Jet Physics in Heavy Ion Collisions: Where are we? Where are we going?

Yen-Jie Lee
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UCLA 2019 Santa Fe Jets and Heavy Flavor Workshop
28-30 January 2019, UCLA, USA

Many thanks to Yang-Ting Chien, Yacine Mehtar-Tani for the discussions
Weak Coupling vs. Strong Coupling Limit

Perturbative QCD
Weak coupling limit

“Radiative energy loss”

“Collisional energy loss”

Holographic calculation
Strong coupling limit

“AdS/CFT drag force”

Note: both processes happen simultaneously

Jet quenching mechanism (before QGP property extraction)
We also don’t know **how much** the medium response (recoil) plays a role in the description of the jet quenching observables and how to describe it correctly.

...and the hadronization of them in QGP
Impression: with tuning, models with different underlying physics could fit the data (both strong and weak coupling calculations)
Both weak and strong coupling based models describe the charged hadron, charm and beauty meson $R_{AA}$ data.

Within pQCD world, models with very different level of complexity describe the data.

No significant difference between beauty and inclusive (di-)jet results (not shown, need better accuracy).
Different conclusions between CMS and ATLAS at low $x_{j\gamma}$

**Example:** HYBRID (AdS/CFT drag) model describes CMS data almost perfectly; inconsistent with ATLAS preliminary results at lowest $X_{j\gamma} \sim 0.5$

Note the difference in the photon $p_T$ and jet $p_T$ selection between CMS and ATLAS
Dijet Asymmetry in PbPb at 2.76 TeV

\[ x_j = \frac{p_{T2}}{p_{T1}} \]

- First unfolded dijet \( p_T \) ratio
- **Narrow peak** at low \( x_j \) (\(~0.5\)) visible after jet resolution correction.
  → Small fluctuation of the sub-leading jet energy loss?
- **Peak goes away rapidly** as one increase leading jet \( p_T \) cut

ATLAS
\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
2011 Pb+Pb data, 0.14 nb\(^{-1}\)
2013 \( pp \) data, 4.0 pb\(^{-1}\)

PLB 774 (2017) 379
Jet $R_{AA}$ vs. $R$

Inclusive, PbPb (2.76 TeV)
- $q_{0.0} = 1.7$ GeV$^2$/fm
- $p_{cut} = 1.0$ GeV/c
- $p_{T}^{jet_{hyd}} > 1.0$ GeV/c

$R_{AA}$ vs. $p_T$

$\sqrt{s_{NN}} = 5.02$ TeV
- $|\eta| < 2$, 0–10%

$R_{AA}$ vs. $p_T$

$g = 2.0 (\pm 0.2)$

Jet Function

JEWEL

CCNU

HYBRID

SCET$_G$

arXiv:1509.07257

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Jet Physics in Heavy Ion Collisions
Jet $R_{AA}$ vs. $R$

**JEWEL**

$R_{AA}$ increase vs. $R$

$1707.01539$

**Jet Function**

**CCNU**

$R_{AA}$ increase vs. $R$

**SCET$_G$**

$R_{AA}$ increase vs. $R$

arXiv:1509.07257

**HYBRID**

$R_{AA}$ decrease vs. $R$

Jet Physics in Heavy Ion Collisions
Spectra-based Observables

• Both strong and weak coupling models describe the charged particle and jet $R_{AA}$ data

• Accumulation of very low $p_T$ jets in ATLAS unfolded data: ATLAS dijet $X_J \sim 0.5$ peak in unfolded results: no model could describe it currently. (Also shown as enhancement in ATLAS photon-jet $X_{J\gamma} \sim 0.5$) Words from CMS and ALICE?

Possible future direction:

• **Raise our standard of “data-model” agreement:** p-value and global fit on multiple dataset

• Treat these observables as baseline data for model parameter extraction and predict other jet substructure (fluctuation) observables

• Comprehensive measurements on the R dependence of jet $R_{AA}$, $X_{J\gamma}$ and h-jet $I_{AA}$ up to large R (with LHC experiments, STAR and sPHENIX)
QGP Rutherford Exp: back scattering

- No significant modification in h-jet and γ-jet.

Possible future direction:

- Need next level of accuracy and resolution at small ΔΦ and high statistics at large ΔΦ at LHC.

