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Direct Photons and Dilepton Measurements at PHENIX

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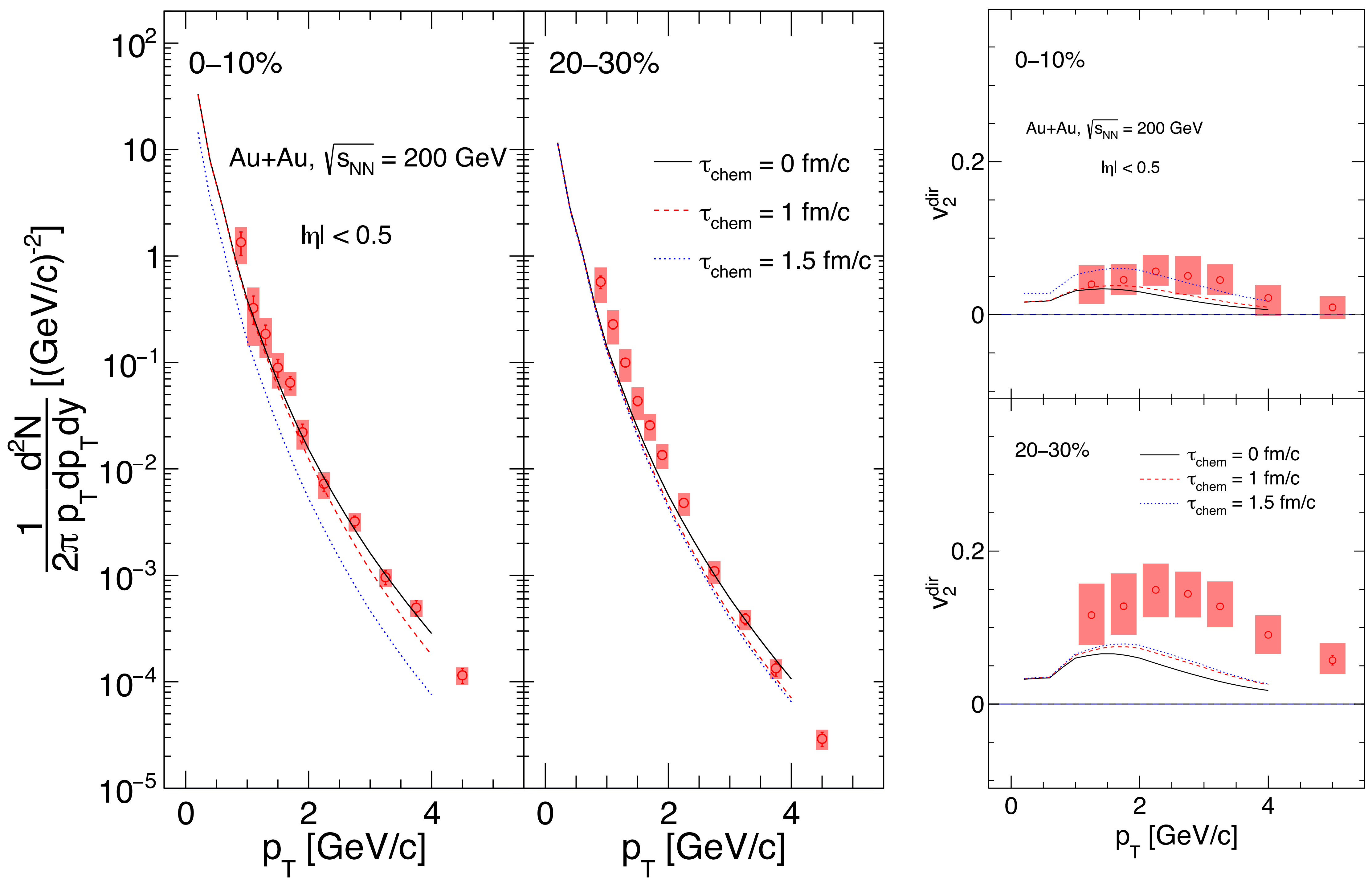
Center for Frontiers in Nuclear Science
PHENIX

Outline

(A)
Direct Photon Spectra
and Flow



Outline

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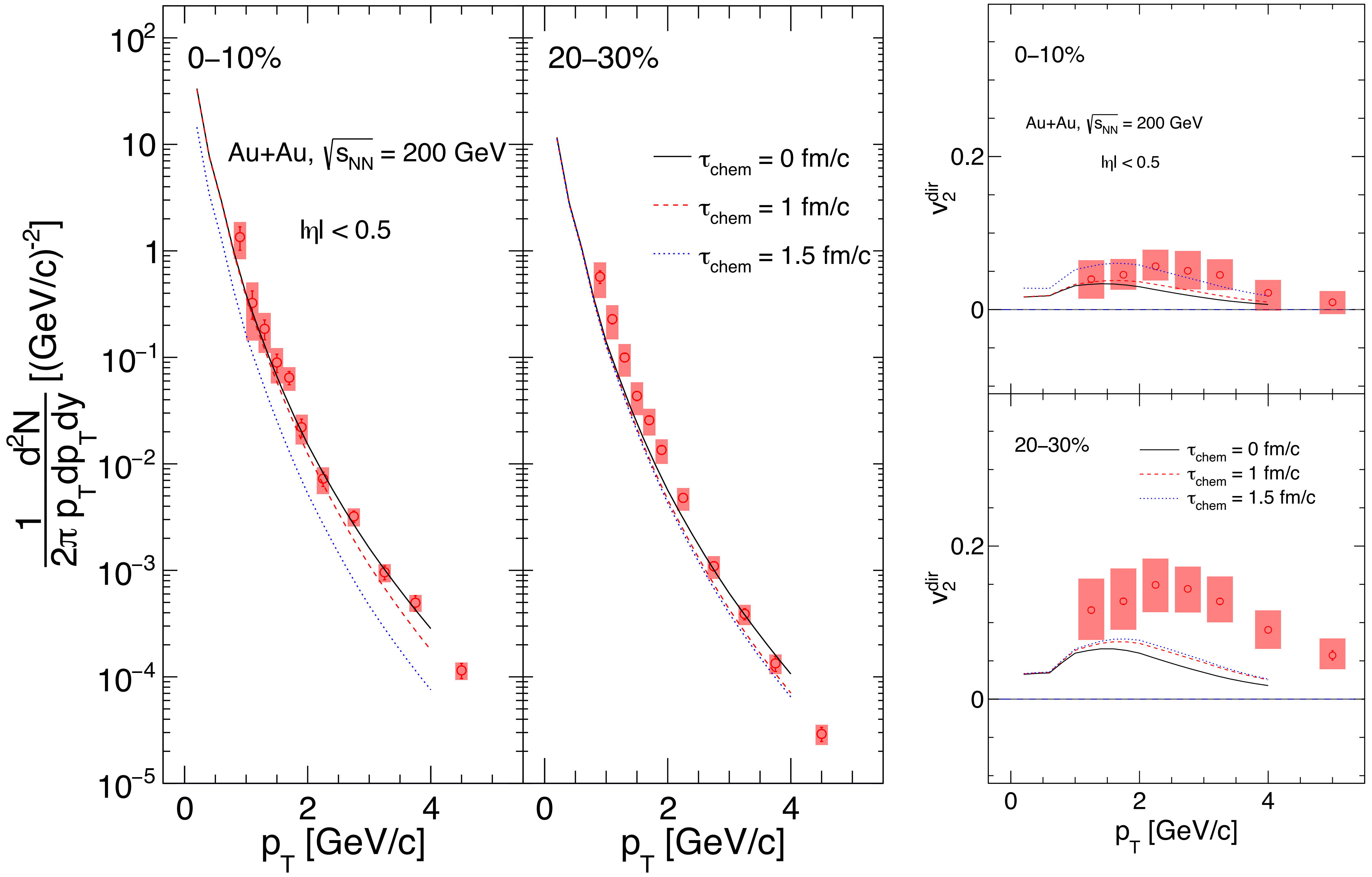
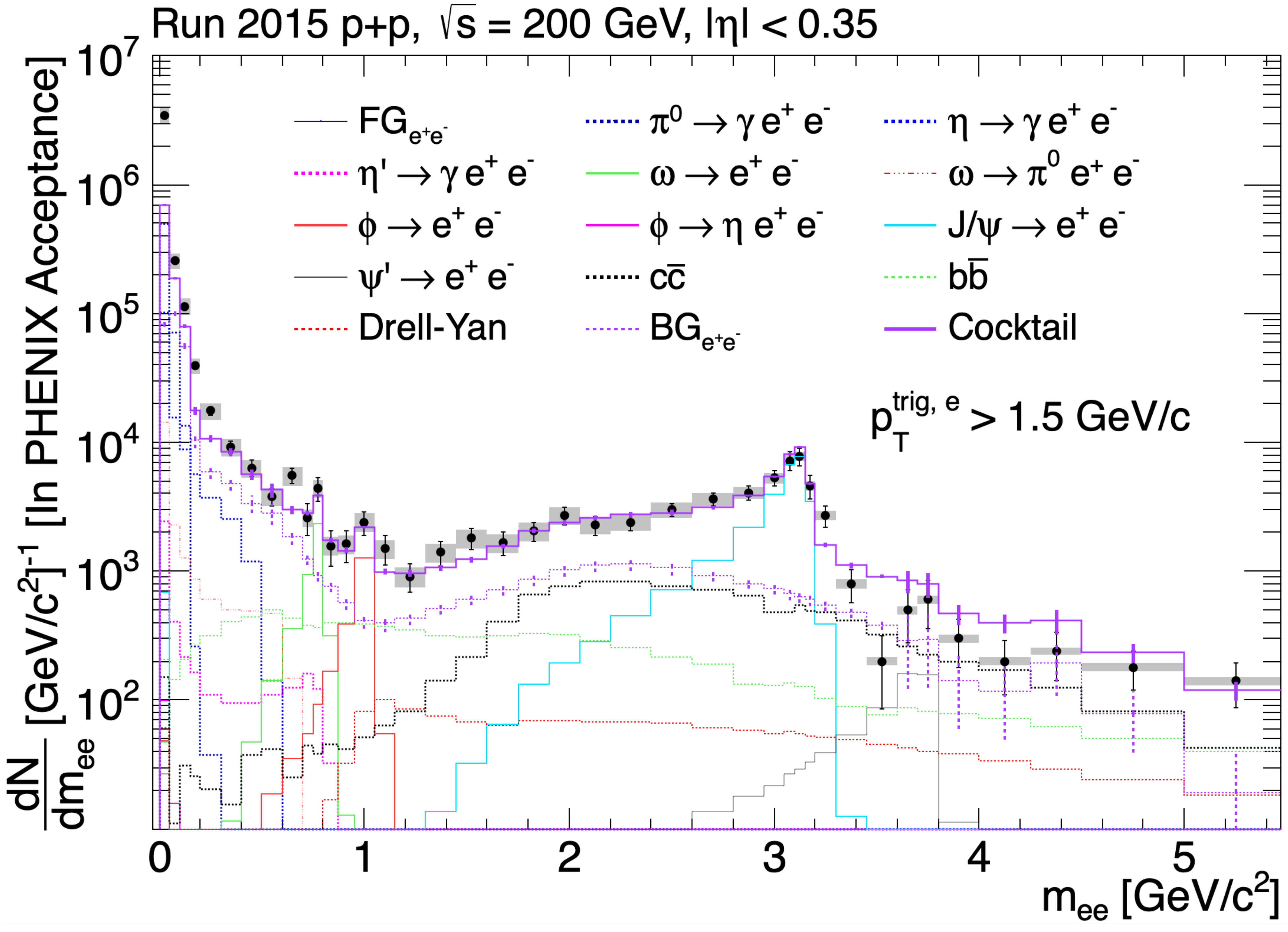
Direct Photon Spectra and Flow



(B)
Dilepton Continuum



Direct Photon Measurements

Introduction

- Photons are color blind probes of Quark Gluon Plasma.

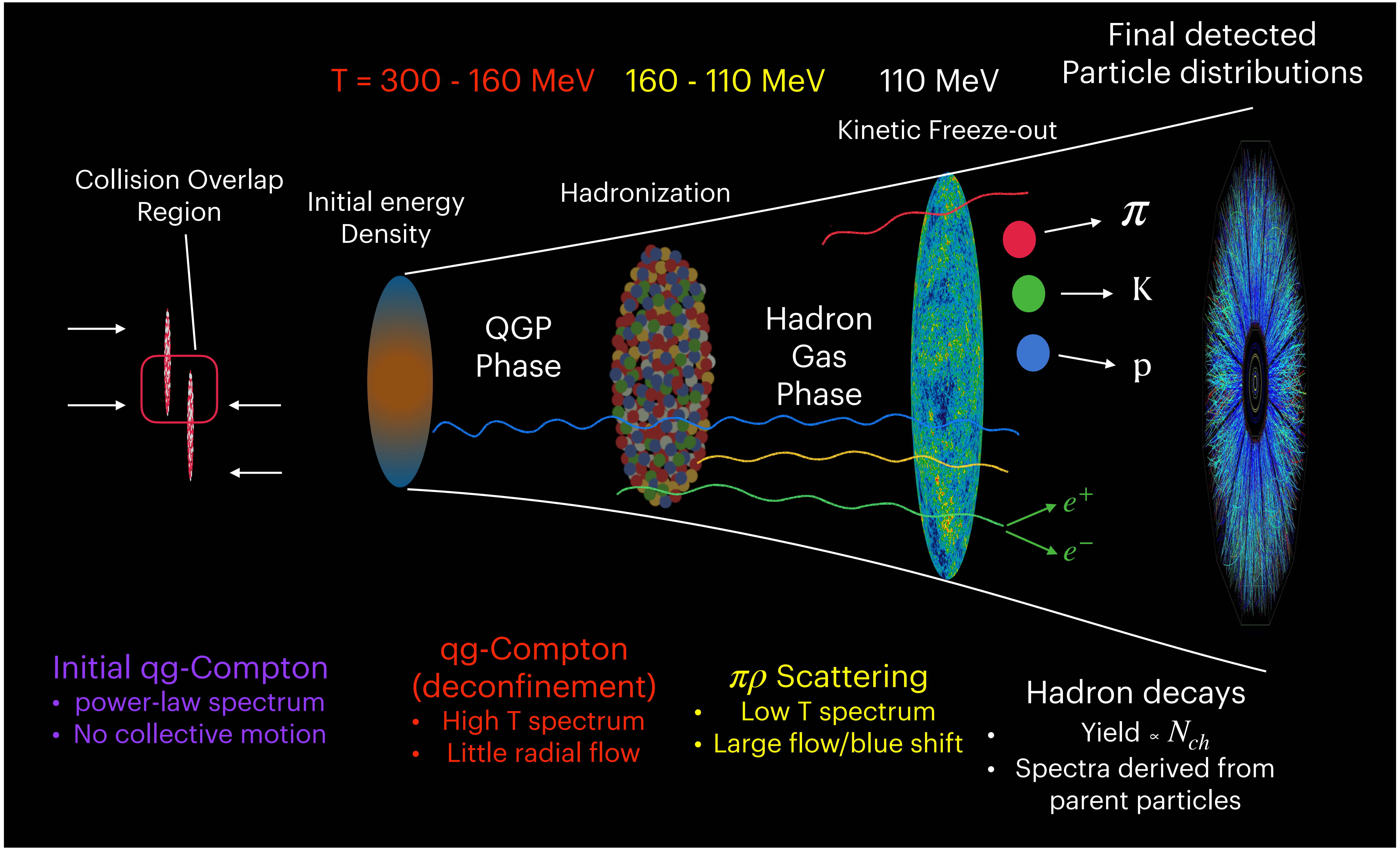
Photon Sources

Decay

Direct

Non-Prompt

Prompt



Photon Measurements with PHENIX

Calorimeter Method → Photons that directly deposit energy into EMCals.

Phys. Rev. Lett. 109, 152302 (2012)

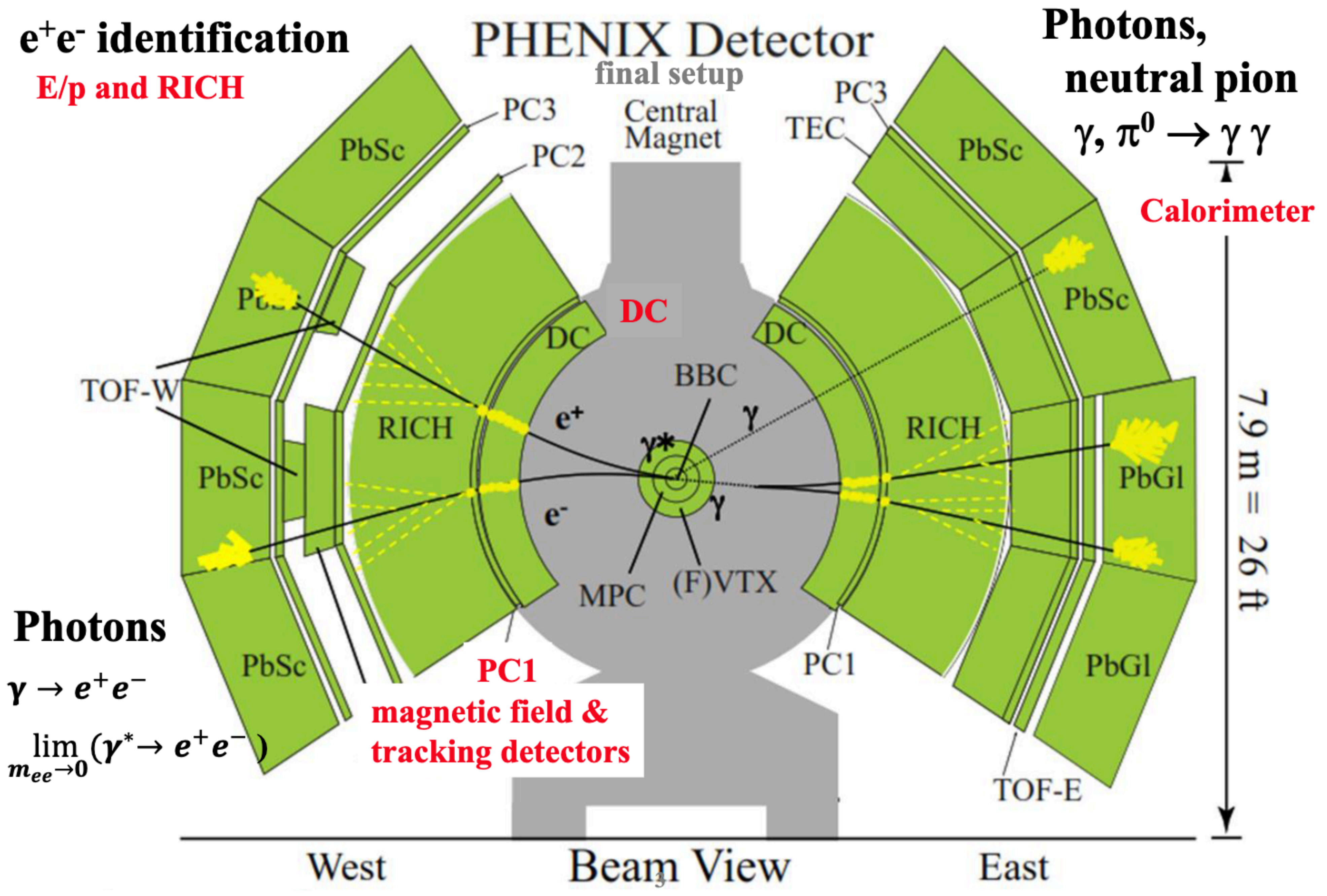
External Conversion Method → Photons that convert into e^+e^- pairs in the detector material. → Au+Au dataset at $\sqrt{s_{NN}} = 200$ GeV (2014)

PHENIX: Phys.Rev.C 109 (2024) 4, 044912
Phys. Rev. C 107, 024914 (2023)
Phys. Rev. C 91, 064904 (2015)

With the Silicon Vertex Detector (~ 13% X_0)

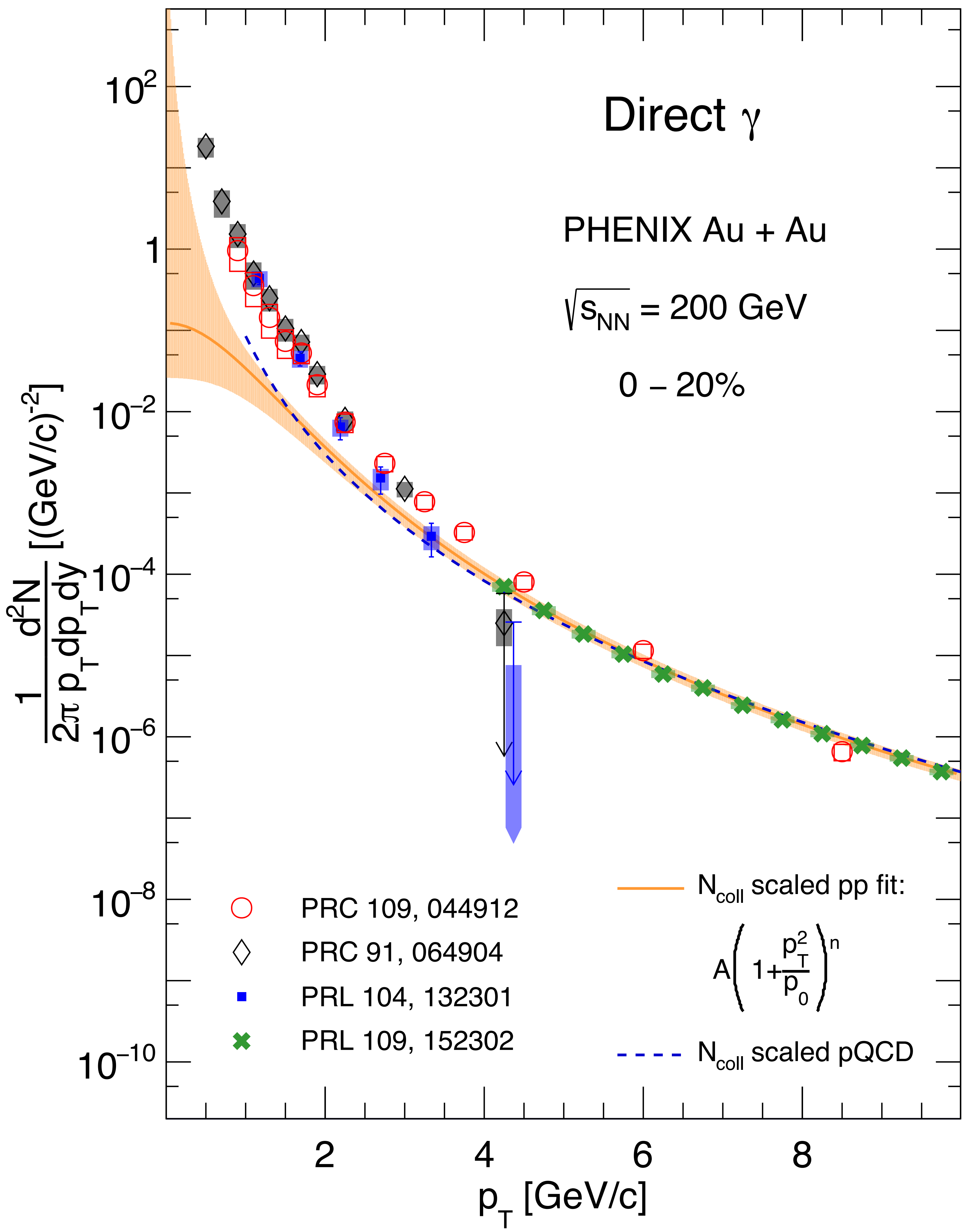
Internal Conversion Method → Virtual photons that internally convert into e^+e^- pairs.

