Hard probes of the hot plasma
Outline

Hard probes of the hot Quark Gluon Plasma

1. **Understand** interactions between the hard partons (quarks, gluons) and the QGP ('microscopic')

2. **Use this** to deduce properties of the QGP (degrees of freedom, viscosity, density, temperature, etc, ‘macroscopic’)

A few questions for this afternoon

- How-to: constrain QGP properties?
- Which process is dominant? (radiative, elastic)
- Where does radiated energy go?
- What drives e-loss? Geometry or fluctuations?

Disclaimer: ... far from complete discussion ... Disclaimer2: ... I’m not a theorist ... Disclaimer3: ... possible slight bias towards ALICE ...
Hard probes of the hot Quark Gluon Plasma

1. Understand interactions between the hard partons (quarks, gluons) and the QGP (‘microscopic’)
2. Use this to deduce properties of the QGP (degrees of freedom, viscosity, density, temperature, etc, ‘macroscopic’)

A few questions for this afternoon
- How-to: constrain QGP properties?
- Which process is dominant? (radiative, elastic)
- Where does radiated energy go?
- What drives e-loss? Geometry or fluctuations?
Outline

Hard probes of the hot Quark Gluon Plasma

1. **Understand** interactions between the hard partons (quarks, gluons) and the QGP (‘microscopic’)

2. **Use this** to deduce properties of the QGP (degrees of freedom, viscosity, density, temperature, etc, ‘macroscopic’)

A few questions for this afternoon

- How-to: constrain QGP properties?
- Which **process** is dominant? (radiative, elastic)
- Where does radiated energy go?
- What **drives** e-loss? Geometry or fluctuations?

Disclaimer: ... far from complete discussion ...  
Disclaimer2: ... I’m not a theorist ...  
Disclaimer3: ... possible slight bias towards ALICE ...
Hard probes
what and why
Pb–Pb collisions in a nutshell

The usual diagram ...

1. Collision, formation of dense system
2. **Deconfined** quarks and gluons interact as fundamental degrees of freedom (**QGP**)
3. Collective expansion
4. Chemical freeze-out to hadrons and finally kinetic freeze-out
Pb–Pb collisions in a nutshell

The usual diagram ...

1. Collision, formation of dense system
2. Deconfined quarks and gluons interact as fundamental degrees of freedom (QGP)
3. Collective expansion
4. Chemical freeze-out to hadrons and finally kinetic freeze-out

General problem in determining QGP properties:
- Medium dynamics as well as hadronization non-perturbative
Pb–Pb collisions in a nutshell

The usual diagram ...

1. Collision, formation of dense system
2. **Deconfined** quarks and gluons interact as fundamental degrees of freedom (QGP)
3. Collective expansion
4. Chemical freeze-out to hadrons and finally kinetic freeze-out

General problem in **determining** QGP properties:
- Medium dynamics as well as hadronization **non-perturbative**
- *How do you look inside a ‘patient’ if you cannot open him up?*
  
  → **Tomography**: imaging through **modification** of penetrating wave
Hard probes

Tomography
‘imaging through modification of penetrating wave’

‘Motivation’ for hard probes similar:
- Use well-known (perturbative) probe (i.e. large $Q^2$ process)
- Deduce medium properties from modification in medium vs. vacuum

\[ \text{nPDF}_i \otimes \text{nPDF}_j \otimes \text{hard scattering} \otimes \text{QCD branching} \otimes \text{hadronization} \otimes h_1 \otimes h_2 \otimes h_3 \text{ jet reconstruction} \]
Chapter 1) $R_{AA}$
‘nuclear modification factor’
single tracks
Nuclear modification factor $R_{AA}$

‘Simplest’ probe: (high-$p_T$) particle production in vacuum vs. in medium

$$R_{AA} = \frac{d^2 N_{AA}^{\text{vac}} / dp_T d\eta}{\langle T_{AA} \rangle \cdot d^2 \sigma_{pp} / dp_T d\eta} \approx \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

$$\langle T_{AA} \rangle \propto \langle N_{\text{coll}} \rangle = \text{no. of binary nucleon-nucleon collisions}$$

Possible scenarios
- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

Assumption
- partons lose energy in the medium
- $R_{AA} < 1$
‘Convenient’ to measure ...

... from spectra to $R_{AA}$ ...

... and qualitatively understand

**Suppression** depends on **centrality**: stronger for more central collisions
- Strongest suppression around 7 GeV/c for all centralities
- Suppression non-zero up to high transverse momenta

More **central** collisions
- longer average path length
- **denser medium**
  → stronger suppression

---

**$R_{AA}$ - from RHIC to LHC**

**Results from LHC and RHIC are qualitatively similar**
- Shape of $R_{AA}$ and maximum agrees, offset however is different
- High $p_T$ $R_{AA}$ is lower for LHC
- Decrease of $R_{AA}$ with increasing $\sqrt{s_{NN}}$ observed at RHIC
- Indicative of higher medium density at the LHC compared to RHIC

---


**ALI−PUB−81798**
... let's be a little more precise ...

Statements up till now are very generic: ‘partons lose energy in QGP, $\sqrt{s_{NN}}$ and density dependent’

- Comparison of $R_{AA}$ to theory necessary
Statements up till now are very generic: ‘partons lose energy in QGP, $\sqrt{s_{NN}}$ and density dependent’
- Comparison of $R_{AA}$ to theory necessary

