Photon measurements with ALICE 3

ALICE 3 workshop, 18-19 October 2021

Klaus Reygers
Universität Heidelberg
Outline

Ultra-soft photons ($p_T \lesssim 50 \text{ MeV/c}$): Low's theorem and the soft photon puzzle

Photons in the O(100 MeV+) range: QGP temperature and dynamics + electrical conductivity

Beyond the Standard Model: Search for axion-like particles
In 1958, Francis Low wrote a seminal paper on how to relate hadron production in a high energy collision to the production of soft photons. Francis E. Low, Phys. Rev. Lett. 110 (1958) 468

Striking discrepancies were found between predictions and experimental measurements. No agreement exists on their possible origin, despite > 40 years of research.

Low’s theorem is an example of a soft theorem in QFT. Considerable theoretical interest as soft theorems are related to symmetries reflecting infrared structure of gravity and gauge theory.*


With the ALICE 3 Forward Conversion Tracker we have come up with a concept for a detector that can provide a soft-photon measurement in the range $p_T < 10 \text{ MeV}/c$ to test Low’s theorem.

* “These theorems tell us that a surprisingly large — in fact, infinite — number of soft particles are produced in any physical process, but in a highly controlled manner that is central to the consistency of quantum field theory”, A. Strominger, arXiv:1703.05448

Peter Braun-Munzinger, EMMI seminar, Feb. 2021 “Soft photons, the Low theorem, and ALICE 3”
Low's theorem and the soft photon puzzle

Relating soft photon to charged hadron production

\[ p_1 + p_2 \rightarrow p_3 + p_4 + k. \]

External propagator contains term
\[
\frac{1}{(p \pm k)^2 - m^2} = \frac{1}{\pm 2p \cdot k}.
\]

Amplitude of the process with a bremsstrahlung photon has a pole whenever \( p \cdot k \rightarrow 0 \).

Internal propagators are never on-shell \( \rightarrow \) no pole \( \rightarrow \) negligible contribution to photon yield.

Soft photon emission related by a simple factor to process without photon emission:

\[
M(p_1p_2; p_3p_4 \ldots p_Nk) = M_0(p_1p_2; p_3p_4 \ldots p_N) \left( \sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k} \right) \]

\( \eta_i = +1 \) for outgoing hadron, \( \eta_i = -1 \) for incoming hadron, polarization
Low’s theorem and the soft photon puzzle

Low’s formula as used by experiments

Photon momentum spectrum (“inner bremsstrahlung”):

\[
\frac{dN_\gamma}{d^3k} = \frac{\alpha}{(2\pi)^2} \frac{-1}{E_\gamma} \int d^3\vec{p}_1 \ldots d^3\vec{p}_N \left( \sum_i \frac{\eta_i e_i P_i}{P_i K} \right)^2 \frac{dN_{\text{hadrons}}}{d^3\vec{p}_1 \ldots d^3\vec{p}_N}
\]

\[\sum_i: \text{sum over } N + 2 \text{ particles (2 incoming, } N \text{ outgoing)}\]

\[K, \vec{k}: \text{photon four- and three momentum } (E_\gamma \equiv |\vec{k}|)\]

\[P_i, \vec{p}_i: \text{four- and three momentum of particle } i\]

\[e_i = 1 \text{ for positive particle, } e_i = -1 \text{ for negative particle}\]

\[\eta_i = 1 \text{ for outgoing particle, } \eta_i = -1 \text{ for incoming particle}\]

Low’s formula for photon production is “tree-level exact”, i.e., it does not receive any loop corrections

First explicitly shown in
Goshaw et al.,

see also
Anomalous soft photon production

Example 1: Omega spectrometer – WA102

Most of the excess above inner bremsstrahlung at $\eta_{\gamma}^{CMS} \gtrsim 1$
Anomalous soft photon production

Example 2: $e^+e^- \rightarrow 2$ jets (DELPHI)

Photon range:
$$0.2 < E_\gamma < 1 \text{ GeV}$$
$$p_T < 80 \text{ MeV}/c$$

Expected from inner bremsstrahlung:
$$(17.1 \pm 0.01 \pm 1.21) \times 10^{-3} \gamma/\text{jet}$$

