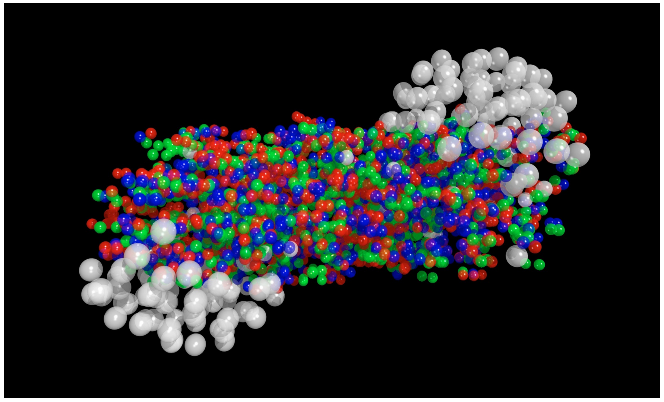
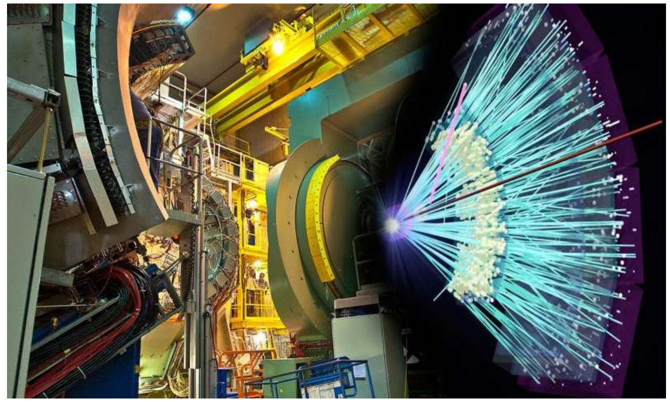




Direct photon production in Au+Au collisions at 200GeV

Wenqing Fan

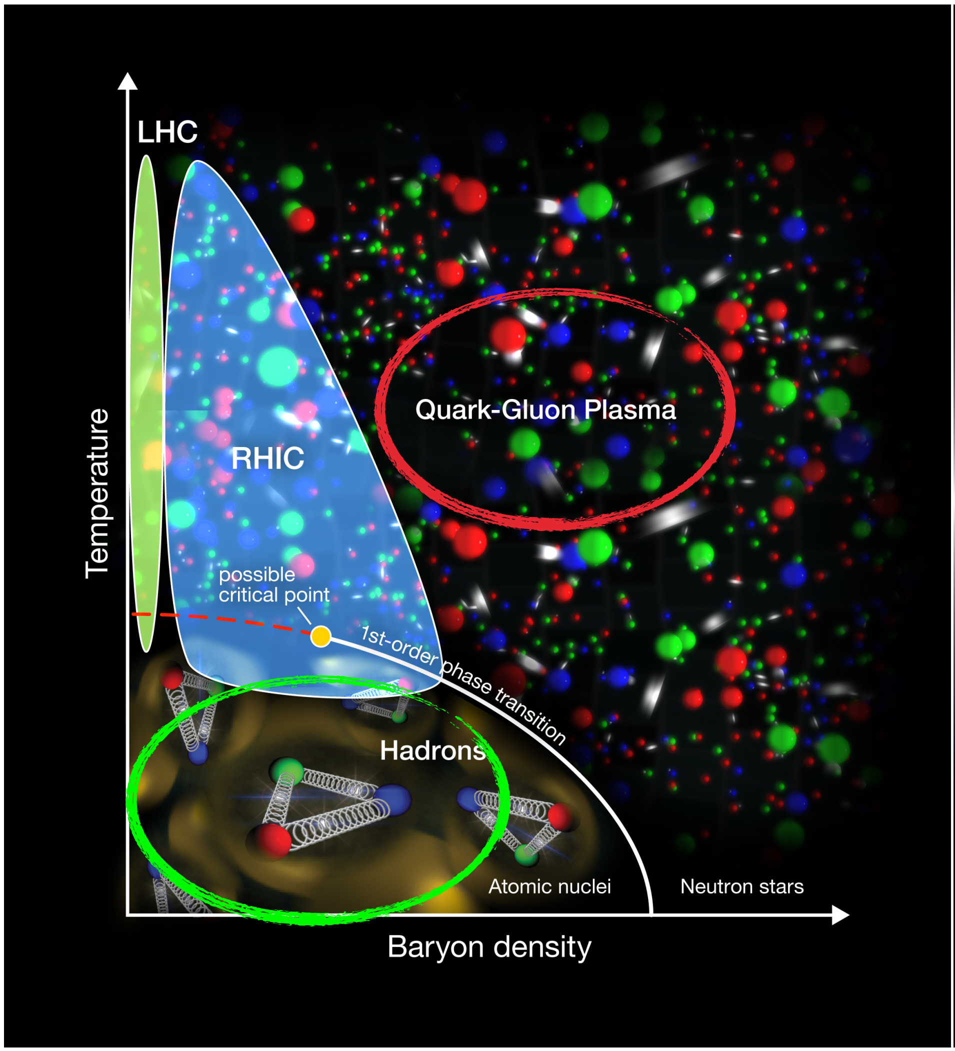
BNL seminar March 2020

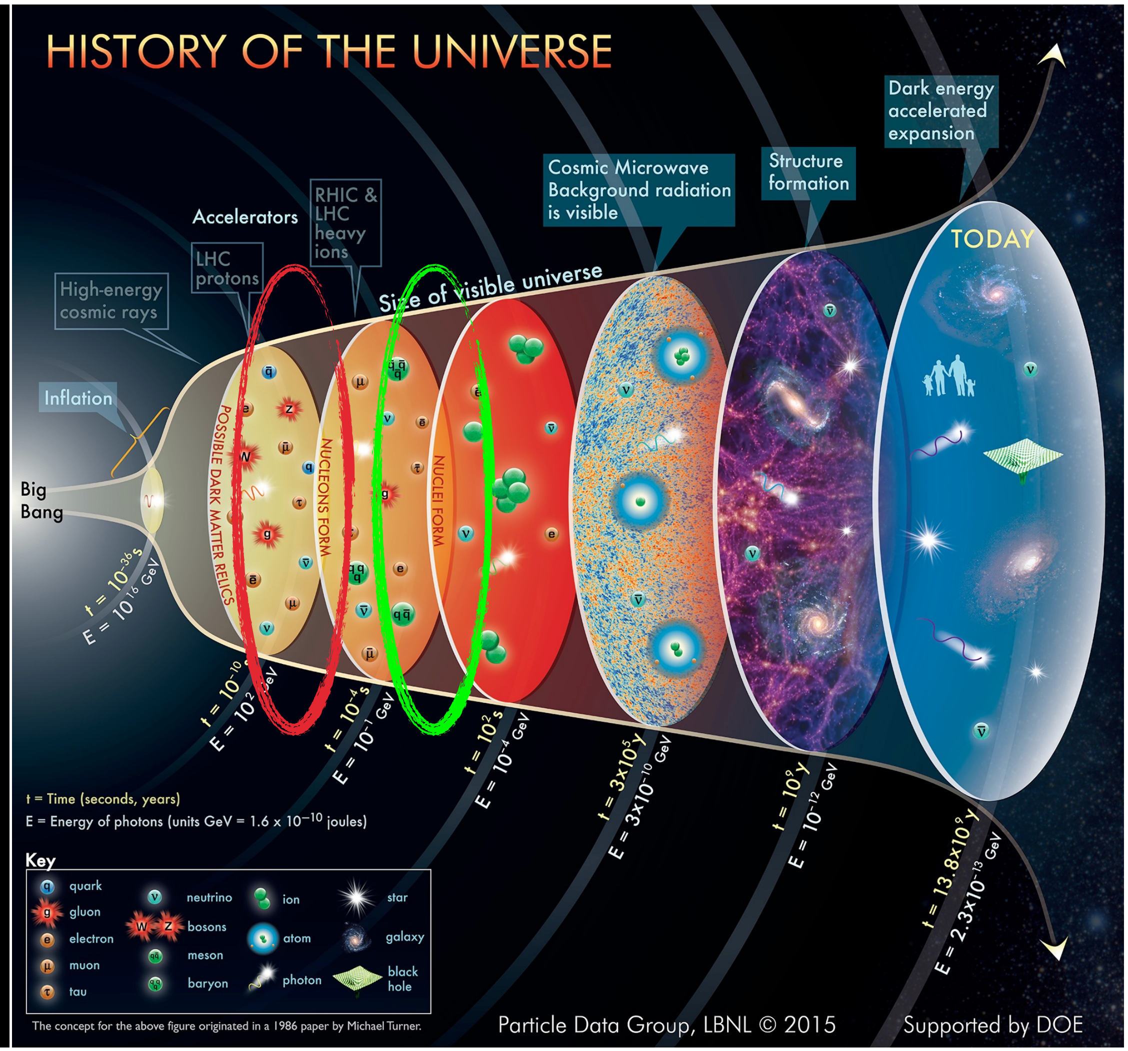
PHENIX

Stony Brook University

From the big bang …

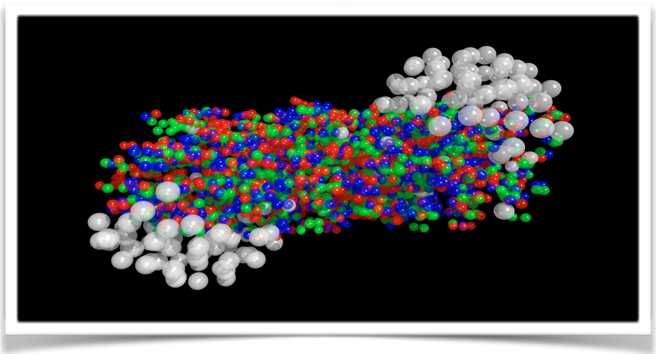
- A millionth of a second after the big bang
  - Extremely high temperature & density ➜ protons and neutrons “boiled” into a “soup” of quarks and gluons (Quark Gluon Plasma or QGP)

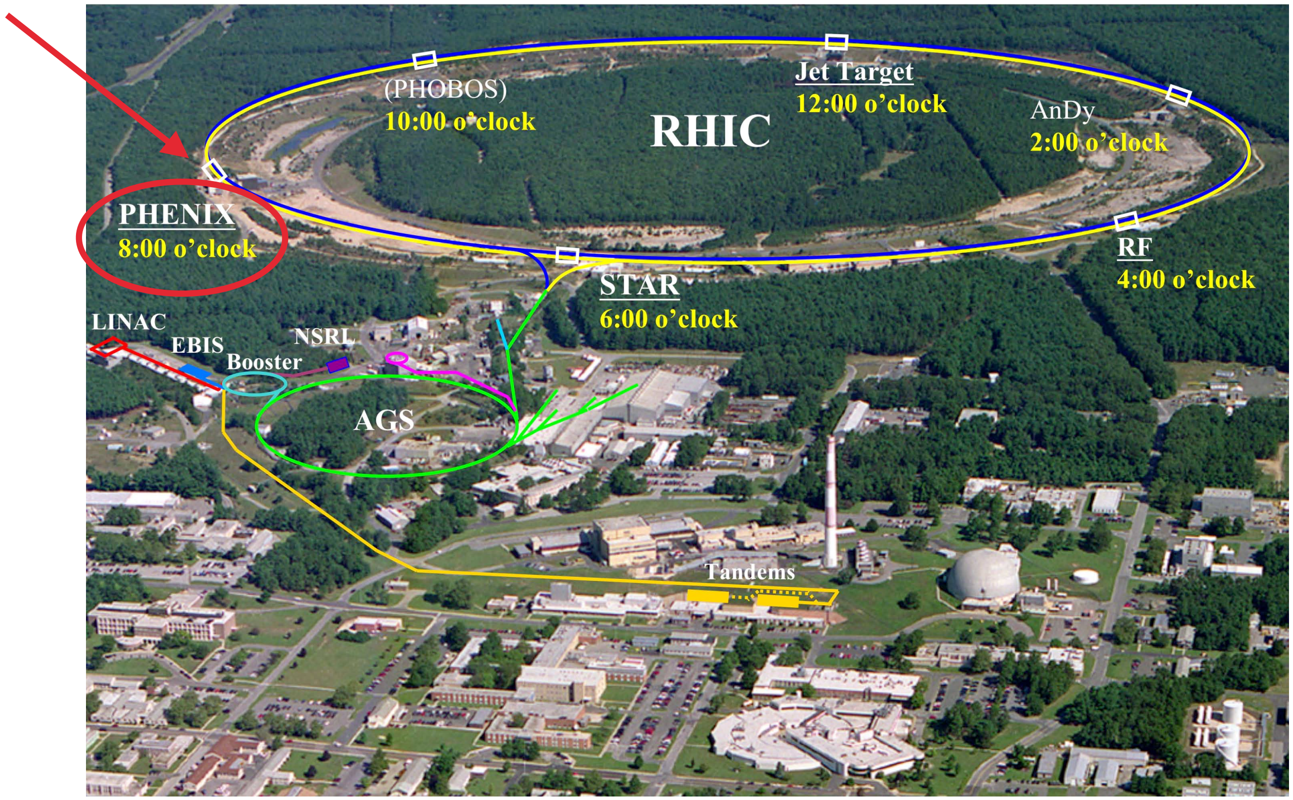




… To the little bang at RHIC

- The main goal of Relativistic Heavy Ion Collider (RHIC) is to create, identify and study the QGP





