Győrfi András: Az úton (On the road)

"Thermal Photons" from HI Collisions

Axel Drees SBU
Budapest, Hungary 12/6/2019

- Introduction
- Thermal Photon Puzzle
  - Large Yields
  - Large Anisotropies
  - Scaling with $\left(\frac{dN_{ch}}{d\eta}\right)^{5/4}$
- Outlook

Thermal Radiation from Hot & Dense Matter

- **Black Body Radiation**
  - Real or virtual photons
  - Sensitive to temperature & density

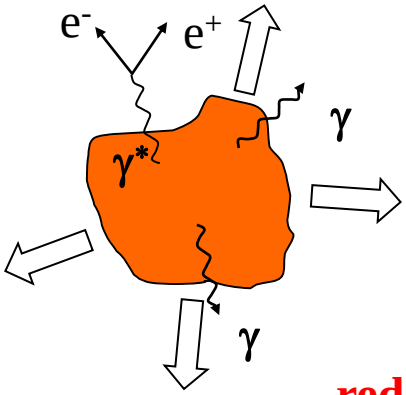
    Boltzmann dist. with avg. inv. slope ∝ T,

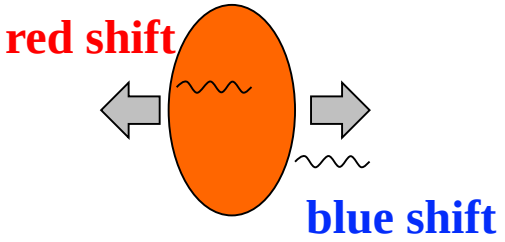
    Photon flux ∝ T^4
  - Hubble expansion of matter

    → temperature drops

    → Doppler shift: γ photons emitted from moving matter

    → Radial expansion anisotropic (elliptic flow): modulation on Doppler shift

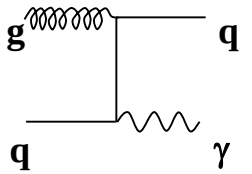




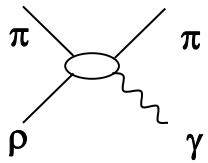
High yield → high T → early emission
Large Doppler shift → late emission

- **Microscopic view of thermal radiation**

QGP:

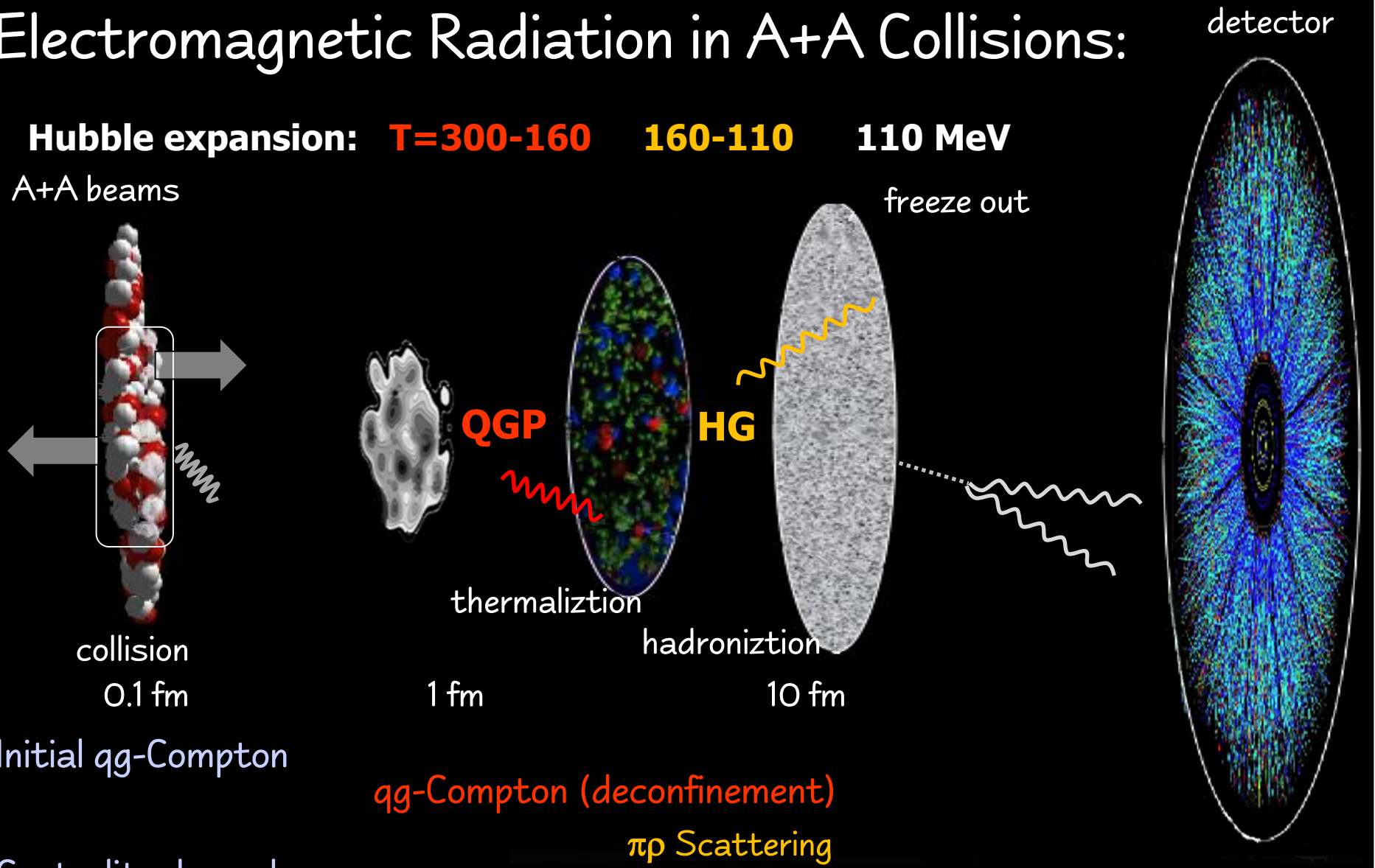


hadron gas:



Emission rate depends on density squared integrated over space-time evolution

Electromagnetic Radiation in A+A Collisions:

