Direct-Photon Production in Heavy Ion Collisions

Axel Drees, Trento, July 2025

PENETRATING PROBES OF HOT HIGH-MU_B MATTER: THEORY MEETS EXPERIMENT

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

July 21-25 , 2025

ECT* Villa Tambosi, Villazzano

Center for Frontiers in Nuclear Science

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Direct-I... eavy Ion Collisions

2025

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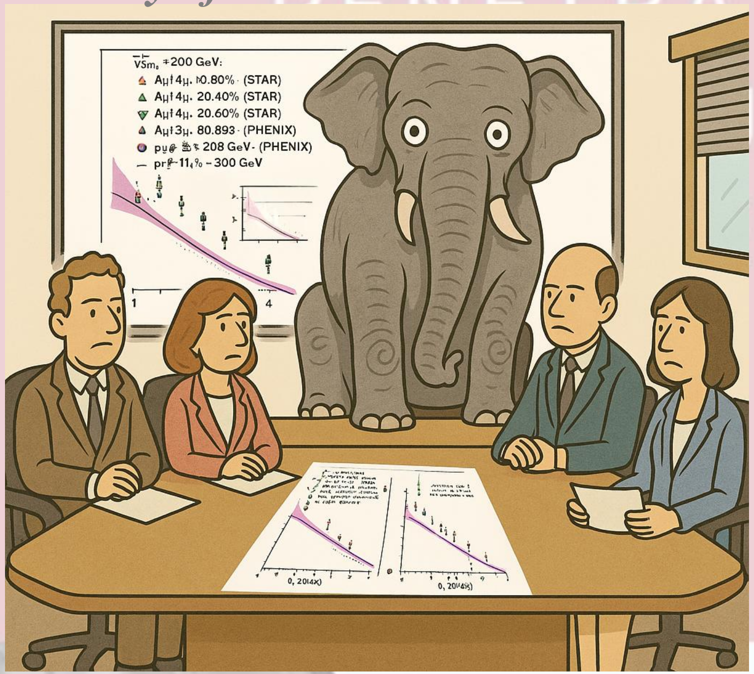
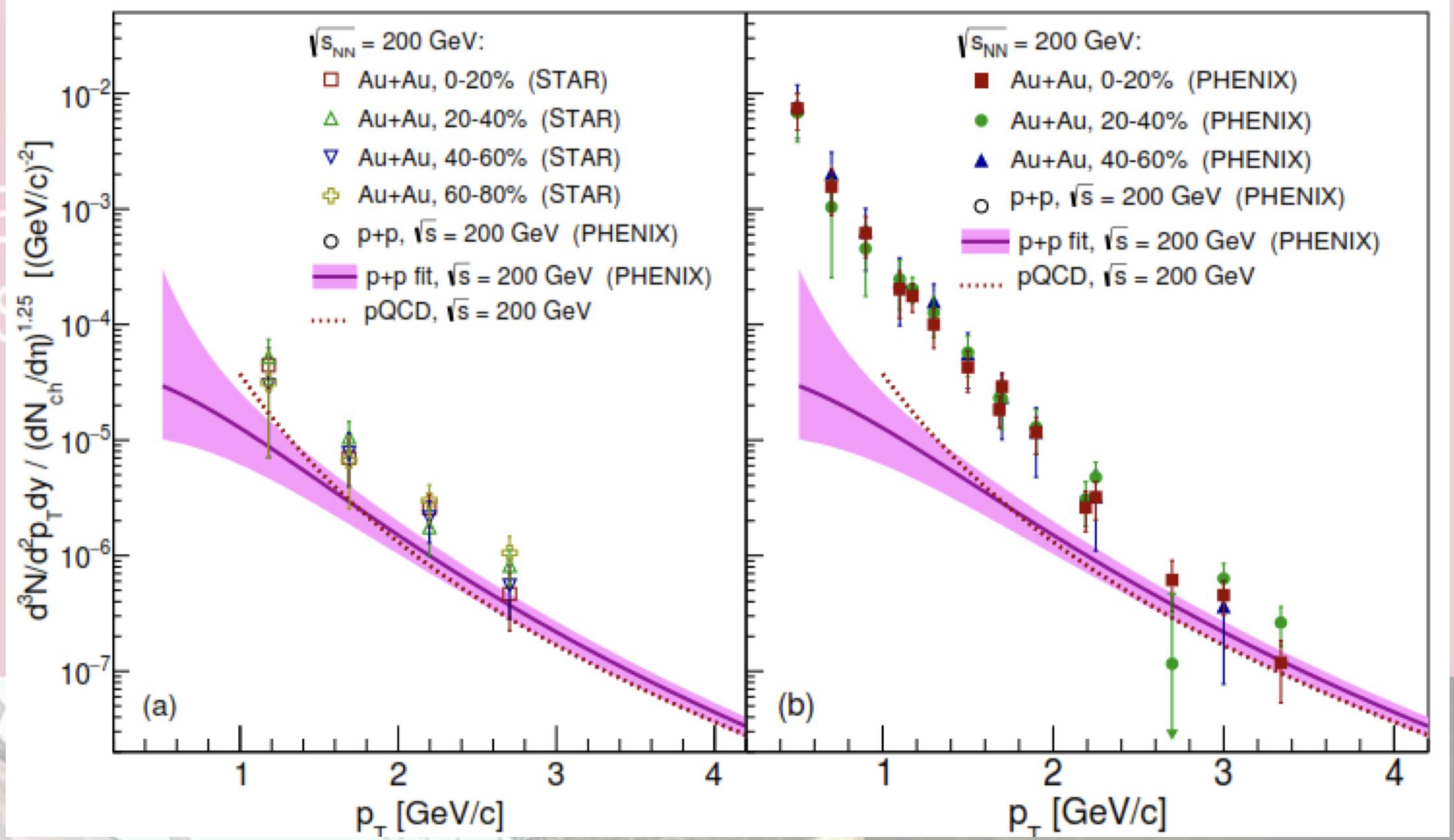
Direct-Photon Production in Heavy Ion Collisions

courtesy of AI





STAR and PHENIX results do not agree!

I will discuss this at the end of the talk!

Direct-Photon Production in Heavy Ion Collisions

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- **Introduction**
- **PHENIX results**
  - Experimental techniques
  - Direct photon spectra and flow
  - Future AuAu dilepton results
- **PHENIX - STAR - ALICE comparison**

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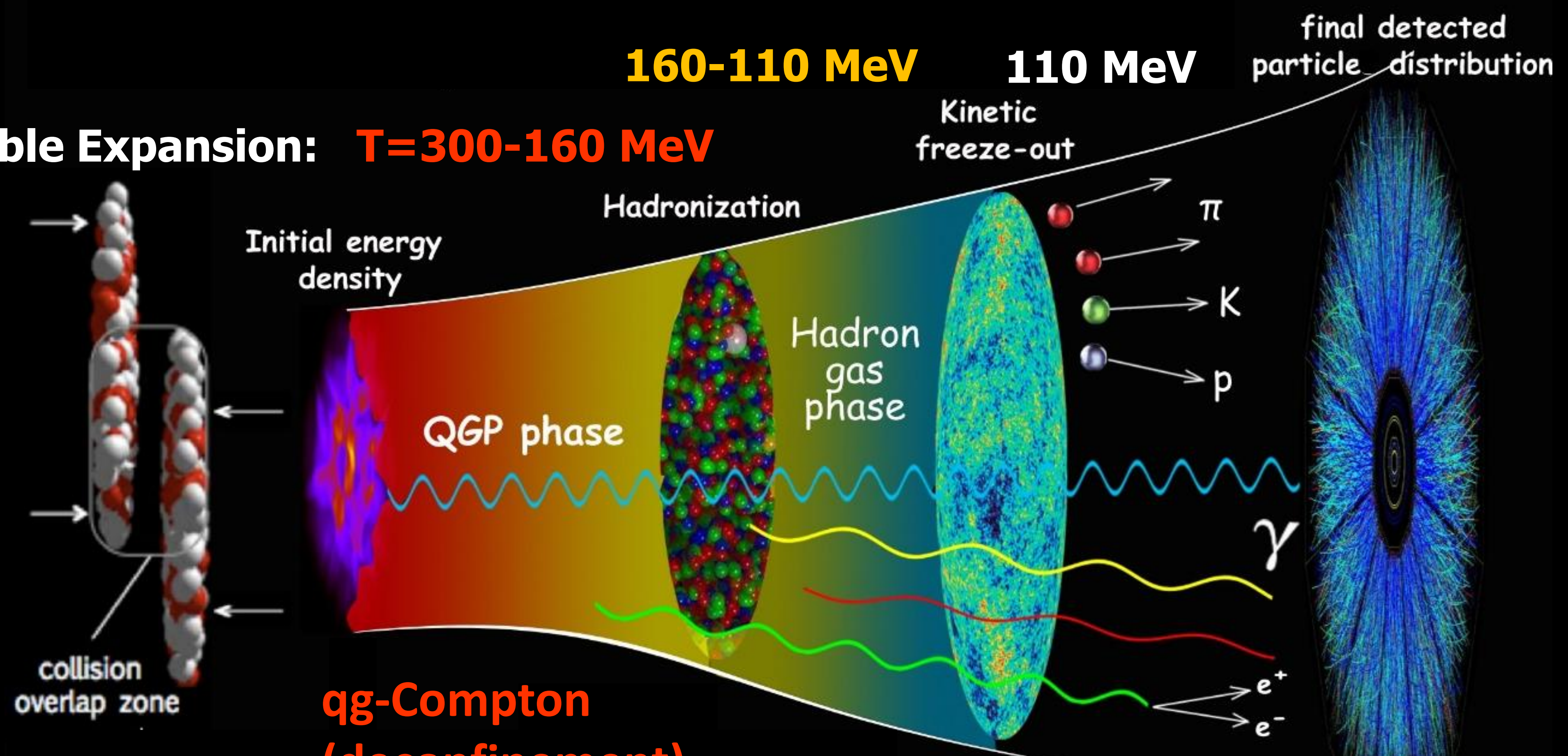
Electromagnetic Radiation in A+A Collisions:

Hubble Expansion: T=300-160 MeV

160-110 MeV

110 MeV



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

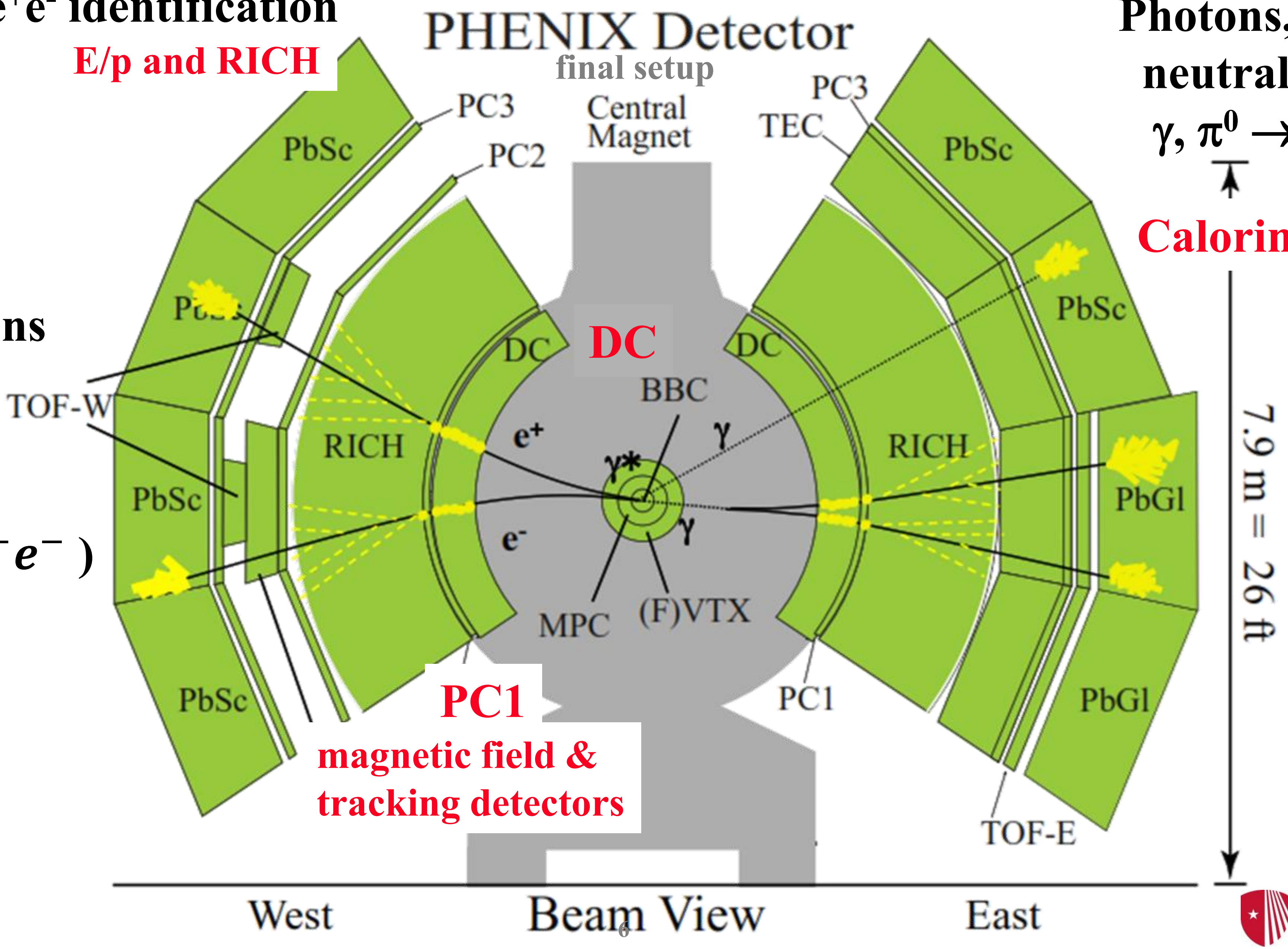
Photon Measurements with PHENIX

e^+e^- identification
E/p and RICH

Photons, neutral pion
$\gamma, \pi^0 \rightarrow \gamma\,\gamma$
Calorimeter

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

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



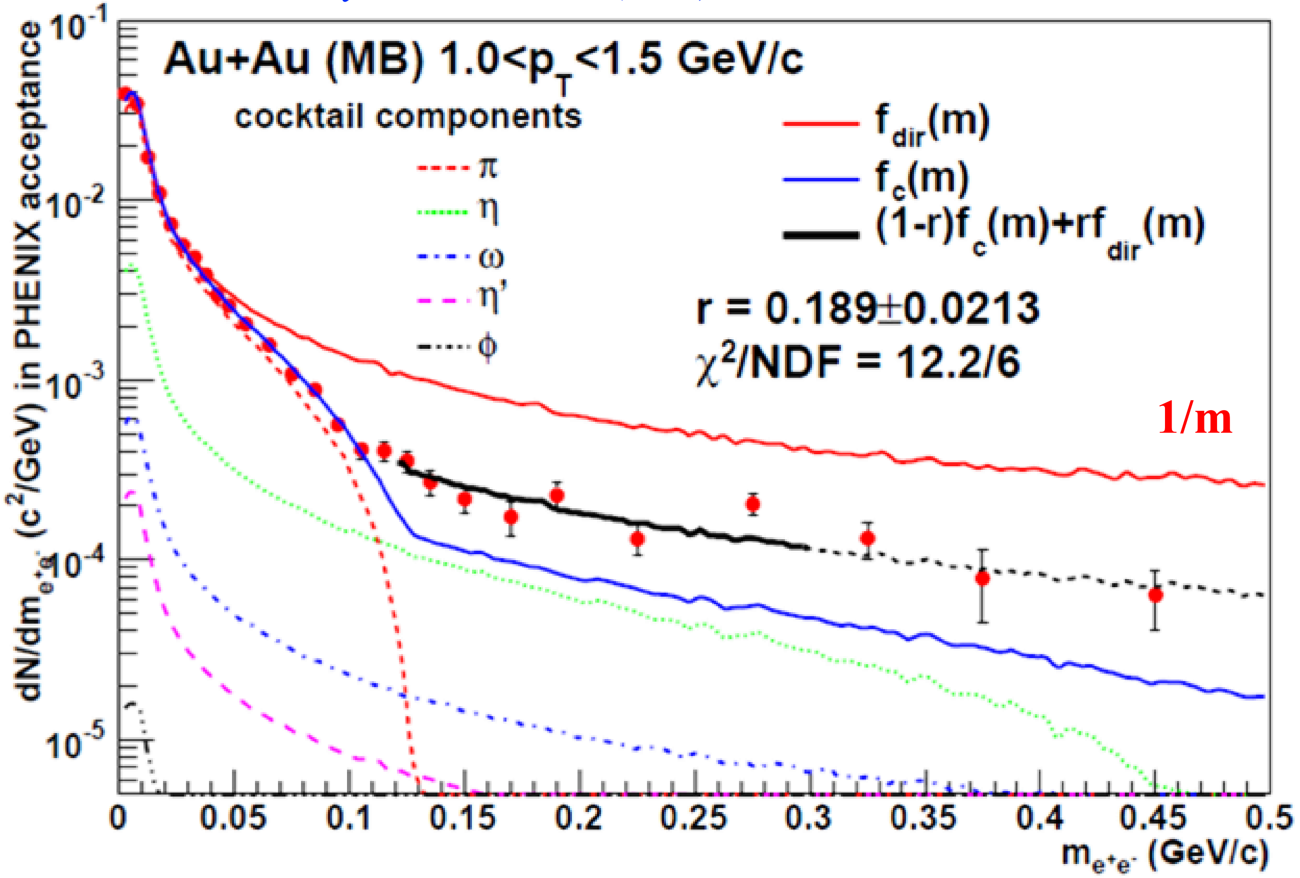
PC1
magnetic field & tracking detectors

PHENIX low p_T Direct Virtual Photon Analyses

$$\frac{d\sigma_{ee}}{dM^2 dp_T^2 dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2 dy}$$

PhD – T. Dahms (2008)

PHENIX: Phys. Rev. Lett. 104 (2010) 132301



Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to π^0 yield

- **Using virtual photons $\gamma^* \rightarrow e^+e^-$:**
  - any process that radiates γ will also radiate γ^*
  - for $m \ll p_T$ extrapolate γ^* to $m = 0$
  - $m > m_\pi$ cut improves S/B by factor 10
  - sys. uncertainty cancelation in ratio $\gamma^*_{dir}/\gamma^*_{incl}$

Increased sensitivity
10% signal relative to $\pi^0 \rightarrow \gamma\gamma$
100% signal relative to $\eta \rightarrow \gamma\gamma$

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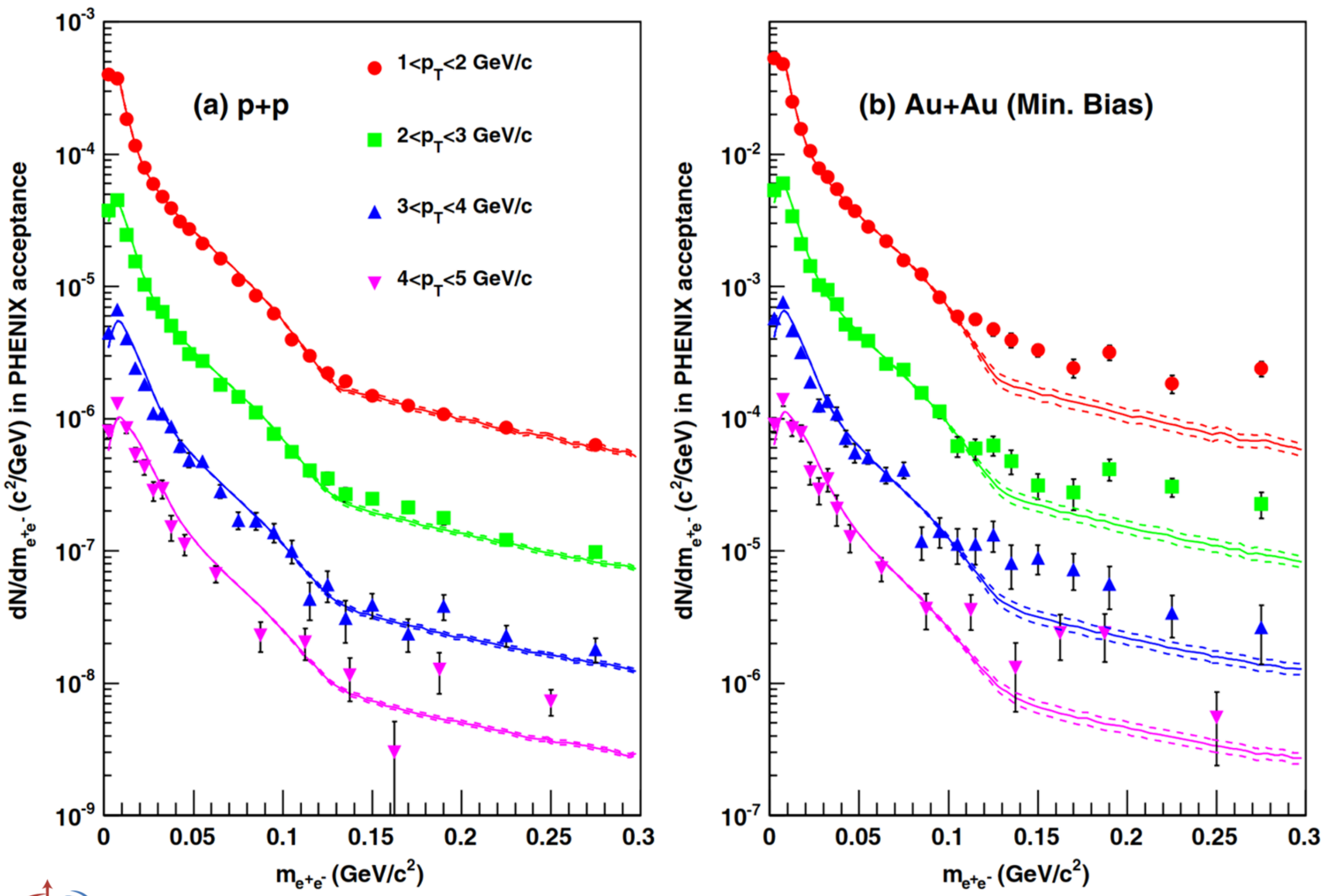
PHENIX Low p_T Direct Virtual Photon Analyses

PHENIX: Phys. Rev. Lett. 104 (2010) 132301



- **Measurement requires accurate knowledge of:**
  - $^{\eta}/_{\pi^0}$ ratio
  - detector resolutions
  - background subtraction

pp data confirm understanding

S/B > 1/10 for p_T > 1 GeV Min. bias AuAu

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PHENIX Direct Photon $\gamma \rightarrow e^+e^-$ (HBD) Measurements

- **Double ratio tagging method minimizes systematic uncertainties**
  - Clean photon sample N_γ with photon conversion
  - Tag π^0 decay photons $N_\gamma^{\pi^0\,tag}$ in N_γ sample
  - Correct for conditional tagging efficiency $\langle \varepsilon f \rangle$
  - Scale for other decay photon contribution

PhD - B. Bannier, R. Petti (2014/2013)