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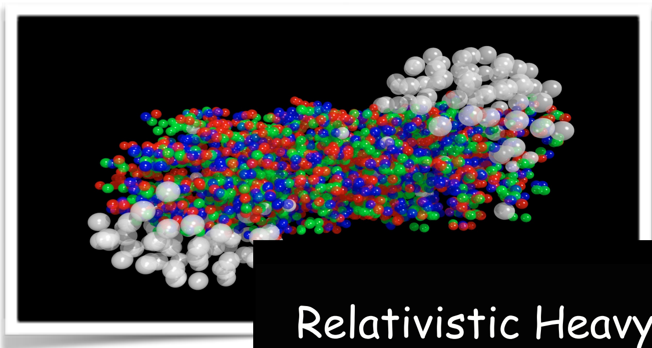
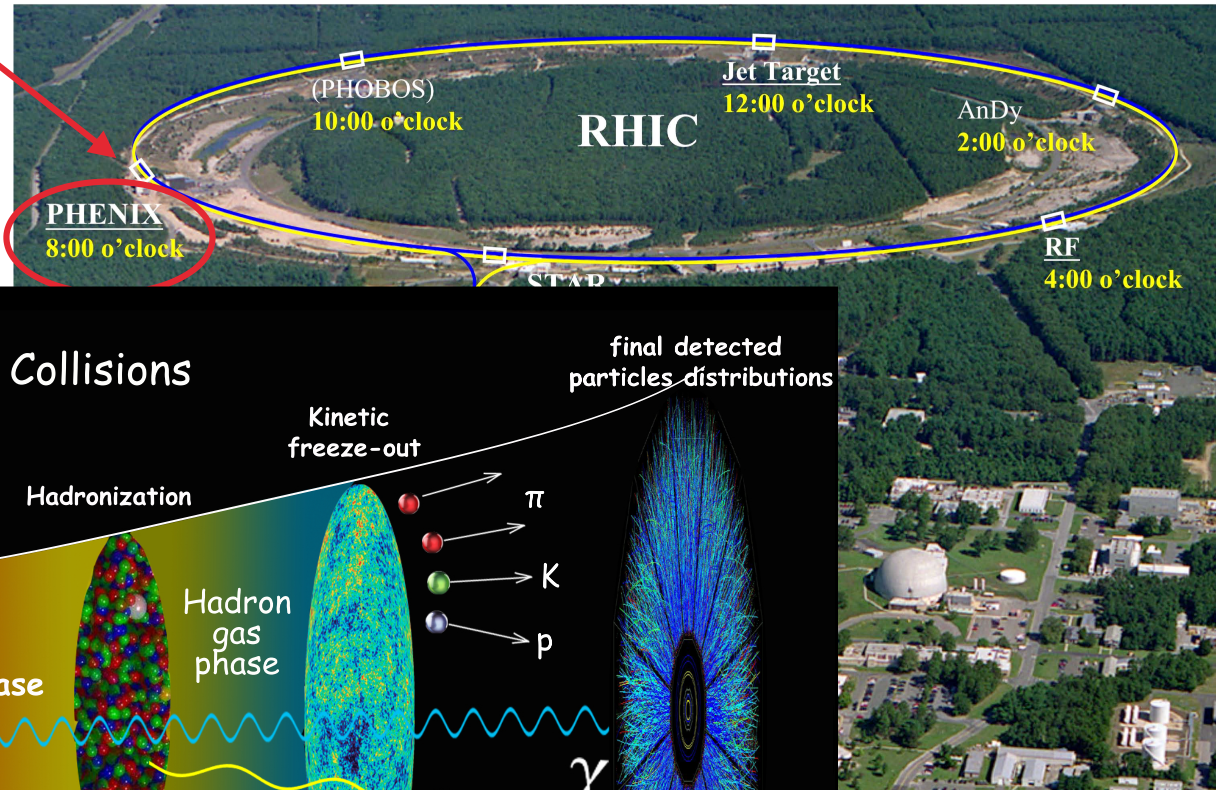
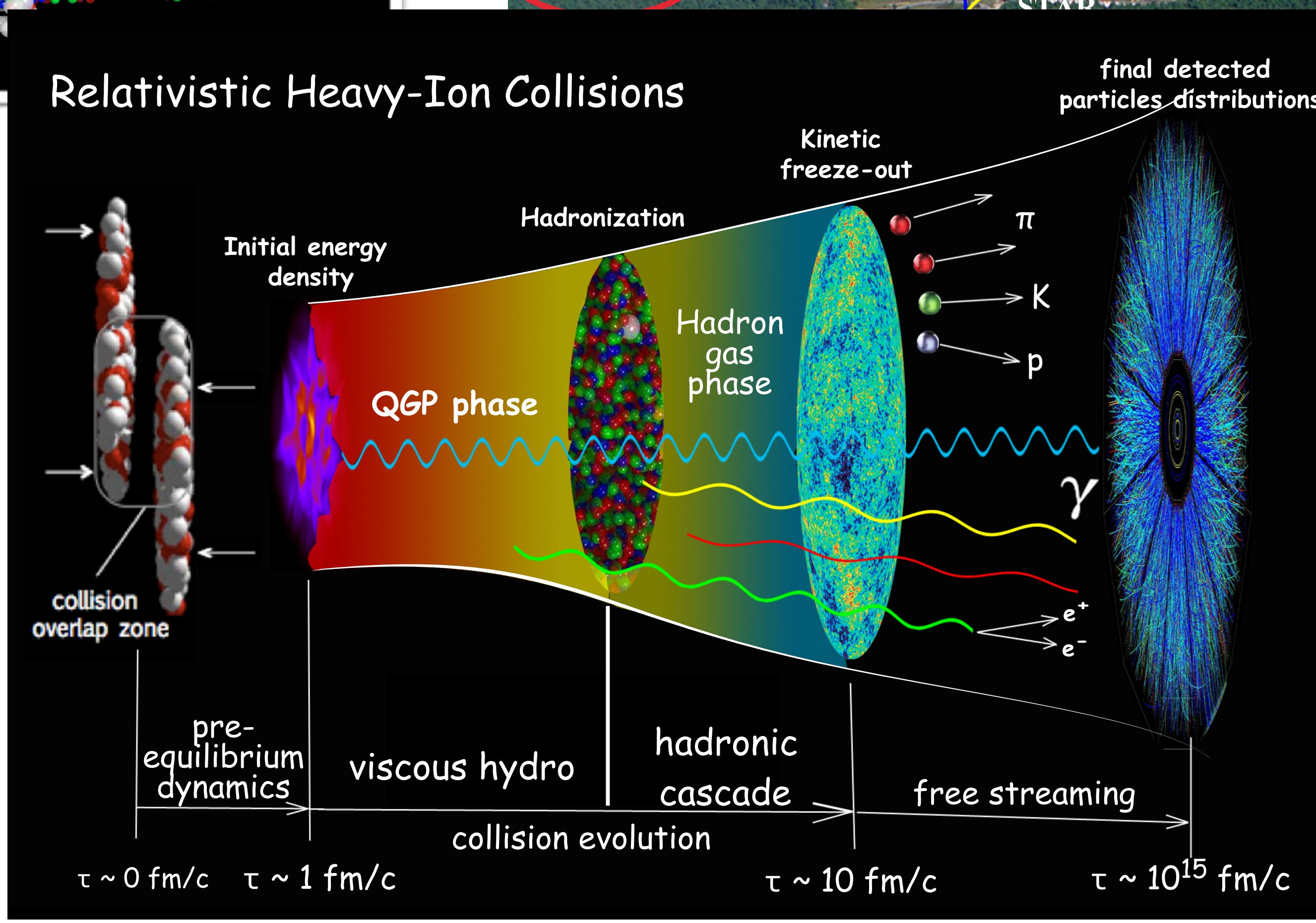


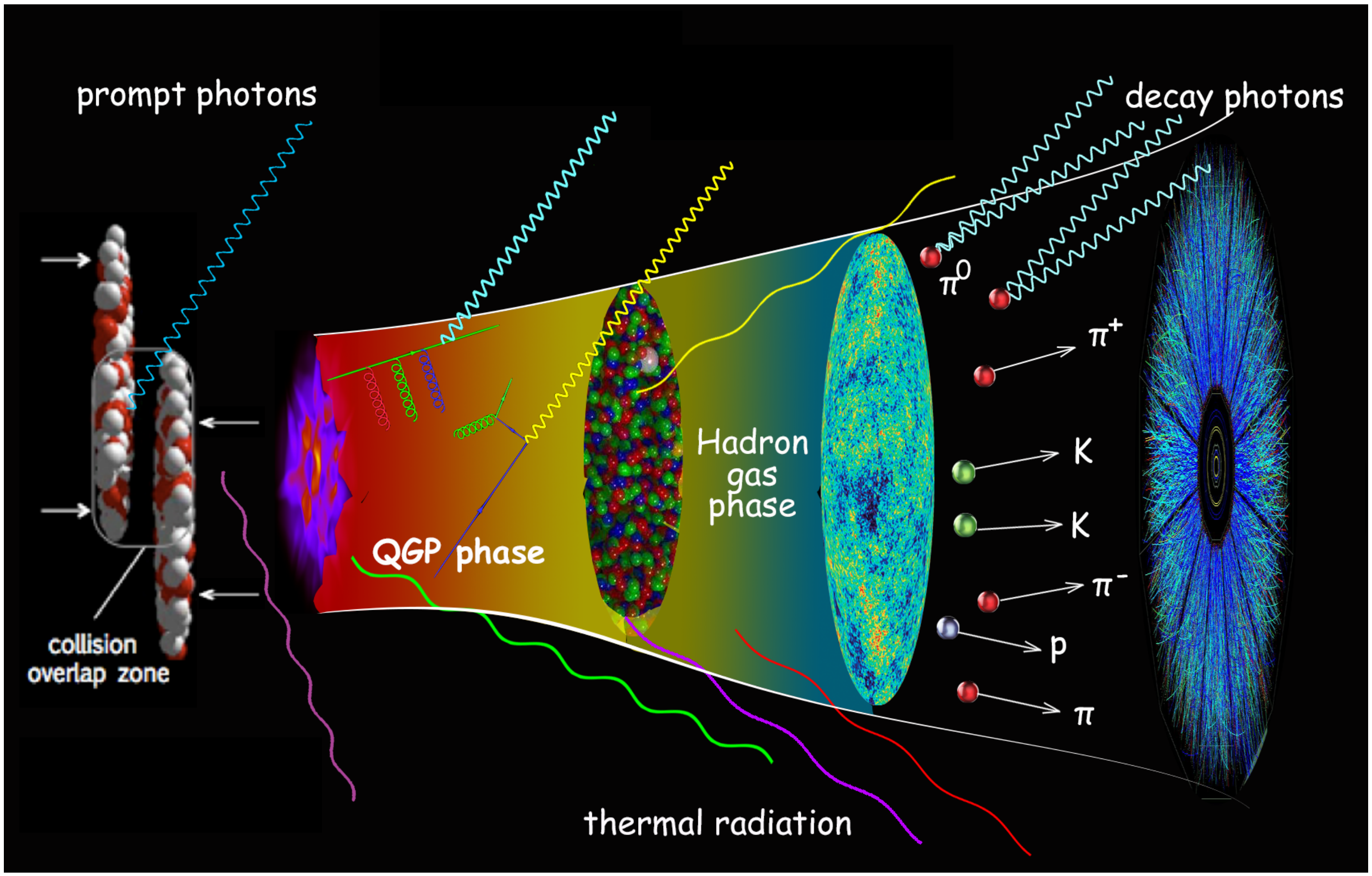




Graphics by Chun Shen

EM radiation in heavy-ion collisions

- **Photons are a unique probe for QGP**
  - **"Color blind" (do not experience strong interaction), provide a direct fingerprint of its creation point**



EM radiation in heavy-ion collisions

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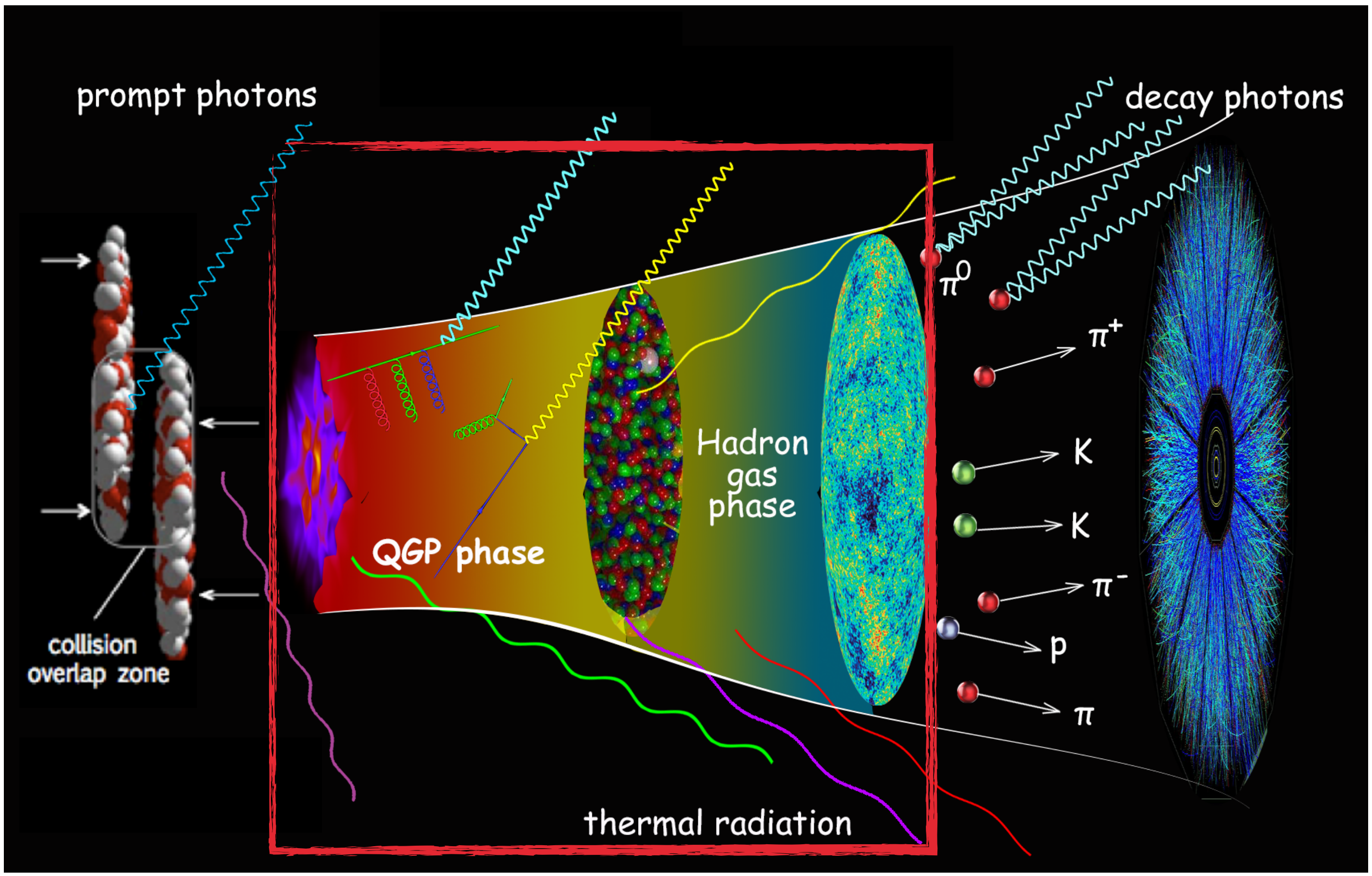

