Energy and system dependence of nuclear modification factors of inclusive charged particles and identified light hadrons measured in p-Pb, Xe-Xe and Pb-Pb collisions with ALICE

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Motivation

- Partons originating from initial hard scatterings lose their energy in the hot and dense medium, which results in suppression of high $p_T$ hadrons.
- Light flavor particles are powerful probes to measure the suppression in a wide $p_T$ range with high precision.

- The suppression is up to a factor of 5 in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC.
- It reaches a factor of 7-8 in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV at LHC.

- Hadron measurements in pp are baseline for pA and AA collisions.
- Results in pA collisions allow to disentangle whether this suppression comes from initial or final state effect.
- Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV allow to study system size and geometry dependence of particle production.
Charged particle tracking
ITS + TPC

Neutral meson ($\pi^0/\eta \rightarrow \gamma \gamma$) reconstruction
Electro-magnetic calorimeters and external conversion in detector materials

<table>
<thead>
<tr>
<th>year</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>$L_{int}$ (nb$^{-1}$)</th>
<th>year</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>$L_{int}$ (nb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 Pb-Pb</td>
<td>2.76</td>
<td>2.3 x 10^{-3}</td>
<td>2015 pp</td>
<td>5.02</td>
<td>2.0</td>
</tr>
<tr>
<td>2011 pp</td>
<td>2.76</td>
<td>13.8</td>
<td>2015 Pb-Pb</td>
<td>5.02</td>
<td>0.012</td>
</tr>
<tr>
<td>2011 Pb-Pb</td>
<td>2.76</td>
<td>0.10</td>
<td>2017 Xe-Xe</td>
<td>5.44</td>
<td>0.19 x 10^{-3}</td>
</tr>
<tr>
<td>2013 p-Pb</td>
<td>5.02</td>
<td>0.05</td>
<td>2017 pp</td>
<td>5.02</td>
<td>18.8</td>
</tr>
<tr>
<td>2013 pp</td>
<td>2.76</td>
<td>47.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(in this analysis)
Neutral meson spectra in pp at different energies

- Baseline measurements of $\pi^0$ and $\eta$ meson in a wide $p_T$ range at different energies.

- Power-law behavior at high $p_T$.

- PYTHIA 8.2 Monash 2013 shows agreement with data.

- NLO pQCD calculations overpredict $\pi^0$ and $\eta$ cross sections.

7 and 0.9 TeV ALICE collaboration: Phys. Lett. B 717 (2012) 162-172
Neutral meson spectra in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE collaboration: arXiv:1801.07051

- $\pi^0 : 0.3 < p_T < 20$ GeV/c
- $\eta : 0.7 < p_T < 20$ GeV/c

- Key measurement to disentangle initial/final state effects.
- EPOS3 describes the data over the entire $p_T$ range for $\pi^0$ and up to $p_T = 4$ GeV/c for $\eta$.
- Hydrodynamic model (VISHNU) agrees with the data at low $p_T$.
- NLO pQCD calculations describe the $\pi^0$ spectrum, but fail to describe the high $p_T$ region for $\eta$.


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$R_{pA}$ of neutral mesons and comparison with theoretical models

ALICE collaboration: arXiv:1801.07051

- The pp reference at $\sqrt{s} = 5.02$ TeV is obtained by the interpolation of the measured spectra at $\sqrt{s} = 2.76/7/8$ TeV.
- $R_{pPb}$ is consistent with unity at $p_T > 2$ GeV/c for $\pi^0$ and $\eta$ mesons.
- Agreement with the measured $R_{pPb}$ and CGC predictions within uncertainties.

$$R_{pA}(p_T) = \frac{1}{\langle T_{pA} \rangle} \frac{dN_{pA}}{dp_T} \frac{d\sigma_{pp}}{dp_T}$$
Neutral meson spectra in Pb-Pb at 2.76 and 5.02 TeV

ALICE collaboration: arXiv:1803.05490 (Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV in 2011)

- $\pi^0$ and $\eta$: $1 < p_T < 20$ GeV/$c$ in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV with centrality triggers.
- $\pi^0$: $0.4 < p_T < 30$ GeV/$c$ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV.

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$\eta/\pi^0$ ratio and $m_T$ scaling at different energies and systems

- In pp and p-Pb, a universal shape, independent of collision energy.
- In Pb-Pb, a hint of deviations from behavior in pp is observed at intermediate $p_T$.
- $\eta/\pi^0$ ratio reaches ~0.48 at high $p_T$.
- $m_T$ scaling overestimates $\eta/\pi^0$ ratio at low $p_T$.

→ $m_T$ scaling violation at low $p_T$ emphasizes importance of precise measurements of all neutral mesons which is needed for cocktail simulations used in several measurements. (direct photons, dileptons e.t.c.)

