EM-Probes in High-Energy pp and AA Collisions

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Outline

• Introduction
• Prompt Photons
  • Saturation Signal
• Thermal Photons
  • Yield and Anisotropy
• Low-Mass Dileptons
• Conclusions
Electromagnetic Probes

- **advantages:**
  - elementary production processes well understood
    - reduce systematic uncertainty in interpretation
  - little modification in final state
    - probing early phases
- **disadvantages:**
  - small signal/large background
The Two Faces of Photons

• prompt photons:
  • produced in hard scatterings
    • described by pQCD, dominate at high $p_T$
  • probing the initial state
    • nPDFs, saturation, …

• thermal photons:
  • thermal QCD (+hadrons)
    • good theoretical understanding, dominate at low $p_T$
  • em radiation from thermal system (QGP)
    • information on temperature from early phase
    … one of the holy grails of heavy-ion physics
Prompt Photons
Prompt Photons in AA

\[ R_{AA} = \frac{dN/dp_T^{2}(AA)}{\langle N_{coll}\rangle \cdot dN/dp_T^{2}(pp)} \]

- compatible with \( N_{coll} \) scaling
- no strong nuclear effects expected
  - large \( p_T \) implies large Bjorken-\( x \)
  \[ x \approx \frac{2p_T}{\sqrt{s}} > 0.01 \]
Nuclear Effects in pA at Forward Rapidity

- good low-x sensitivity for direct photons at forward rapidity
- advantage over hadronic probes
  - no final state interaction
  - well-understood production process
  - well-defined kinematics
- signals expected at low-intermediate $p_T$
- two scenarios:
  - little suppression from EPS09 shadowing
  - strong suppression in direct $\gamma R_{pA}$ for saturation/CGC
- forward direct photons at LHC as signal for gluon saturation

\[
\frac{d\sigma^\gamma}{\sigma} = \frac{d(\log x)}{\log(x^2)}
\]
\[
p_T = 5 \text{ GeV}
\]
\[
\eta^x = 4.5
\]
\[
\sqrt{s} = 8.8 \text{ TeV}
\]
\[
p^T = 20 \text{ GeV}
\]
\[
\eta_{\pi^0} = 4.5
\]
\[
\eta_{\gamma} = 4
\]
\[
R_{pA}
\]
FoCal Upgrade Proposal in ALICE

- main challenge: separate $\gamma/\pi^0$ at high energy
- need small Molière radius, high-granularity read-out
  - Si-W calorimeter, granularity $\approx 1\text{mm}^2$

- R&D ongoing
  - achieved with proof-of-principle prototype:
    - $R_M \approx 11\text{mm}$
    - shower position resolution $\sigma_x < 40\mu\text{m}$

- electromagnetic calorimeter for $\gamma$ and $\pi^0$ measurement
  - hadronic calorimeter for isolation and jet measurement

baseline scenario:
at $z \approx 7\text{m}$ (outside magnet)
$3.3 < \eta < 5.3$

discussed for possible installation in LS3 ($\approx 2024$)
FoCal Upgrade – Direct $\gamma$ Performance in pp

after combined rejection:  
direct photon/all > 0.1  
for $p_T > 4$ GeV/c

20-40% uncertainty  
at $p_T = 4$ GeV/c  
decreases with increasing $p_T$
Thermal Photons
Direct Photons in Au-Au 200 GeV (PHENIX)

- advanced measurements from PHENIX combining:
  - calorimetry
  - low-mass virtual photons
  - photon conversions
- shape in pp and Au–Au at high pT very similar
  - unmodified pQCD
- excess at low pT beyond extrapolation of pp data
  - thermal photons
  - uncertainty of extrapolation?

\[
\frac{1}{2\pi p_T d^2 y} \frac{d^2 N}{d p_T^2} \left(\text{GeV/c}^{-2}\right)
\]

\[
\sqrt{s_{NN}} = 200\text{GeV}
\]

\[ p_T [\text{GeV/c}] \]

PRL 104, 132301 (2010)
PRL 109, 152302 (2012)
PRD 86, 072008 (2012)
PRL 98, 012002 (2010)

Direct Photons in Au–Au 200 GeV (PHENIX)

- direct photons in Au–Au for different centralities
- compared to scaled pp-fit
  - question to theory: how well understood is low-pT non-thermal production?
- scaling assumption can be used to extract direct photon excess: thermal photons
Inclusive Photon Flow at RHIC

- extraction of elliptic flow very challenging
- subtraction of two similar numbers
  - flow of inclusive and decay photons
    \[ v_2^{\text{dir} \gamma} = \frac{R_\gamma \cdot v_2^{\text{incl} \gamma} - v_2^{\text{dec} \gamma}}{R_\gamma - 1} \]
  - very sensitive to systematic errors for values of \( R_\gamma \approx 1 \)
Direct Photon Flow at RHIC