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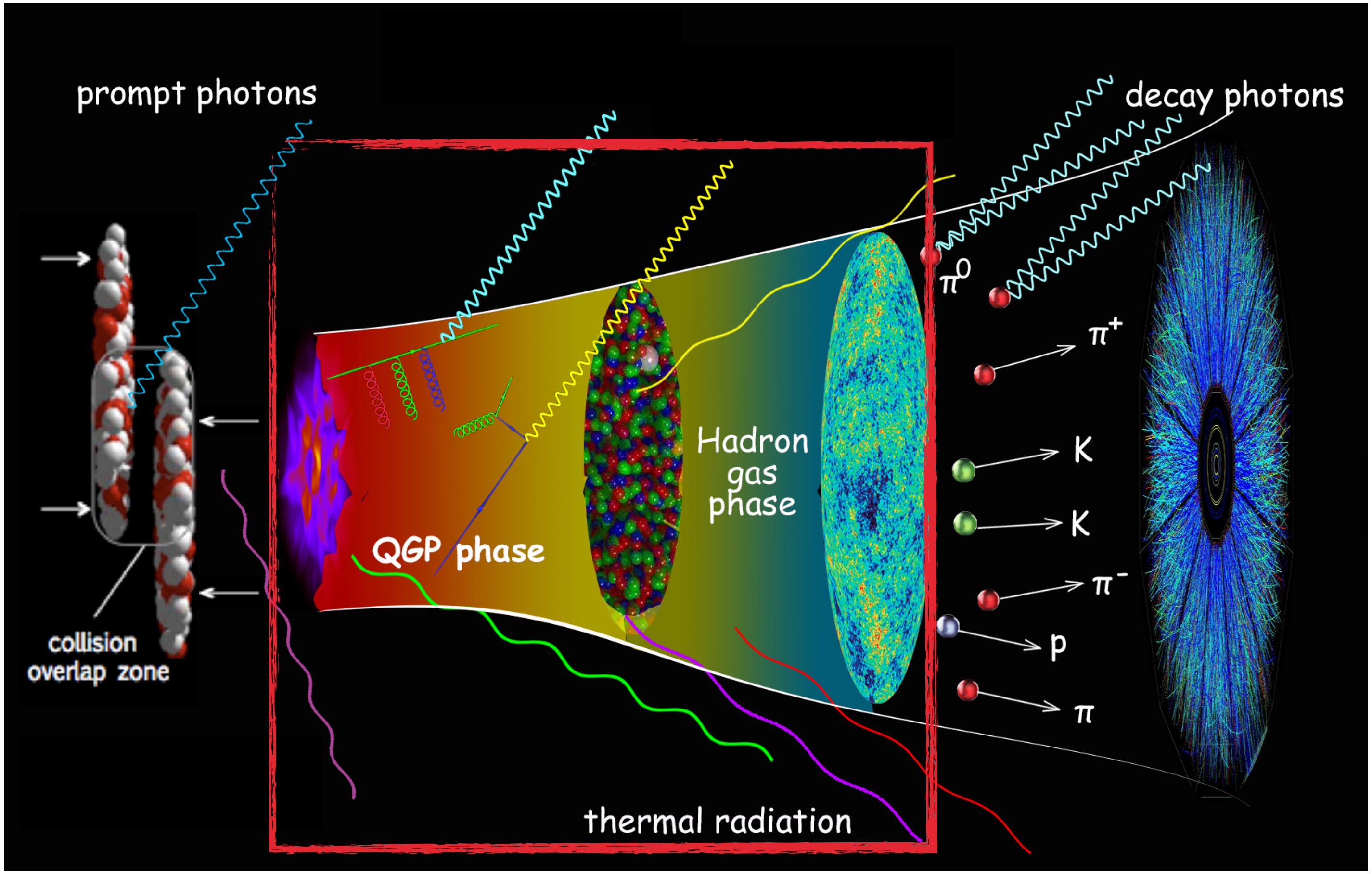

80-90% of the photons are decay photons!

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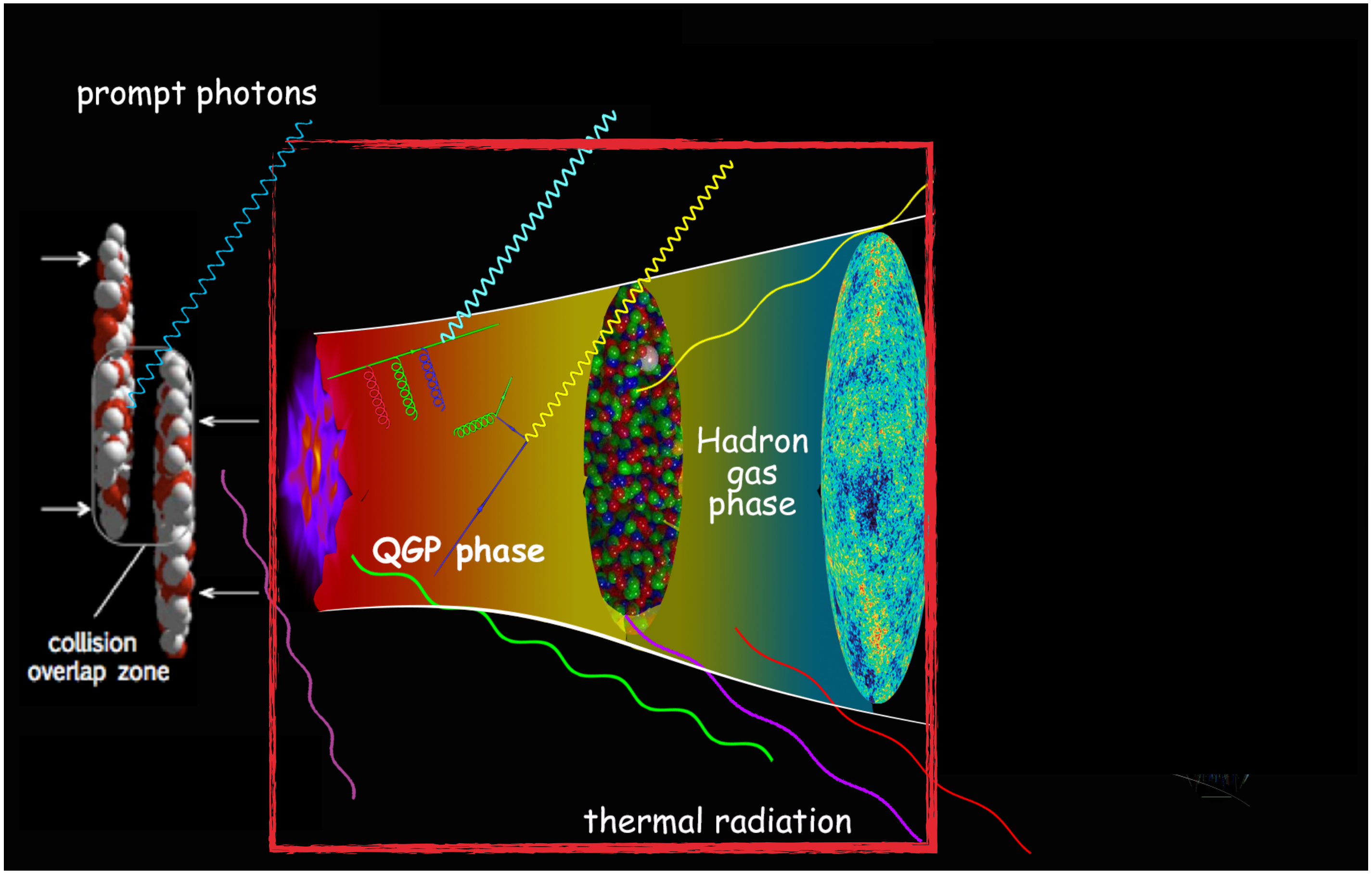

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Direct photon = Inclusive photon - decay photon

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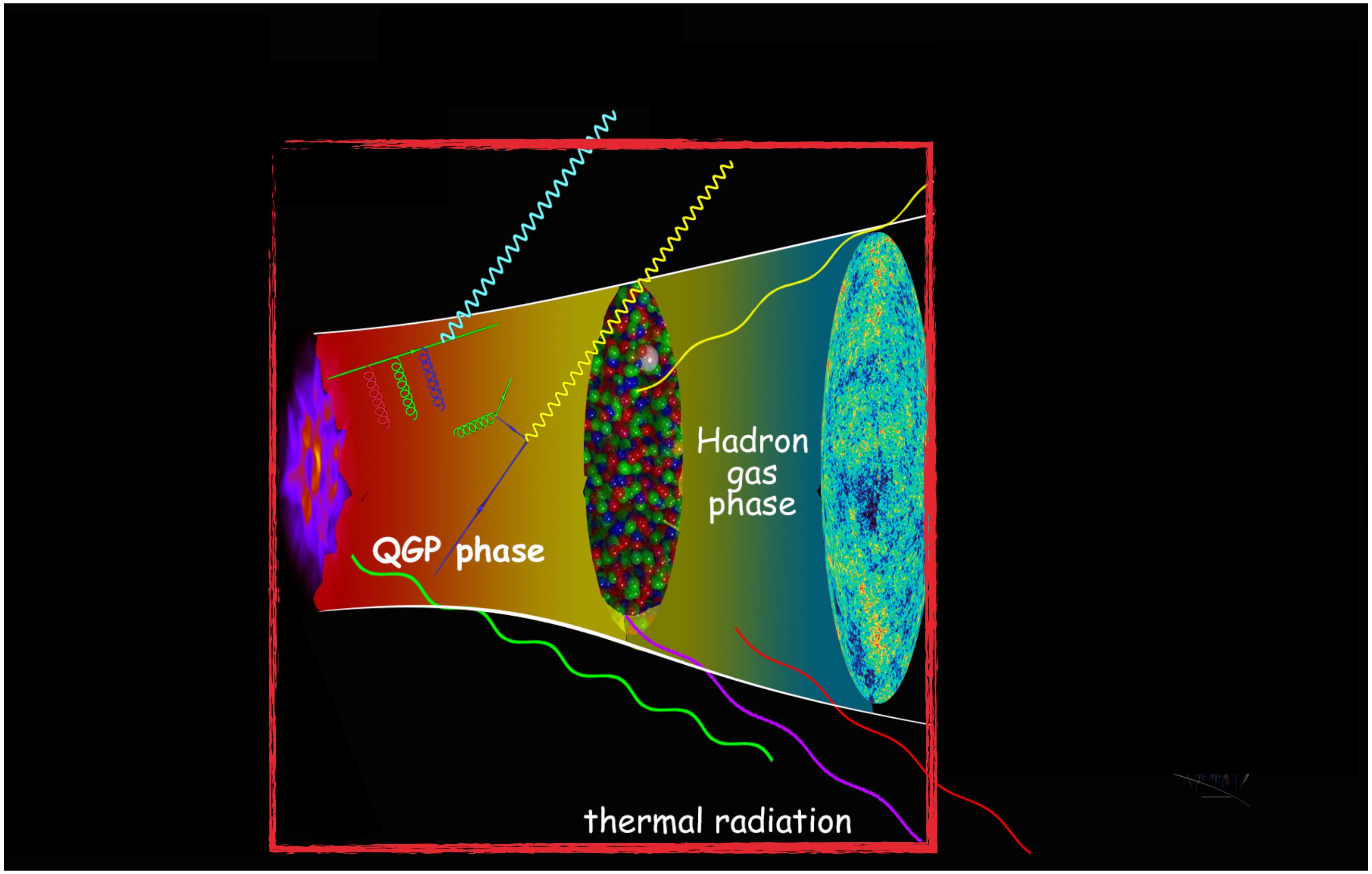

80-90% of the photons are decay photons!

