Direct Virtual Photon Production in Au+Au Collisions at $\sqrt{s_{NN}} = 200\text{GeV}$ at STAR

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Outline

- Motivation
- STAR detector
- Electron identification
- Dielectron production
- Direct virtual photon production
- Summary and outlook

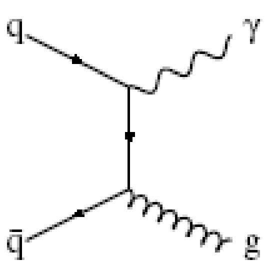
Direct photon and dielectron

------ ideal electroweak probes

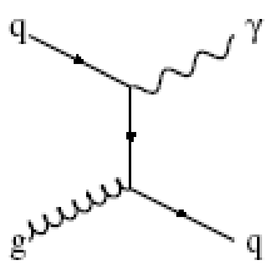
- ✓ suffer no strong interaction, traverse the medium with minimum interaction
- ✓ produced throughout all stages of the evolution of the system

Direct photon:

- ✓ high p_T photons (>5GeV/c) : initial hard scattering
- ✓ low p_T photons (1-5GeV/c) : access QGP production



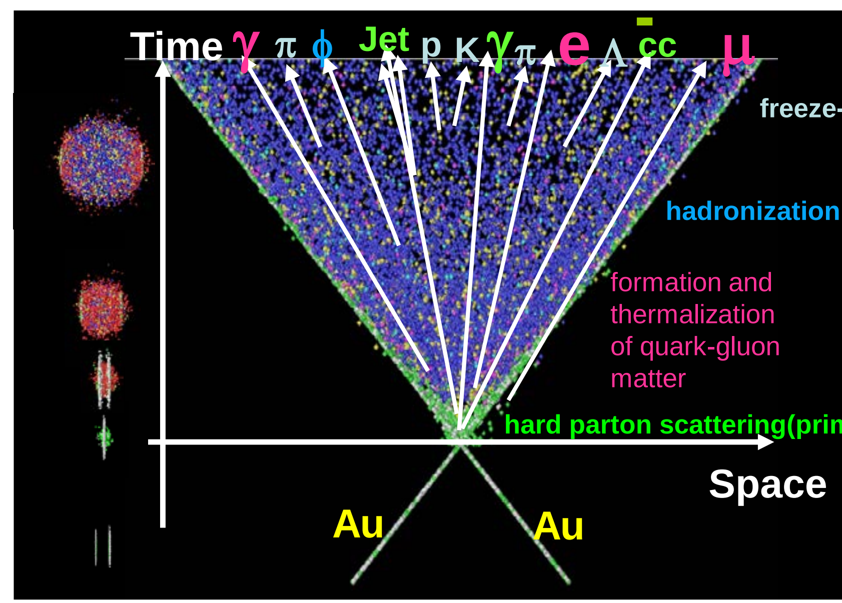
Annihilation



Compton Scattering

Similar process for virtual photon production, which could convert into e^+e^- pair.

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



Motivation

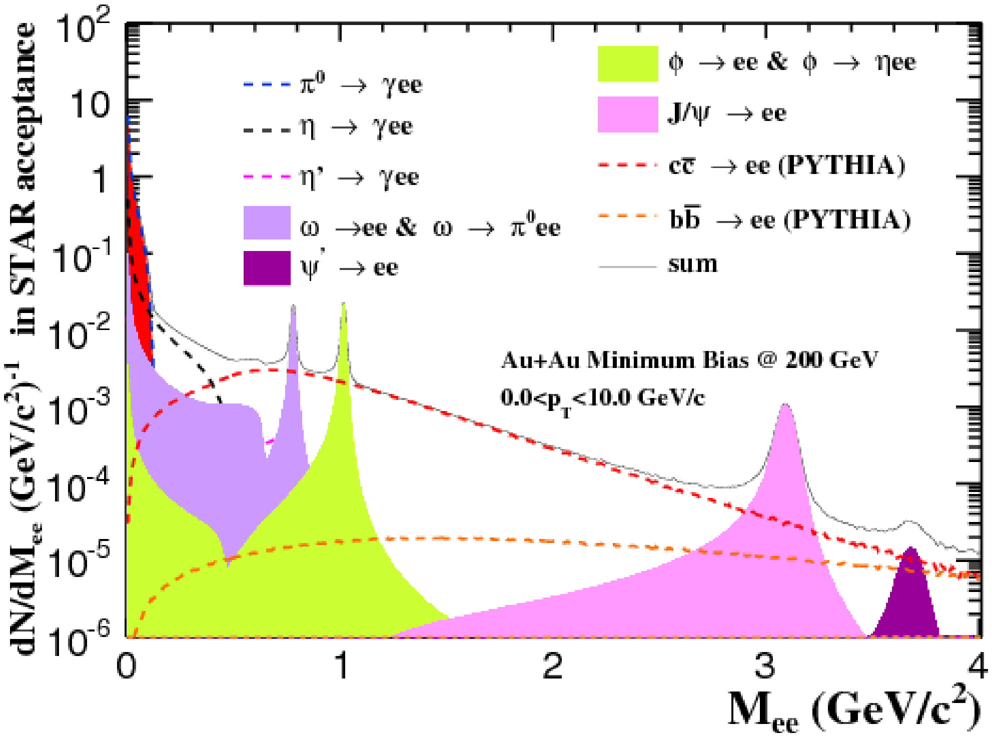
Dielectron:

- *higher invariant mass => earlier production*

➢ Low Mass Region
  - ✓ In-medium modification of vector mesons

➢ Intermediate Mass Region
  - ✓ QGP thermal radiation
  - ✓ Semi-leptonic decay of correlated charm: charm modification in Au+Au

➢ High Mass Region
  - ✓ Heavy quarkonia
  - ✓ Drell-Yan process



Cocktail simulation in Au+Au 200GeV

STAR detectors

Key detectors used in the analysis:

Time Projection Chamber:

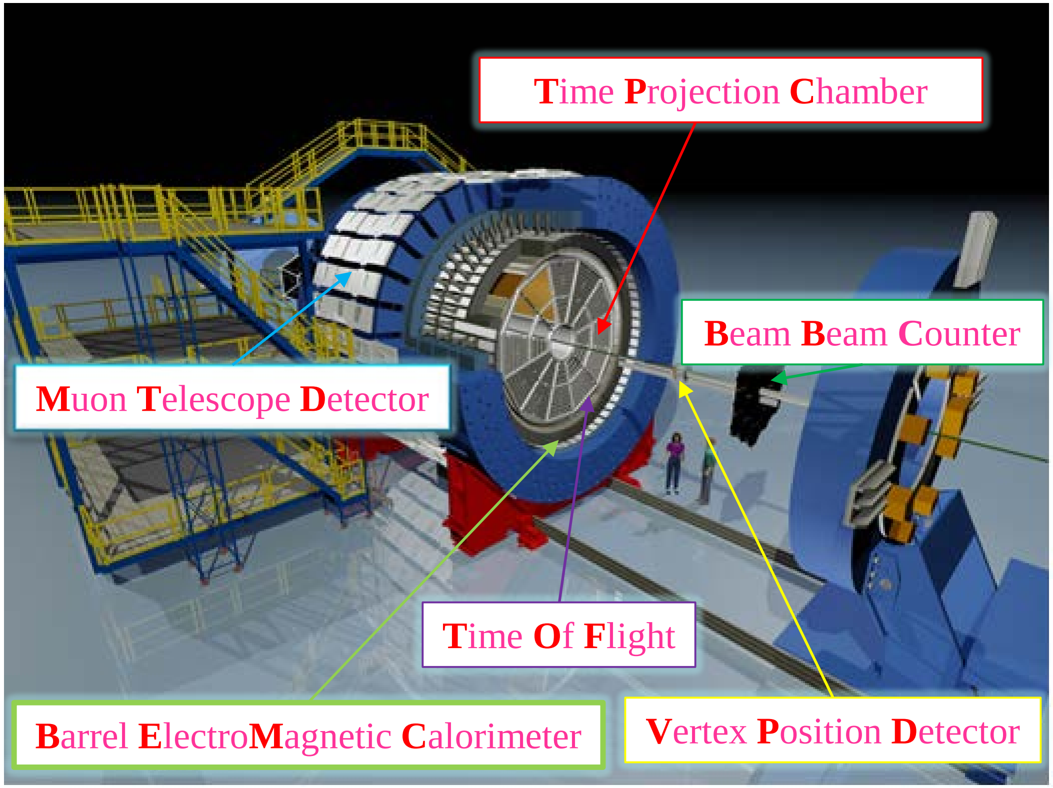
- $|\eta| < 1$ $0<\Phi<2\pi$
- Main tracking detector: track, momenta, ionization energy loss (dE/dx)

Time Of Flight:

- $|\eta| < 0.9$ $0<\Phi<2\pi$
- Intrinsic timing resolution ~ 75 ps
- Time-of-flight measurement

Barrel Electro-Magnetic Calorimeter:

