# Direct Photon Emission from Heavy Ion Collisions

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- Introduction
- Previous Results form PHENIX
  - High low $p_T$ direct photon yield
  - Centrality dependence ~ $N_{part}^{1.4}$
  - Large direct photon angular anisotropy $v_2$ and $v_3$
- Comparison to Theoretical Models
  - Thermal Photon Puzzle
- New Direct Photon Measurements
  - Cu+Cu at 200 GeV
  - Au+Au at 62.4 and 39 GeV
- Outlook and Summary

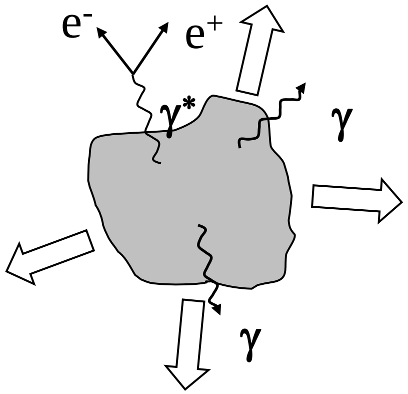
# Thermal Radiation from Hot & Dense Matter

- **Black Body Radiation**
  - **Real or virtual photons**
  - **Spectrum and yield sensitive to temperature**

    **Avg. inv. slope $\propto$ T, Rate $\propto$ $T^4$**
  - **Space-time evolution of matter**

    **collective motion → Doppler shift**

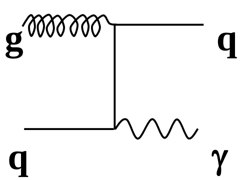
    **→ anisotropy**




**High yield → high T → early emission**
**Large Doppler shift → late emission**

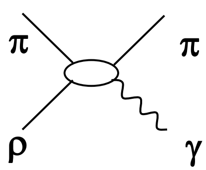
- **Microscopic view of thermal radiation**

**QGP:**




**photons**

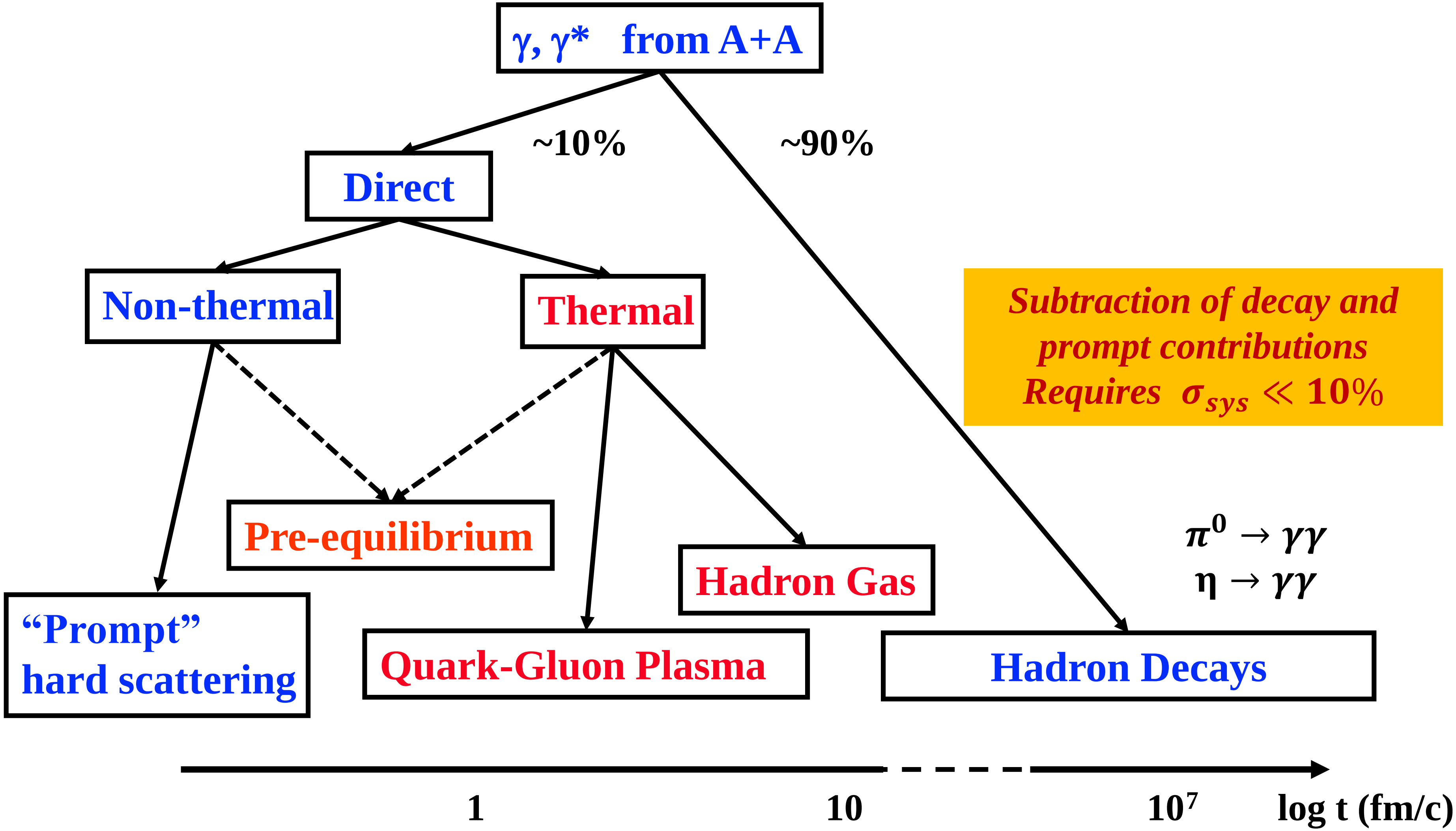
**hadron gas:**




**low mass lepton pairs**

**Direct photons data**
**constrain initial conditions, space-time evolution, emission rates and γ sources**

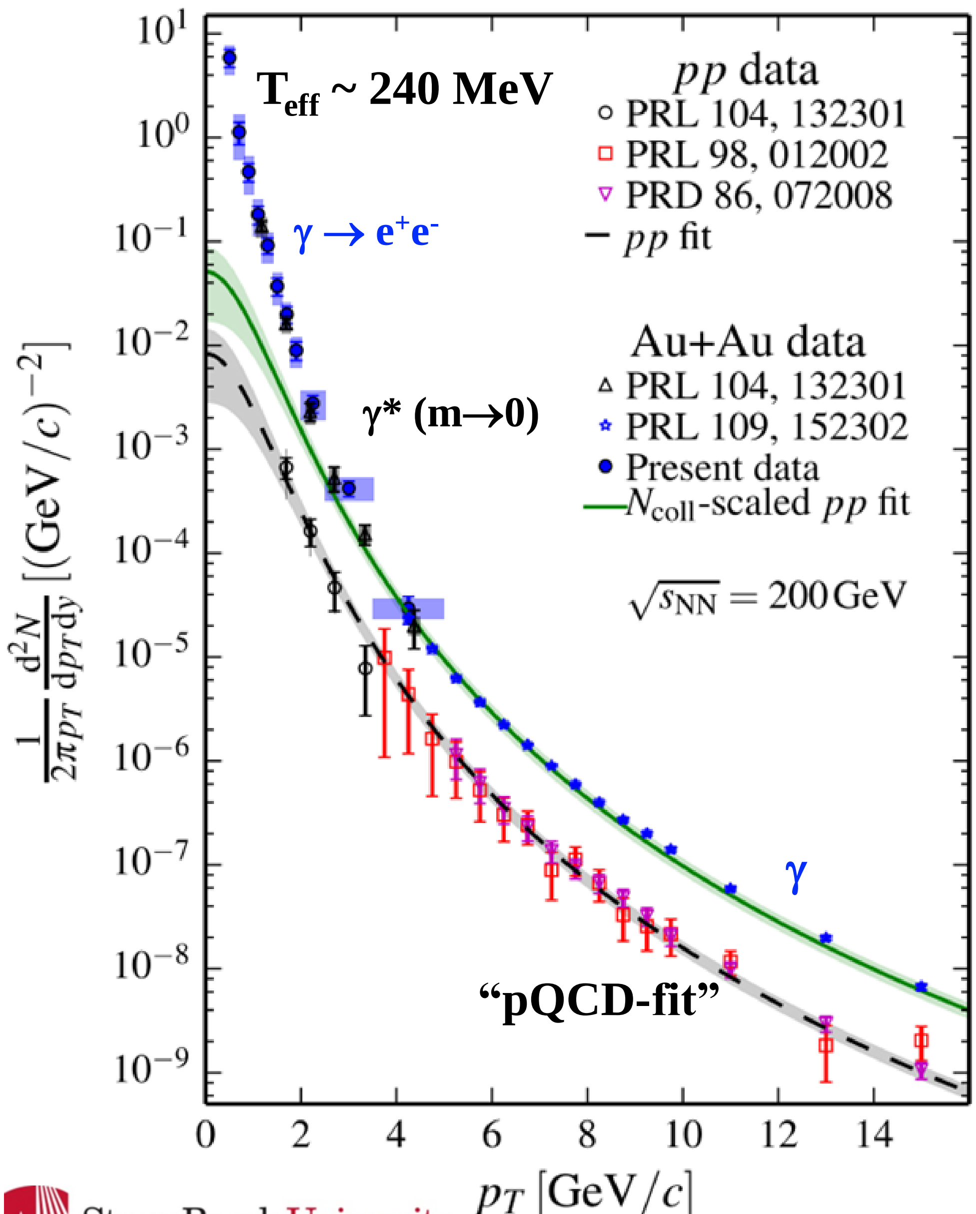
# Experimental Issue: Isolate Thermal Radiation