Modeling $R_{AA}$ is not trivial
- **Initial state** of HI collisions not fully understood (Glauber / CGC)
- Medium **geometry** (density profile, path-length or parton through medium)
- Energy loss is a **distribution**, not single valued
- Energy loss is **partonic**, not hadronic
  - Understanding of medium modified shower / hadronization
  - Quark/gluon fragmentation differences

... and there’s a very large variety of models on the market ...
A common ansatz

Simplest (and most often used in analytical of MC calculations) ansatz is

\[
\left. \frac{dN}{dp_T} \right|_{\text{hadrons}} \bigg|_{\text{final state}} = \left. \frac{dN}{dE} \right|_{\text{jets}} \otimes \left\{ P(\Delta E) \otimes D(p_T/E) \right\} \text{ energy loss distribution} \otimes \text{fragmentation function}
\]

- **Medium** information is in \( P(\Delta E) \)
A common ansatz

Simplest (and most often used in analytical of MC calculations) ansatz is

\[
\left| \frac{dN}{dp_T} \right|_{\text{hadrons}} \quad = \quad \left| \frac{dN}{dE} \right|_{\text{jets}} \quad \otimes \quad P(\Delta E) \quad \otimes \quad D(p_T/E)
\]

- **Medium** information is in \( P(\Delta E) \)

Wealth of models available from low to high (200 GeV/c!) \( p_T \)

- Qualitatively similar outcome: relative e-loss decreases with increasing \( p_T \)
- *let’s look at this in a more systematic way*
A systematic approach: transport coefficients

Not too fast: processes contributing to e-loss

Collisional energy loss

Radiative energy loss

\[ \hat{q} = \rho \int dq_{\perp} q_{\perp}^2 d\sigma dq_{\perp} = \langle q_{\perp}^2 \rangle \lambda \]

\[ \hat{\epsilon} : \text{longitudinal drag (collisional energy loss)} \]

Sidenote: relative importance of radiative vs. elastic e-loss can be disentangled by heavy-flavor e-loss (dead cone: radiative energy loss is suppressed)
A systematic approach: transport coefficients

Not too fast: **processes** contributing to e-loss

Collisional energy loss

Radiative energy loss

- $\hat{q}$: transverse momentum diffusion (radiative energy loss)

\[
\hat{q} = \rho \int dq_\perp q_\perp^2 d\sigma dq_\perp = \frac{\langle q_\perp^2 \rangle}{\lambda}
\]

- $\hat{e}$: longitudinal drag (collisional energy loss)

Ansatz: express model ‘predictions’ in a **common parameter**: transport coefficient $\hat{q}$

Sidenote: relative importance of radiative vs. elastic e-loss can be disentangled by heavy-flavor e-loss (dead cone: radiative energy loss is suppressed)
A systematic approach: transport coefficients

Not too fast: **processes** contributing to e-loss

Collisional energy loss  
Radiative energy loss

- $\hat{q}$: transverse momentum diffusion (radiative energy loss)
\[
\hat{q} = \rho \int dq_\perp^2 q_\perp^2 \frac{d\sigma}{dq_\perp^2} = \frac{\langle q_\perp^2 \rangle}{\lambda}
\]

- $\hat{\epsilon}$: longitudinal drag (collisional energy loss)

**Ansatz**: express model ‘predictions’ in a **common parameter**: transport coefficient $\hat{q}$

**Sidenote**: relative importance of radiative vs. elastic e-loss can be disentangled by heavy-flavor e-loss (**dead cone**: radiative energy loss is suppressed)
systematic approach
(see Phys. Rev. C 90, 014909 (2014))
systematic approach
(see Phys. Rev. C 90, 014909 (2014) )
tune parameters of model to best fit data
systematic approach
(see Phys. Rev. C 90, 014909 (2014) )

- tune parameters of model to best fit data
- repeat for many models
  (MARTINI, HT-BW, HT-M, AMY, CUJET)
systematic approach
(see Phys. Rev. C 90, 014909 (2014))
tune parameters of model to best fit data
repeat for many models
(MARTINI, HT-BW, HT-M, AMY, CUJET)
extract most probable $\hat{q}$
The tuning process

**CUJET2.0**

$$\alpha_{\text{max}}, f_E, f_M$$

**PHENIX 0-5% 2012**

**ALICE 0-5%**

$$\alpha_s = 0.19$$

$$\alpha_s = 0.27$$

**CMS 0-5%**

$$\hat{q}_0 = 2.9 \text{ GeV}^2/\text{fm}$$

Redmer Alexander Bertens - January 21, 2016

Hard probes of the hot plasma - slide 15 of 66
The tuning process cont.

CUJET 2.0

CUJET: $\alpha_s$ is medium parameter
Lower at LHC

HT-BW

HT: $\hat{q}$ is direct parameter
Higher at LHC
... to arrive at a common $\hat{q}$

\[
\frac{\hat{q}}{T^3} \approx \begin{cases} 
4.6 \pm 1.2 \text{ (RHIC)} \\
3.7 \pm 1.4 \text{ (LHC)}
\end{cases}
\]

AdS/CFT correspondence compatible using CUJET $\alpha_s$:

\[
\frac{\hat{q}}{T^3} = 2.27 - 3.64
\]

For a 10 GeV/c quark jet:

\[
\hat{q} \approx \begin{cases} 
1.2 \pm 0.3 \frac{\text{GeV}^2}{\text{fm}} \text{ at } T=370 \text{ MeV} \\
1.9 \pm 0.7 \frac{\text{GeV}^2}{\text{fm}} \text{ at } T=470 \text{ MeV}
\end{cases}
\]