Direct photon = Inclusive photon - decay photon

Estimate the prompt photons from p+p baseline

EM radiation in heavy-ion collisions

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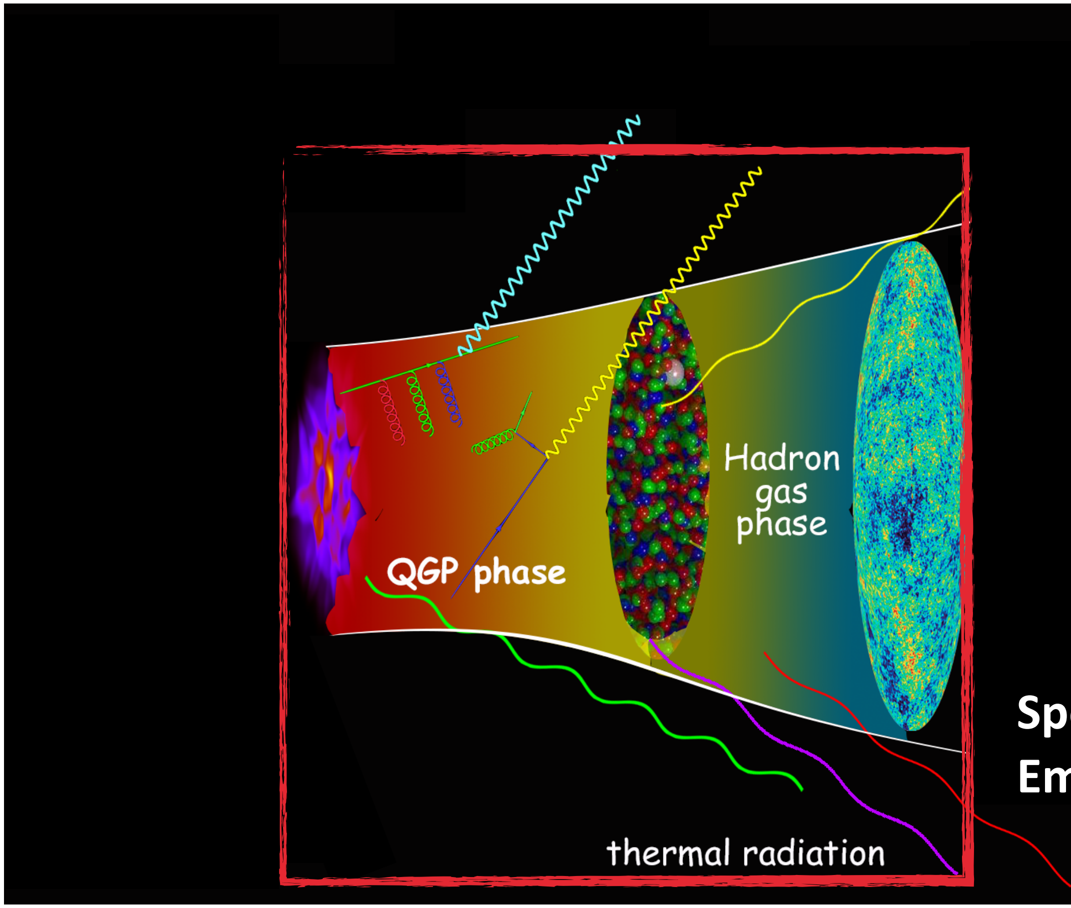
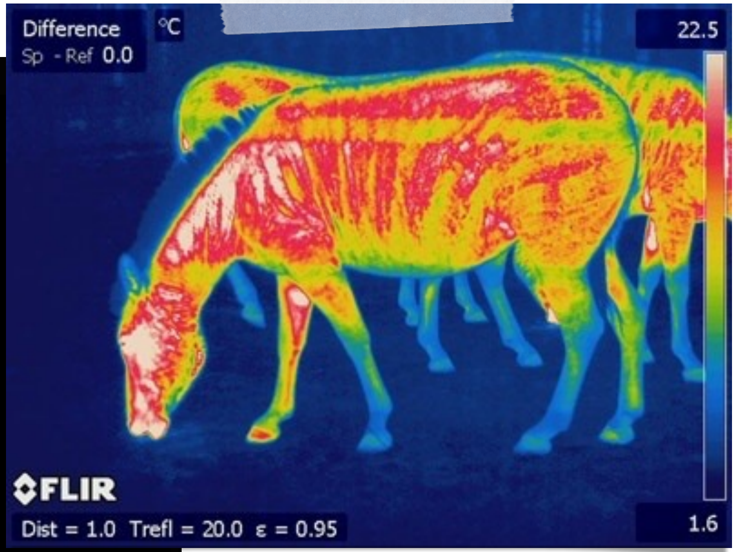




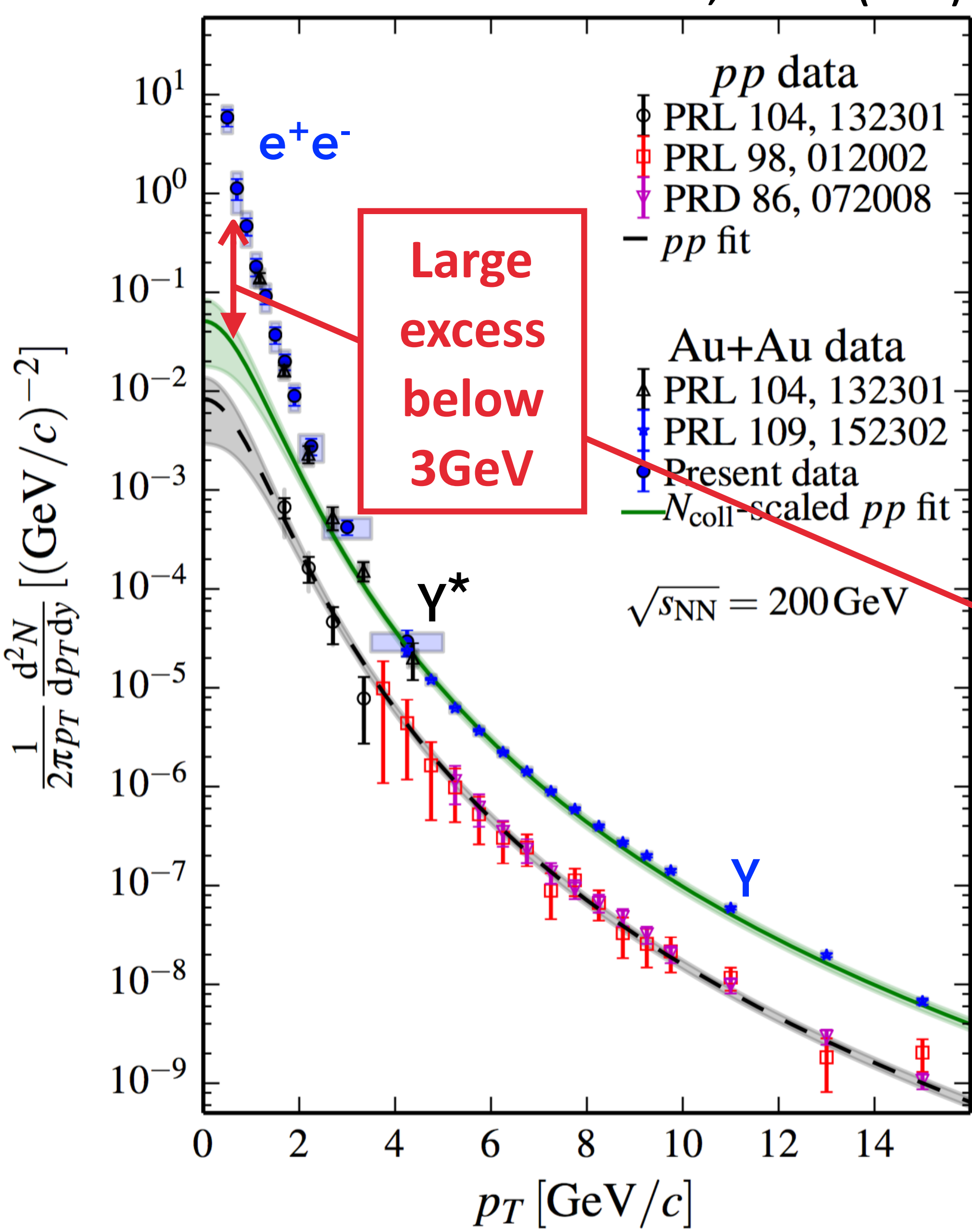
Spectrum $\propto e^{-E\gamma/T}$

Emission rate $\propto T^4$

Extract temperature from thermal photon yield

Thermal photons in Au+Au collisions

PRC 91, 064904 (2015)



inclusive photon yield

— hadronic decay photons

direct photon yield

— hard scattering contribution (N_{coll} scaled p + p)

thermal photon yield

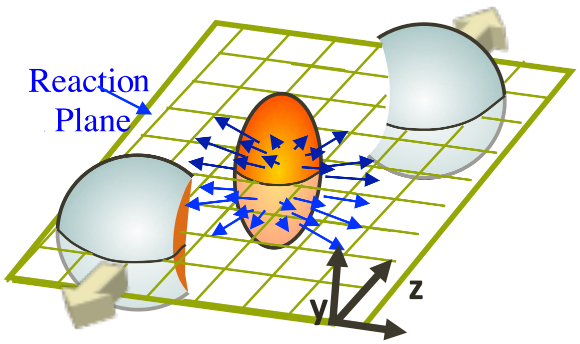
exponential fit: $A\exp(-p_T/T_{eff})$

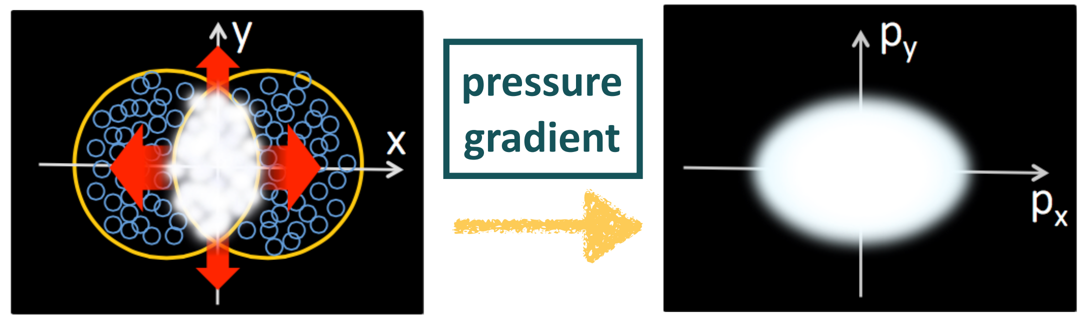
inv. slope T_{eff} ~ 240MeV

T_{init} > 300MeV > T_c (~150MeV)

Anisotropic emission of direct photons

- "Perfect fluid"



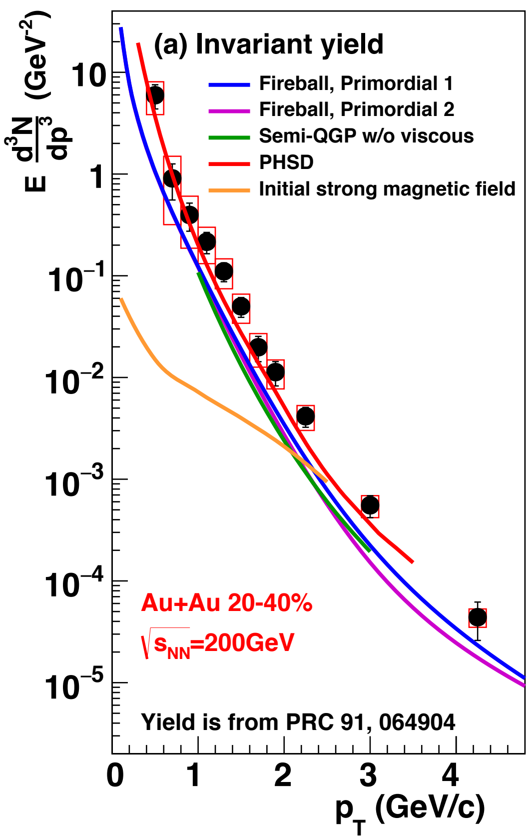


initial state eccentricity

final state anisotropy

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

- **Large yield: emissions from the early stage when temperature is high**



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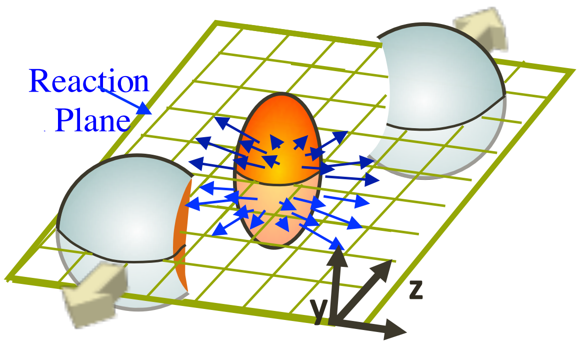

