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Direct photon production and scaling properties in large and small system collisions



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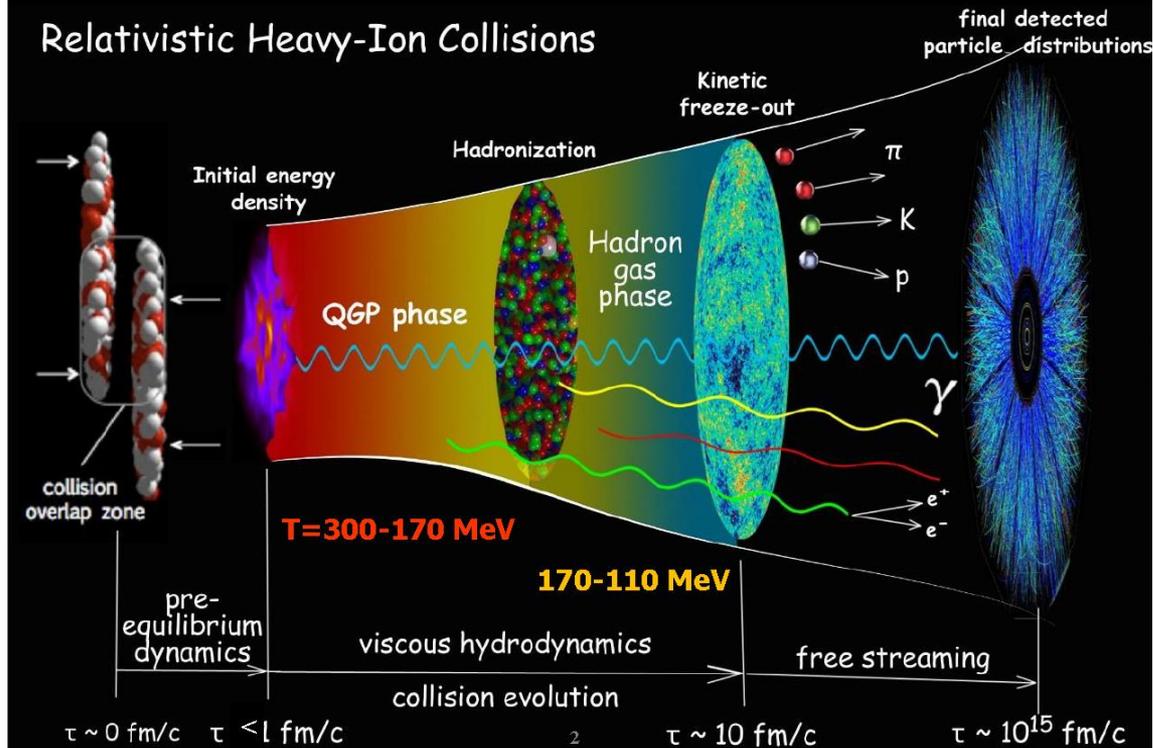
Content

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- PHENIX measurements of low momentum direct photons
- PHENIX large system results: *direct photon relative yield R_γ and direct photon invariant yield (p_T -spectra)*
small system results: *invariant cross section (p_T -spectra) of direct photons*
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- Summary

Introduction: *Direct Photon Production in HIC*

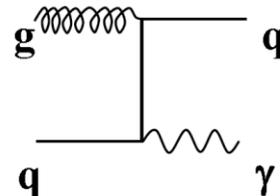
Thermal Photon Emission from a Heavy Ion Collisions

Relativistic Heavy-Ion Collisions

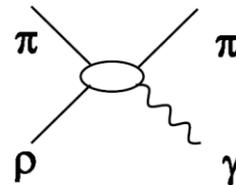


Microscopic view of thermal radiation

Quark Gluon Plasma (QGP) phase



Hadronic phase

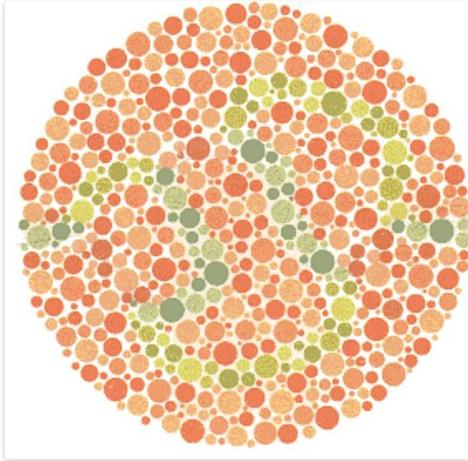


The photon emission rate depends on density squared, integrated over space-time evolution when

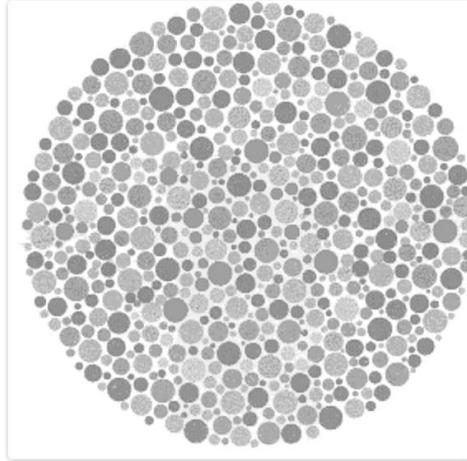
- matter expands
- temperature drops

Introduction: *Direct Photon Production in HIC*

QGP seen by partons



QGP seen by photons



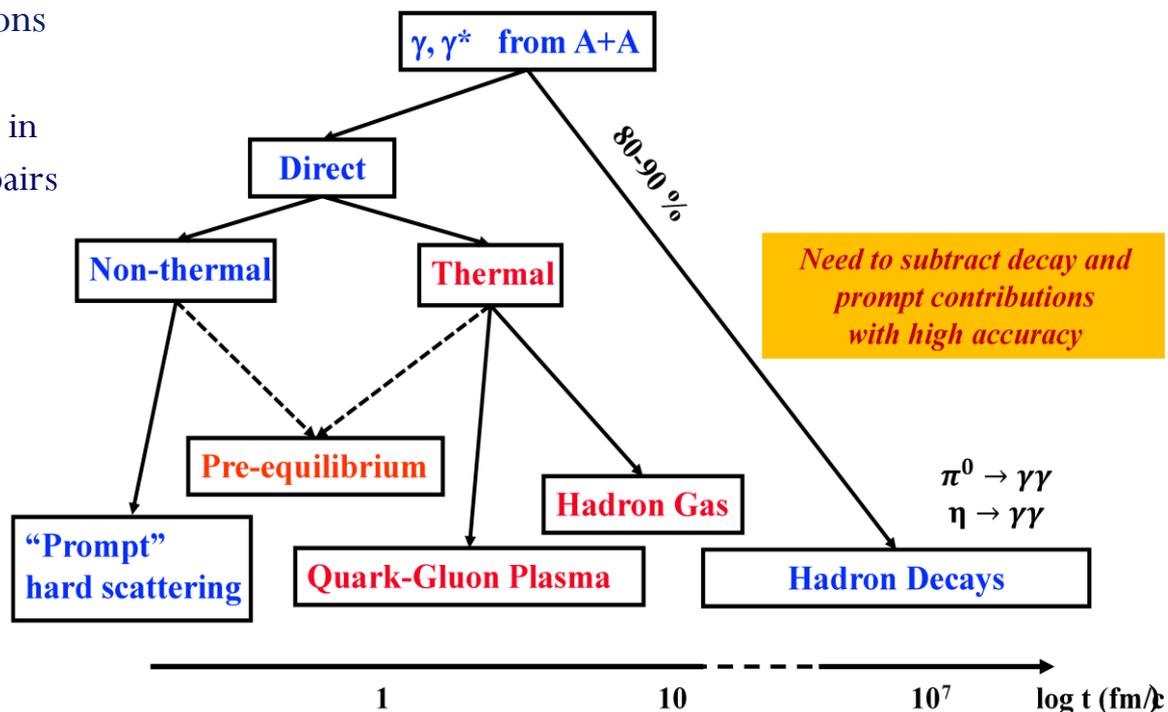
- Photons (contrary to partons) are color blind probes
- By definition, direct photon yield is equal to inclusive photon yield subtracted by hadronic decay photon yield

Direct photons are very important probes: for example,

- for extracting information on the space-time evolution of the matter produced in relativistic heavy ion collisions at the time of their production
- for providing evidence on thermal radiation from Quark Gluon Plasma

Introduction: *Direct Photon Production in HIC*

- Direct photons → thermal photons,
→ non-thermal photons
- All thermal media emit thermal radiation in the form of photons or low mass lepton pairs
- Thermal photons originate from
 - pre-equilibrium phase
 - thermalizing QGP phase
 - hadron gas
- Non-thermal photons originate from initial hard scattering processes



Introduction: *Direct Photon Flow Puzzle*

- Large yield and large anisotropy observed in Au+Au at 200 GeV by PHENIX
- Challenging to explain the sources and emission rates: difficulties to get the yield and anisotropy simultaneously
- In order to help resolve this puzzle, PHENIX has measured low momentum γ in

large systems:

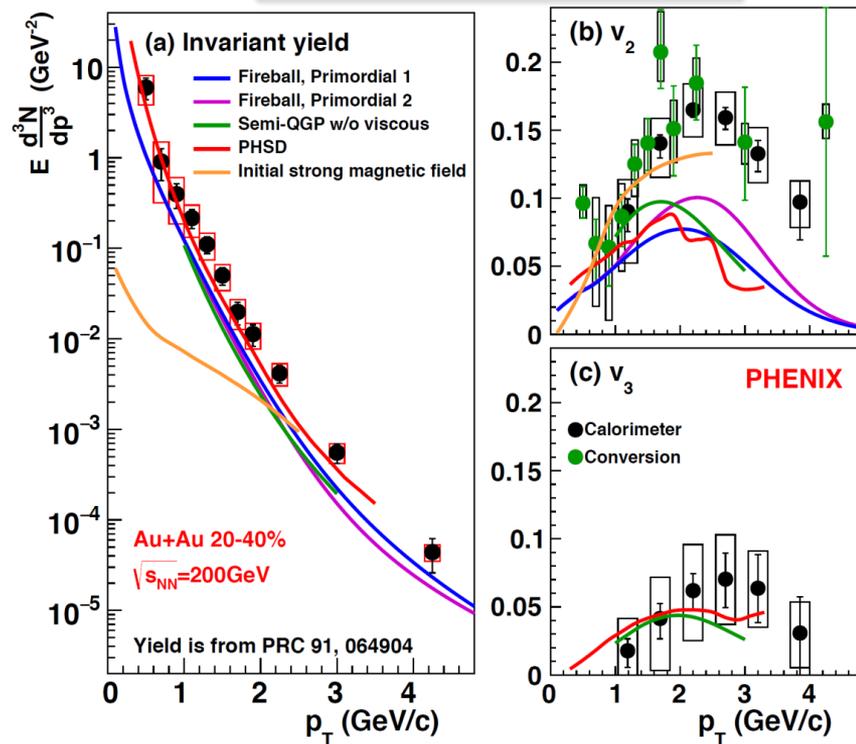
- Au+Au at 200, 62.4, 39 GeV, Cu+Cu at 200 GeV
- observing direct photon scaling independent of center-of-mass energy, centrality, system species

small systems

- p+p, d+Au, p+Au at 200 GeV
- observing direct photon excess in central p+Au within ~ 1 -sigma systematic uncertainties

