Electromagnetic probes of heavy-ion collisions

Yuri Kharlov

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Introduction 1

- Electromagnetic probes were considered as one of the most sensitive observable for studying the properties of quark-gluon medium.
- Under “electromagnetic probes” (**EMP**) one understands production of real of virtual photons, the latter being reconstructed via lepton pairs.
- EMP are convenient for theoretical calculations since at least one coupling constant in perturbative expansion of photon production is a fine coupling $\alpha_{e.m.}$, i.e. calculations may be precise enough in LO or NLO.
- Photon (real or virtual), being produced in initial or final stage of collision, traverses the quark-gluon medium freely, without interaction. Such photon, when detected, carries primordial kinematics acquired at the instance of production.
- Unlike photons, hadrons are subject for interaction with medium: lose energy, dissociate, recreate. Thus, hadronic observables are deteriorated.

Introduction 2

- Small $\alpha_{e.m.}$ is disadvantage for measurement:
  - production cross section is small compared with hadronic processes.
  - Decay photons and dilepton pairs are abundant and obscure direct photons.
  - Direct photons (real or virtual) are produced from different sources, not all of them characterize QCD medium.
- All these challenges results in non-negligible systematic uncertainties of direct photon measurements.

Photon production in HIC

- There are many sources that produce photons in relativistic nuclear collisions, and they can be classified in two categories:

  - on whether or not they depend on the temperature of the medium.

C. Gale. arXiv:0904.2184v1 [hep-ph]

Photon sources at T=0

- **Prompt photons** are emitted during the very first instants of a nuclear collision
- Prompt photons are decomposed in two distinct sources: **direct** and **fragmentation** photons
- **direct photons** are produced from the early hard collisions between partons in the nucleons of the projectile and target nuclei.
- **fragmentation photons**: fragmenting hard QCD jets also contribute to real photon.
  - Can be produced in pp collisions
  - In nucleus-nucleus collisions the jet can propagate through the quark-gluon medium, interact, and thus lose energy prior to its fragmentation. This introduces a non-trivial path and angle-dependence into the process of calculating the yield of photons produced through jet fragmentation

Sources at T ≠ 0

- Photon production through the interaction of thermal components either from the quark-gluon plasma side of the QCD phase diagram, or from the hadrons in the confined sector
- Another thermal component is that of jet-medium photons. Jet propagating in the hot and dense medium will produce electromagnetic radiation through bremsstrahlung.
- jet fragmentation photons acquire a temperature dependence, through the energy loss mechanism and the coupling to the thermal medium
- all of the sources exist for dileptons

Photon radiation from thermal hadrons

- In a heavy ion collision at relativistic energies, a plethora of mesons are produced, from the light to the intermediate mass scale [1]
- To model their interaction, a Massive Yang-Mills approach can be used [2]
- Generic reactions are $X+Y \rightarrow Z+\gamma$, $\rho \rightarrow Y+Z+\gamma$, $K^* \rightarrow Y+Z+\gamma$
  - {X,Y, Z} represent all combinations of π, ρ, K, K* mesons which respect conservation of charge, isospin, strangeness, and G parity
- connection between the electromagnetic signal and the in-medium spectral density is made explicit through the Vector Dominance Model (VDM)

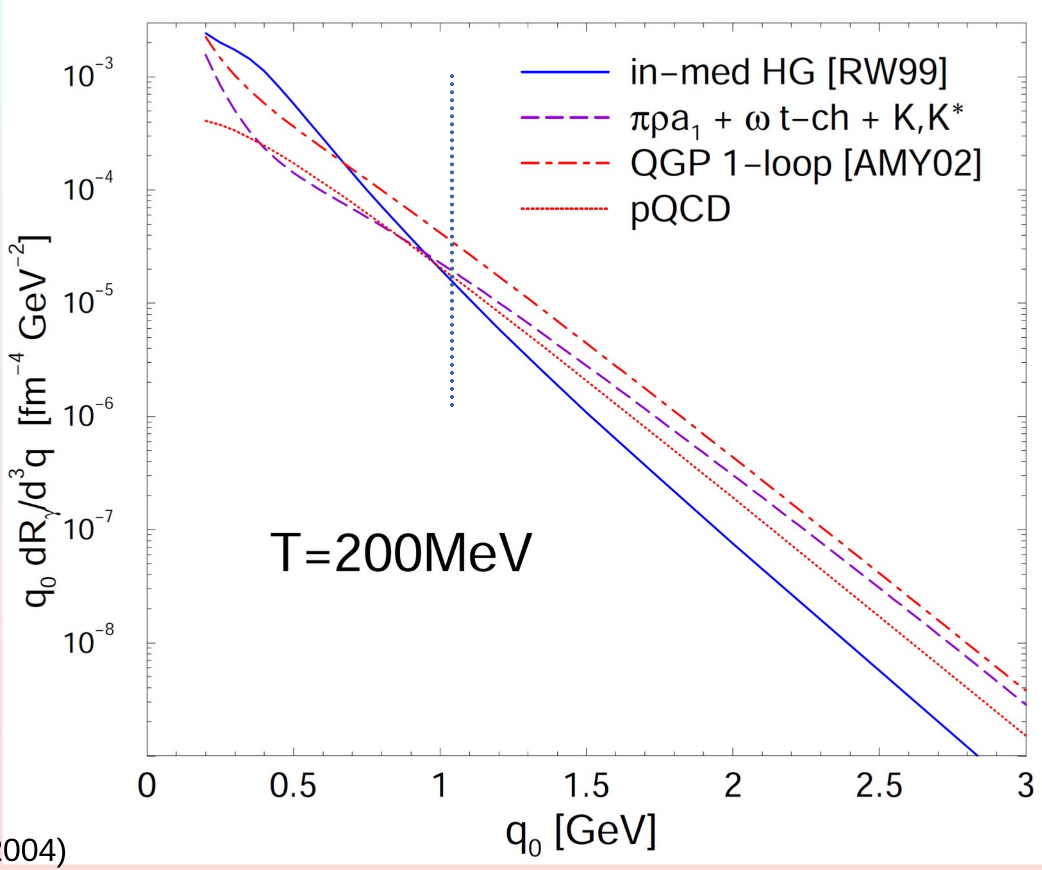
[1] P. Braun-Munzinger, K. Redlich and J. Stachel, arXiv:nucl-th/0304013
[2] H. Gomm, O. Kaymakcalan, and J. Schechter, Phys. Rev. D 30, 2345 (1984)

Thermal radiation from different sources

Photon emission rates from different phases of the QCD phase diagram:

- hadronic many-body approach
- mesonic contributions
- thermal parton contribution
- pQCD

- At low p_T photon spectrum is dominated by radiation from interacting hadrons
- At p_T >1 GeV the photons from thermal QCD shine on more brightly that those from competing sources



[1] S. Turbide, R. Rapp, and C. Gale, Phys. Rev. C 69, 014903 (2004)
[2] C. Gale, arXiv:0904.2184v1 [hep-ph]

Photons in nuclear collisions at CERN SPS

WA98 Collaboration: photon spectrum in Pb-Pb collisions at $\sqrt{s}$=17.3 AGeV

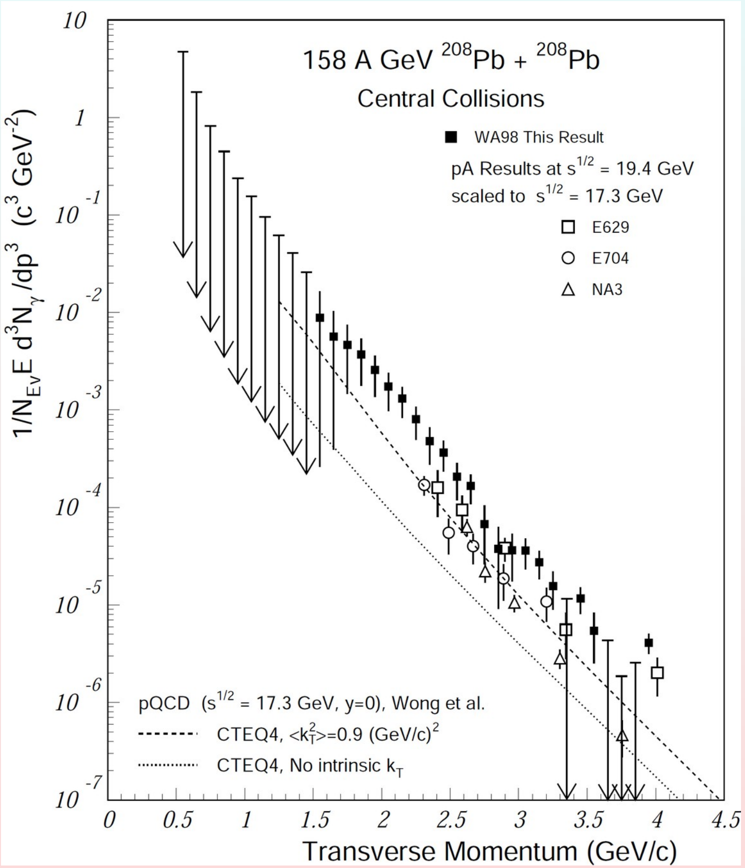
[1] M. M. Aggarwal et al. [WA98 Collaboration], Phys. Rev. Lett. 85, 3595 (2000).

