Measurement of thermal photons at RHIC

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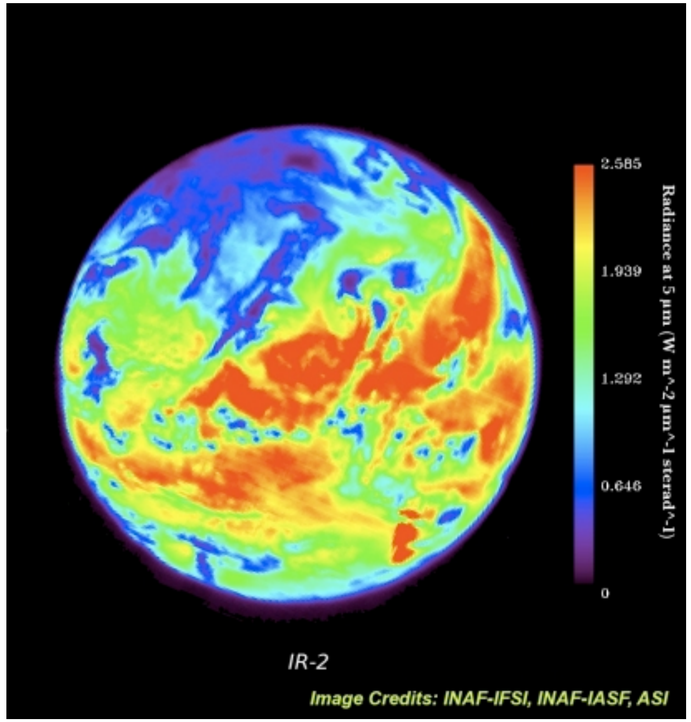
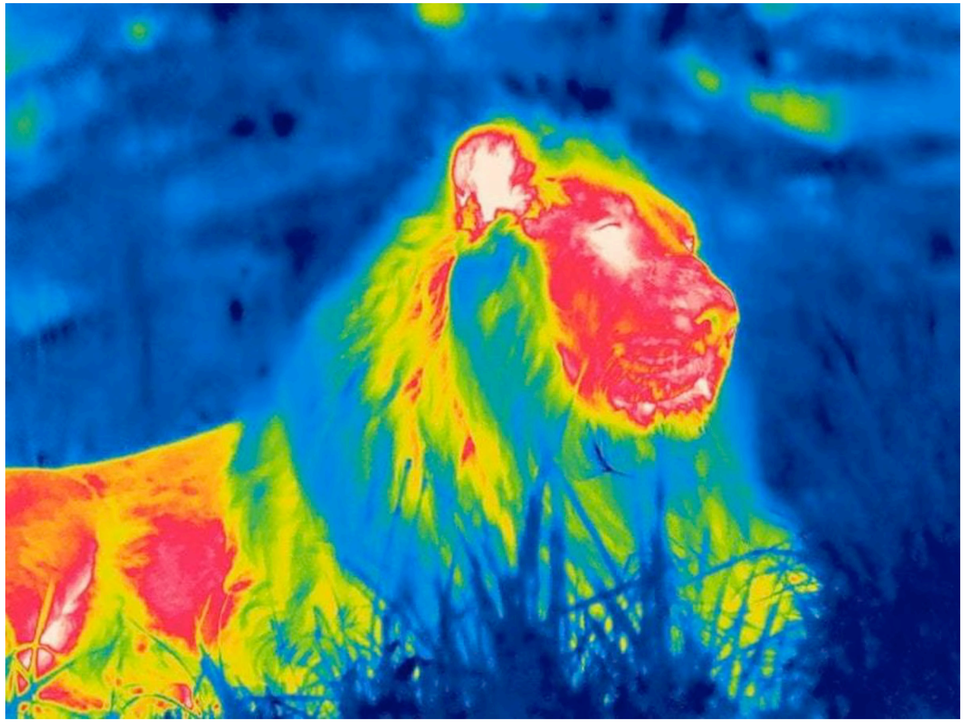
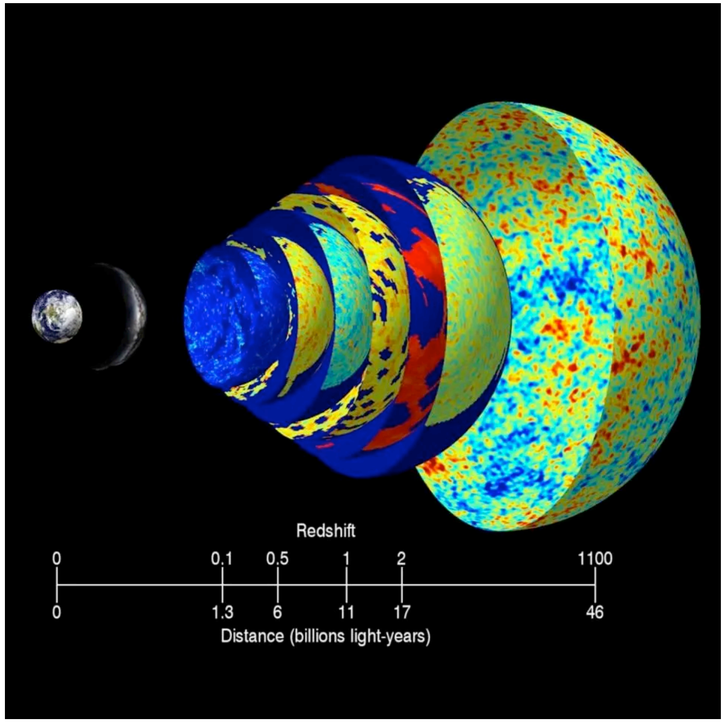
Electromagnetic radiations



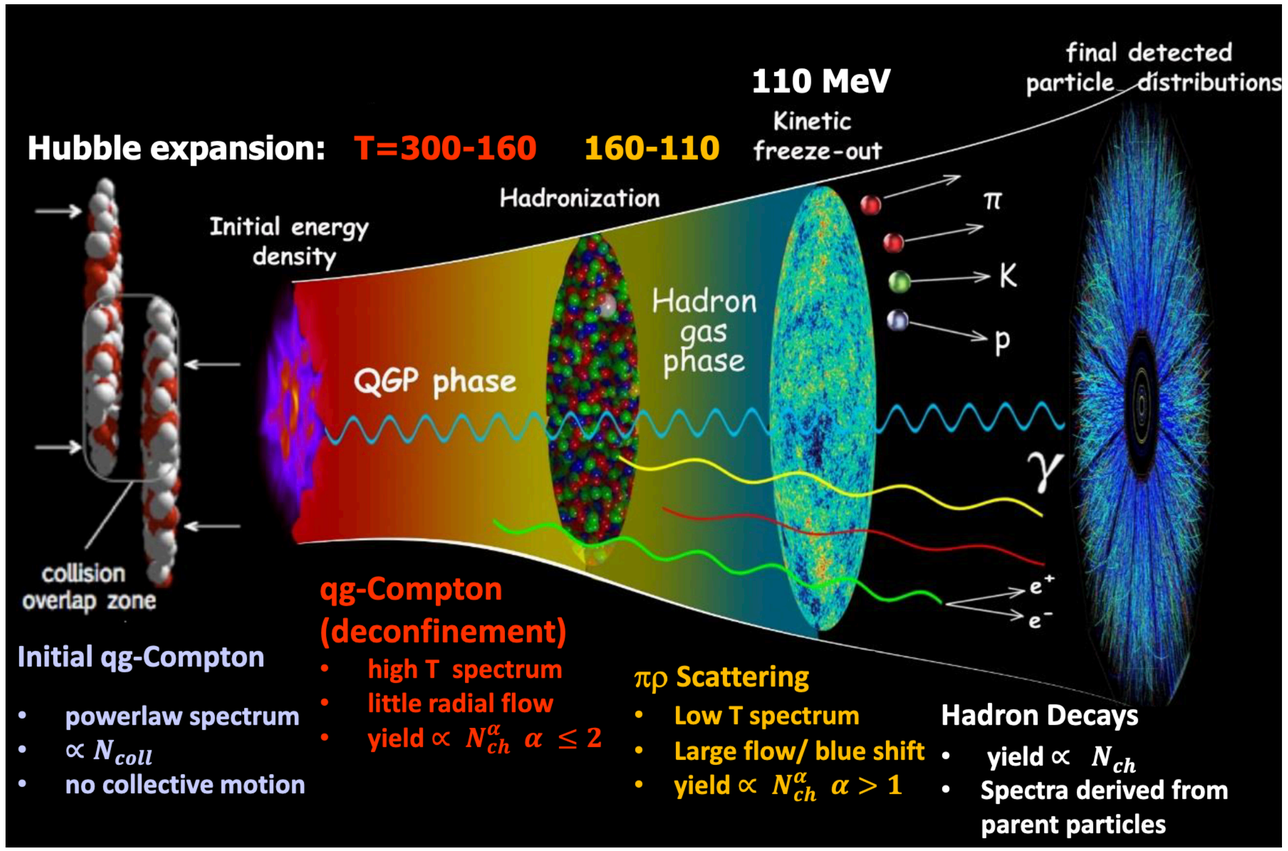




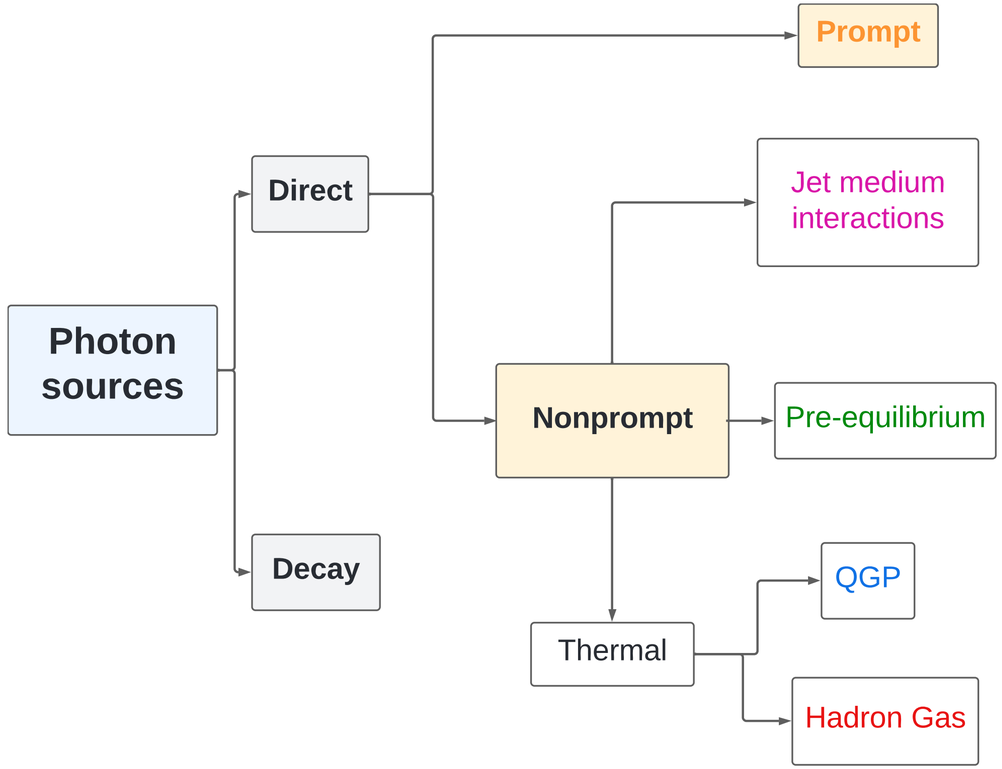
All object emit electromagnetic radiations, characterized by their temperature

Electromagnetic radiations in A+A collisions

Photons are “color blind” probe of Quark Gluon Plasma



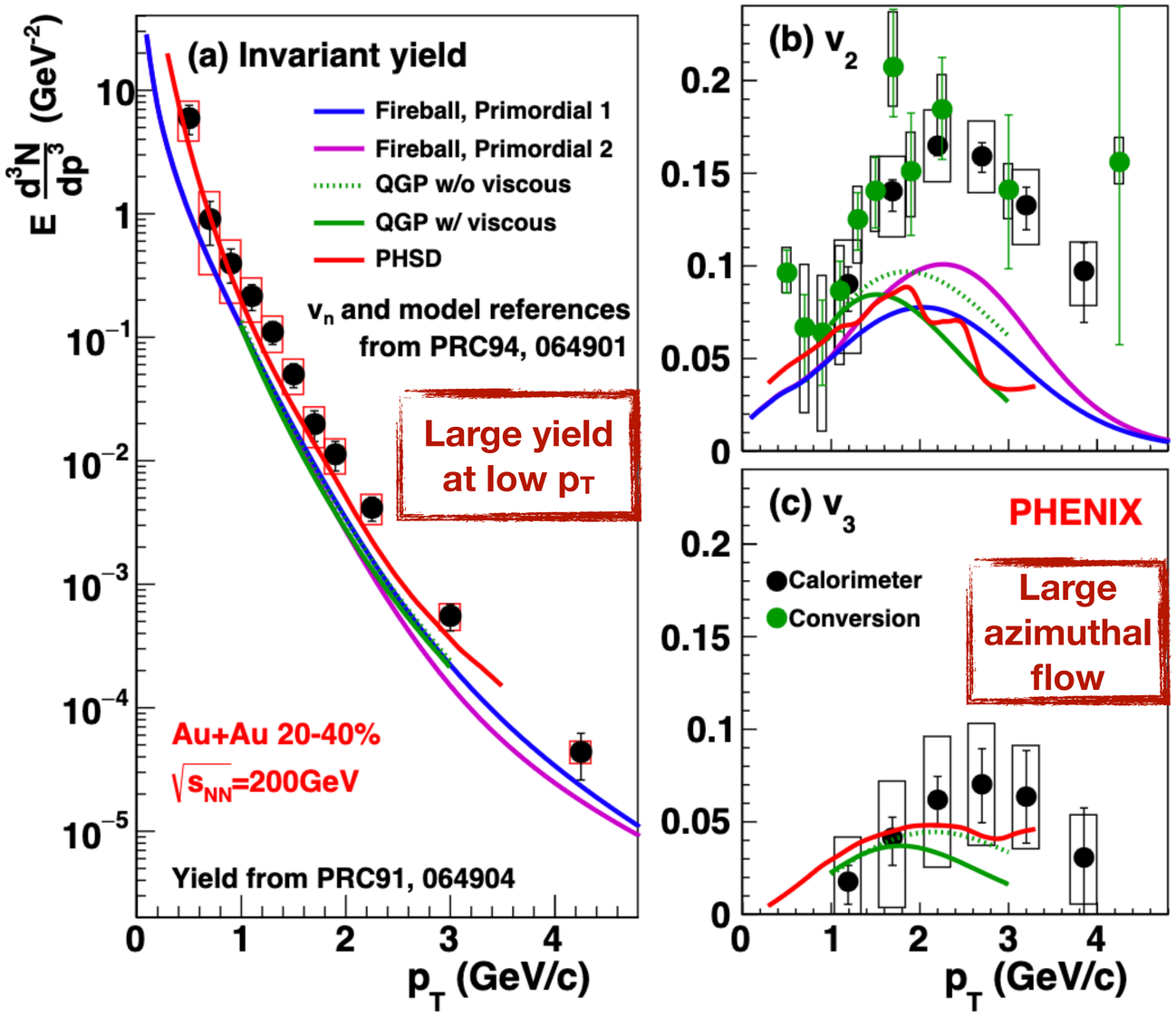
Credit: A. Drees



Measurement of yield constrains initial conditions, sources, emission rates and space-time evolution

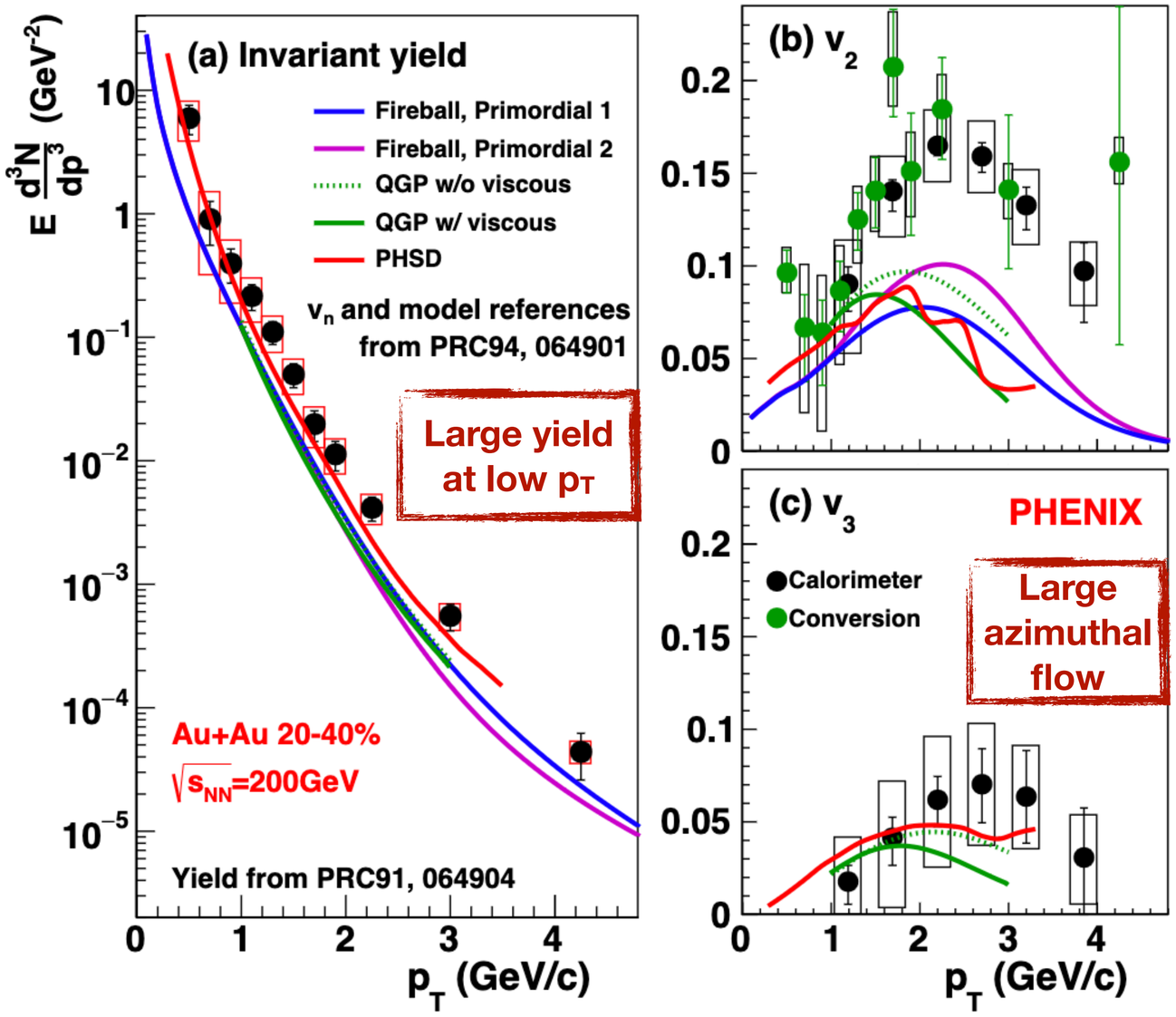
Direct photon puzzle

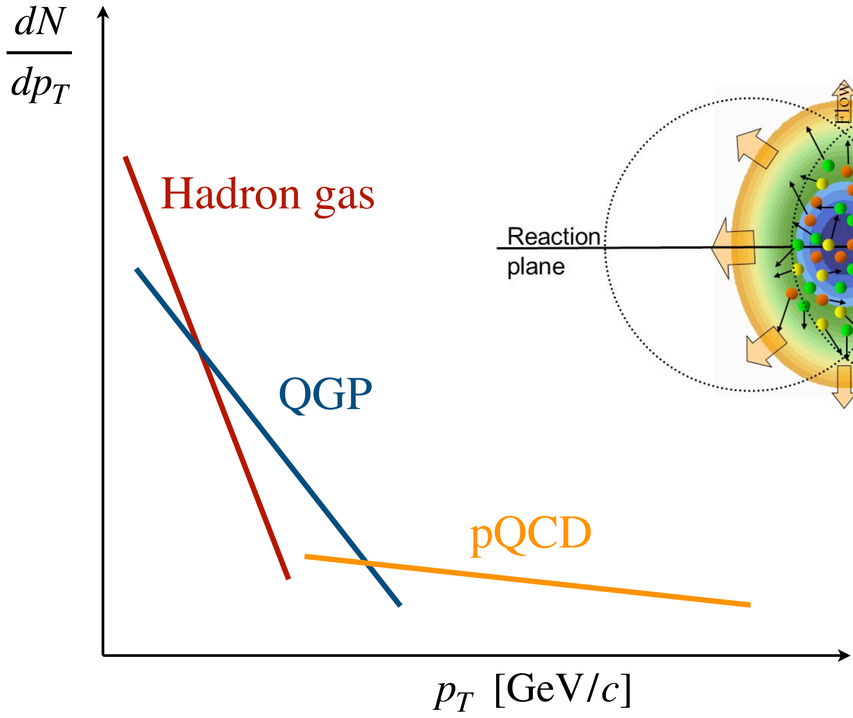
Phys. Rev. C 94 (2016) 064901



Direct photon puzzle

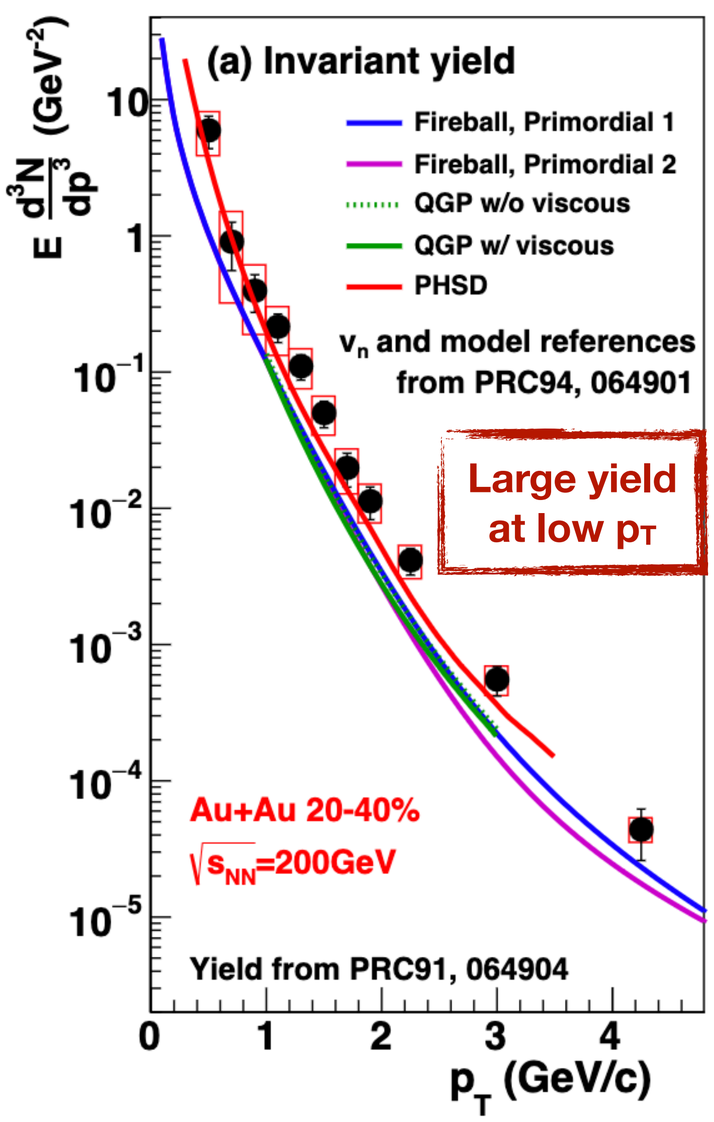
Phys. Rev. C 94 (2016) 064901

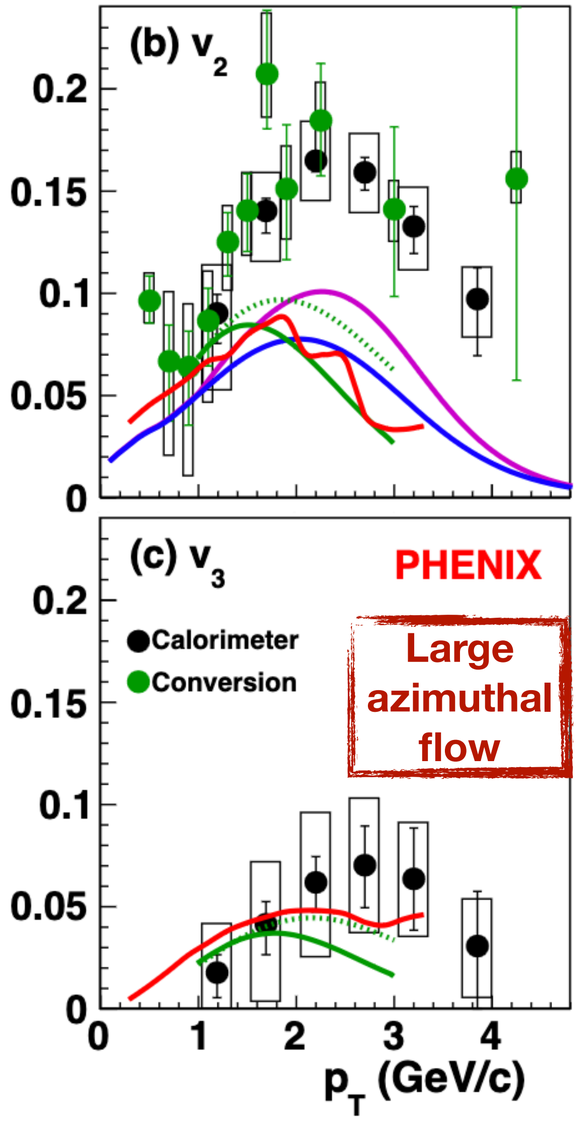


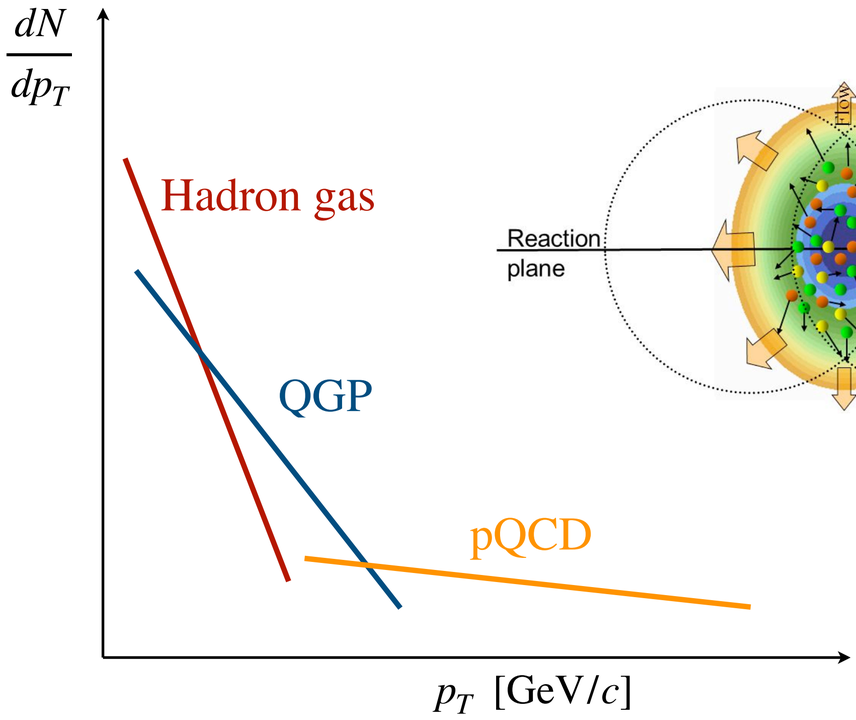


Direct photon puzzle

Phys. Rev. C 94 (2016) 064901







Qualitative agreement with thermal source

Quantitative tension with model predictions

Measurements at RHIC

$\sqrt{s_{NN}}$ [GeV] →	200	200	200	200	200	200	39	62.4	200
Calorimeter	**2003** 2015	2015	**2003** **2016**	2014		2012			**2004** 2014
Virtual $\gamma^\star \longrightarrow e^+ + e^-$	**2005/6**		**2008**		**2005**				**2004 & 2011** **2010 & 2011**
Conversion $\gamma \longrightarrow e^+ + e^-$	2015	2015	2016	2014		2012	**2010**	**2010**	**2007/10** **2014**

