Jets and high-$p_T$ hadrons in CMS

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for the CMS Collaboration

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Objective

- Exploit high $p_T$ particles and jets to understand initial and final state properties of heavy-ion collisions:
  - High $p_T$ partons produced in hard interactions in the initial phase of the collision...
  - **in pp**: understand and characterize the probe
  - ...Undergo multiple interaction inside the collision region prior to hadronization
  - **in pA**: benchmark for $AA$, disentangle initial from final state effects
  - **in AA**: probe the QCD medium created in the collision, identify final state effects
Centrality and comparisons to p+p

- Scaling factor to compare to p+p measurements
  - $N_{\text{part}}$: number of participant nucleons
  - $N_{\text{coll}}$: number of binary N+N collisions
    - both depend on the impact parameter (centrality) in pA and AA

- Centrality estimation:
  - slicing the x-sec in forward energy
  - Simulation
  - Glauber model
    ➔ see Shengquan Tuo’s talk
CMS is a multi-layer detector

- Excellent tracking capabilities
- Momentum resolution of 1-2\% to 100\text{GeV}/c
- Displaced vertices for heavy flavor
- High-granularity calorimetry
- Directly identifiable jets
- $\gamma$-jet studies
- High Level Trigger
- Higher energy reach
- Ultra-central events
- Improved $J/\psi$, $Z^0$, $\Upsilon$
Lessons from HI particles and jets production

- **$R_{AA}$**: Nuclear modification factor

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

- High $p_T$ final state hadrons are strongly suppressed ($R_{AA} \sim 0.5$ for $p_T > 50$ GeV/c)
- About 50% of jets ($R_{AA} \sim 0.5$) are lost at a given $p_T$ in most central PbPb

$\rightarrow$ Jet quenching observed in PbPb collisions
Lessons from HI jet fragmentation and shapes

- Jet fragments into more low $p_T$ hadrons with less intermediate $p_T$ hadrons
- Jet energy re-distributed to large distance from jet axis
Lessons from HI dijets production

- Jet quenching is observed as a pronounced dijet $p_T$ imbalance in central collision, with no visible angular decorrelation
Lessons from HI dijets imbalance

- Energy imbalance increases with centrality
- \( p_T \)-ratio deviates from the unquenched reference in a \( p_T \)-independent way
Baseline for HI collisions

PbPb collisions

- Clear signature of the formation of Quark-Gluon Plasma (QGP)
- Strongly interacting particles affected by the presence of QGP
  - quenched high $p_T$ particles/jets
  - changed jet fragmentation functions/shapes
  - Imbalanced dijets

pPb collisions

- Can we understand the baseline for PbPb?
- How do strongly interacting particles behave in cold nuclear matter? quenching?
- Can we observe effects due to the nuclear structure at small $x$?
Motivation for pPb at LHC

- Elements of proton-proton as well as HI collisions

- Disentangle initial and final state effects

- Characterize nuclear PDFs at small-\(x\)

- Investigate QCD at high gluon density: shadowing and gluon saturation
  - saturation scale (\(Q_s\)) enhanced by \(A^{1/3}\) in nucleus \(A\)
  - at LHC (\(^{208}\)Pb): \(Q_s \sim 2-3\) GeV/c, \(x \sim 10^{-4}\) at \(\eta = 0\)
Dijet in pPb collisions recorded by CMS
Dijet event classes in pPb

- Using HF energy deposition in the most forward and backward regions of the calorimeter as a centrality proxy

- Required double sided selection (DS): at least one particle with $E > 3$ GeV in both forward calorimeters ($3 < |\eta| < 5$)

See Doga's talk
No modification is observed in dijet $p_T$ ratio up to $E_{T}^{\text{HF}[|\eta|>4]} > 40$ GeV (top 0-2.5%)

-> (Not enough statistics to check PbPb collisions in the same $E_{T}^{\text{HF}[|\eta|>4]}$ interval)
- Δφ distribution stays unchanged w.r.t. HF energy compared to pp reference
• With the current systematic uncertainty, no detectable change in $<p_{T,2}/p_{T,1}>$ and $\Delta \phi$ width as a function of forward calorimeter energy