At $p_T \geq 1.5$ GeV/c, this data shows a clear excess beyond what is expected from pA collisions.

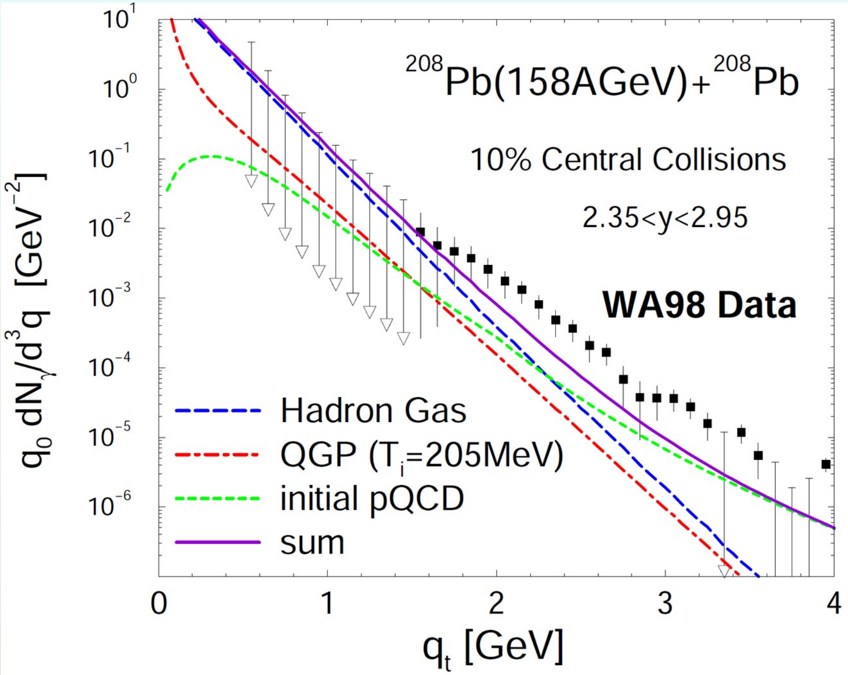
However, WA98 results are still subject to ambiguities:

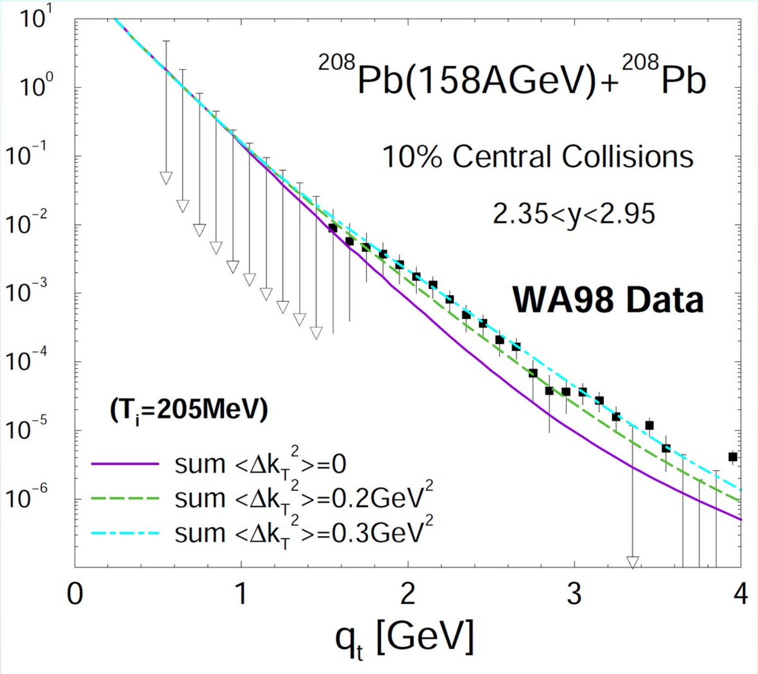
- question of whether the partons colliding at these energies have some amount of intrinsic traverse momentum has remained open

  [2] P. Aurenche et al., Eur. Phys. J. C 9, 107 (1999)



WA98 results vs. theory calculations





Direct photons from WA98 at SPS with theory calculations:

- Hadron gas
- QGP
- Initial-state pQCD

Direct photons from WA98 at SPS with theory calculations assuming momentum broadening parameter $\langle \Delta k_T^2 \rangle$

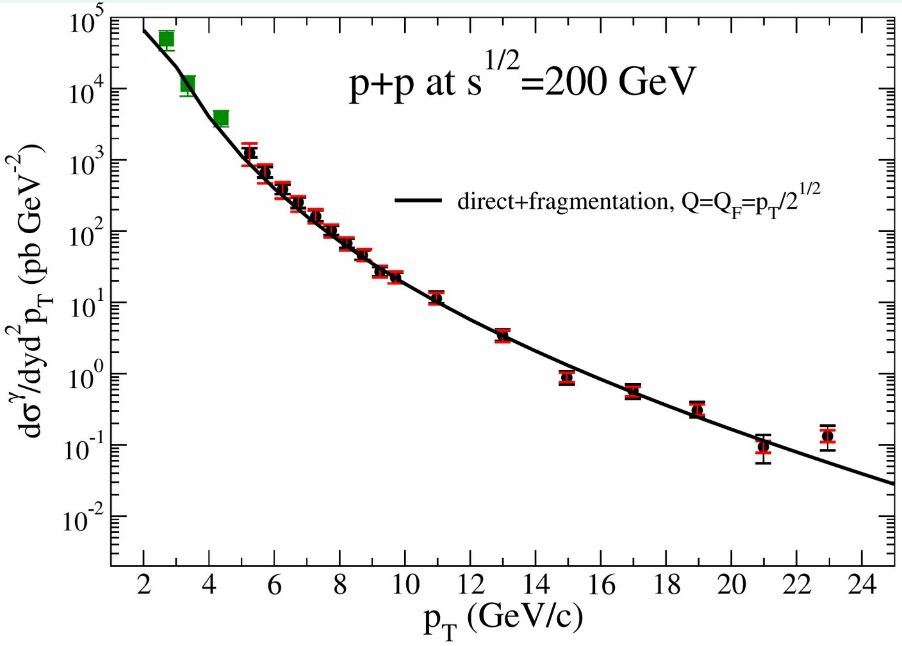
$$f(k_T) = \frac{1}{\pi \langle \Delta k_T^2 \rangle} e^{-k_T^2 / \langle \Delta k_T^2 \rangle}$$

S. Turbide, R. Rapp, and C. Gale, Phys. Rev. C 69, 014903 (2004)

Photons in nuclear collisions at RHIC: non-thermal sources

A source of photons with no thermal component is that of "prompt photons":

- Radiation associated with primary nucleon-nucleon interactions.
- In a HIC, contribute in the very first instants of the scattering process,
- They constitute an irreducible background to the photons associated with the thermal processes
- Prompt photons in pp collisions is an important reference and a baseline requirement for theory.



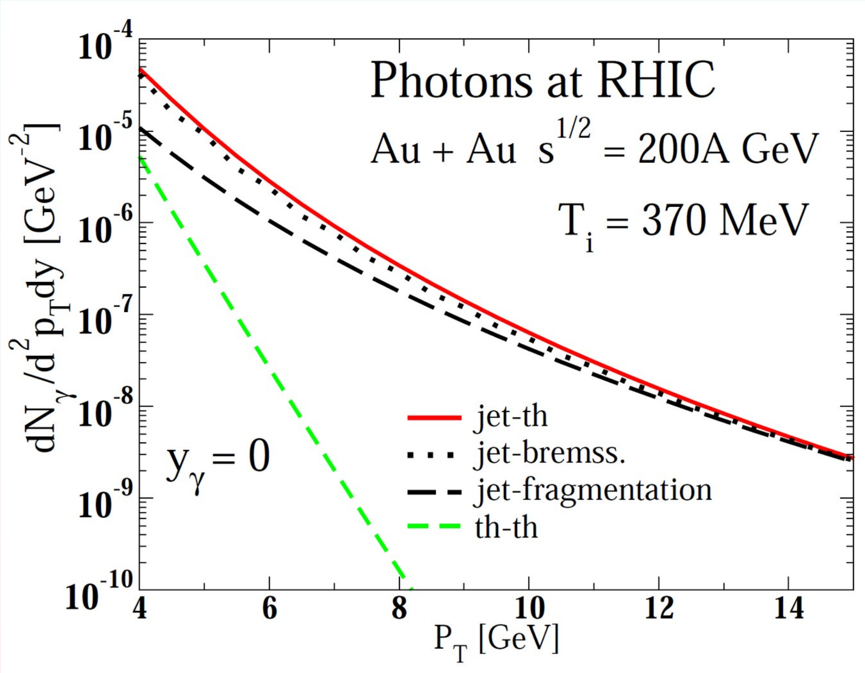
[1] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 104, 132301 (2010)
[2] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 98, 012002 (2007).

