Recent results on hard processes in $p+\text{Pb}, \text{Pb}+\text{Pb}$ collisions from the ATLAS experiment at the LHC

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Characterization of QGP

Different hard probes interact with medium differently.

- Measurements of photons, Z and W bosons.
- Electro-weak bosons don’t interact strongly with the medium so expect no modification to their production rates.
- Provide information about the initial state → nuclear PDFs.
EW boson production

- $W^+$ and $W^-$ bosons per event yield production measured in muon channel in Pb+Pb collisions at 5.02 TeV.
- The yields scaled by $T_{AA}$ (left) have no dependence on number of participating nucleons.
- $W^+$ yield by 10% larger than $W^-$ yield.
- Lepton charge asymmetry (right) consistent with theory with some small deviations in the forward direction.

\[
A_\ell(\eta_\ell) = \frac{dN_{W^+\rightarrow\ell^+\nu}/d\eta_\ell - dN_{W^-\rightarrow\ell^-\bar{\nu}}/d\eta_\ell}{dN_{W^+\rightarrow\ell^+\nu}/d\eta_\ell + dN_{W^-\rightarrow\ell^-\bar{\nu}}/d\eta_\ell}
\]
Nuclear modification factor $R_{AA}$

Partons lose energy through interactions with the medium $\rightarrow$ jet quenching

\[ R_{AA} = \frac{1}{N_{\text{coll}}} \begin{array}{c} 1 \\ \frac{dN_{AA}}{dp_T} \end{array} = \frac{1}{N_{\text{coll}}} \begin{array}{c} 1 \\ \frac{dN_{pp}}{dp_T} \end{array} = \frac{1}{T_{AA}} \begin{array}{c} \frac{dN_{AA}}{dp_T} \\ \frac{d\sigma_{pp}}{dp_T} \end{array} \]

- Compares HI and $pp$ collisions and removes the geometrical scaling.
- Jet nuclear modification factor quantifies the magnitude of jet suppression, which arise mainly from final-state interactions with constituents of the medium.
Jet $R_{AA}$ vs $p_T$ and $N_{part}$ @ 5.02 TeV

- Central events: only modest grow with $p_T$, flattening for $p_T > 200$ GeV.
- Peripheral events: Still significant suppression even in 60-70%.

arXiv:1805.05635
Jet $R_{AA}$ vs rapidity

\[ \frac{R_{AA}(|y|)}{R_{AA}(|y| < 0.3)} \]

No rapidity dependence for low $p_T$ jets.

At high $p_T$, decreasing $R_{AA}$ in the forward region.
Fragmentation functions

ATLAS studies of 3 colliding systems at different centre-of-mass energy:

- $pp$ @ 2.76 TeV & 5.02 TeV
- $p+\text{Pb}$ @ 5.02 TeV
- Pb+Pb @ 2.76 TeV & 5.02 TeV

- How much is the jet structure modified?

- Jet fragmentation functions (FF) are defined as:
  
  $$D(p_T) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T^{\text{ch}}}$$  
  $$D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz}$$  
  $$z = \frac{p_T}{p_T^{\text{jet}}} \cos \Delta R$$

- $N_{\text{ch}}$ is the number of charged particles associated to a jet
- Measurement was done for $R = 0.4$ jets differentially in $\eta$ and $p_T$
- Jet substructure measured using charged tracks starting at $p_T = 1$ GeV
- FF are background subtracted, corrected for tracking efficiency and fully unfolded with 2D Bayesian unfolding
Jet $p_T$ dependence to the FF modification

\[ D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T} \quad D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz}, \text{ where } z \equiv p_T \cos r / p_T^{\text{jet}} \]

\[ R_{D}(p_T, r) = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{\text{pp}}} \]

- No dependence on jet $p_T$ observed at high $z$ for jets up to 400 GeV.
- Enhancement of soft fragments increases for high $p_T$ jets.

