# Path length dependence of jet quenching

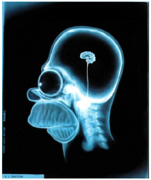
(and quite a bit more)

**Redmer Alexander Bertens**

THE UNIVERSITY OF TENNESSEE KNOXVILLE

**33rd Winter Workshop on Nuclear Dynamics**

# Jet quenching - what and why?

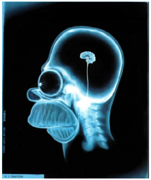


**Tomography**

*'imaging through* **modification** *of penetrating wave'*

# Jet quenching - what and why?

THE UNIVERSITY OF TENNESSEE KNOXVILLE

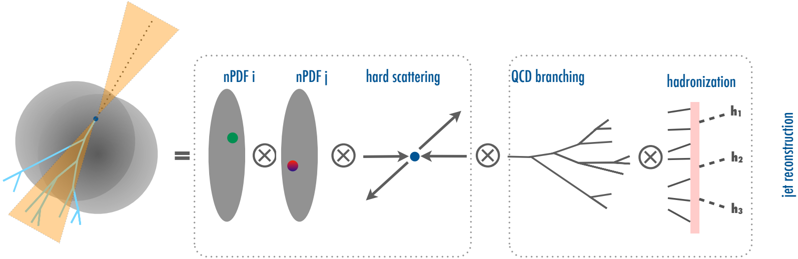


**Tomography**

*'imaging through* ***modification*** *of penetrating wave'*

'**Motivation**' for jets in heavy-ion collisions is similar

- How do you study the non-perturbative QGP ?
- Use **well-known** (perturbative) **probe** (i.e. large $Q^2$ process)
- Deduce medium properties from **modification** of the probe by the medium



# Outline

... so when we talk about jets in heavy ions, we talk about ...

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')

# Outline

... so when we talk about jets in heavy ions, we talk about ...

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 morning

- How-to: experimentally constrain QGP properties?
- Which mechanisms contribute to parton energy loss, and how can we model them?
- What **drives** energy loss? Geometry or fluctuations?

# Outline

... so when we talk about jets in heavy ions, we talk about ...

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 morning

- How-to: experimentally constrain QGP properties?
- Which mechanisms contribute to parton energy loss, and how can we model them?
- What **drives** energy loss? Geometry or fluctuations?


**but let's start with single tracks - to get a feeling of what we're talking about**

# Chapter 1) $R_{\mathrm{AA}}$

# ‘nuclear modification factor’

# of single tracks

.

.

# and a few words on modeling

# Nuclear modification factor $R_{AA}$

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

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

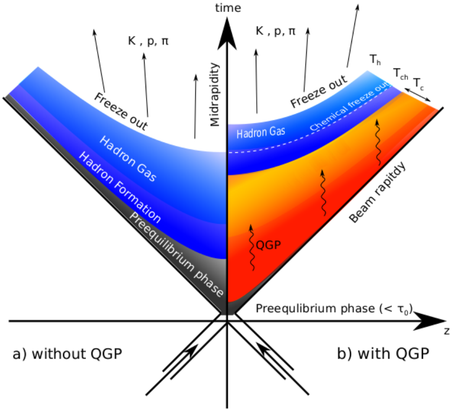
$\langle T_{AA}\rangle \propto \langle N_{coll}\rangle =$ no. of binary nucleon-nucleon collisions

Possible scenarios

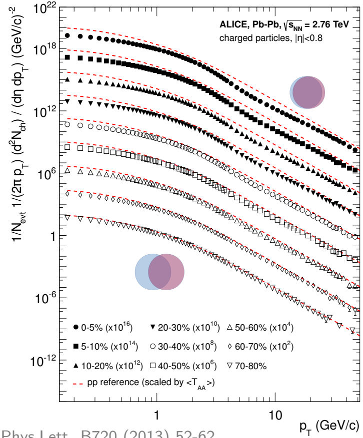
- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (**suppression**)

Assumption ...

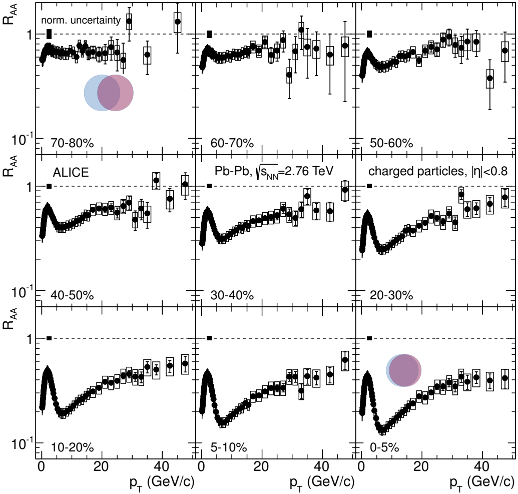
- ... partons **lose** energy in the medium
- $R_{\mathbf{AA}} < \mathbf{1}$