Thermal sources of photons at RHIC

Different photon sources are calculated using a simple time-evolution model
of the nuclear collision.

- 1D Bjorken expansion is considered [1]
- Initial temperature is assumed to scale with the local density

- photons from a purely thermal source (th-th),
- photons from a jet interacting with the thermal QGP (jet-th),
- bremsstrahlung photons (jet-bremss),
- photons from a fragmenting jet that has exited the thermal environment.



[1] J. D. Bjorken, Phys. Rev. D 27, 140 (1983)

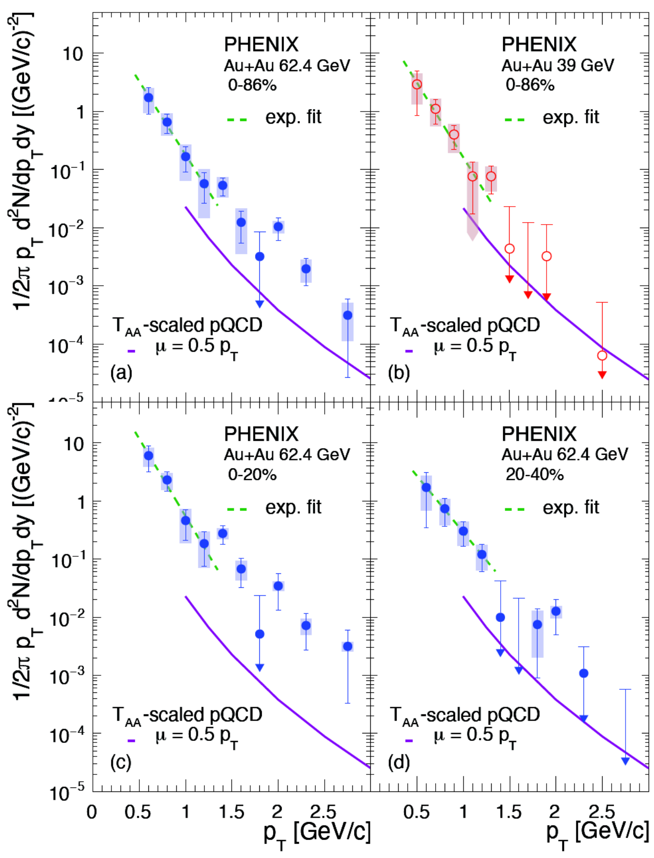
Thermal photon yield at RHIC: PHENIX

PHENIX

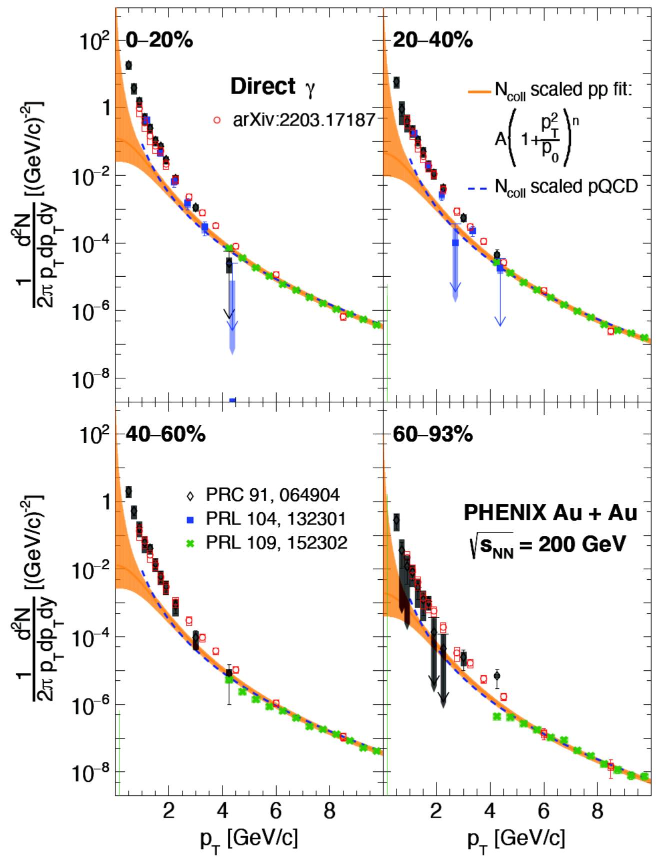
Precise measurement of photons performed via reconstruction of off-vertex photon conversion in the detector medium.

The first analysis where prompt photons were subtracted from direct photon spectra.

Prompt photons measured in pp collisions and N_{coll}-scaled.



PHENIX, Phys. Rev. Lett. 123, 022301 (2019)



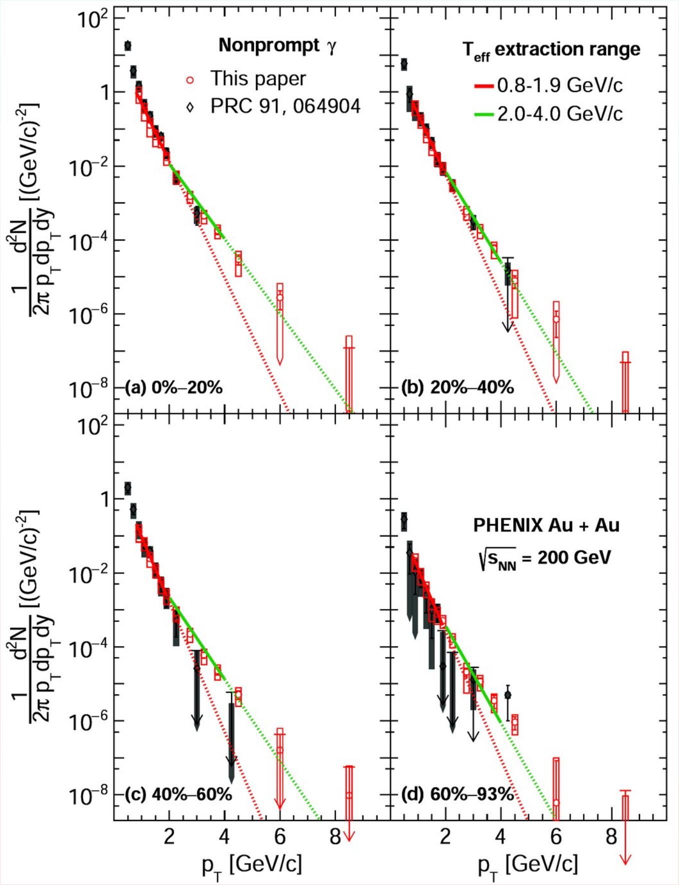
PHENIX, Phys. Rev. C 109, 044912 (2024)

Nonprompt direct-photon excess at RHIC

Direct-photon excess above the prompt-photon contribution is thought to be mostly the radiation emitted during the collision from the hot-expanding fireball, and will be referred to here as nonprompt direct-photon spectra.

Invariant yields are fitted by exponential with inverse slope attributed to T_{eff}.

- T_{eff} = 260 MeV at $0.8<p_T<1.9$ GeV/c
- T_{eff} = 376 MeV at $2<p_T<4$ GeV/c

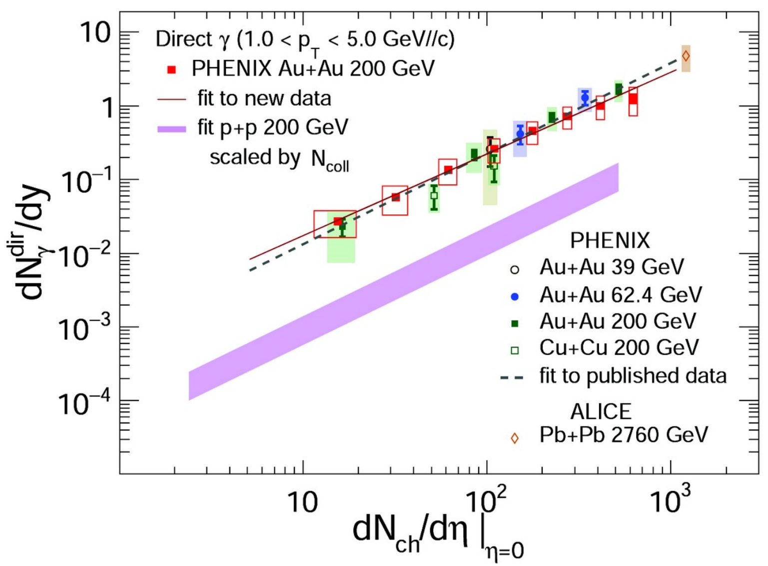


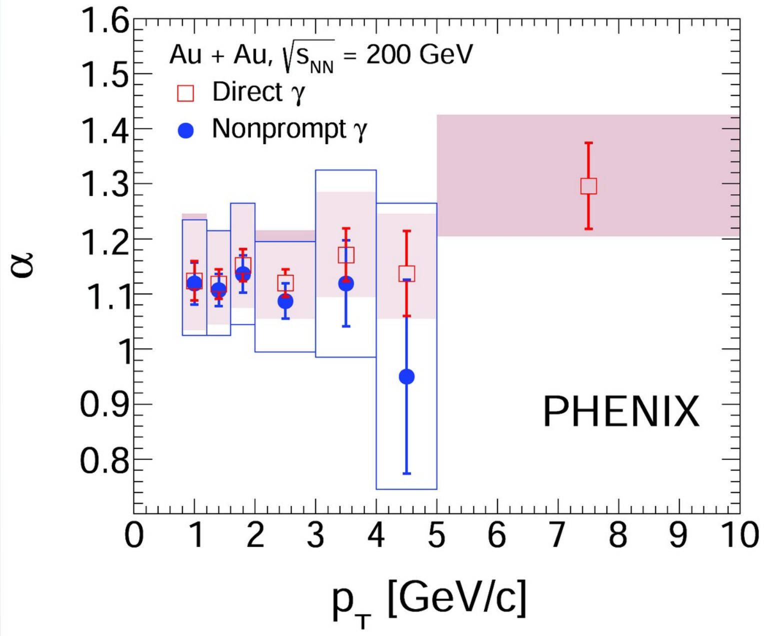
PHENIX, Phys. Rev. C 109, 044912 (2024)

