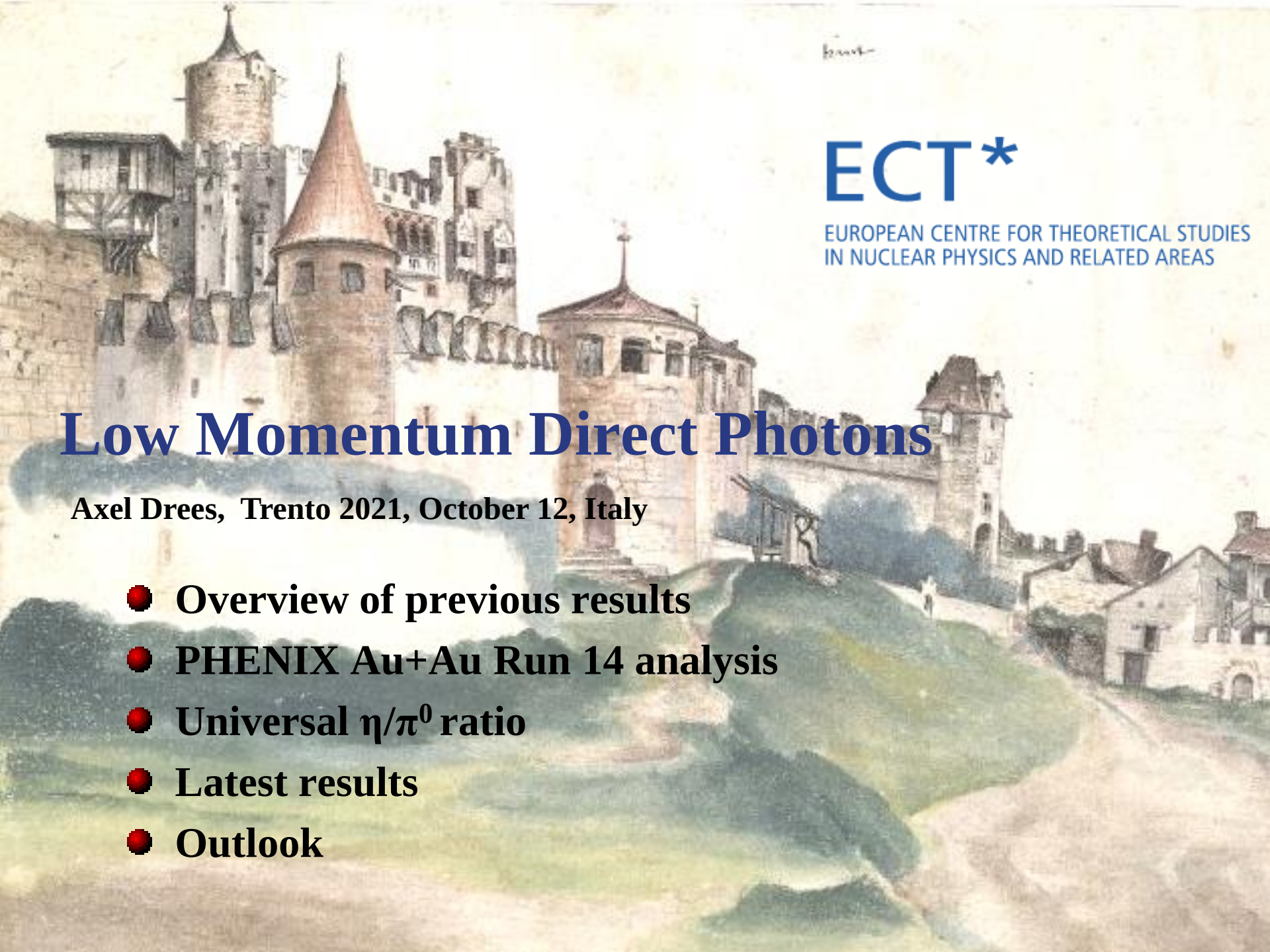
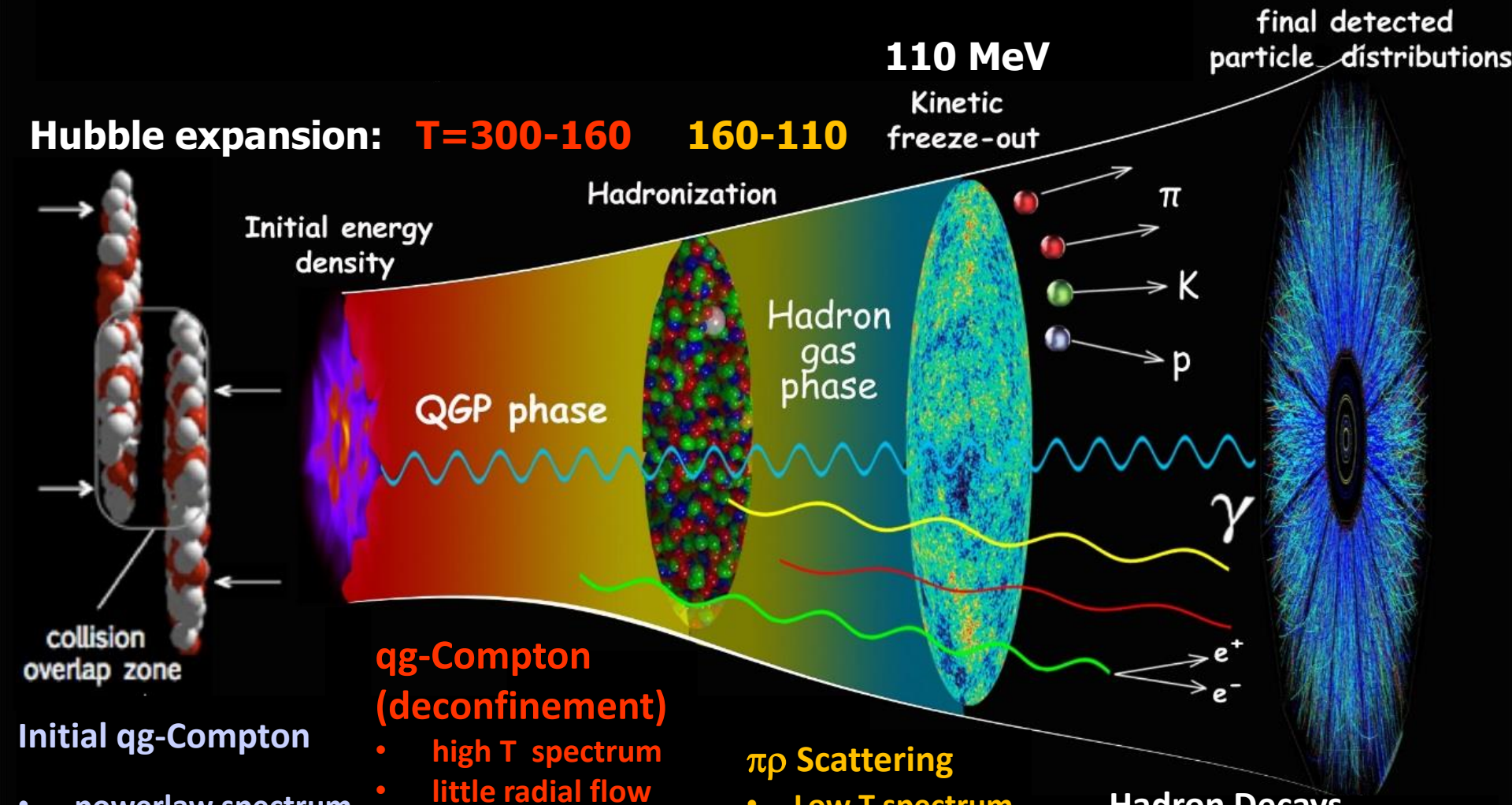


Low Momentum Direct Photons

Axel Drees, Trento 2021, October 12, Italy

- **Overview of previous results**
- **PHENIX Au+Au Run 14 analysis**
- **Universal η/π^0 ratio**
- **Latest results**
- **Outlook**

Electromagnetic Radiation in A+A Collisions:



Initial qg-Compton

- powerlaw spectrum
- $\propto N_{coll}$
- no collective motion

qg-Compton (deconfinement)

- high T spectrum
- little radial flow
- yield $\propto N_{ch}^{\alpha}$ $\alpha \leq 2$

πρ Scattering

- Low T spectrum
- Large flow/ blue shift
- yield $\propto N_{ch}^{\alpha}$ $\alpha > 1$

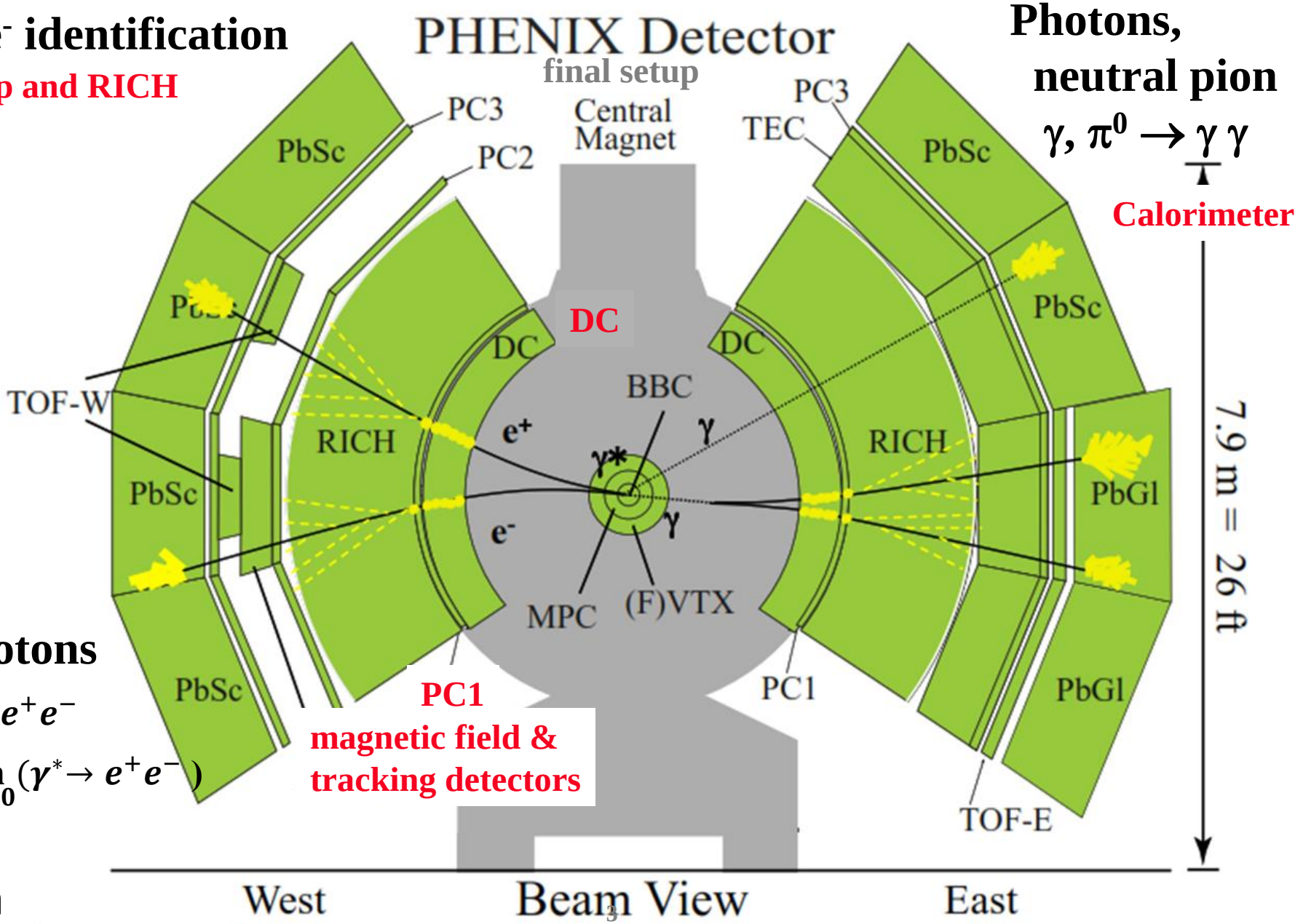
Hadron Decays

- yield $\propto N_{ch}$
- Spectra derived from parent particles

Photon Measurements with PHENIX

e^+e^- identification

E/p and RICH



Photons, neutral pion

$\gamma, \pi^0 \rightarrow \gamma\,\gamma$

Calorimeter

Photons

$\gamma \rightarrow e^+e^-$

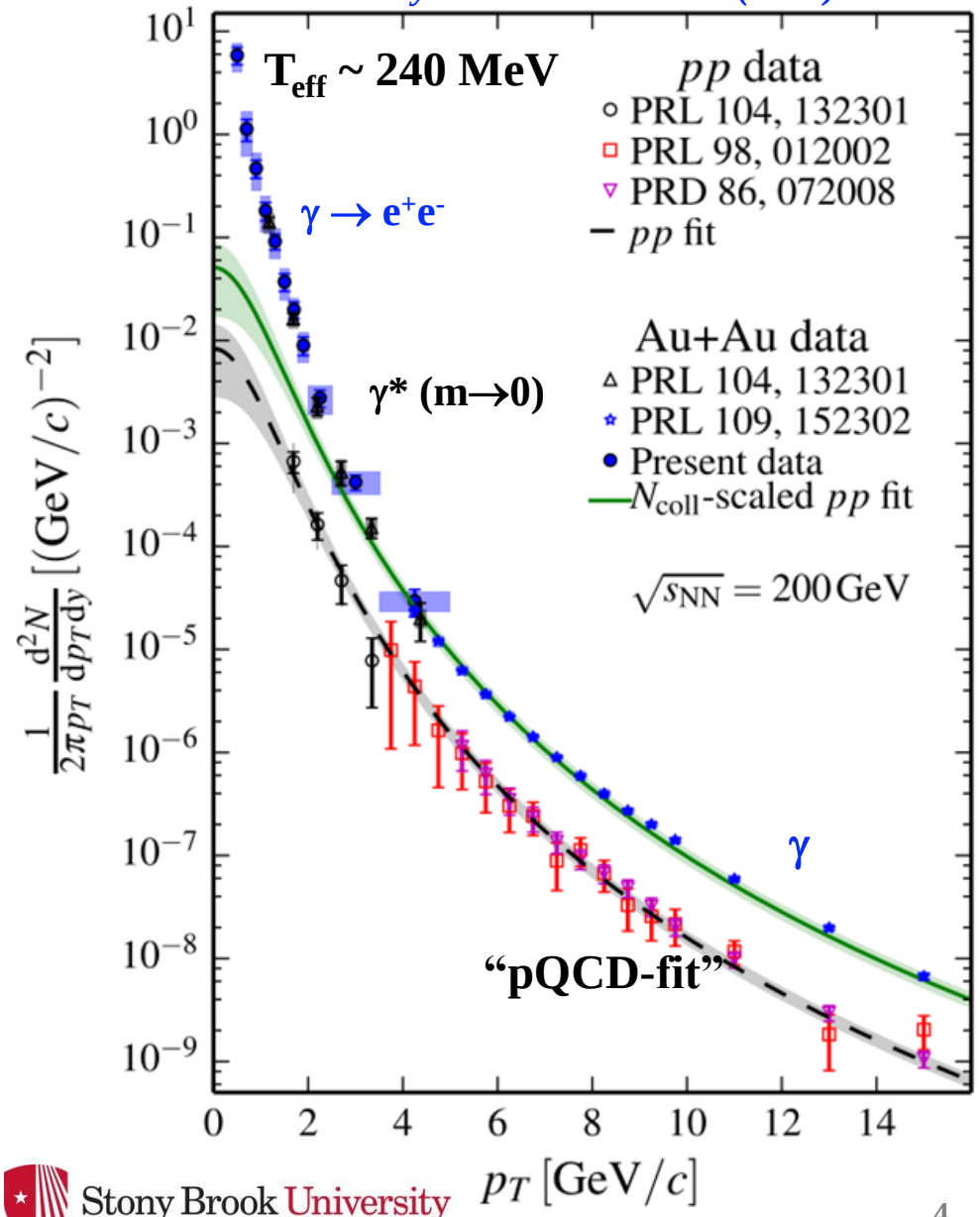
$\lim_{m_{ee}\rightarrow 0}(\gamma^* \rightarrow e^+e^-)$