Phys. Rev. Lett. 104, 132301 (2010)



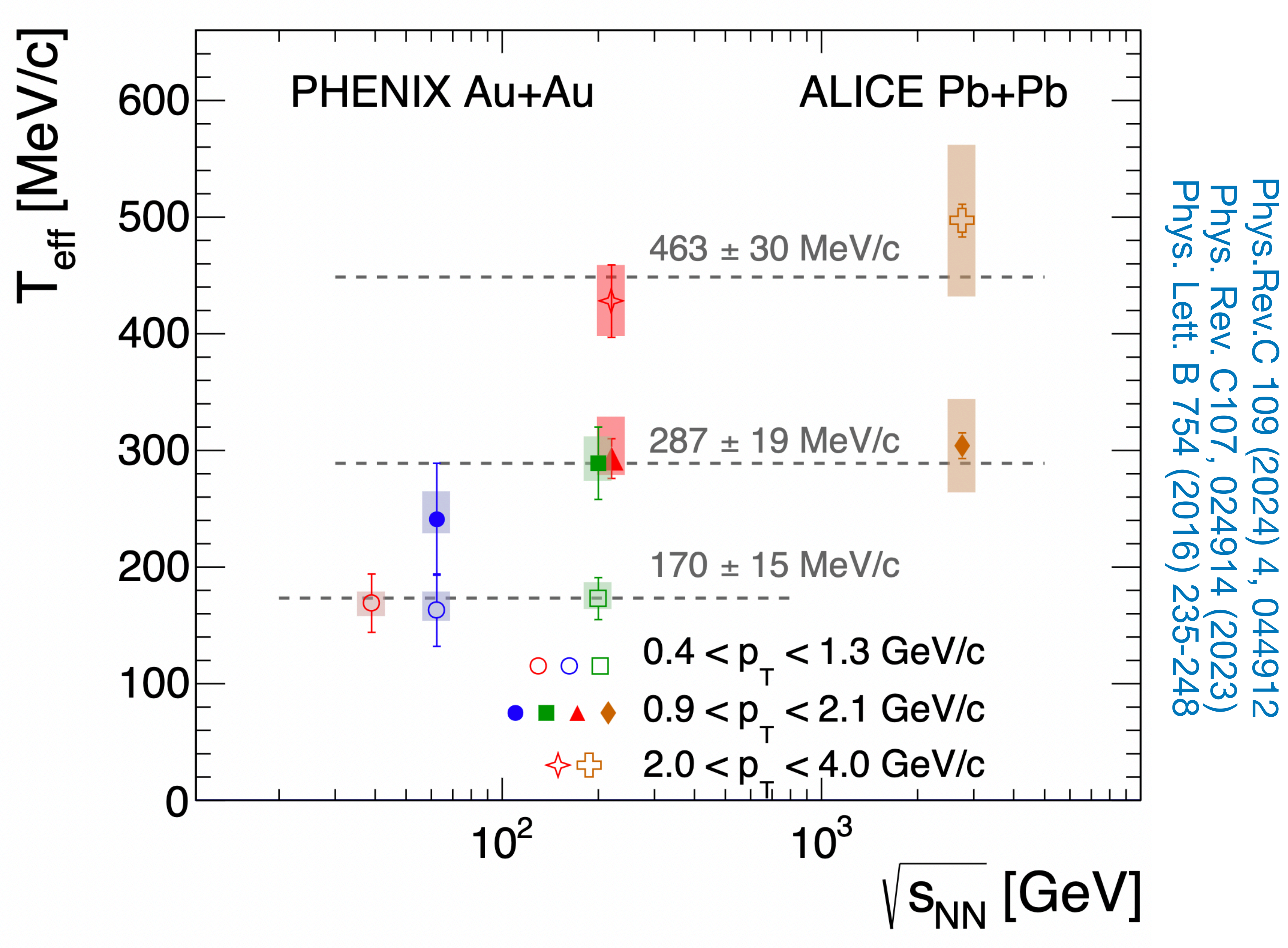
PHENIX

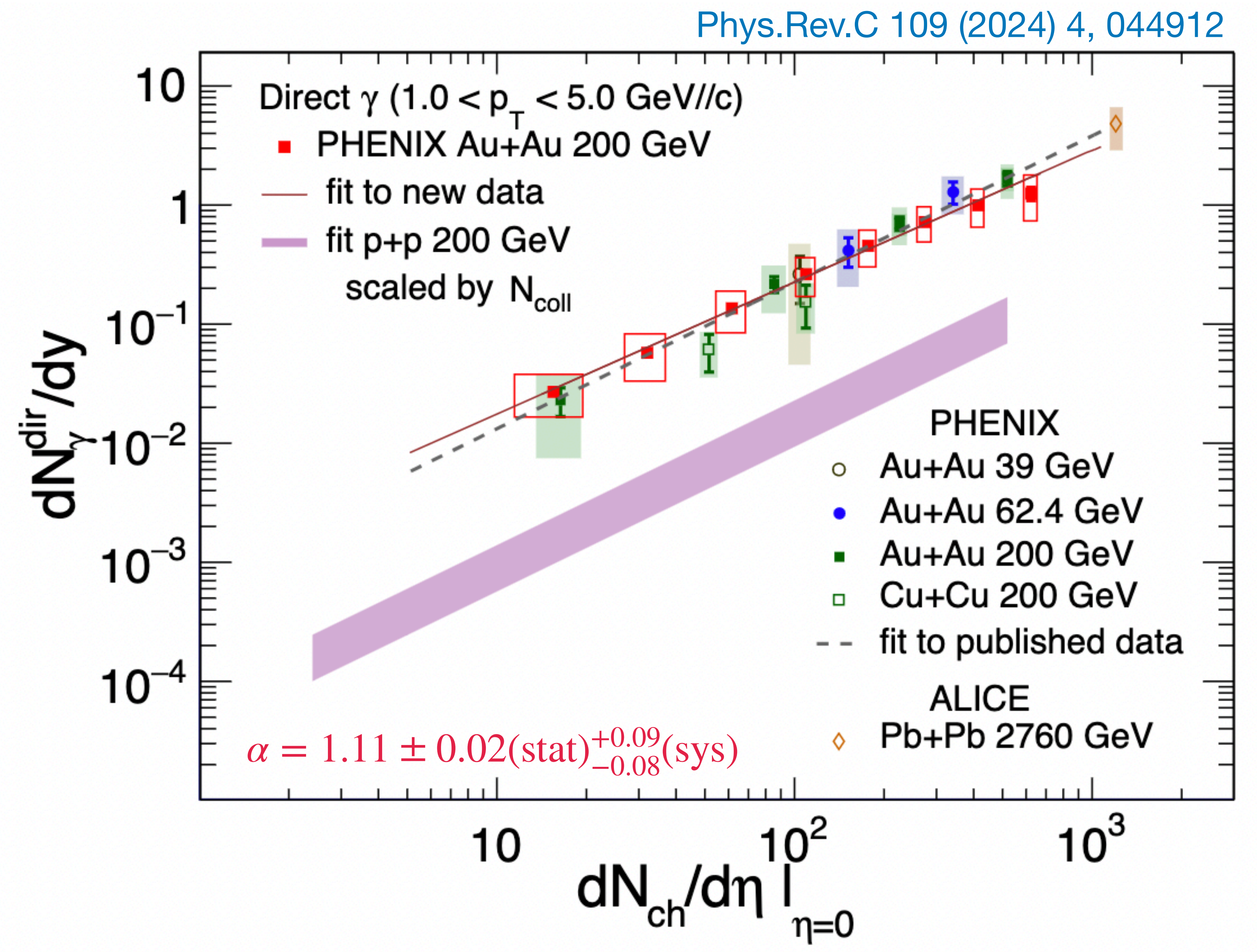
Direct Photons in Au+Au at $\sqrt{s_{NN}} = 200$ GeV



- The p+p data is consistent with pQCD.
- Au+Au follows N_{coll} scaled p+p data above 4 GeV/c
- Significant excess in the direct photon yield below 3 GeV/c in Au+Au
- The results from the high statistics 2014 Au+Au data-set reveal universal features.

System Size and Energy Dependence of Spectral Shape



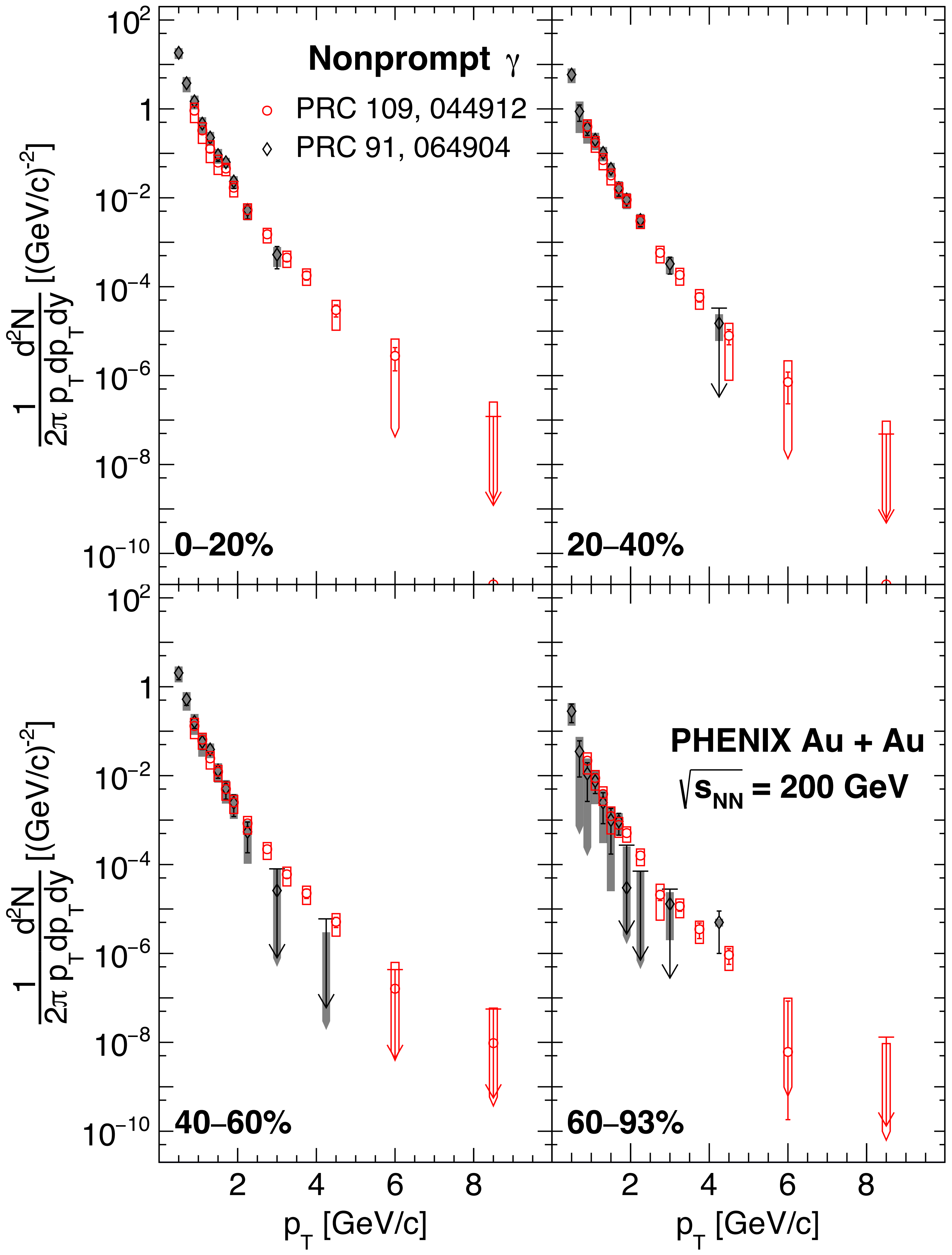


- T_{eff} increases with p_T
- No obvious variation of T_{eff} with $\sqrt{s_{NN}}$

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

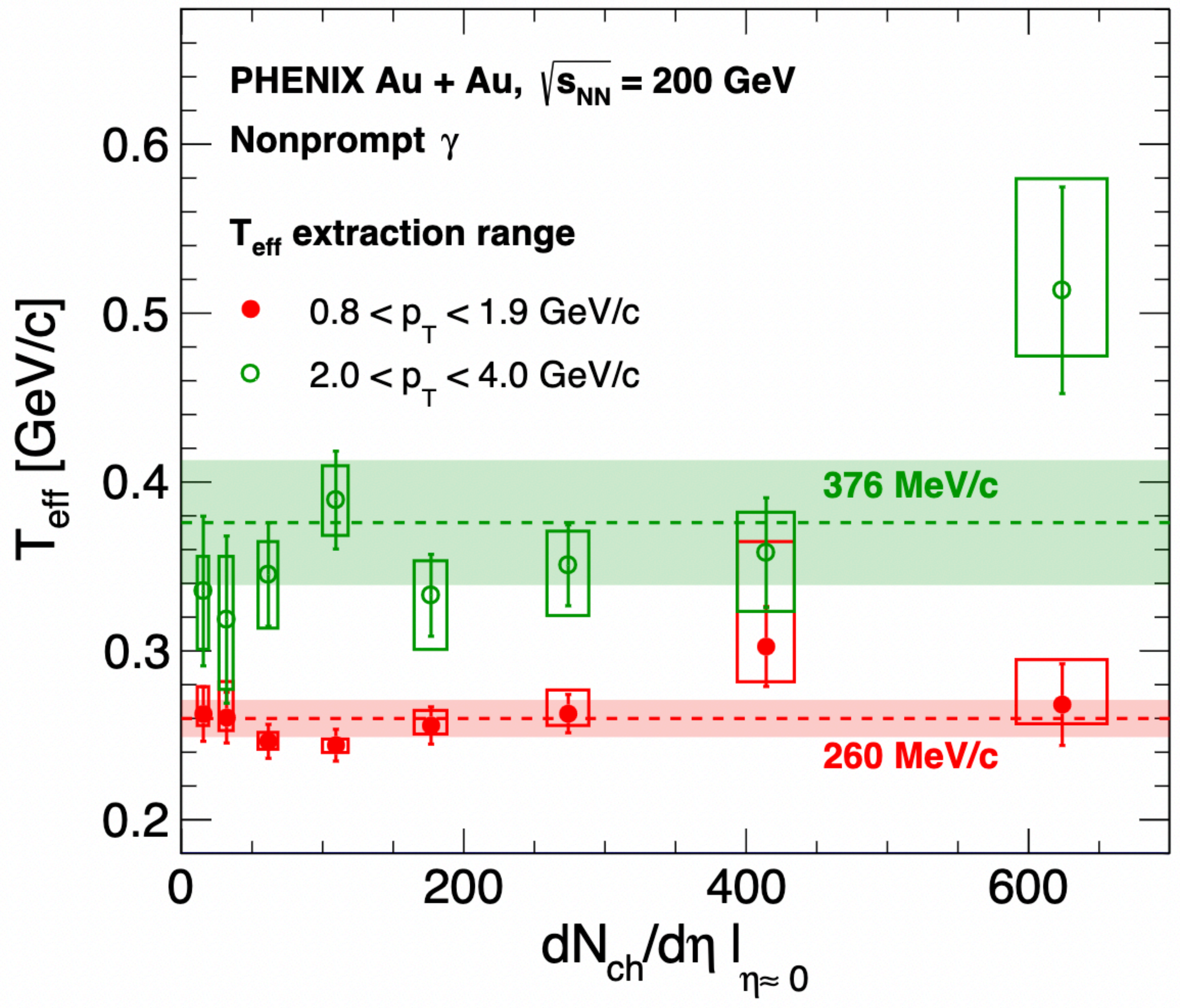
Universal scaling behaviour of direct photon yields in all A+A systems.

Non-Prompt Direct Photons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

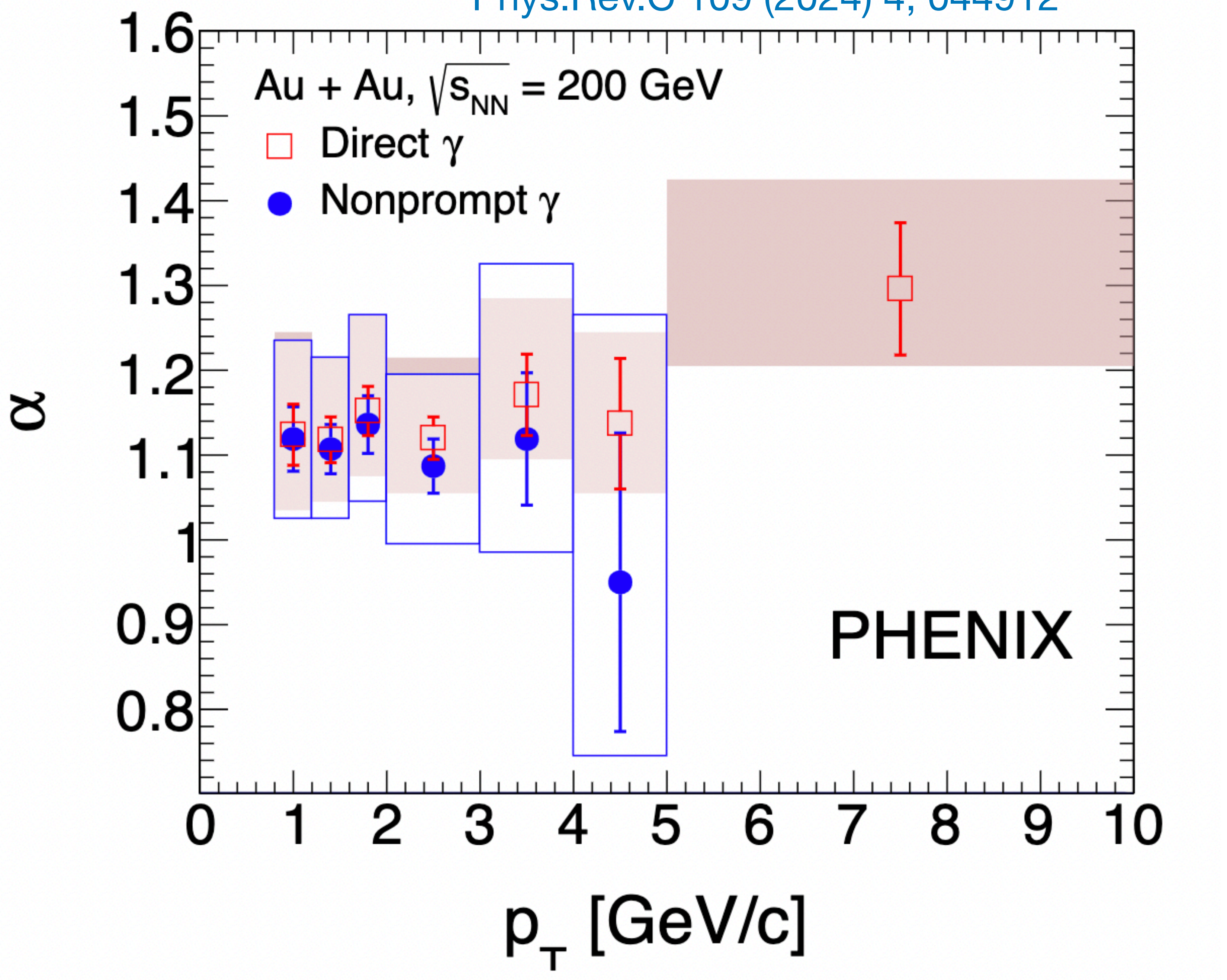


Non-prompt direct photons are measured by subtracting the prompt component, which is estimated as N_{coll}-scaled direct photons from $p + p$ collisions at 200 GeV, from the direct-photon spectrum.

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

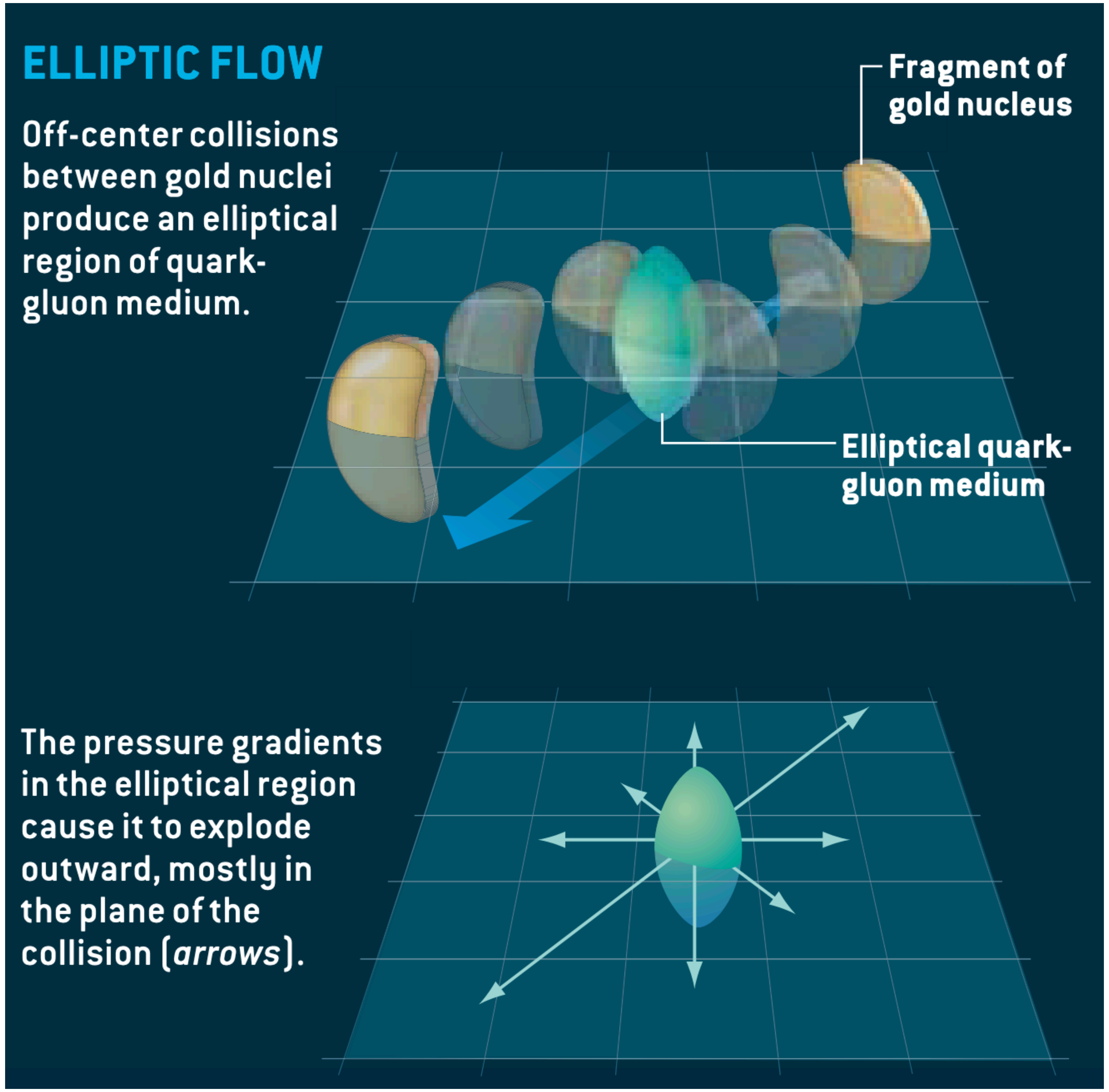


Phys.Rev.C 109 (2024) 4, 044912



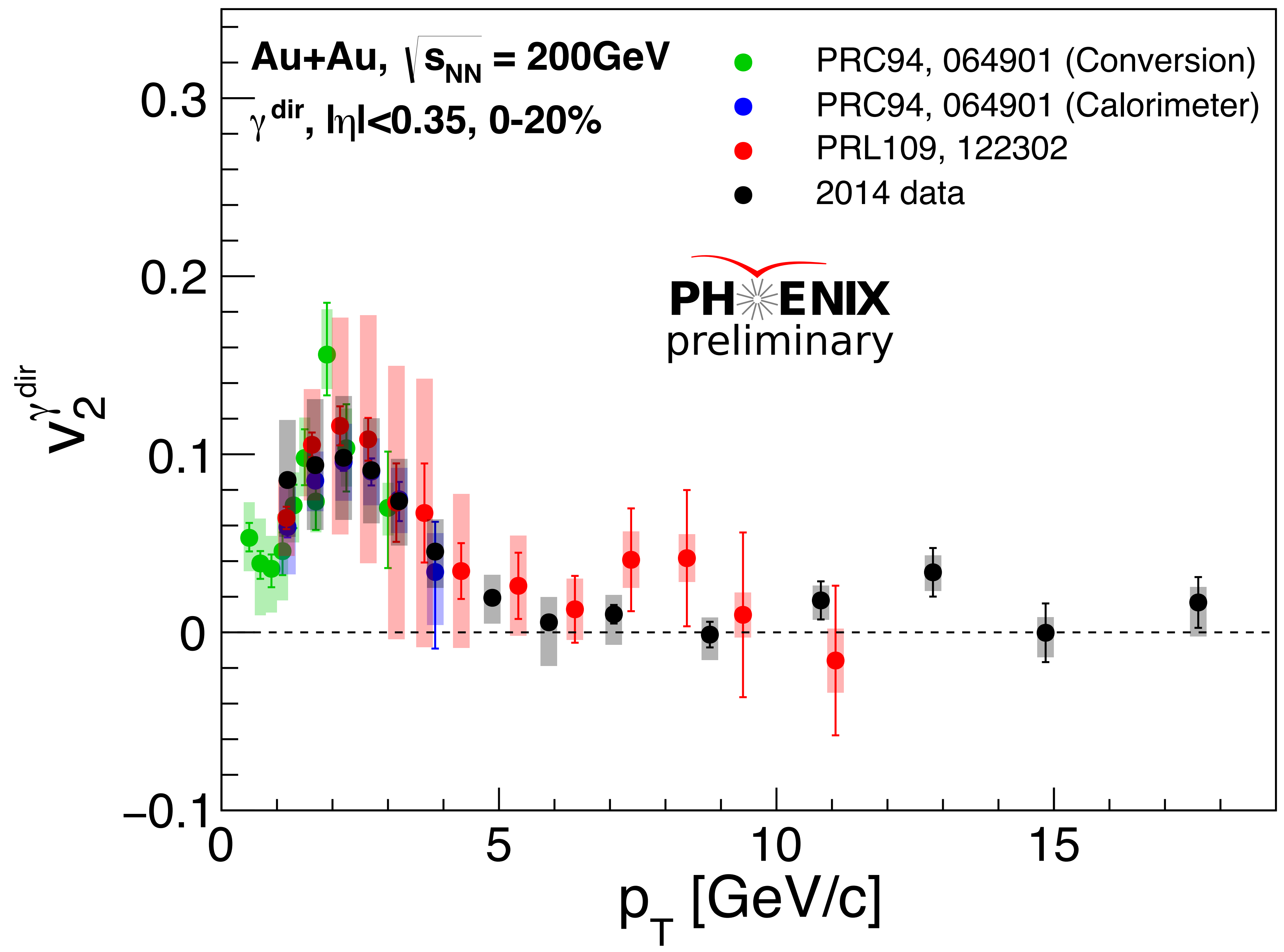
- T_{eff} increases with p_T but no obvious variation with system size
- α independent of p_T in data in contrast to the model calculations.

