Energy and system size dependence of neutral meson and direct photon production at the LHC measured with ALICE

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Motivation: Direct photons

Carry information on the medium’s temperature and space-time evolution
Large background from neutral meson decays ($\pi^0, \eta, \omega,...$).

**Prompt photons:**
Initial hard scattering
Dominant at high $p_T$ ($p_T>\sim5$ GeV/c)
Described by NLO pQCD,
Test binary scaling pp→ AA
Not affected by collective expansion

**Preequilibrium photons**

**Jet medium interactions:**
Scattering of hard partons with thermalized partons

**Thermal photons:** ($p_T<\sim3$ GeV/c)
Dominant at low $p_T$ with exponential shape.
Emitted by thermalized medium
Influenced by flow evolution
Comparison to models employing hydro

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Motivation: Neutral mesons

*Neutral mesons* can be measured in a very wide $p_T$ range

- **AA:**
  - Bulk properties of the medium, collective effects
  - $R_{AA}$ and energy loss in the QGP
  - Main input for direct photon and dielectron cocktails

- **pp collisions:**
  - pQCD predictions, constraints of PDFs and FFs
  - Baseline for pA and AA collisions

- **pA:**
  - Cold nuclear matter effects
  - Test of modifications of nPDFs
  - Study of collective effects in small systems

Comparison to phenomenological models

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ALICE in Run 2 at the LHC

V0: Multiplicity and centrality estimation

ITS: Vertex finding and tracking

TPC: Tracking and Particle identification

γ detection:

- Photon Conversion Method (PCM):
  Photon conversion in detector material
  ITS and TPC ($X/X_0=11.4\pm0.5\%$)

- PHOS and EMCal/DCal: calorimetry

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π⁰ in pp collisions

- π⁰ spectra measured in pp collisions at √s = 0.9, 2.76, 5, 7 and 8 TeV
- PYTHIA 8.2 Monash 2013 reproduces approximately π⁰ spectra at all energies
- NLO pQCD calculations with DSS14 FF predict 20-30% higher yield.

ALICE measurement at √s = 7 TeV included “Parton-to-Pion Fragmentation Reloaded” [PRD91 (2015) no. 1, 014035]
• PYTHIA 8.2 Monash 2013 reproduces approximately \( \eta \) spectra at all energies
• NLO pQCD calculations (PDF: CTEQ6M5, FF:AESSS) predict ~2x higher yield

Revisiting \( \eta \)-meson FF is necessary

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\( \pi^0, \eta: \text{Pb-Pb at } \sqrt{s_{\text{NN}}} = 2.76, 5.02 \text{ TeV} \)

First \( \eta \) measurement in Pb-Pb at the LHC

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$R_{AA}$ in Pb-Pb collisions

\[ R_{AA}(p_T) = \frac{d^2N/dp_Tdy|_{AA}}{\langle T_{AA} \rangle \times d^2\sigma/dp_Tdy|_{pp}} \]

- Suppression depends on centrality
- Same magnitude and $p_T$ dependence of $R_{AA}$ for $\pi^0$ and $\eta$ mesons $p_T > 4$ GeV/c

Model predictions for the $\eta$ meson are scarce

- Vitev and Djordjevic models reproduce $p_T$ and centrality dependence of $\pi^0 R_{AA}$
- WHDG fails to reproduce centrality dependence of $\pi^0$ and $\eta R_{AA}$
- NLO DCZW (central collisions) reproduces $p_T$ dependence of $\pi^0 R_{AA}$ and slightly above measured $\eta R_{AA}$ ($p_T \sim 4.12$ GeV/c)

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Strong centrality dependence
Similar suppression level in two collision energies
π⁰, η in p-Pb collisions

p-Pb collisions: more than a control experiment

To be used in global fits of nPDFs and FFs.

Detailed comparison to theoretical models
Larger differences observed for the η than for π⁰

R_{pPb} consistent with unity for p_T > 2 GeV/c

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$\eta/\pi^0 : m_T$ scaling?