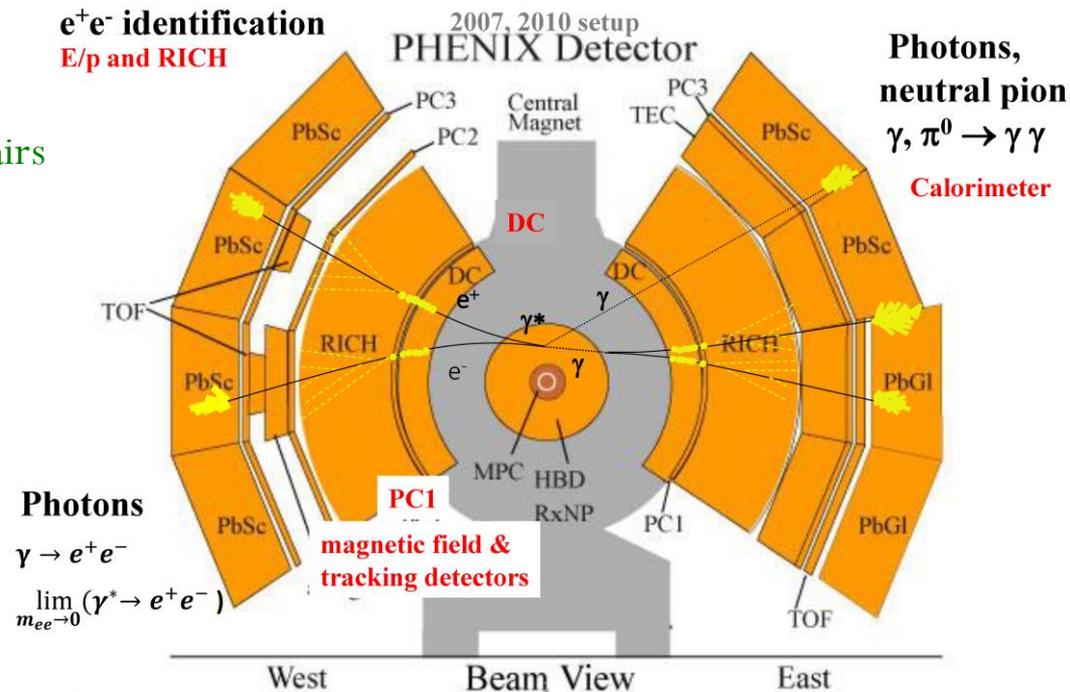
Large yield from early emission ?
Large v_2 from late emission ?

The figures are from PRC 94, 064901



PHENIX measurements of low momentum direct photons

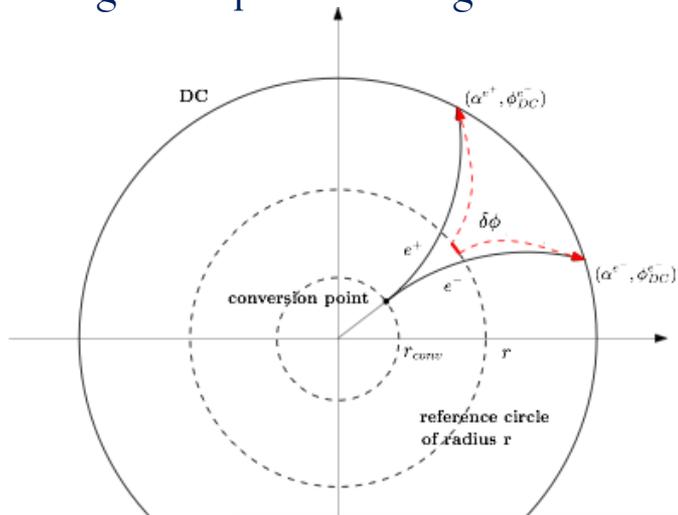
- Photon measurement techniques include
 - γ s that directly deposit energy into EMCals
 - Virtual γ s that internally convert $\rightarrow e^+e^-$ pairs
 - Real γ s that externally convert $\rightarrow e^+e^-$ pair
- Previous measurements of 2010 Au+Au datasets via external conversion method are accomplished
 - in the Readout Plane of HBD
 - with the conversions at fixed radius: 60 cm from the event vertex
 - $X/X_0 \sim 3\%$
 - single e^+/e^- tracks used



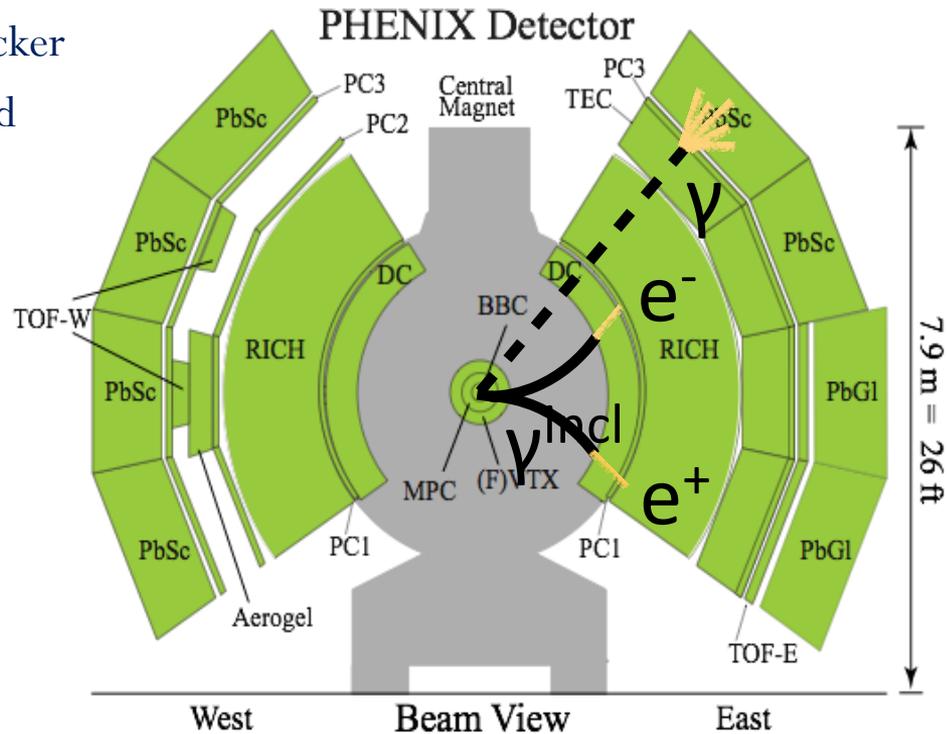
Conversions with the HBD backplane

PHENIX measurements of low momentum direct photons

- A new measurement with 2014 Au+Au dataset is accomplished in the layers of Silicon Vertex Tracker
- The photon conversion position is reconstructed using e^+ / e^- pairs and magnetic field map



Tracking conversion back to its conversion point



Conversions with the VTX layers

PHENIX measurements of low momentum direct photons

➤ Conversions at any material (3rd and 4th layers mostly)

- $X/X_0 \sim 14\%$
- 10 fold statistics

➤ There are more conversions at VTX than at HBD

Then one can measure Direct Photon R_γ with the Double Ratio Tagging Method

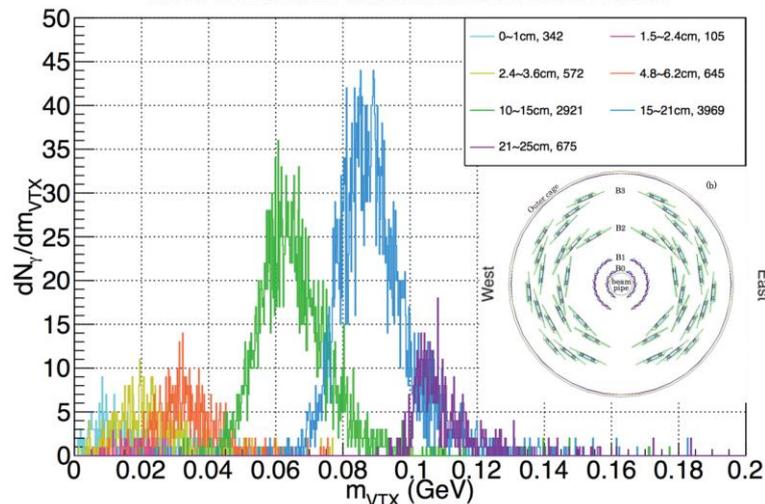
$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadron}} = \frac{\frac{\gamma^{incl}}{\gamma^{\pi^0}}}{\frac{\gamma^{hadron}}{\gamma^{\pi^0}}} = \frac{\langle \epsilon f \rangle \left(\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}} \right)_{Data}}{\left(\frac{\gamma^{hadron}}{\gamma^{\pi^0}} \right)_{Sim}}$$

$N_\gamma^{incl}/N_\gamma^{\pi^0}$ from real data

$\gamma^{hadron}/\gamma^{\pi^0}$ from simulation

$\langle \epsilon f \rangle$ (conditional acceptance and efficiency) from simulation

mass distribution of different conversion radius



After R_γ is constructed

we get the p_T -spectra

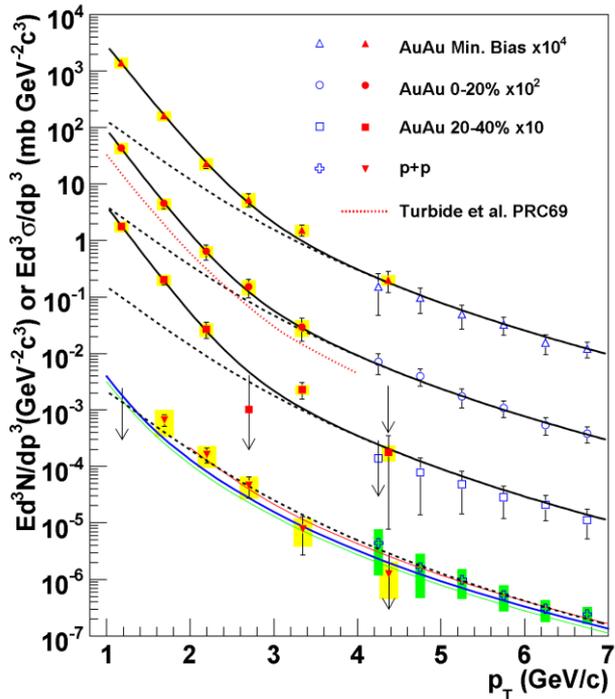
(invariant yield or cross section)

$$\text{Yield} = (R_\gamma - 1) \times \gamma^{had}$$

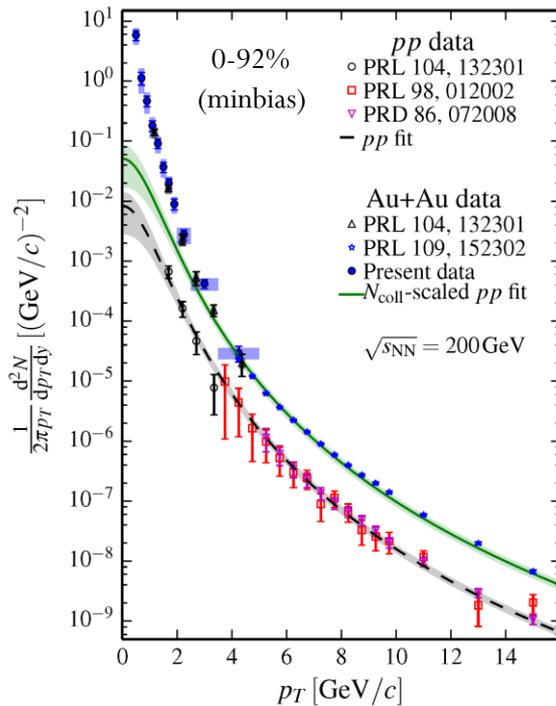
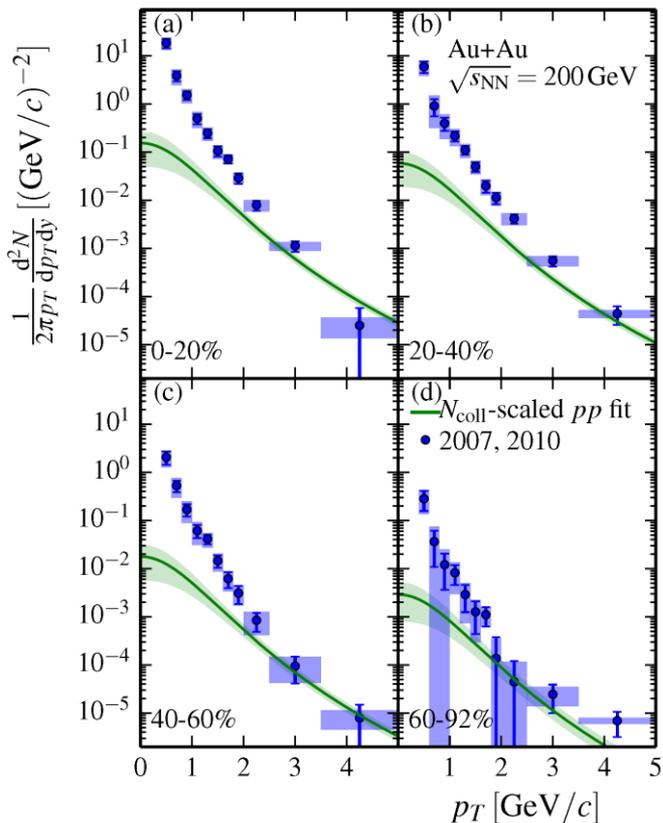
Large Systems: *Direct Photon* p_T -spectra

