6th International Conference on New Frontiers in Physics

New Frontiers in Physics ICNFP 2017

Low Momentum Direct Photon Measurement

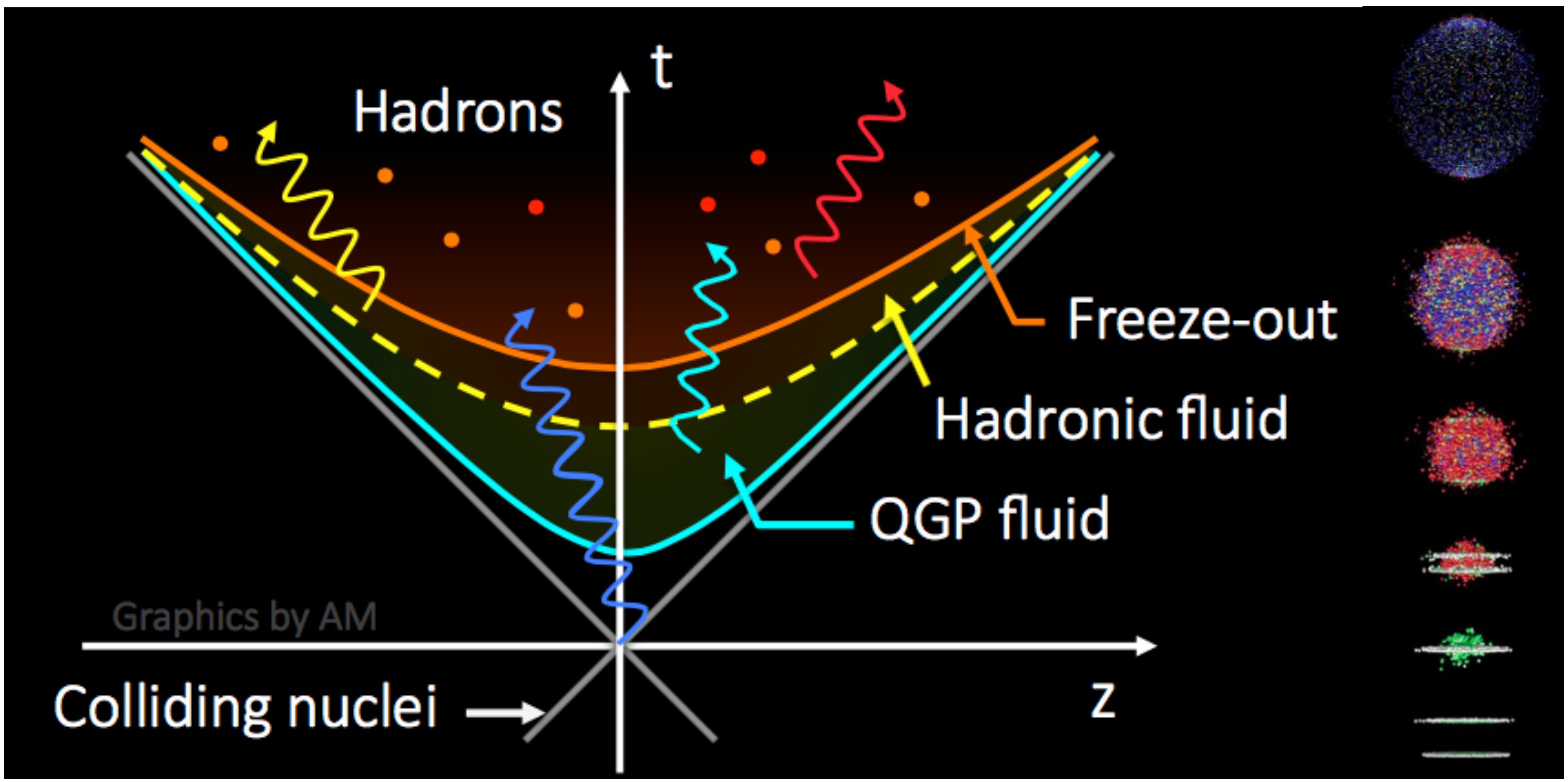
Wenqing Fan for PHENIX Collaboration

ICNFP 2017

Why Photons?

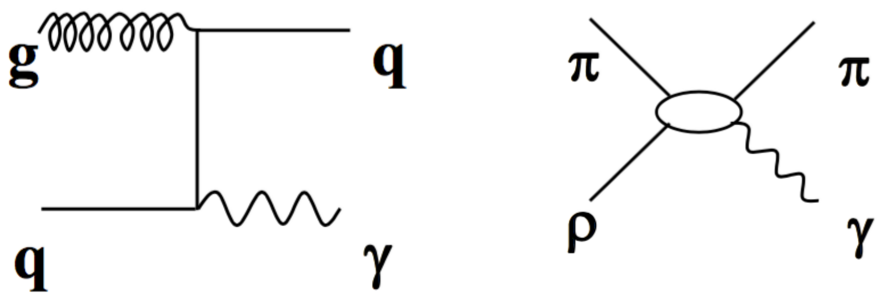
- Photons are a unique probe for Quark Gluon Plasma (QGP)
  - EM probe: "Color blind" (do not suffer strong interaction)
  - Probe the full time evolution

Direct photon = Inclusive photons – hadronic decay photons

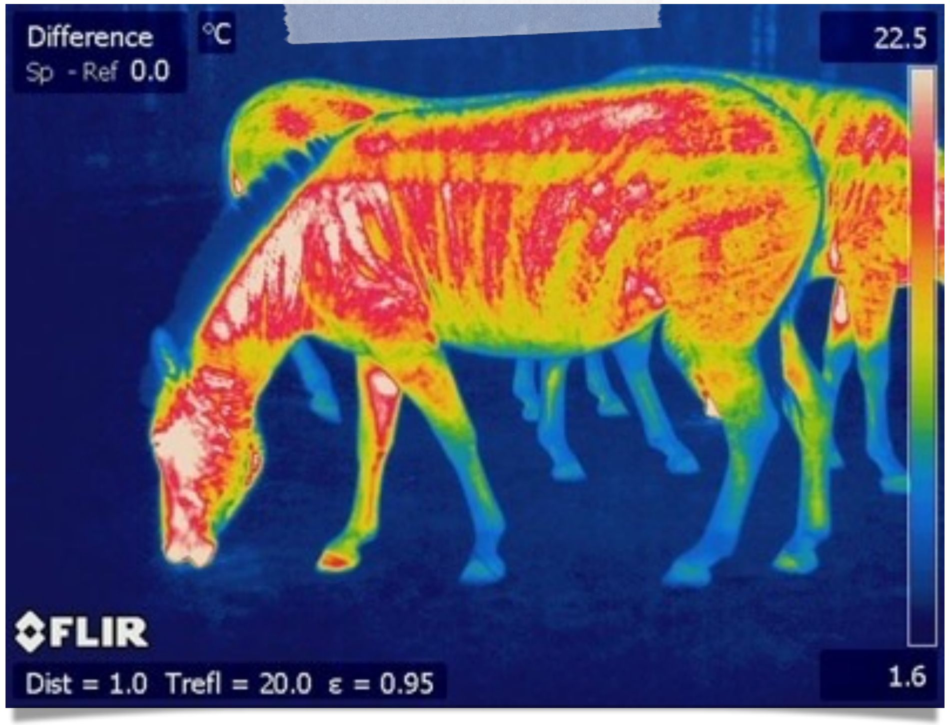


- Black body analogy
  - Hot & dense medium: radiate thermal photons

e.g. QGP Hadron Gas



- photons
- low mass lepton pairs



- Spectrum and yield sensitive to temperature Avg. inv. slope ∝ T, Rate ∝ T^4

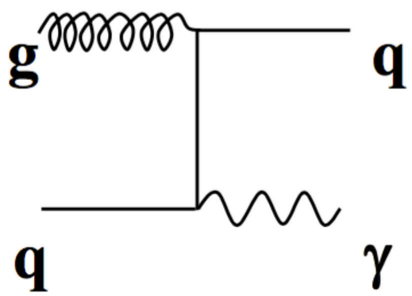
- Spectrum also affected by the space time evolution of matter Doppler shift

What to Measure via Direct Photons? — Thermal Radiation

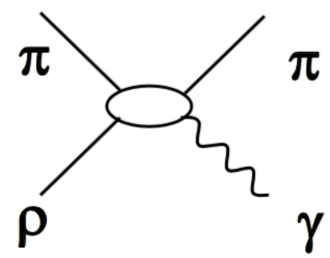
- Black body analogy

  - Hot & dense medium: radiate thermal photons

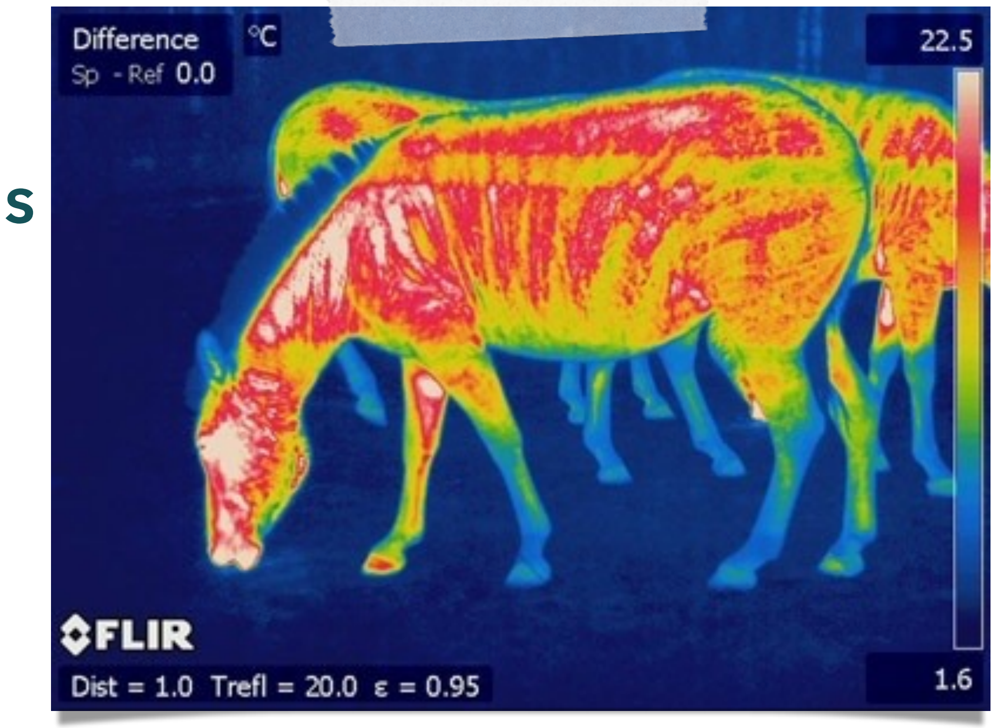
QGP



Hadron Gas



- photons
- low mass lepton pairs



- Spectrum and yield sensitive to temperature Avg. inv. slope ∝ T, Rate ∝ T^4

Large yield → high T → early emission

- Spectrum also affected by the space time evolution of matter Doppler shift

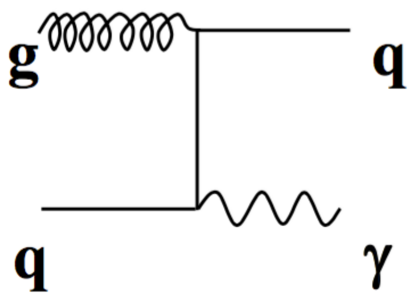
Large Doppler shift → late emission

What to Measure via Direct Photons? — Thermal Radiation

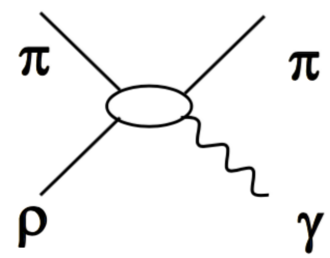
- Black body analogy

  - Hot & dense medium: radiate thermal photons

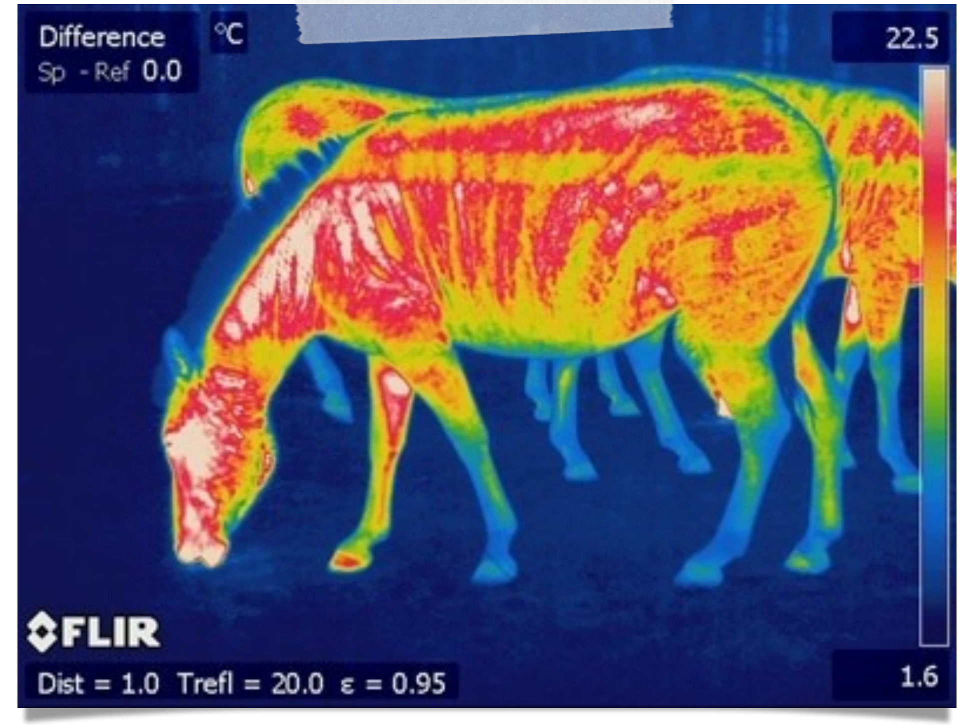
QGP



Hadron Gas



- photons
- low mass lepton pairs



- Spectrum and yield sensitive to temperature Avg. inv. slope ∝ T, Rate ∝ T^4

Large yield → high T → early emission

- Spectrum also affected by the space time evolution of matter Doppler shift

Large Doppler shift → late emission

Measurements of yield will constrain initial conditions, emission rates and space-time evolution

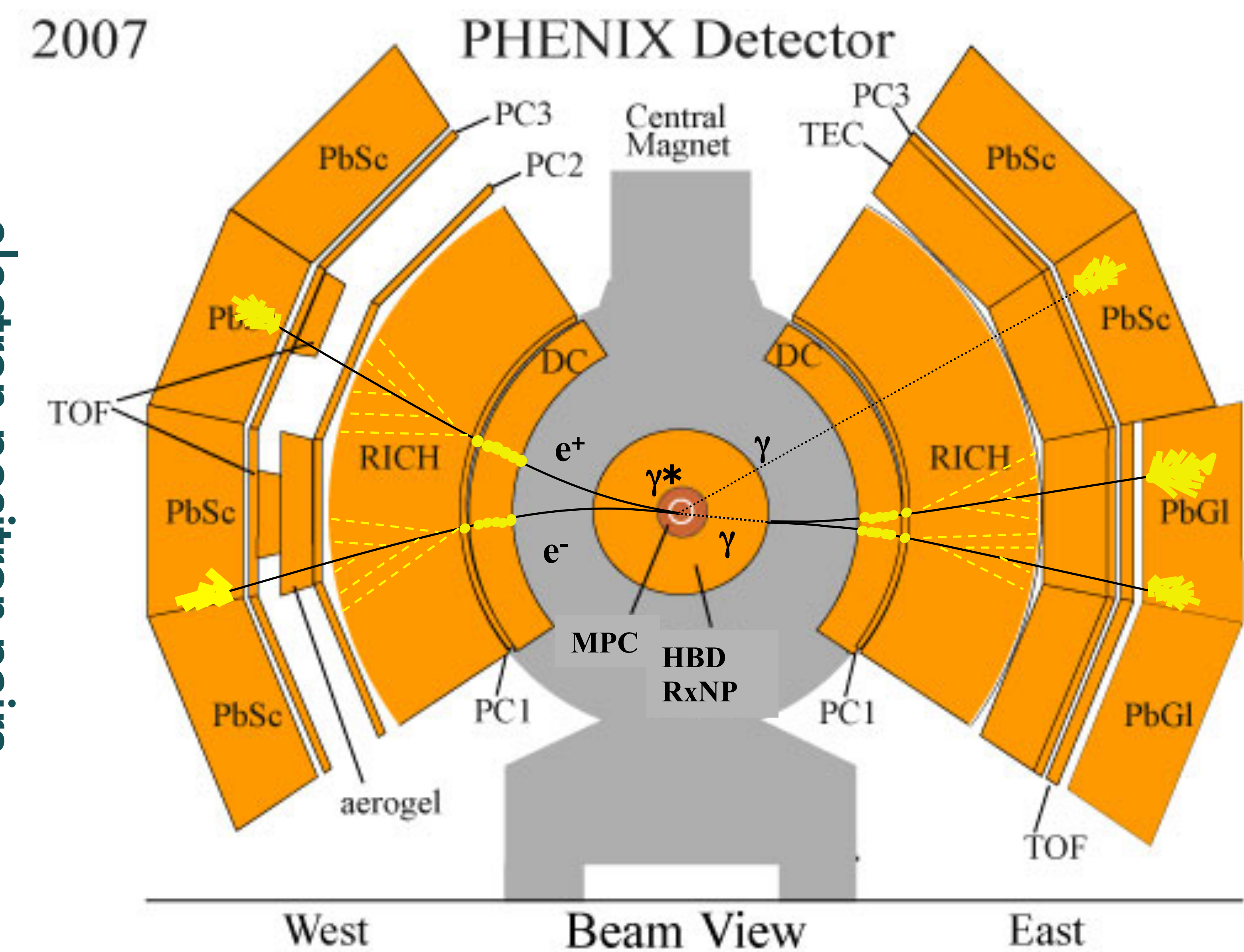
How to Measure Photons? — 3 Methods @PHENIX

- calorimetric method
  - γ
  - good resolution at high p_T
  - low p_T is contaminated by hadrons

photons

- internal conversions
  - $\gamma^* \rightarrow e^+ + e^-$
  - bkg from hadron decay photon reduced by a factor of 5 (small bkg)
  - 1/1000 rate reduction
- external conversions
  - $\gamma \rightarrow e^+ + e^-$
  - more statistics compared to internal conversion
  - good resolution at low p_T

electron-positron pairs

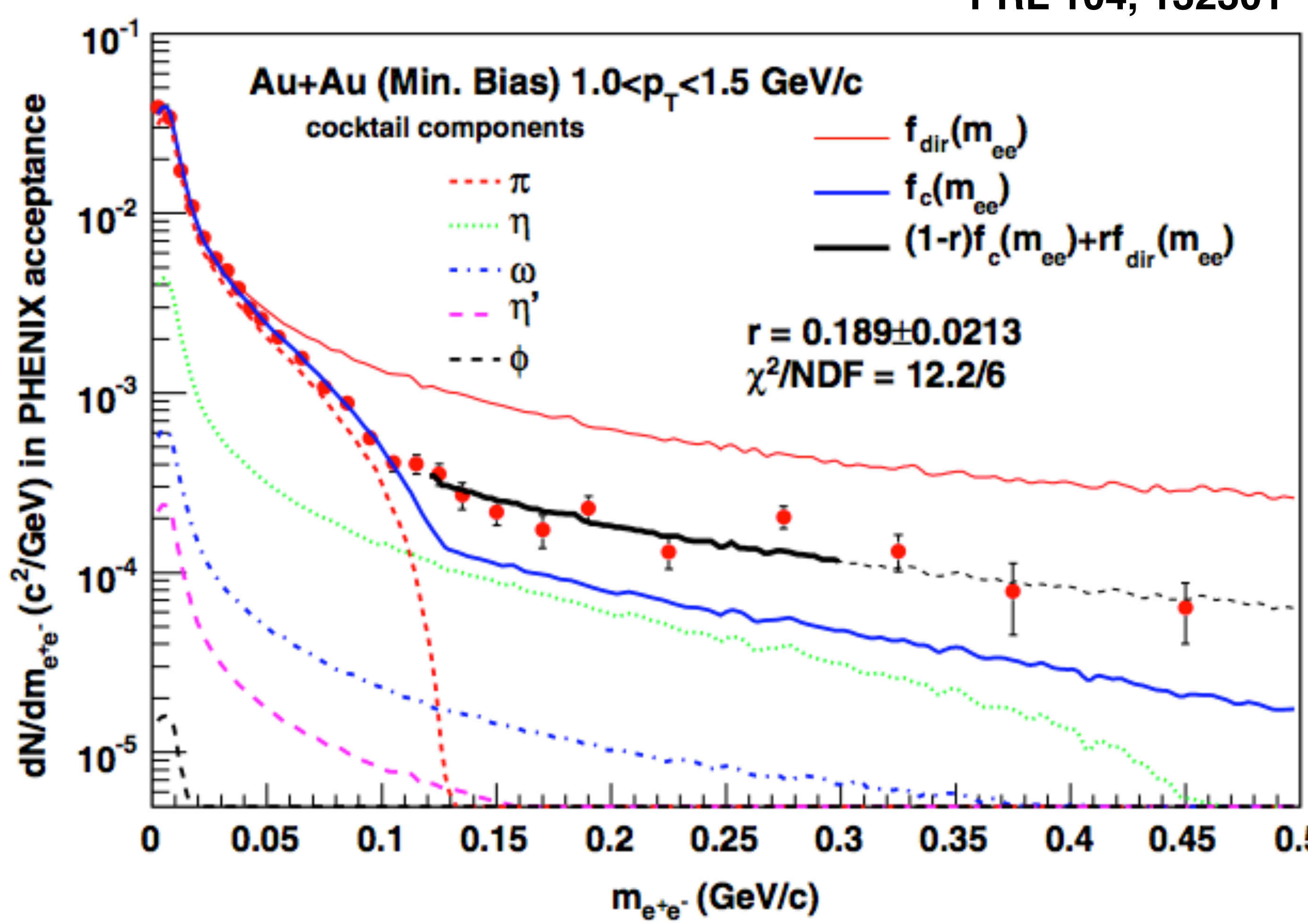


Internal conversion method

- Any process radiate γ will also radiate γ* (e^+e^-)
  - extrapolate γ*(e^+e^-) yield at $m_{ee} \ll p_T$ ➟ dN^γ ↔ dN^{incl}

$$\frac{d^2 N_{ee}}{dm_{ee} dp_T} \simeq \frac{2\alpha}{3\pi} \frac{1}{m_{ee}} \frac{dN_\gamma}{dp_T}$$

