Latest CMS Heavy-Ion Results on Jets

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Compact Muon Solenoid (CMS)

- EM and HAD calorimeters $|\eta| < 5$
- Magnet yoke 3.8 T
- Silicon tracker $|\eta| < 2.4$
- Muon chambers $|\eta| < 2.5$
- Hadron Forward $2.9 < |\eta| < 5.2$
What we measure

Jet & charged hadrons

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Jets: back-to-back dijets or inclusive, anti-kT algorithm, R=0.3, remove heavy ion underlying event with iterative “pileup” or Voronoi/HF algorithm

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
Centrality in heavy ion collisions

- In PbPb: centrality indicates:
  - Nuclear overlap
  - Number of nuclear partonic interactions
- Use the total energy measured in HF, split into percent centrality
- Glauber model of nucleon-nucleon scattering relate measurement to:
  - \( <N_{\text{part}} > \): average number of participants
  - \( <N_{\text{coll}} > \): average number of nucleon collisions

What we know about jet quenching

- Strongly interacting QGP quenches jets
- In central PbPb collisions, there are more unbalanced dijets than in pp (or Monte Carlo)

CMS: PLB 712 (2012) 176

M. B. Tonjes (UMD) CMS Heavy Ion Jets, LHCP 2014
What happened to quenched $p_T$?

\[ \tilde{p}_T \parallel \equiv \sum_{\text{tracks}} -p_{T,\text{track}} \cos (\phi_{\text{track}} - \phi_{\text{leading jet}}) \]

- Sum over tracks projected onto the leading jet axis

**MC**

- All tracks in event
- $p_{T,1} > 120\text{GeV/c}$
- $p_{T,2} > 50\text{GeV/c}$
- $\Delta\phi_{1,2} > \frac{2\pi}{3}$
- $h_{1,2} < 1.6$

**Data**

- Balanced jets
- Unbalanced jets

**CMS**

- $\int L = 6.7$ nb \mu L
- CMS = 2.76 TeV
- Pb+Pb

**ArXiv**


**References**

- CMS: PRC 84 (2011) 024906

- M. B. Tonjes (UMD)

- CMS Heavy Ion Jets, LHCP 2014
Look around jet cone

\[ \hat{p}_T \parallel \equiv \sum_{\text{tracks}} -p_T,\text{track} \ \cos (\phi_{\text{track}} - \phi_{\text{leading jet}}) \]

- Sum over tracks projected onto the leading jet axis
- Imbalance in jet cone restored by low \( p_T \) tracks outside the cone in the subleading direction
- Need a larger cone
Some new measurements
Direction of the dijet:

\[ \phi_{dijet} = \frac{1}{2}(\phi_1 + (\pi - \phi_2)) \]

- Different than in PRC 84 (2011) 024906
- Provides underlying event cancellation differential in \( \Delta R \)

\[ \Delta R = \sqrt{\Delta \phi_{Trk,jet}^2 + \Delta \eta_{Trk,jet}^2} \]

Calculate the missing \( p_T \parallel \) for charged particles that fall in slices of \( \Delta R \)

\[ p_T^\parallel = \left( \sum_i -p_T^i \cos (\phi_i - \phi_{dijet}) \right) \mid_{R_{down} < \Delta R < R_{up}} \]
Sum charged particles for unbalanced \((A_J > 0.22)\) dijets in central \((0-30\%)\) PbPb

- 35 GeV/c of high \(p_T\) tracks missing from jet\(_2\) at \(\Delta R = 0.2\)
Missing $p_T^\parallel$ for unbalanced dijets

- Sum charged particles for unbalanced ($A_J>0.22$) dijets in central (0-30%) PbPb
  - 35 GeV/c of high $p_T$ tracks missing from jet$_2$ at $\Delta R=0.2$
  - Balanced by low $p_T$ particles up to very large $\Delta R = 2.0$
Missing $p_T^{\parallel}$ for unbalanced dijets

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- PbPb - pp: result shows a different $p_T$ distribution
• Sum charged particles for unbalanced \((A_J > 0.22)\) dijets in central (0-30\%) PbPb
  - 35 GeV/c of high \(p_T\) tracks missing from jet_2 at \(\Delta R = 0.2\)
  - Balanced by low \(p_T\) particles up to very large \(\Delta R = 2.0\)
  - PbPb - pp: result shows a different \(p_T\) distribution
  - Take the \(p_T\) cumulative of all tracks: total angular pattern is similar in PbPb and pp

