Recent jet results in heavy-ion collisions with CMS

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Jets as a probe of the QGP

Parton energy loss is related to the thermodynamical and transport properties of the Quark Gluon Plasma

Inclusive and di-jet measurements are good for discovering physics effect:

- e.g. dijet asymmetry of leading and subleading jets

\[ A_J \sim 0 \]

\[ A_J > 0 \]

\[ p_{T,1} > 120 \text{ GeV}, \quad p_{T,2} > 50 \text{ GeV} \]

\[ \Delta \phi > 2\pi/3 \]

CMS, PRC84 (2011) 024906

All jets lose energy while traversing the QGP → controlled configuration of the initial hard scattering is needed
Boson + jets as a probe of the QGP

Parton energy loss is related to the thermodynamical and transport properties of the Quark Gluon Plasma

**Bosons (Z→l⁺l⁻/γ):**

- Do not interact strongly with the QGP
- In “boson + jets” configuration they fix the recoiling jet kinematics (LO)
- At LHC energies enhanced quark jets sample: \( q(\bar{q}) + g \rightarrow Z(\gamma) + q(\bar{q}) \)

**CMS measured:**

- \( X_{jZ} = \frac{p_T^{jet}}{p_T^Z} \)
- \( X_{j\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}} \)
  - Fragmentation functions
  - Jet shapes
CMS detector: photons and electrons

Photons* in ECAL barrel: $|\eta| < 1.44$
Electrons* in ECAL barrel and endcaps: $|\eta| < 2.5$

* objects acceptance for the analysis shown in this talk
jets

Jets* in $|\eta| < 1.6$

* objects acceptance for the analysis shown in this talk
CMS detector: muons

Muons* in |\eta| < 2.4

* objects acceptance for the analysis shown in this talk
Object selections

**Electrons** : $|\eta| < 2.5$, $p_T > 20$ GeV/c, ECAL barrel-endcap gap excluded

**Muons** : $|\eta| < 2.4$, $p_T > 10$ GeV/c

**Photons** : $|\eta| < 1.44$, $p_T > 40$ GeV, isolation $(\text{SumIso}^{\text{UE-sub}}) < 1$ GeV/c

**Jets** : anti-\text{kT} algorithm with $R = 0.3$, $|\eta| < 1.6$, $p_T > 30$ GeV/c

Each Z candidate is paired with all the jets in the event

The highest $p_T$ isolated photon is paired with all the jets in the event

Jets reconstructed within $\Delta R < 0.4$ from lepton are rejected to eliminate jet energy contamination by leptons coming from Z

All “boson+jet” pairs are selected, to suppress initial and final state radiation effect → look into back-to-back pairs only $\Delta \phi_{jZ(\gamma)} > 7\pi/8$
Z+jet correlations

What is the amount of energy lost in jet cone? → Z - jet $p_T$ balance

Back-to-back pairs: $\Delta \phi_{jZ} > 7\pi/8$

PbPb 0-30% collisions:

balance shifts to lower values wrt pp

The results are not unfolded for detector effects → pp data are smeared to simulate poor resolution due to UE fluctuations in PbPb data
Z+jet correlations


JEWEL model – perturbative framework for jet quenching:

- No energy loss case (Pythia6): poor agreement with pp
- Energy loss case: consistent with PbPb data

Hybrid model - weak coupling = (high-$Q^2$) jet evolution, as it would be in vacuum; strong coupling = (low-$Q^2$) interactions between parton shower and medium:

- No energy loss case (Pythia8): describes reasonably well pp
- Energy loss case: strong coupling appears to be the closest to PbPb data

Guylassy-Levai-Vitev (GLV) model – energy loss via out of cone radiation and collisional energy dissipation:

- No energy loss case (Pythia8): describes reasonably well pp
- Energy loss case: strength of the quenching $g = 2.2$ seems to be favored by PbPb data
Z+jet correlations