- new final results: significant elliptic flow $v_2$ for direct photons
  - also $v_3$ component
- difficult to describe theoretically
Thermal Photons – Models 1


“fireball” model

- pQCD, QGP, HG
- ideal hydrodynamics
- initial transverse acceleration
- initial temperature
  \( T_0 = 350 \text{ MeV} \)
- enhanced yields around \( T_c \)
Thermal Photons – Models 2


- Hydrodynamic model
  - pQCD, QGP, HG
  - different scenarios
    - ideal QGP
    - viscous QGP
    - ideal semi-QGP
- Initial energy density
  \[ \varepsilon_0 \approx 40 \text{ GeV/fm}^3 \]
Thermal Photons – Models 3


**microscopic transport model**
- pQCD, QGP, HG
- meson-meson and meson-baryon Bremsstrahlung

**Direct photon puzzle:**
yield and elliptic flow cannot be described simultaneously
- large yield favours early production
- large anisotropy favours late production
New Results from STAR

real photon measurement via zero-mass virtual photons (e⁺e⁻)

- one of the methods also used by PHENIX (in addition to conversion and calorimetry)
- advantage: no π⁰ decay background above m_π
- fit to well known functional shape (Kroll-Wada), extrapolate to m = 0
- fit to mass spectra in p_T-bins to obtain spectrum
New Results from STAR

s spectra for different centralities
• limited significance for central 0-10%
reasonable description by theoretical models
• Rapp et al. (model 1)
• Paquet et al. (model 2)
Comparison STAR–PHENIX

one-to-one comparison difficult
- different binning in $p_T$ and centrality
- indication of significant difference
- supported by direct model comparison

no flow results from STAR (yet?)

new light on the direct photon puzzle?
Direct Photons at LHC

- direct photons in Pb–Pb at 2.76 TeV in ALICE
  - significance judged via
    \[ R_\gamma = \frac{N^{inc}_\gamma}{N^{dec}_\gamma} = 1 + \frac{N^{dir}_\gamma}{N^{dec}_\gamma} \]
  - measurement via photon conversion and calorimetry
  - consistent results
  - good description with pQCD at high \( p_T \)
  - excess beyond pQCD at low \( p_T \) in central and semi-central collisions

\[ R_\gamma \]
Thermal Photons at LHC

• final spectra of direct photons in Pb–Pb at 2.76 TeV

• good description with pQCD at high $p_T$

• can use extrapolation of pQCD towards low $p_T$ to obtain thermal photon spectra
Thermal Photons at LHC

- here: compare to models including thermal and prompt sources
- similar theories as above
  - enhanced yields from e.g. pseudo critical enhancement or hadronic Bremsstrahlung
- photon spectra not fully described
  - smaller (?) discrepancy as compared to PHENIX

\[ \frac{d^2N}{dy dp_T^2} (\text{GeV}^2c^2) = A \exp(-p_T/T_{\text{eff}}) \]

- \( \text{Pb-Pb } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)
- 0-20% ALICE
- 20-40% ALICE
- 40-80% ALICE

- Paquet et al. arXiv:1509.06738
- Linnyk et al. arXiv:1504.05699
- Chatterjee et al. PRC 85(2012) 064910
- v. Hees et al. NPA 933(2015) 256
- + JHEP 1305(2013) 030
Thermal Photons – RHIC vs LHC

central collisions:
• higher yield and
• larger effective slope of photon spectra in ALICE vs PHENIX

less clear picture in semi-central collisions
Direct Photon Flow at LHC: Status

- preliminary results for central collisions (0-40%)
  - measured by conversions only
  - different centrality bins than final yields
- comparison of inclusive photon flow and decay photon flow

Graph showing $v_2^\gamma$ vs $p_T$ for ALICE preliminary data with $\sqrt{s_{NN}} = 2.76$ TeV in 0-40% Pb-Pb collisions. The graph includes data points for $v_2^\gamma,\text{incl}$ and $v_2^\gamma,\text{dec}$, with fits from different models:
- $\text{decay + NLO}$
- $\text{decay + NLO + thermal (Shen et al.)}$
- $\text{decay + NLO + thermal (Holopainen et al.)}$

References:
- arXiv:1308.2111
- Phys.Rev. C84 (2011) 064903
Direct Photon Flow at LHC: Status

- preliminary results for central collisions (0-40%)
  - use preliminary extracted photon yields to extract direct photon flow
- comparison of direct photon flow to theoretical models
  - large uncertainties
  - under-prediction by models

- final results in preparation
  - using final direct photon yields
  - revisit error estimates
Outlook: Zero-Mass Virtual Photons

A. Caliva (ALICE), talk at SQM 2016

- extract real photons from low-mass dielectron mass spectrum
- measurement statistics limited from LHC Run 1
- so far only upper limit for photon yield: looking forward to Run 2!
Low-Mass Dileptons
Low-Mass Dileptons – Status pre-QM2015