$\Rightarrow$ No jet quenching observed in pPb collisions in all centralities

• Establish the basis to use the jets for nPDF determination
Nuclear PDF Predictions at LHC

François Arleo and Jean-Philippe Guillet  
http://lapth.cnrs.fr/npdfgenerator/

- At LHC energies, the $R_{\text{Pb}}$ is expected to have significant shadowing/anti-shadowing effects

$R_{\text{Pb}} = nPDF / PDF$

$Q^2 = 10000 \text{ GeV}^2$

gluons: $Q^2 = 100 \text{ GeV}^2$

Shadowing (gluon saturation?)  
Anti-shadowing

Kinematic reach for CMS, pPb @ $\sqrt{s} = 8.8$ TeV (0.1 pb$^{-1}$)

Observables using jets: covers high $Q^2$ and $10^{-4} < x < 1$

Kinematic range with the dijet selection:

- $p_{T,1} > 120$ GeV/c
- $p_{T,2} > 30$ GeV/c
- $\Delta \phi_{12} > 2\pi/3$
Choice of pseudorapidity observable

\[ \eta_{dijet} = \frac{\eta_1 + \eta_2}{2} \]

\[ \eta_1, \eta_2 \]

- Dijet pseudorapidity has tighter correlation with parton \( x \) compared to single jet pseudorapidity.

**Leading jet pseudorapidity**

- Boosted PYTHIA6 Z2 @ 5.02 TeV

**Dijet pseudorapidity**

- Boosted PYTHIA6 Z2 @ 5.02 TeV

- \( p_T^{1,2} \geq 120 \text{ GeV/c}, \Delta \phi_{12} \geq \frac{2 \pi}{3} \)
\( x_1 \leftrightarrow \eta_{\text{dijet}} \)

Translation from \( \eta_{\text{dijet}} \) to \( x_1 \)

\[ \eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2} \]

\[ p_T,1 > 120 \text{ GeV/c}, p_T,2 > 30 \text{ GeV/c}, \Delta \phi_{12} > 2\pi/3 \]

**Boosted PYTHIA6 Z2 @ 5.02 TeV**

**Anti-shadowing**

**EMC**

**Shadowing**

\( R^{Pb} = nPDF / PDF \)

\( Q^2 = 10000 \text{ GeV}^2 \)

François Arleo and Jean-Philippe Guillet  http://lapth.cnrs.fr/npdfgenerator/

- Different \( \eta_{\text{dijet}} \) probes different effects with different \( x \)
Dijet $\eta$ v.s. forward calorimeter energy

- $\eta_{\text{dijet}}$ distributions plotted against PYTHIA references
- A systematic shift to the Pb going direction vs HF energy

CMS Preliminary

$pPb \int L dt = 18.48 \text{ nb}^{-1}$

(0-100)%

- $p_{T,1} > 120 \text{ GeV}/c$
- $p_{T,2} > 30 \text{ GeV}/c$
- $E_T^{HF[|\eta|>4]} < 20 \text{ GeV}$
- $\Delta\phi_{1,2} > 2\pi/3$
- $20 \text{ GeV} \leq E_T^{HF[|\eta|>4]} < 25 \text{ GeV}$

$25 \text{ GeV} \leq E_T^{HF[|\eta|>4]} < 30 \text{ GeV}$

$30 \text{ GeV} \leq E_T^{HF[|\eta|>4]} < 40 \text{ GeV}$

$E_T^{HF[|\eta|>4]} \geq 40 \text{ GeV}$

CMS PAS HIN-13-001
Dijet $\eta$ v.s. forward calorimeter energy

CMS Preliminary

$p_{T,1} > 120$ GeV/c
$p_{T,2} > 30$ GeV/c
$E_{T}^{HF[|\eta|>4]} < 20$ GeV

anti-$k_T$ (PFlow) $R=0.3$

$\Delta \phi_{1,2} > 2\pi/3$

20 GeV $\leq E_{T}^{HF[|\eta|>4]} < 25$ GeV

$25$ GeV $\leq E_{T}^{HF[|\eta|>4]} < 30$ GeV

$30$ GeV $\leq E_{T}^{HF[|\eta|>4]} < 40$ GeV

$E_{T}^{HF[|\eta|>4]} \geq 40$ GeV

$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$

- $\eta_{dijet}$ distributions plotted against PYTHIA references
- A systematic shift to the Pb going direction vs HF energy