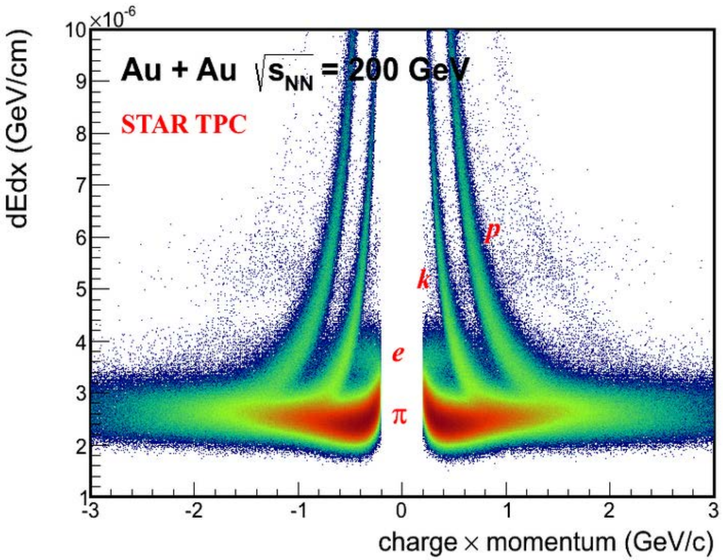
- $|\eta| < 1$ $0<\Phi<2\pi$
- Trigger on and measure high-p_T processes

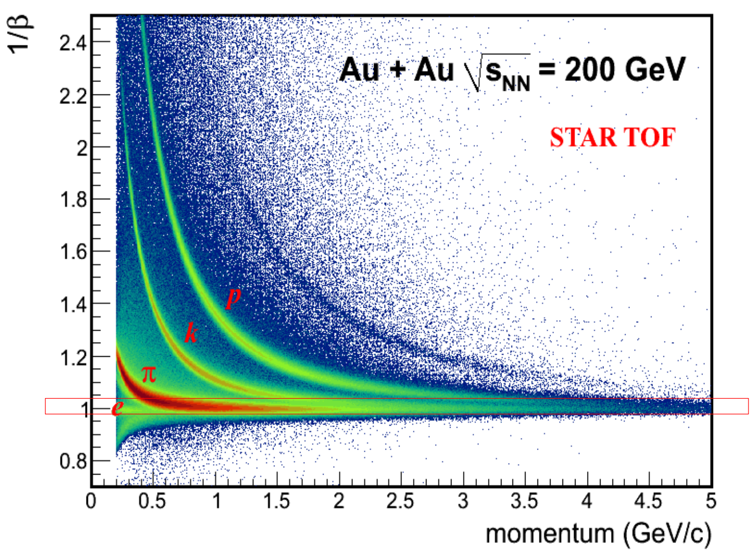


Type	Year	Central	Min.Bias	EMC trigger (energy threshold 4.3GeV)
Au+Au 200GeV	2010	220M	240M	
	2011		490M	39M
p+p 200GeV	2012		375M	

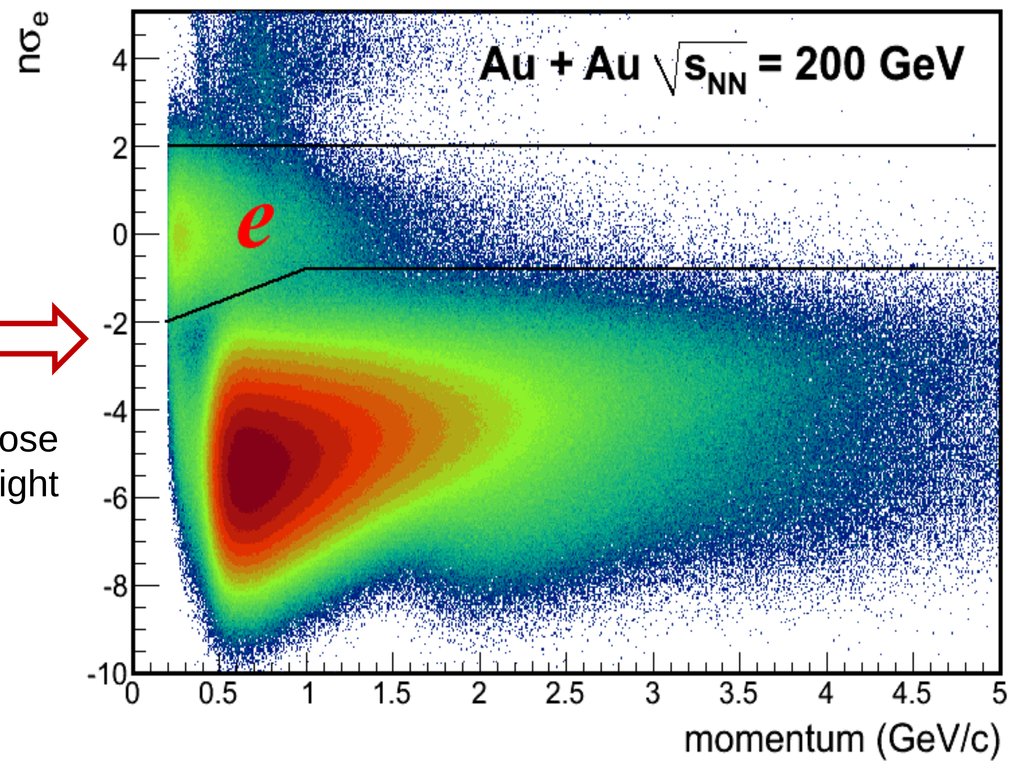
Electron identification

Time-Of-Flight provides clean electron identification from low to intermediate p_T which enables the dielectron measurements.





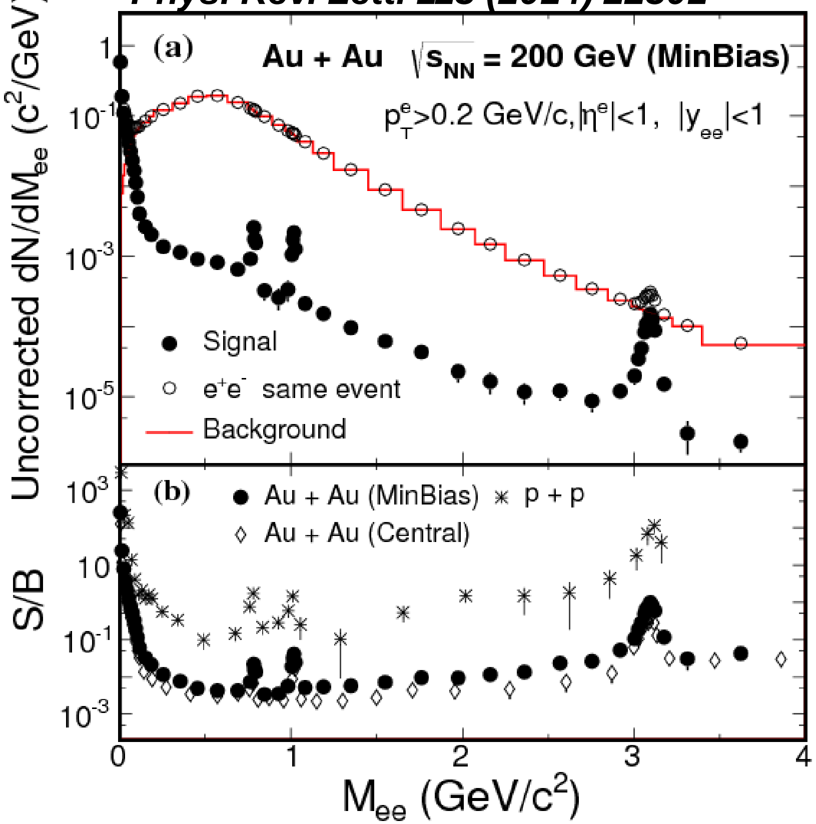
Require β close to speed of light



Collision system	Trigger	Momentum range	Purity
Au+Au 200GeV	Min.Bias	0.2 – 2.0 GeV/c	~95%
	Central	0.2 – 2.0 GeV/c	~93%
	EMC trigger	3.5 – 6.0 GeV/c	Up to 80%
p+p 200GeV	Min.Bias	0.2 – 2.0 GeV/c	~98%