Observation:
$$(69.1 \pm 4.5 \pm 15.7) \times 10^{-3} \gamma/\text{jet}$$

Ratio:
$$4.0 \pm 0.3 \pm 1.0$$

$e^+e^- \rightarrow Z^0 \rightarrow 2$ jets

$B = 1.23$ T

About 7% of all photons convert in front of the TPC ($\rightarrow d/X_0 \approx 9\%$)
Anomalous soft photon production

Factor 2 – 5 excess w.r.t. Low’s formula

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Collision energy</th>
<th>Photon $p_T$</th>
<th>Photon / Brems Ratio</th>
<th>Detection method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-p$, CERN, WA91, OMEGA</td>
<td>1997</td>
<td>280 GeV</td>
<td>$p_T &lt; 20$ MeV/c (0.2 &lt; $E_\gamma$ &lt; 1 GeV)</td>
<td>7.8 ± 1.5</td>
<td>pair conversion</td>
<td>Belogianni et al., Phys. Lett. B 408, 487 (1997)</td>
</tr>
<tr>
<td>$\pi^-p$, CERN, WA91, OMEGA</td>
<td>2002</td>
<td>280 GeV</td>
<td>$p_T &lt; 20$ MeV/c (0.2 &lt; $E_\gamma$ &lt; 1 GeV)</td>
<td>5.3 ± 1.0</td>
<td>pair conversion</td>
<td>Belogianni et al., Phys. Lett. B 548, 122 (2002)</td>
</tr>
<tr>
<td>$p\bar{p}$, CERN, WA102,</td>
<td>2002</td>
<td>450 GeV</td>
<td>$p_T &lt; 20$ MeV/c (0.2 &lt; $E_\gamma$ &lt; 1 GeV)</td>
<td>4.1 ± 0.8</td>
<td>pair conversion</td>
<td>Belogianni et al., Phys. Lett. B 548, 129 (2002)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow 2$ jets, CERN, DELPHI</td>
<td>2006</td>
<td>91 GeV (CM)</td>
<td>$p_T &lt; 80$ MeV/c (0.2 &lt; $E_\gamma$ &lt; 1 GeV)</td>
<td>4.0 ± 0.3 ± 1.0</td>
<td>pair conversion</td>
<td>DELPHI, Eur. Phys. J. C 47, 273 (2006)</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \mu^+\mu^-$, CERN, DELPHI</td>
<td>2008</td>
<td>91 GeV (CM)</td>
<td>$p_T &lt; 80$ MeV/c (0.2 &lt; $E_\gamma$ &lt; 1 GeV)</td>
<td>~1</td>
<td>pair conversion</td>
<td>DELPHI, Eur. Phys. J. C57, 499 (2008)</td>
</tr>
</tbody>
</table>
Anomalous soft photon production

ALICE 3 soft-photon strategy

Establish a baseline by studying a “clean” exclusive process: \( pp \rightarrow pp \pi^+ \pi^- \gamma \)

Precise models for \( pp \rightarrow pp \pi^+ \pi^- \) exist. We expect \( \lim_{\omega \rightarrow 0} \frac{d\sigma_{\exp}/d\omega}{d\sigma_{\text{exact}}/d\omega} = 1 \).

“A violation of these relations would mean a terrible crisis for QFT!”
(Lebiedowicz, Nachtmann, Szczurek, arXiv:2107.10829)

Another interesting channel: \( pp \rightarrow pp J/\psi \gamma \) with \( J/\psi \rightarrow e^+e^-, \mu^+\mu^- \)

Study soft-photon production in inelastic (non-diffractive) \( pp \) collisions

Requirements in terms of statistics are moderate:
1% stat. uncertainty in \( 5 < p_T < 6 \) MeV bin for \( 3 < \eta < 5 \) with 1% conversion probability obtained with \( 160 \times 10^6 \) \( pp \) collisions @ 13 TeV

Extend study to reactions/systems with higher charged particle multiplicities
Ultra-soft photons in A-A collisions

Bremsstrahlung photons from stopping in heavy-ion collisions


“As of today, forward bremsstrahlung from stopping of incoming charges remains a generally expected physics effect that has never been measured experimentally in heavy-ion collisions.”