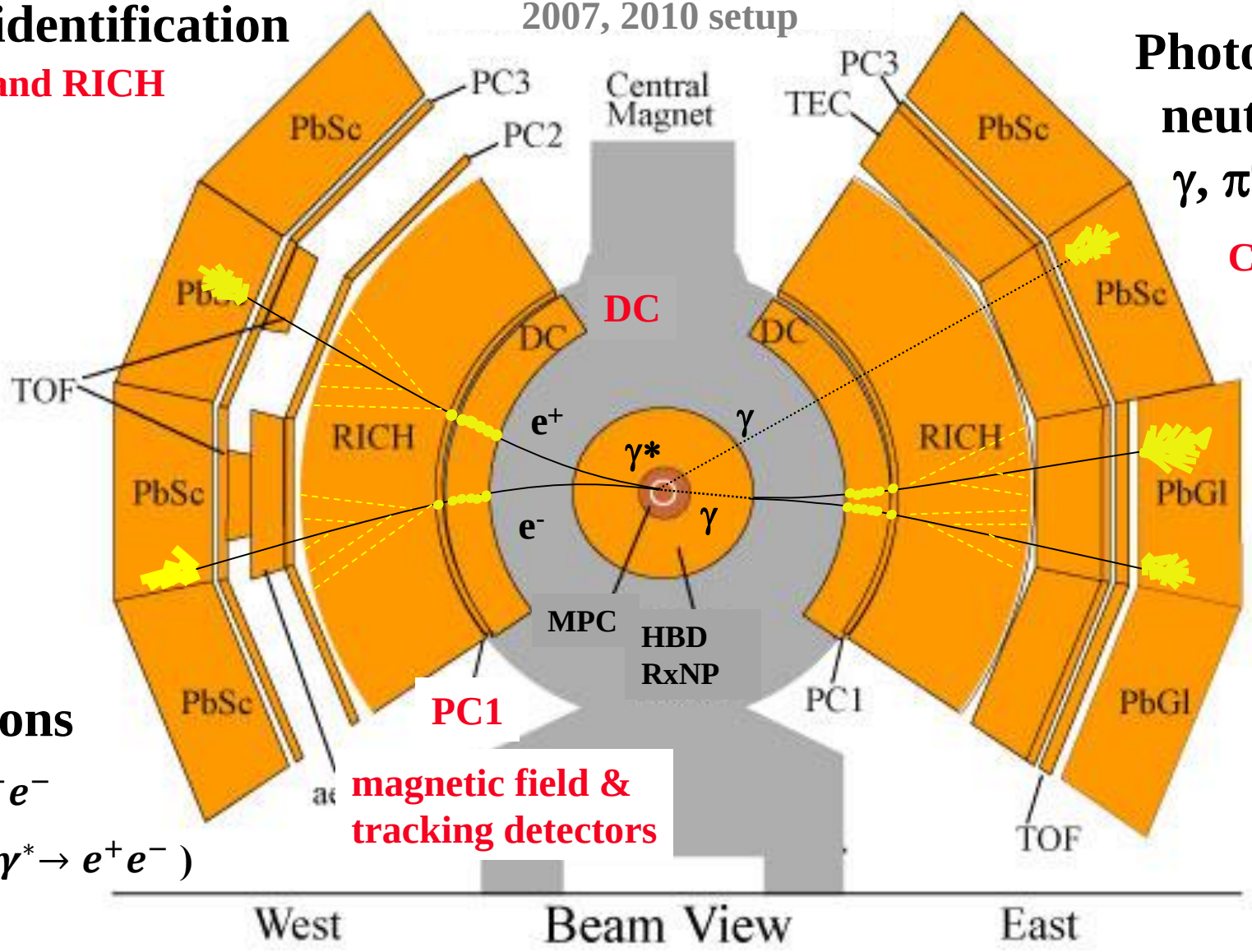


Photon Measurements with PHENIX

e^+e^- identification

E/p and RICH

2007, 2010 setup



Photons, neutral pion

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

Calorimeter

Photons

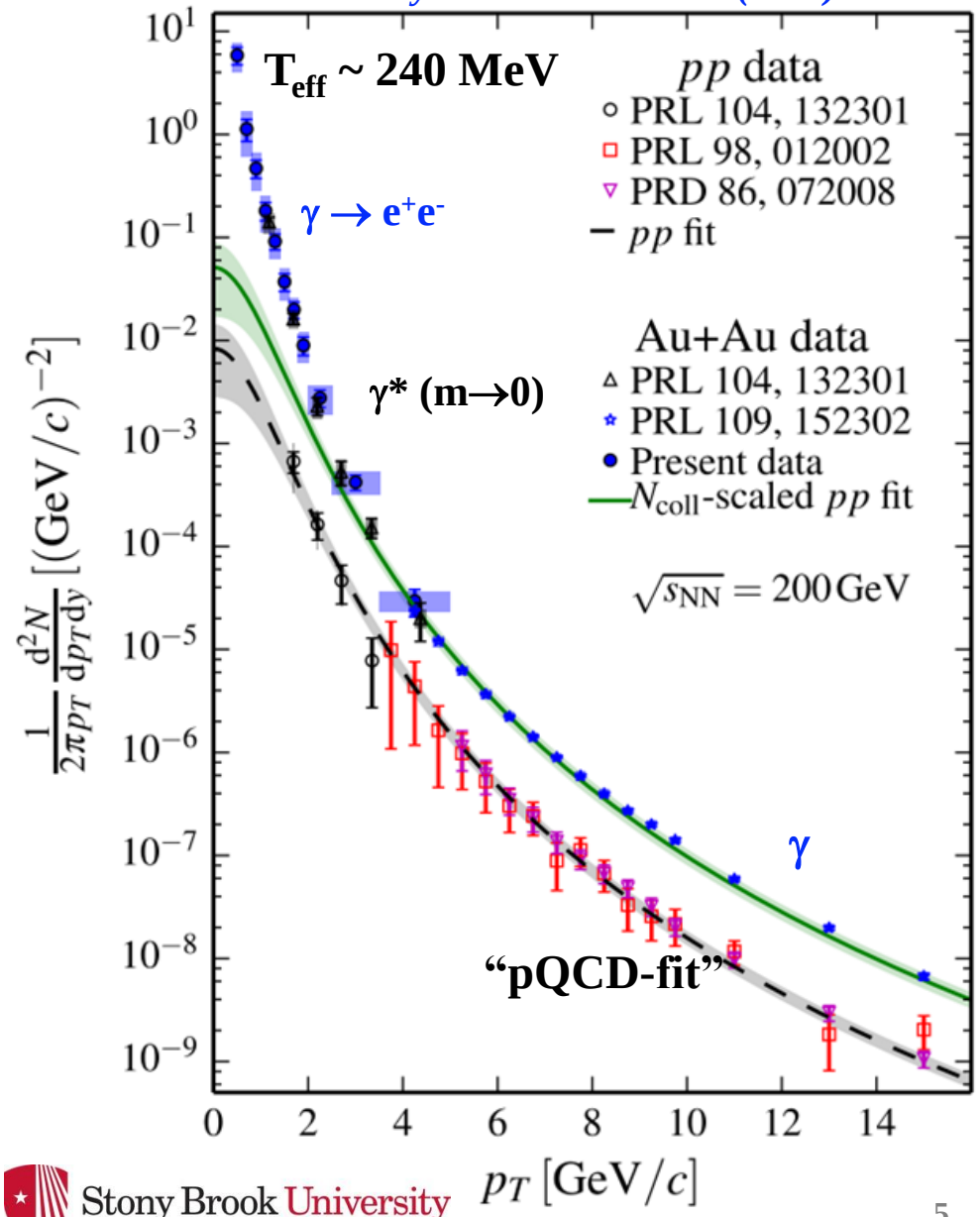
$\gamma \rightarrow e^+e^-$

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

magnetic field & tracking detectors

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

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



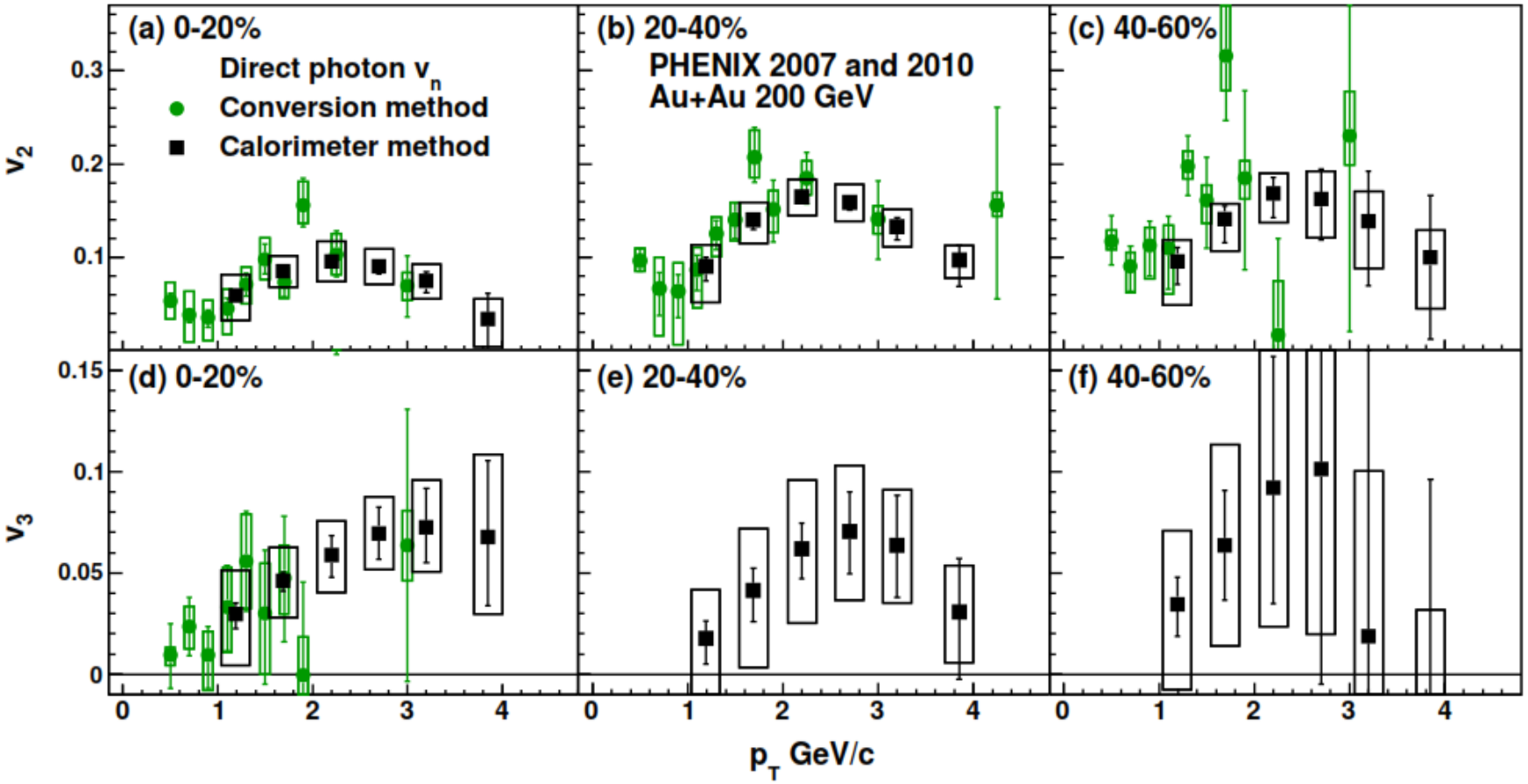
- **Direct photon yield well established**
  - pp consistent with pQCD
  - AuAu follows N_{coll} scaled pp above 3-4 GeV
  - Significant excess below 3 GeV in AuAu
  - Excess has nearly exponential shape with T_{eff} ~ 240 MeV

Large direct photon yield
T_{ini} > 240 MeV > T_C

(Need to consider exploding source!)

Anisotropic Emission of Direct Photons

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



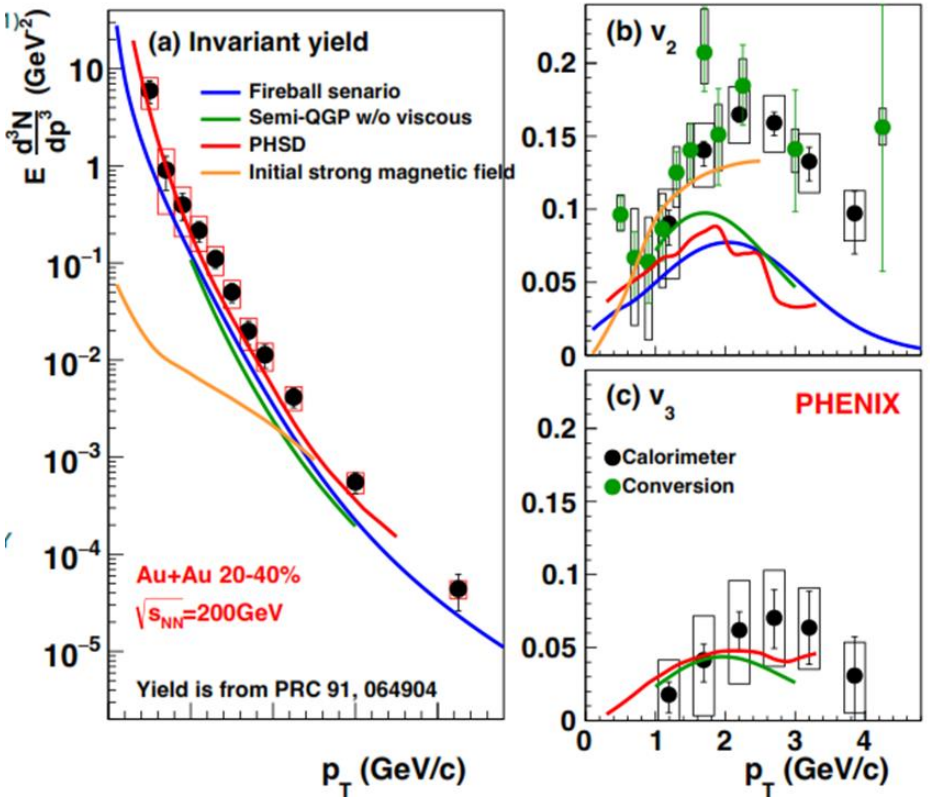
Anisotropic emission of direct photons with large v_2 and v_3

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**

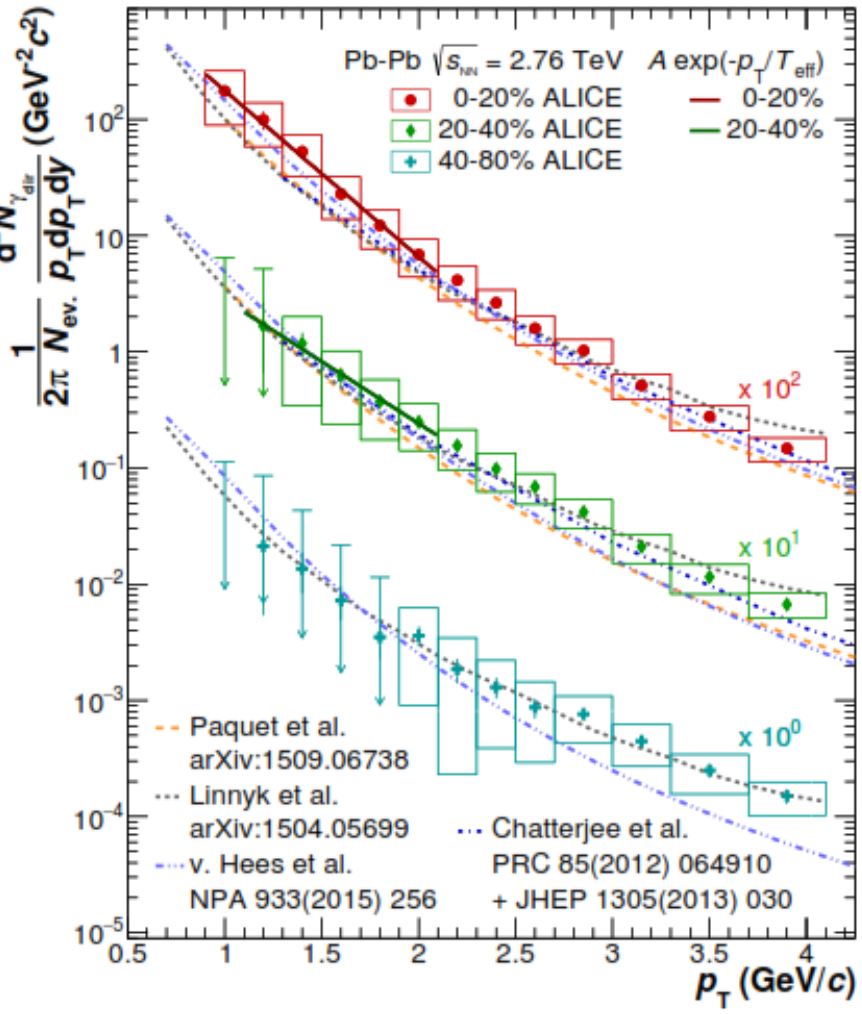


Large yield and v_n challenge understanding of sources, emission rates and space-time evolution

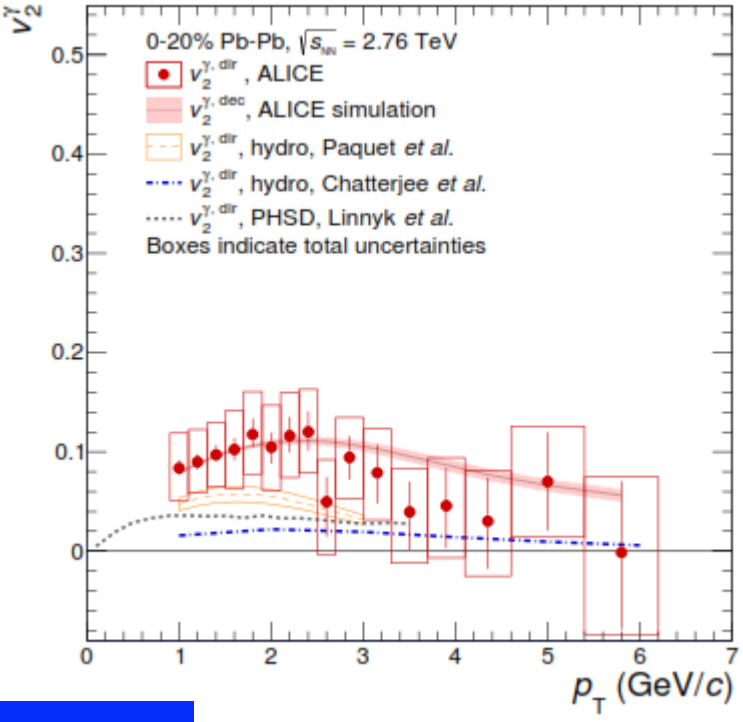
**list not complete*

ALICE Direct Photon Results

ALICE: Phys. Lett. B754 (2016) 235



- **ALICE Pb+Pb 2.76 TeV**
  - **Large yield of direct photons**
  - **Anisotropic emission**
  - **Challenge to reproduce quantitatively with theoretical models**



ALICE and PHENIX results consistent

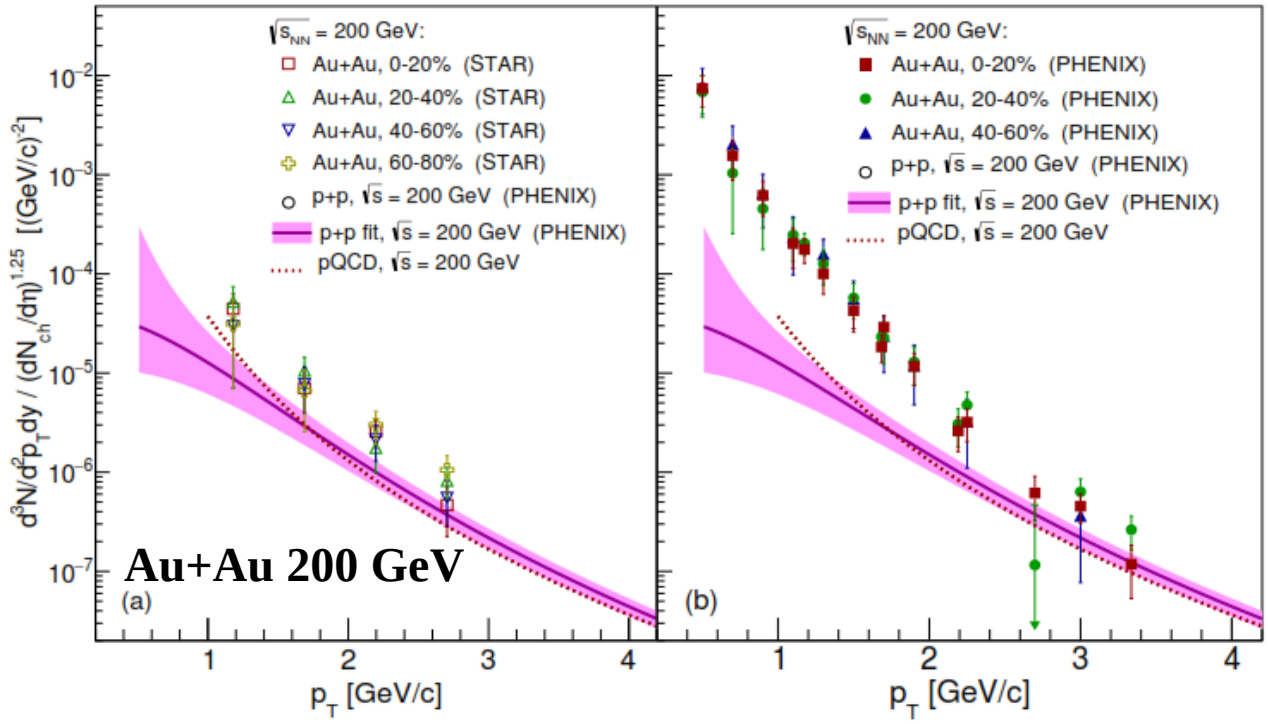
ALICE: Phys. Lett. B789 (2019) 308

PHENIX – STAR Direct Photon Comparison

PHENIX $\gamma \rightarrow e^+e^-$: Phys. Rev. C91 (2015) 064904

STAR: Phys. Lett. B770 (2017) 451

γ^*: Phys. Rev. Lett. 104 (2010) 132301



- **STAR data significantly lower than PHENIX data**

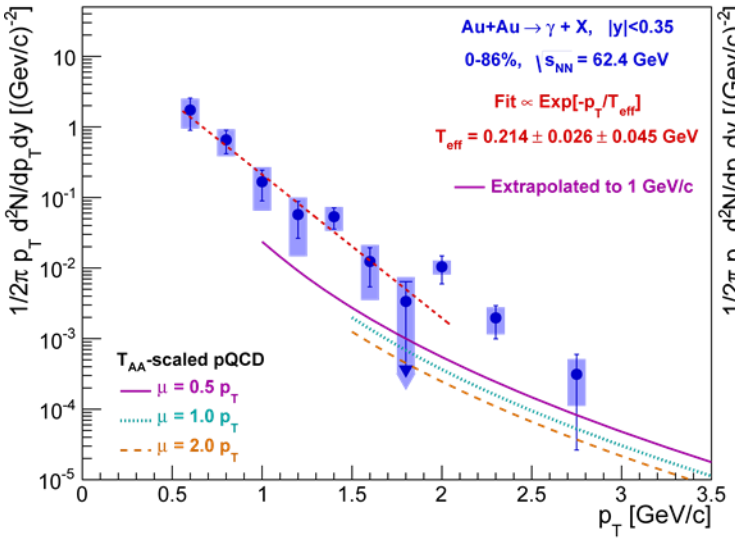
STAR - PHENIX discrepancy remains unresolved

