HL-LHC WORKSHOP - WG5: HEAVY IONS EM RADIATION / LOW MASS DILEPTONS

Outline:
• Physics motivation
• Expected performance in Run3/4
  • Dielectrons
  • Dimuons
  • Dark photons
• Conclusion and ongoing work

Based (mainly) on:
ALICE Upgrade LoI: CERN-LHCC-2012-012
CERN-LHCC-2013-014
ITS TDR: CERN-LHCC-2013-024
TPC TDR: CERN-LHCC-2013-020
MFT TDR: CERN-LHCC-2015-001

MICHAEL WEBER (SMI)
ON BEHALF OF THE ALICE COLLABORATION
31.10.2017
ELECTROMAGNETIC PROBES OF THE QGP

Photons: measure $\gamma$ (Calo, PCM)
Dileptons: measure $e^+e^-$ or $\mu^+\mu^-$ pairs

- Couple to EM current
- Very low interaction with QCD medium (no strong interaction)

- Sensitive to
  - Photons:
    - Thermal radiation
  - Dileptons:
    - Thermal radiation
    - Vector meson spectral shape
    - Beyond SM particles with $J^{PC}=1^-$ (e.g. dark photons)

Dilepton emission rate in thermal equilibrium:

$$
\frac{dN_{ll}}{d^4xd^4q} = - \frac{\alpha^2}{3\pi^3} \frac{L(M^2)}{M^2} \text{Im} \Pi^\mu_{em,\mu}(M, q; \mu_B, T) \times f^B(q_0; T),
$$
THERMAL RADIATION (PHOTONS)

- **Measure thermal radiation** (black body photons)
- **First measurement at LHC** from soft exponential component of photon $p_T$ spectrum (*ALICE, Phys.Lett. B754 (2016) 235*): $T \sim 300$ MeV (effective temperature averaged over system evolution)
- **Direct photon flow** larger than available theory predictions
• **Measure thermal radiation** (black body photons)
• First measurement at LHC from soft exponential component of photon $p_T$ spectrum (*ALICE, Phys.Lett. B754 (2016) 235*): $T \sim 300$ MeV (effective temperature averaged over system evolution)
• Dileptons:
  • **Map temperature during system evolution**
  • Invariant mass method **not sensitive to “blue-shift” from radial flow**
CHIRAL SYMMETRY AND SPECTRAL FUNCTION

\[ \mu = 0 \text{ MeV} \]

\[ m_{\rho}^p, \quad m_{\sigma}^p \]

\[ m_{\rho}^p \]

Jung et al., Phys. Rev. D 95, 03620 (2017)

\[ m_{\rho}^p \]

Vacuum

\[ \rho_{V,A}(s)/\pi s \]

T=170 MeV

\[ s (\text{GeV}) \]

symmetry

<table>
<thead>
<tr>
<th>( SU_V(2) )</th>
<th>( SU_A(2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>unbroken</td>
<td>broken</td>
</tr>
<tr>
<td>high temperature</td>
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<td>unbroken</td>
<td>unbroken</td>
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<tr>
<td>multiplets</td>
<td>(( n, p ), ...)</td>
</tr>
<tr>
<td>(( n, p ), ...)</td>
<td>(( \sigma, \pi ), (( \rho, a_1 ), ...</td>
</tr>
<tr>
<td>order parameter</td>
<td>( \langle \bar{q}q \rangle )</td>
</tr>
<tr>
<td>“Isospin”</td>
<td>“Parity”</td>
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</tbody>
</table>

At LHC energies:
- Vanishing $\mu_B$: direct comparability to Lattice QCD
- Sizeable in-medium modification of $\rho$
- Large thermal radiation contribution above 1 GeV/c$^2$

**FIGURE 10.** Dielectron invariant-mass spectra from thermal radiation in 0-40% central Pb-Pb (2.76 ATeV) (left panel) and 0-10% central Pb-Pb (5.5 ATeV) (right panel), including single-electron cuts to simulate the ALICE acceptance. Hadronic (with in-medium or vacuum EM spectral function) and QGP contributions are shown separately along with the sum of in-medium hadronic plus QGP. Here and in the following LHC plots, both vacuum and in-medium hadronic emission rates in the LMR have been supplemented with the vacuum spectral function in the LMR, i.e., no in-medium effects due to chiral mixing have been included (for all RHIC calculations shown in the previous section full chiral mixing was included).