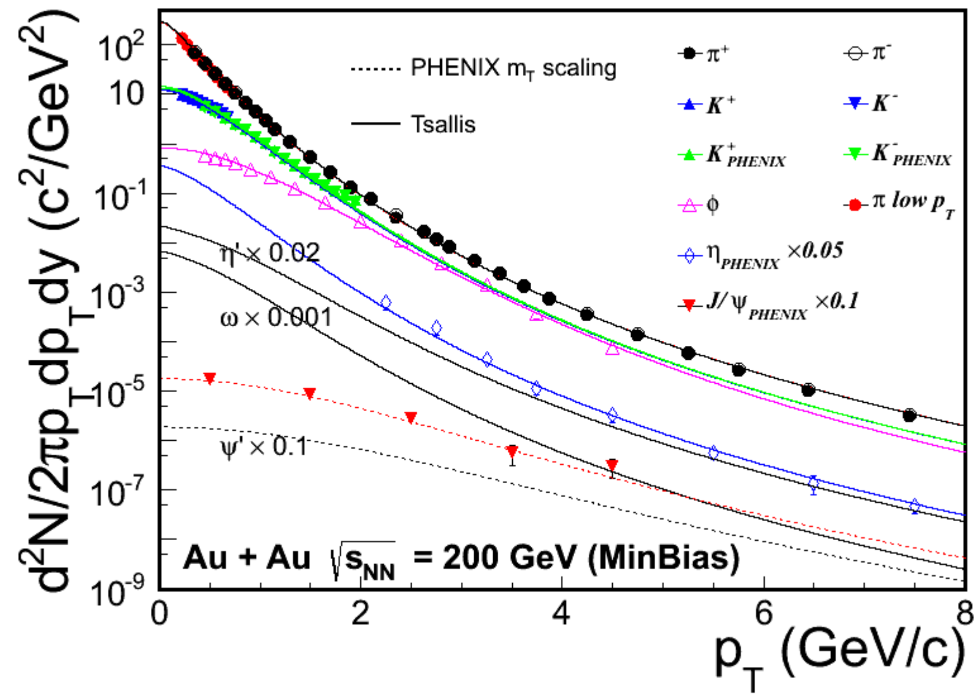
Invariant mass distribution and cocktail input

Phys. Rev. Lett. 113 (2014) 22301



p + p S/B : STAR Collaboration, Phys.Rev. C 86, 024906 (2012).

Input p_T spectra

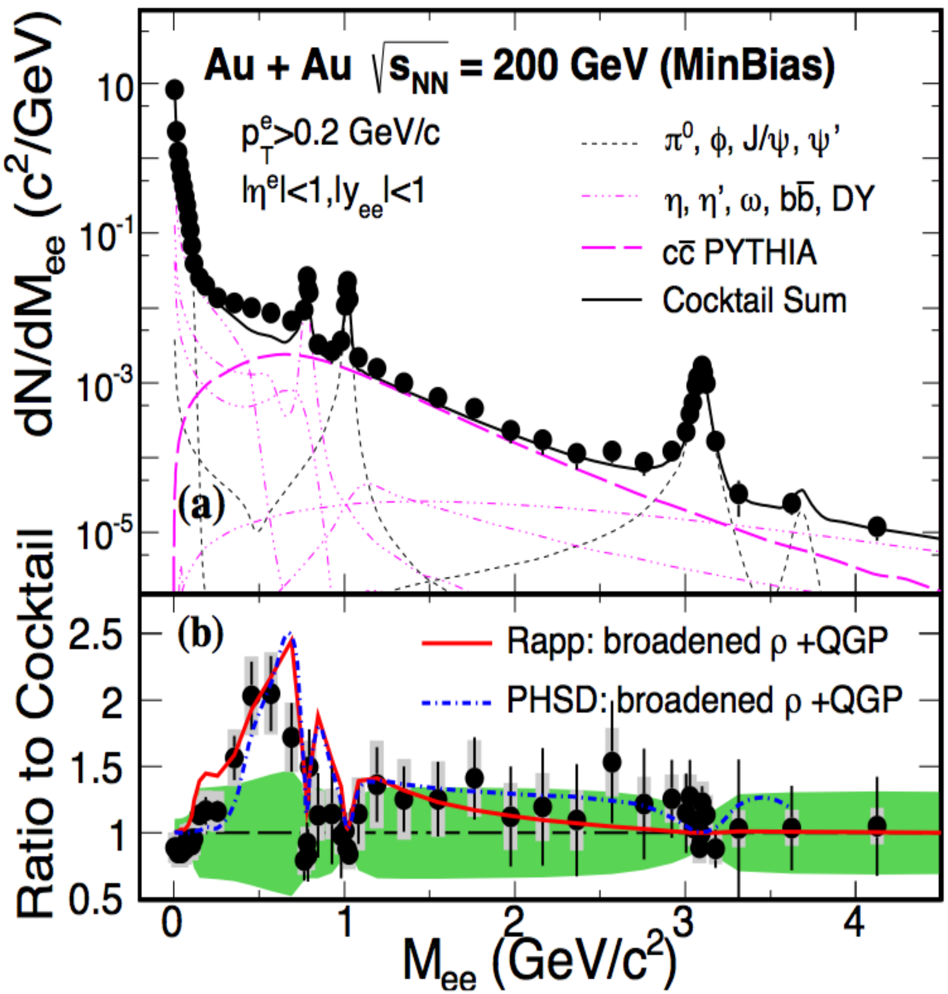


PHENIX Collaboration, Phys. Rev. C 81, 034911 (2010)
STAR Collaboration, Phys. Rev. Lett. 92, 112301 (2004)
STAR Collaboration, Phys. Lett. B 612, 181 (2005).
STAR Collaboration, Phys. Rev. Lett. 97, 152301 (2006)
Z. Tang et al. Phys. Rev. C 79, 051901 (2009)

M_{ee} < 1 GeV/c^2 Like sign background
M_{ee} >= 1 GeV/c^2 Mixed event background

Au+Au 200GeV results from Run10

Phys. Rev. Lett. 113 (2014) 22301



Enhancement at ρ-like region(0.30-0.76 GeV/c^2)
1.77 ± 0.11(stat.) ± 0.24 (sys.) ± 0.33 (cocktail) in Min.Bias

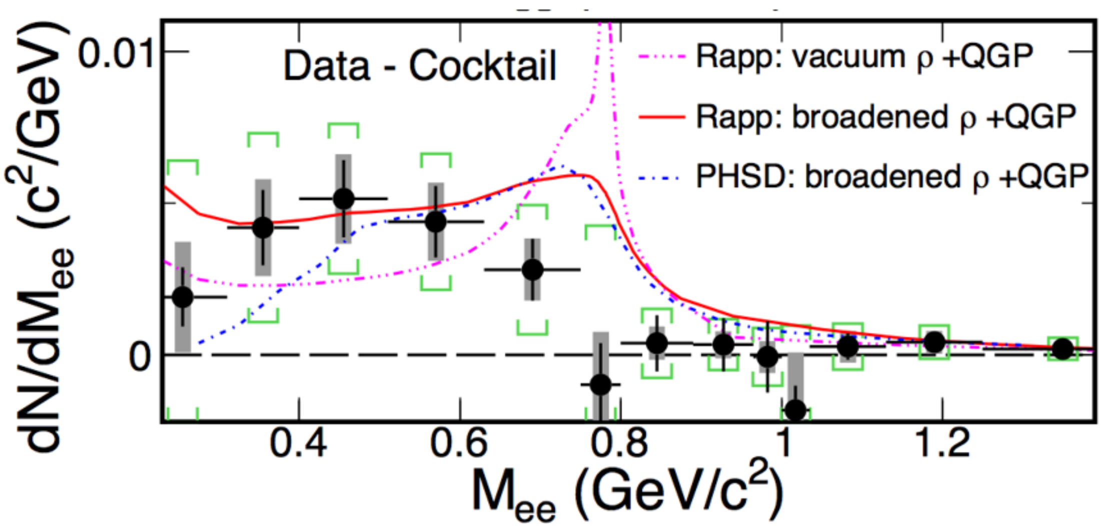
Comparison with models based on a ρ-broadening scenario :

1) Model I : effective many-body model
[*R. Rapp, PoS CPOD2013, 008 (2013)*]

2) Model II : Parton-Hadron String Dynamics (PHSD)
[*O. Linnyk et al., Phys. Rev. C 85, 024910 (2012)*]

Models show good agreement with data within uncertainty.

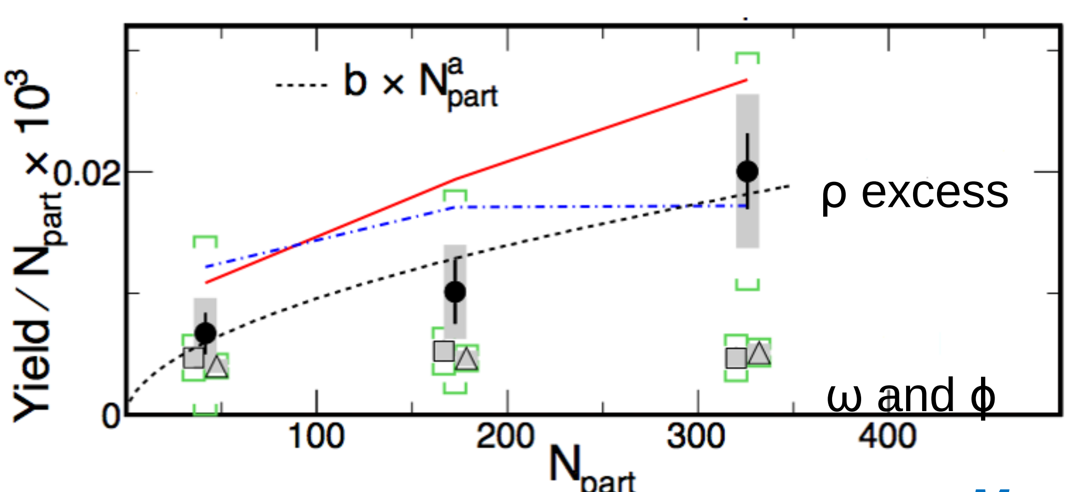
1) invariant-mass dependence :



Broadened ρ model calculations can explain STAR data within uncertainties. Our measurements disfavor a pure vacuum ρ model with a $\chi^2/NDF = 26/8$ in 0.3~1 GeV/c^2.