- More promising at RHIC energy where the correlation is less affected by initial state radiation (STAR and sPHENIX).
Do gluons lose more energy than the quarks?

If yes: Gluon jet to quark jet ratio will decrease (Gluon jets are more suppressed)
Charged Jet $p_T D$ (Dispersion) and Jet Girth

$\sqrt{\sum_i p_{T,i}^2} = \sum_i p_{T,i}$

$g = \sum_{i \in \text{jet}} \frac{p_{T,i}}{p_{T,jet}} r_i$

- Charged jets in PbPb are more Quark-like! (Gluon jets suppressed)

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Jet Physics in Heavy Ion Collisions  
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Jet Longitudinal Structure

- Enhancement at low $p_T$ (low $Z$) and depletion at intermediate $Z$.
- Enhancement at large $z$ (high $p_T$ particles in jet): smaller gluon/quark ratio in PbPb.
- High $Z$ region: Weak or no dependence on the jet $p_T$.

If switch to $γ$-tagged jet (mainly quarks), will this enhancement go away?

Jet Longitudinal Structure

If switch to $\gamma$-tagged jet (mainly quarks), will this enhancement go away? 

Seems to be the case from CMS data (caveat: jet $p_T$ also changed)

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$R_D(z) = \text{PbPb} / \text{pp}$

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PRL 121 (2018) 242301

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High $p_T$ particle (Low $\xi$)

$\xi = \ln(1/\tau)$

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High $p_T$ particle (High $Z$)
Different picture from ATLAS (jet hardening at large z region)
Significant of **photon-tagged jet FF** in both centrality intervals.
Corrected for jet resolution smearing
Hint of enhancement in PbPb/pp ratio at the **high z region?**
**Photon-Tagged Jet and Inclusive Jet Shape**

### Photon-tagged (Quark Enriched)

- $\sqrt{s_{NN}} = 5.02$ TeV, $p_T^\gamma > 60$ GeV/c
- PbPb 404 $\mu$b$^{-1}$, anti-$k_T$ jet $R = 0.3$
- pp 27.4 $\mu$b$^{-1}$, $p_T^{\text{jet}} > 30$ GeV/c, $\Delta\phi_{jy} > \frac{7\pi}{8}$

**CMS Supplementary**

- $\rho(r)/\rho_{pp}^\text{pp}$
- Data
- SCET$_G$ Chien-Vitev
- LBT

### Inclusive (Quark + Gluon)

- CMS PbPb, $\sqrt{s_{NN}} = 2.76$ TeV
- $L dt = 150$ $\mu$b$^{-1}$
- anti-$k_T$ jets: $R = 0.3$

- $p_T^{\text{jet}} > 100$ GeV/c
- $0.3 < |\eta^{\text{jet}}| < 2$
- $p_T^{\text{track}} > 1$ GeV/c

CMS-HIN-18-006
arXiv:1809.08602

- Difference at small $r$ due to the lower jet $p_T$ in photon-tagged jet and larger quark jet fraction
- Photon tagged jet in PbPb are wider than pp reference
- Need to measure higher $p_T$ photon-tagged jet

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Jet Physics in Heavy Ion Collisions
• Mass effect observed in LHC data though various fully / partially reconstructed decay channels
• Indication of mass effect from STAR and PHENIX data at RHIC
Heavy Flavor vs. Light Flavor

- Expect significantly better accuracy with HL-LHC data and future sPHENIX data
Flavor Dependence of Jet Energy Loss

- Heavy quarks lose less energy than the light flavor: Established in LHC data though model comparisons
  - Quarkonia production and suppression similar to open charm: fragmentation process (not shown)
- Overall narrowing (hardening) of the inclusive ‘jet core’ in AA collision
- Larger gluon jet suppression than quark: collected hints from various jet substructure observables + ATLAS jet and charged particle $R_{AA}$ measurements vs. $\eta$

Possible future direction:

- High precision photon-tagged jet shape and FF (LHC+sPHENIX)
- High precision HF-jet measurements down to low $p_T$ (LHC+sPHENIX)
- Q vs. g: Employ unsupervised ML technique: jet topic separation
- A comprehensive HF program at HL-LHC experiments (ALICE upgrade) and at RHIC (sPHENIX)
- Underlying mechanism of HF energy loss: go beyond HF spectra and HF-soft correlation ($v_N$):
  DDbar, Jet-D and $\gamma$-D correlation, HF jet FF and shape