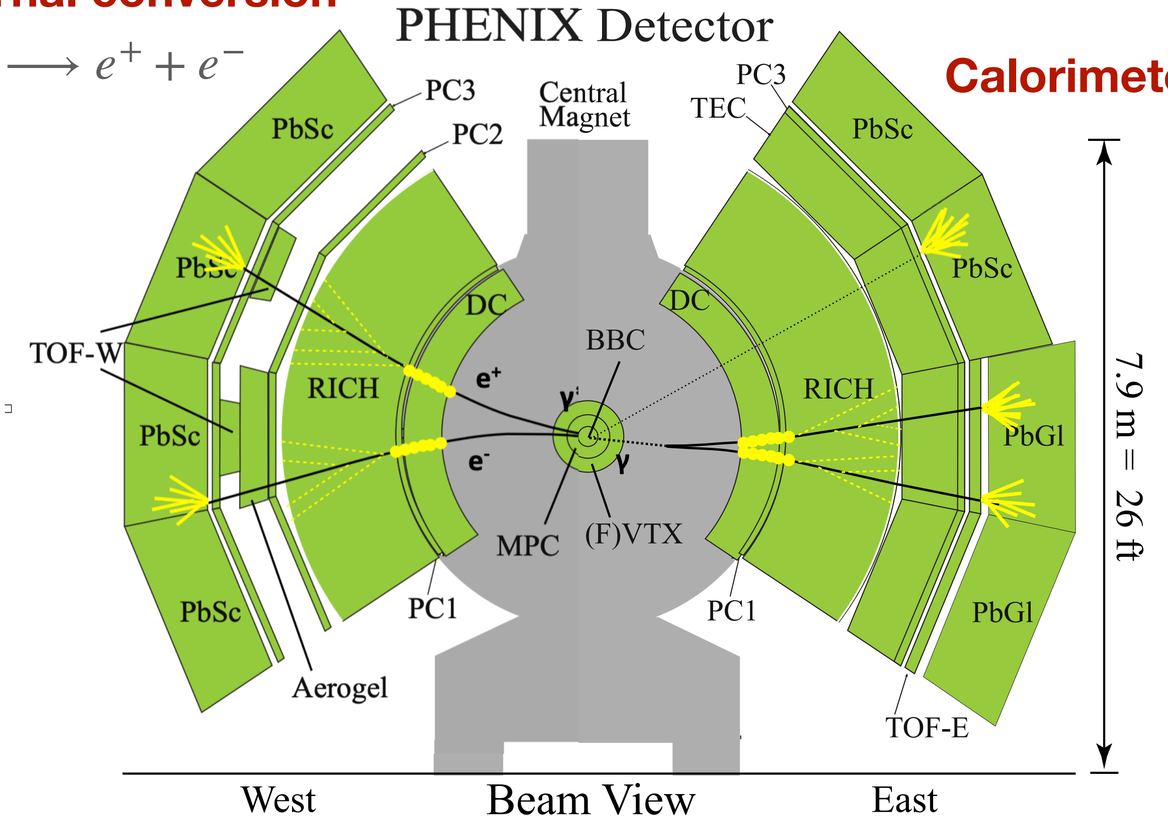
PHENIX : **Published** **Submitted** Ongoing

STAR : **Published**

Direct photons in Au+Au at 200 GeV [PHENIX]

Internal conversion

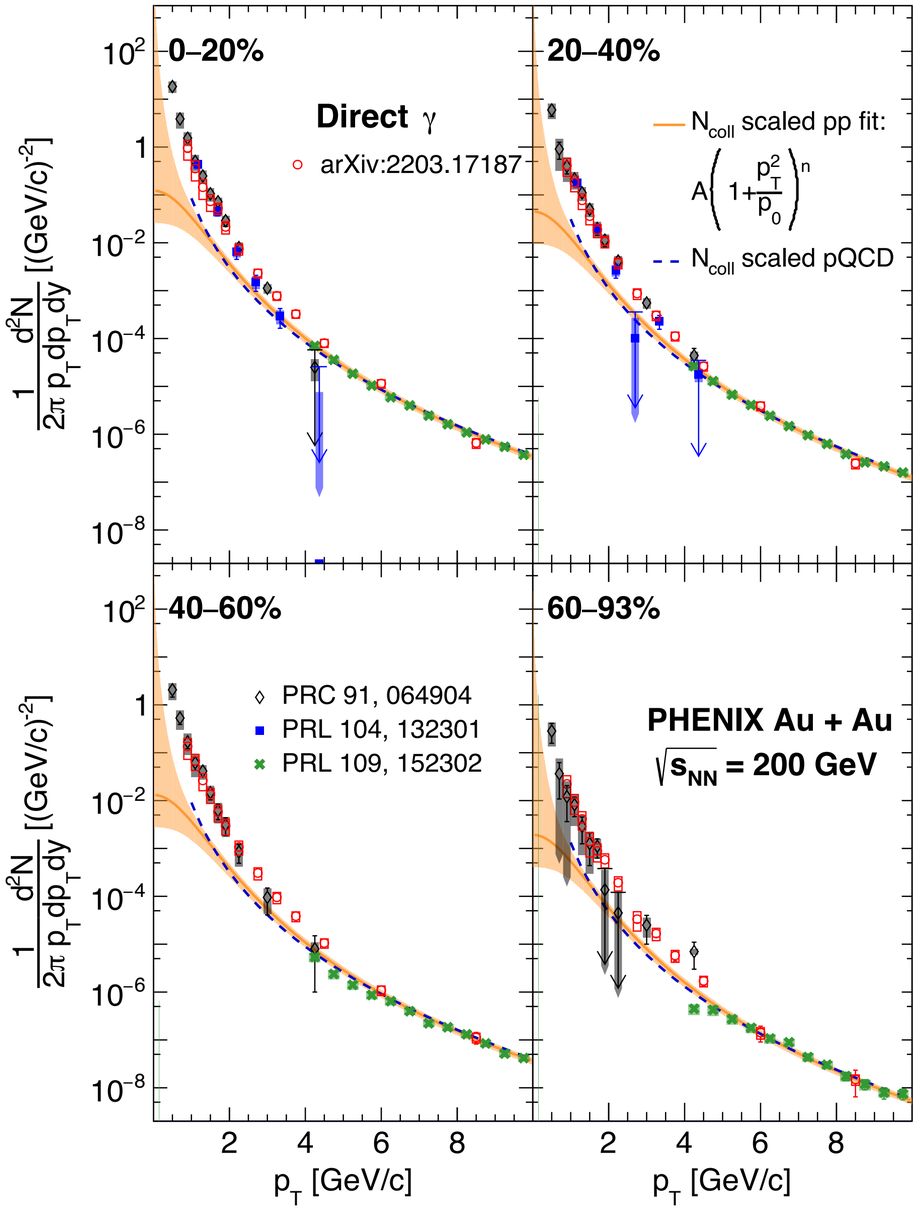
$\gamma^{\star} \longrightarrow e^{+} + e^{-}$



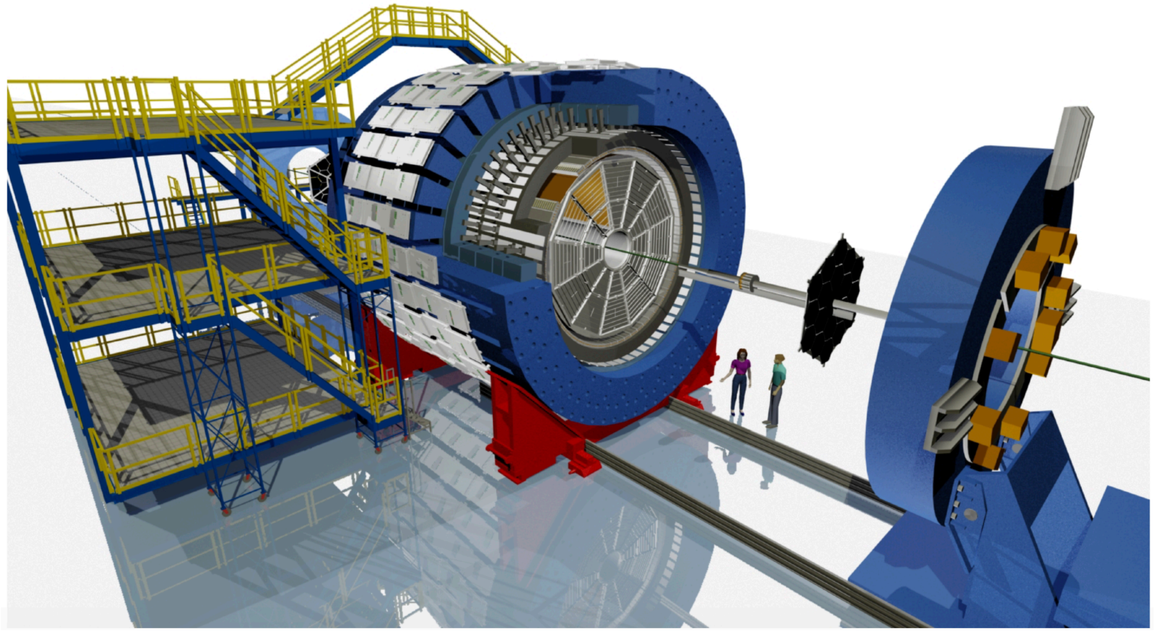
Calorimeter

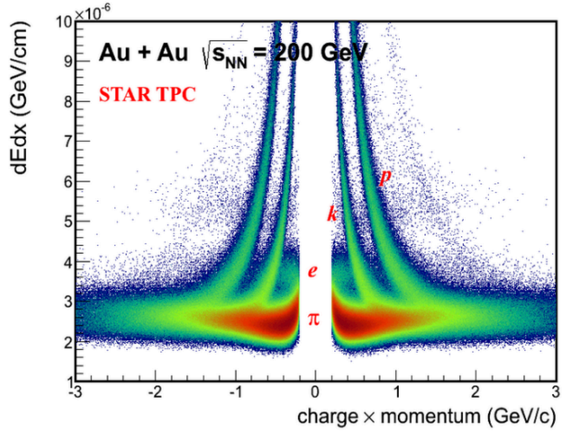
External conversion

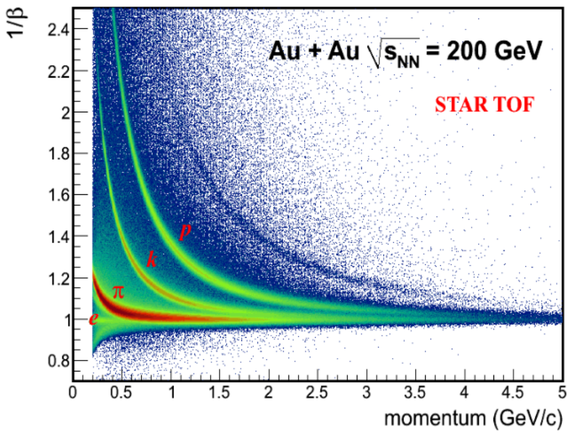
$\gamma \longrightarrow e^{+} + e^{-}$

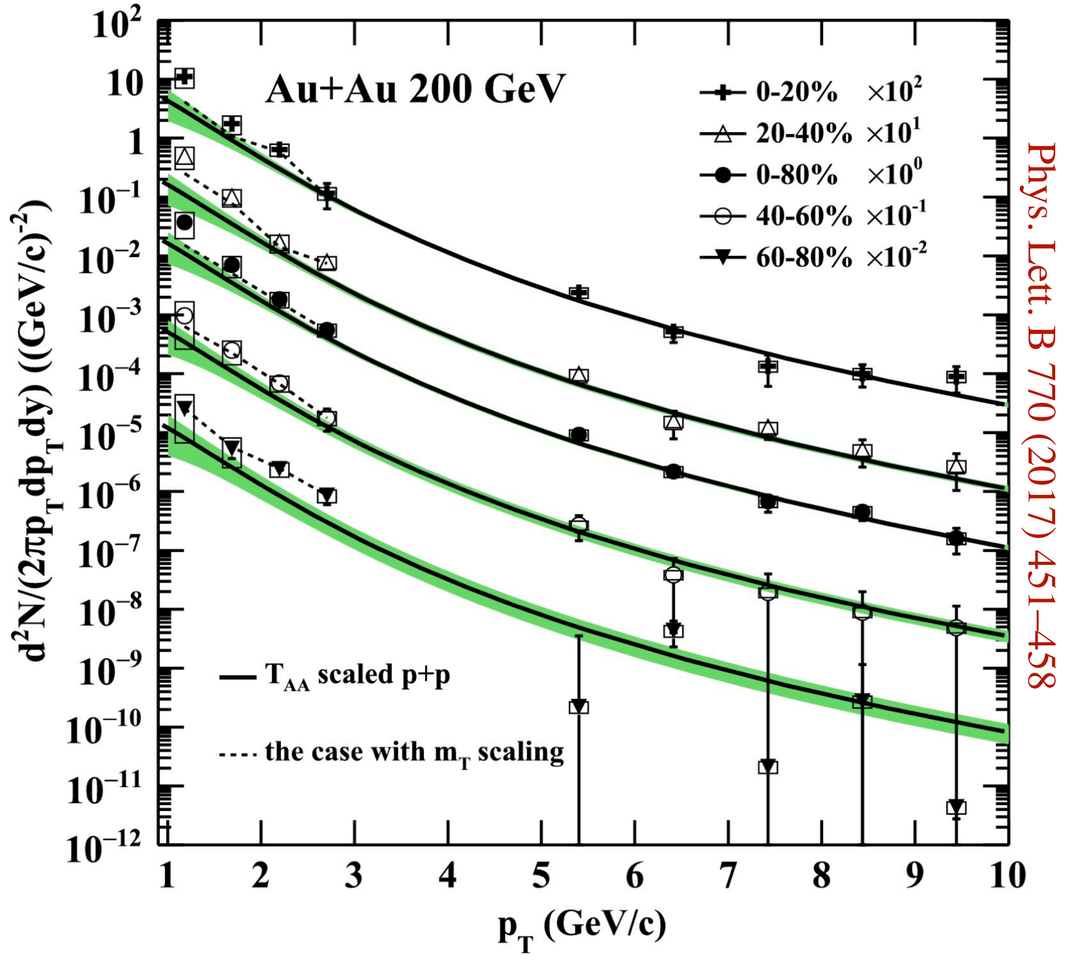


Direct photons in Au+Au at 200 GeV [STAR]



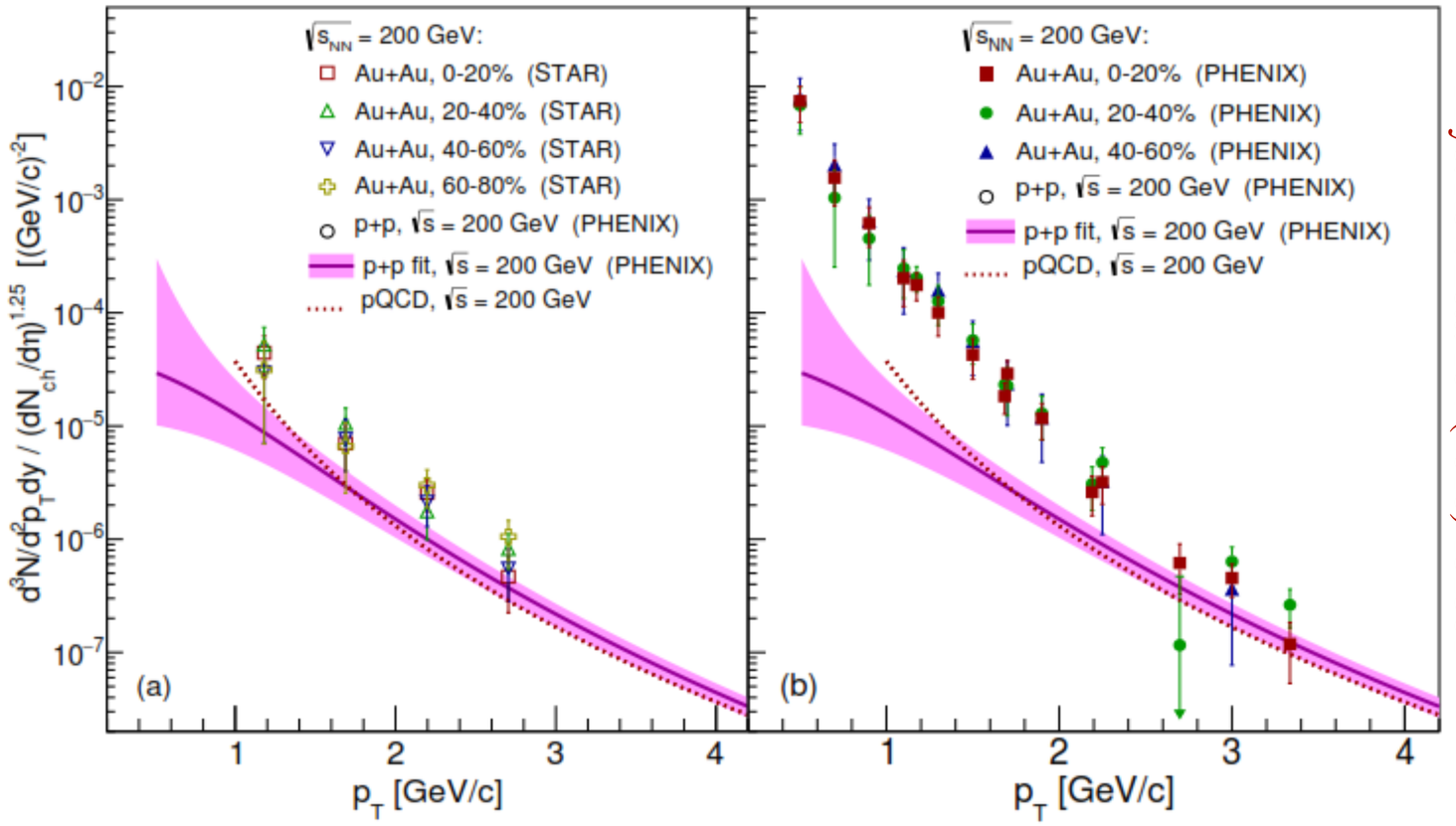






Phys. Lett. B 770 (2017) 451–458

Comparing PHENIX and STAR

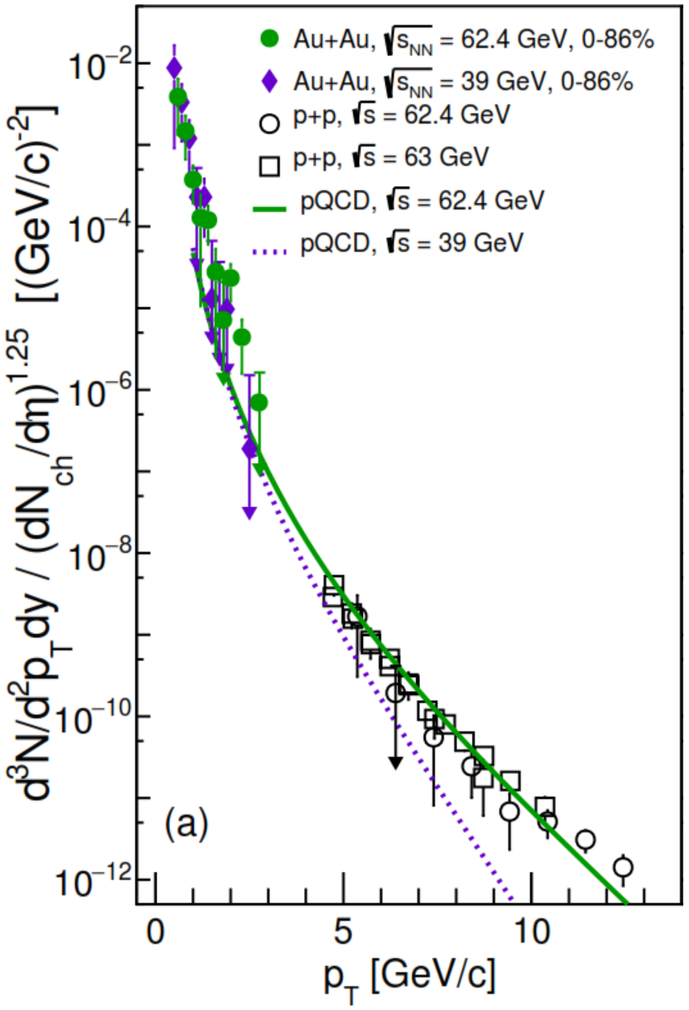


Phys. Lett. B 770 (2017) 451–458
Phys. Rev. C 93 (2016) 1, 014904
Phys. Rev. Lett. 104 (2010) 132301

- PHENIX data is consistent among several measurements using different techniques
- STAR data is significantly lower