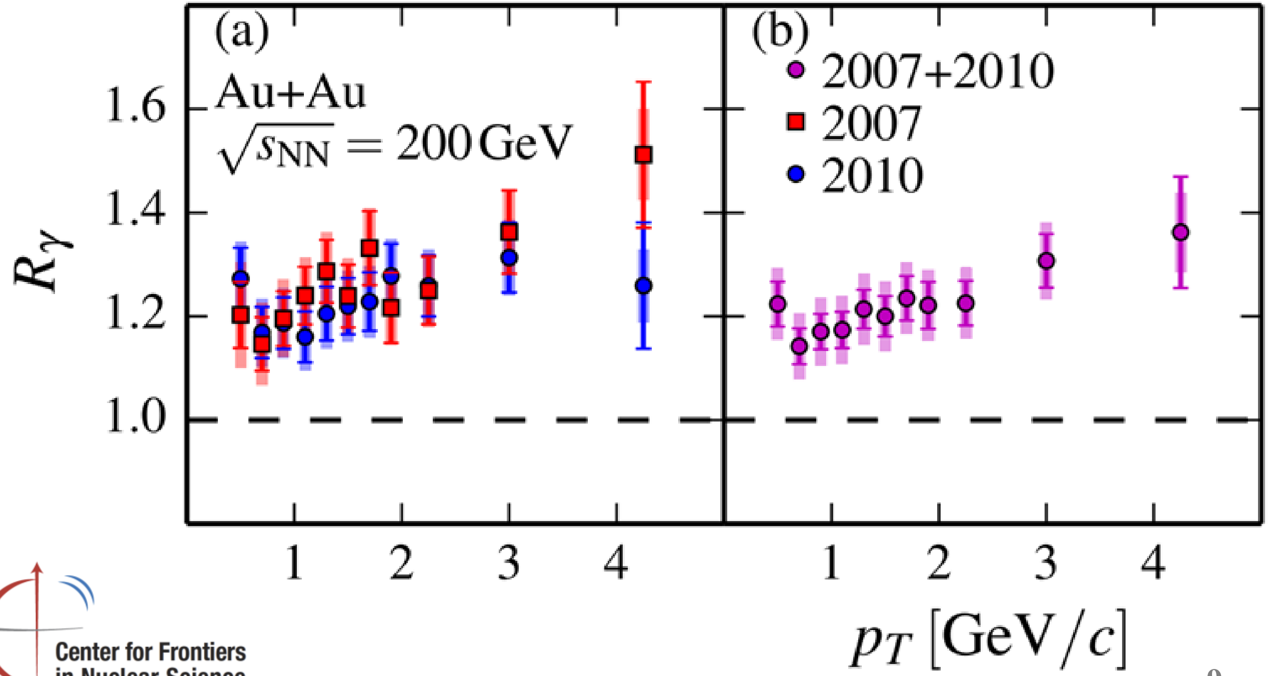
conditional tagging efficiency

measured raw yields

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

simulated based on hadron data

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



2007 & 2010 data sets with HBD

two analyzers
two independent analysis codes
two independent methods for $\langle \varepsilon f \rangle$

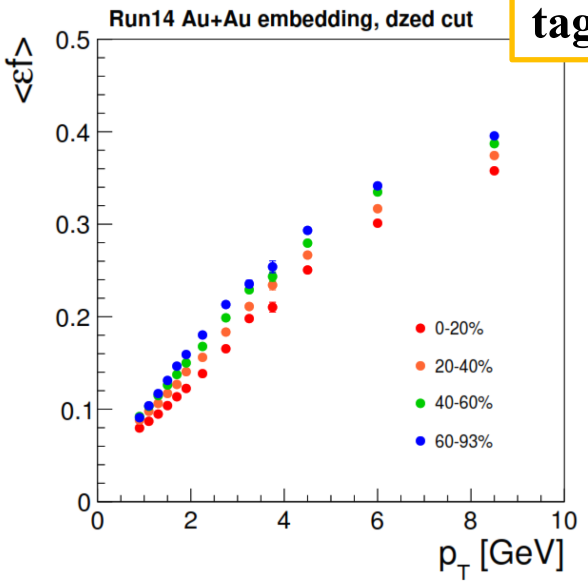
Consistent results

PHENIX Direct Photon $\gamma \rightarrow e^+e^-$ (VTX) Measurements

PHENIX: Phys.Rev.C 109 (2024) 4, 044912

PhD – W.Fan (2019)

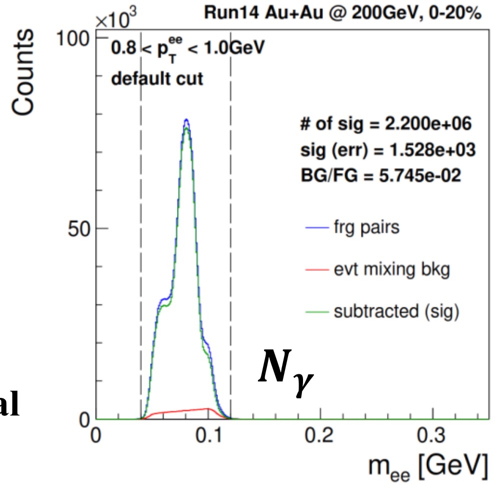
Full MC simulation



conditional tagging efficiency

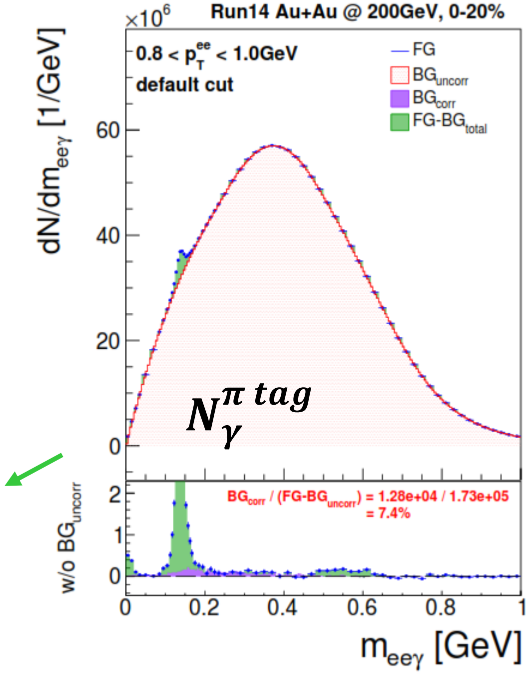
Key contributions

- Energy cut
- Acceptance
- Detector material



Closure test with full high multiplicity MC simulation

measured raw yields



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

η/π^0 ratio main contribution

Photons from hadron decays

2014 high statistics data sets with VTX

independent analyzers
Different detector setup
Full MC closure test

consistent results

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PHENIX Low p_T Direct Photon Analyses

Low pt Direct Photon Spectra

Run	system	energy	type	Thesis			Publication
Run 2004/2005	Au+Au/p+p	200 GeV	γ^*	Dahms	SBU	2008	PRL 104 (2010) 132301 PRC 81 (2010) 34911
Run 2006/2008	p+p/d+Au	200 GeV	γ^*	Yamaguchi	Tokyo	2011	PRC 87 (2013) 54907
Run 2005	Cu+Cu	200 GeV	γ^*	Hoshino	Hiroshima	2017	PRC 98 (2018) 54902
Run 2007	Au+Au	200 GeV	$\gamma \rightarrow ee$	Petti	SBU	2013	PRC 91 (2015) 64904
Run 2010	Au+Au	200 GeV	$\gamma \rightarrow ee$	Bannier	SBU	2014	
Run 2004	Au+Au	200 GeV	γ	Gong	SBU	2014	-
Run 2010	Au+Au	39/62 GeV	$\gamma \rightarrow ee$	Khachatryan	SBU	2015	PRL 123 (2019) 022301 PRC 107 (2023) 024914
Run 2014/2015	Au+Au/p+Au	200 GeV	$\gamma \rightarrow ee$	Fan	SBU	2020	PRC 109 (2024) 044912

Low pt Direct Photon Azimuthal Anisotropy

Run	system	energy	type	Thesis			Publication
Run 2004	Au+Au	200 GeV	γ	Miki	Tsukuba	2009	PRL109 ((2012) 122302
Run 2010	Au+Au	200 GeV	$\gamma \rightarrow ee$	Bannier	SBU	2014	PRC 94 (2016) 64901
Run 2007	Au+Au	200 GeV	γ	Mizuno	Tsukuba	2015	
Run 2014	Au+Au	200 GeV	$\gamma \rightarrow ee$	Giles	SBU	2024	arXiv:2504.02955

γ^* analyses
pp, dAu, AuAu, CuCu

$\gamma \rightarrow e^+e^-$ (HBD)
AuAu 39, 62.4, 200 GeV

$\gamma \rightarrow e^+e^-$ (VTX)
AuAu 200 GeV

ongoing analyses:
$\gamma \rightarrow e^+e^-$ (VTX)
pp, pAu, CuAu 200 GeV

Multiple independent analyses with significant crosschecks
3 different methods, 11 theses, 10 publications

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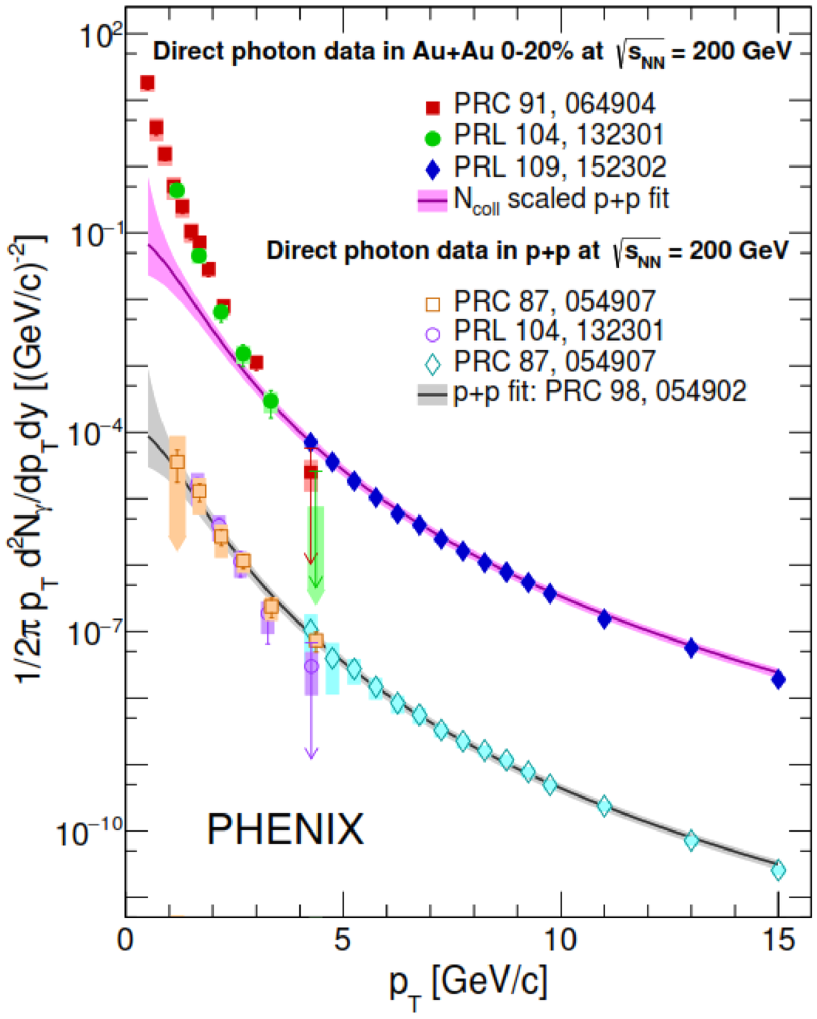
Direct Photons in p+p and Au+Au at $\sqrt{s_{NN}}$= 200 GeV

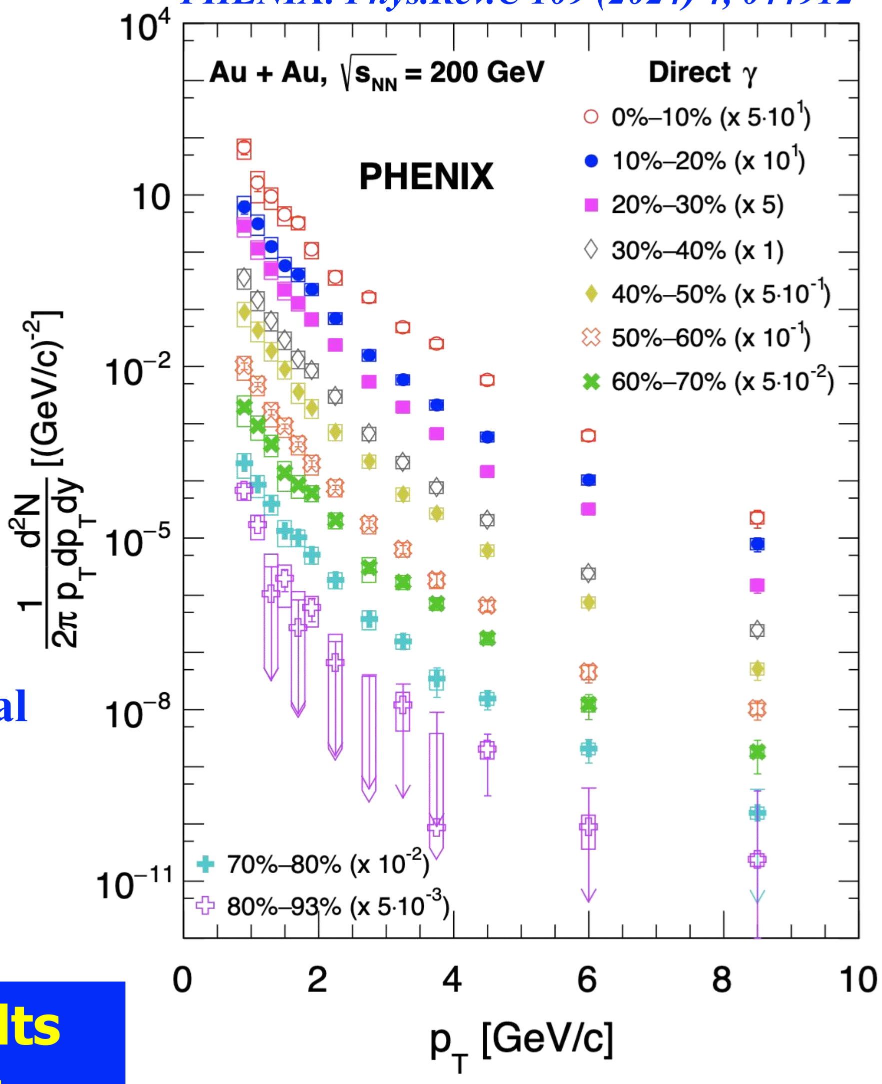
PHENIX: Phys. Rev. C 107 (2023) 2, 024914



- **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 close to exponential shape with T_{eff} ~ 240 MeV**

High statistics Au+Au results reveal universal features

PHENIX: Phys.Rev.C 109 (2024) 4, 044912



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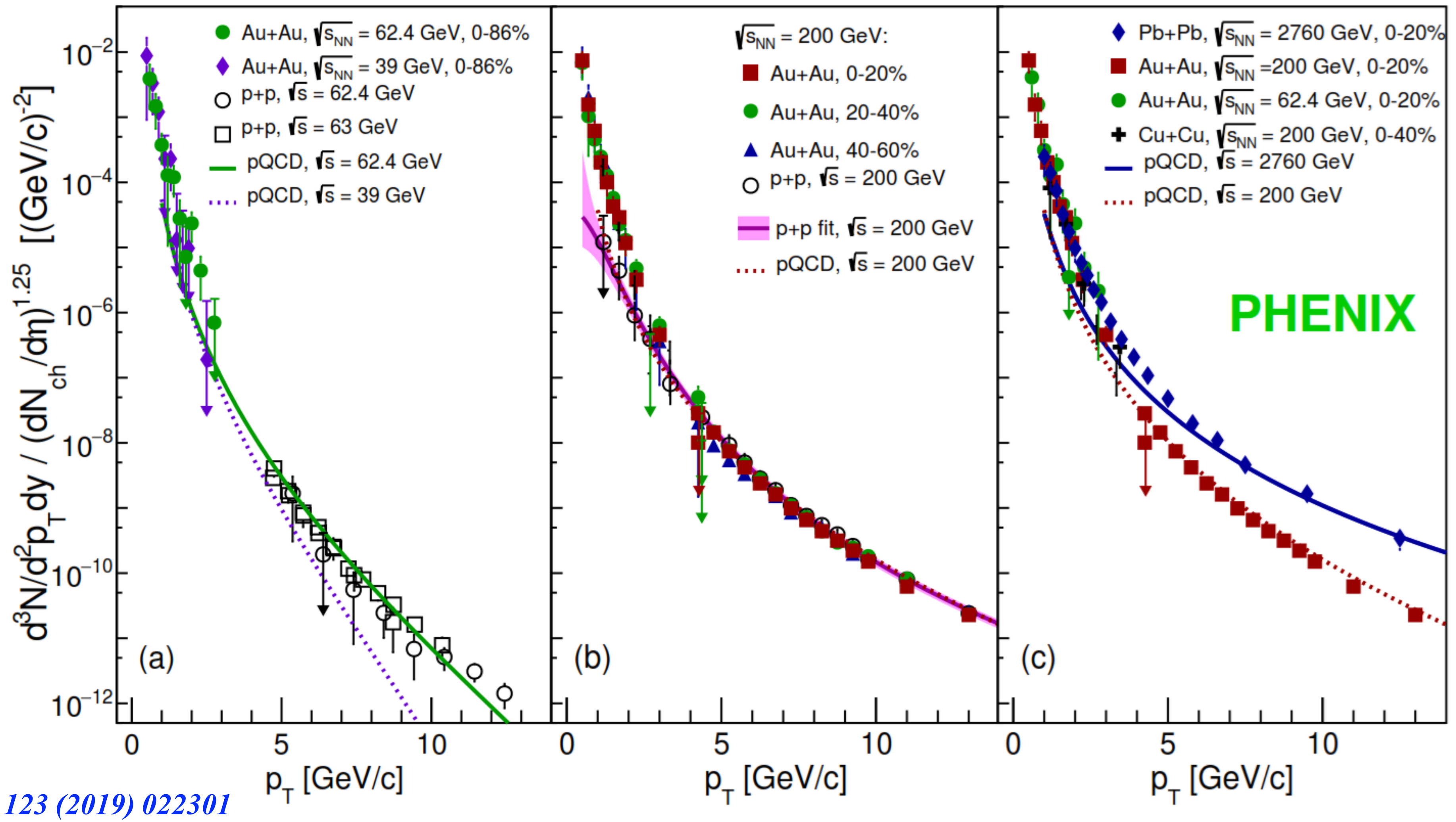
System Size and Energy Dependence of Spectral Shape



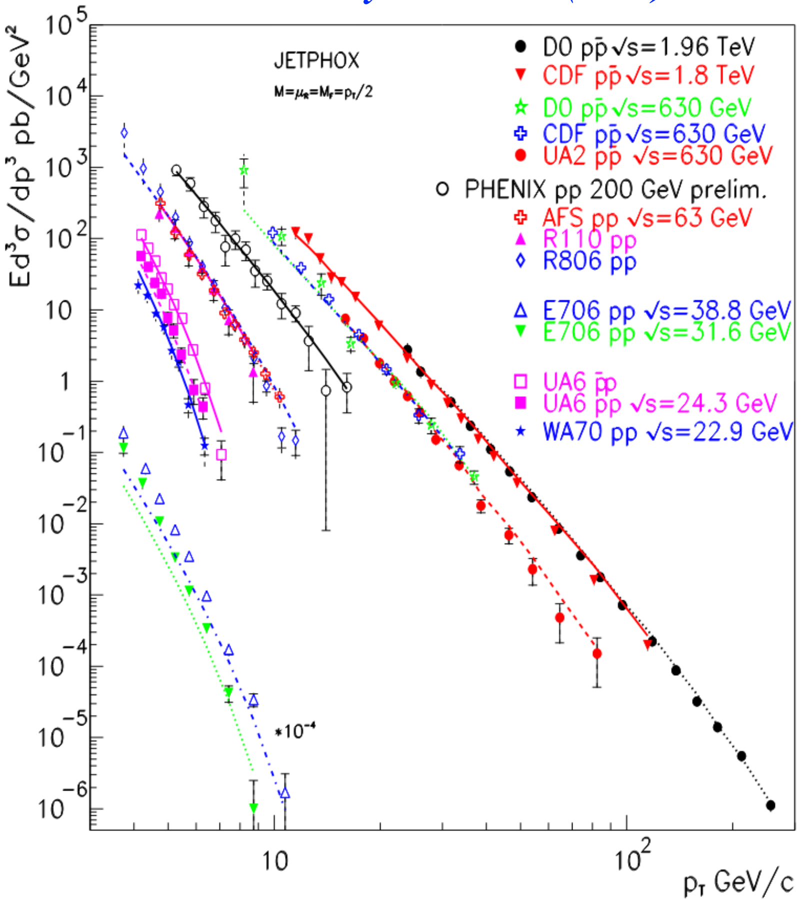
PHENIX: Phys. Rev. Lett. 123 (2019) 022301

Similar thermal photon yield when scaled with $\frac{dN_{ch}}{d\eta}^{1.25}$

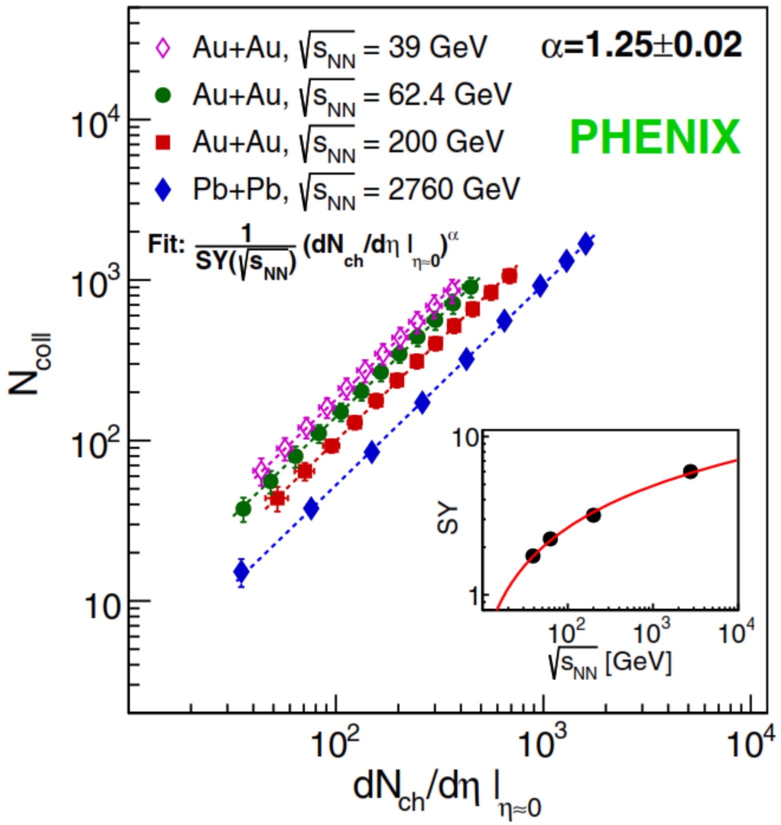
independent of energy, centrality, or system size suggests similar conditions at emission

Prompt Photon Production Cross Section

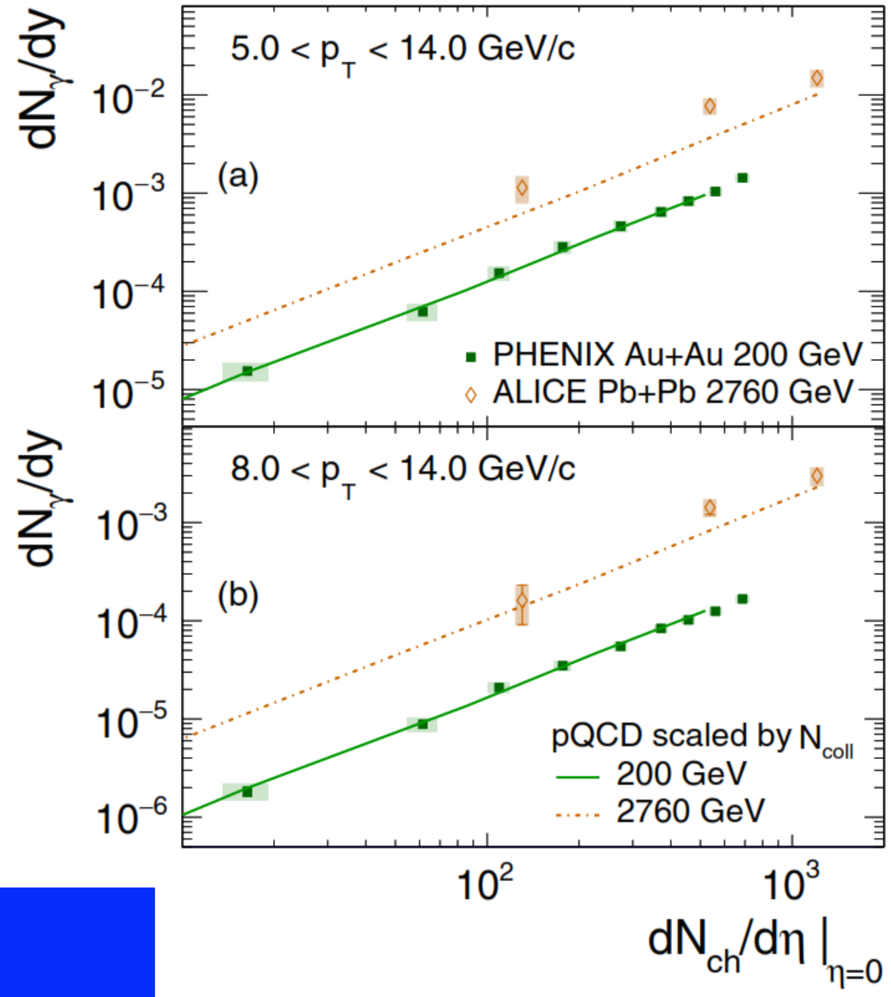
Aurenche et al: Phys. Rev. D73 (2006) 094007