magnetic field & tracking detectors

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

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

PhD - B. Bannier, R. Petti
PhD – T.Dahms



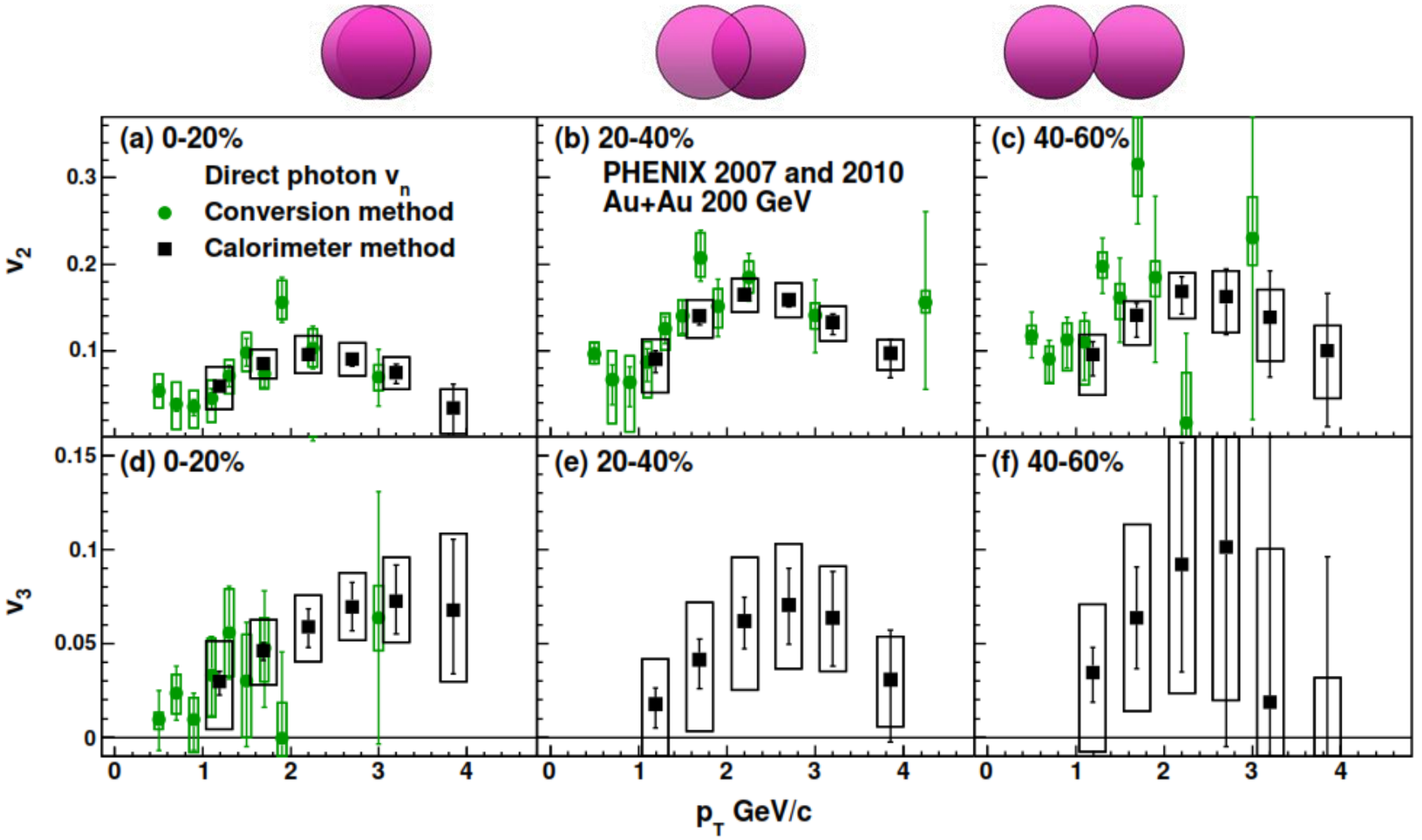
- **Direct photon yield well established**
  - **pp consistent with pQCD**
  - **AuAu follows N_{coll} scaled pp above 4 GeV**
  - **Significant excess below 3 GeV in AuAu**
  - **Excess has nearly exponential shape with T_{eff} ~ 240 MeV**

First thermal photon measurement: T_{ini} > 240 MeV > T_C

(Need to consider exploding source!)

Anisotropic Emission of Direct Photons

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

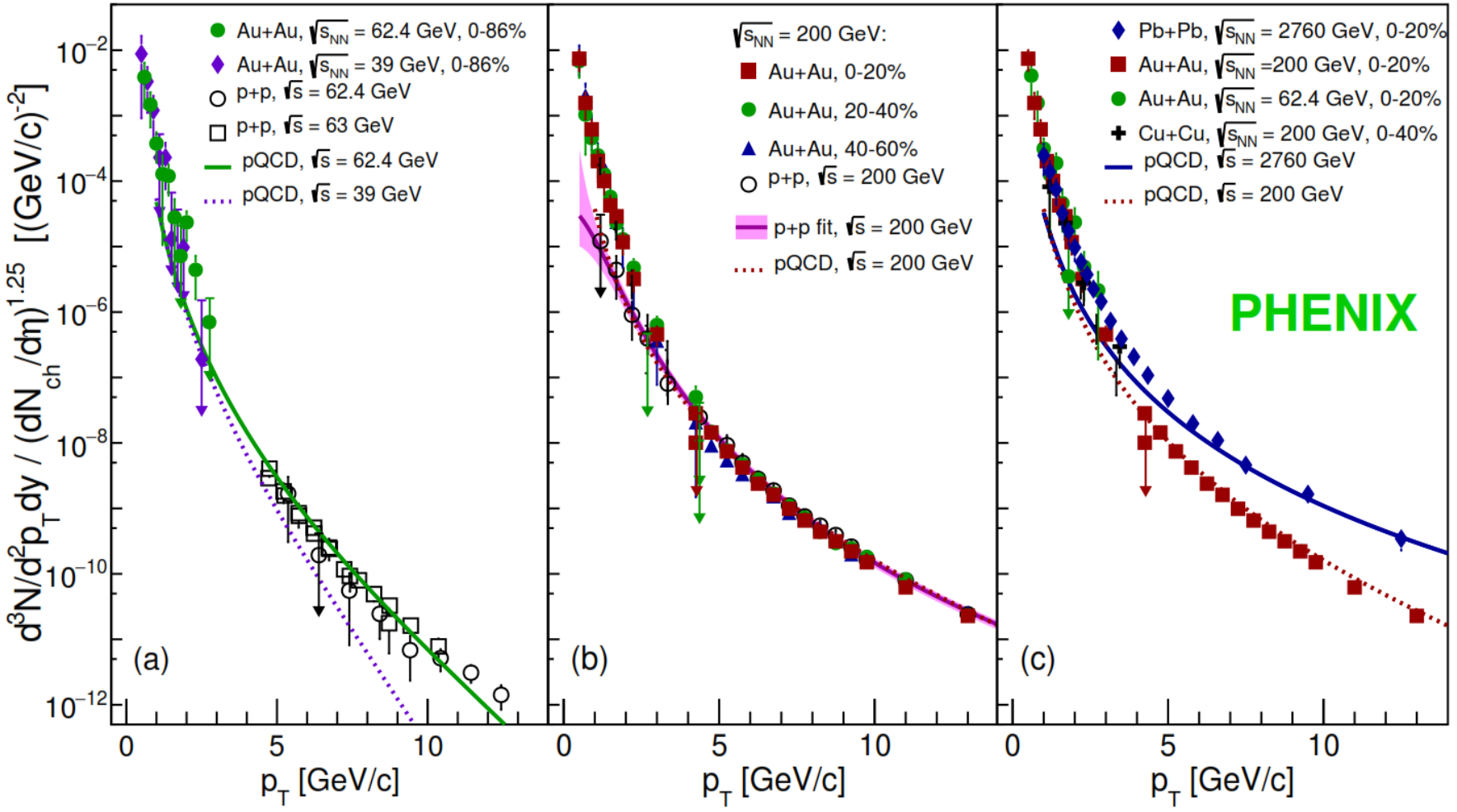


Anisotropic emission of direct photon with large v_2 and v_3

Comparison of Different System Sizes

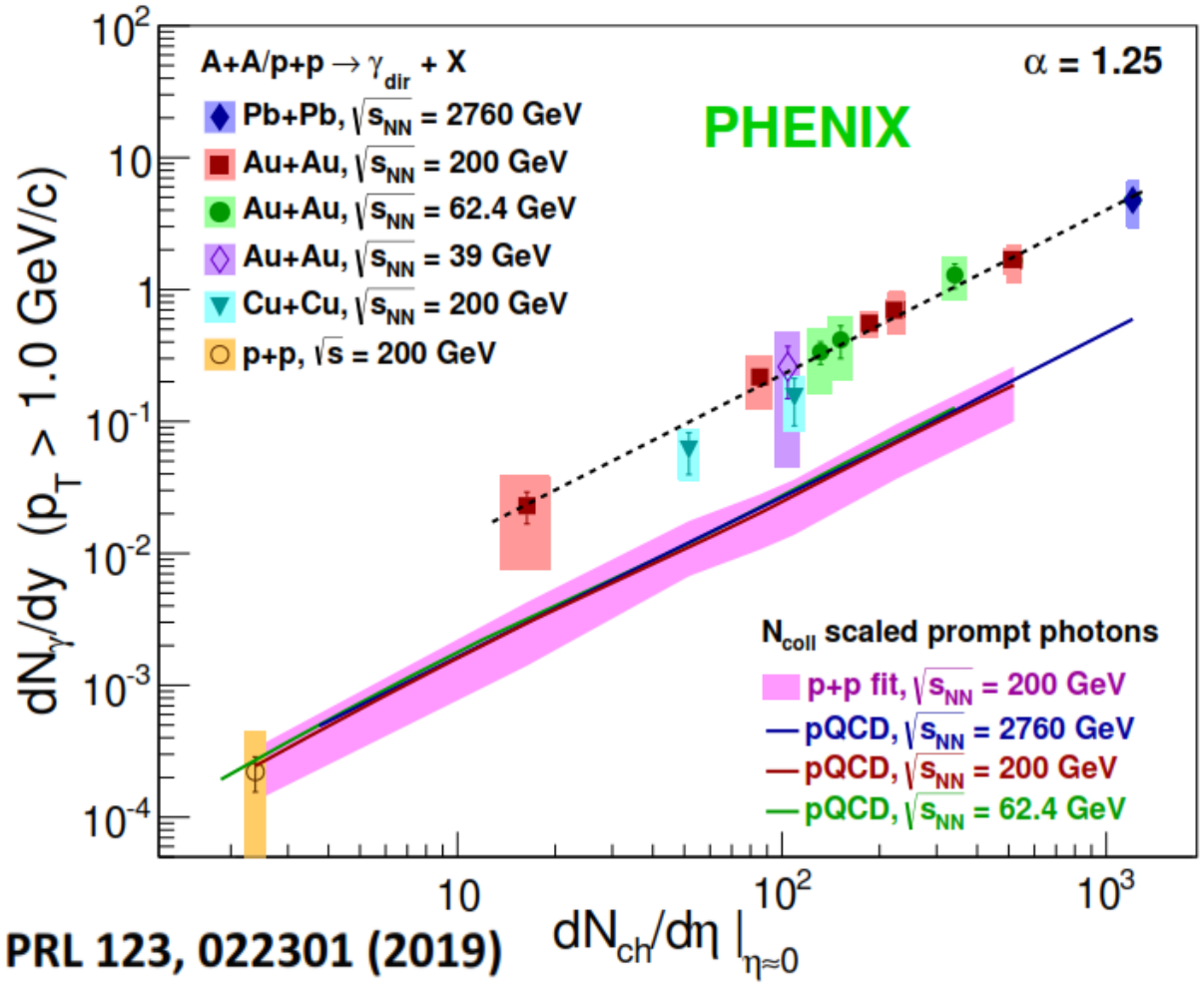
PHENIX: PRL 123 (2019) 022301

ALICE: Phys. Lett. B 754 (2016) 235



Similar thermal photon yield when scaled with $\left(\frac{dN_{ch}}{d\eta}\right)^{1.25}$ independent of energy, centrality, or system size

Integrated "Thermal" Photon Yield



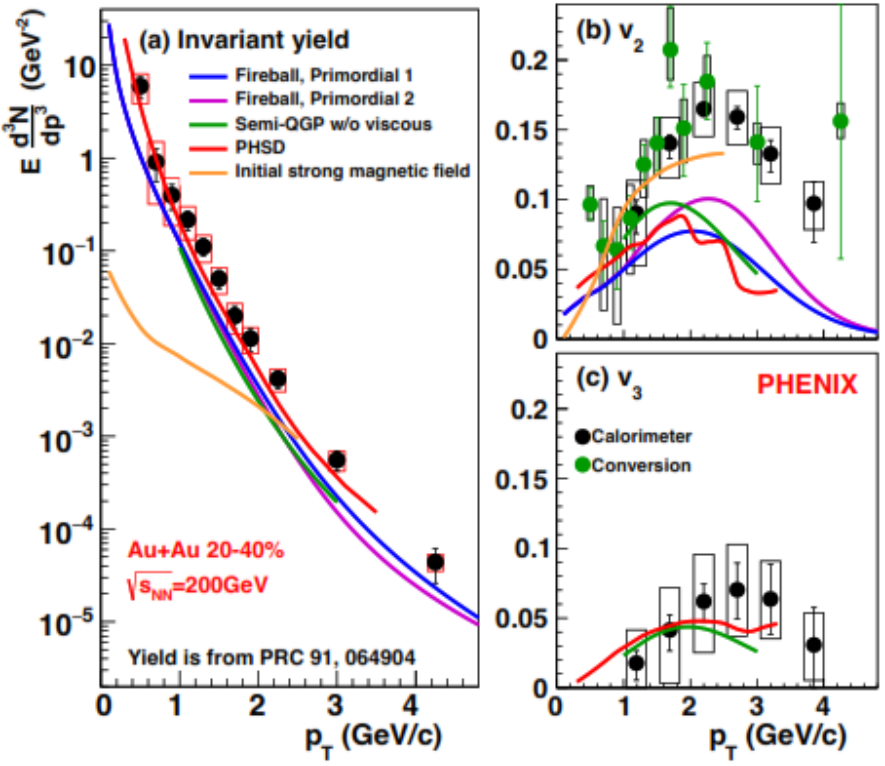
Universal scaling behavior!