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see also J. I. Kapusta, Phys. Rev. C 15 (1977), 1580-1582

Low’s theorem is a general quantum formulation of soft bremsstrahlung

A classical formulation should apply for sufficiently long wavelength:

\[ \frac{d^2 I}{d\omega d\Omega} = |A|^2, \quad A(n, \omega) = \int dt \int d^3x n \times (n \times J(x, t)) e^{i\omega(t-n \cdot x)} \]


\[ n: \text{direction of the outgoing photon} \]
\[ J = J^{(in)} + J^{(in)} + J^{(out)}: \text{incoming and outgoing currents} \]
Soft photons with ALICE 3

Decay photon background small for $p_T \lesssim 5 \text{ MeV/c}$

The 1 – 10 MeV/c transverse momentum range is accessible at forward rapidities

$$p_T = \frac{E_\gamma}{\cosh \eta}, \quad \cosh \eta \approx 10, 27, 74 \text{ for } \eta = 3, 4, 5$$

$E_\gamma = 100 \text{ MeV}:$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (MeV/c)</td>
<td>10</td>
<td>3.7</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Tracking of electrons/positrons from photon conversions directly in front FCT

Dipole field required for good momentum resolution
Soft photons with ALICE 3

Forward Conversion Tracker (FCT)

\[ r \ (m) \]
\[ \eta = 3 \]
\[ \eta = 4 \]
\[ \eta = 5 \]

\[ z \ (m) \]

Photon measurements with ALICE 3 | K. Reygers
Measuring soft photons through conversion

Can measure photons through conversions down to $E_\gamma = 50\text{--}100\text{\,MeV}$

$E_\gamma = 100\text{\,MeV}$: easy

$E_\gamma = 20\text{\,MeV}$: not so easy

tracking layers in a dipole magnetic field ($B = 0.5\text{\,T}$)
FCT performance estimate:

Energy resolution, pointing resolution and efficiency

ALICE 3 Study
FCT performance estimate
converter: 100μm Pb
11 Si layers, thickness: 50μm
dipole field: \( B = 0.5 \text{T} \)

\[ \sigma_{E/E} (\%) \]

\[ \text{pointing angle resol. in (mrad)} \]

\[ \text{photon efficiency } \epsilon (\%) \]

\[ \epsilon = p_{\text{conv}} \times p_{\text{reco}} \]
Background due to external bremsstrahlung
Background photons from primary $e^+/e^-$ and from conversion $e^+/e^-$

**General strategy:** minimize material in front of FCT

Avoid crossing of beampipe at shallow angles ($d = d_\perp \cosh \eta$)

Useful background estimate can be obtained analytically:

$$\frac{dN_\gamma^{\text{bck. per electron}}}{dk} \approx \frac{4}{3} \frac{d}{X_0} \frac{1}{k}$$

for $k \ll E_e$
Background due to external bremsstrahlung

Need to limit material in front of FCT to about 14% $X_0$ or less

Signal = background for $d/X_0 \approx 5\%$

Inner bremsstrahlung (pp, 13 TeV, based on charged particles from PYTHIA 8):

$$\frac{dN_{\text{signal}}}{dk_T} = 0.034 \frac{k_T}{k_T} \text{ for } 3 < \eta < 5$$

Significance (background subtraction):

$$\text{significance} = \frac{s}{\sigma_b^{\text{relative}} \cdot b}$$
Background due to external bremsstrahlung

Geant 4 simulation of background photons

Compare background photons for two cases

1. all events
2. events without electrons/positrons in the pseudorapidity range of the FCT
Background due to external bremsstrahlung

Identification and/or rejection of $e^+/e^-$ in the $\eta$ range of the FCT is key.

Promising. Further simulations needed to optimize detector, refine analysis cuts, and estimate significance.
Photons from equilibrated medium:
 temperature

Once produced, photons and dileptons leave medium unscathed

mean free path length $\approx 500$ fm

Sensitive to electrical conductivity of the QGP

Access to full time evolution of the system:
 pre-hydro and hydro phase

Why photons in AA collisions?
Temperature through the measurement of photons

CMB black-body spectrum (COBE)

Direct photons in Pb-Pb (ALICE)

A start. Significance so far below 3σ. Expect ultimate measurement at LHC from ALICE 3.
Complementarity of real and virtual photons

Combine information from real and virtual photons to extract properties of hydro and pre-hydro phase in A-A collisions