PRL 104, 132301



Example: one p_T bin for Au+Au collisions

- $f_{incl}(m_{ee}) = (1-r)f_c(m_{ee}) + rf_{dir}(m_{ee})$

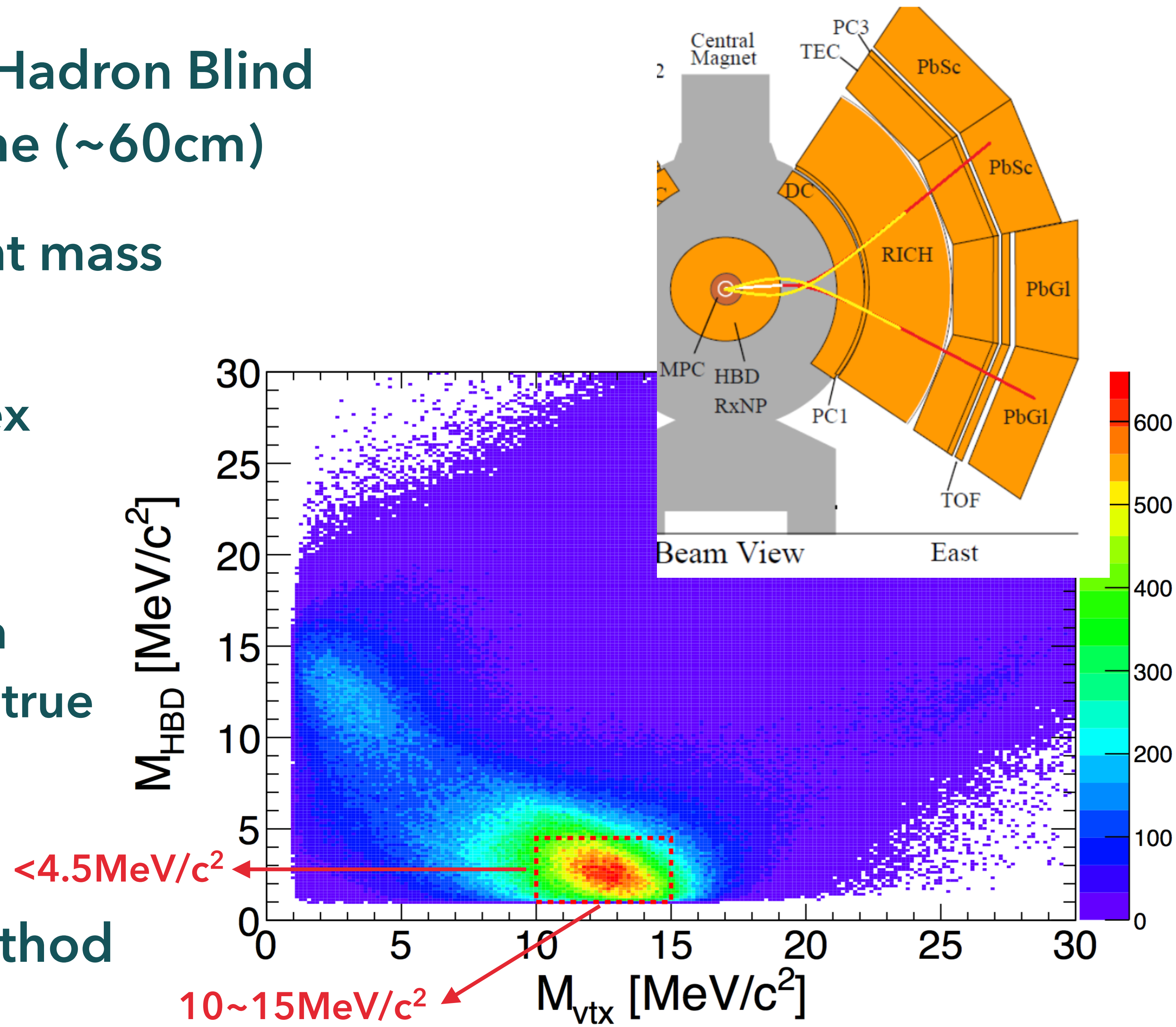
  all hadron contribution — direct photon contribution

  - fit in range 120MeV to 300MeV (insensitive to π^0 contribution)

- $r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$ → $dN^{\text{dir}}(p_T) = r \times dN^{\text{incl}}(p_T)$

External conversion method

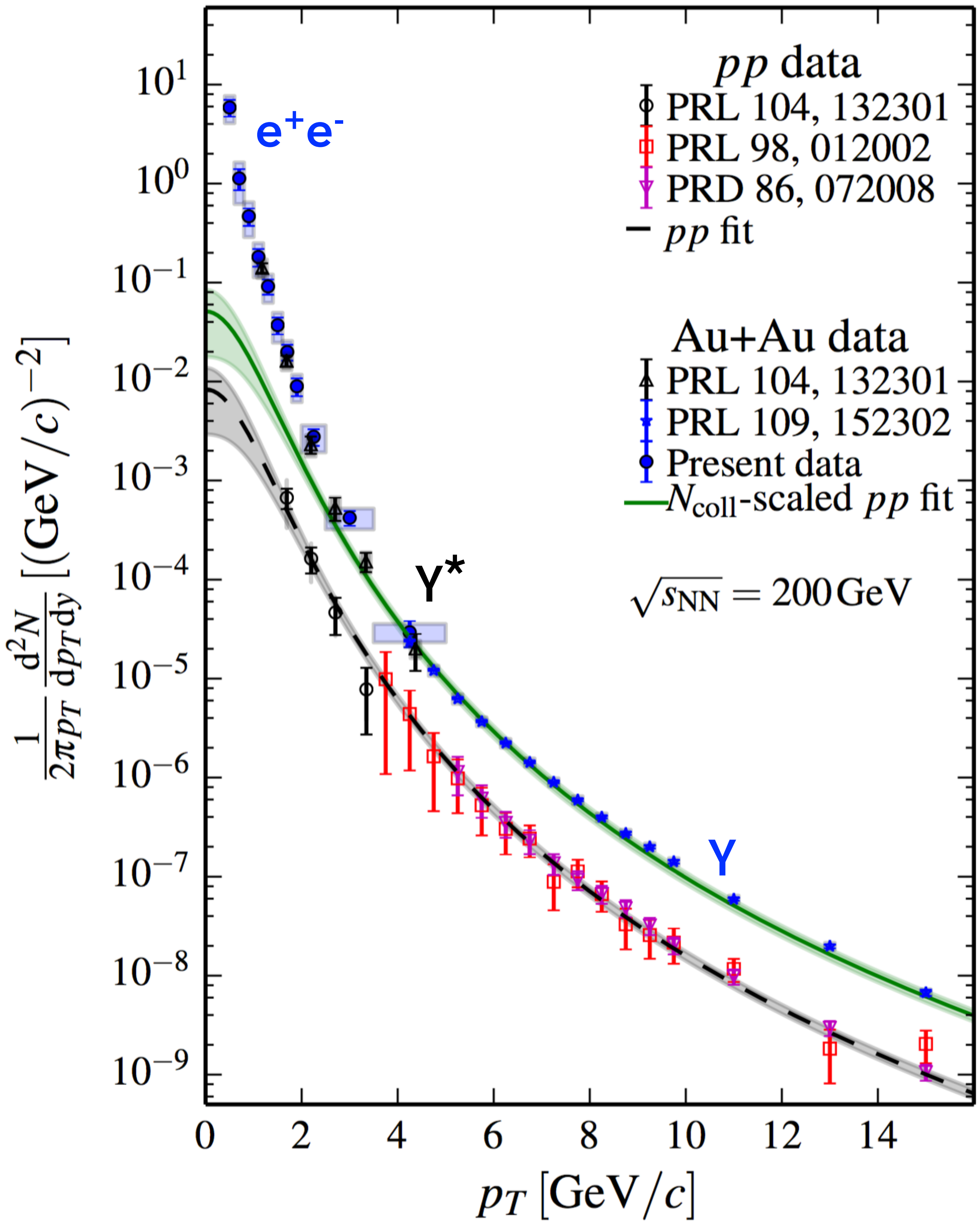
- Focus on conversions at Hadron Blind Detector (HBD) backplane (~60cm)
- Identified by the invariant mass of the e^+e^- pairs
  - Artificial mass due to vertex origin assumption when reconstructing momentum
  - Calculate momentum both assuming vertex origin and true origin
  - Sample purity ~99%



- Double ratio tagging method

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadron}} = \frac{\langle \varepsilon_\gamma f \rangle \left(\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0 tag}} \right)_{Data}}{\left(\frac{\gamma^{hadron}}{\gamma^{\pi^0}} \right)_{Sim}} \longrightarrow \gamma^{\mathrm{direct}} = (R_\gamma - 1)\gamma^{\mathrm{hadron}}$$

Direct Photon Yield in Au+Au @ 200GeV

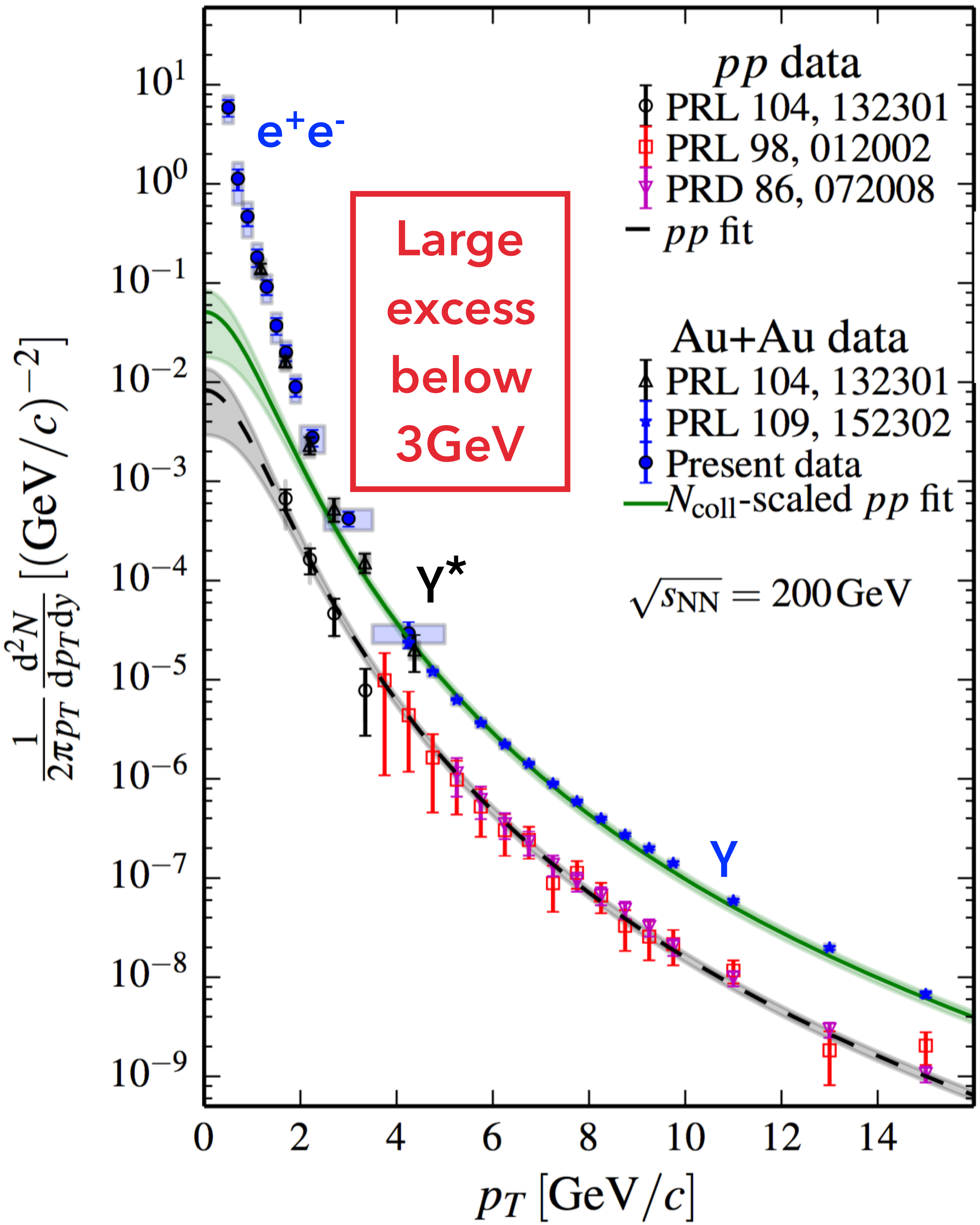


direct photon yield of Au+Au

direct photon yield of p+p

p+p consistent with pQCD

Direct Photon Yield in Au+Au @ 200GeV

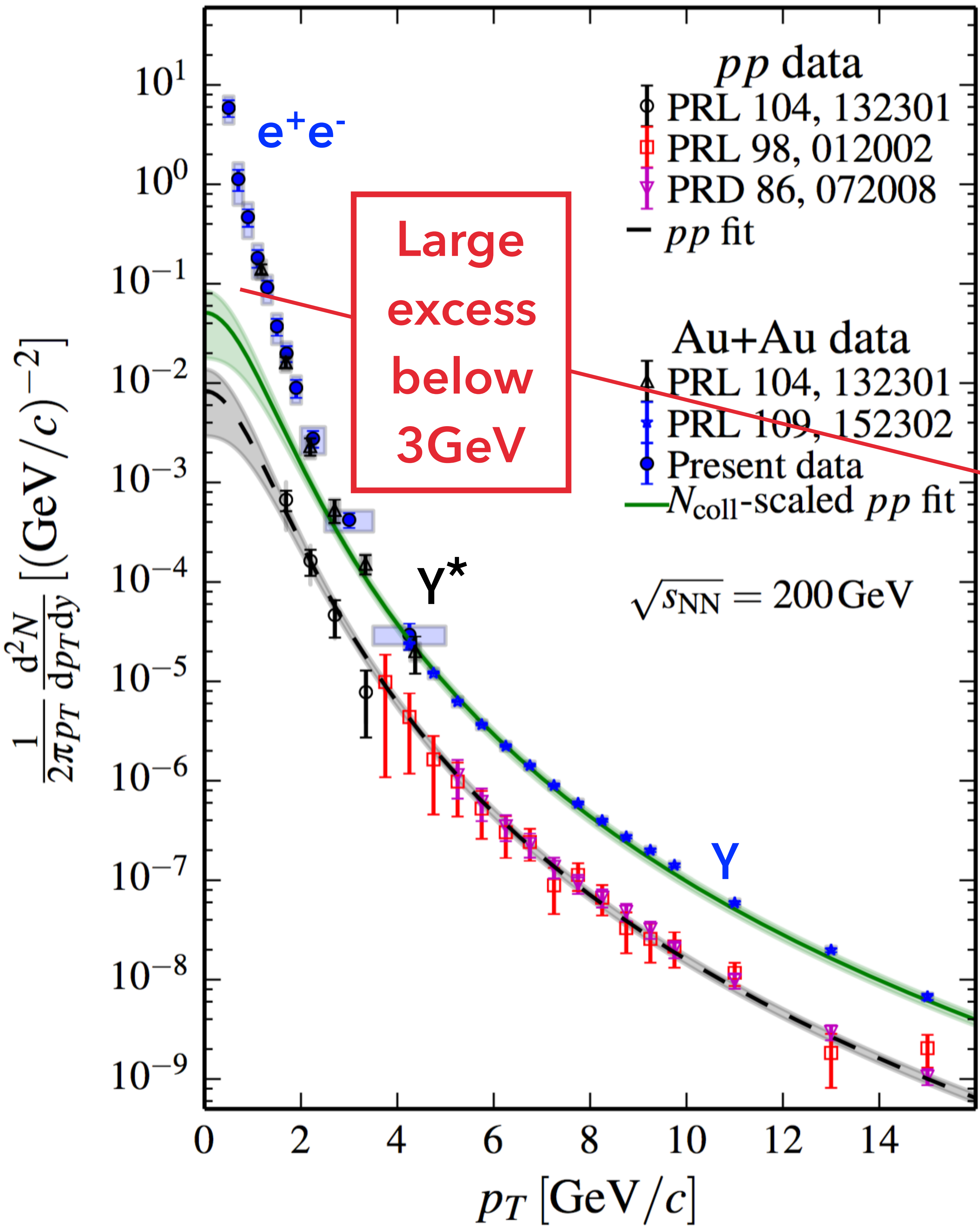


direct photon yield of Au+Au

hard scattering contribution (N_{coll} scaled pp)

