Thermal radiation and direct-photon production in Pb–Pb and pp collisions with dielectrons in ALICE

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for the ALICE collaboration
Motivation

Dielectron production

Several sources of correlated electron pairs in Pb−Pb:
→ Separation via invariant mass
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Several sources of correlated electron pairs in Pb–Pb:
→ Separation via invariant mass

At higher masses (1.1 < \(m_{ee} < 2.7\) GeV/c\(^2\)):
- Correlated semi-leptonic decays of heavy flavour (HF)
- Quark-gluon plasma (QGP)

→ Suppression of HF production

→ Temperature of the QGP
Motivation

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Several sources of correlated electron pairs in Pb–Pb:

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At higher masses ($1.1 < m_{ee} < 2.7 \text{ GeV}/c^2$):

- Correlated semi-leptonic decays of heavy flavour (HF)
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At lower masses ($0.14 < m_{ee} < 0.9 \text{ GeV}/c^2$):

- Pseudoscalar and vector mesons ($\pi^0, \eta, \rho, \omega, \phi$)
- Hadron-gas (HG) phase

→ Temperature of the HG

Modification of the $\rho$ spectral function

![](diagram.png)
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At vanishing mass ($m_{ee} \to 0$):
- Equivalent to real-photon measurement

Yield

Dielectron spectrum

$Y$

$m_{ee} (\text{GeV}/c^2)$
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At vanishing mass ($m_{ee} \rightarrow 0$):
- Equivalent to real-photon measurement

Measurements in pp:
- Vacuum baseline for Pb–Pb studies (HF, direct photons)
- Search for new phenomena in high-multiplicity (HM) events or at low momenta

Dielectron production in pp at $\sqrt{s} = 13$ TeV
Minimum bias (MB)

- Analysis of the full Run 2 data set → Poster by H. Murakami: Session 2 T13

  MB: a factor of 3.8 & HM: a factor of 4.4

- Updated hadronic cocktail estimation with independent measurements at $\sqrt{s} = 13$ TeV
  → $\pi^0$ and $\eta$ mesons in the same multiplicity intervals → Poster by J. König: Session 1 T14_2

- MB ($p_{T,ee} > 1$ GeV/c) well described by hadronic sources
Analysis of the full Run 2 data set
→ Poster by H. Murakami: Session 2 T13

Increase of statistics compared to previous publication:
MB: a factor of 3.8 & HM: a factor of 4.4

Updated hadronic cocktail estimation
with independent measurements at $\sqrt{s} = 13$ TeV

→ $\pi^0$ and $\eta$ mesons in the same multiplicity intervals
→ Poster by J. König: Session 1 T14_2

→ Larger cocktail uncertainties due to multiplicity
dependence of HF production

Within uncertainties no sign of thermal radiation in
HM pp events
Direct photons in pp
→ Important baseline for Pb–Pb
→ Search for possible thermal contributions in HM pp events

Kroll-Wada formula $f_{\text{dir}}$ used for extraction:

$$f_{\text{fit}} = r \times f_{\text{dir}} + (1 - r) \times f_{\text{LF}} + f_{\text{HF}}$$

Direct-photon fraction $r$:

$$r = \frac{\gamma_{\text{dir}}^*}{\gamma_{\text{incl}}^*} \quad m_{\text{ee}} \to 0$$

- Direct-photon fraction $r$ as the only free parameter
- Spectrum fitted above pion mass
→ Large reduction of systematic uncertainties compared to real-photon measurement
Direct-photon fraction in pp at $\sqrt{s} = 13$ TeV

Comparison to published results and theory

Significant reduction of statistical and systematic uncertainties in new analysis

→ Direct-photon fraction in MB in good agreement with pQCD calculations

→ Measurement in HM compatible with MB results

Poster by H. Murakami: Session 2 T13
Dielectron production in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Invariant-mass spectrum

Comparison to hadronic cocktail, including:

- $N_{\text{coll}}$-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  
  
  $\rightarrow$ Vacuum baseline

Data at the edge of the uncertainty of hadronic cocktail

However: HF contribution is expected to be modified
  
  $\rightarrow$ CNM and hot medium effects
Dielectron production in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Invariant-mass spectrum

Comparison to hadronic cocktail, including:

- $N_{\text{coll}}$-scaled HF measured in pp at $\sqrt{s} = 5.02$ TeV
  
  *Phys. Rev. C* 102 (2020) 055204
  
  → Vacuum baseline

- Include measured $R_{AA}$ of $c/b \rightarrow e^\pm$
  
  
  → Modified-HF cocktail

Intermediate-mass region (IMR) from $1.1 < m_{ee} < 2.7$ GeV/$c^2$

→ Consistent with HF suppression & therm. radiation from QGP

Indication for an excess at lower mass

→ Compatible with thermal radiation from HG
Direct-photons fraction in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Direct-photon fraction $r$ extracted with same method as in pp

$$ R_\gamma = \frac{1}{1-r} = \frac{Y_{\text{incl}}}{Y_{\text{decay}}} $$

First measurements in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV:

- Good agreement with real-photon method
  Talk by M. Danisch: Parallel Session T13

- Smaller syst. uncertainties at low $p_T$ compared to real photons

- Virtual-photon measurement limited by statistics

Figure corrected after the conference
Direct-photons Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Direct-photon yield – Effective-temperature extraction

Direct-photon yield

- Constructed with inclusive-photon spectrum from PCM
  \[ \gamma^{\text{dir}} = \gamma^{\text{inc}}(\text{PCM}) \times r \]

- Data consistent with pQCD with a hint for an excess above pQCD expectation at low $p_T$

Figure corrected after the conference
Direct-photons Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Direct-photon yield – Theory comparison

Data compared to models including thermal & pQCD photons:

Thermodynamic models:
- **C. Gale**: Radiation from all stages of the collision including the pre-equilibrium phase
- **H. van Hees**: Therm. radiation from QGP & hadr. many body calc. and meson-exchange reactions
- **P. Dasgupta**: Thermal photons with fluctuations in the initial-state

Microscopic transport model:
- **O. Linnyk**: Direct photons via PHSD

$\rightarrow$ Models including thermal radiation tend to overestimate the data at lower $p_T$
Direct-photons Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Experimental comparison overview

Real-photon measurement in 0-20% Pb–Pb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

$\rightarrow T_{\text{eff}} = 297 \pm 12(\text{stat.}) \pm 41(\text{syst.})$ MeV


New ALICE results:

Virtual-photon measurement in central Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

$\rightarrow$ Need to decrease uncertainties first in order to extract a temperature

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Direct-photons Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Experimental comparison overview

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New ALICE results:
Virtual-photon measurement in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
\[ \rightarrow \text{Need to decrease uncertainties first in order to extract a temperature} \]

Consistent with a universal scaling behaviour of direct-photon yield with charged-particle multiplicity postulated by PHENIX

Figure corrected after the conference
Excess yield = Data – cocktail (w/o ρ contribution)

Invariant mass allows to separate different thermal contributions:

\(m_{ee} < 1 \text{ GeV}/c^2\) : Contributions from Hadron Gas
\(m_{ee} > 1 \text{ GeV}/c^2\) : QGP radiation

→ Current understanding of the cocktail limits the interpretation of the data

→ Develop cocktail independent approach
**DCA\textsubscript{ee} analysis in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV**

Separation of prompt and non-prompt sources based on their decay topology:

$\Rightarrow$ DCA\textsubscript{ee}(thermal) < DCA\textsubscript{ee}(HF)

Gives access to measurements of:

$\Rightarrow$ Thermal radiation at low DCA\textsubscript{ee}

$\Rightarrow$ Suppression of HF production at high DCA\textsubscript{ee}

Distance-of-closest approach (DCA):

$$DCA_{ee} = \sqrt{\frac{DCA_1^2 + DCA_2^2}{2}}$$
**DCA\textsubscript{ee} analysis in central Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV**