Direct photon data in Au+Au collisions at 200 GeV

PRL 104, 132301

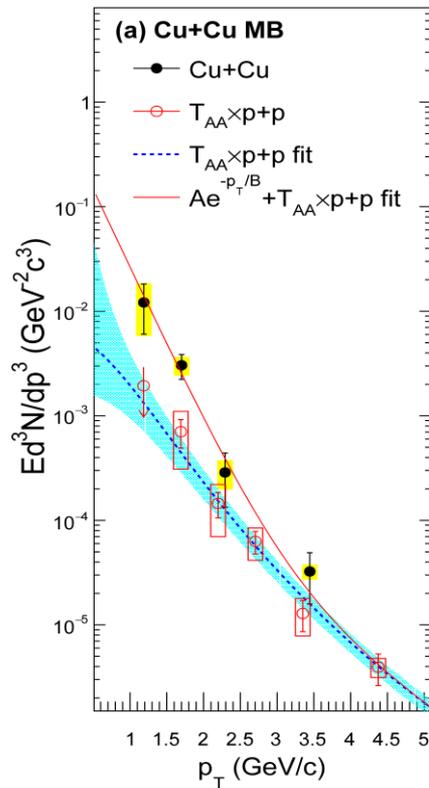


PRC 91, 064904



Large Systems: *Direct Photon* p_T -spectra

PRC 98, 054902

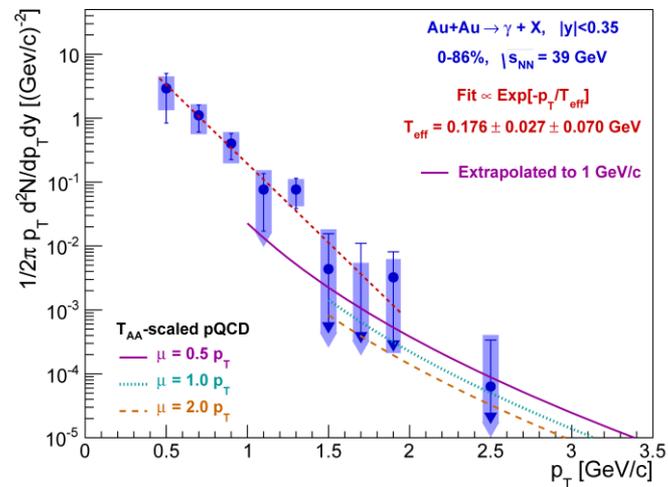
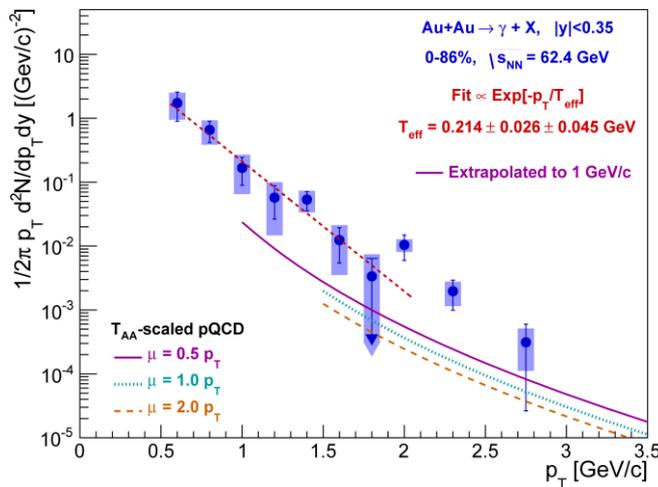


➤ We have also recent direct photon data

- from Au+Au at 62.4 GeV and 39 GeV
- from Cu+Cu at 200 GeV

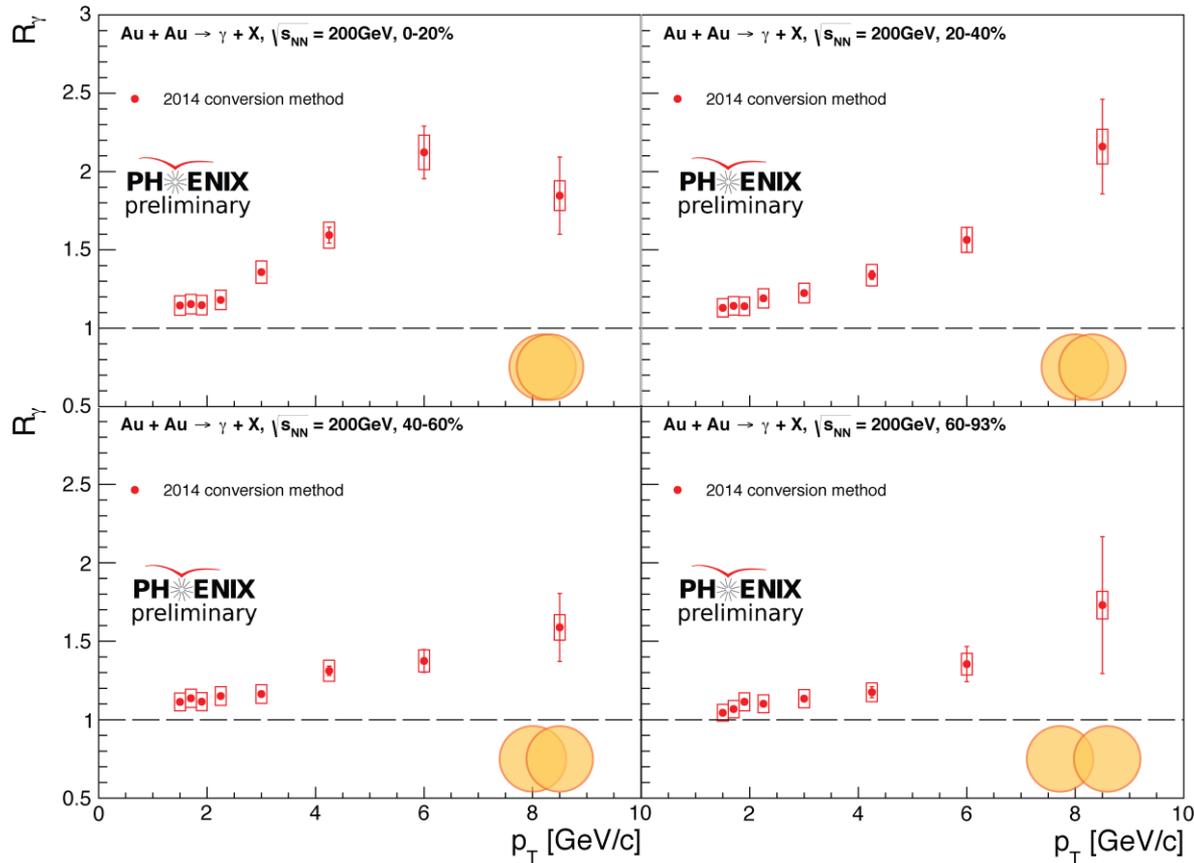
All three p_T spectra are shown in minimum bias

Quark Matter 2018, Hard Probes 2018



➤ Data from various colliding species and collision centrality selections at different beam energies may constrain the sources of direct photons

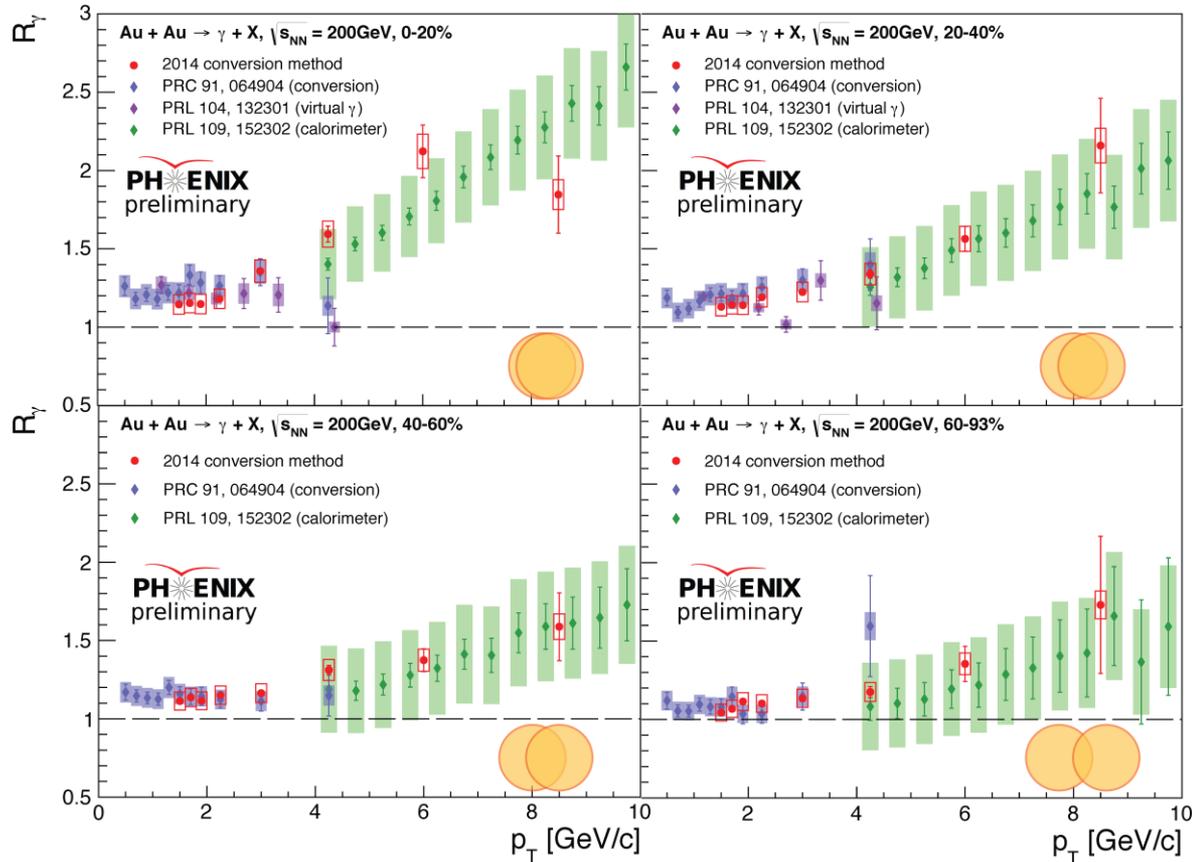
New results on Large Systems: *Direct photon relative yield* R_γ