AuAu follows N_{coll} scaled pp above 4GeV

Direct Photon Yield in Au+Au @ 200GeV



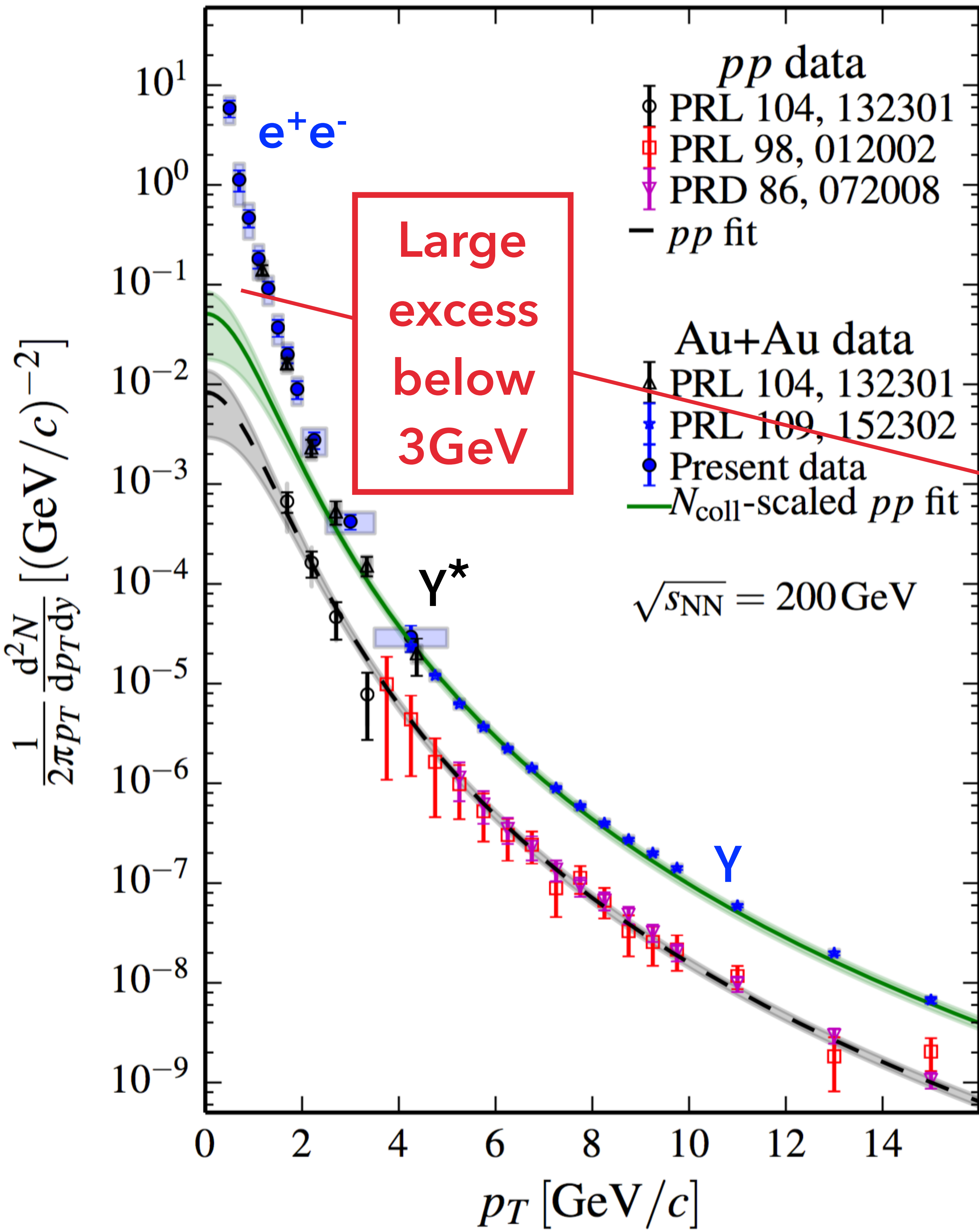
direct photon yield of Au+Au

– hard scattering contribution (N_{coll} scaled pp)

thermal photon yield

Excess has nearly an exponential shape

Direct Photon Yield in Au+Au @ 200GeV



direct photon yield of Au+Au

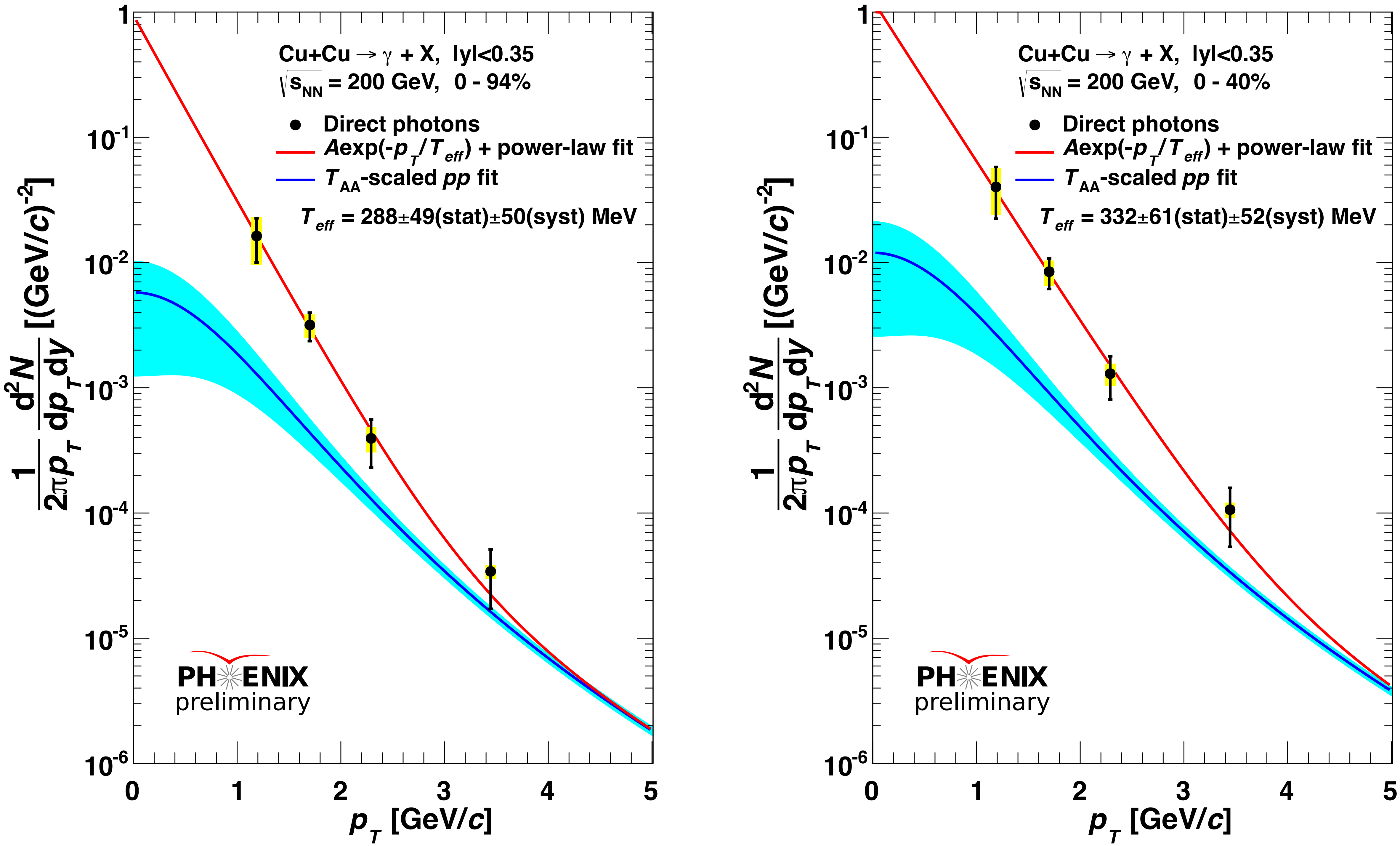
– hard scattering contribution (N_{coll} scaled pp)

thermal photon yield

exponential fit: $A\exp(-p_T/T_{eff})$

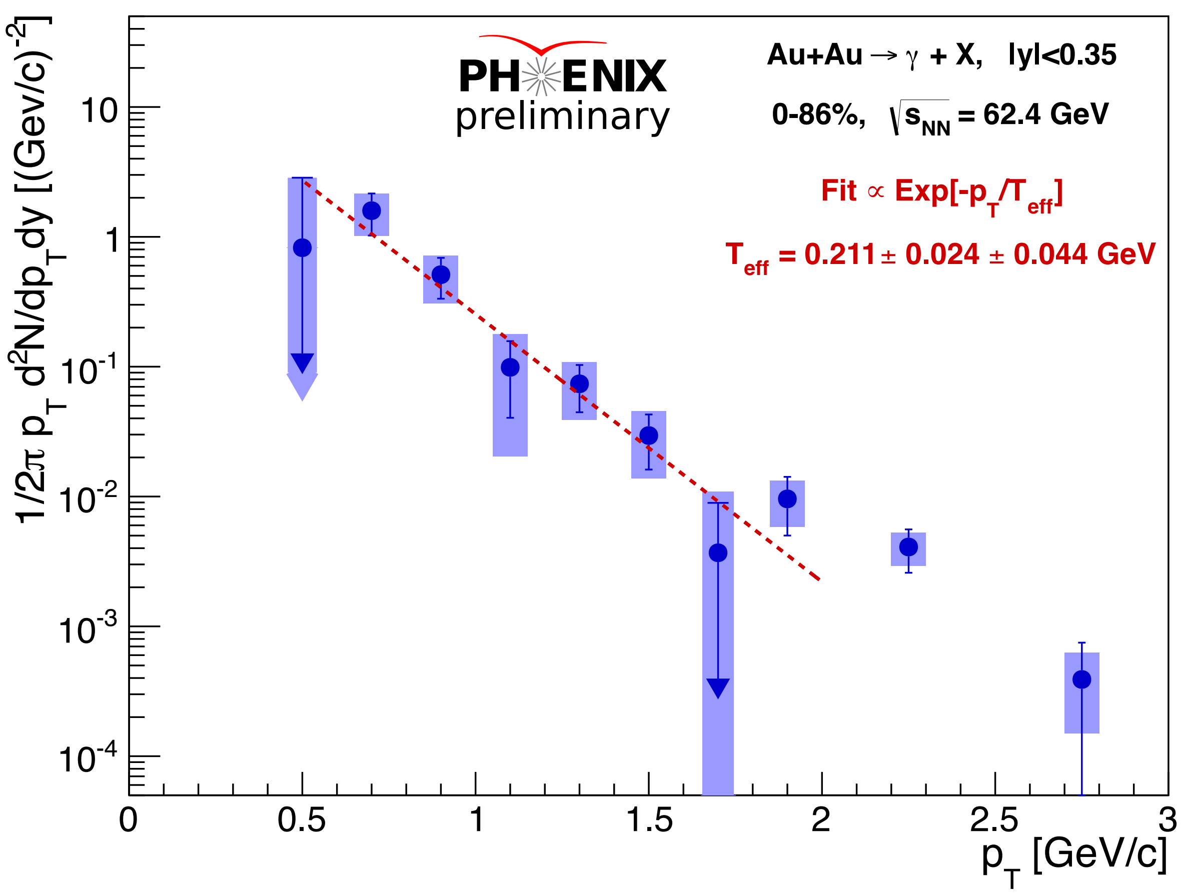
inv. slope T_{eff} ~ 240MeV >T_c

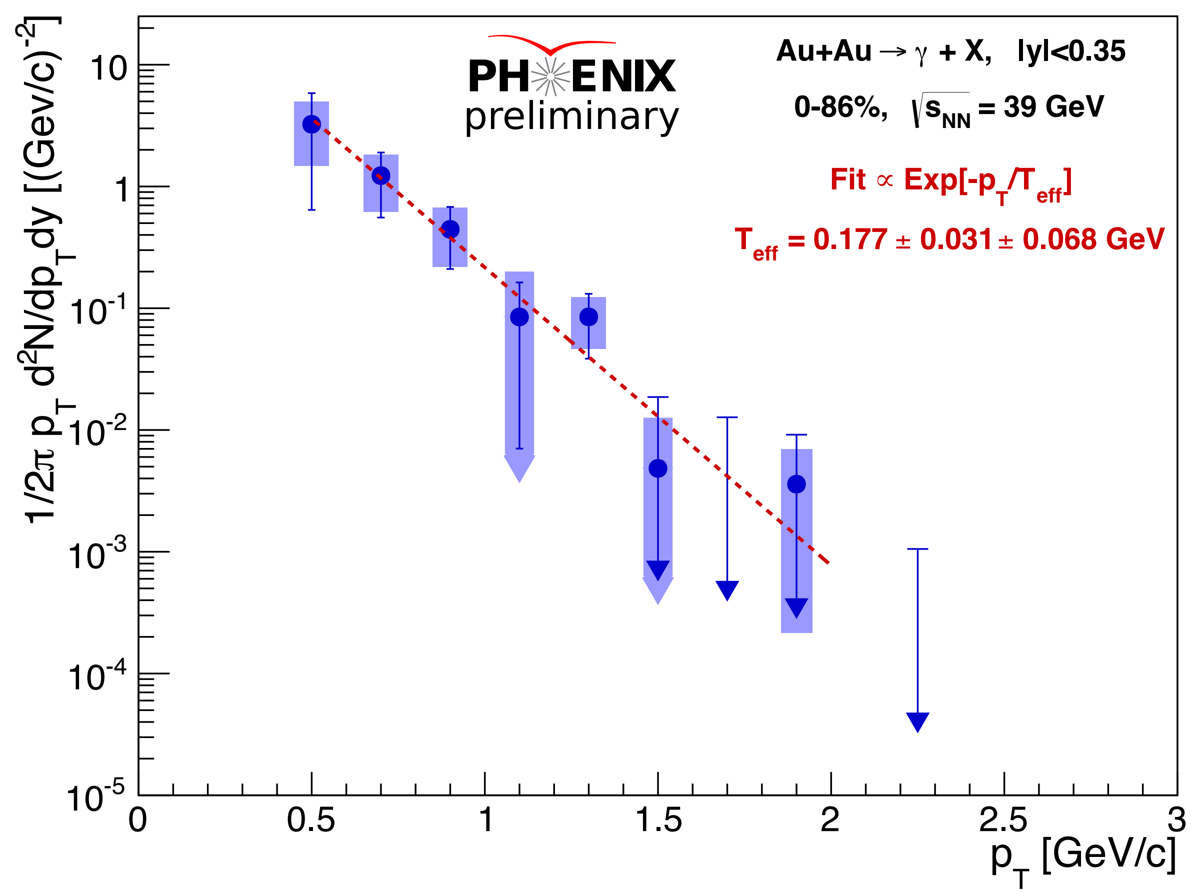
Direct Photon Yield in Cu+Cu @ 200GeV



- Clear direct photon excess in Cu+Cu at 200GeV
- Inverse slopes consistent within large uncertainty with Au+Au

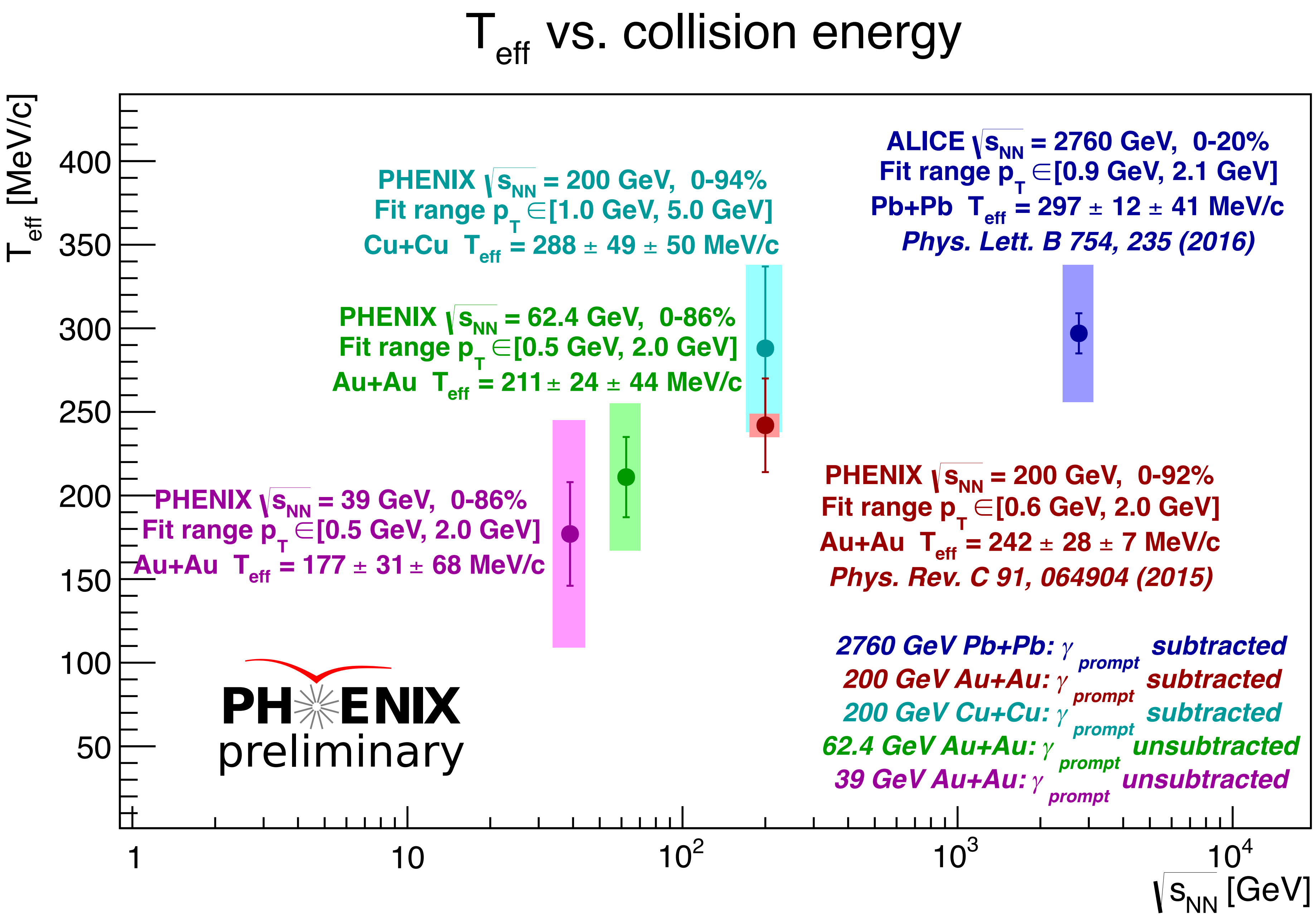
Direct Photon Yield in Au+Au @ 62.4GeV and 39GeV





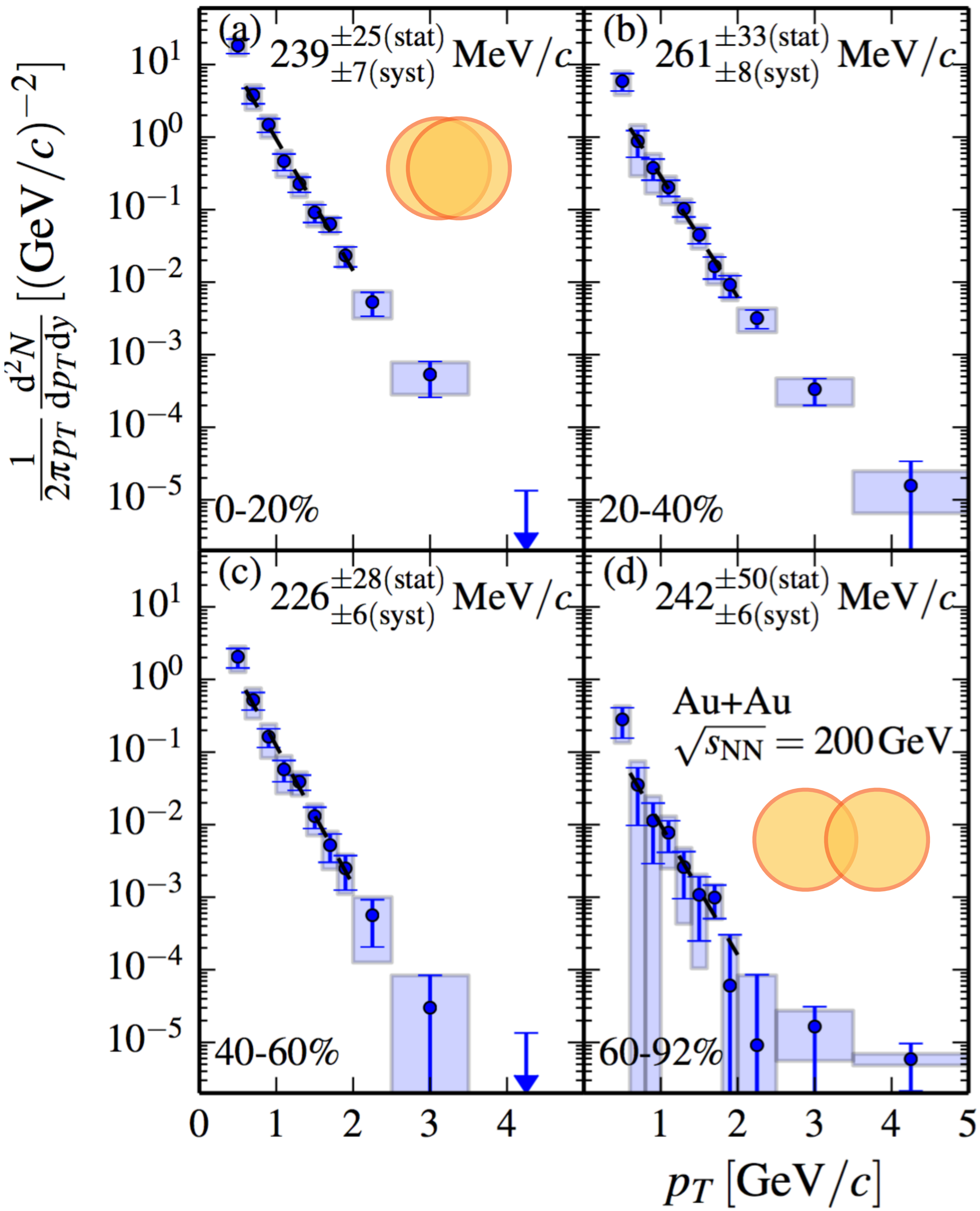
- Clear direct photon signal in Au+Au at 62.4GeV and 39GeV
- T_{eff} ~ 211MeV for 62.4GeV and ~177MeV for 39GeV

