New direct and non-prompt photon yield and flow results from PHENIX in 200GeV Au+Au collision

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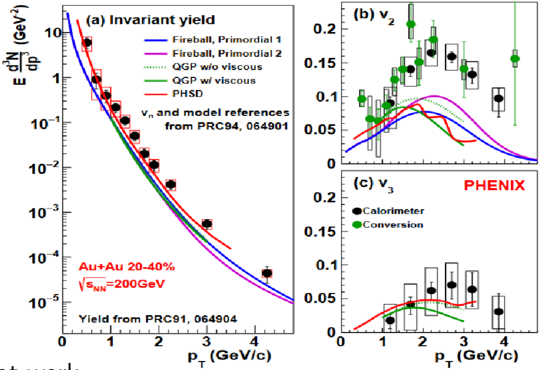
Introduction

- Direct photons have long been considered a golden probe to understand of the evolution of relativistic heavy-ion collisions – from the quark-gluon plasma (QGP) phase to the hadron-gas (HG) phase.
- Direct photons traverse the medium unmodified due to the small cross section of electromagnetic interaction
- These penetrating photons encode information about the environment
- High transverse momentum p_t direct photons $\rightarrow$ dominated by photons created from initial hard-scattering processes
- Low p_T is dominated by radiation from the evolving partonic/hadronic medium $\rightarrow$ earlier terminology: *thermal photons*
- Current measurements $\rightarrow$ additional sources and mechanisms of direct-photon production $\rightarrow$ new name: *non-prompt photons*

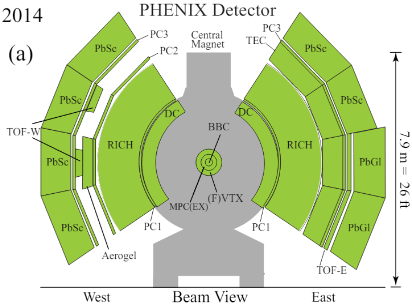
Direct photon puzzle



- Several theoretical models have been developed
- Most of the models qualitatively ✓
- For quantitatively ⌀
- What was seen earlier?
  - high yield and high v_2 at the same time
  - $\leftrightarrow$ old paradigm will not work
  - high yields means high T (early emission) $\leftrightarrow$ high v_2 means late emission, where T is low
- Theoretical curves are below the yield and flow

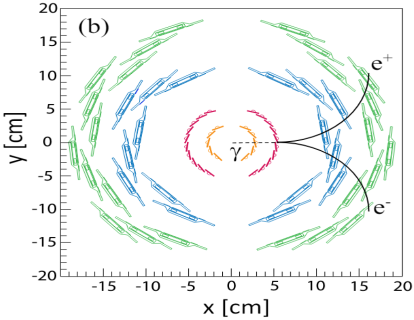
Experimental Setup

- For further insights → PHENIX results from the 2014 Au+Au data at $\sqrt{S_{NN}} = 200 GeV$, with a 10× more statistics
- A new analysis method using the silicon-vertex detector (VTX) as photon converter
- The direct-photon measurement is based on the tracking and identification of e^- and e^+ from photon conversions in the detector material
- Earlier 3 measurements at PHENIX → Internal conversion; External conversion far from vertex; Real photons in calorimeter
- This measurement → External photon conversions close to the vertex



Experimental Setup

- The VTX here acts as the photon converter, which is critical for this analysis
- Charged tracks are identified as electrons or positrons with a ring-imaging Ĉerenkov detector
- For the calorimetric identification of the e^-e^+ pair, E/p cut was used
- For the calorimetric identification of photons, two types of calorimeters are used: PbSc and PbGl



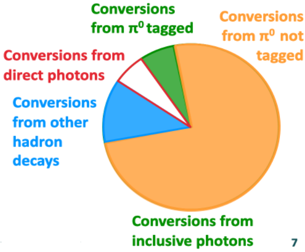
- A new track-reconstruction algorithm is developed → the e^+ and e^- from a conversion have the same origin and that their momenta were initially parallel in radial direction

Double-ratio tagging method

- The number of direct photons is small $\leftrightarrow$ the number of photons from hadron decays $\rightarrow$ for a precise measurement we need a **tagging method**

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadr}} = \frac{\frac{\gamma^{incl}}{\gamma^{\pi^0}}}{\frac{\gamma^{hadr}}{\gamma^{\pi^0}}} = \frac{< \epsilon_\gamma f > \left(\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0,tag}}\right)_{Data}}{\left(\frac{\gamma^{hadr}}{\gamma^{\pi^0}}\right)_{Sim}} \quad (1)$$

- $N_\gamma^{incl}/N_\gamma^{\pi^0,tag}$ the ratio of measured photon yields
- $< \epsilon_\gamma f >$ is the conditional acceptance and efficiency
- $\gamma^{hadr}/\gamma^{\pi^0}$ is the cocktail ratio



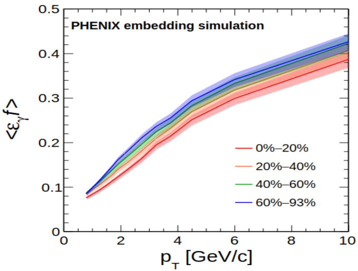
Ratio of the measured photon yields $N_{\gamma}^{incl}/N_{\gamma}^{\pi 0,tag}$