PHENIX: Phys. Rev. Lett. 123 (2019) 022301



PHENIX: Phys. Rev. C 107 (2023) 2, 024914



Calcuable with pQCD

Scales with $N_{coll} \sim (N_{ch})^{1.25}$

from RHIC to LHC energies

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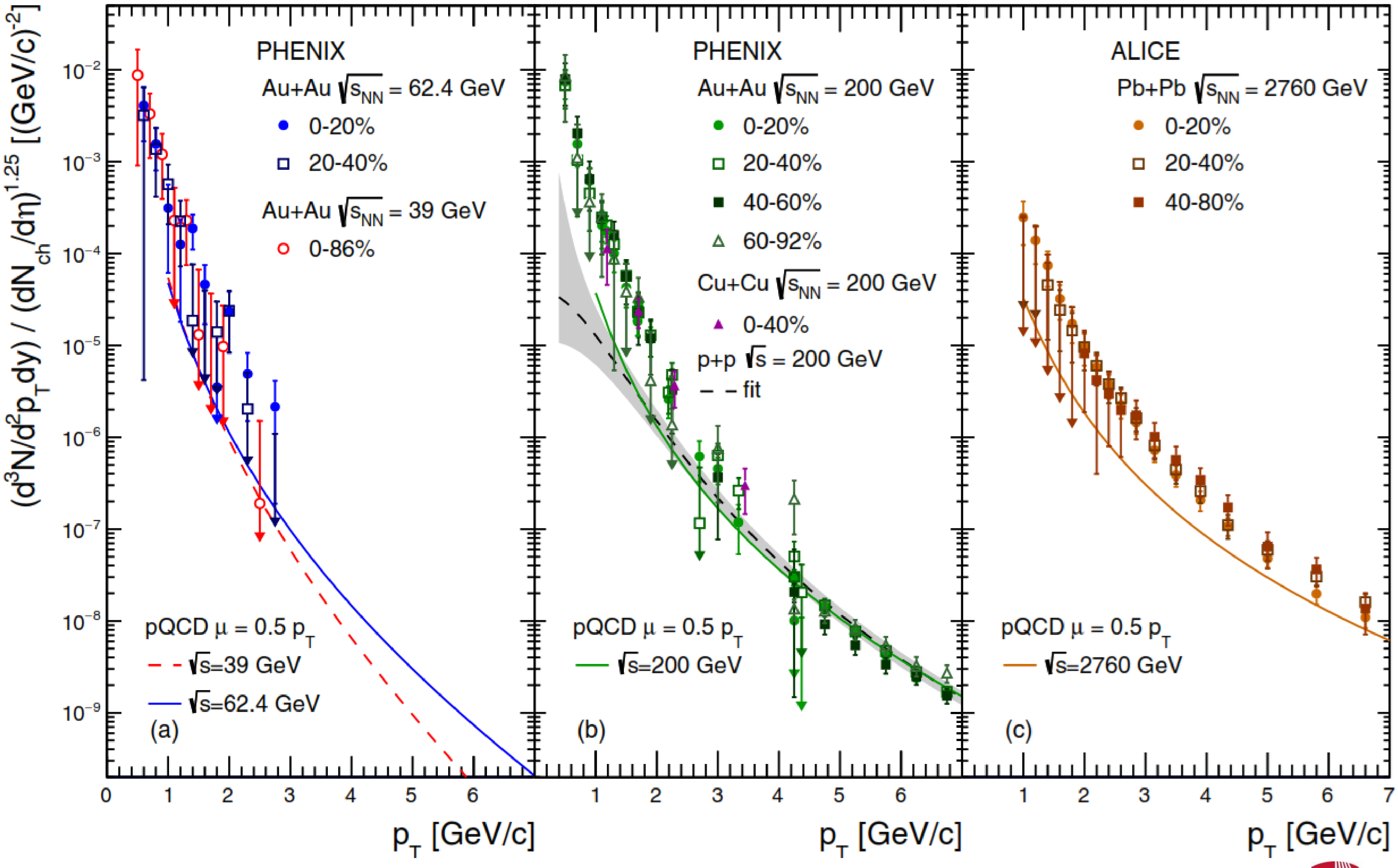
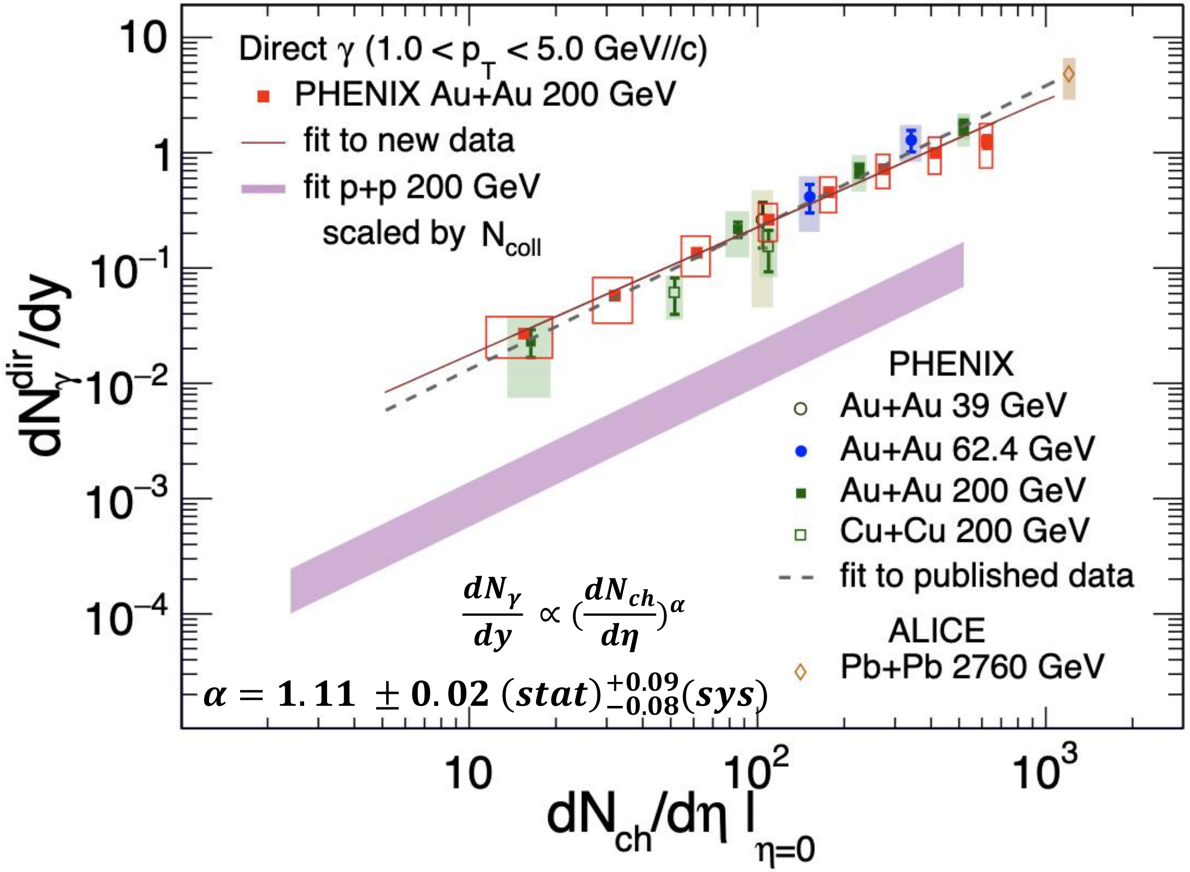
Low p_T "Thermal" Photon Region

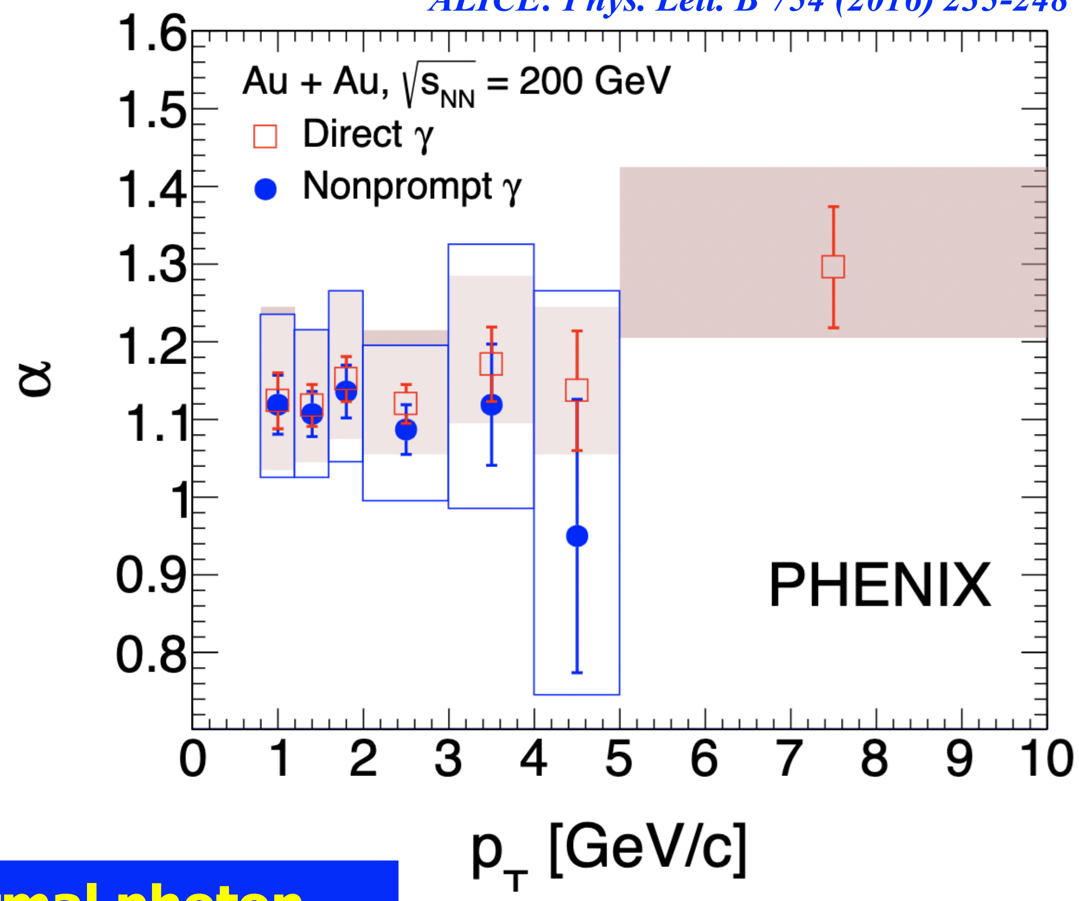
PHENIX: Phys. Rev. C 107 (2023) 2, 024914



System Size and Energy Dependence of Direct Photon Yield

PHENIX: Phys. Rev. C 109 (2024) 4, 044912
PHENIX: Phys. Rev. C 107 (2023) 2, 024914
ALICE: Phys. Lett. B 754 (2016) 235-248





Scaling behavior of thermal photon yields in all A+A with $N_\gamma^{dir} \sim (N_{ch})^{1.1}$ with no obvious dependence on p_T

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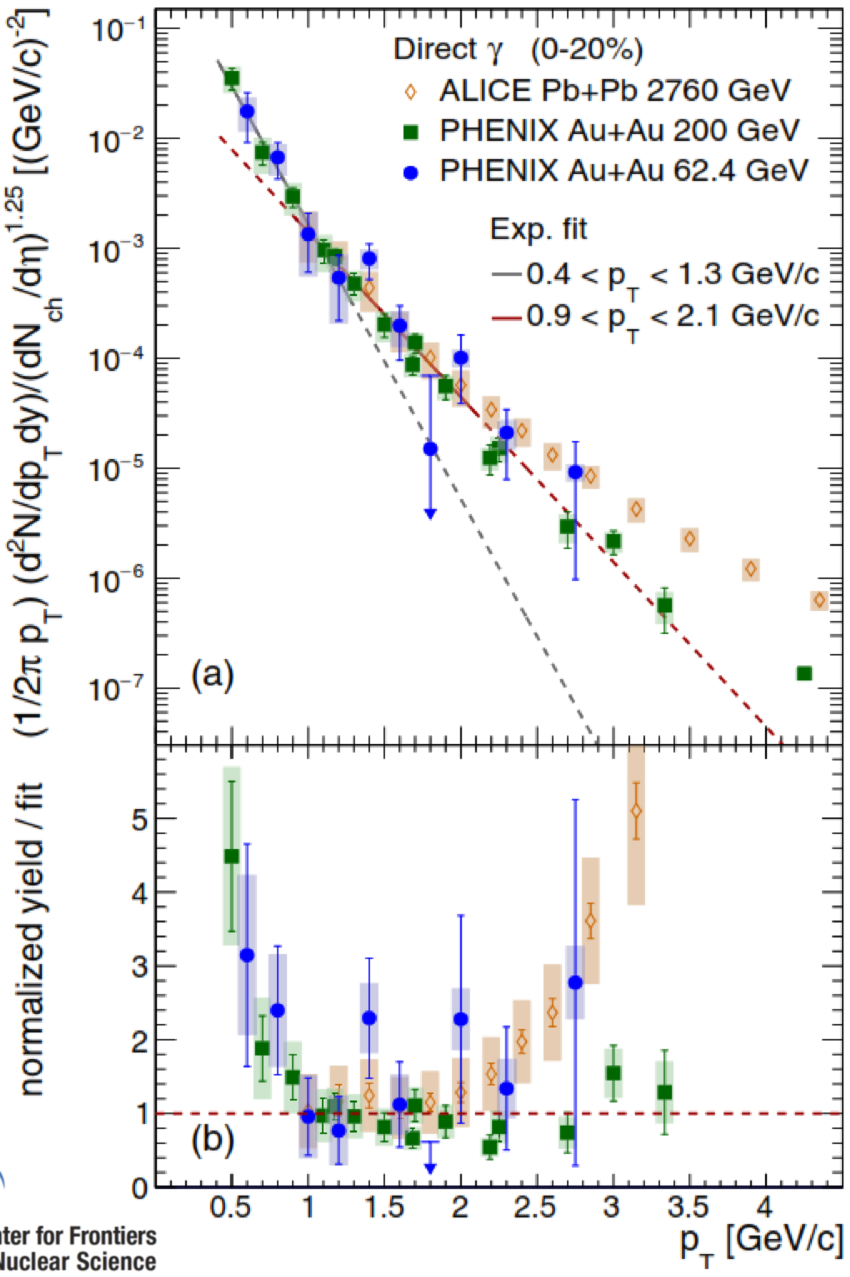
Energy Dependence of Spectral Shape



PHENIX: Phys. Rev. C 109 (2024) 4, 044912
PHENIX: Phys. Rev. C 107 (2023) 2, 024914
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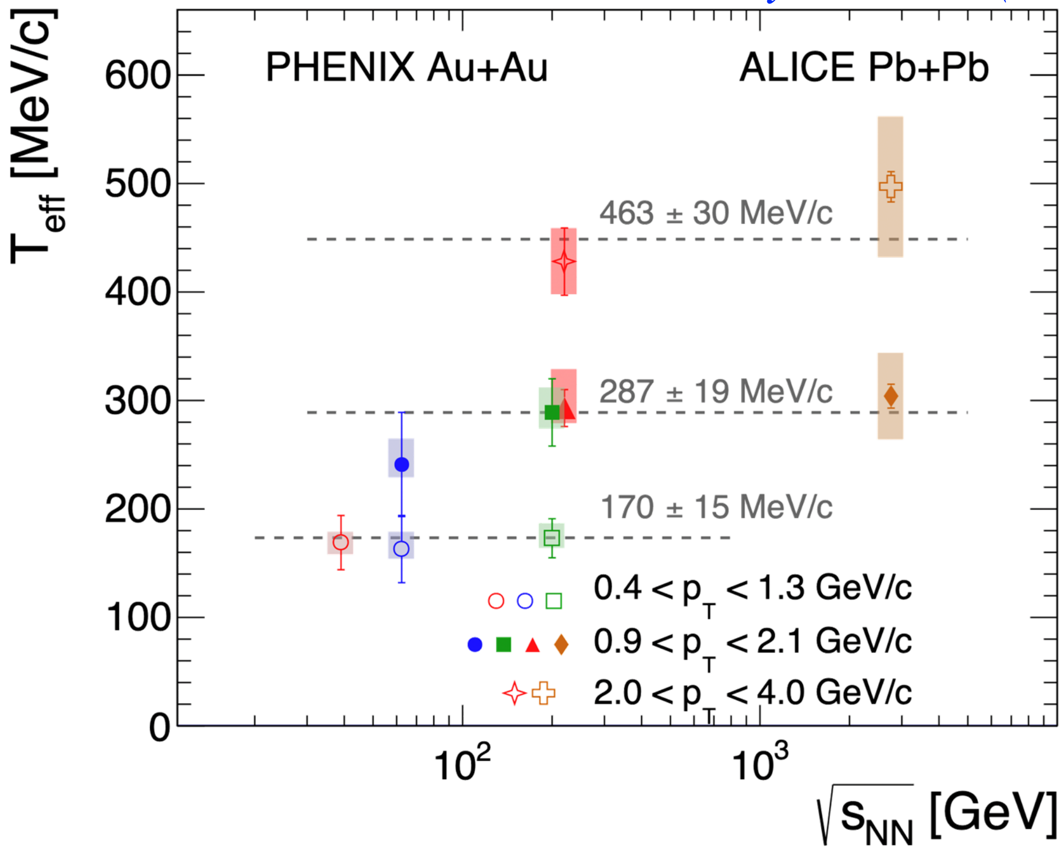

T_{eff} increases with p_T

No obvious variation of T_{eff} with $\sqrt{s_{NN}}$

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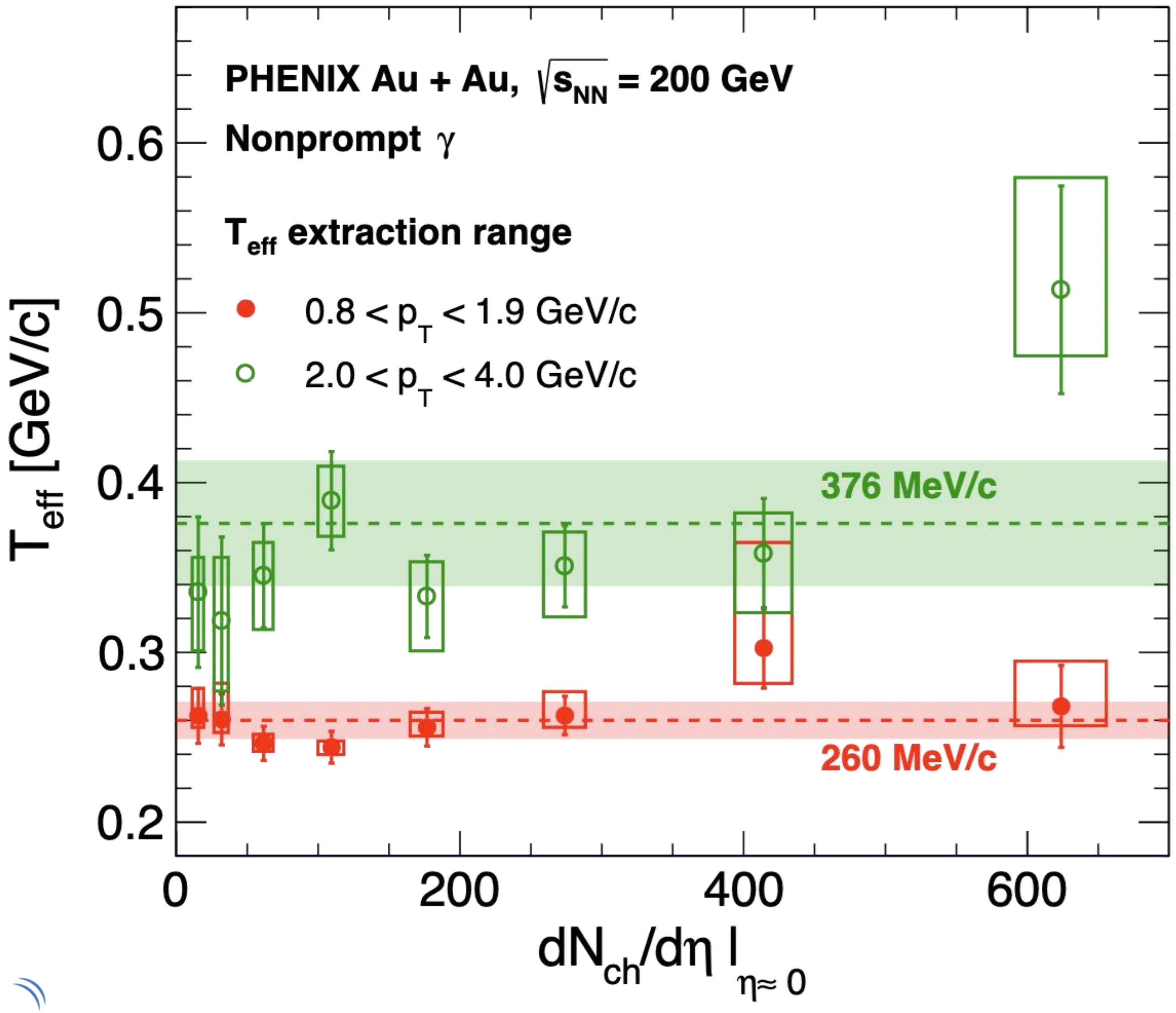
Centrality or System Size Dependence of Spectral Shape