Elliptic Flow of Direct Photons

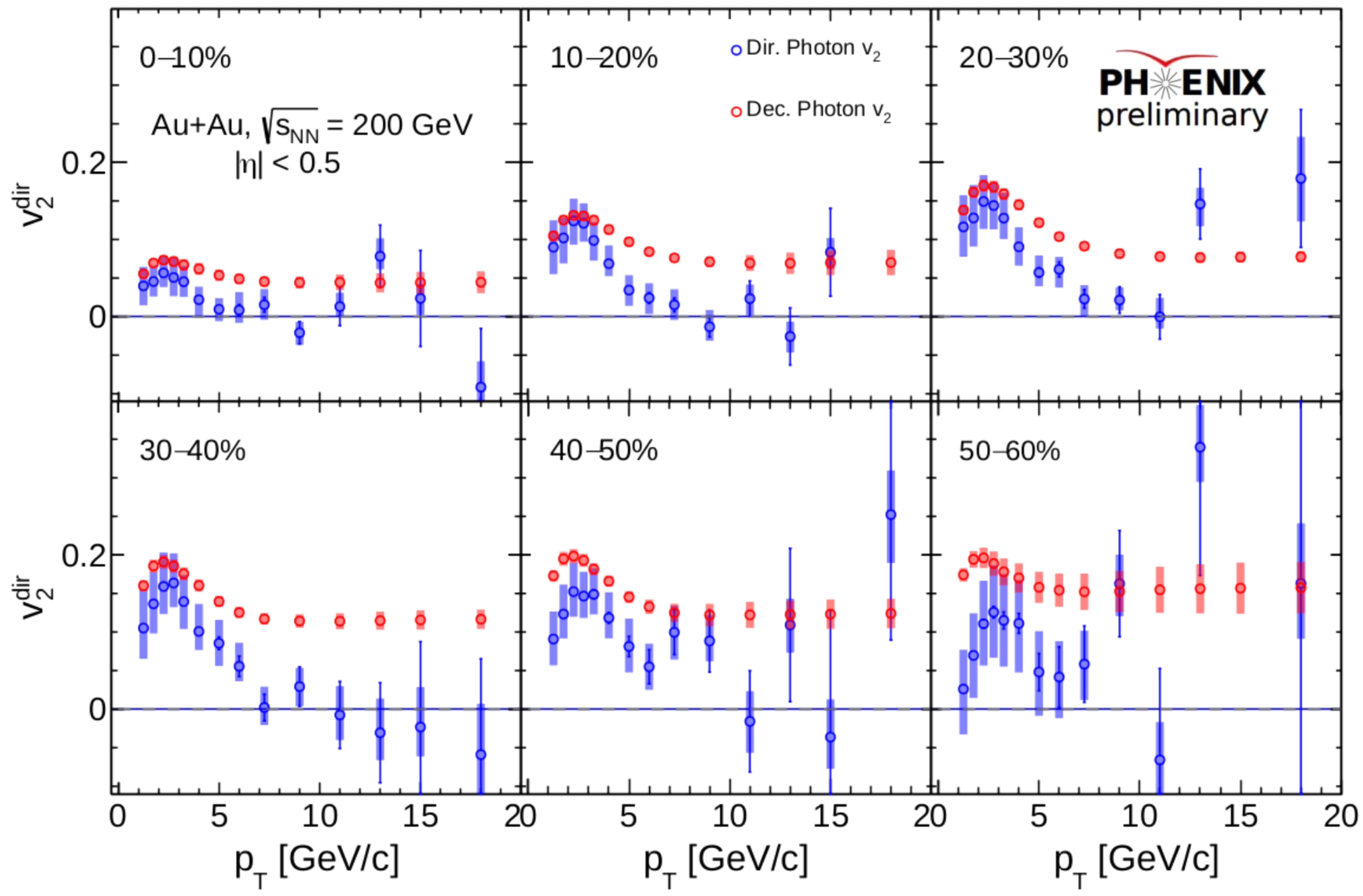


Quantified by the second Fourier moment of the particle azimuthal distribution with respect to the reaction plane.

$$\frac{dN}{d\phi} = N_0[1 + 2v_2 \cos(2\phi)]$$



Elliptic Flow of Direct Photons in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV



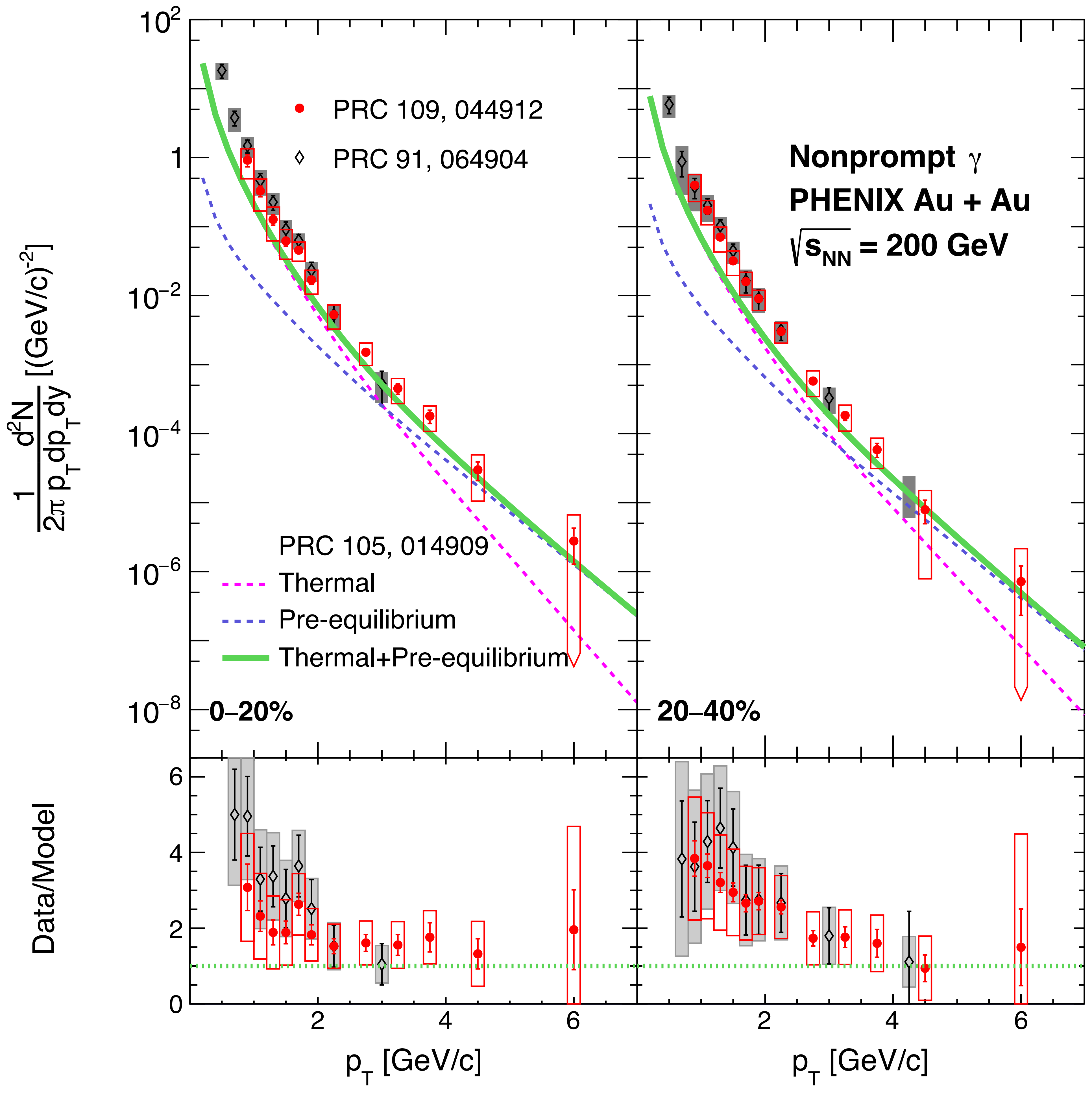
Significant flow for p_T < 5 GeV/c

- Similar to decay photons
- Clear centrality dependence

High p_T dominated by prompt photon production

- v_2 consistent with 0
- No centrality dependence

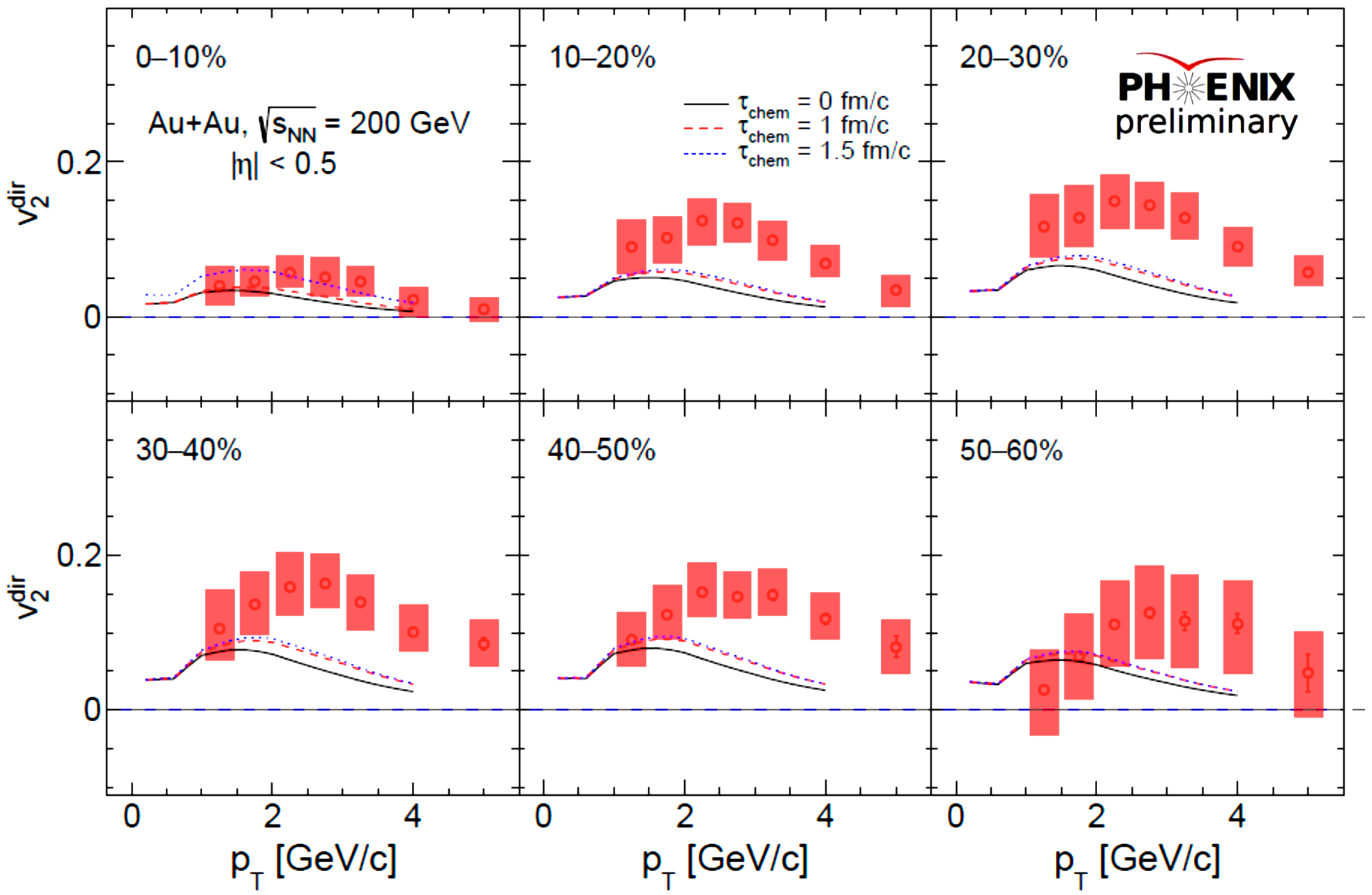
Model Calculations



Multi-messenger heavy-ion physics

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

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

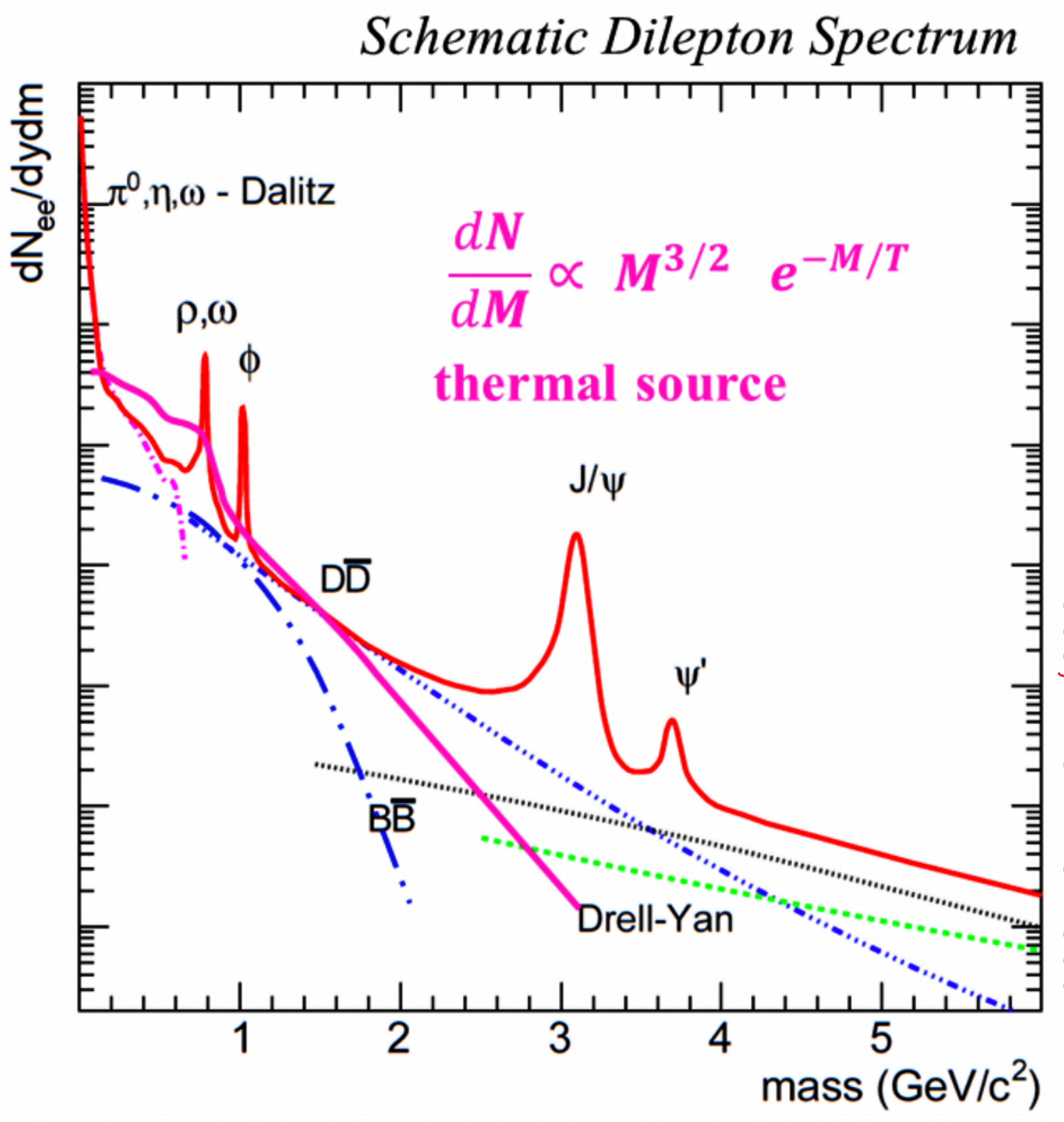


Theoretical models qualitatively reproduce the shape but falls short quantitatively.

Dilepton Continuum Measurements

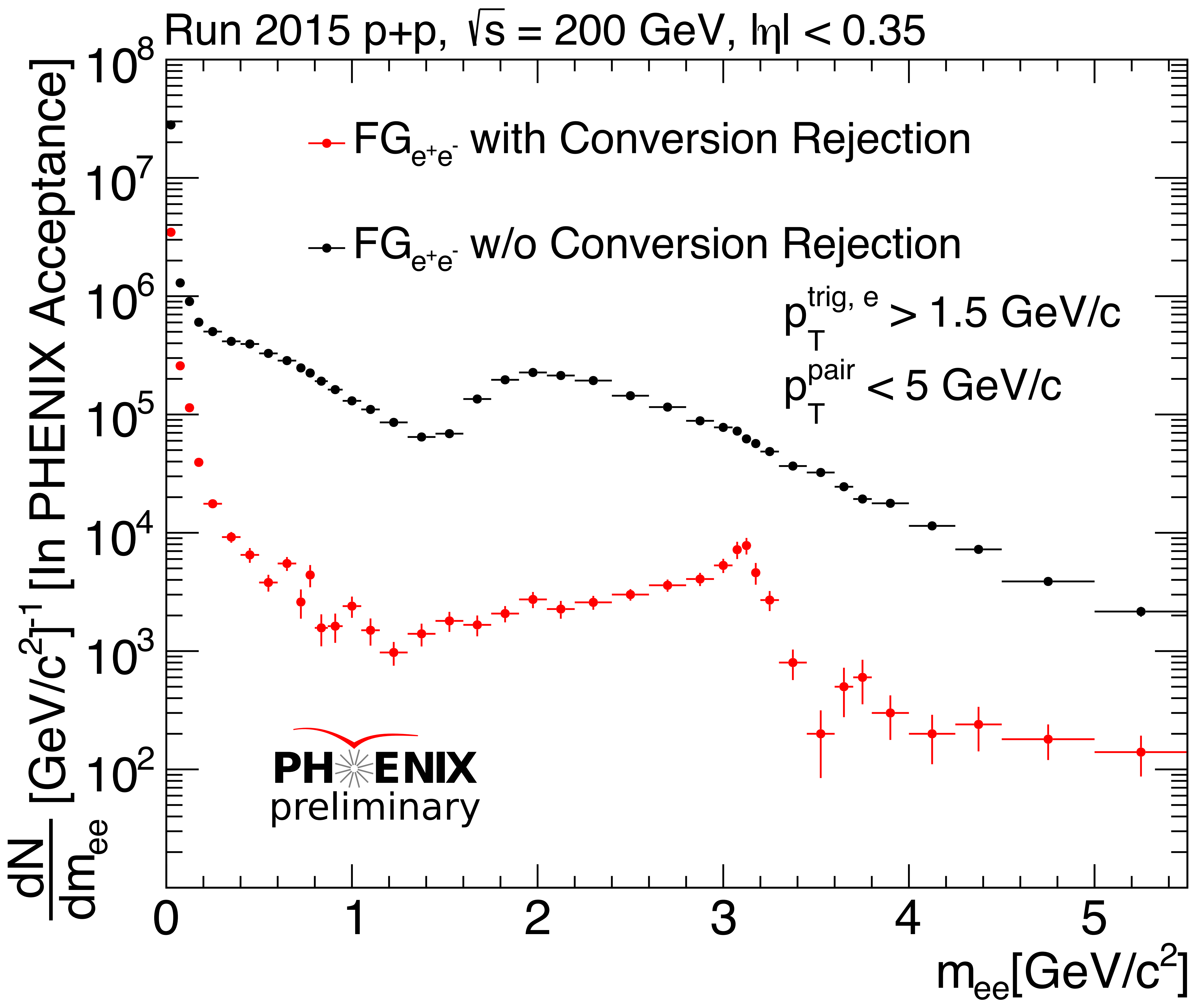
Thermal radiation in dilepton spectra

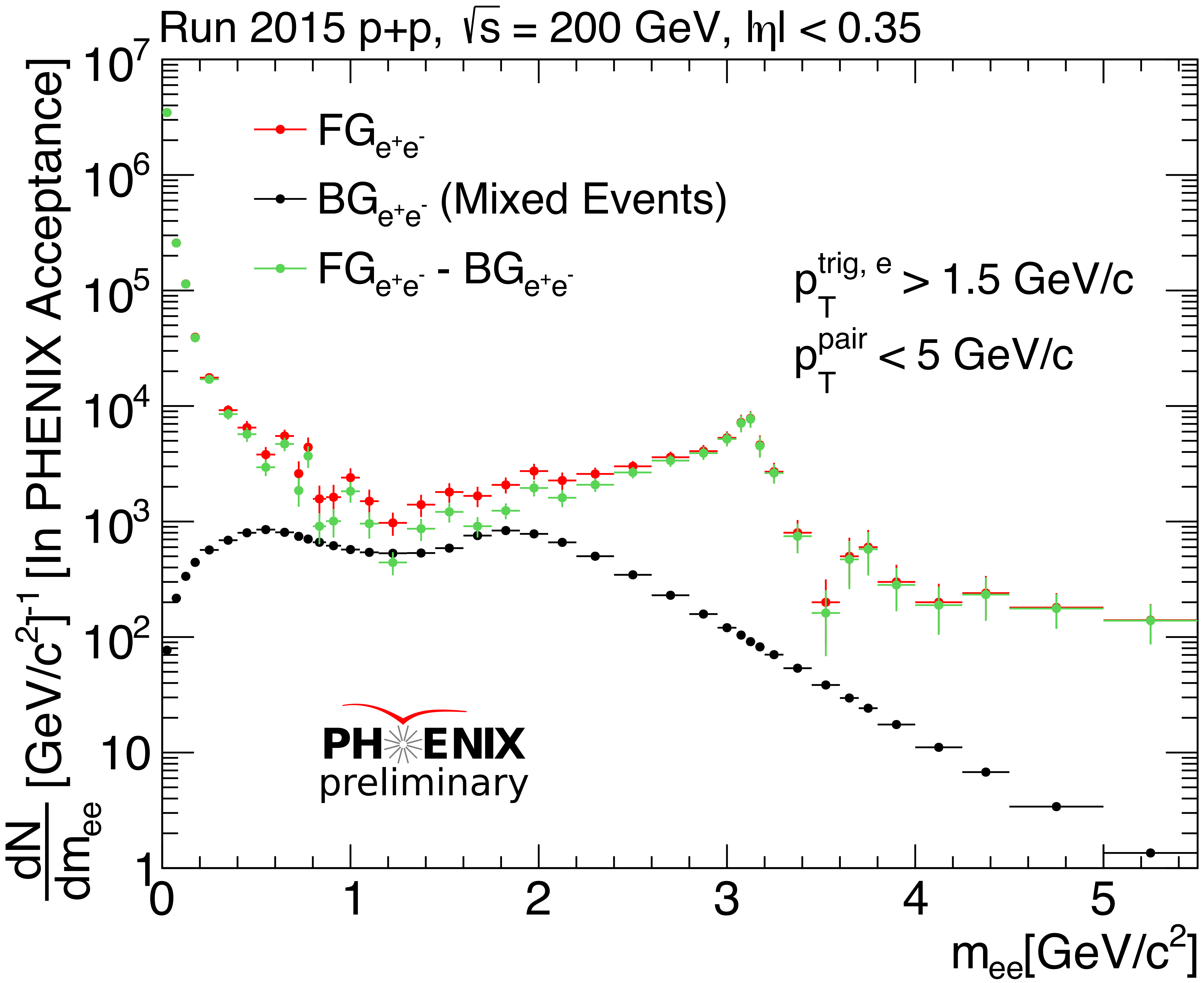
- In the dilepton invariant mass range from about 1 to 3 GeV/c^2, there is a significant contribution from thermal emission from the QGP.
  - Background from semi-leptonic decays of open heavy flavor.
  - Small contribution from Drell-Yan.
  - Vertex detector is required to disentangle the thermal and semi-leptonic components (PHENIX installed Silicon Vertex Detector in 2011).
- Silicon Vertex detector presents a huge photon conversion background.