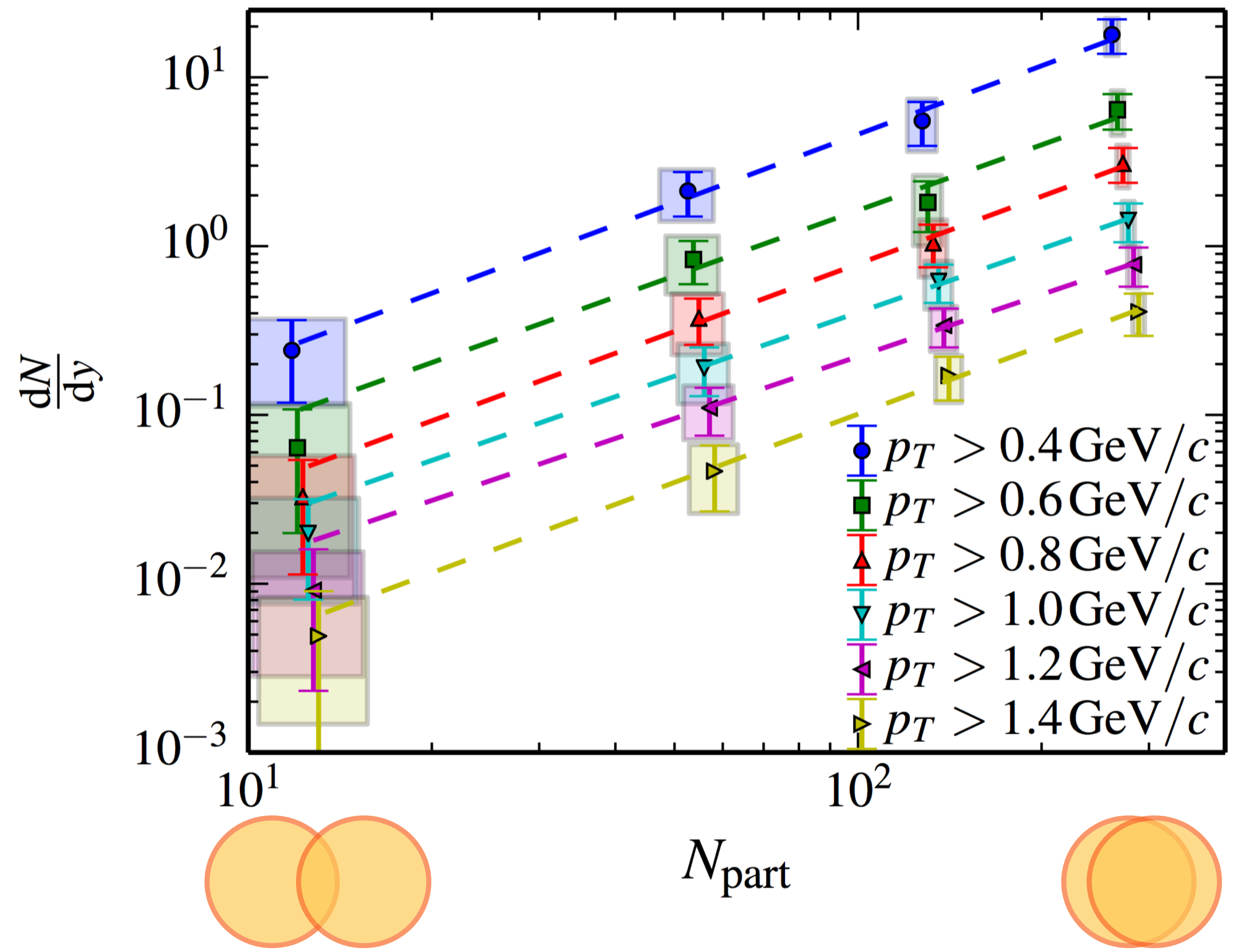
T_{eff} vs Collision Energy



- Possible increase of T_{eff} with beam energy

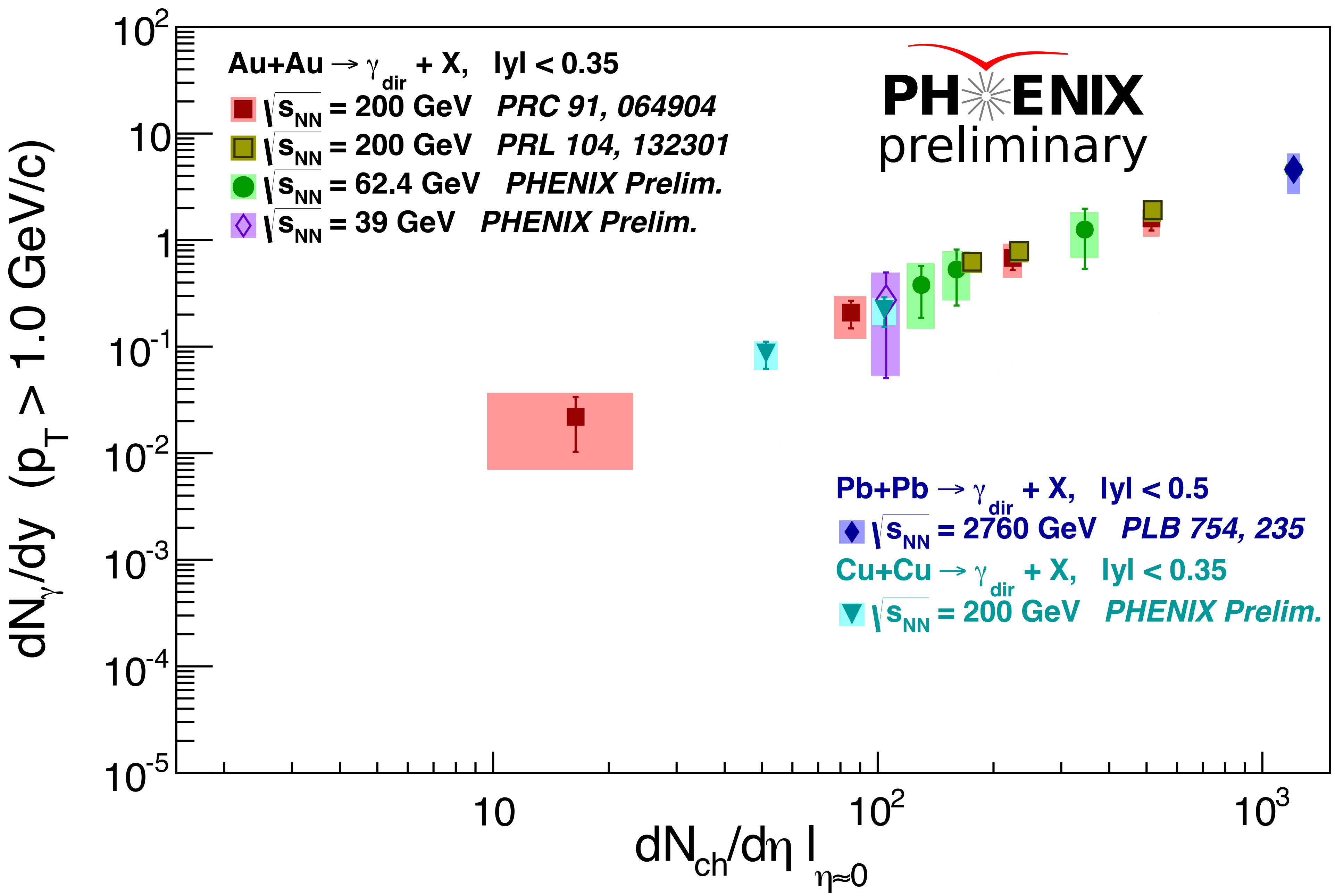
Integrated Yield vs Centrality in Au+Au @ 200GeV



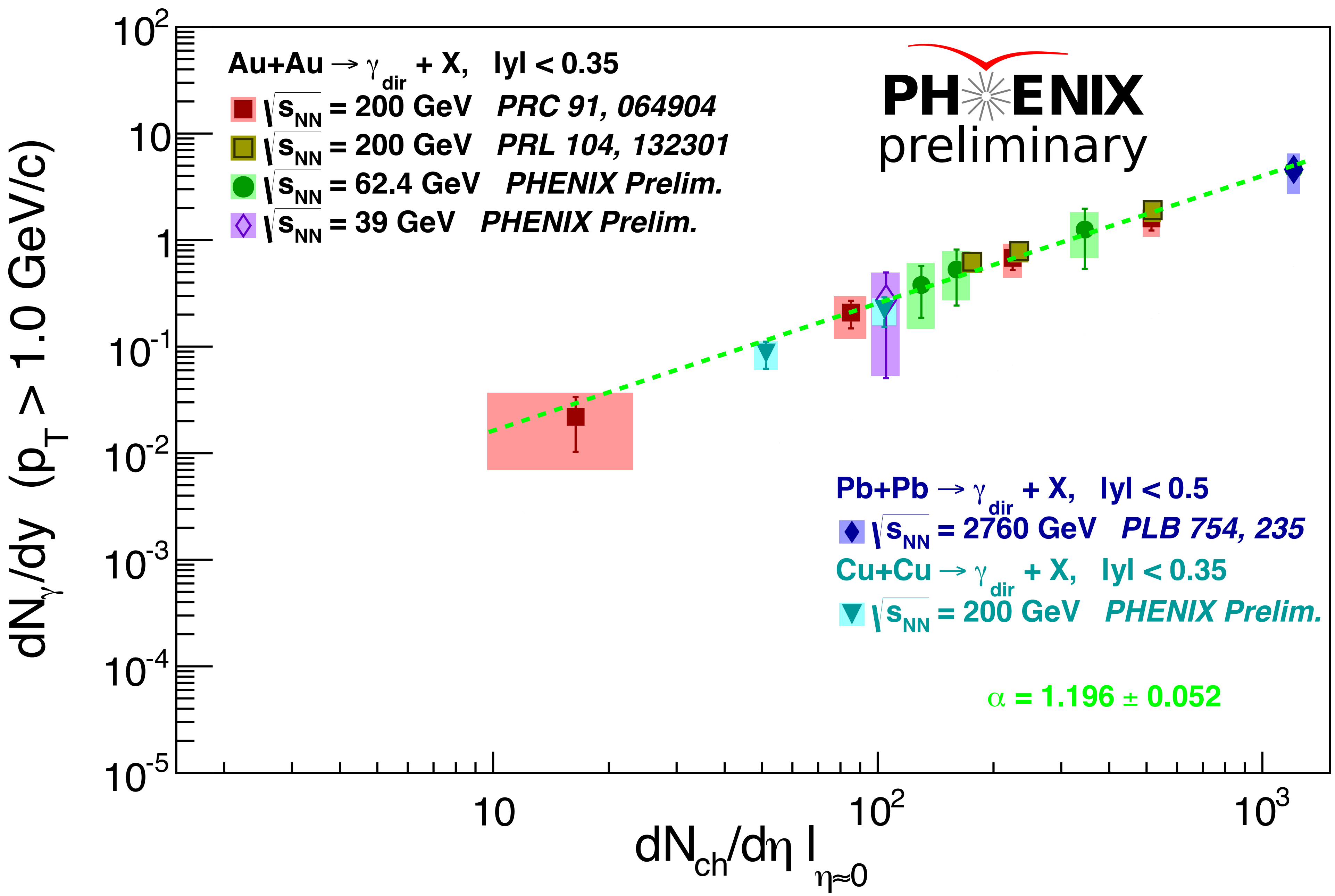


- Large direct photon excess with inv. slope ~240MeV
- Yield ∝ $N_{part}^{1.38\pm0.3\pm0.07}$
- Yield increases faster than reaction volume

Integrated Yield vs N_{charge}

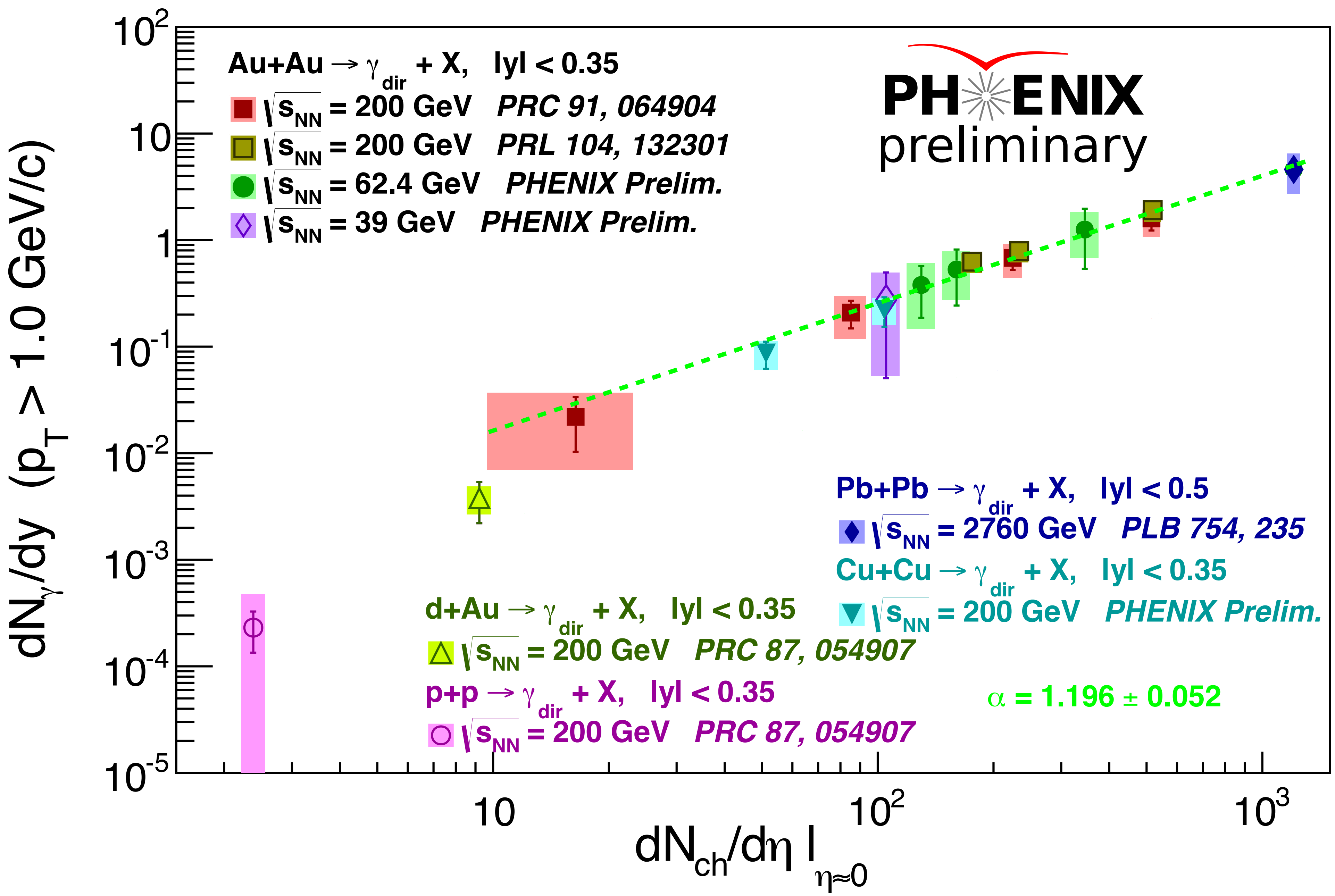


Integrated Yield vs N_{charge}



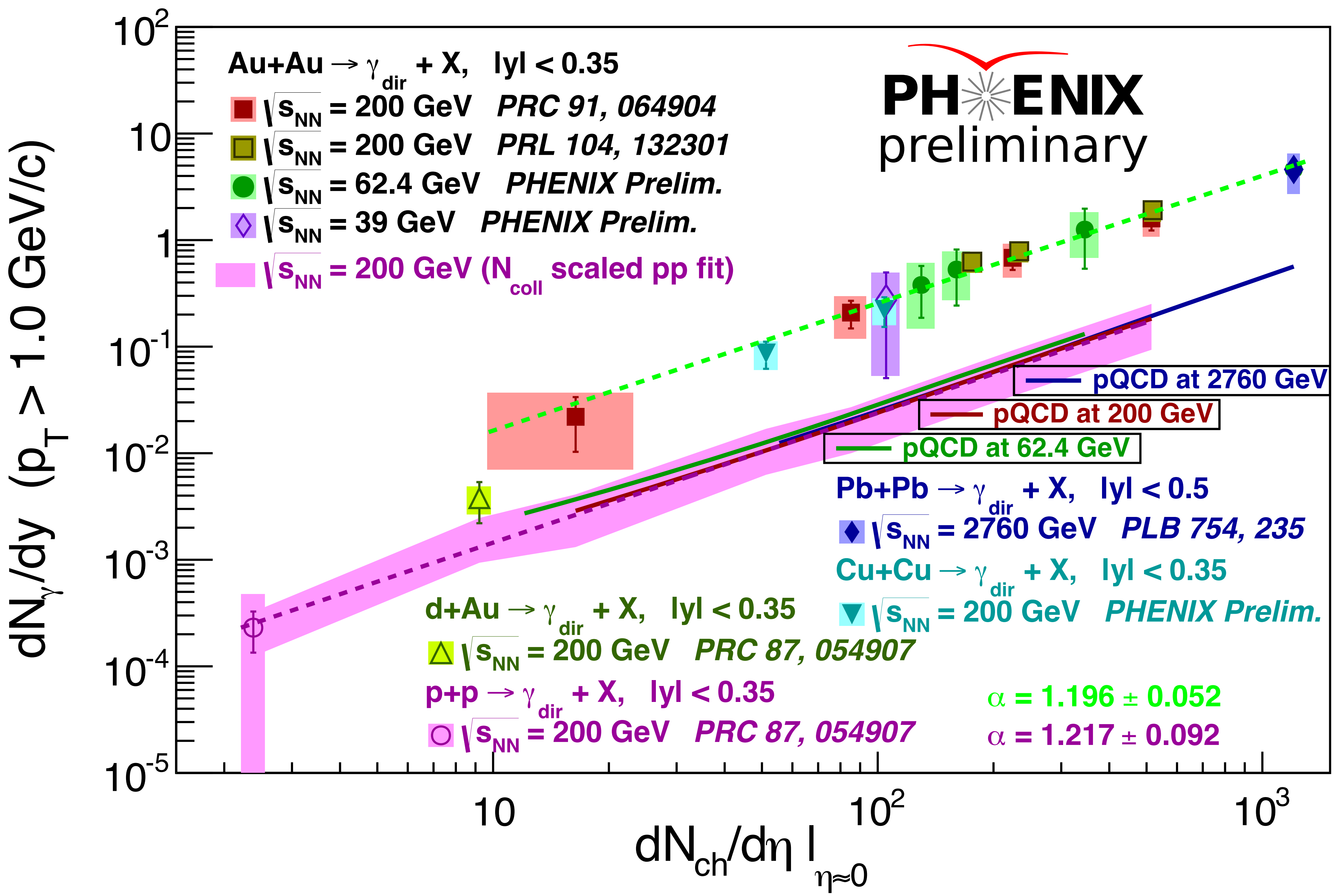
- Scaling of direct photon yield with multiplicity in heavy ion collisions, α~1.2

Integrated Yield vs N_{charge}



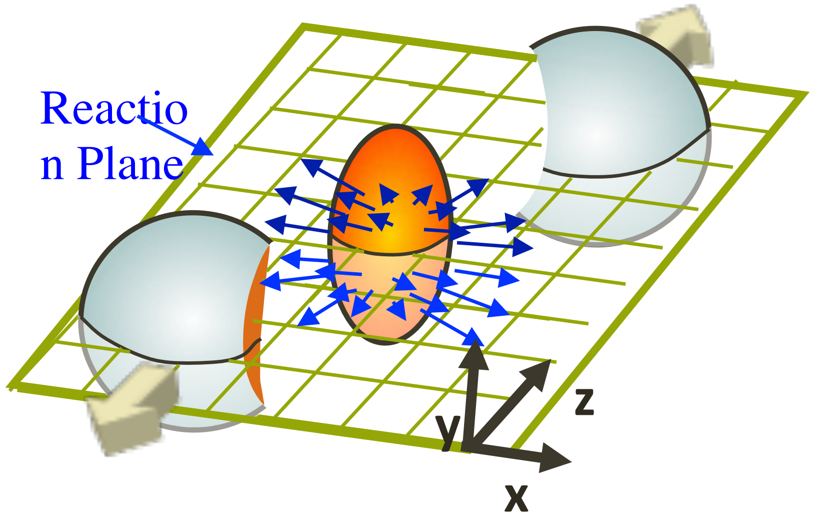
- Scaling of direct photon yield with multiplicity in heavy ion collisions, α~1.2