ALICE AFTER 2020

- Improved **vertex resolution**
  - Better separation of electrons from charm and bottom decays

- **Reduced material budget** and improved **low \( p_T \) efficiency**
  - Smaller background from conversion electrons

- Dedicated **low B field** run
  - Recover low \( p_T \) tracks
  - 3 \text{ nb}^{-1} at \( B = 0.2 \text{ T} \)

- **Higher rate** capability
  - 50 kHz Pb-Pb

- Muon forward tracker (MFT) in addition to muon spectrometer
  - Improved **mass resolution**
  - Reduced background
LOW MASS DIELECTRONS
The ALICE Collaboration

$M_{ee}$ ($\text{GeV}/c^2$)

- $dN/dM_{ee} (\text{dy})$
- $dN/dM_{ee} (\text{GeV})$

$S/B$

- $S/B$
- $S/B (\text{GeV})$

Significance

- $S/\sqrt{S+B (\text{Event GeV}^{-1})}$
- $S/\sqrt{S+B (\text{GeV}^{-1})}$

Upgrades and improvements in the ALICE Collaboration's performance, focusing on the inclusive electro-production (inclusive dilepton yield) in 0–10% and 40–60% Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5$ TeV.

The study aims to measure $p_T$ and $h_T$ down to low $p_T$ via conversions and can thereby constrain uncertainties on the hadronic cocktail. For the subtraction of the charm contribution, a relative systematic uncertainty of 20% is assumed.

2.3.3.5 Results

In the following, the results of the physics performance study described before are discussed. Figure 2.54 (left) shows the inclusive $e^+e^-$ invariant mass spectrum in the 0–10% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.5$ TeV in Scenario 1, i.e., current ITS and $2.5 \cdot 10^7$ events. No particular DCA cuts are applied to reject displaced electrons. The same spectrum after subtraction of the hadronic cocktail and the charm contribution (the 'excess spectrum') is shown in the right panel of Figure 2.54. The low–mass region $M_{ee} < 1 \text{ GeV}/c^2$ is dominated by systematic uncertainties related to the subtraction of the combinatorial background. In the mass region $M_{ee} > 1 \text{ GeV}/c^2$, the systematic uncertainties from the charm subtraction do not allow quantitative analysis of the thermal radiation spectrum.

The DCA resolution of the current ITS allows for some limited suppression of displaced electrons (see also Figure 2.51). In the left panel of Figure 2.55, the inclusive $e^+e^-$ in Scenario 1 is shown after application of tight DCA cuts. The relative contribution from charm can be suppressed by about a factor 2 (compare to Figure 2.54, left), at the expense of an additional loss in statistics. In the right panel of Figure 2.55, the corresponding excess spectrum is shown which indicates improved systematic uncertainties from charm subtraction, but still large errors from combinatorial background and insufficient statistics.
A key element of the ALICE upgrade strategy is therefore a concept for a continuously operated TPC, measurement would not allow for a quantitative analysis of the thermal dilepton excess.

Uncertainties related to charm subtraction is also achieved. However, the statistical limitations of the uncertainties, as compared to the current ITS system (see Figure).

In Scenario 1 (current ITS), in Scenario 3 (new ITS), and in Scenario 2 (new ITS).

Current readout

- New ITS: less conversion, better DCA resolution
- New readout: x100 statistics
A key element of the ALICE upgrade strategy is therefore a concept for a continuously operated TPC, with uncertainties related to charm subtraction also achieved. However, the statistical limitations of the Figures indicate systematic errors related to the subtraction of the cocktail and charm contribution. Pb–Pb collisions at Figure 2.55:

- Boxes indicate systematic errors related to the subtraction of the cocktail and charm contribution.
- The green boxes show the systematic uncertainties from the combinatorial background subtraction, the magenta boxes from charm subtraction, and the blue boxes from Rapp QGP.