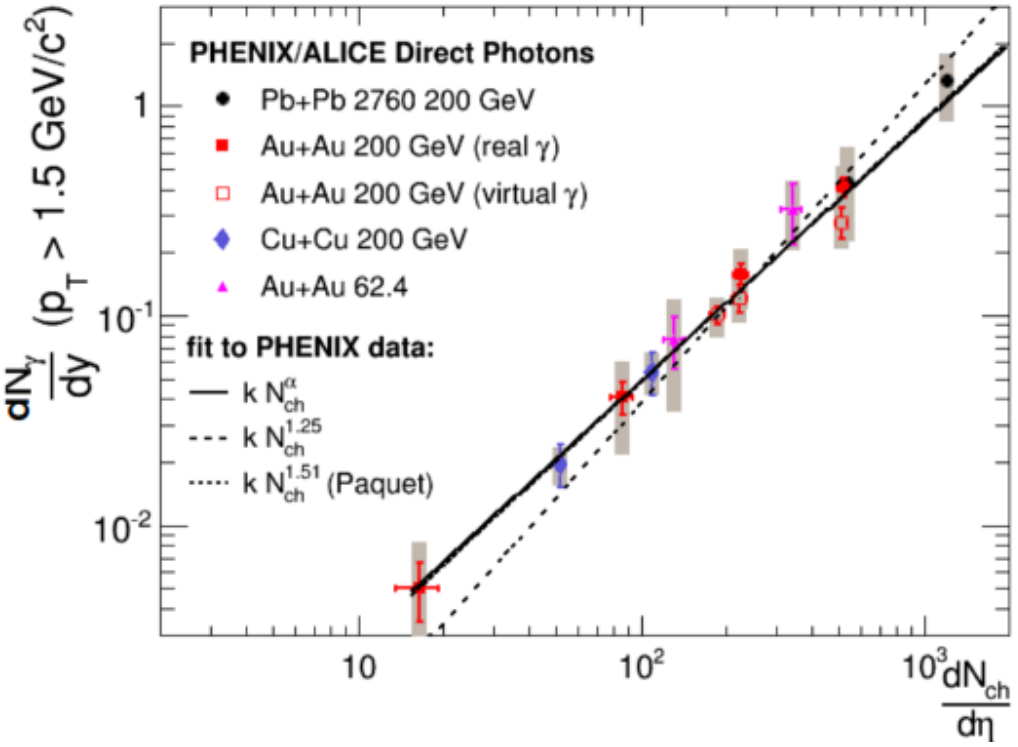
Source of thermal photons must be similar!

Ncoll x pQCD and Ncoll x p+p follow same scaling at 0.1 of yield

Direct Photon Puzzle

- **Qualitative agreement with thermal source**
  - **Large yield of low p_T direct photons**
  - **Large anisotropy in emission (Doppler effect)**
  - **Faster than liner increase: $\frac{dN_\gamma}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$ with $\alpha \sim 5/4$**
- **Quantitative tension with current model predictions**

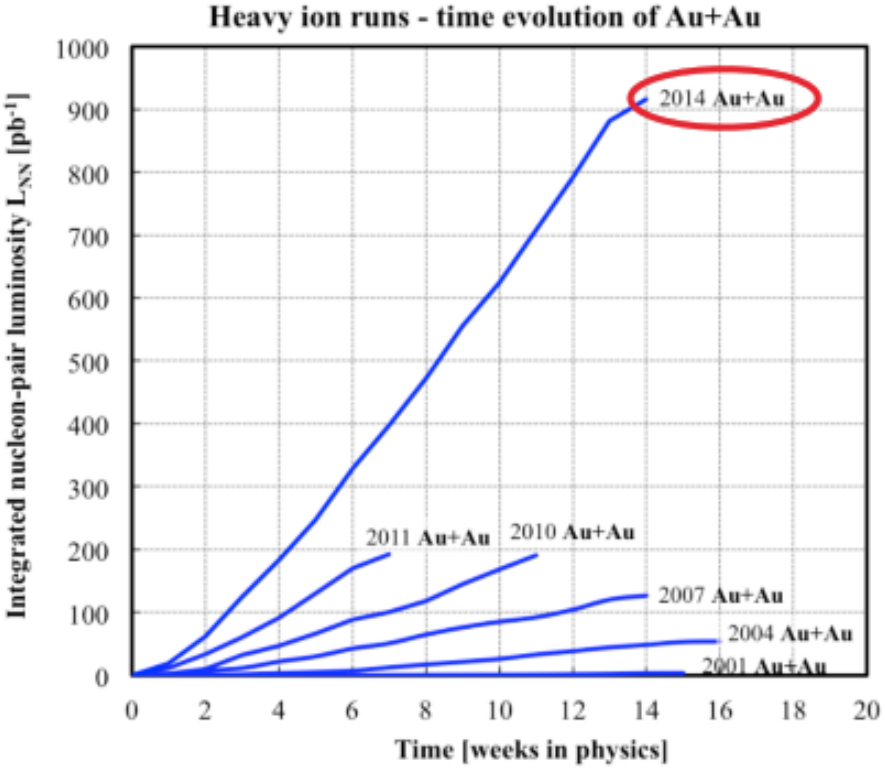


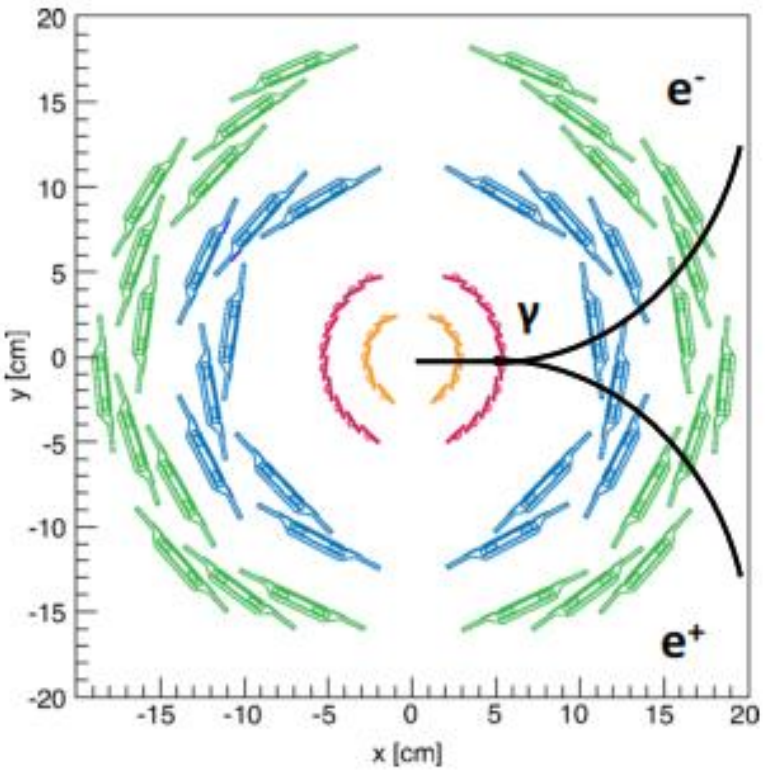


PHENIX Run 14 Analysis

Ph.D. Thesis Wenqing Fan, SBU 2020 – 2020 RHIC/AGS Thesis Award

- **Direct photon analysis with photon conversions**
  - **Nearly 10x previous integrated luminosity**
  - **More conversions at silicon vertex detector (VTX X/X_0~14%)**





Results shown here are for thesis, with publication in preparation

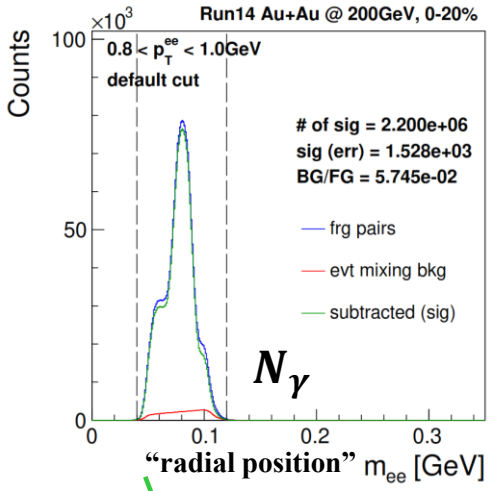
Thermal Photon Measurements

PhD – W.Fan

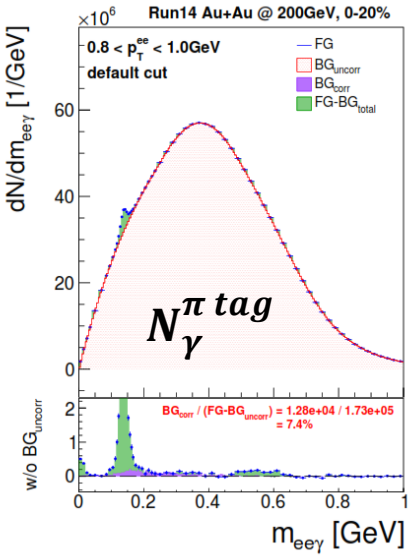
$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

Thermal Photon Measurements

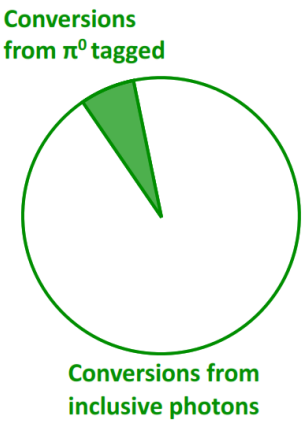
PhD – W.Fan



Closure test with full high multiplicity MC simulation



measured raw yields



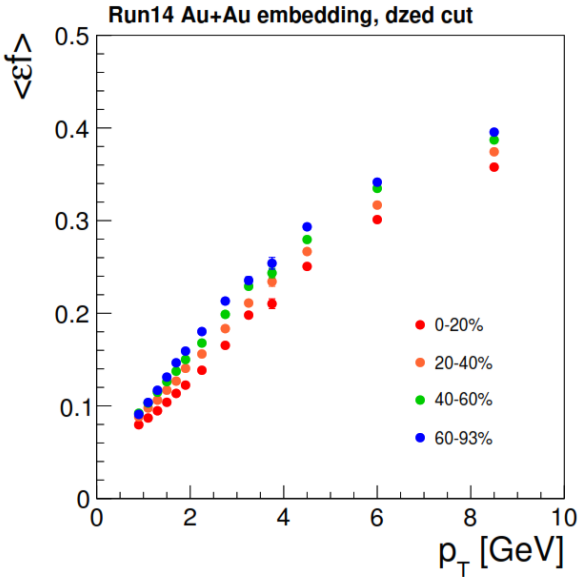
$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

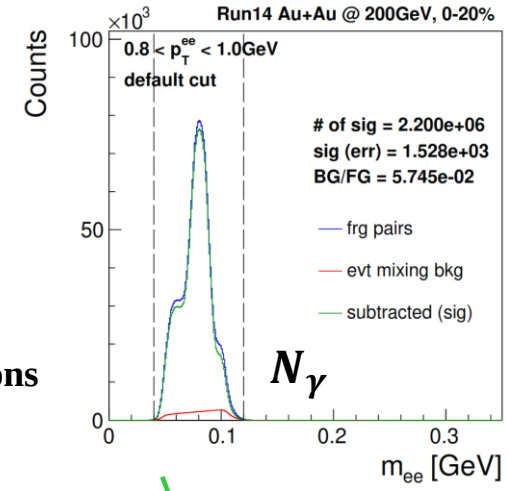
Thermal Photon Measurements

PhD – W.Fan

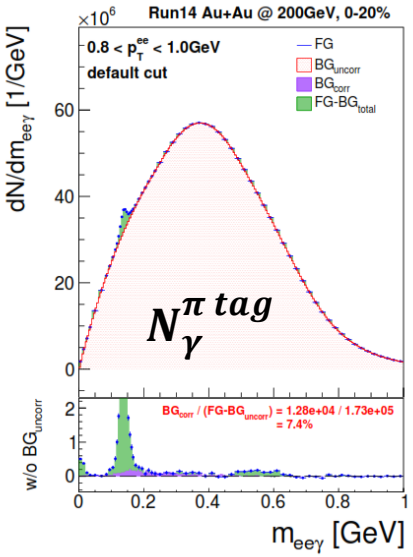
Full MC simulation

conditional tagging efficiency





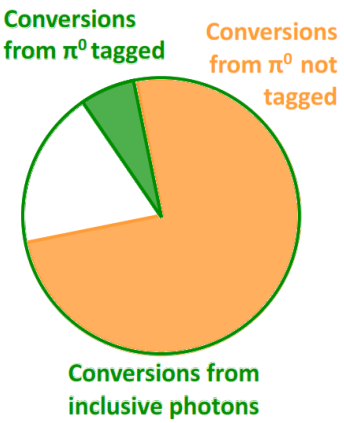
Closure test with full high multiplicity MC simulation