[*Phys. Rev. Lett. 113 (2014) 22301*]

2) N_{part} dependence of excess yield:



(A) ρ-like region : 0.3~0.76 GeV/c^2
(B) ω-like region: 0.76~0.80 GeV/c^2
(C) ϕ-like region: 0.98~1.05 GeV/c^2

ω-like and ϕ-like region (B), (C):
--- Yield shows N_{part} scaling.
ρ-like region (A):
--- Significant excess is observed.

More details in [Phys. Rev. C 92(2015) 024912]

e^+e^- pairs from internal conversion

- Relation between real photon yield and the associated e^+e^- pairs:

$$\frac{d^2N_{ee}}{dM} = \frac{2\alpha}{3\pi}\frac{L(M)}{M}S(M,q)dN_\gamma$$

$$L(M) = \sqrt{1-\frac{4m_e^2}{M^2}}\left(1+\frac{2m_e^2}{M^2}\right)$$

$$S(M,q) = \frac{dN_{\gamma^*}}{dN_\gamma}$$

✓ pass STAR acceptance
✓ normalize to 0-30MeV/c²

cocktail normalized to 0-30MeV/c²

Direct photons can be measured by the associated dielectron production.
S = 1 => direct virtual photon ($p_T \gg M$, $M \gg m_e$)

$$(1-r)f_c + r f_{dir}$$

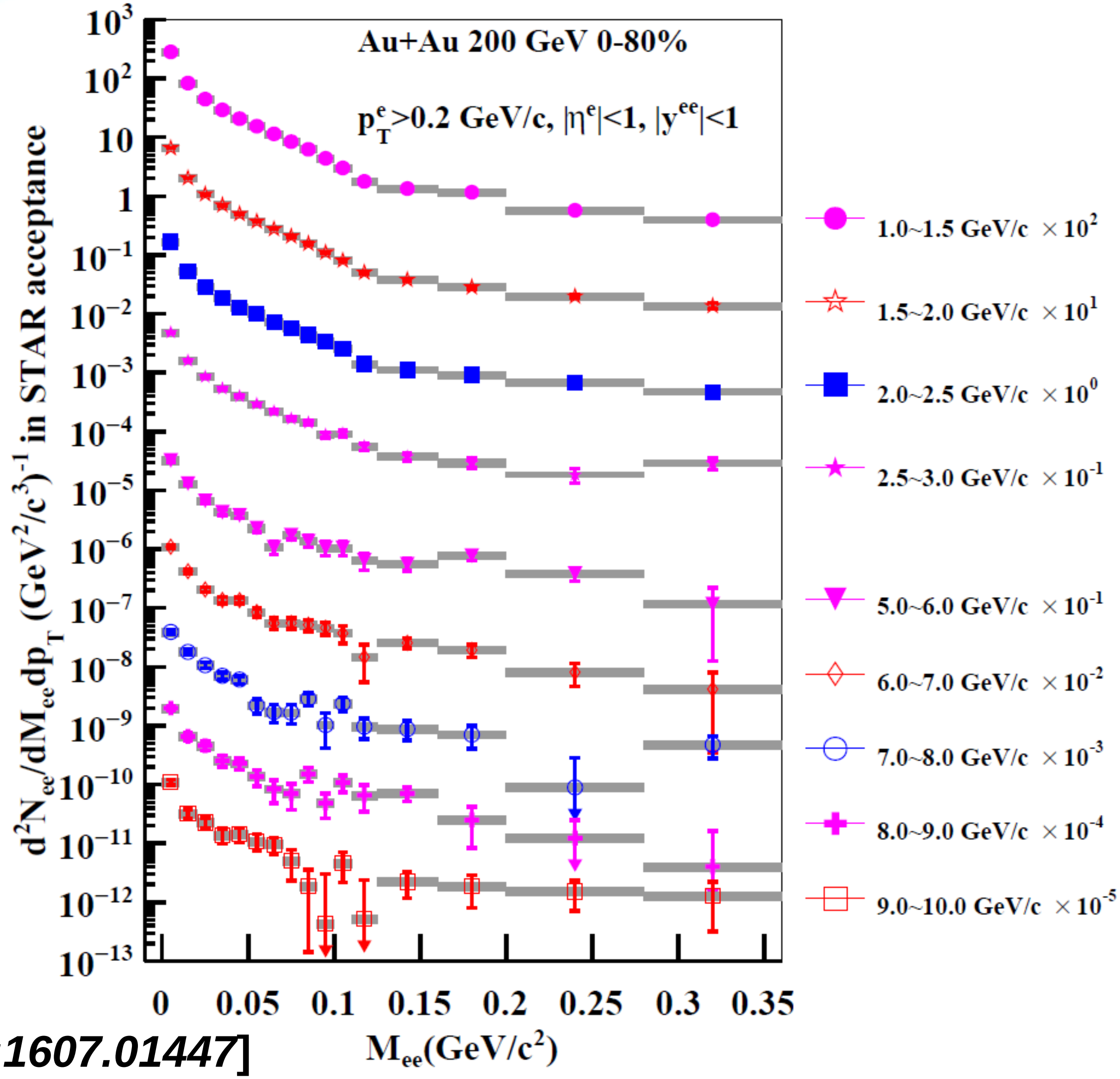
: two-component fit to dielectron continuum.

cocktail component

direct virtual photon component

$$r = \frac{yield\ of\ direct\ virtual\ photon}{yield\ of\ inclusive\ photon}$$

Low mass dielectron continuum



[*arXiv:1607.01447*]