- $\hat{q}$ determined with $\approx 35\%$ certainty
- $\hat{q}$ needs input from heavy-flavor jet measurements (stay tuned for the next hard probes seminar)
... to arrive at a common $\hat{q}$

\[
\frac{\hat{q}}{T^3} \approx \begin{cases} 
4.6 \pm 1.2 \text{ (RHIC)} \\
3.7 \pm 1.4 \text{ (LHC)}
\end{cases}
\]

AdS/CFT correspondence compatible using CUJET $\alpha_s$:

\[
\frac{\hat{q}}{T^3} = 2.27 - 3.64
\]

For a 10 GeV/c quark jet

\[
\hat{q} \approx \begin{cases} 
1.2 \pm 0.3 \text{ GeV}^2 \text{fm}^{-1} \text{ at } T=370 \text{ MeV} \\
1.9 \pm 0.7 \text{ GeV}^2 \text{fm}^{-1} \text{ at } T=470 \text{ MeV}
\end{cases}
\]

- $\hat{q}$ determined with $\approx 35\%$ certainty
- Needs input from heavy-flavor jet measurements (stay tuned for the next hard probes seminar)
And then there is the bulk

What about the medium evolution?

![Graph showing the evolution of a quantity $q^2/\xi^2$ vs. $\xi$ for different models: 2+1d ideal, 2+1d vCGC, 2+1d vGlb, and 3+1d ideal. The graph includes a point $b = 7.49$ fm, in plane.]

- when does e-loss start?
- when does e-loss stop?
- what is the medium density profile?
- initial conditions?

... so ... hard probes constrain \( \hat{q} \) connection to soft observables ?
Short intermezzo: ‘hydrodynamic’ flow

In a nutshell ...

- *Almond-shaped* overlap region
- *Collective* expansion of *thermalized* medium in vacuum
- *Geometric* anisotropy is converted to *momentum* anisotropy
Short intermezzo: ‘hydrodynamic’ flow

In a nutshell ...

- **Almond-shaped** overlap region
- **Collective** expansion of **thermalized** medium in vacuum
- **Geometric** anisotropy is converted to **momentum** anisotropy

![Diagram showing azimuthal modulation of tracks](image)

Result: low $p_T$ **azimuthal** modulation of tracks $v_n = \langle \cos n[\varphi - \Psi_n] \rangle$
Connecting \( \hat{q} \) to viscosity

Shear viscosity \( \eta(1/s) \)

\[ \eta \propto \rho \langle p \rangle \lambda \]

can be related to \( \hat{q} \)


\[ \frac{\hat{q}}{T^3} \propto \left( \frac{\eta}{s} \right)^{-1} \]

for a QCD medium

\[ \frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \]

depending on coupling

I realize the font is too small, but take away: a lot of progress has been made for \( \eta/s \) via flow measurements

Redmer Alexander Bertens - January 21, 2016
Hard probes of the hot plasma - slide 21 of 66
Reasonable agreement with QGP expectation of \( \frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \)

- \( \eta/s \) slightly **larger** at LHC vs. RHIC
- \( \hat{q}/T^3 \) slightly **lower** at LHC vs. RHIC
... so in summary ...

$R_{AA}$ is a **valuable** probe ($\hat{q}$)

\[
\left. \frac{dN}{dp_T} \right|_{\text{hadrons}} \bigg|_{\text{final state}} = \left. \frac{dN}{dE} \right|_{\text{jets}} \bigg|_{\text{pQCD, nPDF's}} \otimes P(\Delta E) \otimes D(p_T/E) \text{ fragmentation function}
\]
... so in summary ...

\[ R_{AA} \text{ is a valuable probe } (\hat{q}) \]

\[ \frac{dN}{dp_T} \bigg|_{\text{hadrons}} \quad \text{final state} \quad \frac{dN}{dE} \bigg|_{\text{jets}} \quad \text{pQCD, nPDF's} \]

\[ \quad \times P(\Delta E) \times \text{e-loss} \quad \text{D}(p_T/E) \quad \text{fragmentation function} \]

... bus has its limitations

- ‘hadronic observable’ (not parton spectrum)
- sensitive to ill-understood hadronization physics
- ... and where does the lost energy go?

‘Solutions’
- Jets as a partonic probe
... so in summary ...

\[ R_{AA} \text{ is a valuable probe } (\hat{q}) \]

\[
\left. \frac{dN}{dp_T} \right|_{\text{hadrons}} \bigg|_{\text{final state}} = \left. \frac{dN}{dE} \right|_{\text{jets}} \left( \left. \frac{dN}{dE} \right|_{\text{PQCD, nPDF's}} \right) \left( P(\Delta E) \right) \left( D(p_T/E) \right).
\]

... bus has its limitations

- ‘hadronic observable’ (not parton spectrum)
- sensitive to ill-understood hadronization physics
- ... and where does the lost energy go?

‘Solutions’

- Jets as a partonic probe
Chapter 2) Jets
Jets in heavy-ion collisions

Hard scattering \((Q^2 > 1 \text{ (GeV/c)}^2)\)

- (induced) **radiation** of quarks and gluons
- Hadronization into colorless spray: ‘jets’
- Reconstructed jet: as close as one can experimentally get to **original parton**
Jets in heavy-ion collisions

Hard scattering \((Q^2 > 1 \text{ (GeV/c)}^2)\)
- (induced) **radiation** of quarks and gluons
- Hadronization into colorless spray: ‘jets’
- Reconstructed jet: as close as one can experimentally get to **original parton**

Let’s try to answer
- Are jets suppressed?
- Where does the energy go?
- What determines e-loss? (geometry or fluctuations?)
but before going into results ...