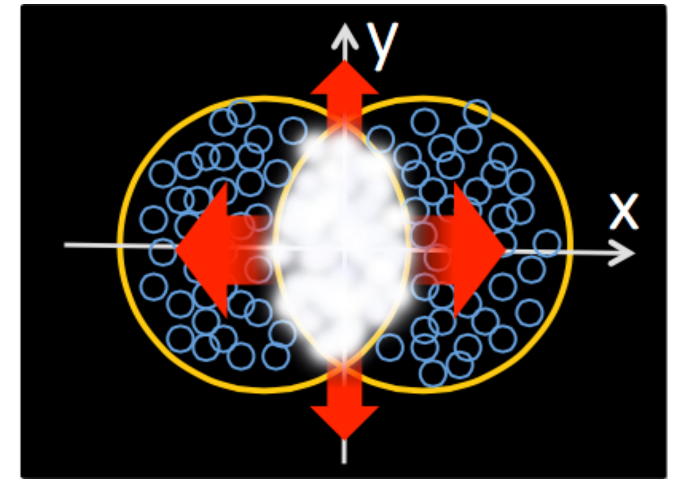
Integrated Yield vs N_{charge}



- Scaling of direct photon yield with multiplicity in heavy ion collisions, α~1.2
- Similar scaling in pQCD contribution

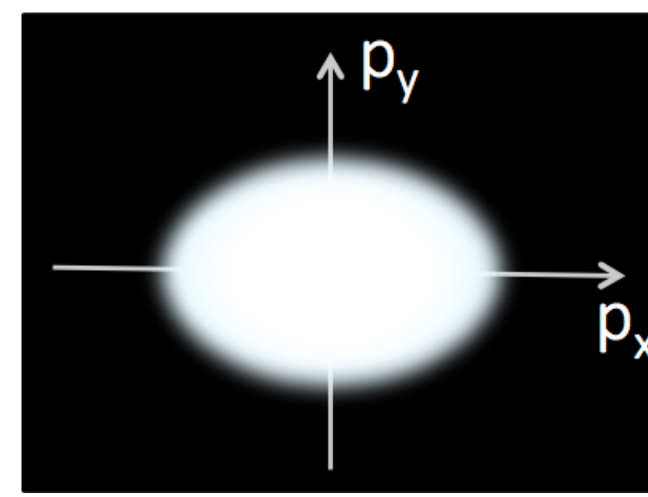
- **Hydro Model**
  - Strongly interacting medium: “perfect fluid”





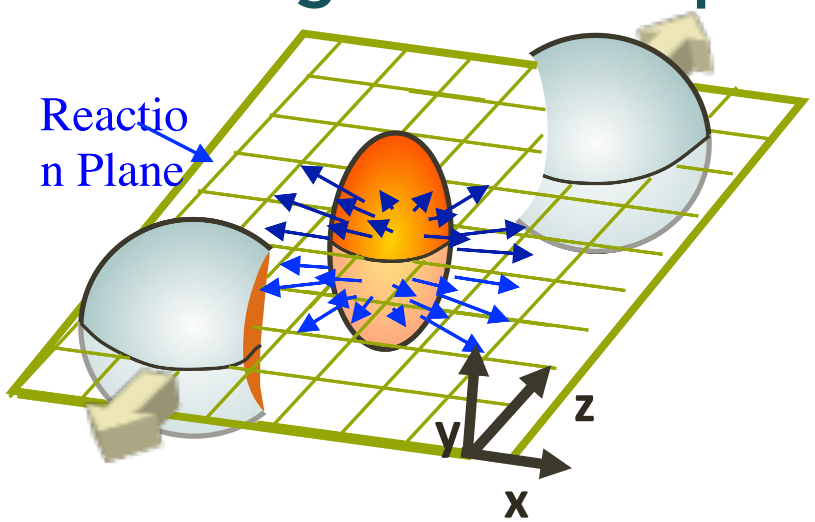
initial state eccentricity

pressure gradient



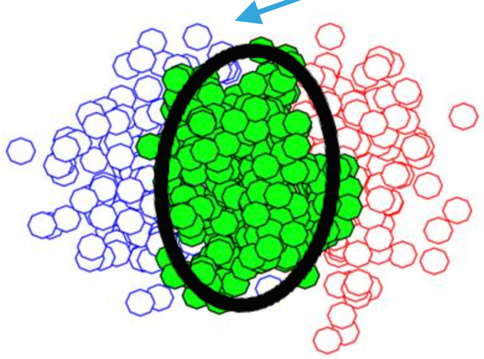
final state anisotropy

- **Hydro Model**
  - Strongly interacting medium: “perfect fluid”

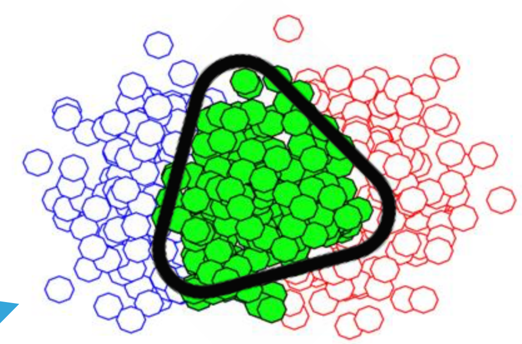


- $$\frac{dN}{d(\phi - \Psi_{2,RP})} \propto 1 + 2v_2 cos2(\phi - \Psi_{2,RP}) + ...$$

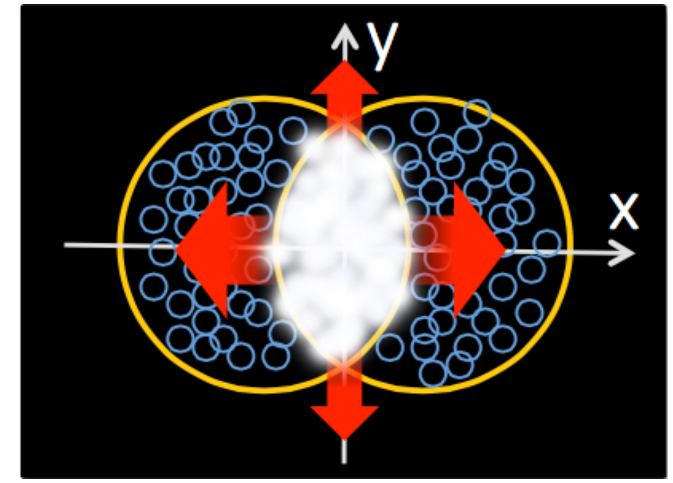
elliptical flow



triangular flow

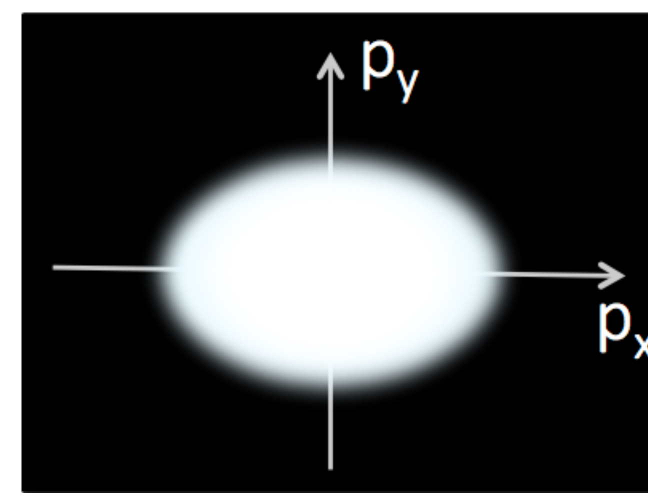


$$\frac{dN}{d(\phi - \Psi_{3,RP})} \propto 1 + 2v_3 cos3(\phi - \Psi_{3,RP}) + ...$$



initial state eccentricity

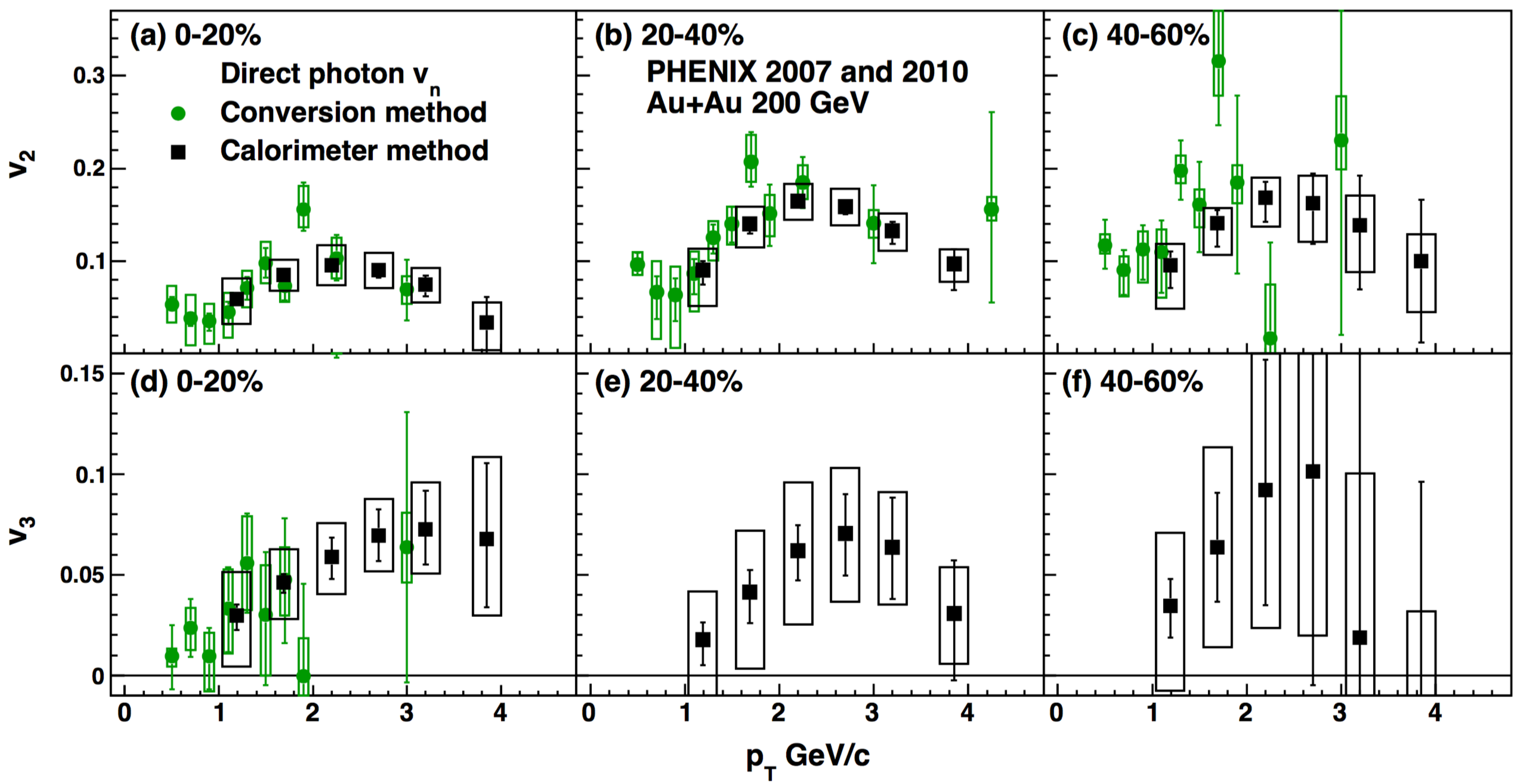
pressure gradient



final state anisotropy

Measurements of flow will constrain initial conditions, fluctuations and some QGP properties (η/s, partonic level flow)

Direct Photon Flow in Au+Au @ 200GeV



PRC 94, 064901

- Large v_2 and v_3 (~ $v_2/2$) observed
- Strong centrality dependence for v_2, not so clear in v_3

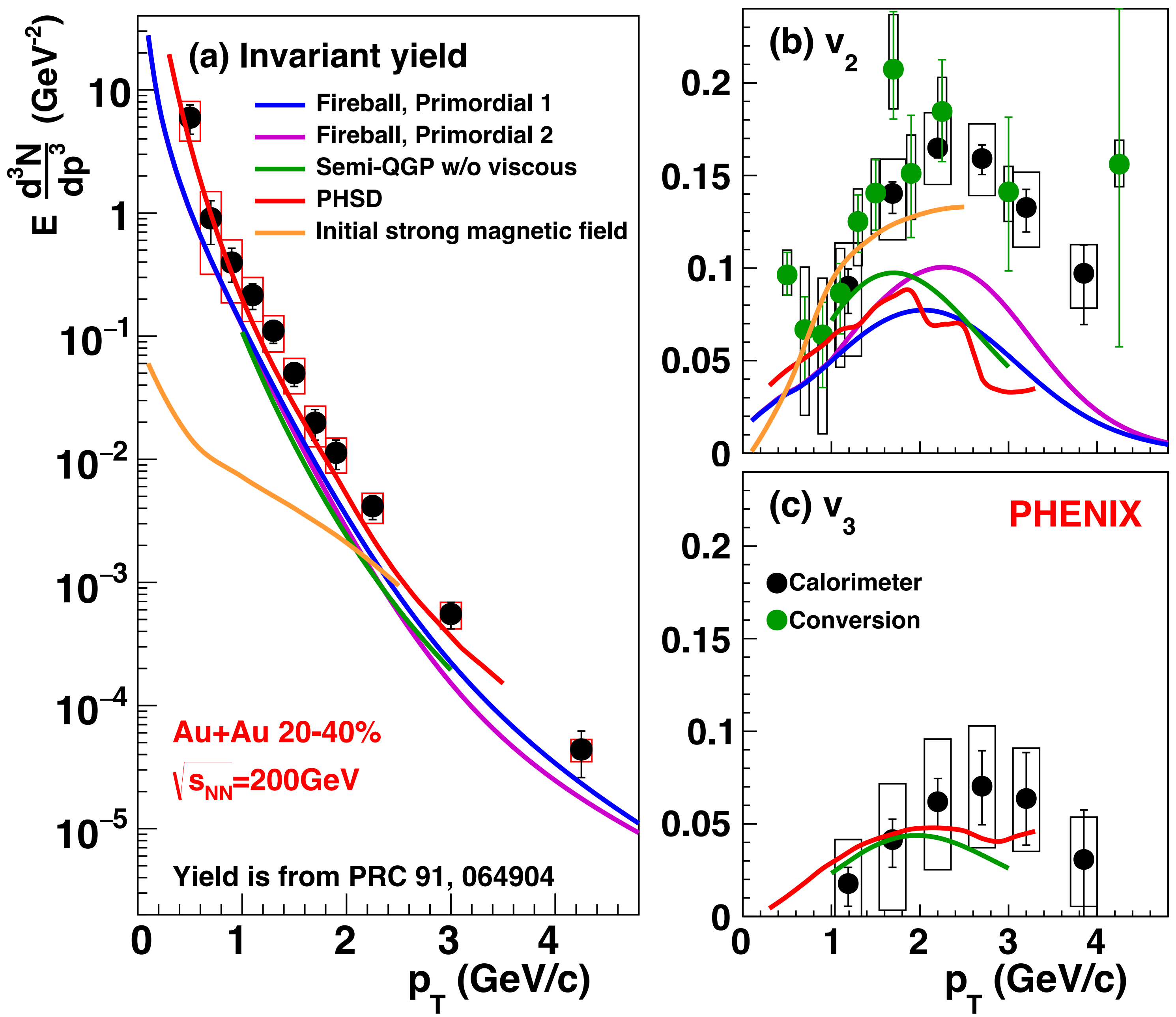
Model comparisons

- Thermal photons (HG+QGP), pQCD with fireball scenario

- Microscopic transport (PHSD)

- Enhanced emission from non-equilibrium effects (glasma, etc.)

- Enhanced early emission from magnetic field



Model comparisons

- Thermal photons (HG+QGP), pQCD with fireball scenario

- H.van Hees, C. Gale, R. Rapp PRC 84 054906 (2011)
- Include finite initial flow at thermalization
- Include resonance decays and hadron-hadron scattering
- Blue shift of HG spectrum included

- Microscopic transport (PHSD)

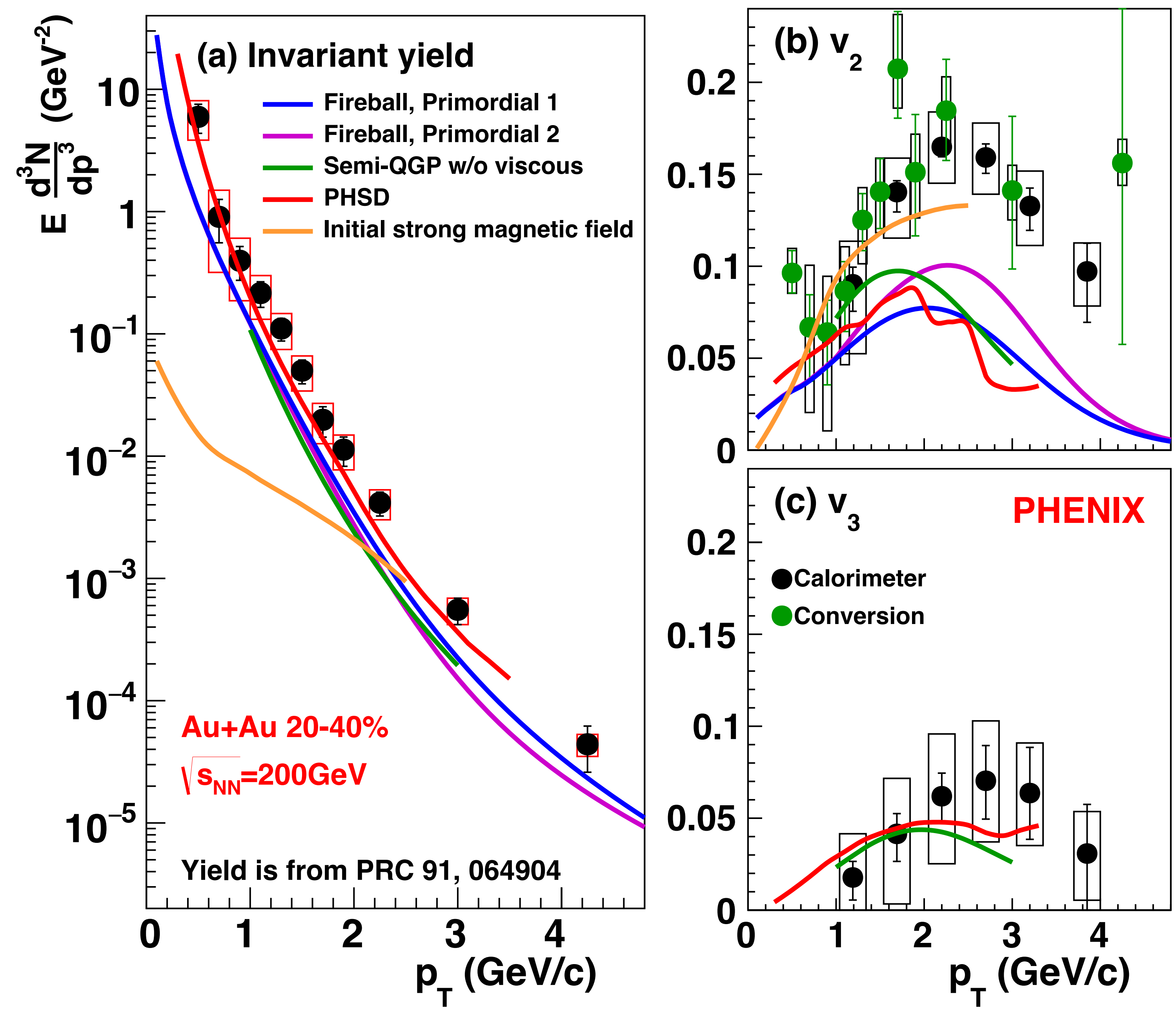
- O. Linnyk, W. Cassing, E.L. Bratkovskaya, PRC 89, 034908 (2014)
- Parton-Hadron-String dynamics
- Include large contribution from hadron-hadron interaction in HG using Boltzmann transport
- Include thermal photons from QGP

- Enhanced emission from non-equilibrium effects (glasma, etc.)