***Subtraction of decay and prompt contributions***
***Requires $\sigma_{sys} \ll 10\%$***

# Direct Photons p+p and Au+Au at $\sqrt{s_{NN}}$= 200 GeV

*PHENIX: Phys. Rev. C 91 064904 (2015)*




- **Direct photon yield well established**
  - **pp consistent with pQCD**
  - **AuAu follows $N_{coll}$ scaled pp above 4 GeV**
  - **Significant excess below 3 GeV in AuAu**
  - **Excess has nearly exponential shape**

**Significant low momentum direct photon production beyond prompt (pQCD) component**

**Qualitative consistent with expected thermal radiation**

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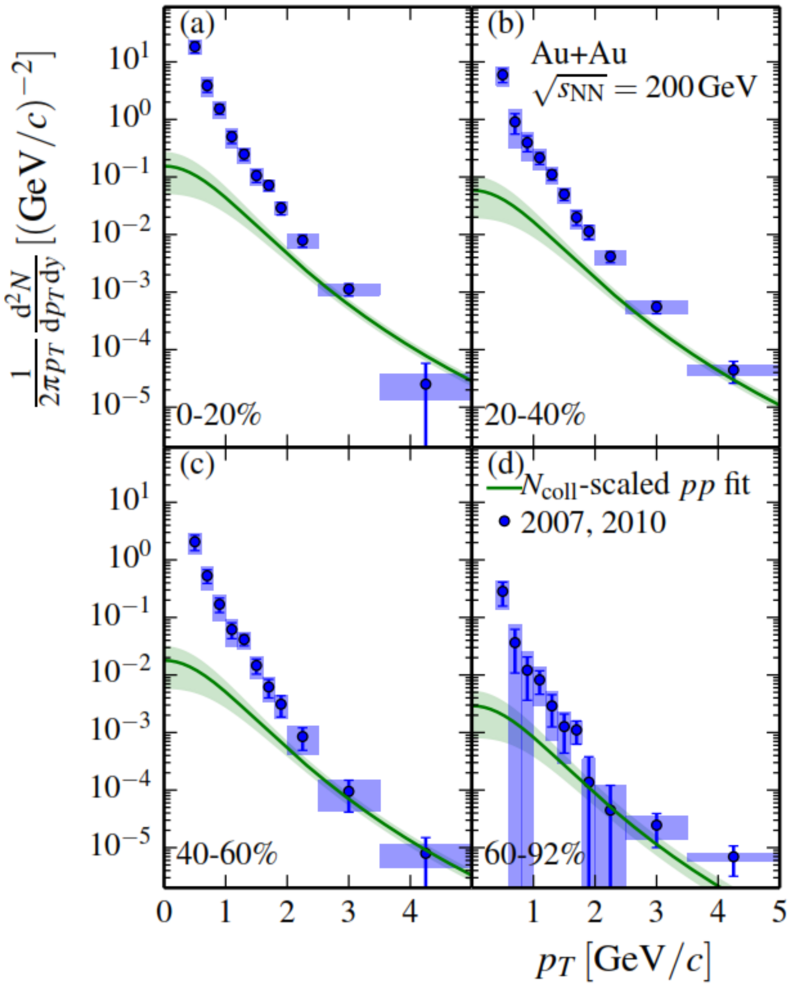
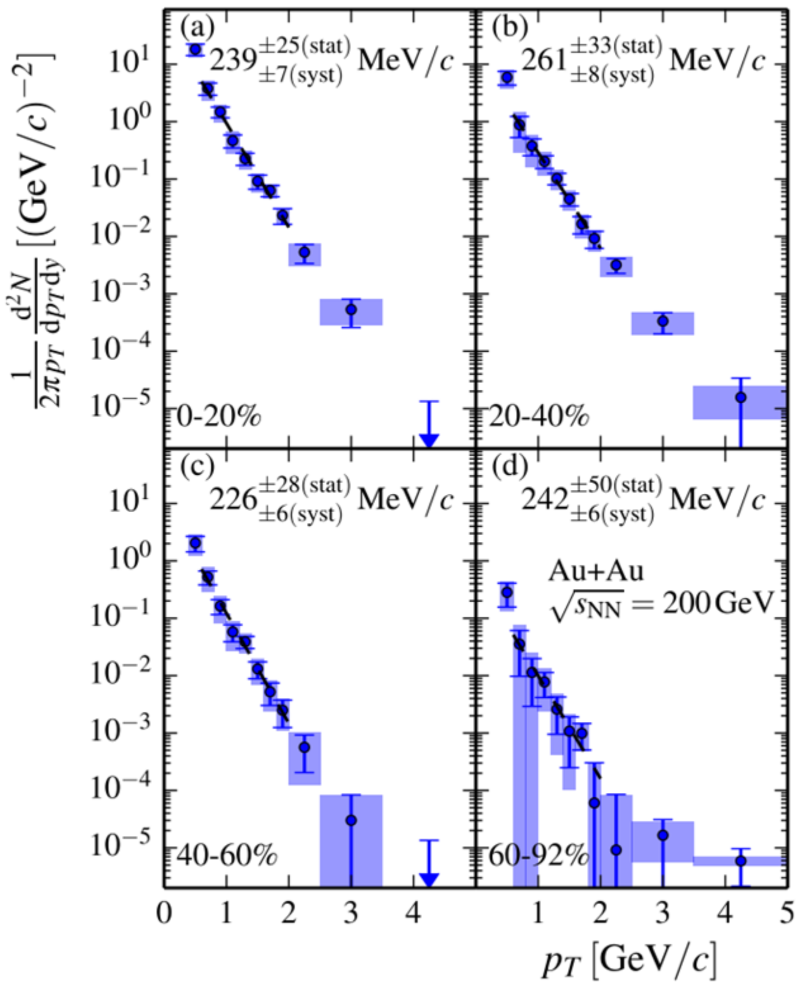
PHENIX