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Charged particles spectra in Pb-Pb at 2.76 and 5.02 TeV

ALICE collaboration: arXiv:1802.09145

- $0.15 < p_T < 50$ GeV/c at mid-rapidity.

- Thanks to better understanding of tracking efficiency correction, systematic uncertainties are reduced.
• $p_T$ spectra at higher collision energy are significantly harder for both Pb-Pb and pp collisions.

• Similar energy dependence of the shape of the ratio in peripheral Pb-Pb and in pp collisions.

• Smaller ratio towards central Pb-Pb collisions.
\( R_{AA} \) of charged particles at 2.76 and 5.02 TeV

ALICE collaboration: arXiv:1802.09145

- Strong centrality dependence.

- Similar \( R_{AA} \) for the two collision energies, but harder \( p_T \) slope at higher collision energy.
  \[ \rightarrow \] Larger energy loss at higher collision energy.

- Strongest suppression by a factor of about 8 at \( p_T = 6-7\text{ GeV}/c \) in the most central collisions (0-5%).

- The suppression is about 30% for the intermediate \( p_T \) and reaches unity for the highest \( p_T \) bin in peripheral collisions (70-80%).
Comparison with theoretical models

- All models presented here describe the main features of the data.

- The models by Vitev et al., Djordjevic et al. and CUJET 3.0 give quantitatively good description of the data.

ALICE collaboration: arXiv:1802.09145

SCET\textsubscript{G} - Vitev : Phys. Rev. D 93, 074030 (2016)
Bianchi et al. : arXiv:1702.00481
Comparison of $\pi^0 R_{AA}$ at 2.76 and 5.02 TeV

- Well defined fragmentation function for an identified hadron, compared to inclusive charged particles.
- Strong centrality dependence.
- Similar $R_{AA}$ for the two collision energies.

2010 data

2011 data
ALICE collaboration: arXiv:1803.05490
The predictions by both Djordjevic et al. and Vitev et al. describe the data in all centrality classes.

arXiv:1805.03494:  
Energy loss in evolving finite-size QGP

$R_{AA}$ and $R_{pA}$ of charged particles and $\pi^0$

ALICE collaboration: [arXiv:1802.09145]

- $R_{pPb}$ exhibits a maximum for $2 < p_T < 6$ GeV/c (Cronin peak).
- $R_{pPb}$ is consistent with unity at high $p_T$.

→ This demonstrates that the strong suppression observed in central Pb-Pb collisions is related to the formation of hot and dense QCD matter.
Charged particles spectra in \(^{129}\text{Xe}-^{129}\text{Xe}\) at 5.44 TeV

- The pp reference at \(\sqrt{s} = 5.44\) TeV is obtained by the interpolation of the measured spectra at \(\sqrt{s} = 5.02\) and 7 TeV.

- The systematic uncertainty of the pp reference spectrum is dominated by the interpolation uncertainty.

- Necessary for systematic study of system size and geometry dependence, complementary for centrality dependence in \(^{208}\text{Pb}-^{208}\text{Pb}\).
$R_{AA}$ in Xe-Xe at 5.44 TeV

- Strong centrality dependence.
- A minimum around $p_T = 6-7$ GeV/c and an almost linear rise at higher $p_T$.
- The strongest suppression by a factor of about 6 at the minimum in the most central collisions (0-5%).
- $R_{AA} = 0.6$ at the highest $p_T$ bin (30-50 GeV/c) in the most central collisions.

arXiv:1805.04399
$R_{AA}$ in Xe-Xe and Pb-Pb vs. $p_T$ at similar $dN_{ch}/d\eta$

- Similar $R_{AA}$ in the most central Xe-Xe collisions to that in 10-20% Pb-Pb collisions over the entire $p_T$ range.

- Agreement of $R_{AA}$ between 30-40% Xe-Xe and 40-50% Pb-Pb collisions within uncertainties.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$N_{part}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5% Xe-Xe</td>
<td>236 ± 2</td>
</tr>
<tr>
<td>10-20% Pb-Pb</td>
<td>263 ± 4</td>
</tr>
<tr>
<td>30-40% Xe-Xe</td>
<td>82.2 ± 3.9</td>
</tr>
<tr>
<td>40-50% Pb-Pb</td>
<td>86.3 ± 1.7</td>
</tr>
</tbody>
</table>

arXiv:1805.04399
A remarkable similarity in $R_{AA}$ is observed between Xe-Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and $2.76$ TeV for $dN_{ch}/d\eta > 400$.

\[
<\Delta E> \propto \varepsilon \times L^2 \propto <dN_{ch}/d\eta>/A_T \times L^2
\]

$\Delta E$ : radiative energy loss
$\varepsilon$ : energy density
$L$ : path length (related to the radius of the nucleus)
$A_T$ : initial transverse area $= \pi \times r^2$ ($r$ : radius of the colliding nuclei)

Phys. Rev. C 97, 034904

This result can provide insight on the path length dependence of medium induced parton energy loss.
Summary

• The spectra and nuclear modification factors of primary charged particles in p-Pb, Pb-Pb and Xe-Xe collisions and neutral mesons in p-Pb, Pb-Pb collisions at different collision energies were presented.