# 'Convenient' to measure ...




Phys.Lett. B720 (2013) 52-62




Phys.Lett. B720 (2013) 52-62

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

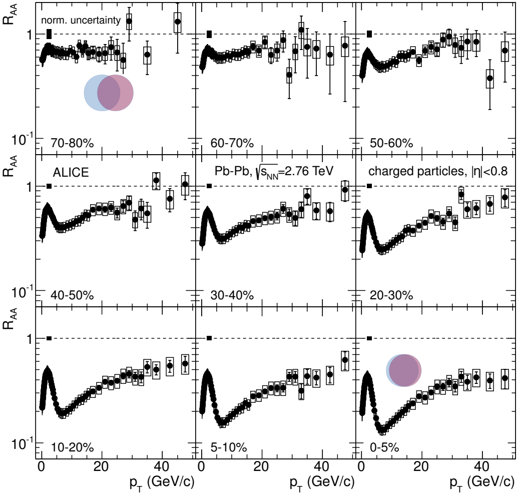
**Suppression** depends on **centrality**: stronger for more central collisions

- Strongest suppression around 7 GeV/$c$ for all centralities
- Suppression non-zero up to high transverse momenta

More **central** collisions

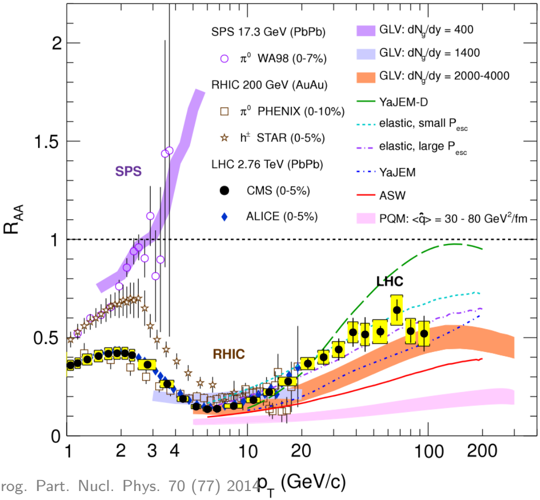
- longer average path length
- **denser medium**

$\longrightarrow$ stronger suppression




Phys.Lett. B720 (2013) 52-62

# $R_{AA}$ - from SPS to RHIC to LHC




Prog. Part. Nucl. Phys. 70 (77) 2014

Results from LHC and RHIC are qualitatively similar

- $R_{AA} < 1$ points at **energy loss**

Decrease of $R_{AA}$ with increasing $\sqrt{s_{NN}}$

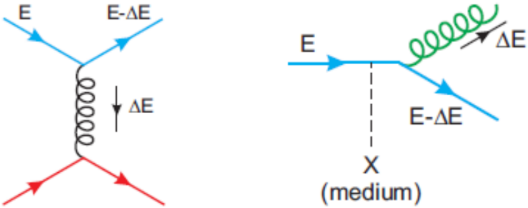
- Indicative of higher medium **density** at the LHC compared to RHIC

Data (and models) suggest **decrease** of relative e-loss at high $p_T$

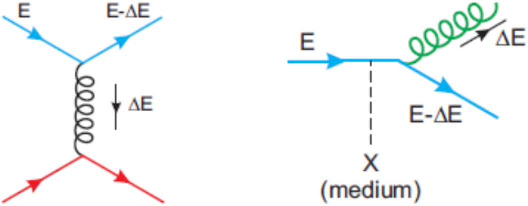
**so the $R_{AA}$ s a nice 'educational' tool - but let's go a bit deeper**

# How do parton's lose energy?

in the **'classic'** (vs. AdS/CFT) QCD picture energy loss is either **collisional** or (induced) **radiative**



in the **'classic'** (vs. AdS/CFT) QCD picture energy loss is either **collisional** or (induced) **radiative**




**both** mechanisms have an explicit dependence on the **length** of the parton's tracjectory through the QGP ($L$, $L^2$) and medium **density**

.

.

**LPM interference** - if parton and gluon are still in a **coherent state** further radiation is **suppressed**

# Modeling and the factorization theorem

Constraining QGP properties starts with **comparing** our data to **models**
**factorization** is the basis for all parton energy loss models

$$\underbrace{\left.\frac{dN}{dp_{\mathrm{T}}}\right|_{\text{hadrons}}}_{\text{final state}} = \underbrace{\left.\frac{dN}{dE}\right|_{\text{jets}}}_{\text{pQCD, nPDF's}} \otimes \underbrace{P(\Delta E)}_{\text{energy loss distribution}} \otimes \underbrace{D(p_{\mathrm{T}}/E)}_{\text{fragmentation function}}$$

or - in words

- a **parton** is created in a hard scattering
- it 'travels' through the QGP along a **trajectory** $L$
- along its path it has a **probability** of scattering and/or radiating gluons
- $P(\Delta E)$ 'holds' medium information ($\hat{q}, \eta/s, T, ...$)