# Centrality Dependence of Thermal Component

*PHENIX: Phys. Rev. C 91 064904 (2015)*




**Large direct photon excess**

**yield $\propto N_{part}^{1.38\pm0.3\pm0.07}$ with inv. slope T ~ 240 MeV**

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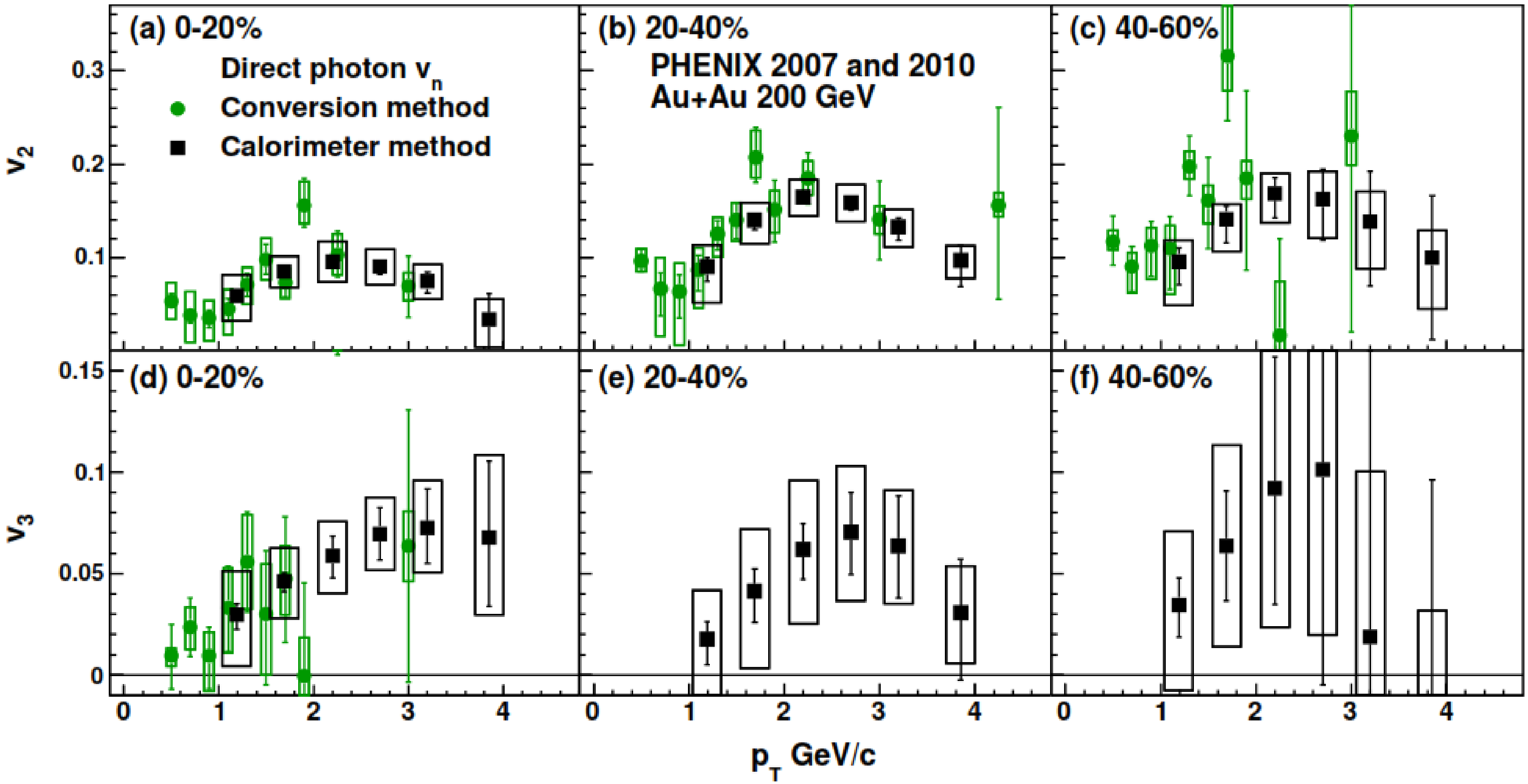
# Anisotropic Emission of Direct Photons

*PHENIX: Phys. Rev. C 91 064904 (2015)*



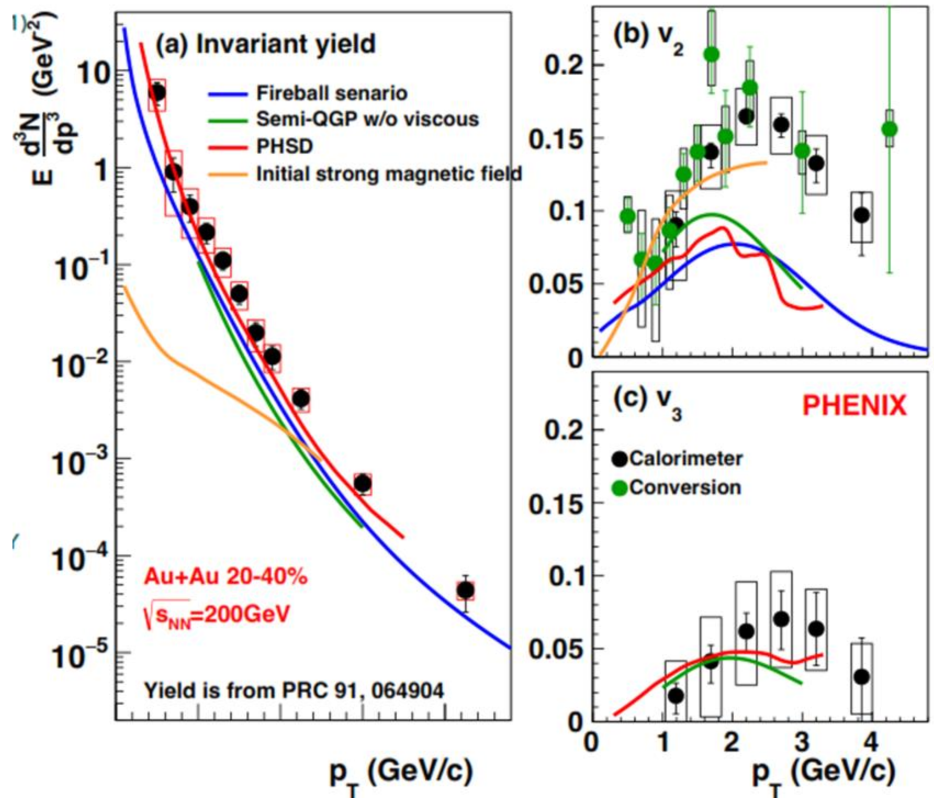

**Anisotropic emission of direct photon with large $v_2$ and $v_3$**

# Direct Photon Puzzle

*PHENIX: Phys. Rev. C 91 064904 (2015)*

**Many model calculations and consideration*:**

- **More traditional, large contribution from hadron gas**
  - Thermal rate in QGP & HG, with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)
- **New early contributions**
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions
- **New effects at phase boundary**
  - Extended emission
  - Emission at hadronization