PHENIX: Phys. Rev. C 109 (2024) 4, 044912

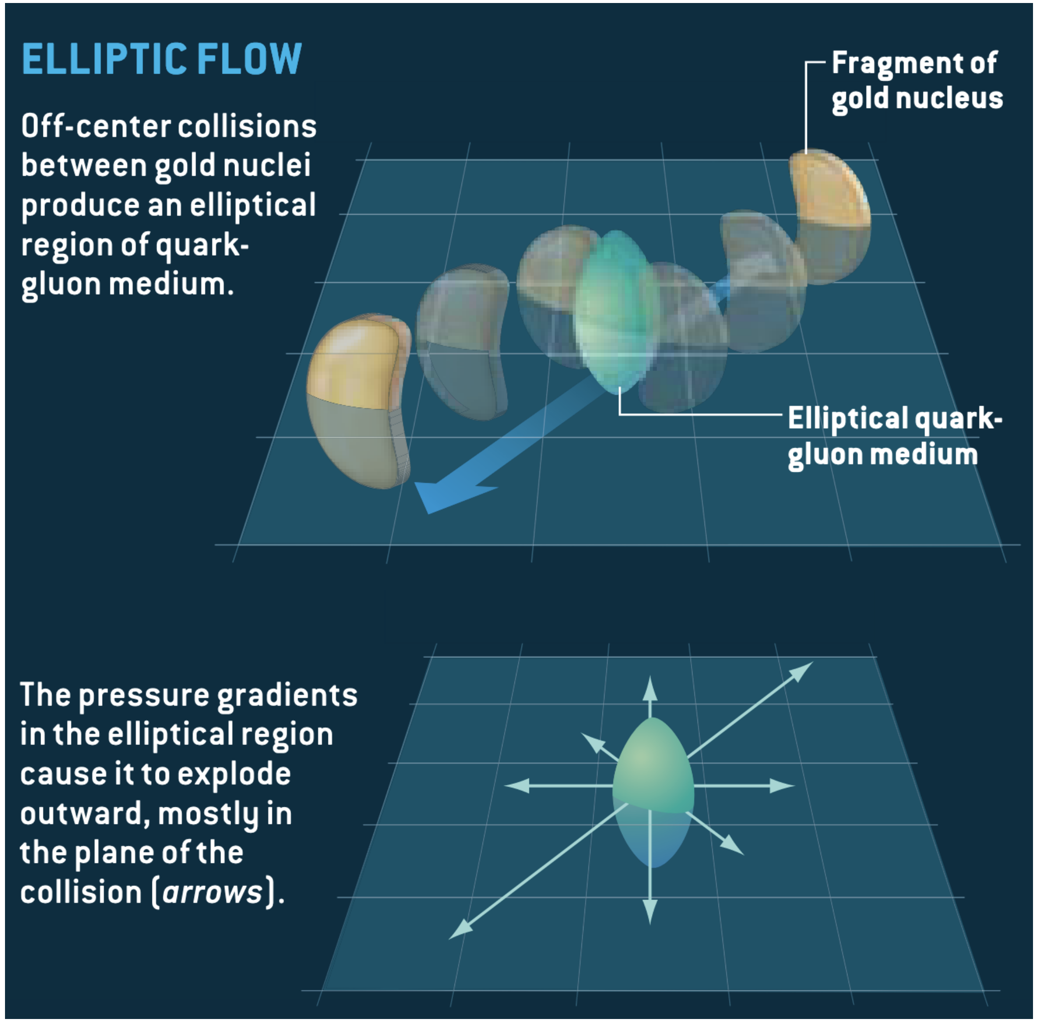


- **Nonprompt direct photons, i.e. photons from the fireball**
  - Teff increases with pt
  - No obvious centrality dependence
- **T_{eff} ~ 260 MeV for 0.8 < p_T < 1.9 GeV**
  - Consistent with emission at chemical equilibrium + blue shift
- **T_{eff} ~ 370 MeV for 2.0 < p_T < 4.0 GeV**
  - Consistent with earlier emission, possible from pre-equilibrium phase

Data suggest bulk of emission near phase boundary

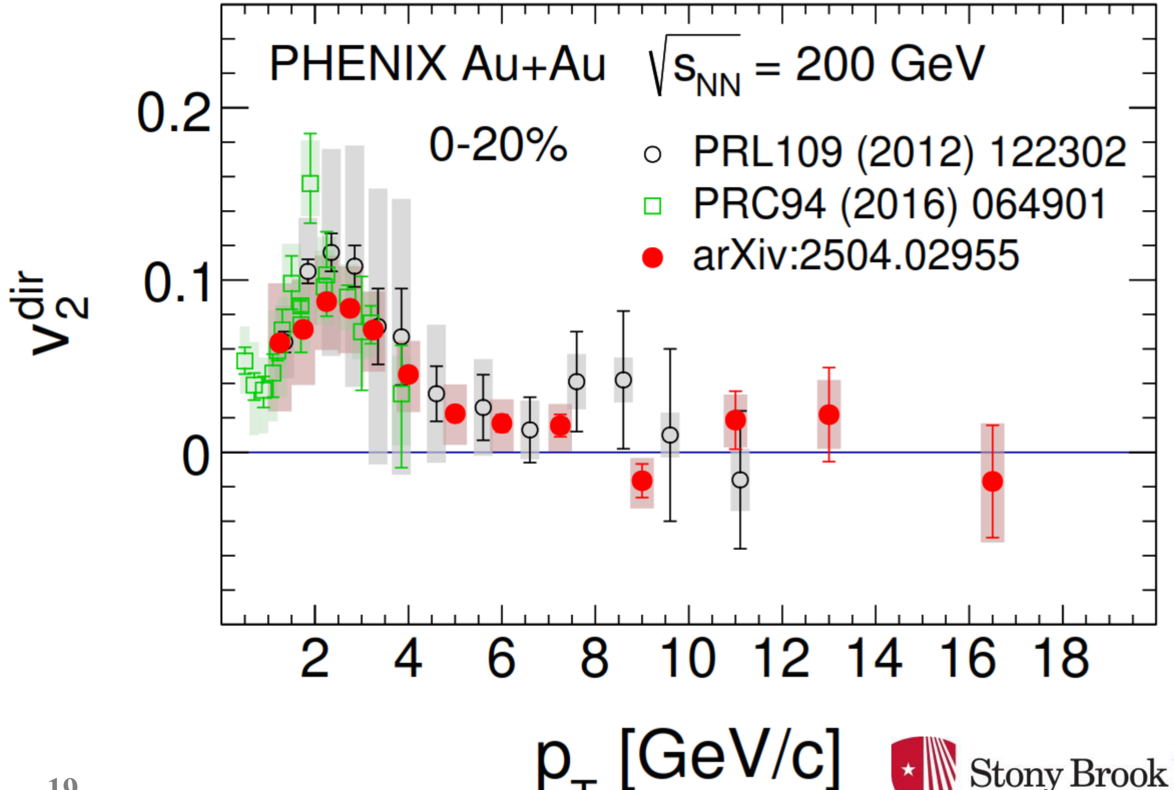
Indication of preequilibrium emission

Azimuthal Anisotropy of Direct Photon Production



- **Fireball from collision rapidly expands**
  - **Radial flow with anisotropy with respect to the reaction plane (elliptic flow)**
- **Direct photons emitted from collectively expanding matter**
  - **Anisotropic Doppler shift**

PHENIX: arXiv:2504.02955



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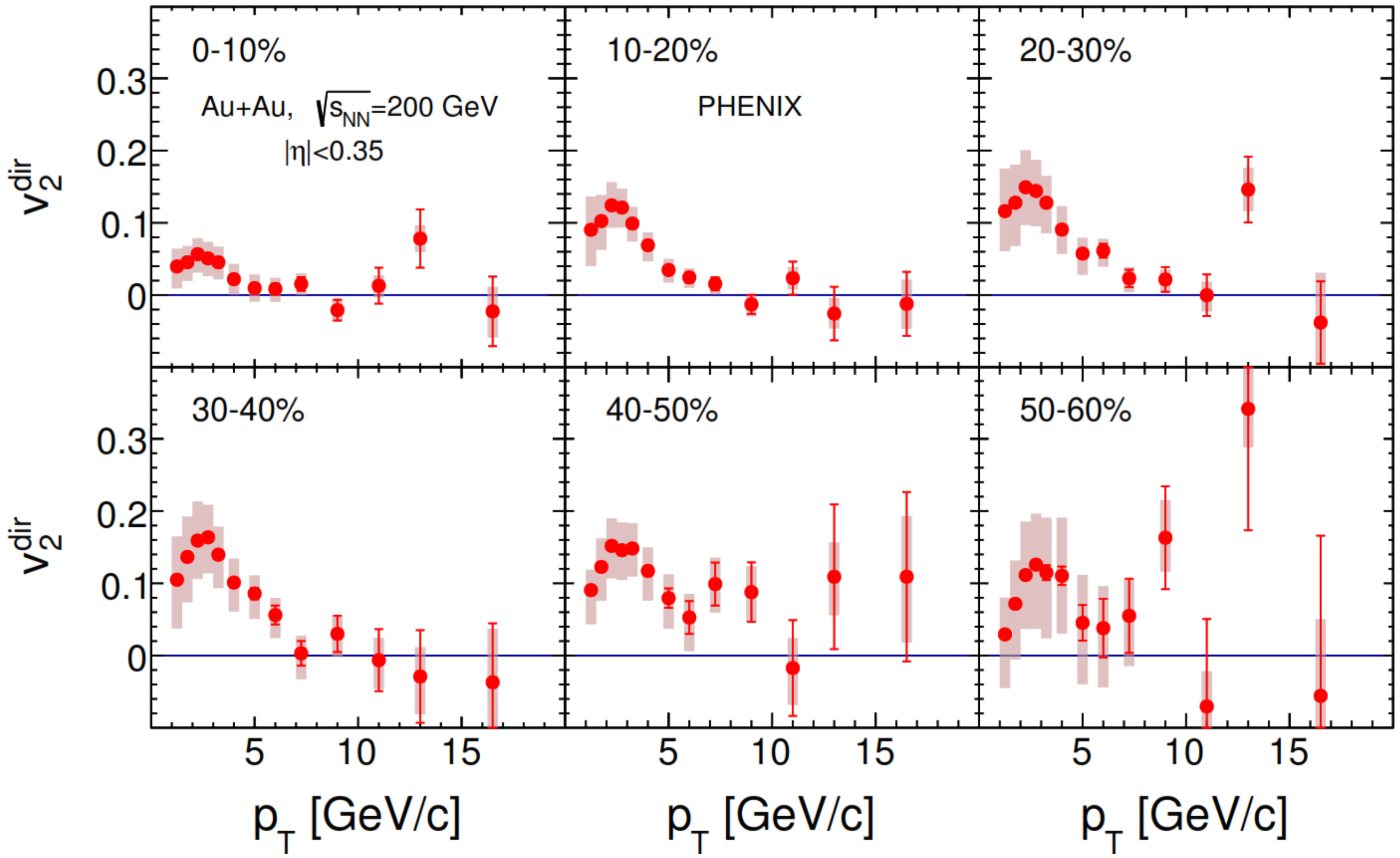
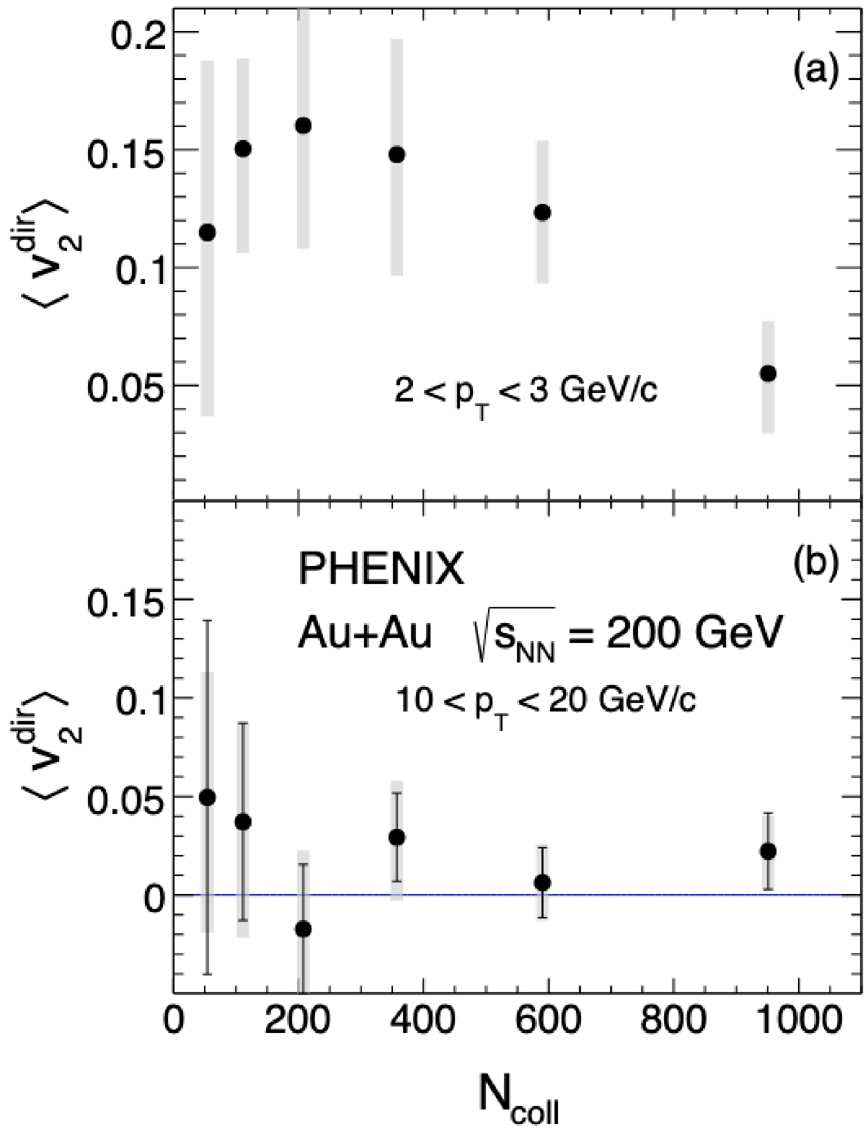
Direct Photon Azimuthal Anisotropy

PHENIX: arXiv:2504.02955





Low p_T v_2^{dir} as large as hadrons
High p_T v_2^{dir} consistent with zero

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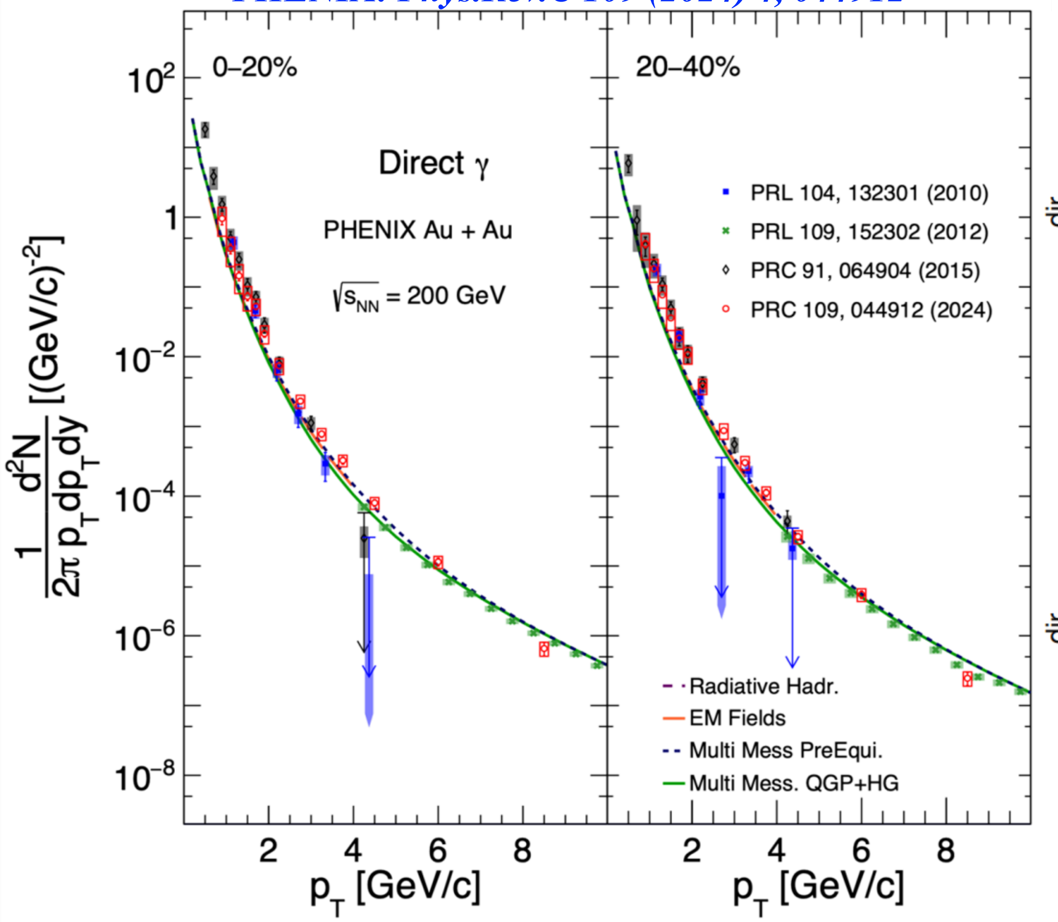
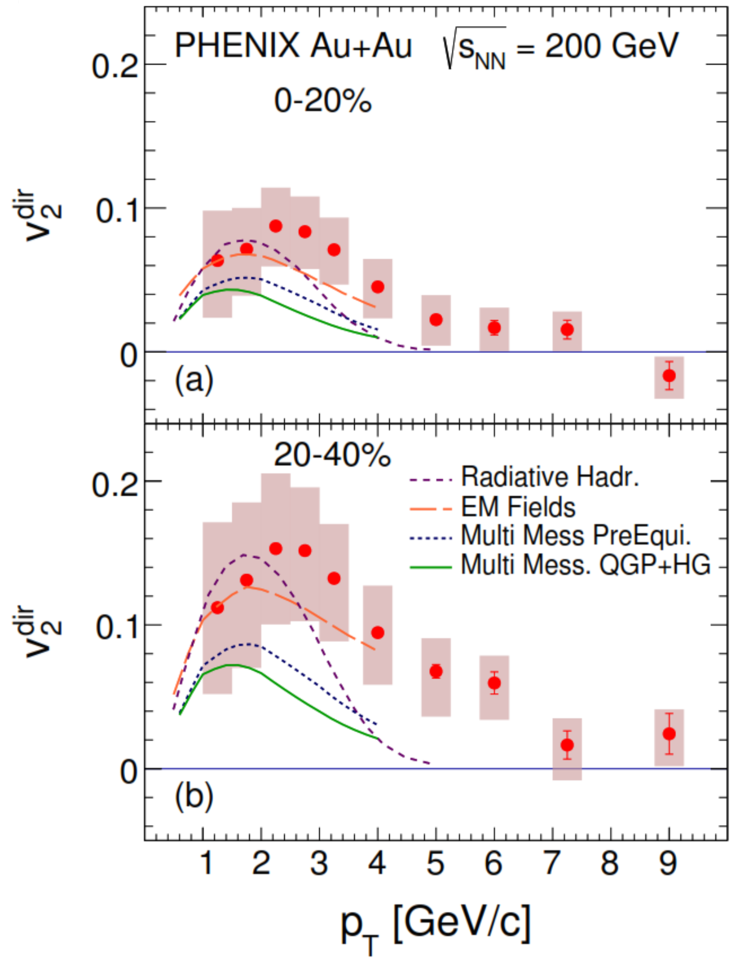
Comparison to Multi Messenger+ Model Calculations

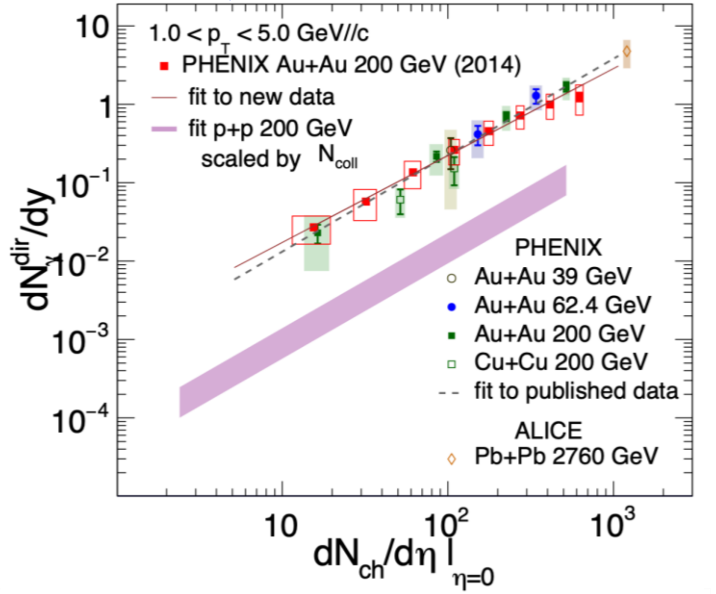
PHENIX: Phys.Rev.C 109 (2024) 4, 044912

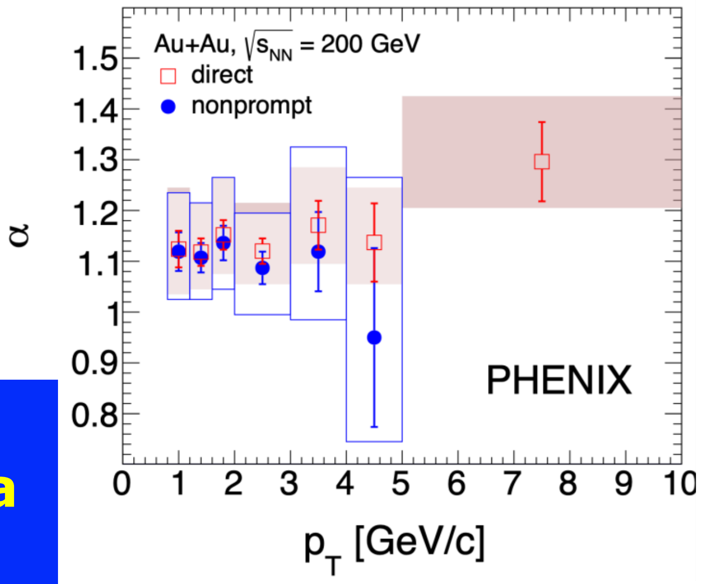


PHENIX: arXiv:2504.02955



PHENIX: Phys.Rev.C 109 (2024) 4, 044912





Model Calculations:

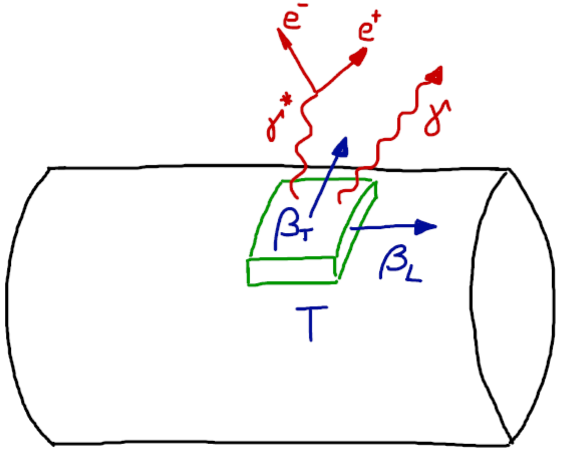
Gales et al. Phys. Rev. C 105 (2022) 014909

Sun et al. Nucl.Phys.Rev. 41 (2024) 558

Fujii et al. Acta Phys. Polon. Supp. 16 (2023) 1

Thermal Photon Puzzle:
Models qualitatively reproduce data
but fall short quantitatively

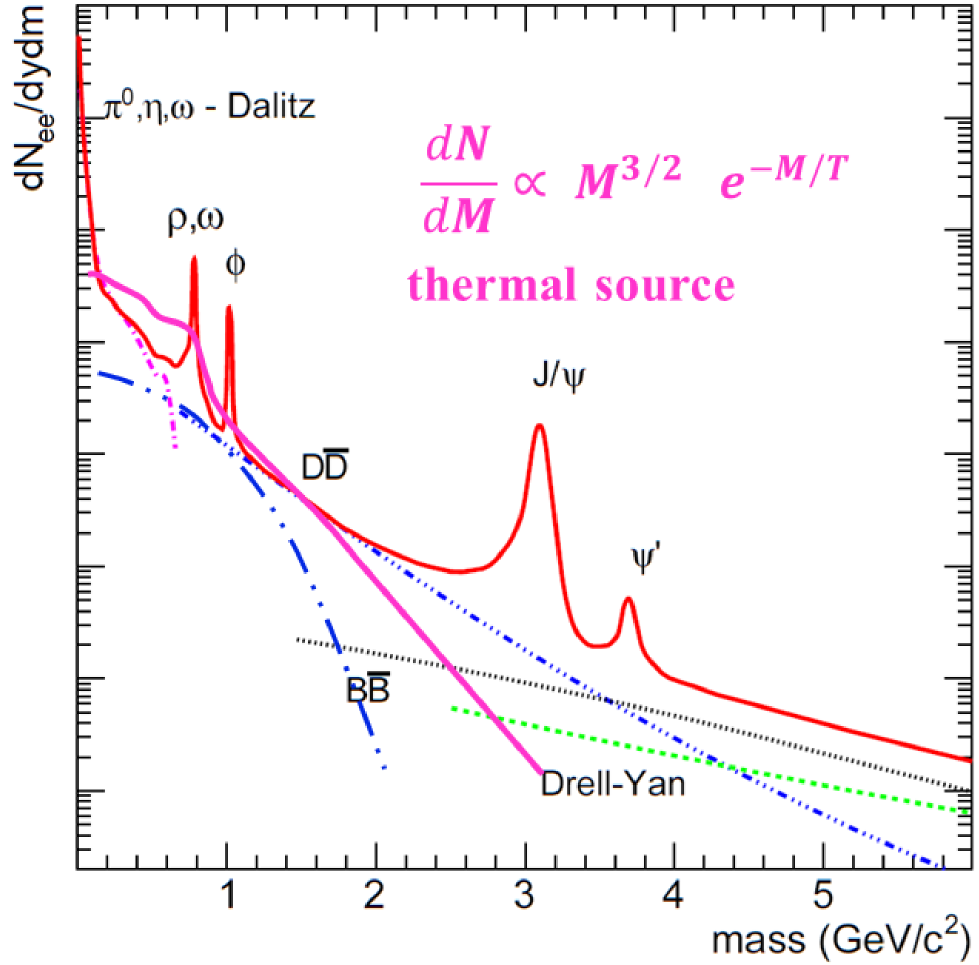
Virtual Photon (e^+e^- Pair) Continuum Measurement in PHENIX