$m_T$ scaling: parametrization used when particle is not measured

Hold at high $p_T$ ($p_T > 4$ GeV/$c$)

Deviations of $\sim 40\%$ at $p_T \sim 0.6$ GeV/$c$
\( \eta/\pi^0: \) Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

- EQ model is favoured against NEQ
- EPOS model overestimates \( \eta \) at high \( p_T \)
- NLO DCZW: \( \eta/\pi^0 \) sensitive to medium transport coefficient

- Evidence of \( m_T \) scaling violation at intermediate \( p_T \) (radial flow) and at low \( p_T \)?
Answer with available Run 2 data

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Early emission of photons: high yield ↔ low $\nu_2$

Late emission of photons: low yield ↔ high $\nu_2$

\[ E \frac{dR}{d^3p} = \frac{5 \alpha \alpha_s}{9 \pi^2} T^2 e^{-E/T} \ln \left( \frac{2.912 E}{g^2 T} \right) \]

\[ v_2^{\gamma,\text{dir}} = \frac{v_2^{\gamma,\text{inc}} R_\gamma - v_2^{\gamma,\text{dec}}}{R_\gamma - 1} \]

- Inclusive photon $\nu_2$ via scalar product:

\[ \nu_2 = \sqrt{\frac{\left(\langle \bar{u}_2 \cdot \bar{Q}_2^A \rangle \langle \bar{u}_2 \cdot \bar{Q}_2^C \rangle\right) \langle \bar{Q}_2^A \rangle \langle \bar{Q}_2^C \rangle}{\langle \bar{Q}_2^C \rangle \langle \bar{Q}_2^C \rangle}} \]

- Reference particles: charged hadrons in V0-A, V0-C
- Particles of interest: photons

- Decay $\gamma \nu_2$ from simulation based on measured meson $\nu_2$

- $R_\gamma$ from previous measurements:
  \[ R_\gamma = \frac{Y_{\gamma \text{incl}}}{Y_{\gamma \text{decay}}} \approx \left( \frac{Y_{\gamma \text{incl}}}{Y_{\pi^0}} \right)_{\text{meas}} \left/ \left( \frac{Y_{\gamma \text{decay}}}{Y_{\pi^0}} \right)_{\text{sim}} \right. \]

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\[ \gamma_{\text{dir}} \text{ Pb-Pb at } \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ R_{\gamma}^{pQCD} = 1 + N_{\text{coll}} \frac{\gamma_{pQCD}}{\gamma_{\text{decay}}} \]

pQCD agrees with data for \( p_T \gtrsim 5 \text{ GeV/c} \)

Excess beyond known prompt yield

1\(<p_T<4 \text{ GeV/c}:

Increases for more central collisions

15\% excess in 0 \(-\) 20\%

9\% in 20 \(-\) 40\%

Consistent with thermal radiation

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Inclusive $\gamma v_2$

- $p_T < 3$ GeV/$c$: $v_2^{\gamma,\text{inc}} = v_2^{\gamma,\text{dec}}$
  $\Rightarrow$ Either no contribution of $\gamma_{\text{dir}}$ or $v_2^{\gamma,\text{dir}} = v_2^{\gamma,\text{dec}}$
  Theory $\sim 30 - 40\%$ too high

- $p_T > 3$ GeV/$c$: $v_2^{\gamma,\text{inc}} < v_2^{\gamma,\text{dec}}$
  $\rightarrow$ prompt photon contribution

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• Large direct photon $v_2$ for $p_T < 3$ GeV/c
• Measured magnitude of $v_2^{\gamma,\text{dir}}$ comparable to hadrons
• Result points to late production times of direct photons after flow is established

$\nu_2^{\gamma,\text{dir}}$ larger than models predictions (in qualitative agreement with PHENIX)

• But: null hypothesis $\nu_2^{\text{dir}} = 0$ not inconsistent with the data
$v_2^{\gamma, \text{dir}}$: RHIC vs LHC

$0\% - 20\%$ Pb-Pb, $\sqrt{s_{\text{NN}}} = 2.76$ TeV
$0\% - 20\%$ Au-Au, $\sqrt{s_{\text{NN}}} = 200$ GeV

$\gamma_2^{\text{dir}}$, ALICE
$\gamma_2^{\text{dir}}$, PHENIX conv.
$\gamma_2^{\text{dir}}$, PHENIX calo.
Boxes indicate total uncertainties

$v_2^{\text{dir}}(\text{LHC}) \approx v_2^{\text{dir}}(\text{RHIC})$

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Direct $\gamma$ in pp, p-Pb collisions

No significant excess observed at low $p_T$.