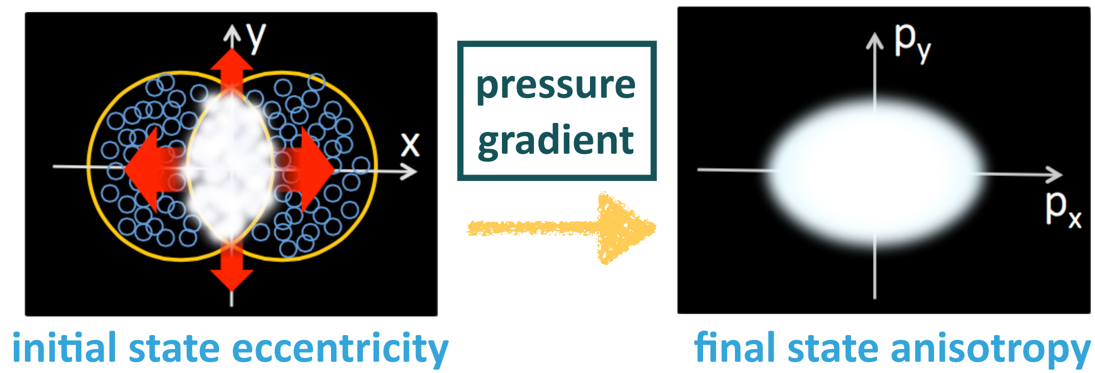

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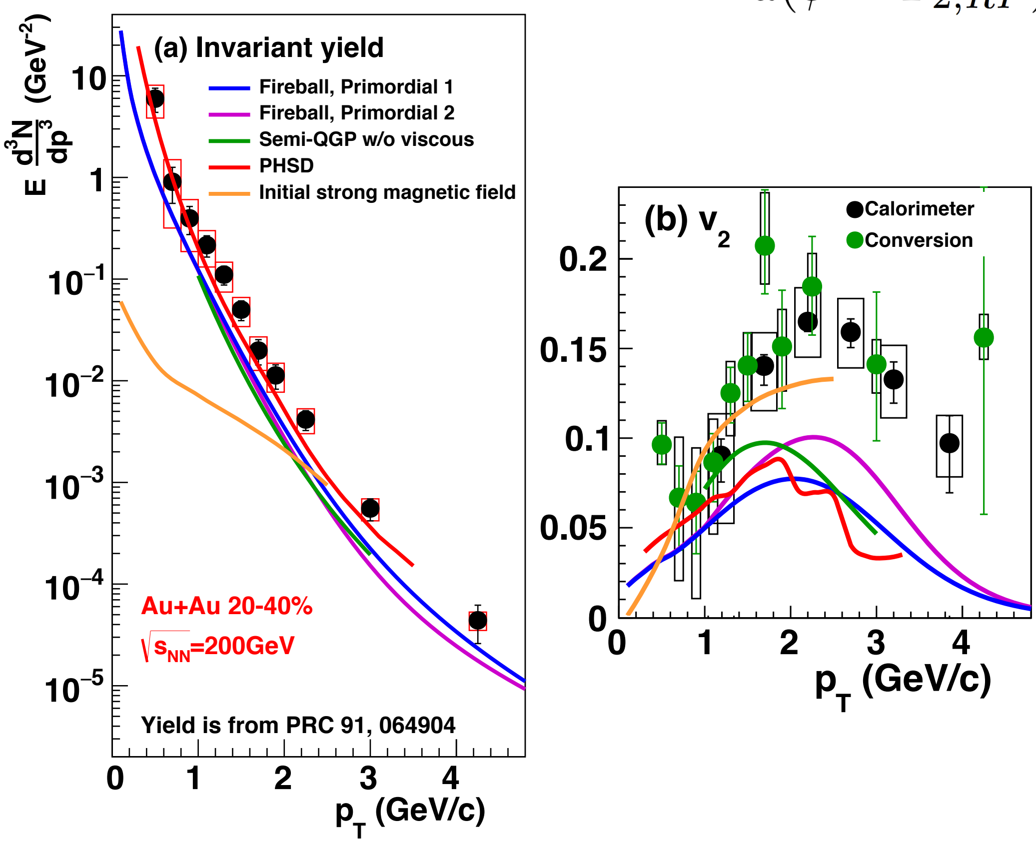
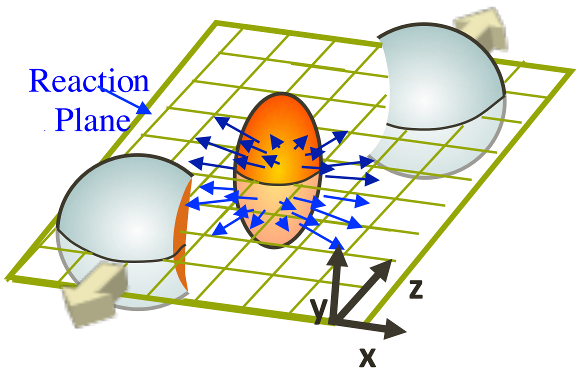
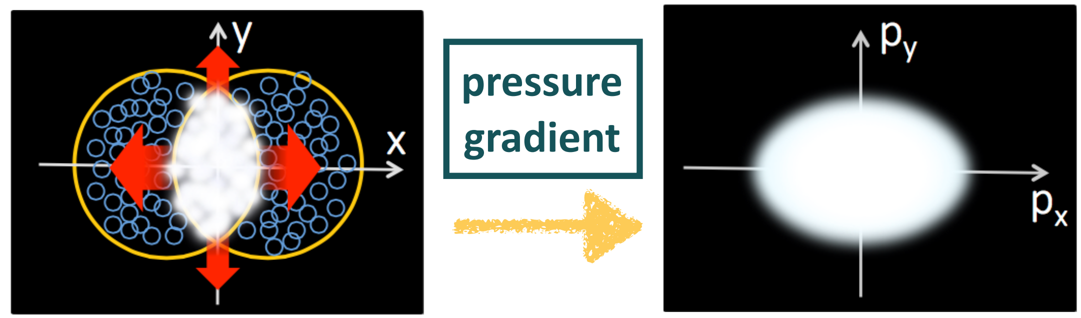


- Large yield: emissions from the early stage when temperature is high
- Large v_2 observed!

Anisotropic emission of direct photons

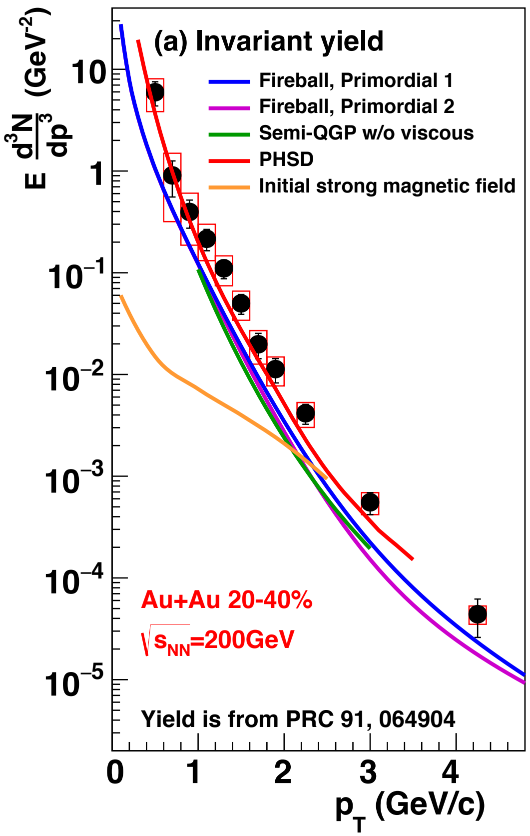
- "Perfect fluid"

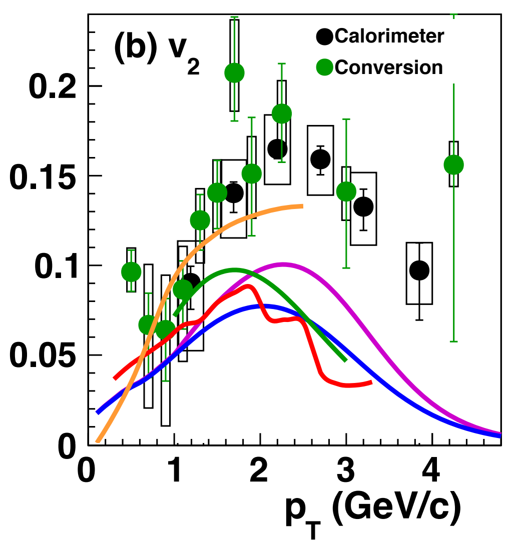




initial state eccentricity   final state anisotropy

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





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

Challenging for current theoretical models to describe large yield and v_2 simultaneously!

Integrated low p_T direct photon yield — universal scaling

- Integrate the low p_T direct photons and use $dN_{ch}/d\eta$ to compare data from different beam energies, collisions species, and collision centralities

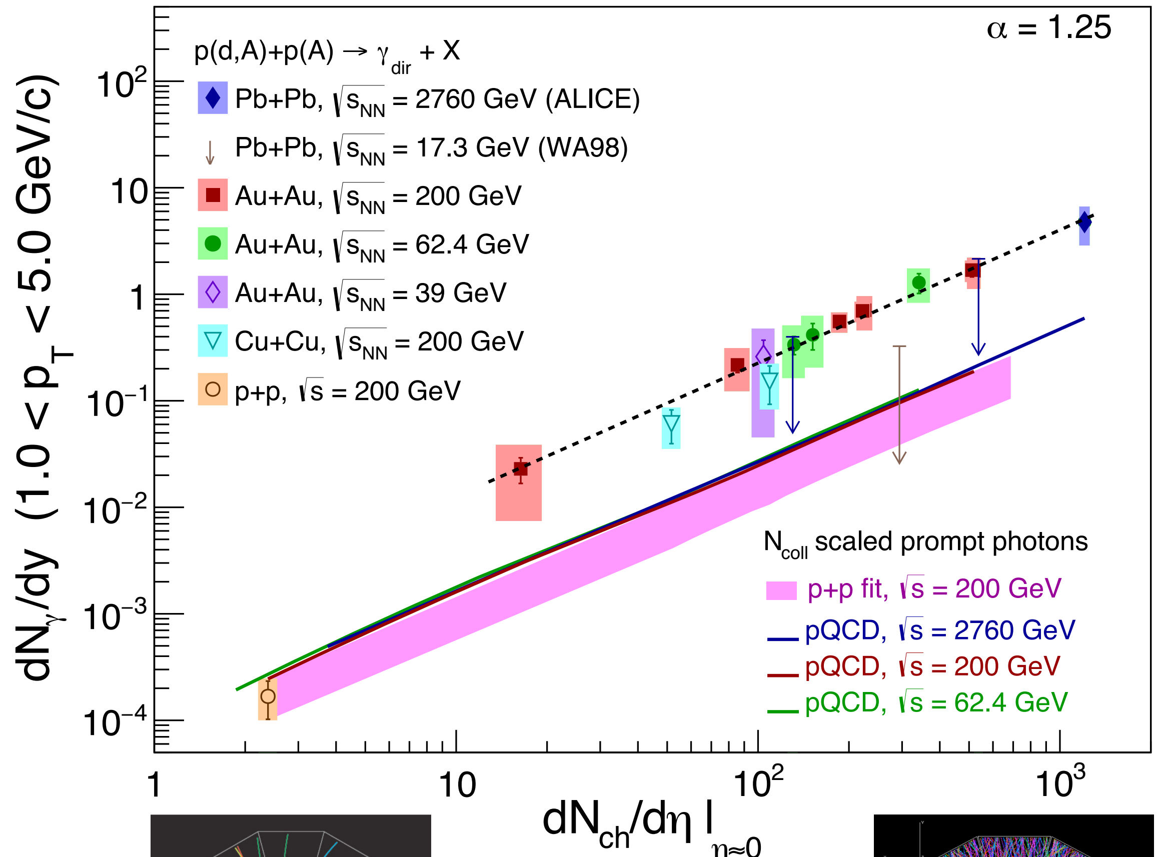
Universal scaling behavior in all A+A systems

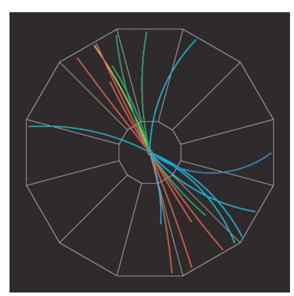
$$dN_\gamma/dy = A \times (dN_{ch}/d\eta)^\alpha$$

Source of photons must be similar

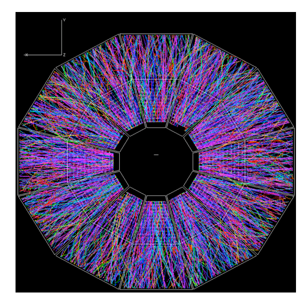
N_{coll} x pQCD and N_{coll} x p+p follow same scaling at 0.1 of yield

PRL 123, 022301 (2019)





more central collision
higher beam energy
heavier nuclei A



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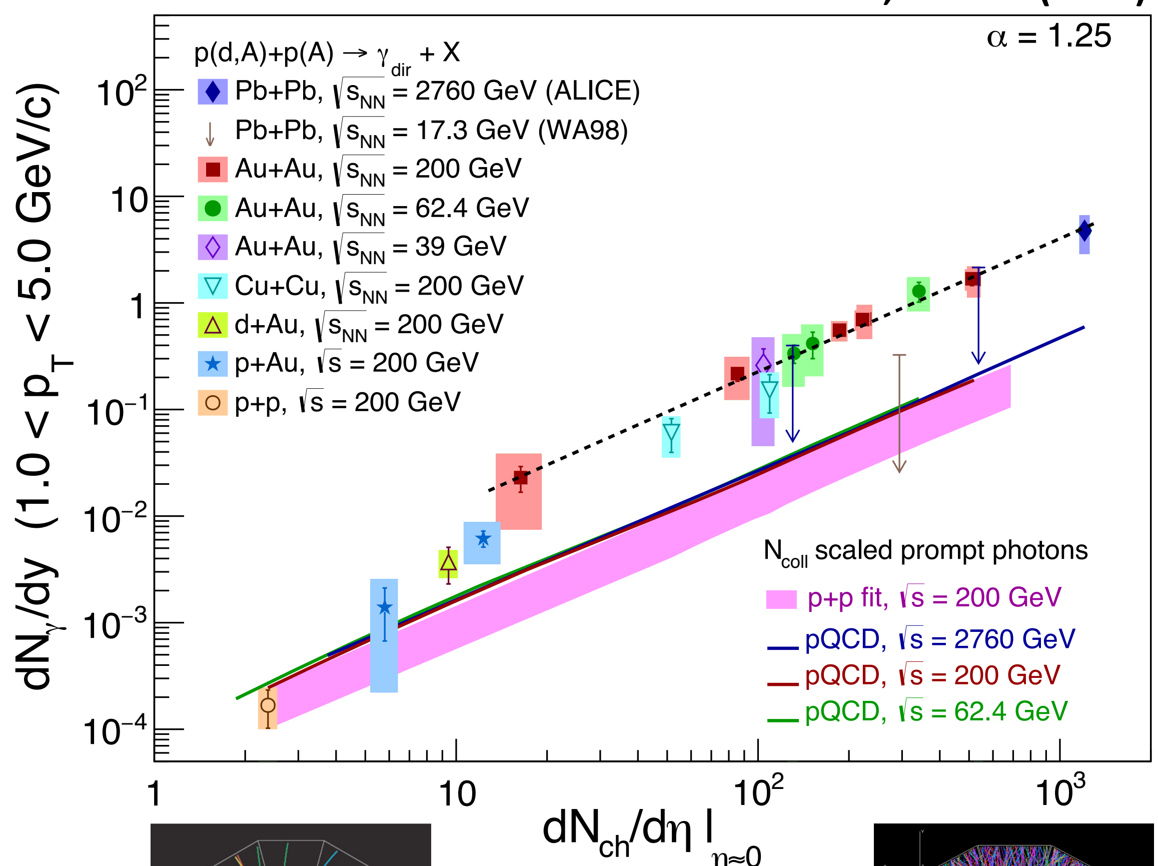
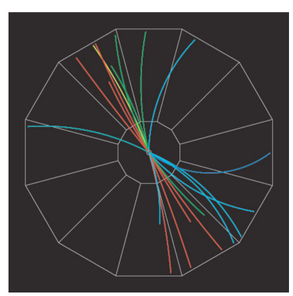
Onset of low p_T radiation excess at $dN_{ch}/d\eta$ ~10?