Requires high statistics and simultaneous measurement of open heavy flavor pairs

PHENIX 2014 (2016) datasets
19B (34B) Au+Au events

Schematic Dilepton Spectrum



$$\frac{dN}{dM} \propto M^{3/2} \; e^{-M/T}$$

thermal source

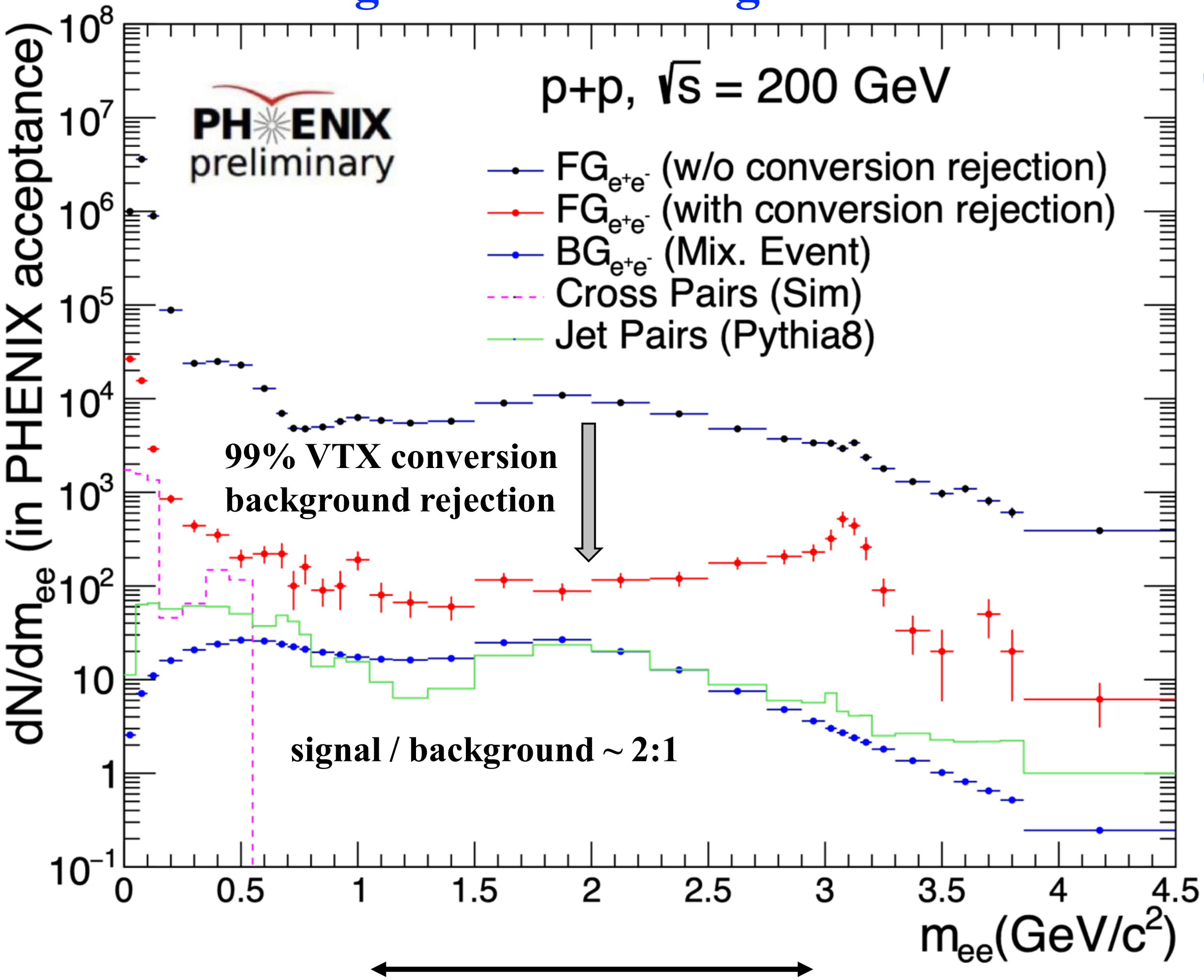
Direct Measurement of the Temperature

- **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

Proof of Principle: p+p Collisions with Vertex Tracker (VTX)

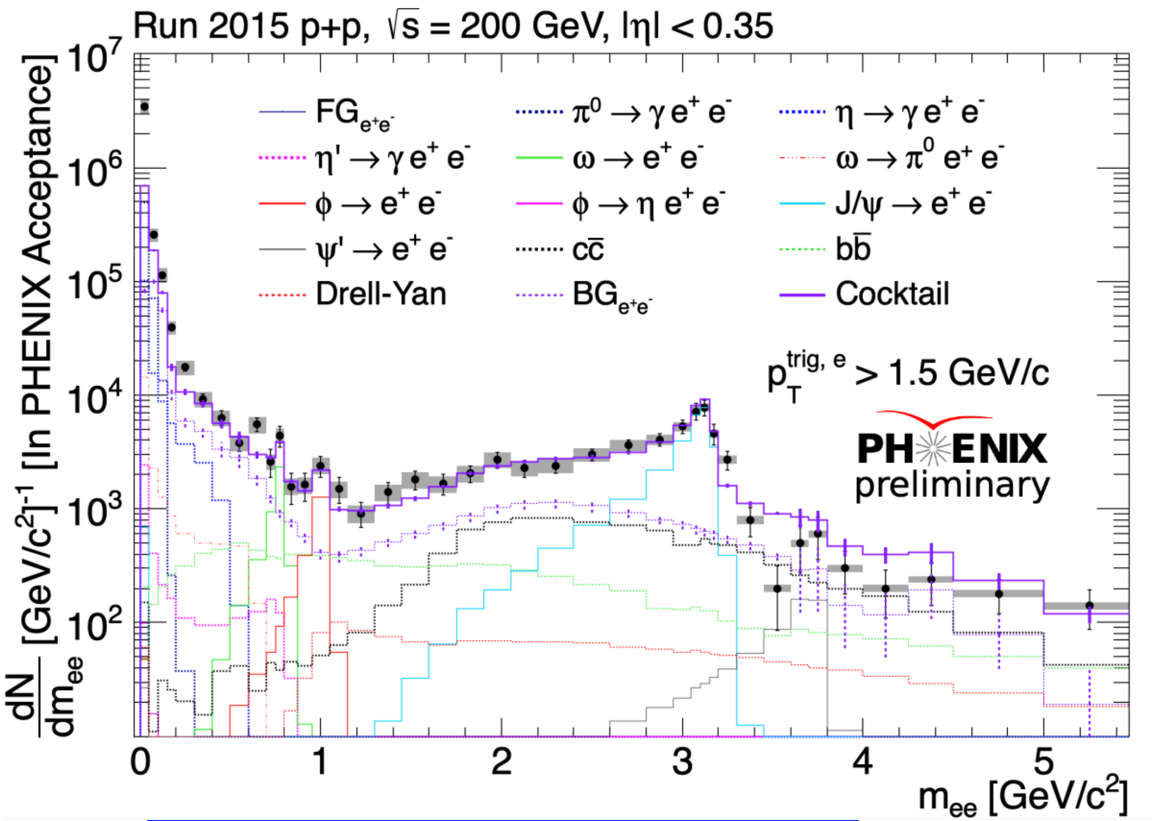
PhD – V. Doomra (2025)

Foreground and Background



mass region of interest

Signal = Foreground - Background

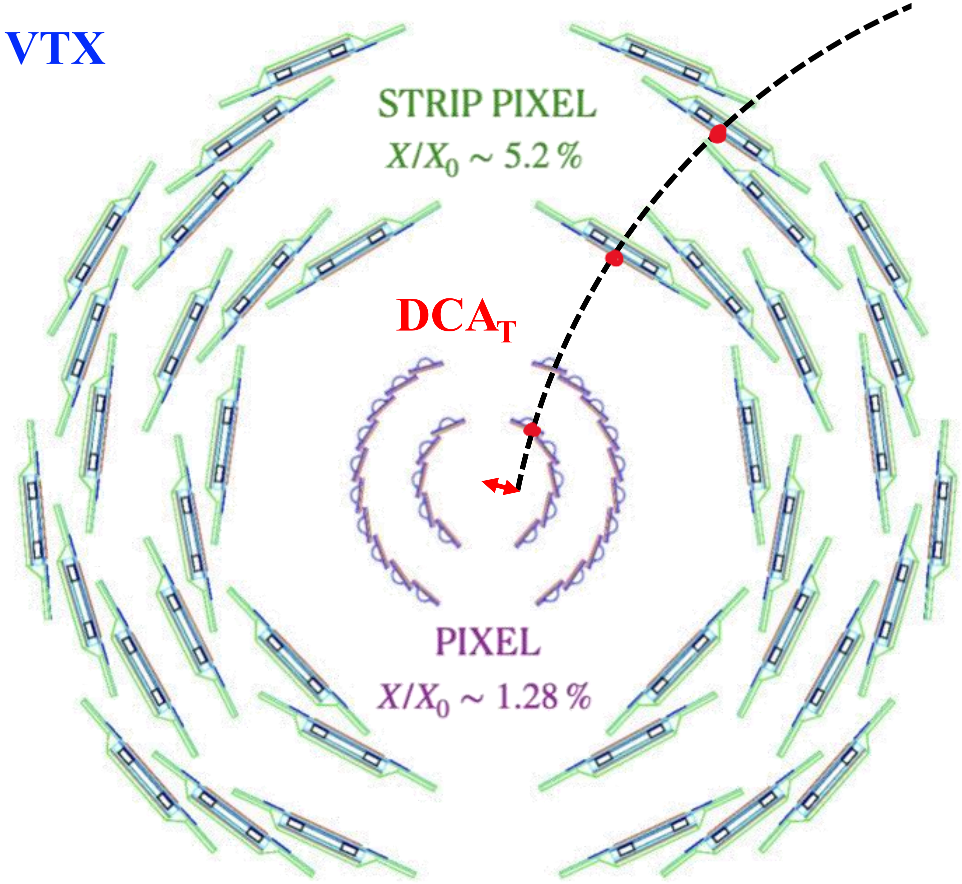


Clear signal in heavy flavor region

Separating Prompt and Heavy Flavor Signal

PhD – V. Doomra (2025)

- **Transverse Distance of Closest Approach**
  - **Require 2+ hits – PIXEL and STRP PIXEL layer of VTX**
  - **Momentum measurement from DC/PC1 tracking**
  - **Constant magnetic field**



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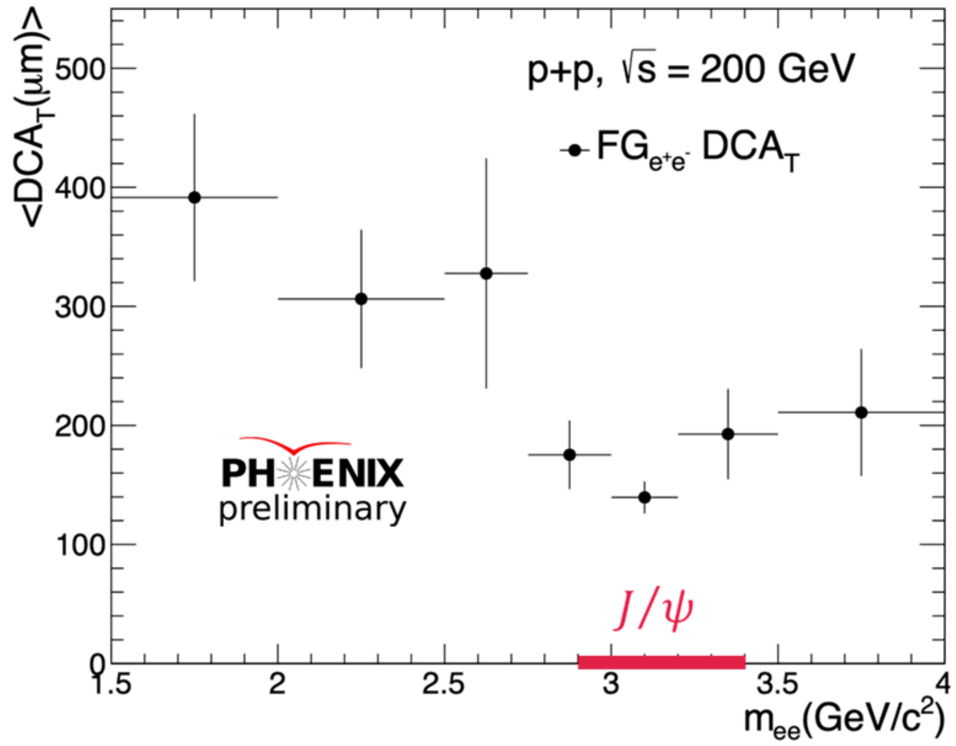
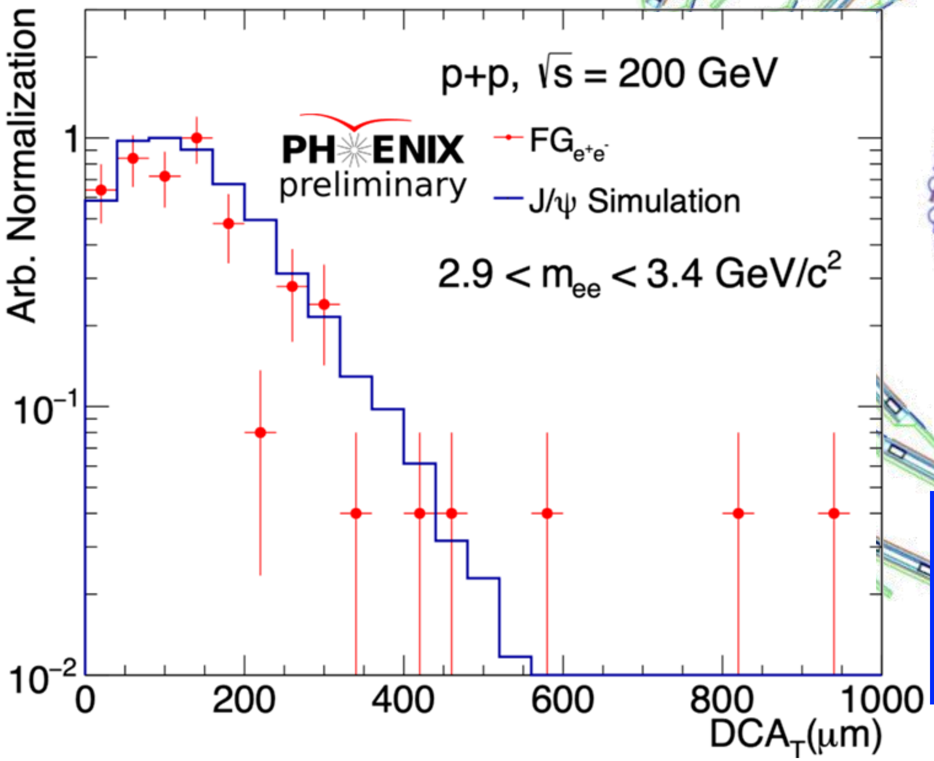
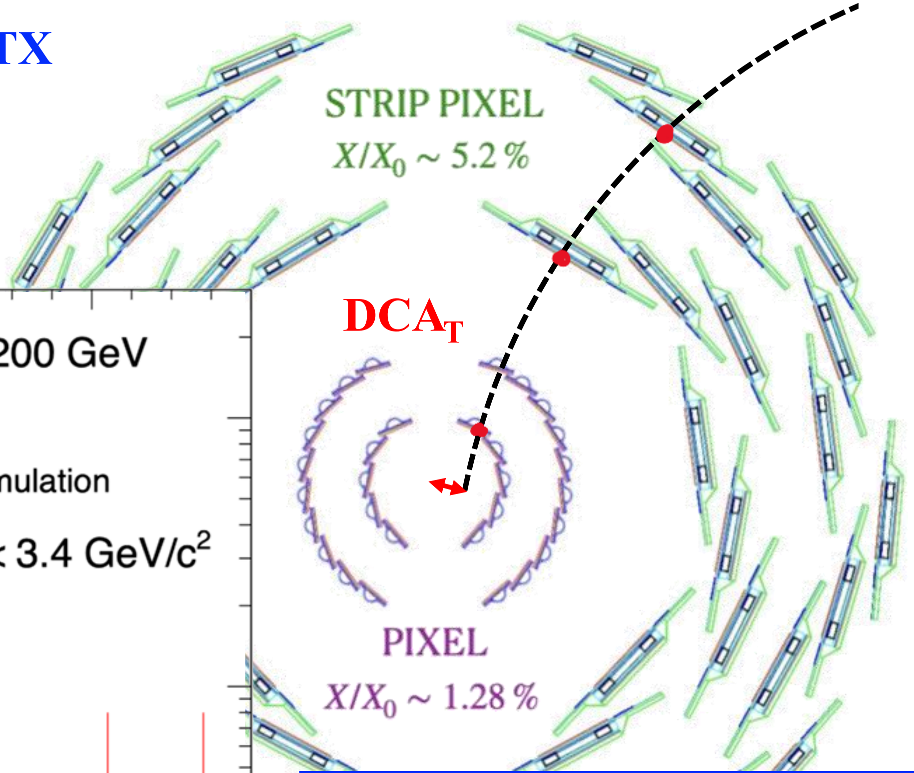
Separating Prompt and Heavy Flavor Signal

PhD – V. Doomra (2025)

- **Transverse Distance of Closest Approach DCA_T**
  - **Require 2+ hits – PIXEL and STRP PIXEL layer of VTX**
  - **Momentum measurement from DC/PC1 tracking**
  - **Constant magnetic field**

