Jet Quenching via Jet Collimation

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jets [what has the LHC done for us]

- LHC data on full jets in PbPb collisions [previous talks] offers the possibility to probe the QCD dynamics in the presence of a medium

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a wealth of information encoded in substructure, ...
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  → consistently describe details of jet structure

  → consummate the unique role of jets as detailed probes of medium properties
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- no full theoretical description yet available
  - many important developments [solidly grounded on RHIC data]
    - importance of radiative and collisional energy loss, ...

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Does available LHC data imply qualitative rethinking/development of fundamental ingredients of ‘Jet Quenching’?
**measurement of di-jet asymmetry**

- **imbalance of jet energy within a cone of radius R**

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

|          | int. luminosity [\(\mu\text{b}^{-1}\)] | \(R\) | \(E_{T1}^{\text{min}}\) [GeV] \(\text{[leading jet]}\) | \(E_{T2}^{\text{min}}\) [GeV] \(\text{[recoiling jet]}\) | \(\Delta\phi^{\text{min}}\) |
|----------|----------------------------------------|-------|-----------------------------------|-----------------------------------|------------------|
| ATLAS    | 1.7                                    | 0.4   | 100                               | 25                                | \(\pi/2\)        |
| CMS      | 6.7                                    | 0.5   | 120                               | 50                                | \(2\pi/3\)       |

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**Image:**
- E\(_{T1}\) and E\(_{T2}\) with a cone indicating the imbalance of jet energy within a cone of radius R. The cone extends from E\(_{T1}\) to E\(_{T2}\), with R = \(12\text{ fm}\).
measurement of di-jet asymmetry

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- imbalance of jet energy within a cone of radius \( R \)

| int. luminosity [\( \mu b^{-1} \)] | \( R \) | \( E_{T1\text{min}} \) [GeV] [leading jet] | \( E_{T2\text{min}} \) [GeV] [recoiling jet] | \( \Delta \phi \text{min} \) |
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requires [challenging] jet identification in large and fluctuating background
measurement of di-jet asymmetry

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- concerns have been raised [Cacciari, Salam, Soyez :: 1101.2878] that background fluctuations can significantly affect the measured asymmetry
measurement of di-jet asymmetry

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measurement of di-jet asymmetry

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- imbalance of jet energy within a cone of radius \( R \)

\[ E_{T1} \]

\[ E_{T2} \]

\[ \Delta \phi \]

\[ R \]

\[ \text{int. luminosity} \quad [\mu b^{-1}] \]

\[ E_{T1}^\text{min} \quad [\text{GeV}] \]

\[ E_{T2}^\text{min} \quad [\text{GeV}] \]

\[ \Delta \phi^\text{min} \]

|       | int. luminosity [\mu b^{-1}] | \( R \) | \( E_{T1}^\text{min} \) [GeV] | \( E_{T2}^\text{min} \) [GeV] | \( \Delta \phi^\text{min} \) |
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\[ \text{extensive cross checks carried out by both ATLAS and CMS} \]

\[ \text{see Klein-Boesing’s [ALICE] later in the session} \]
Measurement of di-jet asymmetry

Imbalance of jet energy within a cone of radius $R$.

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

- Requires [challenging] jet identification in large and fluctuating background.
- Concerns have been raised [Cacciari, Salam, Soyez :: 1101.2878] that background fluctuations can significantly affect the measured asymmetry.
- Extensive cross checks carried out by both ATLAS and CMS.
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::for the purpose of this talk::

Observed asymmetry robust against background issues at [least at] the level of qualitative features.
Di-jet asymmetry [qualitative features]

- Asymmetry increases with centrality
- [Increased in-medium path length for recoiling jet]
# di-jet asymmetry [qualitative features]

- ➔ asymmetry increases with centrality
  ➔ [increased in-medium path length for recoiling jet]

- ➔ very mild centrality dependence for azimuthal distribution and essentially unchanged from pp
  ➔ [minor medium-induced jet deflection]
di-jet asymmetry [qualitative features]

- o asymmetry increases with centrality
  ➡️ [increased in-medium path length for recoiling jet]