Pb+Pb @ 5.02 TeV
Track-to-jet correlation

- Study distribution of charged particles inside and around the jet cone ($r < 0.6$) in Pb+Pb and $pp$ collisions at 5.02 TeV.
- Dependence on centrality, jet- and charged-particle $p_T$ is extracted.
- Quantities $D(p_T, r)$ and ratios $R_D(p_T, r)$ are fully unfolded and can be compared to theory.

\[ D(p_T, r) = \frac{1}{N_{jet}} \frac{1}{2\pi r} \frac{d^2 n_{ch}(r)}{dr dp_T} \]

\[ R_D(p_T, r) = \frac{D(p_T, r)_{Pb+Pb}}{D(p_T, r)_{pp}} \]
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$R_D(p_T, r) = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{\text{pp}}}$

Increase of yields of soft fragments with increasing $r$.
Decrease of yields of intermediate $p_T$ particles with $r$. 

ATLAS-CONF-2018-010
Dijet asymmetry

- Dijets in $pp$ collisions are approximately balanced in energy.
- In Pb+Pb the two jets lose different amounts of energy because of they travel different paths in the plasma or they are caused by jet-by-jet fluctuations in the energy loss.
- Use ratio of the lower jet $p_T$ (sub-leading jet) to the higher jet $p_T$ (leading jet):
  \[ x_J \equiv \frac{p_{T2}}{p_{T1}} \]
- Compare Pb+Pb to $pp$ dijets where we expect the $x_J \sim 1$. 

Jets
Xe+Xe collisions recorded in Oct 2017 for the first time at the LHC.

- Left: Xe+Xe consistent with Pb+Pb in same centrality percentiles.
- Right: Xe+Xe consistent with Pb+Pb in same FCal $E_T$ bin.

$\chi_J \equiv \frac{p_T^2}{p_T^1}$
Charged hadron $R_{AA}$ in Xe+Xe and Pb+Pb

- Measurement of charged-hadron spectra in Xe+Xe collisions at 5.44 TeV and Pb+Pb at 5.02 TeV.
- $R_{AA}$ in Xe+Xe collisions shows a centrality-dependent suppression with characteristics qualitatively similar to that observed in Pb+Pb collisions.
- In central events, hadron yields in Xe more suppressed to those in Pb, while in peripheral events, milder suppression in Xe+Xe than Pb+Pb collisions.
- Baseline estimated from $pp$ data with 5.02 TeV and extrapolated to the Xe+Xe center-of-mass energy.
Photon-tagged jet studies in Pb+Pb @ 5.02 TeV

What is the (absolute) amount of energy lost in cone?

$p_T^\gamma$-jet $p_T$-balance

$x_{j\gamma} = \frac{p_T^{\text{jet}}}{p_T^\gamma}$ (for $\Delta \Phi > 7\pi/8$)

ATLAS-CONF-2018-009

How is the parton shower in cone modified by hot and dense medium?

Photon-tagged fragmentation function (with respect to the jet)

$D(p_T^h)$ or $D(z = \frac{p_T^h}{p_T^{\text{jet}}})$

Kinematic selection intended to pick out only leading (dominantly quark) jets:

$p_T^\gamma = 79.6 - 125$ GeV

$p_T^{\text{jet}} = 63.1 - 144$ GeV

ATLAS-CONF-2017-074
Photon-tagged jet FF ratios in Pb+Pb @ 5.02 TeV

- In peripheral (left): similar behaviour for photon-tagged and inclusive jets.
- In central (right): differences between photon-tagged and inclusive jet FF - additional suppression at high $p_T$ and enhancement at low $p_T$.  

ATLAS-CONF-2017-074
Inclusive photons in $p+$Pb

- Measurement of inclusive prompt photons in $p+$Pb collisions at 8.16 TeV:
  - At forward and central rapidity, $R_{pPb}$ consistent with unity.
  - At backward rapidity, $R_{pPb} < 1$ due to isospin effects.