**Large yield and $v_n$ challenge understanding of sources, emission rates and space-time evolution**

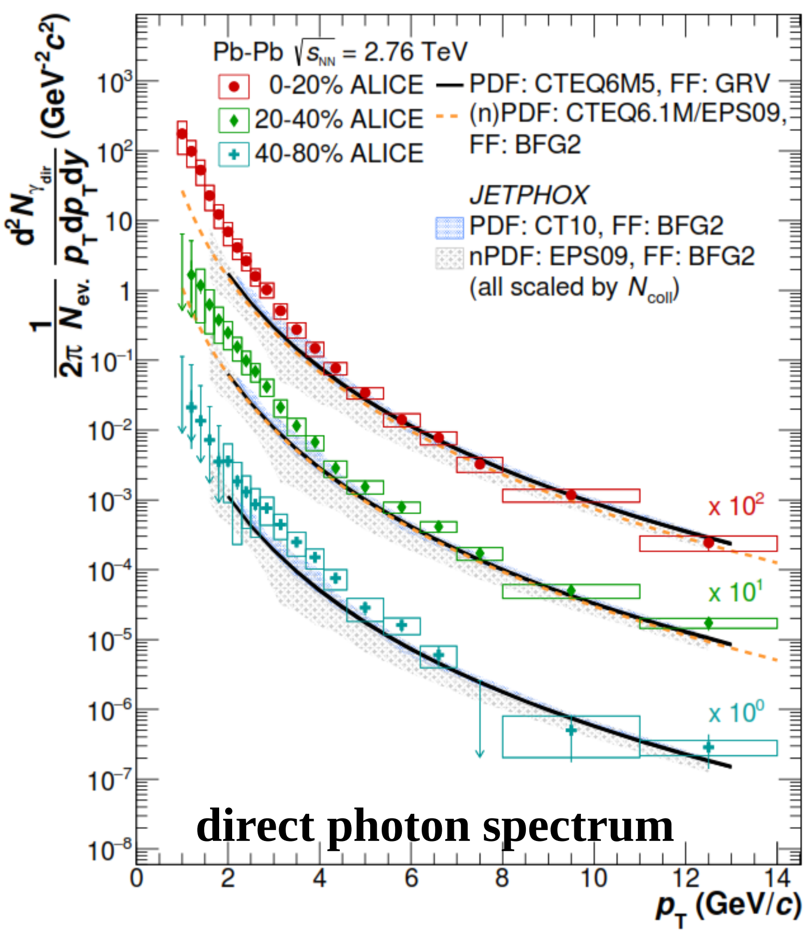
**list not complete*

# First Results from LHC

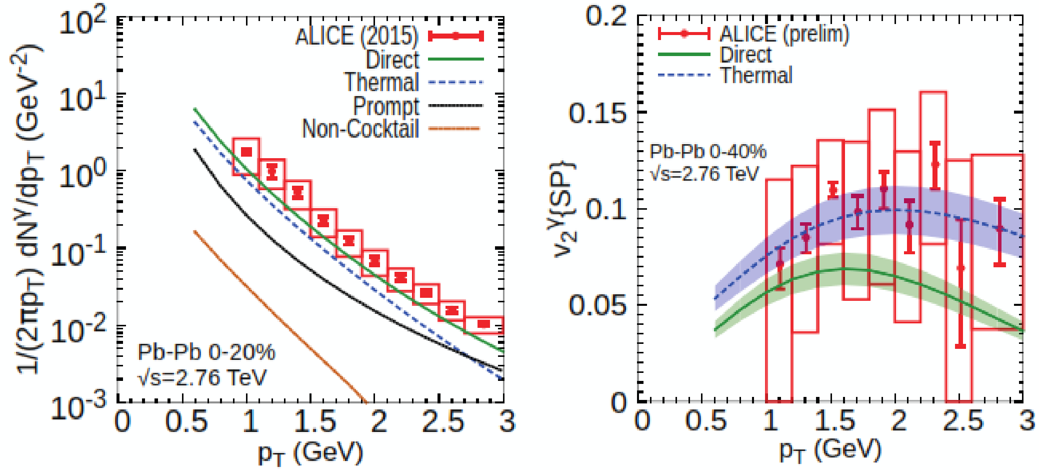
*ALICE: Phys. Lett. B 574 (2016) 235*

Central Pb+Pb 2.76 TeV:

$$T_{\mathrm{eff}}^{\mathrm{no\,subtr}} = (304 \pm 11^{\mathrm{stat}} \pm 40^{\mathrm{syst}})\,\mathrm{MeV}$$




*JF. Paquet et al. Phys. Rev. C 93 (2016) 044906*

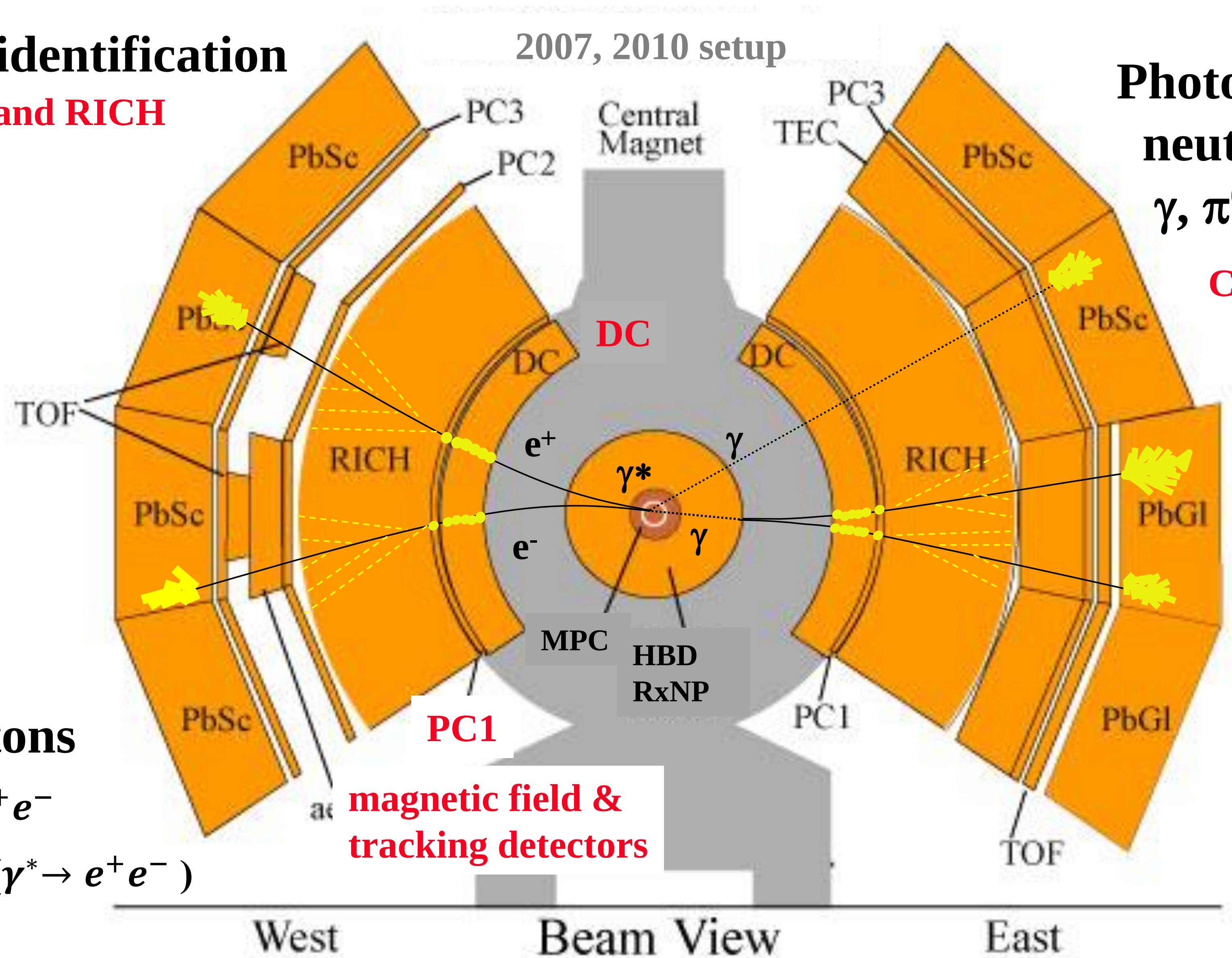



**Direct photon flow and yield at LHC:**
**Similar trend as PHENIX, within large $\sigma_{sys}$**

# Photon Measurements with PHENIX

**e+e- identification**

E/p and RICH




**Photons, neutral pion**

$\gamma, \pi^0 \to \gamma\,\gamma$

Calorimeter

**Photons**

$\gamma \to e^+e^-$

$\lim_{m_{ee}\to 0}(\gamma^* \to e^+e^-)$

# Using $\gamma^*$ to Measure Direct Photons

- **Searches for thermal photons ongoing since late 1980's at SPS**
  - **WA80 & successors, HELIOS, CERES …**
  - **Established mostly upper limits in relevant range $p_T$ < few GeV**

- **Breakthrough at PHENIX: Measuring direct photons via virtual photons – published 2010** *PHENIX Phys.Rev.Lett 104 (2010) 132301*
  - **Method originally proposed by UA1 for prompt photons**

- **Using virtual photons $\gamma^*$:**
  - **any process that radiates $\gamma$ will also radiate $\gamma^*$**
  - **for $m \ll p_T$ $\gamma^*$ are "almost real"**
  - **extrapolate $\gamma^* \to e^+e^-$ yield to $m = 0$ → direct $\gamma$ yield**
  - **$m > m_\pi$ cut removes 90% of hadron decay background**
  - **S/B improves by factor 10 so that 10% direct $\gamma$ → 100% direct $\gamma^*$**
  - **measure ratio $\gamma^*_{direct}/\gamma^*_{inclusive}$ for sys. uncertainty cancelation**