The most recent PHENIX R_γ results from Au+Au measurements in four centrality bins at 200 GeV

Quark Matter 2019

New results on Large Systems: *Direct photon relative yield* R_γ



The most recent results

overlaid with the previously published PHENIX results

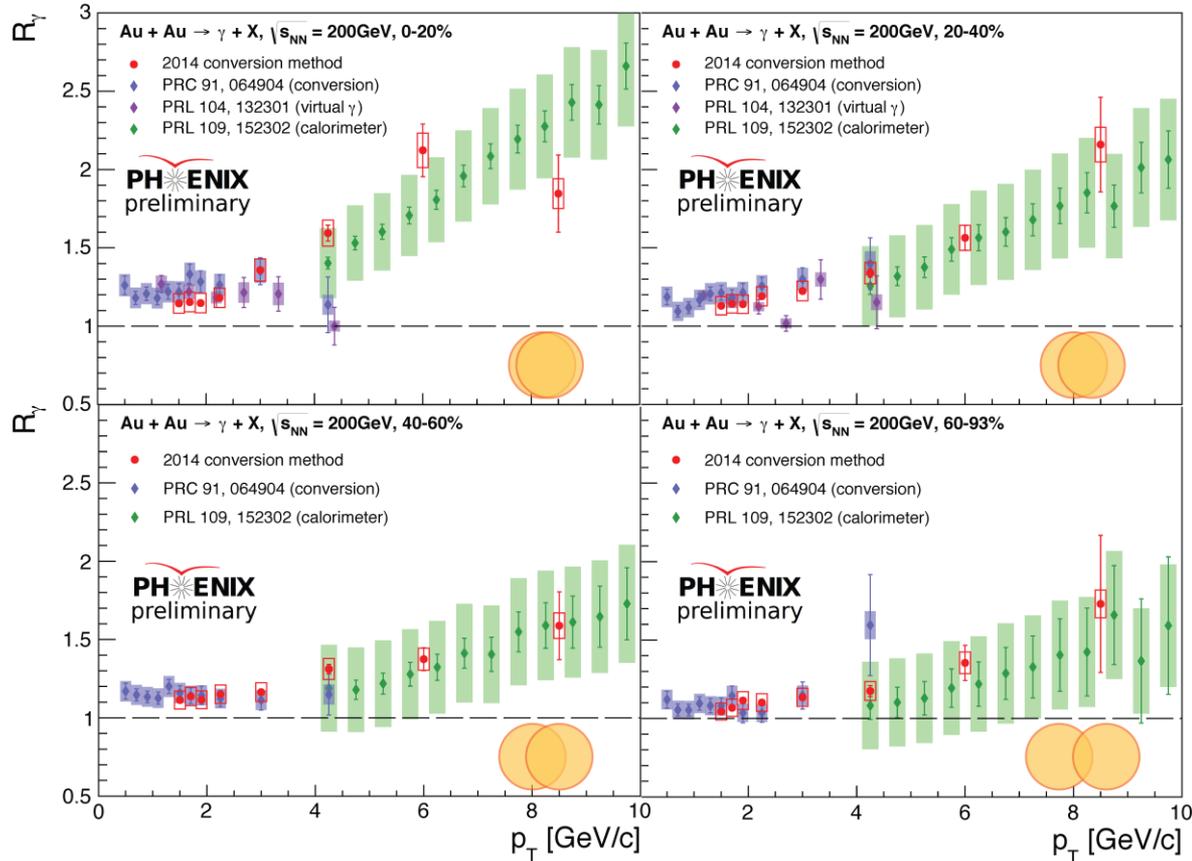
External conversion method

Internal (virtual) conversion method

Calorimeter method

Quark Matter 2019

New results on Large Systems: *Direct photon relative yield* R_γ

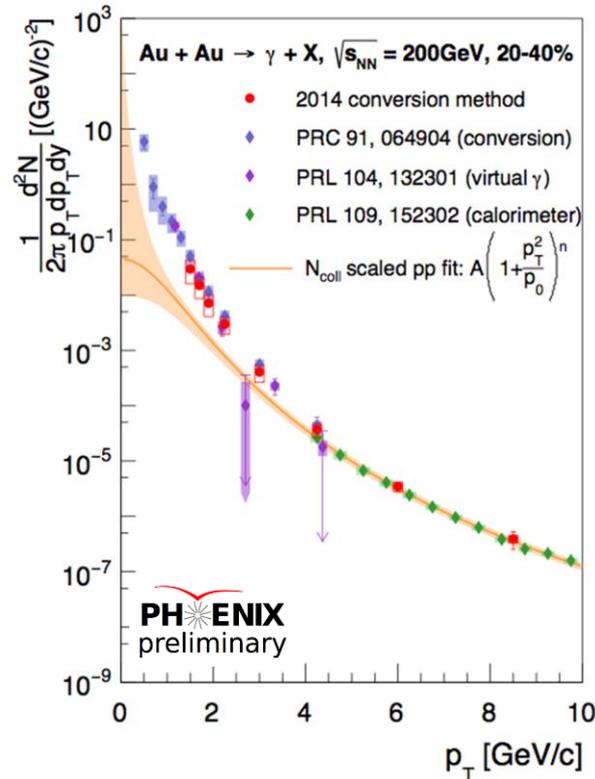
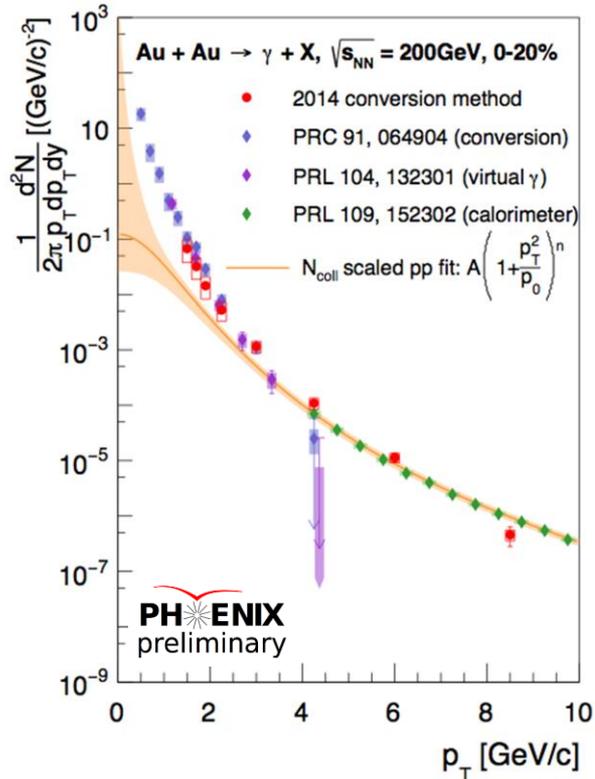


Thus, we have four independent measurements from separate datasets

Consistent with each other within statistical and systematic uncertainties

Quark Matter 2019

New results on Large Systems: *Direct Photon* p_T -spectra

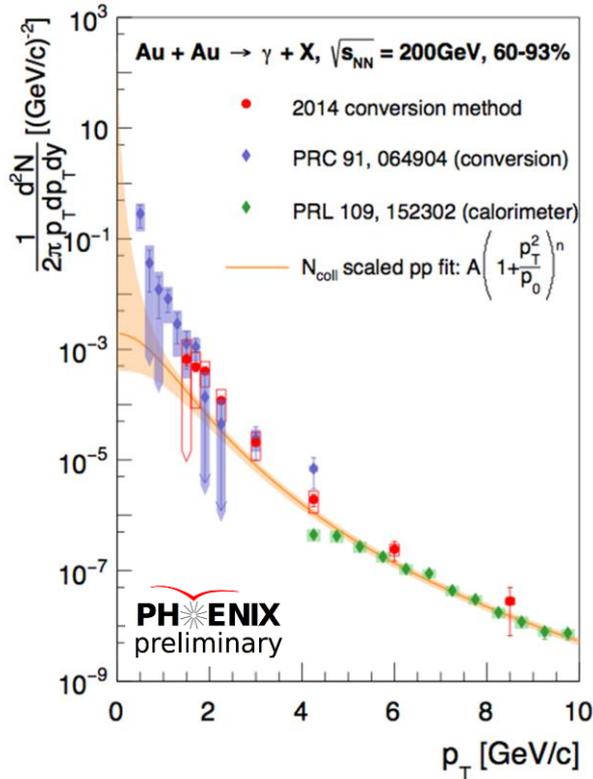
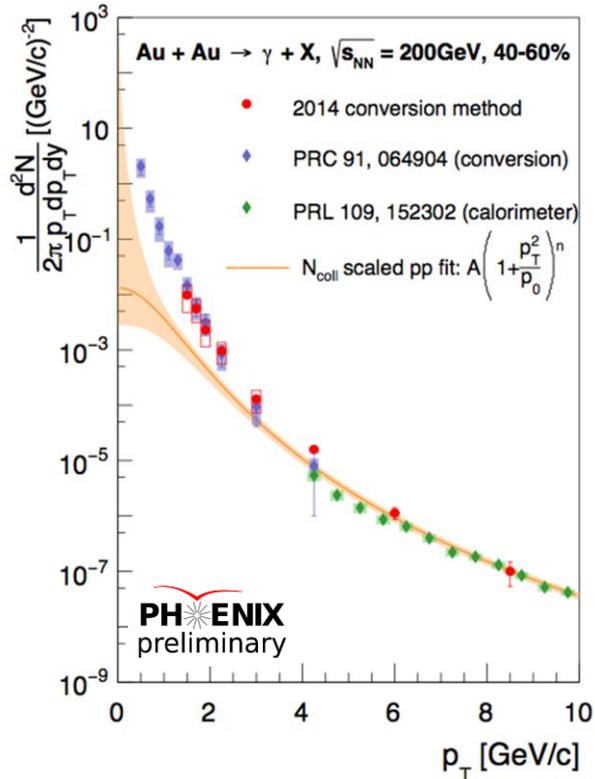


At high p_T Au+Au data are consistent with N_{coll} scaled p+p fit

Clear enhancement observed below 3 GeV/c in (semi-)central Au+Au collisions

Quark Matter 2019

New results on Large Systems: *Direct Photon* p_T -spectra



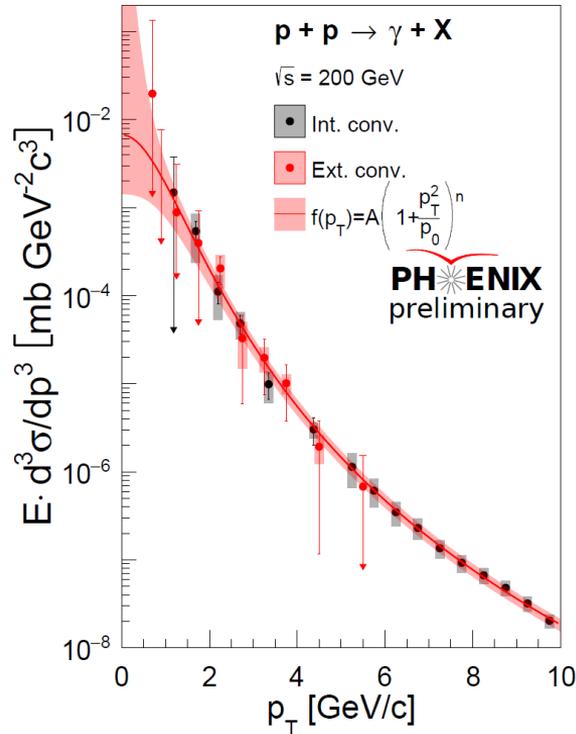
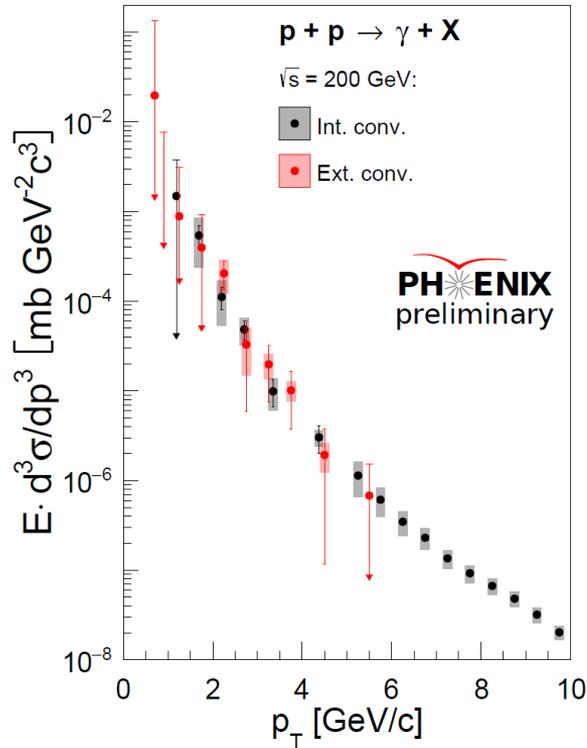
At high p_T Au+Au data are consistent with N_{coll} scaled p+p fit