- *1-3 GeV/c*

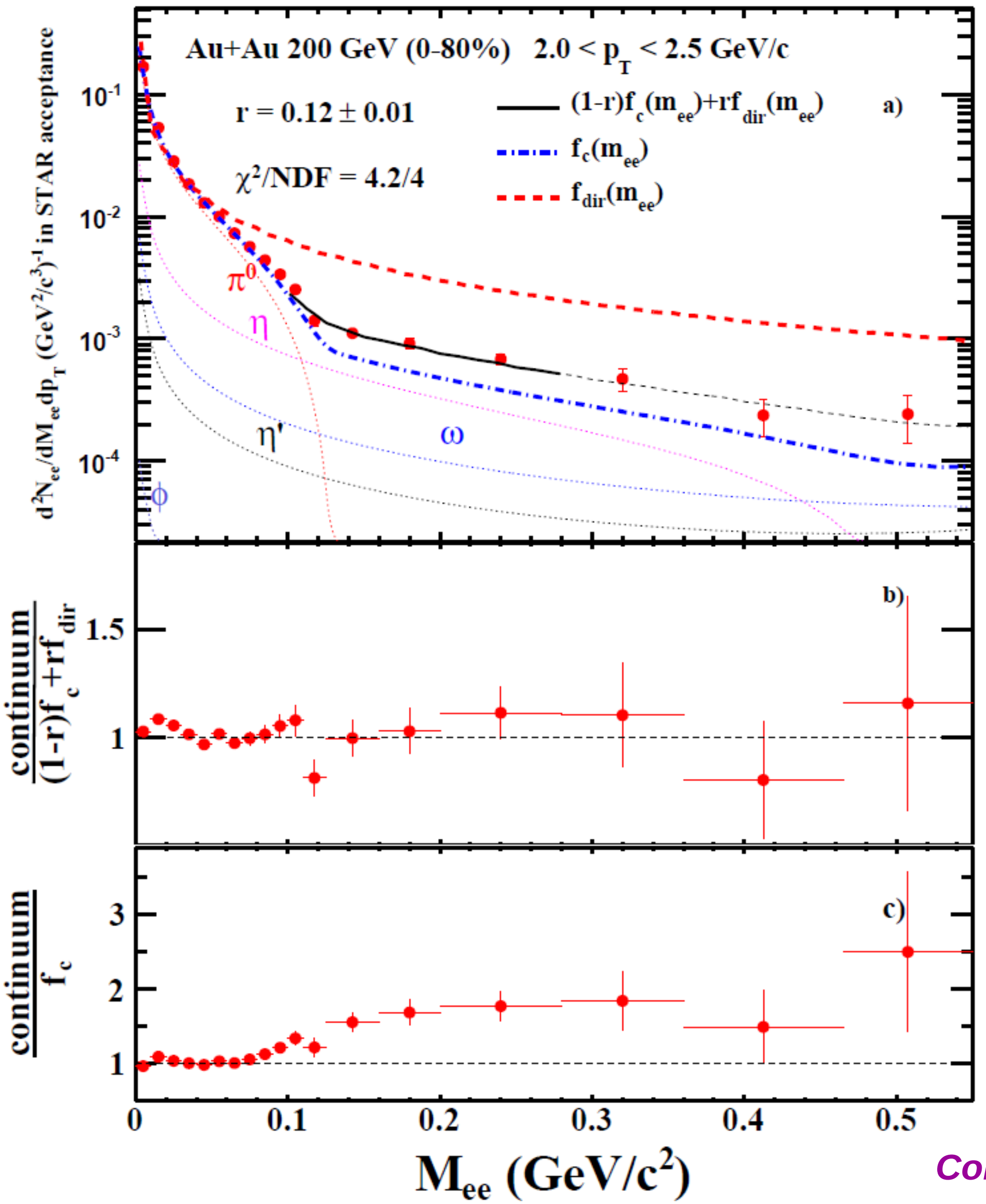
Run10+Run11 MB data

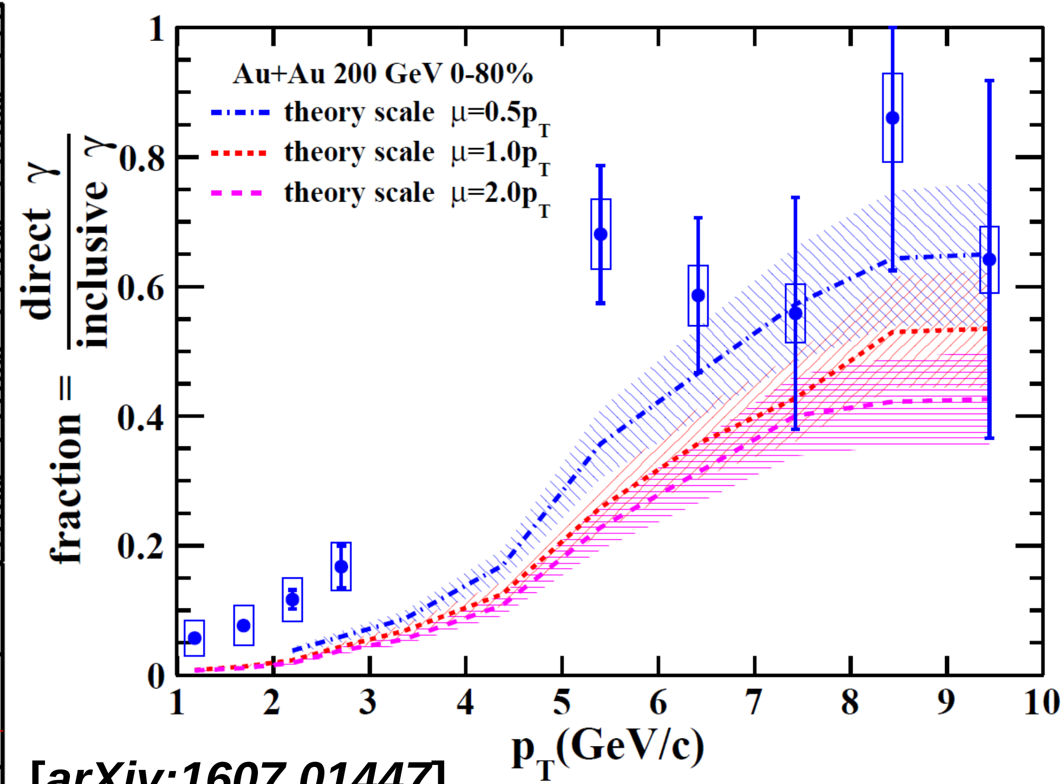
- *5-10 GeV/c*

Run11 EMC triggered data

The statistical and systematic uncertainties are shown by the bars and bands, respectively.

Two component fit and fraction of direct virtual photon





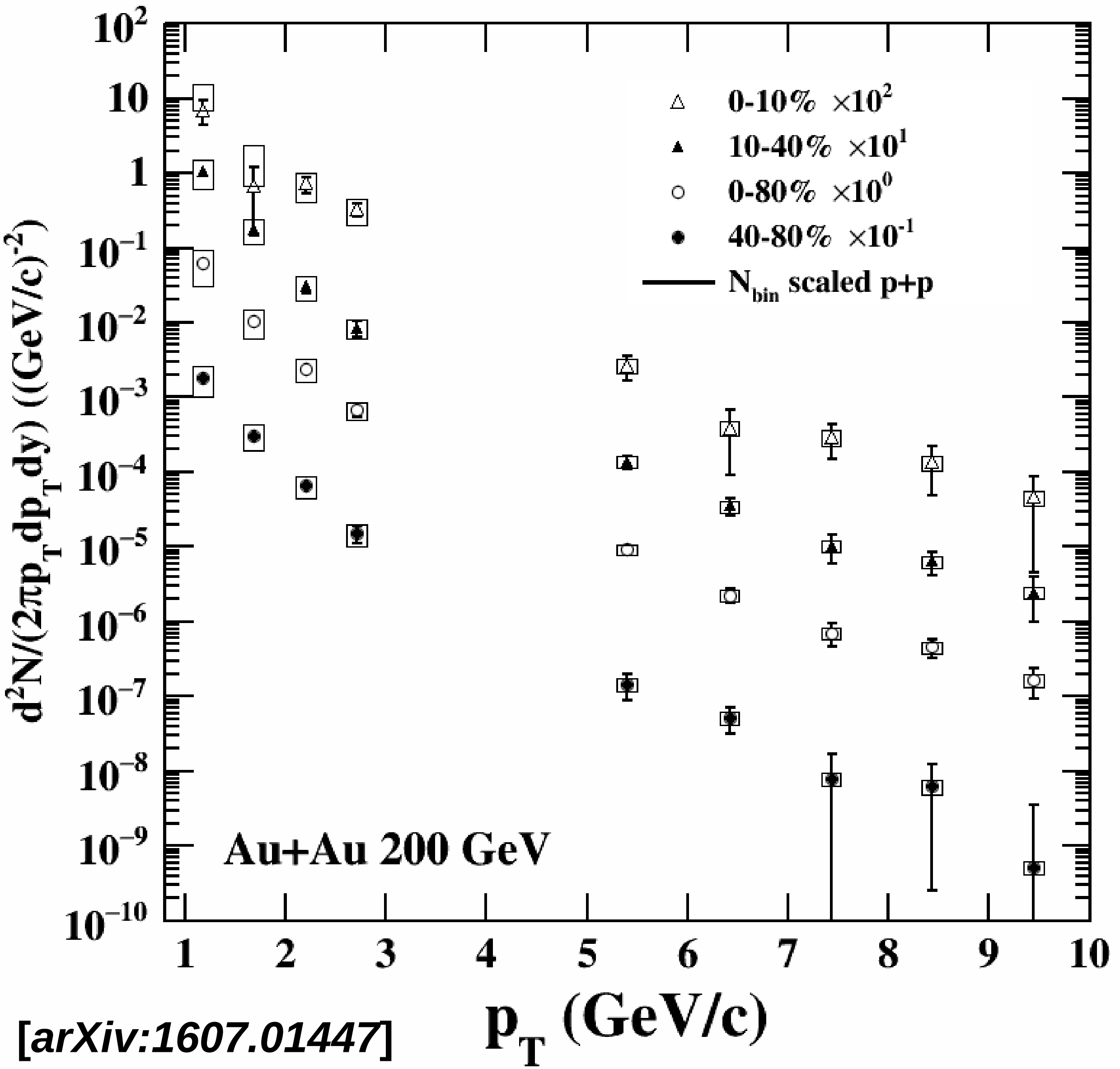
[*arXiv:1607.01447*]

The curves represent NLO pQCD prediction: $\frac{T_{AA} d\sigma_{\gamma}^{NLO}(p_T)}{dN_{\gamma}^{inclusive}(p_T)}$

L. E. Gordon and W. Vogelsang, Phys. Rev. D 48, 3136 (1993).
PHENIX Collaboration, Phys.Rev.L 98, 012002 (2007).
PHENIX Collaboration, Phys.Rev.L 104,132301(2010).