CMS-PAS-HIN-14-010
Jet fragmentation function in PbPb

Inside the cone of central PbPb jets: enhancement of low $p_T$ particles in the jet cone, and suppression of intermediate $p_T$ particles.
Jet nuclear modification factor

\[ R_{AA} = \frac{\frac{\sigma_{\text{inel}}^{\text{pp}}}{\langle N_{\text{coll}} \rangle}}{\frac{d^2 N_{\text{AA}}}{dp_T d\eta}} \]

How many we measured in PbPb (pPb)

How many we expect if superimpose <N_{coll}> pp events?

- In **central PbPb**: inclusive and b-jets show similar suppression in PbPb \((R_{AA} \approx 0.5)\)
- In **pPb (all centralities)**, the inclusive and b-jets have no suppression \((R_{pA} \approx 1)\)
Charged hadron pPb mystery

- PbPb shows similar suppression at high \( p_T \) for charged particles and jets
- Charged particles in pPb for all centralities show enhancement at the \( p_T \)
  - What causes this to affect charged hadrons and not jets?
  - Need pp data at 5.02 TeV


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Summary

• Jets are quenched in central PbPb, not in pPb

• Charged hadrons show enhancement at high $p_T$ in pPb

• Inclusive jets and b-jets show similar behavior
  • $R_{pPb} \approx 1$
  • $R_{PbPb} \approx 0.5$

• In central PbPb unbalanced dijets are balanced by low $p_T$ tracks (<2 GeV/c) out to $\Delta R$ of 2
  • Different jet fragmentation in particle $p_T$ for PbPb and pp
  • Angular pattern of the energy flow of tracks is similar in pp and central PbPb
Jet $p_T$ scale and resolution comparison

CMS Preliminary Simulation $|\eta|<2$ $\sqrt{s_{NN}} = 2.76$ TeV anti-$k_T$ Calo $R=0.3$

- PYTHIA
- PYTHIA+HYDJET

HF/Voronoï subtraction

Iterative “pileup” subtraction

CMS-PAS-HIN-14-010

CMS-HIN-12-004
Performance of HF/Voronoi UE subtraction

Sum of $E_T$ of UE subtracted calo towers that fall in $R=0.3$ in random directions in MB events:

- Minimum bias
  - PbPb
  - HYDJET
  - $\sigma = 0.7$ GeV
- Calo R=0.3
  - HF/Voronoi
  - $30-50\%$
  - $\sigma = 2.0$ GeV
  - $|\eta|<2$
- $\sqrt{s_{NN}} = 2.76$ TeV
  - $10-30\%$
  - $\sigma = 3.9$ GeV
  - CMS Preliminary
  - $0-10\%$
  - $\sigma = 6.0$ GeV

Good agreement between data and MC

Mean random cone $E_T$ as a function of $\eta$:

- Minimum bias
  - PbPb
  - HYDJET
  - $50-100\%$
  - $50-100\%$

Deviation from zero $<0.5-1$ GeV

CMS-PAS-HIN-14-010
Projection axis choice: PbPb dijet

Leading jet axis

- $\Delta \phi_{1,2} \neq \pi$ → Projection of $p_T$ of charged particles in small $\Delta R$ near subleading jet is smaller than those near leading jet

Dijet axis

- Restores the symmetry of particles near leading and subleading jet → UE cancels by azimuthal symmetry
Charged particle $R_{pPb}$ (QM2014)

Charged particle $R_{pPb}$

- CMS, $|\eta| < 1$
- ATLAS, $|\eta| < 1$
- ALICE, $|\eta| < 0.3$

$\sqrt{s_{NN}} = 5.02$ TeV, charged particles

(Charged) Jet $R_{pPb}$

- CMS full jet, $-0.5 < \eta_{cm} < 0.5$
- ALICE charged jet, $-0.5 < \eta_{cm} < 0.5$
- ATLAS full jet, $-0.3 < \eta_{cm} < 0.3$

Yen-Jie Lee QM2014
Do jets get deflected in position?

No significant angular decorrelation across different jet $p_{T,1}$

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