Evolution of thermal photon yield with density

$$\frac{dN_\gamma}{dy} = \int_{p_{T,\min}}^{p_{T,\max}} \frac{dN_\gamma^{\rm dir}}{dp_T dy} dp_T = A \times \left(\frac{dN_{\rm ch}}{d\eta}\right)^\alpha$$

$$\alpha \ = \ 1.11 \pm 0.02({\rm stat}) \ {}^{+0.09}_{-0.08}({\rm sys})$$

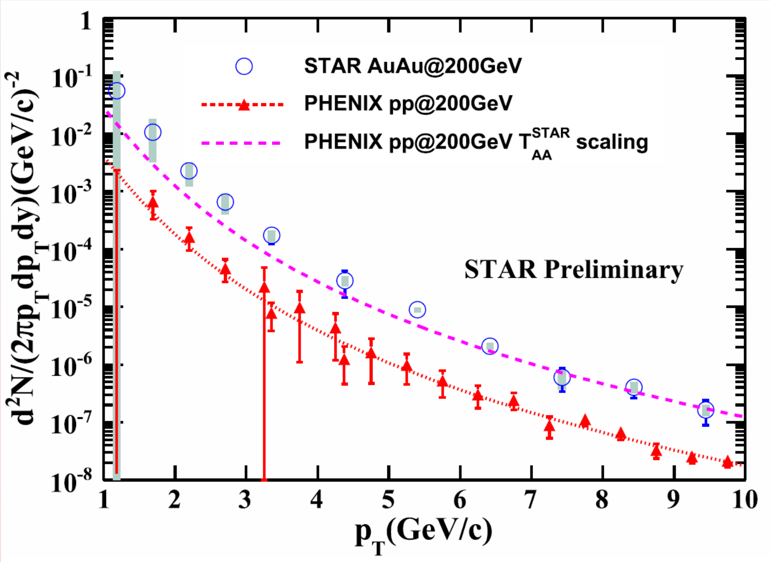


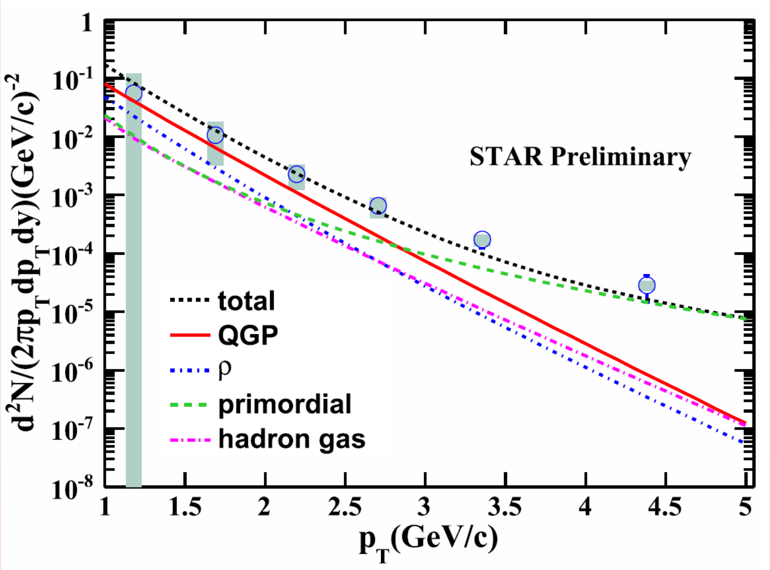


The values of α for the nonprompt component are remarkably constant with no evident p_T dependence.

Thermal photon yield at RHIC: STAR

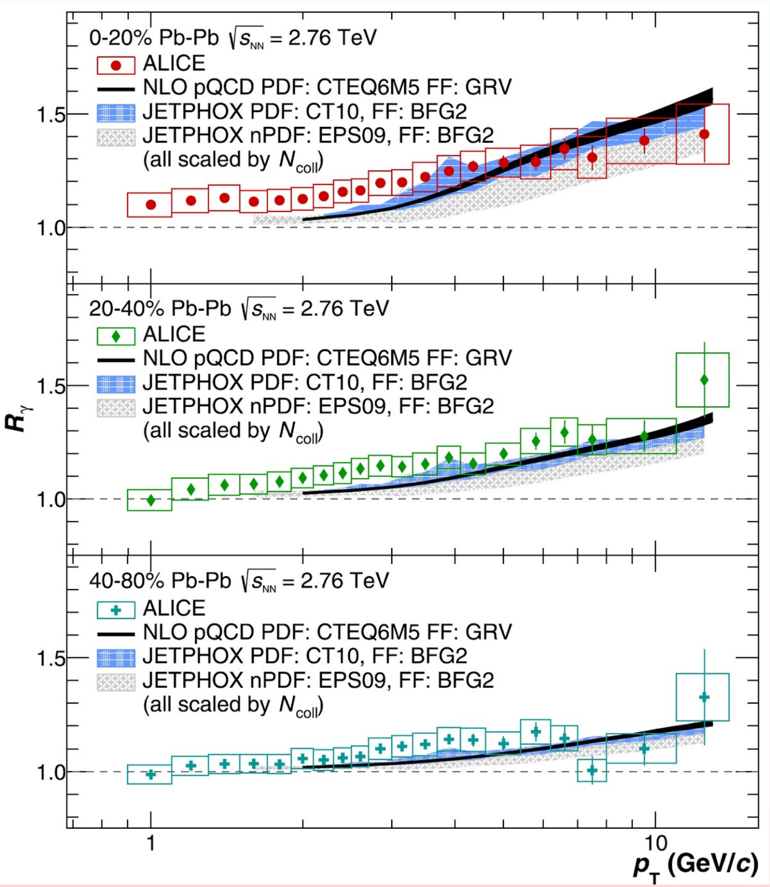
In STAR, direct photon yields are extracted by fitting the dielectron invariant mass spectra in the low mass region with two components.