Wrap-up: prospective for jet physics
Quenched Energy out of the Jet Cone

Do we see medium response?
Quenched Energy Flow at RHIC

Matched jets of different $\theta_{SJ}$ selections are balanced at RHIC

- STAR high tower triggered $A_J$: lost energy recovered within $R=0.4$
- On the other hand, STAR h-Jet and PHENIX $\gamma$-hadron correlations (not shown): the quenched energy goes to large angle
Excess in Jet-Hadron Correlation

Depletion of high $p_T$ charged particles at large $\Delta r$

Enhancement of low $p_T$ charged particles at large $\Delta r$

Interpretations of the low $p_T$ enhancement at large $\Delta R$ include medium response, medium induce radiation / splitting, and vacuum-like emissions out of the medium (Edmond Iancu QM'18)

JHEP 1805 (2018) 006
Different explanations of the large angle enhancement in jet shape measurement

- **SCET$_G$:** Splitting function (large angle radiation)
- **JEWEL & JETSCAPE:** medium recoil parton
- **CCNU:** recoil parton + hydro dynamical evolution
- **HYBRID:** fully thermalized medium response
- **McGill:** medium response + shower
Theoretical Interpretation of the Excess

Different explanations of the large angle enhancement in jet shape measurement

- **SCET**\(_G\): Splitting function (large angle radiation)
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How do we make progress?
(1) Look into the Excess

- One possibility is to look at the particle composition which carry the large angle radiation: (exciting opportunity for ALICE)

- An attempt to check the mass dependence with Jet-D correlation from CMS: Hint of longer distance between jet axis and D⁰ meson, relation to D⁰ v₂?
Measure the **near-side associated yield** with photon-jet and Z-jet
Does the magnitude of quenching depend on the structure of parton shower? One could remove the soft radiation (isolate the hard jet core)
“Ungroomed” Jet Mass

- No modification of the distribution is observed in ALICE and ATLAS data with respect to pp reference
- Cancelling effects from medium modifications of the shower and medium response
Many Exciting Developments

Edmond Iancu

Lund primary planes

anti-$k_t(R=0.4)$, $p_t=200$ GeV

$q=1$ GeV²/fm, $L=4$ fm, $a_s=0.25$

med/vac ratio

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Mateusz Ploskon

Yen-Jie Lee

Jet Physics in Heavy Ion Collisions

And many more…
Groomed Jet Substructure with Soft Drop

- CMS: used two grooming settings with $\Delta R > 0.1$ cut

\[ z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2} > z_{\text{cut}} \left( \frac{\Delta R}{R_0} \right)^\beta \]

Phase diagram from Yi Chen (CERN)

Soft Drop:
JHEP 1405 (2014) 146

"Flat Grooming"
- (0.1, 0.0)
- (0.5, 1.5)

"Jet Core"
- (0.1, 0.0)
- (0.5, 1.5)
Groomed Jet Mass

\[(z_{\text{cut}}, \beta) = (0.1, 0.0) \quad \Delta R > 0.1\]

"Flat Grooming"

\[(z_{\text{cut}}, \beta) = (0.5, 1.5) \quad \Delta R > 0.1\]

"Jet Core"

- Enhancement of large mass when looking at a less aggressive grooming setting
- Results with a “more aggressive grooming”
- Smaller or no significant modification of the “jet core”
Quark and gluon \( Z_g \) distributions are very similar in pp. Jets with **two hard subjets** (large \( Z_g \)) “relatively” more suppressed!