- Comparison to JETPHOX with nPDF from EPPS16, nCTEQ15:
  - With the current uncertainties, the data is unable to constraint nPDF.
  - Ongoing work to reduce uncertainties.
Charmonia are bound states of $c$ and $c\bar{c}$ quarks. An important probe to study the hot, dense system created in nucleus-nucleus (A+A) collisions.
Quarkonia production in Pb+Pb @ 5.02 TeV

- Measurement of per-event yields of prompt and non-prompt production of J/ψ and ψ(2S) for different centrality classes.
- Meson kinematics determined from a dimuon system: 9 < \( p_T < 40 \) GeV and |\( y | < 2\).
- J/ψ \( R_{AA} \) as a function of \( p_T \), rapidity and \( N_{\text{part}} \) for both prompt and non-prompt component.
- Strong suppression is found for both J/ψ and ψ(2S) and increasing with centrality.
- \( R_{AA} \) dependence of prompt and non-prompt J/ψ on centrality seems to be quite similar.
- For 0-10% centrality, \( R_{AA} \sim 0.25 \).
Quarkonia production in Pb+Pb @ 5.02 TeV

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- Meson kinematics determined from a dimuon system: $9 < p_T < 40$ GeV and $|y| < 2$.
- $J/\psi R_{AA}$ as a function of $p_T$, rapidity and $N_{\text{part}}$ for both prompt and non-prompt component.
- Strong suppression is found for both J/ψ and ψ(2S) and increasing with centrality.
- $R_{AA}$ dependence of prompt and non-prompt J/ψ on centrality seems to be quite similar.
- Result largely consistent with colour screening and colour transparency and parton energy-loss predictions.
Exclusive dimuons in non-UPC Pb+Pb collisions

- Exclusive production of $\mu^+\mu^-$ pairs in non-Ultra-Peripheral collisions.
- Muons are back-to-back in azimuth $\Phi$.
- Acoplanarity, $\alpha$, is defined as: $\alpha = |1 - \Delta \Phi / \pi|$
- What happens to acoplanarity in the QGP?

Can a "non-UPC" $\mu\mu$ event "see" the QGP?
Exclusive dimuons in non-UPC Pb+Pb collisions

- Exclusive production of $\mu^+\mu^-$ pairs in non-Ultra-Peripheral collisions.
- Muons are back-to-back in azimuth $\Phi$.
- Acoplanarity, $\alpha$, is defined as: $\alpha = |1 - \Delta \Phi / \pi|$.
- What happens to acoplanarity in the QGP?

- A clear centrality-dependent broadening is observed for $\alpha$ distribution.
- Modification qualitatively consistent with re-scattering of muons in the QGP.
- MC model (signal from STARlight+MB event from data) does not describe the data in the central events.
- First observation of EM interactions with the QGP?
Conclusions

- EW boson measurements improve our understanding of the geometry.
- Inclusive jet suppression in 5.02 TeV Pb+Pb collisions:
  - Significant suppression seen up to ~1 TeV with weak $p_T$ dependence.
  - Sign of rapidity dependence of $R_{AA}$ observed for high-$p_T$ jets.
- Dijet asymmetry in 5.44 TeV Xe+Xe collisions: No differences in comparison to Pb+Pb collisions observed.
- Measured spectra and nuclear modification factor for charged hadrons in Xe+Xe collisions:
  - The suppression is similar to that measured in Pb+Pb collisions.
- Jet Fragmentation in 5.02 TeV Pb+Pb collisions:
  - Yields of soft and hard fragments are enhanced in Pb+Pb compared to $pp$ collisions.
- Photon-jet fragmentation functions:
  - Different modification in central events compared to inclusive jets FF.
- Strong suppression is found for both J/ψ and ψ(2S).
- Observation of broadening of acoplanarity distribution for muons from γγ→μμ process.
ATLAS public results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylonsPublicResults
Heavy-ion collisions

- One of the main goals of heavy-ions physics is to study the hot and dense deconfined matter called quark-gluon plasma (QGP).

This should allow us to:

- Study non-perturbative aspects of QCD and collective phenomena connected with the strong interaction.
- Study the phase diagram of nuclear matter and the transition from quarks and gluons to hadrons.
- Study matter which is similar to the matter present in the early stages of the universe.
- Study the electromagnetic processes in ultra-peripheral collisions (growing program).
Centrality in HI collisions

- Centrality is a measure of overlap of two colliding nuclei
- Determined by the sum of the transverse energy deposited in the Forward calorimeters
- It is closely related to the average number of participant nucleons $N_{\text{part}}$ and number of binary inelastic collisions $N_{\text{coll}}$
- Events divided into successive percentiles of the $\sum E_T^{FCal}$
- Central collisions: Large overlap, high number of participating nucleons $N_{\text{part}}$
- Peripheral collisions: Small overlap, low number of participating nucleons $N_{\text{part}}$
Characterizing the QGP using jets

Different hard probes interact with medium differently.