... a small experimental detour
Experimentally, jets are tricky

Need to define jet in experiment and theory
Jets and jet finding

For a rainy afternoon: (anti)-$k_T$ jet finding:

define for all protojets (tracks)

\[
d_i = p_{T,i}^2
\]

\[
d_{i,j} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \frac{\Delta_i^2}{R^2}
\]

\[
\Delta_{i,j}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2
\]

- smallest $d_x = d_{i,j} \rightarrow$ merge tracks
- smallest $d_x = d_i \rightarrow d_i$ is a jet

... go back to the beginning

$R$: resolution parameter (maximum angular separation of tracks in $\eta, \varphi$)

Fast, infrared / collinear safe

... but all tracks get clustered
Jet reconstruction in Pb–Pb collisions

‘ ... all tracks get clustered ’
- Generally not so problematic in pp collisions ...
- ... but in Pb–Pb this means including overwhelming energy from uncorrelated emissions

![Diagram of jet reconstruction](image)
Jet reconstruction in Pb–Pb collisions

‘... all tracks get clustered’

- Generally **not** so problematic in pp collisions ...
- ... but in Pb–Pb this means including **overwhelming** energy from **uncorrelated emissions**

**Challenge:** inclusive measurement of jets while **removing** UE

- ‘Background’ (**Underlying Event**) **large** [1] compared to jet energy
- UE is **not uniform** (e.g. flow [2]) and has large **statistical** fluctuations [3]
To get a feeling

Leading hadron cut removes fake jets
At low $p_T$ contribution from fake clusters is overwhelming
Event-by-event estimate of energy density of UE

\[ \langle \rho_{ch} \rangle = \text{median} \left( \frac{p_T^{\text{jet}}}{A_{\text{jet}}} \right) \]

Linear dependence of \( \langle \rho_{ch} \rangle \) on multiplicity

Quick example: 0–10% centrality
- \( \langle \rho_{ch} \rangle \approx 140 \text{ GeV/c} \ A^{-1} \)
- \( A \propto \pi R^2 \)

\( \propto 70 \text{ GeV/c} \) charged background for \( R = 0.4 \)
Jet-by-jet UE subtraction

Adjust jet-by-jet for UE energy

\[ p_{T, \text{ch}}^{\text{jet}} = p_{T, \text{ch}}^{\text{raw}} - \rho_{\text{ch local}} A \]

using jet area A and UE energy density \( \rho_{\text{ch local}} \)

UE flow (\( v_2 \) and \( v_3 \) and ...) can be accounted for in \( \rho_{\text{ch local}} \)

\[ \rho_{\text{ch}}(\varphi) = \rho_0 \left( 1 + 2 \{ v_2 \cos[2(\varphi - \psi_{\text{EP}, 2}^0)] + v_3 \cos[3(\varphi - \psi_{\text{EP}, 3}^0)] + \ldots \} \right) \]
[3] Fluctuations of UE

UE fluctuations in $\varphi$, $\eta$ around $\langle \rho_{ch} \rangle$

- A jet of $p_T = x$ sitting on an upward fluctuation of magnitude $a$ will be reconstructed at $p_T = x + a$ ...
- ... likewise a jet of $p_T = x$ sitting on a downward fluctuation of magnitude $a$ will be reconstructed at $p_T = x - a$

Use e.g. random cone procedure to determine magnitude of fluctuations

$$\delta p_T = \sum_{\text{cone } p_T} p_{\text{track}} - \langle \rho \pi R^2 \rangle_{\text{expectation}}$$

$\delta p_T$ distribution used to unfold jet spectra:

$$f_{\text{meas}}(x) = \int R(x|y)f_{\text{true}}(y)dy$$
**Fluctuations of UE**

**UE fluctuations in \( \varphi, \eta \) around \( \langle \rho_{ch} \rangle \)**

- A jet of \( p_T = x \) sitting on an **upward** fluctuation of magnitude \( a \) will be reconstructed at \( p_T = x + a \) ...
- ... likewise a jet of \( p_T = x \) sitting on a **downward** fluctuation of magnitude \( a \) will be reconstructed at \( p_T = x - a \)

**Use e.g. random cone procedure to determine magnitude of fluctuations**

\[
\delta p_T = \sum \rho_{\text{track}}^{\text{cone}} - \frac{\rho_{\pi R^2}}{\text{expectation}}
\]

\( \delta p_T \) distribution used to **unfold** jet spectra:

\[
f_{\text{meas}}(x) = \int R(x|y)f_{\text{true}}(y)dy
\]
... and no jet talk without unfolding ...

\[ f_{\text{meas}}(x) = \int R(x|y)f_{\text{true}}(y)dy \]

- \( f_{\text{true}}(y) \): ‘true’ jet \( p_T \)
- \( f_{\text{meas}}(x) \): ‘measured’ jet \( p_T \)
- \( R(x|y) \): response function
... and no jet talk without unfolding ...

\[ f_{\text{meas}}(x) = \int R(x|y) f_{\text{true}}(y) dy \]

- \( f_{\text{true}}(y) \): ‘true’ jet \( p_T \)
- \( f_{\text{meas}}(x) \): ‘measured’ jet \( p_T \)
- \( R(x|y) \): response function

A particle level jet at 200 GeV ....