New Experimental Data from Different Systems

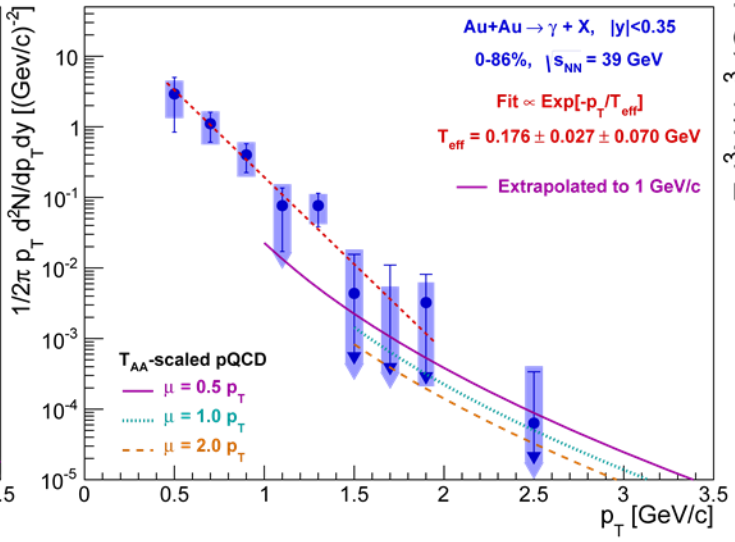
PHENIX: Phys. Rev. C98 (2018) 54902

- **New PHENIX data**
  - Vary collision energy: Au+Au at 39 and 62.4 GeV
  - Vary system size: Cu+Cu at 200 GeV
  - Small systems p+Au at 200 GeV (N.Novitzky's talk)

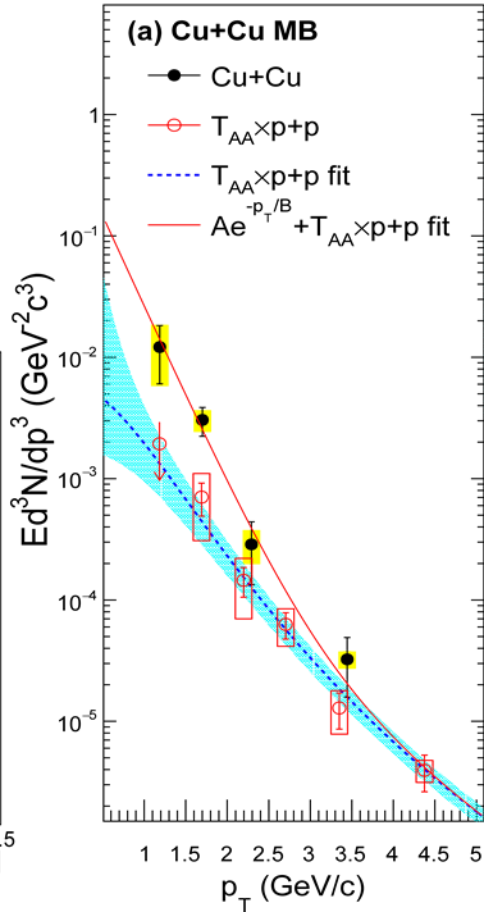
PHENIX: Phys. Rev. Lett. 123 (2019) 22301



Au+Au 62.4 GeV



Au+Au 39 GeV

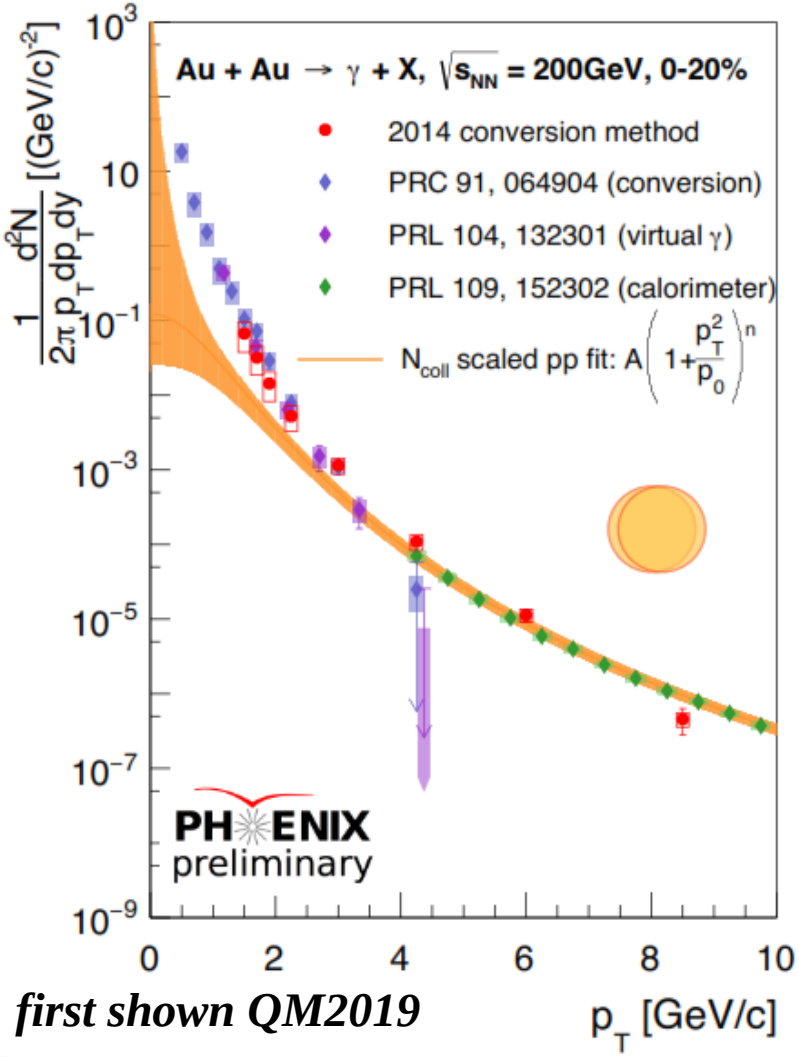


Cu+Cu 200 GeV

Low p_T direct photons in all systems

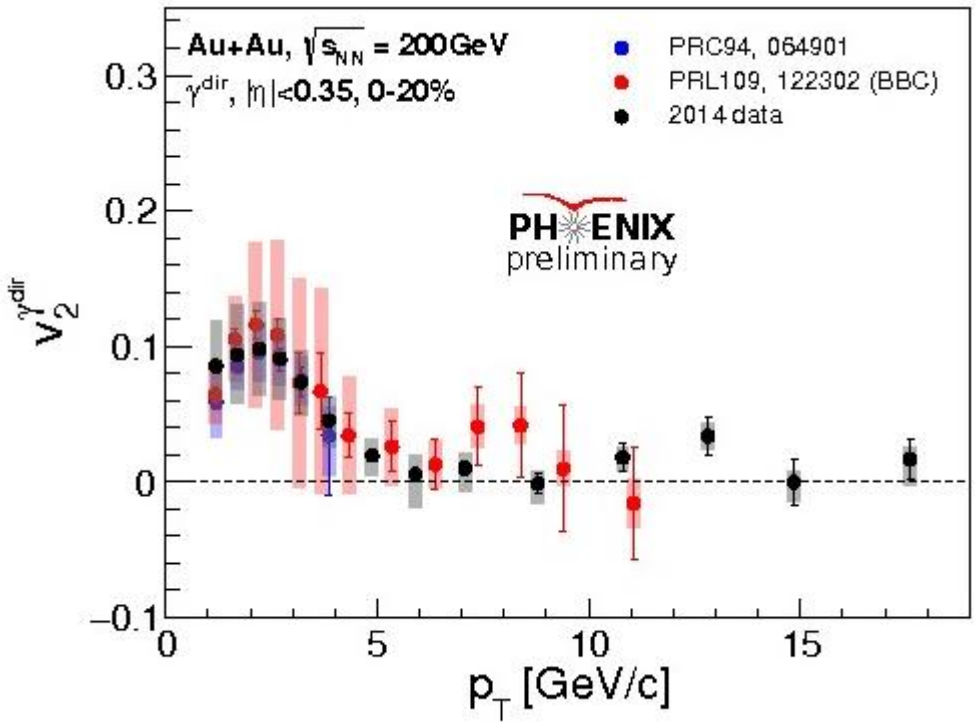
Analysis of 2014 Au+Au PHENIX Data

- **New independent analysis of direct photon emission from data set with 10x statistics**



first shown QM2019

first shown QM2018

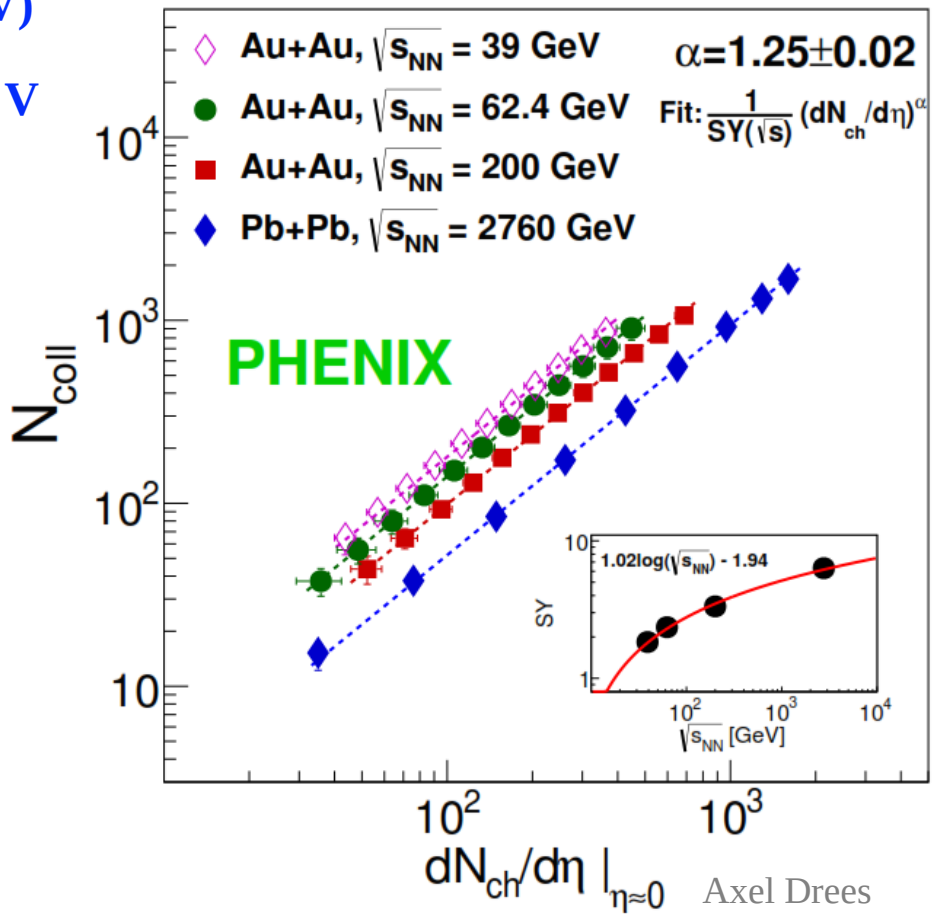


Preliminary Results Consistent with Published Results

New Insight: Vary System Size

- **Vary size: collision system, centrality, √s**
- **Measure system size via $\frac{dN_{ch}}{d\eta}$ or similar**
  - $\frac{dN_{ch}}{d\eta}$ **is an experimental observable**
  - **At fixed √s** $\frac{dN_{ch}}{d\eta} \sim N_{part} \sim$ **Volume (V)**
  - **Varying √s** $\frac{dN_{ch}}{d\eta} \sim$ **energy density × V**

Compare data as function of $\frac{dN_{ch}}{d\eta}$



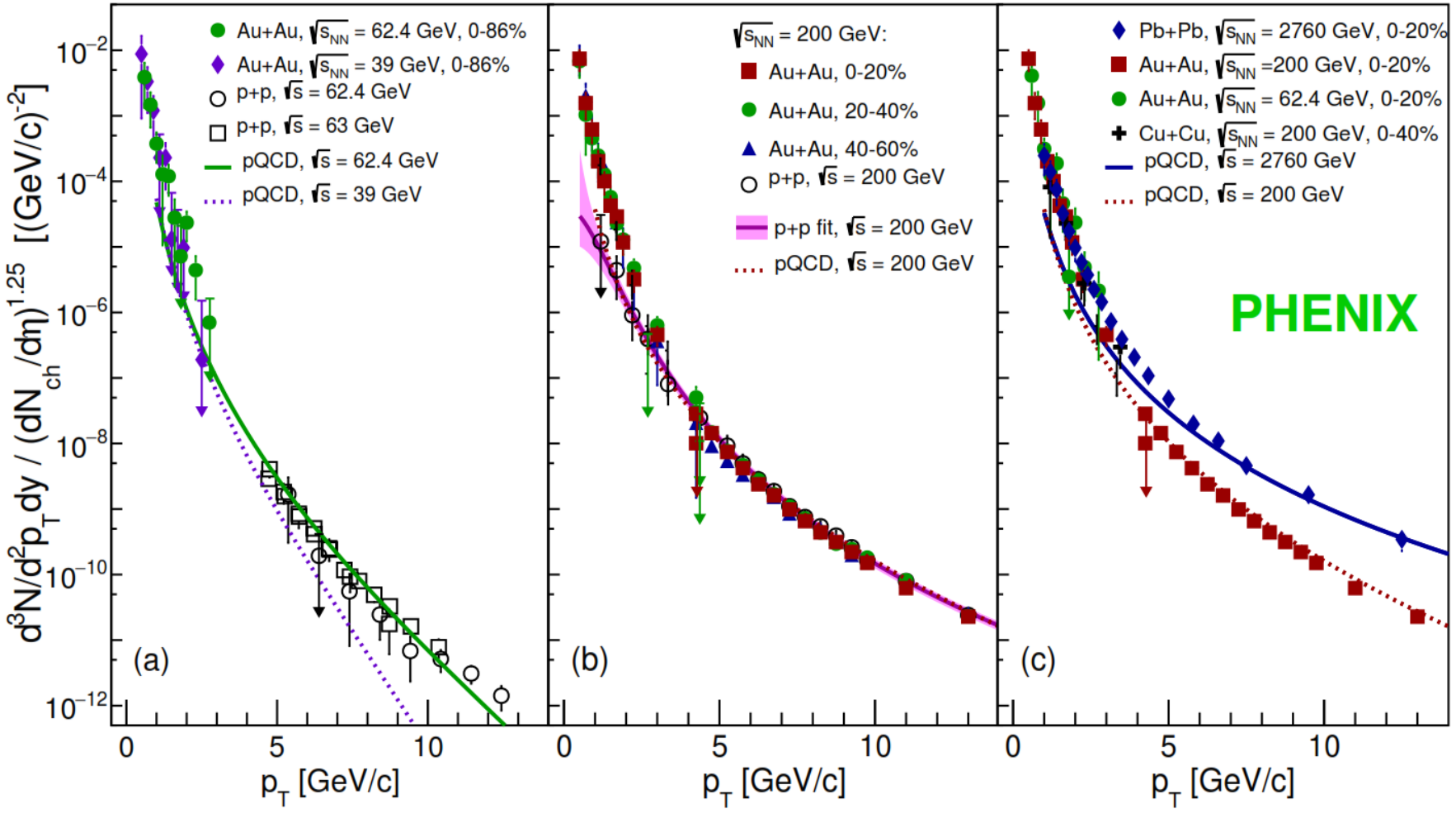
- **Discovery of scaling behavior**
  - **Connects bulk particle production and hard scattering processes**