**Interpretation:**
- **JEWEIL**: enhancement of low \( Z_g \) jets (due to medium recoil)
- **SCET\( _g \)**: modification due to medium induced splitting function
- **HT & Coherent antenna BDMPS**: Data prefer coherent energy loss
- **Measurement of \( \Delta R \) spectra and groomed \( R_{AA} \)** would help
Effect of $\Delta R$ selection on $Z_g$ spectra

- No enhancement of low $Z_g$ jets, different from JEWEL prediction
- Too high correlation between medium recoil and jet in JEWEL?
  (hints also seen in jet mass measurements)
- $\Delta R$ cut increase the suppression of large $Z_g$ jets

Normalized by total number of jets

Unselected = Untagged (SD) + cut by $\Delta R$ cut

Harry Andrews (QM2018)
Possible Direction: Hybrid Observable

- Jet tagging with jet substructure: beyond flavor dependence
- Jet structure dependence of jet quenching
- Old Observables + New Excitement

Konrad et. al
arXiv:1808.03689
Sub-jet momentum sharing and groomed jet mass are modified in LHC data. Hint from STAR data (not shown)

**New Era:** Observables with different grooming settings could provide **stress tests** on theoretical models

Open issue:

- Sizable effects from UE fluctuation on groomed Zg and mass measurements; difficulty in detector effect unfolding

Possible direction:

- Develop new algorithms with minimal sensitivity to soft background (for instance, use WTA axis)

- Design jet substructure observables which maximize or minimize the medium effect (also need to be measurable and calculable)

- Iterative feedback cycle: use the state-of-art generator which is tuned to describe the data for resolution unfolding (ex. JETSCAPE, JEWEL++, QPYTHIA++ …)

- To extract medium properties from different variables
Jet Quenching in Small System

- Collective behavior is observed in small systems down to pp
- Not observed (yet) in high multiplicity $e^+e^-$
- Have we detected jet quenching in small system?
Jet Quenching in Small System

• No suppression observed in pPb collisions from those observables
• Also centrality / activity dependent results:
  Charged Particle $Q_{pPb}$ from ALICE, $R_{dAu}$ in PHOBOS and CMS dijet: need higher accuracy and better event classification
• Indication of suppression (2$\sigma$) in PHENIX di-hadron correlation function (shown in this workshop)
Jet Quenching in Small System

- Sizable $v_2$ signal at high $p_T$ in identified hadrons!
- Effect of residual non-flow?
- Indication that CGC and/or Escape Mechanism effects in pPb?

Possible Future Direction:
- Crucial to understand the minimum requirement for jet quenching
- Search for additional final state effect in high multiplicity pPb
- Exp: How can we do better in centrality classification?
- Theory: what do we expect? How big is the modification in $R_{AA}$, photon-jet asymmetry and jet substructure in 0.001% pPb collisions?
Other Ways to Very System Size

- **Use smaller ions**
- Charged Particle $R_{AA}$: Approximate scaling with $N_{\text{part}}$
- Future measurements in even smaller systems like OO, ArAr and KrKr at the LHC could be of interest
- Possibility to perform this survey with sPHENIX at RHIC?
LHC Timeline and CMS Upgrade

**LHC**

- **PbPb 2 nb⁻¹**
  - **Run 2** Long shutdown 2
  - **Run 3**
  - **Run 4** Long Shutdown 3

<table>
<thead>
<tr>
<th>2018</th>
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**CMS Phase 1 Upgrade**

- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- **2018 Performance:**
  - pp L1 100kHz
  - PbPb L1 30kHz (3x of 2015)
  - DAQ: 6 GB/s
    - Up to 6.5 kHz MinBias events to tape (20x of 2015)

**CMS Phase 2 Upgrade**

- 2024-26
  - Tracker |η|<4
  - Muon ID up to |η|<3
  - High Granularity Calo 1.6<|η|<3.0
  - MIP timing detector
    - 4D vertexing
    - Possible p/K/π PID
  - pp L1: 750 kHz
  - DAQ: 60 GB/s

**HL-LHC**

- PbPb 7 nb⁻¹

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LHC and sPHENIX timeline

LHC

PbPb 2 nb⁻¹ → PbPb 7 nb⁻¹

Run 2 | Long shutdown 2 | Run 3 | Long Shutdown 3 | Run 4

| 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 |

CMS Phase 1 Upgrade

CMS Phase 2 Upgrade

sPHENIX construction

sPHENIX Installation commissioning

First data taking campaign
p+p, p+Au, Au+Au

Second campaign
p+p, Au+Au

RHIC

Year-1 | Au+Au | 200 | 16.0 | 7 nb⁻¹ | 8.7 nb⁻¹ | 34 nb⁻¹
Year-2 | p+p | 200 | 11.5 | — | 48 pb⁻¹ | 267 pb⁻¹
Year-2 | p+Au | 200 | 11.5 | — | 0.33 pb⁻¹ | 1.46 pb⁻¹
Year-3 | Au+Au | 200 | 23.5 | 14 nb⁻¹ | 26 nb⁻¹ | 88 nb⁻¹
Year-4 | p+p | 200 | 23.5 | — | 149 pb⁻¹ | 783 pb⁻¹
Year-5 | Au+Au | 200 | 23.5 | 14 nb⁻¹ | 48 nb⁻¹ | 92 nb⁻¹