The enhancement persists below 3 GeV/c in (semi-)peripheral Au+Au collisions

Quark Matter 2019

Small Systems: *Direct Photon p_T -spectra*

- Invariant cross section in p+p at 200 GeV. The last data are in red, the previously published data are in black



Above $p_T \approx 5.0 \text{ GeV}/c$,
the published p+p data are from
calorimeter measurements:
PRL 109, 152302

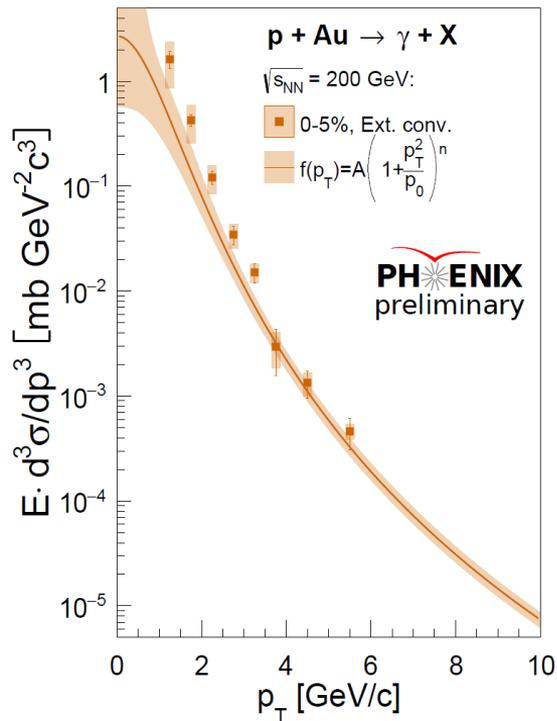
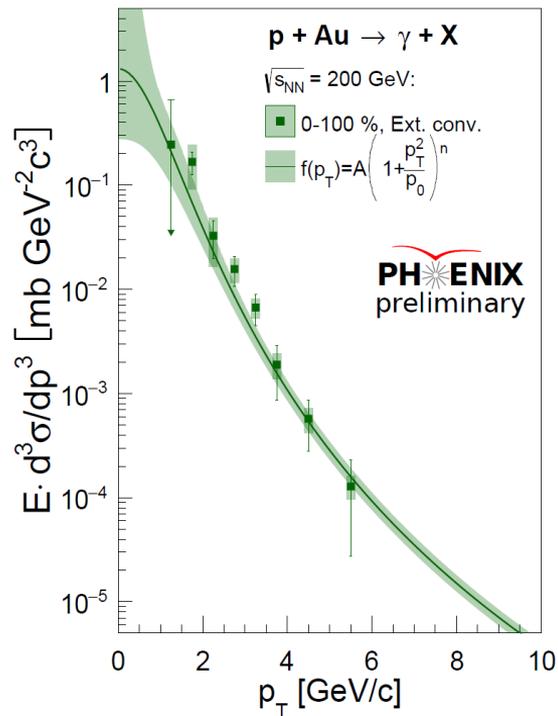
The PHENIX new p+p fit is made
by using three p+p data sets

Quark Matter 2018, 2019; Hard Probes 2018

Small Systems: *Direct Photon* p_T -spectra

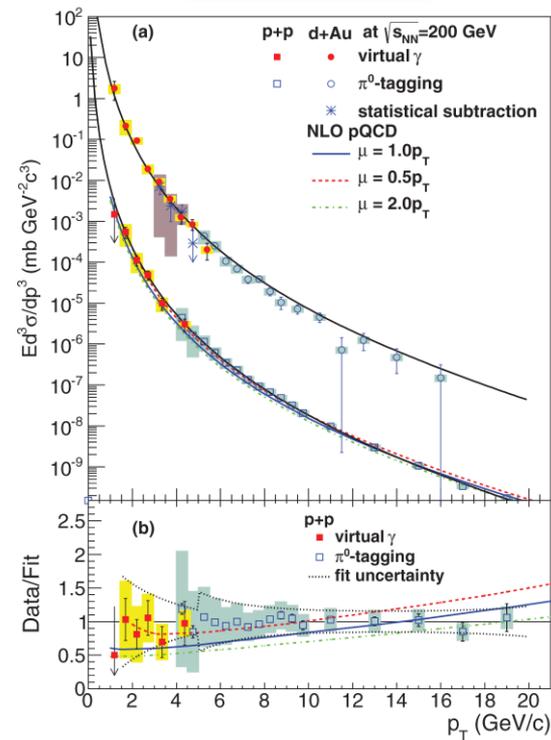
➤ Invariant cross section in minimum bias and central p+Au at 200 GeV

Quark Matter 2018, 2019; Hard Probes 2018



➤ Invariant cross section in p+p and minimum bias d+Au at 200 GeV

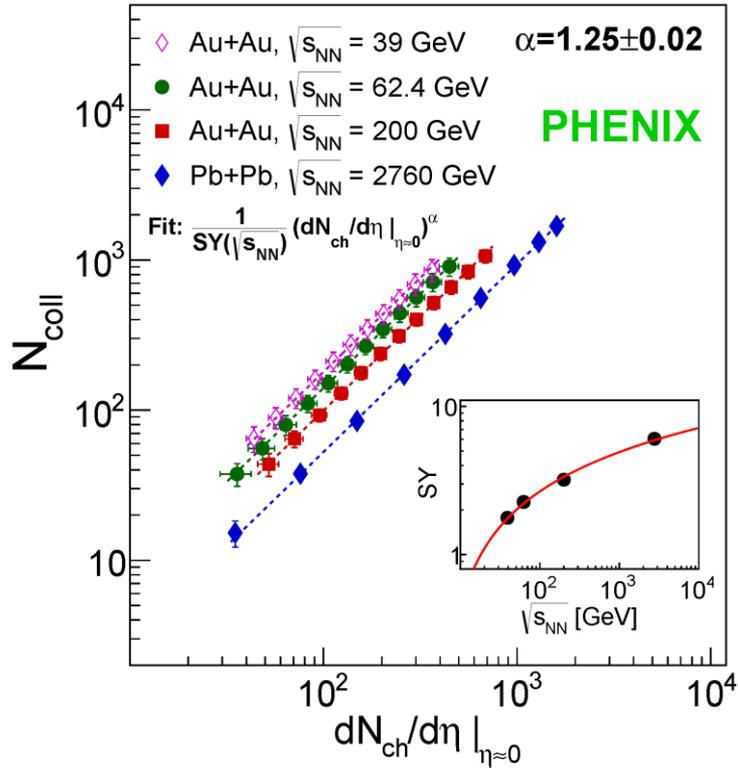
PRC 87, 054907



Direct Photon Scaling

- For a given center-of-mass energy one can compare data from different centralities (or system size) using N_{part} or N_{coll} .
- On the other hand, such a comparison is not useful for data at different energies.
- Therefore, for this purpose one can use an experimental observable such as the charged hadron multiplicity at midrapidity, $dN_{\text{ch}}/d\eta|_{\eta \approx 0}$, by which the system size is measured
- $dN_{\text{ch}}/d\eta|_{\eta \approx 0}$ itself has an interesting scaling behavior with N_{coll} as shown in the next slide

Direct Photon Scaling



- At fixed center-of-mass energy, $dN_{ch}/d\eta \sim N_{part} \sim \text{Volume}$
- At varying energy, $dN_{ch}/d\eta \sim \text{Energy density} \times \text{Volume}$
- N_{coll} scales like $(dN_{ch}/d\eta)^{1.25}$ for all energies with a logarithmically increasing parameter (called specific yield)

Compare the system size with number of collisions:

N_{coll} scales with $dN_{ch}/d\eta$, such as

$$N_{coll} = \frac{1}{SY(\sqrt{s_{NN}})} \left(\frac{dN_{ch}}{d\eta} \right)^\alpha$$

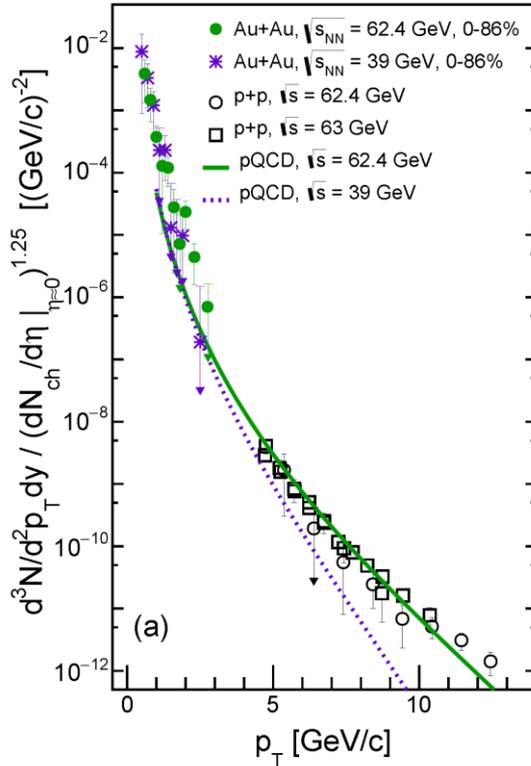
The specific yield, SY, is a function of energy $\sqrt{s_{NN}}$

$$SY(\sqrt{s_{NN}}) = c_1 \log(\sqrt{s_{NN}}) - c_2$$

PRL 123, 022301

Direct Photon Scaling

PRL 123, 022301



Direct photon p_T -spectra normalized by

$$\left(\frac{dN_{\text{ch}}}{d\eta}\right)^\alpha, \text{ where } \alpha = 1.25$$