$$N_{coll} = \frac{1}{SY(\sqrt{s})}\left(\frac{dN_{ch}}{d\eta}\right)^{5/4}$$

Comparison of Different System Sizes

PHENIX: Phys. Rev. Lett. 123 (2019) 22301

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



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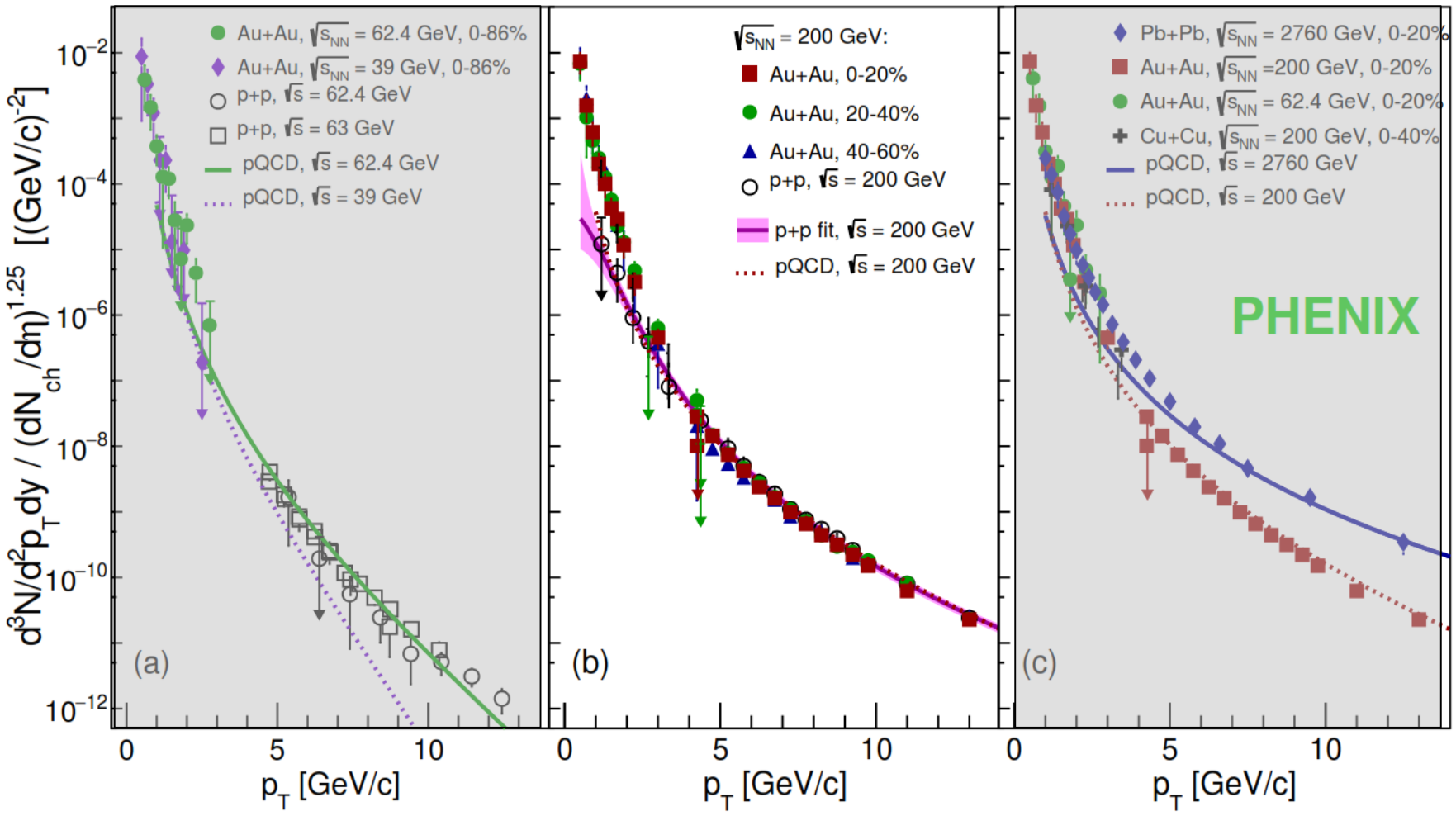

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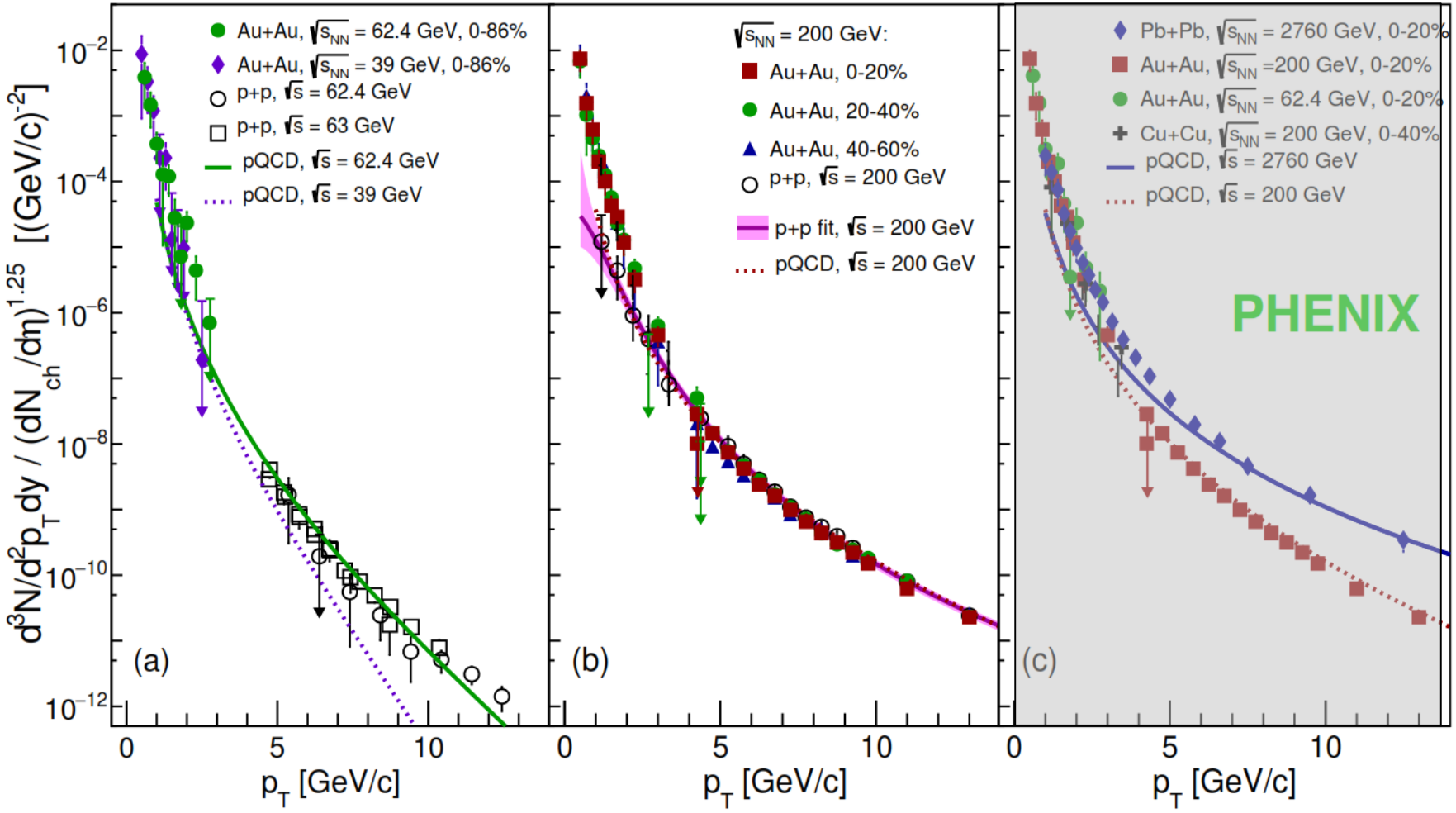

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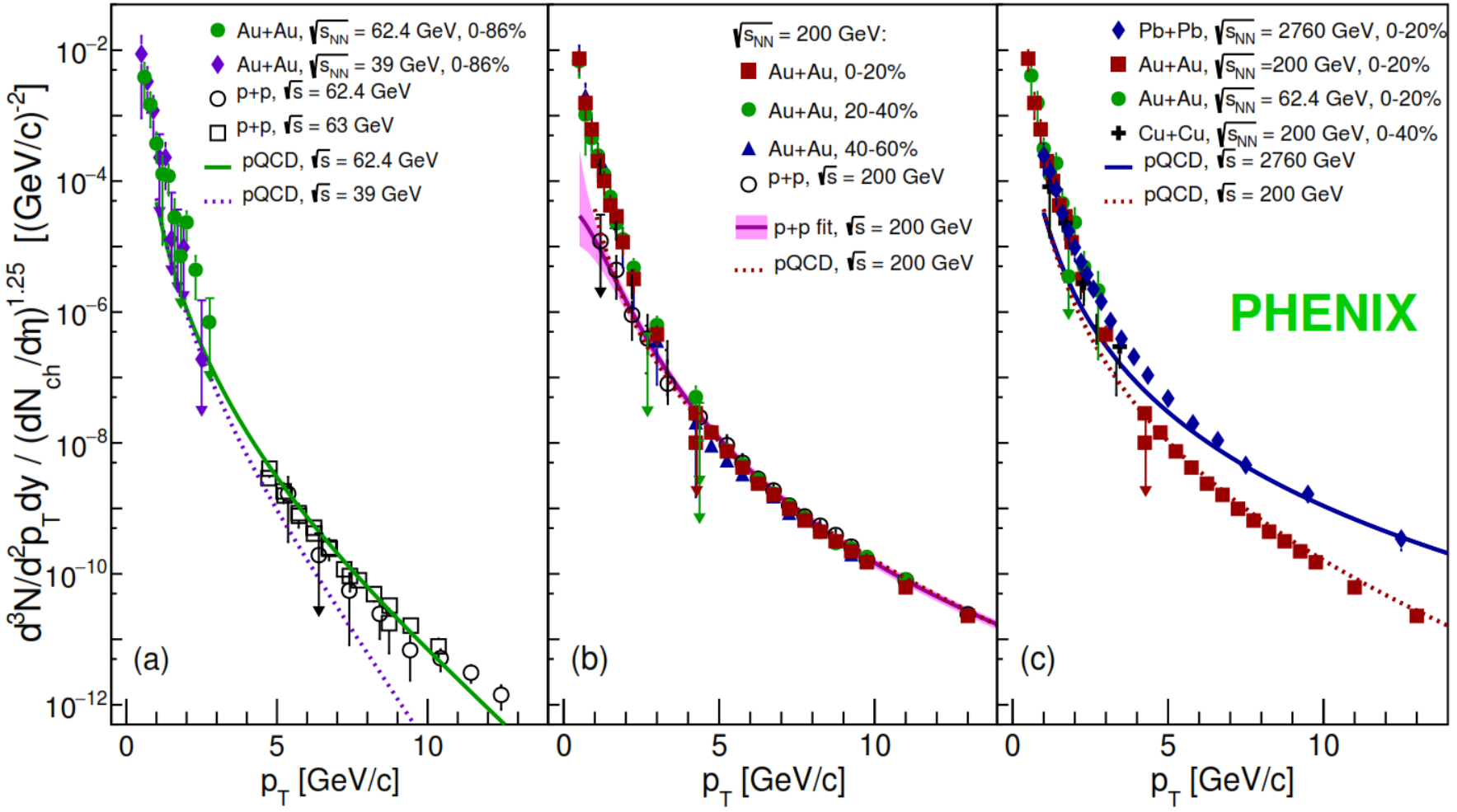
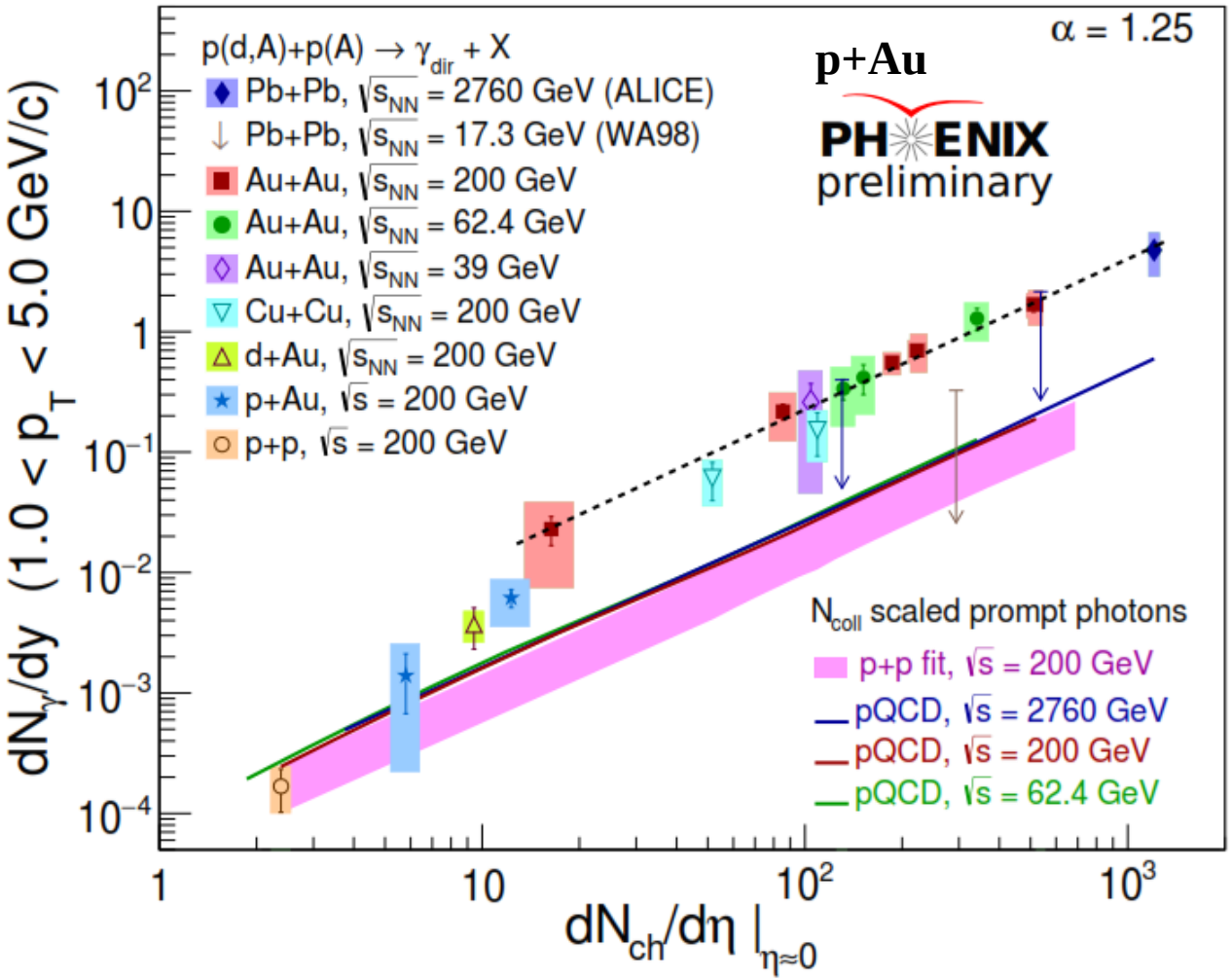