Key contributions

- **Energy cut**
- **Acceptance**
- **Detector material**

measured raw yields



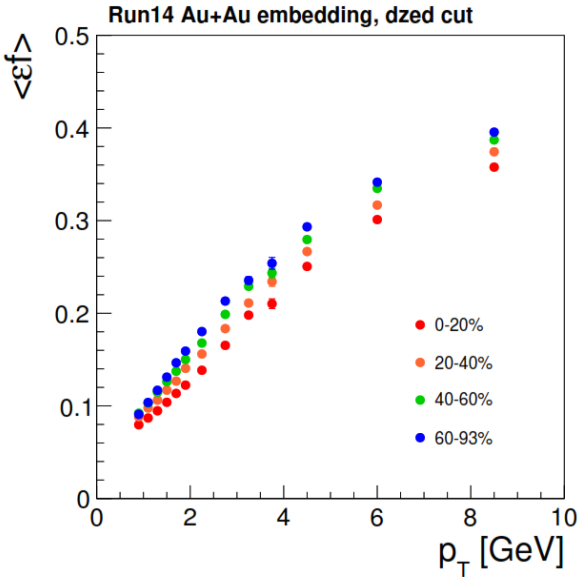
$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\langle \varepsilon f \rangle \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

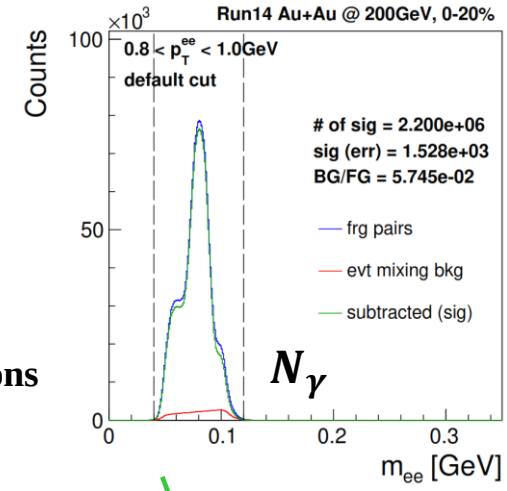
Thermal Photon Measurements

PhD – W.Fan

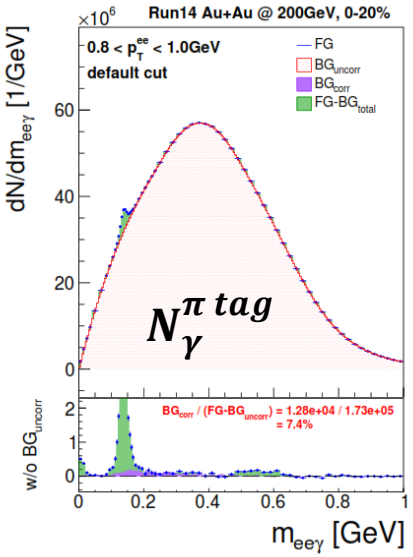
Full MC simulation

conditional tagging efficiency





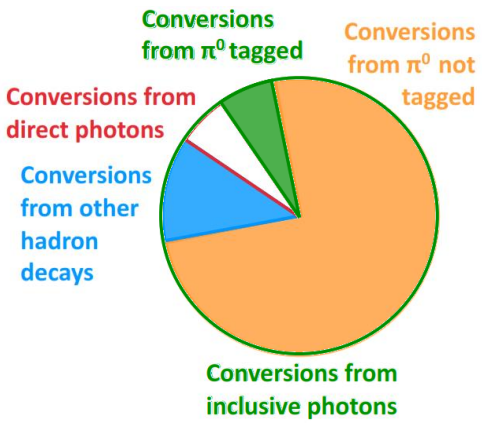
Closure test with full high multiplicity MC simulation



Key contributions

- **Energy cut**
- **Acceptance**
- **Detector material**

measured raw yields



$$\langle \varepsilon f \rangle \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}} \right)^{Data}$$

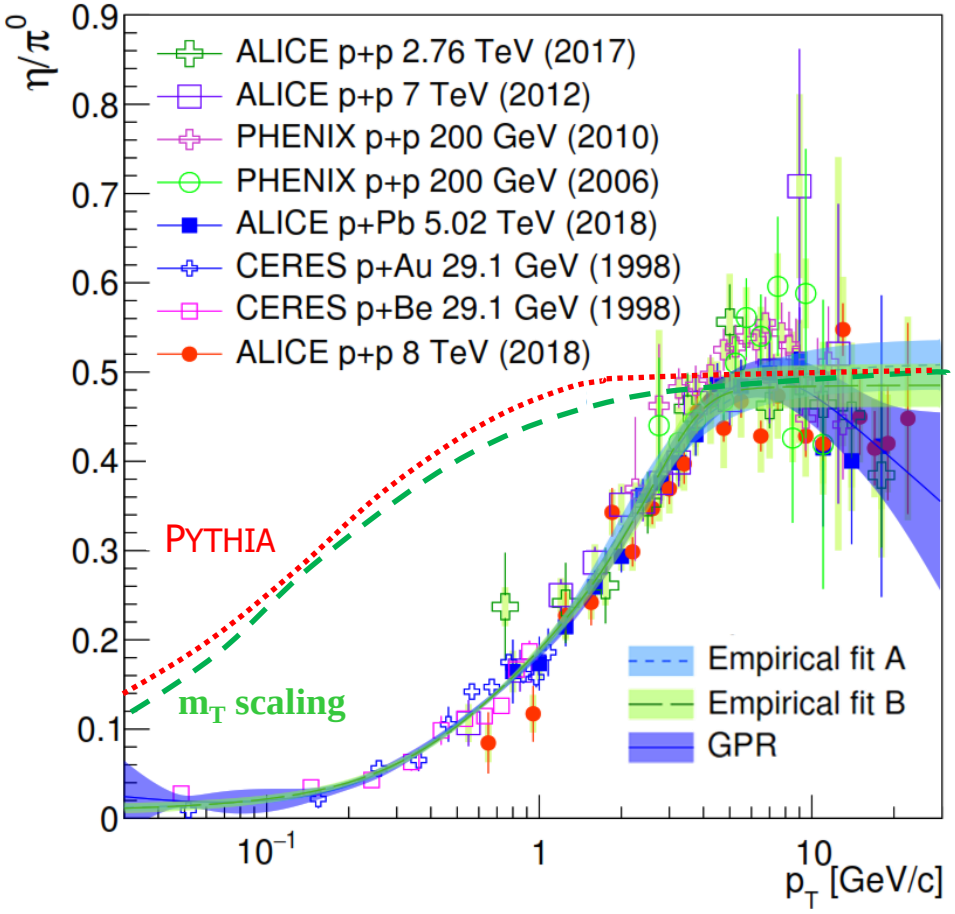
$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

η/π^0 ratio main contribution

Photons from hadron decays

Universal η/π^0 Ratio

Master Thesis Yuanjie Ren, SBU 2020 – arXiv:2102.05220 – accepted for publication by PRC



- **Universal η/π^0**
  - **For p+p and p+A collisions**
  - **Covering factor ~ 300 in $\sqrt{s}$ from 29 GeV to 8 TeV**
- **Significant deviation from m_T scaling below 2-3 GeV p_T**
- **High p_T value:**

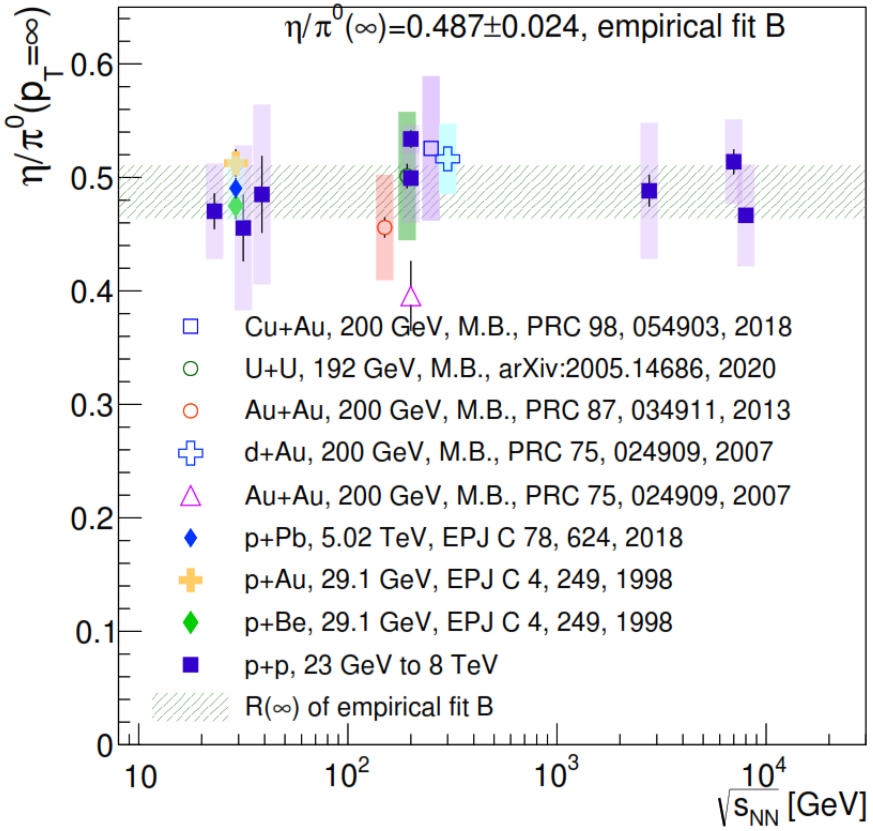
$$\frac{\eta}{\pi^0} = 0.487 \pm 0.024$$

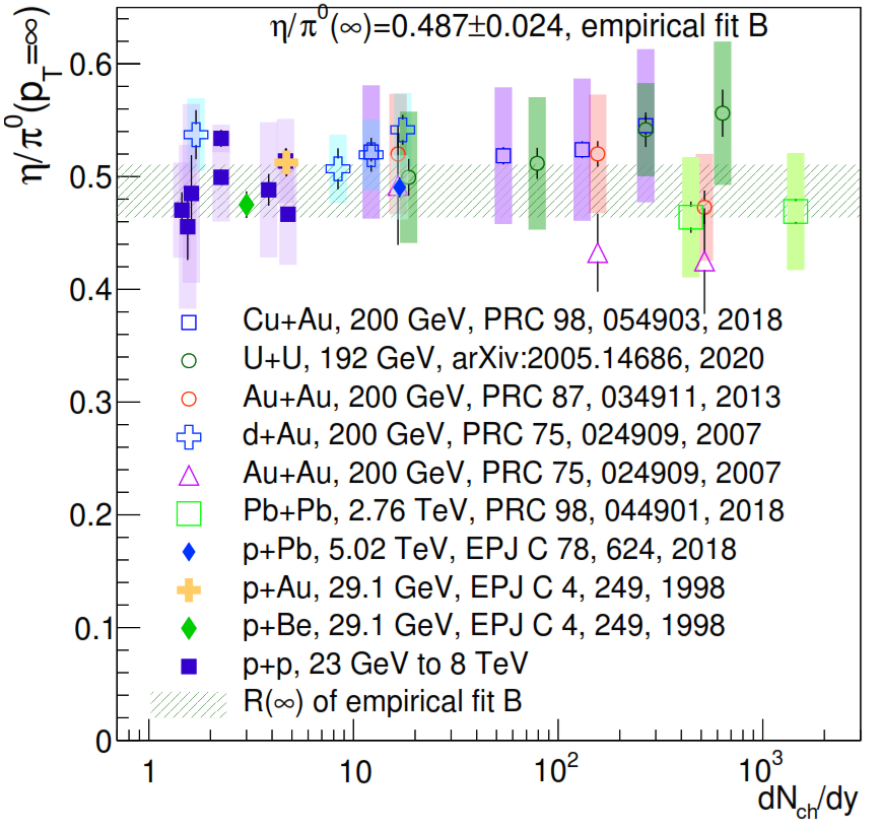
- **Use empirical description for all collision systems:**

$$\frac{dN_\eta}{dp_T} = \left(\frac{\eta}{\pi^0}\right)^{universal} \left(\frac{dN_{\pi^0}}{dp_T}\right)^{data}$$

Test of Universality of η/π^0 Ratio

- **Fit all available data (with empirical fit B)**
  - **Independent of $\sqrt{s}$, particle multiplicity, and centrality**





Universality of η/π^0

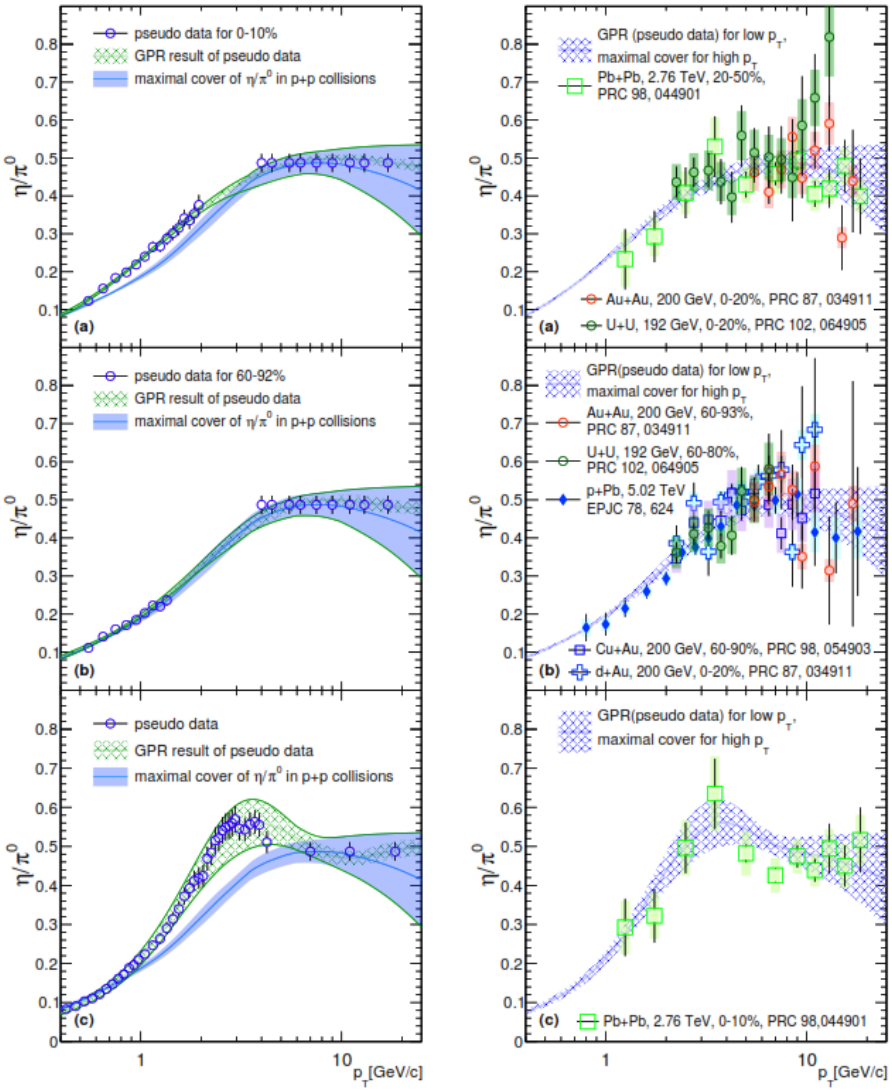
What about Radial Flow at Low p_T?