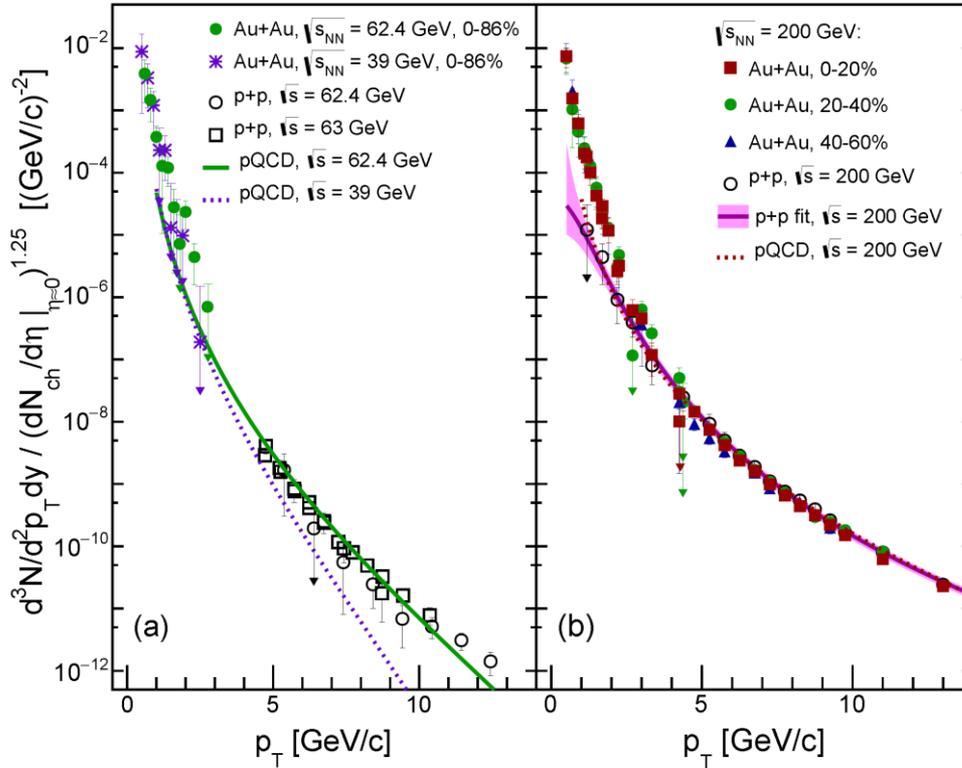
ISR data from p+p at 62.4 GeV are included and normalized

The pQCD curves are also normalized

- PHENIX low beam energy 62.4/39 GeV data are above $p_T = 0.4$ GeV/c
- The data at 62.4/39 GeV falls on top of each other
- At high- p_T , the 62.4 GeV normalized pQCD is consistent with ISR data

Direct Photon Scaling

PRL 123, 022301



Direct photon p_T -spectra normalized by $(dN_{ch}/d\eta)^\alpha$, where $\alpha = 1.25$

The pQCD curves and p+p fit are also normalized

- All Au+Au data are on top of each other at low- and high- p_T at 200 GeV
- At low- p_T they are distinctly above the p+p data/fit/pQCD

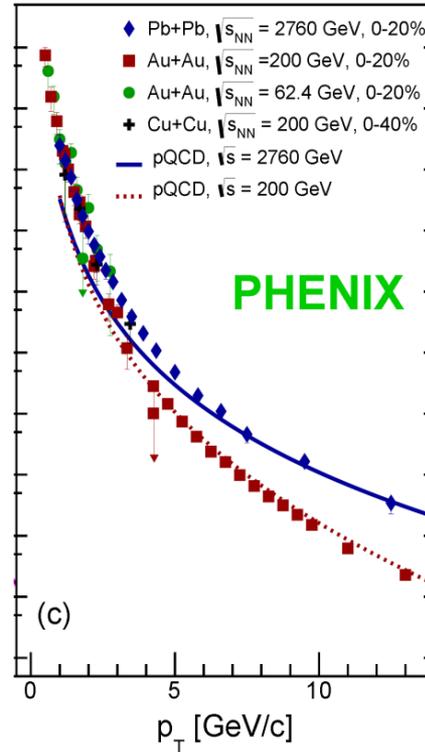
Direct Photon Scaling

- Now we compare data at different energies from 39 GeV to 2760 GeV
- Again all data coincides at low- p_T
- We see the expected difference with the energy and N_{coll} scaling at high- p_T

For A+A collisions this scaling picture seems to be independent of

- colliding species,
- collision centrality (system size),
- center-of-mass energy

PRL 123, 022301



Direct photon
 p_T -spectra normalized
by $(dN_{\text{ch}}/d\eta)^\alpha$,
where $\alpha = 1.25$

ALICE data from Pb+Pb
at 2760 GeV are
included and normalized

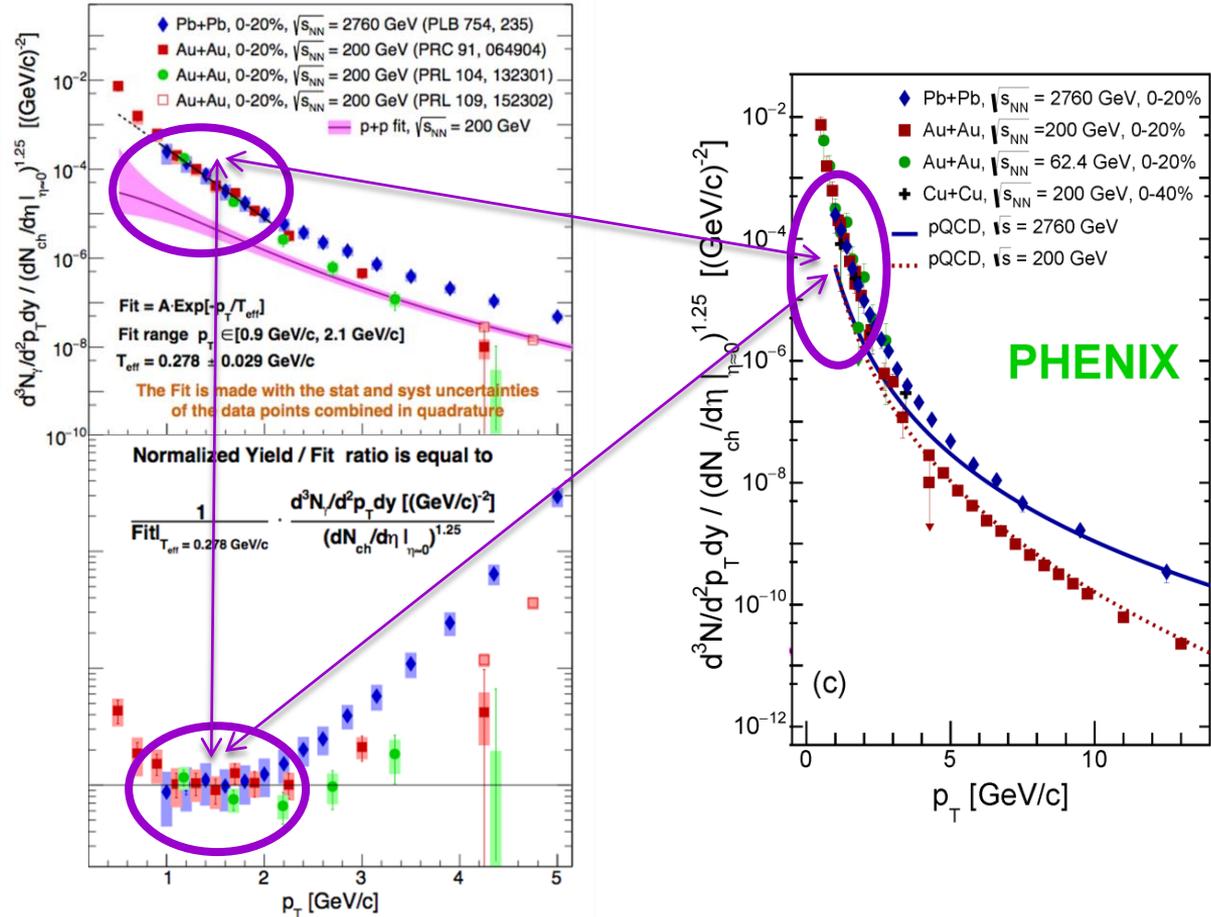
The pQCD curves are
also normalized

Direct Photon Scaling

Exponential fit to scaled
PHENIX 200 GeV Au+Au
and
ALICE 2760 GeV Pb+Pb
in the central 0-20% bin,
in the range of 0.9 to 2.1 GeV/c

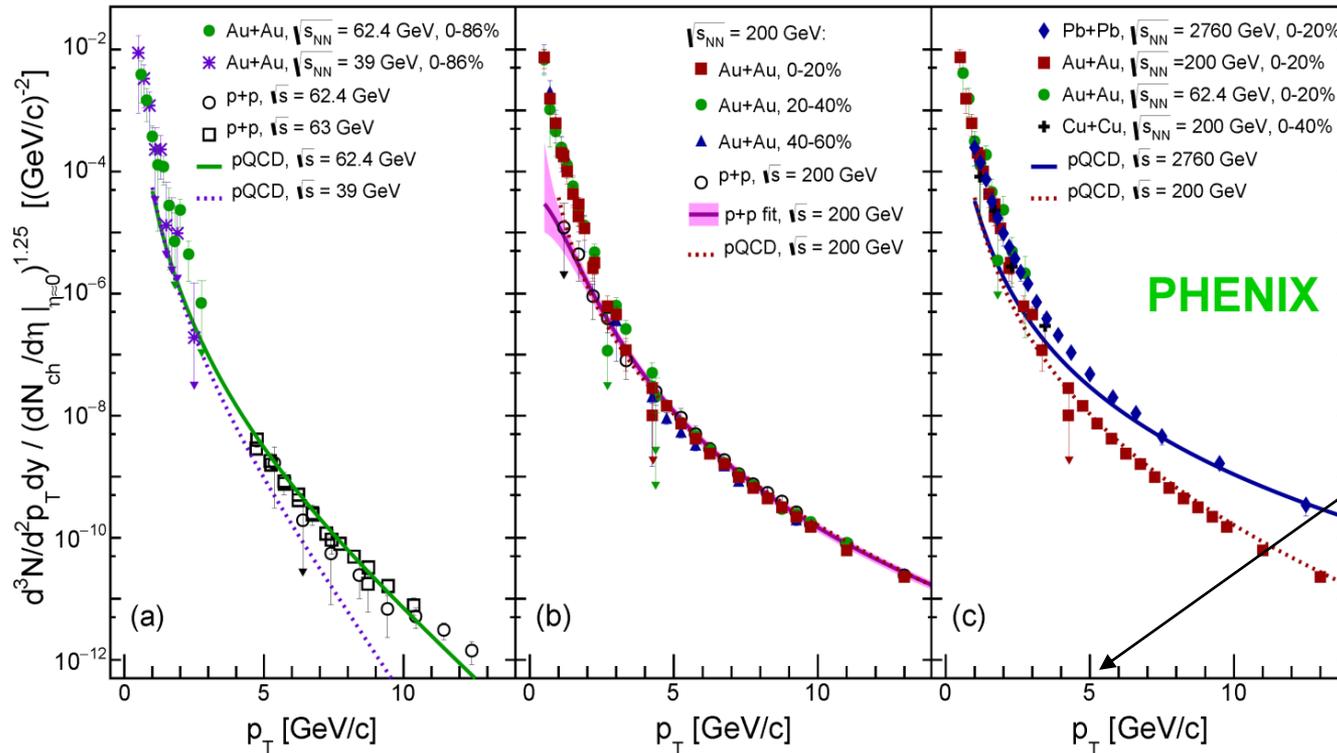
The same slope in fitted
 p_T range ~ 280 MeV

The spectra are not
exponential over large
 p_T range



Direct Photon Scaling

➤ Direct photon p_T spectra can be quantified by integrating the invariant yield from a min p_T value