... can end up between 20 and 100 GeV in the detector ...

Unfolding spectra introduces a systematic uncertainty

- Unavoidable for meaningful comparison to theory and between experiments

ALICE Preliminary Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV 10-30% Centrality

anti-\( k_T \) \( R = 0.2 \) \( p_{T,\text{charged}}^{\text{leading}} > 5 \) GeV/ \( c \)

Combined Response Matrix
Jet analysis is tricky

needs large statistics data sample

UE is well-understood, but this comes at
the price of (large) systematic
unfolding !!!!!
Jet analysis is tricky
needs large statics data sample
Jet analysis is tricky
needs large statics data sample
UE is well-understood, but this comes at
the price of (large) systematic uncertainties
Jet analysis is tricky needs large statics data sample UE is well-understood, but this comes at the price of (large) systematic uncertainties unfolding !!!
Chapter 2 cont.
Jets and physics
Are jets suppressed &
Where does the energy go?
Two qualitative scenarios

1) Out-of-cone radiation: $R_{AA} < 1$
2) In-cone radiation: $R_{AA} = 1$, fragmentation function changes

Of course, these are not exclusive ...
**Out-of-cone radiation: \( R_{AA} \) of jets**

\[
R_{AA} = \frac{d^{2}N_{AA}^{\text{jet}}/dp_{T}d\eta}{\langle T_{AA} \rangle \cdot d^{2}\sigma_{pp}/dp_{T}d\eta} \approx \frac{\text{QCD in medium}}{\text{QCD in vacuum}}
\]

- **Strong** suppression in central and semi-central collisions
- Resonable model agreement (JEWEL\(^1\), YaJEM\(^2\))

**Indication of out-of-cone radiation**

---

\(^1\) K.C.Zapp et al. JHEP 1303 080

\(^2\) T.Renk, PRC 78 034908

Redmer Alexander Bertens - January 21, 2016

Hard probes of the hot plasma - slide 40 of 66
... and what about inside the jet?

\[ g(\delta r) = \frac{QGP}{\sim QGP_{\text{vacuum}}} \]
Where does the energy go?

\[ \rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{tracks} \in [r_a, r_b]} \frac{p_T}{p_T^{\text{jet}}} \]

- **Ratio** \( \text{Pb–Pb to pp} \): distribution close to the jet axis approximately **unmodified**
- **\( p_T \) excess** at large \( R \) for \( \text{Pb–Pb jets: jet broadening} \)

---

Redmer Alexander Bertens - January 21, 2016 | Hard probes of the hot plasma - slide 42 of 66
Lower panels: energy recovered at very large angles and low $p_T$?
e-loss: strong out-of-cone radiation

moderate change in jet shape
e-loss: strong out-of-cone radiation
moderate change in jet shape

What is driving e-loss: fluctuations or geometry?
ATLAS observes striking imbalance of jet energies in heavy ion collisions

The ATLAS experiment has made the first observation of an unexpectedly large imbalance of energy in pairs of jets created in lead-ion collisions at the LHC (Aad et al. 2010). This striking effect, which is not seen in proton–proton collisions, may be a sign of strong interactions between jets and a hot, dense medium.
Path-length dependence: di-jet systems

\[
\frac{dN}{dp_T} \bigg|_{\text{hadrons}} \bigg|_{\text{final state}} = \frac{dN}{dE} \bigg|_{\text{jets}} \otimes P(\Delta E) \otimes D(p_T/E)
\]

\(P(\Delta E)\) combines geometry and energy loss

Di-jet system: 2 \(\rightarrow\) 2 process

- Jets traveling in opposite direction with equal transverse momentum
- \(L_1 < L_2\)
Path-length dependence: di-jet systems

\[
\frac{dN}{dp_T} \Bigg|_{\text{hadrons}} \bigg|_{\text{final state}} = \frac{dN}{dE} \Bigg|_{\text{jets}} \otimes P(\Delta E) \otimes D(p_T/E)
\]

- \( P(\Delta E) \) combines **geometry** and **energy loss**

Di-jet system: 2 \( \rightarrow \) 2 process
- Jets traveling in **opposite** direction with **equal** transverse momentum
- \( L_1 < L_2 \) (... ?)
Path-length dependence: di-jet systems

\[ \frac{dN}{dp_T} \bigg|_{\text{hadrons}} = \frac{dN}{dE} \bigg|_{\text{jets}} \otimes P(\Delta E) \otimes D(p_T/E) \]

\( P(\Delta E) \) combines geometry and energy loss

Di-jet system: 2 \( \rightarrow \) 2 process
- Jets traveling in **opposite** direction with **equal** transverse momentum
- \( L_1 < L_2 \) ( ... ?)

In the lab, \( p_{T1} \neq p_{T2} \)
- pp: recoil, out-of-cone radiation
- AA: energy loss fluctuations, different path-lengths

Difference probes medium

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

\[ x_j = p_{T1}/p_{T2} \]
New observable $x_j = \frac{p_{T1}}{p_{T2}}$

Asymmetry quantified as $x_j = \frac{p_{T1}}{p_{T2}}$

Fully unfolded
- Direct comparison to theory
- ... and (eventually) other experiments

In $pp$
- most probable dijet configuration: $x_j \approx 1$

In $\text{Pb–Pb}$
- most probable configuration: subleading jet has half as much energy as leading jet

Strong centrality dependence
New observable \( x_j = \frac{p_{T1}}{p_{T2}} \)

Asymmetry: \( x_j = \frac{p_{T1}}{p_{T2}} \)

- With increasing \( p_T \rightarrow x_j \) goes towards 1
New observable $x_j = \frac{p_{T1}}{p_{T2}}$

Asymmetry: $x_j = \frac{p_{T1}}{p_{T2}}$
- With increasing $p_T \rightarrow x_j$ goes towards 1

Confirms sl. 16 ‘Relative loss decreases with $p_T$’
New observable $x_j = \frac{p_{T1}}{p_{T2}}$

Let’s back up a bit ...