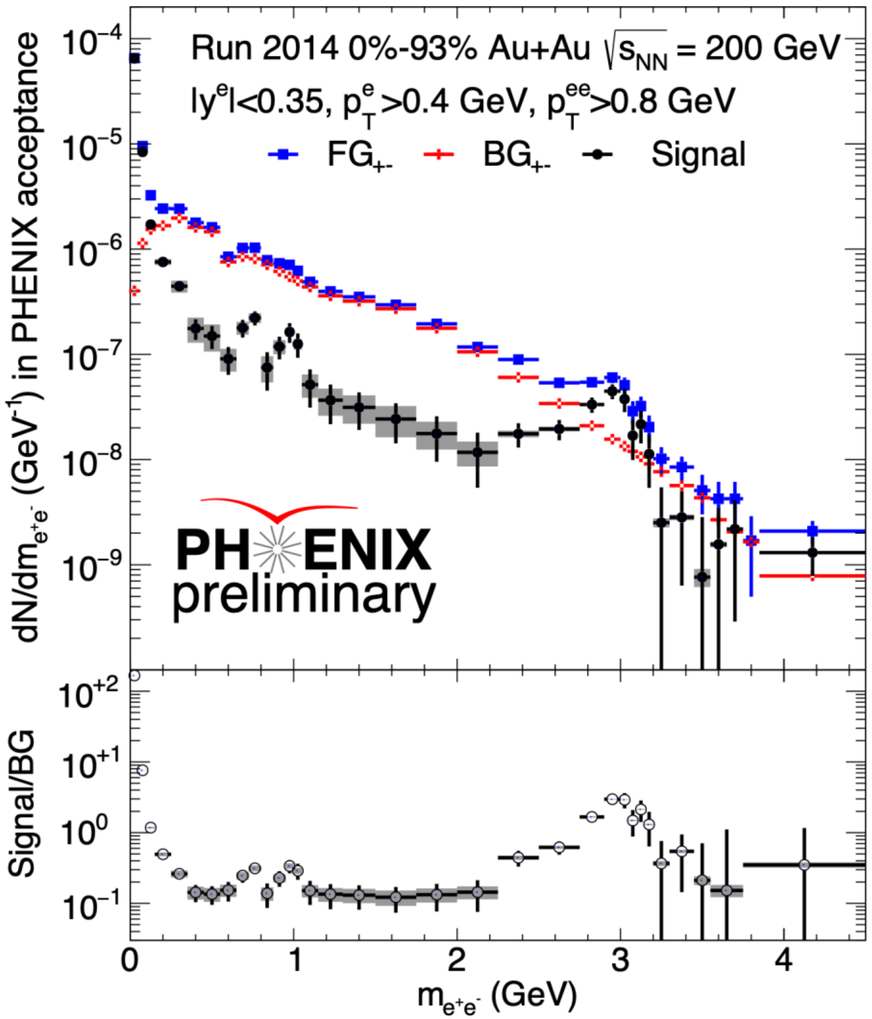


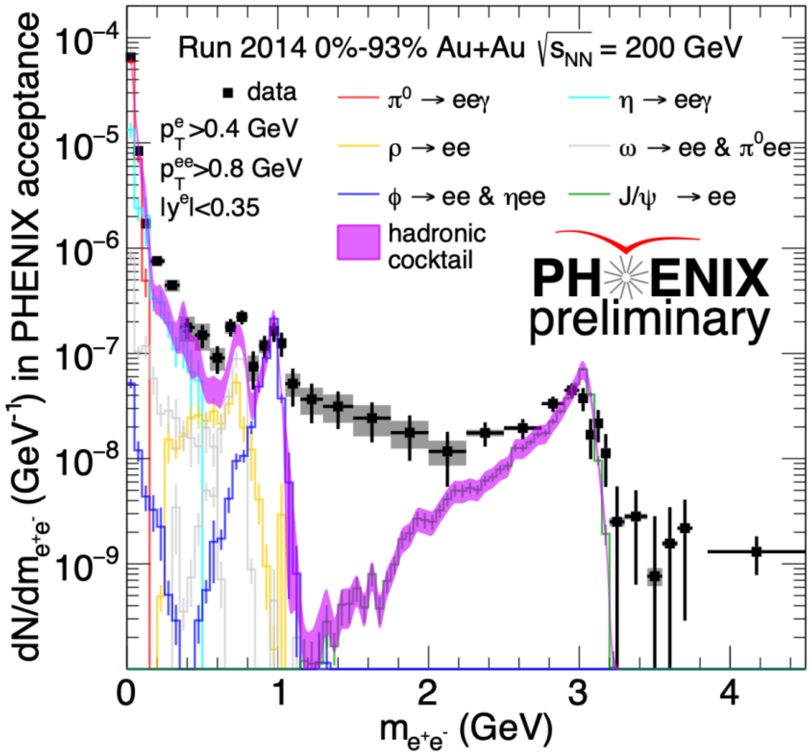


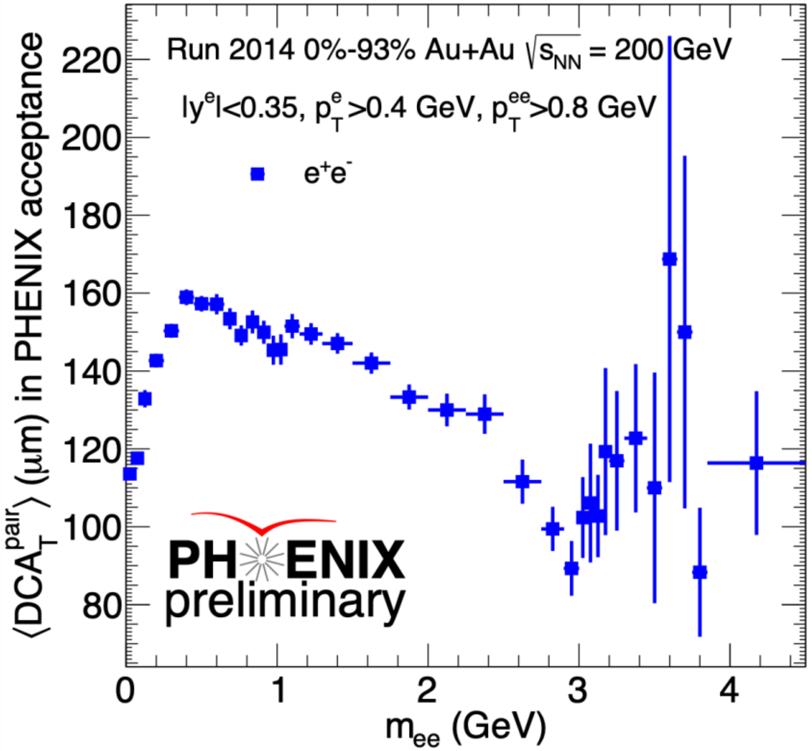


Separation between prompt and HF components possible

Separating Prompt and HF Signal in AuAu at 200 GeV







Promising early results from AuAu 200 GeV

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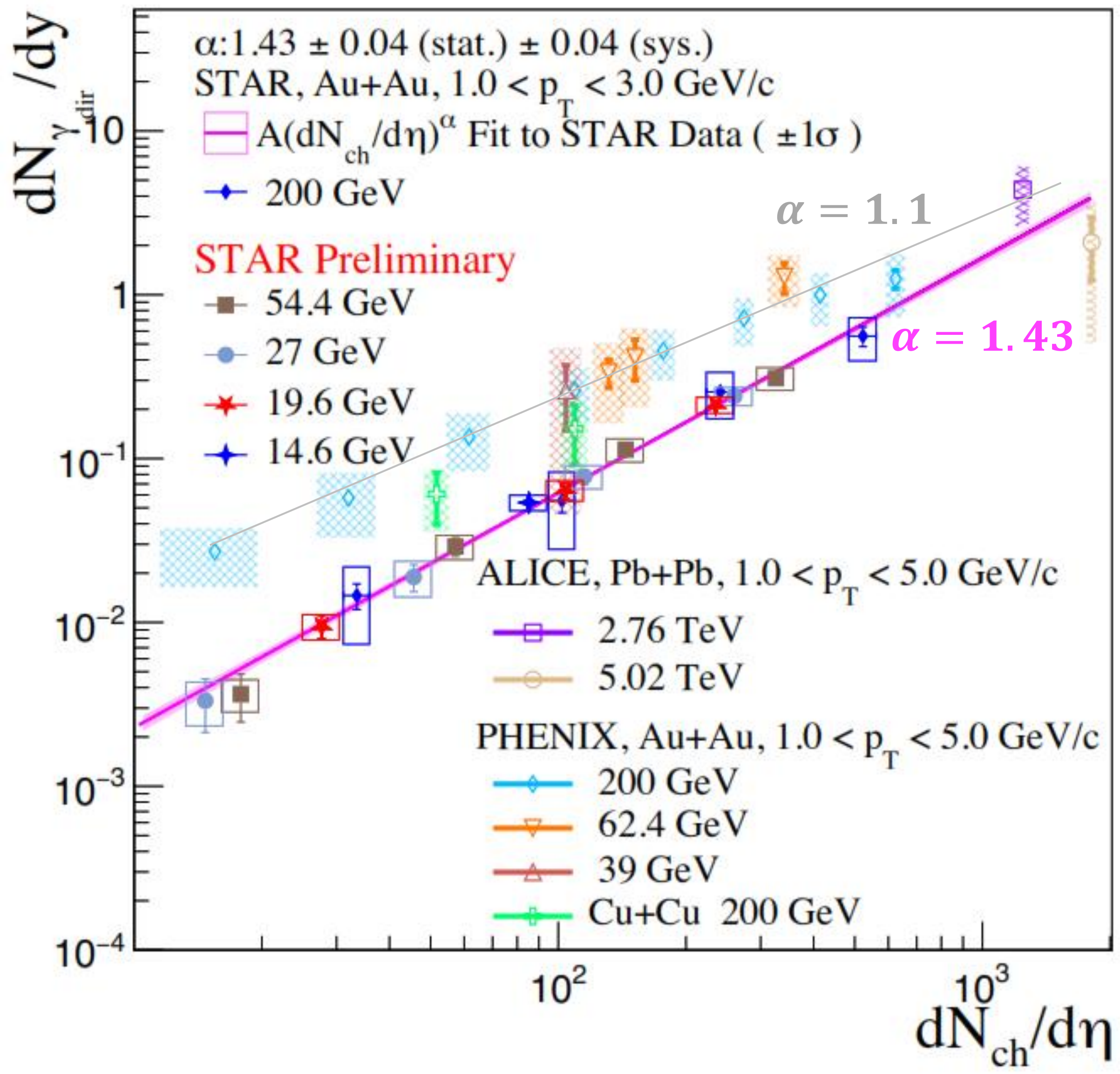
Summary: PHENIX Direct Photon Results

- **New high statistics Au+Au results reveal/confirm universal features**
- **Large "thermal" yield for p_T < 4 GeV**
  - **T_{eff} increases with p_T**
  - **No obvious variation of T_{eff} with $\sqrt{s_{NN}}$ or centrality**
  - **$N_\gamma^{dir} \sim (N_{ch})^\alpha$ scaling of direct photon yields in all A+A systems**
  - **α=1.1 independent of p_T**
  - **Large anisotropy v_2 with max at 2-3 GeV**
- **Prompt photon production dominates p_T > 5 GeV**
  - **No modification of yield beyond N_{coll} scaling of p+p**
  - **No anisotropy**
- **Outlook: measure T through e^+e^- pair continuum in Au+Au**
  - **Proof of principle in p+p**
  - **Separation between prompt and HF components possible in Au+Au**

STAR vs PHENIX Discrepancy

STAR: QM2025



- **STAR results:**
  - Virtual photon analysis $\gamma^* \to e^+e^-$ for Au+Au at 14.6, 19.6, 27, 54.4, 200 GeV
  - Self consistent analyses & results across energies
  - Direct photon yield scales with $N_\gamma^{dir} \sim \left(\frac{dN_{ch}}{d\eta}\right)^\alpha$ with $\alpha \sim 1.43$
- **Compared to PHENIX results:**
  - STAR yield a factor of 3-5 below PHENIX
  - $\alpha \sim 1.43$ versus $\alpha \sim 1.1$ for PHENIX

Differences need to be resolved!

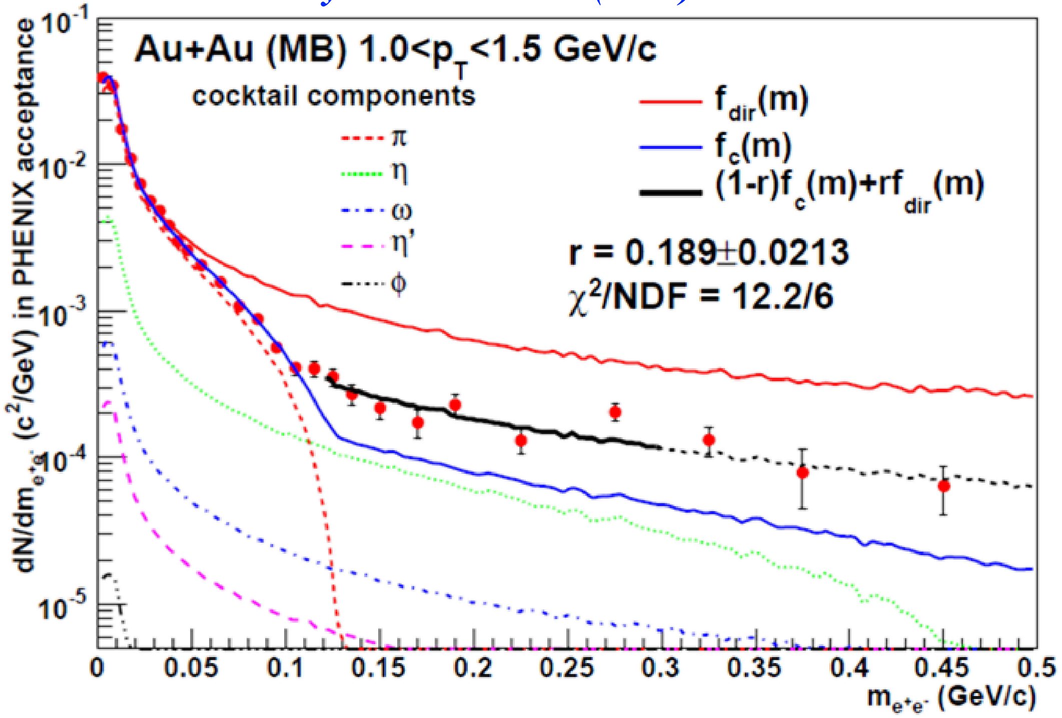
Best option compare Au-Au 200 GeV virtual photon analyses

Comparing Virtual Photon Analyses

Au+Au min. bias 200 GeV

PHENIX

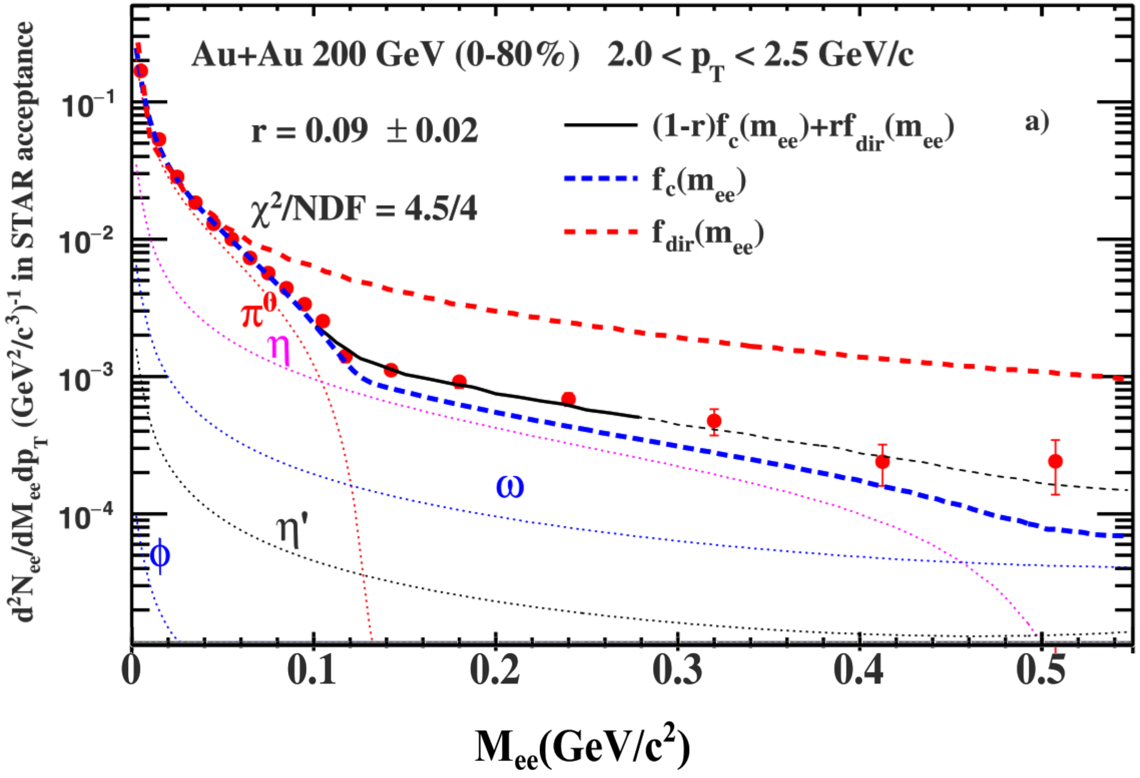
PHENIX: Phys. Rev. Lett. 104 (2010) 132301



$1.0 < p_T < 1.5$ GeV/c

STAR

STAR: Phys. Lett. B 770 (2017) 451



$2.0 < p_T < 2.5$ GeV/c

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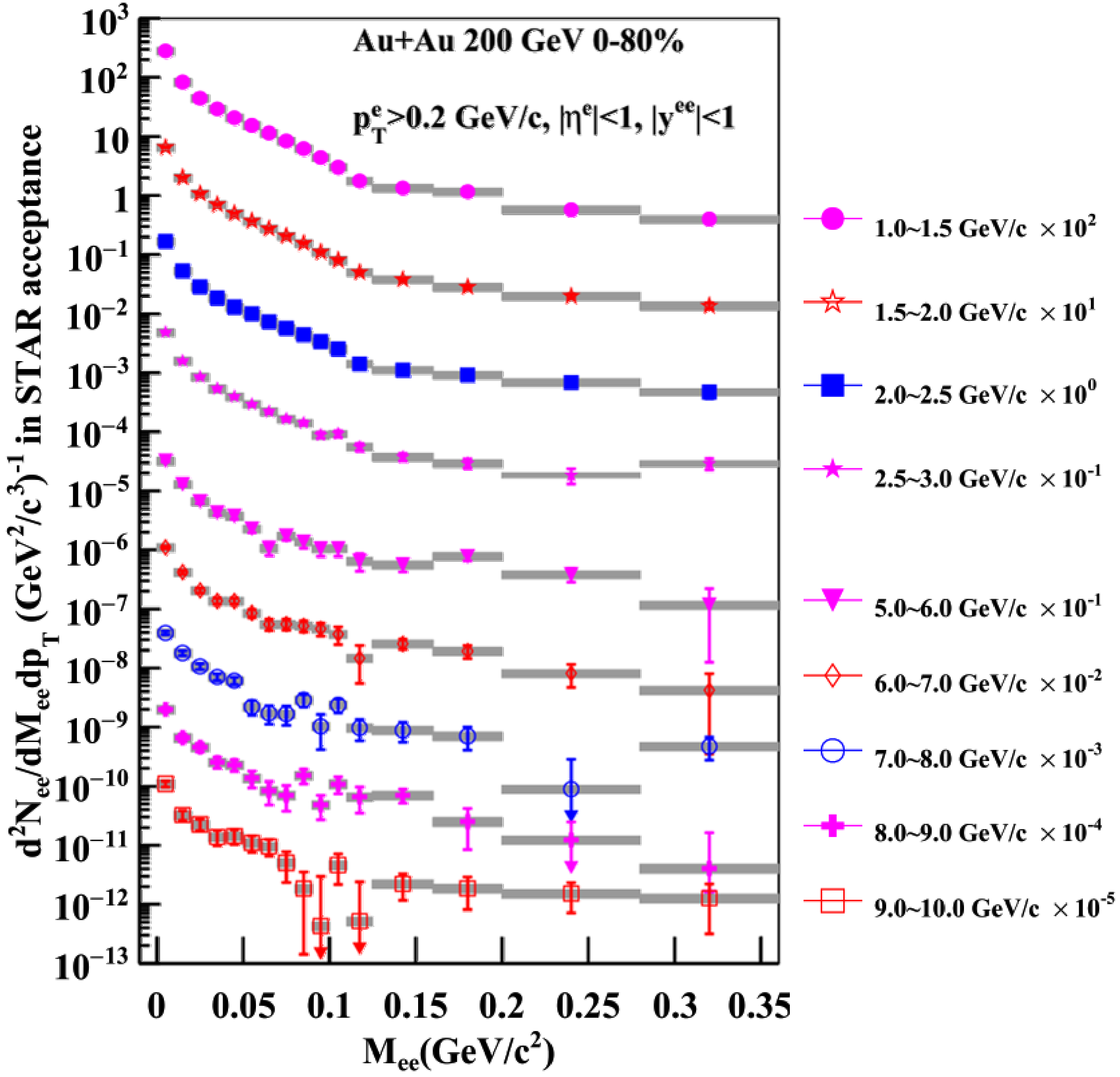
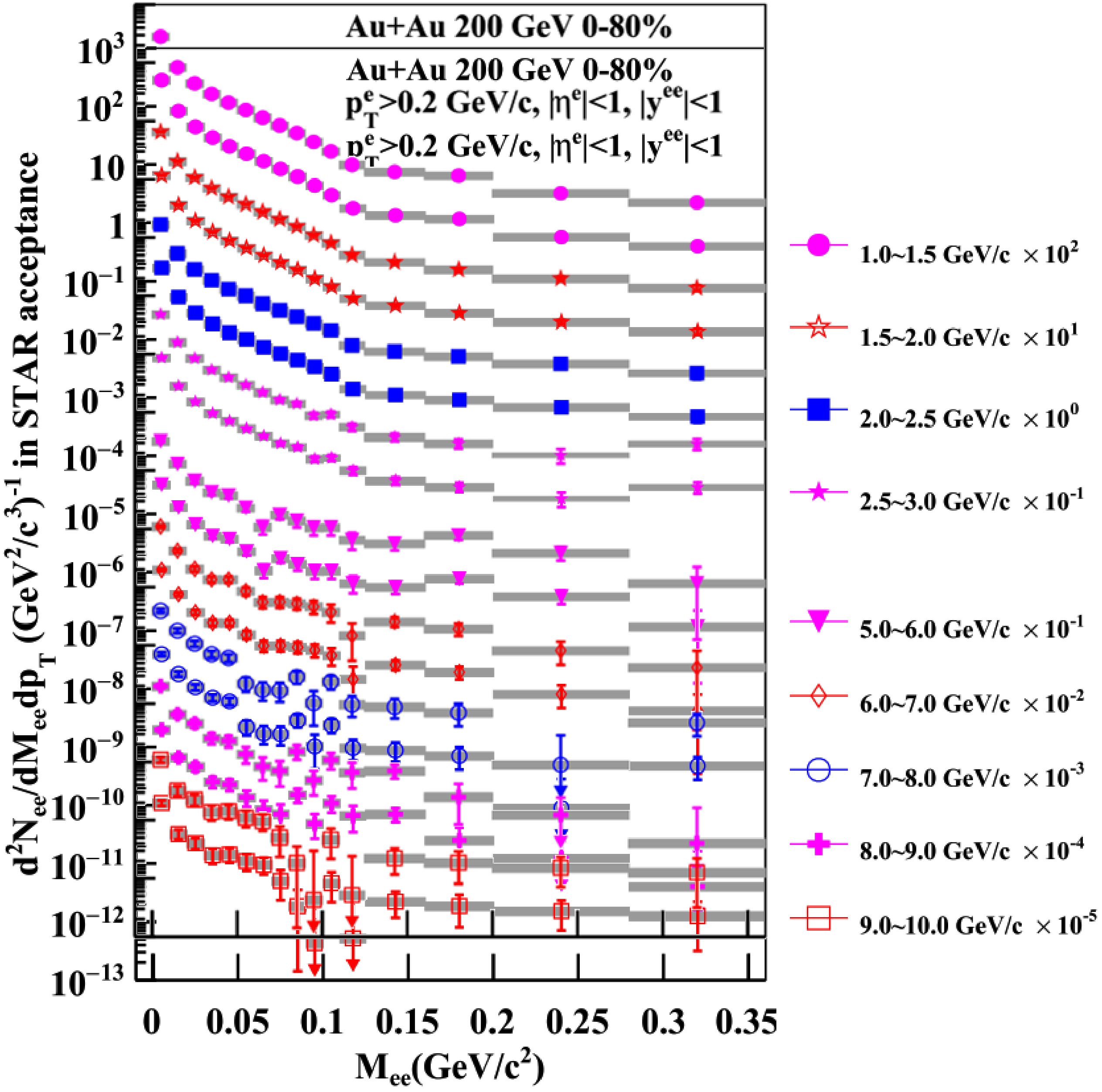
A Little Bit of Power Point Tricks

STAR: Phys. Lett. B 770 (2017) 451



A Little bit of Power Point Tricks

STAR: Phys. Lett. B 770 (2017) 451



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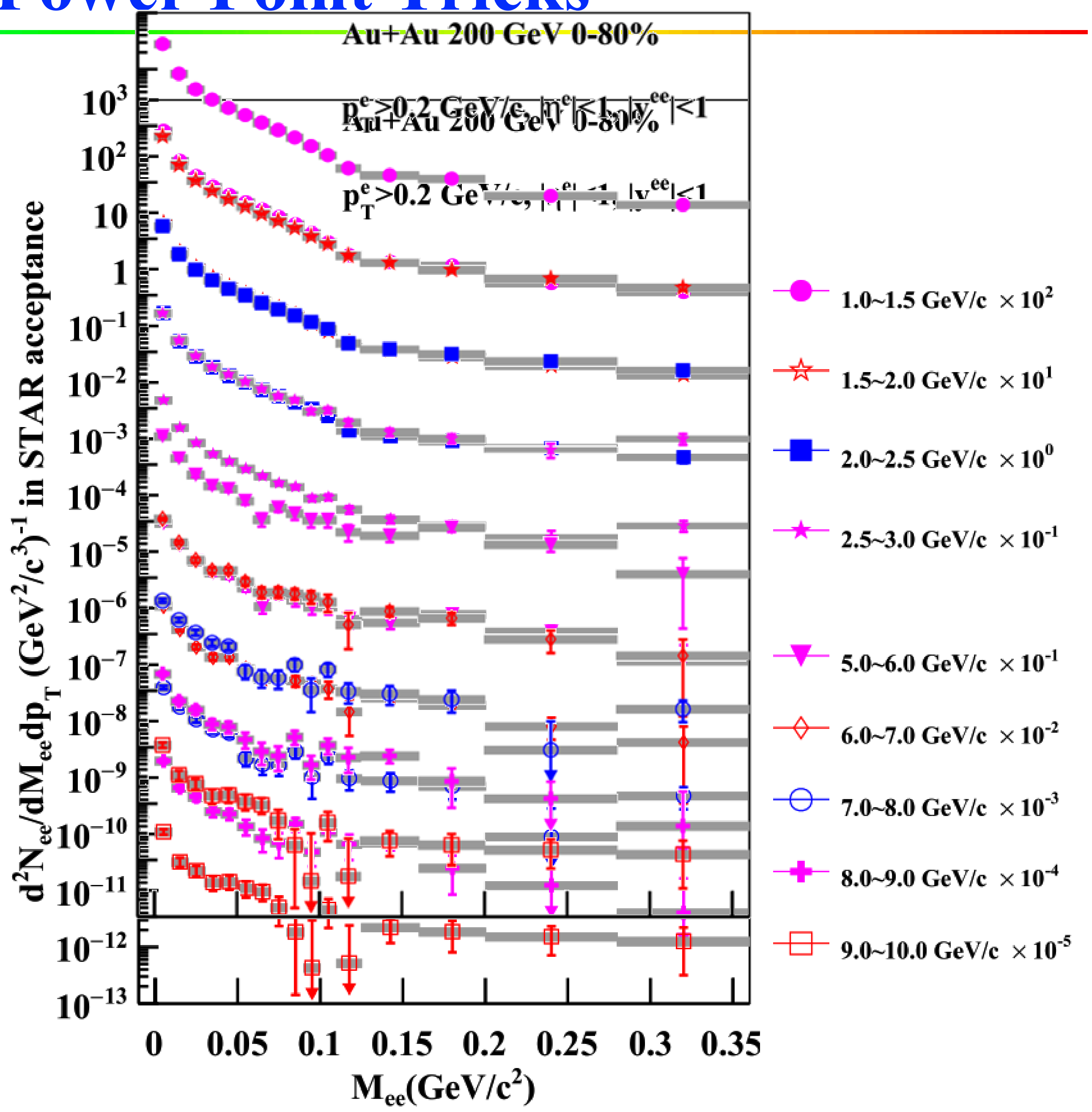
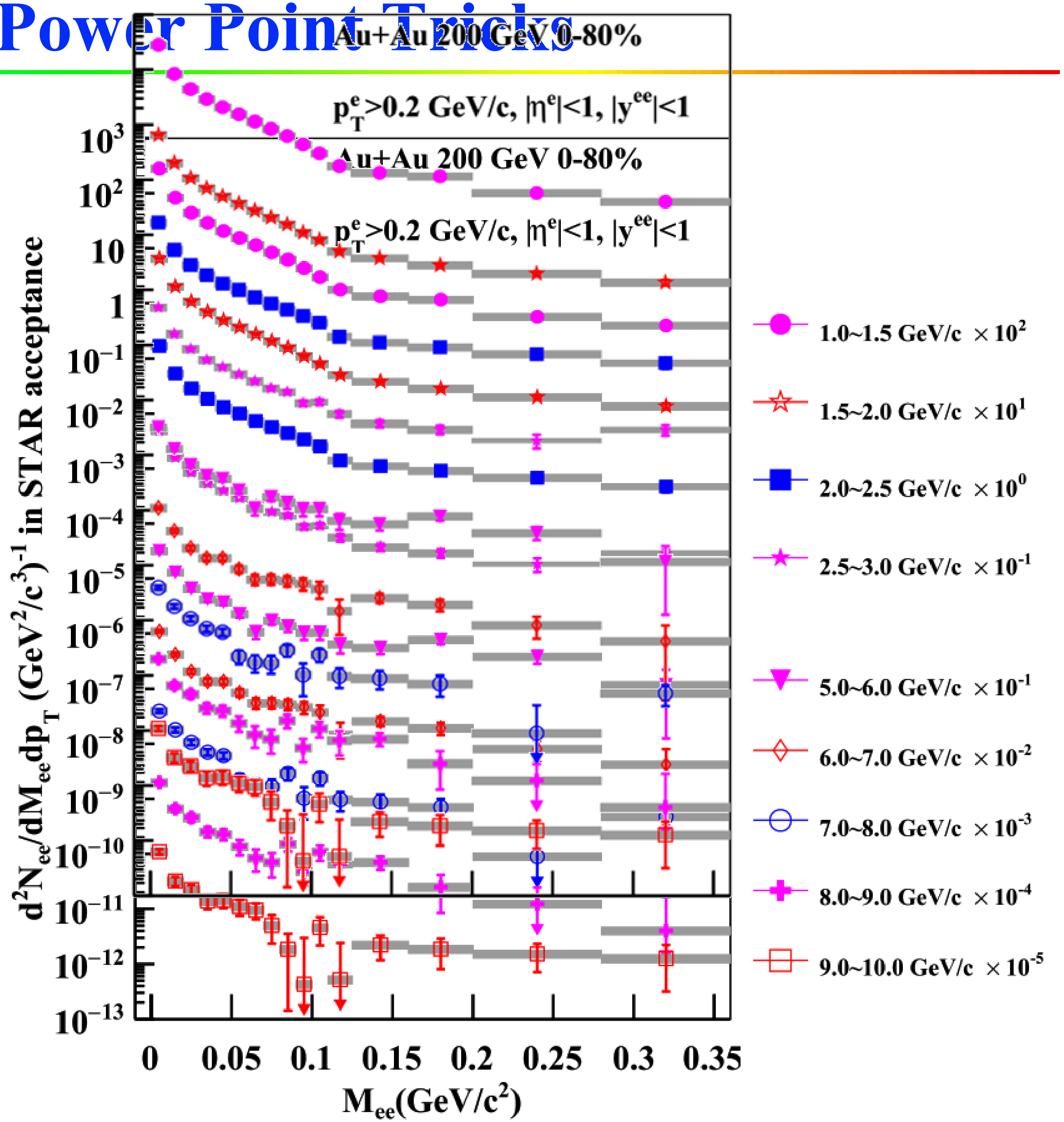
A Little bit of Power Point Tricks