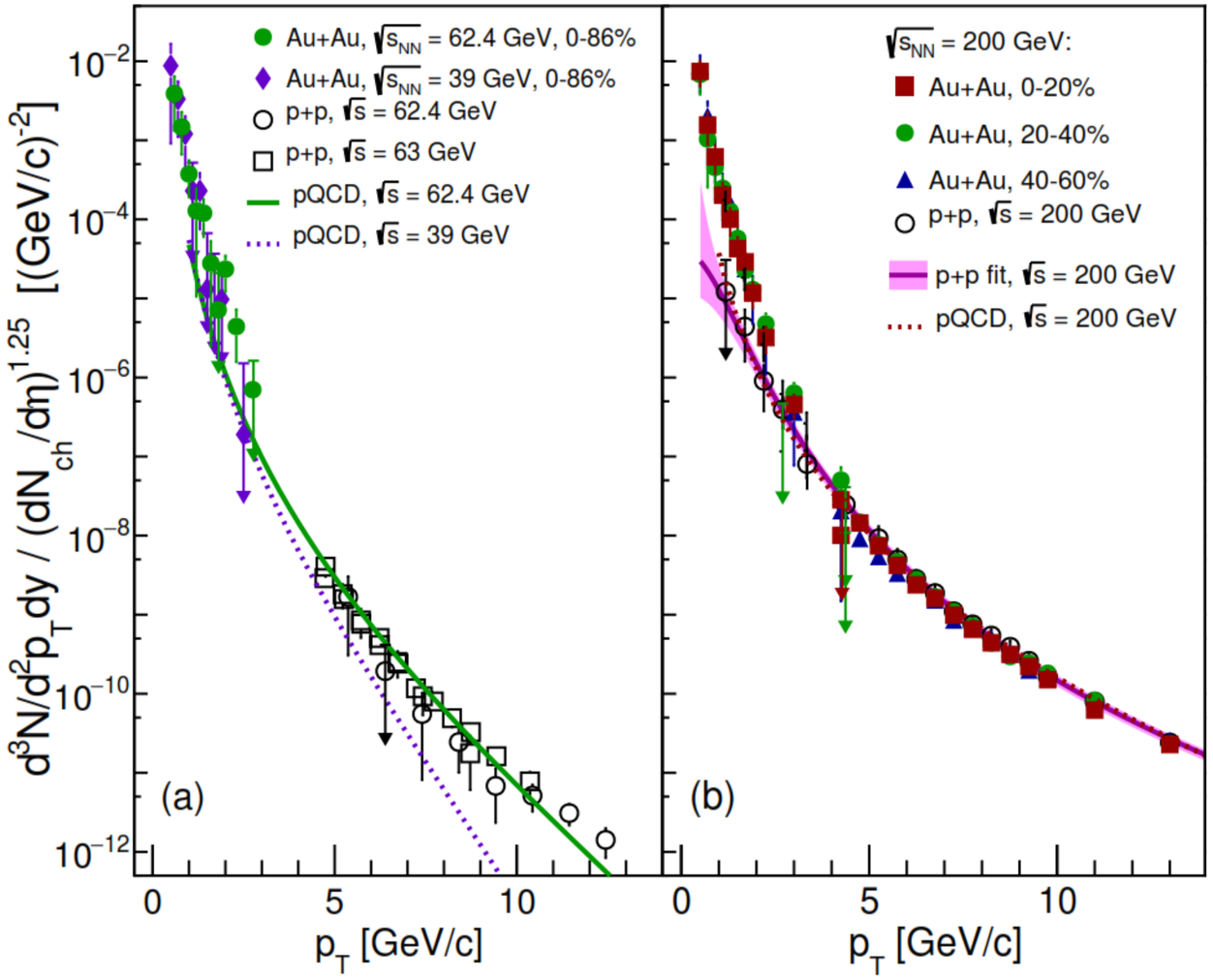
The discrepancy is not yet resolved

Universal behavior



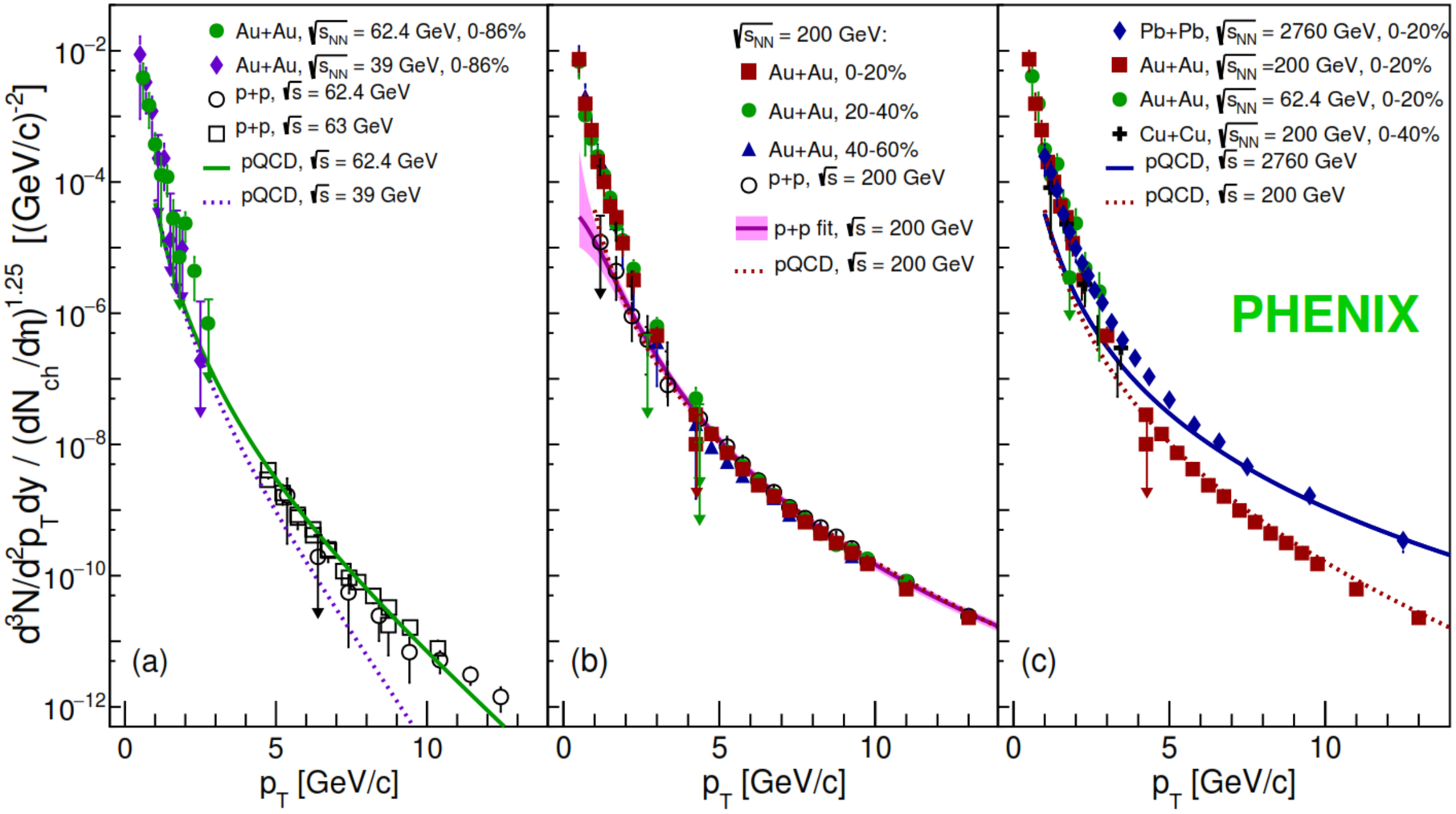
Similar direct photon yields when scaled with $\left(\frac{dN_{\rm ch}}{d\eta}\right)^{1.25}$ **independent of energy**

Universal behavior



Similar direct photon yields when scaled with $\left(\frac{dN_{\rm ch}}{d\eta}\right)^{1.25}$ **independent of energy, centrality**

Universal behavior



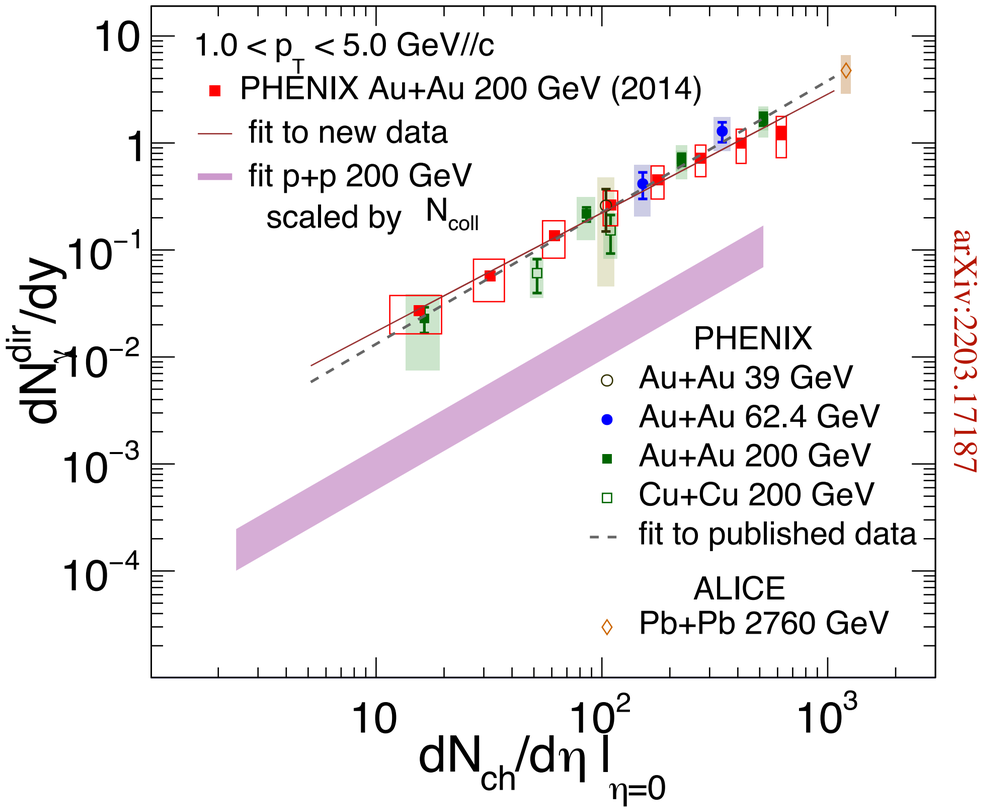
Phys. Rev. Lett. 123 (2019) 2, 022301

Similar direct photon yields when scaled with $\left(\frac{dN_{\rm ch}}{d\eta}\right)^{1.25}$ **independent of energy, centrality and system size**

Scaling of yields

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

Universal scaling behavior in all A+A systems



arXiv:2203.17187

Scaling of yields

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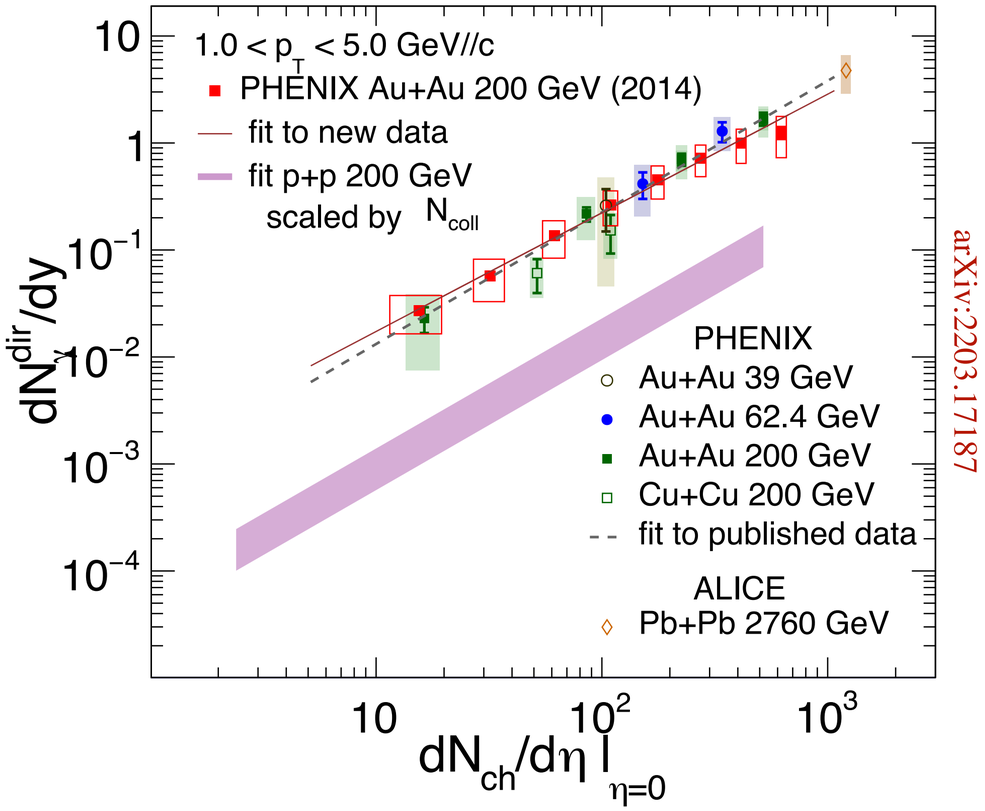
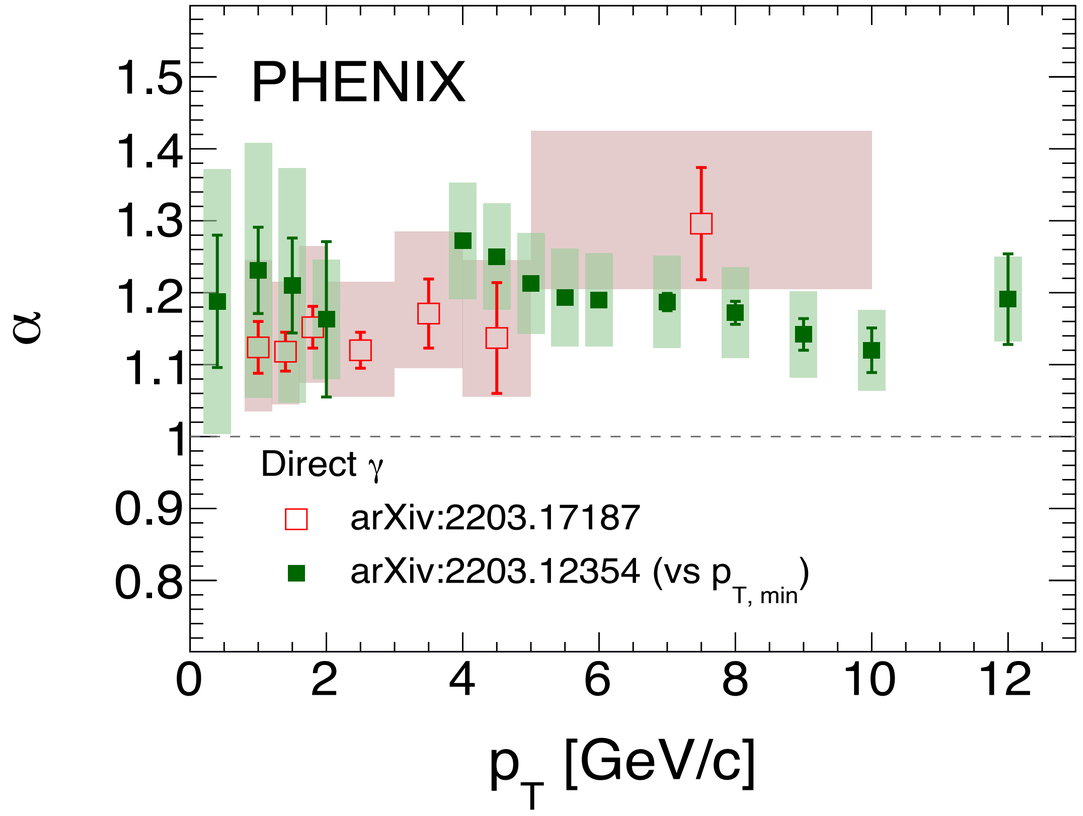
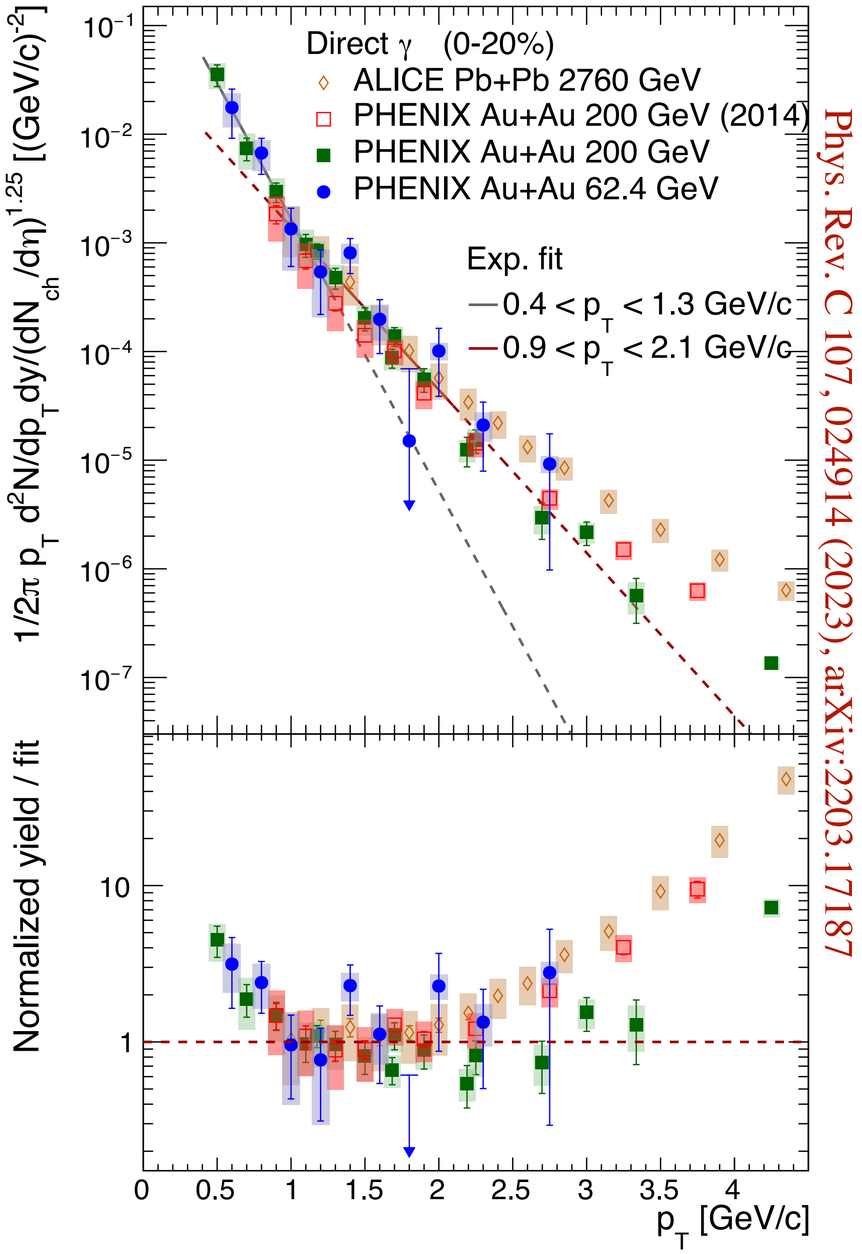




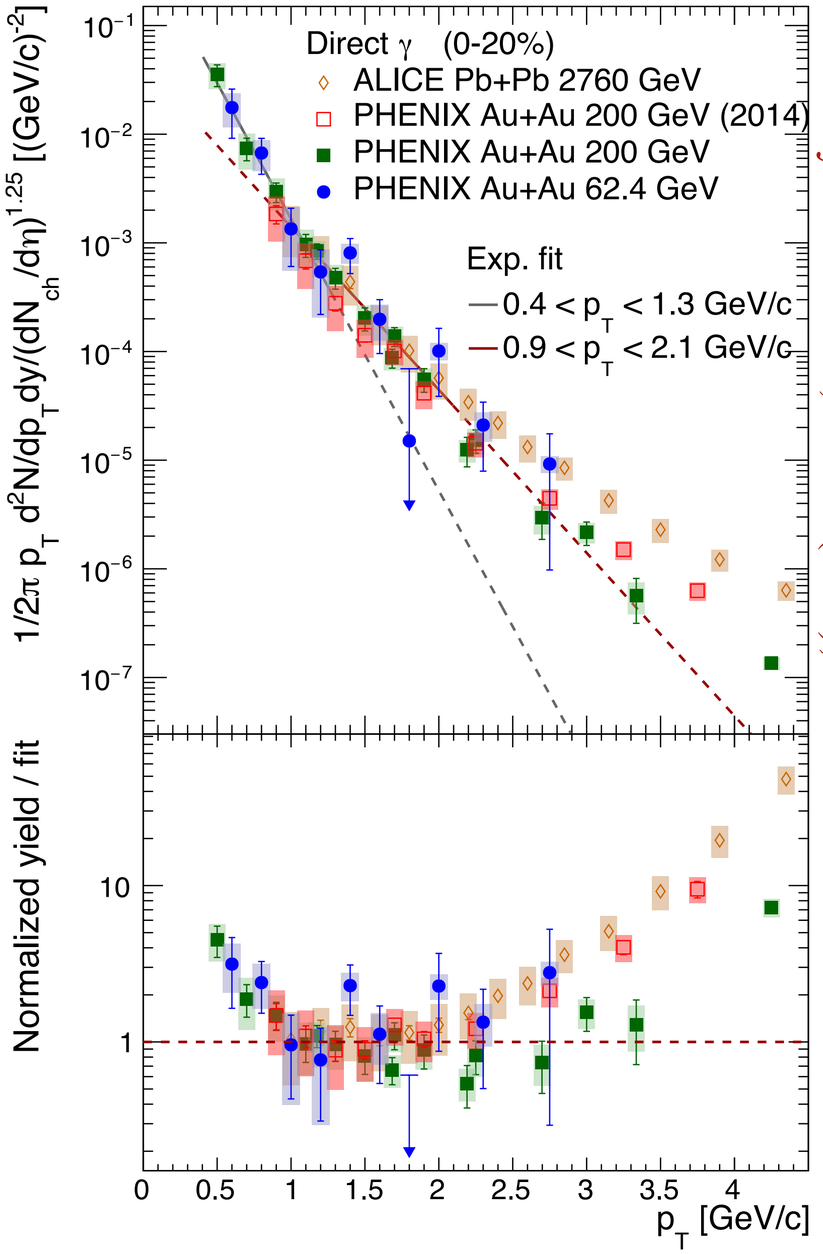
$\alpha > 1$ and independent of p_T

Comparing local inverse slopes



Phys. Rev. C 107, 024914 (2023), arXiv:2203.17187

Comparing local inverse slopes



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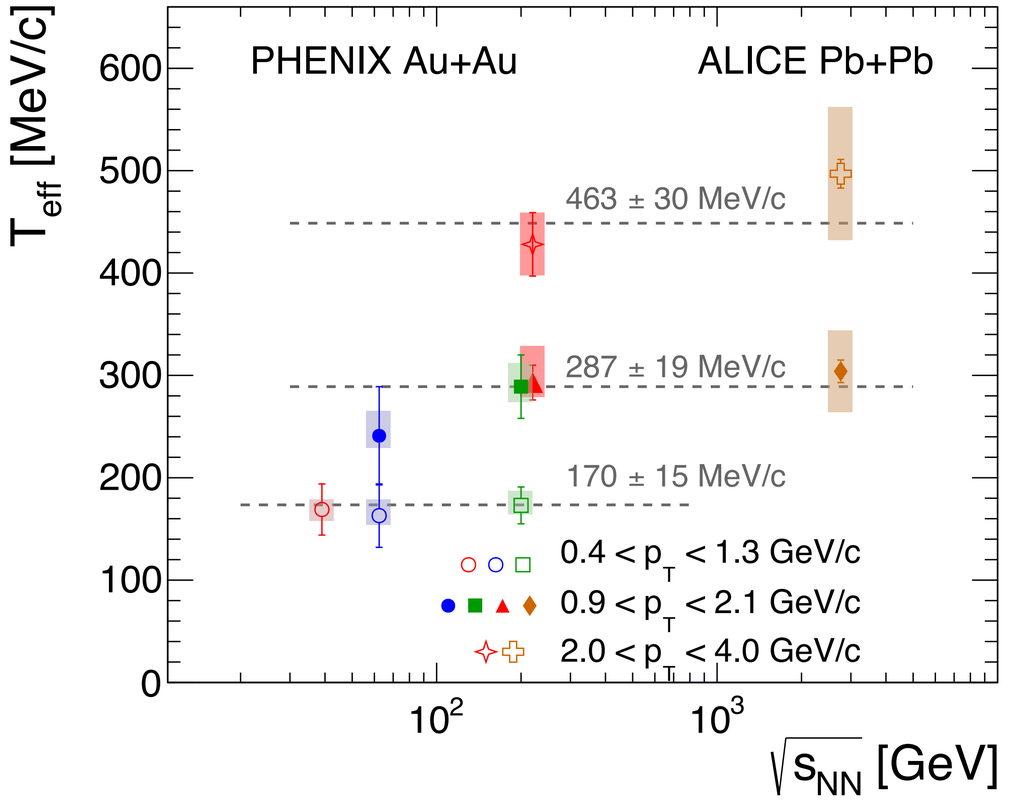