...EIC
Summary

Final Goal: consistent QGP properties from soft and hard probes

- **Emerging Strongly Interacting Medium**
  - Snapshot of “thermalizing jets” taken by the recorded jet data in the form of modified jet shapes and fragmentation

- **Jet Quenching Mechanism**
  - Indication of larger gluon energy loss than quarks
  - Narrowing of the inclusive jet core
  - Broadening of the photon-tagged jet shape
  - Jet energy loss depends on jet substructure
    “Parton shower shape dependence of jet quenching”

- **Indication of Medium Response Signal**
  - Interpretation of the data: still model dependent

- **Small System and Peripheral Events**
  - Search for jet quenching effect in small system
  - Significant bias in the peripheral AA data
ATLAS Jet Mass
Centrality Selection Bias

- Selection bias plays a very important role in peripheral events
- Models which interpreted peripheral data as cold nuclear effects are wrong

Incoherent superposition of PYTHIA events according to the # of multiparton interaction in HIJING

Amount of bias: Process dependent! (i.e, can not be resolved by using # of Z boson as scale factor)

Austin Baty (QM’18)
CMS Groomed Jet Splitting Function

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

CMS

- Centrality: 50-80%
  - PbPb
  - pp smeared

- Centrality: 30-50%
  - PbPb
  - pp smeared

- Centrality: 10-30%
  - PbPb
  - pp smeared

- Centrality: 0-10%
  - PbPb
  - pp smeared

**anti-k_T R = 0.4, |$p_{T,jet}$| < 1.3**

160 < $p_{T,jet}$ < 180 GeV

**Soft Drop**

$\beta = 0, z_{cut} = 0.1, \Delta R_{12} > 0.1$

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Jet Physics in Heavy Ion Collisions
CMS Groomed Jet Splitting Function

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \text{ pp } 27.4 \text{ pb}^{-1}, \text{ PbPb } 404 \mu\text{b}^{-1} \]

Centrality: 0-10%

anti-\( k_T \), \( R = 0.4 \), \( |\eta_{\text{jet}}| < 1.3 \)

Soft Drop \( \beta = 0 \), \( z_{\text{cut}} = 0.1 \), \( \Delta R_{12} > 0.1 \)

\( 140 < p_{T,\text{jet}} < 160 \text{ GeV} \)

\( 160 < p_{T,\text{jet}} < 180 \text{ GeV} \)

\( 180 < p_{T,\text{jet}} < 200 \text{ GeV} \)

\( 200 < p_{T,\text{jet}} < 250 \text{ GeV} \)

\( 250 < p_{T,\text{jet}} < 300 \text{ GeV} \)

\( 300 < p_{T,\text{jet}} < 500 \text{ GeV} \)

Jet Physics in Heavy Ion Collisions
Z-Jet vs calculations

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \quad \text{pp 27.4 pb}^{-1} \quad \text{PbPb 404 \mu b}^{-1} \]

- Important to have correct pp baseline
- Reasonable agreement between data and theory curves from JEWEL, HYBRID and GLV

The CMS graph shows distributions in various channels with conditions for cuts on jet transverse momentum and pseudorapidity. The left panel focuses on pp collisions, while the right panel on PbPb collisions at 0-30% centrality. The notation for cuts includes:

- \( p_T^Z > 60 \text{ GeV/c} \)
- Anti-\( k_T \) jet \( R = 0.3 \)
- \( p_T^{\text{jet}} > 30 \text{ GeV/c} \)
- \(|\eta^{\text{jet}}| < 1.6\)
- \( \Delta\phi_{ij} > \frac{7}{8}\pi \)
Charged Particle $R_{AA}$ vs. Theoretical Models