# Fit $e^+e^-$ Mass Distribution to Extract the Direct Yield:

- **Example: one $p_T$ bin for Au+Au collisions**

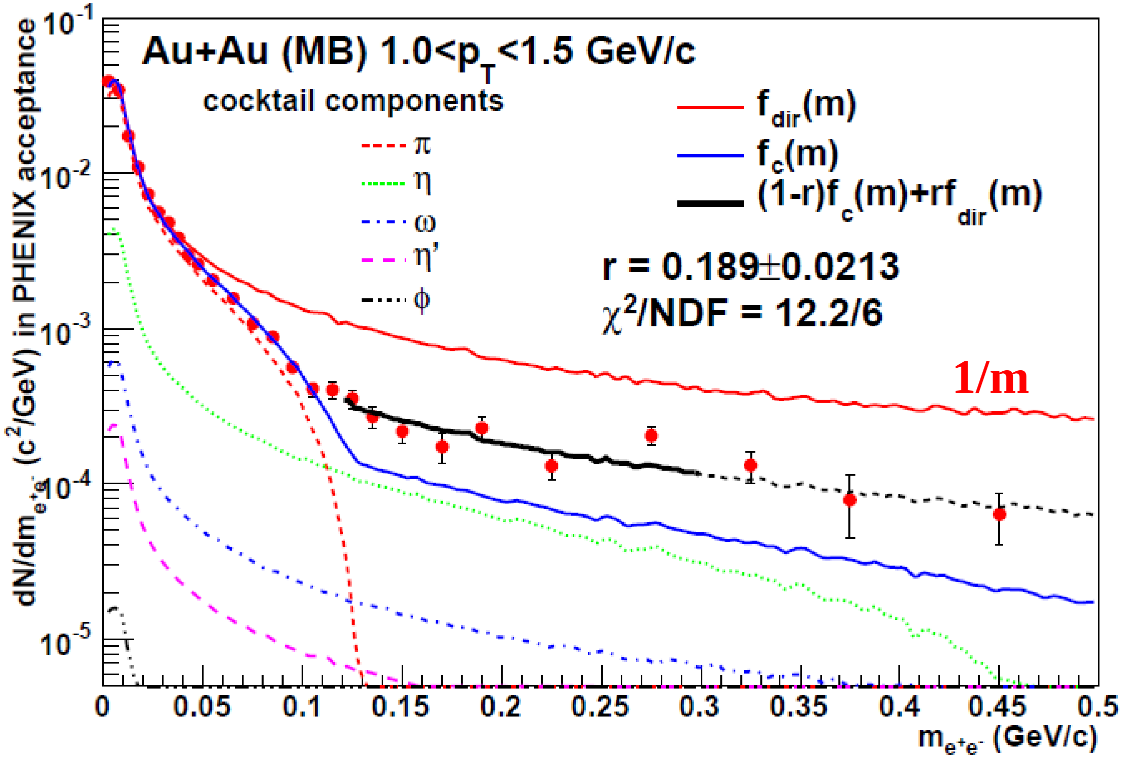
*PHENIX PRL104 (2010) 132301*

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

$f_c(m_{ee})$ and $f_{dir}(m_{ee})$ normalized to data for $m_{ee} < 30\,MeV$

$$r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$$

$$\frac{dN_\gamma^{dir}}{dp_T} = \frac{r}{1-r}\frac{dN_\gamma^{had}}{dp_T}$$




Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to $\pi^0$ yield

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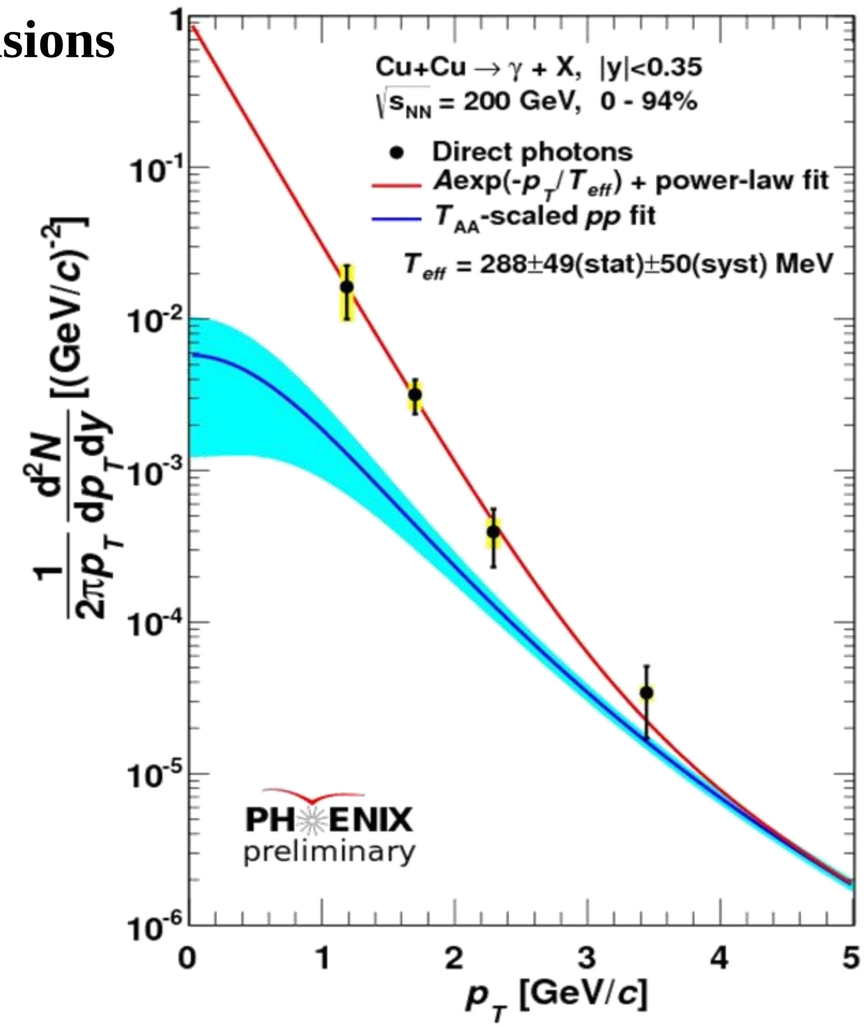



**Clear direct photon signal in Cu+Cu data at $\sqrt{s_{NN}}$ = 200 GeV !**
**Inverse slopes consistent within large uncertainty with Au+Au**

# Direct Photons from Photon Conversions

- **Double ratio tagging method** *(PHENIX: Phys. Rev. C 91 064904 (2015))*
  - **Clean photon sample with photon conversion in detector material (HBD)**

$$\gamma \to e^+e^-$$

  - **Explicit cancelation of  systematic uncertainties**
  - **Data taken in 2010 together with published 200 GeV data**

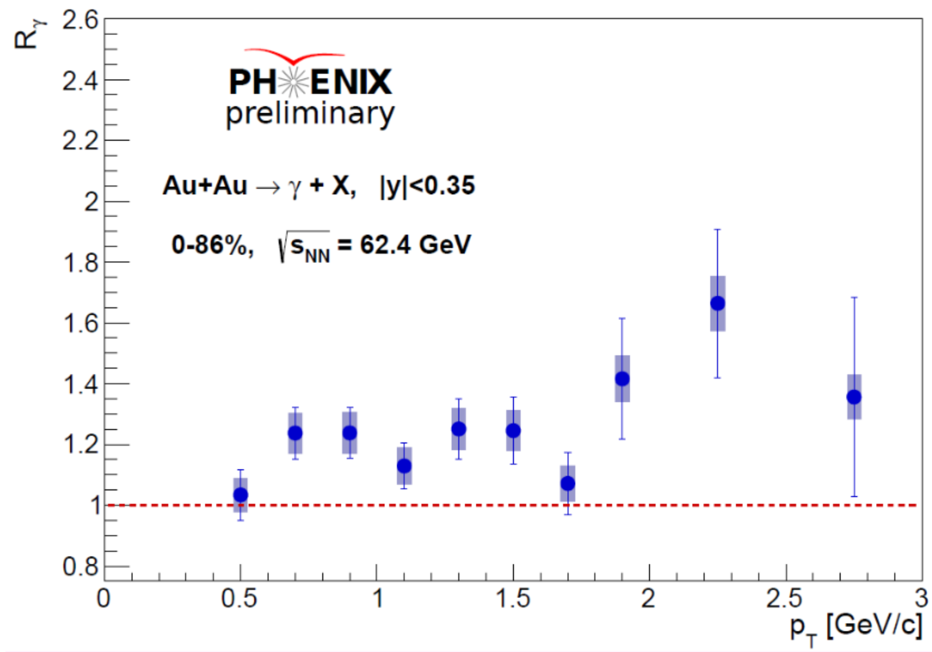
$$\frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} = \frac{N_\gamma^{incl} \; p_{conv} a_{ee} \varepsilon_{ee}}{N_\gamma^{\pi^0 tag} \; p_{conv} a_{ee} \varepsilon_{ee} \langle \varepsilon f \rangle} = \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag} \langle \varepsilon f \rangle}$$