Phys. Rev. C 107, 024914 (2023)
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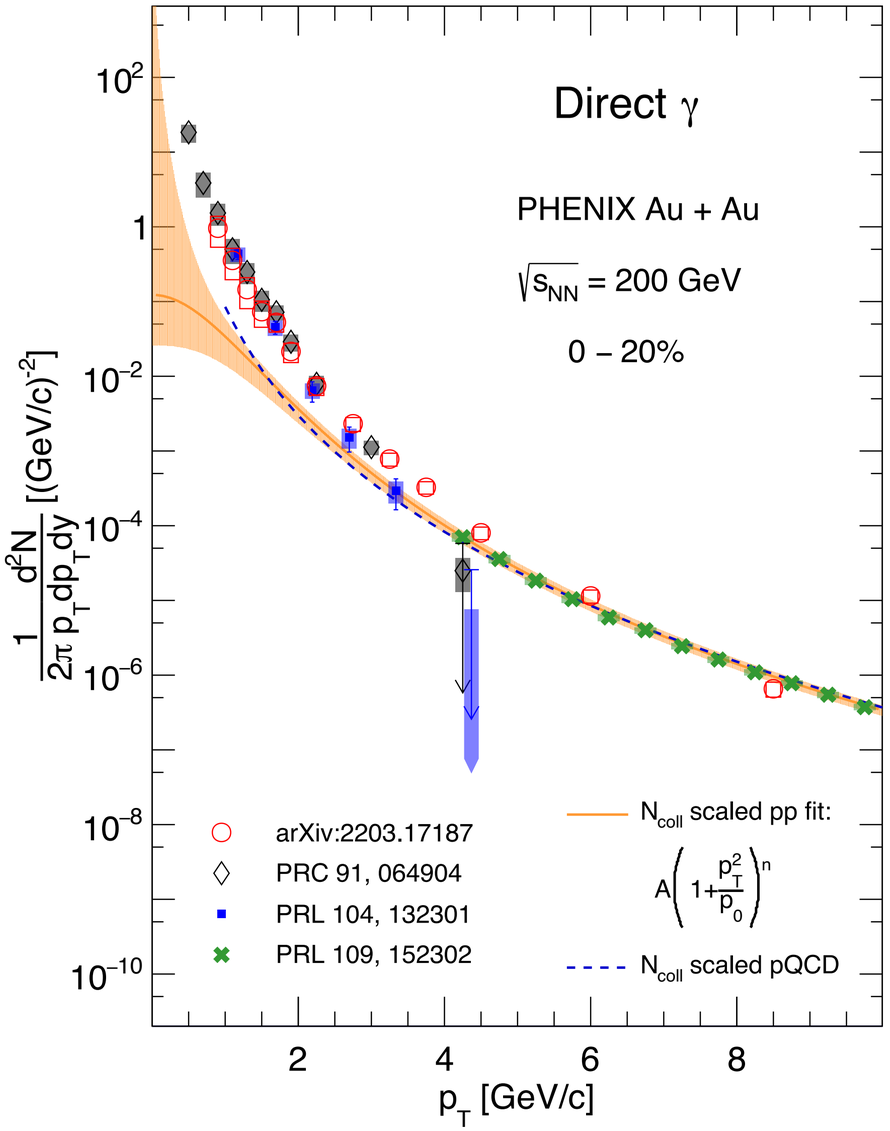
Similar spectra around 2 GeV/c — common source of photon production independent of $\sqrt{s_{NN}}$

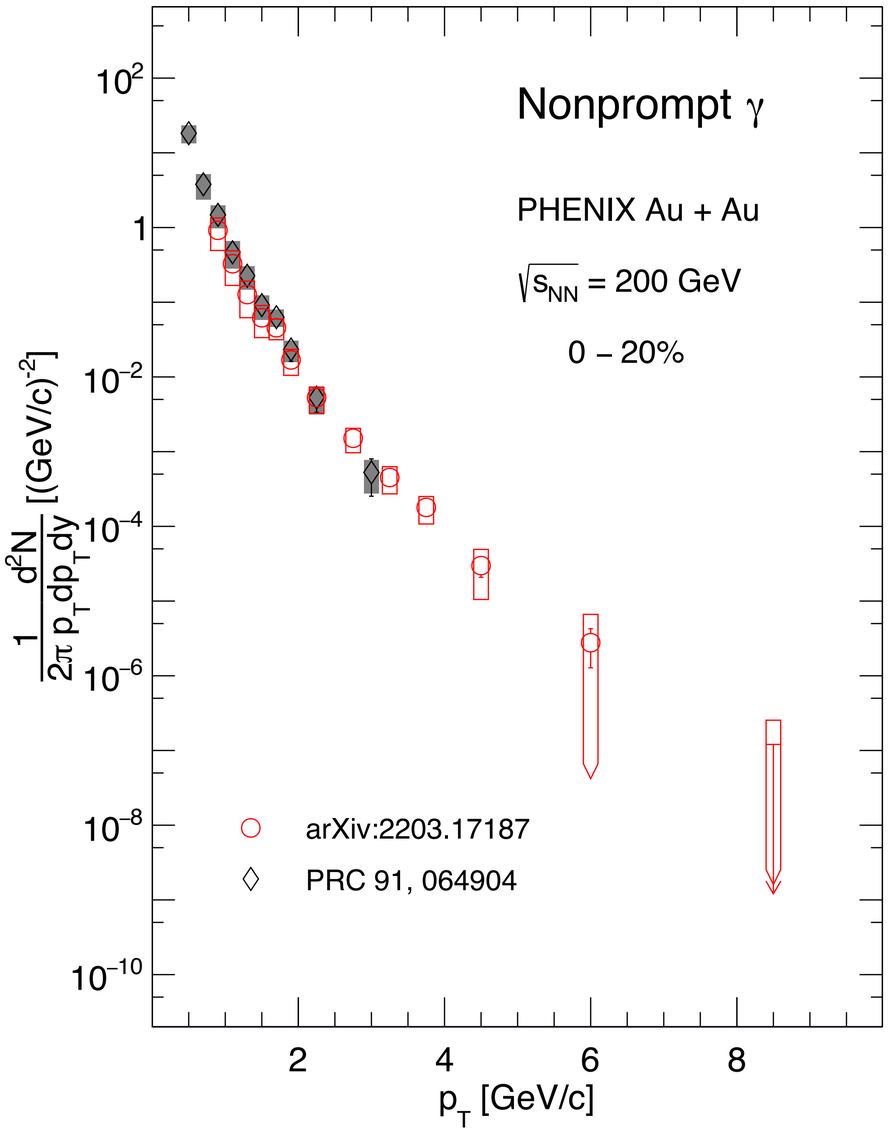
Non-prompt direct photons



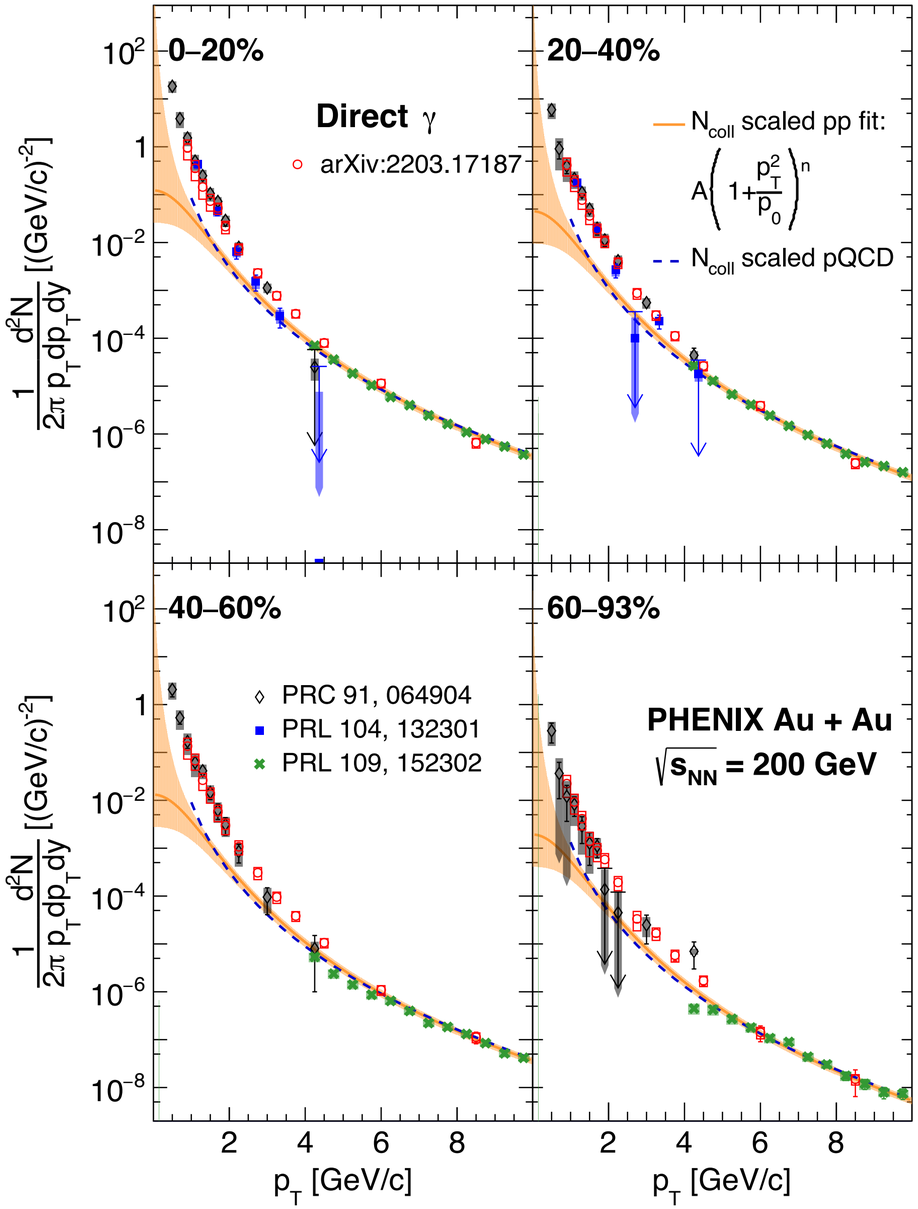
Direct photon

— N_{coll} **scaled p+p fit**

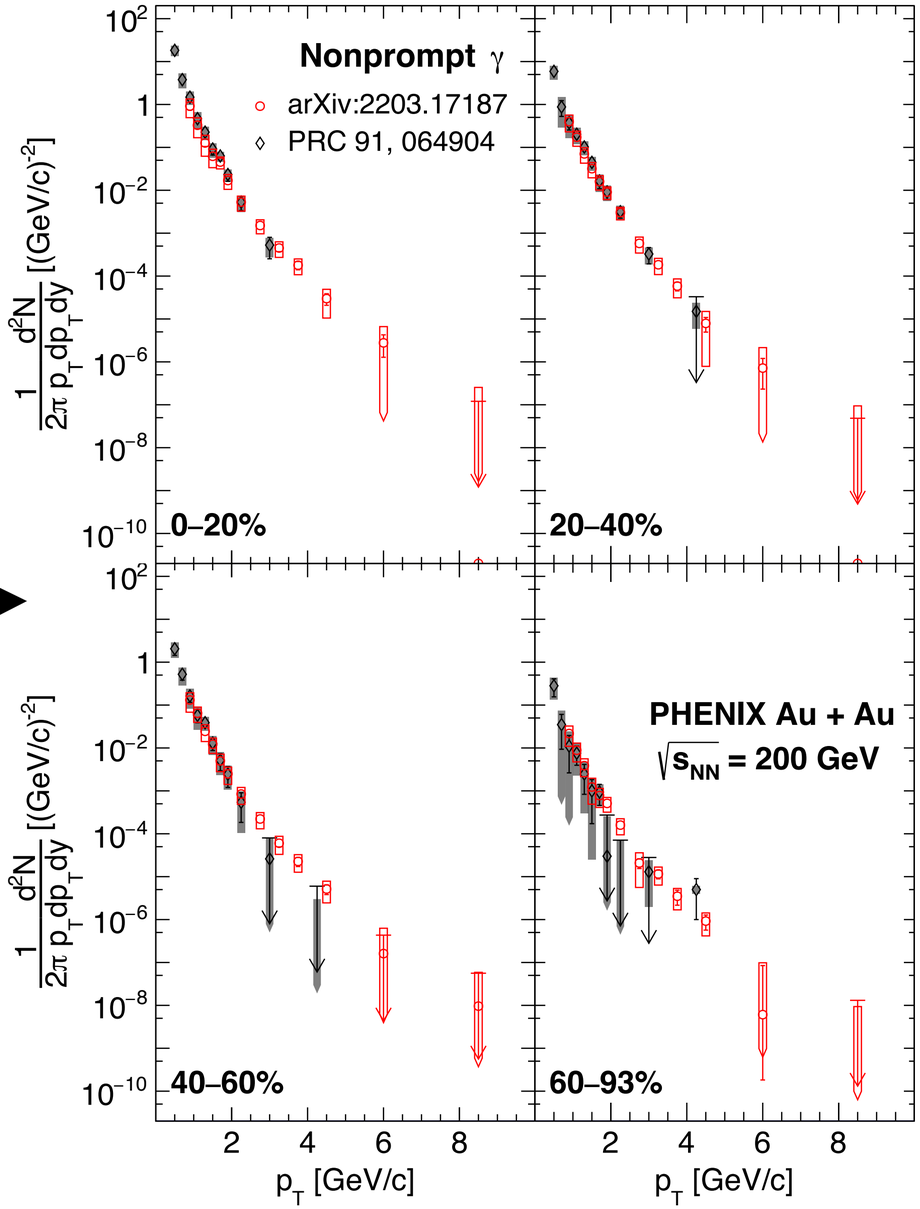
Non-prompt direct photon



Non-prompt direct photons



— N_{coll} **scaled p+p fit**



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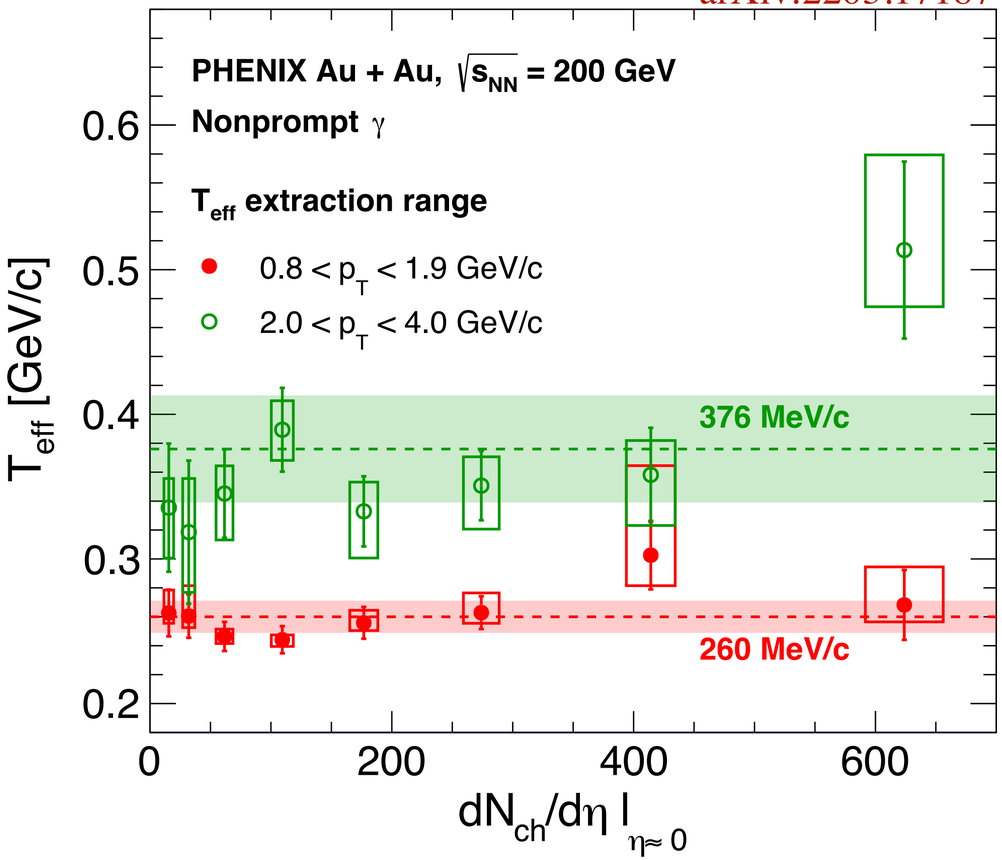
arXiv:2203.17187



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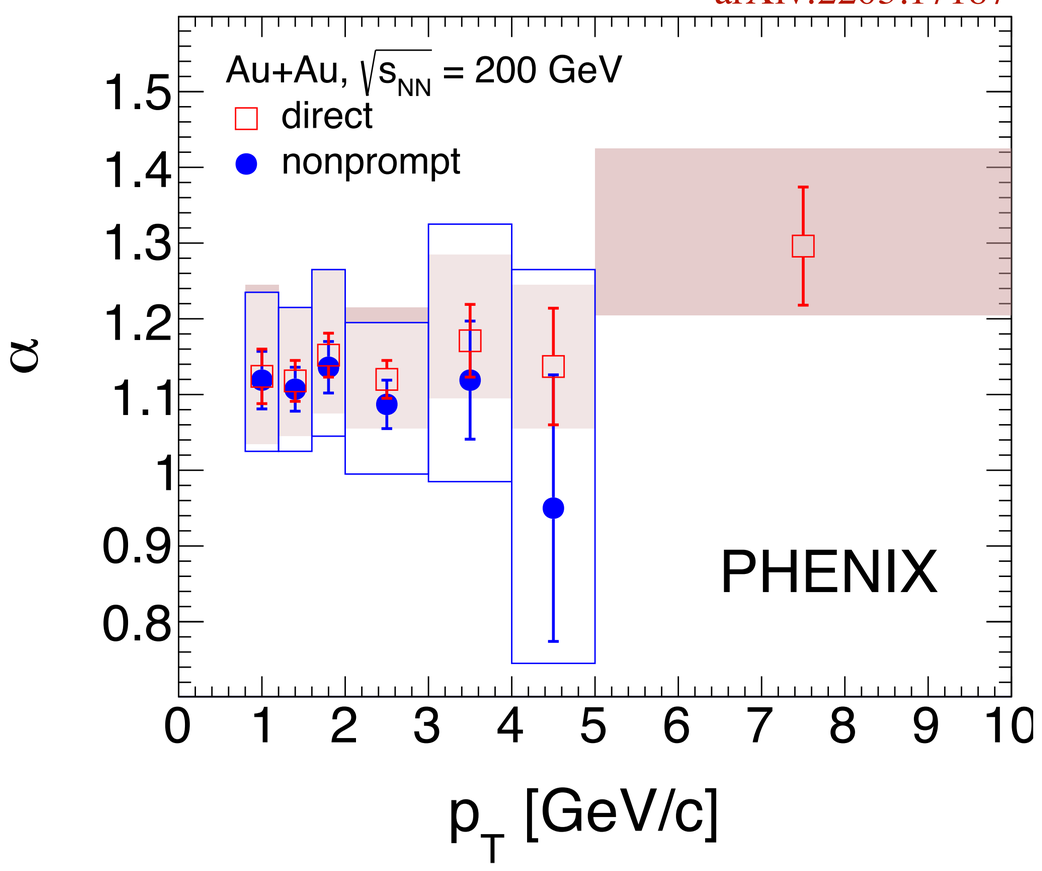
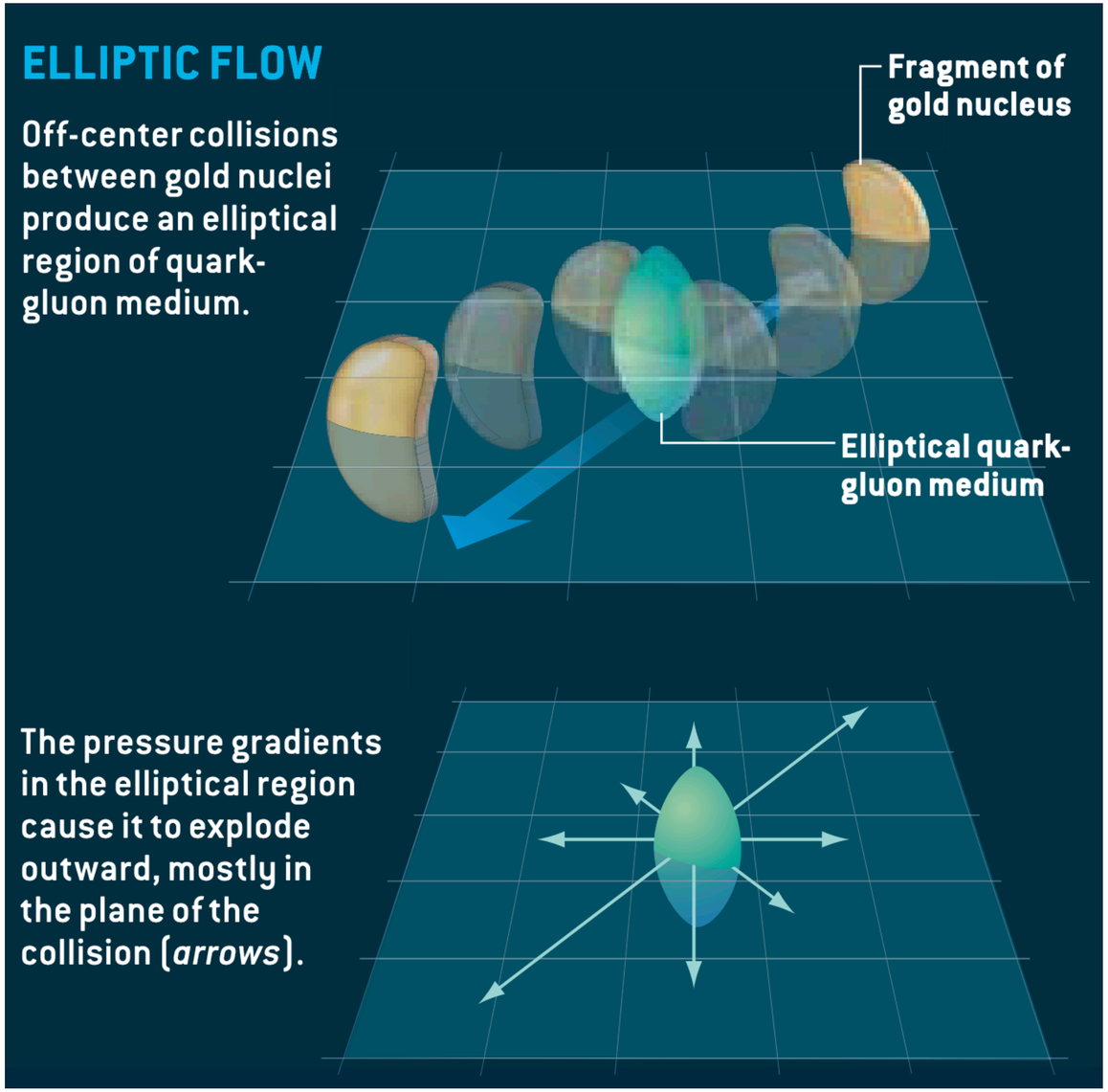


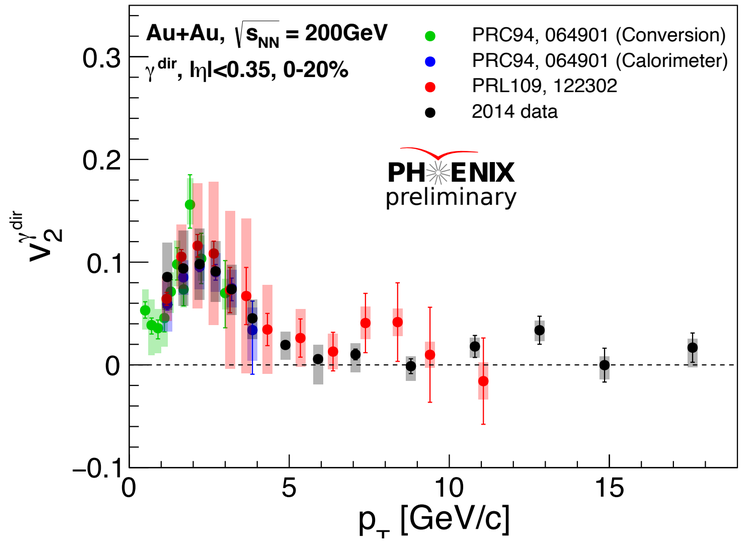
Increasing inverse slope with p_T to above 350 MeV/c suggests contributions from sources beyond those from Hadron Gas

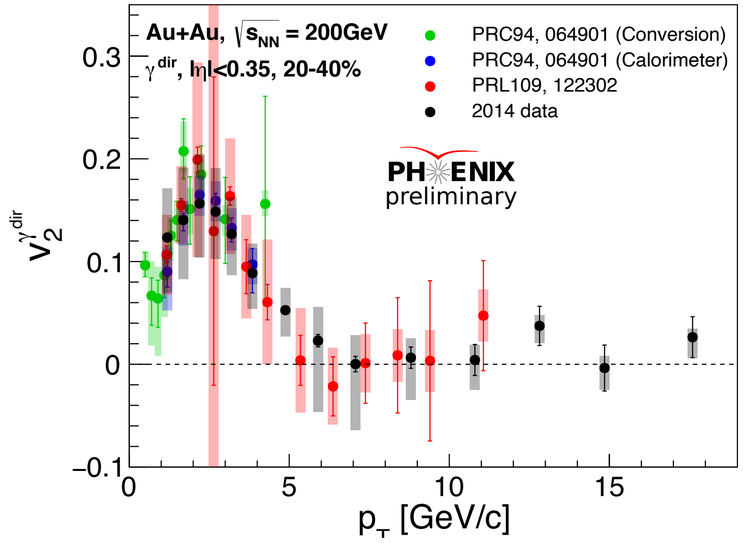
α independent of p_T for direct and nonprompt photons