... doesn’t this raise more questions than it answers? (at least, for me it does)
New observable $x_j = \frac{p_{T1}}{p_{T2}}$

Let’s back up a bit ...

- ... doesn’t this raise more questions than it answers? (at least, for me it does)

We have

- $R_{AA}$: moderate average energy loss
- di-jets: wide variation in possible energy loss

What is the balance between

- per-jet energy loss fluctuations? (analogous to fluctuations in vacuum radiation)
- average energy loss from kinematics, medium composition and geometry?

Remember that e-by-e fluctuations turn out to be crucial in explaining hydro flow phenomena
How can we *disentangle* geometry and fluctuations?
How can we disentangle geometry and fluctuations?
Theory: fix path-lengths
How can we disentangle geometry and fluctuations?

Theory: fix path-lengths

Experiment: try also fixing path-lengths
Theory: fix path-lengths
Briefly introducing the model: JEWEL

JEWEL (Jet Evolution With Energy Loss)
- **Radiative** energy loss and elastic **scatterings** (plus momentum exchange [recoil] with medium)
- Radiation: **LPM** interference (matches multiple soft scattering)
- Longitudinally expanding Glauber overlap
- Very successful in describing RHIC and LHC data
Briefly introducing the model: JEWEL

**JEWEL** (Jet Evolution With Energy Loss)

- **Radiative** energy loss and elastic **scatterings** (plus momentum exchange [recoil] with medium)
- Radiation: **LPM** interference (matches multiple soft scattering)
- Longitudinally expanding Glauber overlap
- Very succesful in describing RHIC and LHC data

In earlier slides (42) we saw that JEWEL gives good description of $R_{AA}$ of jets

Also reasonable agreement with CMS di-jet imbalance (slide 47)

- $p_{T1} > 120$ GeV/c
- $p_{T2} > 30$ GeV/c
- $\Delta \varphi_{1,2} > 2\pi/3$

Folded with detector resolution
Study original of imbalance by using random (left) or fixed (right) di-jet production points

- Fixed points: both jets ‘see’ same medium distance $L$
Fixing path-lengths

‘Origins of the di-jet asymmetry in heavy ion collisions’
(26/12/2015, arXiv:1512.08107)

(≈ verbatim) from the paper

- Path-length difference plays **no significant role** in generating di-jet asymmetry
- **Increase** w.r.t. pp due to fluctuations in vacuum-like fragmentation and medium related fluctuations
- Amount of energy lost is determined strongly by ratio of $m/p_T$ of original parton
‘Origins of the di-jet asymmetry in heavy ion collisions’
(26/12/2015, arXiv:1512.08107)

\[ \approx 35\% \text{ of cases } L_1 > L_2 \text{ (density weighted path-length)} \]

Dependence of \( A_J \) on \( \Delta L_n \) small compared to width (strong fluctuations)

experimental answers ?
Experiment: try also fixing path-length event-plane dependence
Distance traveled by di-jet depends on orientation w.r.t. $\Psi_{EP,2}$.

- $\langle A_j \rangle$ smaller for dij-ets in direction of $\Psi_{EP,2}$.
Distance traveled by di-jet depends on orientation w.r.t. $\Psi_{EP, 2}$

\[ \langle A_j \rangle = A_j^0 \left( 1 + 2c_2 \cos(2(\phi_{lead} - \Psi_{EP, 2})) \right) \]

- $\langle A_j \rangle$ \textbf{smaller} for dij-ets in direction of $\Psi_{EP, 2}$
- Reasonably described by cosine modulation
- Anti-correlation is \textbf{significant}
Event-plane dependence of di-jets

Distance traveled by di-jet depends on orientation w.r.t. $\Psi_{EP, 2}$

\[ \langle A_j \rangle = A_j^0 \left( 1 + 2c_2 \cos(2(\varphi_{lead} - \Psi_{EP, 2})) \right) \]

- $\langle A_j \rangle$ smaller for di-jets in direction of $\Psi_{EP, 2}$
- Reasonably described by cosine modulation
- Anti-correlation is significant

Points at small but significant contribution to asymmetry from geometry
$v^\text{ch jet}_2$ : ‘fixing’ the medium geometry

Different theoretical predictions on path-length ($L$) dependence of parton energy loss ($\Delta E$)$^3,^4,^5$

$$\Delta E \propto L \leftrightarrow \Delta E \propto L^2 \leftrightarrow \Delta E \propto L^3 ?$$

$\Delta E$ \text{collisional} \leftrightarrow \Delta E \text{radiative} \leftrightarrow \Delta E \text{AdS/CFT}$

$v^\text{ch jet}_2$: comparing short to long $L$ at fixed medium density

$\langle L_{\text{in}} \rangle \approx \langle L_{\text{out}} \rangle$ \quad $\langle L_{\text{in}} \rangle < \langle L_{\text{out}} \rangle$

$v^\text{ch jet}_2 \approx 0$? \quad $v^\text{ch jet}_2 > 0$?