- Produced early in the collision where the initial state is well understood such that any differences from $pp$ in the final state are from interactions with the medium.
- Interactions of medium and colored probe (elastic scattering, induced radiation).
- Partons lose energy through interactions with the medium → jet quenching
Jet mass in Pb+Pb @ 5.02 TeV

- First fully-unfolded measurement of jet mass in Pb+Pb/pp collisions at 5.02 TeV by ATLAS
- Jets: $126 < p_T < 500$ GeV, $|y| < 2.1$
- Distribution of $m/p_T$ is measured, where $m$ is the norm of jet four-momentum from calo towers

$$R_{AA}(m/p_T, p_T) = \frac{\int \frac{1}{N_{evt}} \frac{dN_{jet}^{Pb+Pb}}{d(m/p_T)}(p_T) \left|_{cent} \right.}{\langle T_{AA} \rangle \frac{d\sigma^{Pp}_{jet}}{d(m/p_T)}(p_T)}$$

- $R_{AA}$ has no significant dependence on $m/p_T$
- $R_{AA}$ values are consistent with inclusive jet $R_{AA}$
Reminder: Dijet asymmetry in Pb+Pb @ 5.02 TeV

\[ x_J \equiv \frac{p_{T2}}{p_{T1}} \]

- Measured for:
  - \( p_{T, sublead} > 25 \text{ GeV}, \)
  - \( p_{T, lead} > 100 \text{ GeV} \)
  (various bins),
  - \( |\Delta \phi| > 7\pi/8 \)
  - \( |\eta| < 2.1 \)
  - \( R=0.4, R=0.3 \) jets
Jet cross-section in $pp$ and yields in Pb+Pb

ATLAS
2015 $pp$ data, 25 pb$^{-1}$
anti-$k_t$, $R=0.4$ jets
$s = 5.02$ TeV

ATLAS
2015 Pb+Pb data, 0.49 nb$^{-1}$
2015 $pp$ data, 25 pb$^{-1}$
anti-$k_t$, $R=0.4$ jets

$|\eta| < 2.8$ ($\times 10^{15}$)
$|\eta| < 0.3$ ($\times 10^{15}$)
$0.3 < |\eta| < 0.8$ ($\times 10^9$)
$0.8 < |\eta| < 1.2$ ($\times 10^9$)
$1.2 < |\eta| < 1.6$ ($\times 10^9$)
$1.6 < |\eta| < 2.1$ ($\times 10^9$)
$2.1 < |\eta| < 2.8$

arXiv:1805.05635
Dijet asymmetry in Xe+Xe @ 5.44 TeV

Xe+Xe: smaller system, larger eccentricity … impact on jet suppression?

- Not unfolded for detector effects but still similar to Pb+Pb
- Larger dijet asymmetry decreases with increasing $p_T$

$$x_J \equiv \frac{p_{T2}}{p_{T1}}$$
Dijet asymmetry in Xe+Xe @ 5.44 TeV

Xe+Xe: smaller system, larger eccentricity ... impact on jet suppression?

- Not unfolded for detector effects
- $x_J$ decreases with decreasing centrality

\[ x_J \equiv \frac{p_{T2}}{p_{T1}} \]
Fragmentation functions measured at ATLAS

- **FF @ 2.76 TeV:**

- **FF @ 5.02 TeV:**
  - Pb+Pb & *pp* reference, *arXiv:1805.05424*

This talk
Jet $p_T$ dependence to the FF modification

\[ D(p_T) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dp_T} \quad D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}, \text{ where } z = p_T \cos \theta / p_T^{jet} \]

No modification of jet structure within experimental precision in the $p$+Pb system.

Result consistent with unmodified hadron $R_{pPb}$ measured with the 5.02 TeV $pp$ reference data.