- C. Gale et al., PRL114, 072301 + priv.comm. with Y Hidaka and J-F. Paquet
- Semi-QGP is the QGP near T_c
- Annihilation and Compton processes around hadronization time are naturally included

- Enhanced early emission from magnetic field

- G. Basar, D. E. Kharzeev, V. Skokov, PRL 109 202303 (2012)
- Initial strong magnetic field produces anisotropy of photon emission
- magnetic field + thermal photons (lattice QCD)

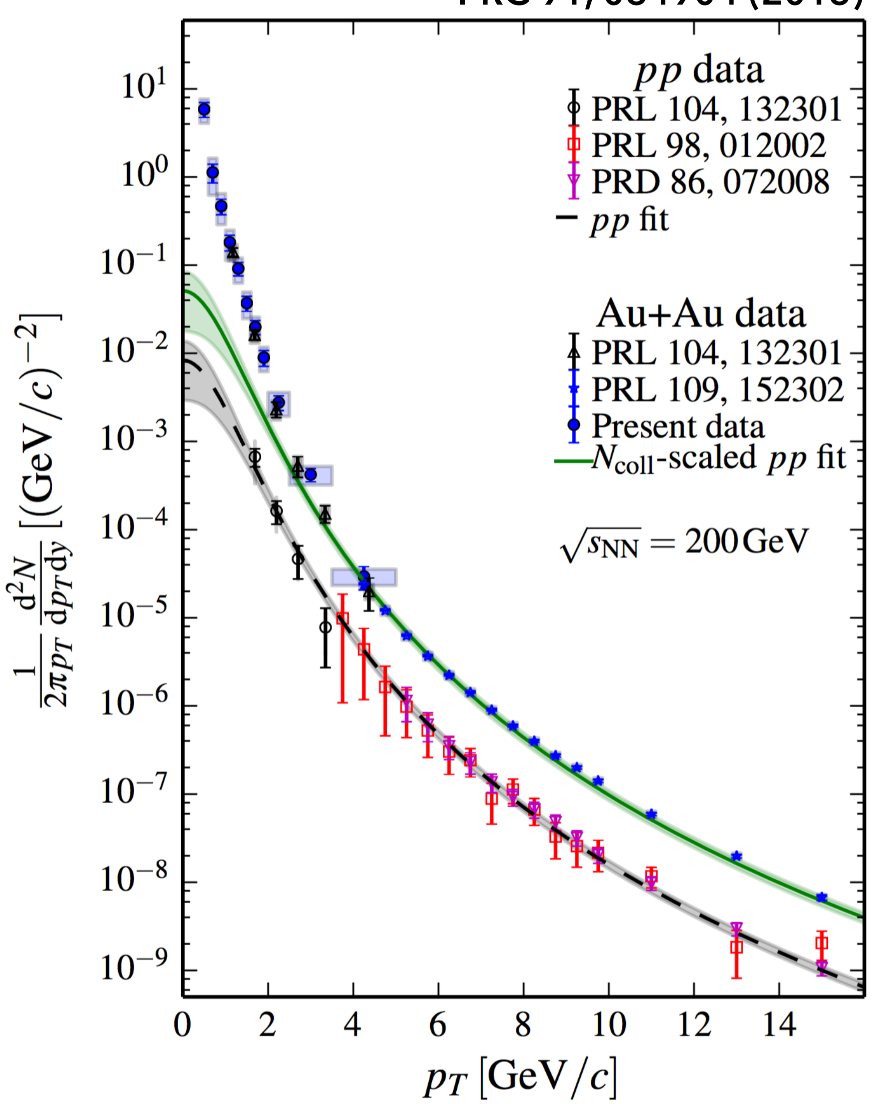


Direct Photon Puzzle

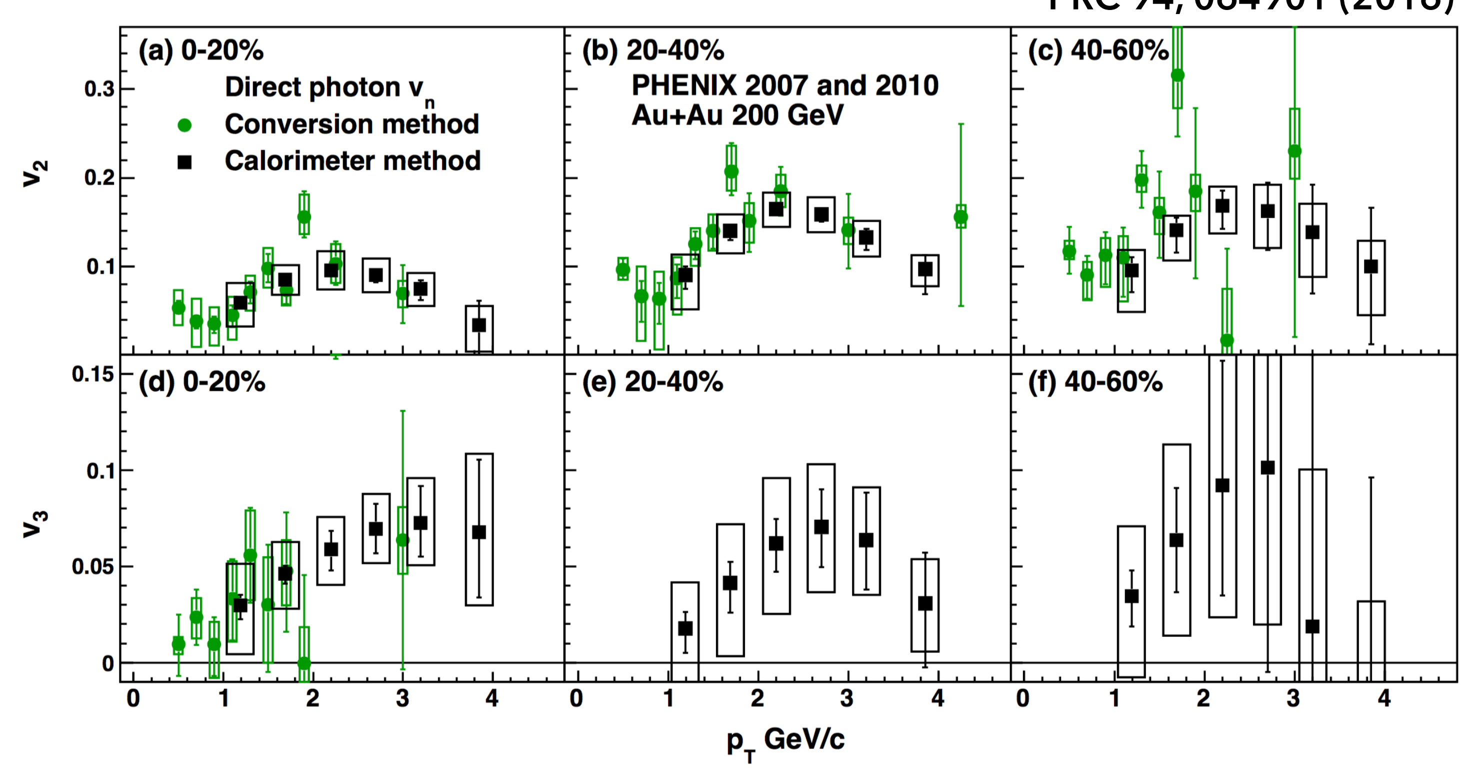
- Large yield & large v_2
  - Large yield: emission from the early stage when temperature is high
  - Large v_2: emission from the late stage when the collective flow is sufficiently built up

Challenge for current theoretical model to describe large yield and v_2 simultaneously!

PRC 91, 064904 (2015)

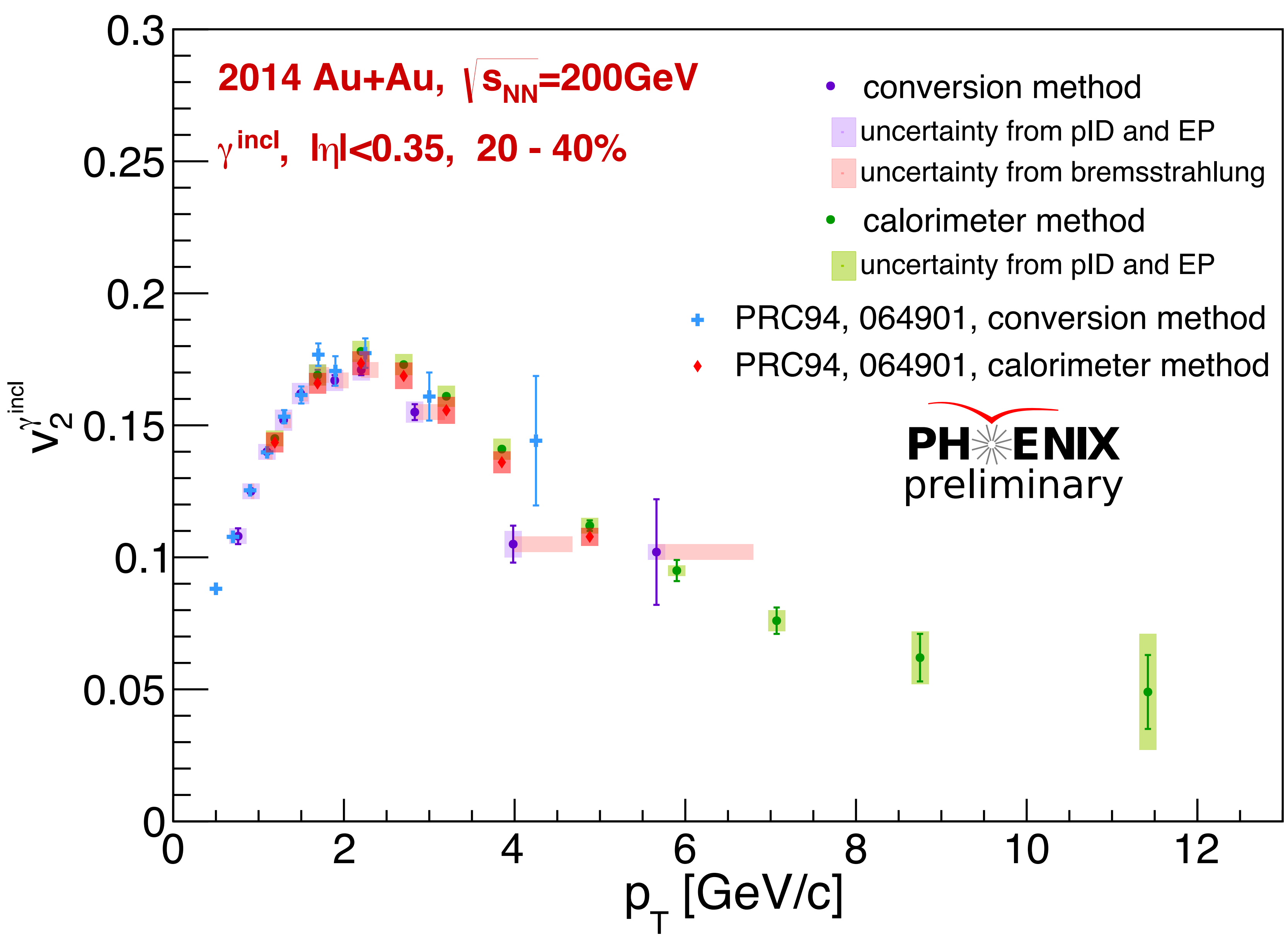


PRC 94, 064901 (2016)

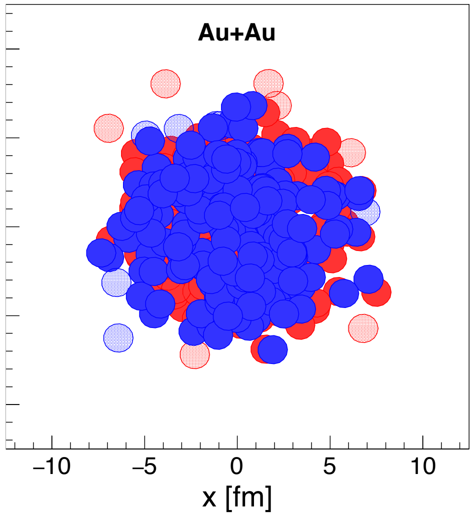


Future Measurements: High Statistics Au+Au

- Comparison of inclusive photon v_2 for Au+Au at 200GeV
  - Good agreement with published v2 result
  - ~22% of total 2014 data
  - 2014 + 2016 Au+Au data more than 10x statistics compared to published results



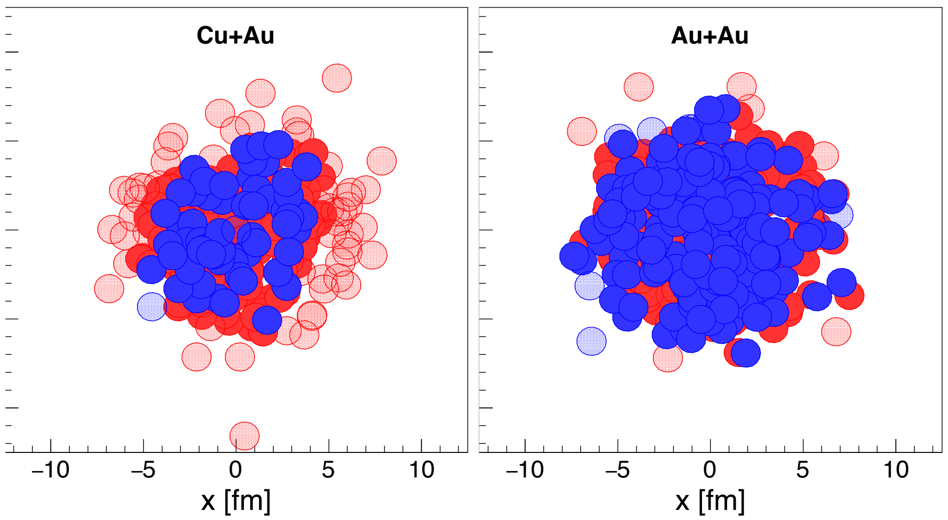
Future Measurements: Different Systems



high statistics

- High statistics Au+Au data will provide accurate measurement of v_n (v_2, v_3, v_4) at low p_T

Future Measurements: Different Systems

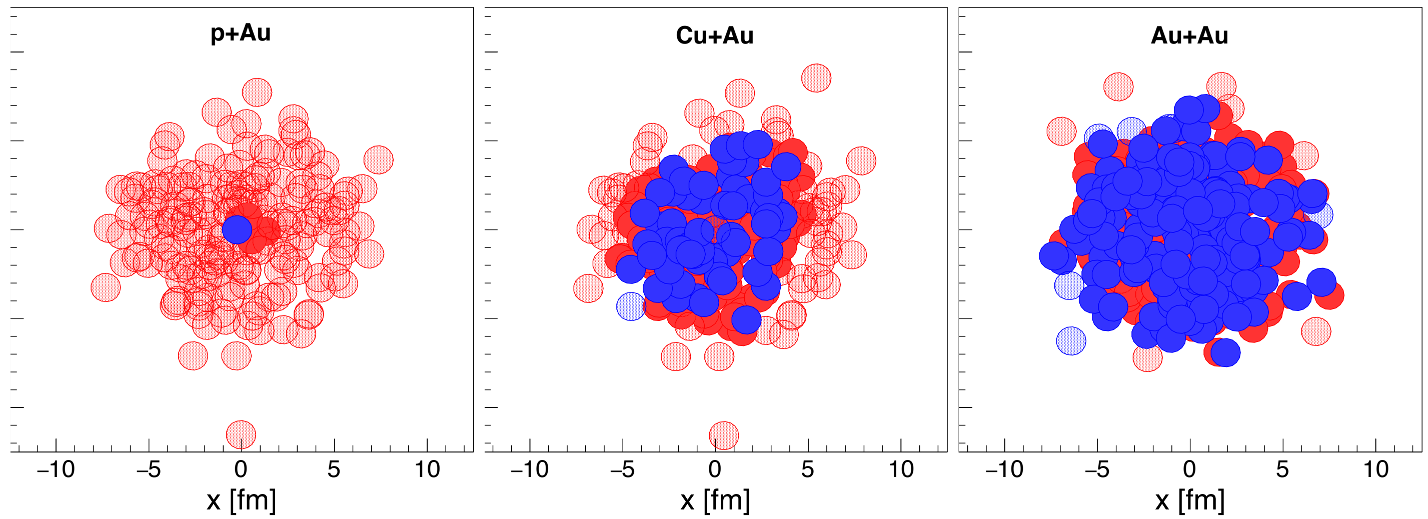


different collision geometry

high statistics

- High statistics Au+Au data will provide accurate measurement of v_n (v_2, v_3, v_4) at low p_T
- Flow measurement in Cu+Au might provide useful input in understanding of chiral magnetic field effect, if any

Future Measurements: Different Systems



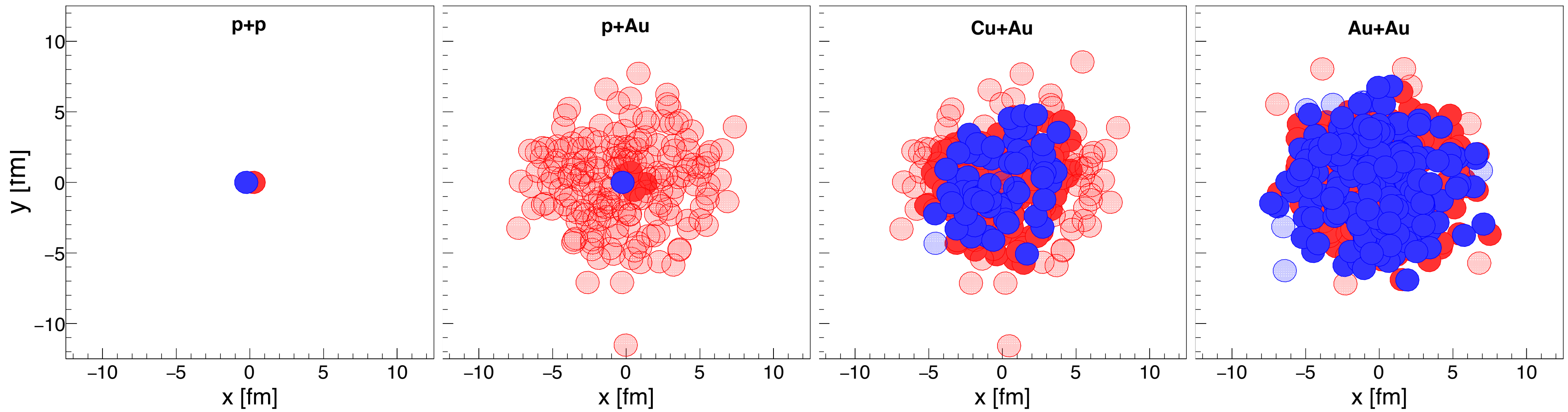
small systems

different collision geometry

high statistics

- High statistics Au+Au data will provide accurate measurement of v_n (v_2, v_3, v_4) at low p_T
- Flow measurement in Cu+Au might provide useful input in understanding of chiral magnetic field effect, if any
- Search for thermal photons in small systems like p+Au, ^{3}He+Au, d+Au