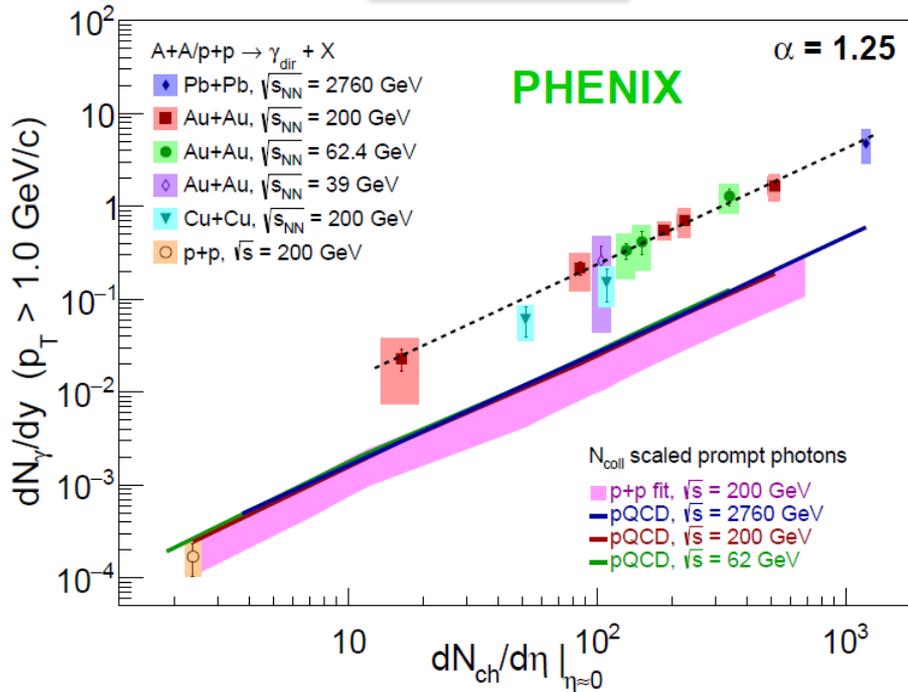


For example,
integrate from 1.0 GeV/c

Direct Photon Scaling

Integrated direct photon yield above $p_T = 1.0$ GeV/c

PRL 123, 022301



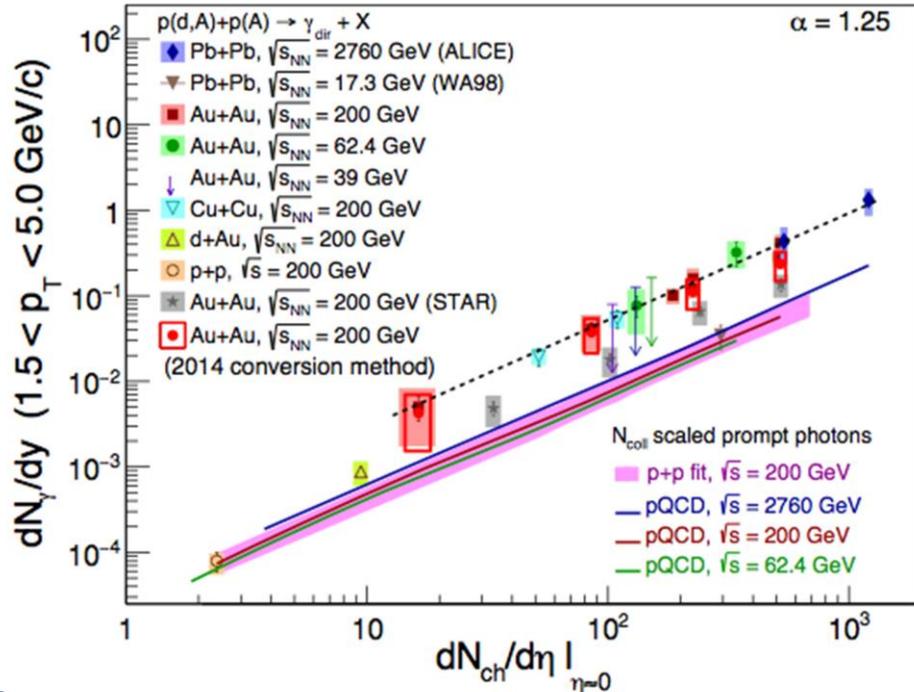
- Another representation of the direct photon scaling
- The integrated yield grows faster than the multiplicity
- The plot seems to show a universal scaling behavior in A+A collisions
- $N_{\text{coll}} \times \text{pQCD}$ and $N_{\text{coll}} \times \text{p+p}$ follow the same scaling trend at ~ 0.1 of yield

$$dN_{\gamma}/dy = A \times (dN_{ch}/d\eta)^{\alpha}$$

Direct Photon Scaling

Integrated direct photon yield above $p_T = 1.5$ GeV/c

Quark Matter 2019



- The data from the last PHENIX Au+Au 200 GeV measurements are shown as well
- The data is consistent with the observed scaling behavior in A+A systems
- STAR Au+Au 200 GeV data show the scaling behavior too
- However, systematically lower as compared to the PHENIX data

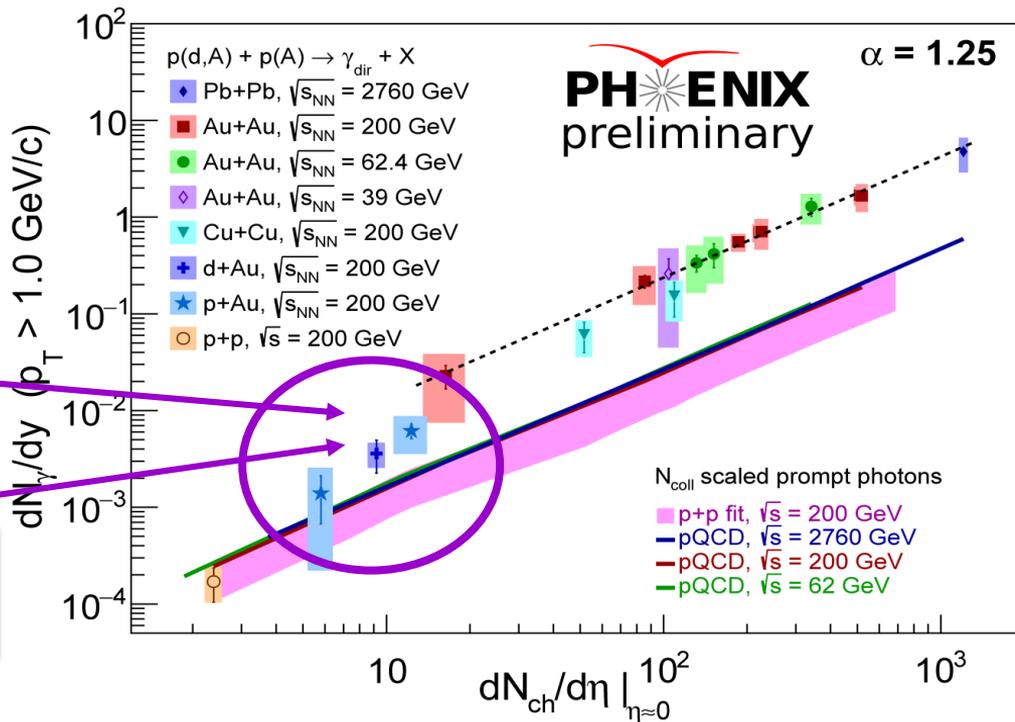
$$dN_{\gamma}/dy = A \times (dN_{ch}/d\eta)^{\alpha}$$

Possible Connection Between Small and Large Systems

- There seems to be another trend coming from small systems, different from that of large systems
- Both trends suggest a “transition region”: QGP turn off/on ?

More peripheral
A+A data
as well as
small system data
can fill the
“transition region”

p+Au and d+Au
data in between



Onset of low- p_T
radiation excess
at $\sim 5 - 20$?

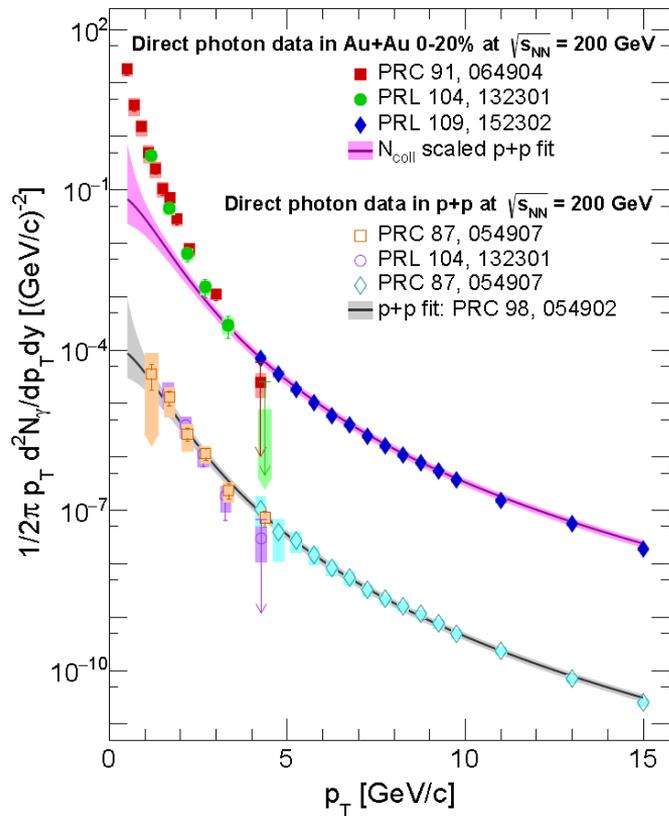
Quark Matter 2018, 2019;
Hard Probes 2018

Summary

- PHENIX has measured low momentum direct photon data in Au+ Au at 200, 62.4, 39 GeV; Cu+Cu at 200 GeV; p+p, p+Au, d+Au at 200 GeV
- Recent measurement in Au+ Au at 200 GeV with higher statistical precision is consistent with the previous measurements in Au+ Au at 200 GeV within experimental uncertainties
- Discovered a new scaling behavior in large systems
 - at a given center-of-mass energy, the low and high- p_T yields scale with N_{coll}
 - across different energies, N_{coll} is proportional to $(dN_{\text{ch}}/d\eta)^{1.25}$
 - for all energies, the low- p_T yield scales like $(dN_{\text{ch}}/d\eta)^{1.25}$
- Observed excess of direct photons in central p+Au at 200 GeV within syst uncertainties
 - above N_{coll} scaled reference p+p yield
 - these data suggests QGP turn off/on - like transition between p+p / A+A systems

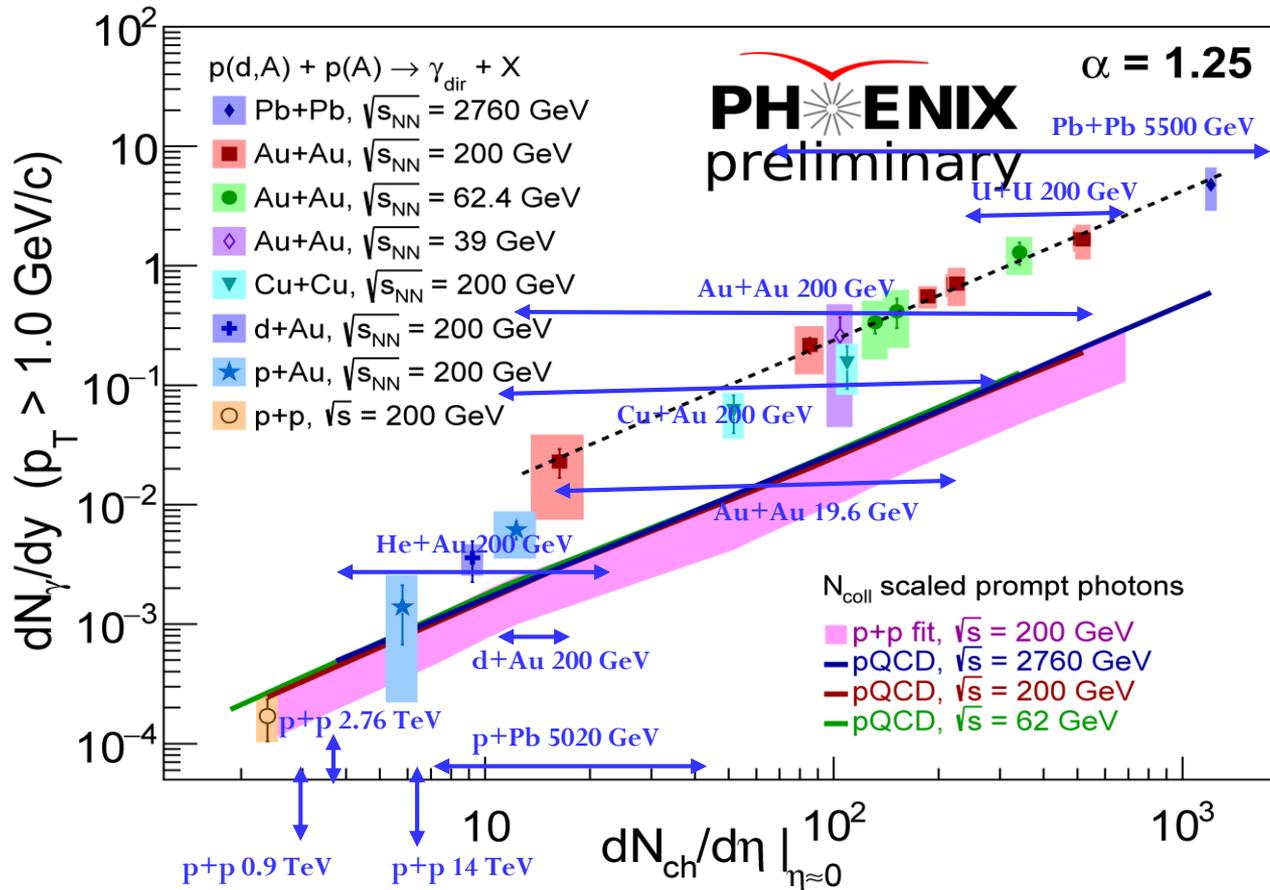
Back-Ups

Large Systems: *Direct Photon p_T -spectra*



Previous three PHENIX independent direct photon measurements are in good agreement with each other