**conditional tagging efficiency**

**measured raw yields**

$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left( \frac{Y_\gamma^{incl}}{Y_\gamma^{\pi^0 tag}} \right)^{Data}}{\left( \frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

**simulated based On hadron data**

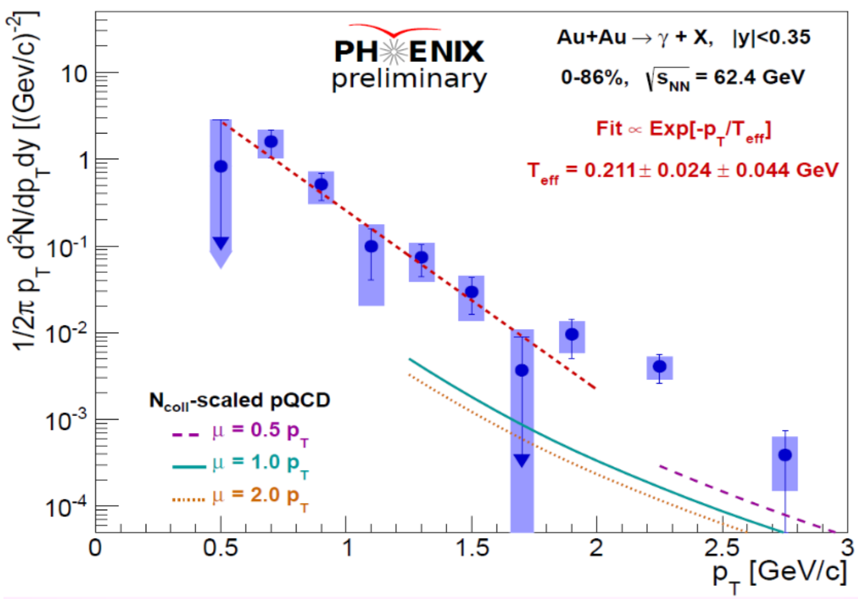



**New Au+Au data at 62.4 and 39 GeV!**

# Au+Au Data at 62.4 GeV and 39 GeV

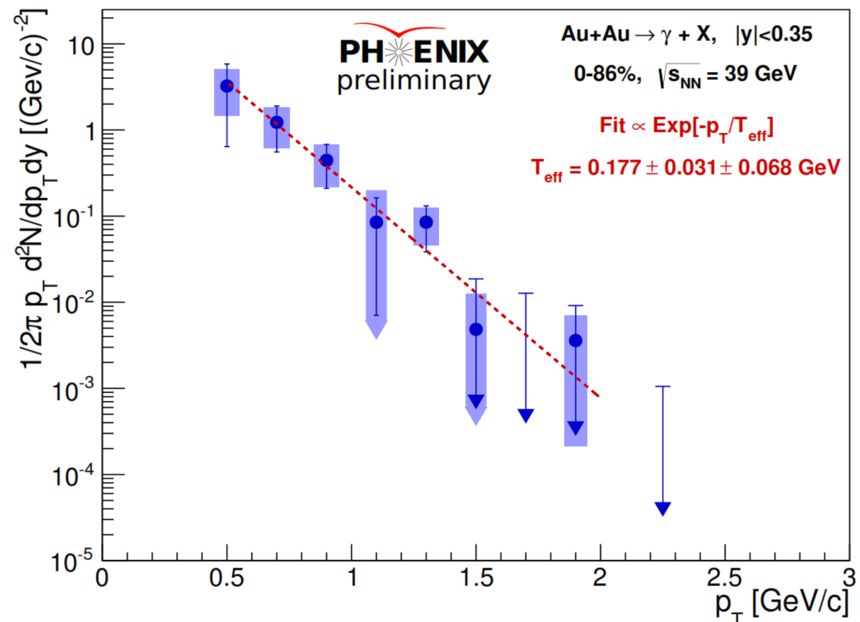
$$\frac{dN_\gamma^{dir}}{dp_T} = (R_\gamma - 1)\frac{dN_\gamma^{had}}{dp_T}$$