The invariant mass spectrum (left) and excess spectrum (right) for 0–10% most central events. Tight DCA cuts are applied. The tracking capability of the new ITS leads to an increase of the long-lived light- and heavy-flavour sources.

After subtraction of long-lived light- and heavy-flavour sources, the low mass spectral function with ~20% uncertainty.
From a fit to the invariant mass spectrum from 1.1 to 1.5 GeV/c^2
ELLTIPOC FLOW (20-40% CENTRALITY)

- Current ITS
- Current readout

• New ITS: less conversion, better DCA resolution
• New readout: x100 statistics
**SMALL SYSTEMS**

- Thermal radiation in small systems?
- R. Rapp, IS2014:
  - 10% thermal contribution in MB p-Pb collisions
ESTIMATES FOR RUN 3/4  (p-Pb, 50 nb\(^{-1}\))

- Run 1 results based on \( L_{\text{int}} \sim 50 \mu\text{b}^{-1} \).
- **Stat. uncertainties**
  - In the interesting mass regions (0.3<\( m_{ee} \)<0.7 GeV/\( c^2 \)) and (1<\( m_{ee} \)<3 GeV/\( c^2 \)):
    - \( \sigma_{\text{stat}} \sim 20 - 50\% \)
- For Run 3/4 (50 nb\(^{-1}\))
  - \( \sigma_{\text{stat}} \sim 1 - 2\% \)
- Measurement will not be limited by stat. uncertainties

From Run 1 performance:

- **p-Pb** NSD \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- \( p_{T}^{c} > 0.2 \text{ GeV}/c \)
- \( |\eta| < 0.8 \)
- **Data/cocktail**

\[ 1/M_{e^{+}e^{-}} dN/dm_{ee} \text{ (GeV}/c^2)^{-1} \]

- \( \sigma_{\text{stat}} = 1\% \)
- \( \sigma_{\text{stat}} = 0.8\% \)
- Measurement will not be limited by stat. uncertainties

ALICE Preliminary

- Cocktail sum with uncertainties
- \( \pi^0 \rightarrow \gamma e e \)
- \( \eta \rightarrow \gamma e e \)
- \( \omega \rightarrow e e \) and \( \omega \rightarrow \pi^0 e e \)
- \( \phi \rightarrow e e \) and \( \phi \rightarrow \gamma e e \)
- \( \eta' \rightarrow \gamma e e \)
- \( \rho \rightarrow e e \)
- \( c_{\text{col}}^{pp} \) x pp PYTHIA MNR, \( \sigma_{\text{col}} = 6.9 \text{mb} \)
- \( b_{\text{col}} \) x pp PYTHIA MNR, \( \sigma_{\text{col}} = 210 \text{mb} \)
  - (Like-sign subtracted)
- \( J/\psi \rightarrow e e \) and \( J/\psi \rightarrow \gamma e e \)

ALICE Preliminary

- Measurement will not be limited by stat. uncertainties
LOW MASS DIMUONS
UPGRADE IMPROVEMENT (Pb-Pb)

- **MUON** spectrometer only
  - **MUON + MFT**: better mass resolution, less background
SPECTRAL FUNCTION

After subtraction of long-lived light- and heavy-flavour sources

• Low mass spectral function with ~20% uncertainty
• Thermal radiation (M > 1 GeV/c²) difficult

**Figure 2.36:** Expected low mass dimuon spectrum in 0-10% central Pb–Pb collisions at \( \sqrt{s_{NN}} = 5.5 \) TeV after subtraction of the combinatorial background, normalised to an integrated luminosity of 10 nb

**Figure 2.37:** Expected sensitivity to the measurement of QGP signatures in 0-10% central Pb–Pb collisions at \( \sqrt{s_{NN}} = 5.5 \) TeV in a \( L_{\text{int}} = 10 \text{ nb} \) scenario without (left panel) and with (right panel) the MFT.
DARK PHOTONS
• Light scalar or vector BSM bosons could be observed in high-energy (with large QGP volumes produced), high-luminosity nuclear collisions