Mean value of the balance ($<X_{jZ}>$) vs $p_T$:

$\rightarrow$ For full $p_T$ range it is lower in PbPb wrt pp

Probability to find an associated jet per Z ($R_{jZ}$):

$\rightarrow$ Overall decrease in PbPb as jet falls below $p_T$ threshold

$\rightarrow$ pp and PbPb difference $\sim$ constant with $p_T$:

relatively smaller fraction of jets is lost in PbPb for larger initial parton energies

Both are the indication of the jet energy loss in QGP

Isolated-photon+jet correlations

What is the amount of energy lost in jet cone? → γ - jet $p_T$ balance

Back-to-back pairs: $\Delta \phi_{j\gamma} > 7\pi/8$

In PbPb central events balance shifts to lower values wrt pp

Consistent with Z-jet measurement
Isolated-photon+jet correlations

In 0-30% PbPb suppression (compared to smeared pp) of both $<X_{j\gamma}>$ and $R_{j\gamma}$ is observed.

Consistent with significant in medium energy loss.
Isolated-photon+jet correlations

Main features of $x_{J\gamma}$ distributions are reproduced by all models
Jet fragmentation

Fragmentation pattern wrt $p_T$ of the reconstructed jet
(jet that may have lost energy via interactions with the medium)

\[ \xi_{jet} = \ln \frac{-|\vec{p}_{jet}|^2}{\vec{p}_{trk} \cdot \vec{p}_{jet}} \]

50-100% PbPb consistent with pp

0-10% PbPb:

- enhancement for $\xi_{jet} > 2.5$ ($p_T^{trk} < 2.5$ GeV)
- Slight suppression at $0.5 < \xi_{jet} < 2.5$ ($2.5 < p_T^{trk} < 18$ GeV)

$\sqrt{s_{NN}} = 5.02$ TeV, PbPb 404 μb⁻¹, pp 27.4 pb⁻¹

CMS

\[ p_T^{trk} > 60$ GeV/c, $|\eta| < 1.44, \Delta\eta^{jet} > \frac{7\pi}{8} \]
anti-k T, jet R = 0.3, $p_T^{jet} > 30$ GeV/c, $|\eta^{jet}| < 1.6$
$p_T^{trk} > 1$ GeV/c
Jet fragmentation

Fragmentation pattern wrt $p_T$ of the initial parton **before energy loss occurred**

$$\xi_T^\gamma = \ln \frac{-|p_T^\gamma|^2}{p_T^{trk} \cdot p_T^\gamma}$$

50-100% PbPb consistent with pp

0-10% PbPb:

- enhancement for $\xi_T^\gamma > 3$ ($p_T^{trk} < 3$ GeV)
- suppression at $0.5 < \xi_T^\gamma < 3$ ($3 < p_T^{trk} < 36$ GeV)

Parton showers emerging from QGP contain more lower energy particles
Jet shapes of isolated photon-tagged jets

Jet shapes is an observable for studying distribution of parton energy in radial direction.

[Diagram showing jet axis, photon axis, and tracks with equations]

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

\[
r = \sqrt{(\eta^{jet} - \eta^{trk})^2 + (\phi^{jet} - \phi^{trk})^2}
\]

\(\rho(r)\) is normalized to unity for \(r = 0.3\)

How the jet \(p_T\) is distributed in a direction transverse to the jet axis?
Jet shapes of isolated photon-tagged jets


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

PbPb 404 $\mu$b$^{-1}$, pp 27.4 pb$^{-1}$

$p_T^{\gamma} > 60$ GeV/c, $|\eta| < 1.44$, $p_T^{\text{trk}} > 1$ GeV/c

anti-$k_T$ jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c, $|\eta| < 1.6$, $\Delta\phi_{jj} > \frac{7\pi}{8}$

Direct observation of jet broadening in the QGP
Summary

- Energy loss manifests itself in the balance shift to lower values and overall decrease of “Z/γ + jet” pairs