$R_{\gamma}^{pQCD} = 1 + N_{\text{coll}} \frac{\gamma_{pQCD}}{\gamma_{\text{decay}}}$

$\sim 1 - 2 \sigma$ deviation from unity for $p_T > 7$ GeV/c
Towards better precision

- Analysis of large statistics Run 2 samples
  \[ \sqrt{s_{NN}} \]
  - Pb–Pb 5.02 TeV
  - pp 5 TeV, 13 TeV
  - p–Pb 5.02 TeV

- Reduction of material budget systematic uncertainties
  - Run 3 and Run 4 (2021-29):
    - Installation of well-known photon converter in ITS
    - Part of data taking at lower B field \( \Rightarrow \) increased efficiency at low \( p_T \)

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Conclusion

- $\pi^0$ and $\eta$ spectra measured in pp collisions at $\sqrt{s}=0.9, 2.76, 5.02, 7$ and $8$ TeV
  - $\pi^0$: PDF: MSTW, FF :DSS14 predicts 20-30% higher yield
  - $\eta$: PDF: CTEQ6M5, FF: AESSS10 predicts 2x higher yield.
  - **Update of $\eta$ FF necessary**

- $\pi^0$ and $\eta$ yield in Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV and $\sqrt{s_{NN}}=5.02$ TeV
  - $R_{AA}$ of $\pi^0$ and $\eta$ similar for $p_T > 4$ GeV/c
  - $R_{AA}$ at $\sqrt{s_{NN}}=2.76$ and 5.02 TeV are very close
  - Models of Djordjevic et al. and Vitev et al., reproduce $p_T$ and centrality dependence

- $\pi^0$ and $\eta$ spectra in p-Pb at $\sqrt{s_{NN}}=5.02$ TeV
  - Precise data can be used in fits of nPDFs and FF

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Conclusion

- $v_2^{\gamma, \text{dir}}$ in Pb-Pb collisions:
  - Measured in two centrality classes: 0-20% & 20-40%
  - Similar size as the charged hadron flow and inclusive photon flow
  - ... but null hypothesis $v_2^{\text{dir}} = 0$ not inconsistent with the data

- $\gamma^{\text{dir}}$ production in pp & p-Pb collisions:
  - No significant direct photon excess observed in thermal photon region
  - Consistent with $N_{\text{coll}}$ scaled NLO pQCD calculations at higher $p_T$

**Better precision is needed in direct $\gamma$ measurements**
- Analysis of the large Run 2 samples (pp, pPb and PbPb),
- New calibration methods and use of a well known photon converter (Run 3) to reduce total uncertainties in the (near) future

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Backup
Neutral pion and $\eta$ meson production in proton-proton collisions at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV, PLB 717 (2012), arxiv:1205.5727

Neutral pion production at midrapidity in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, EPJ C 74 (2014), arxiv: 1405.3794

Direct Photon Production in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV, PLB 754 (2016), arxiv:1509.07324

Jet-like correlations with neutral pion triggers in pp and central Pb-Pb collisions at 2.76 TeV, PLB 763 (2016), arxiv:1608.07201


Neutral pion and $\eta$ meson production in proton-proton collisions at $\sqrt{s} = 8$ TeV, EPJC 78 (2018), arxiv: 1708.08745

Neutral pion and $\eta$ meson production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, EPJ C 78 (2018) 624, arxiv: 1801.07051

Neutral pion and $\eta$ meson production in Pb–Pb collisions at central rapidity and $\sqrt{s_{NN}} = 2.76$ TeV, PRC 98 (2018) 44901, arxiv:1803.0549

Direct photon production at low transverse momentum in proton-proton collisions at $\sqrt{s} = 2.76$ and 8 TeV, PRC 99 (2019) 024912, arxiv:1803.09857

Direct-photon elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, PLB 789 (2019) 308, arxiv:1805.0440

Measurement of the inclusive isolated photon production cross section in pp collisions at $\sqrt{s} = 7$ TeV, arxiv: 1906.01371

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20-40% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
ALICE
$1.9 < p_T < 2.1$ GeV/$c$
Cocktail: Decay photon $v_2$

- $K_{ET}$ scaling: $v_2$ of mesons scales with $K_{ET}$
  
  $K_{ET} = m_T - m = \sqrt{p_T^2 + m^2} - m$

  $\Rightarrow v_2^{\pi^0} \approx v_2^{\pi^\pm}$ ($m^{\pi^0} \approx m^{\pi^\pm}$)