---

$^3$ R. Baier et al. NPB484 265-282 ($\propto L$)
$^4$ R. Baier et al. NPB483 291-320 ($\propto L^2$)
$^5$ C. Marquet, T. Renk, PLB685 270-276 ($\propto L^3$)
$v_2^{\text{ch jet}}$ is measured using the ‘in-plane’ and ‘out-of-plane’ $p_T$-differential jet yields $N_{\text{in}}, N_{\text{out}}$

$$v_2^{\text{ch jet}} = \frac{\pi}{4} \frac{N_{\text{in}} - N_{\text{out}}}{R N_{\text{in}} + N_{\text{out}}}$$

resolution $R$ corrects for the finite precision of symmetry plane estimate $\Psi_{\text{EP, 2}}$

$v_2^{\text{ch jet}}$ is the second coefficient of a Fourier series

$$\frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_n)} \propto 1 + \sum_{n=1}^{\infty} 2v_n^{\text{ch jet}} \cos[n(\varphi_{\text{jet}} - \Psi_n)]$$

$$N_{\text{in}} = \int_{\text{in}} \frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_{\text{EP, 2}}^{V_0})} = a \left( \pi + 4v_2^{\text{ch jet}} \right)$$

$$N_{\text{out}} = \int_{\text{out}} \frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_{\text{EP, 2}}^{V_0})} = a \left( \pi - 4v_2^{\text{ch jet}} \right)$$
Non-zero $v_2^{ch \ jet}$ over full $p_T$ range

Good agreement with JEWEL
What about central collisions?

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{ALICE: Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, $R = 0.2$ anti-$k_T$, $|\eta_{\text{jet}}| < 0.7$

\(\langle L_{\text{in}} \rangle \approx \langle L_{\text{out}} \rangle\)

\(v_2^{\text{ch jet}} \approx 0?\)

\(p_T^{\text{track}} > 0.15 \text{ GeV/c}, p_T^{\text{lead}} > 3 \text{ GeV/c}\)

\textbf{Strong effect} of fluctuations in the \textbf{participant} distribution? ... but beware the \textbf{large} and \textbf{correlated} systematic uncertainties

PLB 753 (2016) 511-525
\end{figure}

Redmer Alexander Bertens - January 21, 2016
Hard probes of the hot plasma - slide 61 of 66
In a broader context

Different energy scales for $v_2^{\text{part}}$, $v_2^{\text{ch jet}}$ and $v_2^{\text{ch+emjet}}$, qualitative comparison only

Non-zero $v_2^{(*)}$ indicative of dependence on (effective) path-length
Needs high-precision follow-up
... concluding ...

first ‘hard probe’
measurement
15 years ago

but the field
has
evolved
quite a bit

Redmer Alexander Bertens - January 21, 2016
Hard probes of the hot plasma - slide 63 of 66
How-to: constrain QGP properties?

Which processes is dominant? (radiative, elastic)

Where does radiated energy go?

What drives e-loss? Geometry or fluctuations?

#questions ≫ #answers
How-to: constrain QGP properties?

Which **processes** is dominant? (radiative, elastic)
How-to: constrain QGP properties?

Which **processes** is dominant? (radiative, elastic)

Where does radiated energy **go**?
How-to: constrain QGP properties? Which **processes** is dominant? (radiative, elastic) Where does radiated energy **go**? What **drives** e-loss? Geometry or fluctuations? #questions ⇒ #answers
Hot and Dense QCD matter, Unraveling the Mysteries of the Strongly Interacting QGP & The Hot QCD White Paper

Redmer Alexander Bertens - January 21, 2016

Hard probes of the hot plasma - slide 65 of 66
fin

thanks for your attention / patience
BACKUP
\( v_{2}^{\text{ch jet}} \) in 0-5\% and 30-50\% collision centrality

\( v_{2}^{\text{ch jet}} \) is measured in 0-5\% (left) and 30-50\% (right) collision centrality

- [0-5\%] \( \approx 2 \sigma \) deviation from 0
- [30-50\%] \( \approx 3 - 4 \sigma \) deviation from 0

\[ v_{2}^{\text{ch jet}} \text{(0-5\%)} \approx 2 \sigma \text{ deviation from 0} \]
\[ v_{2}^{\text{ch jet}} \text{(30-50\%)} \approx 3 - 4 \sigma \text{ deviation from 0} \]

\begin{align*}
\tilde{\chi}^2(\epsilon_{\text{corr}}, \epsilon_{\text{shape}}) &= \left[ \sum_{i=1}^{n} \frac{(v_{2i} + \epsilon_{\text{corr}} \sigma_{\text{corr},i} + \epsilon_{\text{shape}})^2}{\sigma_{i}^2} \right] + \epsilon_{\text{corr}}^2 + \frac{1}{n} \sum_{i=1}^{n} \frac{\epsilon_{\text{shape}}^2}{\sigma_{\text{shape},i}^2} \\
\end{align*}

\(^{6}\) Phys. Rev. C77, 064907 (2008), 0801.1665
**Expected** $\delta p_T$ width **without** flow from charged particles from $N_A$ (multiplicity in a cone) $\langle p_T \rangle$ (mean $p_T$ of particle spectrum) $\sigma(p_T)$ (width of particle spectrum)

\[
\sigma(\delta p_T^{\nu_n=0}) = \sqrt{N_A\sigma^2(p_T) + N_A\langle p_T \rangle^2}
\]