Intermediate-mass region

First DCA\textsubscript{ee} analysis in Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Comparison to $N_{\text{coll}}$-scaled cocktail:

- Beauty dominates the spectrum at high DCA\textsubscript{ee}
- Charm more prominent at low DCA\textsubscript{ee}

→ Data below HF expectation
  → Clear indication of HF suppression
DCA_{ee} analysis in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

DCA template fit

Extraction of prompt thermal signal via template fits:

- Beauty contribution fixed via separate fit at high DCA_{ee}
  \[ \text{bb}: \quad 0.74 \pm 0.24(\text{stat.}) \pm 0.12(\text{syst.}) \quad (\text{w.r.t. } N_{\text{coll}} \text{ scaling}) \]

- Simultaneous fit of charm and prompt contribution
  \[ \text{c\bar{c}}: \quad 0.43 \pm 0.40(\text{stat.}) \pm 0.22(\text{syst.}) \quad (\text{w.r.t. } N_{\text{coll}} \text{ scaling}) \]
  \[ \text{prompt}: \quad 2.64 \pm 3.18(\text{stat.}) \pm 0.29(\text{syst.}) \quad (\text{w.r.t. R. Rapp}) \]
**DCA\textsubscript{ee} analysis in central Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV**

DCA spectra – template fits

**Fit result**

Extraction of prompt thermal signal via template fits:

- Beauty contribution fixed via separate fit at high DCA\textsubscript{ee}
  
  $\text{bb}^-$: $0.74 \pm 0.24\text{(stat.)} \pm 0.12\text{(syst.)} \text{ (w.r.t. } N_{\text{coll}} \text{ scaling)}$

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  prompt: $2.64 \pm 3.18\text{(stat.)} \pm 0.29\text{(syst.)} \text{ (w.r.t. R. Rapp)}$

Results in agreement with:

- Charm suppression
- Thermal contribution in the order of Rapp/PHSD

Method independent of hadronic cocktail:

- Smaller syst. uncertainties
- More statistics enables the extraction of a thermal dielectron yield in the IMR
Outlook

Dielectron production in Run 3 and 4

New Pb–Pb data taking at the end of this year

New ITS and upgrade of the TPC to a GEM based readout system:

- Increase the readout rate in Pb–Pb by a factor 100 → 13 nb\(^{-1}\) MB Pb–Pb planned

- Improve the vertex pointing resolution by a factor 3-6 → Improves topological separation (DCA\(_{ee}\))

→ Talks by A. Alkin: Parallel Session T15
Summary

Analysis of full Run 2 dataset of pp at $\sqrt{s} = 13$ TeV
→ Significant increase in statistics & reduction of syst. uncertainties
→ Extraction of direct-photon fraction in MB & HM events

Measurement of dielectron production in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
→ First measurement of direct-photon yield
→ Limits for thermal radiation
→ First DCA$_{ee}$ analysis in Pb–Pb to separate thermal radiation & heavy-flavor background
Backup
ALICE apparatus
Low-mass dielectrons

Inner Tracking System
- Vertexing
- Tracking
- PID

Time Projection Chamber
- Tracking
- PID

Time of Flight
- PID

V0 at forward rapidity
- MB & HM event triggering
- Multiplicity estimation
- Centrality determination

<table>
<thead>
<tr>
<th>System</th>
<th>Analysed luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV</td>
<td>10 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>pp $\sqrt{s} = 13$ TeV</td>
<td>X.XX nb$^{-1}$</td>
</tr>
</tbody>
</table>
Dielectron production in semi-central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Cocktail weighting method

Parametrisation of measured of HF electron $R_{AA}$
→ Contains CNM effects & energy loss in the medium

Disentangle CNM effects using EPS09

CNM effects & energy-loss affect pair production differently

<table>
<thead>
<tr>
<th>CNM</th>
<th>Energy loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affects whole pair</td>
<td>Affects each electron independently</td>
</tr>
</tbody>
</table>