Similar thermal photon yield when scaled with $\left(\frac{dN_{ch}}{d\eta}\right)^{1.25}$ independent of energy, centrality, or system size

Integrated Low p_T > 1 GeV/c Photon Yield

PHENIX: Phys. Rev. Lett. 123 (2019) 22301

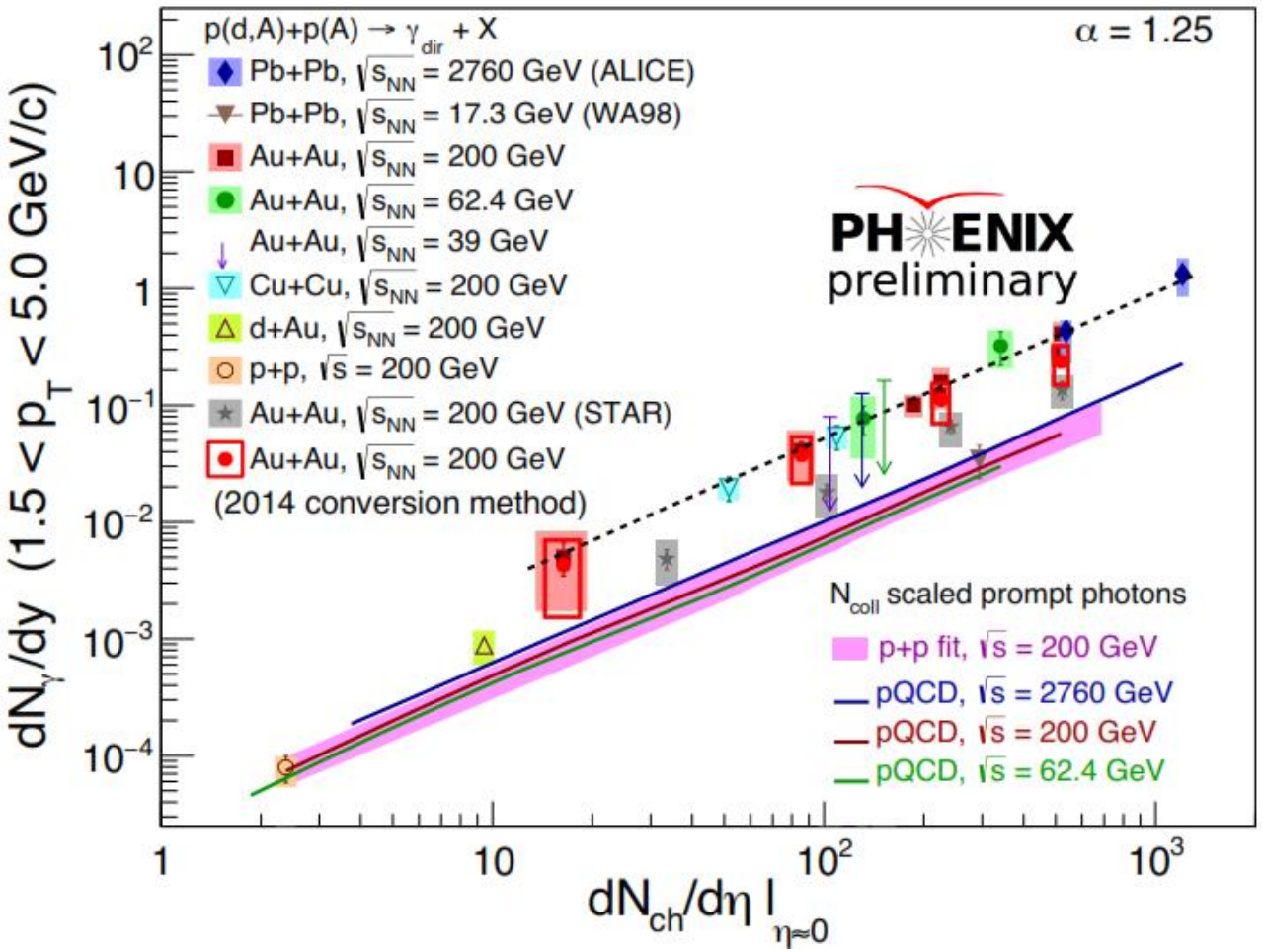


$$\frac{dN_\gamma}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{5/4}$$

- **Universal scaling**
  - **From 39 GeV to 2.76 TeV**
  - **For all centralities**
  - **For different system sizes**
- **N_{coll} × pp: same scaling at 0.1 of yield**
- **Apparent transition for $dN_{ch}/d\eta$ ~ 5 to 30**

Universal scaling behavior!
Suggest similar source of low p_T direct photons!

Integrated Low p_T > 1.5 GeV/c Photon Yield

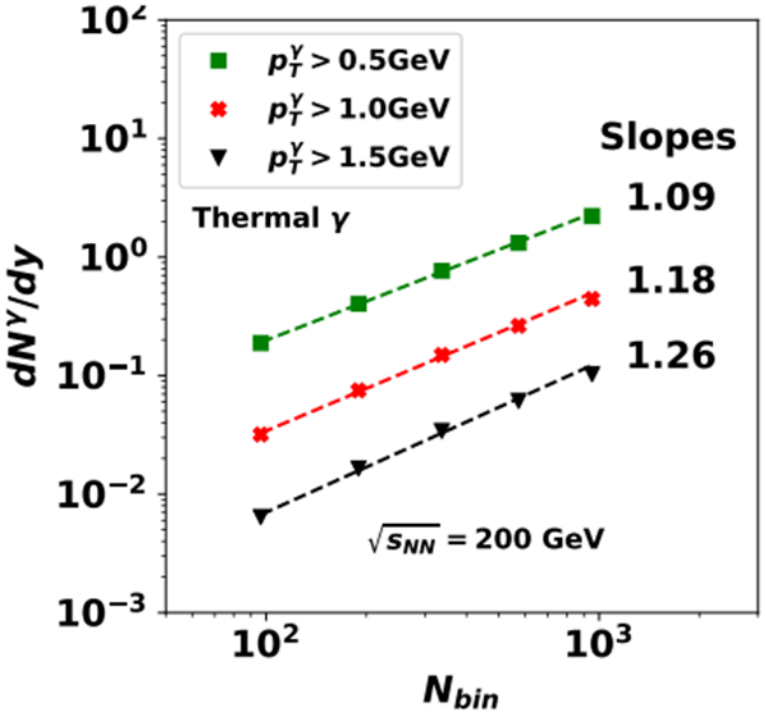


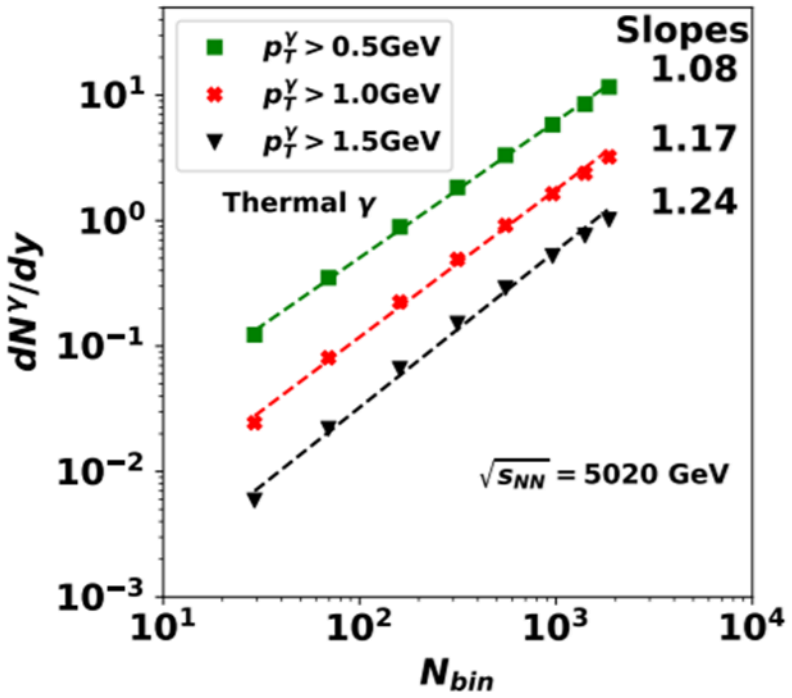
$$\frac{dN_\gamma}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{5/4}$$

- **Universal scaling**
  - **From 39 GeV to 2.76 TeV**
  - **For all centralities**
  - **For different system sizes**
- **N_{coll} × pp: same scaling at 0.1 of yield**
- **Apparent transition for $dN_{ch}/d\eta$ ~ 5 to 30**

Universal scaling behavior with power independent of p_T!

Models for Thermal Photon Emission





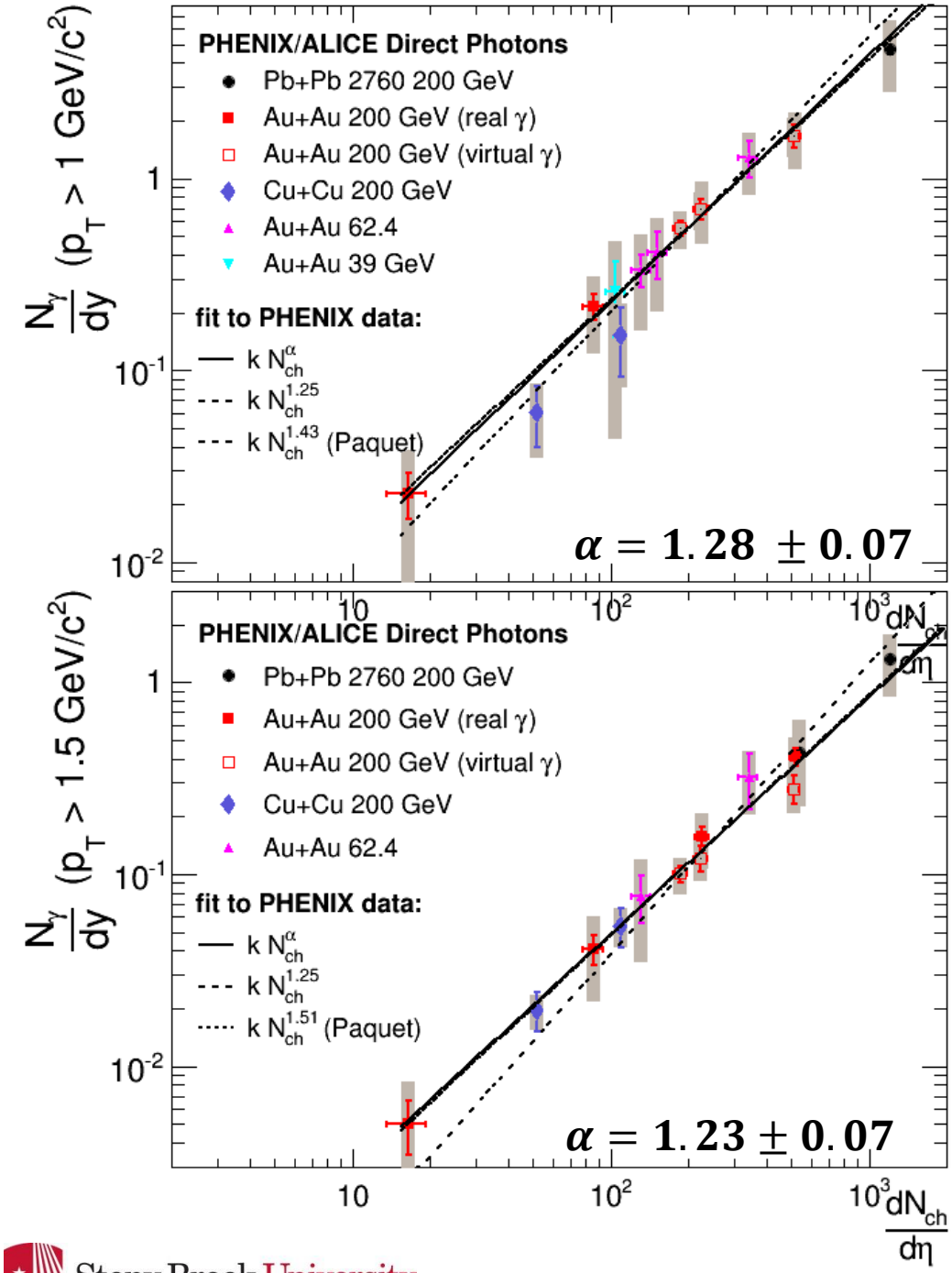
- **Models of thermal photon emission show similar scaling behavior**
  - **Small dependence on energy**
  - **Significant p_T dependence**
  - **Is large than power observed experimentally**