• Resonance in the thermal dilepton production from the QGP for masses up to 3 GeV/c²: dilepton measurements in ALICE could set limits on quark- and lepton-couplings of light BSM bosons

• ALICE: feasibility studies on dark photons of mass < 100 MeV/c²
DARK PHOTONS (RUN1)

\[ c^2 \in \begin{align*} 90\% \text{ CL} \\ 8 \times 10^{-10} & \leq c^2 < 2 \times 10^{-8} \end{align*} \]

ALICE Real data from Run1 (pp 276M + p-Pb: 85M)

ALICE Preliminary

\[ \varepsilon \leq 90\% \text{ CL} \]

\[ M_U \text{ (MeV/}c^2) \]

KLOE
COSY-WASA
HADES
PHENIX

\[ g-2 \text{ Upper} \]
\[ g-2 \text{ Lower} \]

ALICE expected

\[ \sigma_{1\text{ALICE}} \]
\[ \sigma_{2\text{ALICE}} \]

\[ g-2 \text{ 3}_{\text{KLOE}} \]
\[ g-2 \text{ 2}_{\text{HADES}} \]

KLOE
COSY-WASA
HADES
PHENIX

BaBar

ALICE-1_{\text{ALICE}}
ALICE-2_{\text{ALICE}}
DARK PHOTIONS (RUN3)

Run3 pp, p-Pb, Pb-Pb:
- pp: 400G (5.5 TeV), p-Pb: 10G (5.5 TeV)
- Pb-Pb: 80G (MB, 5.5 TeV)

$\sigma_{\text{ALICE}}$ ±

$\sigma_{\text{KLOE}}$ ±

$\sigma_{\text{COSY-WASA}}$ ±

$\sigma_{\text{HADES}}$ ±

$\sigma_{\text{PHENIX}}$

Preliminary

ALICE Simulation

ALI-SIMUL-85317
Dark Sector Community Report 2016

arXiv:1608.08632

J. Davis, C. Boehm, arXiv:1306.3653
• intermediate-mass dileptons: precision temperature measurement above the ϒ mass via thermal radiation to be checked also in high-multiplicity p-Pb, pp
• masses below to be seen, current minimal $p_\mu$ with ID 3 GeV/c: $p_T = 200, 400$ MeV/c ($\eta = 4.0, 2.5$)

OTHER LHC EXPERIMENTS, e.g. LHCb

90% CL exclusion regions on \([m(A'), \varepsilon^2]\)

- Possibility to measure below 100 MeV?

CONCLUSIONS

• Low mass dielectrons:

<table>
<thead>
<tr>
<th>Observable</th>
<th>Statistical uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (intermediate mass)</td>
<td>10 %</td>
</tr>
<tr>
<td>Elliptic flow ($v_2 = 0.1$) [4]</td>
<td>10 %</td>
</tr>
<tr>
<td>Low-mass spectral function [4]</td>
<td>20 %</td>
</tr>
</tbody>
</table>

• Low mass dimuons:
  • Higher statistics (10 nb$^{-1}$), but higher $p_T$ cut and larger HF background than dielectrons
  • **prompt signals from QGP measurable within 20% uncertainty**

• Small systems:
  • Thermal radiation from high multiplicity pp and p-Pb collisions?
  • Will not be limited by stat. uncertainties

• Dark photons:
  • **Sensitivity $\varepsilon^2 \sim 10^{-7}$ for 20$<M_{ee}<90$ MeV/c$^2$**
ONGOING WORK

- **Dielectrons:**
  - **Improving simulations** with better understanding of combinatorial background and pointing resolution
  - **Improve understanding of systematic uncertainties:** HF (mass shape), background subtraction,…
  - Deduce virtual photon method performance

- **Dimuons:**
  - Tuning analysis cuts for **heavy-flavour reduction** above 1 GeV/c²
  - **Improve understanding of systematic uncertainties:** HF (mass shape),…

- **Photons:**
  - Higher precision and statistics needed
  - Better understanding of **material budget** (main source of systematic uncertainties), explore new observables with canceling systematics
  - Performance plots for physics cases (**thermal radiation**, **flow**, **interferometry**,…)
BACKUP
WHY NOT REAL PHOTONS?

