR] measurements
THE MEASUREMENT

:: carried out by both CMS and STAR [previous talks in the session]
THE MEASUREMENT

:: carried out by both CMS and STAR [previous talks in the session]

CMS

➤ angular ‘resolution’ cut

➤ configurations where prongs are close \([\Delta R_{12} < 0.1]\) are removed from sample

➤ removes \(\sim 50\%\) of events

➤ strong modification of \(z_g\) distribution

➤ modification decreases and eventually vanishes for high \(p_\perp\)
THE MEASUREMENT

:: carried out by both CMS and STAR [previous talks in the session]

**CMS**
- angular ‘resolution’ cut
  - configurations where prongs are close $[\Delta R_{12} < 0.1]$ are removed from sample
  - removes $\sim 50\%$ of events
- strong modification of $z_g$ distribution
- modification decreases and eventually vanishes for high $p_\perp$

**STAR**
- no angular ‘resolution’ cut
- only jets with hard cores
- results consistent with no modification of $z_g$ distribution
THE TOOL: JEWEL

- jet evolution and interaction with medium described within single formalism
  - jet evolution well understood in pp :: use standard tools from pp description
  - dynamical model of jet evolution anchored in analytical understanding of pQCD
- key assumptions
  - medium seen by jet as collection of quasi-free partons
  - use infra-red continued perturbation theory to describe all jet-medium interactions
  - formation times govern the interplay of different sources of radiation [vacuum-like and medium induced]
  - LPM effect encoded through eikonal limit analytical results
two possible operating modes in JEWEL
JEWEL: MEDIUM RESPONSE

- two possible operating modes in JEWEL
  - medium partons **not included** in event record :: no tracking of medium response
JEWEL: MEDIUM RESPONSE

- Two possible operating modes in JEWEL
  - Medium partons **not included** in event record :: no tracking of medium response
  - Medium partons that interact with jet **included** in event record
    - Part of the medium becomes correlated with jet and thus part of jet
    - Requires subsequent background subtraction :: only 4-momentum acquired by medium partons should survive
    - No further re-scattering of medium partons :: jet-correlated medium arguably too hard

Zapp and Kunnawalkam Elayavalli
WITHOUT JET-CORRELATED MEDIUM
WITHOUT JET-CORRELATED MEDIUM

- small modification of $z_g$ distribution from ‘additional splittings’ and ‘energy loss’
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- angular distribution narrower in AA [prongs are closer together]
**z_g WITHOUT JET-CORRELATED MEDIUM**

- small modification of z_g distribution from ‘additional splittings’ and ‘energy loss’
- angular distribution narrower in AA [prongs are closer together]
  - jets with softer fragmentation more affected by the medium :: lost from sample :: also seen elsewhere [di-jet asymmetry]
THE LOST JETS

- γ-jet without ISR as cleanest possible environment
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- $z_{\text{split}}$ [the energy sharing of first FSR] well correlated with $z_g$
γ-jet without ISR as cleanest possible environment

- $z_{\text{split}}$ [the energy sharing of first FSR] well correlated with $z_g$
- high $z_{\text{split}}$ parton configurations less likely to result in jet with $p_T > 100$ GeV
γ-jet without ISR as cleanest possible environment

z_{split} [the energy sharing of first FSR] well correlated with z_{g}

high z_{split} parton configurations less likely to result in jet with pt > 100 GeV

effect stronger in AA
WITH JET-CORRELATED MEDIUM
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parton level, with recoils, 4-momentum subtraction

$\frac{1}{N} \frac{dN}{dz_g}$

- JEWEL+PYTHIA p+p
- JEWEL+PYTHIA Pb+Pb without recoils
- JEWEL+PYTHIA Pb+Pb with recoils

anti-$k_T$ $R=0.4$

$p_T^{(j)} > 140$ GeV

$\Delta R_{12} > 0.1$

additional component at large $\Delta R_{12}$ :: this distribution can be measured
WITH JET-CORRELATED MEDIUM

- additional component at large $\Delta R_{12}$ :: this distribution can be measured
  - predominantly low $z_g$
    - correlated background [medium response] spread out over large angles
  - $z_g$ distribution is steeply falling, additional $p_\perp$ from correlated background [recoils] in sub-leading prong promotes configurations above $z_{\text{cut}}$
effect seen in CMS data compatible with promotion of below $z_{cut}$ configuration into the sample
EFFECT OF ANGULAR CUT

parton level, with recoils, 4-momentum subtraction

- \( JEWEL + PYTHIA p+p \)
- \( JEWEL + PYTHIA Pb+Pb \)
- anti-\( k_\perp \), \( R=0.4 \)
- \( p_\perp^{(f)} > 140 \text{ GeV} \)
- all \( \Delta R_{12} \)
**EFFECT OF ANGULAR CUT**

- $\Delta R_{12}$ cut responsible for significant part of the modification
- Removes $\sim 50\%$ of events from sample
- Jets with narrower configurations [harder fragmentation] less modified
- STAR does not impose cut [is that why no modification is seen?]
MOMENTUM FRACTION DUE TO JET-CORRELATED MEDIUM

- much more important for sub-leading prong and for low $z_g$
- absolute $p_\perp$ due to jet correlated medium weakly dependent on $z_g$ [not shown]
- consistent with modification of $z_g$ distribution being due to promotion of below $z_{cut}$ configurations
A CROSS-CHECK: GIRTH

\[ g = \sum_i \frac{p_{\perp,i} \Delta R_{ij}}{p_{\perp}^J} \]

first radial moment of the intra-jet $p_{\perp}$ distribution
A CROS-S-CHECK: GIRTH

parton level, 4-momentum subtraction

\[ g = \sum_i \frac{p_{\perp,i} \Delta R_{ij}}{p_{\perp}^J} \]

first radial moment of the intra-jet \( p_{\perp} \) distribution

- negligible modification of whole jet girth [ALICE QM 2015] is compound effect of narrowing and re-population with jet-correlated background
A CROSS CHECK: THE GIRTH OF PRONGS
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- girth of leading prong [jet core] unmodified and $z_g$
  independent :: narrowing and re-population as for whole jet
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- girth of leading prong [jet core] unmodified and $z_g$ independent :: narrowing and re-population as for whole jet
- girth of sub-leading prong $z_g$-dependent in $pp$
A CROSS CHECK: THE GIRTH OF PRONGS

- girth of leading prong [jet core] unmodified and \( z_g \) independent :: narrowing and re-population as for whole jet
- girth of sub-leading prong \( z_g \)-dependent in pp
  - re-population a very large effect for low \( z_g \)