- e^- and e^+ in a given event are combined to e^+e^- pairs and conversion candidates are selected
- The conversion photon candidates are paired with all photons in the EMCal and the invariant mass is calculated; if it falls in the π^0 mass window, the conversion photon is "tagged"
- For e^+e^- pairs, there are two possible combinations, signal pairs of interest + uncorrelated background pairs: $FG^{ee} = SG^{ee} + BG^{ee}$
- For $e^+e^-\gamma$ combinations, both types of e^+e^- pairs are combined with photons that are either correlated or uncorrelated with the pair: $FG^{ee\gamma} = SG^{ee\gamma} + BG^{ee\gamma}_{corr} + BG^{ee\gamma}_{uncorr}$
- The final correction:

$$N_{\gamma}^{\pi^0,tag} = FG^{ee\gamma} - BG^{ee\gamma}_{corr} - (1 + f_{ee\gamma}) \times BG^{ee\gamma}_{uncorr} \tag{2}$$

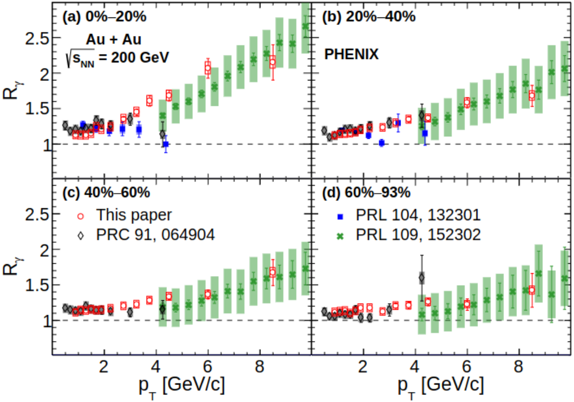
Conditional probability $<\epsilon_\gamma f>$

- The conditional acceptance $<\epsilon_\gamma f>$ is the probability that IF a conversions photon is detected AND it comes from a π^0 decay, it's partner in the EMCal will be found and their invariant mass will be in the π^0 window
- Individual π^0 are tracked through the PHENIX MC-simulation framework
- The $\pi^0 \rightarrow \gamma\gamma$ decay channel was used
- $<\epsilon_\gamma f> = \frac{N_{ee}^{\pi^0,tag}}{N_{ee}^{\pi^0}}$



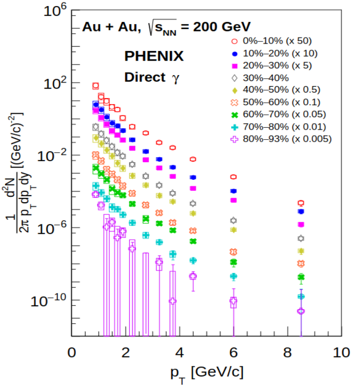
Result - 4 different R_γ PHENIX measurment

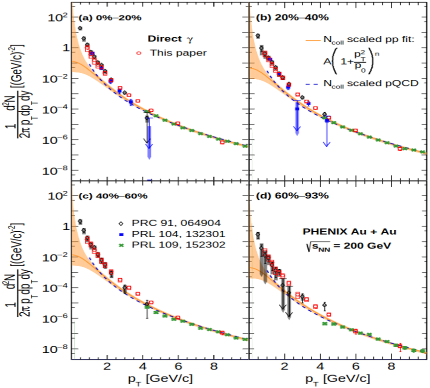
- The new results are compared with all other published PHENIX results $\rightarrow$ different methods + independent systematic uncertainties.
- Internal conversion (PRL 104, 132301)
- External conversion far from vertex (PRL 91, 064904)
- Real photons in calorimeter (PRL 109, 152302)
- External conversion close to the vertex (arXiv:2203.17187)



Result - Direct photon yield comparison

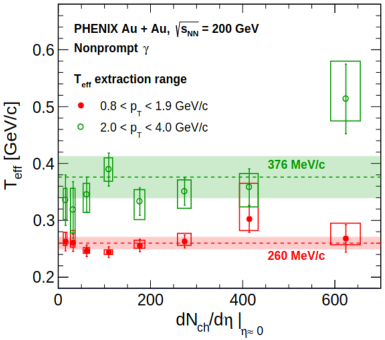
- The direct photon yield: $\gamma^{dir} = (R_\gamma - 1)\gamma^{hadr}$ $\rightarrow$ left picture for all centralities
- $p_T > 5 GeV/c$ is well described by the N_{coll}-scaled p+p result and pQCD calculations $\rightarrow$ high-pT direct photons are from hard-scattering processes
- Non-prompt photon yield = measured direct γ yield - N_{coll} scaled (pp fit or pQCD)