- $v_2$ of various mesons (X) calculated via $K_{ET}$ (quark number) scaling from $v_2^{K^\pm}$

  $v_2^X(p_T^X) = v_2^{K^\pm}(\sqrt{(K_{ET}^X + m^{K^\pm})^2 - (m^{K^\pm})^2})$

- Decay photon $v_2$ from different mesons obtained from cocktail calculation

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Projections for Run 3

ALICE Upgrade projection
20-40% Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \) TeV, \( L_{\text{int}} = 3.1 \) nb\(^{-1} \)

- \( v_2^{\text{dir}} \), Run 3+4 projections
- \( v_2^{\text{abs}} \), ALICE simulations
- \( v_2^{\text{dir}} \), hydro, Paquet et al.
- \( v_2^{\text{dir}} \), hydro, Chatterjee et al.
- \( v_2^{\text{dir}} \), PHSD, Linnik at al.

\( p_T \) (GeV/c)
**π⁰, η in p-Pb collisions**

**p-Pb collisions: more than a control experiment**

To be used in global fits of nPDFs and FFs.

Detailed comparison to theoretical models. Larger differences observed for the η than for π⁰:

- EPOS3 describes π⁰ over the entire \( p_T \) range, η up to \( p_T = 4 \) GeV/c
- DPMJet predicts smaller yield for \( p_T > 1 \) GeV/c
- Hydrodynamic model (VISHNU) agrees with the data at low \( p_T \)

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$R_{pPb}: \pi^0$ and $\eta$

$R_{pPb}(p_T) = \frac{d^2N_{\pi^0,\eta}^{pPb}/dydp_T}{\langle T_{pPb} \rangle \cdot d^2\sigma_{\pi^0,\eta}^{pPb}/dydp_T}$

$R_{pPb}$ consistent with unity for $p_T > 2 \text{ GeV}/c$

$\pi^0$, $\eta$ suppression in central Pb-Pb consistent with parton energy loss

pQCD calculations reproduce the data.

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\textbf{\( \gamma \) detection in ALICE}

- **PHOS calorimeter:**
  - \( \text{PbWO}_4 \) crystal
  - 3 modules at 4.6 m from the ALICE IP
  - \(| \eta | < 0.13, 260^\circ < \varphi < 320^\circ\)

- **EMCal/DCal calorimeter:**
  - 77 layers 1.4 mm lead + 1.7 mm scintillator
  - 10 modules at 4.4 m from ALICE IP
  - **EMCal:** \(| \eta | < 0.7, 80^\circ < \varphi < 180^\circ\)
  - **DCal:** \(0.22 < | \eta | < 0.7, 260^\circ < \varphi < 320^\circ\)
  - **DCal:** \(| \eta | < 0.7, 320^\circ < \varphi < 327^\circ\)

- **Photon Conversion Method (PCM):**
  - Photon conversion in detector material ITS and TPC \((X/X_0 = 11.4 \pm 0.5\%\))
  - 8.5\% conversion probability
  - \(| \eta | < 0.9, 0^\circ < \varphi < 360^\circ\).

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Meson reconstruction

Invariant mass analysis of photon pairs:

\[ M_{\gamma\gamma} = \sqrt{2E_{\gamma_1} E_{\gamma_2} (1 - \cos \theta_{\gamma_1\gamma_2})} \]

- Combinatorial background subtraction using mixed events
- Gaussian plus exponential function to fit the peaks
Meson reconstruction

- Peak position and width properly described in Monte Carlo simulations
- Very different performance in the different methods.
- Combination of all methods (using the BLUE method) results in a wide $p_T$ range coverage

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Comparison to D-mesons and hadrons

- Similar suppression at high $p_T > 10$ GeV/c for all species
- Smaller suppression of D-mesons compared to pions and charged at low $p_T$ in central and semicentral collisions
  
  Quark mass difference?
  Collective flow and recombination?
  Soft pion production?
  Another reason?

- Similar behaviour in peripheral collisions

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TABLE III. Comparison of $\langle N_{\text{coll}} \rangle$ values. In the first column results are listed for centrality classes obtained by ordering the events according to the impact parameter distribution ($b$). In the next three columns $\langle N_{\text{coll}} \rangle$ values are given for the various centrality estimators CL1, V0A, V0M. The systematic uncertainty on $\langle N_{\text{coll}} \rangle$ (in parentheses on $T_{p,\text{ph}}$) is obtained by changing all Glauber parameters by 1σ; the second column is obtained from the MC-closure test; those two are added in quadrature to obtain the total systematic uncertainty on $\langle N_{\text{coll}} \rangle$. The last column gives the $\langle N_{\text{coll}} \rangle$ values obtained for the ZNA (see Sec. IV) and the uncertainty on the slow nucleon model (SNM, see Sec. IV).