$w_1 = \frac{R_{AA}(p_T,e^+) + R_{AA}(p_T,e^-)}{2}$
$w_2 = R_{AA}(p_T,e^+) \times R_{AA}(p_T,e^-)$

→ Total weight $w = w_1 \times w_2$ applied as a function of $m_{ee}$ & $p_{T,ee}$

However: Correction with large uncertainties from HFe $R_{AA}$ & EPS09
Assumes same suppression for charm & beauty
Dielectron production in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Cocktail comparison – Pair-momentum spectra at low masses

Excess yield: $p_{T,ee} < 4$ GeV/$c$ dominated by thermal radiation

$p_{T,ee} > 4$ GeV/$c$ more prompt photons expected

Inclusion of HF modification crucial to describe $p_{T,ee}$ shape
Dielectron production in semi-central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
Cocktail comparison – Pair-momentum spectra at low masses

0.14 < $m_{ee}$ < 0.5 GeV/c²

0.5 < $m_{ee}$ < 1.1 GeV/c²

Excess yield: $p_{T,ee} < 4$ GeV/c dominated by thermal radiation

$p_{T,ee} > 4$ GeV/c more prompt photons expected
Comparison to binary scaled HF
→ Data overall in good agreement

Inclusion of HF modification in the cocktail
→ Data above cocktail expectation
Direct-photons Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Direct-photon fraction extraction

Direct-photon fraction $r$ extracted with same method as in pp: (Kroll-Wada function $f_{\text{dir}}$)

$$f_{\text{fit}} = r \times f_{\text{dir}} + (1 - r) \times f_{\text{LF}} + f_{\text{HF}}$$
Dielectron production in central Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Nuclear modification factor

Indication of HF suppression in the IMR in Pb–Pb collisions
Dielectron production in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Nuclear modification factor

Signs of suppression as a function of $p_{T,ee}$ in Pb–Pb collisions
Dielectron production in semi-central Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Cocktail comparison – Invariant-mass spectrum

First measurement of the dielectron production in semi-central collisions

Compared to different hadronic cocktails:

Binary $N_{\text{coll}}$ scaled HF measurement $\rightarrow$ vacuum baseline

Input: HF measurement from pp at $\sqrt{s} = 5.02$ TeV $\rightarrow$ Phys. Rev. C 102 (2020) 055204

Data on the edge of the uncertainty of hadronic expectations $\rightarrow$ Tension in the region $0.5 < m_{ee} < 1.1$ GeV/$c^2$

However: HF contribution is expected to be modified $\rightarrow$ CNM and hot medium effects
Dielectron production in semi-central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Cocktail comparison – Invariant-mass spectrum

First measurement of the dielectron production in semi-central collisions

Compared to different hadronic cocktails:

- Binary $N_{\text{coll}}$ scaled HF measurement → vacuum baseline
- Weighted HF based $R_{AA}$ of $c/b \to e^\pm$ → to model a HF suppression

Inclusion of HF modification improves the overall description

Compared to theory calculations including thermal radiation

However: Therm. signal in the order of syst. uncertainties of the modified cocktail
Excess yield = Data – cocktail (w/o $\rho$ contribution)

Invariant mass allows to separate different thermal contributions

$m_{ee} < 1 \text{ GeV}/c^2$: Contributions from Hadron Gas

$m_{ee} > 1 \text{ GeV}/c^2$: QGP radiation

→ Current understanding of the cocktail limits the understanding of the data

→ Develop cocktail independent approach
**DCA\textsubscript{ee} analysis in central Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV**

Cocktail-scaled DCA spectra – J/$\psi$ region

Well suited as a control region:

- Mixture of prompt & non-prompt sources
- J/$\psi$ production well constrained

Data well described by DCA\textsubscript{ee} templates scaled with the hadronic cocktail
Dielectron production in central PbPb at 5.02 TeV

Scaled DCA spectra – Intermediate-mass region

Inclusion of weighting with HFe $R_{AA}$:
- Better description of high DCA$_{ee}$ values
- Spectrum consistent with theory calculations for thermal radiation by R. Rapp

Prompt signal ➔ Non-prompt signal