- “γ + jet” fragmentation functions: parton showers emerging from the QGP contain more lower-energy particles

- “γ + jet” jet shapes: a direct observation of the jet broadening in the QGP
Backup slides
Dijet $p_T$ balance

If **no energy loss**, typically two jets have equal $p_T$ wrt the beam axis $\rightarrow$ ~**back-to-back**

In PbPb more typical picture is **highly unbalanced dijets**

How to quantify the effect?
Dijet asymmetry of leading and subleading jets

\[ p_{T,1} > 120 \text{ GeV}, \ p_{T,2} > 50 \text{ GeV} \]
\[ \Delta \phi > 2\pi/3 \]

"no energy loss": peak \( \sim 0.1 \)
PbPb data: peak \( \sim 0.3 \)

Fraction of all events with "balanced" jets

In the most central PbPb \( \sim 2 \) times less "balanced" dijets

High degree of jet quenching
Z-jet correlations

Distributions of the azimuthal angle difference $\Delta \phi_{jZ}$ between the Z boson and the jet

No difference in the angular difference between PbPb and pp
Z-jet correlations

Comparison pp and PbPb to models:

CMS

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

PbPb 404 $\mu$b$^{-1}$

$\frac{1}{N_z} \frac{dN_z}{d\Delta\phi_{jZ}}$

CMS

$\sqrt{s} = 5.02$ TeV

pp 27.4 pb$^{-1}$

$\frac{1}{N_z} \frac{dN_z}{d\Delta\phi_{jZ}}$

$P_{T} > 60$ GeV/c

anti-$k_{T}$ jet $R = 0.3$

$p_{T}^{\text{jet}} > 30$ GeV/c

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

$P_{T} > 60$ GeV/c

anti-$k_{T}$ jet $R = 0.3$

$p_{T}^{\text{jet}} > 30$ GeV/c

$|\eta|^{\text{jet}} < 1.6$
Photon-jet correlations

Distributions of the azimuthal angle difference $\Delta \phi_{j\gamma}$ between the photon and the jet

No difference in the angular difference between PbPb and pp
Jet fragmentation function in ATLAS

Distribution of charged-particle $p_T$ inside the jet (fragmentation function):

$$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$

Jet fragmentation function in ATLAS

Distribution of charged-particle $p_T$ inside the jet (fragmentation function):

$$D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T}$$

How much is the jet structure modified?

$$R_D(p_T) = \frac{D(p_T)_{PbPb}}{D(p_T)_{pp}}$$

PbPb compared to pp:

→ more soft particles due to interaction with the medium

→ suppression at mid $p_T$

→ enhancement at high $p_T$: consistent with quenching dependence on quark/gluon initiated jets

Gluon vs quark jet:

→ larger charged hadron multiplicity
→ contain more softer particle
→ wider

Photon+jet pT balance in ATLAS

What is the amount of energy lost by the jet?

Balance: \( X_{J\gamma} = \frac{p_{T,\text{jet}}}{p_{T}^{\gamma}} \)

The jet energy decreases with centrality

- **in peripheral events**: a peak-like structure is present in the same position as in pp
- **in the most central events**: strongly modified, no peak, jet energy decrease

Photon+jet fragmentation function in ATLAS

How is substructure modified by medium?

Fragmentation function:

\[ D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T} \]

Modifications compared to pp:

→ more soft particles due to interaction with the medium
→ suppression at mid \( p_T \)
→ no modification at high \( p_T \)

ATLAS-CONF-2017-074
Photon+jet fragmentation function in ATLAS

How is substructure modified by medium?