**min. bias Au+Au 62.4 GeV**




$T_{eff}$ = 0.211 ± 0.024 ± 0.044 GeV

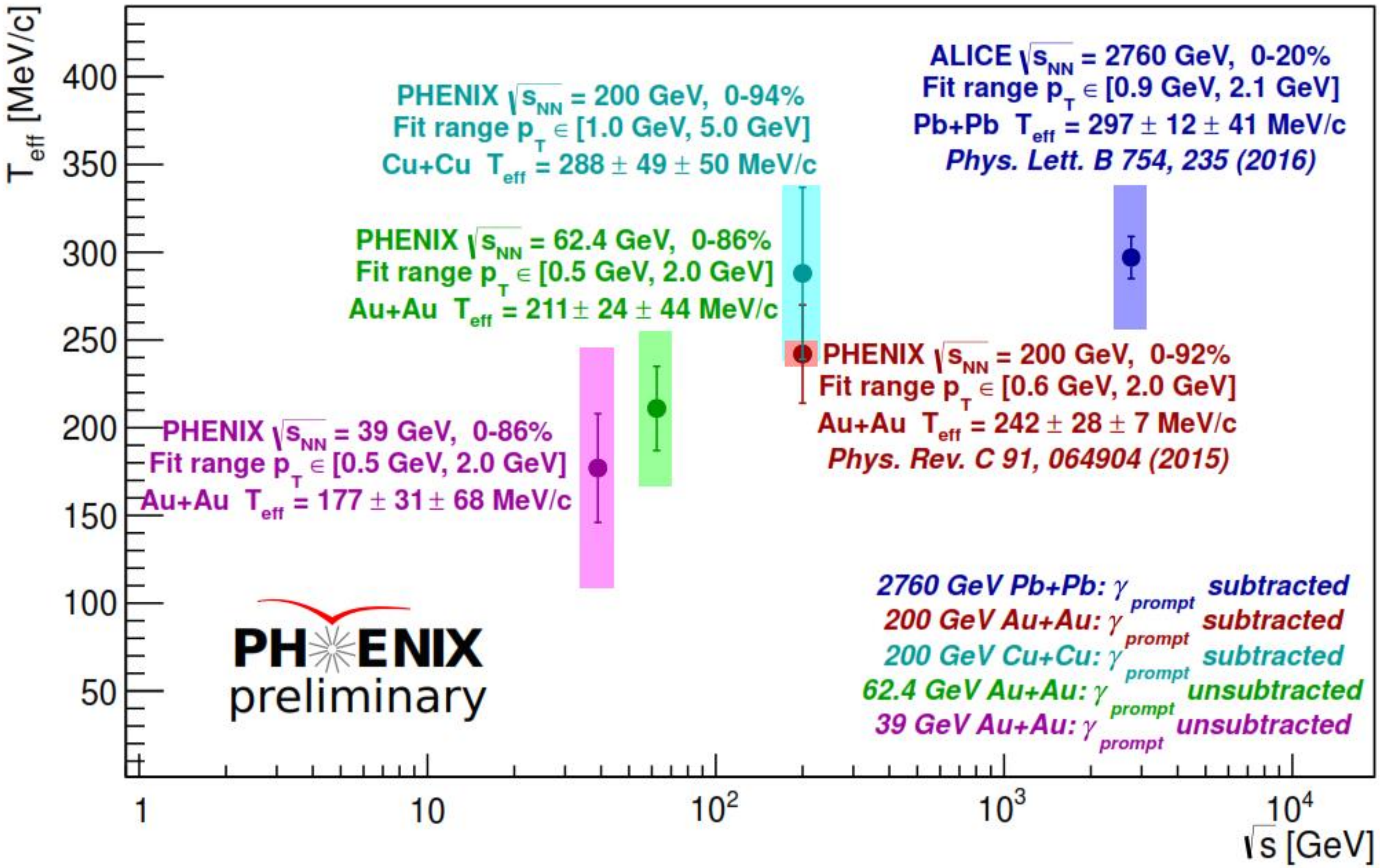
**min. bias Au+Au 39 GeV**




$T_{eff}$ = 0.177 ± 0.031 ± 0.068 GeV

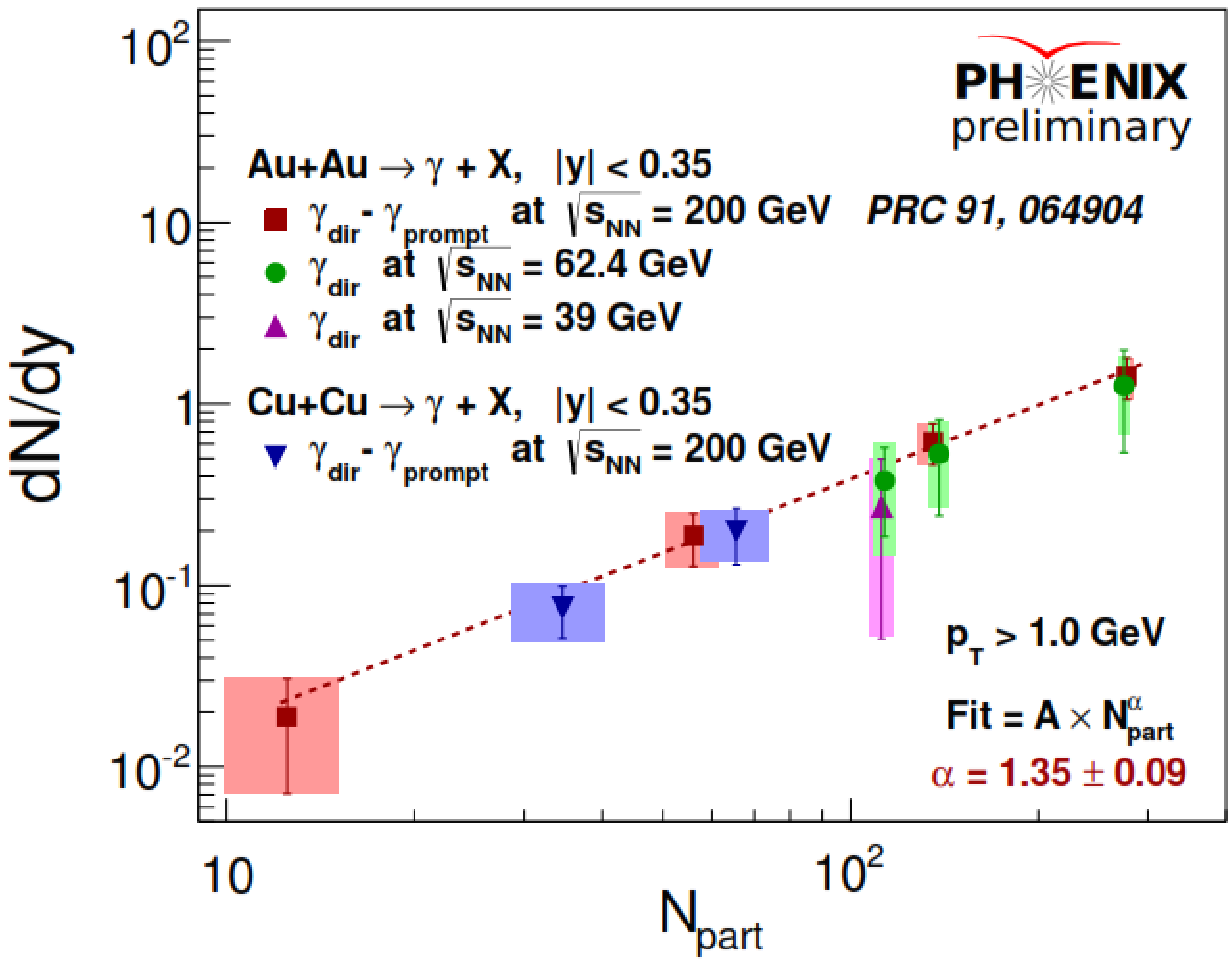
**Clear direct photon signal in Au+Au at 62.4 GeV and 39 GeV**

# $T_{eff}$ vs Collision Energy




**Possible increase of $T_{eff}$ with increasing beam energy**

# Direct Photon Yield vs $N_{part}$




yield $\propto N_{part}^{\alpha}$
with α ~ 1.4

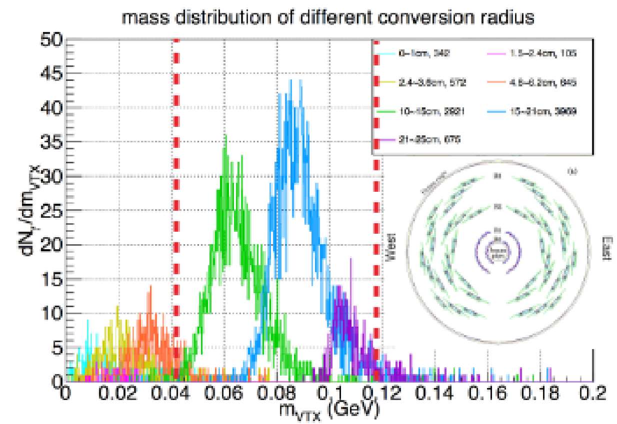
$N_{part} \propto$ volume

**Similar increase with $N_{part}$ for different systems**
**Yield increases faster than reaction volume**

# New $\gamma \rightarrow e^+e^-$ Reconstruction Technique

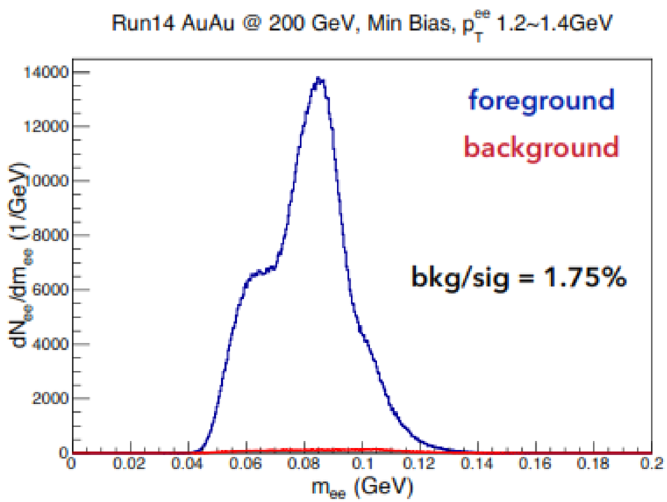
Identify and reconstruct photons via external conversion to $e^+e^-$ pairs

- Previous method used single $e^+/e^-$ tracks (2010)
  - Conversions at fixed radius (Hadron Blind Detector readout plane at 60cm, ~3%)
- New method used $e^+e^-$ pairs (>2011)
  - Conversions at any material (VTX 3rd and 4th layer, ~10%)