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>$\langle N_{\text{coll}}^b \rangle$</th>
<th>$\langle N_{\text{coll}}^{\text{CL1}} \rangle$</th>
<th>$\langle N_{\text{coll}}^{\text{V0M}} \rangle$</th>
<th>$\langle N_{\text{coll}}^{\text{V0A}} \rangle$</th>
<th>Sys. Glauber</th>
<th>Sys. MC closure</th>
<th>Sys. Total</th>
<th>$\langle N_{\text{coll}}^{\text{ZNA}} \rangle$</th>
<th>Sys. SNM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>14.4</td>
<td>15.6</td>
<td>15.7</td>
<td>14.8</td>
<td>10% (3.7%)</td>
<td>3%</td>
<td>10%</td>
<td>15.7</td>
<td>7%</td>
</tr>
<tr>
<td>5–10</td>
<td>13.8</td>
<td>13.6</td>
<td>13.7</td>
<td>13.0</td>
<td>10% (3.5%)</td>
<td>1%</td>
<td>10%</td>
<td>13.9</td>
<td>5%</td>
</tr>
<tr>
<td>10–20</td>
<td>12.7</td>
<td>12.0</td>
<td>12.1</td>
<td>11.7</td>
<td>10% (3.2%)</td>
<td>2%</td>
<td>10%</td>
<td>12.4</td>
<td>2%</td>
</tr>
<tr>
<td>20–40</td>
<td>10.2</td>
<td>9.49</td>
<td>9.55</td>
<td>9.36</td>
<td>8.8% (3.1%)</td>
<td>2%</td>
<td>9%</td>
<td>9.99</td>
<td>2%</td>
</tr>
<tr>
<td>40–60</td>
<td>6.30</td>
<td>6.18</td>
<td>6.26</td>
<td>6.42</td>
<td>6.6% (4.3%)</td>
<td>3%</td>
<td>7.2%</td>
<td>6.53</td>
<td>4%</td>
</tr>
<tr>
<td>60–80</td>
<td>3.10</td>
<td>3.40</td>
<td>3.40</td>
<td>3.81</td>
<td>4.3% (6.7%)</td>
<td>20%</td>
<td>20%</td>
<td>3.04</td>
<td>4%</td>
</tr>
<tr>
<td>80–100</td>
<td>1.44</td>
<td>1.76</td>
<td>1.72</td>
<td>1.94</td>
<td>2.0% (9.3%)</td>
<td>23%</td>
<td>23%</td>
<td>1.24</td>
<td>8%</td>
</tr>
<tr>
<td>0–100</td>
<td>6.88</td>
<td>6.83</td>
<td>6.87</td>
<td>6.87</td>
<td>8% (3.4%)</td>
<td>8%</td>
<td>8%</td>
<td>6.88</td>
<td></td>
</tr>
</tbody>
</table>

TABLE VII. $\langle N_{\text{coll}} \rangle$ values obtained under the three assumptions discussed in the text.

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>$N_{\text{coll}}^\text{mult}$</th>
<th>$N_{\text{coll}}^\text{high-}\rho_T$</th>
<th>$N_{\text{coll}}^\text{Pb-side}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>12.2</td>
<td>12.5</td>
<td>13.3</td>
</tr>
<tr>
<td>5–10</td>
<td>11.6</td>
<td>12.1</td>
<td>12.3</td>
</tr>
<tr>
<td>10–20</td>
<td>11.0</td>
<td>11.3</td>
<td>11.4</td>
</tr>
<tr>
<td>20–40</td>
<td>9.56</td>
<td>9.73</td>
<td>9.60</td>
</tr>
<tr>
<td>40–60</td>
<td>7.08</td>
<td>6.81</td>
<td>6.74</td>
</tr>
<tr>
<td>60–80</td>
<td>4.30</td>
<td>4.05</td>
<td>4.00</td>
</tr>
<tr>
<td>80–100</td>
<td>2.11</td>
<td>2.03</td>
<td>2.06</td>
</tr>
</tbody>
</table>
p-Pb and Pb-Pb