PHENIX, PRC 81 (2010) 034911

STAR, PRC 92 (2015) 024912

• significant difference of enhancement in low-mass region
Low-Mass Dileptons

PHENIX, PRC 93 (2016) 014904

STAR, PRC 92 (2015) 024912

- new analysis of PHENIX data:
- good agreement with STAR, similar LM excess
Low-Mass Dileptons at RHIC

- good description of dileptons in LMR by theory
- main contribution to excess beyond known decays:
  - thermal radiation of hadronic origin with broadened $\rho$ meson spectral function
LMR Dileptons at LHC: ALICE Upgrades

- uncertainties with current ITS
  - limited by background subtraction and statistics
- high rate measurement with new ITS ($B = 0.2T$ instead of $0.5T$)
  - more efficient cuts to reduce background, high statistics:
    allows for detailed measurement of low-mass dielectrons

**Present**

**Upgrade**

![Graph of present measurements](image1)

![Graph of upgrade measurements](image2)
Conclusions

• **High $p_T$ prompt photons well described by pQCD**
  - test initial state modifications: non observed
  - proposed forward measurement: promising signal for CGC

• **Thermal photons observed at RHIC and LHC**
  - very prominent at RHIC with high yield and strong $v_2$.
    - challenge for theory
    - new STAR results: what do they tell us?
  - also high yield at LHC, possibly less tension with theory
    - coming: final $v_n$ results, future: higher statistics from Run 2

• **Consistent picture for low-mass dileptons at RHIC**
  - agreement between experiments and good description by theory
Backup
Direct Photons in Au-Au 200 GeV (PHENIX)

- for thermal photons:
  - lower $p_T$
- more difficult:
  - smaller S/B expected
  \[ R_\gamma = \frac{N_{\text{inc}}^{\gamma}}{N_{\text{dec}}^{\gamma}} = 1 + \frac{N_{\text{dir}}^{\gamma}}{N_{\text{dec}}^{\gamma}} \]
  - S/B improves for central Au–Au
  - main contribution to decay photons (neutral mesons) suppressed in Au–Au

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**Graphical Representation**


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**Legend**

- **(a)**
  - 0-20%
  - 20-40%
  - 40-60%
  - 60-92%
- **(b)**
  - PRL 104, 132301 (2010)
  - Present data
- **(c)**
  - Au+Au
  - $\sqrt{s_{\text{NN}}}$ = 200 GeV
- **(d)**
  - 60-92%

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**Equation**

\[ R_\gamma = \frac{N_{\text{inc}}^{\gamma}}{N_{\text{dec}}^{\gamma}} = 1 + \frac{N_{\text{dir}}^{\gamma}}{N_{\text{dec}}^{\gamma}} \]
Thermal Photons in Au-Au 200 GeV (PHENIX)

- centrality dependence of photon excess
  - increases more strongly than number of participants
- fit with exponential yield similar slope parameter for all with $T \approx 240$ MeV
  - expectation from theory?

\[ \frac{1}{\Delta p_T \Delta y} \frac{d^2N}{dp_T dy} \propto e^{-p_T/T} \]

- $T_{\text{eff}} = (239 \pm 25 \pm 7)$ MeV/c
- $T_{\text{eff}} = (260 \pm 33 \pm 8)$ MeV/c
- $T_{\text{eff}} = (225 \pm 28 \pm 6)$ MeV/c
- $T_{\text{eff}} = (238 \pm 50 \pm 6)$ MeV/c

\[ \sqrt{s_{\text{NN}}} = 200 \text{GeV} \]
Thermal Photon Puzzle?

R. Rapp, H. van Hees, M. He, arXiv 1408.0612

- theoretical challenges:
  - high photon rates with relatively small (constant?) slope

- large anisotropy
  - favours late photon emission

- proposed:
  - “pseudocritical enhancement”?
    - maximum photon emission near transition
  - enhanced hadronic rates
    - baryonic contribution
Prompt Photons Overview

Direct photon ($y\sim0$)

$n=4.5 \{\exp (\sqrt{s})\}$
FoCal Strawman Design

• main challenge: separate $\gamma/\pi^0$ at high energy
• need small Molière radius, high-granularity read-out
  • Si-W calorimeter, granularity $\approx 1\text{mm}^2$

studied in performance simulations:

24 layers:
$W$ (3.5mm $\approx 1\text{ X}_0$) + Si-sensors (2 types)
• low granularity ($\approx 1\text{ cm}^2$), Si-pads
• high granularity ($\approx 1\text{ mm}^2$), obtained with pixels (e.g. CMOS-MAPS)
Low Granularity Measurement

- low granularity (1cm$^2$) does not allow efficient decay rejection
- direct photon/all $\approx 0.1$ for all $p_T$

NB: conditions similar to LHCb