Real and virtual photons rates closely related:

\[
\frac{\omega}{d^3p} \frac{dR}{d^3p} = \frac{1}{(2\pi)^3} n_B(\omega) \rho(\omega, |\vec{p}|) \quad \frac{dR}{d^4p} = \frac{\alpha^2}{3\pi^2} \frac{1}{M^2} n_B(\omega) \rho(\omega, |\vec{p}|) \left(1 + \frac{2m^2}{M^2}\right) \sqrt{1 - \frac{4m^2}{M^2}} \Theta(M^2 - 4m^2)
\]

\(\rho_T\) spectrum of real photons:

(effective) temperature + flow dynamics

sensitive to pre-hydro phase

\(M_{\text{inv}}\) spectrum of virtual photons:

(effective) temperature, not affected by flow

\[dN/dM \propto M^{3/2} \times \exp(-M/T) \quad \text{for } M > 1 \text{ GeV}\]

sensitive to pre-hydro phase

Doppler blue-shift for real photons

\[E_\gamma \frac{d^3N_\gamma}{d^3p_\gamma} \propto e^{-E_\gamma/T_{\text{eff}}} \quad T_{\text{eff}} = \sqrt{\frac{1 + \beta_{\text{flow}}}{1 - \beta_{\text{flow}}}} \times T\]

2 for \(\beta_{\text{flow}} = 0.6\)
Electrical conductivity via direct photons

Decay photons are a significant background

Electrical conductivity is a fundamental transport property (like, e.g., viscosity)

Low-$p_T$ direct photon yields related to electrical conductivity $\sigma$:

$$\lim_{p_T \to 0} \frac{dN}{p_T dp_T} \propto \sigma$$

Spectral function with conductivity peak folded with space-time evolution (FluiduM)

Decay photon background ($\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, …) is expected to be large

C. Gebhardt, EMMI Rapid Reaction Task Force (RRTF), “Signals of Electric Conductivity”
Electrical conductivity via direct photons

Promising experimental approach: photon interferometry


WA98 measured low-$p_T$ photons yields through Hanbury Brown-Twiss (HBT) correlations of photons:

$$\frac{N_{\gamma_{\text{direct}}}}{N_{\gamma_{\text{total}}}} = \sqrt{2\lambda} \approx 8\%$$

Direct-photon yields without decay-photon cocktail

Model for electrical conductivity of a meson gas consistent with WA98 data

Promising method for ALICE 3

- Sufficient statistics
- Can combine conversion photon with ECal photon
Search for axion-like particles

Low two-photon invariant masses accessible with ALICE 3

BSM studies with ALICE 3 include

- axion-like particles (ALPs) searches
- $\tau g-2$
- dark photon search

ALP searches in ultra-peripheral collisions:

**Existing constraints on ALP mass and ALP-photon coupling**
(from JHEP 12 (2017) 044)

Search for peaks in the two-photon invariant mass spectrum
Search for axion-like particles

ALICE 3 has the potential to fill the mass gap from 0.05 to 5 GeV

ALICE 3 projections for ALP exclusion limits assuming 35/nb Pb-Pb (6 years of data taking)

Signal ALPs from STARLight generator

Background includes:

- $\pi^0\pi^0$ photoproduction
- Light-by-light scattering

Existing limits from ATLAS, JHEP 03, 243 (2021)
Projections for ATLAS/CMS from PRL 118 (2017), 171801
Projections for LHCb from Goncalves et al. EPJC 81 (2021), 522

Evgeny Kryshen, EMMI RRTF meeting, Sep. 2021
“Light-by-light measurements, ALP searches, and tau g-2 constraints with UPCs”

Photon measurements with ALICE 3 | K. Reygers
Conclusions: Photons with ALICE 3

Ultra-soft photons: ALICE 3 Forward Conversion Tracker
- Access to ultra-soft photons in the $p_T < 10$ MeV/c range
- Resolve soft-photon puzzle
- Relation to infrared structure of quantum field theories

Real photons in the $O(100$ MeV+) range) with ALICE 3
- Photon conversion method and ECal measurement
- Combine information from real and virtual photons for best possible information about pre-hydro and hydro phase
- Electrical conductivity accessible through photon Hanbury Brown-Twiss correlations

Beyond standard model physics: ALPs searches, $\tau g-2$, dark photon searches
- ALICE 3 can fill the gap in the ALP mass range from 50 MeV to 5 GeV