• The strong suppression in central Pb-Pb collisions is related to the formation of hot and dense QCD matter.

• The similar suppression level is found at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV.

• A similar $R_{AA}$ for the same $<dN_{ch}/d\eta>$ is found for Xe-Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 2.76 TeV for $dN_{ch}/d\eta > 400$. 
backup
$N_{\text{part}}$ in Pb-Pb at 5.02 TeV and Xe-Xe at 5.44 TeV

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$\langle dN_{\text{ch}}/d\eta \rangle$</th>
<th>$\langle N_{\text{part}} \rangle$</th>
<th>$\langle 2/\langle N_{\text{part}} \rangle \rangle \langle dN_{\text{ch}}/d\eta \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%–2.5%</td>
<td>2035 ± 52</td>
<td>398 ± 2</td>
<td>10.2 ± 0.3</td>
</tr>
<tr>
<td>2.5%–5.0%</td>
<td>1850 ± 55</td>
<td>372 ± 3</td>
<td>9.9 ± 0.3</td>
</tr>
<tr>
<td>5.0%–7.5%</td>
<td>1666 ± 48</td>
<td>346 ± 4</td>
<td>9.6 ± 0.3</td>
</tr>
<tr>
<td>7.5%–10%</td>
<td>1505 ± 44</td>
<td>320 ± 4</td>
<td>9.4 ± 0.3</td>
</tr>
<tr>
<td>10%–20%</td>
<td>1180 ± 31</td>
<td>263 ± 4</td>
<td>9.0 ± 0.3</td>
</tr>
<tr>
<td>20%–30%</td>
<td>786 ± 20</td>
<td>188 ± 3</td>
<td>8.4 ± 0.3</td>
</tr>
<tr>
<td>30%–40%</td>
<td>512 ± 15</td>
<td>131 ± 2</td>
<td>7.8 ± 0.3</td>
</tr>
<tr>
<td>40%–50%</td>
<td>318 ± 12</td>
<td>86.3 ± 1.7</td>
<td>7.4 ± 0.3</td>
</tr>
<tr>
<td>50%–60%</td>
<td>183 ± 8</td>
<td>53.6 ± 1.2</td>
<td>6.8 ± 0.3</td>
</tr>
<tr>
<td>60%–70%</td>
<td>96.3 ± 5.8</td>
<td>30.4 ± 0.8</td>
<td>6.3 ± 0.4</td>
</tr>
<tr>
<td>70%–80%</td>
<td>44.9 ± 3.4</td>
<td>15.6 ± 0.5</td>
<td>5.8 ± 0.5</td>
</tr>
</tbody>
</table>

Table 1: The $\langle dN_{\text{ch}}/d\eta \rangle$ and $N_{\text{ch}}^{\text{var}}$ values for different centrality classes, defined by $V_{0}$ multiplicity. The errors are total uncertainties, the statistical contribution being negligible. The values of $\langle N_{\text{part}} \rangle$ obtained with the Glauber model are also reported. The errors are obtained by varying the parameters of the NBD-Glauber calculation.

ALICE collaboration: PRL 116, 222302 (2016)

ALICE_PUBLIC-2018-003

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Comparison of $R_{AA}$ of neutral mesons in Pb-Pb at 2.76 TeV with theory

ALICE collaboration: arXiv:1803.05490

- Djordevic et al. describes the $\pi^0$ suppression in both centrality classes within uncertainties.
- WHDG predicts larger suppression for both mesons in the centrality class 20-50%.