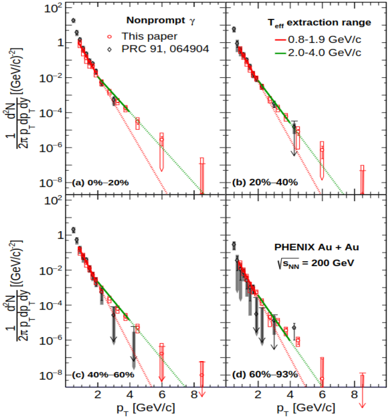




Result - Non-prompt photons

- The invariant yields are very consistent in the region of overlap
- The p_T-dependent inverse slopes (T_{eff}) for different fitting ranges are shown as a function of $dN_{ch}/d\eta$, a measure of centrality
- T_{eff} depends on the fitted p_T range, but almost no dependence on centrality



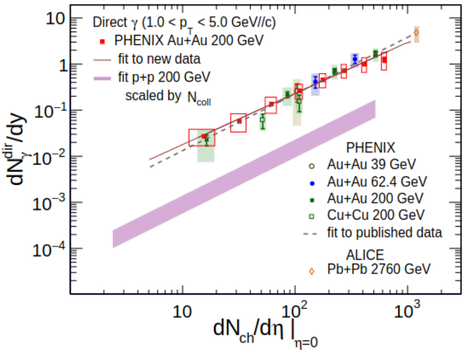


Scaling with multiplicity - integrated yields

- The integrated direct photon yield scaling function:

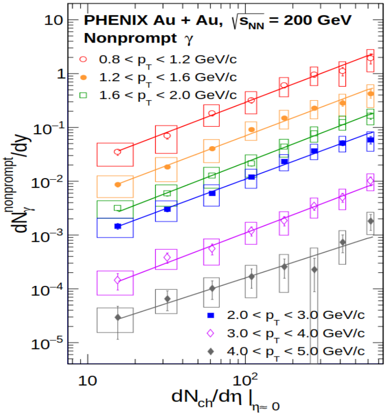
$$\frac{dN_\gamma}{dy} = \int_{p_T,min}^{p_T,max} \frac{dN_\gamma^{dir}}{dp_T dy} dp_T = A \times (\frac{dN_{ch}}{d\eta})^\alpha \quad (3)$$

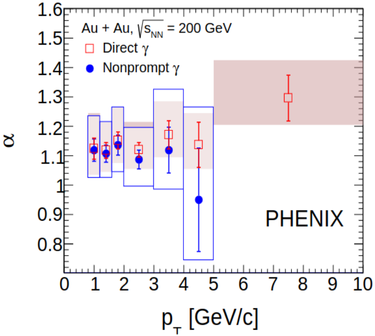
- Agreement with other direct-photon results
- Fit for previously published data: $\alpha = 1.23 \pm 0.06 \pm 0.18$
- Fit from the current data: $\alpha = 1.11 \pm 0.02 \pm 0.09$
- α smaller than predicted $\rightarrow$ HG $= 1.25$ and QGP $= 1.8$
- The same scaling holds over vastly different collision energies (39-2760GeV) and systems (CuCu - PbPb)



Scaling with charged multiplicity - p_T yields

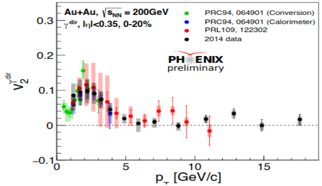
- At higher p_T the α corresponds to the N_{coll} scaling $\leftrightarrow$ in lower p_T it tends to be smaller
- The values of α for the non-prompt component are constant with no evidence p_T dependence

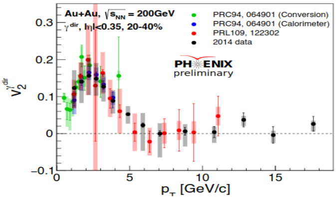


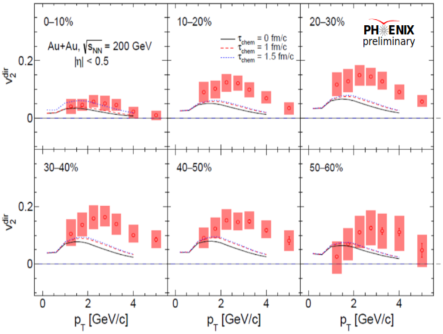


Elliptic flow - v_2

- Preliminary results from a recent analysis of direct photon elliptic flow
- Finer centrality bins than previously published
- The new results are consistent with earlier measurements → the elliptic flow of direct photons in the low p_T region is large, and consistent with that of final state hadrons







Summary

- New PHENIX data: $10\times$ more statistic $\rightarrow$ + confirm earlier results + new kind of analysis $\rightarrow$ "direct photon puzzle" is still alive
- The experimentally observed inverse slopes of the p_T spectra are qualitatively consistent with predictions for thermal and pre-equilibrium radiation
- More photons emitted from Au+Au collisions than can be accounted for in model calculations
- Large anisotropy is observed for photons at ≈ 2–$3 GeV/c$
- In this p_T range, the yield is larger than what would be expected from a rapidly but anisotropically expanding hadronic fireball
- The centrality dependence of the nonprompt direct-photon yield, expressed in terms of the scaling power $\alpha(p_T)$, shows no indication of changing with p_T range

Thank you for your attention!

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