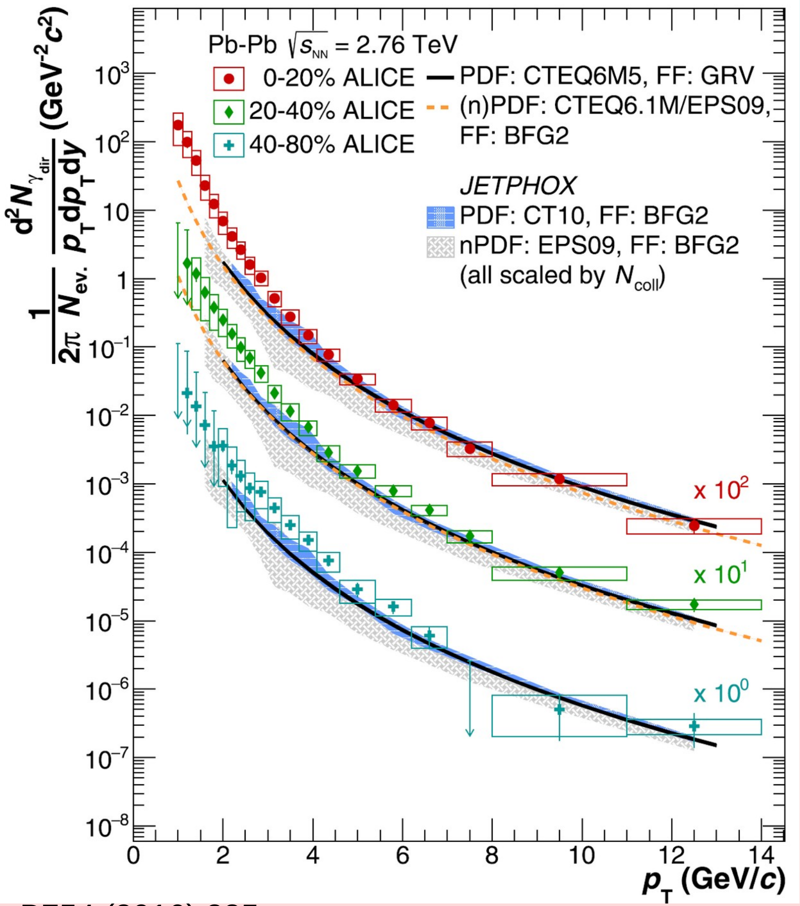




STAR, C. Yang / Nuclear Physics A 931 (2014) 691

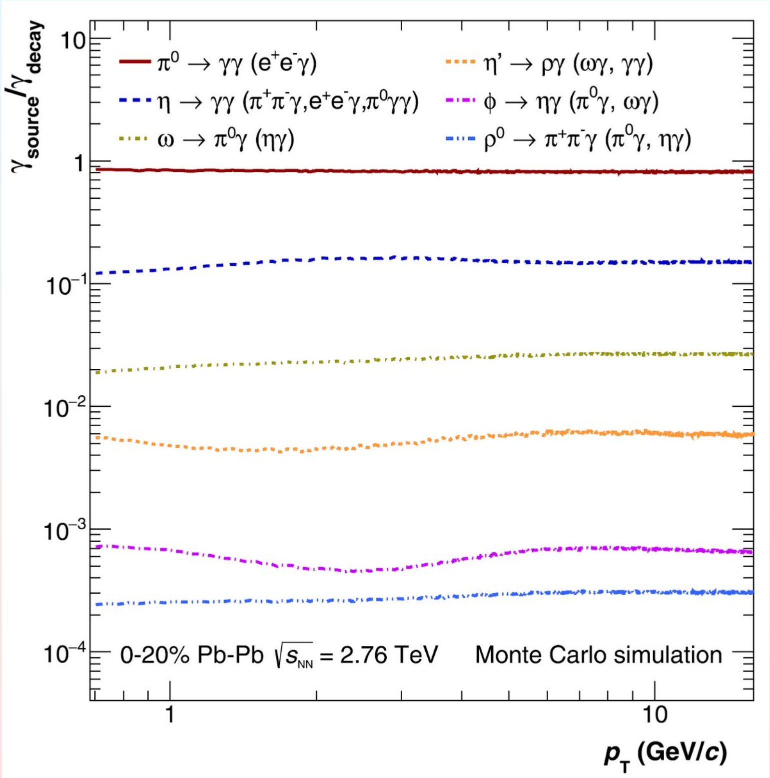
Direct photon yield at LHC ALICE (2.76 TeV)





ALICE, Physics Letters B754 (2016) 235

Background for direct photons



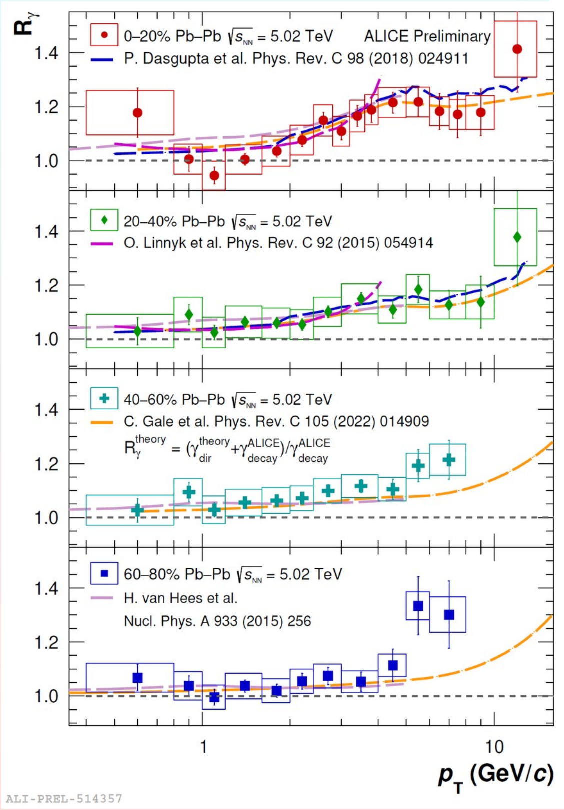
Background for direct photons consists of photon decays from all known hadrons.

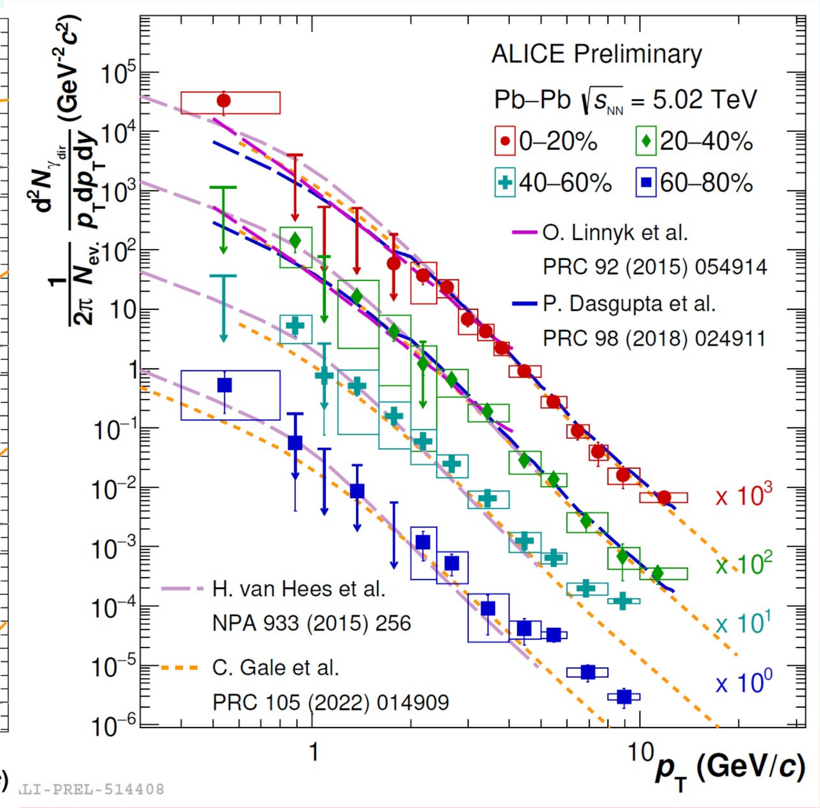
Therefore, accuracy of the measurement rely on precise knowledge of neutral meson spectra, where possible.

For those mesons which could not be measured in the same experiment, one has to adapt assumption on phenomenological observation: m_T-scaling

ALICE measured inclusive production of π^0, η, ω

Direct photon yield at LHC ALICE (5.02 TeV)





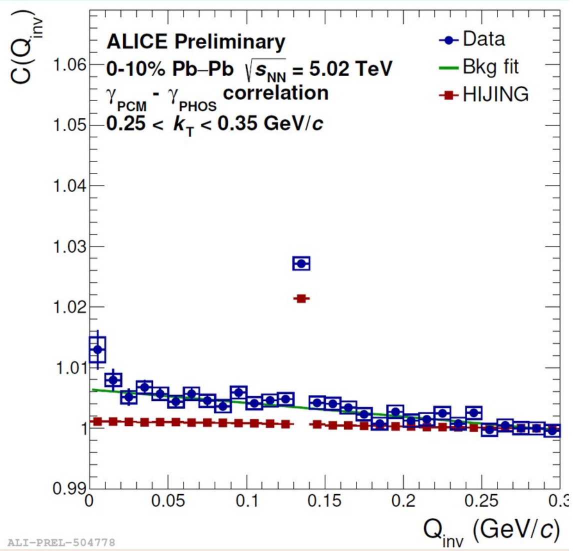
- Direct photon excess ratio R_γ at $0.4<p_T<14$ GeV/c for four classes of collision centrality was reported.
- The direct photon signal ($R_\gamma>1$) for $p_T>3$ GeV/c can be attributed to prompt photons from hard scatterings.
- At lower p_T, where the medium radiation should dominate, no significant direct photon signal is observed.
- This is in agreement with theoretical predictions.

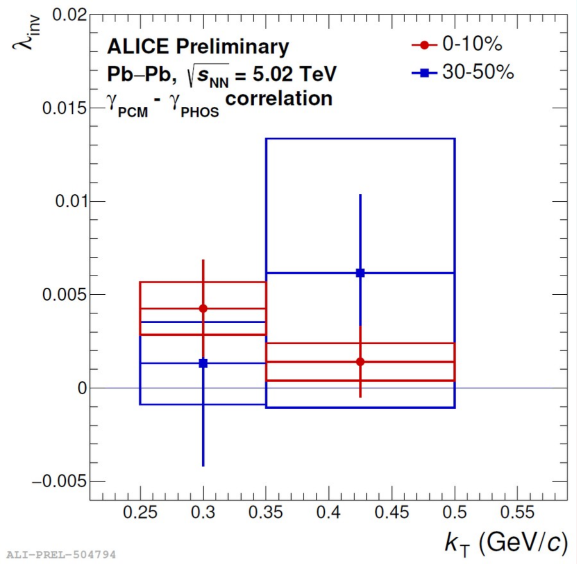
Acta Phys. Pol. B Proc. Supp. 16, 1-A122 (2023)

Bose–Einstein photon–photon correlations in Pb–Pb collisions at LHC

- Using a HBT (Hanbury-Brown, Twiss) correlations, one measures the the space-time extent of the emitting source at earlier times [1]
- Correlation strength is sensitive to the direct photon fraction [2]

- ALICE measured preliminarily photon HBT from data of Pb-Pb at 5.02 TeV using one photon measured via photon conversion and the other one measured in calorimeter PHOS [3].