$R_{AA}$ suppression is a final state effect

$\sqrt{s_{_{NN}}} = 5.02$ TeV

ALICE

$0-10\%$ Pb-Pb, $\sqrt{s_{_{NN}}} = 2.76$ TeV

$0-100\%$ p-Pb, NSD, $\sqrt{s_{_{NN}}} = 5.02$ TeV

$\pi^0$, $\eta$

ALICE Preliminary

$R_{pPb}$, $R_{PbPb}$

$\sqrt{s_{_{NN}}} = 5.02$ TeV

$\pi^0$ : Pb-Pb 0-10 %

$\pi^0$ : Pb-Pb 60-80 %

$\pi^0$ : p-Pb NSD (arXiv:1801.07051)
Both theoretical models reproduce $p_T$ and centrality dependence of the suppression.

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$R_{AA}$: energy dependence

$$R_{AA}(p_T) = \frac{d^2N/dp_Tdy|_{AA}}{\langle T_{AA} \rangle \times d^2\sigma/dp_Tdy|_{pp}}$$

Larger hadron suppression with increasing energy (SPS $\rightarrow$ RHIC $\rightarrow$ LHC): higher energy density of the medium

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\( Q_{pA} \)

\[
Q_{pPb}(p_T; \text{cent}) = \frac{dN_{pPb}^{pPb}}{dN_{\text{cent}}^{pPb}} \frac{dN_{pp}}{dN_{\text{coll}}} \frac{dN_{pp}}{dN_{\text{coll}}}
\]

- No strong centrality dependence with ZNA estimator
- Visible centrality dependence for estimators with smaller pseudorapidity gap
- No trivial autocorrelations with cent. estimator

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$Q_{pA}$ : Particle comparison

$Q_{pA}$ is similar for $\pi^0$ and $\eta$

$D^0$ is consistent

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$P_T$ (GeV/c)

$P_T$ (GeV/c)

$P_T$ (GeV/c)

$P_T$ (GeV/c)


$D^0$: JHEP 1608 (2016) 078, 2016
No multiplicity dependence is observed
After $\pi^0$ and $\eta$, next in importance as $\gamma$ or $e^+e^-$ source

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Direct photons: statistical subtraction method and double ratio

Subtraction method:

\[ \gamma_{direct} = \gamma_{inc} - \gamma_{decay} = (1 - \frac{\gamma_{decay}}{\gamma_{inc}}) \cdot \gamma_{inc} = (1 - \frac{1}{R_\gamma}) \cdot \gamma_{inc} \]

Inclusive photons: All produced photons
Decay photons: Calculated from measured particle spectra with photon decay channels (\(\pi^0, \eta,\ldots\))

Double ratio:

\[ \frac{\gamma_{inc}}{\pi^0} \bigg/ \frac{\gamma_{decay}}{\pi^0_{\text{param}}} \sim \frac{\gamma_{inc}}{\gamma_{decay}} \]

>1 if direct photon signal

Advantage: Cancellation of uncertainties
Direct photons @LHC

Inclusive photon spectrum

\[ R_\gamma \]

Significance of the excess for \( 0.9 < p_T < 2.1 \text{ GeV}/c: 2.6\sigma \) for 0-20%

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Comparison to models

Approximately exponential spectrum for $p_T \lesssim 3$ GeV/c

PLB 754 (2016) 235

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Models (all with QGP formation)

- **Paquet et al.**:
  2+1 viscous hydro with IP-Glasma initial conditions,
  \((\tau = 0.4 \text{ fm/c}, T_{0-20\%} = 385 \text{ MeV})\)

- **Linnyk et al.**:
  Off-shell transport, microscopic description of evolution

- **v. Hees et al.**:
  Ideal hydro with initial flow,
  \((\tau = 0.2 \text{ fm/c}, T_{0-20\%} = 682 \text{ MeV})\)

- **Chatterjee et al.**:
  2+1 hydro, fluctuating initial conditions,
  \((\tau = 0.14 \text{ fm/c}, T_{0-20\%} \approx 740 \text{ MeV})\)

Currently not possible to rule out one or more of these models

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Comparison to models

Models (all with QGP formation)

• Paquet et al.:
  2+1 viscous hydro with IP-Glasma initial conditions,
  \( (\tau = 0.4 \text{ fm/c}, T_{0-20\%} = 385 \text{ MeV}) \)