A. Drees, Knoxville 2009

Invariant Mass Spectrum in p+p at $\sqrt{s_{NN}} = 200$ GeV





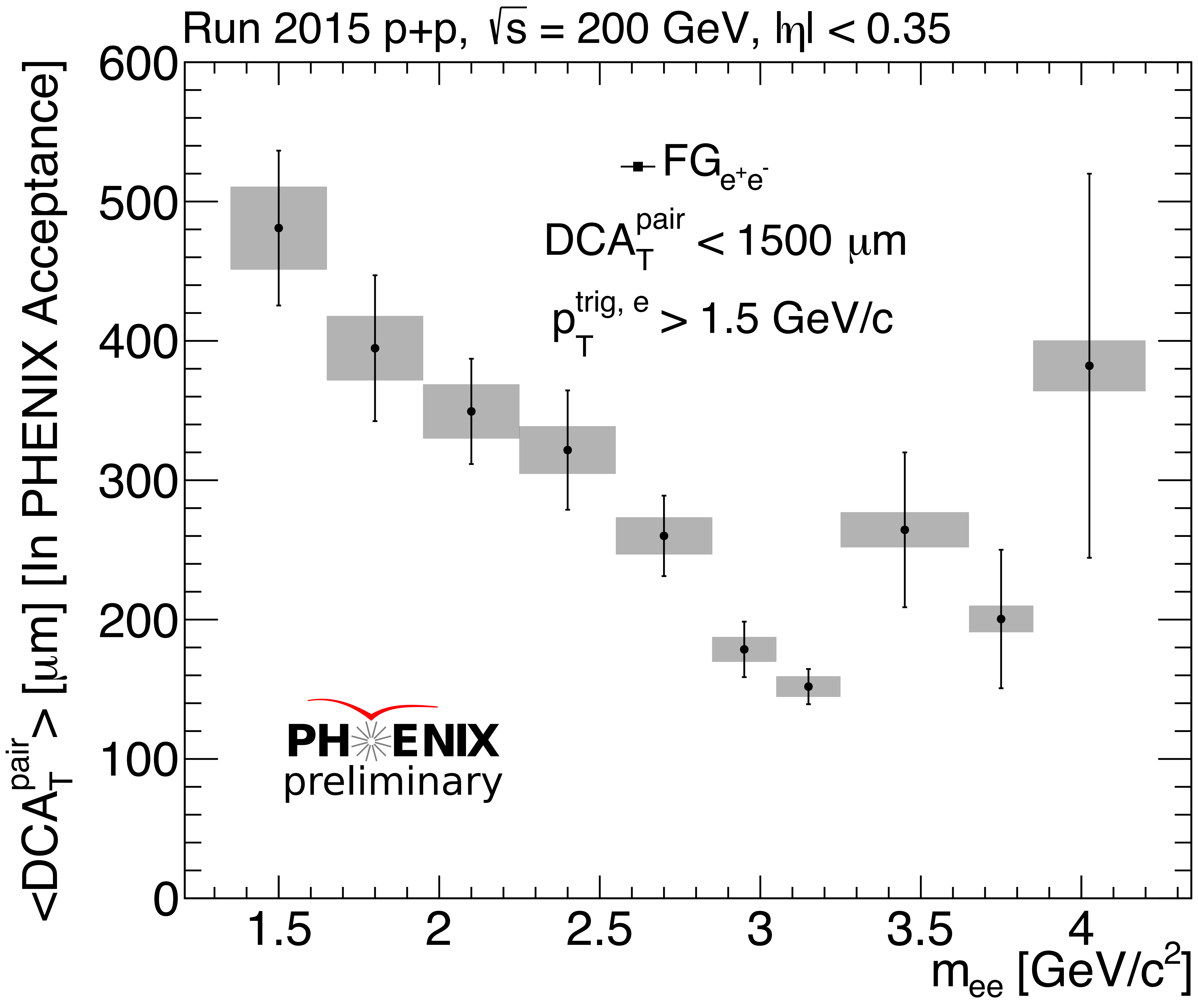
Significant Conversion Background Rejection

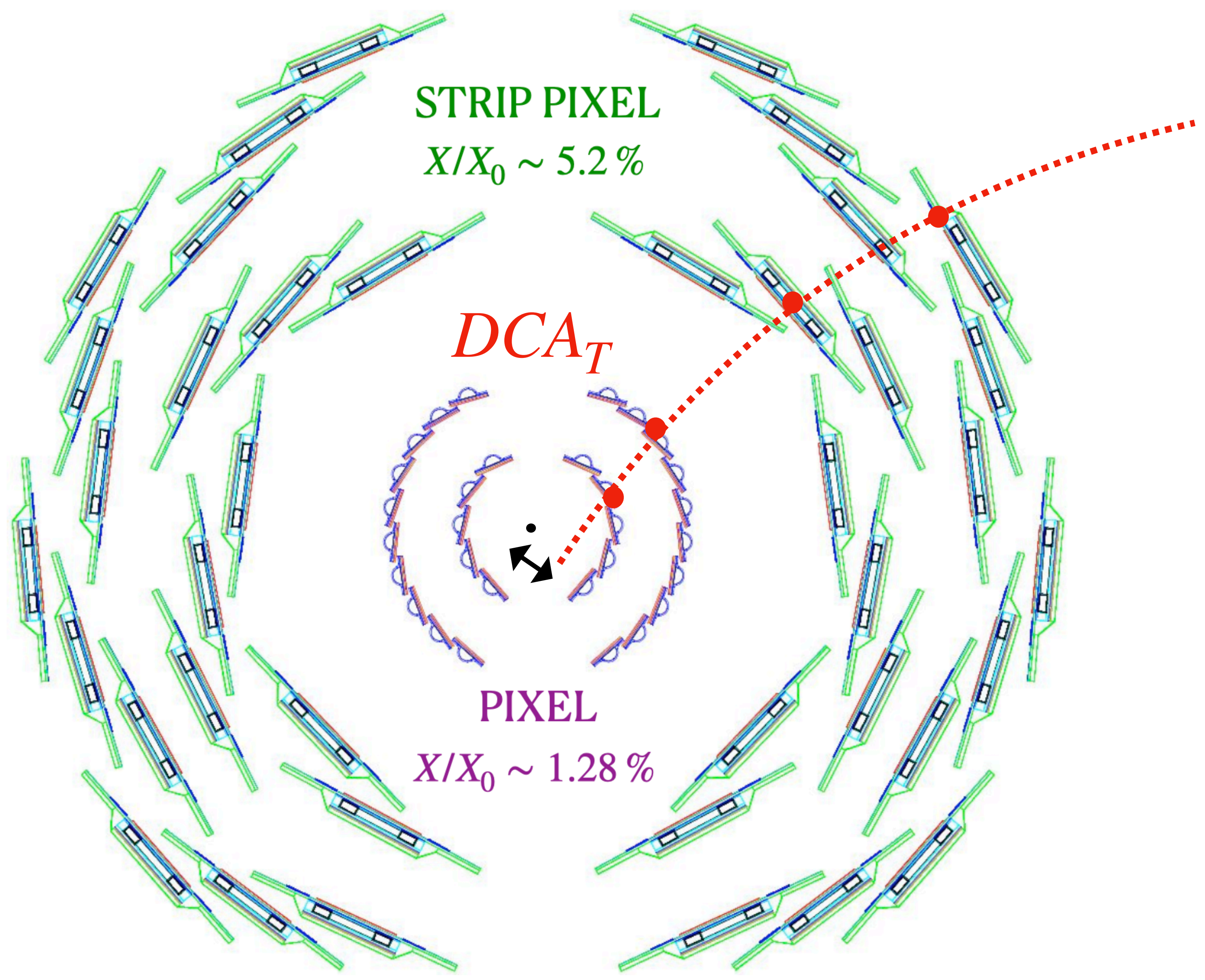
$\frac{SG}{BG} > 1$ at all masses

Measurements in the DCA Space

We calculate a transverse DCA of the central arm tracks to the interaction vertex determined by the VTX given by

$$DCA_T = L - R$$

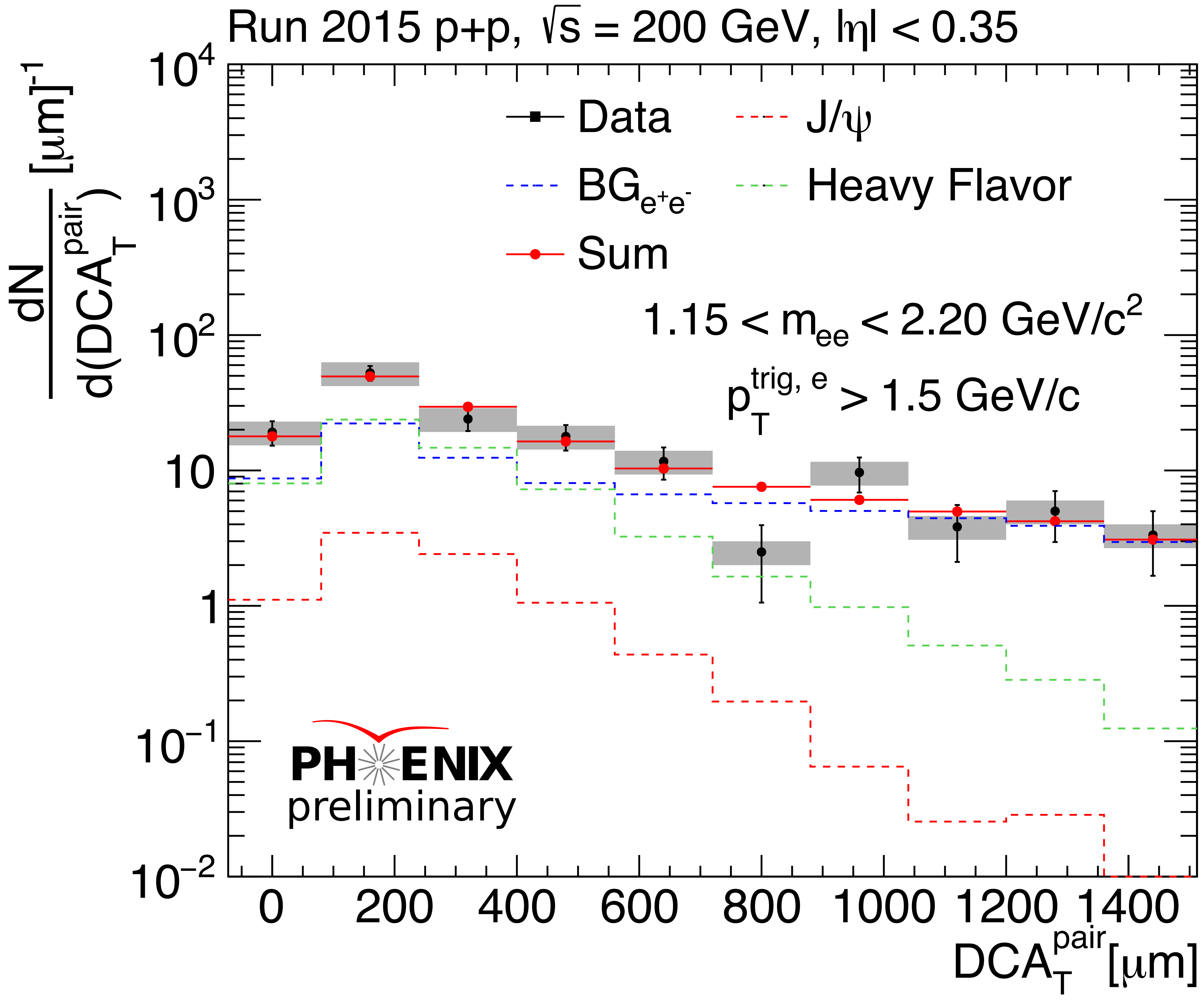


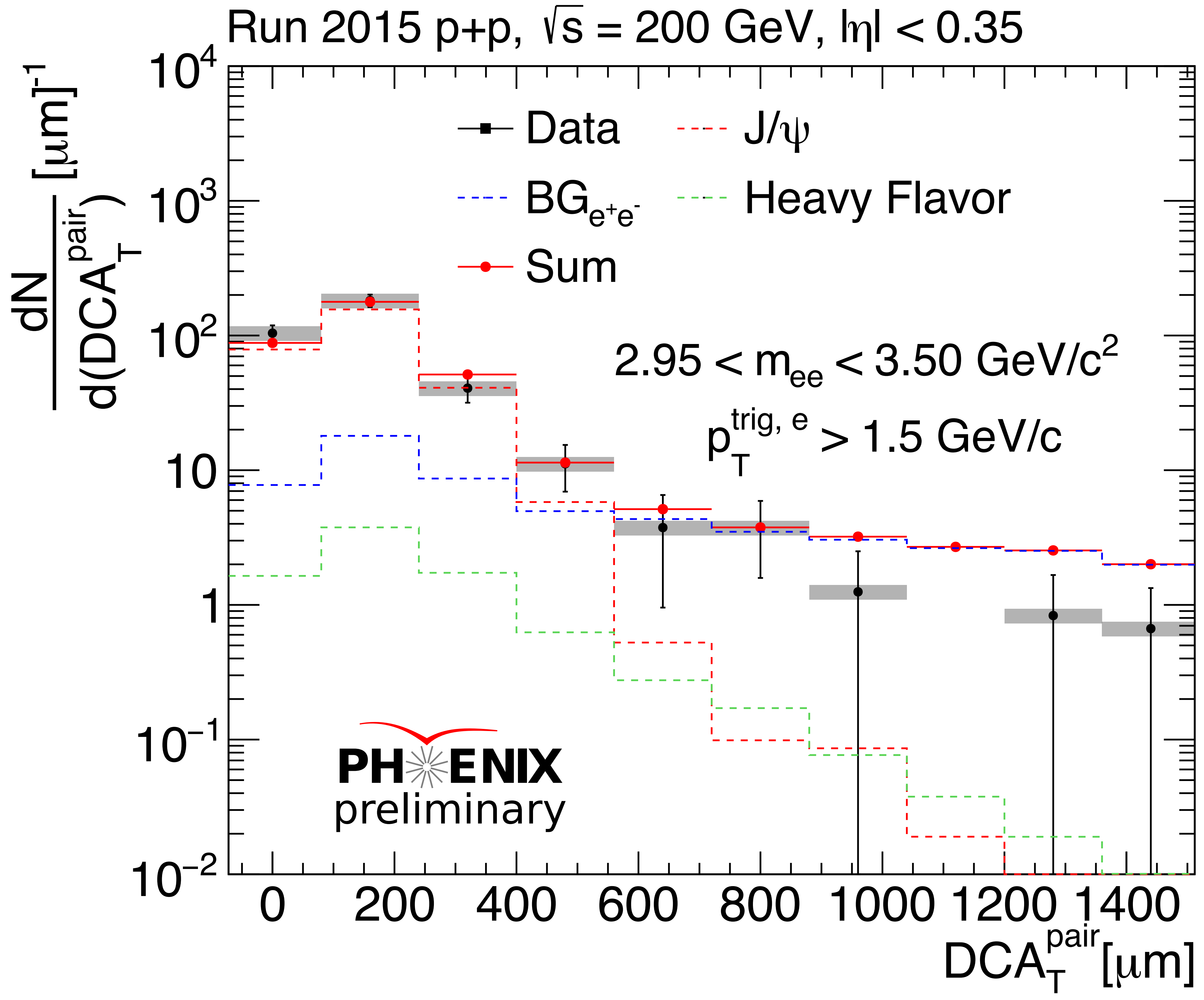


$< DCA_T >$ exhibits a minimum around the J/ψ mass region as expected.

$$DCA_T^{pair} = \sqrt{|DCA_{e^-}^2 - DCA_{e^+}^2|}$$

Distributions in the DCA Space



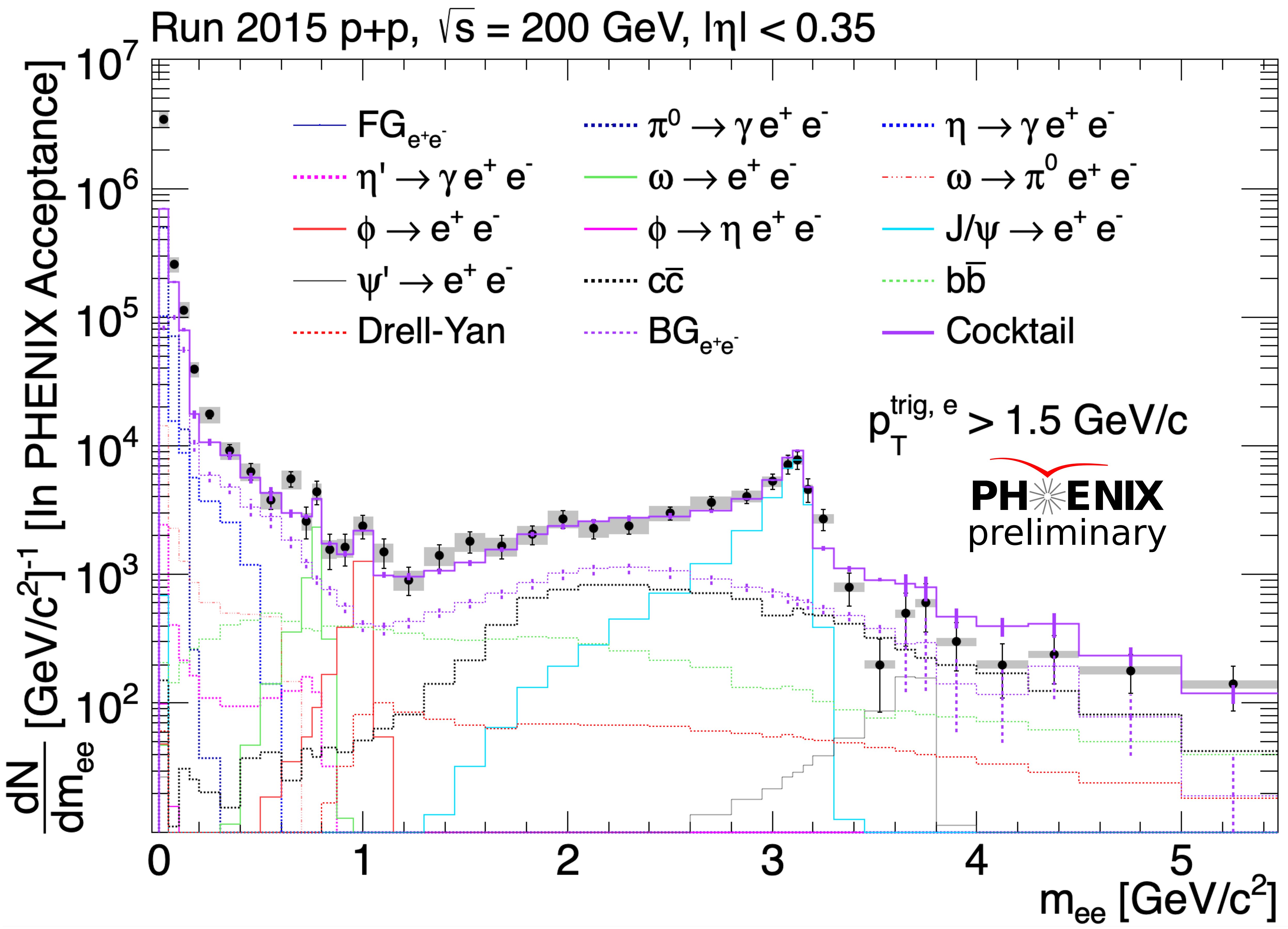


- Mostly dominated by Heavy Flavor and Background contributions.
- A little contribution from J/ψ, an artifact of Bremsstrahlung.

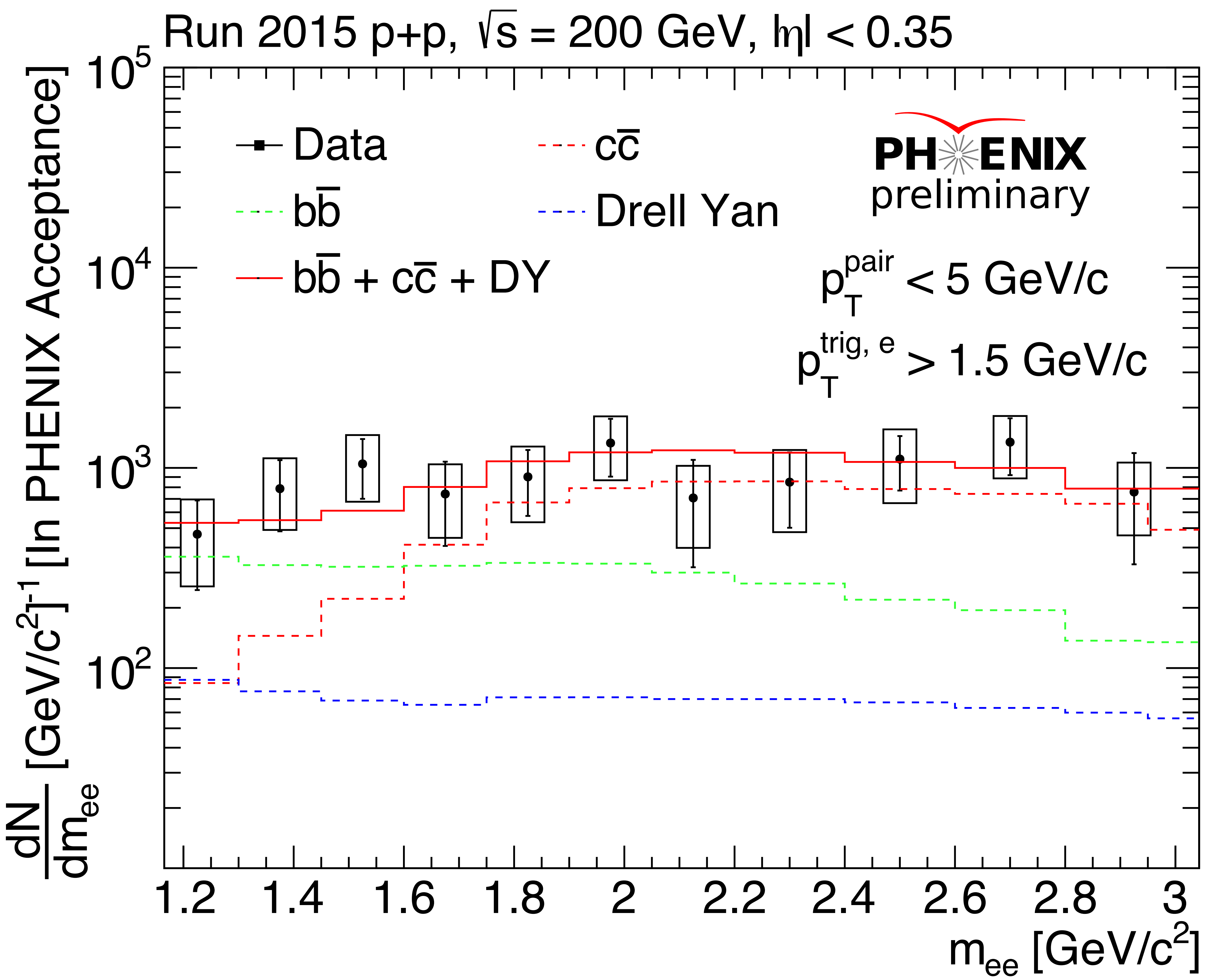
Moving to the lower mass region

- Mostly dominated by J/ψ, the prompt component
- Some contribution from background dominating the higher DCA_T values.
- A little contribution from heavy flavor.

Comparison to known sources and the continuum plot



There is good agreement between the measured Foreground and the sum of all the known sources.