# Modeling and the factorization theorem

Constraining QGP properties starts with **comparing** our data to **models**
**factorization** is the basis for all parton energy loss models

$$\underbrace{\left.\frac{dN}{dp_{\mathrm{T}}}\right|_{\mathrm{hadrons}}}_{\text{final state}} = \underbrace{\left.\frac{dN}{dE}\right|_{\mathrm{jets}}}_{\text{pQCD, nPDF's}} \otimes \underbrace{P(\Delta E)}_{\color{red}{\text{energy loss distribution}}} \otimes \underbrace{D(p_{\mathrm{T}}/E)}_{\text{fragmentation function}}$$

or - in words

- a **parton** is created in a hard scattering
- it 'travels' through the QGP along a **trajectory** $L$
- along its path it has a **probability** of scattering and/or radiating gluons
- $P(\Delta E)$ 'holds' medium information ($\hat{q}, \eta/s, T, ...$)

which brings us to the main point of these slides

.

.

to **understand** the nature of energy loss, experiments must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution

# let's move a bit closer to partons

.

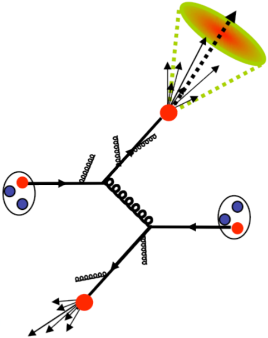
.

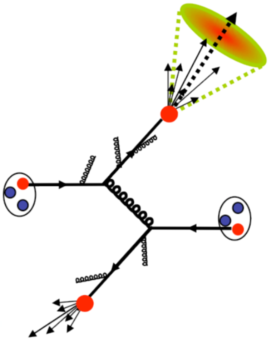
.

# Chapter 2) Jets

Hard scattering ($Q^2 > 1$ (GeV/$c$)$^2$)

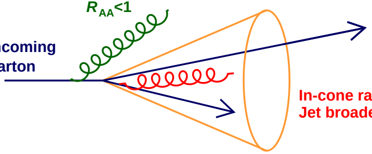
- Parton travels through the QGP, **scattering** and **radiation** of quarks and gluons
- Hadronization into colorless spray: **'jet'**
- Reconstructed jet: as close as one can experimentally get to **original parton**
- 'Removes' ill-understood hadronization from modeling





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

- Parton travels through the QGP, **scattering** and **radiation** of quarks and gluons
- Hadronization into colorless spray: **'jet'**
- Reconstructed jet: as close as one can experimentally get to **original parton**
- 'Removes' ill-understood hadronization from modeling




Energy loss has **two** distinct effects on jets

- **Out-of-cone** radiation: $R_{\mathrm{AA}} < 1$
- **In-cone** radiation: $R_{\mathrm{AA}} = 1$, fragmentation function changes

Of course, these are **not exclusive ...**

# Path-length dependence: di-jet systems

‘so to **understand** the nature of energy loss, we must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution’

# Path-length dependence: di-jet systems

‘so to **understand** the nature of energy loss, we must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution’

Di-jet system: $2 \longrightarrow 2$ process

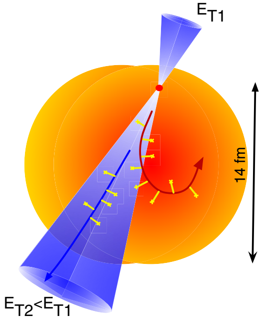
- Jets traveling in **opposite** direction with **equal** initial transverse momentum $p_{T1} = p_{T2}$
- $L_1 \neq L_2$
- $\Delta E_1 \neq \Delta E_2$
- **Final** state $p_T$ is **not** equal $p_{T1} \neq p_{T2}$

Some caveats ... in all collision systems $p_{T1} \neq p_{T2}$

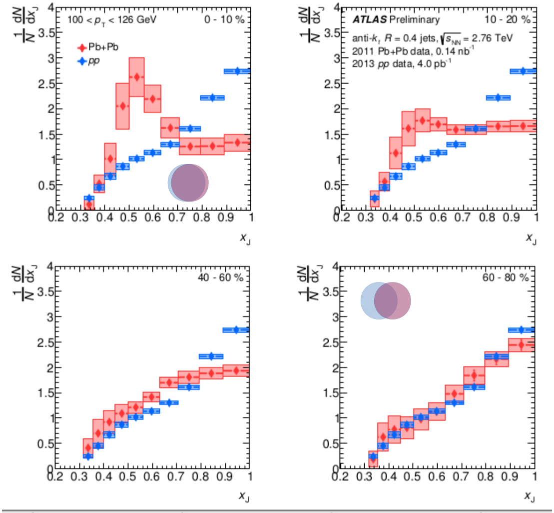
- pp: recoil, out-of-cone radiation (vacuum fluctuations)
- AA: energy loss **fluctuations**, **different path-lengths**