Adding $\nu_n$ by introducing non-Poissonian fluctuations $\sigma_{NP}(N_A) = 2N_A(v_2^2 + v_3^2)$

\[
\sigma(\delta p_T^{\nu_n}) = \sqrt{N_A\sigma^2(p_T) + (N_A + \sigma_{NP}(N_A))\langle p_T \rangle^2}
\]

- ‘expected’ as above: from $N_A$ and $\langle p_T \rangle$, etc.
- ‘measured’: from $\delta p_T$ distributions
  - $\sigma(\delta p_T^{\nu_n})$ from $\langle \rho_{ch} \rangle$
  - $\sigma(\delta p_T^{\nu_n=0})$ from $\rho_{ch\ local}$

$\rho_{ch\ local}$ gives expected reduction of flow contribution to the $\delta p_T$ width
Fluctuations quantified by $\delta p_T$

$\delta p_T$ distribution built using $\langle \rho_{ch}\rangle$

$\delta p_T$ distribution built using $\rho_{\text{ch\ local}}$

**UE subtraction technique successfully removes flow bias from UE**

- Modulation of mean $\delta p_T$ decreases strongly
- Width of $\delta p_T$ in-plane is larger than out-of-plane
- In-plane and out-of-plane jet spectra need to be unfolded independently to properly treat UE fluctuations
\( Q_{pPb} \) and centrality in \( p-Pb \) collisions

\[ \langle N_{\text{coll}} \rangle \text{ not easy to determine in } p-Pb \text{ collisions} \]

\[ Q_{pPb}(p_T, \text{cent}) = \frac{dN_{pPb}^{\text{cent}}}{d\langle N_{\text{coll}}^{\text{cent}} \rangle \cdot dN_{pp}^{\text{cent}}/dp_T} \]

‘Pb–Pb approach’(a) is biased

Hybrid centrality method (b):

- Estimate centrality from Zero Degree Calorimeter
- \( \langle N_{\text{coll}}^{\text{cent}} \rangle \) scales with charged particle multiplicity in mid-rapidity or Pb-going side

Figures on this slide: arXiv 1412.6828 (submitted to Phys. Rev. C)
$R_{AA}$, $R_{pPb}$ of identified particles and jets

$R_{AA}$ of identified particles gives deeper insight into energy loss mechanisms in the plasma and hadron production

Light flavor hadrons
- Medium modification of hadronization process

Jets
- Energy loss of hard partons
- High $Q^2$ process: perturbative probes of the QGP

Open charm mesons ($D^0$, $D^+$, $D^{*+}$) $R_{AA}$ and quarkonium
- Heavy quarks probe the full evolution of the medium
- Quark vs gluon energy loss, dead cone effect
Light flavor hadron $R_{AA}$

- Mass ordering at intermediate $p_T$: less suppression of protons
- At large $p_T$ no difference between species

**Figure:**

- **Peak at 3 GeV/c for $p/\pi$ and $K/\pi$ ratios**
  - More pronounced for $p/\pi$ ratio
  - Indicative of radial flow? What about e.g. the $\phi$-meson (next slide)?
  - High $p_T$ suggests hadronization through fragmentation

---

**PLB 736 (2014) 196-207**
Light flavor hadron $R_{AA}$

- Mass ordering at intermediate $p_T$: less suppression of protons
- At large $p_T$ no difference between species

Peak at 3 GeV/$c$ for $p/\pi$ and $K/\pi$ ratios

- More pronounced for $p/\pi$ ratio
- Indicative of radial flow? What about e.g. the $\phi$-meson (next slide)?
- High $p_T$ suggests hadronization through fragmentation
Particle production - more ratios

\[ \text{Baryon/Meson Ratio} \]

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ \text{Centrality 0-10\%} \]

\( p/\pi \)

\( \phi/p \times 0.1 \)

\( \Lambda/K_S^0 \)

\( \phi\text{-meson and } p \text{ have similar mass} \)

\( \bullet \text{ Ratio } \phi/p \text{ flat for central collisions} \)

\( \text{Shape of } p_T \text{ distributions} \)

\( \text{determined by particle mass, not recombination} \)

\( \text{Phys. Rev. Lett. 111 222301 (2013)} \)


\( \text{Phys. Rev. C 91 (2015) 024609} \)
Several models describe $R_{pPb}$

- Gluon saturation models (color glass condensate) agree with the data, however only small effects are expected.
- NLO pQCD with EPS09s agrees with data for transverse momenta $> 6$ GeV/$c$.
- LO pQCD + cold nuclear matter under-predicts data at high $p_T$.

Known potential nuclear effects (CGC/saturation and nPDF) are small at mid-rapidity/high $p_T$: consistent with measurement.
$Q_{pPb}$ of jets

$R = 0.2$ (left) and $R = 0.4$ (right) charged jets, anti-$k_T$

- $Q_{pPb}$ following hybrid centrality estimation
- Results compatible with no final state effect on jet spectra

See also arXiv:1503.00681
Is this really a medium vs. vacuum effect?

$R_{pPb}$ in p–Pb collisions
- Compound system (p–nucleus)
- Expected to be sensitive to initial state, but not final state (QGP) effects

$R_{pPb}$ is consistent with unity for $p_T > 2$ GeV/$c$
- Small Cronin-like enhancement visible at low $p_T$
- Consistent with $R_{AA}$ of particles which are not sensitive to QGP dynamics ($\gamma, W^\pm, Z^0$)

Suppression of hadron production in Pb–Pb collisions is **final state** effect

PRL 110, 082302 (2013)