PRL 123, 022301 (2019)





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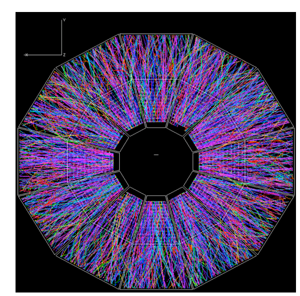
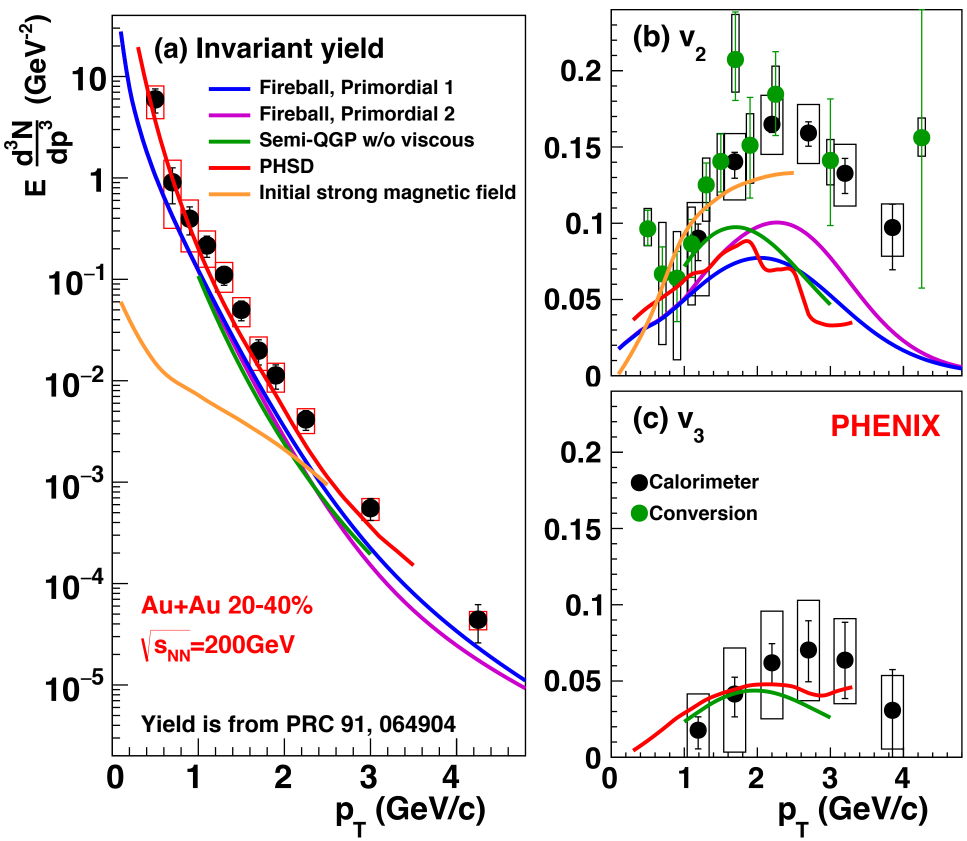
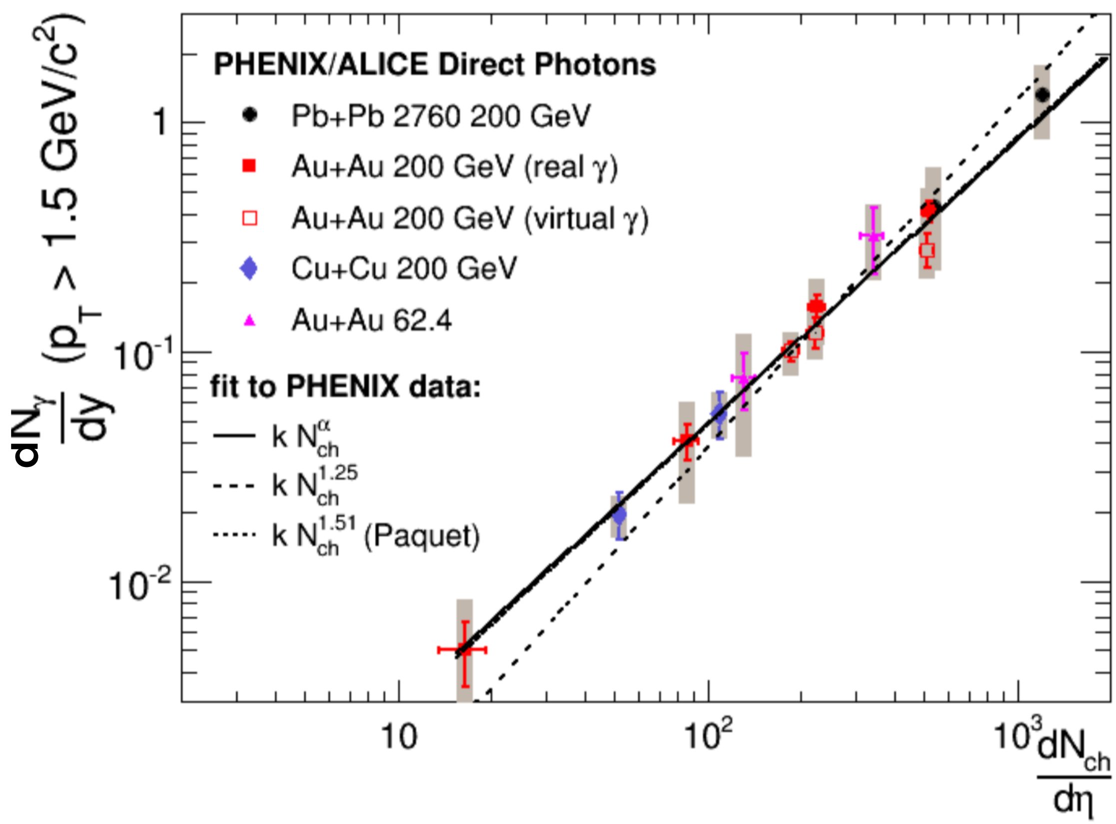


Direct photon puzzle

- Experimental observations
  - Large yield of low p_T direct photons
  - Large anisotropic emission
  - Universal scaling with α ~5/4
- Challenging to explain by thermal source

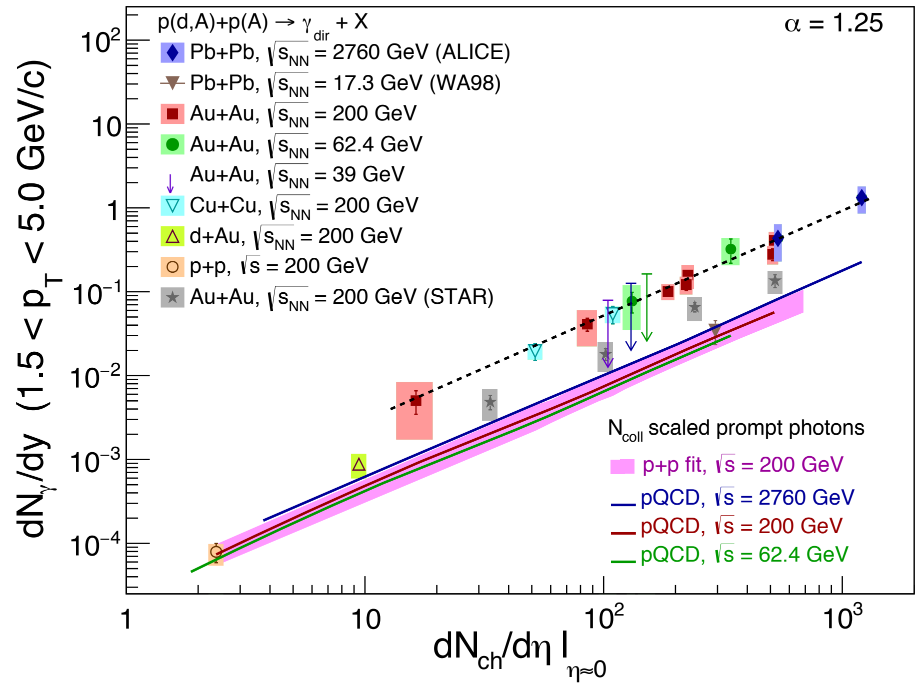
What is the main source for low p_T direct photons?



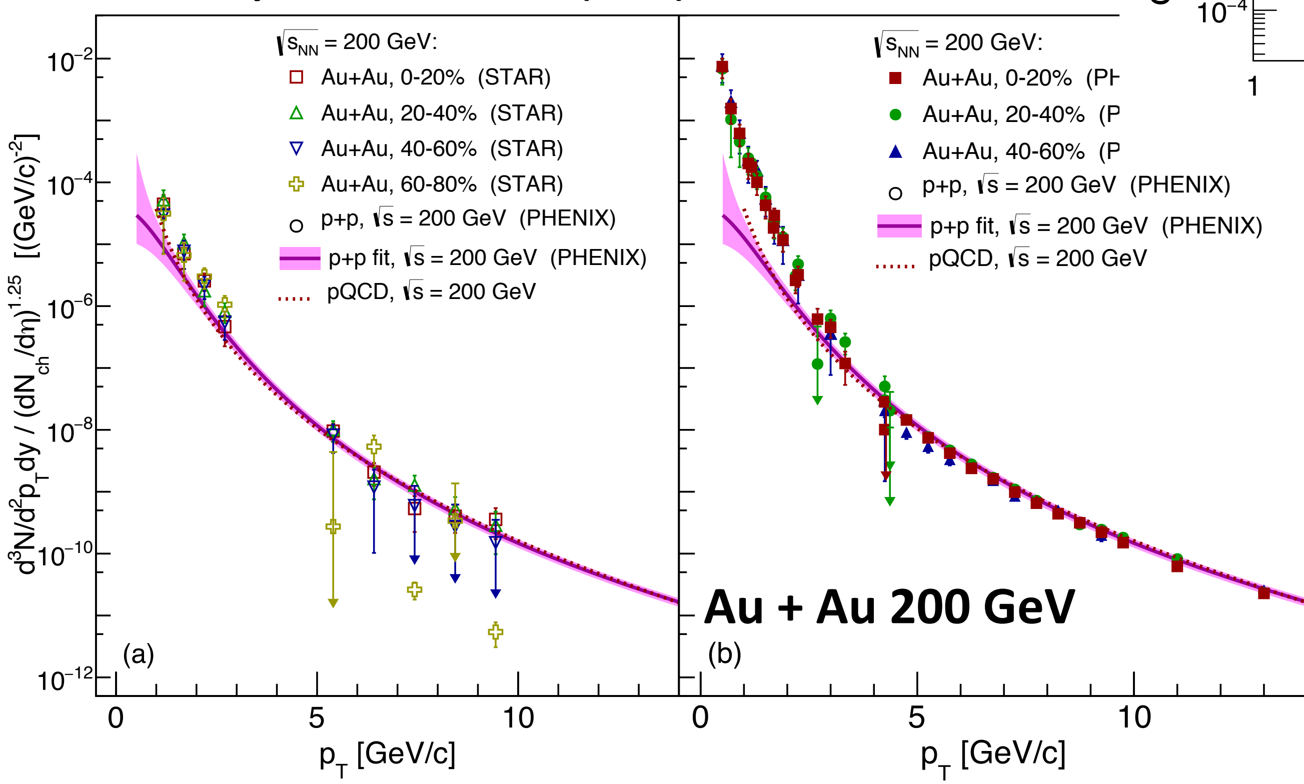


Tension with STAR direct photon measurement

STAR data significantly lower than PHENIX data



STAR: Phys. Lett. B 770, 415 (2017)



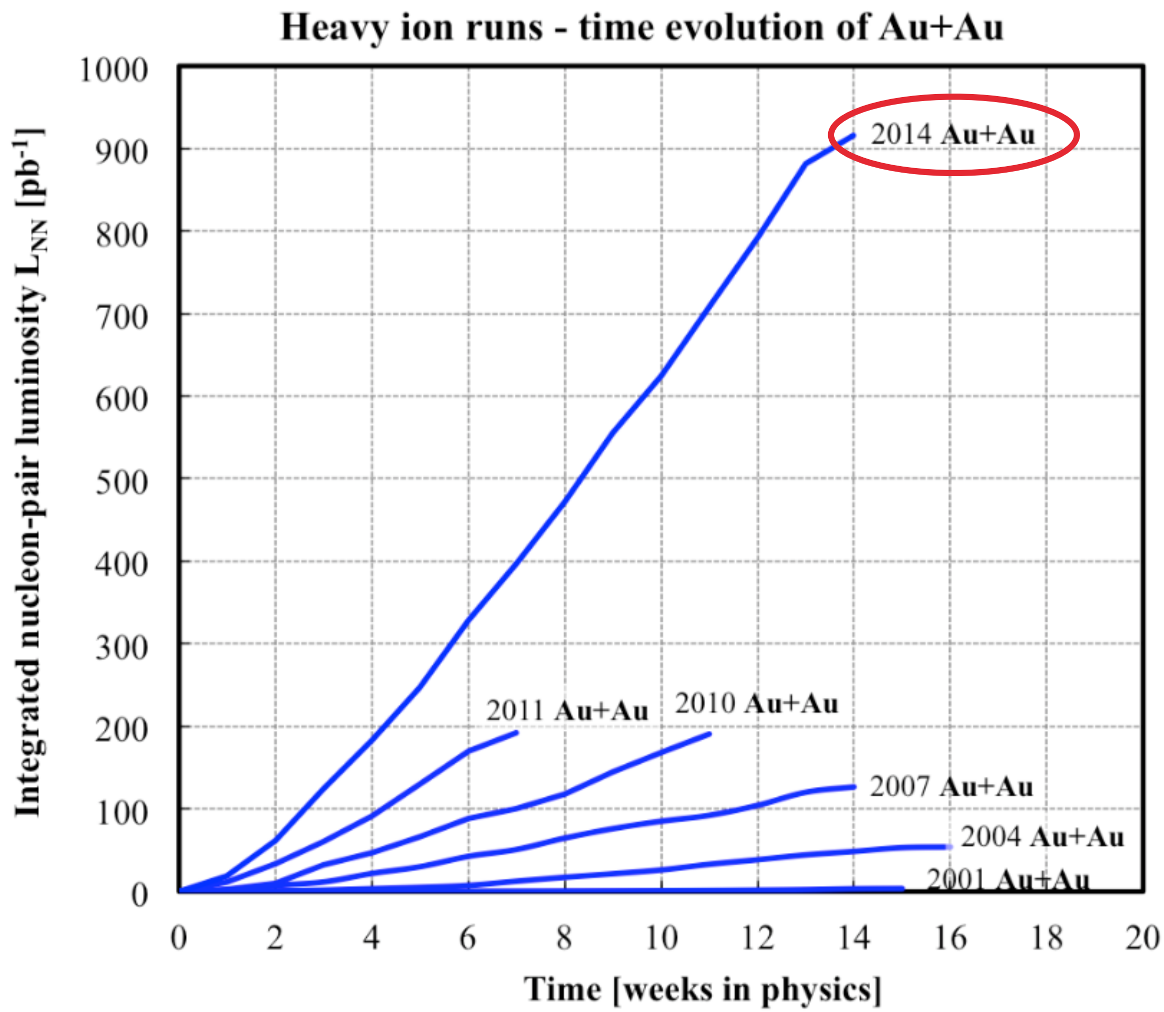
PHENIX:

PRL 85, 132301 (2010)

PRC 91, 064904 (2015)

Towards precision measurement with the "Golden Dataset"

- Theoretically
  - Modification in thermal photon emission?
  - Modification in prompt photon emission?
  - Other sources of photons? (pre-equilibrium? hadronization? B field)
- Experimentally (to confirm and to study in more detail)
  - Experimental data needs more statistics
  - 2014 Au+Au dataset
  - More conversions at the PHENIX silicon vertex detector (VTX) ($X/X_0 \sim 14\%$)



How to measure photons?