- o very mild centrality dependence for azimuthal distribution and essentially unchanged from pp
  ➡️ [minor medium-induced jet deflection]

focus on most central events [where the effect is maximal]
most central events

- clear suppression of more symmetric events \([0 < A_J < 0.2]\)
- enhancement of events with \(A_J \approx 0.4 \div 0.5\)
- sharp fall-off at large \(A_J\) not entirely physical [focus on not too large \(A_J\)]
- very mild modification of the azimuthal angle distribution
most central events

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requires medium induced transverse broadening
out-of-cone radiation in PbPb

\[ x = \frac{E_{T2}}{E_{T1}} \]

replicated from ATLAS data

\( \frac{1}{N_{\text{evt}}} \frac{dN}{dx} \)

\( E_{T1} \) good approximation to \( E_{\text{tot}} \)
[data sample biased to leading jets with ‘little’ energy loss]

\( x = \frac{E_{T2}}{E_{T1}} \)
[fractional energy in recoiling jet]
out-of-cone radiation in PbPb

- pp di-jet events are substantially asymmetric
- significant out of cone radiation
  \[
  \langle x \rangle_{pp} \lesssim \frac{1}{N_{evt}} \int dx \, x \frac{dN}{dx} = 0.67 \text{ [ATLAS]} \div 0.70 \text{ [CMS]}
  \]
- wide energy distribution
**out-of-cone radiation in PbPb**

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'**moderate**' additional out-of-cone radiation in PbPb

\[ \langle x \rangle_{PbPb} \lesssim 0.54 \text{ [ATLAS]} \div 0.62 \text{ [CMS]} \quad \langle x \rangle_{pp} - \langle x \rangle_{PbPb} \lesssim 0.12 \text{ [ATLAS]} \div 0.08 \text{ [CMS]} \]
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estimate energy loss

::underestimate::

all jets interact equally

\[ \frac{\Delta E}{E_T} > 0.8 \ (\langle x \rangle_{pp} - \langle x \rangle_{PbPb}) \ [\text{ATLAS}] \div 0.9 \ (\cdots) \ [\text{CMS}] \sim 0.10 \ [\text{ATLAS}] \div 0.07 \ [\text{CMS}] \]
out-of-cone radiation in PbPb

- pp di-jet events are substantially asymmetric
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estimate energy loss

::overestimate::
only fraction \((1-\alpha)\) interact [corona effect]
\[ \frac{\Delta E}{E_T} < \frac{\langle x \rangle_{pp} - \langle x \rangle_{PbPb}}{1 - \alpha} \sim 0.21 \text{ [ATLAS]} \div 0.15 \text{ [CMS]} \]
out-of-cone radiation in PbPb

- pp di-jet events are substantially asymmetric
- significant out of cone radiation
  \[ \langle x \rangle_{pp} \lesssim \frac{1}{N_{evt}} \int dx \frac{dN}{dx} = 0.67 \text{ [ATLAS]} \div 0.70 \text{ [CMS]} \]
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‘moderate’ additional out-of-cone radiation in PbPb

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estimate energy loss

\[ 8.4 \text{ GeV} < \Delta E < 18 \text{ GeV} \text{ [CMS]} \quad 10 \text{ GeV} < \Delta E < 21 \text{ GeV} \text{ [ATLAS]} \]

\[ E_T = 120 \text{ GeV} \text{ [CMS]} \quad E_T = 100 \text{ GeV} \text{ [ATLAS]} \]
underlying dynamics

increased large angle medium induced radiation

at given fixed angle

\[ \tau \sim \frac{1}{\omega \theta^2} \]

:: harder gluons are emitted earlier

:: [semi-]hard gluons deflect jet
increased large angle medium induced radiation

at given fixed angle

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:: [semi-]hard gluons deflect jet

sizeable out-of-cone radiation implies sizeable modification of azimuthal distribution
underlying dynamics must be such that medium effects
LEAD
to significant out of cone radiation
WITHOUT
significant distortion of azimuthal distribution

at given fixed angle
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:: harder gluons are emitted earlier
:: [semi-]hard gluons deflect jet

sizeable out-of-cone radiation implies sizeable modification of azimuthal distribution
underlying dynamics

transport of radiated gluons

radiation of soft gluons at small angle :: no sizeable effect on jet direction
underlying dynamics

transport of radiated gluons

radiation of soft gluons at small angle :: no sizeable effect on jet direction

all jet components accumulate an average transverse momentum [Brownian motion]

\[ \langle k_\perp \rangle \sim \sqrt{\hat{q}L} \]

in the presence of a medium soft modes are formed early

\[ \tau \sim \frac{\omega}{k_\perp^2} \quad \langle k_\perp^2 \rangle \sim \hat{q} \tau \]

sufficiently soft modes are decorrelated from the jet direction

\[ \omega \leq \sqrt{\hat{q}L} \]
underlying dynamics

- all jet components accumulate an average transverse momentum [Brownian motion]
  \[ \langle k_\perp \rangle \sim \sqrt{\hat{q}L} \]