Azimuthal anisotropy

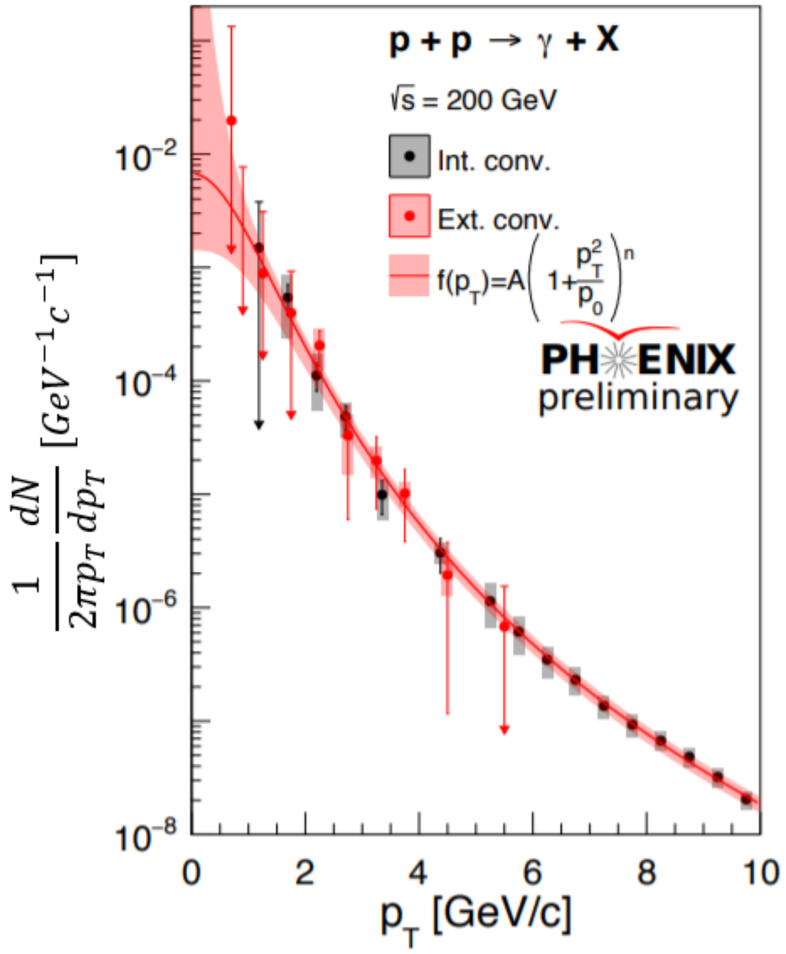


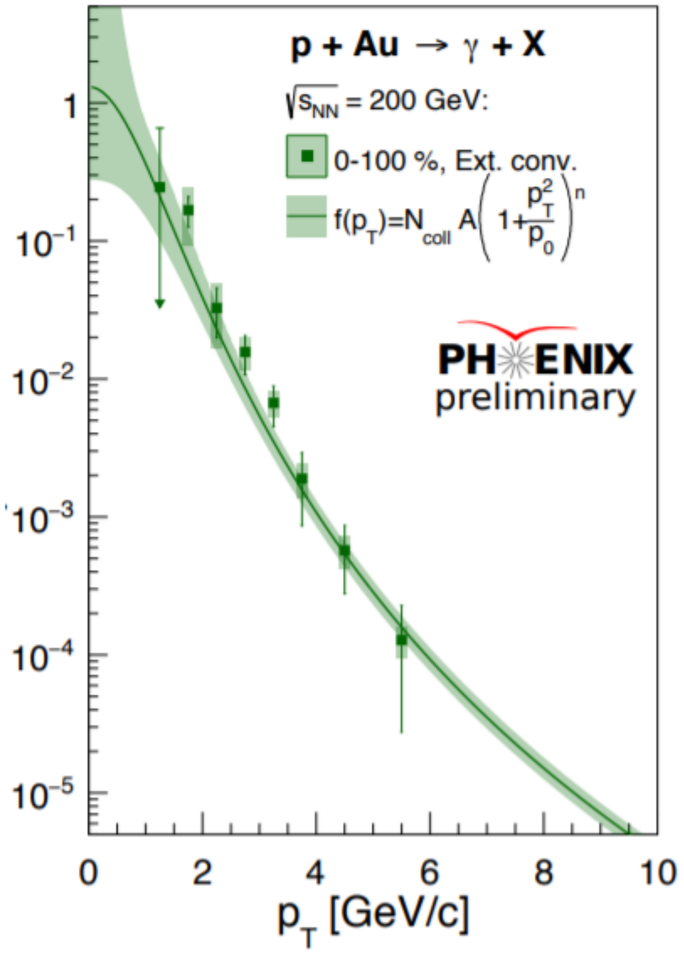
$$\frac{dN}{d\varphi} = N_0\,(1 + 2v_2\cos(2\varphi))$$

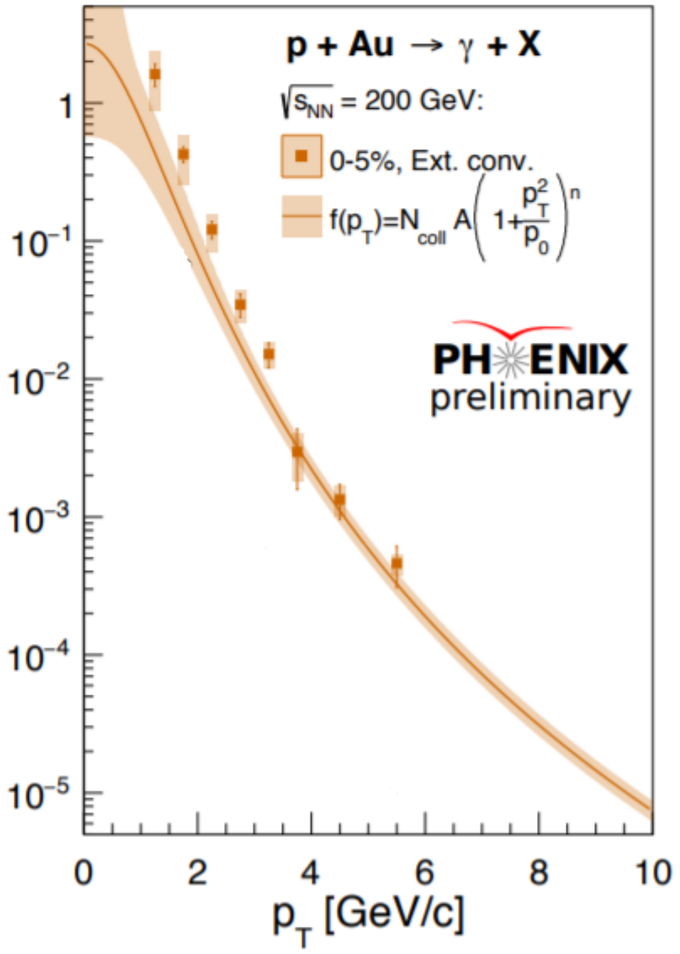




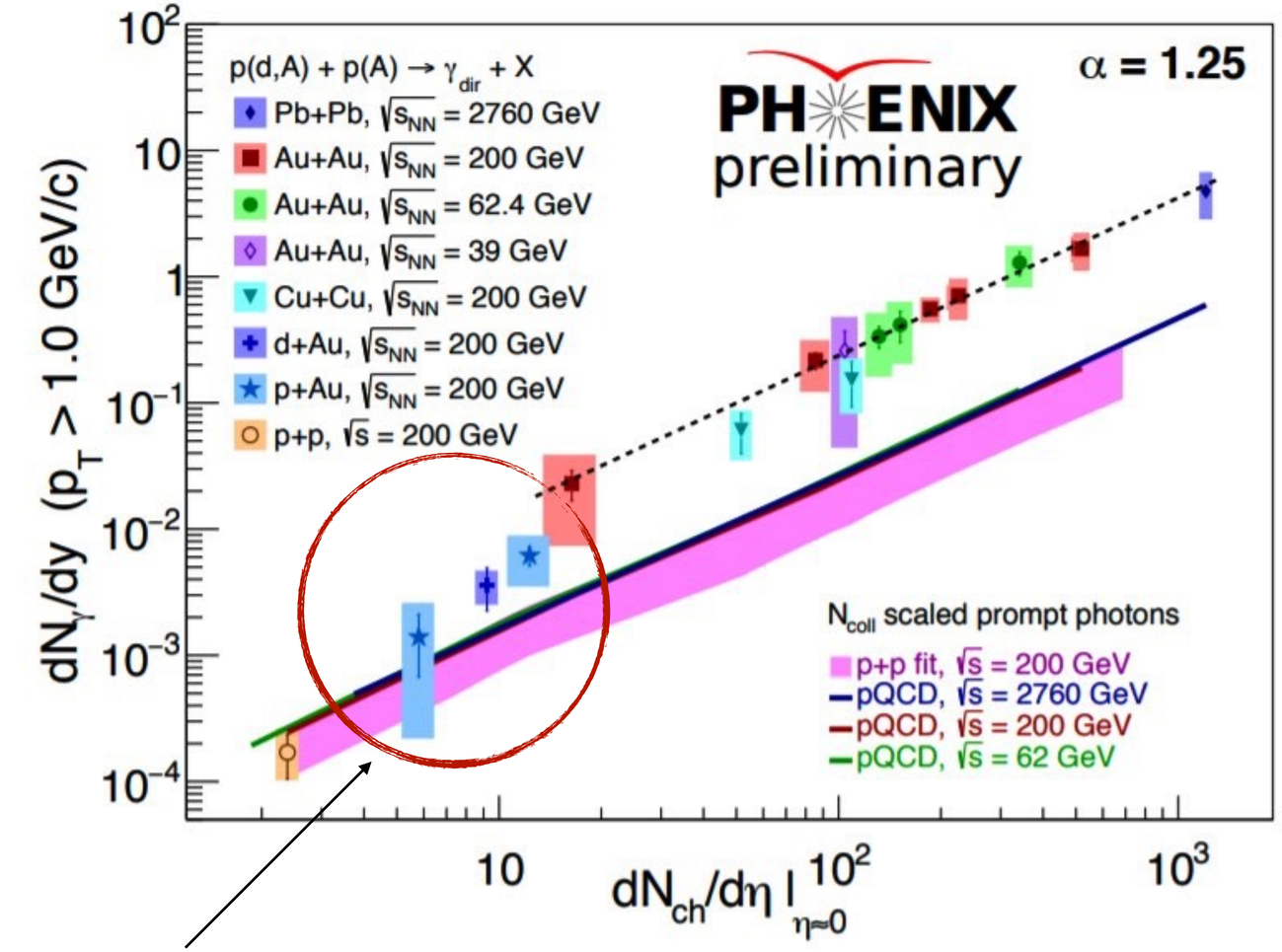
Direct photons in small systems





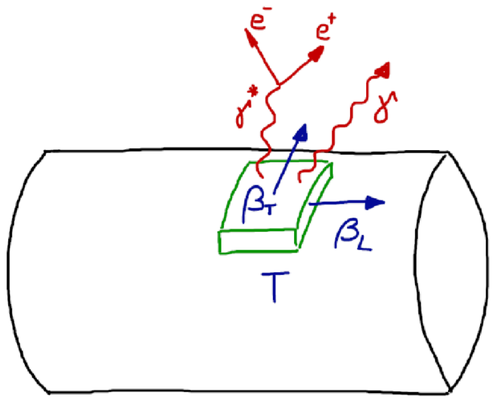


Bridging the gap



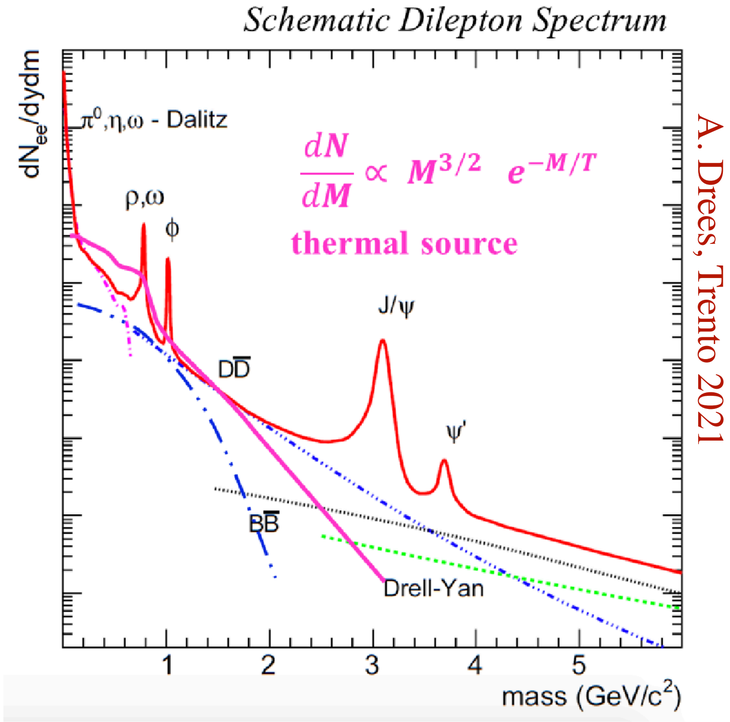
Onset of QGP (?)

Dileptons as direct radiations



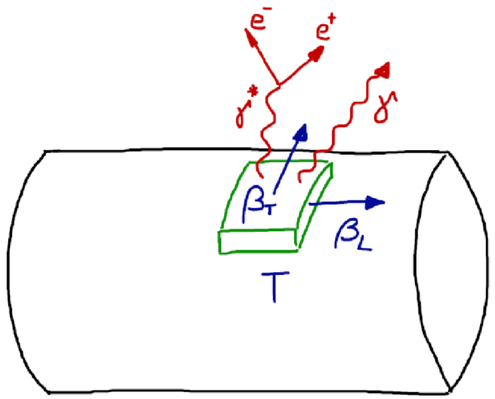
- Momentum — doppler shifted
- Mass — Lorentz invariant
- In $1 < m_{ee} < 3$ GeV, the only significant physics background is open heavy flavor

Direct measurement of the temperature



A. Drees, Trento 2021

Dileptons as direct radiations



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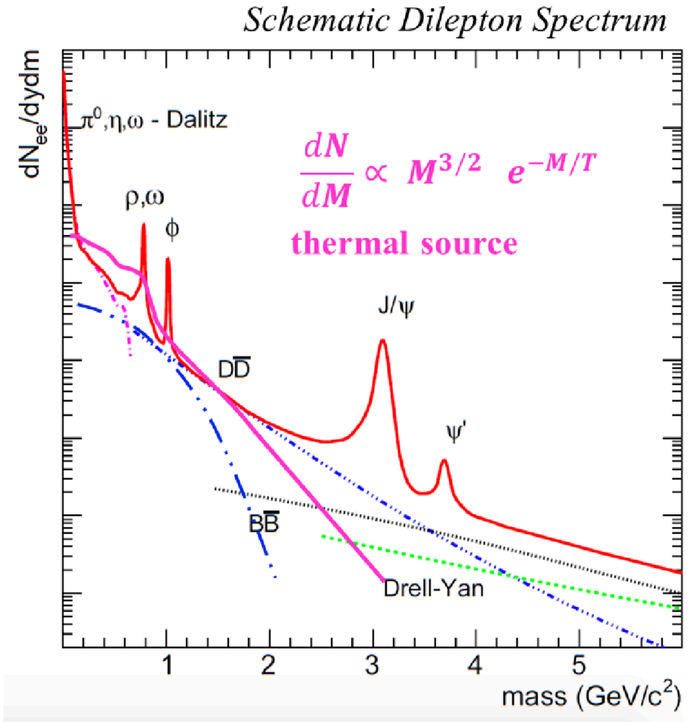
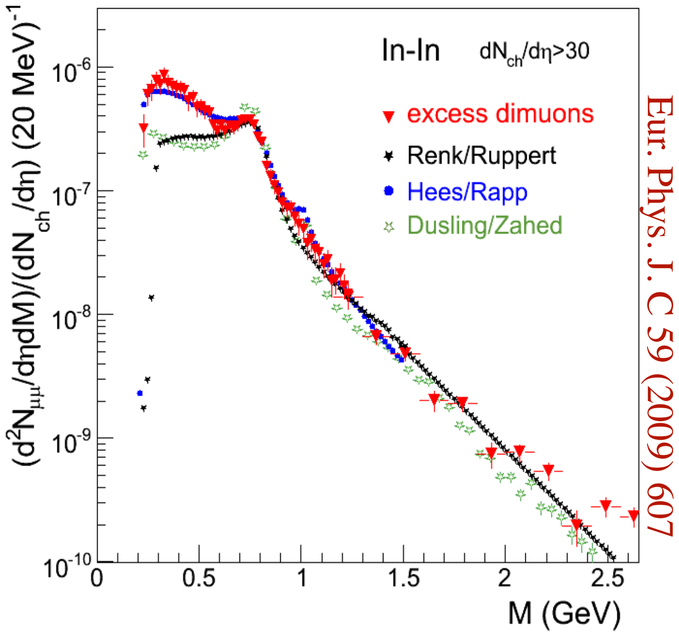
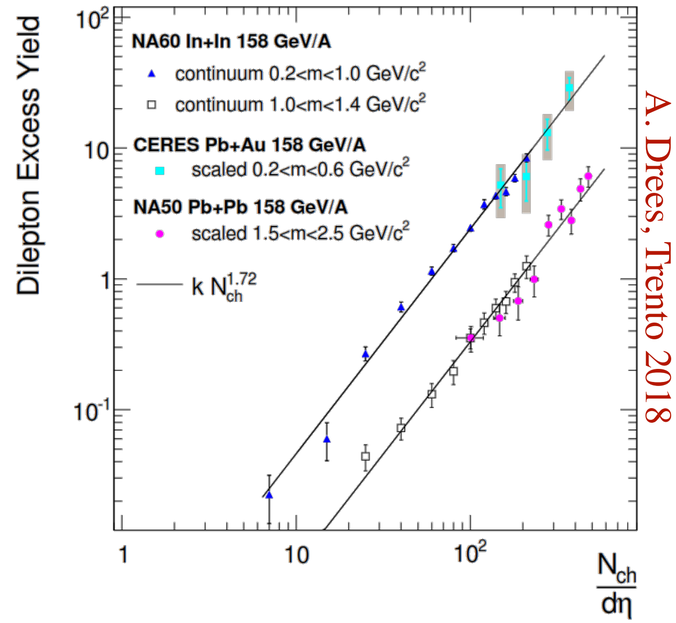


A. Drees, Trento 2021



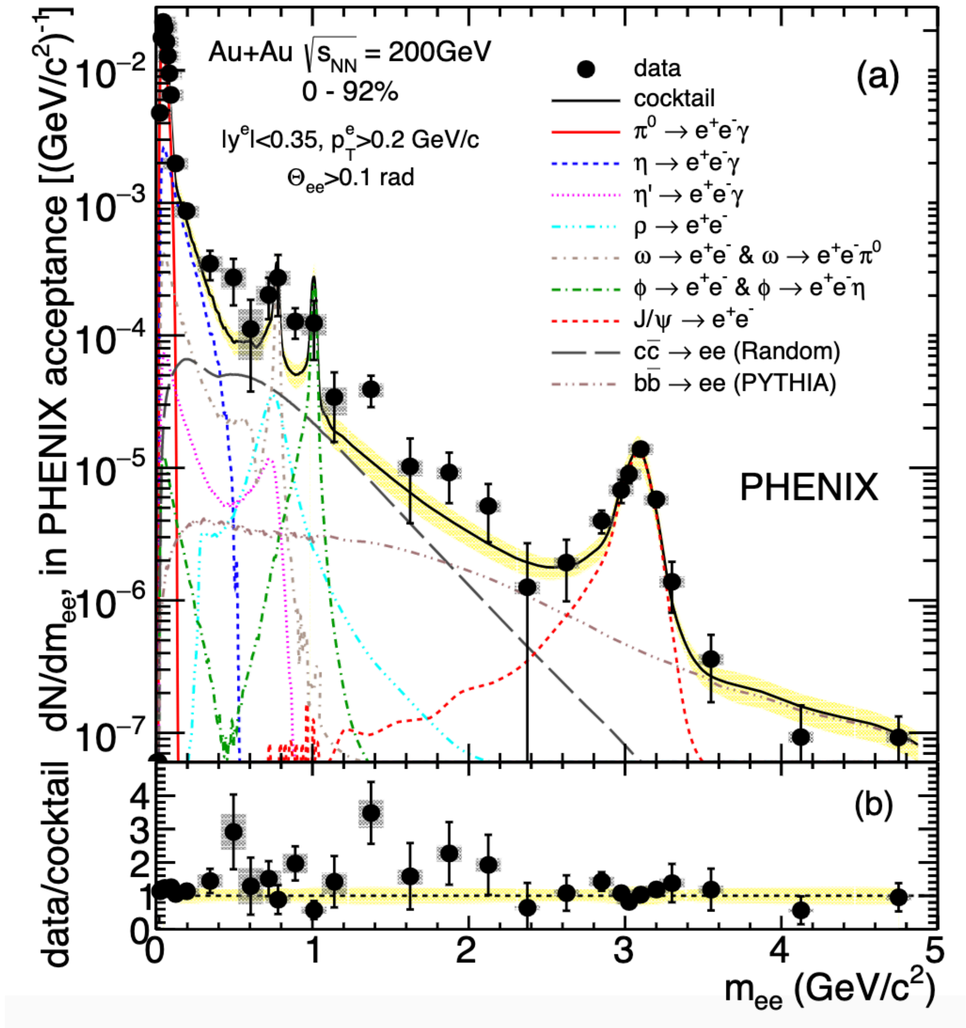
Eur. Phys. J. C 59 (2009) 607



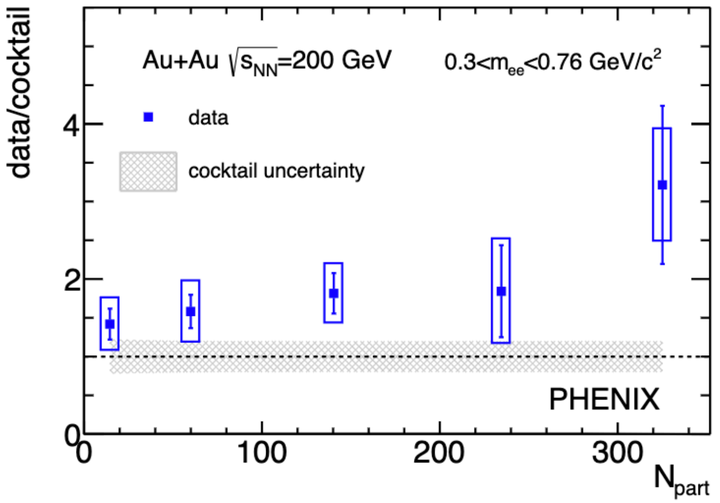
A. Drees, Trento 2018

Dielectron measurements [PHENIX]