- Large blueshift at late times when $T \approx 150 - 200$ MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

\[
E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\text{eff}}}
\]

\[
T_{\text{eff}} = \frac{\sqrt{1 + \beta_{\text{flow}}}}{1 - \beta_{\text{flow}}} \times T
\]

2 for $\beta_{\text{flow}}=0.6$

LOW B FIELD

Figure 2.49: Acceptance for $e^+e^-$-pairs from PYTHIA at $B = 0.5$ T (left) and $B = 0.2$ T (right).
NEW INNER TRACKING SYSTEM

Figure 2.50: Left: Combined ITS-TPC-TOF efficiencies for electrons in |h| < 0.84 at B = 0.2 T for the current ITS (blue circles) and the new ITS (green rectangles) as a function of p_T. Also shown for comparison is the efficiency with current ITS at B = 0.5 T (open circles). Right: Standalone tracking efficiency of the current and the new ITS system.

2.3.3.2 Signal Generation

A realistic physics input into the simulation of the expected dilepton signal is mandatory in order to perform a solid investigation of the physics performance. To this end, we compute the dilepton signal composed of the contributions listed below. The signal is calculated for central (0–10%) and semi-central (40–60%) Pb–Pb collisions at \( p_{NN} = 5.5 \) TeV.

**Hadronic cocktail**
The hadronic cocktail includes contributions from the decays of light pseudoscalar and vector mesons. The yield is adjusted to charged particle densities \( h_{dNch}/dN = 1750 \) and \( h_{dNch}/dN = 248 \) in 0–10% and 40–60% most central Pb–Pb at \( p_{NN} = 5.5 \) TeV, respectively. The particle ratios and the spectral shapes are extrapolated from existing heavy-ion data at lower energies.

**Charm**
The contribution from correlated semi-leptonic charm decays is based on calculations from the PYTHIA event generator. A total charm cross section of \( s_{cc} = 7.55 \) mb in pp at \( p_{sNN} = 5.5 \) TeV has...
Current ITS
Current readout

New ITS
New readout
VIRTUAL PHOTON MEASUREMENT (PB-PB,RUN 1)

Fit the following function to the data

$$f(m_{ee}) = (1-r) \cdot f_{\text{cocktail}}(m_{ee}) + r \cdot f_{\text{direct}}(m_{ee})$$

- $r$ is the ratio of direct to inclusive photons

Cocktail contributions

Photon input from Kroll-Wada

Under the assumption that the ratio of direct to inclusive is the same as real to virtual

$\rightarrow$ direct $= r \times$ inclusive (yields)
VIRTUAL PHOTON MEASUREMENT (PP,RUN 1)

ALICE preliminary
pp, $\sqrt{s}=7$ TeV

2.4 < $p_T^{ee}$ < 3.2 GeV/c

$|\eta|<0.8$

ALICE preliminary
pp, $\sqrt{s}=7$ TeV

$\pi^0$, $\eta$, $\eta'$, $\omega$, $\phi$, $c$

data
$f_{\gamma,\text{dir}}$
$(1-r)f_{\text{cocktail}} + r f_{\gamma,\text{dir}}$
cocktail sum

$\gamma_{\text{direct}} = r \times \gamma_{\text{incl}}$

$\gamma_{\text{incl}}$ (PCM)

$\gamma_{\text{direct}}$ (W.V.)
$
\mu=0.5$
$\mu=1.0$
$\mu=2.0$

95 % C.L.

ALICE preliminary
pp, $\sqrt{s}=7$ TeV

$E \frac{d^3\sigma}{d^3p} \text{ (pb GeV}^{-2}c^3)$

$1 \rightarrow 2 \rightarrow 3$

$\pi^0$, $\eta$, $\eta'$, $\omega$, $\phi$, $c$

ALICE preliminary
pp, $\sqrt{s}=7$ TeV

$|\eta|<0.8$

ALICE preliminary
pp, $\sqrt{s}=7$ TeV

$\mu=0.5$
$\mu=1.0$
$\mu=2.0$

95 % C.L.