- General trend described by pQCD based and Hybrid models
- A full description of the $R_{AA}$ is still challenging for some models
Description of the $D^0$ Meson Data

- At high $D^0$ $p_T$: Trend captured by pQCD and AdS/CFT based models
- Reasonable description of the data could be achieved
- Details doesn’t work perfectly, especially the slope of the $D^0 R_{AA}$ vs. $p_T$

arXiv:1708.04962

CUJet3.0

SCET$G$
ALICE Charged Jet Mass

- Data sit between JEWEL recoil on and off
- HYBRID need medium recoil to describe the ALICE data

HYBRID
Groomed Jet Mass

\[(z_{\text{cut}}, \beta) = (0.1, 0.0) \quad \Delta R > 0.1\]

\[(z_{\text{cut}}, \beta) = (0.5, 1.5) \quad \Delta R > 0.1\]

- Enhancement of large mass when looking at a less aggressive grooming setting
- Results with a “more aggressive grooming”
- No significant modification of the “jet core”
Charged Particle $R_{AA}$

- Strong suppression of charged particles (up to a factor of 6) in PbPb
- Almost no suppression at very high $p_T$ compared to pp reference ($p_T \sim 400$ GeV)
- Similar charged particle $R_{AA}$ in PbPb at 5 TeV compared to 2.76 TeV

- General trend described by both pQCD and Hybrid models
- Description of the $R_{AA}$ over the whole $p_T$ range is still challenging

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Jet Physics in Heavy Ion Collisions

ATLAS-CONF-2017-012
JHEP 04 (2017) 039
Collimated jets vs. Large Opening Angle

- **$\Delta R < 0.1$**
  - Normalized by total number of jets
  - Small or no modification of “collimated jets”
    (small $\Delta R$ between subjets)

- **$\Delta R > 0.2$**
  - Larger $\Delta R$ cut ($\Delta R > 0.2$ large opening angle between subjets): Significant suppression at large $Z_g$

Unselected = Untagged (SD) + cut by $\Delta R$ cut

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Jet Physics in Heavy Ion Collisions

Harry Andrews (QM2018)
• No enhancement in the number of splitting passing Soft Drop in PbPb compared to pp
• Decrease the population of gluon jets: >70% of the tagged jets are quark jets

• Observation of modified jet fragmentation function in PbPb with respect to pp
  • No significant high z (or small $\xi=\ln(1/z)$) enhancement observed
  • CMS only measured down to $\xi$>=0.5 (or z <= 0.7)
  • It would be good to have high $p_T$ associated jet version of this analysis
Jet Transverse Structure

Jet shapes in pp and PbPb at 5.02 TeV

Jet axis

\[ \Delta r = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

- Jet shapes and fragmentation functions in pp and PbPb collisions at 5 TeV
- Sensitive to the possible medium response to hard probes and induced radiation

CMS-PAS-HIN-16-020
arXiv 1803.00042
Larger $|y|$ : steeper $p_T$ spectra slope and higher quark fraction
Flat $R_{AA}$ vs rapidity: less jet suppression at larger $|y|$, i.e., quarks lose less energy than gluons.

arXiv 1805.05635
Flavor Dependence of Parton Energy Loss

Do light quarks lose more energy than heavy quarks?
Dead-cone effect at low meson $p_T$, disappearance at high meson $p_T$

Do gluons lose more energy than the quarks?
If yes: Gluon jet to quark jet ratio will decrease (Gluon jets are more suppressed)
Flavor Dependence of Parton Energy Loss

\[ \text{PbPb 0-100\%} \]
\[ 27.4 \text{ pb}^{-1} (5.02 \text{ TeV pp}) + 530 \mu \text{b}^{-1} (5.02 \text{ TeV PbPb}) \]

- \( R_{\text{AA}} \) is meson flavor dependent at low \( p_T \);
- disappearance of the effect at high \( p_T \);
- Consistent with the expectation from parton flavor dependent energy loss

- Prompt \( J/\psi \) \( R_{\text{AA}} \) ~ Charged particle \( R_{\text{AA}} \) at high \( p_T \): FF+parton energy loss in play
- Relevance of the fragmentation process for the interpretation of low \( p_T \) \( J/\psi \)?