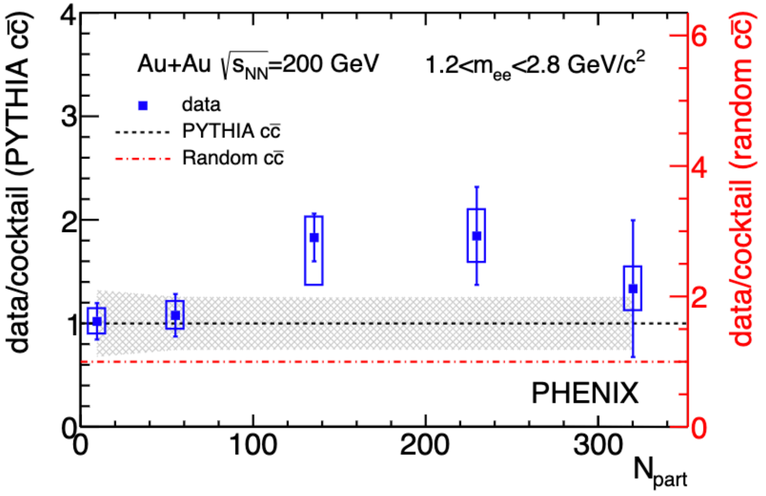
Phys. Rev. C 93 (2016) 1, 014904



Low mass region

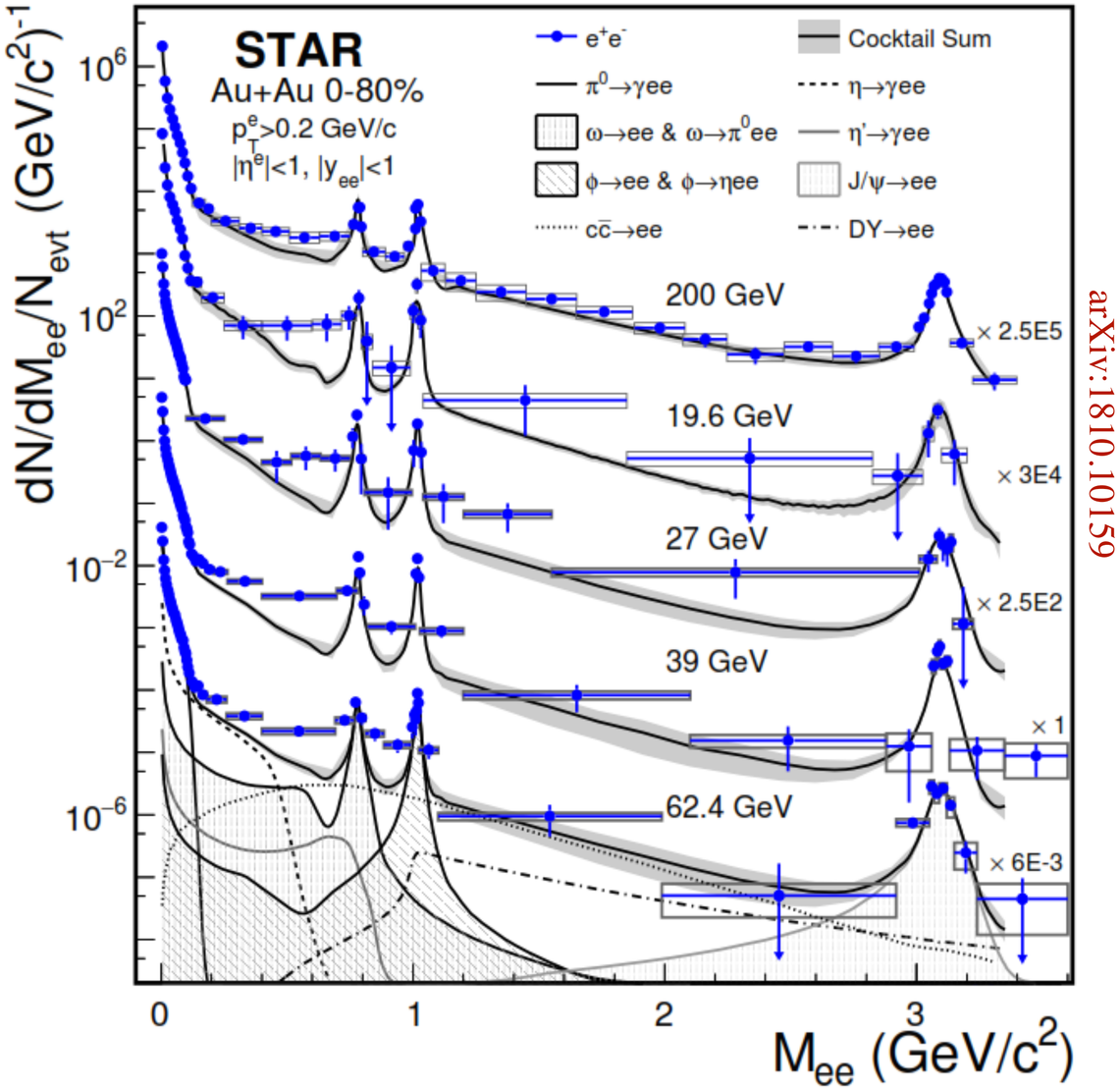


Intermediate mass region

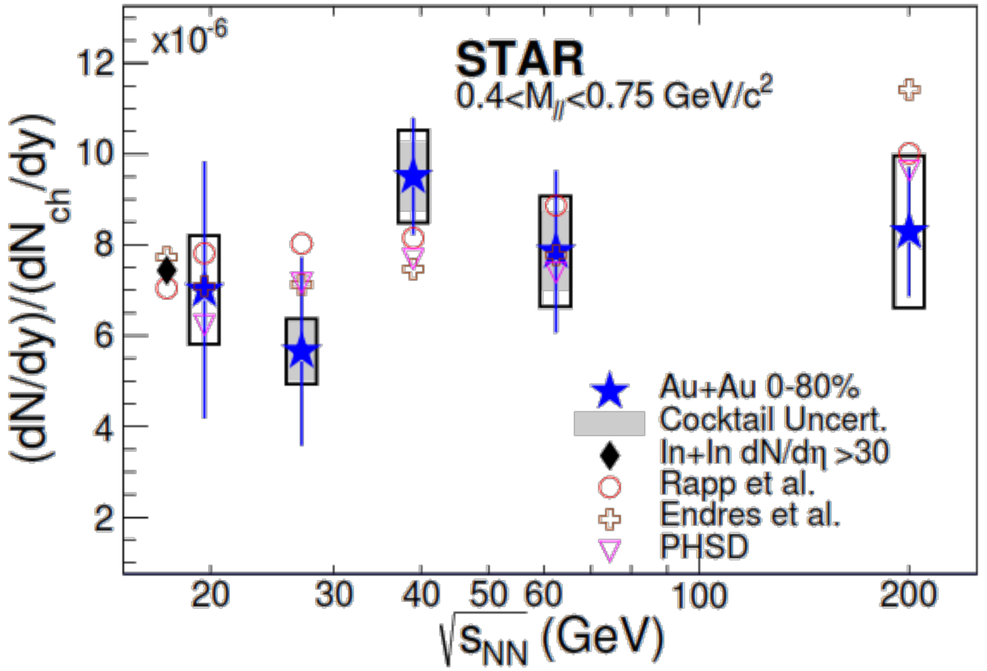


Enhanced production of dileptons in low and intermediate mass regions

Dielectron measurements [STAR]



arXiv:1810.10159

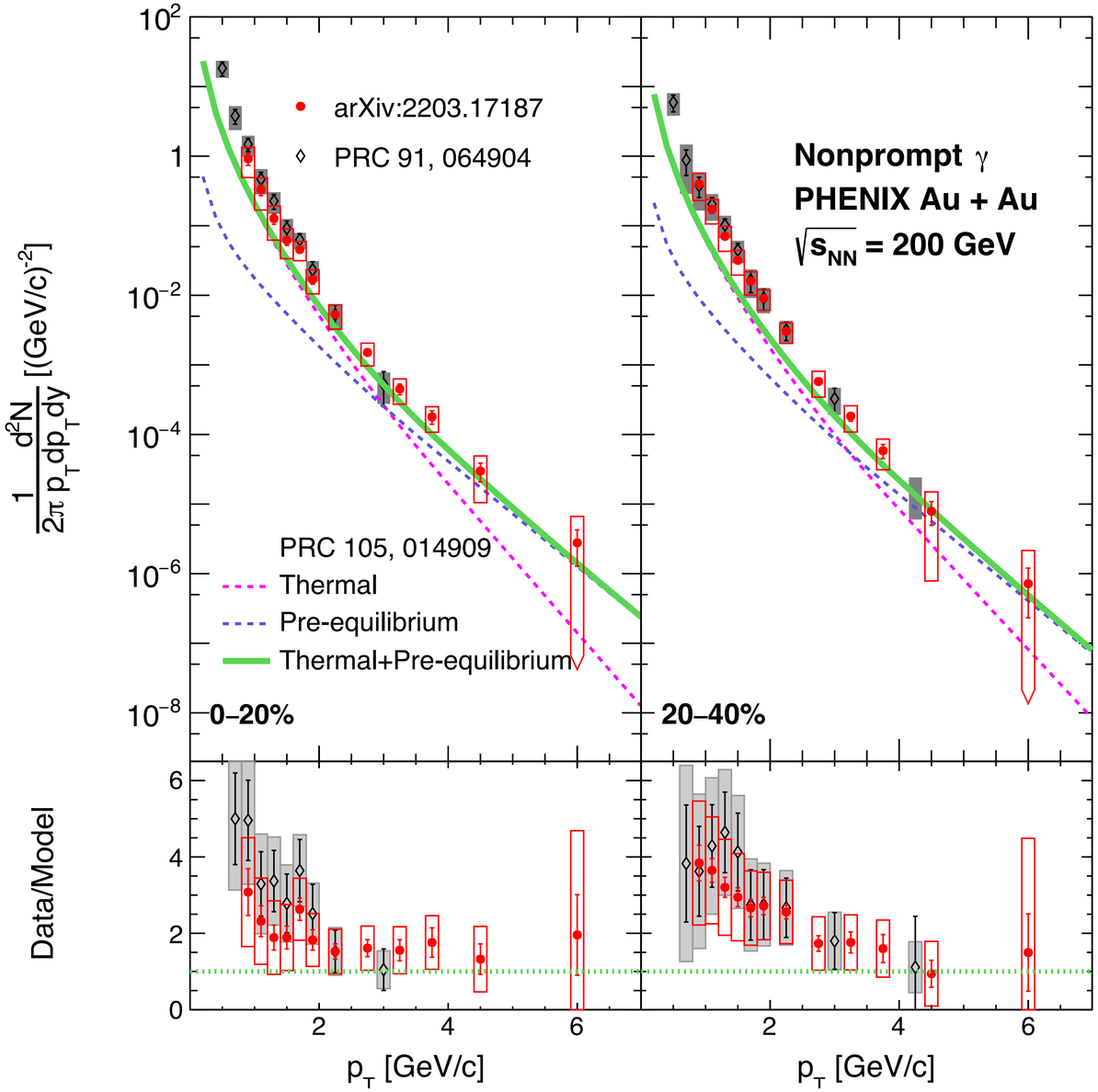


arXiv:1810.10159

Low mass excess is consistent with ρ broadening

$$\frac{\text{Excess Yield}}{dN_{\text{ch}}/d\eta} \text{ constant with } \sqrt{s_{NN}}$$

Comparisons with theory



C. Gale, J.-F. Paquet, B. Schenke & C. Shen,
Phys. Rev. C **105** (2022) 014909

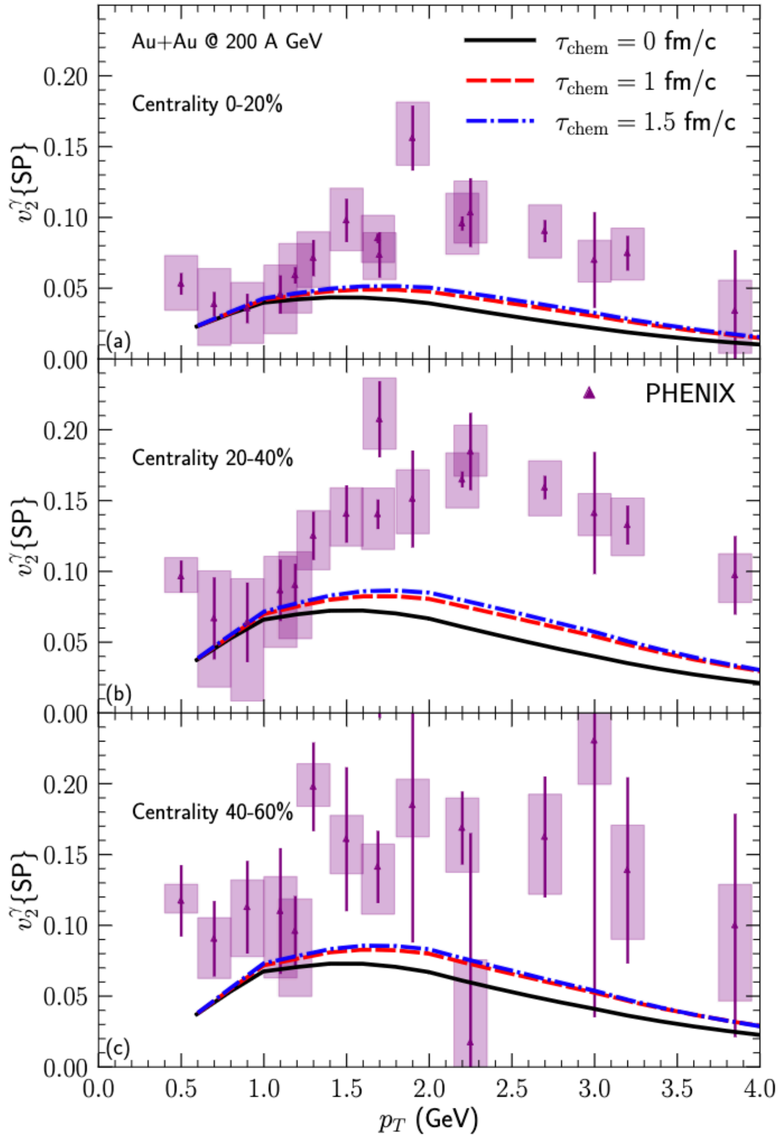
Multi-messenger heavy-ion physics

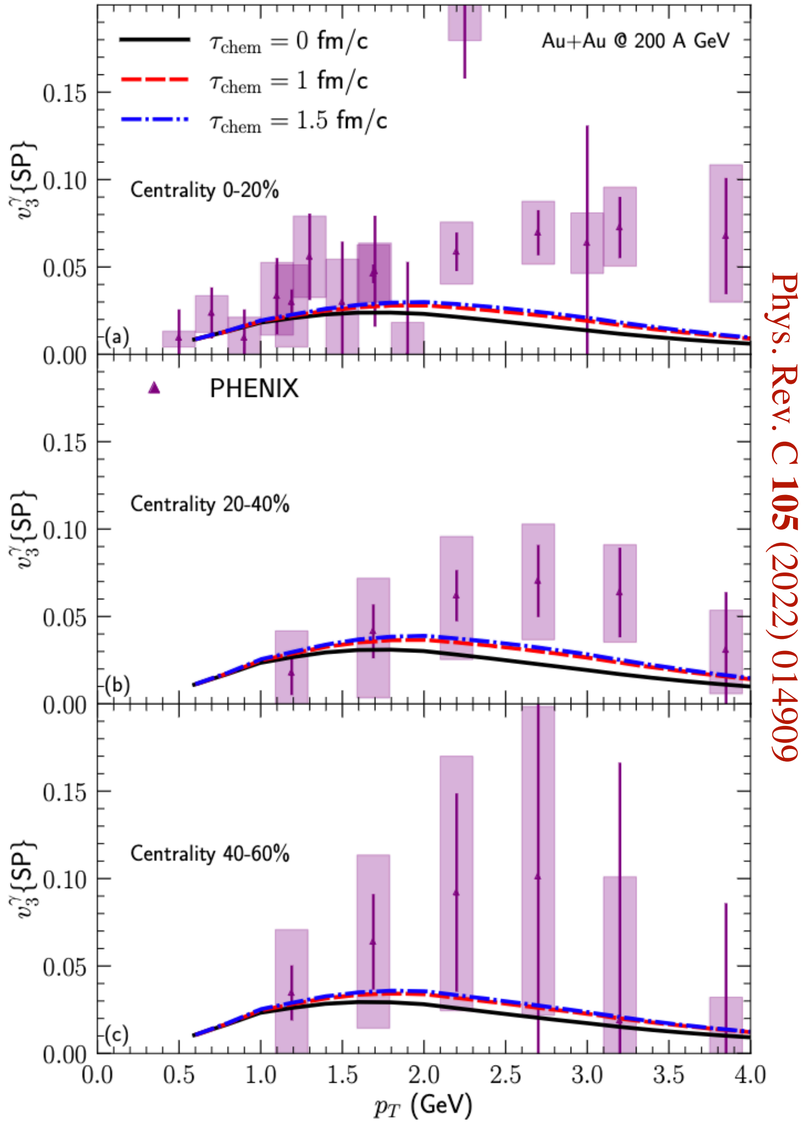
- Hybrid model that describes all stages of relativistic heavy-ion collisions
- Effect of the pre-equilibrium phase on both photonic and hadronic observables highlighted

Dominant contribution from pre-equilibrium above 3 GeV/c in the model seems to align well with the data

Overall yield falls short, especially below 2 GeV

Comparisons with theory

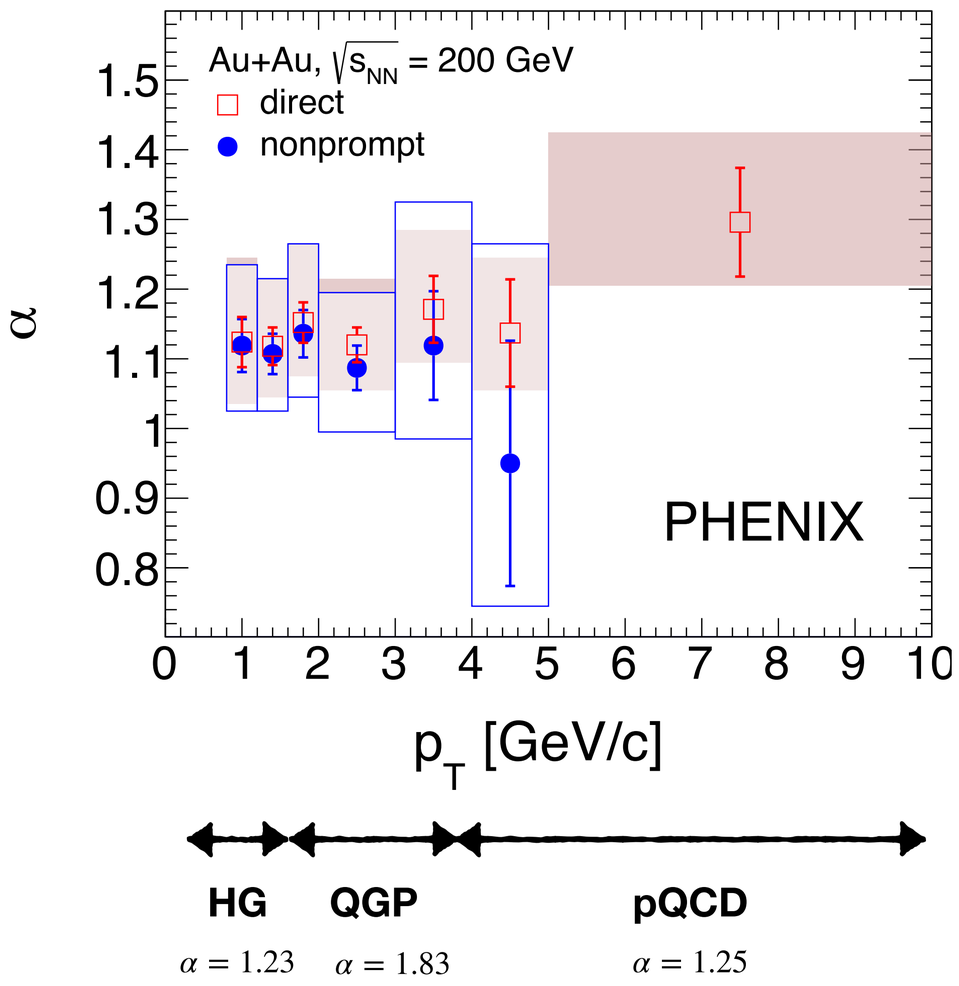


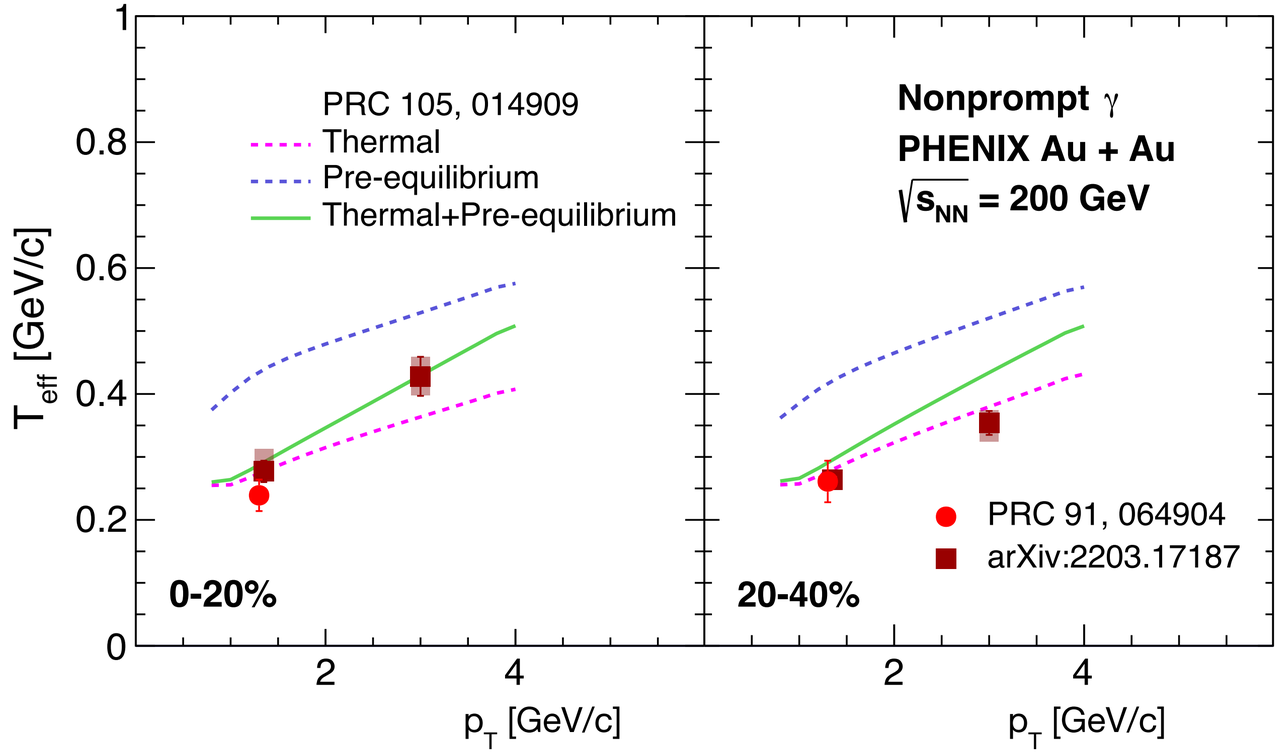


Phys. Rev. C **105** (2022) 014909

Comparisons with theory

arXiv:2203.17187





Contributions from pre-equilibrium may be important at intermediate p_T

Phys. Rev. C 89 (2014) 044910

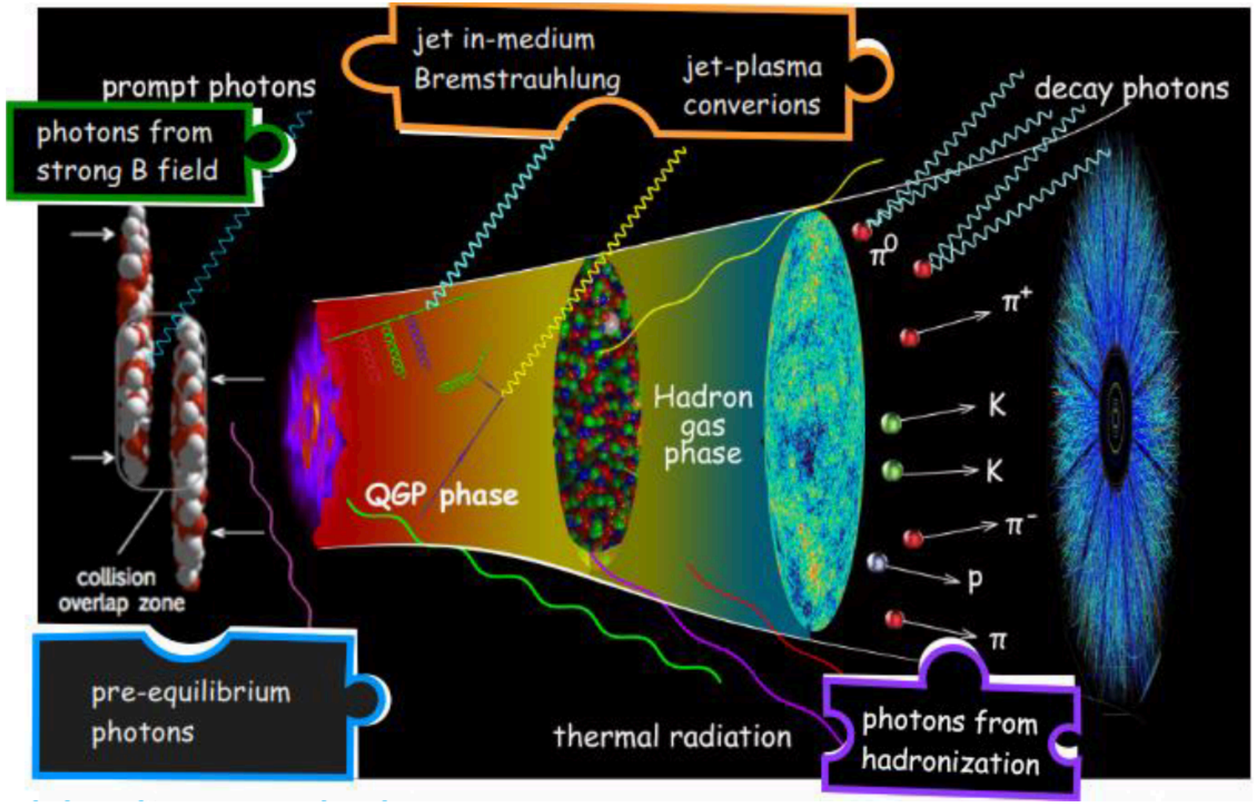
Future directions

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}



Credit: W. Fan

Pre-equilibrium emissions

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Hadronization

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- Large v_2; v_3 like hadrons
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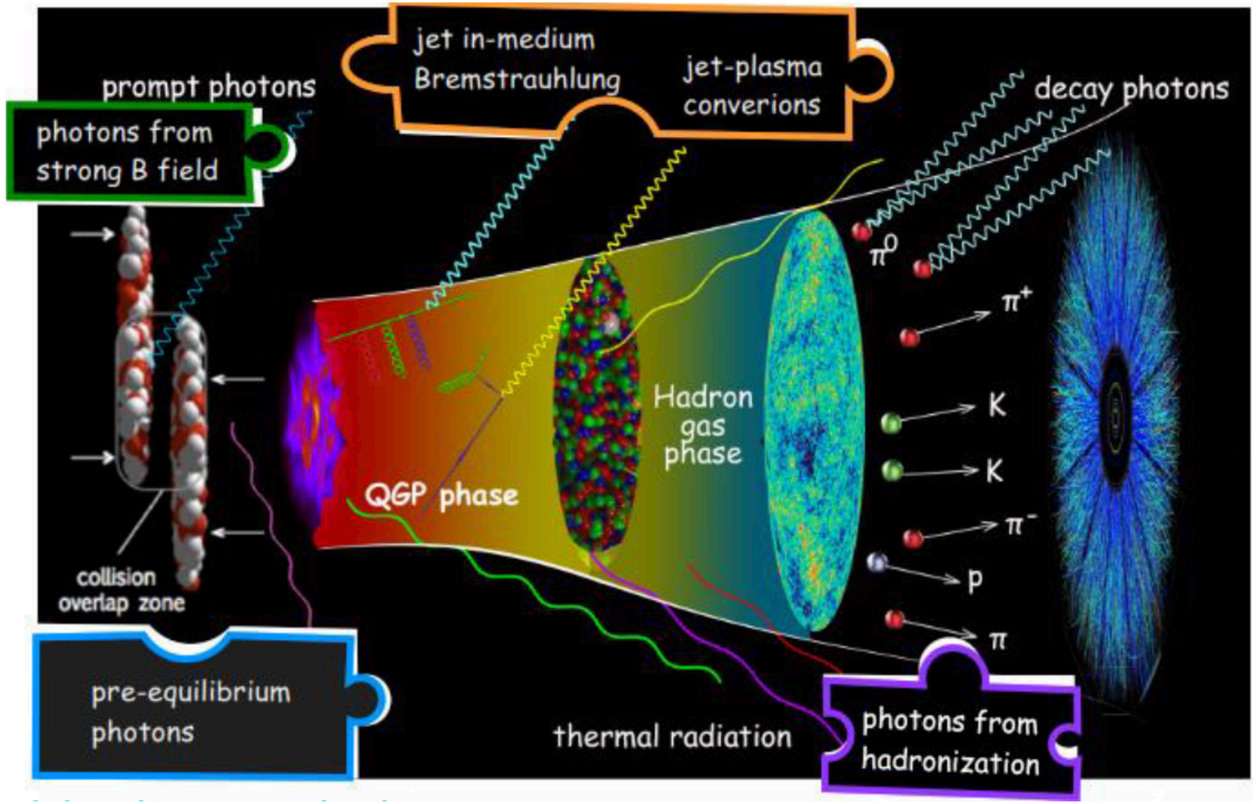