STAR: Phys. Lett. B 770 (2017) 451



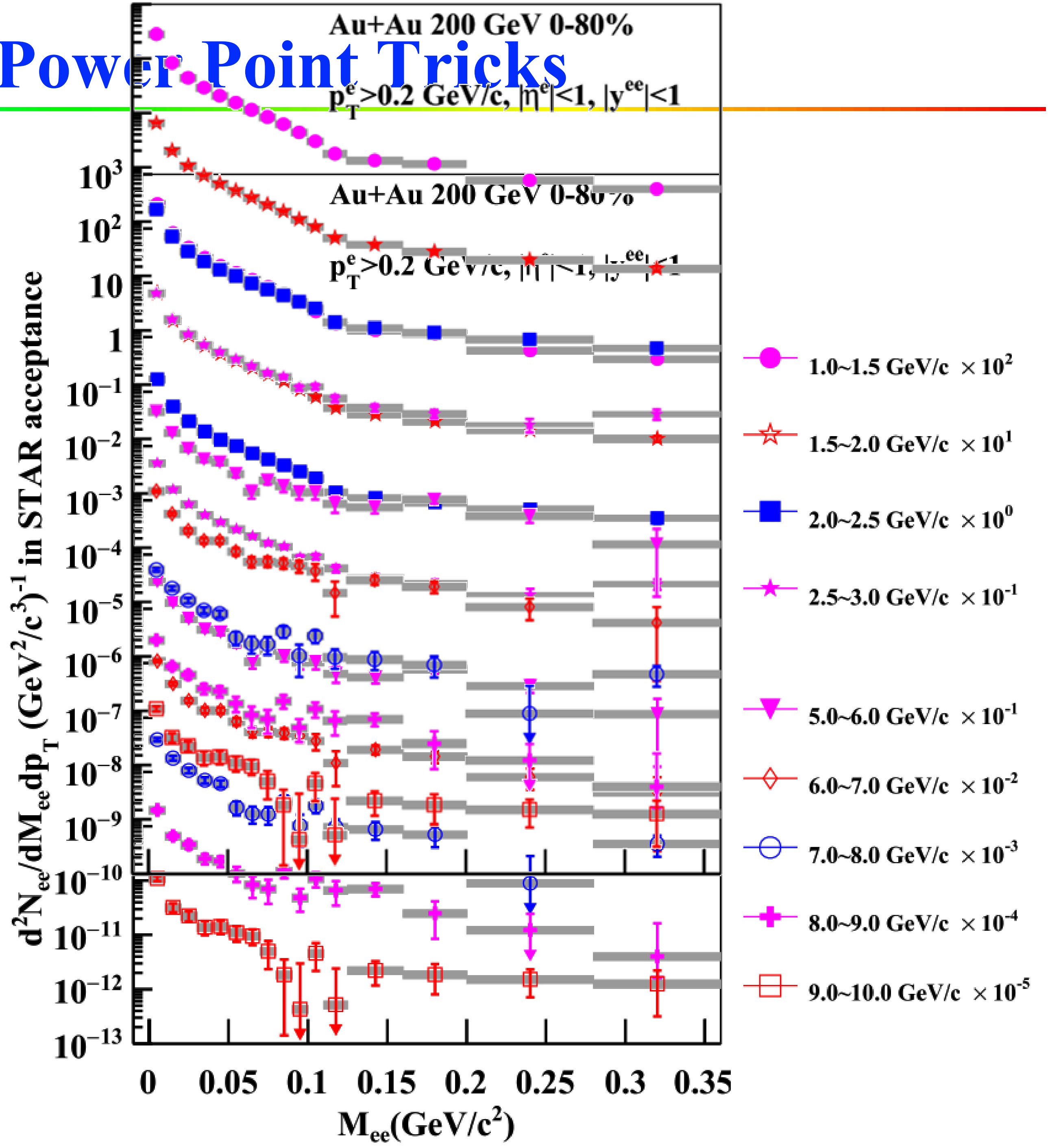
A Little bit of Power Point Tricks

STAR: Phys. Lett. B 770 (2017) 451



A Little bit of Power Point Tricks

STAR: Phys. Lett. B 770 (2017) 451

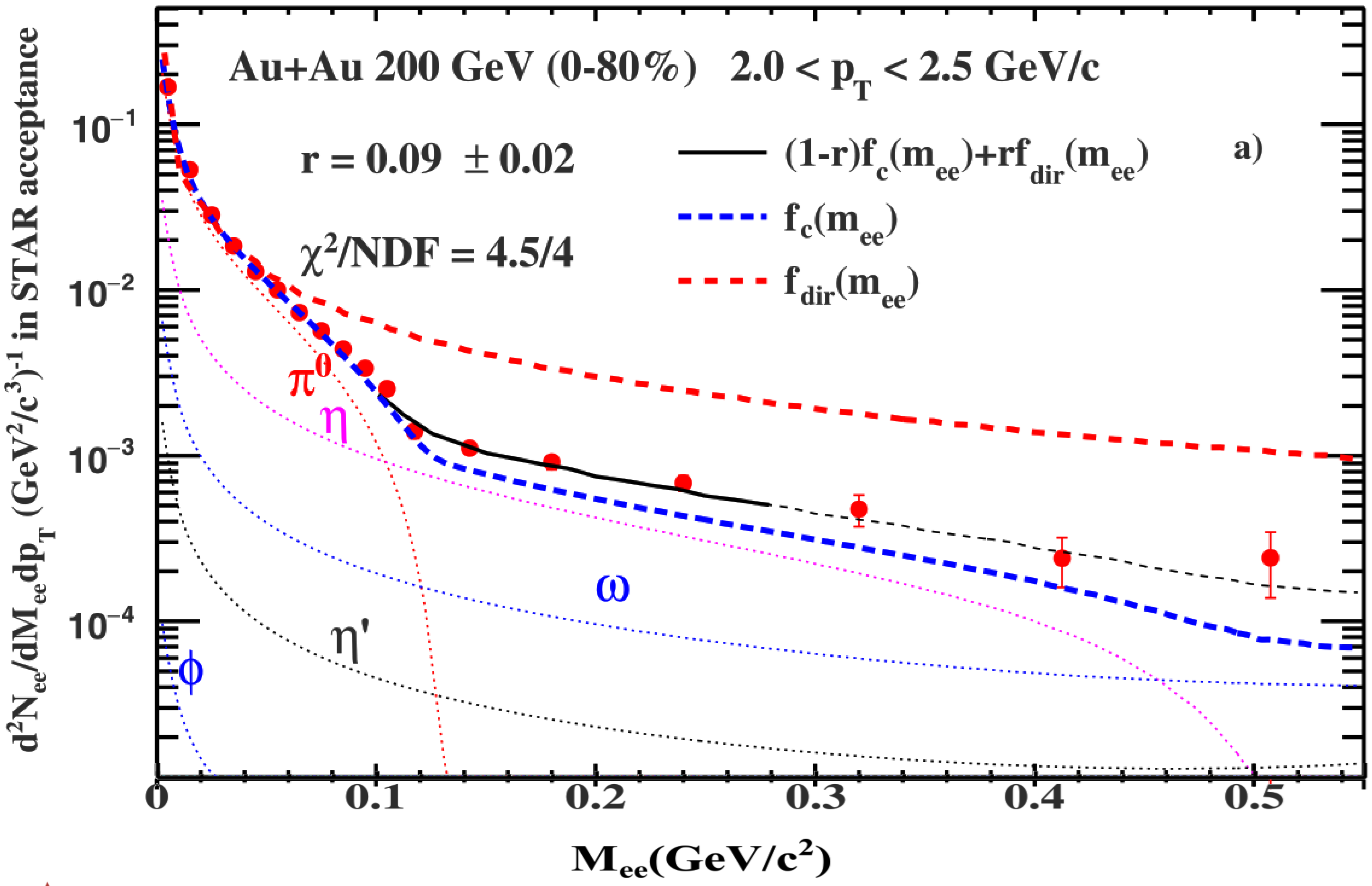


No significant shape difference with p_T!

Compare PHENIX
$1.0 < p_T < 1.5$ GeV/c

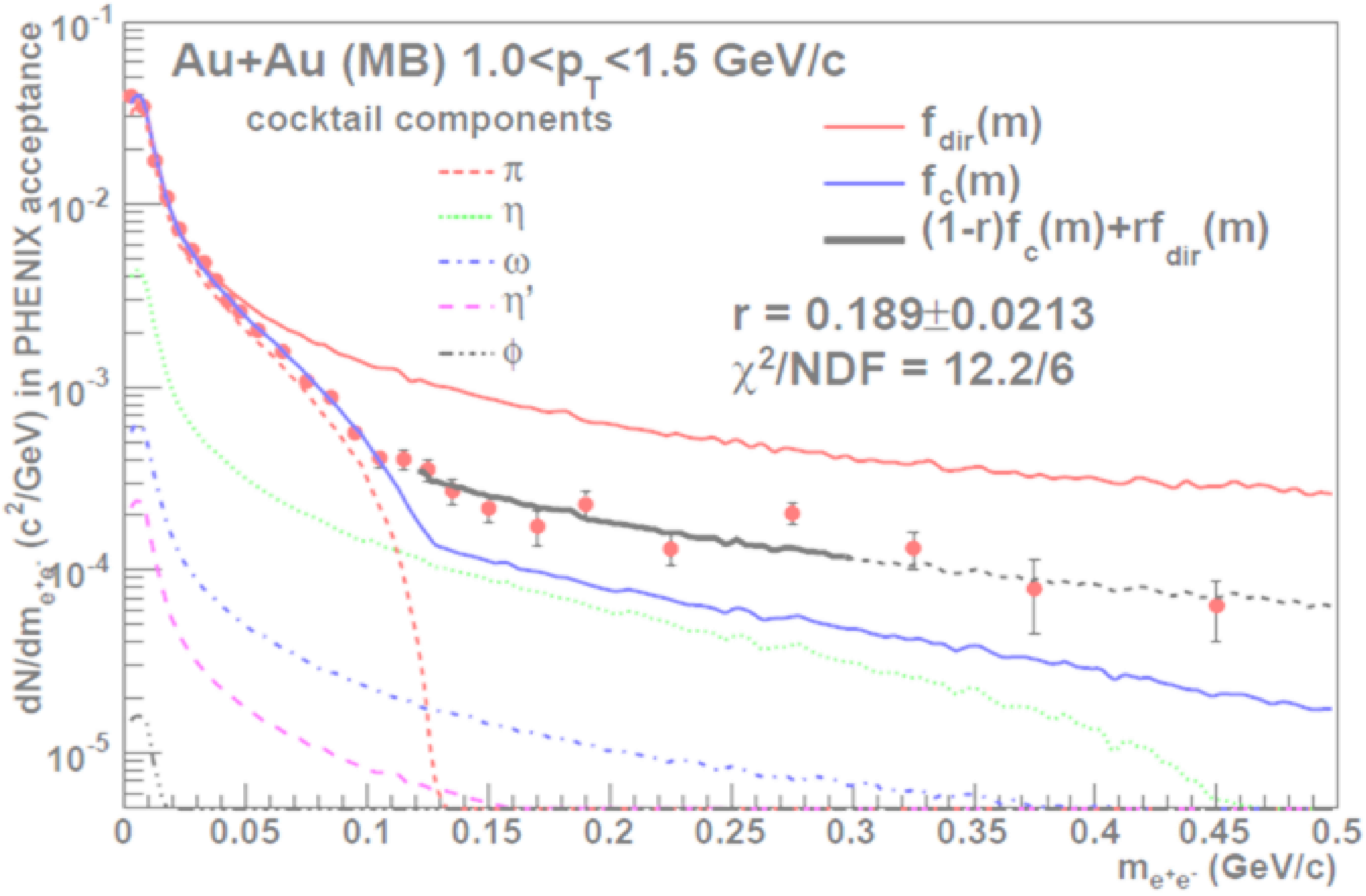
Directly to STAR
$2.0 < p_T < 2.5$ GeV/c

More Power Point Tricks



Start with STAR data

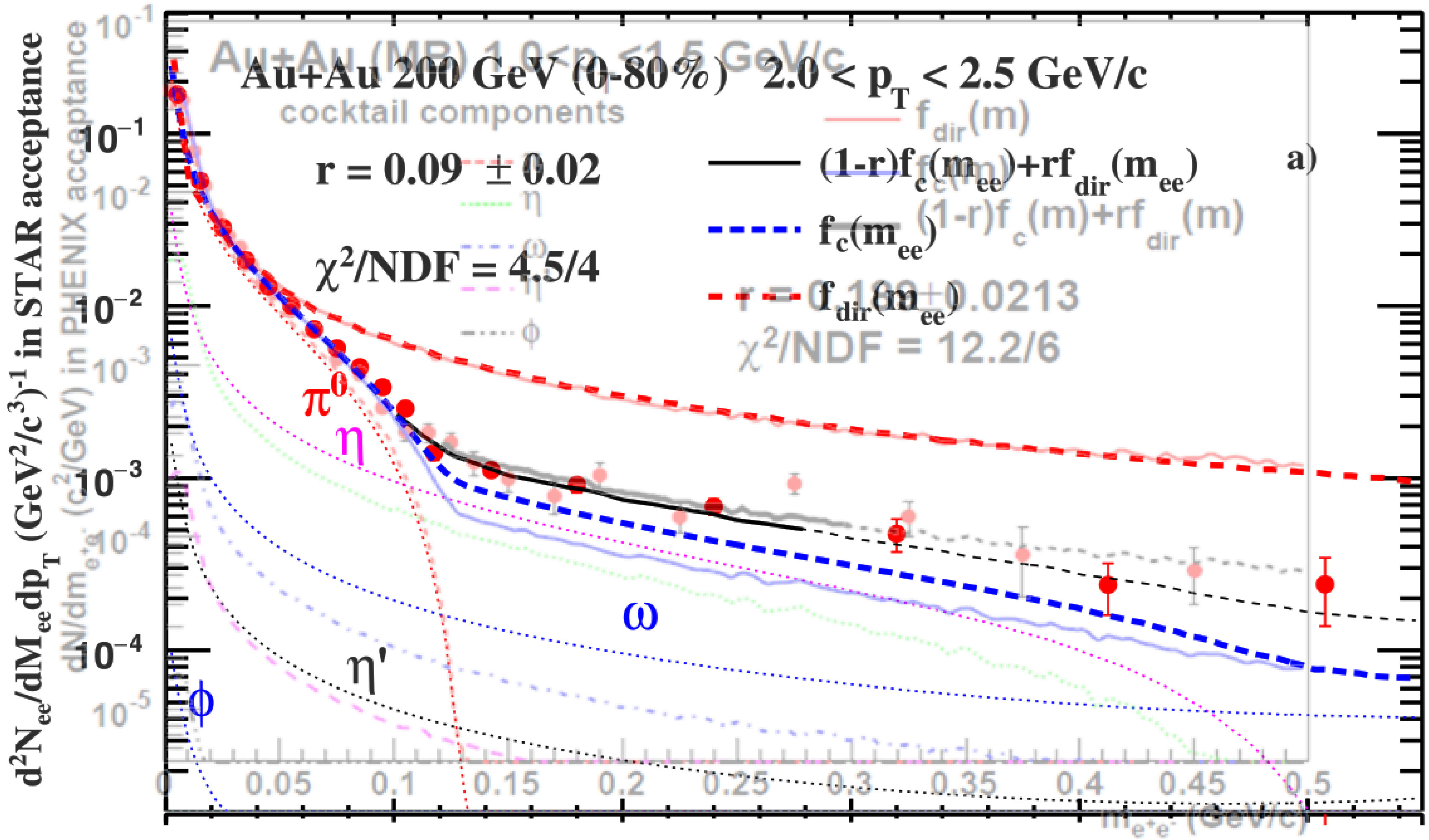
More Power Point Tricks



Start with STAR data

Adjust PHENIX plot to have same scale

More Power Point Tricks



Start with STAR data

Adjust PHENIX plot to have same scale

And overlay

STAR and PHENIX data seem consistent!

η/π^0 in STAR larger than in PHENIX

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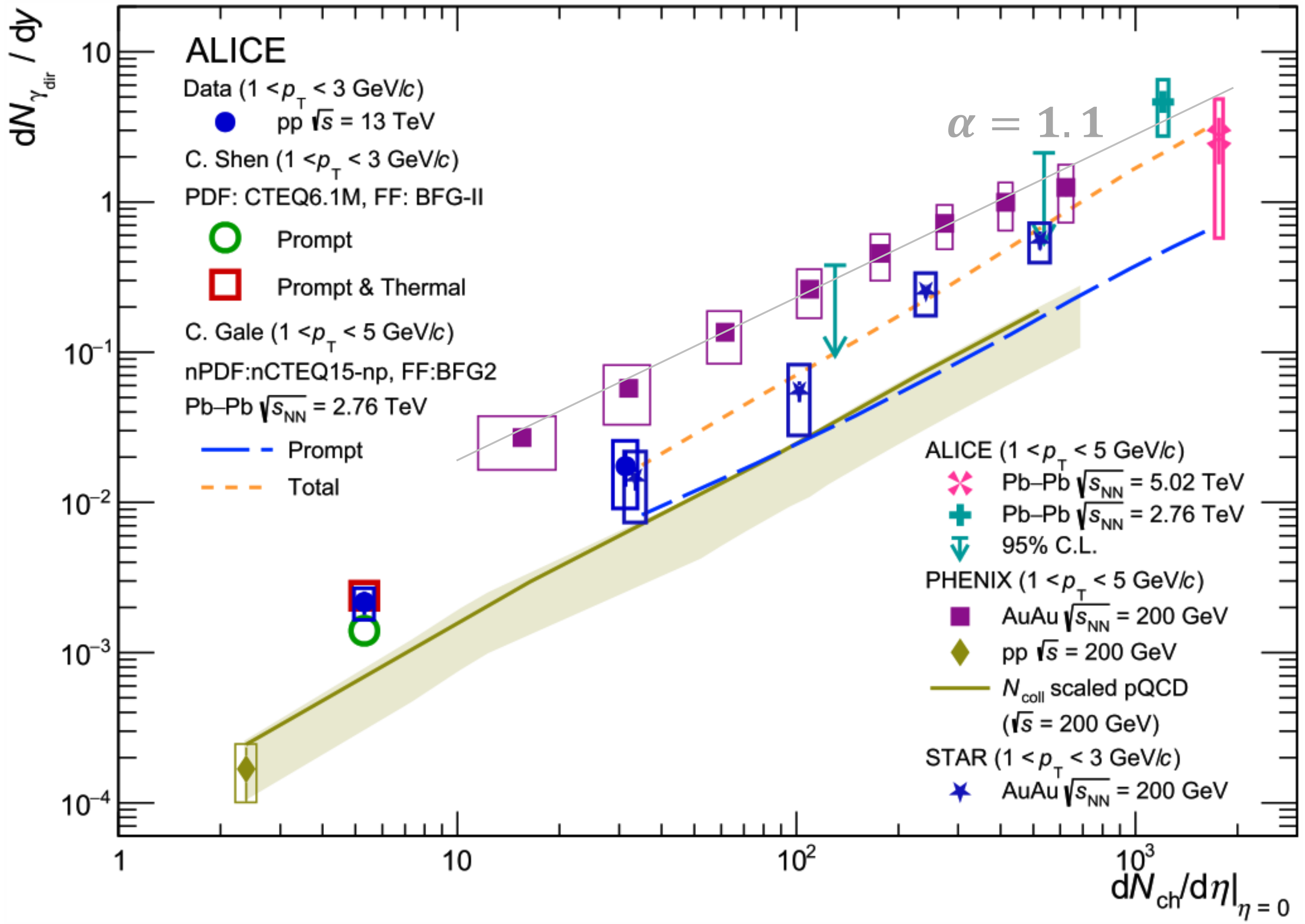
ALICE – PHENIX – STAR Direct Photon Comparison

ALICE: Phys. Lett. B 104 (2025) 139645



ALICE Pb-Pb data:
2.56 TeV: Phys. Lett. B 754 (2016) 235-248
5.02 TeV: arXiv:2308.16704

- **Pb-Pb 2.56 TeV (γ, $\gamma \rightarrow e^+e^-$)**
  - **Largely consistent with PHENIX data (see earlier comparison plots)**
- **Pb-Pb 5.02 TeV ($\gamma^* \rightarrow e^+e^-$)**
  - **Central value consistent with STAR**
  - **Large uncertainties, within those consistent with PHENIX or only prompt photons**
- **p-p 13 TeV ($\gamma^* \rightarrow e^+e^-$)**
  - **Yields apparently consistent with STAR**