• Linnyk et al.:
  Off-shell transport, microscopic description of evolution

• v. Hees et al.:
  Ideal hydro with initial flow,
  \( (\tau = 0.2 \text{ fm/c}, T_{0-20\%} = 682 \text{ MeV}) \)

• Chatterjee et al.:
  2+1 hydro, fluctuating initial conditions,
  \( (\tau = 0.14 \text{ fm/c}, T_{0-20\%} \approx 740 \text{ MeV}) \)

Currently not possible to rule out one or more of these models

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Higher effective temperature at LHC than at RHIC
Combination of several reconstruction techniques via BLUE method. Theoretical NLO pQCD prediction plotted as

\[ R_{γ}^{pQCD} = 1 + N_{coll} \frac{γ_{pQCD}}{γ_{decay}} \]

No significant excess observed at low \( p_T \).
About \( 1 - 2σ \) deviation from unity for \( p_T > 7 \text{ GeV/c} \)

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Direct $\gamma$ in pPb collisions

No significant excess observed at low $p_T$. Accuracy is not yet sufficient to confirm/exclude thermal radiation in p-Pb collisions.

Run 2 larger statistics. Explore 0-1%.
No significant excess observed at low $p_T$. Accuracy is not yet sufficient to confirm/exclude thermal radiation in p-Pb collisions.

Run 2 larger statistics. Explore 0-1%
$R_\gamma$: Pb-Pb vs pp

 ALICE

0-20% Pb-Pb, $\sqrt{s_{nn}} = 2.76$ TeV
pp, $\sqrt{s} = 2.76$ TeV

20-40% Pb-Pb, $\sqrt{s_{nn}} = 2.76$ TeV
pp, $\sqrt{s} = 2.76$ TeV

40-80% Pb-Pb, $\sqrt{s_{nn}} = 2.76$ TeV
pp, $\sqrt{s} = 2.76$ TeV

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$R_\gamma$ consistent using two different methods
PHENIX: Direct photons


\[
\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \quad \text{[GeV/c]}^{-2}
\]

- **pp data**
  - ○ PRL 104, 132301
  - ▲ PRL 98, 012002
  - ▲ PRD 86, 072008
  - - pp fit

- **Au+Au data**
  - ▲ PRL 104, 132301
  - ▲ PRL 109, 152302
  - ● Present data
  - - \( N_{\text{coll}} \)-scaled pp fit

\( \sqrt{s_{\text{NN}}} = 200 \text{GeV} \)

- **(a)** 0-20%
- **(b)** 20-40%
- **(c)** 40-60%
- **(d)** 60-92%

\[ 0 < p_T < 5 \text{ GeV/c} \]

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$Q_{pA}$

$ZP$

$ZN$

ZNA: $|\eta| > 8.7$, Pb side

$Q_{pPb}(p_T; \text{cent}) = \frac{dN_{\text{cent}}^{\text{pPb}}/dp_T}{(N_{\text{Glauber}}^{\text{coll}}) dN_{pp}/dp_T}$

- $Q_{pA}$ is similar for $\pi^0$ and $\eta$
- $D^0$ is consistent

No strong centrality dependence with ZNA estimator (large pseudorapidity gap)

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Electromagnetic cocktail: direct photons, dielectrons $m_T$ scaling to pions when particle not measured. **Does not hold at low $p_T$!**

$\omega$ and $\eta'$ measurement for better precision

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$\pi^0$ and $\eta$ in p-Pb collisions. Centrality dependence

- $\pi^0$ and $\eta$ spectra measured in p-Pb collisions in 4 centrality classes: 0-20%, 20-40%, 40-60%, 60-100%
- $p_T$ range extended up to 40 GeV/c by using PHOS trigger
Inclusive $\gamma \nu_2$

$\nu_2^{inc} \gamma$

Consistent PCM and PHOS measurements

- $p_T < 3 \text{ GeV}/c$: $\nu_2^{\gamma, inc} = \nu_2^{\gamma, dec}$
  - Either no contribution of $\gamma, dir$ or $\nu_2^{\gamma, dir} = \nu_2^{\gamma, dec}$
  - Theory $\sim 30 - 40\%$ too high

- $p_T > 3 \text{ GeV}/c$: $\nu_2^{\gamma, inc} < \nu_2^{\gamma, dec}$
  - prompt photon contribution

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