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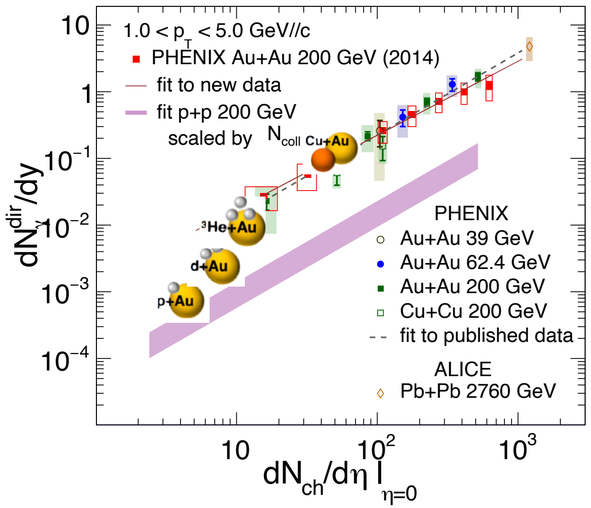

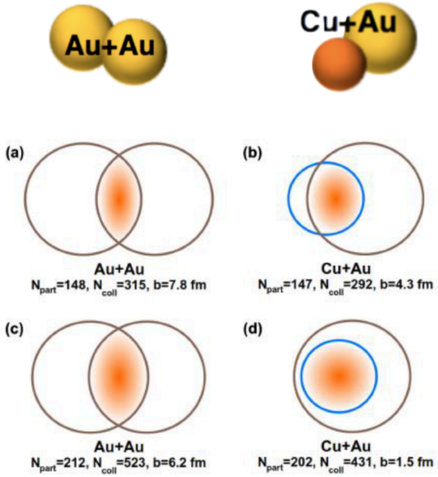

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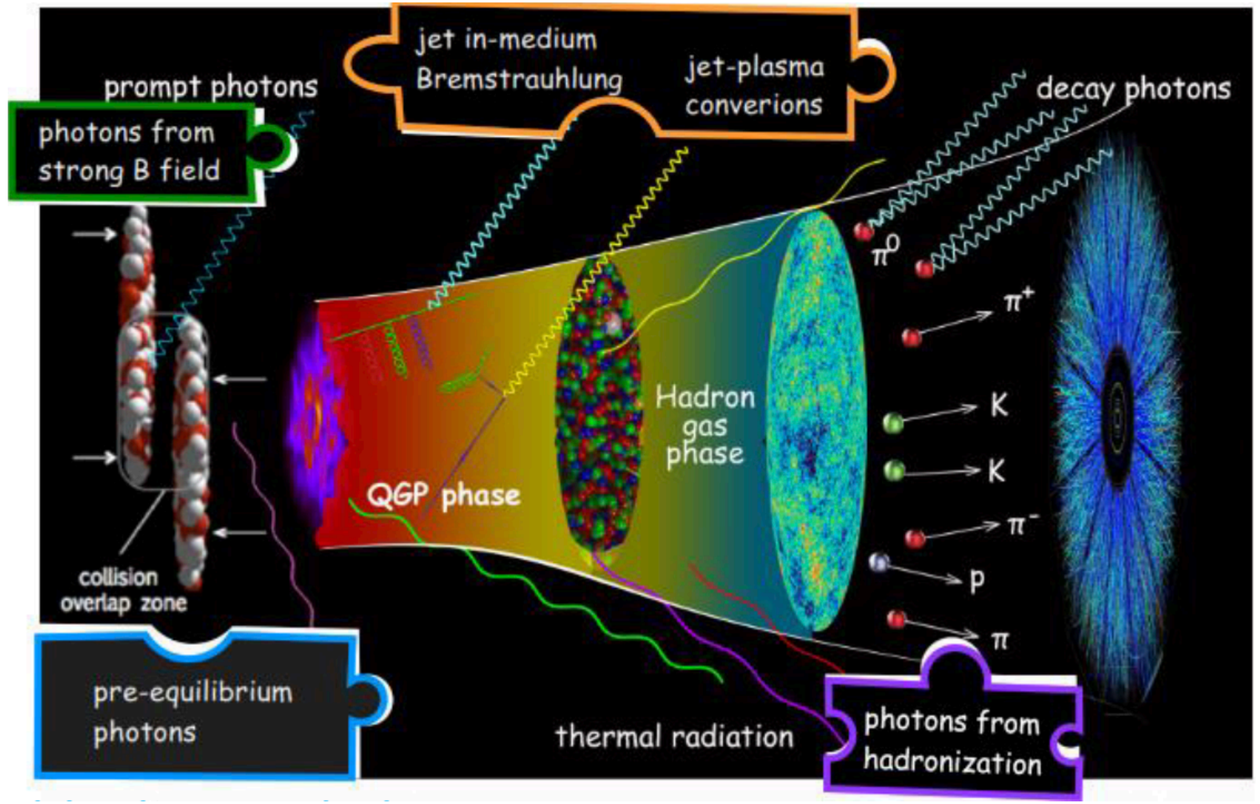

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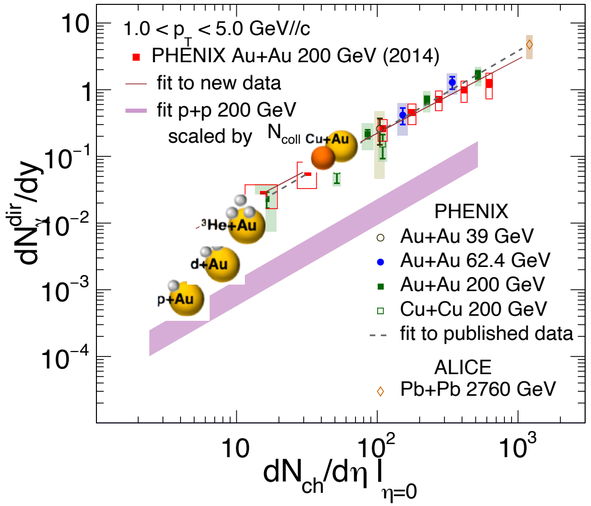

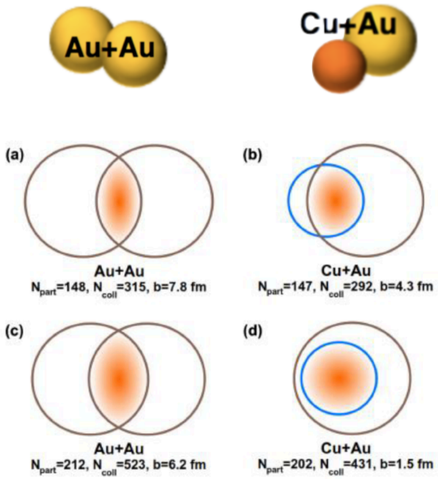

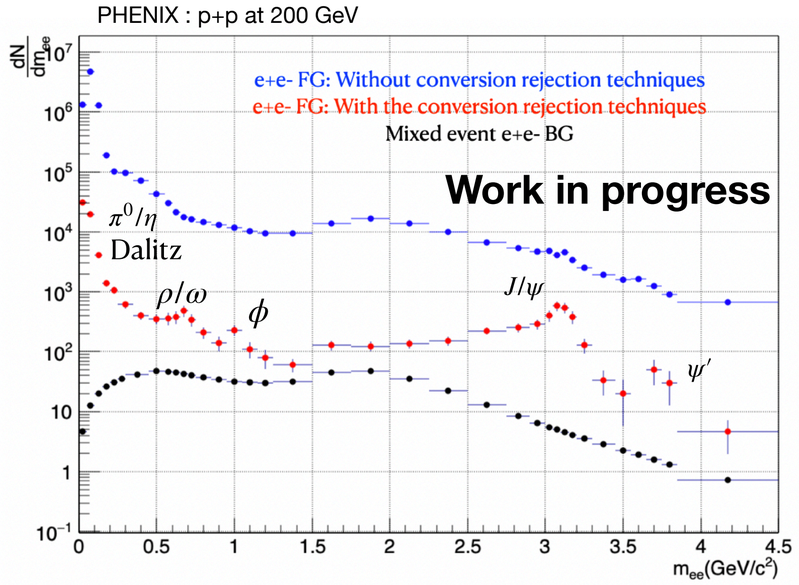

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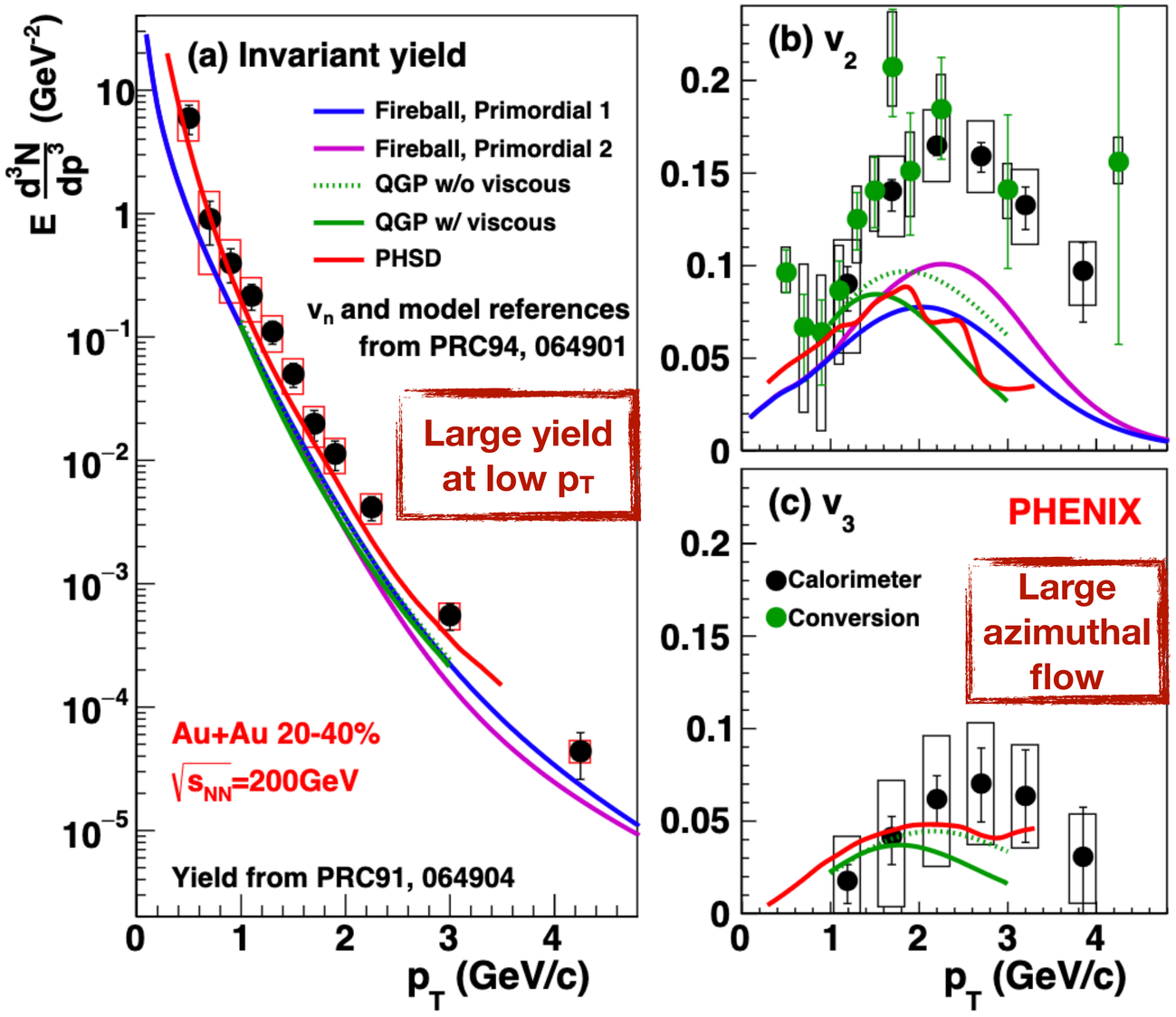
Summary

- Plethora of direct photon measurements from RHIC
    - Different experiments - STAR and PHENIX
    - Different methods - calorimeter, internal conversion, external conversion
    - Different systems and collision energies
- Simultaneous description of data (may still be) a challenge to theory

Thank you for your attention!

Direct photon puzzle

Phys. Rev. C 94 (2016) 064901



- Large contribution from hadron gas and QGP
  - Thermal rates with hydro (viscous/non viscous) or blastwave evolution
  - Microscopic transport (PHSD)
- Early contributions
  - Non-equilibrium effects (glasma, etc.)
  - Enhanced thermal emission in large B-fields
  - Modified formation time and initial conditions
- Effects at phase boundary
  - Extended emission
  - Emission at hadronization

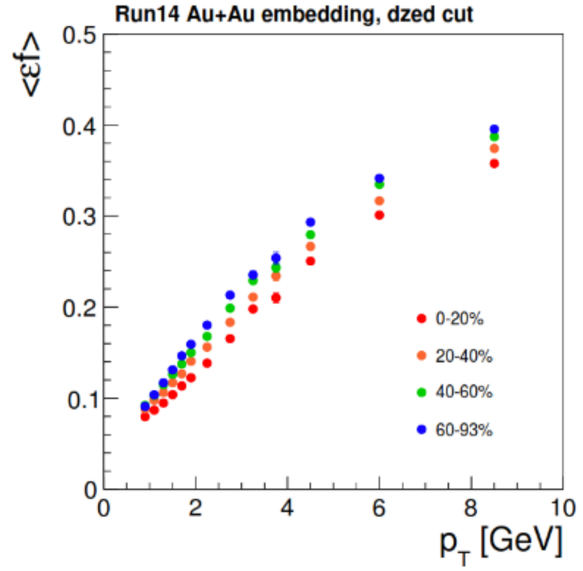
Qualitative agreement with thermal source

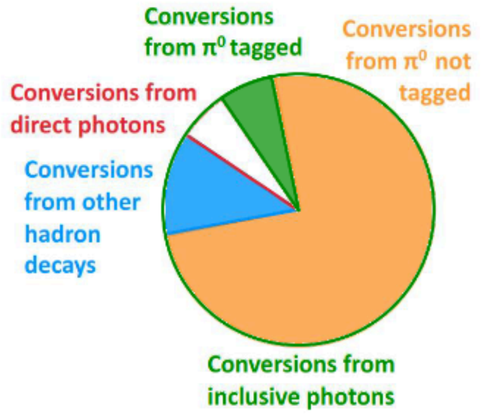
Quantitative tension with model predictions

External conversion

Full MC simulation

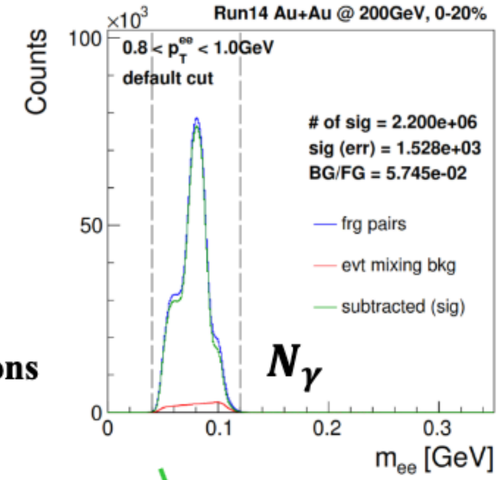
conditional tagging efficiency





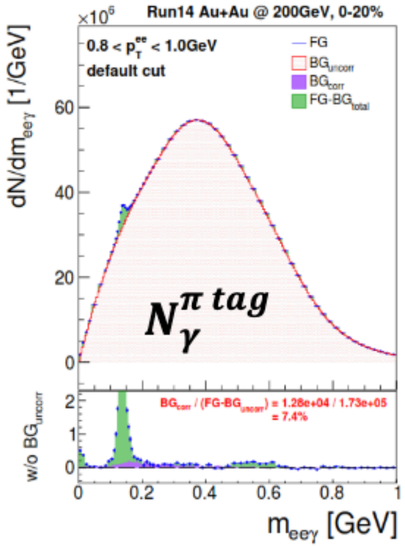
Key contributions

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



measured raw yields

Closure test with full high multiplicity MC simulation

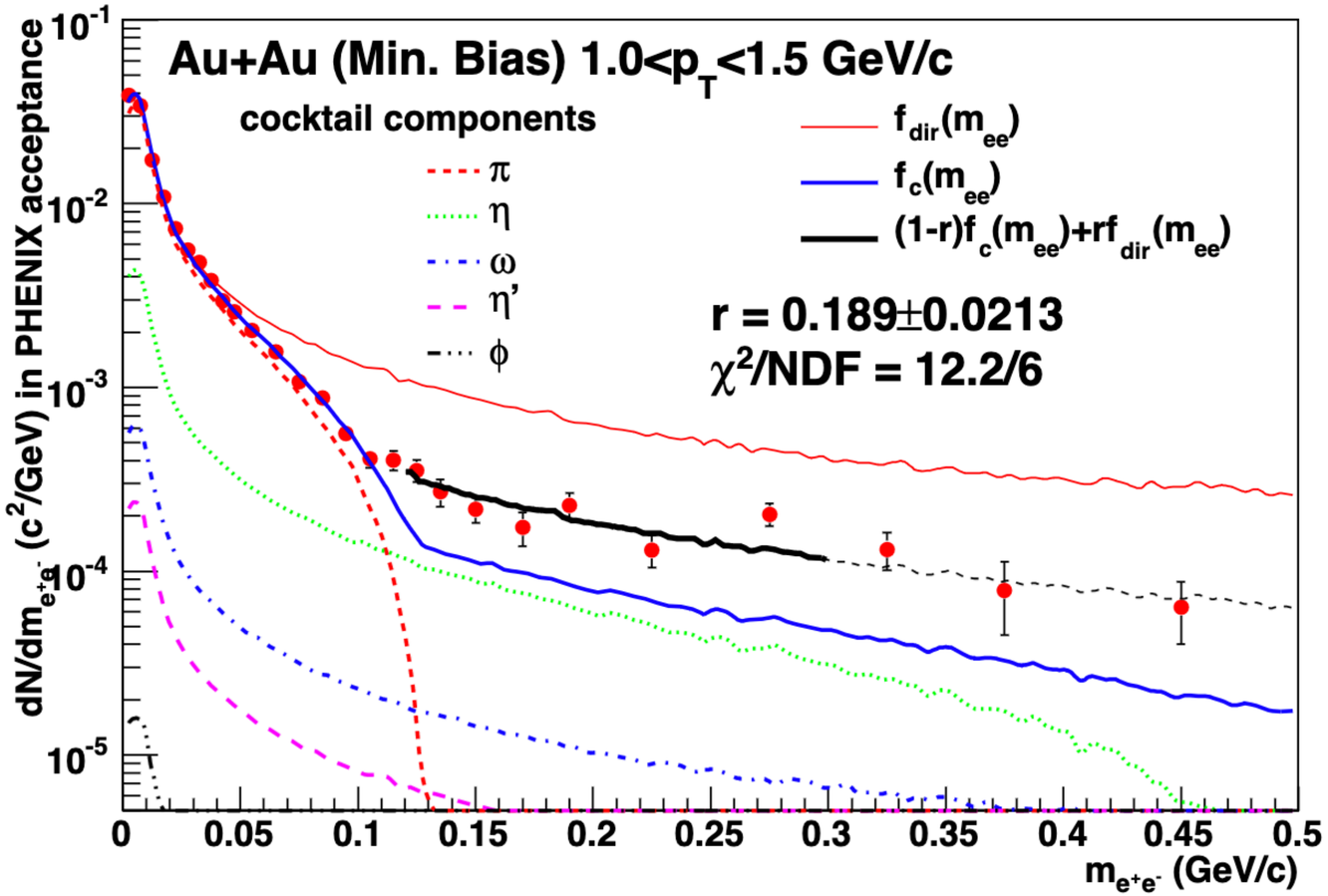


$$R_\gamma = \frac{N_\gamma^{incl}}{N_\gamma^{hadr}} = \frac{\left\langle \varepsilon f \right\rangle \times \left(\frac{N_\gamma}{N_\gamma^{\pi^0 tag}} \right)^{Data}}{\left(\frac{N_\gamma^{hadr}}{N_\gamma^{\pi^0}} \right)^{MC}}$$

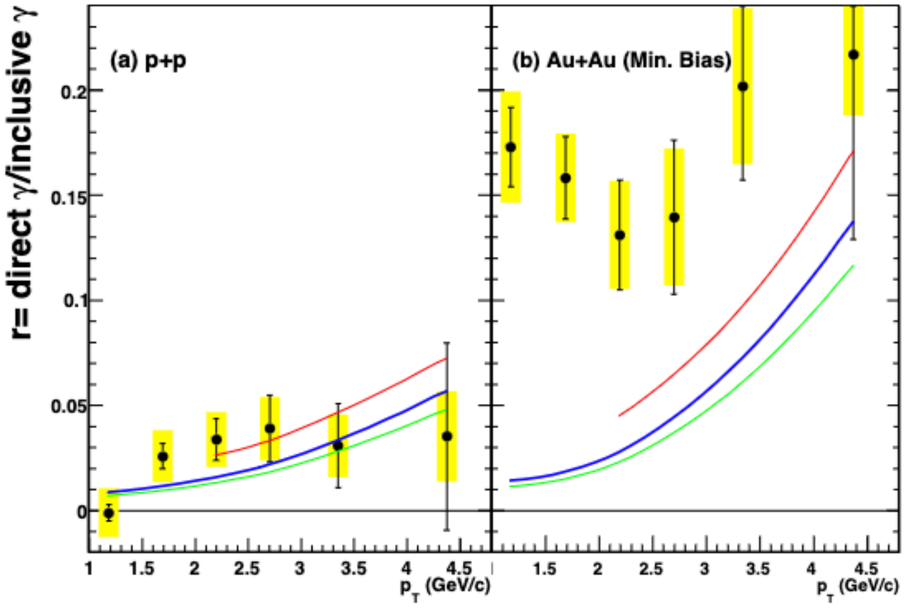
η/π^0 ratio main contribution

Photons from hadron decays

Internal conversion

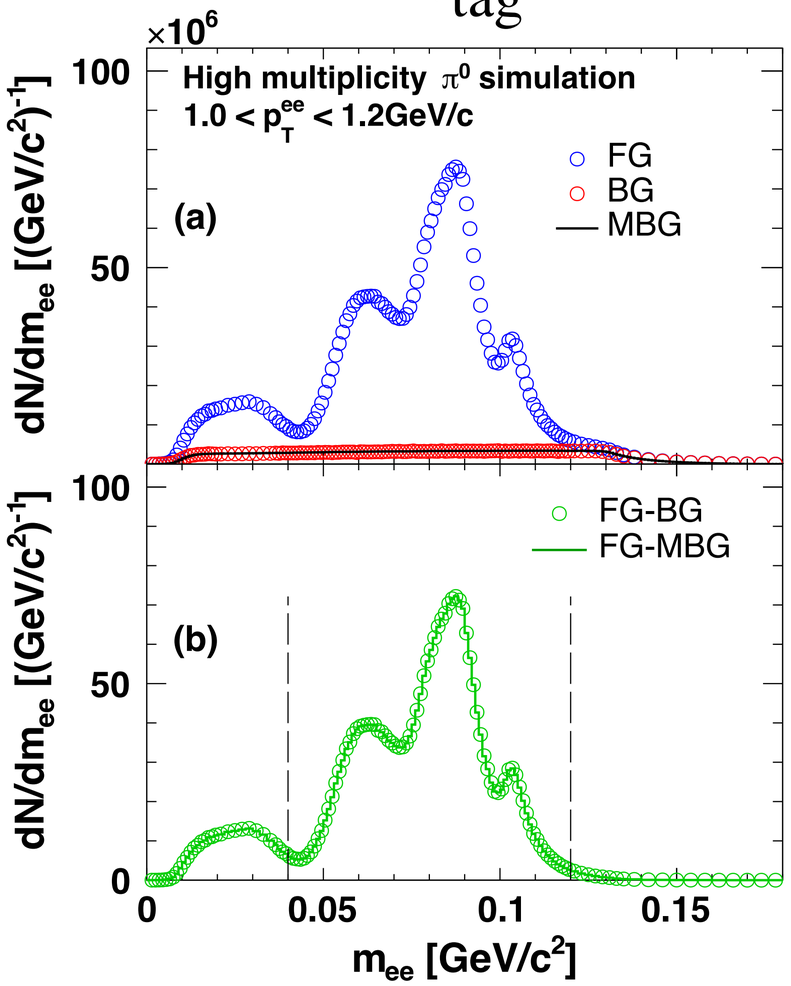


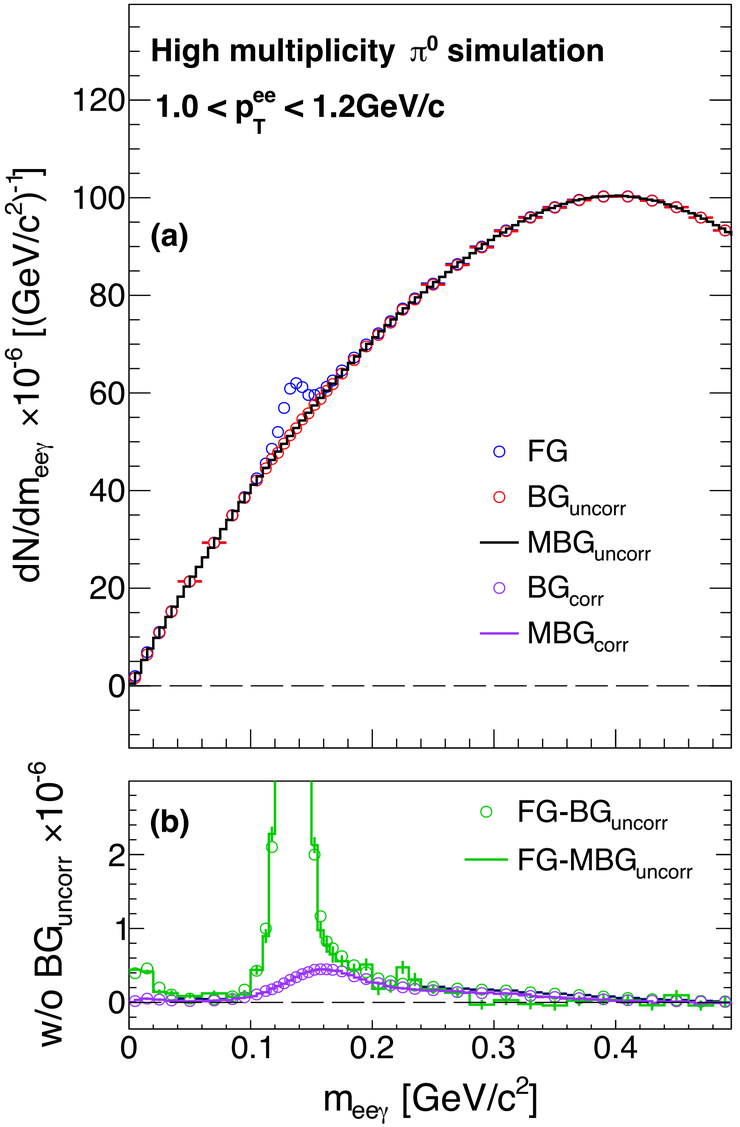
$$f(m_{ee};r) = (1-r)f_c(m_{ee}) + r f_{\mathrm{dir}}(m_{ee})$$