- **Approximate η with K meson at low p**
  - **Similar mass**
  - **More complete low p_T data**

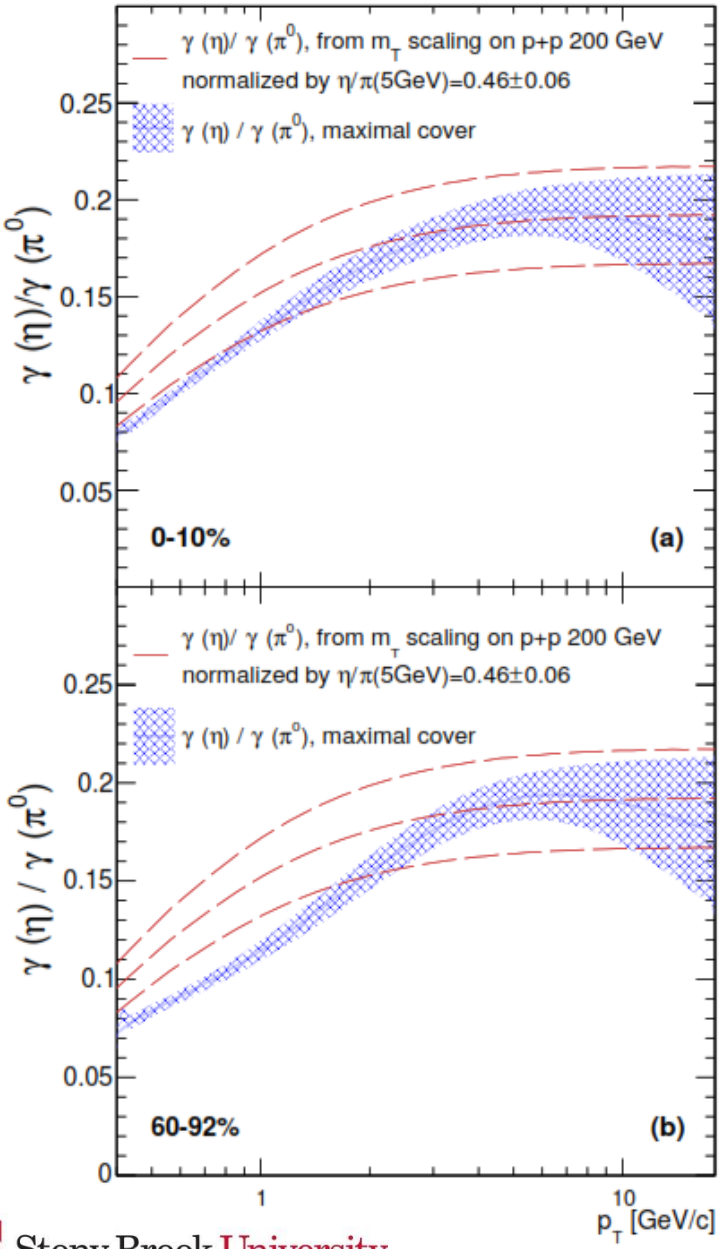
$$R_{flow} \equiv \frac{\left(\frac{\eta}{\pi^0}\right)_{C_i}}{\left(\frac{\eta}{\pi^0}\right)_{p+p}} \approx \frac{\left(\frac{K^{\pm}}{\pi^{\pm}}\right)_{C_i}}{\left(\frac{K^{\pm}}{\pi^{\pm}}\right)_{\mathrm{p+p}}} \equiv \frac{\left(R_{AA}^{K^{\pm}}\right)_{C_i}}{\left(R_{AA}^{\pi^{\pm}}\right)_{C_i}}$$

- **Apply correction to universal η/π^0**

RHIC: small correction
LHC: more substantial correction



Improved Photon Contribution from η Meson



- **Significant improvement of uncertainties on η/π^0 Ratio at RHIC**
  - **Smaller contribution below 10 GeV compared to m_T scaling assumption**
  - **Partially compensated in central collisions be flow effect**
  - **Consistent with previous estimate within quoted systematic uncertainty**
- **Use new empirical η/π^0 Ratio moving forward:**

$$\frac{dN_\eta}{dp_T} = \left(\frac{\eta}{\pi^0}\right)^{universal} \left(\frac{dN_{\pi^0}}{dp_T}\right)^{data}$$

  - **Applicable to all collision systems**
  - **Does not require η data at low p_T**
  - **Requires K meson data at low p_T**
- **m_T scaling based on η meson for heavier mesons**

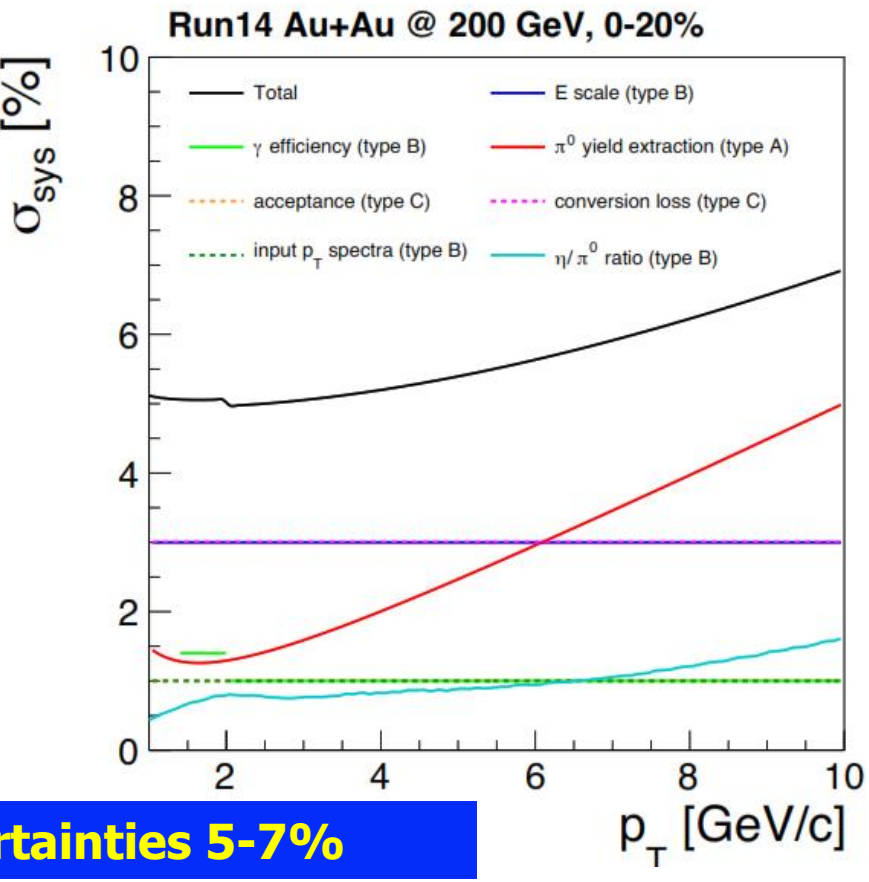
Run 14 Systematic Uncertainties

- **Yield Extraction $N_\gamma^{incl}/N_\gamma^{\pi^0\ tag}$**
  - $N_\gamma^{\pi^0\ tag}$ background subtraction (2%)
  - Conversion sample purity (<1%)

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

- **Conditional Acceptance and efficiency $\langle \varepsilon f \rangle$**
  - Energy scale and resolution (3%)
  - Loss due to conversion of second photon material budget (3%)
  - Photon reconstruction efficiency (~1%)
  - Live detector area (1%)
  - Shape of input π^0 spectrum (1%)

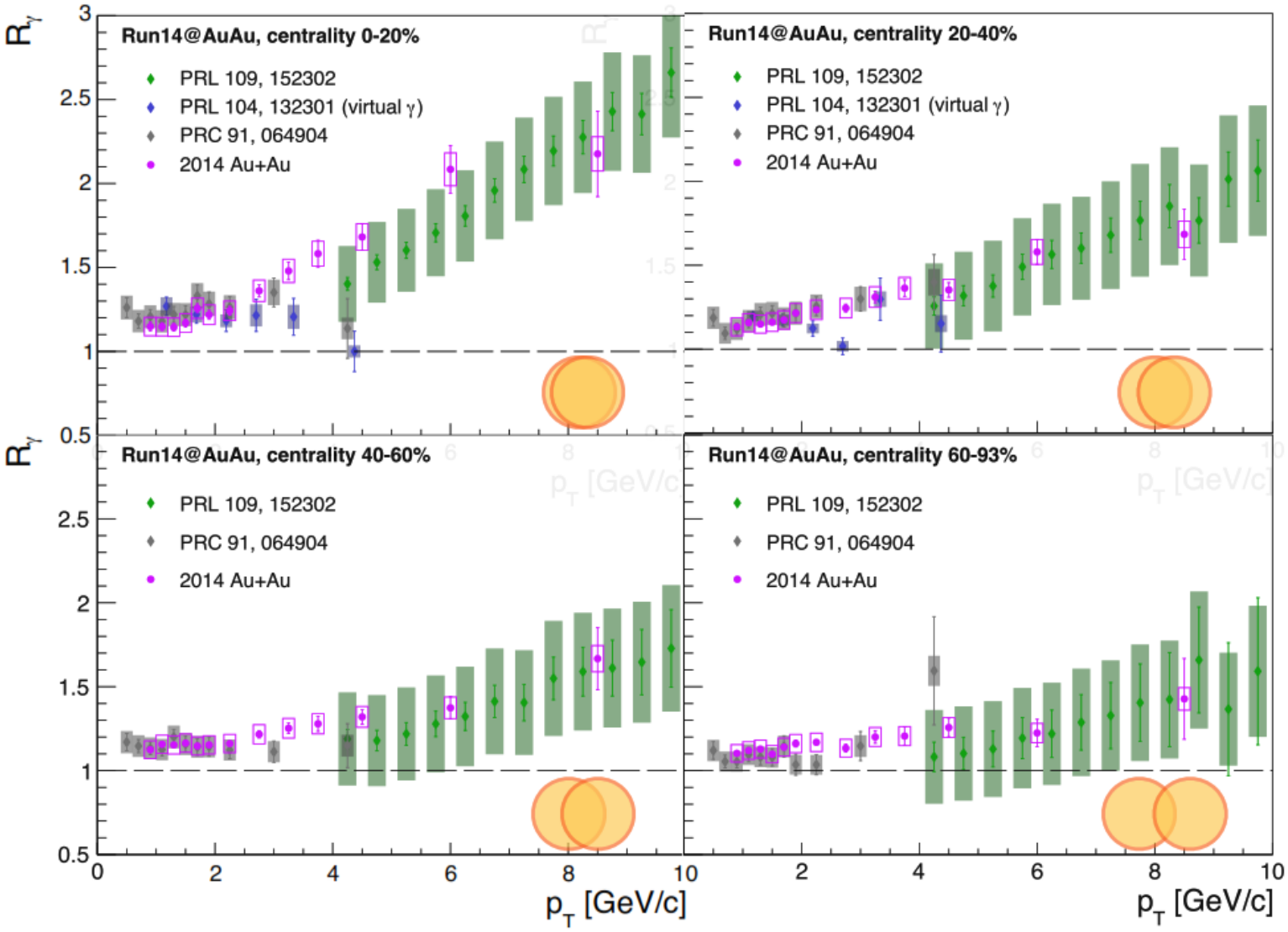
- **Photon from other hadron decays**
  - η/π^0 ratio (1%)
  - Other mesons (<<1%)



Systematic uncertainties 5-7%

Run 14 Au+Au Results

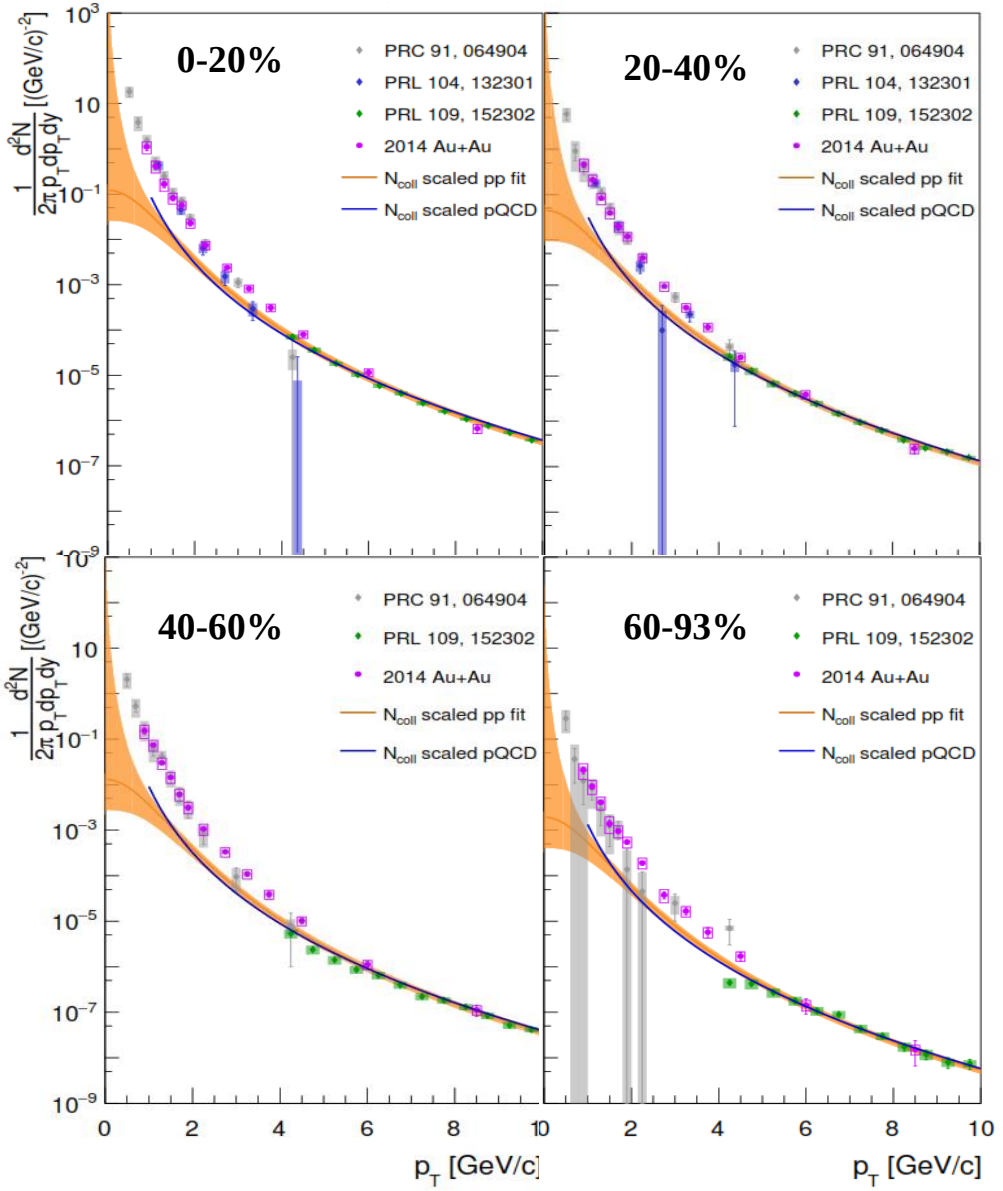
Ph.D. Thesis Wenqing Fan, SBU 2020 – 2020 RHIC/AGS Thesis Award