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

$$x_j = p_{T1}/p_{T2}$$



# Di-jet imbalance $x_j = p_{T1}/p_{T2}$



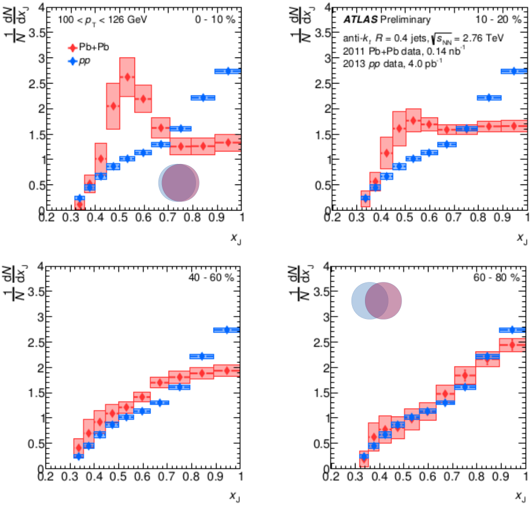

Asymmetry quantified as

$$x_j = p_{T1}/p_{T2}$$

Fully **unfolded**

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

# Di-jet imbalance $x_j = p_{T1}/p_{T2}$




Asymmetry quantified as

$$x_j = p_{T1}/p_{T2}$$

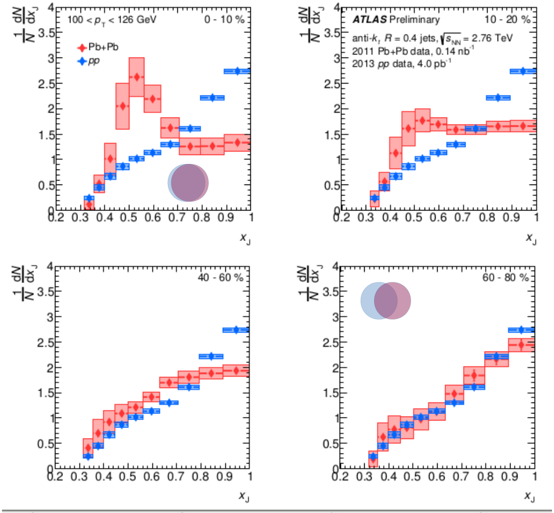
Fully **unfolded**

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

In **pp**

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

# Di-jet imbalance $x_j = p_{T1}/p_{T2}$




Asymmetry quantified as

$$x_j = p_{T1}/p_{T2}$$

Fully **unfolded**

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

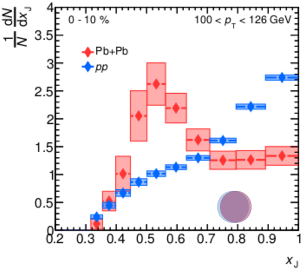
In **pp**

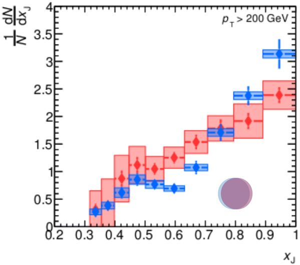
- most probable dijet configuration: $x_j \approx 1$

In **Pb–Pb**

- most probable configuration: subleading jet has **half** as much energy as leading jet

Strong **centrality** dependence

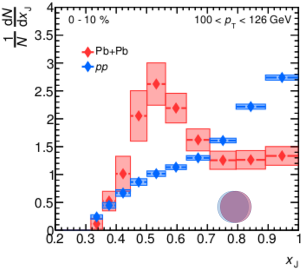


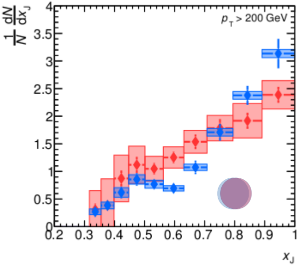




Asymmetry: $x_j = p_{T1}/p_{T2}$

- With **increasing** $p_T \longrightarrow x_j$ goes **towards 1**

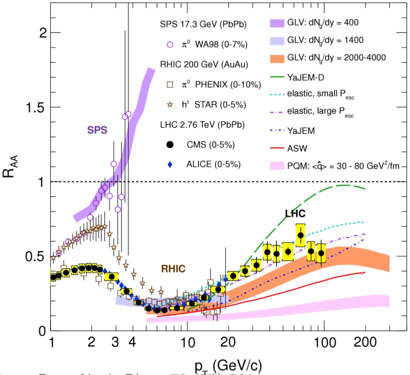
# Di-jet imbalance $x_j = p_{T1}/p_{T2}$




Asymmetry: $x_j = p_{T1}/p_{T2}$

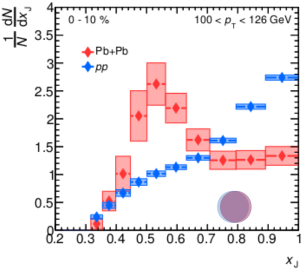
- With **increasing** $p_T \longrightarrow x_j$ goes **towards 1**