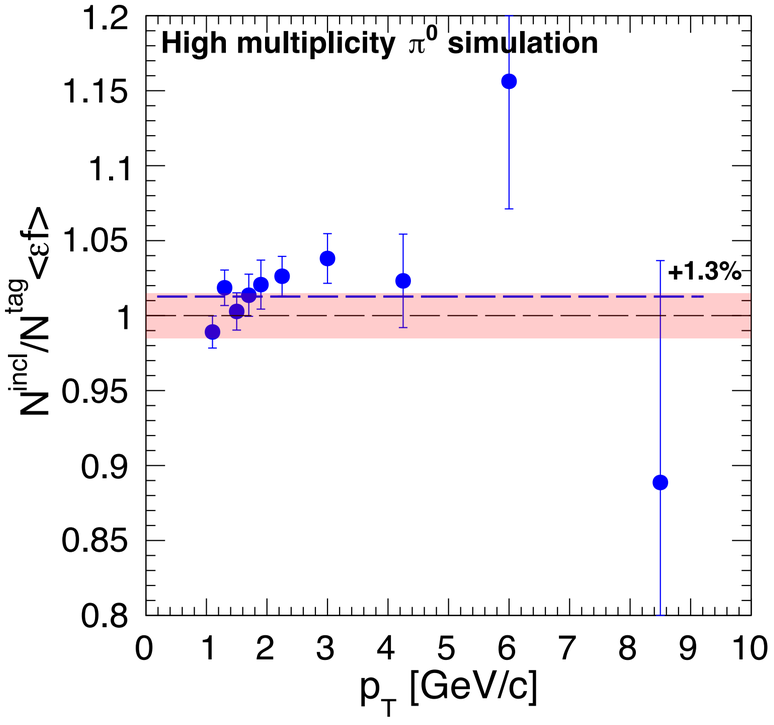


Closure test with high-multiplicity π^0 simulation

$$R_\gamma = \frac{N_{\mathrm{inc}}}{N^{\pi^0}_{\mathrm{tag}}} \langle \varepsilon f \rangle$$





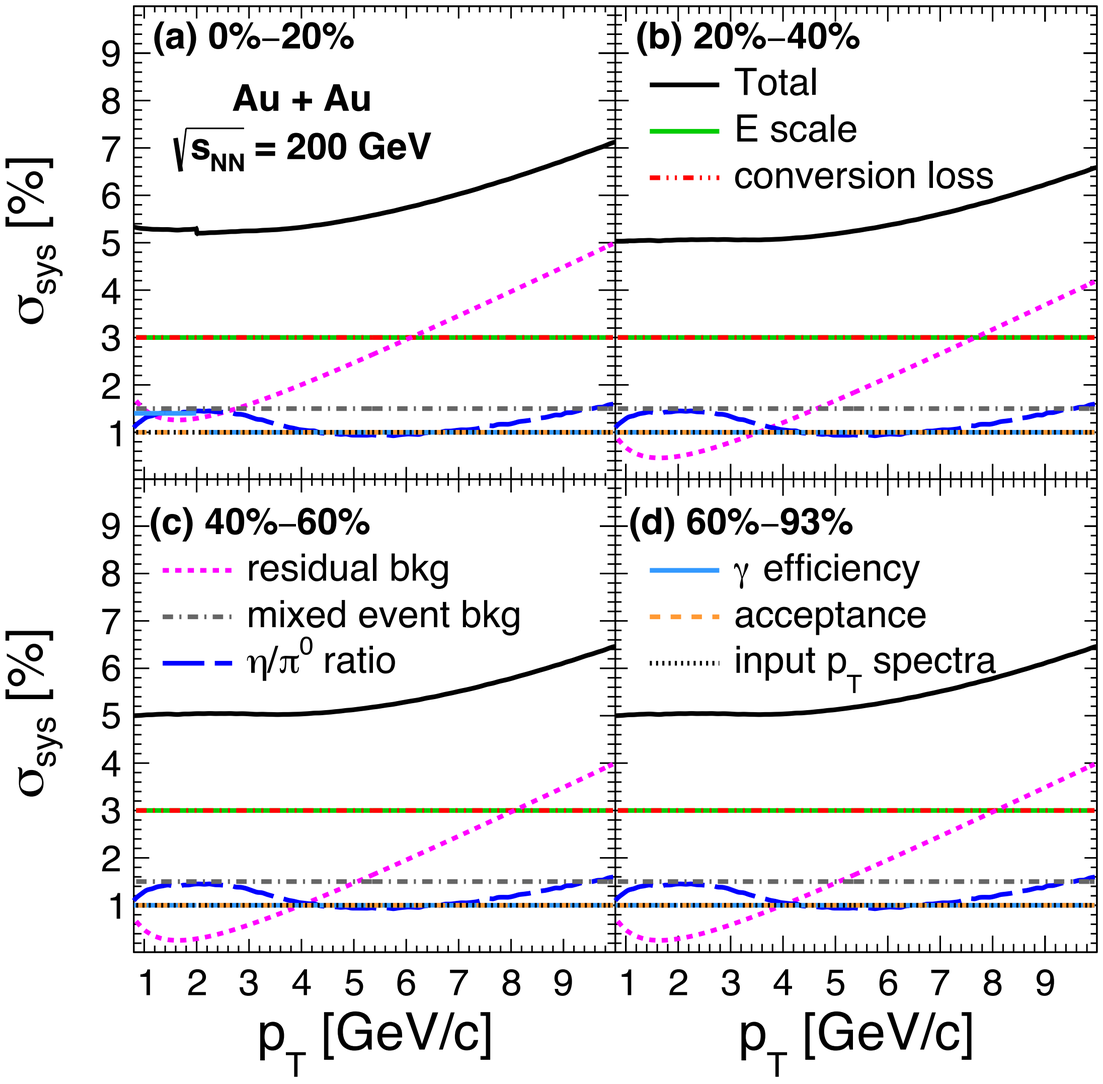


Simulating 280 π^0 per event through the PHENIX reconstruction and analysis framework

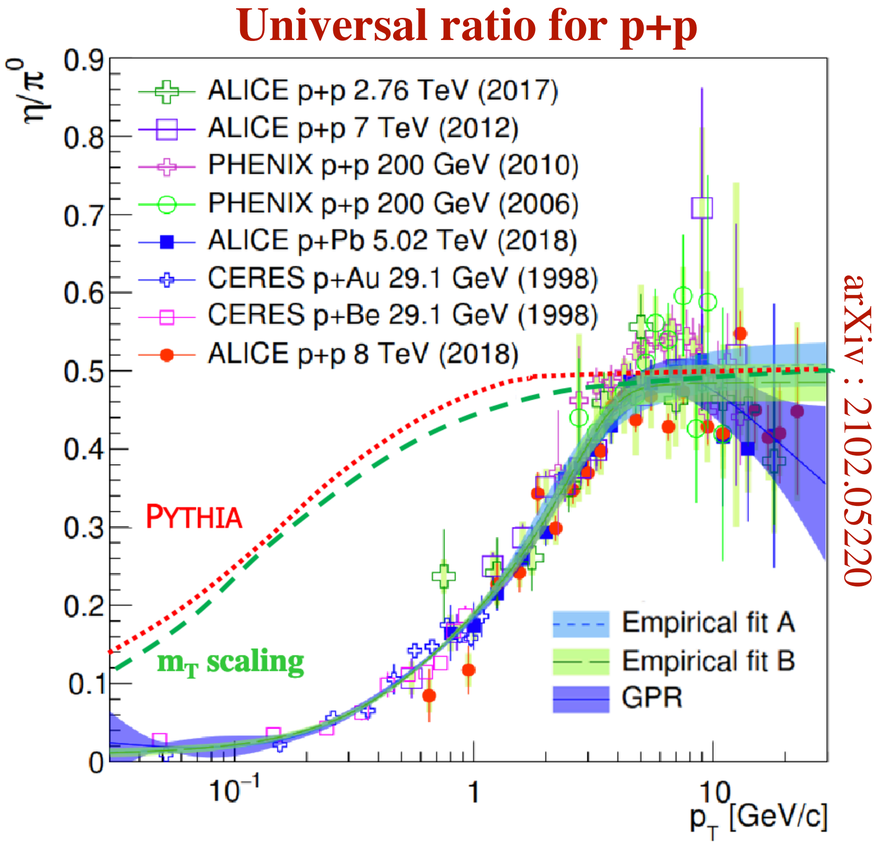
Systematic uncertainties

Systematic uncertainty source (39 GeV)	σ_{sys}/R_γ	Type
π^0 *reconstruction*		
tagged photon yield	8%	A
Conditional acceptance		
input Hagedorn p_T spectra and energy scale	8%	B
Cocktail ratio		
γ^{hadron}/π^0	2%	B

Systematic uncertainty source (62.4 GeV)	σ_{sys}/R_γ	Type
π^0 *reconstruction*		
tagged photon yield	5%	A
Conditional acceptance		
input Hagedorn p_T spectra and energy scale	5%	B
Cocktail ratio		
γ^{hadron}/π^0	2%	B

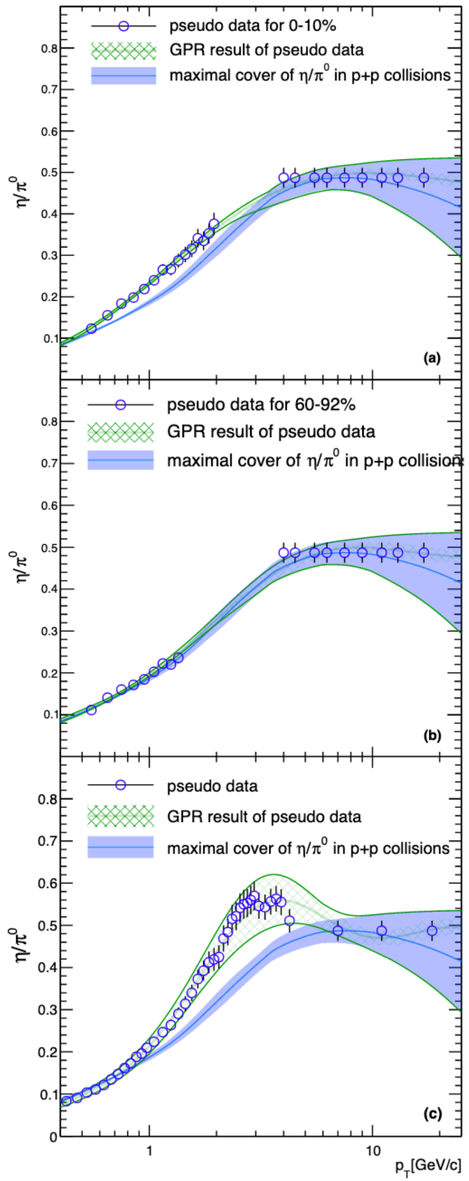


η/π^0 from world data

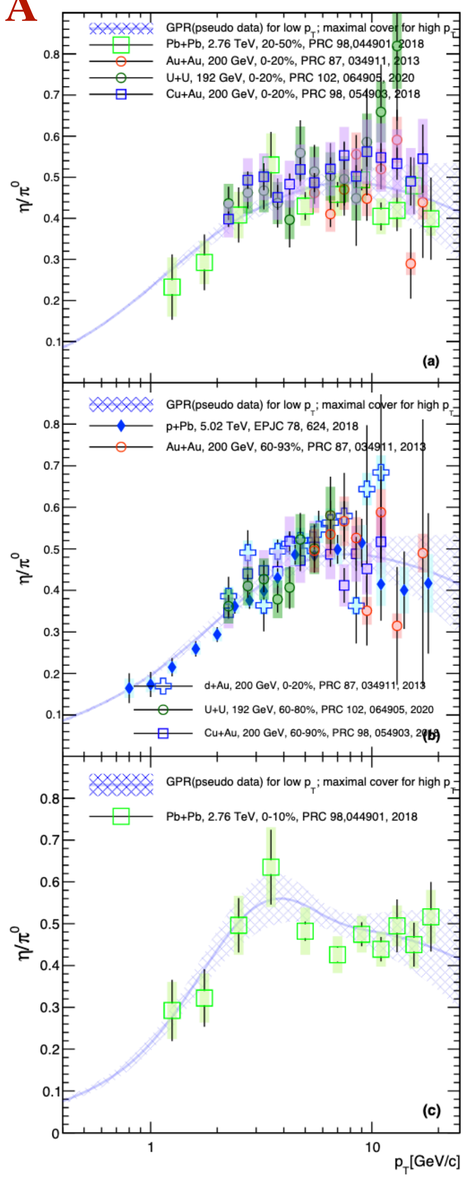


arXiv : 2102.05220

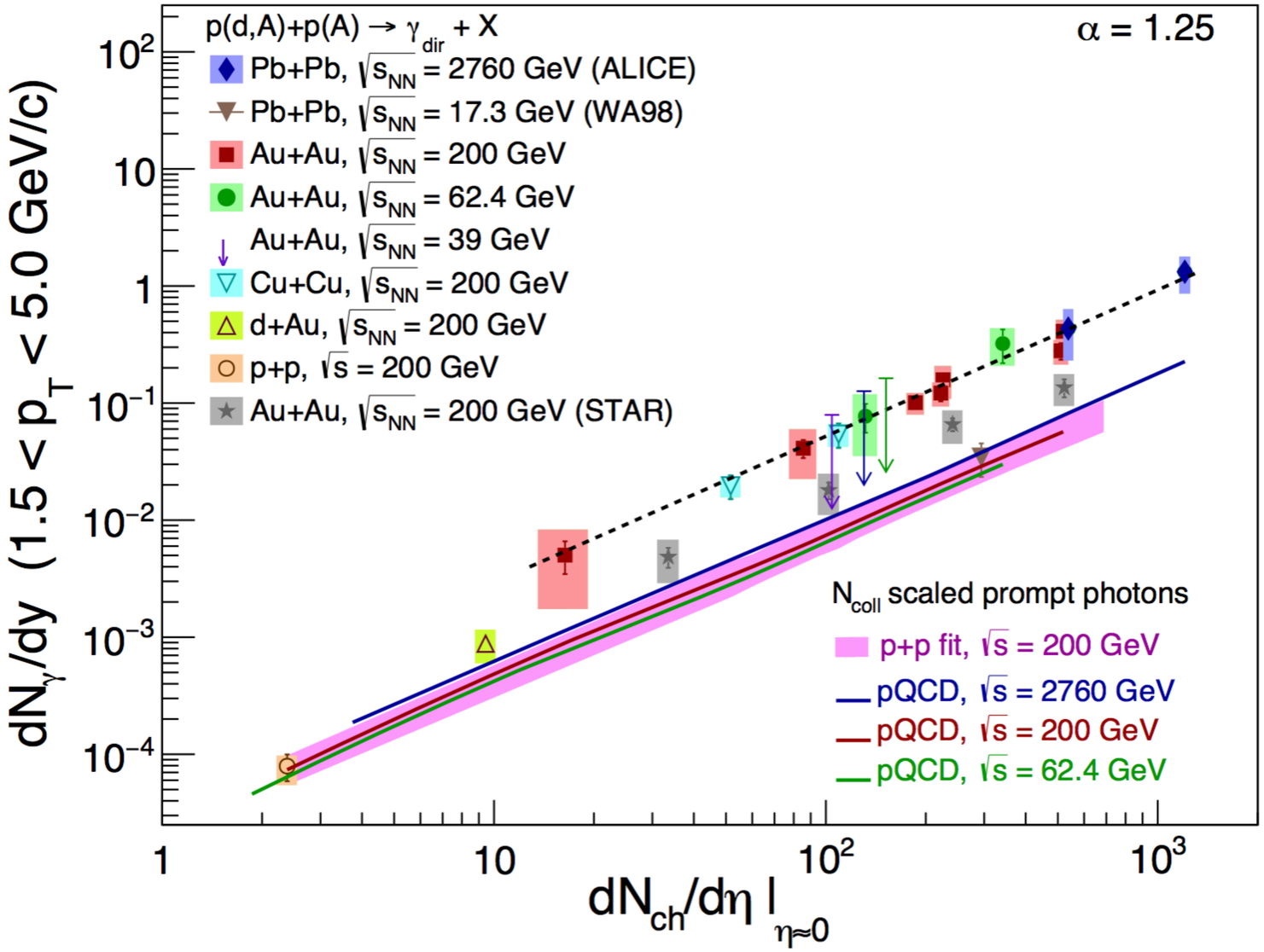
Accounting for effects of radial flow



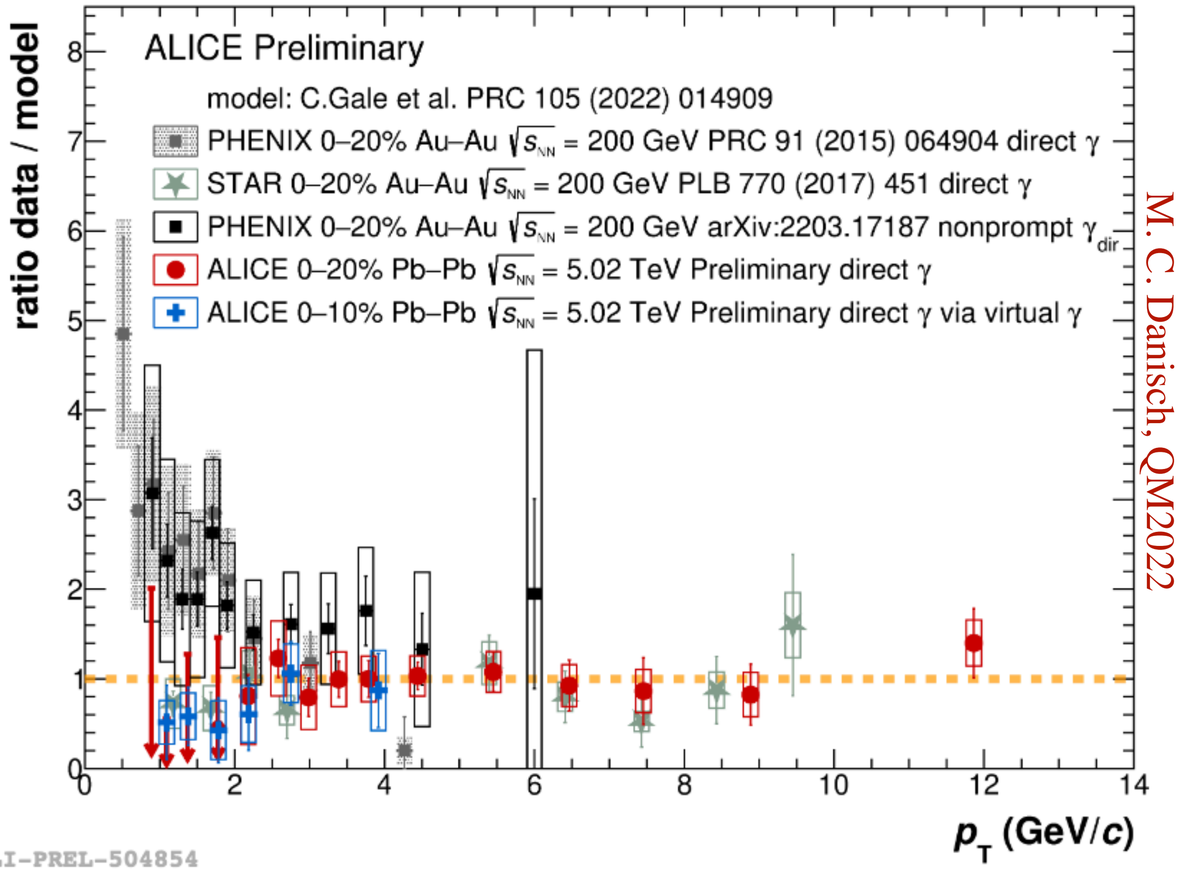
A + A



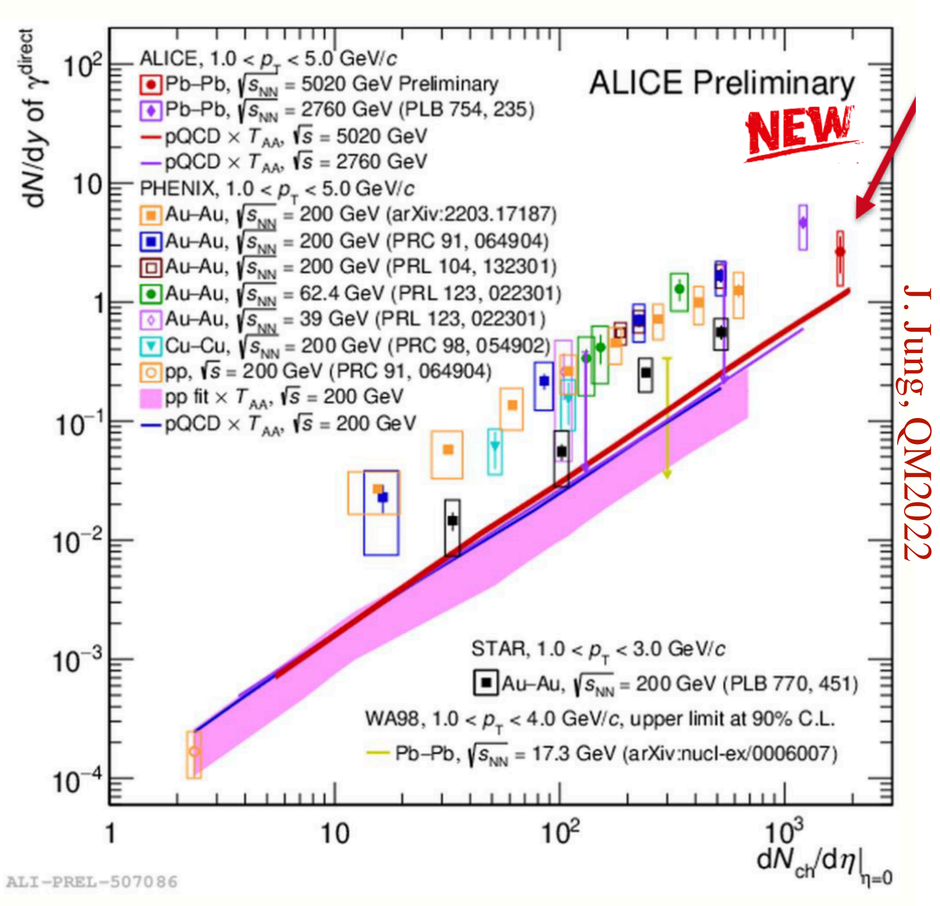
Universal scaling of direct γ



Recent ALICE results



M. C. Danisch, QM2022



J. Jung, QM2022