Compared to p+p reference, an excess is observed in low p_T

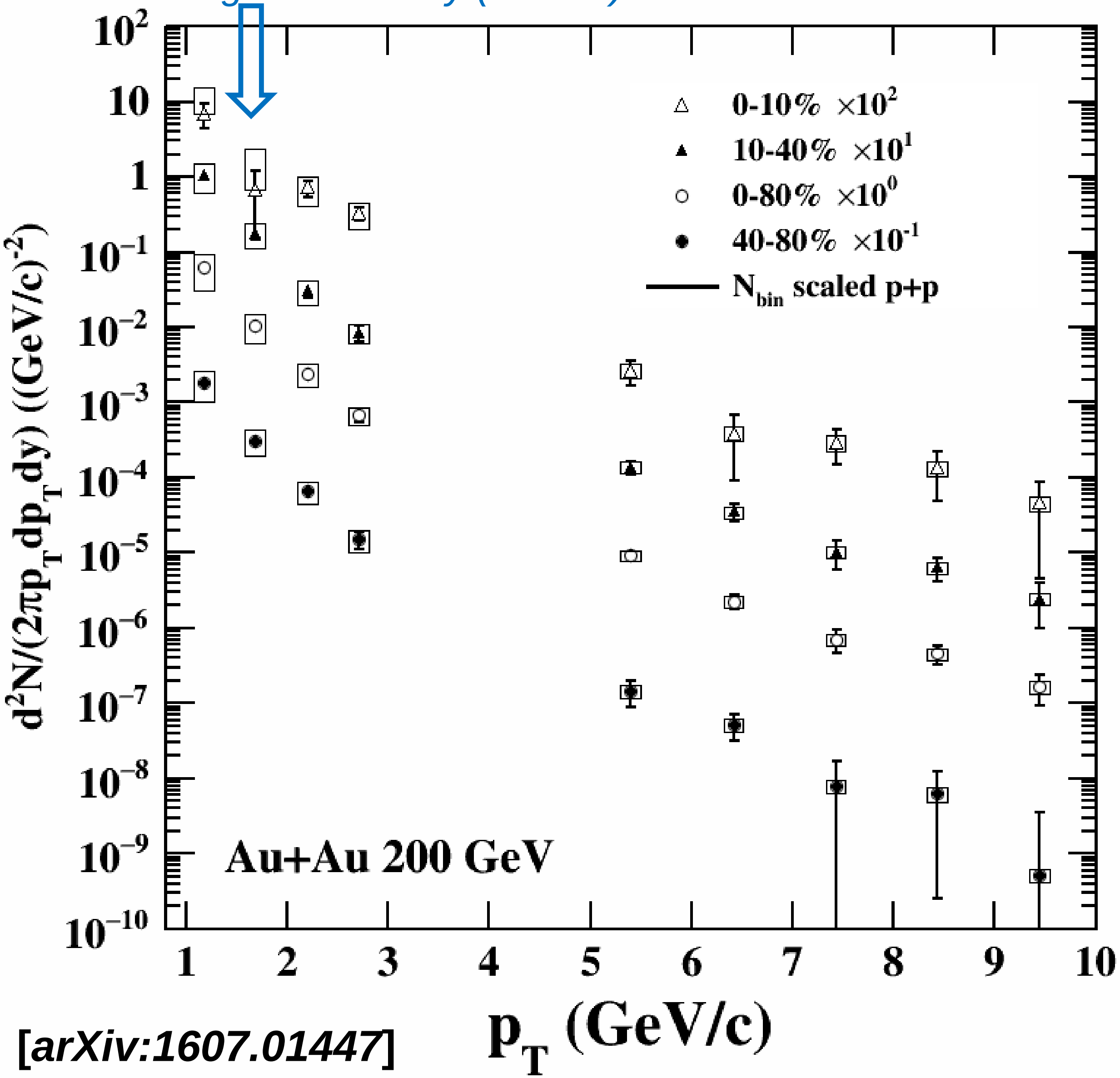
Direct virtual photon invariant yield



[*arXiv:1607.01447*]

Direct virtual photon invariant yield

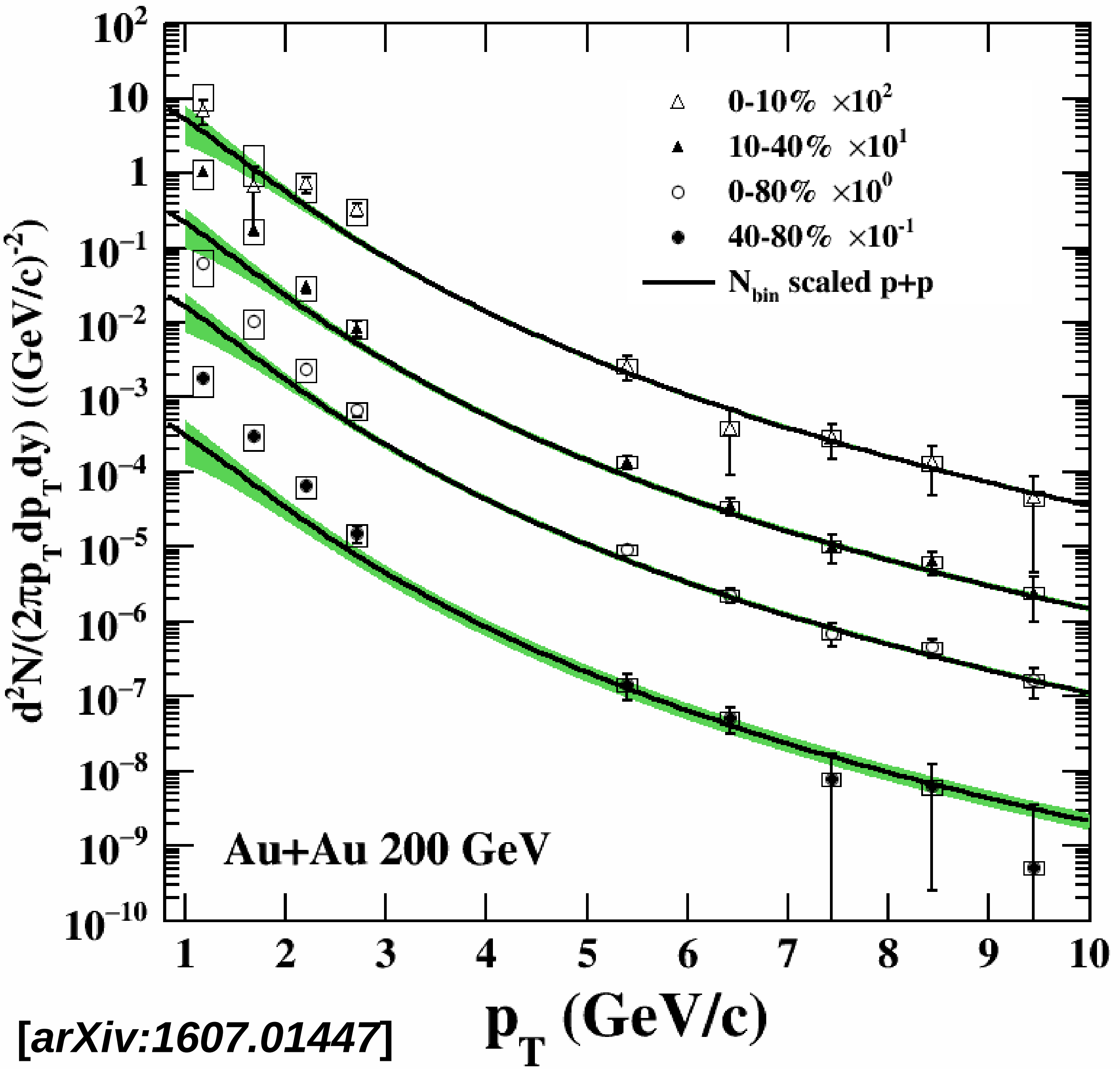
No η measurement for cocktail simulation input
Large uncertainty (>100%)



[*arXiv:1607.01447*]

$3<p_T<5$ GeV/c
low purity and statistics

Direct virtual photon invariant yield



[*arXiv:1607.01447*]

