Heavy ion physics at CMS and ATLAS: hard probes
Hard probes in heavy ion physics

- **Starting point**: nuclear PDFs. Gluon saturation
  - Comparisons to proton-proton collisions
  - Cold nucleus: proton-lead collisions
  - Final states: photons, dijets with large rapidity separation

- **Probing** the QGP, transport
  - Varying the size of the ions
  - Suppression of charged hadrons and jets
  - photon-jet $p_T$ balance

- **Plasma temperature**, HF
  - Quarkonium “melting”
  - Heavy quarks: suppression, coalescence

- **Substructure** of the QGP and medium response
  - Modification of the **transverse** structure of jets
  - Modification of the **longitudinal** structure of jets
Isolated photons in p+Pb

- Nuclear modification factor of photons

\[ R_{pPb} = \frac{(d\sigma^{p+Pb\rightarrow\gamma+X}/dE_T^\gamma)}{(A \cdot d\sigma^{pp\rightarrow\gamma+X}/dE_T^\gamma)} \]

- Sensitive to modified nPDFs and initial state energy loss

- The data disfavor a large amount of energy loss

- Constraints on nuclear PDF

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arXiv:1903.02209
Dijets in p+Pb

- Saturation at low $x$ ($10^{-4}$-$10^{-3}$)?
- No broadening of azimuthal angular correlations for dijets in p+Pb
- Forward-forward jet pairs: (p-going) p+Pb/p+p ratio of conditional yields is suppressed
- Forward-central dijets: no modification
Larger ions: suppression and energy loss

Suppression of charged particles in $^{129}\text{Xe}$ data at 5.44 TeV (2017): $R_{AA}$

- Slightly greater suppression in Xe+Xe at the same $N_{\text{part}}$.
- Xe+Xe: smaller suppression than Pb+Pb at the same centrality.

JHEP 10 (2018) 138
Suppression of jets in Pb+Pb collisions

Nuclear modification factor: increases to high $p_T$ and from central to peripheral

ATLAS anti-$k_t$ $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV

$R_{AA}$ vs $p_T$ for $|y| < 2.8$

2015 data: Pb+Pb 0.49 nb$^{-1}$, pp 25 pb$^{-1}$

$\langle T_{AA} \rangle$ and luminosity uncer.

Suppression of jets in Pb+Pb collisions

Nuclear modification factor: increases to high $p_T$ and from central to peripheral
Photon-jet $p_T$ balance

We have seen that photons are not affected by the QGP
Demonstrates (quark) energy loss in the medium
Data is corrected for accidental pairings and unfolded for resolution
Even in central events, some jets lose only very little energy

$$x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}}$$

**ATLAS**

$pp$ 5.02 TeV, 25 pb$^{-1}$
Pb+Pb 5.02 TeV, 0.49 nb$^{-1}$

$p_T^{\gamma} = 79.6-100$ GeV

$pp$ (same each panel)
Pb+Pb
Quarkonium suppression

Debye-screening. $T_{\text{dissoc}} = 2T_c, 1.2T_c, T_c$

Successive suppression of Y states (according to binding energy).

Gradual suppression as a function of centrality (not shown here)
Quarkonium suppression

J/ψ and b-decays to J/ψ: very different suppression mechanisms
Strong suppression of prompt and non-prompt J/ψ, and non-prompt ψ(2S)
Prompt: ψ(2S) more suppressed than J/ψ
Suppression of non-prompt ψ(2S) is equal to that of the non-prompt J/ψ
Muons from heavy quark decays

heavy quarks: energy loss at high $p_T$,
partial thermalization and flow at low $p_T$

Very small irreducible background

$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{evt}} \frac{d^2N}{dp_Td\eta}_{\text{cent}}$

Heavy flavor is less suppressed than hadrons

Heavy quarks

Testing the deconfined medium (1st result in AA) B_s^0: beauty-strangeness coalescence at low p_T μμKK decay channel
Possible enhancement of the B_s^0/B^+ ratio

28 pb^-1 (pp) + 351 μb^-1 (PbPb) 5.02 TeV

CMS

R_s^B^0 / R_s^B^+ |

| y | < 2.4

TAMU

CUJET3.0

Cent. 0-100%

p_T (GeV/c)

Non-prompt D^0 → K^-π^+ (b quarks)
Collisional and radiative energy loss

27.4 pb^-1 (5.02 TeV pp) + 530 μb^-1 (5.02 TeV PbPb)

CMS

D^0 from b hadrons |y|<1
B^+ |y|<2.4
J/ψ from b hadrons:
1.8<|y|<2.4
|y|<2.4

Global uncertainty

Submitted to Phys. Lett. B
arXiv:1810.03022

arXiv:1810.11102
QGP substructure

What happens to our jets precisely in the **quark soup**?
Jet transverse structure

Isolated photon tagged jets: information on jet energy and flavor
Medium induced modification with little sensitivity to hadronization: jet shape
Observations: jet broadening, energy redistribution
No depletion at medium r (as the case for inclusive jets)

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arXiv:1809.08602
Jet longitudinal structure

Jet fragmentation:

**Enhancement** of particles with a **small** or **very large** fraction of the jet momentum

**Suppression** of particles with an **intermediate** fraction of the jet momentum
Jet longitudinal structure

Jet fragmentation:
photon-tagged jets: removing jet selection bias and restricting to quark jets
Quark- and inclusive jets are modified in a different way in central Pb+Pb events. Interpretation is complicated due to different selection biases in the two cases.

Submitted to PRL  arXiv:1902.10007
Jets: groomed mass

Jet grooming removes large-angle, soft radiation $\rightarrow$ hard subjets
Opening angle is sensitive to medium modifications $\rightarrow$ jet mass of groomed jets
Models overestimate the yield of jets with large groomed mass

$PbPb$ 404 $\mu$b$^{-1}$ (5.02 TeV), pp 27.4 pb$^{-1}$ (5.02 TeV)

### CMS

- anti-$k_T$ $R = 0.4$, $|\eta_{jet}| < 1.3$
- Soft Drop $z_{cut} = 0.5$, $\beta = 1.5$
- $\Delta R_{12} > 0.1$

Centrality: 0-10%

#### Results

- $140 < p_{T,jet} < 160$ GeV
- $160 < p_{T,jet} < 180$ GeV
- $180 < p_{T,jet} < 200$ GeV
- $200 < p_{T,jet} < 300$ GeV

#### Models

- Data
- Jewel (Recoil off)
- Jewel (Recoil on)
- QPythia

JHEP 10 (2018) 161
Summary

- Studies of the **cold nucleus**: proton-lead collisions
  - Nuclear PDFs are verified with *isolated photons*
  - Forward-forward *jet pairs* suppressed (saturation)

- **Strongly interacting** QGP, transport
  - *Geometry* and ion size is important: Xe+Xe collisions
  - Precise *jet nuclear modification factors* measured
  - Photon-jet *momentum balance*: unfolded; wide E loss distribution

- Plasma **temperature**, HF
  - Quarkonia “*melting*”, suppression of heavy quark mesons
  - Heavy quarks: *suppressed less than most hadrons*
  - Hint of *b-s coalescence*?

- **Jet modifications**
  - Jet *broadening*, modified FFs, measured even with photon tag
  - Jets with high *groomed mass*: *less frequent* than predicted
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