Acceptance: |η|<0.35, Δφ 2x90°

- **Electromagnetic Calorimeter:**
  - 2 PbGl: 0.8 % + 5.9 %/√E
  - 6 PbSc: 2.1 % + 8.1 %/√E
- **Tracking:**
  - Drift Chambers (DC)
    δp/p = 0.7 % + 1.1%p
  - Pad Chambers (PC)
    σ = ±1.7 mm
- **Particle Identification:**
  - RICH – $e^{\pm}$
  - TOF East and TOF West:
    - σ_T ≅ 100ps
    - π/K p_T < 2.5 GeV/c
    - K/p p_T < 4.0 GeV/c
  - EMCal timing:
    - σ_T ≅ 600ps

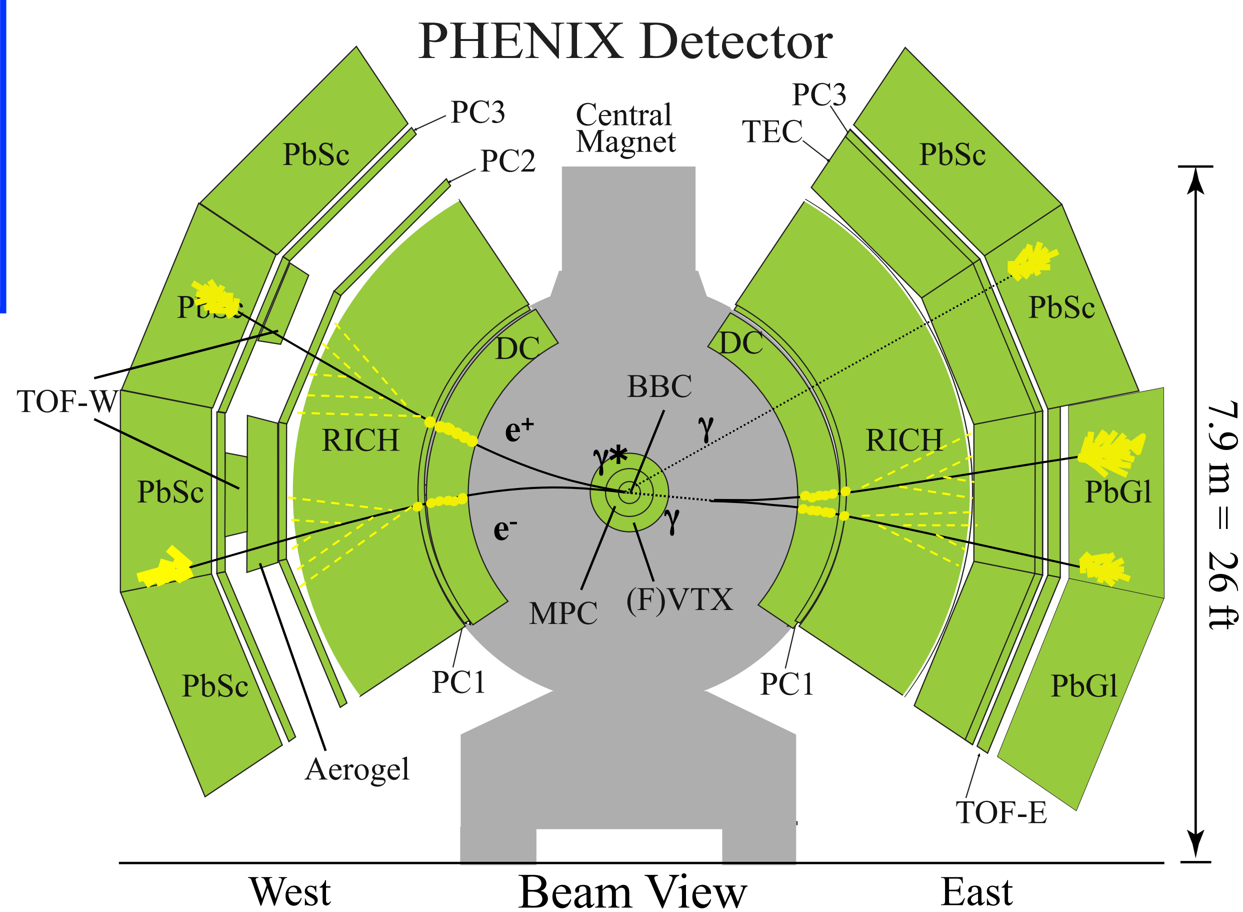
Measure photon via its energy deposit at calorimeter

☺ **good resolution at high p_T**

Measure photon via conversions

☺ **good resolution at low p_T**

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



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  - TOF East and TOF West:
    - $\sigma_T \cong 100$ps
    - π/K $p_T < 2.5$ GeV/c
    - K/p $p_T < 4.0$ GeV/c
  - EMCal timing:
    - $\sigma_T \cong 600$ps

Measure photon via its energy deposit at calorimeter

☺ good resolution at high p_T

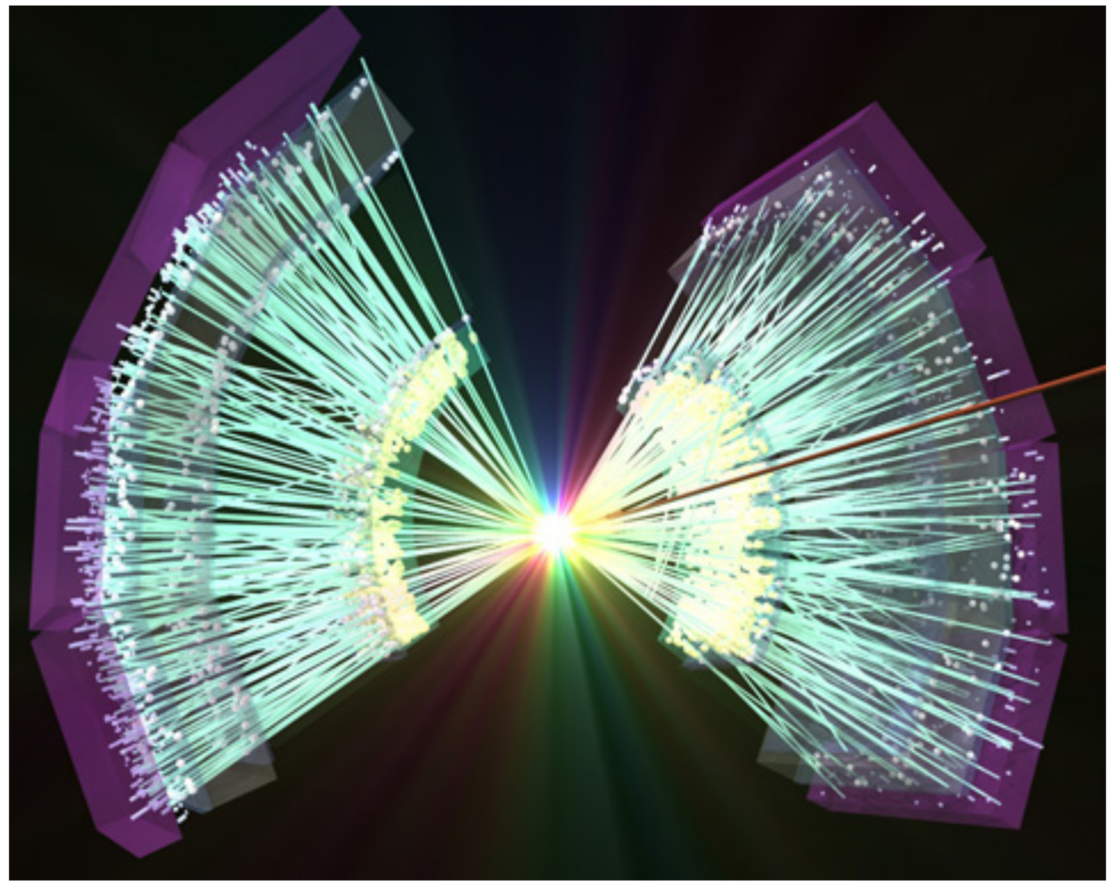
☹ low p_T is contaminated by hadrons

Measure photon via conversions

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

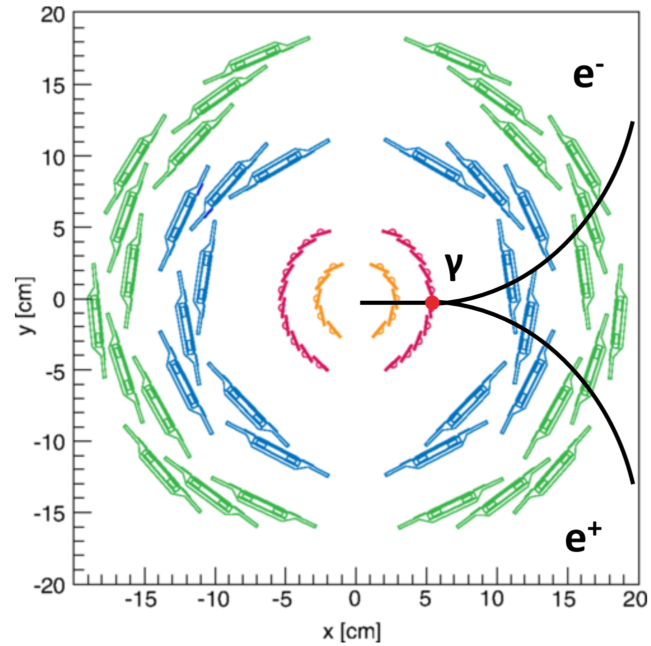
☺ good resolution at low p_T

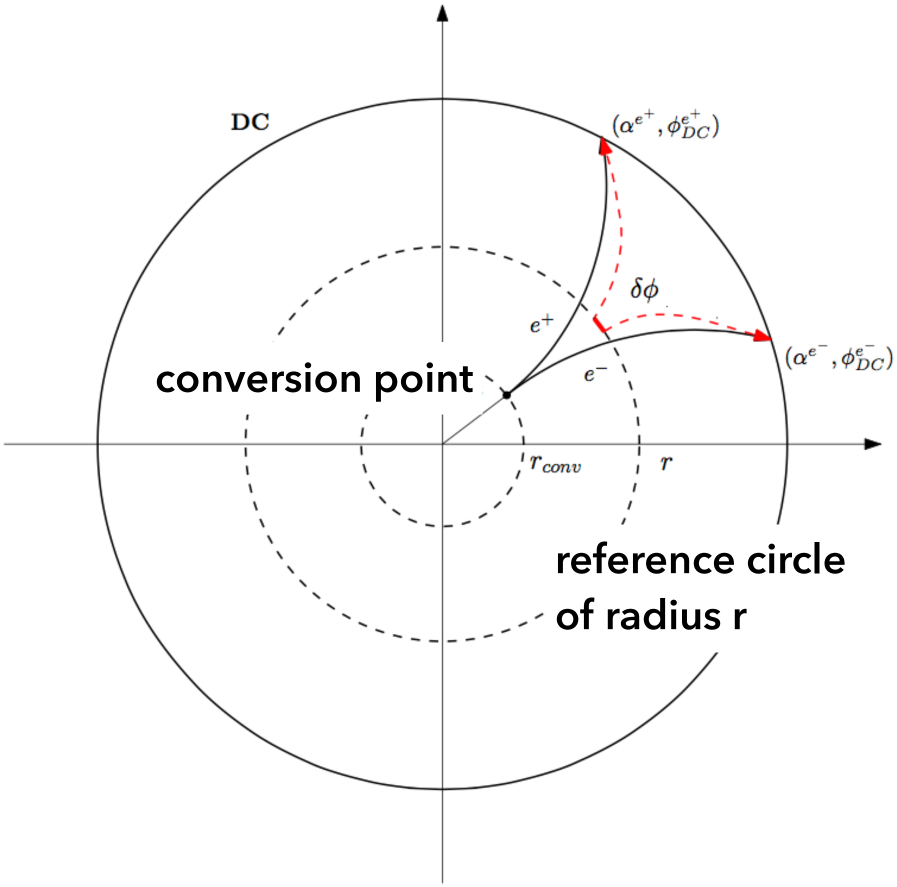
☺ good purity at low p_T after proper eID