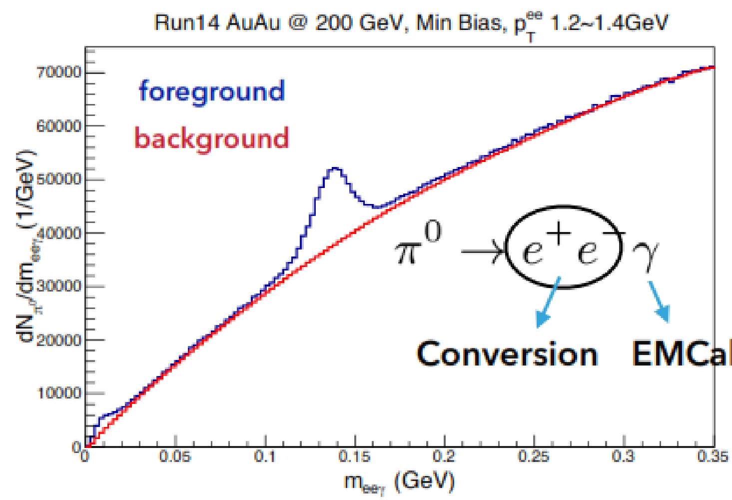



MC simulation

**inclusive photon ($e^+e^-$) mass**



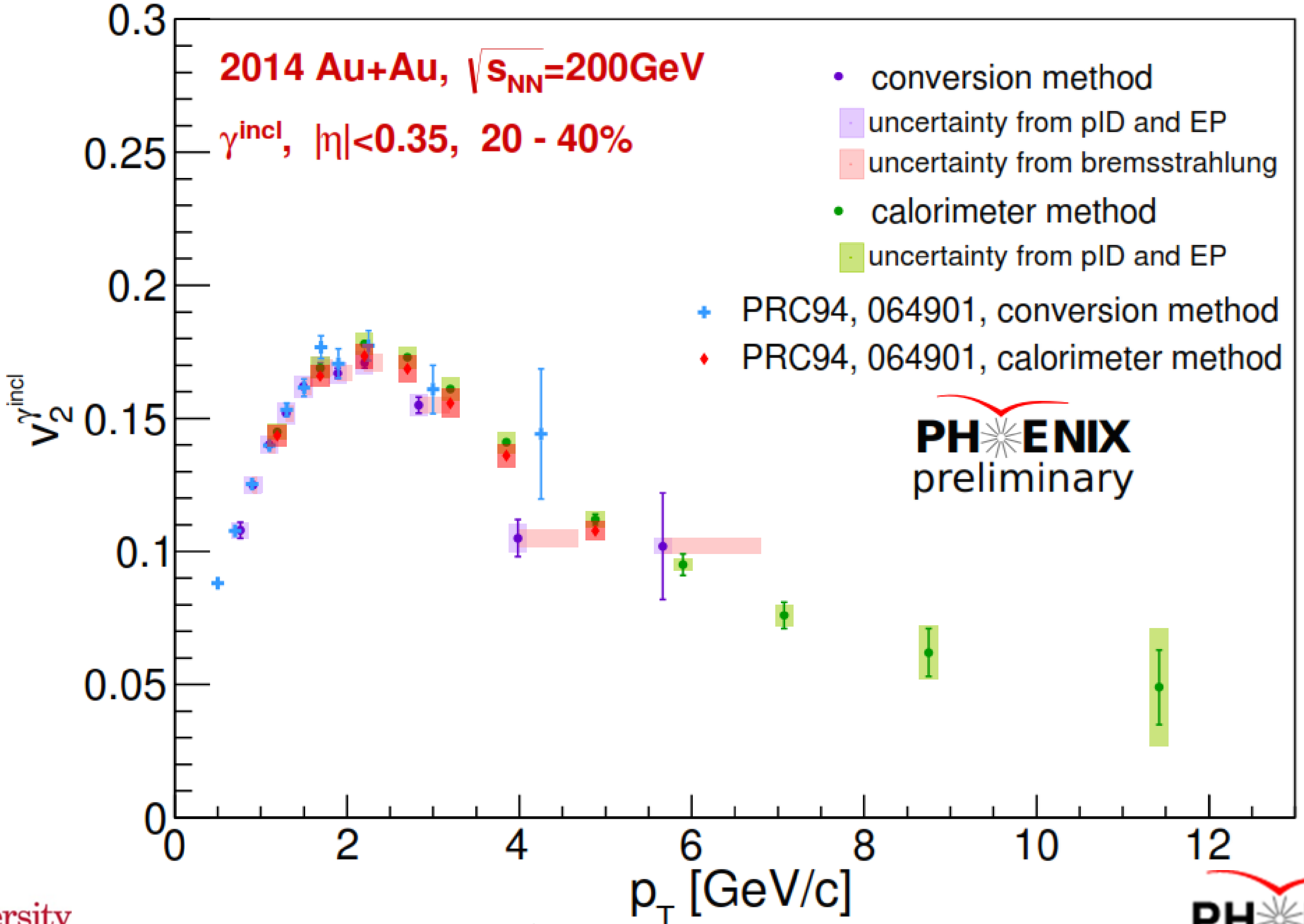

**$\pi^0$ ($e^+e^-\gamma$) mass**




- Other systems: AuAu, CuAu, He3Au, pp, pA, dAu

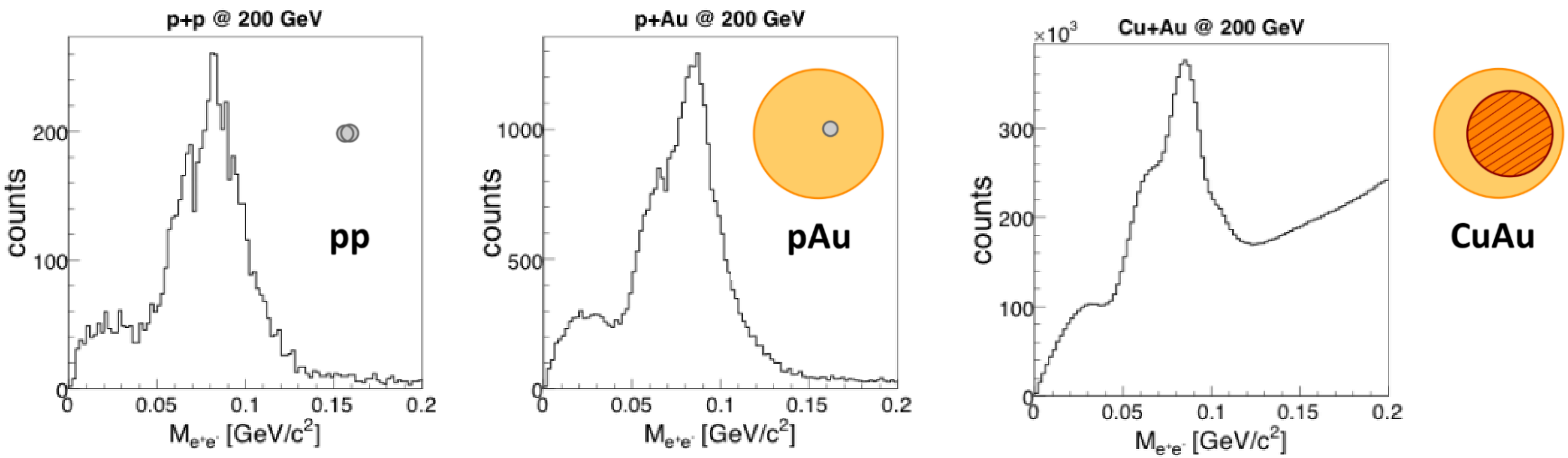
# Future Measurements: High Statistics Au+Au

- **Comparison of inclusive photon $v_2^{incl}$ from Au+Au at 200 GeV**
  - **Combined statistics 2007 & 2010 data** *PHENIX: Phys. Rev. C 91 064904 (2015)*
  - **22% of 2014 data**
  - **2014 + 2016 Au+Au data more than 10x statistics compared to published results**



# Future Measurements: Different Systems

## $2.0 < p_T < 2.5$ GeV/c




**Clear photon signal in all systems**

- **Data will provide interesting new information on:**
  - **Direct photon spectrum from p+p at low $p_T$**
  - **Search for thermal photons from small systems p+Au, d+Au and $^3$He+Au**
  - **Variation of collision geometry with Cu+Au to test origin of $v_2$**

# Summary and Outlook

- **Well established measurement of low momentum direct photon in Au+Au at 200 GeV from PHENIX**
  - **Large yield above expected contribution from pQCD**
  - **Centrality dependence of yield ~ $N_{part}^{1.4}$**
  - **Large anisotropy $v_2$ with respect to reaction plan**
- **Consistent data from LHC in Pb+Pb at 2.76 TeV**
- **Thermal photon puzzle persists**
- **New data from Cu+Cu at 200 GeV and Au+Au at 62.4 & 39 GeV**
  - **Consistent with observed ~ $N_{part}^{1.4}$ dependence**
  - **Possible trend of inverse slope $T_{eff}$ with beam energy**
- **More measurements to come in from future:**
  - **High statistics Au+Au data (factor >10) from 2014 & 2016**
  - **Data from different collision geometry Cu+Au**
  - **Low momentum data from p+p (2015)**
  - **Search for direct photons in small systems p+Au (2015), d+Au (2016), 3He+Au (2014)**

**Thank you**