$$\frac{dN_\gamma}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha(pT)}$$

Thermal photons:
$\alpha(p_T) \sim 1.43 \rightarrow 1.51$ for pT > 1 → 1.5 GeV

Universal Scaling

$$\frac{dN_\gamma}{dy} = k\left(\frac{dN_{ch}}{d\eta}\right)^{\alpha}$$

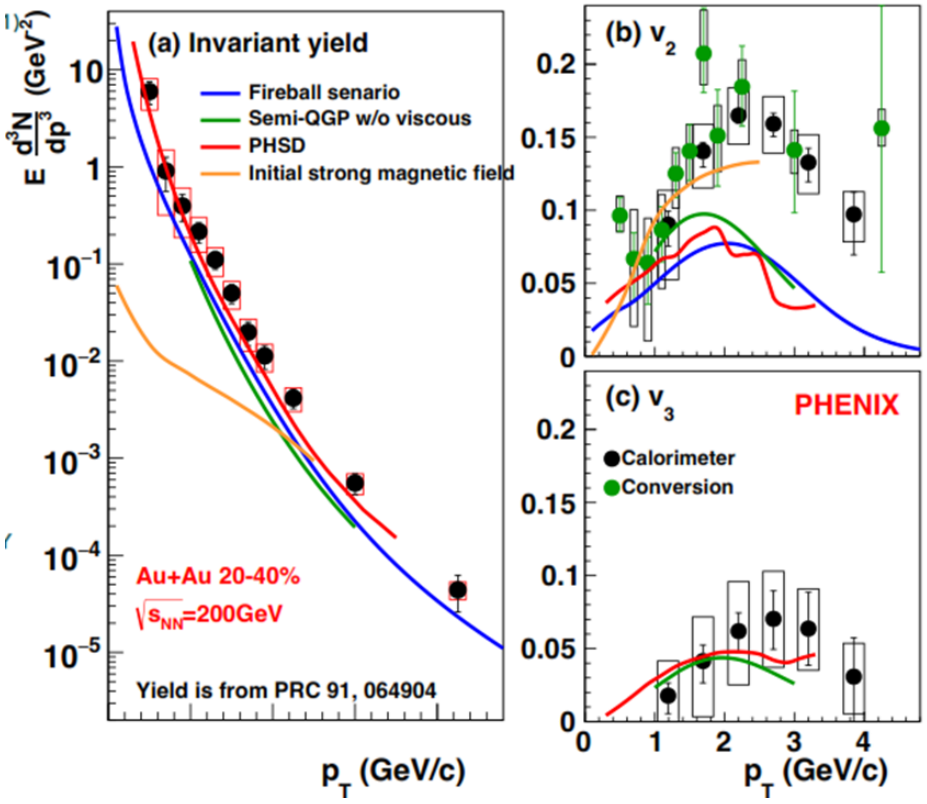


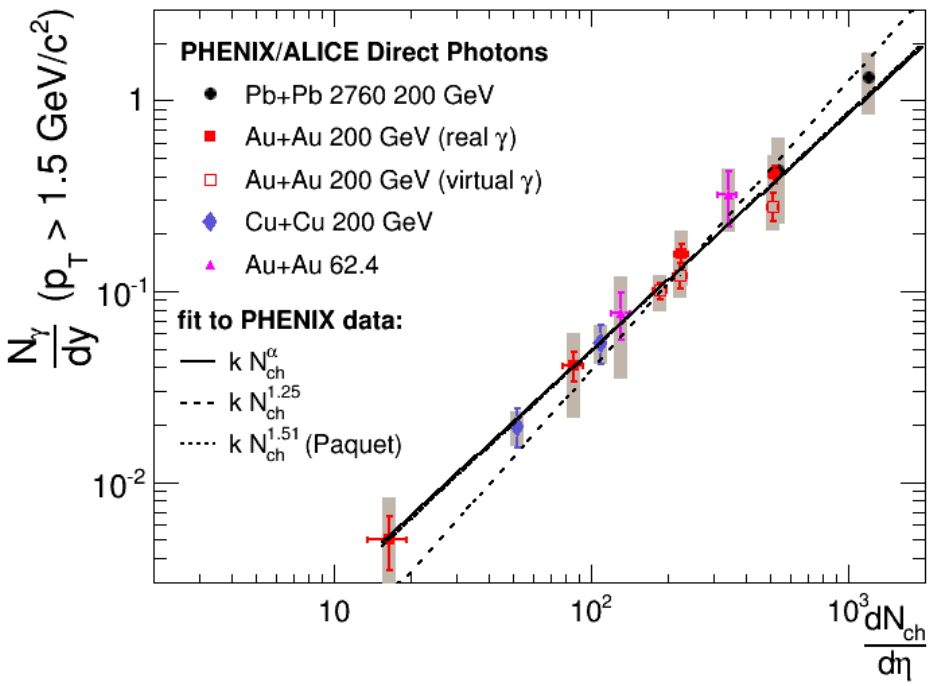
- **Data: universal scaling**
  - **from 39 GeV to 2.76 TeV**
  - **independent of centrality**
  - **independent of p_T cut**
- **Thermal Model:**
  - **N_{coll} × pp: same scaling at 0.1 of yield**
- **Apparent transition**

  for $dN_{ch}/d\eta \sim 5$ to 30

Observed system size dependence not expected for thermal radiation

"Thermal Photon Puzzle"



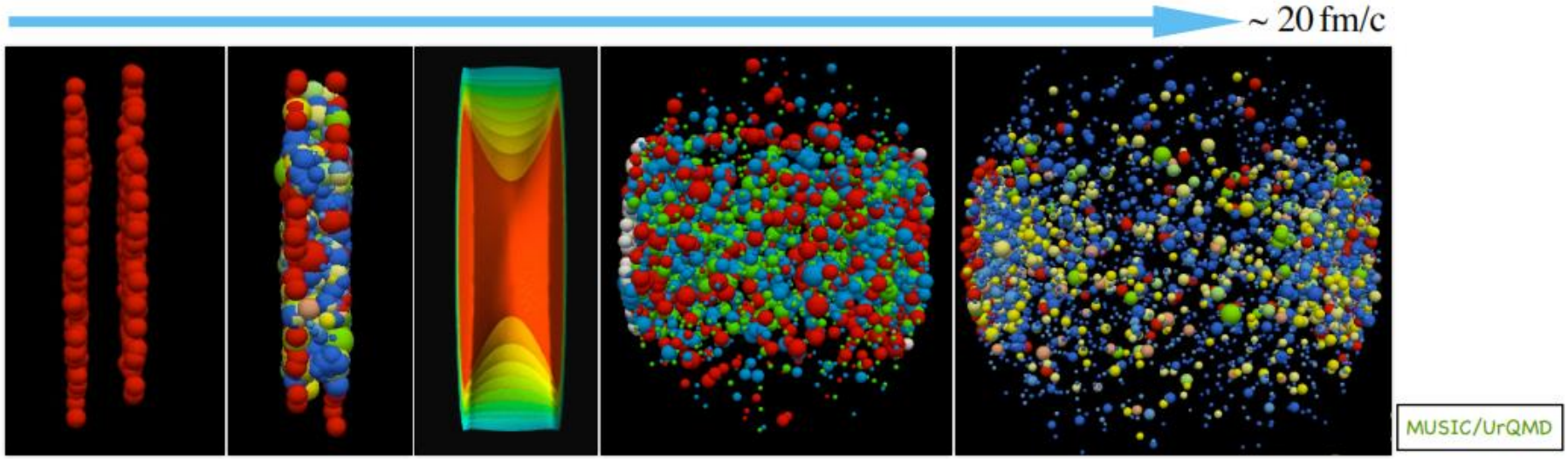


What is the source of low p_T direct photons?

- **Experimental observation**
  - **Large yield of low p_T direct photons**
  - **Large Anisotropic Emission**
  - **Universal Scaling with $\alpha \sim 5/4$**
- **Challenging to explain by thermal source**

Outlook

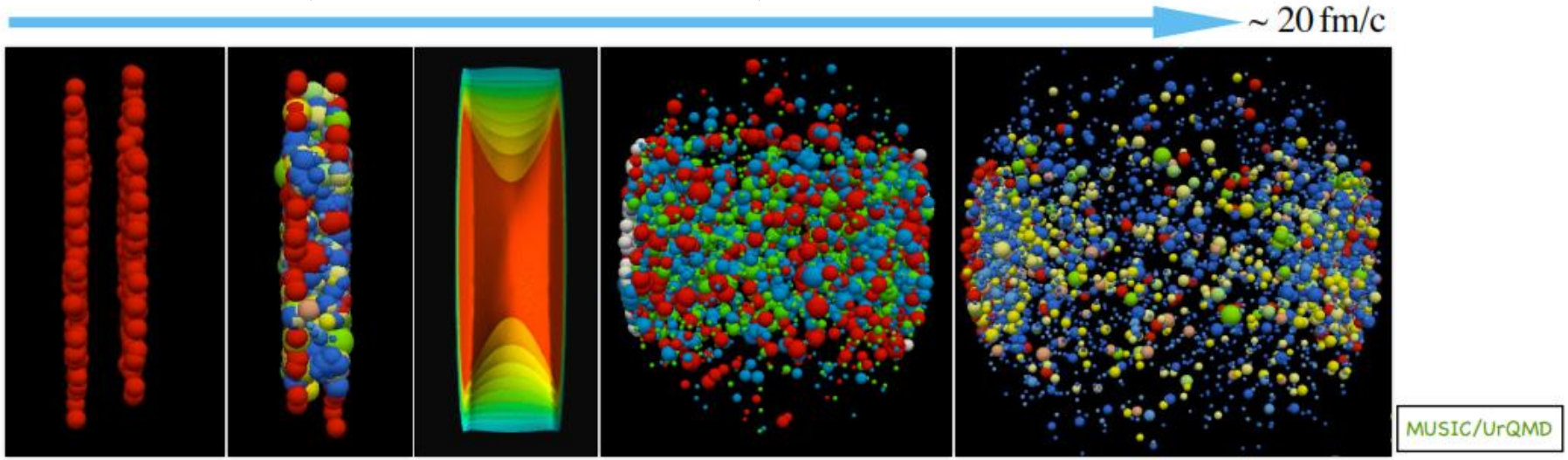
Relativistic nuclear collisions: The emergence of a "standard picture"



Charles Gale
McGill

Outlook

Role of large B-field? **Additional light from hadronization?**

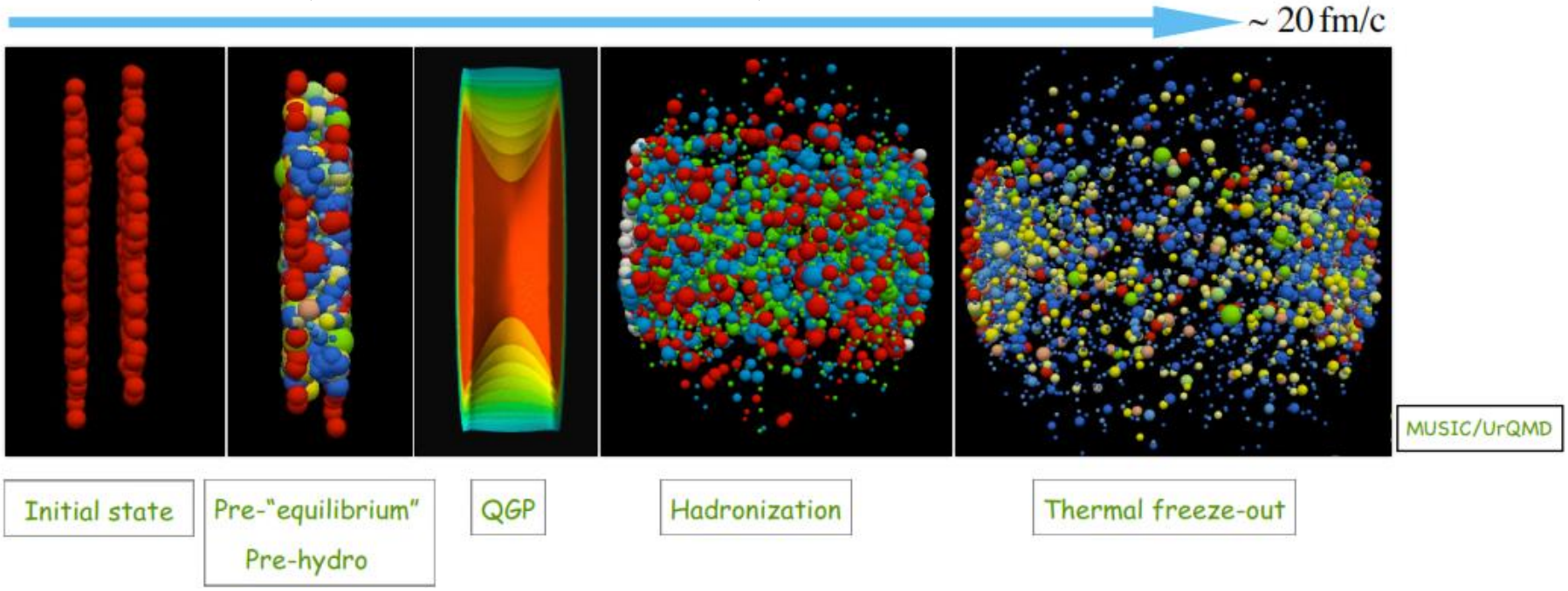


Charles Gale
McGill

Outlook from PHENIX

Role of large B-field?

Additional light from hadronization?



- **Small system data sets**
  - p-Au, ^{3}He-Au, d-Au
  - "engineer" collision geometry
  - Search for onset of QGP
- **High statistics large systems**
  - Au-Au, Cu-Au
  - More precise measurements
  - New insights into thermal photon puzzle

Backup

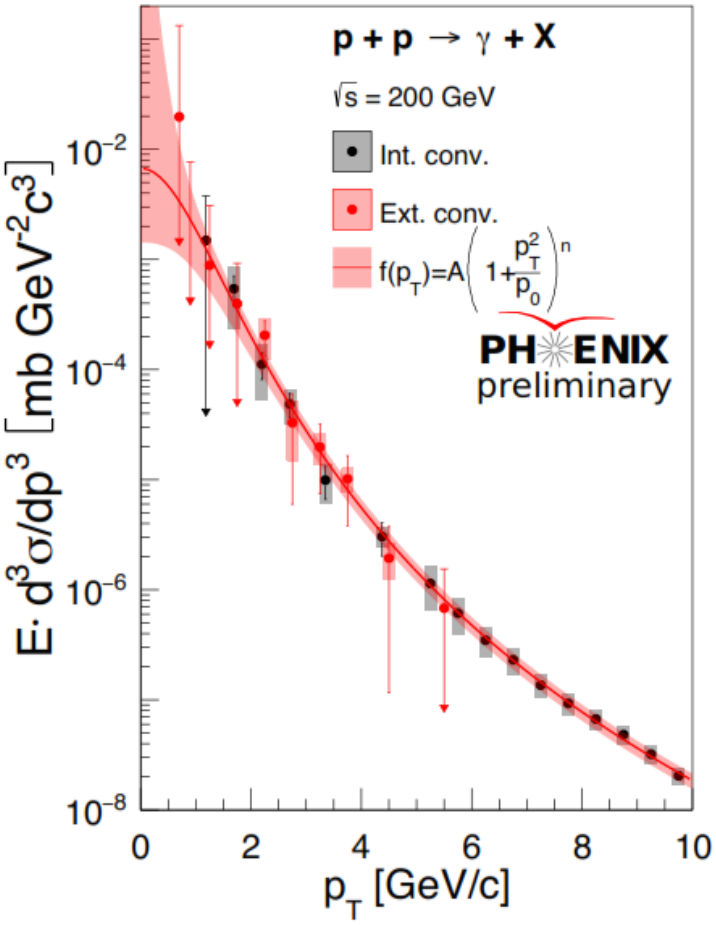
Undated p+p Reference for Direct Photons