In the high p_T range above 6 GeV/c

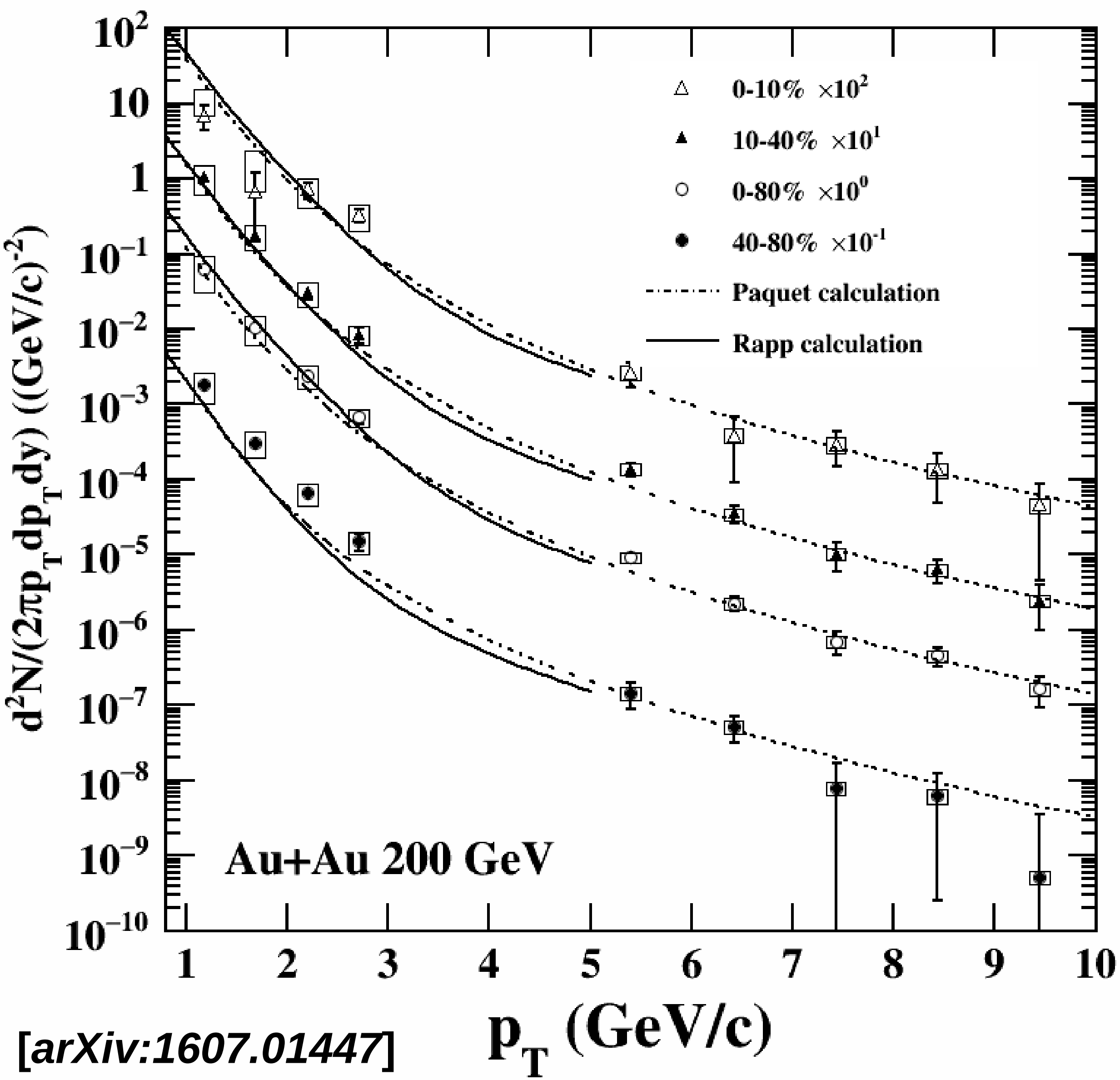
- ✓ **the yield is consistent with a T_{AA} scaled fit function to PHENIX pp data.**

[A. Adare et al. Phys.Rev.C.81:034911, (2010)]
[S.S. Adler et al. Phys.Rev.Lett., 98:012002, (2007)]

In the p_T range 1~3 GeV/c

- ✓ **Compared to the pp reference, an excess is observed in 10-40% and 40-80%.**

Compared to model prediction



[*arXiv:1607.01447*]

Rapp calculation:

elliptic thermal fireball evolution
(consistent with their (2+1)-D hydrodynamic evolution (beam-direction independent))

Paquet calculation:

(2+1)-D hydrodynamic evolution

both models include:

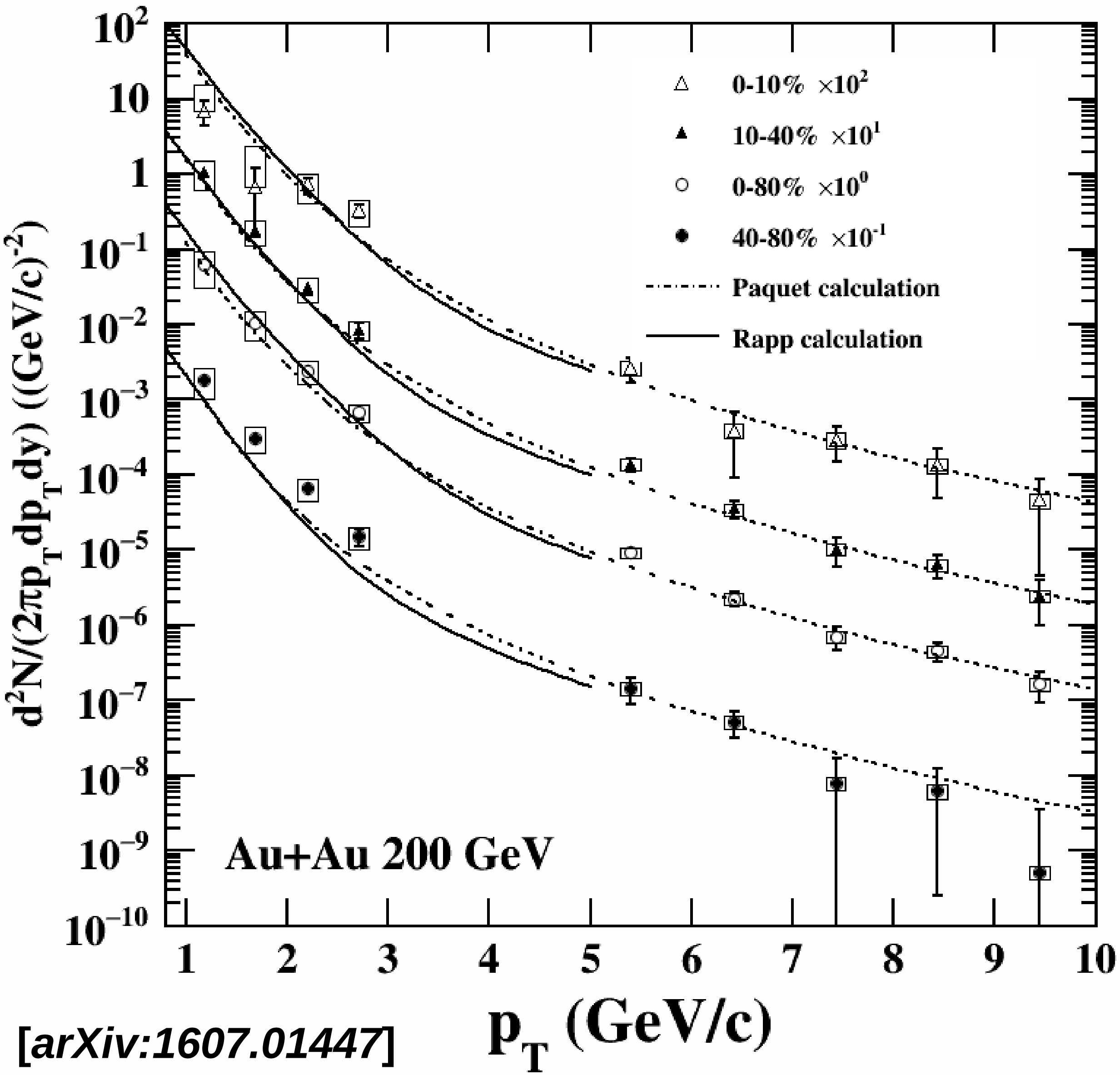
- ✓ QGP thermal radiation
- ✓ in-medium meson
- ✓ mesonic interactions in the hadronic gas
- ✓ primordial contributions from the initial hard parton scattering

H. van Hees, C. Gale, and R. Rapp
[Phys. Rev. C 84, 054906 (2011)]

H. van Hees, M. He, and R. Rapp
[Nucl. Phys. A 933, 256 (2015)]

J.-F. Paquet et al.,
[Phys. Rev. C 93, 044906 (2016)]
private communications

Compared to model prediction



[*arXiv:1607.01447*]

p_T 1-3 GeV/c:

thermal radiation dominant

p_T > 6 GeV/c:

initial hard-parton scattering dominant

The comparison shows consistency between both model calculations and measurements within uncertainties for all the other centralities except 40-80% centrality.