Direct Photon Spectra Au+Au at 200 GeV

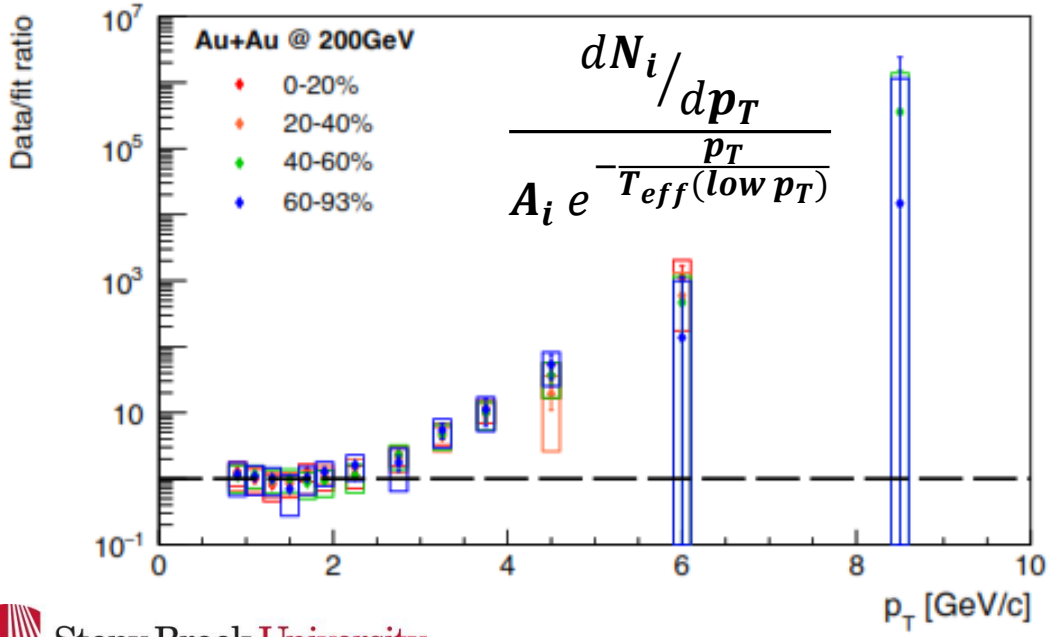
$$\gamma^{\text{direct}} = (R_\gamma - 1)\gamma^{\text{hadron}}$$

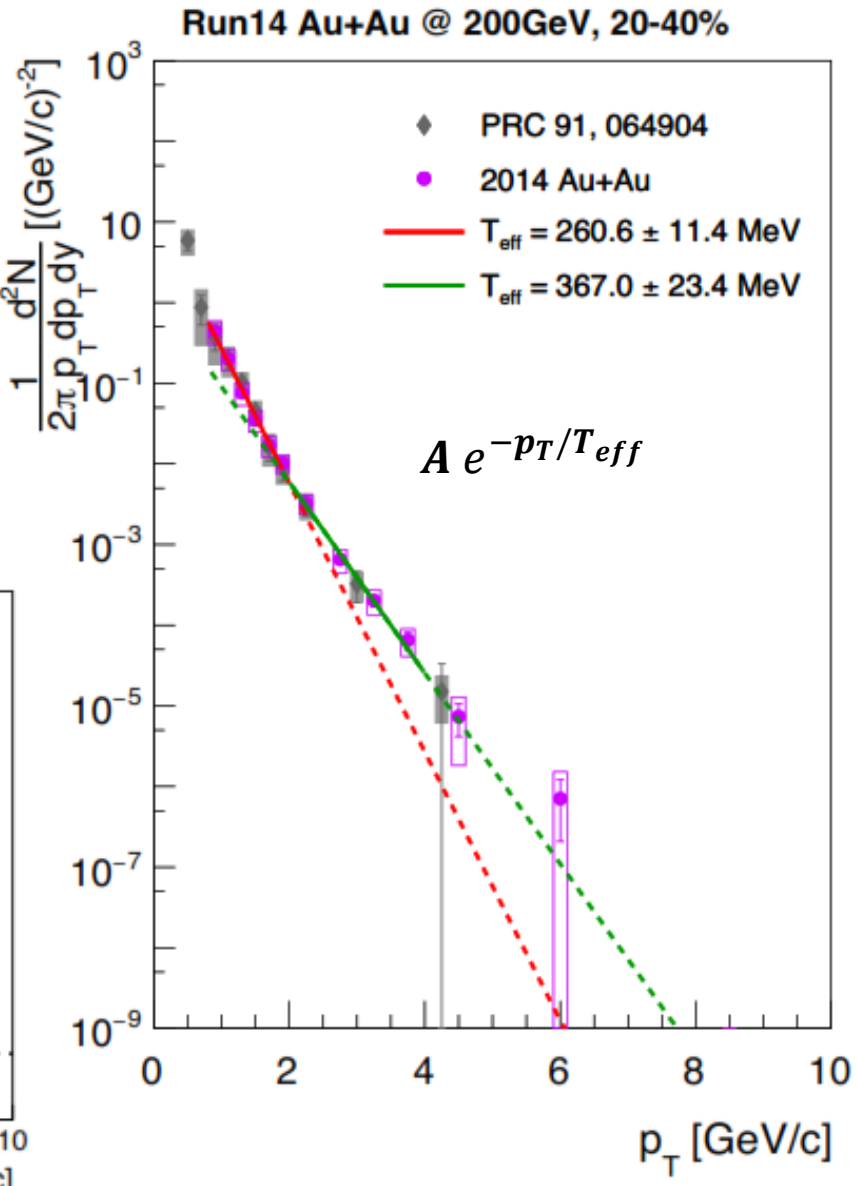
- **New result improve statistical precision**
  - Higher p_T reach
  - Overlap with low & high p_T data
  - Enables 10% centrality bins
- **Results consistent with previous measurements**
  - Virtual photon, calorimeter, and conversion measurement
  - High p_T consistent with hard scattering
  - Below 4-5 GeV significant enhancement



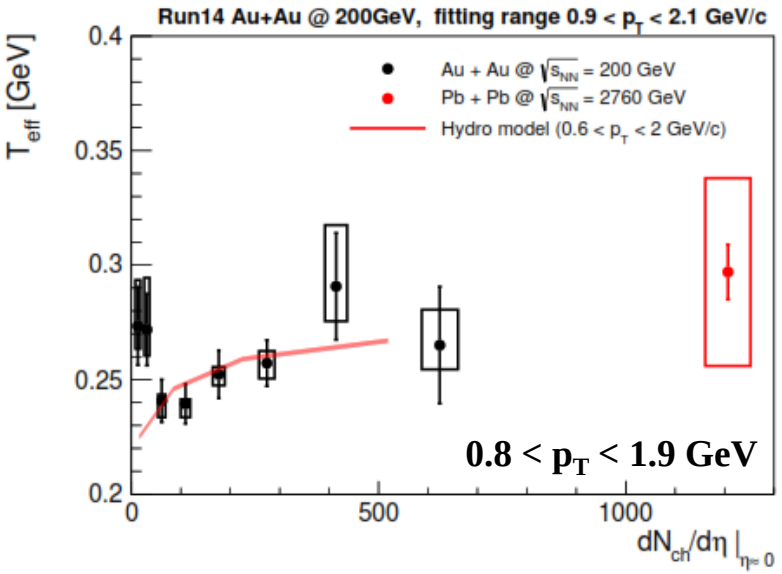
"Thermal" (non prompt) Photon Spectrum

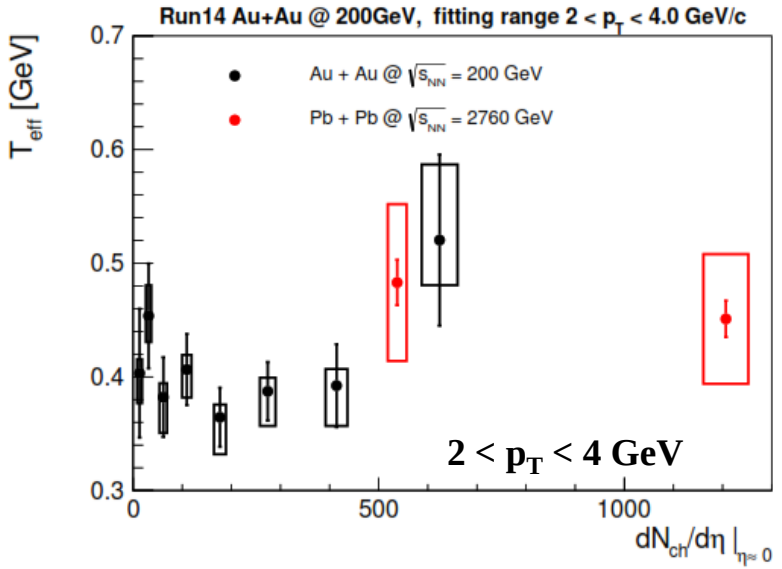
- Subtract N_{coll} scaled fit to p+p data
- Fit spectra with exponential function
  - Low p_T (0.8-1.9 GeV) T_{eff} = 261 ± 11 MeV
  - Medium p_T (2-4 GeV) T_{eff} = 367 ± 23 MeV
- Shape of p_T spectra independent of centrality





System Size Dependence of Inverse Slopes





Inverse slope of data:

- No clear trend with system size
- Within uncertainties consistent with increasing trend

Expectation from Hydro Models

- Low p_T region: increase of T_{eff}
  - Emission near QGP/HG transition and later in HG
  - Large blue shift
  - Shift increases towards central collisions
- Medium p_T region: increase of T_{eff}
  - Emission from QGP
  - Small blue shift
  - Increase of T_{ini} towards central collisions

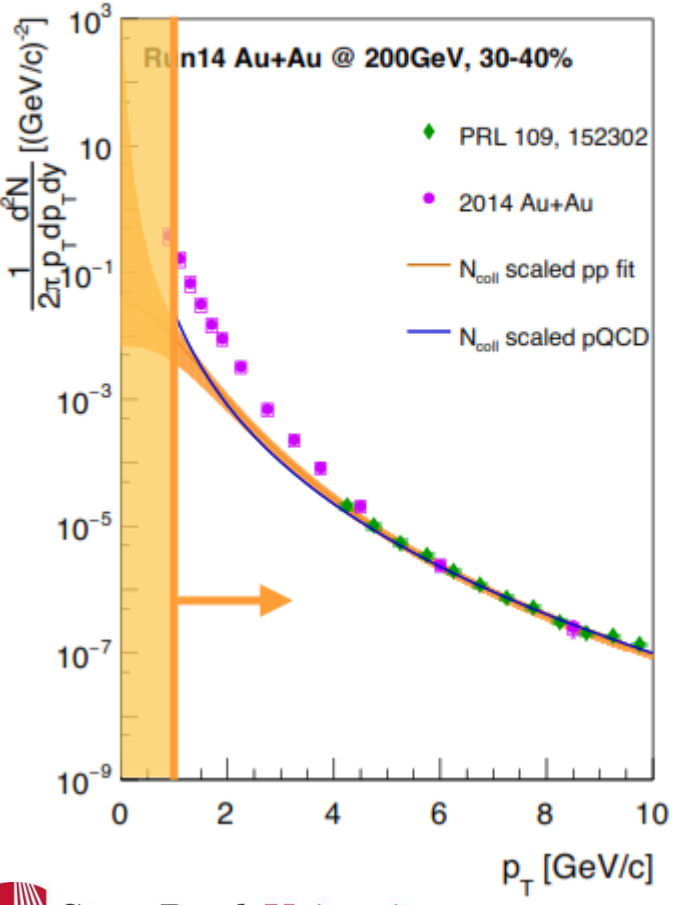
PRC 89, 044910 (2014)

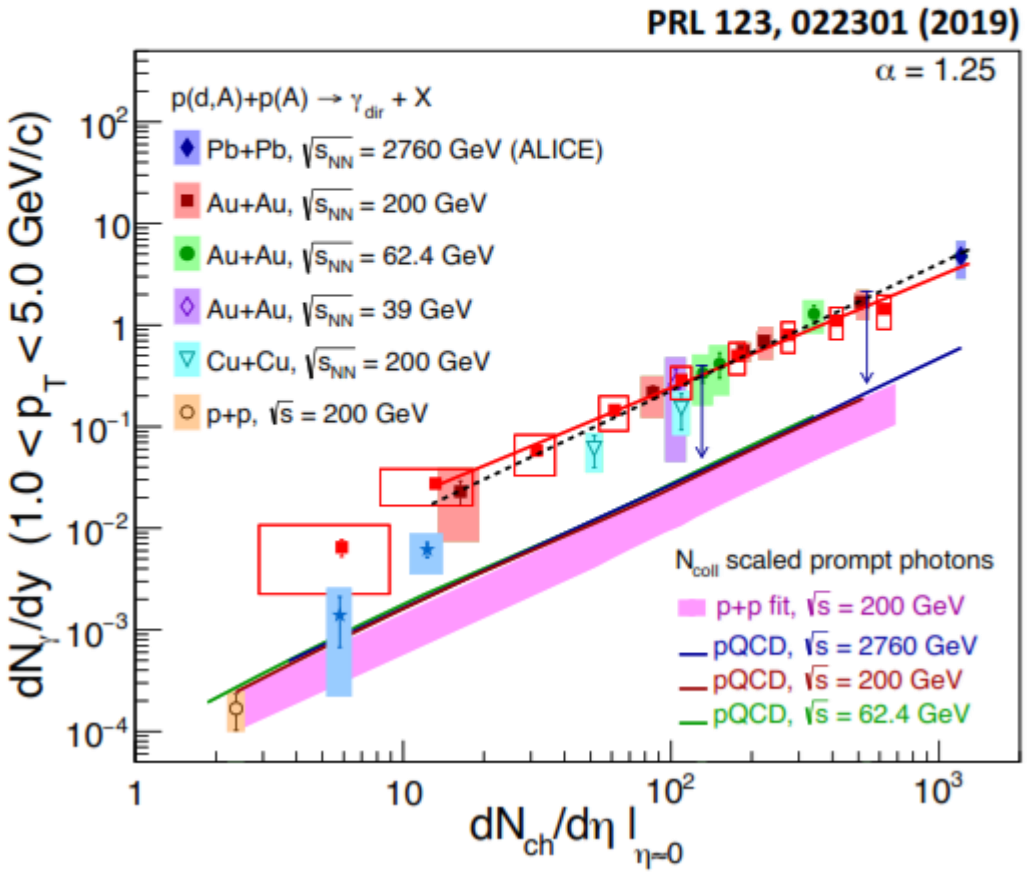
System Size Dependence of Direct Photon Yield