[1] S. Pratt, Phys. Rev. Lett. 53, 1219 (1984)
[2] WA98 Collaboration, Phys. Rev. Lett. 93, 022301 (2004).
[3] Acta Phys. Pol. B Proc. Supp. 16, 1-A122 (2023)

Azimuthal anisotropy of photons

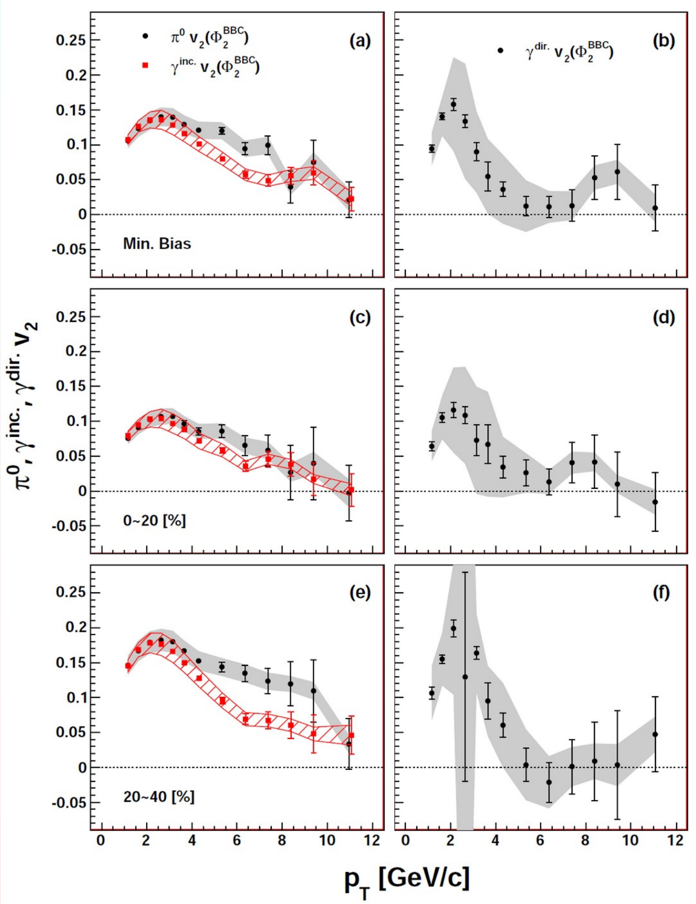
sizeable azimuthal asymmetry characterized by a coefficient v_2 can be expected for intermediate to large p_T photons produced in non-central high energy nuclear collisions.

$$\frac{dN}{p_T\, dp_T\, d\phi} = \frac{dN}{2\pi\, p_T\, dp_T}\left[1 + \sum_n 2 v_n(p_T)\cos(n\phi)\right]$$

Photon flow at RHIC

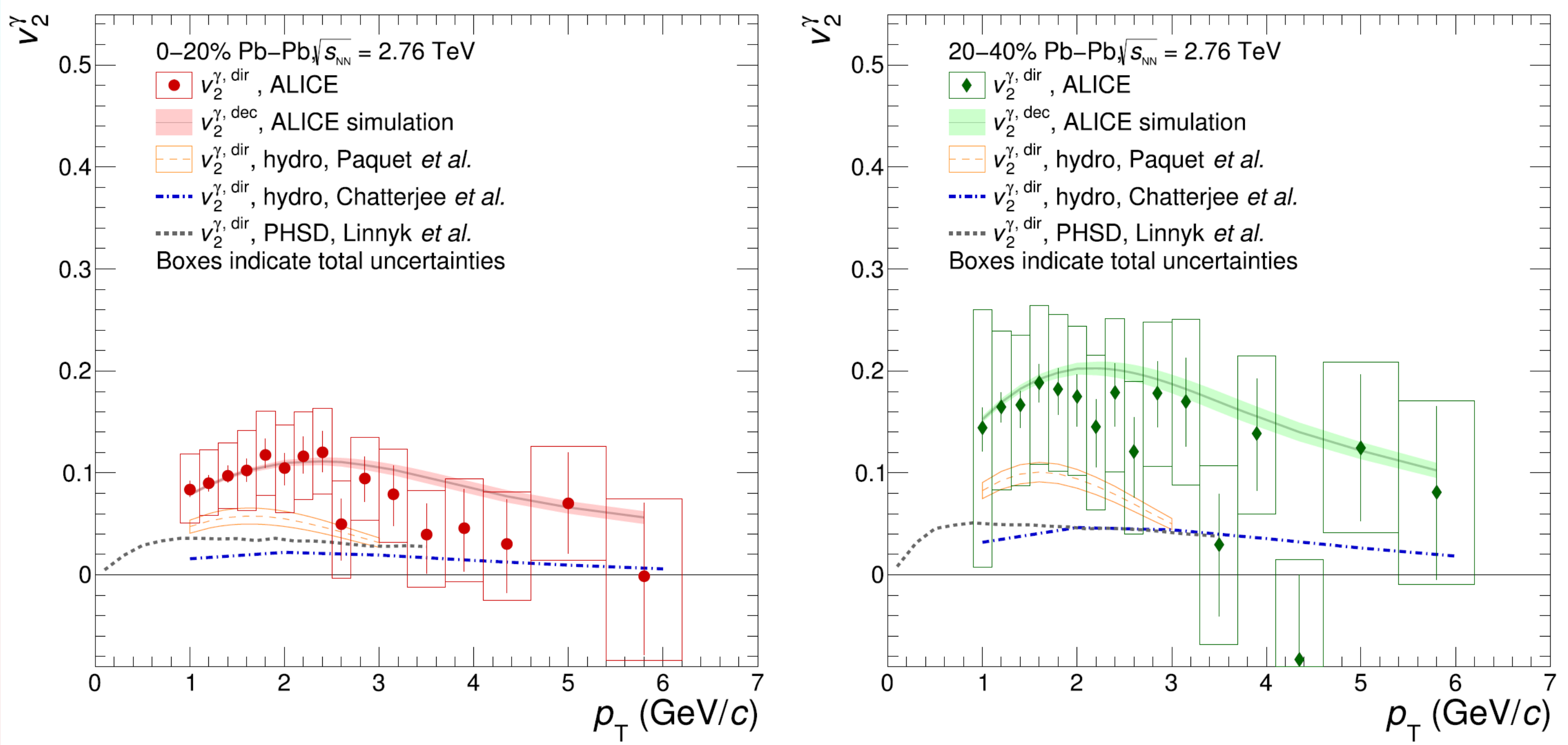
- At higher p_T (> 6 GeV/c) the direct photon v_2 is consistent with zero at all centralities, as expected if the dominant source of photon production is initial hard scattering

- In the thermal region (p_T < 4 GeV/c), a positive direct photon v_2 is observed which is comparable in magnitude to the π^0 v_2 and consistent with early thermalization times and low viscosity, but its magnitude is much larger than current theories predict.