**CMS Supplementary**

- \( D^0 + D^0 \)
- Charged hadrons
- \( B^+ |y| < 2.4 \)
- Nonprompt \( J/\psi \)
- \( 1.8 < |y| < 2.4 \)
- \( |y| < 2.4 \)

\[ R_{\text{AA}} \]

\[ ATLAS \]
\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, 0.42 \text{ nb}^{-1} \]

- Charged particles, 0-5\%, 2.76 TeV
- Non-prompt \( J/\psi \), 0-10\%
- Prompt \( J/\psi \), 0-10\%

**Prompt \( J/\psi \)**

\[ h^\pm \]

\[ h^\pm \]

**\( p_T \) [GeV]**
$R_{AA}$ in peripheral events

M. Spousta (ATLAS)  
Tues. 12:10pm

- 60-80% Pb+Pb, $R_{AA} = 0.65$
- $\langle N_{\text{part}} \rangle = 23$ (ATLAS similar)
- <1% $p$+Pb (0-5% in Glauber-Gribov!)

N. Jacazio (ALICE)  
Wed. 4:50pm

- 70-90% Pb+Pb, $R_{AA} = 0.7$
- $\langle N_{\text{part}} \rangle = 11$
- ~20-30% $p$+Pb

Y.-J. Lee (CMS)  
Monday 12:10pm

- 80-93% Au+Au, $R_{AA} = 0.8$
- $\langle N_{\text{part}} \rangle = 5$
- ~50-70% $p$+Pb

S. Zharko (PHENIX)  
Wed. 10:40am

With ALICE data analysis (also CMS generator studies) shown in QM’18

Models which interpreted these data as cold nuclear effects are wrong

From Dennis Perepelisa QM’17

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Jet Physics in Heavy Ion Collisions  
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larger energy loss for gluons than quarks followed by pythia fragmentation
## Total Charm Production Cross-section

<table>
<thead>
<tr>
<th>Charm Hadron</th>
<th>Cross Section $d\sigma/dy$ (\mu b)</th>
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<tbody>
<tr>
<td>$D^0$</td>
<td>$41 \pm 1 \pm 5$</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$18 \pm 1 \pm 3$</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$15 \pm 1 \pm 5$</td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>$78 \pm 13 \pm 28^*$</td>
</tr>
</tbody>
</table>

**Au+Au 200 GeV (10-40%)**

- **Total**: $152 \pm 13 \pm 29$

**p+p 200 GeV**

- **Total**: $130 \pm 30 \pm 26$

Total charm X-section follows $\sim N_{\text{bin}}$ scaling from p+p to Au+Au

However, charm hadron fractions are different from p+p to Au+Au collisions
Heavy Quark Hadronization
Z-Jet in pp and PbPb at 5.02 TeV

Jet quenching (E-loss)

First Z-jet measurement in PbPb collisions at 5 TeV

$x = p_T^{\text{Jet}} / p_T^{\text{boson}}$
**Z\textsubscript{g} vs. \Delta R Phase Space**

Momentum Sharing of Subjets

\[
Z_{g} = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}
\]

Cartoon

- Vacuum-like Splitting
- Medium Induced Radiation
- Medium cascade
- Broadening
- Soft Radiation
- Medium recoil/response

One hard subjet

One hard subjet

\(Z_{g}\) small

Two hard subjets

\(Z_{g} \sim 0.5\)

Ideal world, different phase space correspond to different physics
\[ Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \]

- The reality may be much more complicated than that
- The excitement: One could construct different observables which are sensitive to different part of the phase space and provide stress test on models
Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"

The Quark Soup probed is very smooth!

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Search for Quasi-Particles in the QGP

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The Quark Soup probed is very smooth!
QGP Rutherford Experiment

No significant broadening (Also in LHC Photon-Jet, Dijet measurements)

QGP probed looks smooth
Moreover, groomed jet mass distributions in pp with CMS selection criteria are similar between quark and gluon jets (due to the $\Delta R$ cut)
Impression: with tuning, models with different underlying physics could fit the data (both strong and weak coupling calculations)
• **Both weak and strong coupling based models** describe the charged hadron, charm and beauty meson $R_{AA}$ data

• Within pQCD world, models with very different level of complexity describe the data

• No significant difference between beauty and inclusive (di-)jet results (not shown, need better accuracy)