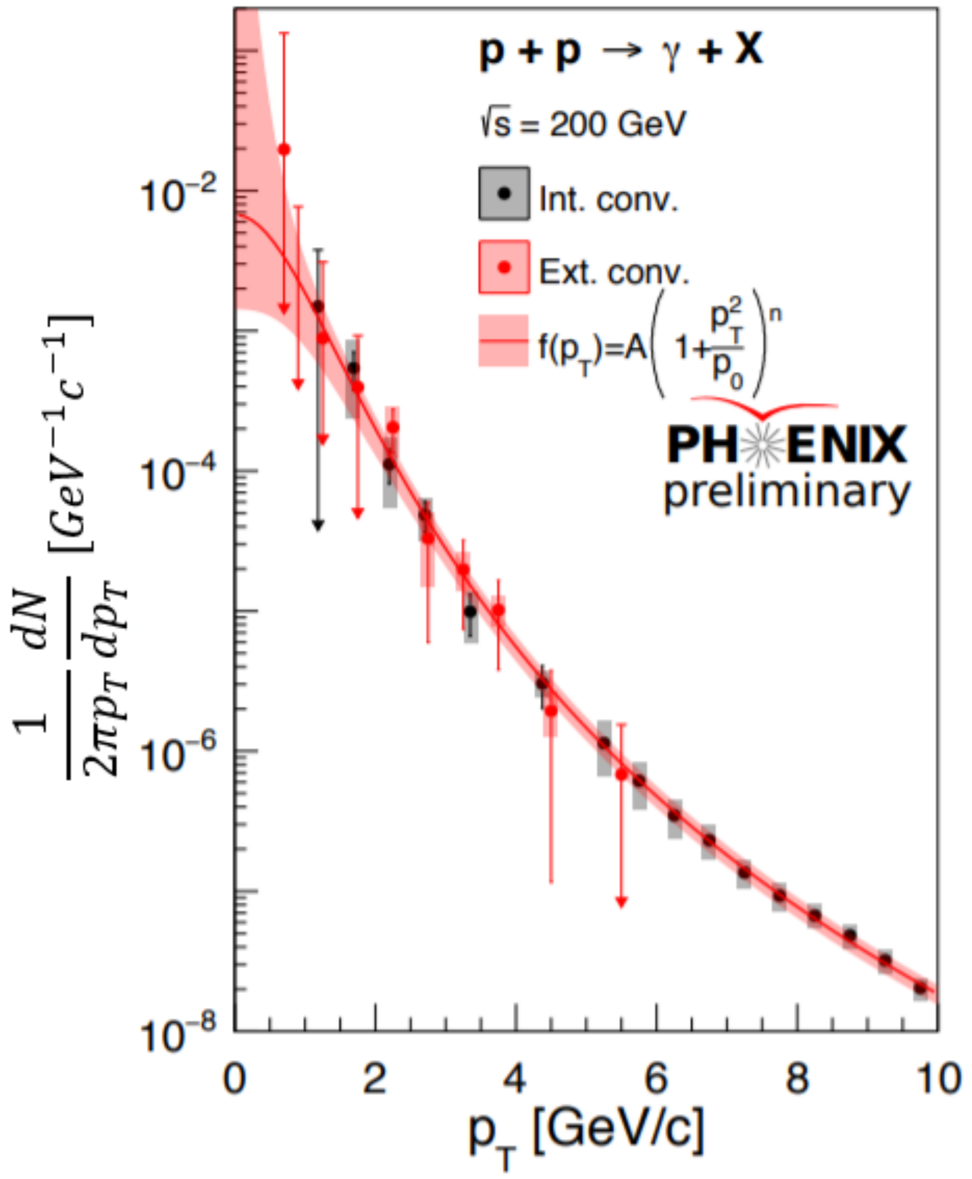
The Heavy-Flavor and Drell-Yan contributions obtained from Pythia8 reproduce the data pretty well

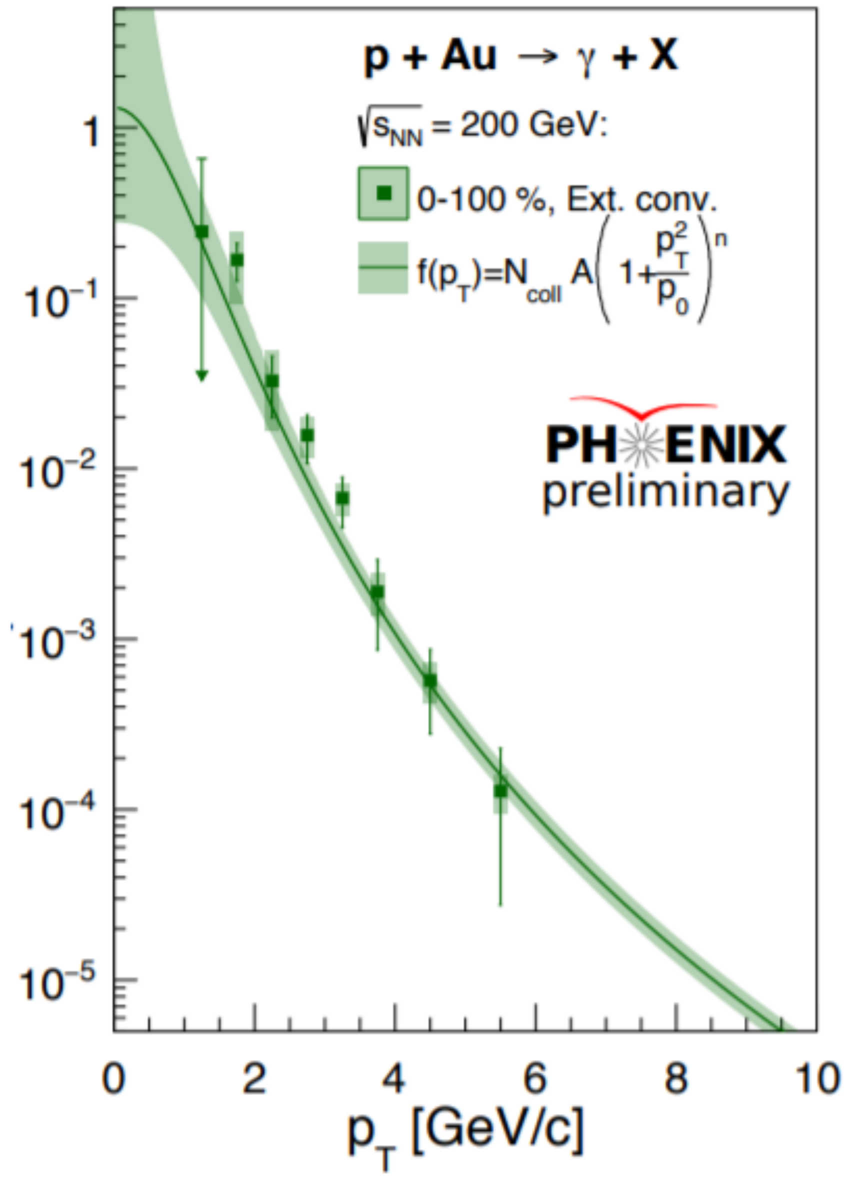
Summary: PHENIX Direct Photons and Dilepton Results

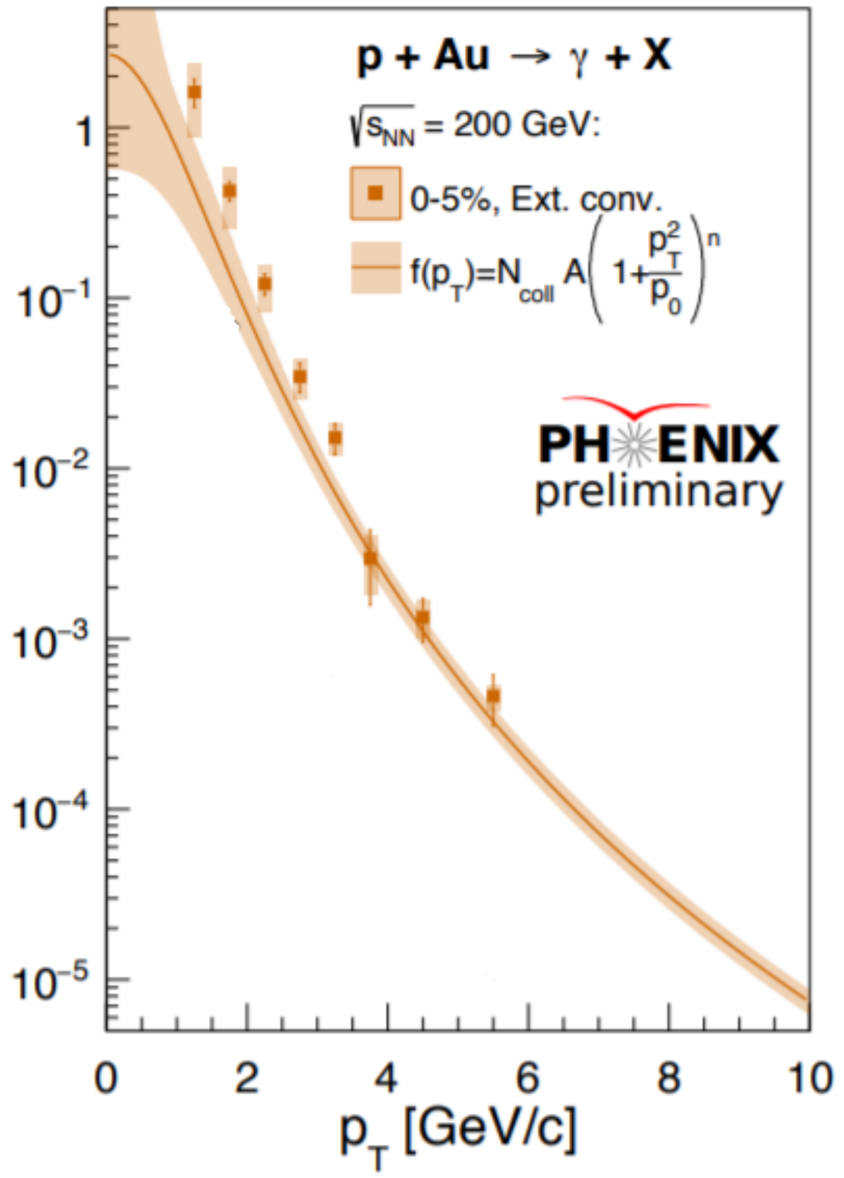
- New high-statistics Au+Au results reveal universal features.
- Large “Thermal” yield for $p_T < 3$ GeV/c
  - T_{eff} increases with p_T
  - No obvious variation of with T_{eff} or $\sqrt{s_{NN}}$ or centrality
  - $N_\gamma^{dir} \sim N_{ch}^\alpha$ scaling of direct photon yields in all A+A systems $\alpha = 1.1$ independent of p_T.
  - Large anisotropy v_2 with max at 2-3 GeV
- Dilepton Continuum measured in p+p at $\sqrt{s_{NN}} = 200$ GeV
  - Effective conversion rejection techniques result in a Signal/Background > 1 at all masses
  - DCA_T distributions hinge the heavy-flavor, prompt and background contributions in the intermediate mass region.
  - The data agree well with the cocktail of known sources.

Back Up

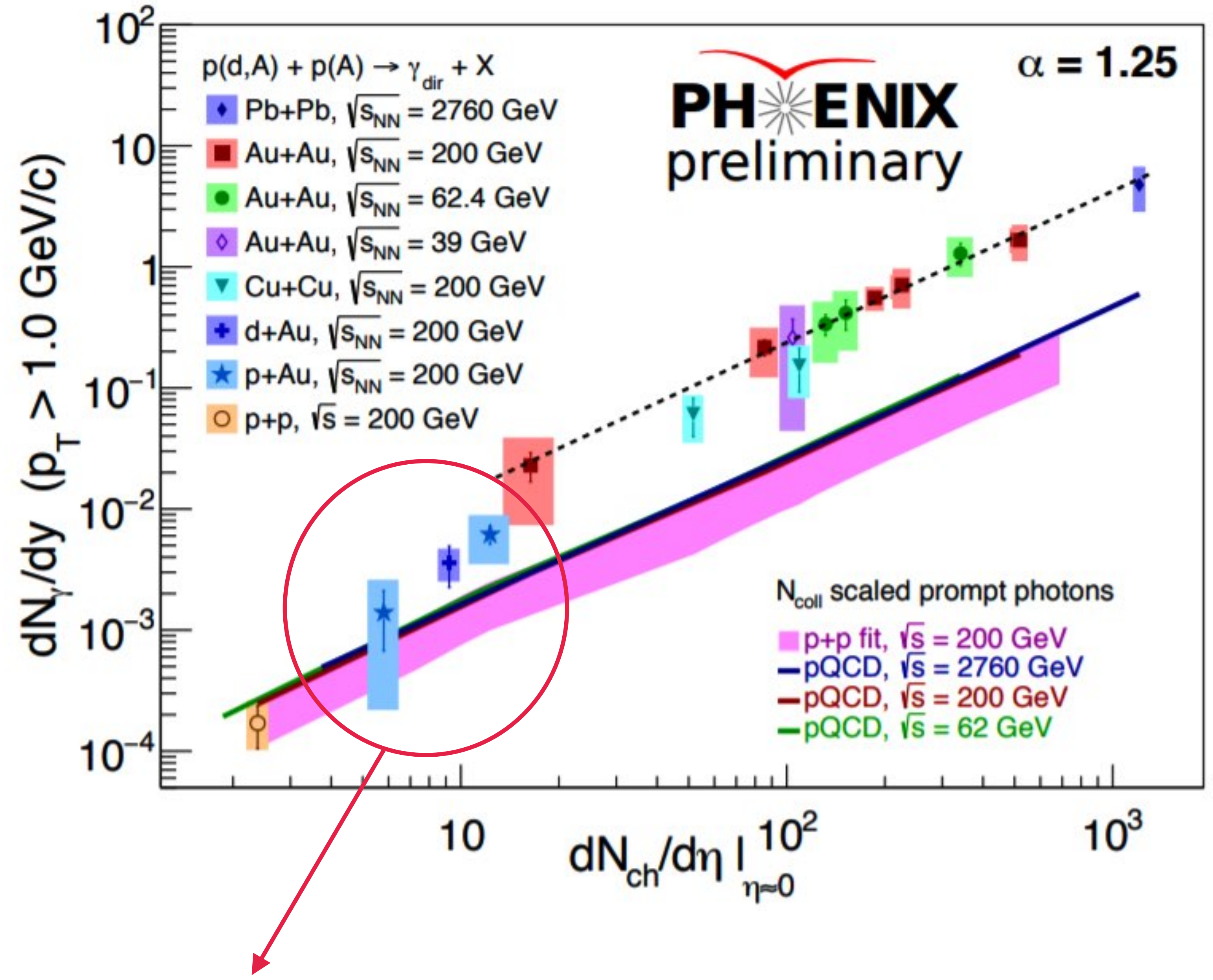
Direct γ in small systems







Bridging the gap



Onset of QGP?

PHENIX

$p+p$ Fit

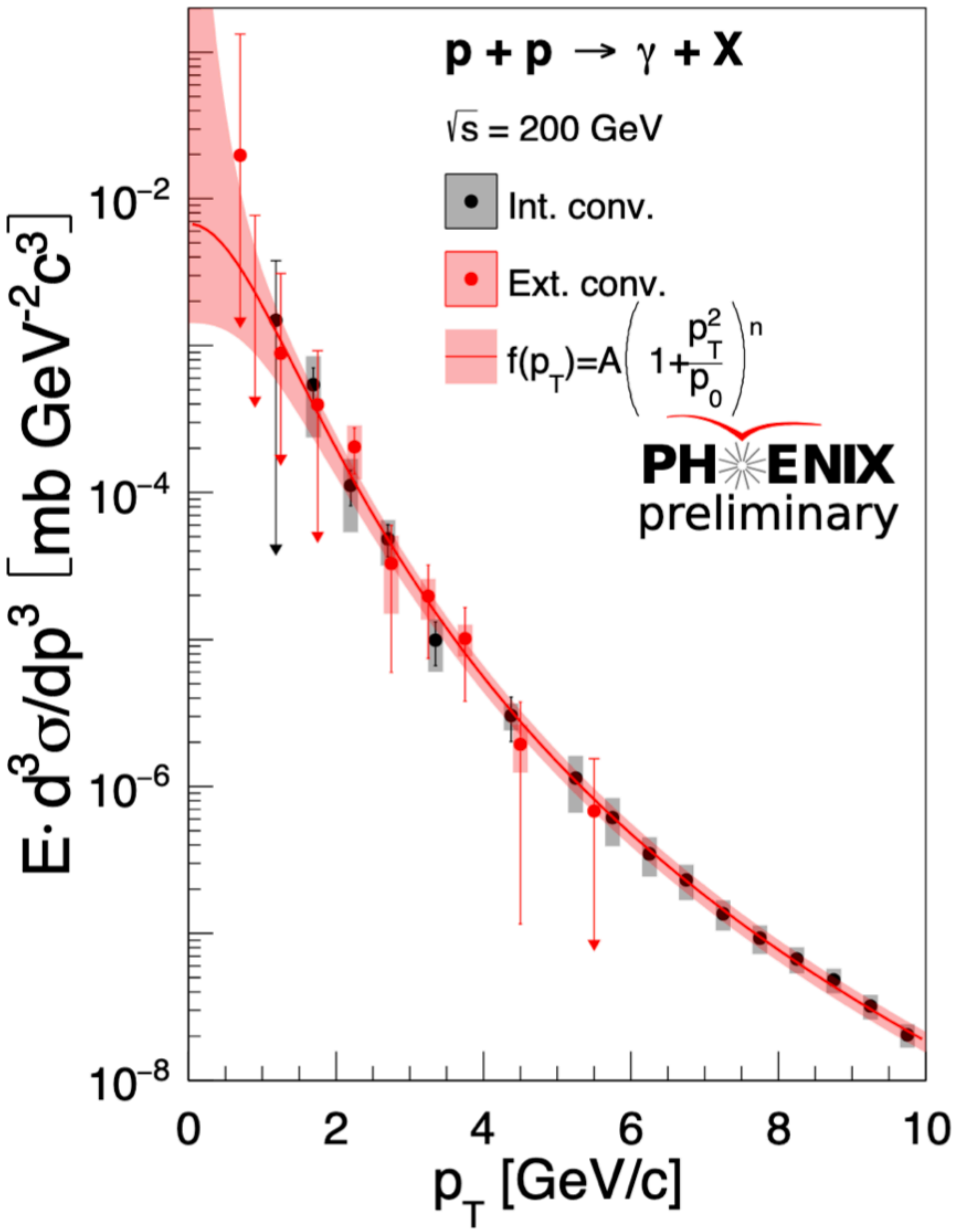
Functional form inspired by pQCD

Fit below 1 GeV/c motivated by Drell Yan measurements [Ito, et al, PRD23, 604 (1981)]

Systematic errors include the fit errors, different functional forms

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

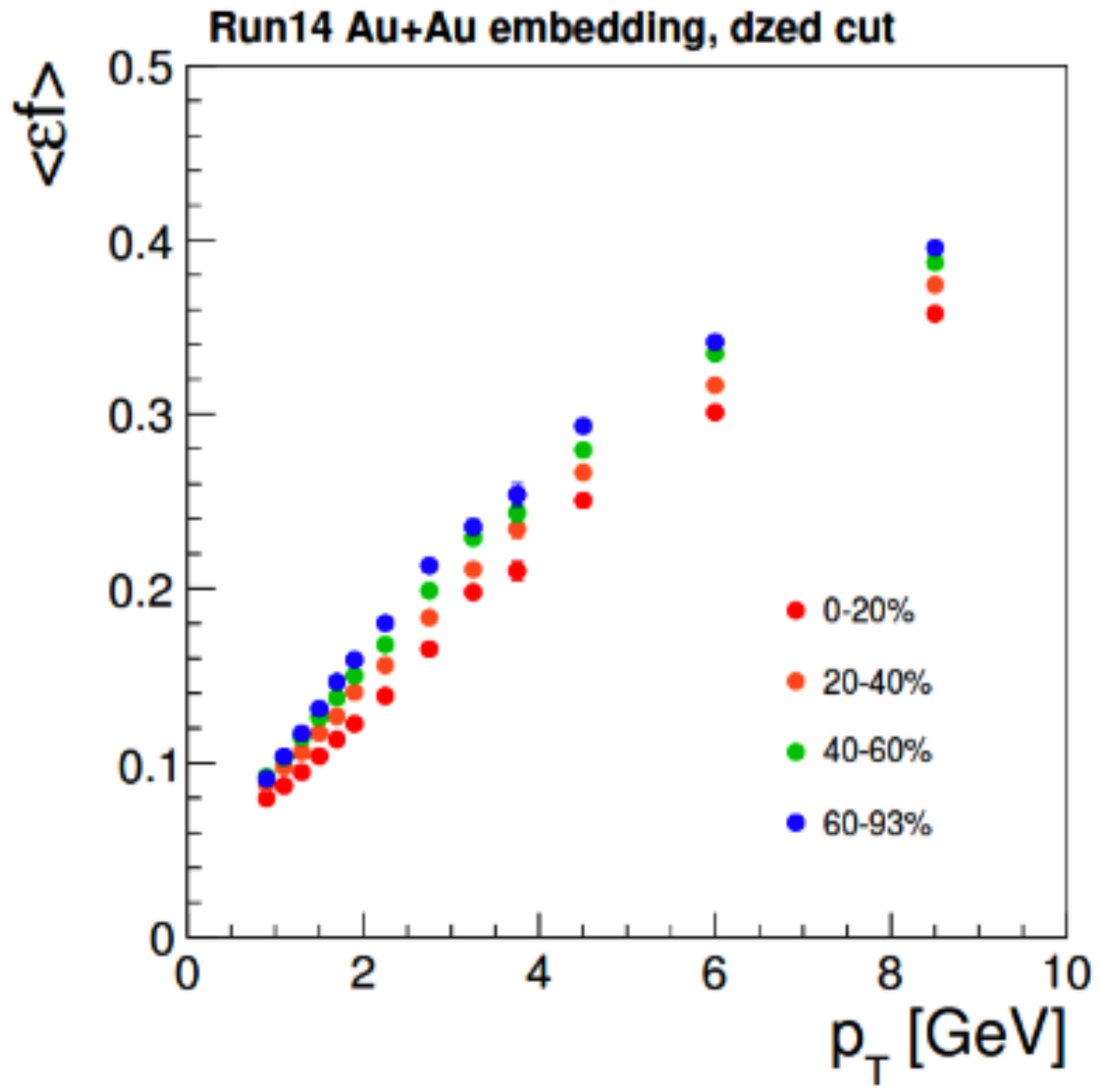
$a = 6.4 \times 10^3$ $\quad$ $b = 1.45$ $\quad$ $c = -3.30$