Possible Connection Between Small and Large Systems

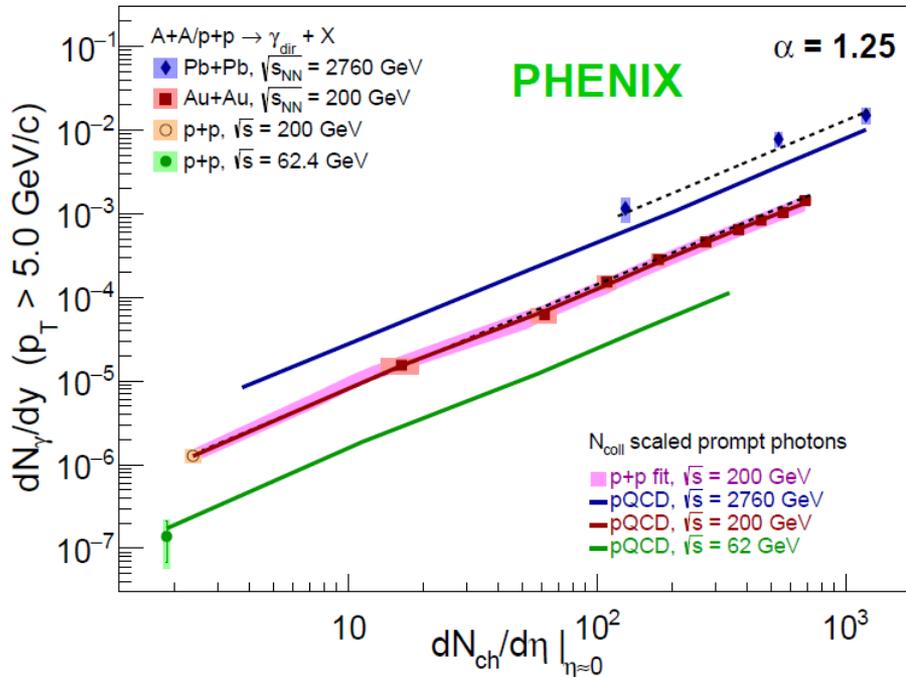


Upcoming and future possible measurements

Direct Photon Scaling

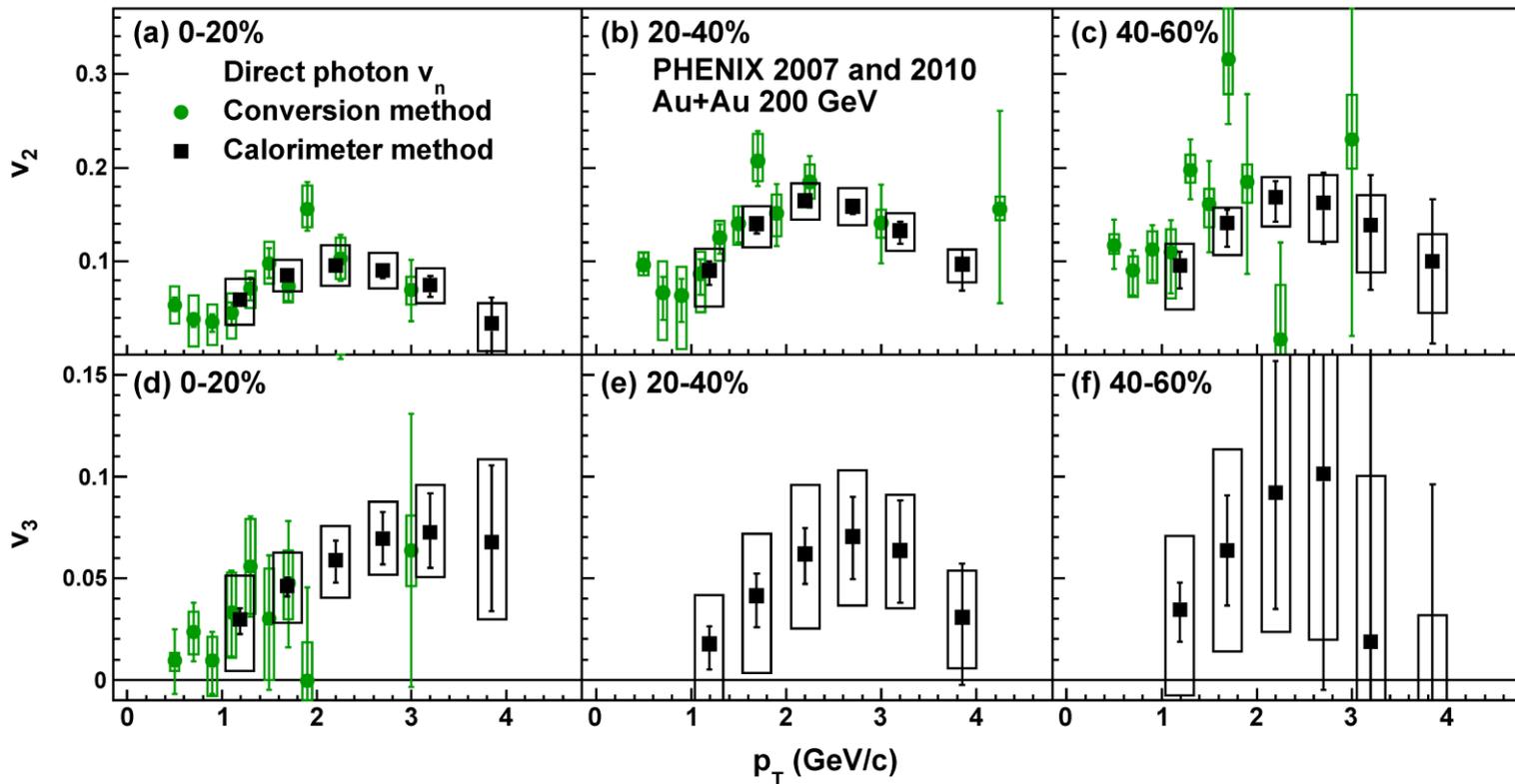
Integrated direct photon yield above $p_T = 5.0 \text{ GeV}/c$

PRL 123, 022301



- The Au+Au yield at 200 GeV is
 - consistent with $N_{\text{coll}} \times p+p$
 - consistent with $N_{\text{coll}} \times \text{pQCD}$
- The Pb+Pb yield at 2760 GeV is
 - 25% – 30% above $N_{\text{coll}} \times \text{pQCD}$

Large Systems: *Direct Photon* v_n



PHENIX
 $v_{2,3}$ results
in Au+Au
at 200 GeV

PRC 94, 064901

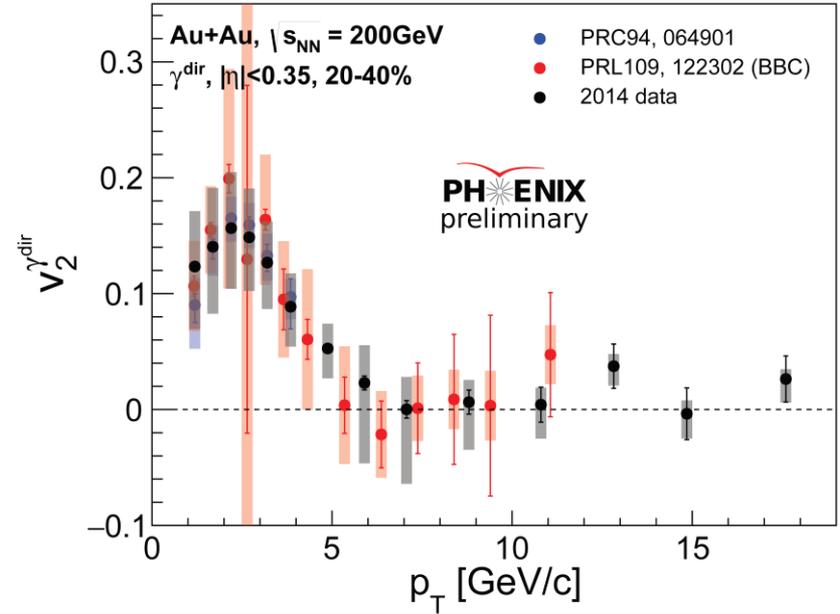
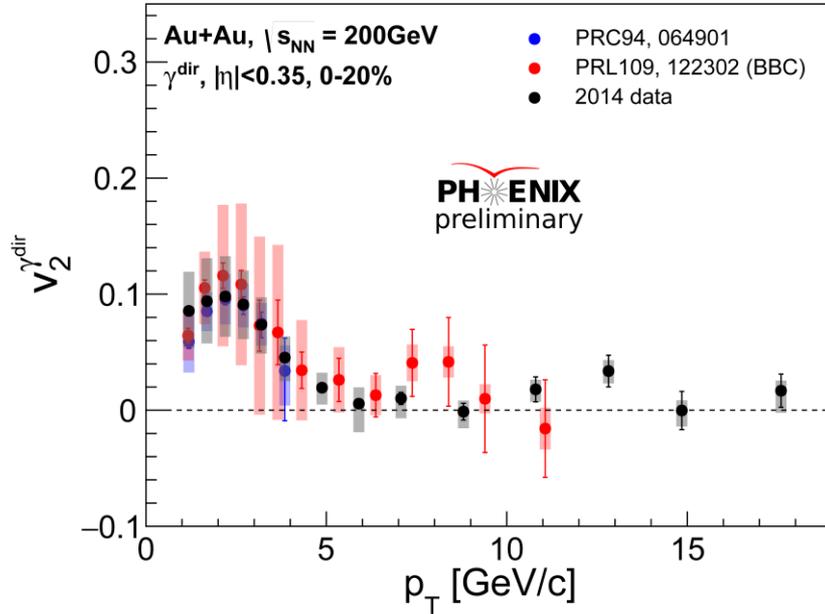
The vertical lines are statistical errors, the boxes are systematic errors

Large Systems: *Direct Photon* v_n

v_2 in Au+ Au 0-20% centrality bin at 200 GeV

v_2 in Au+ Au 20-40% centrality bin at 200 GeV

The vertical lines are statistical errors, the boxes are systematic errors



➤ Higher p_T reach is accessible as compared to the previous v_2 results

Quark Matter 2018