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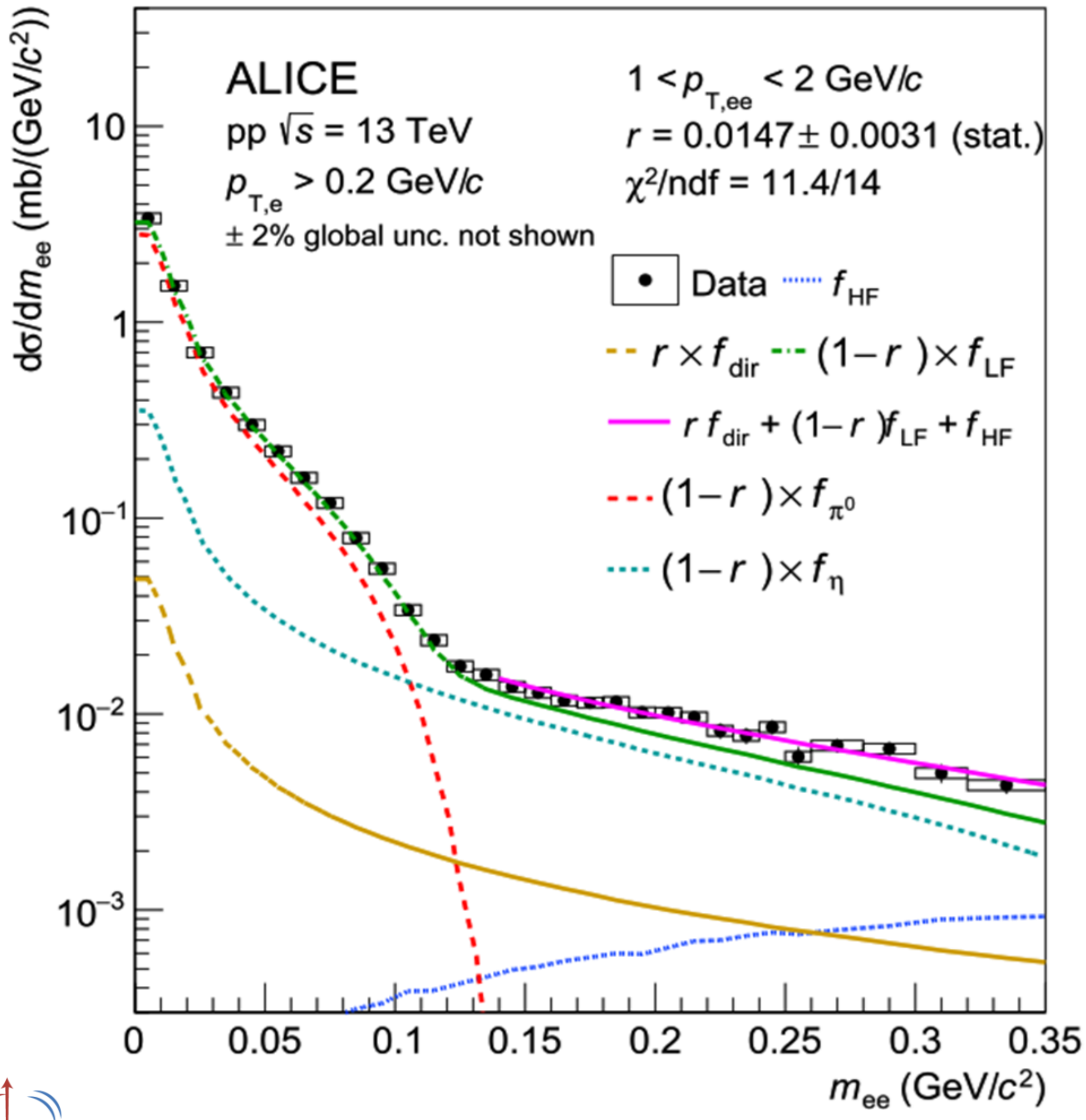
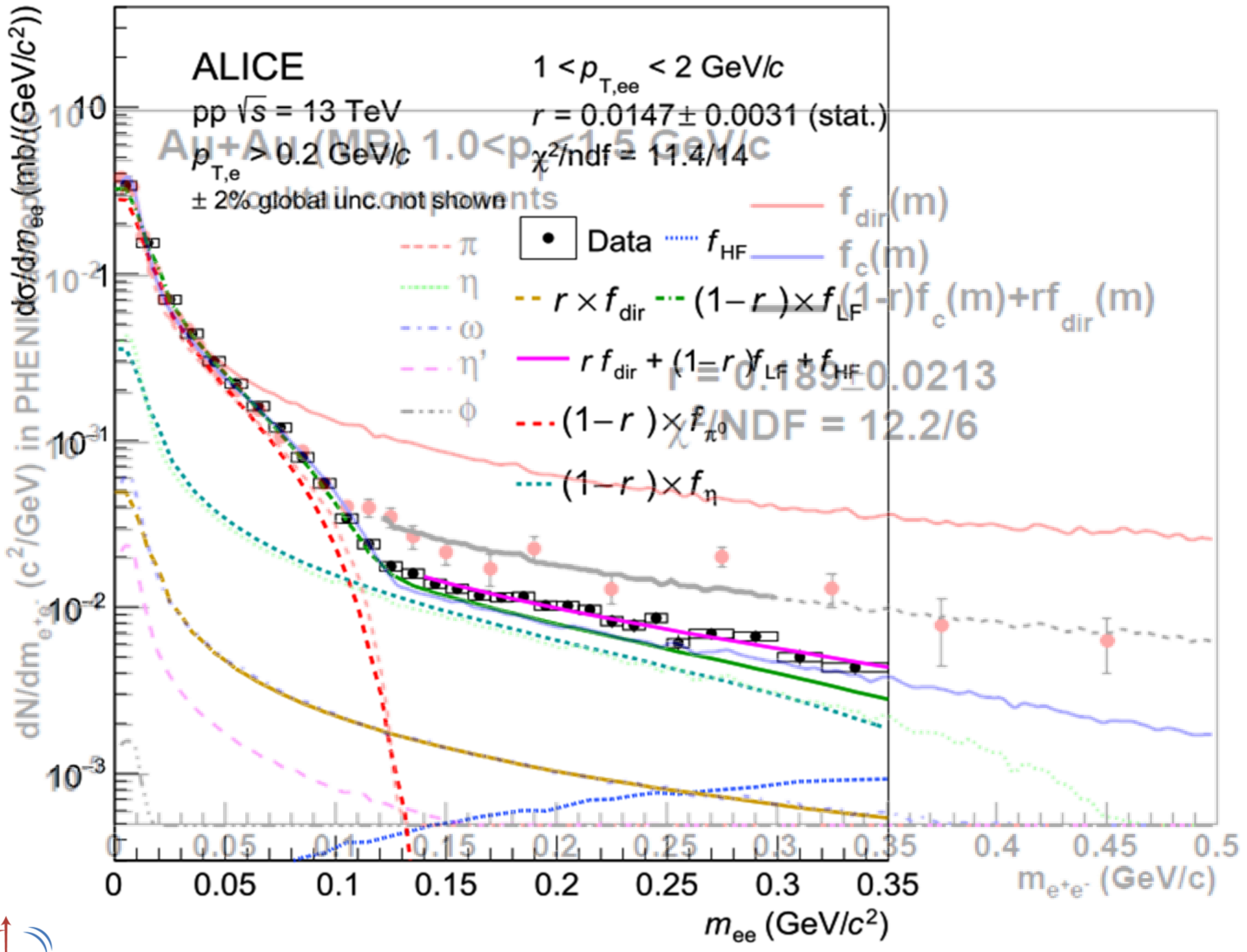
ALICE p-p at $\sqrt{s} = 13$ TeV



ALICE e^+e^- pair data for pp 13 GeV

More Power Point Tricks



ALICE e^+e^- pair data for pp 13 GeV

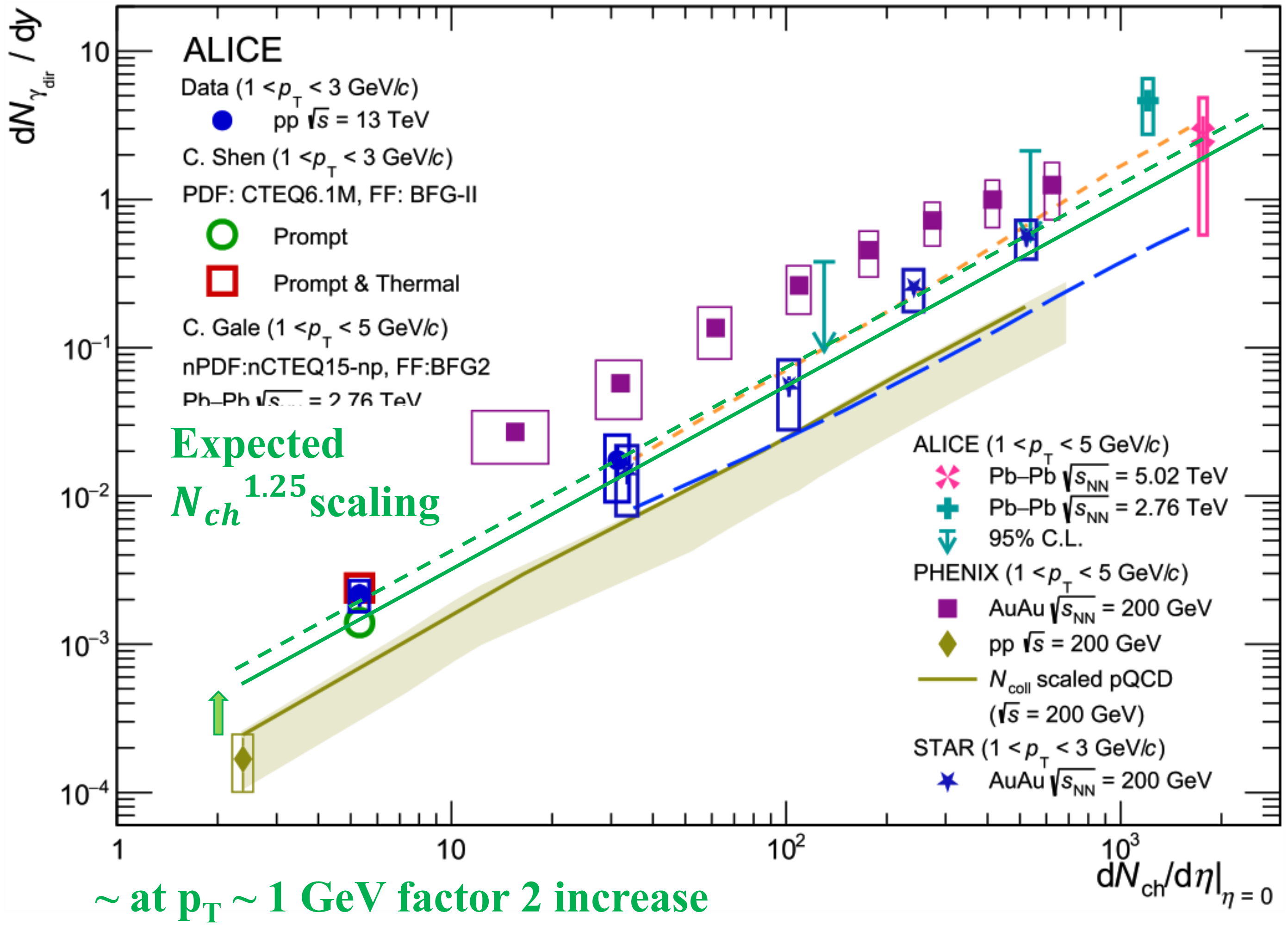
Compared to min. Bias AuAu 200 GeV data from PHENIX

ALICE pp 13 TeV data
Yield small but significant

η/π^0 ratio used in ALICE and PHENIX similar

pp at 13 GeV – pp at 200 GeV Comparison

ALICE: Phys. Lett. B 104 (2025) 139645



~ at p_T ~ 1 GeV factor 2 increase
of prompt yield from 0.2 TeV → 13 TeV

- **ALICE data:**
  - consistent with $N_\gamma^{dir} = \left(\frac{dN_{ch}}{d\eta}\right)^{1.25}$ scaling for hard scattering
- **Prompt photon pQCD calculation:**
  - Yield increases with $\sqrt{s}$
  - Increase is smallest at low p_T
  - N_γ/N_{ch} 1 GeV/c increases by factor ~2 from 0.2 to 13 TeV
- **ALICE to PHENIX N_γ/N_{ch} :**
  - Increases by ~ 4
  - Increase is consistent with factor 2 within uncertainties
  - But leaves room for some additional increase

ALICE pp data at 13 TeV likely consistent with PHENIX pp 200 GeV data

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Summary: PHENIX – STAR – ALICE Comparison

- At face value: STAR & PHENIX direct photon results are inconsistent
  - STAR yield a factor of 3-5 below PHENIX
  - $\alpha \sim 1.43$ versus $\alpha \sim 1.1$ for PHENIX

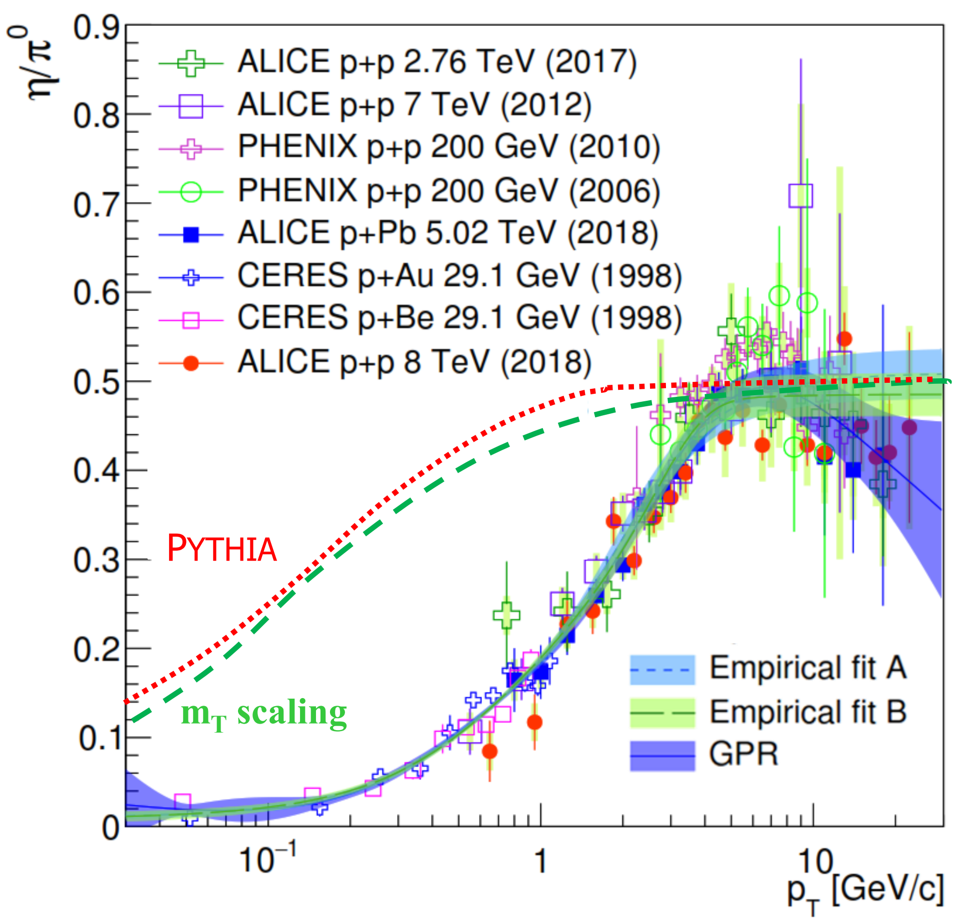
- Direct comparison of $\gamma^* \rightarrow e^+e^-$ pair spectra from Au+Au 200 GeV
  - STAR and PHENIX data seem consistent
  - Difference seems to be in hadron decay contribution

- ALICE – PHENIX comparison
  - Pb-Pb data at 2.56 TeV consistent with all trends observed by PHENIX
  - Pb-Pb data at 5.02 TeV has large uncertainties and is not inconsistent with PHENIX
  - pp data at 13 GeV is different from PHENIX pp data at 200 GeV, but consitant within expectations from pQCD

Backup

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:**

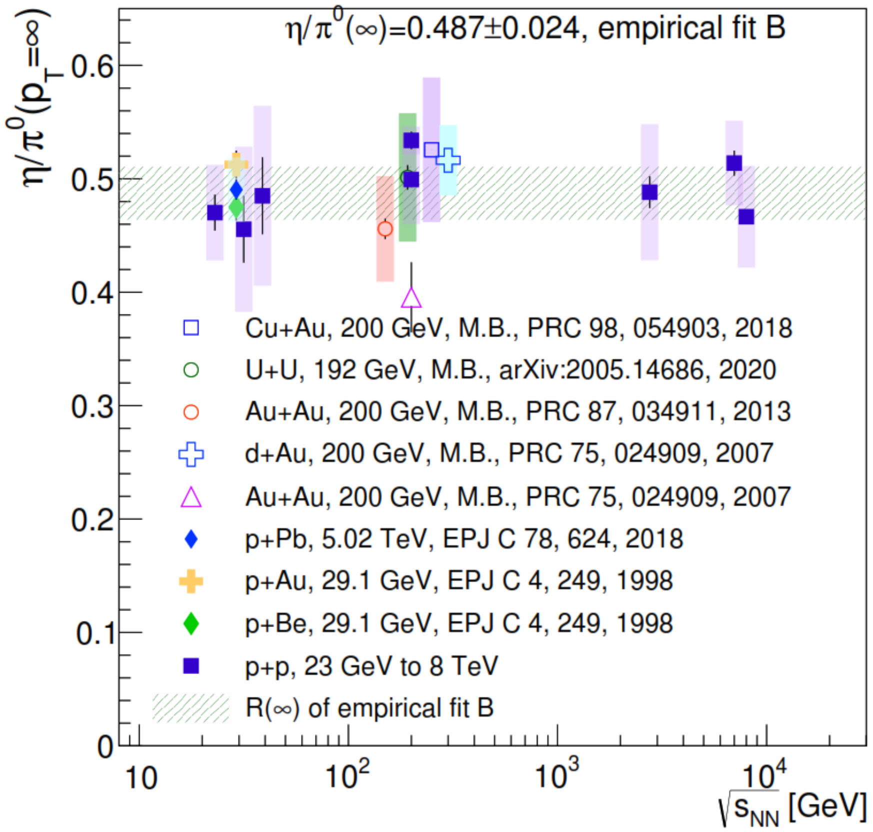
$$\frac{\eta}{\pi^0} = 0.487 \pm 0.024$$

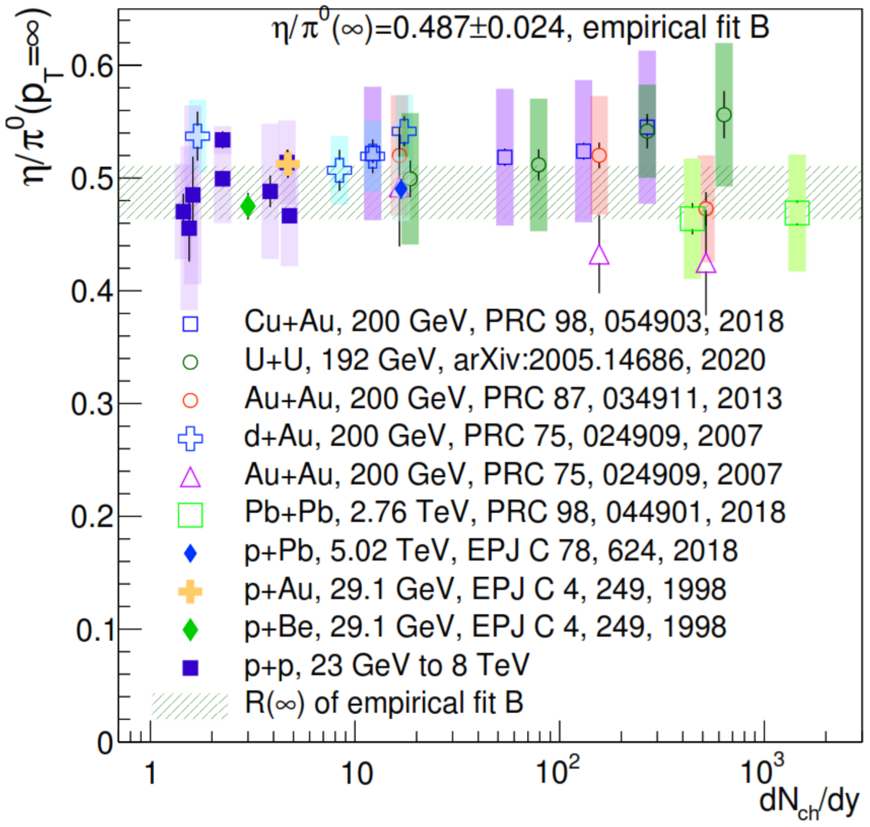
- **Use empirical description for all collision systems:**

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

Test of Universality of η/π^0 Ratio

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

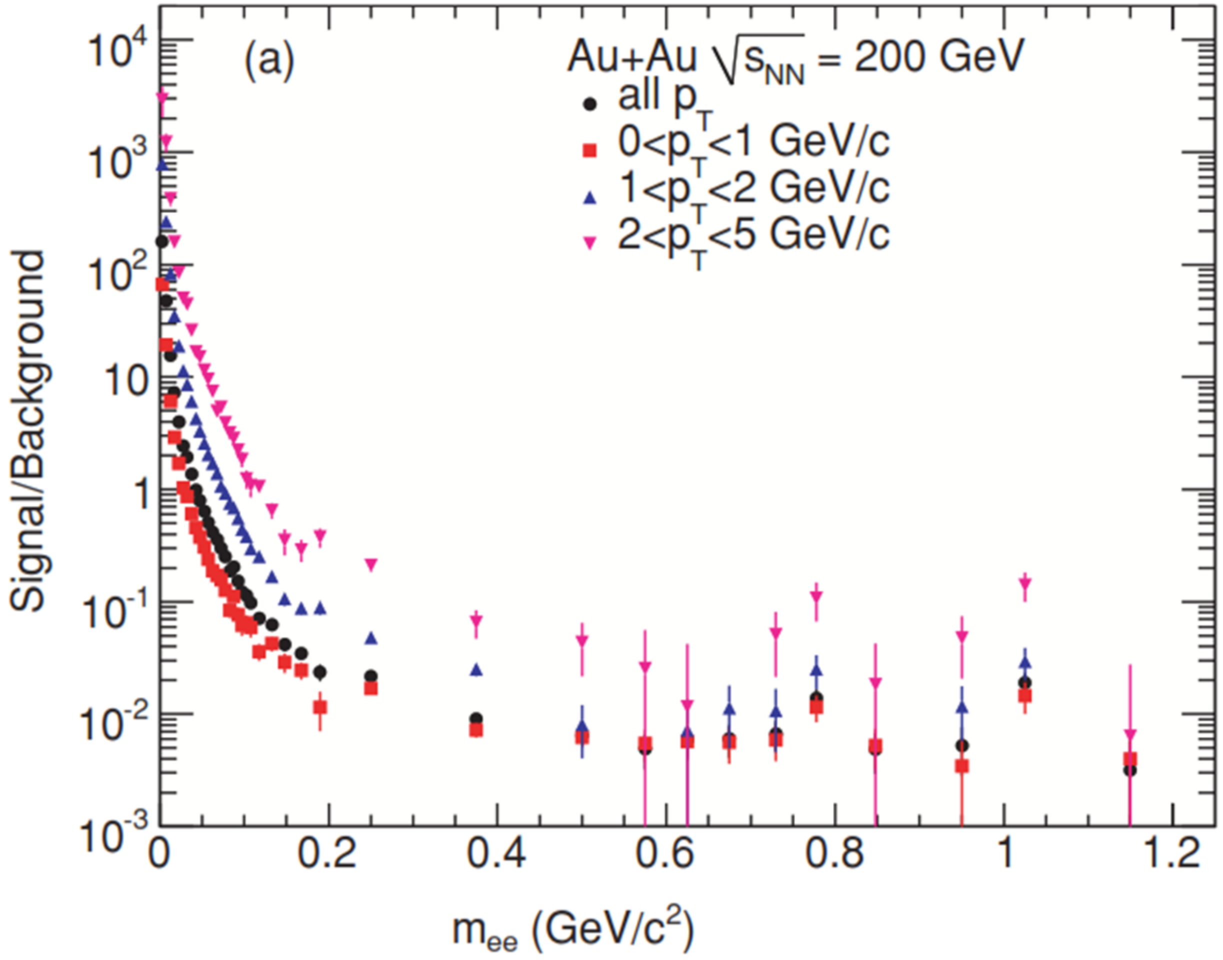




Universality of η/π^0

PHENIX Low p_T Direct Virtual Photon Analyses

PHENIX: Phys. Rev. Lett. 104 (2010) 132301



- Measurement requires accurate knowledge of:
  - η/π^0 ratio
  - detector resolutions

pp data confirm understanding

  - background subtraction