ATLAS-CONF-2016-108
Track-to-jet correlation

Reminder: measurement of the fragmentation functions:

\[ D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{d n_{\text{ch}}}{d p_T} \quad D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{d n_{\text{ch}}}{d z}, \quad \text{where} \quad z \equiv p_T \cos r / p_T^{\text{jet}} \]

\[ D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2 \pi r} \frac{d^2 n_{\text{ch}}(r)}{d r d p_T} \]

where \( r < 0.6 \)

- Study distribution of charged particles inside and around the jet cone \((r < 0.6)\) in Pb+Pb and \( pp \) collisions at 5.02 TeV
- Dependence on centrality, jet- and charged-particle \( p_T \) is extracted
- Quantities \( D(p_T, r) \) and ratios \( R_{D(p_T, r)} \) are fully unfolded and can be compared to theory
Jets are broader in more central collisions. Smallest modification seen in the jet core.

Increase of yields of soft fragments with increasing $r$. Decrease of yields of intermediate $p_T$ particles with $r$.

Energy lost by jets is being transferred to particles with $p_T < 4.0$ GeV with larger radial distances.

$R_{D(p_T,r)}$ is above unity for particles with $1.6 < p_T < 4$ GeV, and below unity for particles with $p_T > 4$ GeV in 0-10% centralities.

This observation is in agreement for $r < 0.4$ with the inclusive jet FF results.

For a given particle $p_T$ interval, $R_{D(p_T,r)}$ changes for $r < 0.3$ and then saturates.
Charmonia bound states of c and c̅quarks, could be a unique probe to study the hot, dense system created in nucleus-nucleus (A+A) collisions.

However, the full picture is much more complicated:
- Color-Screening: melting
- Color-exchange: absorption
- Medium induced energy loss
- Regeneration via statistical recombination
- Feed-Down of excited charmonium states and B-hadrons
Photon-tagged jet FF in $pp @ 5.02$ TeV

- Use photon-tagged jets with photons acting as unmodified probes in QGP
- Photon-tagged jets are more likely to be initiated by quarks, inclusive jets are gluon jet-dominant
- Fully unfolded ratios of jet FF for photon-tagged and inclusive in Pb+Pb and pp systems

Inclusive to γ-tagged jet FF ratio

[Graph showing ATLAS Preliminary results for $pp$, 26 pb$^{-1}$, 5.02 TeV]
Photon-tagged jet FF ratios in Pb+Pb @ 5.02 TeV

- Familiar pattern of modification for peripheral events wrt inclusive FF (left) but different pattern for central events (right)
Jet asymmetry for gamma-jet in Pb+Pb @ 5.02 TeV

- Photons act as calibration probes in HI collisions.
- Measure $x_{J\gamma}$ in Pb+Pb/pp collisions at 5.02 TeV.
- Centrality and photon $p_T$ dependence measured:

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

- $x_{J\gamma}$ fully unfolded for detector effects.
- $x_{J\gamma}$ evolves smoothly with centrality.
- In 50-80%, comparable to $pp$.
- In 0-10%, no clear peak anymore.
Jet asymmetry for gamma-jet in Pb+Pb @ 5.02 TeV

- Photons act as calibration probes in HI collisions.
- Measure $x_{J\gamma}$ in Pb+Pb/pp collisions at 5.02 TeV.
- Centrality and photon $p_T$ dependence measured:

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

- Comparison to several theory predictions.
- Main features of the data described by models.
Quarkonia production in $p+\text{Pb} @ 5.02 \text{ TeV}$

- Measurement of cross-section for prompt and non-prompt production of $J/\psi$ and $\psi(2S)$ for different rapidity intervals and inclusive yields of $Y(nS)$, $n = 1, 2, 3$.
- $J/\psi$ cross-section are in agreement with NRQCD (prompt) and FONLL (non-prompt) predictions.
- $J/\psi R_{p\text{Pb}}$ is consistent with unity for $p_T$ between 8 - 40 GeV.
- $\Upsilon(1S) R_{p\text{Pb}}$ is found to be suppressed for $p_T < 15 \text{ GeV}$.