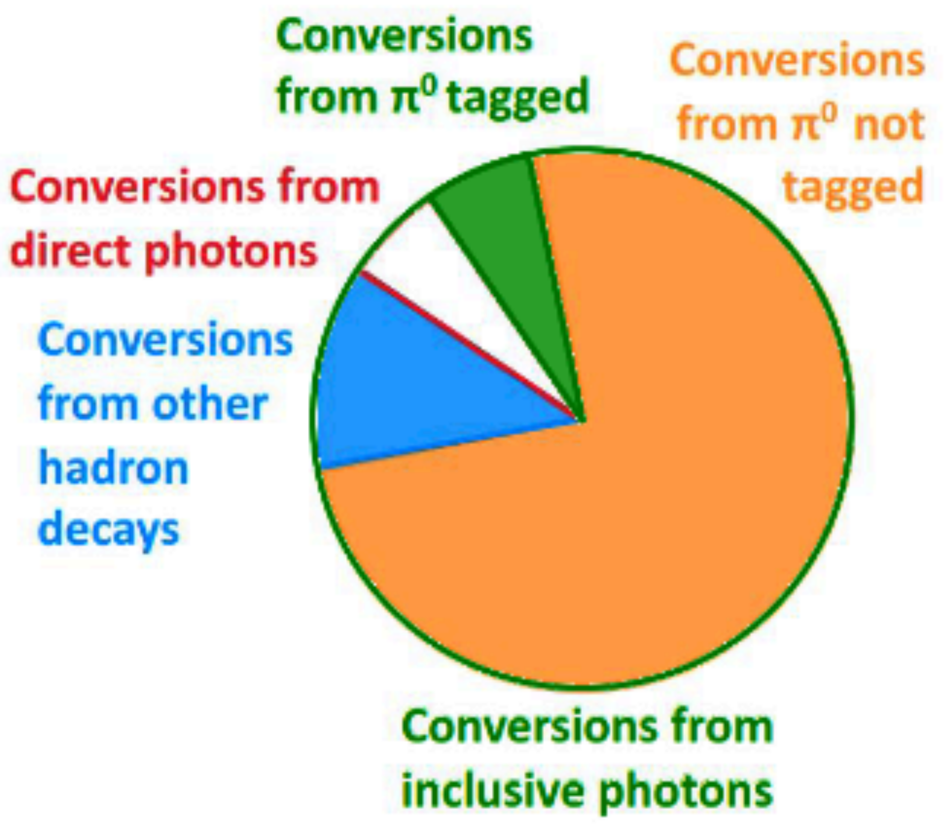


External Conversion Method

Full MC simulation

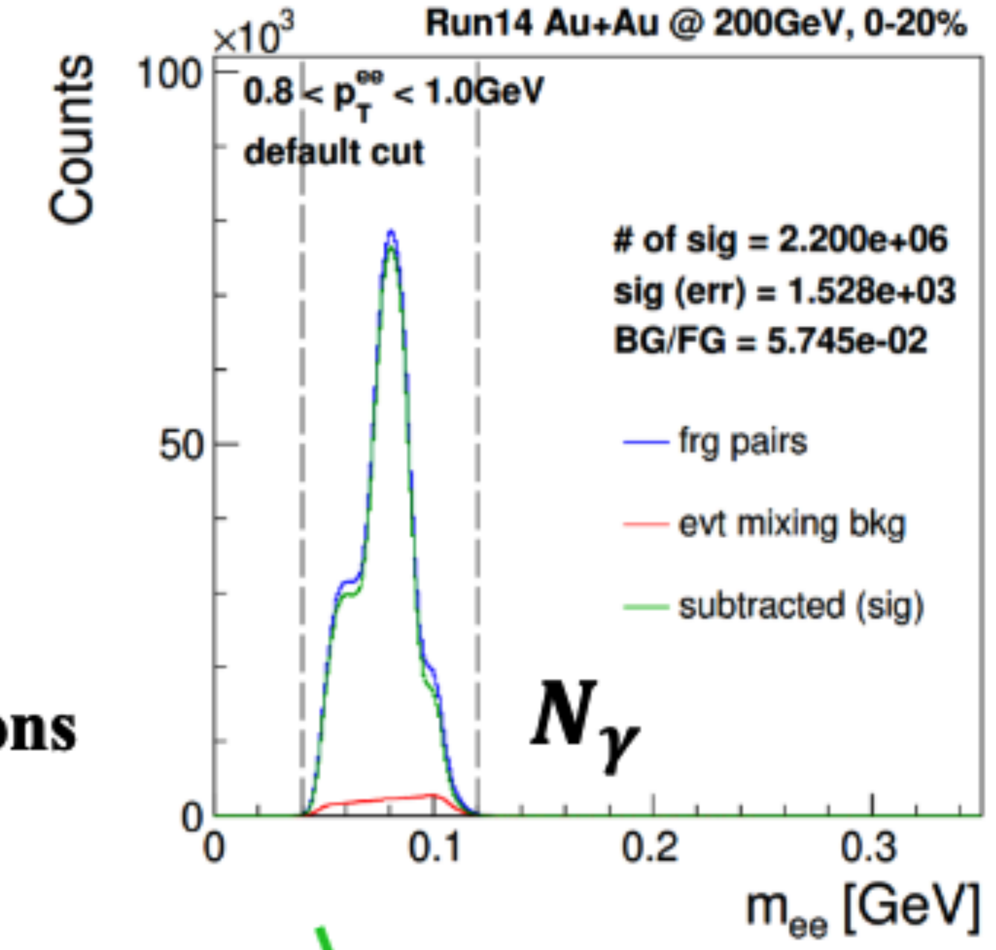
conditional tagging efficiency





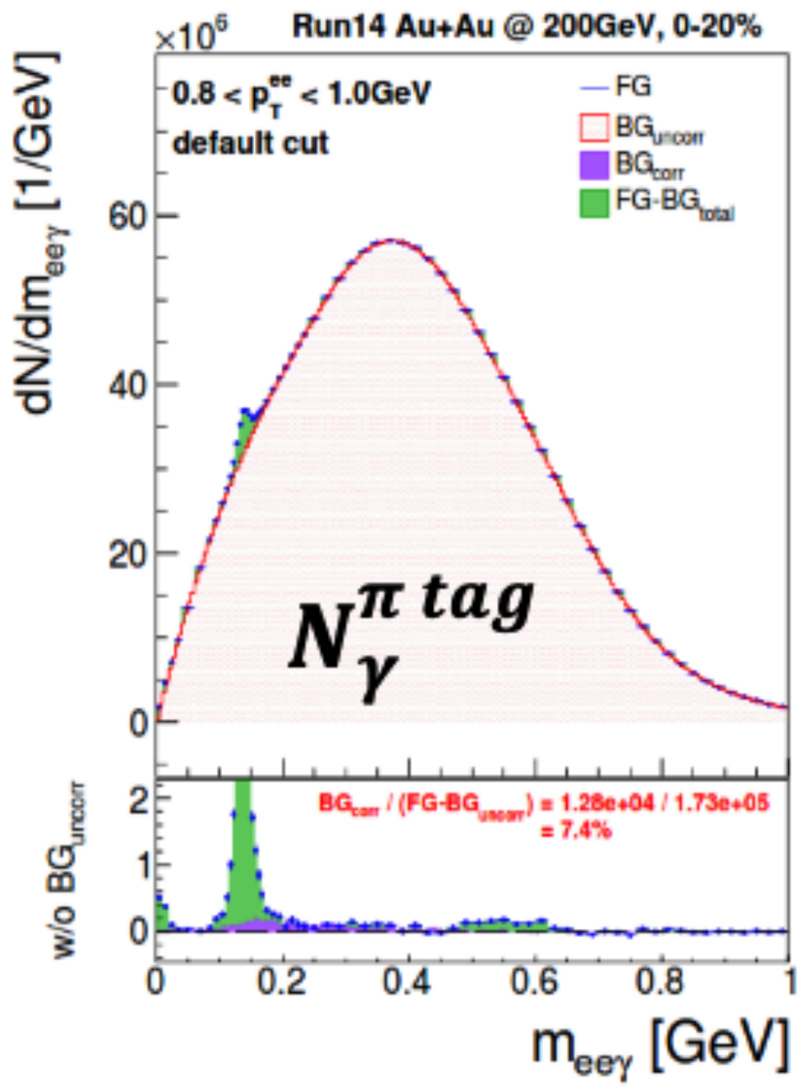
Key contributions

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



measured raw yields

Closure test with full high multiplicity MC simulation



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

η/π^0 ratio main contribution

Photons from hadron decays

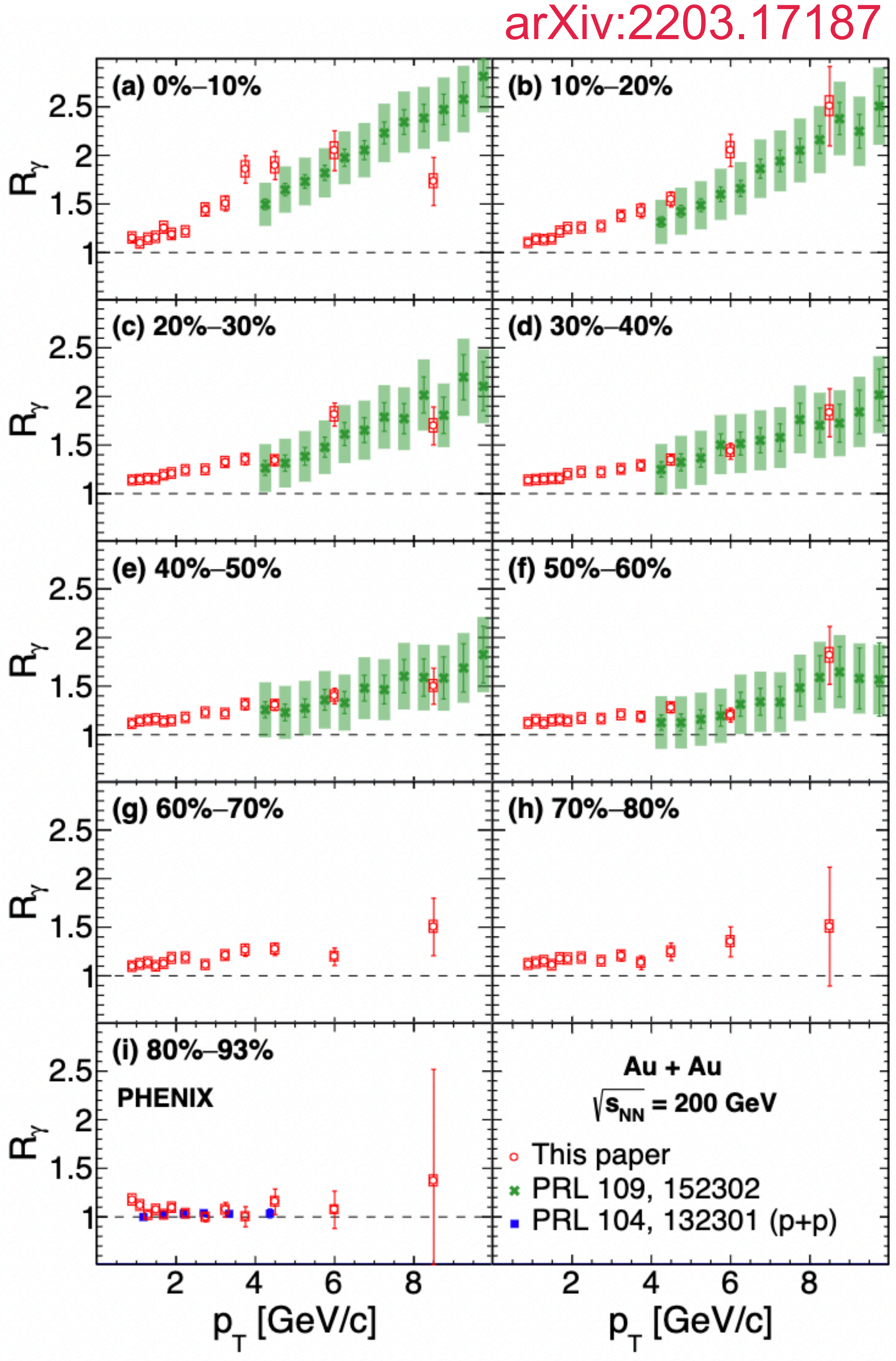
Direct γ for Au+Au at 200 GeV

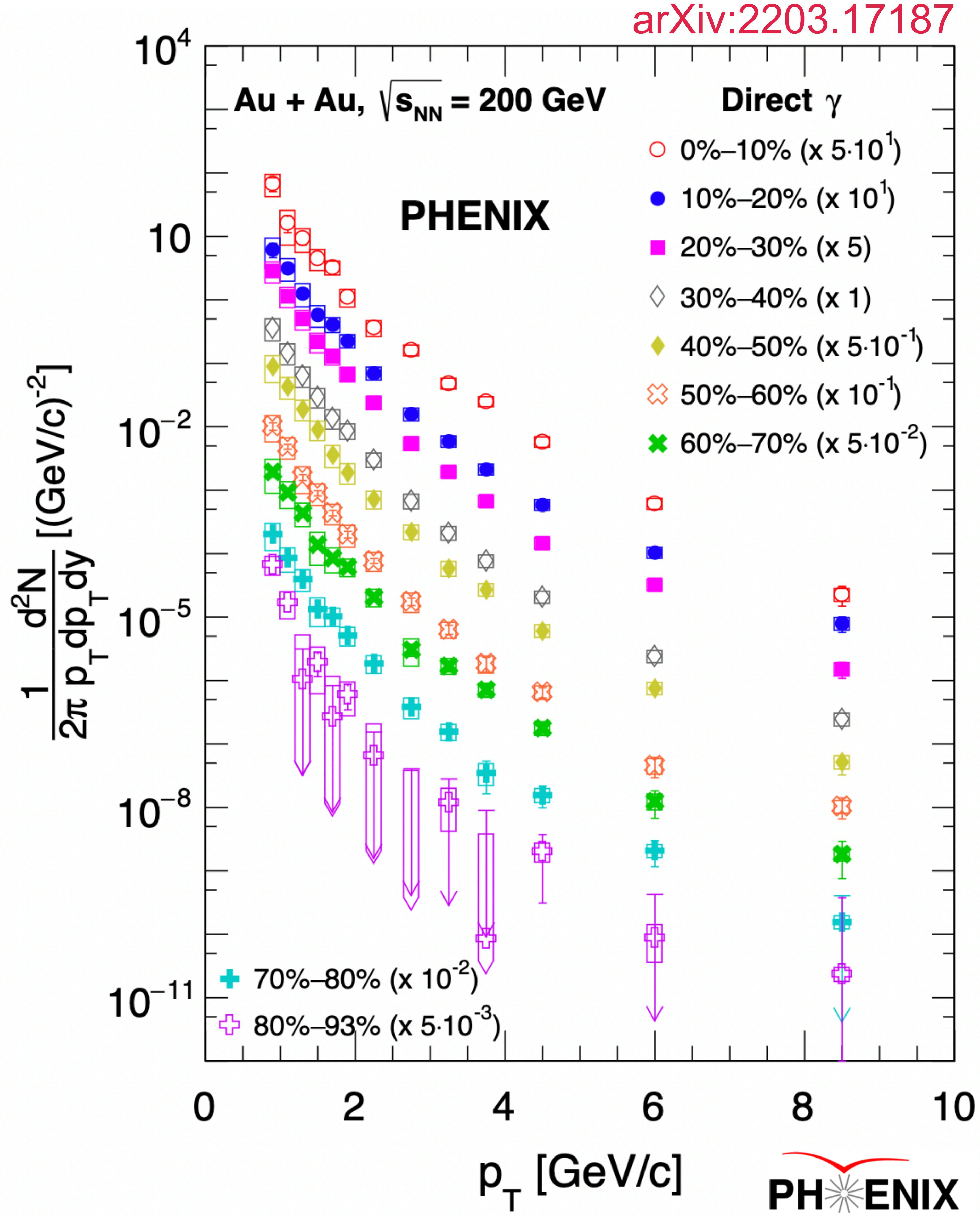
The quantity of interest is

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{decay}}$$

$$\gamma^{dir} = (R_\gamma - 1)\ \gamma^{hadron}$$

About 20% direct photon component is seen in more central collisions.

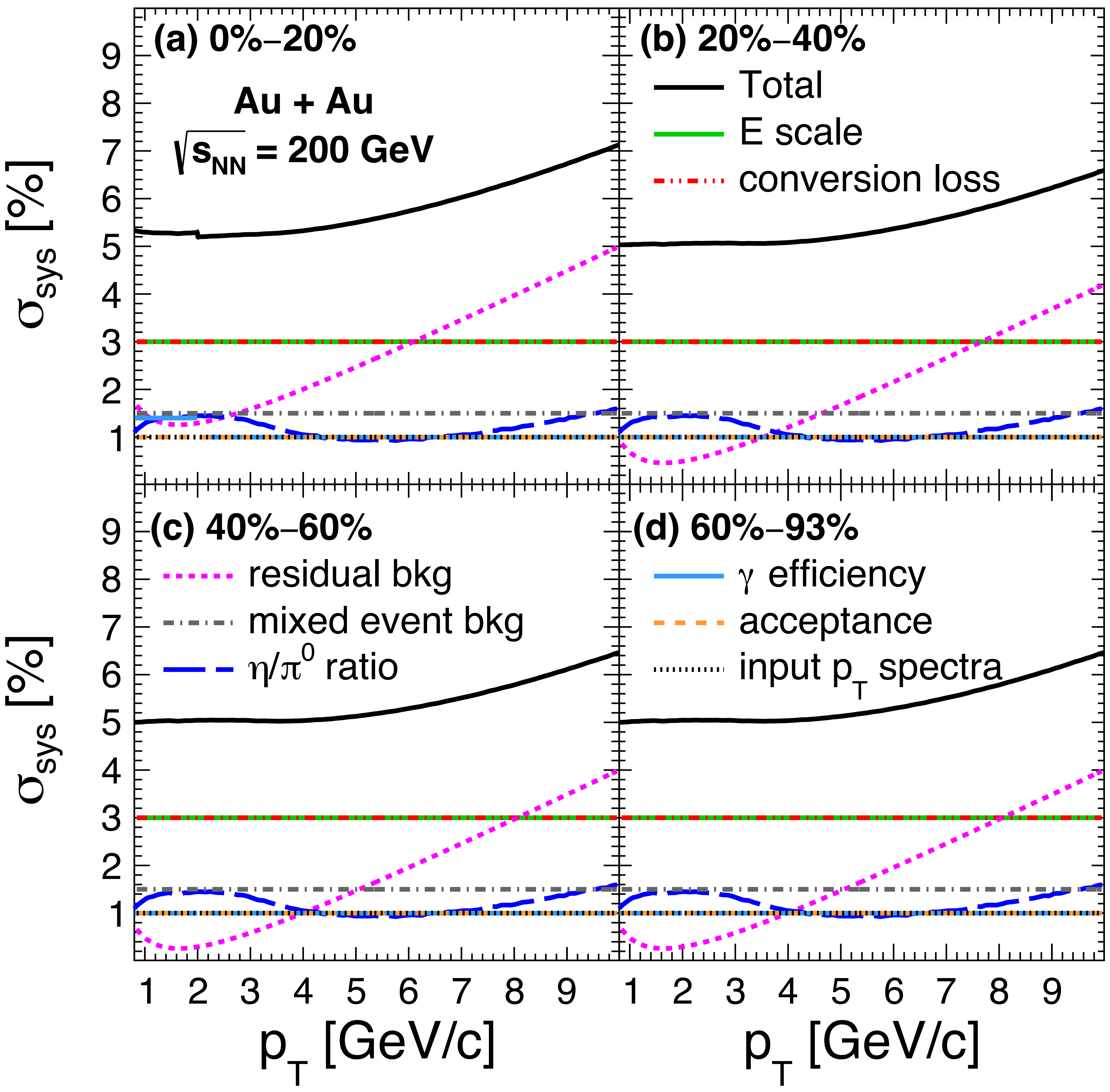




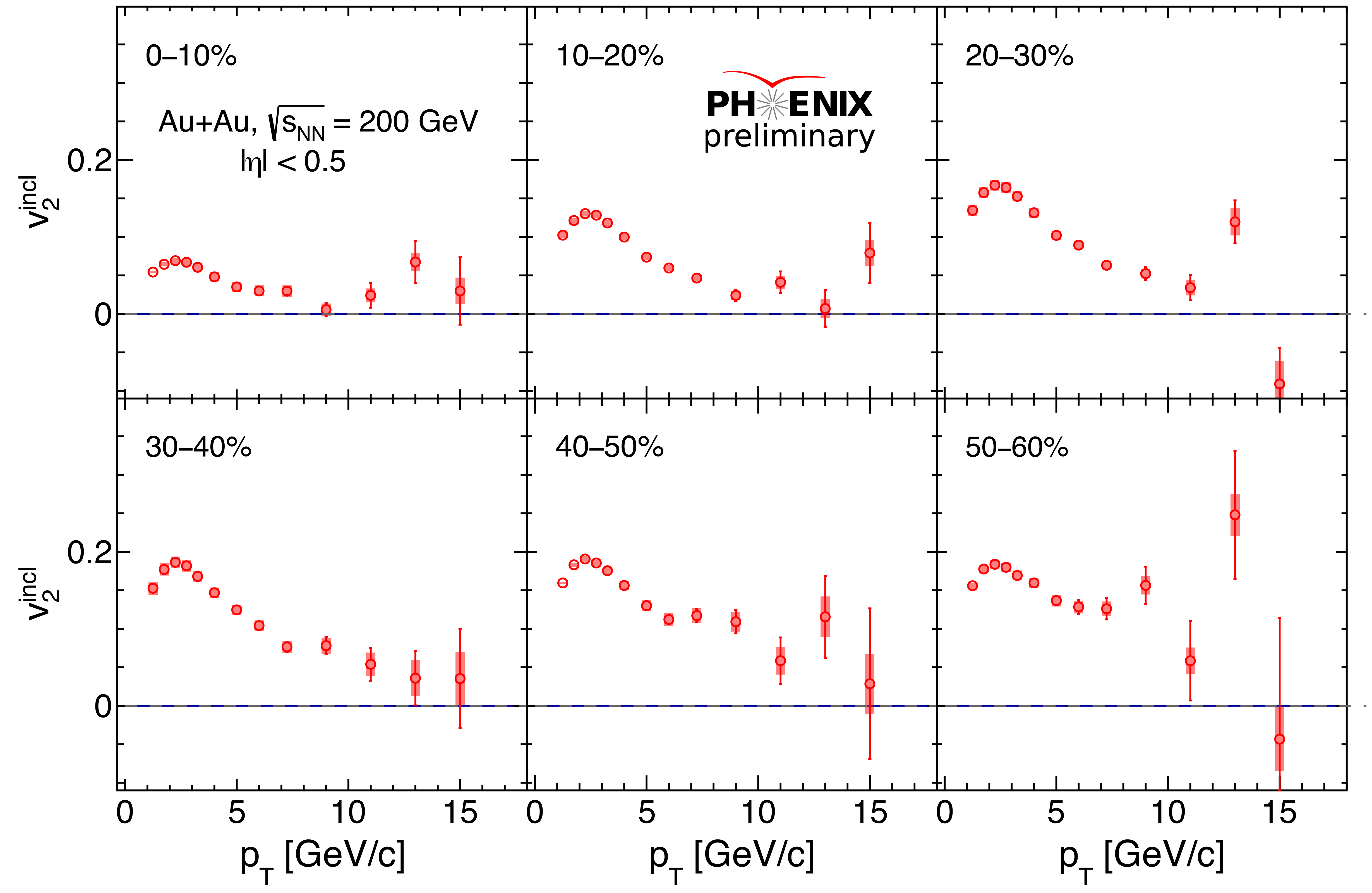
Systematic Uncertainties

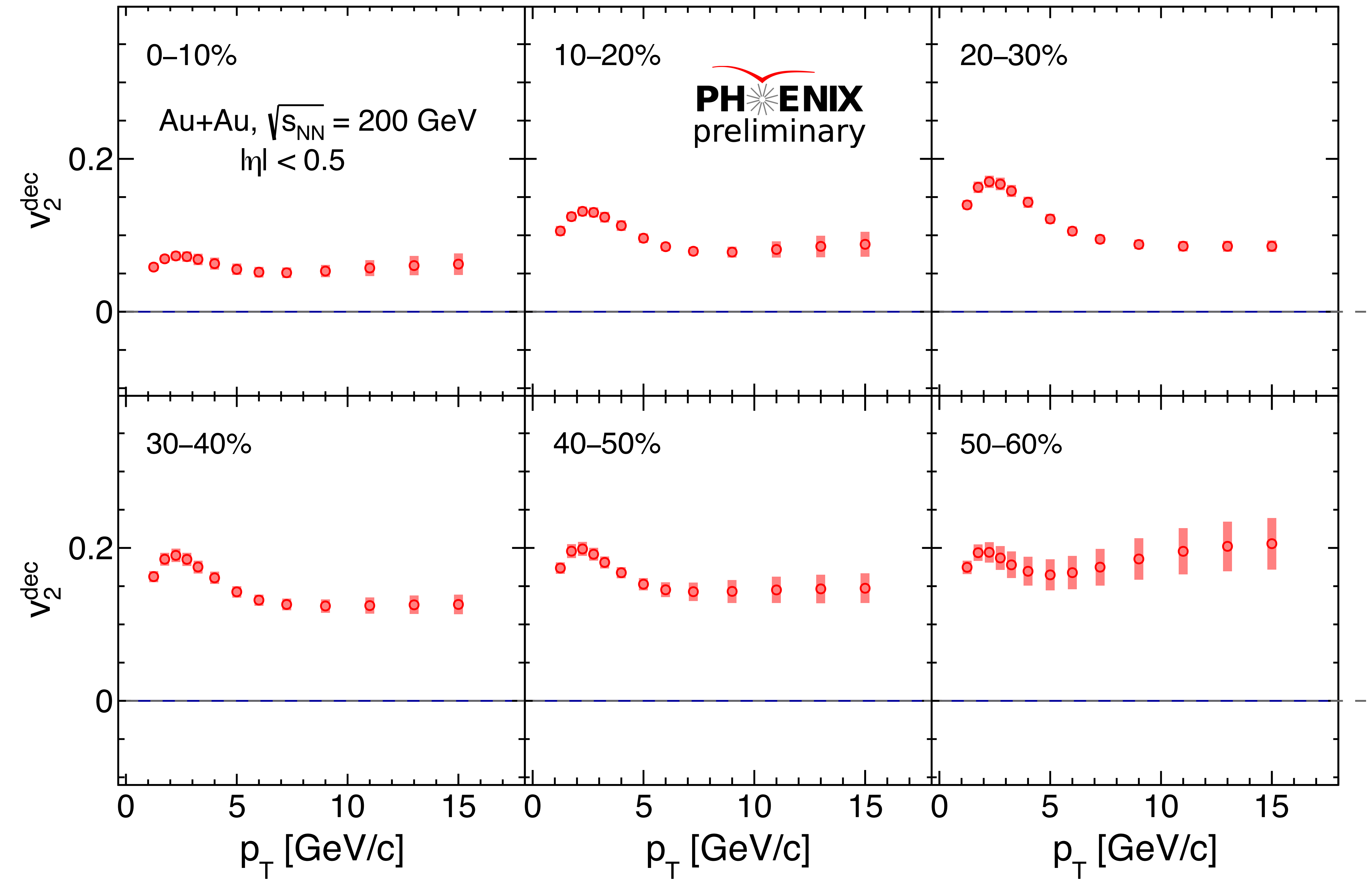
Systematic uncertainty source (39 GeV)	σ_{sys}/R_γ	Type
π^0 reconstruction		
tagged photon yield	8%	A
Conditional acceptance		
input Hagedorn p_T spectra and energy scale	8%	B
Cocktail ratio		
γ^{hadron}/π^0	2%	B