- Fitting function

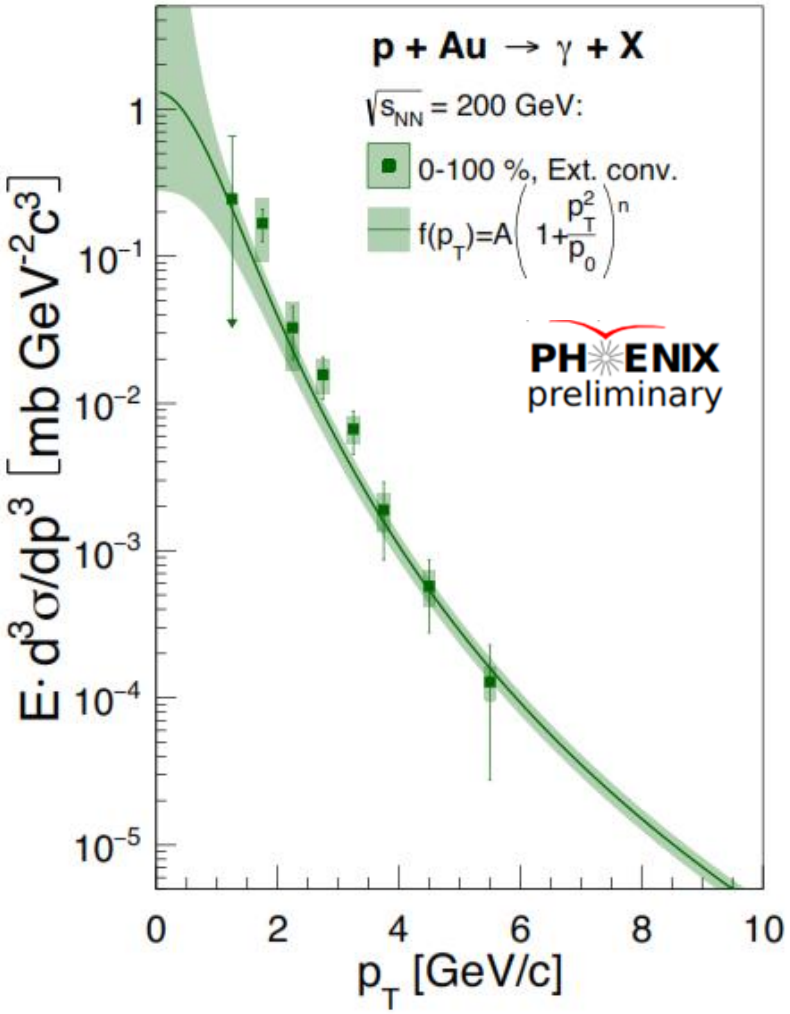
$$\frac{dN}{dy} = a\left(1+\frac{p_T^2}{b}\right)^c$$

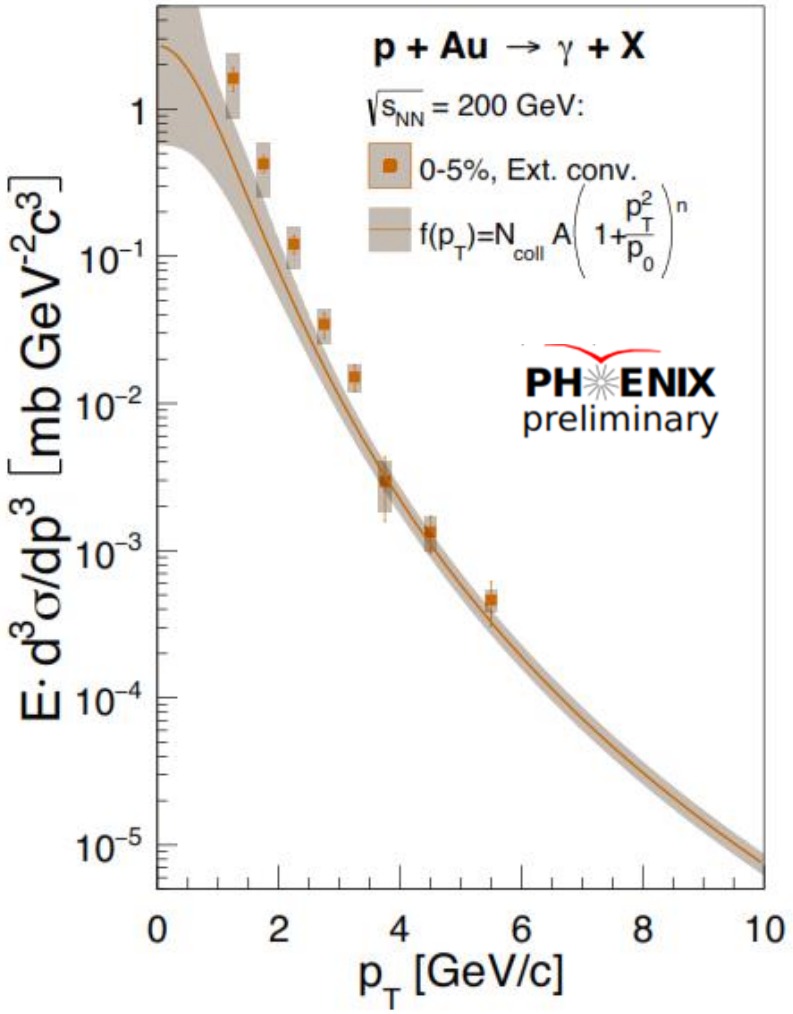
a	b	c
6.74×10^3	2.10	-3.30

- pQCD inspired function
- The fit <1GeV is motivated by Drell-Yan measurement [Ito, et al, PRD23, 604 (1981)]
- Systematic errors include the fit errors, different functional forms



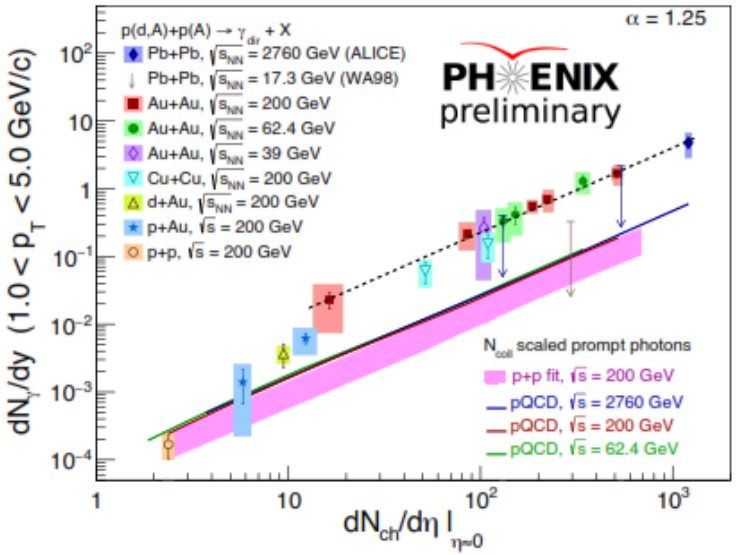
PHENIX Direct Photons from p+Au

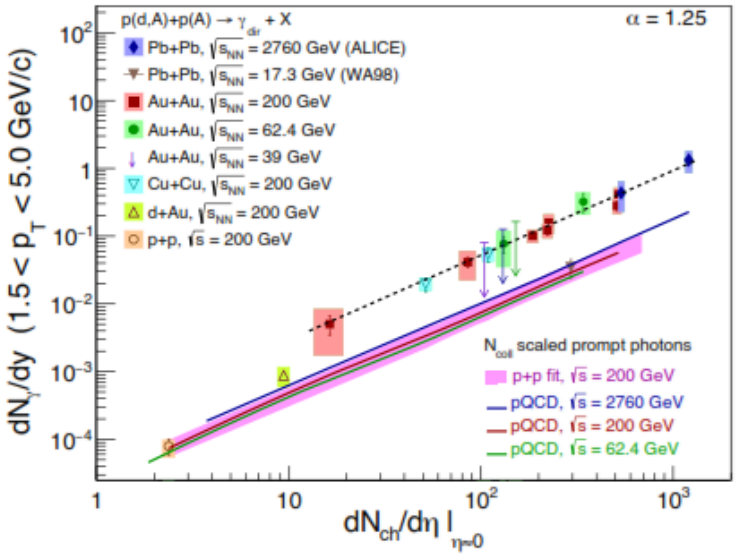


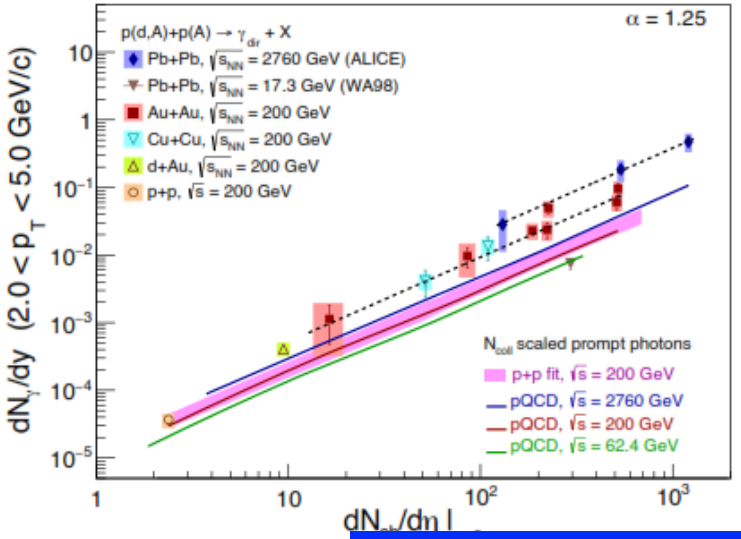


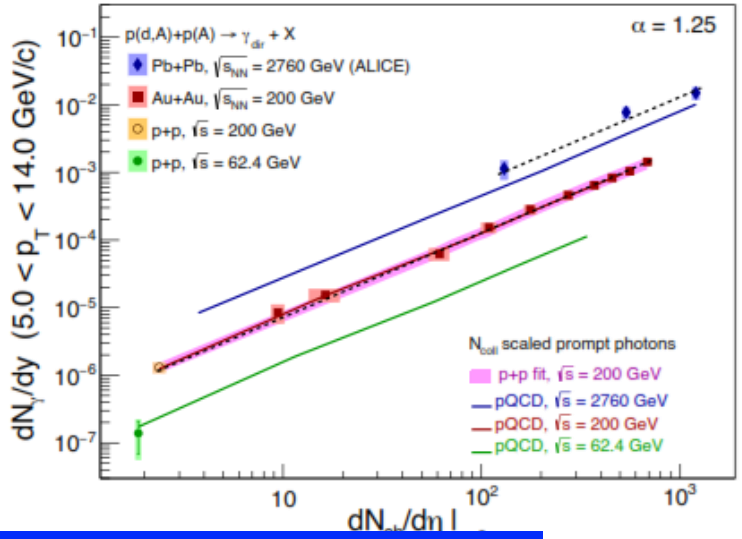
Evidence for low pT direct photon enhancement in p+Au