HL-LHC workshop | 31.10.2017 | Michael Weber (SMI)
FIG. 3. Same as Fig. 1 of the main text, but scaling the 15 fb⁻¹ baseline up to 50 fb⁻¹ and 500 fb⁻¹, for both the $D^\ast \rightarrow D_0 A_0$ search \cite{48} and the inclusive di-muon search (this work). For reference, the green dashed line shows where the $A_0$ lifetime is the same as the LHCb di-muon lifetime resolution and the orange dashed line shows where the average $A_0$ transverse displacement matches the distance at which the muons from $A_0 \rightarrow \mu^+ \mu^-$ decays likely no longer have enough hits in the LHCb VELO.

• Search strategy: Here, we considered the reach assuming three distinct search regions: prompt, pre-module, post-module. One could optimally combine these regions following \cite{73} which should improve the reach in the low-mass region.

• Semi-inclusive search: Instead of using the inclusive di-muon spectrum, a similar search could be done in semi-inclusive hadron decays such as $M \rightarrow \pi^+ \pi^-$, more in the spirit of \cite{48}. Depending on the channel, one could use the invariant mass of the $M$ or $Y$ system as a constraint to help control fake muon backgrounds.

• Di-electron search. To cover the mass range $m_{A_0}^2 \approx [m_e^2, 2m_\mu^2]$, one could pursue a similar inclusive search strategy for the di-electron final state. That said, the di-electron mass resolution is significantly degraded by Bremsstrahlung radiation and multiple scattering \cite{48}. In \cite{48}, the $m_{ee}$ resolution could be improved by imposing the kinematic constraints from charm meson decays, which is not an option in an inclusive search. For the displaced $A_0$ search, these same effects degrade the vertex resolution, and $e^+e^-$ pairs from photon conversion are a challenging background in the post-module region. For these reasons, we suspect that $A_0 \rightarrow e^+e^-$ is best probed using an exclusive (or semi-inclusive) strategy, but it would be worth testing the fully inclusive approach on LHCb data.

• Luminosity: Our study is based on 15 fb⁻¹ of data collected by LHCb, which is a conservative estimate of what is expected in Run 3. LHCb expects to collect at least 50 fb⁻¹ of data in Runs 3 and 4 combined, and may eventually collect 10–30 times more data than considered in this study. The impact on the dark photon reach from scaling up the LHCb luminosity is shown in Fig. 4.

Extended Reach Plot

To better show the array of proposed dark photon experiments, in Fig. 4 we show the same reach plot from the main text, but with an extended $\varepsilon^2$ range including supernova bounds (SN) \cite{78, 79}.
GEV-SCALE NEW GAUGE BOSONS

Dilepton spectra in Au-Au collisions

- Background Cocktail (Random $\phi$)
- Photon (QGP $\bar{q}q \rightarrow e^+ e^-$)
- Cocktail + Photon
- Cocktail + Photon + $\gamma'$ ($m_{\gamma'} = 1.6$ GeV)
- PHENIX Data ($|y| < 0.35$, $p_T > 0.2$ GeV)

$\chi_q x_e = 0.00121$
Normalisation = 0.355

$m_{ee}$ [GeV]

1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8

10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}

Dilepton spectra in Au-Au collisions

- Background Cocktail (Correlated $\phi$)
- Photon (QGP $\bar{q}q \rightarrow e^+ e^-$)
- Cocktail + Photon
- Cocktail + Photon + $\gamma'$ ($m_{\gamma'} = 1.6$ GeV)
- PHENIX Data ($|y| < 0.35$, $p_T > 0.2$ GeV)

$\chi_q x_e = 0.00363$
Normalisation = 0.12

$m_{ee}$ [GeV]

1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8

10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}

J. Davis, C. Boehm, arXiv:1306.3653