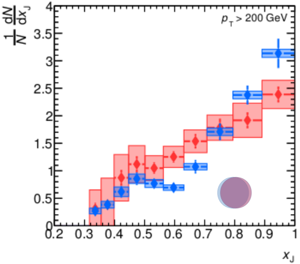



Prog. Part. Nucl. Phys. 70 (77) 2014

**confirms** sl. 6 'Relative loss decreases with $p_T$'

# Di-jet imbalance $x_j = p_{T1}/p_{T2}$




In summary

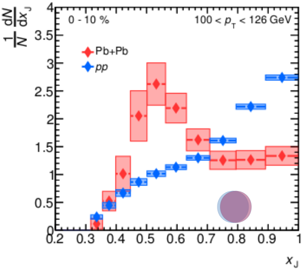
- $R_{AA}$: moderate **average** energy loss
- di-jets: **wide variation** in possible energy loss

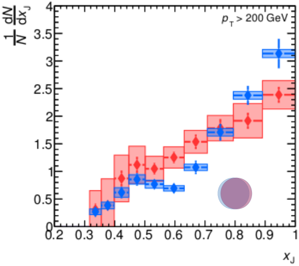
So di-jet asymmetry very nicely illustrates

- centrality dependence hints on **path length** dependence
- e-loss is a **distribution**

# Di-jet imbalance $x_j = p_{T1}/p_{T2}$

THE UNIVERSITY OF TENNESSEE KNOXVILLE




In summary

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

So di-jet asymmetry very nicely illustrates

- centrality dependence hints on **path length** dependence
- e-loss is a **distribution**

But it doesn't tell what the **balance** is between

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

‘to **understand** the nature of energy loss, experiments must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution’

‘to **understand** the nature of energy loss, experiments must get as close to **partons** as possible, constrain the **trajectory** and measure the **shape** of the e-loss distribution’

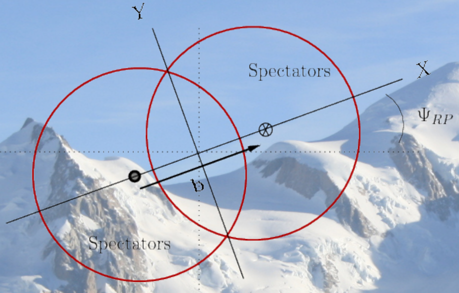
.

.

.

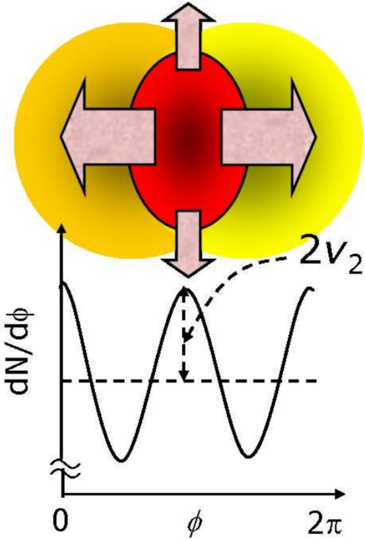
so let’s give that a go from both the **experimental** and **theory** side

# Experimentally fixing pangth length



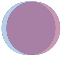

## event-plane dependence of jet production

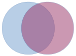
# $v_2^{\text{ch jet}}$: 'selecting' path lengths




$v_2^{\text{ch jet}}$: comparing short to long $L$ at fixed medium density

$\langle L_{\text{in}} \rangle \approx \langle L_{\text{out}} \rangle$
$v_2^{\text{ch jet}} \approx 0$?



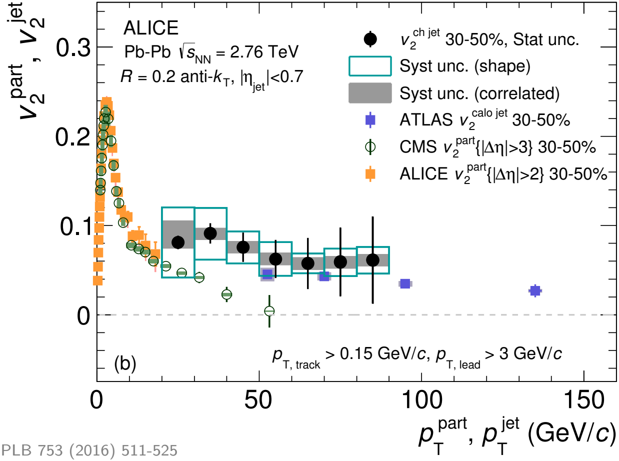


$\langle L_{\text{in}} \rangle < \langle L_{\text{out}} \rangle$
$v_2^{\text{ch jet}} > 0$?

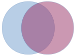
so this is **not** hydro flow! the contribution of $v_n$ to $v_2^{\text{ch jet}}$ has been **removed**

# $v_2^{\text{ch jet}}$ in semi-central collisions

THE UNIVERSITY OF TENNESSEE KNOXVILLE




PLB 753 (2016) 511-525



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

$v_2^{\text{ch jet}} > ?$

**Non-zero** $v_2^{\text{ch jet}}$ over full $p_T$ range - strong path length dependence

**Good agreement** between measurements of ALICE, ATLAS, CMS

# ‘Theorically’ fixing path lengths

.

.