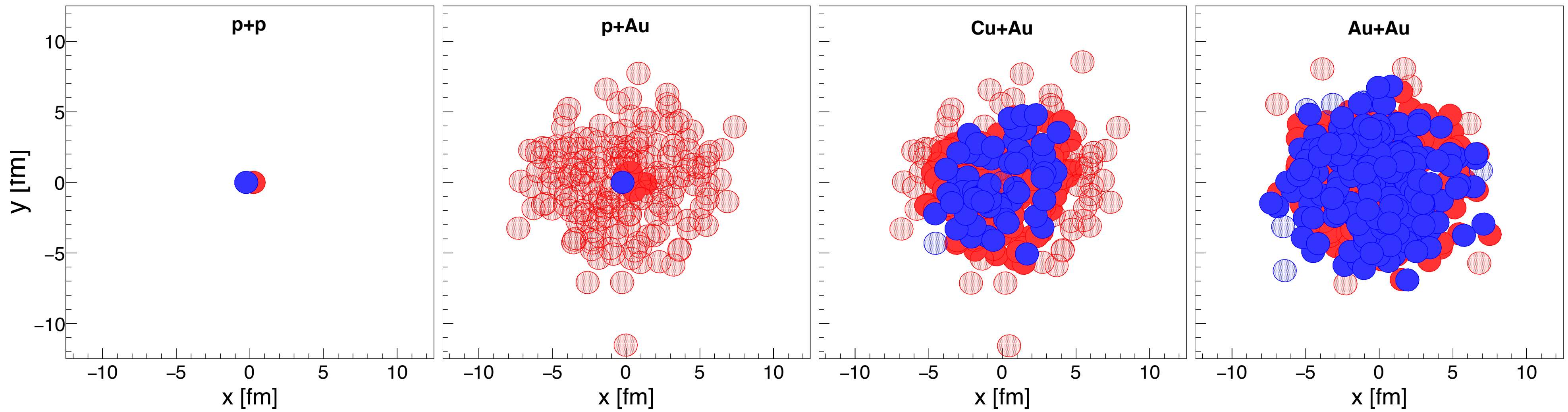
Future Measurements: Different Systems



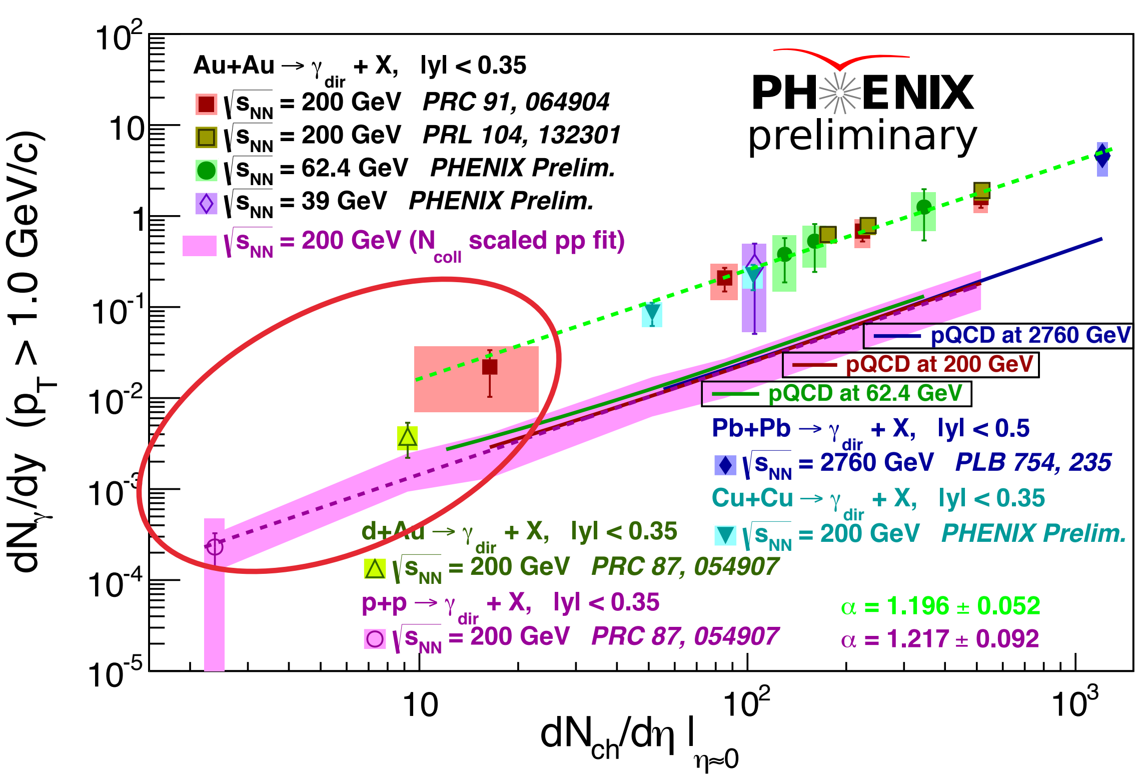
- High statistics Au+Au data will provide accurate measurement of v_n (v_2, v_3, v_4) at low p_T
- Flow measurement in Cu+Au might provide useful input in understanding of chiral magnetic field effect, if any
- Search for thermal photons in small systems like p+Au, ^{3}He+Au, d+Au
- New p+p results will extend the measurement to lower p_T

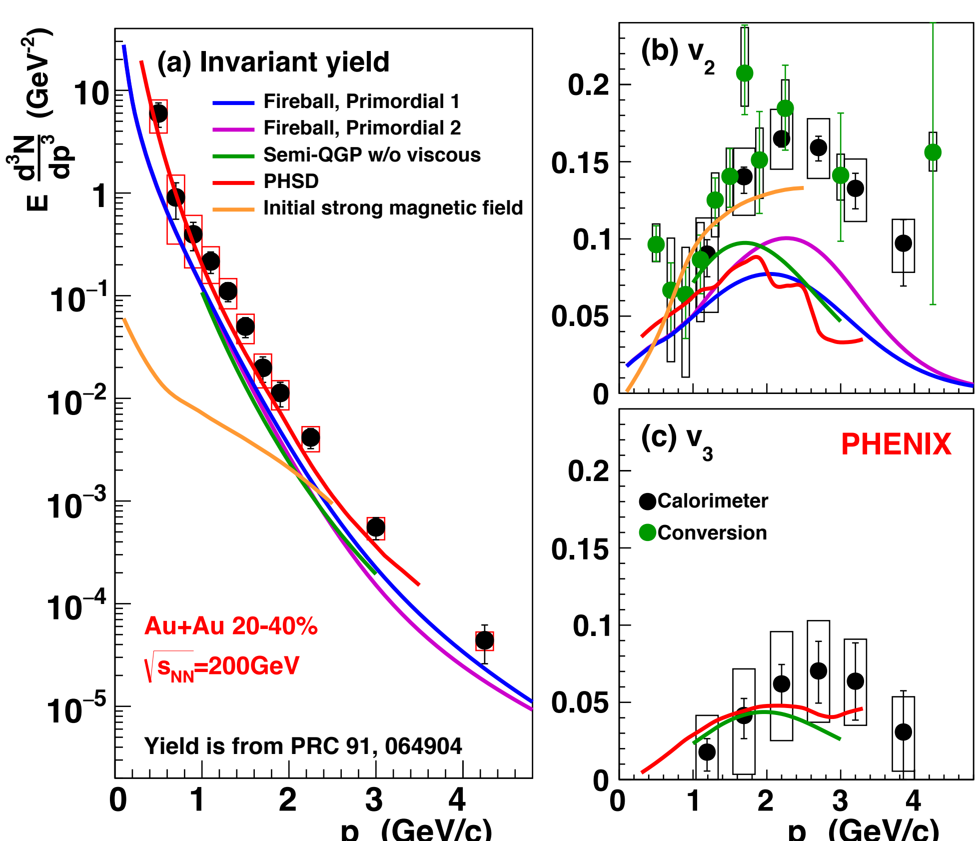
Future Measurements: Different Systems

2.0 < p_T < 2.5GeV/c



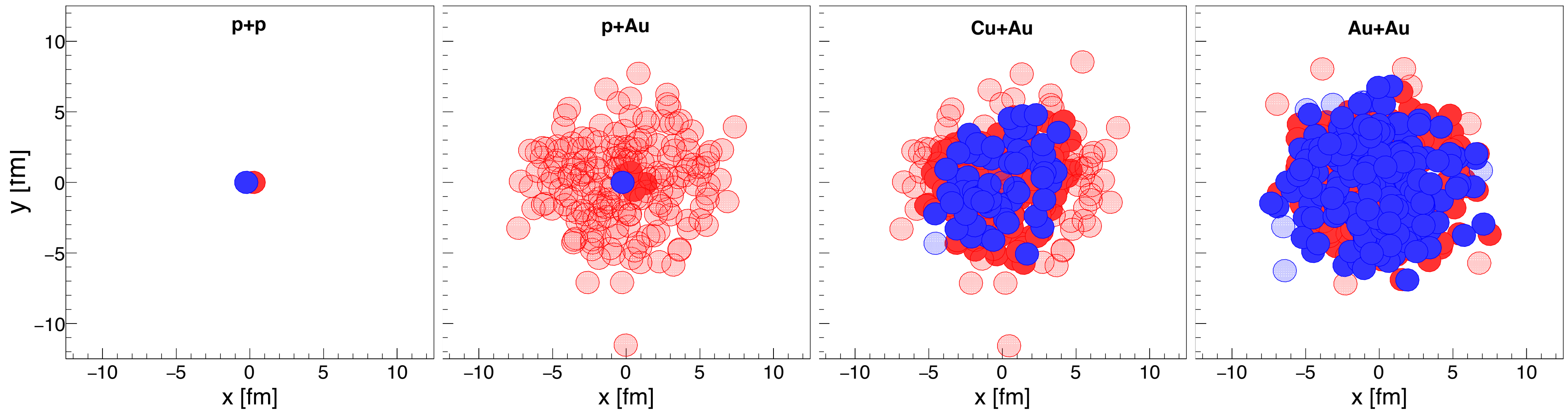
baseline | **small systems** | **different collision geometry** | **high statistics**





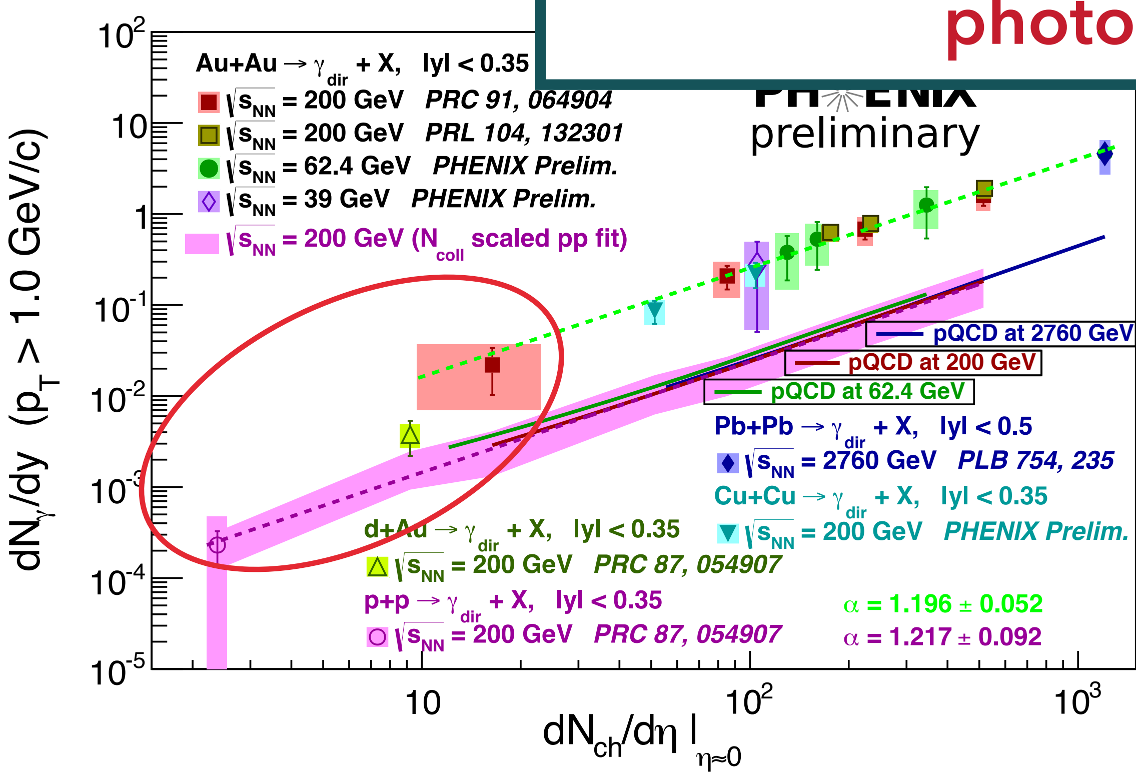
Future Measurements: Different Systems

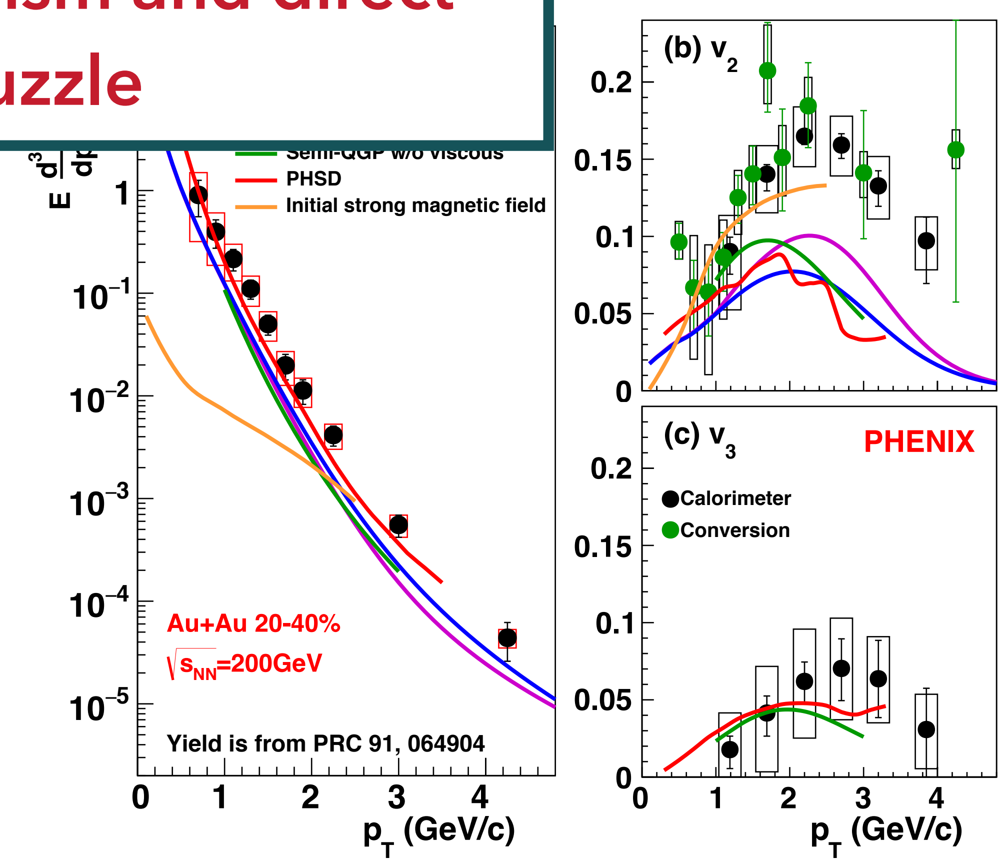
2.0 < p_T < 2.5GeV/c



baselin … h statistics

More differential measurements to shed light on the thermal photon production mechanism and direct photon puzzle





Summary and Outlook

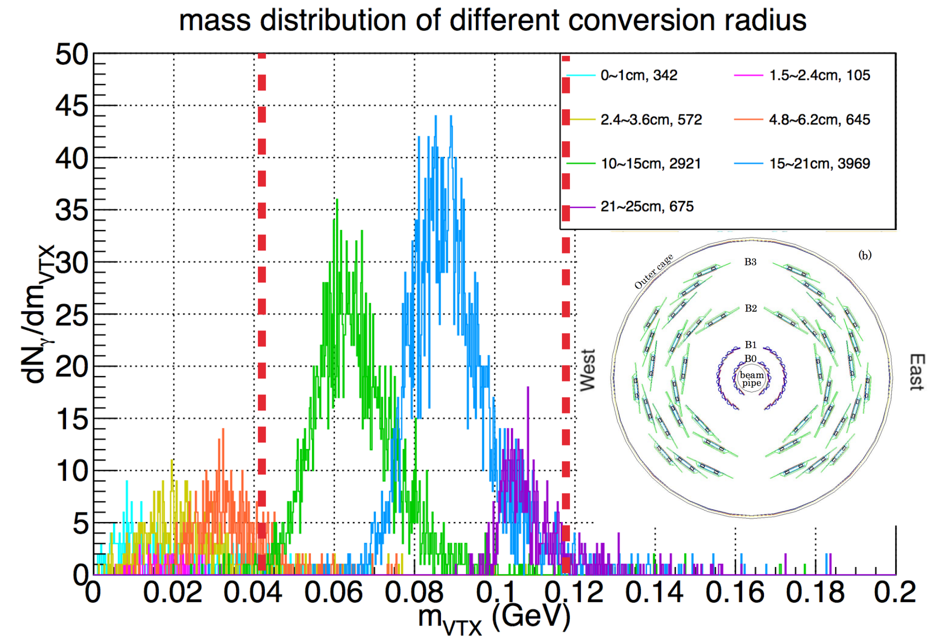
- Well established measurements of low p_T direct photons in Au+Au at 200 GeV
  - Large excess above reference p+p collisions at low p_T region
  - Large anisotropy v_2 observed for the excess photons
- Theoretical picture still incomplete to describe large yield and v_2 simultaneously
- New results from Cu+Cu at 200 GeV and Au+Au at 62.4GeV & 39GeV
  - Possible increase of T_{eff} with beam energy
  - Scaling of direct photon yield with multiplicity in heavy ion collisions
- More future measurements from PHENIX are coming
  - High statistics (factor>10) Au+Au data from 2014 & 2016
  - Data from different collision geometry Cu+Au (2012)
  - Search for direct photons in small systems: p+Au (2015), d+Au (2016), ^{3}He+Au (2014)
  - Low momentum measurement of p+p (2015)

THANKS

New Conversion Photon Reconstruction Technique

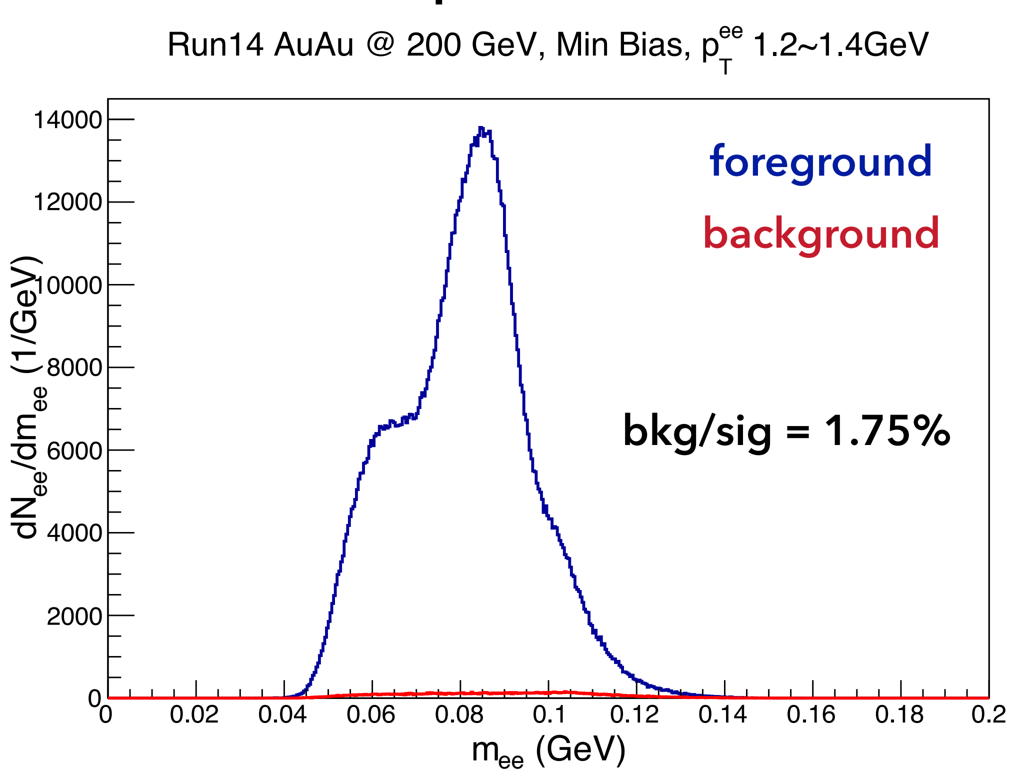
Identify and reconstruct photons via external conversion to e^+e^- pairs

- 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%)