- in the presence of a medium soft modes are formed early
  \[ \tau \sim \frac{\omega}{k_\perp^2} \quad \rightarrow \quad \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}} \]

- sufficiently soft modes are decorrelated from the jet direction
  \[ \omega \leq \sqrt{\hat{q}L} \]

radiation of soft gluons at small angle :: no sizeable effect on jet direction

transport of radiated gluons

the medium acts as a frequency collimator efficiently trimming away the soft components of the jet
jet [frequency] collimation

- energy carried by soft modes [that can be decorrelated] necessary to account for observed energy loss from jet cone

jet frequency collimation affects all soft modes in the jet ‘wave-function’
  :: mechanism effective even if there is no additional medium induced radiation/splittings
    [transports vacuum soft gluons out of the jet cone]
  :: softening of the spectrum [from medium induced radiation] enhances the effect

\[
\frac{E(z)}{E_T} = \int_{\log 1/z}^{\infty} d\xi \ e^{-\xi} \frac{dD}{d\xi}
\]
**jet [frequency] collimation**

- energy carried by soft modes [that can be decorrelated] necessary to account for observed energy loss from jet cone

![Graph showing dD/d\(\xi\) and \(E(z)/ET\) for vacuum and medium](image)

\[
\frac{E(z)}{ET} = \int_{\log 1/z}^{\infty} d\xi \ e^{-\xi} \frac{dD}{d\xi}
\]

- if jet collimation is the sole medium effect [or with additional medium induced softening], transport coefficient needed to account for asymmetry can be estimated from earlier energy loss bounds

vac: MLLA
med: medium modified MLLA
Jet [frequency] collimation

- Energy carried by soft modes [that can be decorrelated] necessary to account for observed energy loss from jet cone

\[
\frac{dD}{d\xi} = \frac{E(z)}{E_T} = \int_{\log 1/z}^{\infty} d\xi e^{-\xi} \frac{dD}{d\xi}
\]

If jet collimation is the sole medium effect [or with additional medium induced softening], transport coefficient needed to account for asymmetry can be estimated from earlier energy loss bounds

\[
\omega^2 = z^2 \frac{E_T^2}{E_0^2} \leq \hat{q}L
\]

| Scenario   | Bound                                                                 |
|------------|----------------------------------------------------------------------|
| Vacuum     | \[35 \left( \frac{E_T}{E_0} \right)^2 \leq \hat{q}L \leq 85 \left( \frac{E_T}{E_0} \right)^2 \text{ GeV}^2\] ATLAS [\(E_0 = 100\text{ GeV}\)] |
| Medium     | \[30 \left( \frac{E_T}{E_0} \right)^2 \leq 60 \left( \frac{E_T}{E_0} \right)^2 \text{ GeV}^2\] |
| Vacuum     | \[24 \left( \frac{E_T}{E_0} \right)^2 \leq 62 \left( \frac{E_T}{E_0} \right)^2 \text{ GeV}^2\] CMS [\(E_0 = 120\text{ GeV}\)] |
| Medium     | \[18 \left( \frac{E_T}{E_0} \right)^2 \leq 40 \left( \frac{E_T}{E_0} \right)^2 \text{ GeV}^2\] |
energy lost from cone via jet collimation is soft

[medium strongly enhances soft out-of-cone radiation]

soft modes can be transported to large angles

in given asymmetry class, jet collimation leaves hard modes unchanged
(in vs. out) of cone radiation

- energy lost from cone via jet collimation is soft
- [medium strongly enhances soft out-of-cone radiation]
- soft modes can be transported to large angles
- in given asymmetry class, jet collimation leaves hard modes unchanged

\[ p_T^\parallel = \sum_i -p_i^T \cos(\phi_i - \phi_{\text{Leading Jet}}) \]
:: a simple dynamical mechanism
:: consistent with data
:: necessary ingredient for jet quenching theory and related event-generators