.

generate di-jets with $L_1 = L_2$
compare to $L_1 \neq L_2$

# Briefly introducing the model: JEWEL

JEWEL (Jet Evolution With Energy Loss)

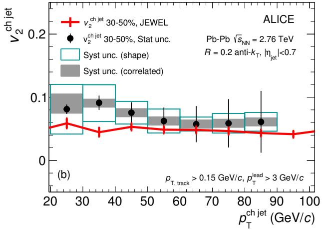
- **Radiative** energy loss with **LPM** interference and elastic **scatterings** (plus momentum exchange [recoil] with medium)
- Glauber initial conditions + PYTHIA hard scatterings
- Bjorken expanding medium

# Briefly introducing the model: JEWEL

JEWEL (Jet Evolution With Energy Loss)

- **Radiative** energy loss with **LPM** interference and elastic **scatterings** (plus momentum exchange [recoil] with medium)
- Glauber initial conditions + PYTHIA hard scatterings
- Bjorken expanding medium

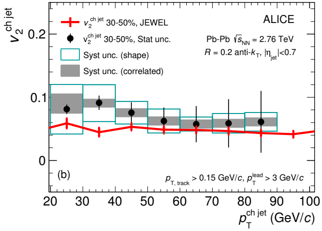
Very succesful in describing RHIC and LHC



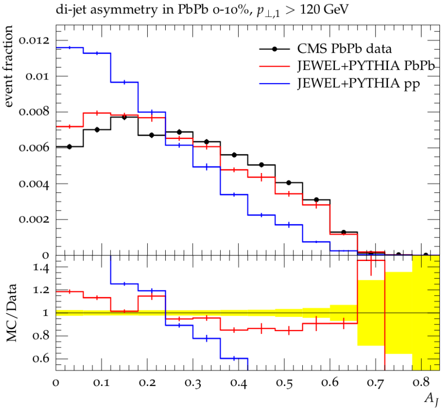
JEWEL (Jet Evolution With Energy Loss)

- **Radiative** energy loss with **LPM** interference and elastic **scatterings** (plus momentum exchange [recoil] with medium)
- Glauber initial conditions + PYTHIA hard scatterings
- Bjorken expanding medium

Very succesful in describing RHIC and LHC

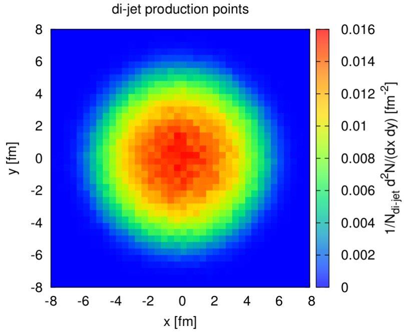


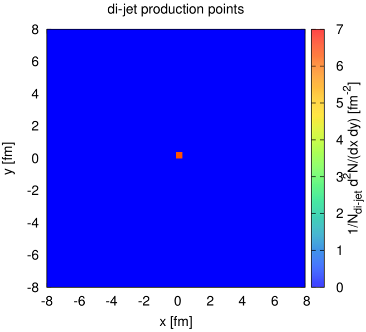

Especially interesting: agreement with CMS **di-jet** imbalance



# Fixing path lengths with JEWEL

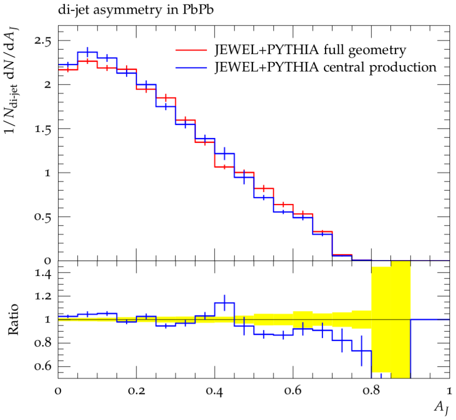
**‘Origins of the di-jet asymmetry in heavy ion collisions’**
(26/12/2015, arXiv:1512.08107)

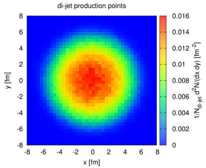


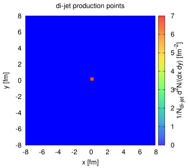




Study original of imbalance by using random (**left**) or fixed (**right**) di-jet production points - fixed points: both jets **‘see’ same** medium distance $L$