CMS PAS HIN-13-001
Anatomy of the dijet $\eta$ distribution

CMS Preliminary

$p\text{Pb} \int L \, dt = 18.48 \text{ nb}^{-1}$

$\eta_{\text{dijet}}$

Event Fraction

$Q^2 = 10000 \text{ GeV}^2$

$R(x, Q^2, A)$

- $g$ EPS09 LO
- $u$ EPS09 LO
- $b$ EPS09 LO

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IS2013, 10/09/2013, Illa da Toxa, Spain
Anatomy of the dijet $\eta$ distribution

CMS PAS HIN-13-001

CMS Preliminary

$pPb \int L \, dt = 18.48 \text{ nb}^{-1}$

$\eta_{\text{dijet}}$

Shadowing

$R(x, Q^2, A)$

$Q^2 = 10000 \text{ GeV}^2$

- $g$ EPS09 LO
- $u$ EPS09 LO
- $b$ EPS09 LO

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Anti-shadowing

Shadowing

CMS Preliminary

$pPb \int L \, dt = 18.48 \, nb^{-1}$

$\eta_{\text{dijet}}$

$Q^2 = 10000 \, GeV^2$

$R(x, Q^2, A)$

$g$ EPS09 LO

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Shadowing

Anti-shadowing

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$Q^2 = 10000 \text{ GeV}^2$

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$R(x, Q^2, A)$

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$\eta_{\text{dijet}}$

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EMC
Summary from dijet $\eta$

- Mean of $\eta_{\text{dijet}}$ increases v.s. forward calorimeter energy
- Width of $\eta_{\text{dijet}}$ decreases v.s. forward calorimeter energy

$$\eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2}$$
Scaling in EMC region

Normalized by $N_{\text{dijet}}$

CMS Preliminary

- $p_{\text{Pb} \int L dt}=18.48 \text{ nb}^{-1}$
- anti-$k_T$(PFlow) $R=0.3$
- $\Delta \phi_{1,2} > 2\pi/3$
- $p_{T,1} > 120, p_{T,2} > 30 \text{ GeV/c}$

- $E_T^{HF|\eta|>4} < 20 \text{ GeV}$
- $20 \text{ GeV} \leq E_T^{HF|\eta|>4} < 25 \text{ GeV}$
- $25 \text{ GeV} \leq E_T^{HF|\eta|>4} < 30 \text{ GeV}$
- $30 \text{ GeV} \leq E_T^{HF|\eta|>4} < 40 \text{ GeV}$
- $E_T^{HF|\eta|>4} \geq 40 \text{ GeV}$

The distribution of $\eta_{\text{dijet}}$ can be calculated as:

$$\eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2}$$

- Evolution of $\eta$ shift vs HF energy in full $\eta_{\text{dijet}}$
Scaling in EMC region

CMS PAS HIN-13-001

If we normalize the distribution by the area in the interval \( \eta_{dijet} > 0 \)

\[
\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}
\]

- Evolution of \( \eta \) shift vs HF energy in full \( \eta_{dijet} \)

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Scaling in EMC region

The same shape in “EMC region”? 

If we normalize the distribution by the area in the interval $\eta_{dijet} > 0$

$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$

- Evolution of $\eta$ shift vs HF energy remains in “shadowing regime”
Summary

• Jet quenching:
  - **No significant modification** observed in dijet $p_T$ ratio and azimuthal angle correlation in pPb collisions
  - A **final state effect** due to hot QCD medium produced in HI collisions

• Dijet pseudorapidity distributions:
  - Provide strong constraints for nPDF determination
  - Interesting trend in $\eta_{\text{dijet}}$ v.s. forward calorimeter energy is observed in the shadowing and EMC regions

• More results to come in the future, please stay tuned!

Thanks for your attention!