- **Consistent with previously observed universal scaling behavior**

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

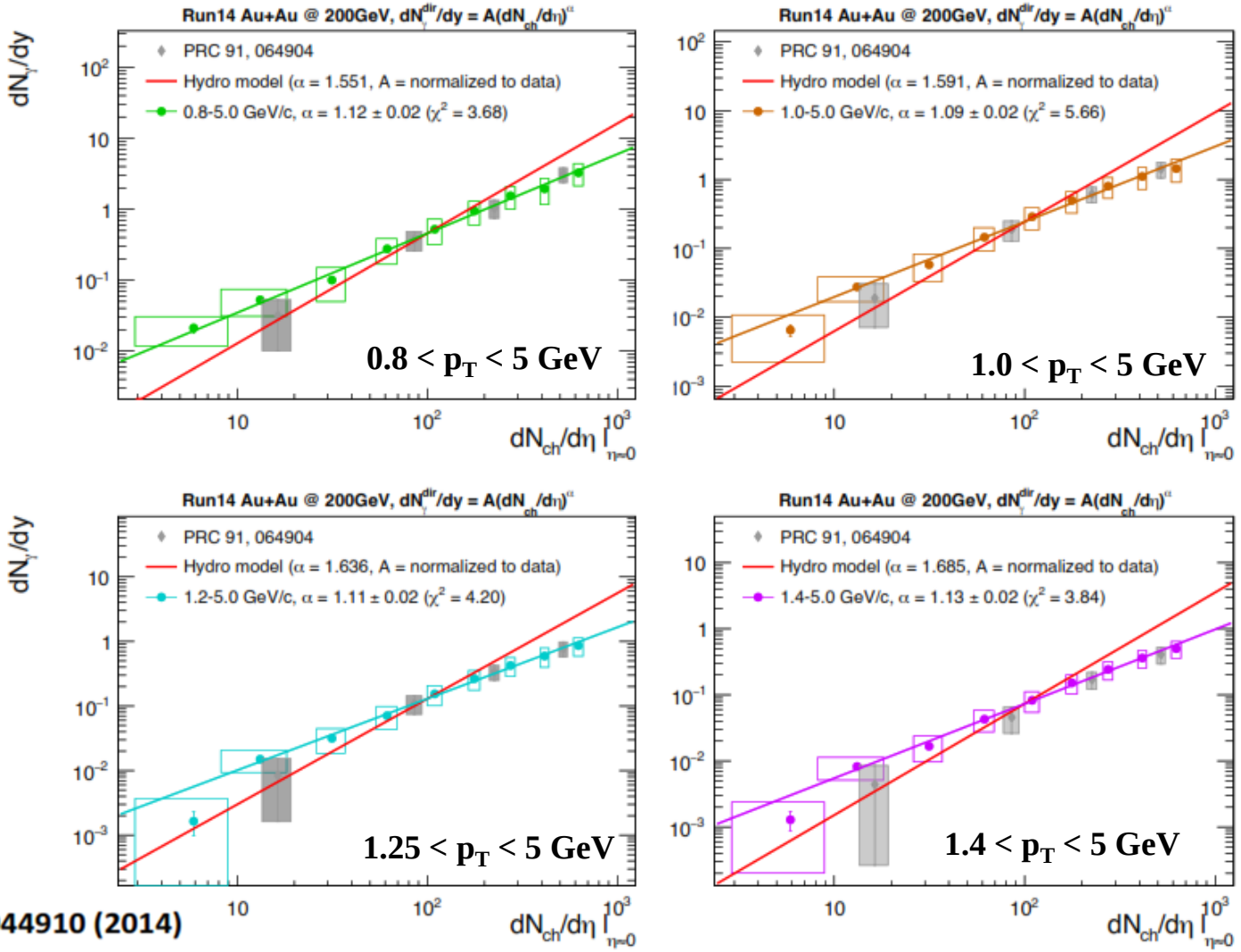
$$\alpha = 1.09\ ^{+0.02}_{-0.02}(\text{stat})\ ^{+0.09}_{-0.07}(\text{sys})$$





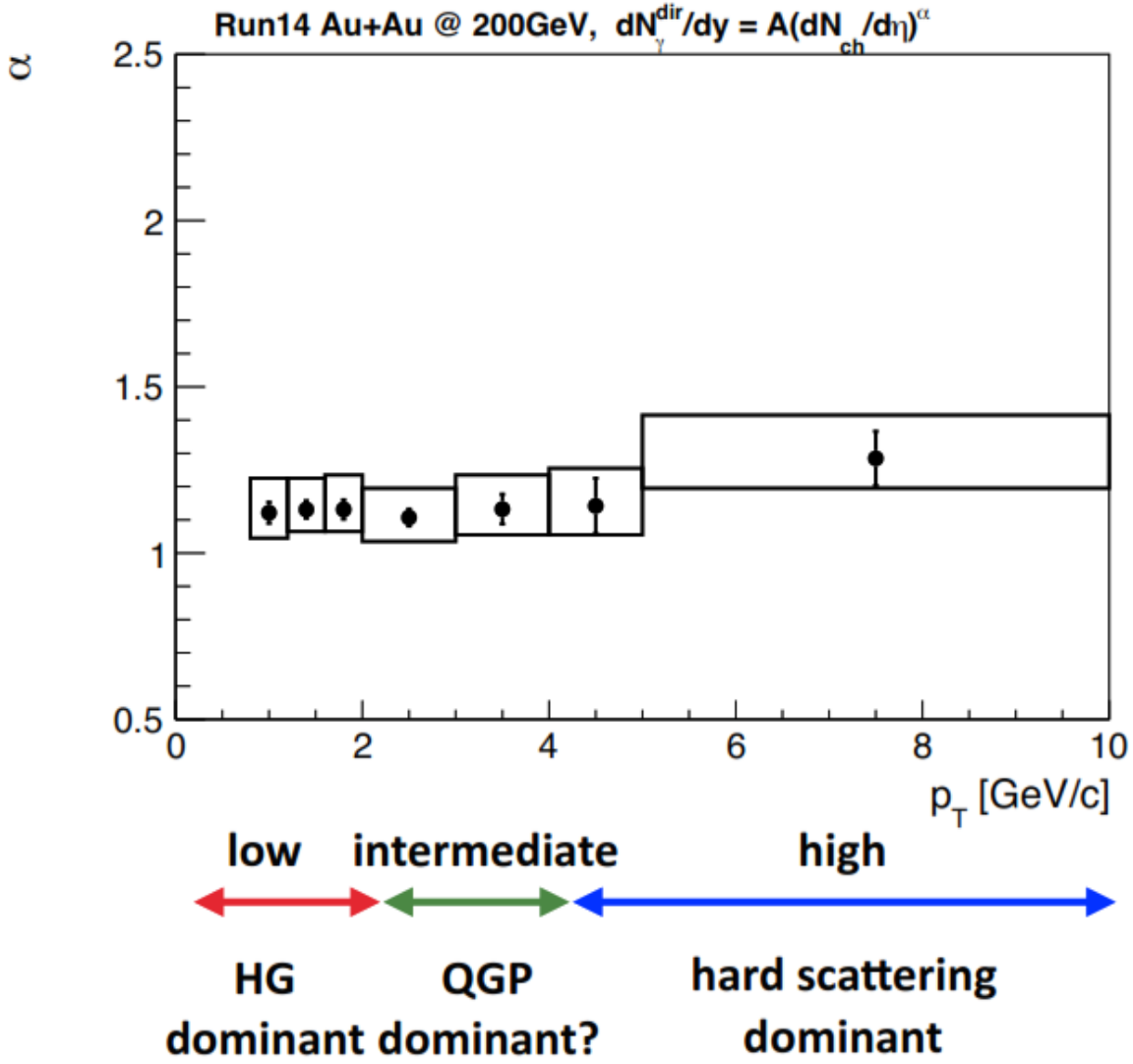
Comparison to Hydro Models

- **Model expectation: α increasing with p_T ranges from 1.5 to 1.7**
- **Data: α ~ 1.1 with no visible p_T dependence**



PRC 89, 044910 (2014)

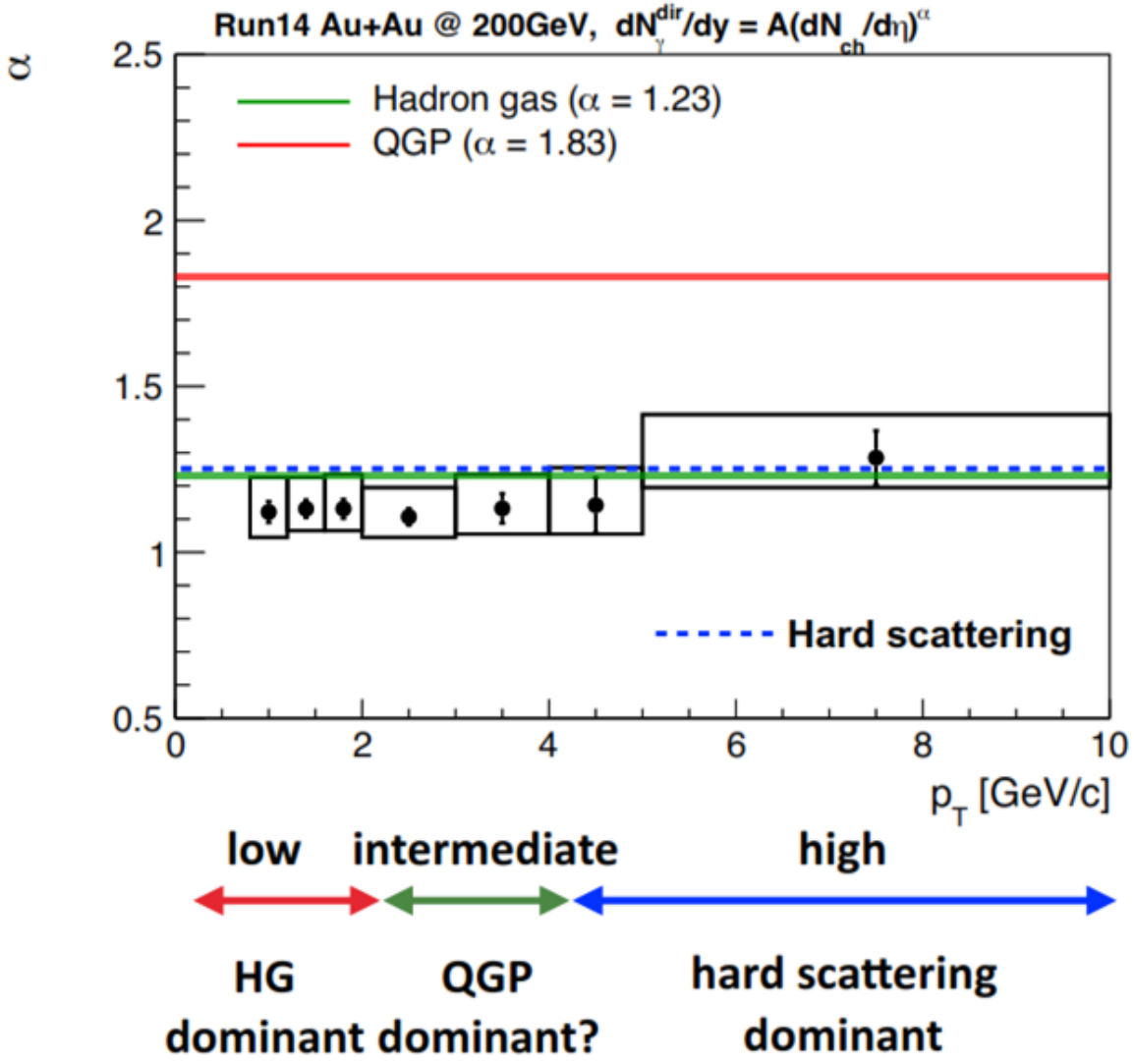
p_T Dependence of System Size Dependence



$$\frac{dN_\gamma}{dp_T} = A\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha(p_T)}$$

- **Data:**
  - Constant $\alpha(p_T) \sim 1.1$

p_T Dependence of System Size Dependence



$$\frac{dN_\gamma}{dp_T} = A\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha(p_T)}$$