Fragmentation function:

\[ D(p_T) = \frac{1}{N_{jet}} \frac{\Delta N(p_T)}{\Delta p_T} \]

\( \gamma + \text{jet} \) vs inclusive jets:

→ more enhancement at low \( p_T \)
→ shift of mid \( p_T \) minimum
→ no enhancement at high \( p_T \)

Indication: quark initiated jets are modified differently

0-30% Pb+Pb / pp

ATLAS-CONF-2017-074
Jet suppression in ATLAS

Inclusive jet cross-sections are measured in pp and PbPb up to 1 TeV

\[ R_{AA} = \frac{\text{per-event yield}_{AA}}{\text{number of binary collisions} \times \text{per-event yield}_{pp}} \]

\[ \langle T_{AA} \rangle \text{ and luminosity uncer.} \]

At large pT: flat suppression in central collisions
Jet reconstruction at the LHC

Jets consist of hadrons and photons → energy can be measured by the calorimeters only

Particle Flow reconstruction:
Combine tracks and calorimeter clusters

Particle Flow jet composition:
→ 65% charged hadrons
→ 25% photons
→ 10% neutral hadrons

Jet energy resolution improves by factor 2 at lower $p_T$ thanks to the tracker resolution
Jet clustering

Jet clustering: reverse-engineering of the fragmentation and hadronization

Sequential clustering: combines the closest particles into jets

\[ d_{ij} = \min \left( p_{t_i}^{2p}, p_{t_j}^{2p} \right) \frac{\Delta R_{ij}^2}{R^2} \]

Distance between pairs of particles

Jet radius

Distance to the beam

JHEP 0804:063, 2008
Underlying event in pp and PbPb collisions

Underlying Event (UE) - particles not associated with the hardest parton-parton process quantified as transverse momentum density ($\rho$)

PileUp (PU) – concurrent interactions coming from the same bunch crossing

UE in pp with $<\text{PU}> \sim 200$ looks like central PbPb
Jets in PbPb collisions

Before UE subtraction

After UE subtraction

What amount of UE to subtract? How?
UE subtraction in CMS: constituent subtraction

Particle-by-particle: correct the 4-momentum of a jet and substructure

- signal
- underlying event
- ghost (artificial particles)

Add ghosts with
\[ p_T^{\text{ghost}} = A_{\text{ghost}} \cdot \rho \]
in random locations;
\[ A_{\text{ghost}} \] - area occupied

Combine them with the closest real particle
\[ p_T^{\text{particle}} > p_T^{\text{ghost}} \]
\[ p_T^{\text{particle}} < p_T^{\text{ghost}} \]

The largest \( p_T \)
\[ p_T^{\text{particle}} = p_T^{\text{particle}} - p_T^{\text{ghost}} \]
\[ p_T^{\text{ghost}} = p_T^{\text{ghost}} - p_T^{\text{particle}} \]

Repeat until no ghosts/particles left

Remaining particles get clustered into a jet
UE subtraction in CMS: iterative pedestal

What amount to subtract? How?

1. $<E_T>$ calculated in strips of $\eta$. Subtract $<E_T> + \sigma$

2. Run anti-$k_T$ algorithm on background-subtracted towers

3. Exclude reconstructed jets and re-estimate background

4. Re-run anti-$k_T$ algorithm to get final jets

CMS, EPJC 50 (2007) 117
Jet clustering algorithms: requirements

Collinear and IR safety:

→ Collinear splittings should not bias jet finding
→ Soft radiation should not effect jet configuration

Collinear

Infra-red

Minimal sensitivity to hadronization, underlying event (UE), Pile-Up(PU)

Applicable at detector-level:

→ good computational performance
→ not too complex to correct
Jet performance in pp collisions

Very good resolution in ATLAS and CMS in pp collisions
Jet performance in PbPb collisions

Very good resolution in PbPb collisions for jets with $R = 0.4$
Dijet asymmetry in CMS

Complementary information about the overall momentum balance in the dijet events: the projection of missing pT of reconstructed charged tracks onto the leading jet axis

\[ p_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}}) \]

Subleading jet energy is moved from high pT to lower pT and from small to large angles