# Fixing path lengths with JEWEL



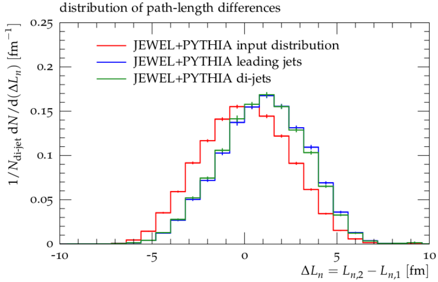



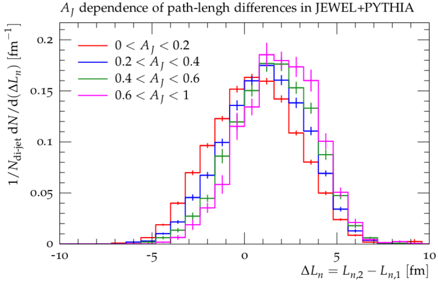




**(≈ verbatim) from the paper**

- 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

# Path lengths dissected

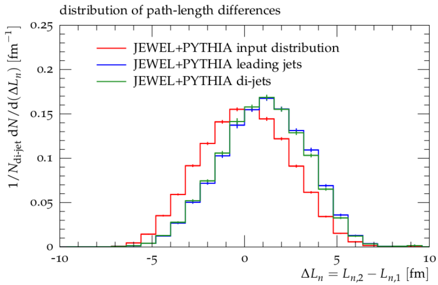


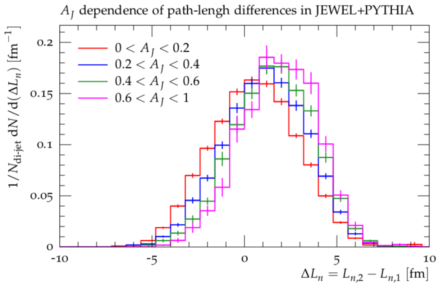




$\approx$ 35% of cases $L_1 > L_2$ (**density** weighted path-length)
Dependence of $A_j$ on $\Delta L_n$ **small** compared to **width** (strong fluctuations)

# Path lengths dissected





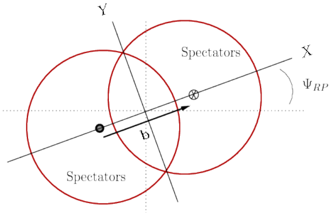




$\approx 35\%$ of cases $L_1 > L_2$ (**density** weighted path-length)
Dependence of $A_j$ on $\Delta L_n$ **small** compared to **width** (strong fluctuations)

**conflict with measurements? experimental answers ?**

# Event-plane dependence of di-jets

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

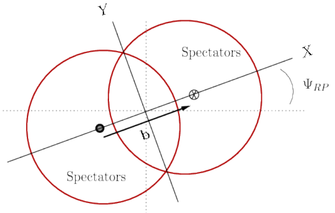


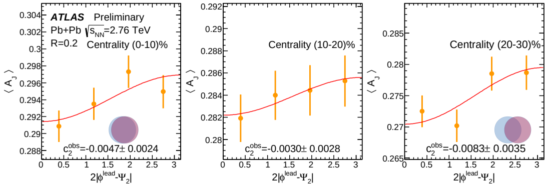

- $\langle A_j \rangle$ **smaller** for dij-ets in direction of $\Psi_{\text{EP, 2}}$

# Event-plane dependence of di-jets

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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



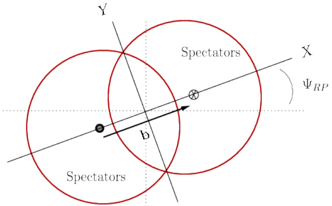



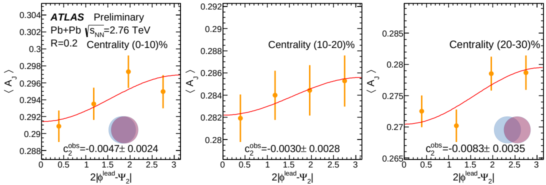

$$\langle A_j \rangle = A_J^0 \left(1 + 2c_2 \cos(2(\varphi^{\text{lead}} - \Psi_{\text{EP, 2}}))\right)$$

- $\langle A_j \rangle$ **smaller** for dij-ets in direction of $\Psi_{\text{EP, 2}}$
- Reasonably described by cosine modulation
- Anti-correlation is **signficant**

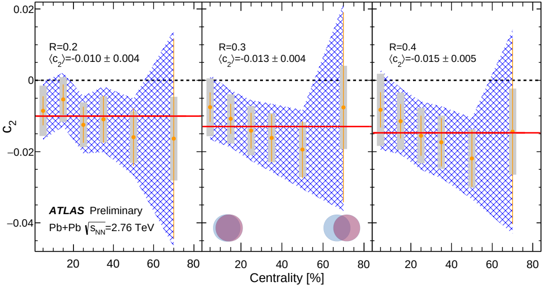
# Event-plane dependence of di-jets

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




$$\langle A_j \rangle = A_J^0 \left(1 + 2c_2 \cos(2(\varphi^{\text{lead}} - \Psi_{\mathrm{EP},\,2}))\right)$$




- $\langle A_j \rangle$ **smaller** for dij-ets in direction of $\Psi_{\mathrm{EP},\,2}$
- Reasonably described by cosine modulation
- Anti-correlation is **signficant**

Points at small but **significant**(?) contribution to asymmetry from **geometry** that's all

.

.