- **Data:**
  - Constant $\alpha(p_T) \sim 1.1$
- **Hydro model:**
  - Different dependence on $dN_{ch}/d\eta$ for QGP, HG, and prompt component

increasing p_T

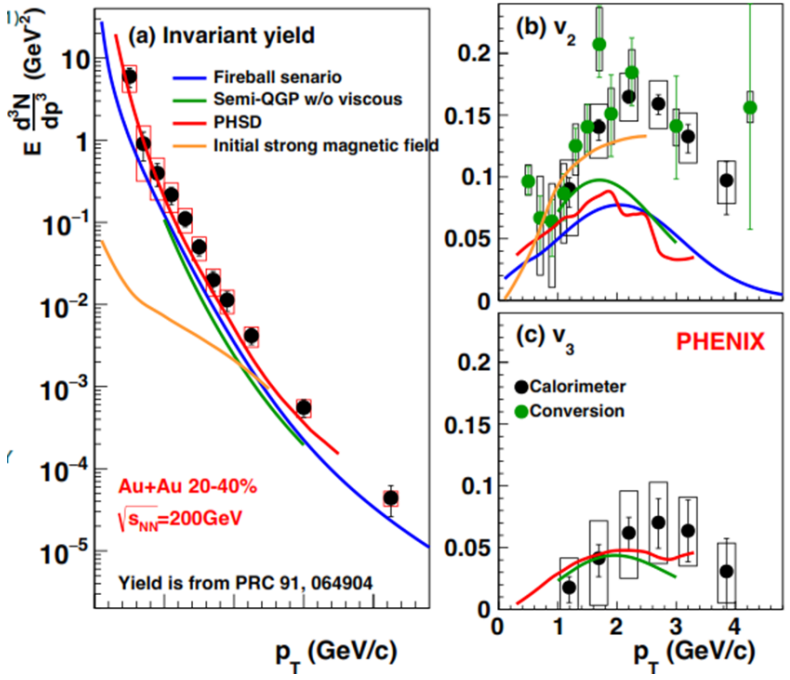
$\alpha_{HG} = 1.23$

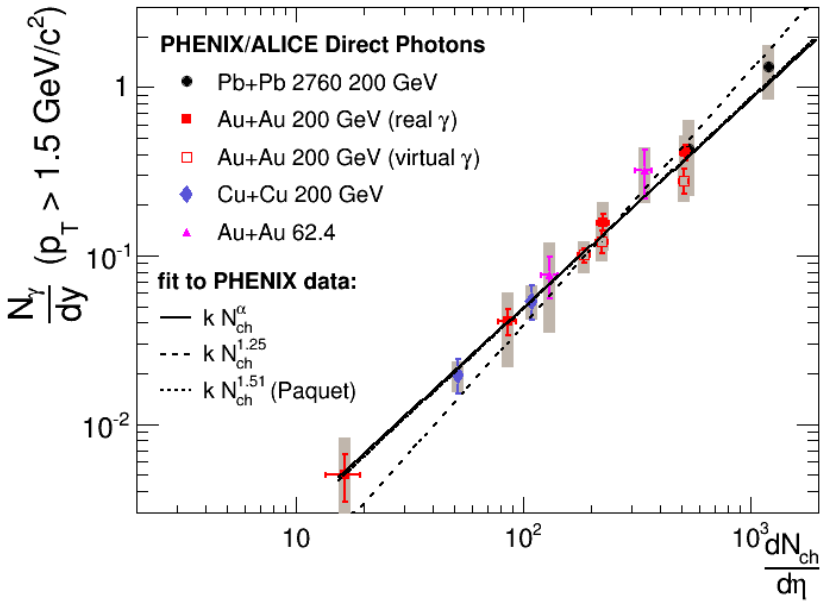
$\alpha_{QGP} = 1.83$

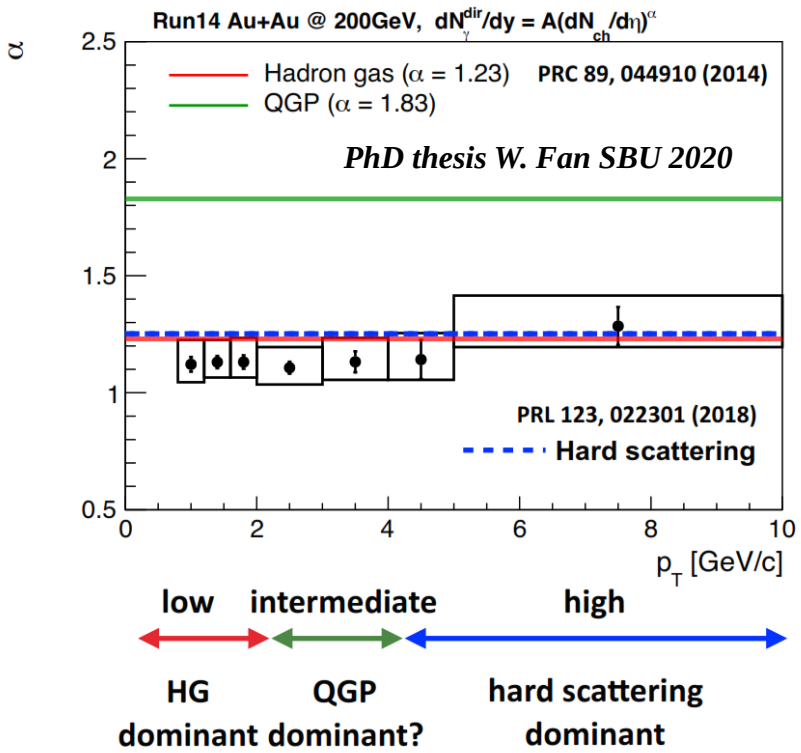
$\alpha_{hard} = 1.25$

  - Expect significant p_T dependence of α

"Thermal Photon Puzzle"



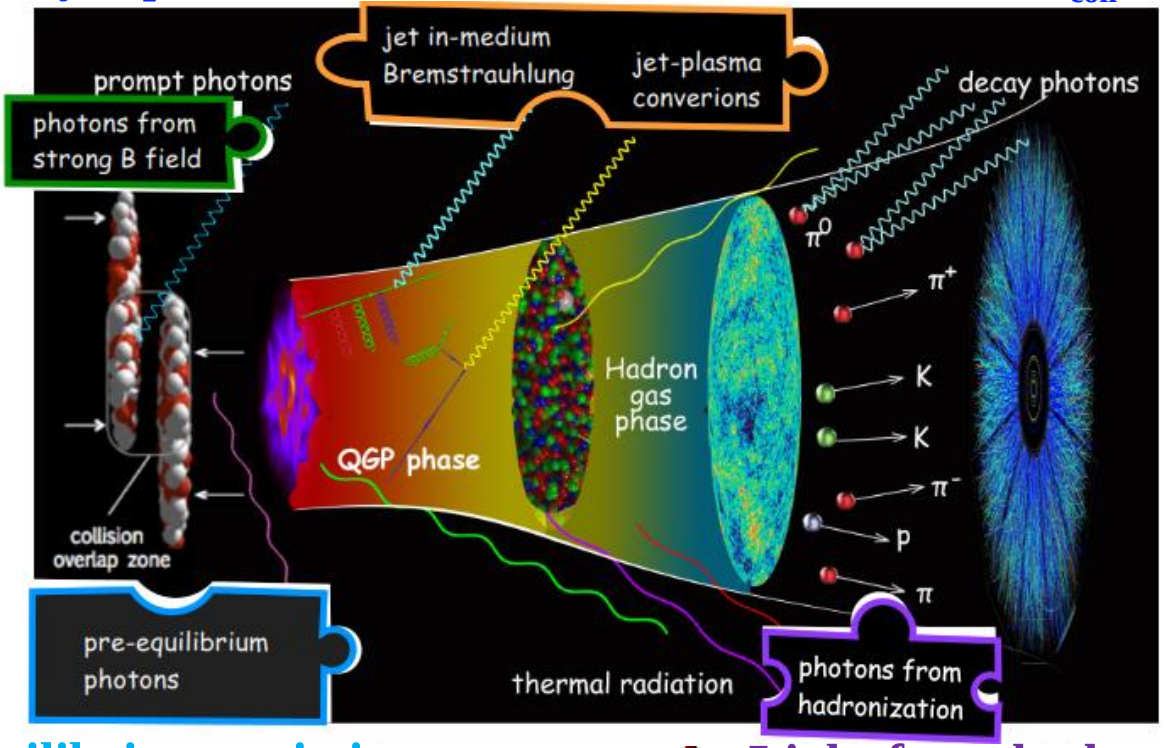




- **Qualitative: in agreement with thermal sources**
  - **Large yield of low p_T direct photons**
  - **Large Anisotropic Emission**
  - **Universal Scaling with $\alpha \sim 5/4$**
- **Quantitative: Challenging to explain by current models**

What is the Source of Direct Photons?

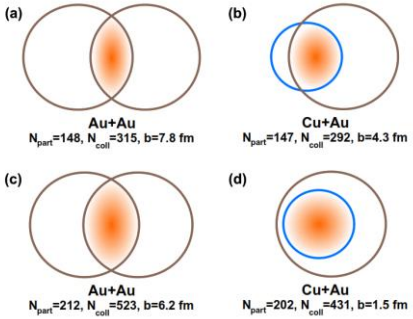
- **Photons from strong B field**
  - Significant intermediate p_T yield
  - Large v_2 – no v_3
  - Centrality dependence ?
- **Jet medium interactions**
  - Significant intermediate p_T yield
  - Small v_2
  - Scales with N_{coll}

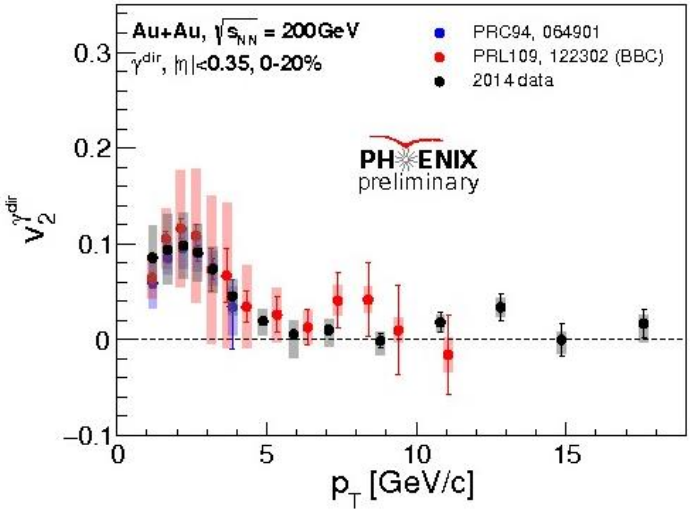


- **Pre-equilibrium emission**
  - Significant intermediate p_T yield
  - Small v_2
  - Centrality dependence ?
- **Light from hadronization**
  - Large low p_T yield
  - large v_2, v_3 like hadrons
  - Centrality dependence similar to HG?

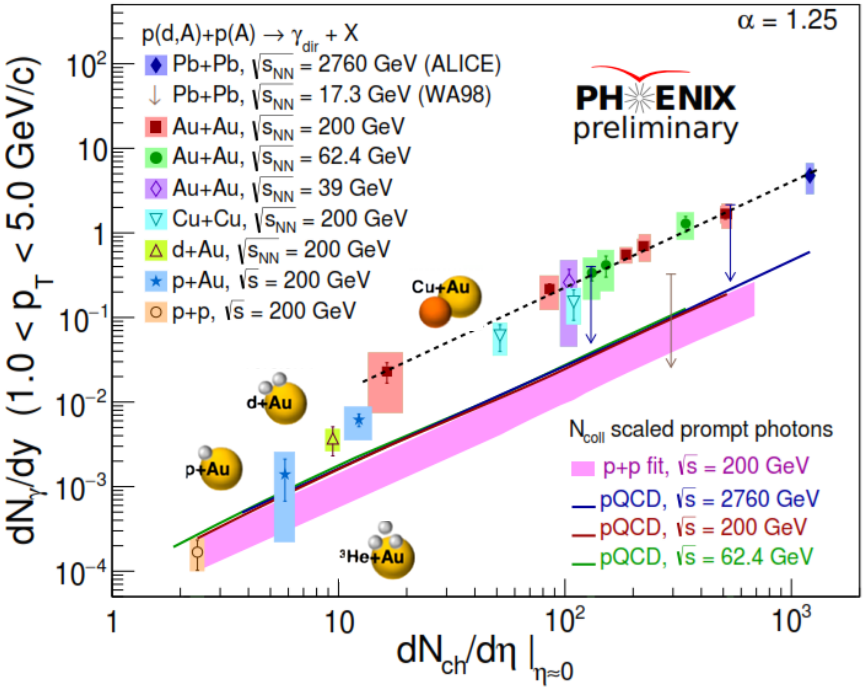
Future Direct Photon Measurements with PHENIX

- **High statistics large systems**
  - Au-Au, Cu-Au at 200 GeV
  - v2, v3 out to high p_T
  - Different collision geometry at same N_{ch}



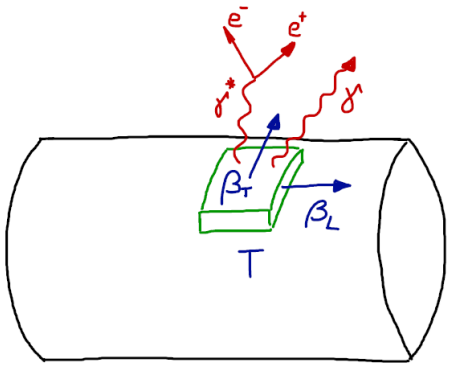


- **Small system data sets**
  - p-Au, He-Au, d-Au
  - "engineer" collision geometry
  - Search for onset of QGP



Unique ongoing measurements from PHENIX

e^+e^- Pair measurements with PHENIX?

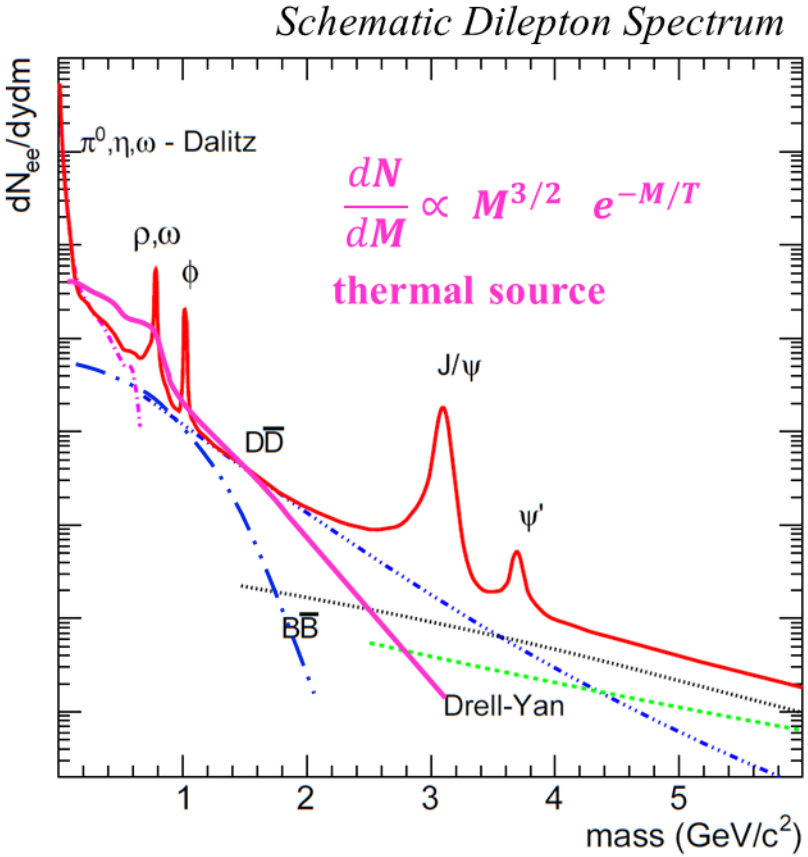


Requires high statistics and simultaneous measurement of open heavy flavor pairs

PHENIX 2014 + 2016 datasets
15 nb^{-1} or 34B events

Direct Measurement of the Temperature

- **Thermal virtual photons: mass and momentum**
  - **Momentum Doppler shifted**
  - **Mass Lorentz invariant**
  - **Mass directly measures time averaged temperature**
- **Mass range 1 – 3 GeV**
  - **Only significant physics background open heavy flavor**



Backup