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



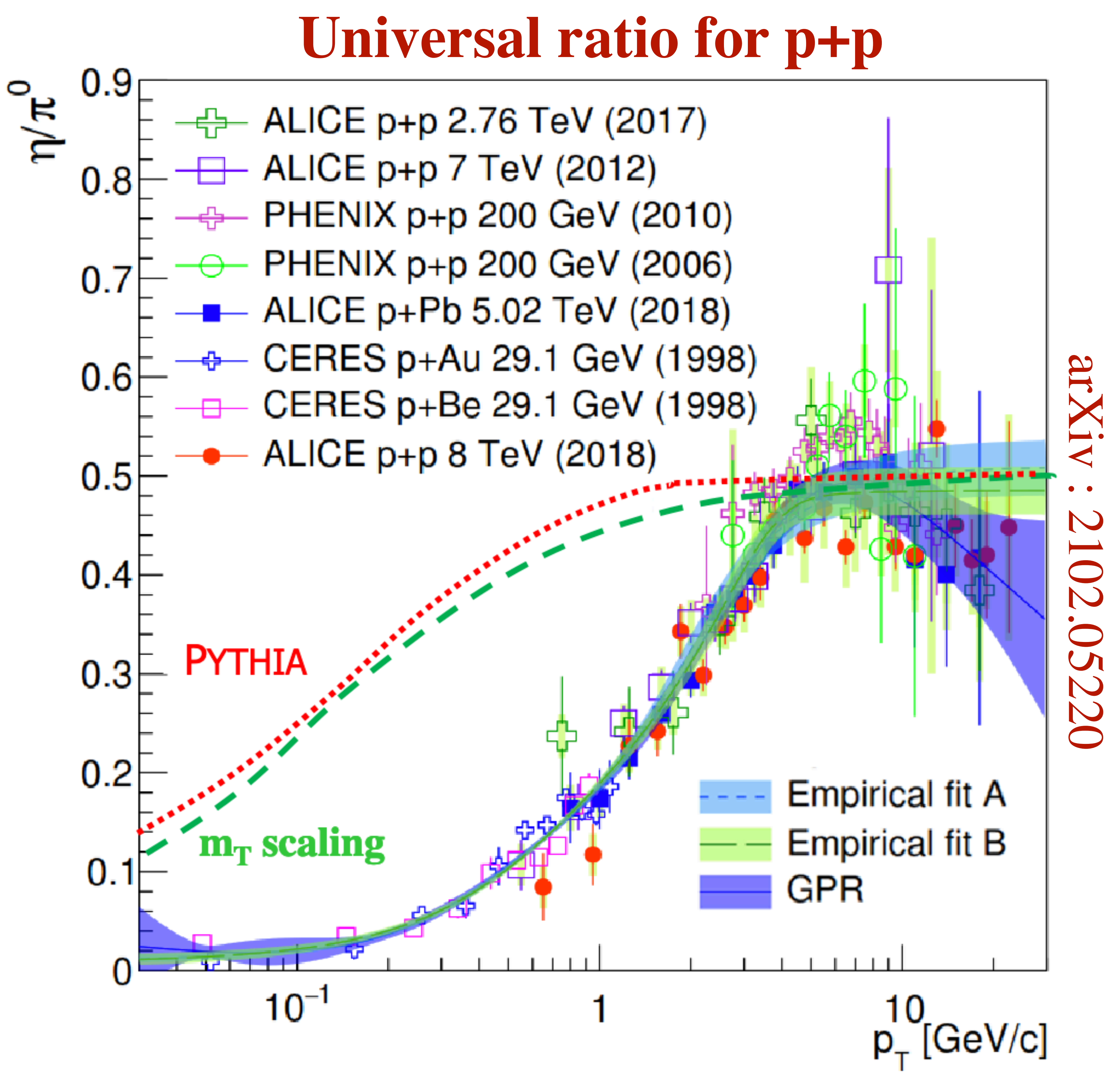
Inclusive and Decay Photons v_2



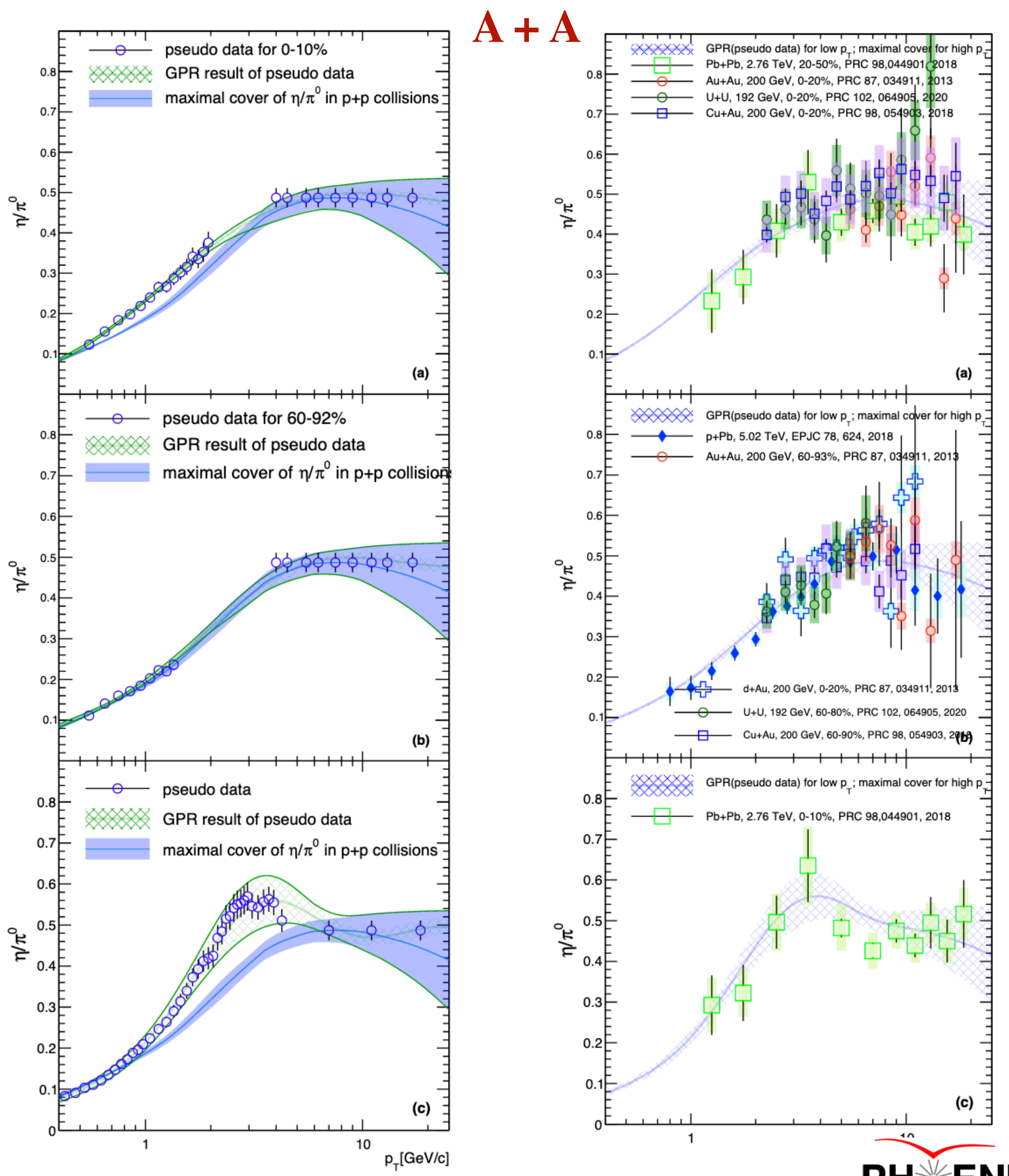


Quantitatively, elliptic flow of both the inclusive and decay photons is very similar!

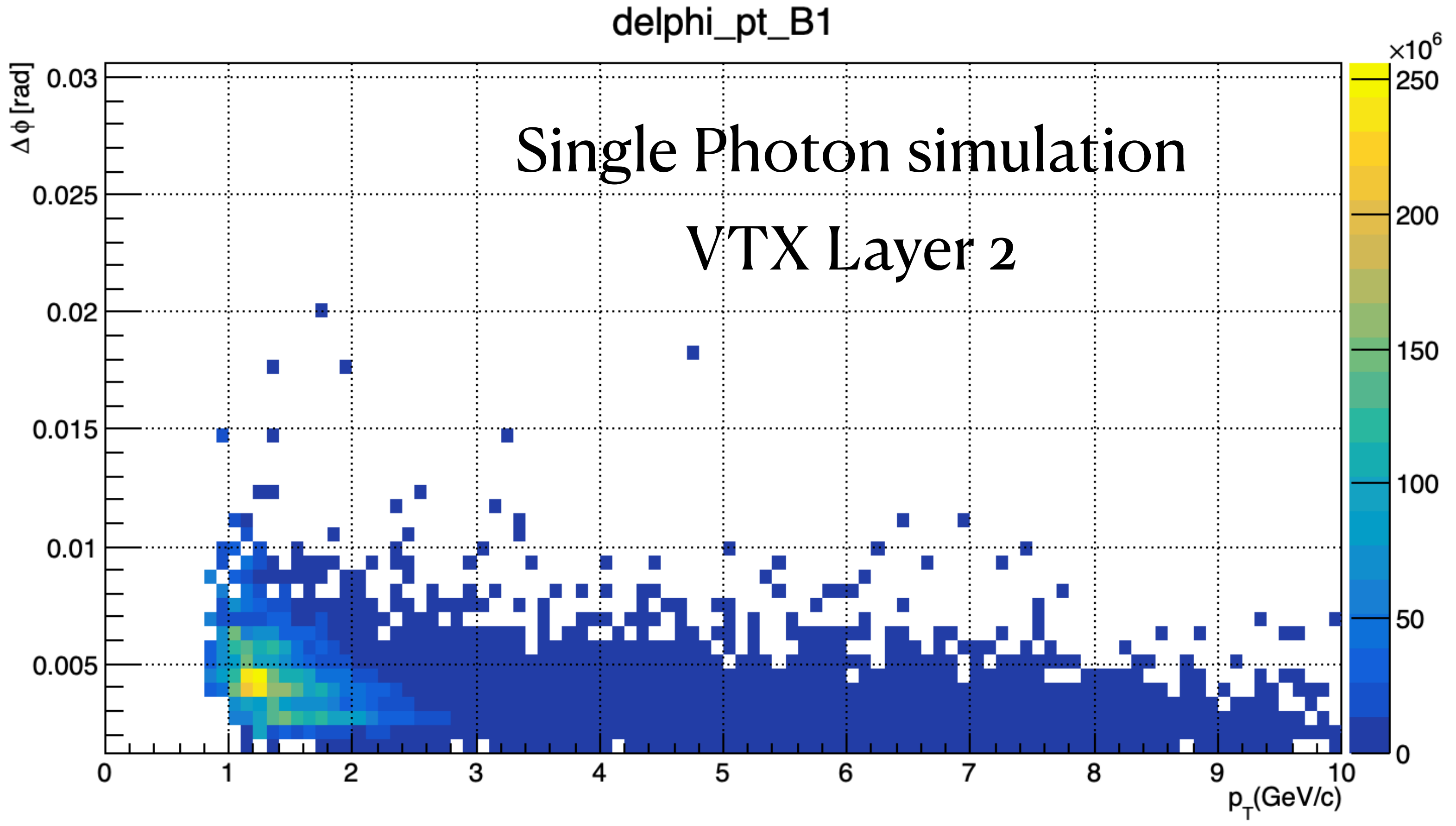
η/π^0 from world data

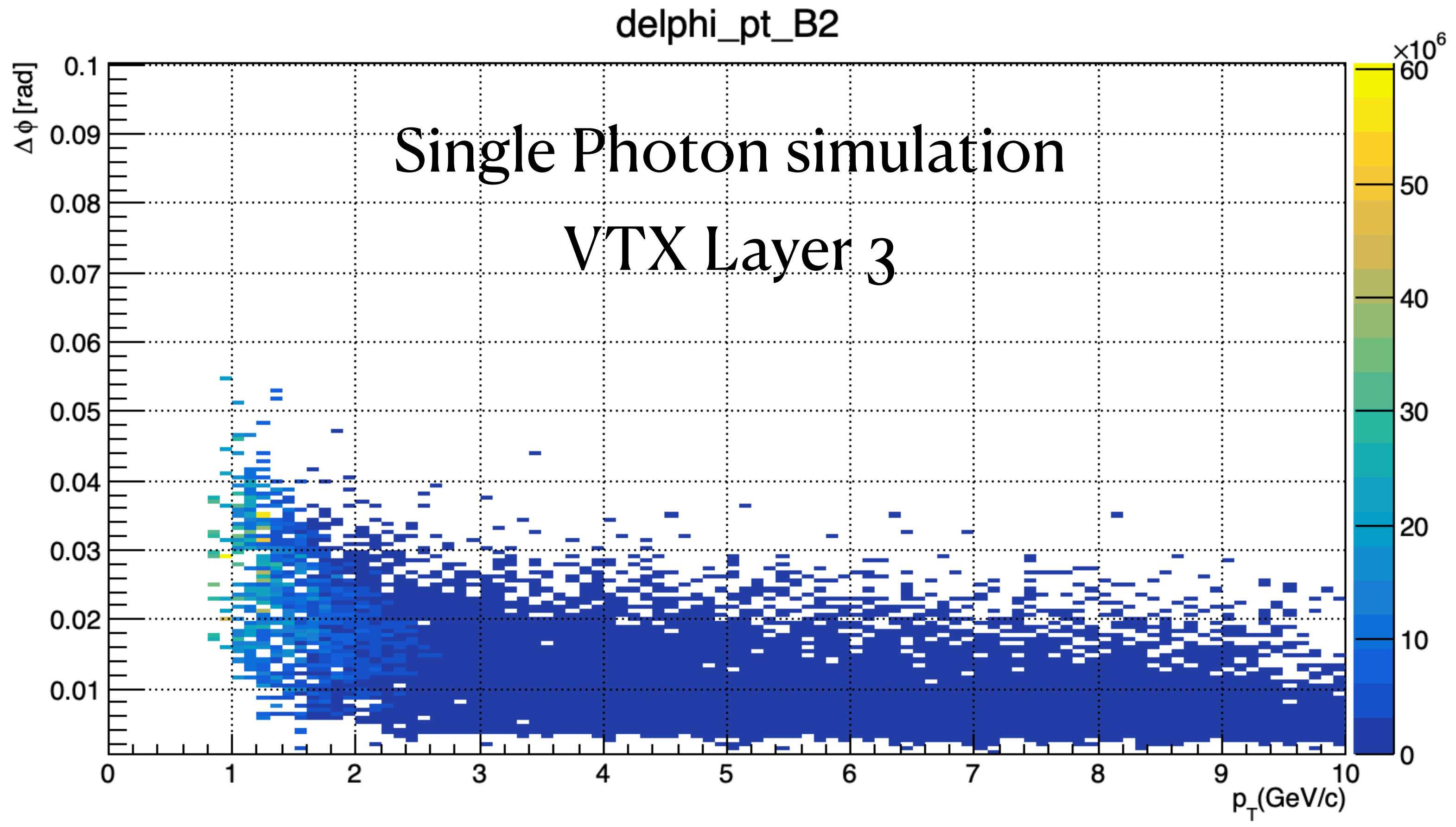


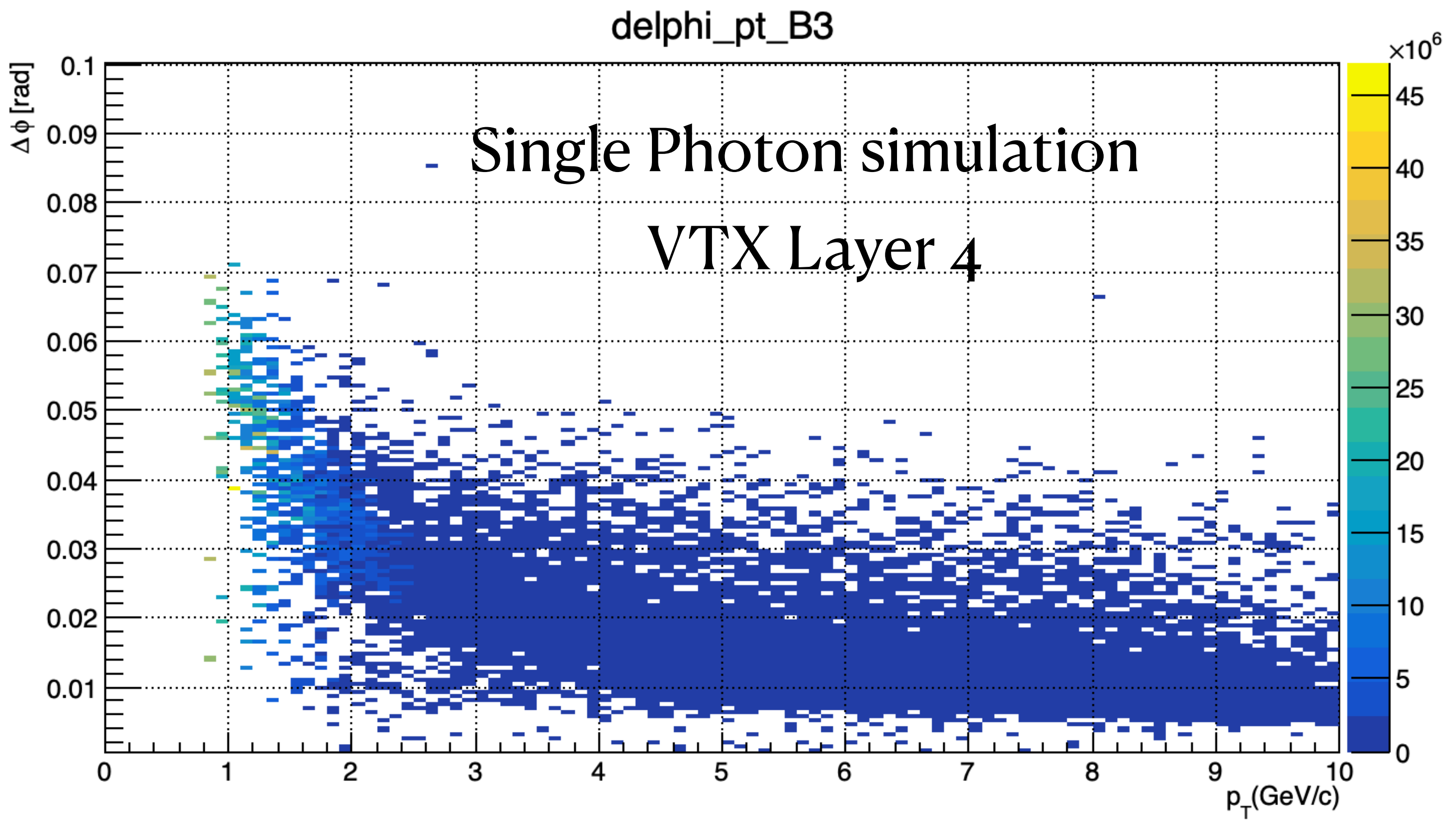
Accounting for effects of radial flow



Using the track-hit association to remove conversions: Conversion Veto







Opening angle as a function of the parent photon pT between the electron and the positron track for conversions happening at the beam pipe and the innermost VTX Layer.

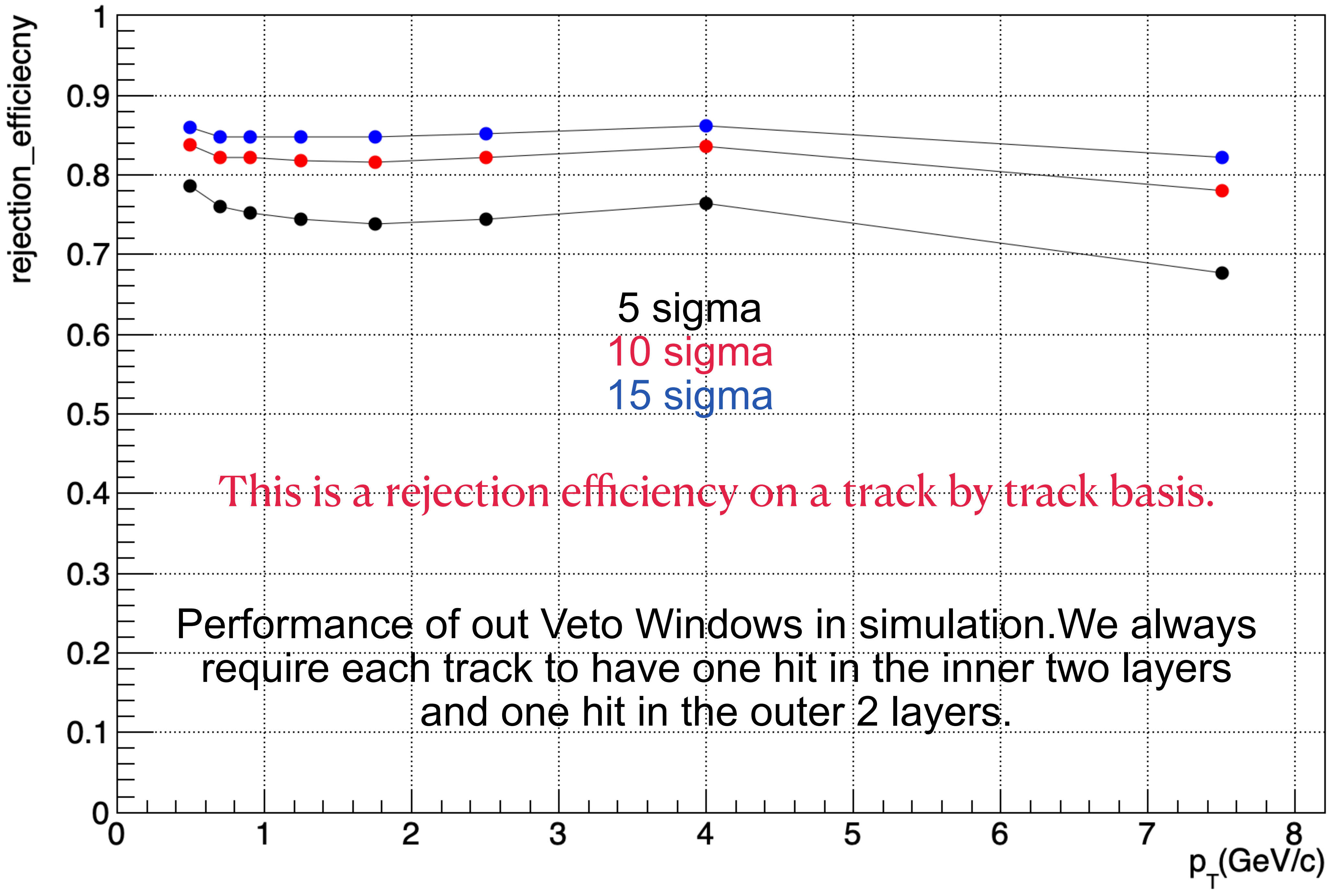
p_T (GeV/c)	B1 [mrad]	B2 [mrad]	B3 [mrad]
1.00	4.09	30.97	51.53
5.00	2.36	8.68	13.19

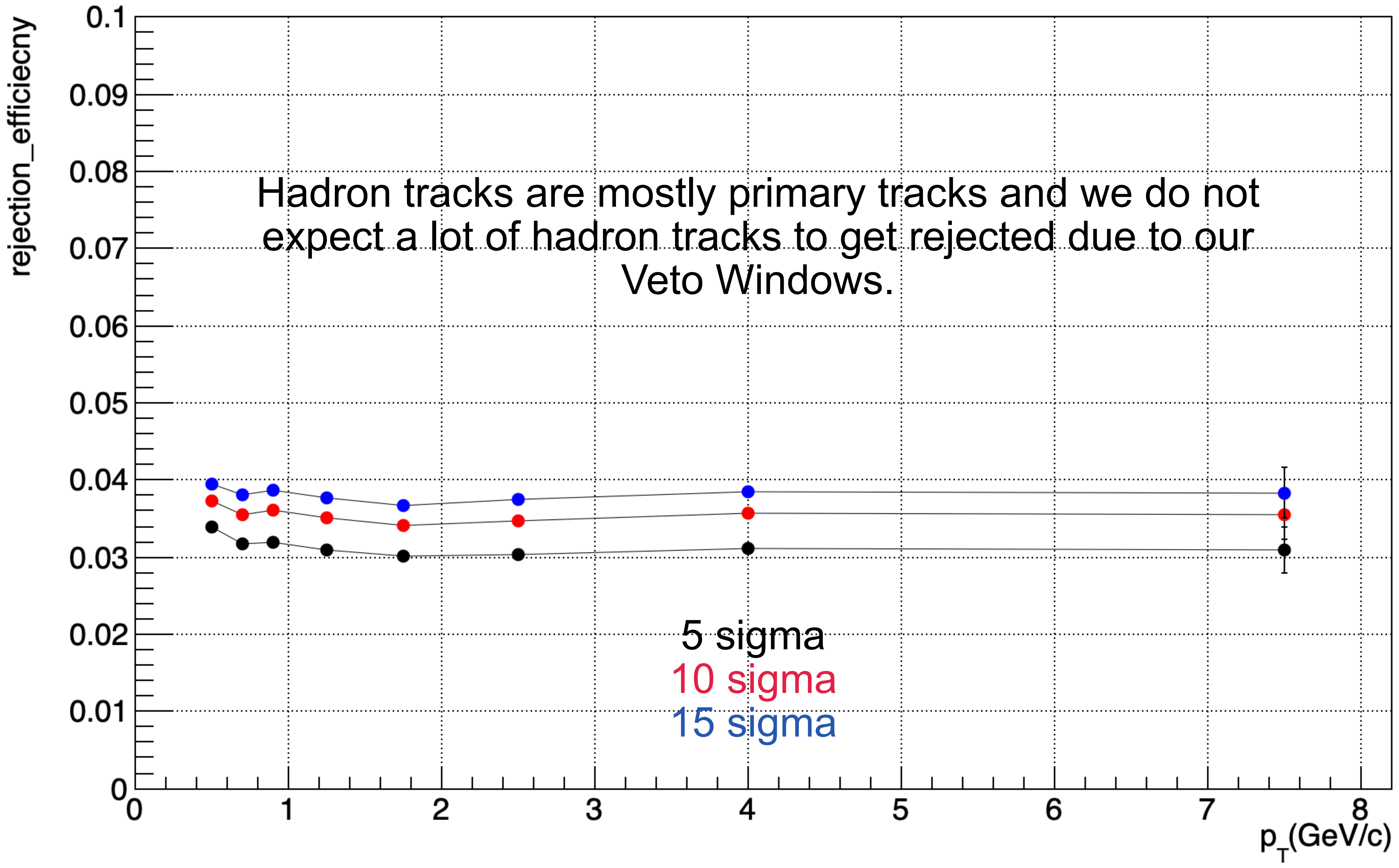
ϕ extent of the sensor for VTX L2: ~ 1 mrad

ϕ extent of the sensor for VTX L3 and L4: ~ 0.7 mrad

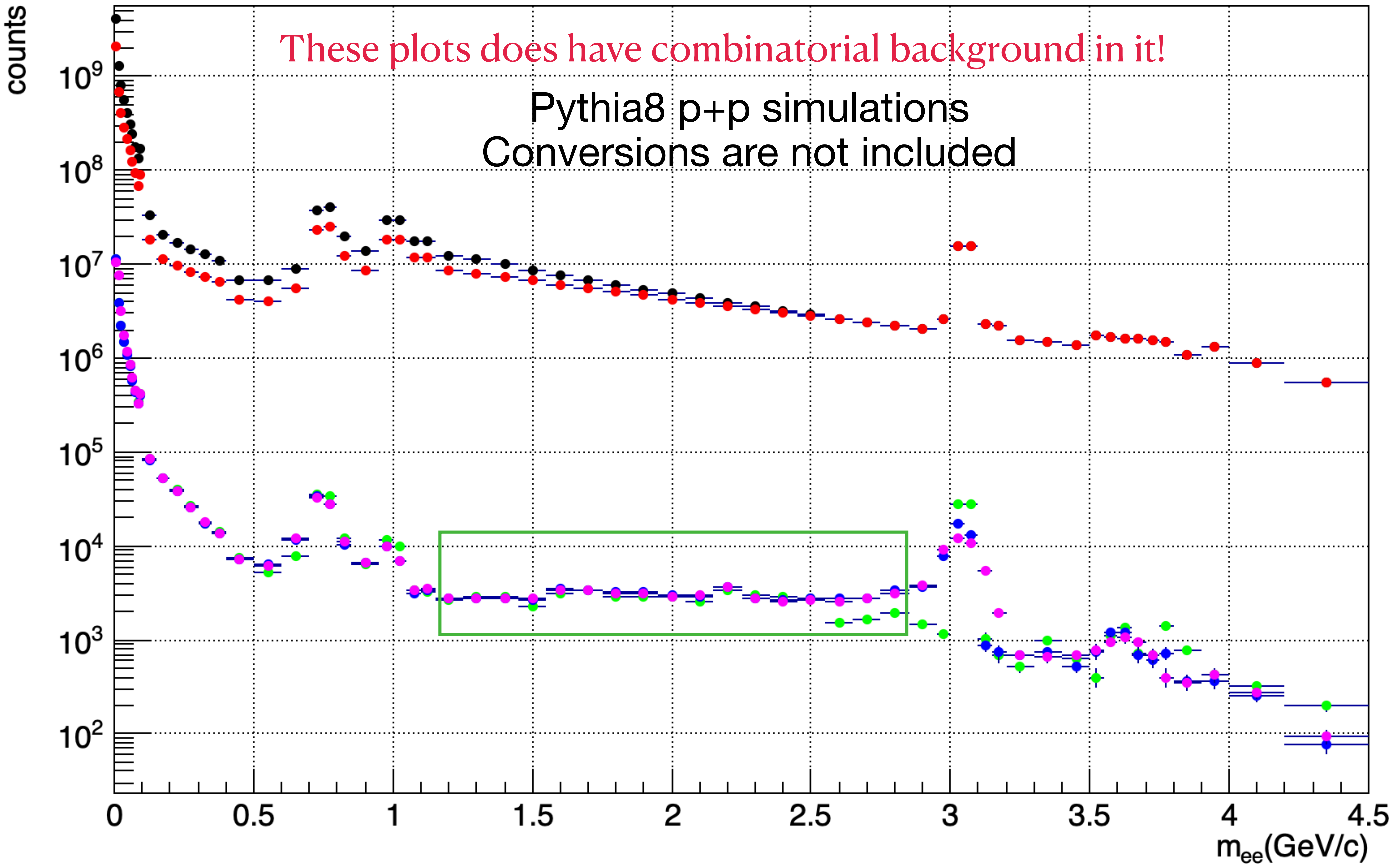
Even if only one of the conversion tracks is reconstructed by the DC we will always find a hit in the vicinity of a conversion track!