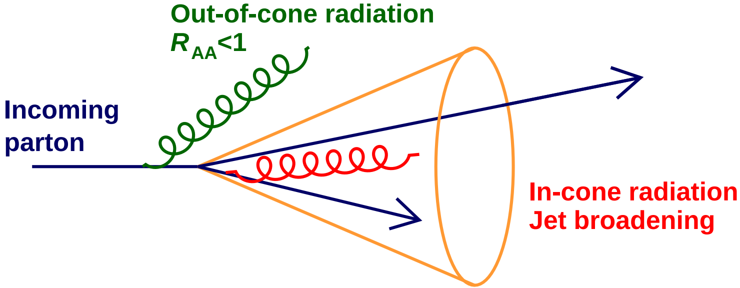
.

How-to: experimentally constrain QGP properties?

Which mechanisms contribute contribute to parton energy loss, and how can we model them?

What drives energy loss? Geometry or fluctuations?


BACKUP




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 ...**

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} =$$

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \underbrace{\sum_{p=q,g} \int d^3k}_{\text{sum over states}}$$

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \underbrace{\sum_{p=q,g} \int d^3k}_{\text{sum over states}} \quad \overbrace{\rho_p(k)}^{\text{plasma density}}$$

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \underbrace{\sum_{p=q,g} \int d^3k}_{\text{sum over states}} \overbrace{\rho_p(k)}^{\text{plasma density}} \int \mathrm{d}q^2 \overbrace{J}^{\text{flux}}$$

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \underbrace{\sum_{p=q,g} \int d^3k}_{\text{sum over states}} \overbrace{\rho_p(k)}^{\text{plasma density}} \int \mathrm{d}q^2 \overbrace{J}^{\text{flux}} \omega \underbrace{\frac{\mathrm{d}\sigma^{Qp\rightarrow Qp}}{\mathrm{d}q^2}}_{\text{cross section}}$$

As a 'back of the envelope' thought, ingredients for **collisional** energy loss where $\omega = E^{\text{initial}} - E^{\text{final}}$ is transferred one can write

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \underbrace{\sum_{p=q,g} \int d^3k}_{\text{sum over states}} \overbrace{\rho_p(k)}^{\text{plasma density}} \int \mathrm{d}q^2 \overbrace{J}^{\text{flux}} \omega \underbrace{\frac{\mathrm{d}\sigma^{Qp \rightarrow Qp}}{\mathrm{d}q^2}}_{\text{cross section}}$$

with a **lot of trickery that we'll skip** this can be integrated

$$-\frac{\mathrm{d}E}{\mathrm{d}z} = \pi\alpha_s^2 \sum_p C_p \int \frac{d^3k}{k} \rho_p(k) \ln\left(\frac{q^2_{\text{max}}}{q^2_{\text{min}}}\right)$$

$$\simeq \frac{4\pi\alpha_s^2 T^2}{3}\left(1 + \frac{N_f}{6}\right) \ln\left(\frac{cE}{\alpha_s T}\right)$$

The energy loss for **radiative** processes is directly connected to the **energy of the radiated gluon** $\omega$

$$\langle \Delta E \rangle = \int \mathrm{d}\omega \mathrm{d}z \; \omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z}$$

# Radiative energy loss - an incompleter picture

The energy loss for **radiative** processes is directly connected to the **energy of the radiated gluon** $\omega$

$$\langle \Delta E \rangle = \int \mathrm{d}\omega \mathrm{d}z \, \omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z}$$

The difficulty enters here: gluons have a finite **formation time** during which the parton and gluon are still a **coherent** object

$$\tau_f \simeq \frac{\omega}{k_\perp^2}$$

The energy loss for **radiative** processes is directly connected to the **energy of the radiated gluon** $\omega$

$$\langle \Delta E \rangle = \int \mathrm{d}\omega \mathrm{d}z \, \omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z}$$

The difficulty enters here: gluons have a finite **formation time** during which the parton and gluon are still a **coherent** object

$$\tau_f \simeq \frac{\omega}{k_\perp^2}$$

if parton and gluon are still in a **coherent state** further radiation is **suppressed** - this effect is known as **LPM interference**

# LPM interference in radiative processes

Because of the finite $\tau_f$ the gluon spectrum has **three** distinct regimes depending on mean free path $\lambda$ and screening mass $\mu$

$$\omega \frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}z} \simeq \begin{cases} \frac{\alpha_s}{\lambda} & \omega < \omega_{\mathrm{BH}} \\ \frac{\alpha_s}{\lambda}\sqrt{\frac{\lambda\mu^2}{\omega}} & \omega_{\mathrm{BH}} < \omega < \omega_{\mathrm{fact}} \\ \frac{\alpha_s}{L} & \omega_{\mathrm{fact}} < \omega < E \end{cases}$$

1. **Low** gluon energies: **all constituents** act as single sources of radiation
2. **Intermediate** energies: **multiple** constituents act as a **coherent** scattering source (LPM interference)
3. **Highest** energies: the entire medium acts as **one** scattering center

$$\langle \Delta E \rangle (L) \sim c_1 \alpha_s E + c_2 \alpha_s \frac{\mu^2 L^2}{\lambda}$$