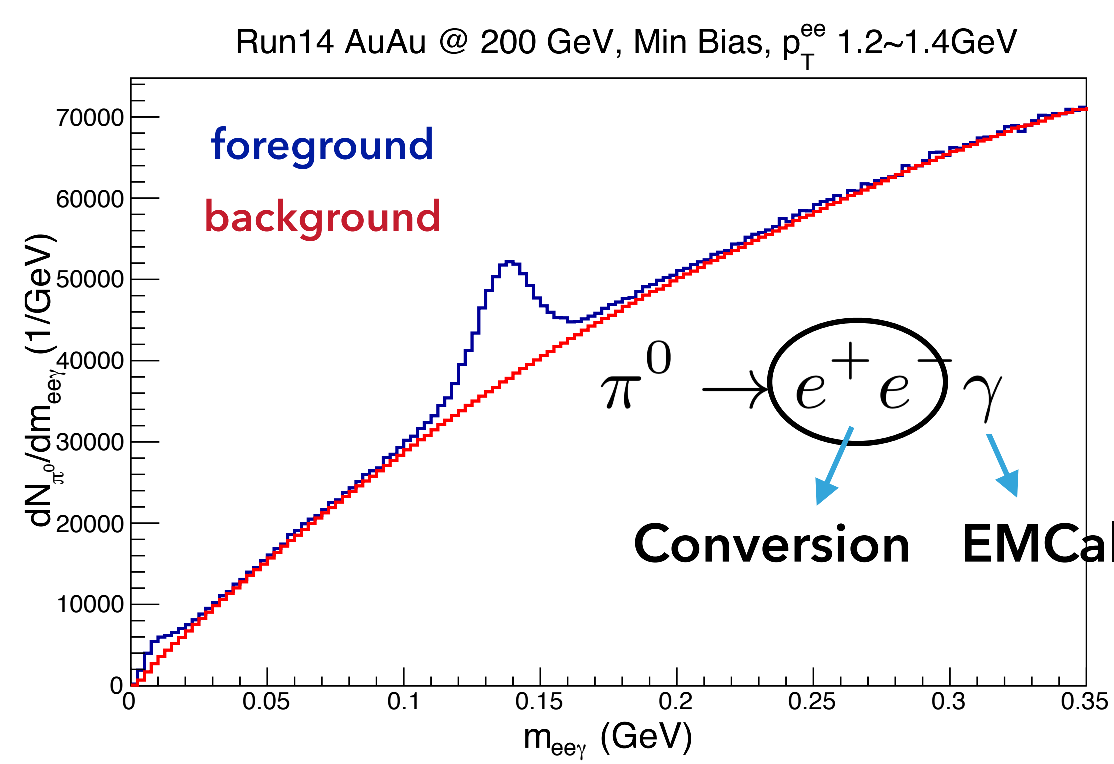


MC simulation

inclusive photon (e^+e^-) mass



π^0 ($e^+e^-\gamma$) mass



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

Direct Photon Yield in Au+Au @ 62.4GeV and 39GeV

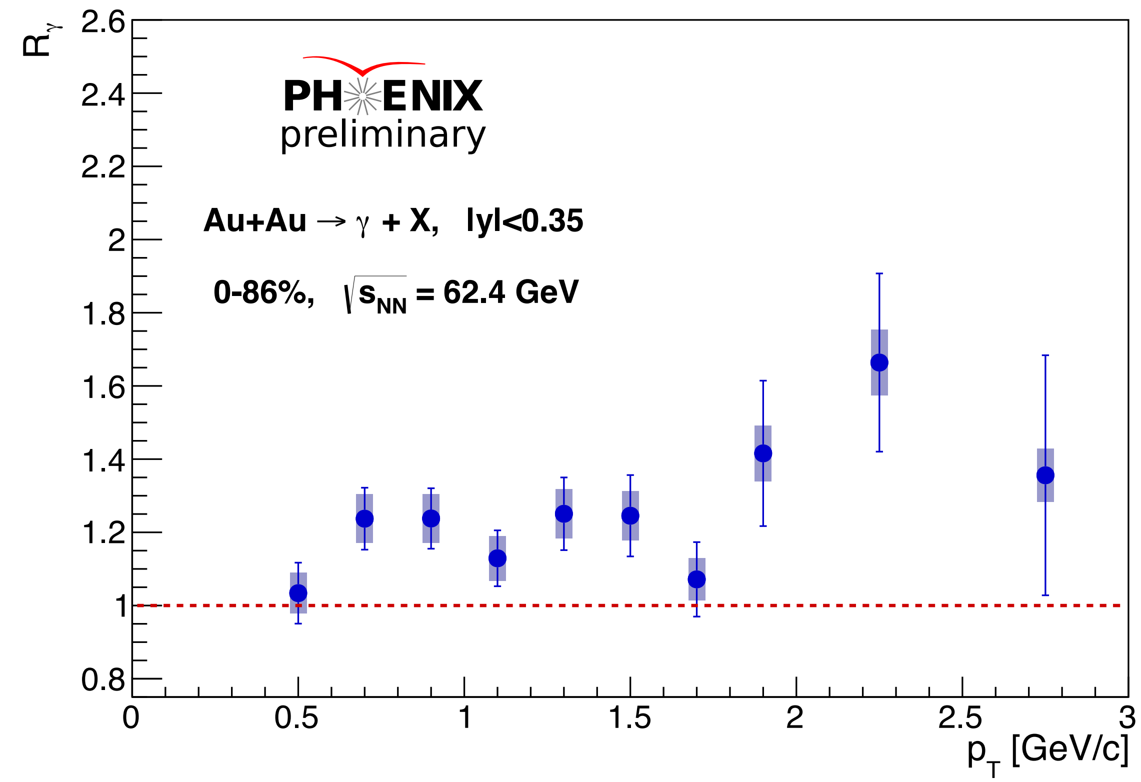
- Double ratio tagging method

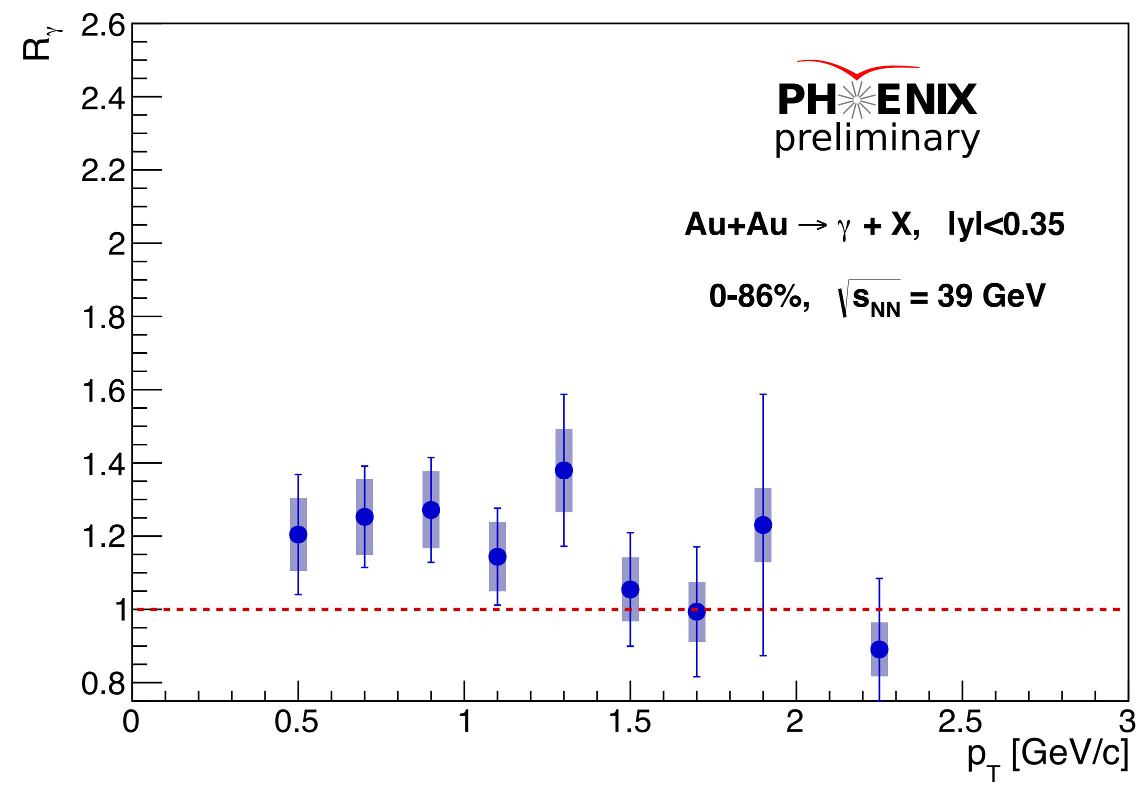
conditional acceptance of the second decay photon

measured raw yields

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

simulation based on hadron data





pp fit

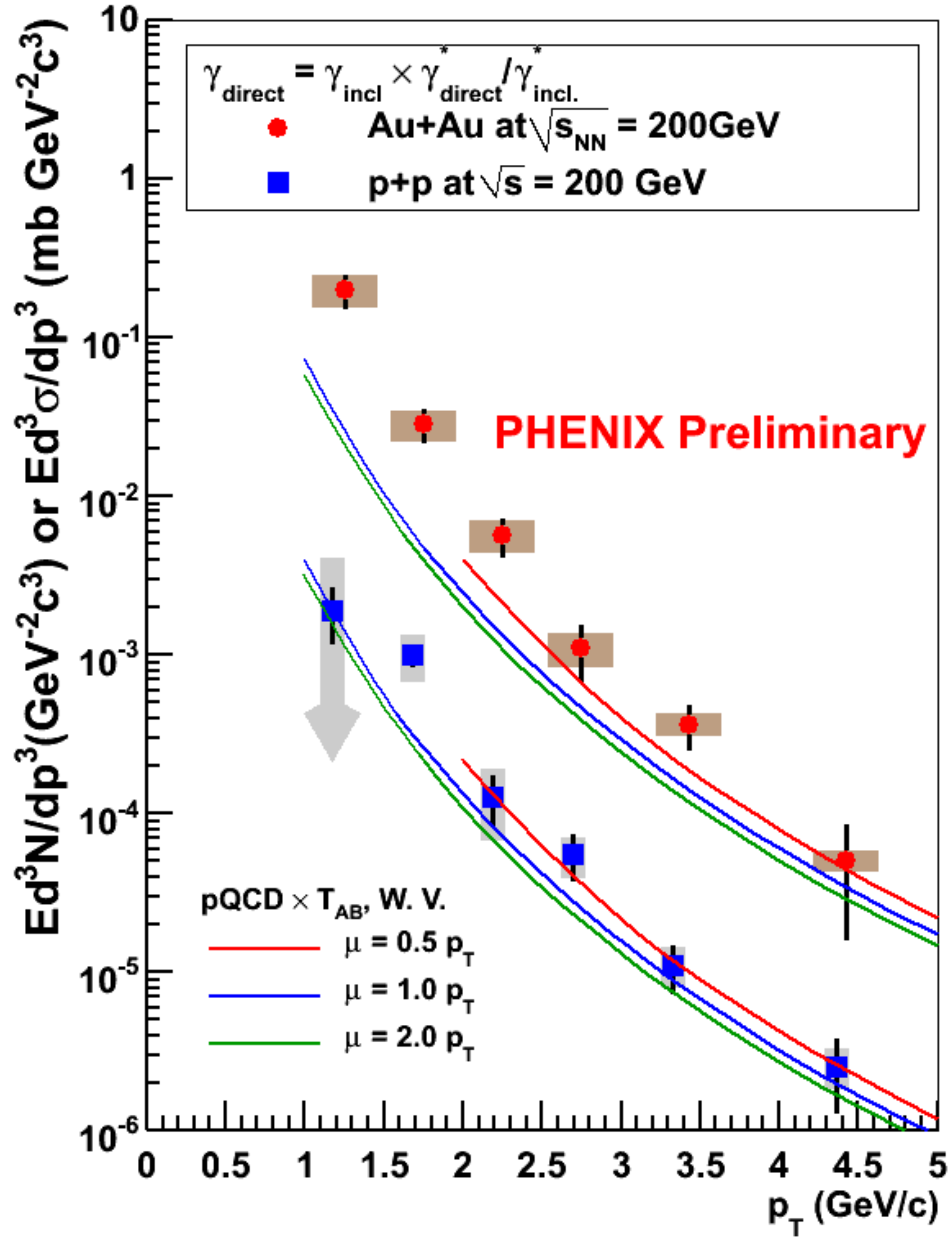
- Fitting function

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

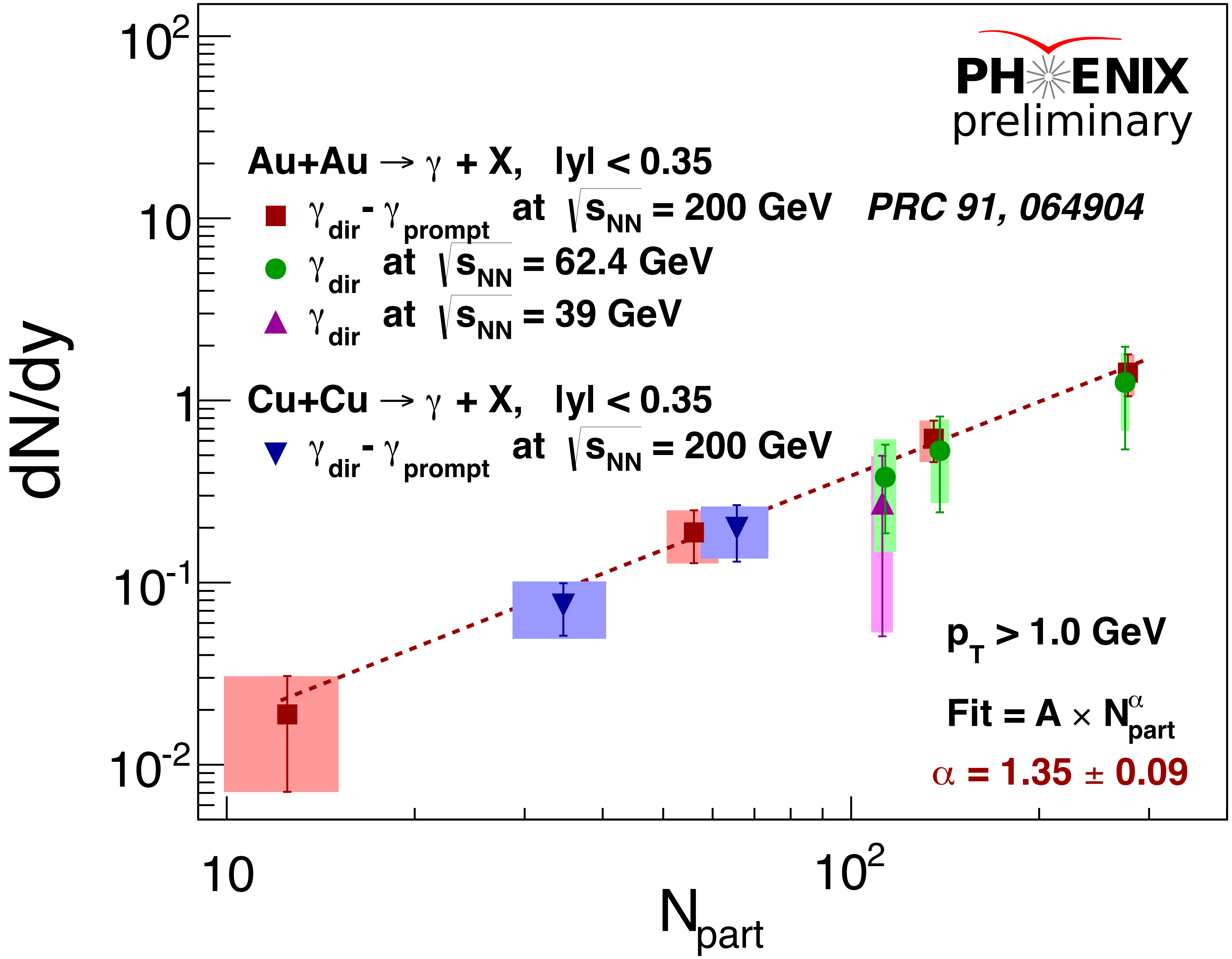
a	b	c
$(8.3\pm7.5)\times10^3$	2.26±0.78	-3.45±0.08

- The actual lowest data point in the fit is 1GeV

- The fit <1GeV is motivated by Drell-Yan measurement [Ito, et al, PRD23, 604 (1981)]



Direct Photon Yield vs N_{part}



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

Internal conversion method

- Any process radiate γ will also radiate γ* (e^+e^-)
  - for $m_{ee} \ll p_T$, γ* are "almost real"

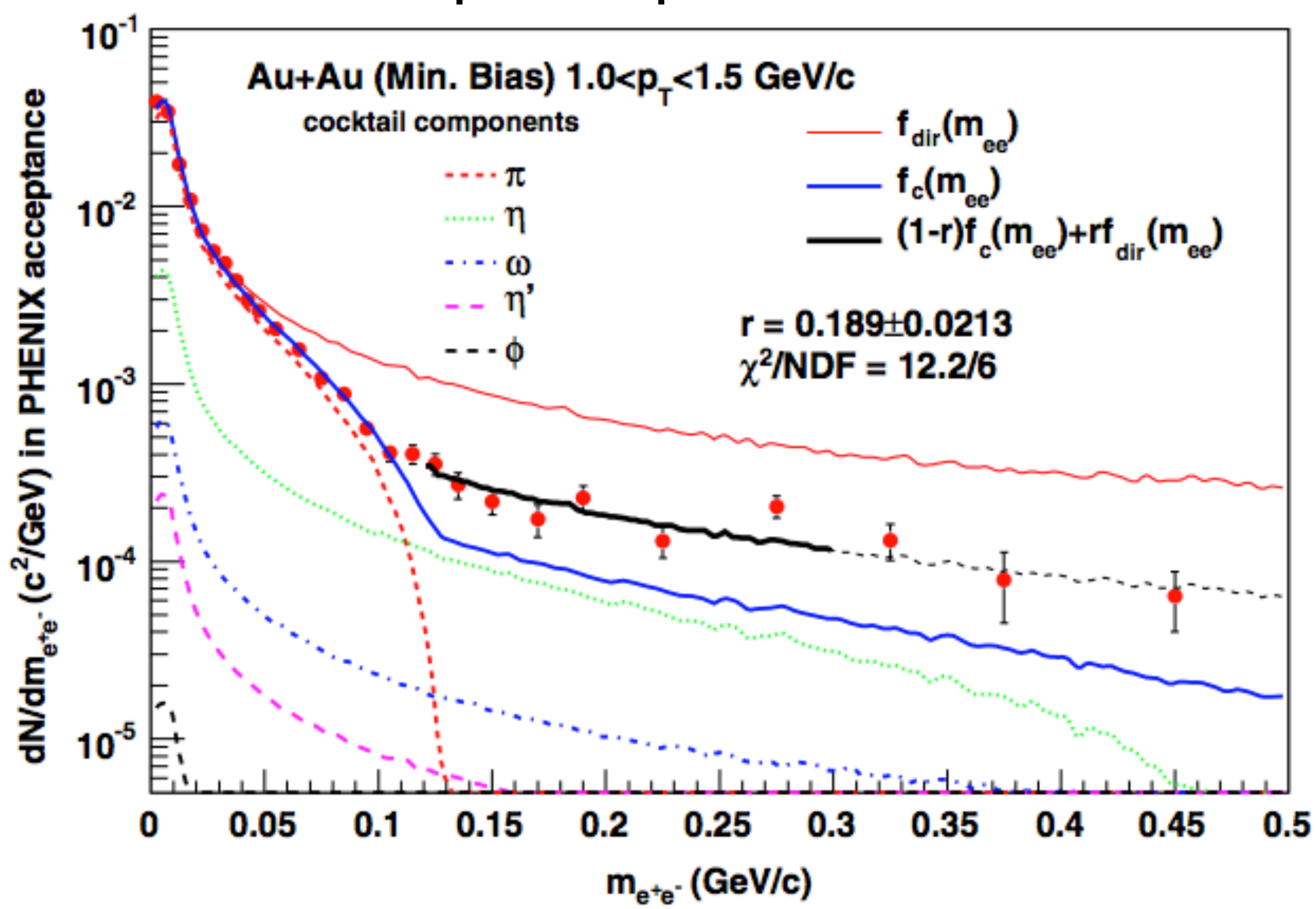
$$\frac{d^2 N_{ee}}{dm_{ee} dp_T} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}} L(m_{ee}) S(m_{ee}, p_T) \frac{dN_\gamma}{dp_T}$$

($m_{ee} \ll p_T$: $S \rightarrow 1$)

- $f_{incl}(m_{ee}) = (1\text{-}r)f_c(m_{ee}) + r f_{dir}(m_{ee})$

all hadron contribution — direct photon contribution

Example: one pT bin for Au+Au collisions



- f_{dir} and f_c are normalized to data m_{ee}< 30 MeV/c²: in both $L(m_{ee})/m_{ee}$ is dominant (independent of r)
- $(1\text{-}r)f_c + r f_{dir}$ fitted in range 120MeV to 300MeV (insensitive to π^0 contribution)
- $r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$ → $dN^{\text{dir}}(p_T) = r \times dN^{\text{incl}}(p_T)$