NLO DCZW:

WHDG:

Djordjevic:

Vitev et al.:
Phys. Rev. D 93, 074030 (2016)
### Summary of systematic uncertainties of neutral mesons in Pb-Pb at 2.76 TeV


<table>
<thead>
<tr>
<th></th>
<th>PCM</th>
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<th>EMCal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–10%</td>
<td>20–50%</td>
<td>0–10%</td>
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<tr>
<td></td>
<td>$\pi^0$</td>
<td>$\eta$</td>
<td>$\pi^0$</td>
</tr>
<tr>
<td></td>
<td>1.1 GeV/c</td>
<td>5.5 GeV/c</td>
<td>2.5 GeV/c</td>
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<tr>
<td>Material budget</td>
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<td>9.0</td>
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<tr>
<td>Track reconstruction</td>
<td>2.3</td>
<td>2.6</td>
<td>6.0</td>
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<tr>
<td>Yield extraction</td>
<td>1.5</td>
<td>2.1</td>
<td>6.4</td>
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<td>$e^+/e^-$ identification</td>
<td>1.7</td>
<td>2.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Photon reconstruction</td>
<td>3.7</td>
<td>2.1</td>
<td>13.7</td>
</tr>
</tbody>
</table>

**Table 2:** Summary of the systematic uncertainties in percent for selected $p_T$ regions for the PCM and EMCal analyses.
Neutral pion spectrum in pp at $\sqrt{s_{NN}} = 5.02$ TeV

NEW

$\frac{d^3\sigma}{dE_{\pi^0}^3}(pb \text{ GeV}^{-3})$

- Data
- norm. unc. 2.4%
- TCM fit
- Levy-Tsallis fit
- PYTHIA 8.2, Monash 2013
- NLO, PDF:CT10 - FF:DSS14

$\mu = 0.5 \mu_T$
$\mu = \mu_T$
$\mu = 2 \mu_T$

ALICE preliminary
$\pi^0 \rightarrow \gamma\gamma$

ALI-PREL-146126

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π⁰ spectra in Pb-Pb at \( √s_{NN} = 5.02 \) TeV

NEW

ALICE Preliminary

Pb-Pb at \( √s_{NN} = 5.02 \) TeV

\[ \frac{d^2N}{dy dt} \left( \text{GeV/c} \right)^2 \]

0-10 % \( \times 2^4 \)
20-40 % \( \times 2^4 \)
60-80 % \( \times 2^4 \)

TCM fits to Pb-Pb

SHM (V. Begun et al.)
NEQ : 0-10 % \( \times 2^4 \)
EQ : 0-10 % \( \times 2^4 \)
NEQ : 20-40 % \( \times 2^4 \)
EQ : 20-40 % \( \times 2^4 \)
NEQ : 60-80 % \( \times 2^4 \)
EQ : 60-80 % \( \times 2^4 \)
Comparison with theoretical models

Andrés et al.
- consists of fitting a K factor defined as $K \equiv q/2\varepsilon^{3/4}$, based on the perturbative estimate, $\hat{q}_{\text{ideal}} \sim 2\varepsilon^{3/4}$. The local energy density $\varepsilon$ is taken from a hydrodynamical model of the medium. K factor is the only free parameter in the fitting to nuclear modification factors.

Bianchi et al.
- pQCD-based radiative energy loss in a hydrodynamically expanding medium. High $p_T$ hadrons arise from fragmentation of hard partons, which lose their energy prior to hadronization via interactions with the medium.
Bianchi et al.: arXiv:1702.00481

ALICE collaboration: arXiv:1802.09145
Tracking efficiency of inclusive charged particles in pp

ALICE collaboration: arXiv:1802.09145
Tracking efficiency of inclusive charged particles in Pb-Pb

ALICE collaboration: arXiv:1802.09145
Tracking efficiency of inclusive charged particles in Xe-Xe

\[ \alpha \times \varepsilon \]

- **ALICE Simulation**
- **HIJING**
- \( |\eta| < 0.8 \)

- \( \pi^+ + \pi^- \)
- \( K^+ + K^- \)
- \( p + \bar{p} \)

- **Full**: Xe-Xe, \( \sqrt{s_{NN}} = 5.44 \text{ TeV} \)
- 0-5% \( B = 0.2 \text{ T} \)
- **Open**: Pb-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- 10-20% \( B = 0.5 \text{ T} \)
Identified charged particles spectra in pp at 5.02 TeV

\( \frac{1}{N_{\text{INEL}}} \frac{d^2 N}{d(p_T^2 \, dy)} \) (GeV/c)

- \((\pi^+ + \pi^-) \times 2^2\)
- \((K^+ + K^-) \times 2^1\)
- \((p + \bar{p}) \times 2^0\)

ALICE Preliminary

pp |\( \sqrt{s} = 5.02\) TeV (INEL)

Normalization uncertainty 2.51%
Uncertainties: stat. (bars), sys. (boxes)
Identified charged particles spectra in Pb-Pb at 5.02 TeV

ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}} = 5.02$ TeV

Uncertainties: stat. (bars), sys. (boxes)

$\pi^+ + \pi^-$

$K^+ + K^-$

$p + \bar{p}$
$R_{AA}$ of identified charged particles at 2.76 and 5.02 TeV