PHENIX, Phys.Rev.Lett. 109 (2012) 122302

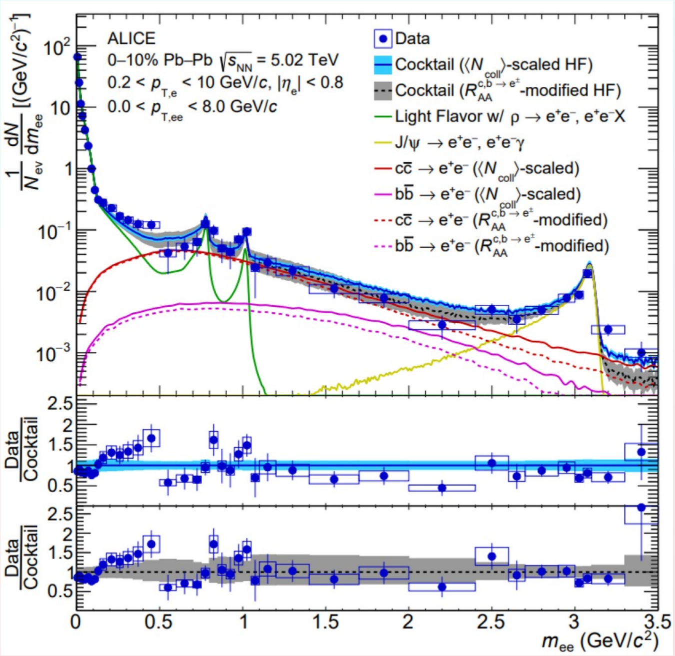
Photon flow at LHC

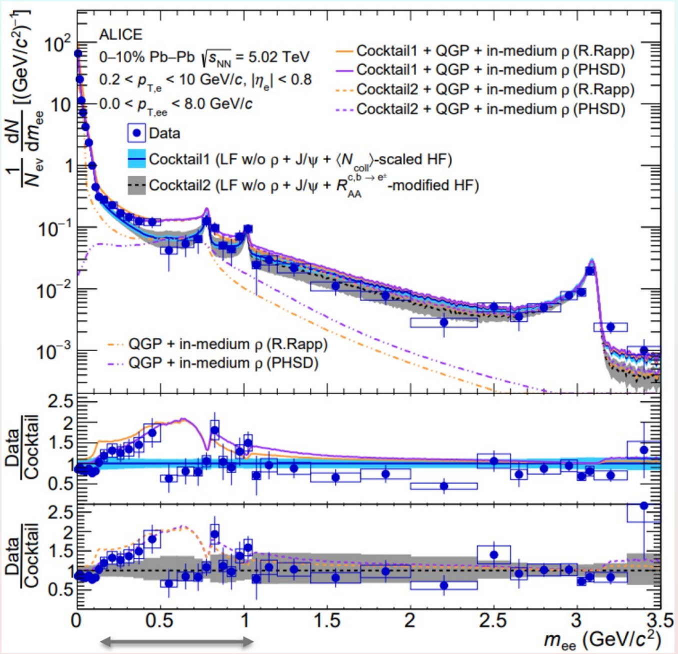


Significance of deviation from hypothesis $v_2(\gamma_{dir})=0$ is less than 1σ for both centrality classes

ALICE, Physics Letters B789 (2019) 308

Direct photons from dielectrons at LHC





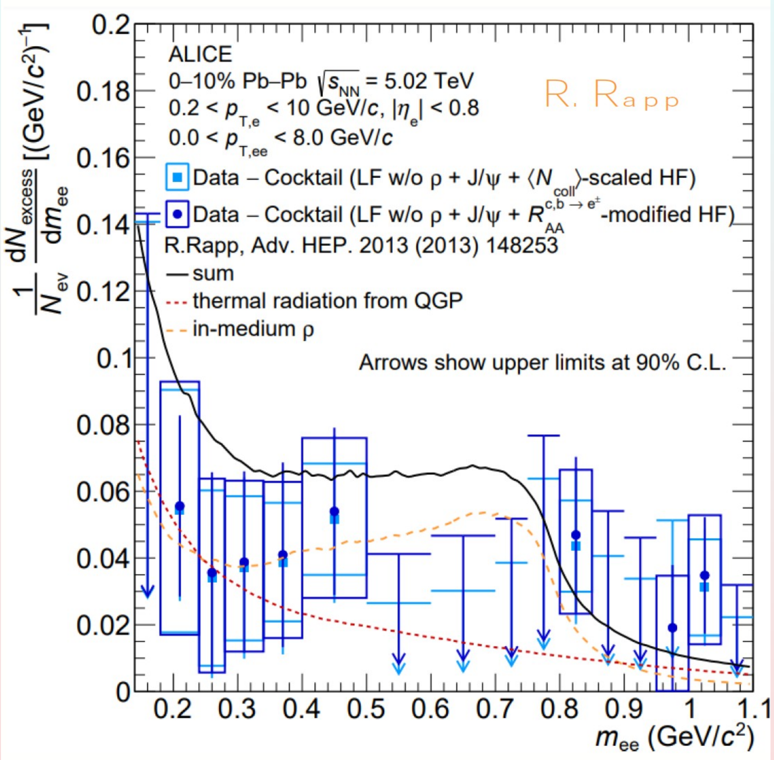
ALICE measured e^+e^- production in Pb-Pb collisions at 5.02 TeV

Comparison to hadronic cocktail, including:

- N_{coll} - scaled HF measured in pp at $\sqrt{s}$ = 5.02 TeV
  - Vacuum baseline
- Include measured RAA of $c/b \rightarrow e\pm$
  - Modified-HF cocktail
- Subtraction of known hadronic sources without ρ

[ALICE Collaboration] arXiv:2308.16704v1 [nucl-ex]

Direct dielectron excess



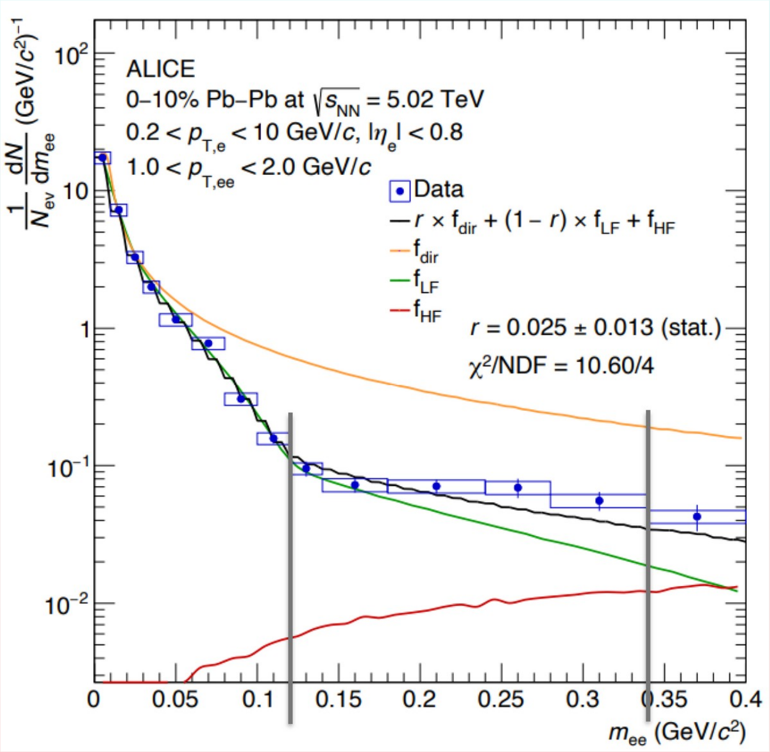
Subtraction of known hadronic sources without ρ
R. Rapp
Compared with sum of 2 contributions:

- in-medium ρ produced thermally in hot hadronic matter
- Thermal radiation from **QGP**

Implemented in 2 different ways:

- R. Rapp’s expanding fireball model hadronic many-body theory with in-medium modified ρ
- Parton-Hadron-String Dynamics (PHSD) transport model with in-medium modified spectral fct., off-shell production from dynamical quasiparticle model

Extracting direct-photon signal



Direct photons: Not originating from hadronic decays

Template fit with 3 components:

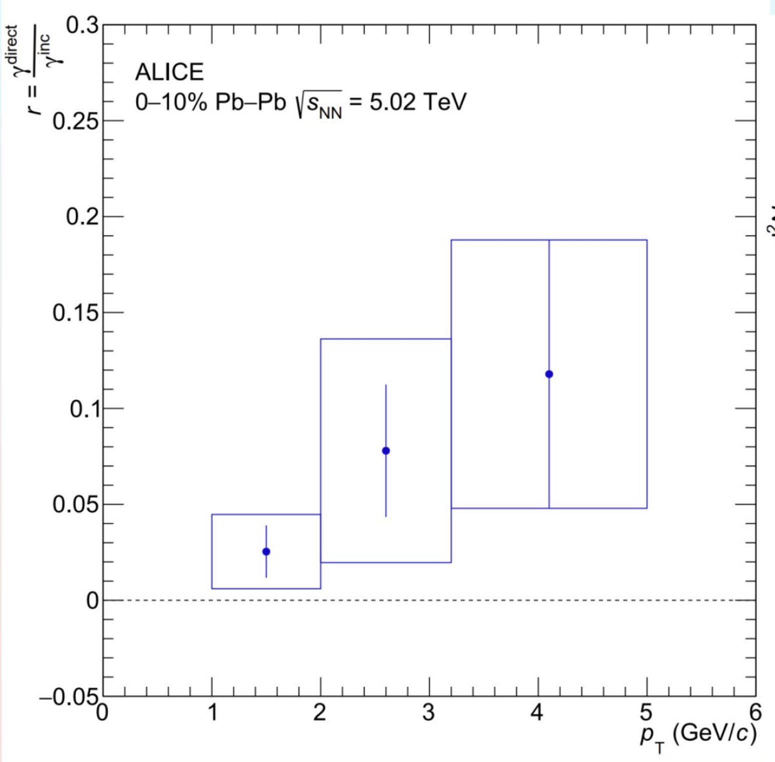
- Light flavor (**LF**): without ϱ meson
- Heavy flavor (**HF**): fixed from hadr. cocktail
- Virtual direct photons (**dir**): Kroll-Wada shape