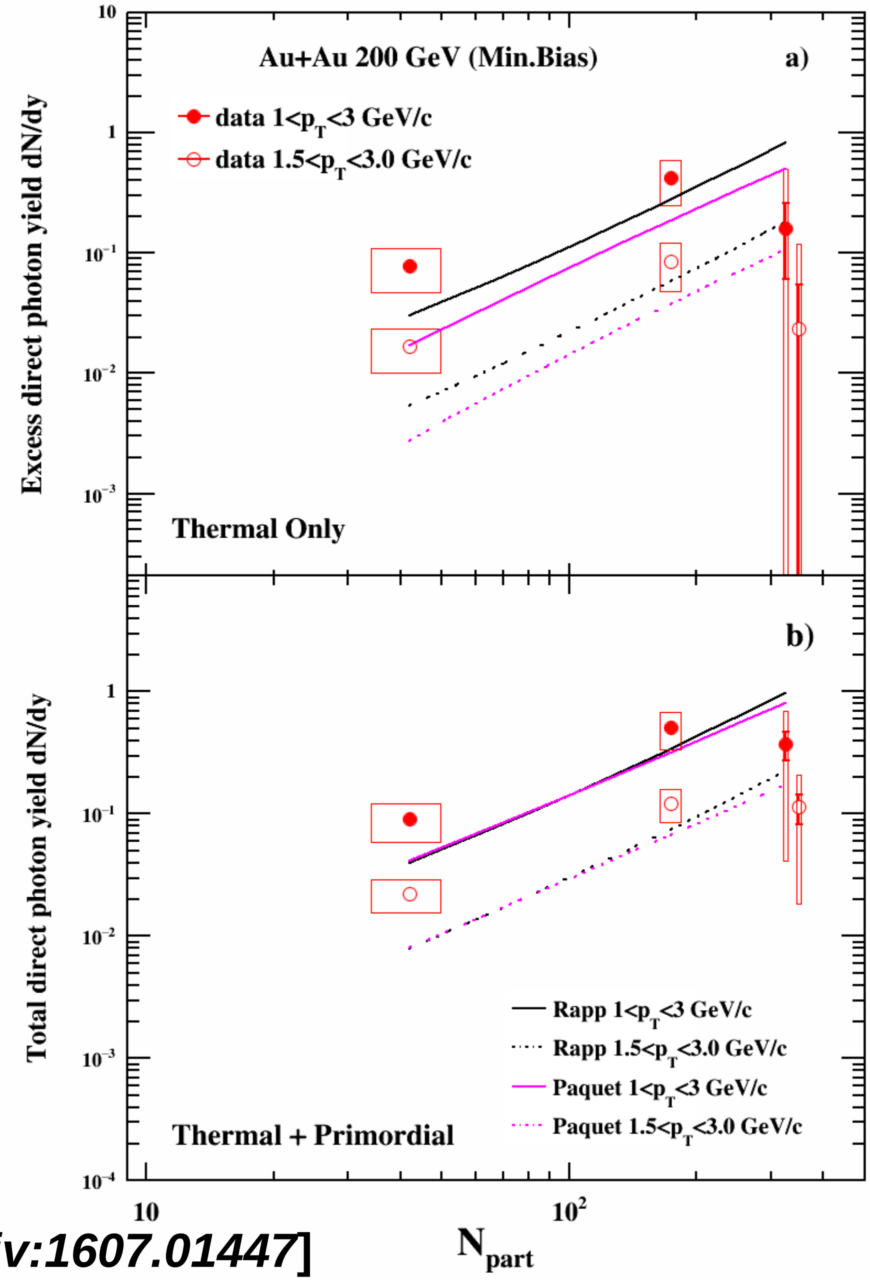
40-80% includes peripheral collisions, where hydrodynamic calculations might not be applicable.

H. van Hees, C. Gale, and R. Rapp [Phys. Rev. C 84, 054906 (2011)]

H. van Hees, M. He, and R. Rapp [Nucl. Phys. A 933, 256 (2015)]

J.-F. Paquet et al., [Phys. Rev. C 93, 044906 (2016)] private communications

Total yield and excess yield



[*arXiv:1607.01447*]

The model calculations are consistent with our measurements within uncertainties in central and semi-central for both excess and total direct photon yield.

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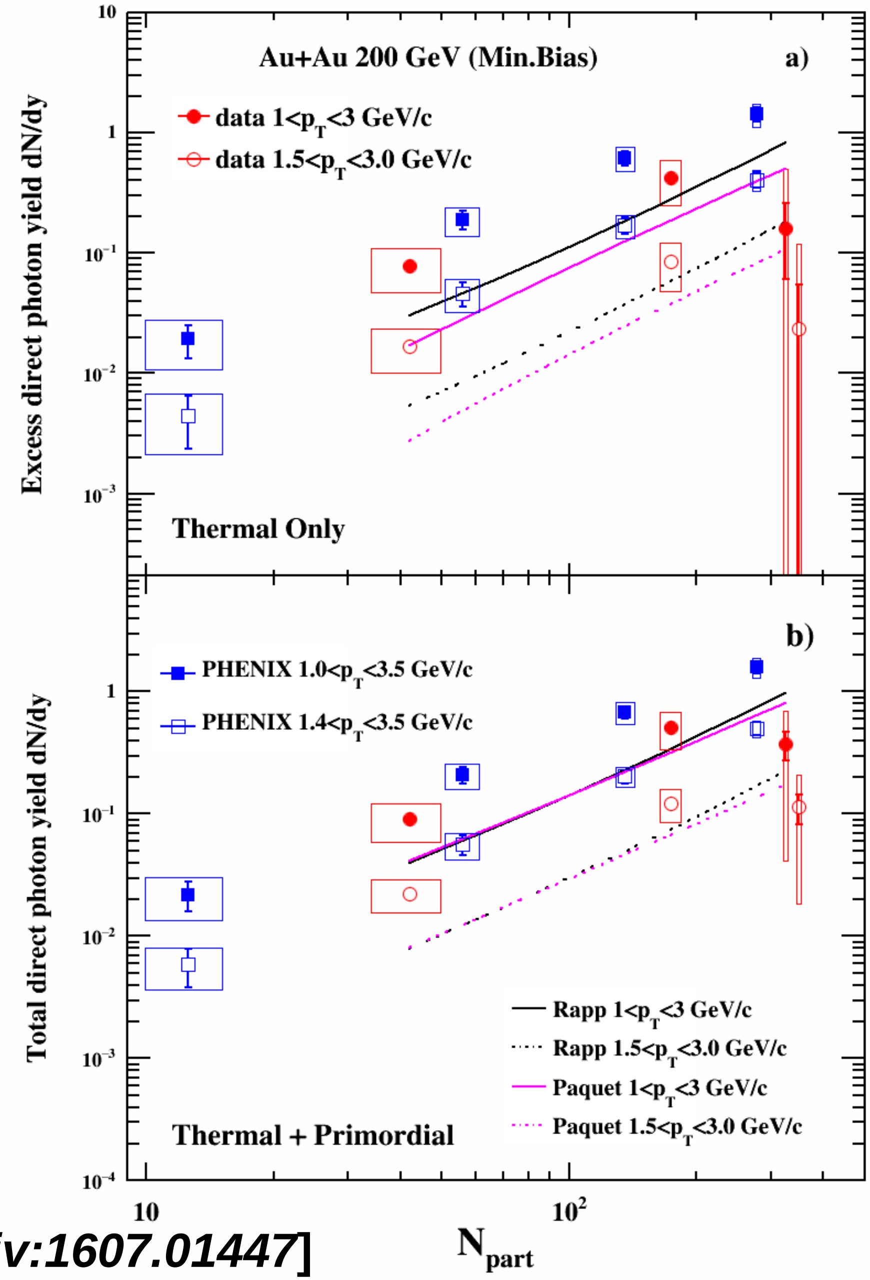
Total yield and excess yield



[*arXiv:1607.01447*]

Comparison	χ^2/NDF	p-value
Excess yield		
STAR data to Rapp	4.26/2	0.119
STAR data to Paquet	2.81/2	0.245
PHENIX data to Rapp	11.1/2	0.0038
PHENIX data to Paquet	16.9/2	2.2e-04
Total yield		
STAR data to Rapp	3.98/2	0.137
STAR data to Paquet	2.78/2	0.249
PHENIX data to Rapp	12.8/2	0.0017
PHENIX data to Paquet	15.0/2	5.6e-04

PHENIX collaboration
[Phys. Rev. C 91, 064904 (2015)]

H. van Hees, C. Gale, and R. Rapp
[Phys. Rev. C 84, 054906 (2011)]

H. van Hees, M. He, and R. Rapp
[Nucl. Phys. A 933, 256 (2015)]

J.-F. Paquet et al.,
[Phys. Rev. C 93, 044906 (2016)]
private communications

Summary

- *Presented the direct virtual photon measurement (1-3 and 5-10 GeV/c) in Au+Au collisions at STAR at $\sqrt{s_{NN}}$=200GeV*
- *An enhancement compared with PHENIX p+p results is observed for 1-3 GeV/c in 10-40% and 40-80%*
- *In the p_T range above 6 GeV/c there is no clear enhancement observed for all the centralities*
- *Model predictions including the contributions from thermal radiation and initial hard-processes are consistent with our direct photon yield within uncertainties in central and mid-central collisions*
- *In 40-80% centrality bin, the model calculation results are systematically lower than our data for 1<p_T <3 GeV/c*

Outlook:

Direct photon in 62 GeV Au+Au collisions to study its behavior close to critical temperature

May have enough statistics from future RHIC run

Backup

Background

Like sign background:

- can reconstruct both the combinatorial and correlated background.
- low statistics
- need to correct acceptance difference between unlike sign and like sign ee pair

$$B_{likesign} = 2\sqrt{N_{++}N_{--}}\frac{B_{+-}}{2\sqrt{B_{++}B_{--}}}$$

$$for\ EMC\ triggered\ events\ in\ p_T > 5GeV/c\ \ B_{likesign} = (N_{++}+N_{--})\frac{B_{+-}}{2\sqrt{B_{++}B_{--}}}$$

N: same event B: mixed event

Mixed event background:

- High statistics
- Do not need to correct acceptance
- Can't reconstruct correlated background
- normalized to Like Sign in mass region [1,2] GeV/c^2