Performace of our rejection techniques





Understanding the important aspects of the spectra using Pythia8 Simulations



MinBias (4π Acceptance)

MinBias + ERT (4π Acceptance)

MinBias + ERT (PHENIX Acceptance)

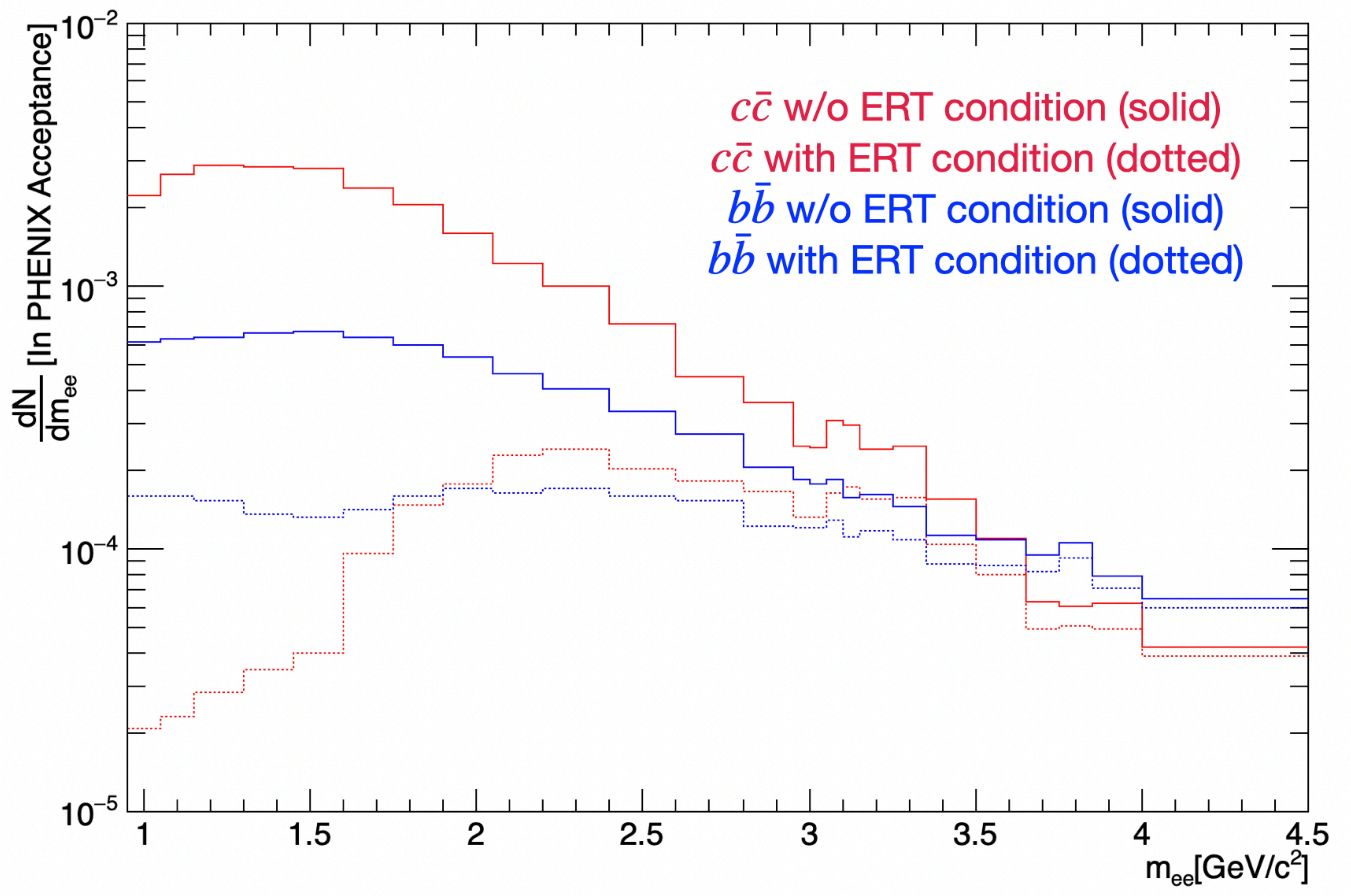
MinBias + ERT + PHENIX Acceptance + Bremstruhlung

MinBias + ERT + PHENIX Acceptance + Bremstruhlung + pT Smearing

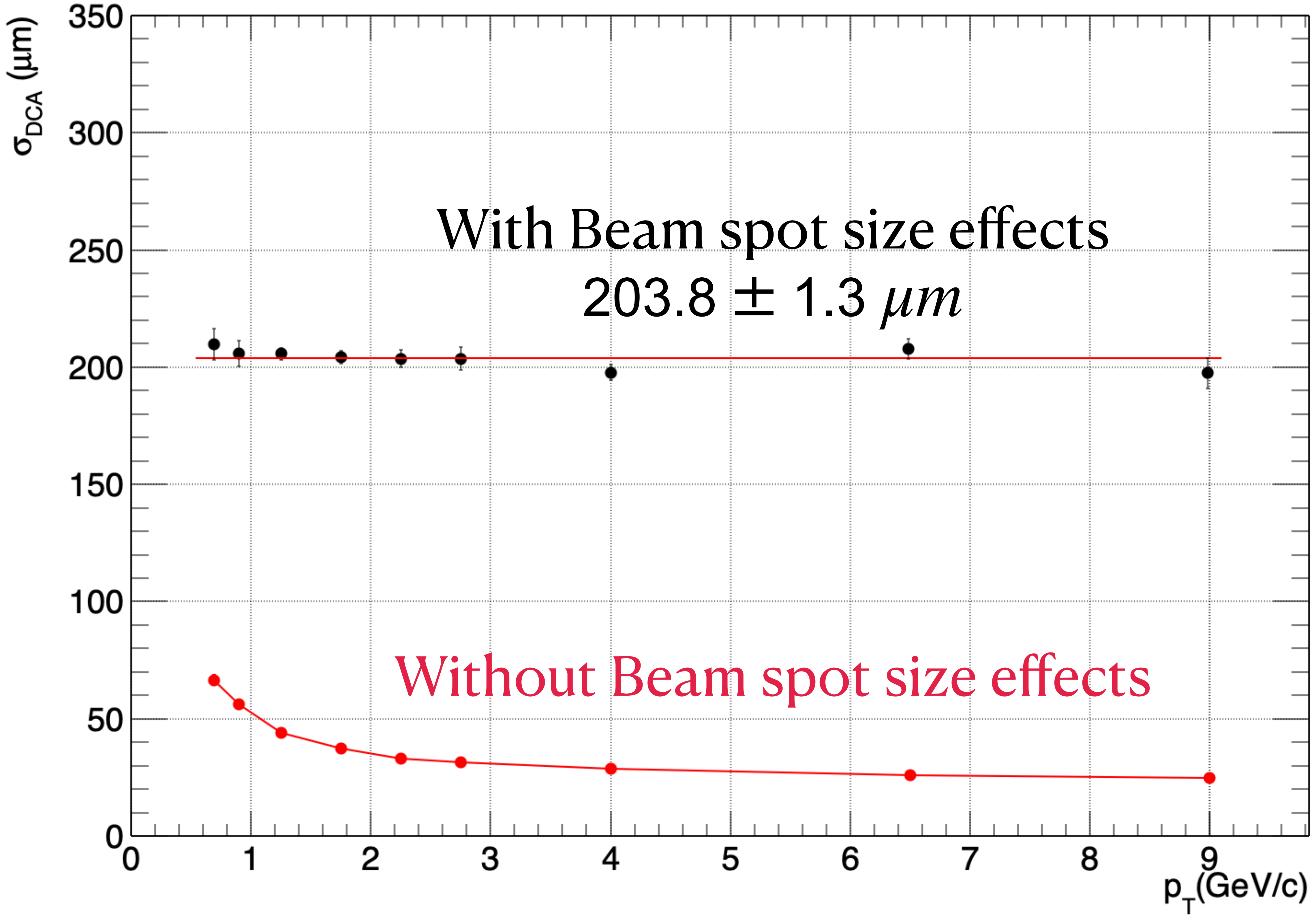
In the intermediate mass region, the combination of acceptance and ERT trigger flattens out the curve.

PHENIX

Effect of the ERT Trigger condition



DCA Resolution



Factors affecting the DCA resolution:

•Beam Spot resolution

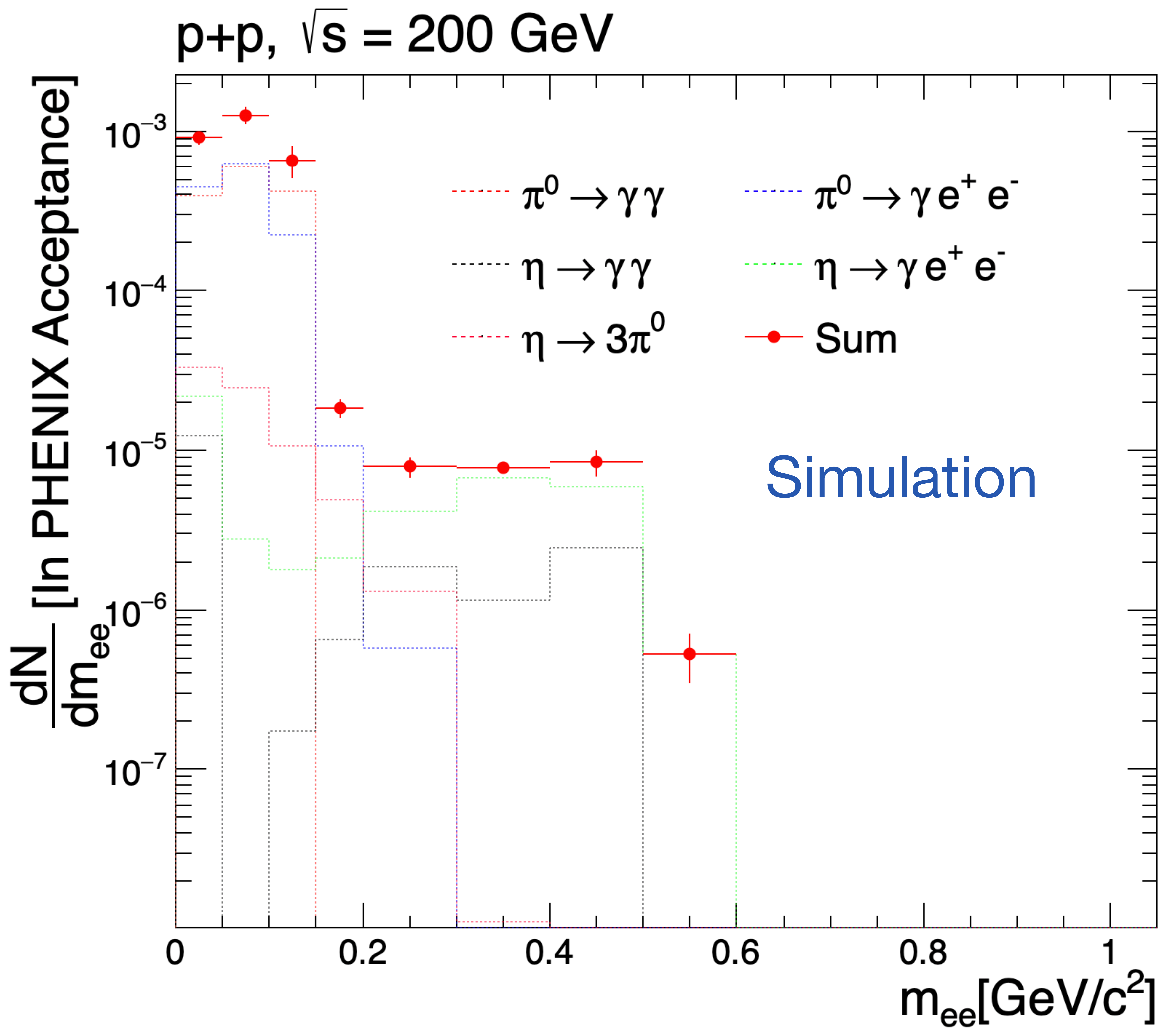
•Detector resolution has two contributions: A constant term and another term arising from multiple scattering

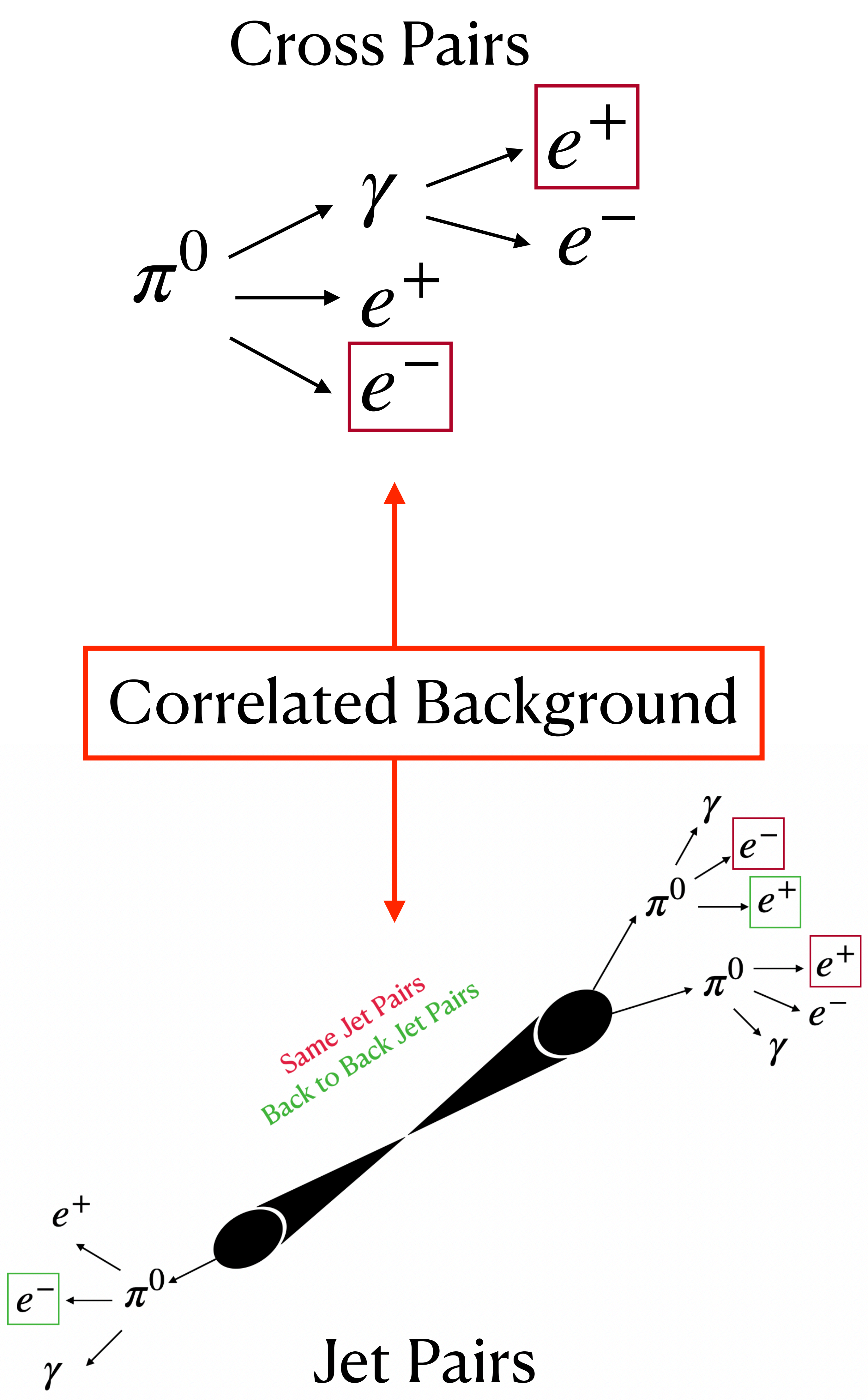
•Finally there is the bremsstrahlung effect.

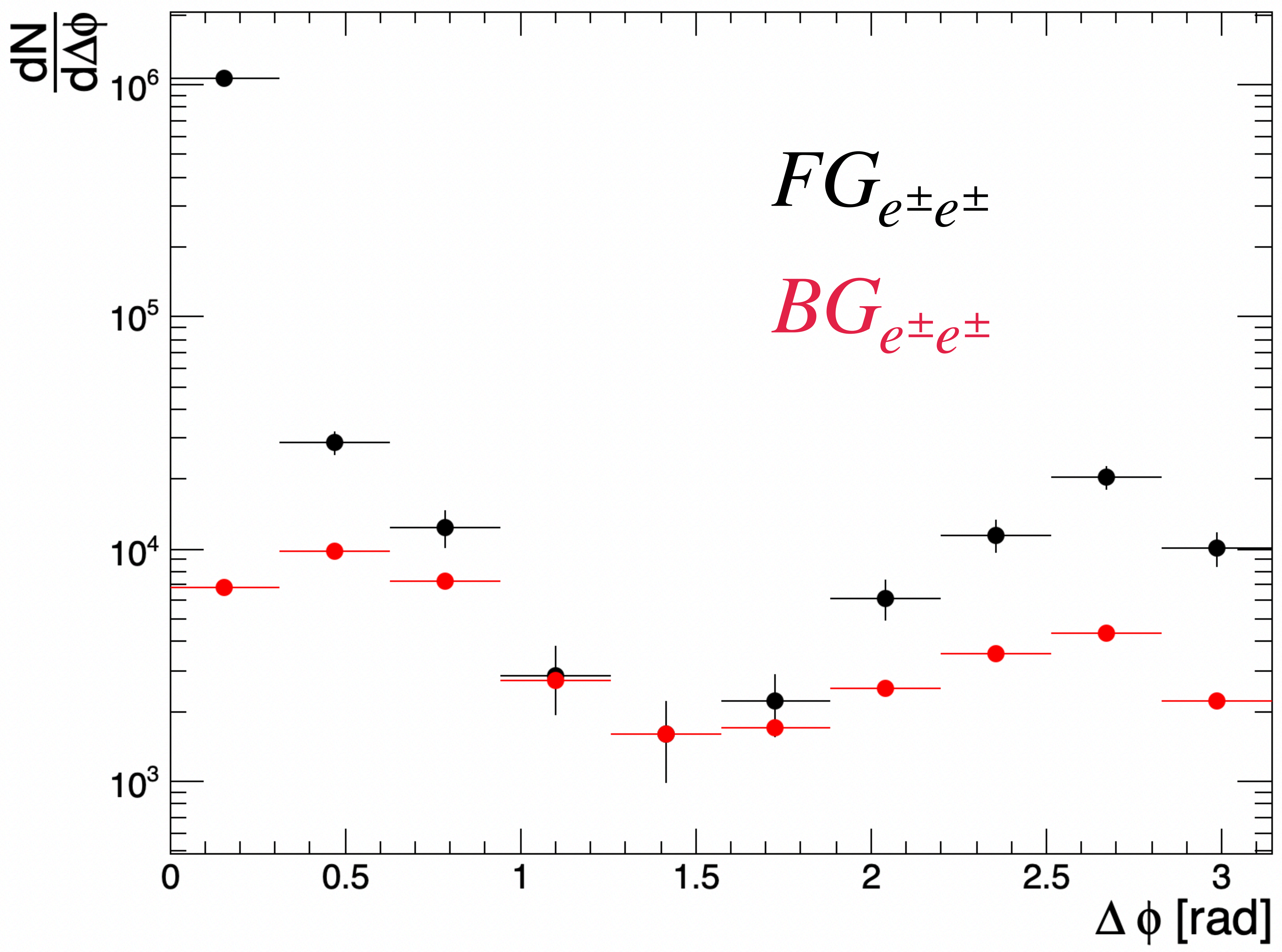
By restricting in a very narrow mass range around J/ψ, we are largely not taking into account the effect of bremsstrahlung.

Restricting in the mass range from $3.0 < m_{ee} < 3.2\, GeV/c^2$ and using the beam spot size as 200 microns in simulation , we can plot the individual track DCA as a function of p_T and extract σ_{DCA} .

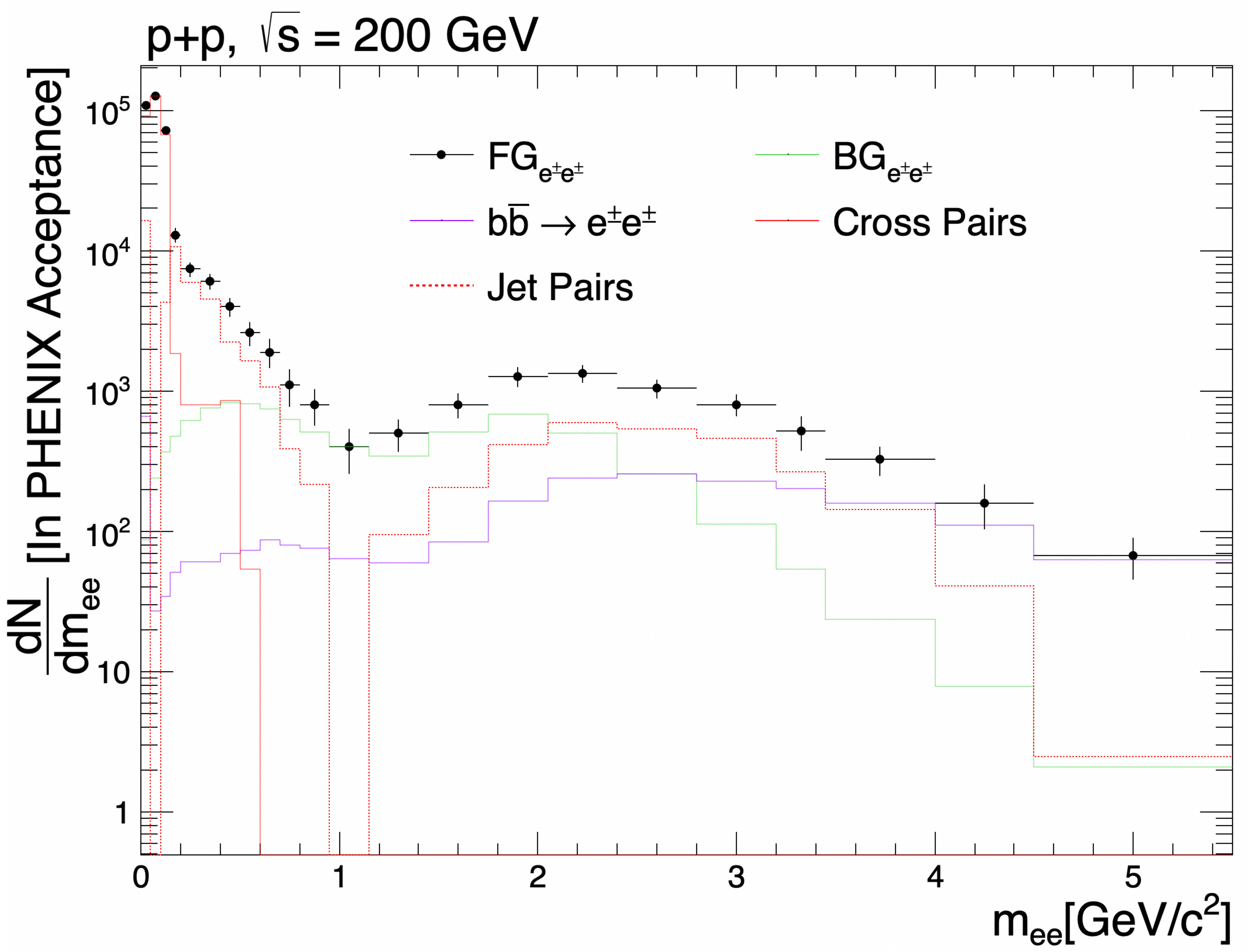
LikeSign Analysis







Normalization for the Like Sign combinatorial BG using the ZYAM Technique



$b\bar{b}$ Simulation