p_T Dependence of Integrated Direct Photon





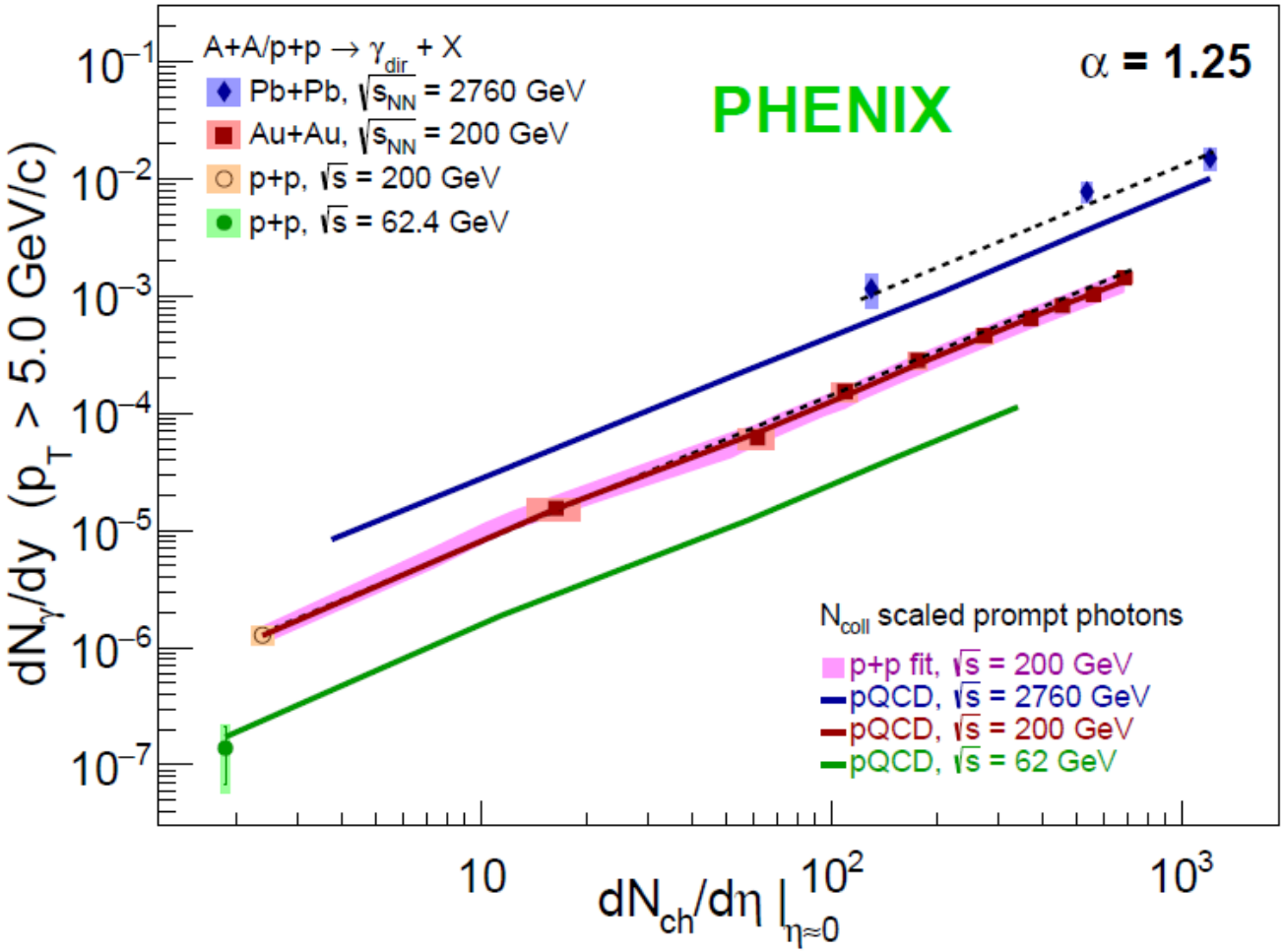




Power independent of p_T cut

Integrated Photon Yield $p_T > 5$ GeV/c

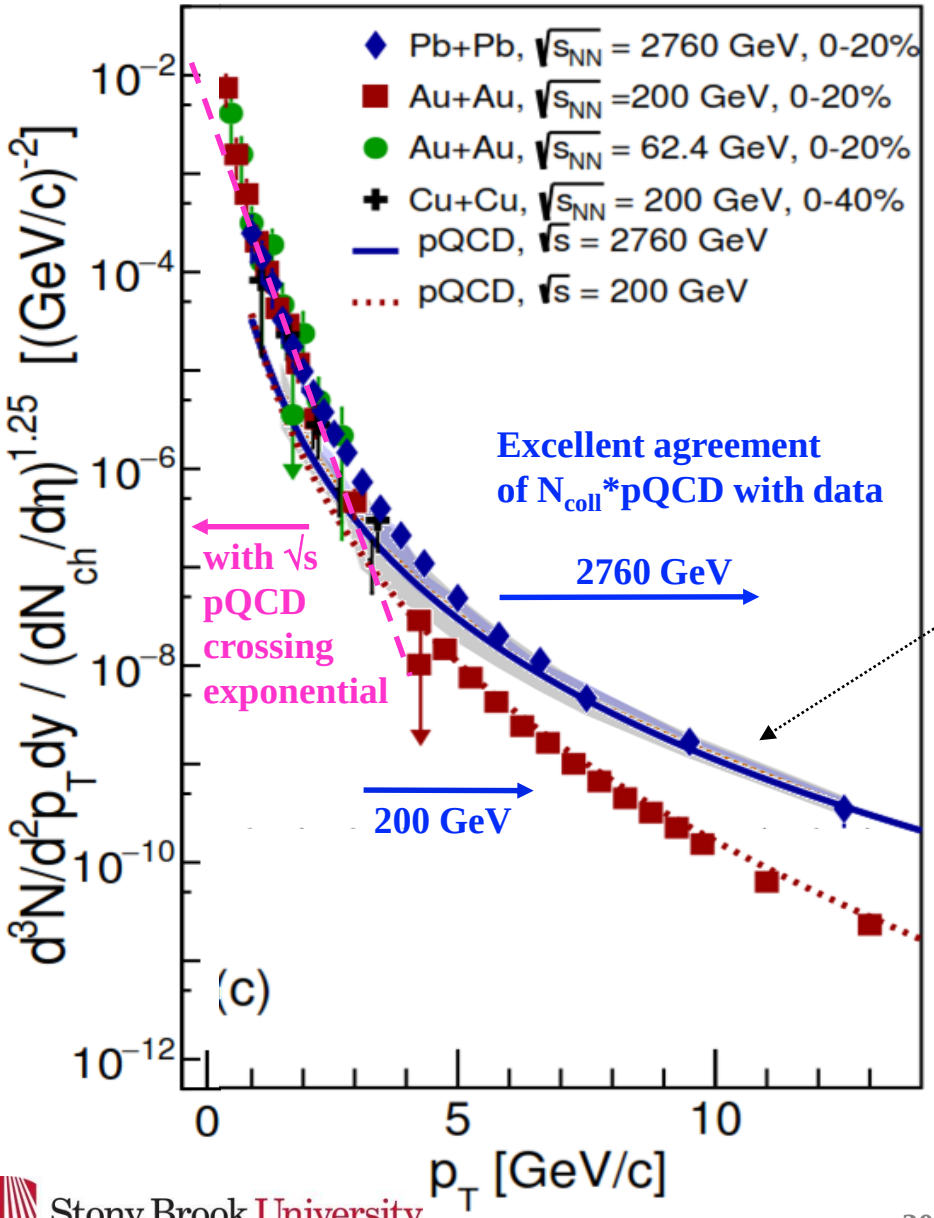
PHENIX: Phys. Rev. Lett. 123 (2019) 22301



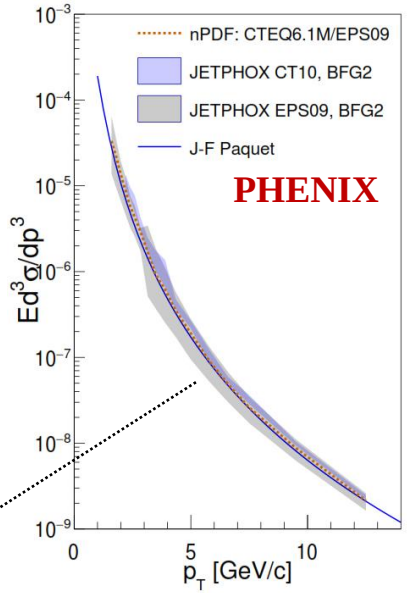
Au+Au at 200 GeV consistent with Ncoll x p+p and Ncoll + pQCD

Pb+Pb same scaling but 30% above Ncoll x pQCD p+p

Comment on p_T > 5 GeV ALICE data



Systematic uncertainty of pQCD calculation

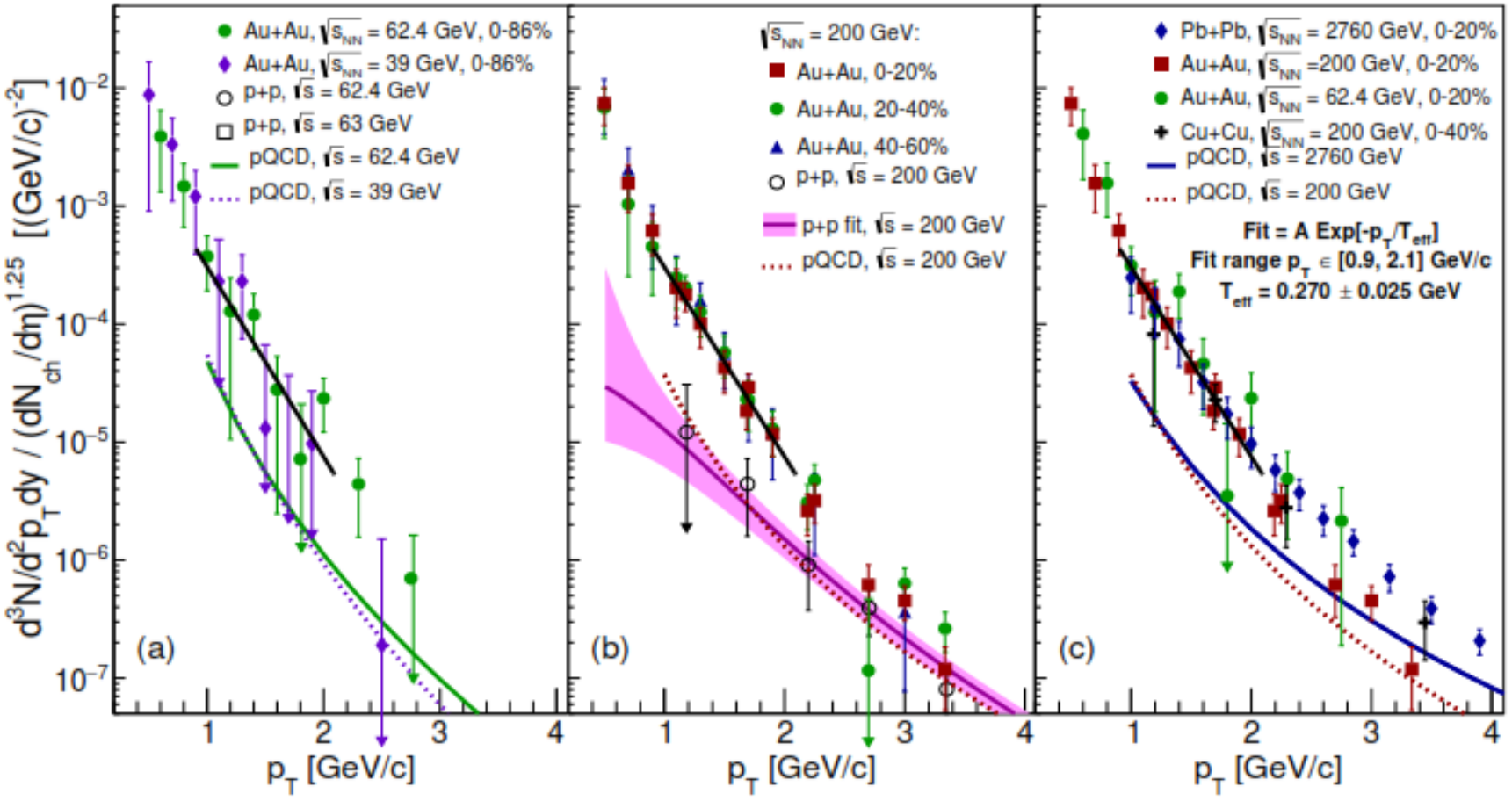


ALICE

scale uncertainties
PDF uncertainties

- **Comparison Data to N_{coll} * pQCD**
  - Agreement moves higher p_T with increasing √s
  - Exponential + pQCD would move to lower p_T with increasing √s
  - Significant if scale uncertainties dominate pQCD uncertainties

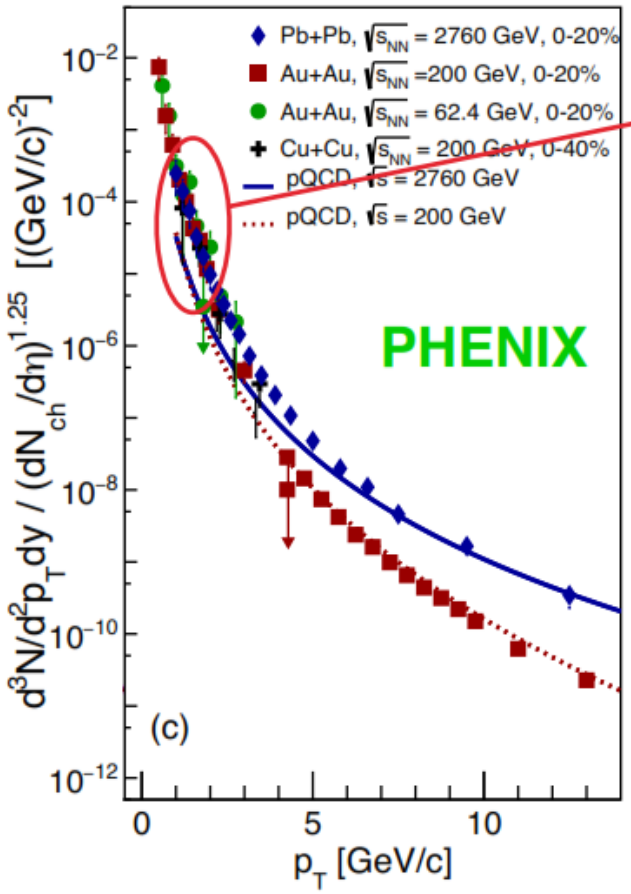
Focus on low p_T Region

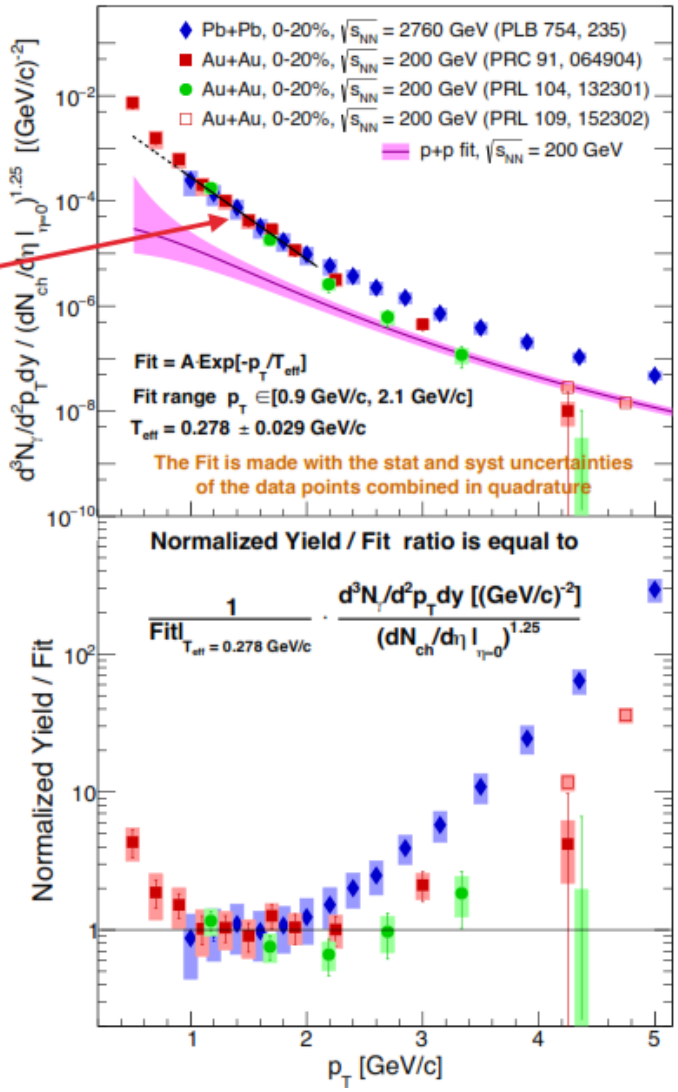


- **Similar inverse slope**
  - T_{eff} ~ 270 MeV for all spectra 0.9 < pT < 2.1 GeV/c
  - Independent of centrality and √s from 39 to 2760 GeV

More Detailed Look at Low p_T Range

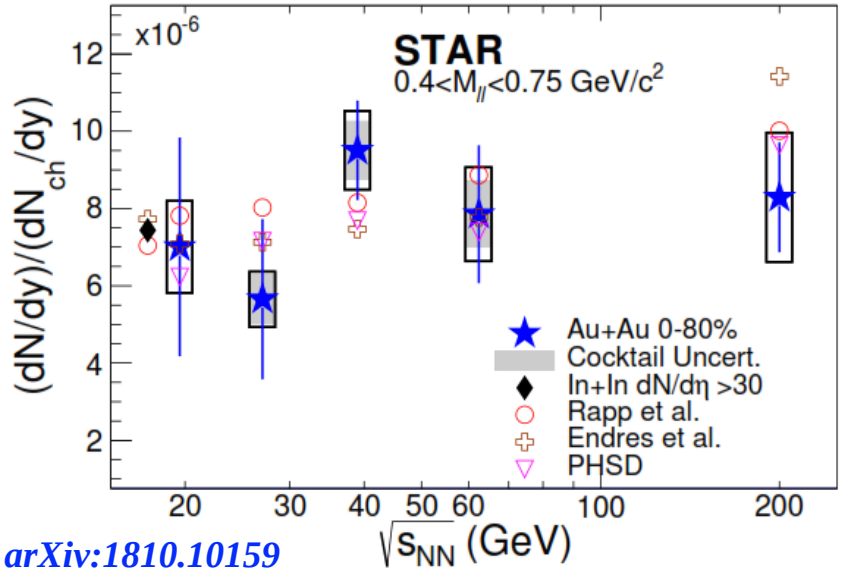
Fit exponential to scaled PHENIX 200 GeV Au +Au centrality selected and ALICE 2.76 TeV data in range of 0.9 to 2.1 GeV





STAR Dileptons

- **Dileptons form beam energy scan**
  - Au+Au collisions
  - √s = 19.6, 27, 39, 62.4 and 200 GeV
  - Fully corrected dilepton excess
  - √s dependence as Excess/$\frac{dN_{ch}}{d\eta}$



STAR: arXiv:1810.10159