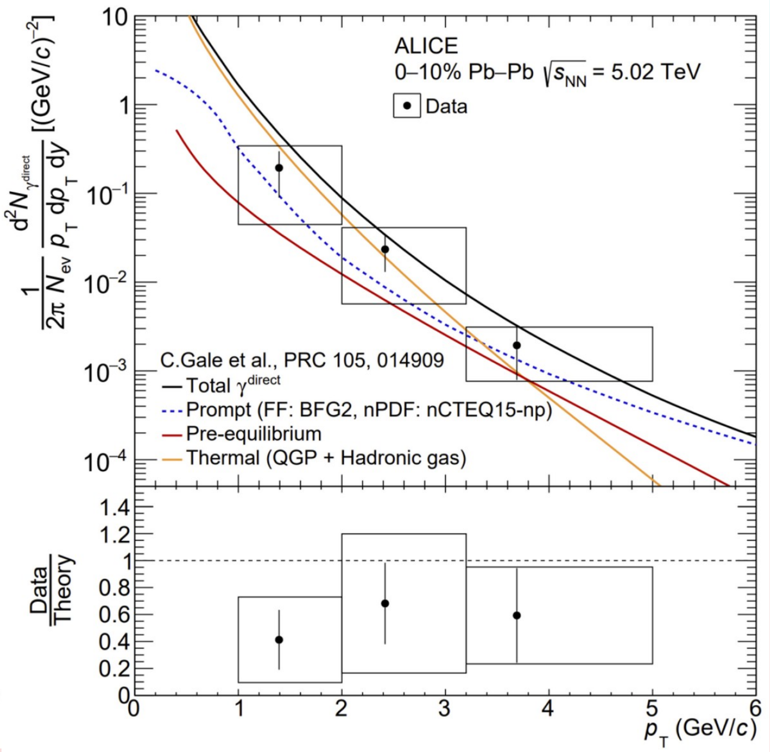
$$f_{\mathrm{fit}} = r \cdot f_{\mathrm{dir}} + (1 - r) \cdot f_{\mathrm{LF}} + f_{\mathrm{HF}}$$

$$r = \left(\frac{\gamma^*_{\mathrm{dir}}}{\gamma^*_{\mathrm{incl}}}\right) = \left(\frac{\gamma_{\mathrm{dir}}}{\gamma_{\mathrm{incl}}}\right) \text{ for } p^2_{\mathrm{T,ee}} \gg m^2_{,\mathrm{ee}}$$

fit range: $0.12 < m_{ee} < 0.34$ GeV/c^2 to bypass pion-mass region in the fit
→ Main background in real-photon measurement (85% of all decay photons)

Direct photon yield in Pb-Pb at 5.02 TeV





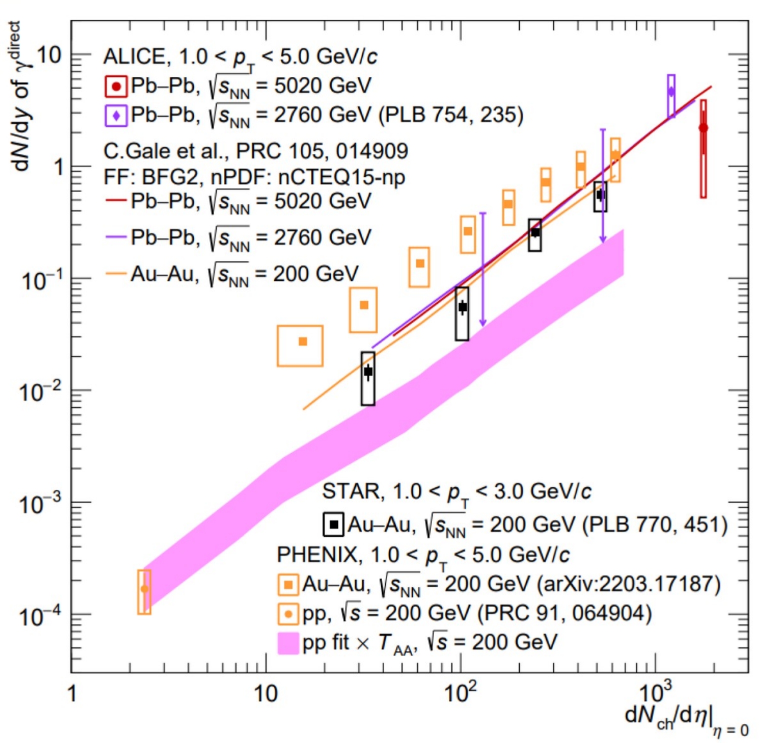
First direct-photon p_T - differential spectrum at $\sqrt{s_{NN}}$ = 5.02 TeV

Hybrid model with contributions from all stages of the collision
- Prompt photons from NLO pQCD calculations
- Pre-equilibrium contributions
- Thermal (QGP & hadronic gas)

C. Gale et al., Phys.Rev.C 105 (2022) 1, 014909

$N_{\gamma dir}$ consistent with only prompt photons
However: all central values above pQCD baseline

Integrated direct photon yields



$$\frac{dN_\gamma}{dy} = \int_{p_{T,\min}}^{p_{T,\max}} \frac{dN_\gamma^{\mathrm{dir}}}{dp_T dy} dp_T = A \times \left(\frac{dN_{\mathrm{ch}}}{d\eta}\right)^\alpha$$

Power-law dependence of direct-photon yield on charged-particle multiplicity proposed by PHENIX

- Suggests production independent of energy or centrality

Real-photons in 0-20% Pb−Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

- Phys. Lett. B 754 (2016) 235-248

Virtual-photons in 0-10% Pb−Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- arXiv:2308.16704v1

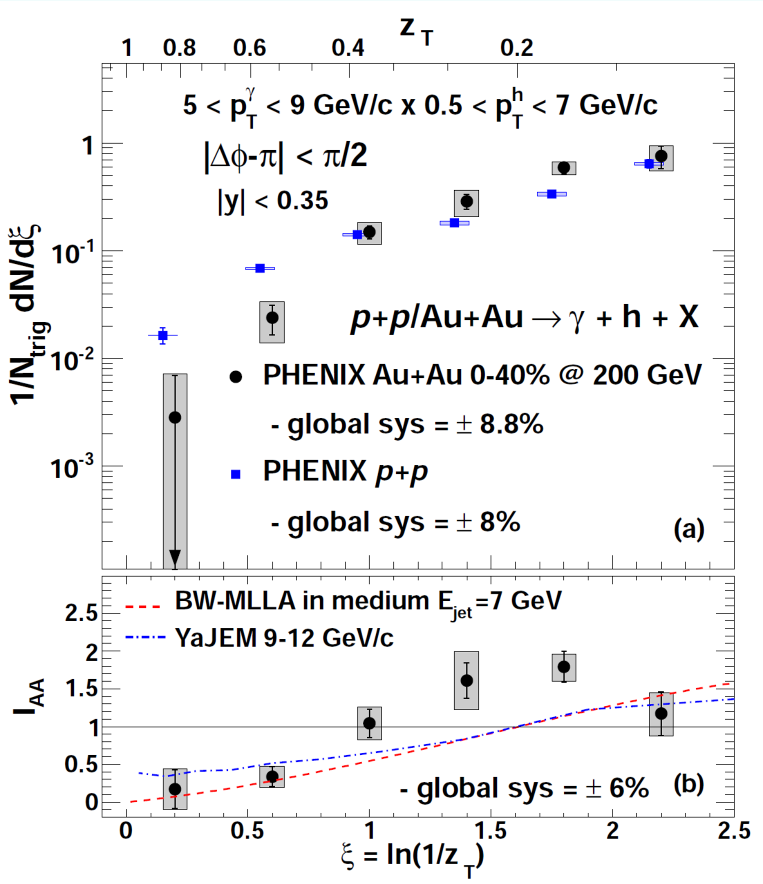
Both measurements consistent with model predictions

Results at LHC energies not sensitive enough yet to confirm a universal scaling behavior

EMP relation with parton energy loss

- Photon-tagged jets at collider experiments is another application of EMP in HIC.
- Associated production of prompt photon with a jet is described in LO as a gluon-quark Compton scattering.
- Prompt photons and jets are not balanced even in pp collisions (T=0) because of final-state radiation.
- Jet fragmentation function modification is measured to assess parton energy loss in medium.

$$I_{AA} = Y^{Au+Au} / Y^{p+p}$$



[PHENIX Collaboration] Phys.Rev.Lett. 111 (2013) 3, 032301

Summary remarks

- Electromagnetic probes, observed via direct real or virtual photons, have been addressed by theory and experiment since decades.
- From theory calculations, various sources of direct photons contribute to the net direct photon spectrum in heavy-ion collisions.
- Precision experimental measurements can discriminate those photon sources at different p_T regimes.
- From experiment side, the task of direct photon measurements is very challenging:
  - Small cross section
  - Large background from hadronic decays
  - Requires large statistics
  - Limited by systematic uncertainties
- Experiments address EMP simultaneously from various complementary aspects:
  - Direct photon yield in AA collisions vs centrality
  - Real and virtual photons are measured using different techniques
  - Discrimination of thermal and prompt photons
  - Direct photon flow
  - HBT correlation of photon pairs
  - Photon-tagged jets of parton energy loss
- Experimental studies continue. New LHC Run3 data brings an order of magnitude more statistics