New conversion reconstruction algorithm

- Identify and reconstruct photons via external conversion to e^+e^- pairs
  - Reconstruct conversion position using e^+e^- pair and magnetic field map
  - Track conversions back to its conversion position and reconstruct photon momentum





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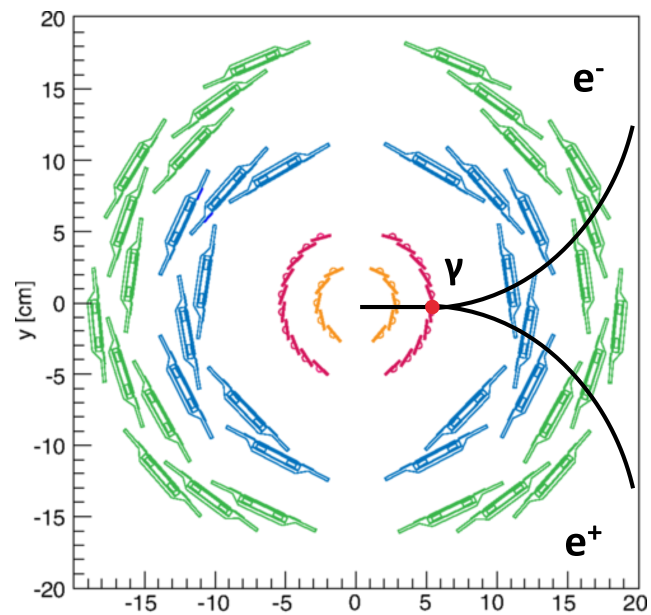

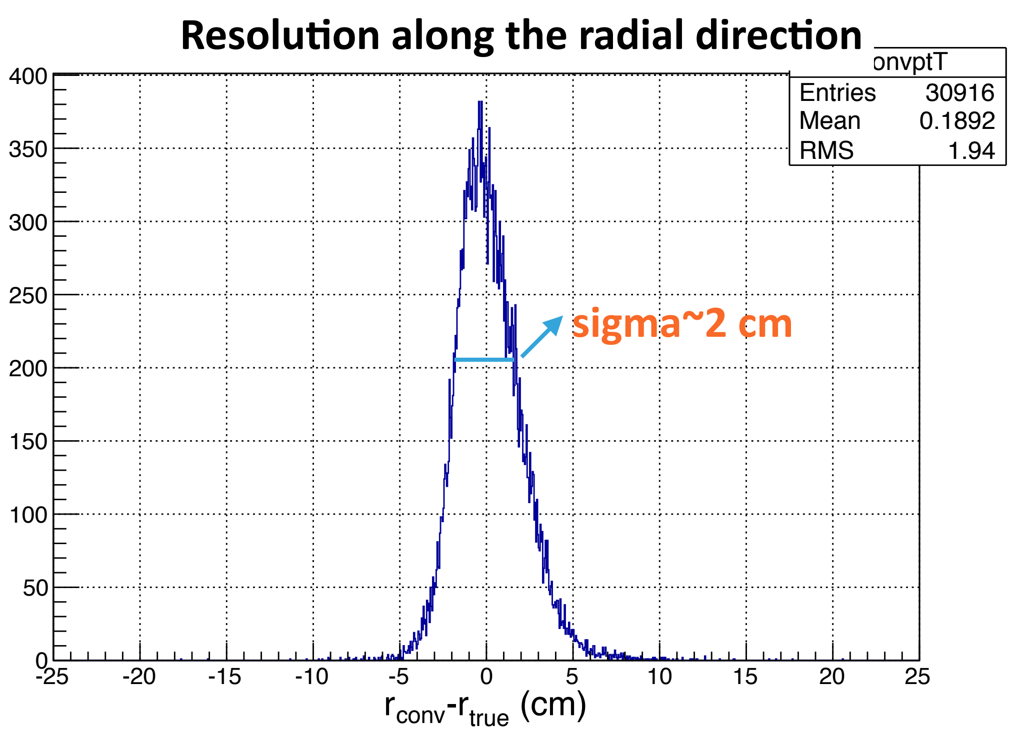

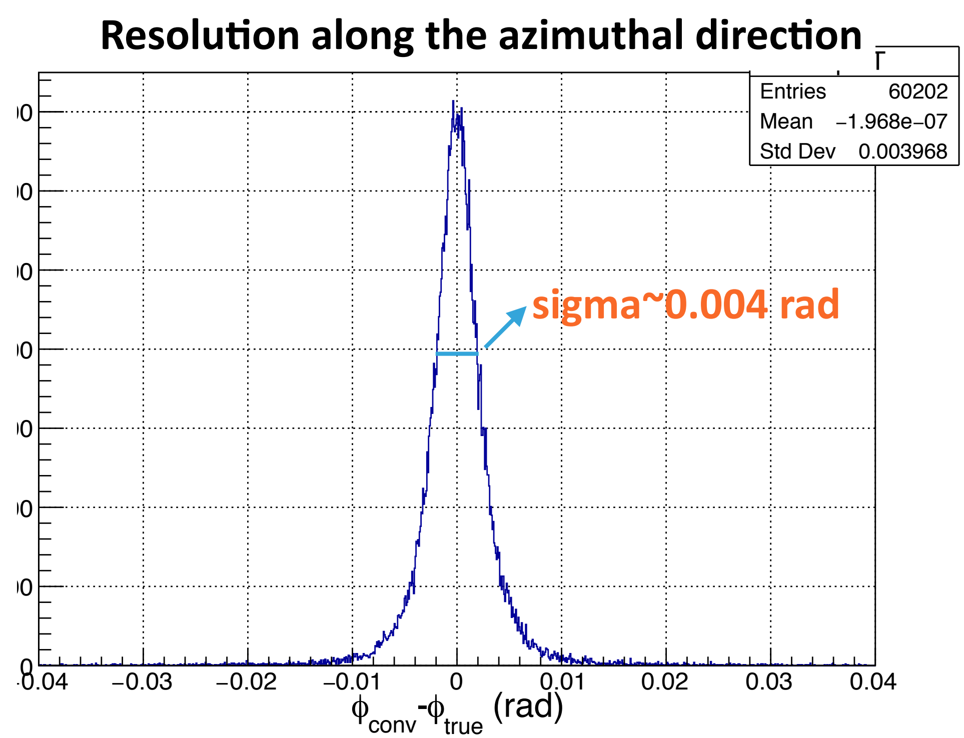

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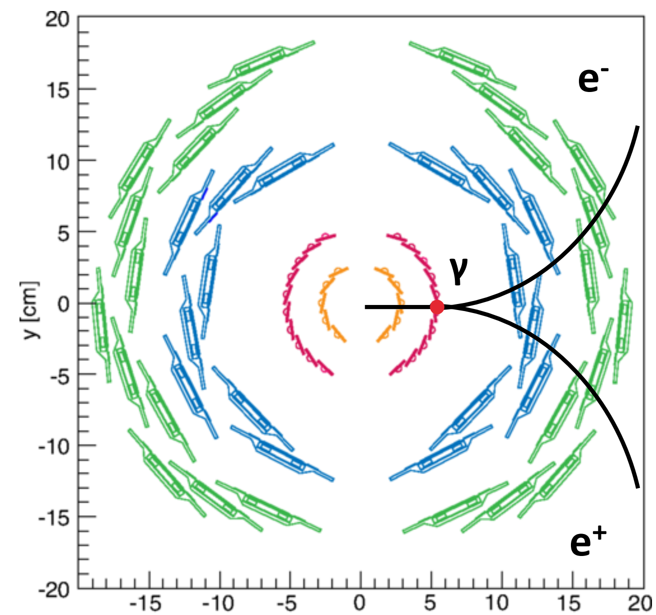
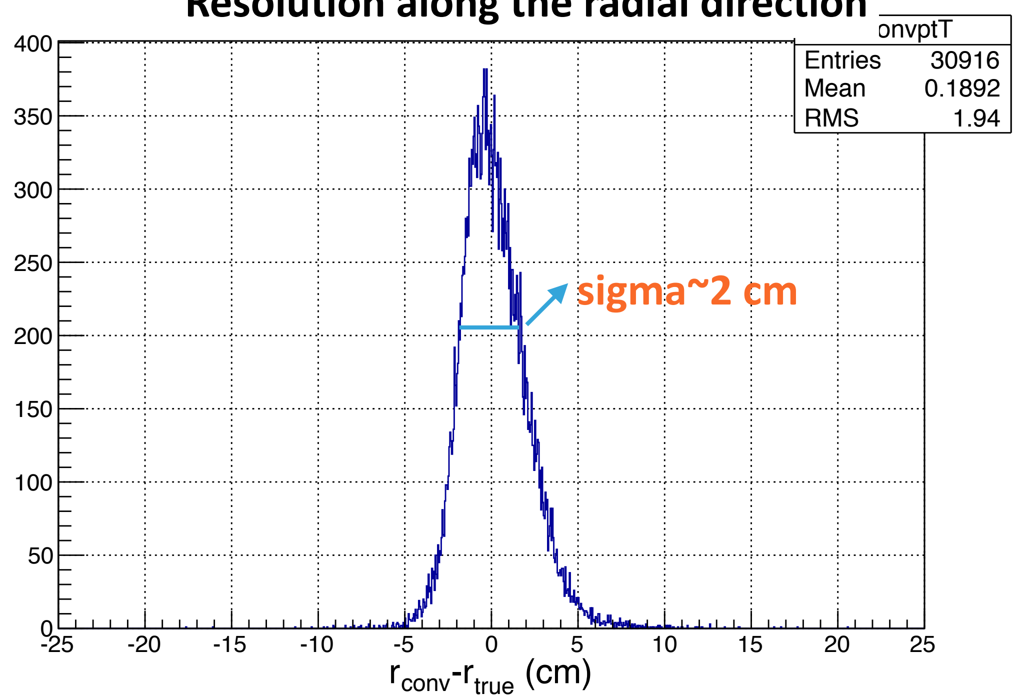
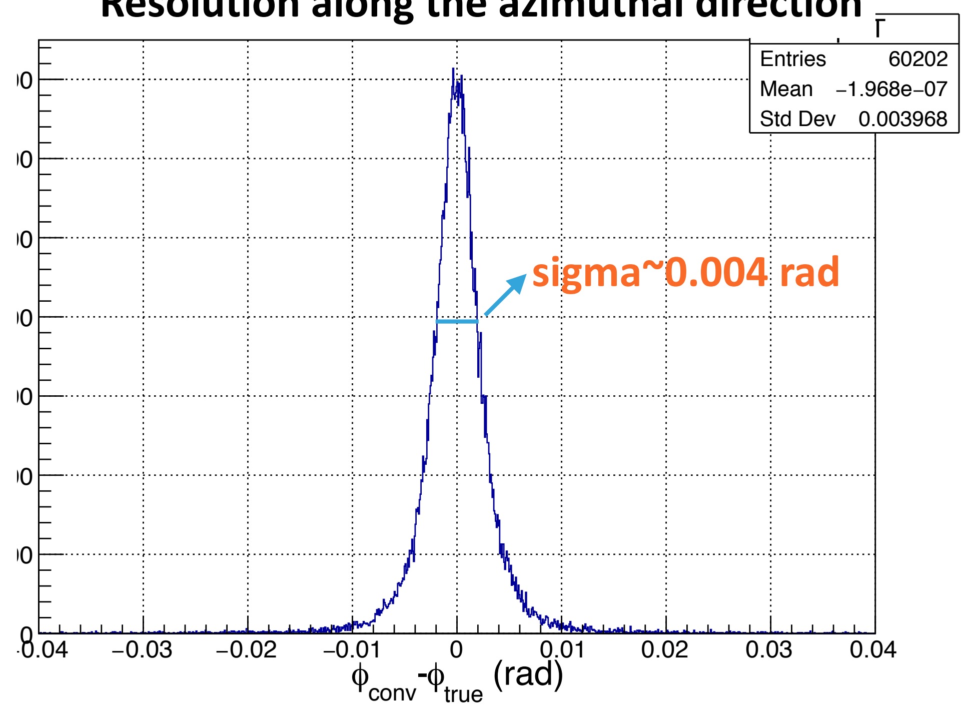
- **Identify and reconstruct photons via external conversion to e^+e^- pairs**
  - **Reconstruct conversion position using e^+e^- pair and magnetic field map**
  - **Track conversions back to its conversion position and reconstruct photon momentum**
  - **Other systems: <u>Au+Au</u>, Cu+Au, ^{3}He+Au, d+Au, p+Au, p+p**



Resolution along the radial direction



Resolution along the azimuthal direction



External conversion method

- **Double ratio tagging method (R_γ>1 indicating direct photon signal)**

Inclusive = Direct + Hadronic decay

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadron}} \longmapsto \gamma^{\text{direct}} = (R_\gamma - 1)\gamma^{\text{hadron}}$$

External conversion method

- **Double ratio tagging method (R_γ>1 indicating direct photon signal)**

$$R_\gamma = \frac{\gamma^{incl}}{\gamma^{hadron}} = \frac{\frac{\gamma^{incl}}{\gamma^{\pi^0}}}{\frac{\gamma^{hadron}}{\gamma^{\pi^0}}}$$

Detector efficiency and acceptance for the conversion photon cancel out in the ratio

$$\frac{N_\gamma^{incl} = \gamma^{incl} \cdot p_{conv} \cdot \epsilon_{e^+e^-} a_{e^+e^-}}{N_\gamma^{\pi^0 tag} = \gamma^{\pi^0} \cdot p_{conv} \cdot \epsilon_{e^+e^-} a_{e^+e^-} \cdot \langle \epsilon_\gamma f \rangle}$$

$$\frac{\gamma^{incl}}{\gamma^{\pi^0}} = \langle \epsilon f \rangle \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}}$$

External conversion method

- **Double ratio tagging method (R_γ>1 indicating direct photon signal)**

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

Reduce systematics!

Detector efficiency and acceptance for the conversion photon cancel out in the ratio

$$\frac{N_\gamma^{incl} = \gamma^{incl} \cdot \cancel{p_{conv}} \cdot \cancel{\epsilon_{e^+e^-}} \cancel{a_{e^+e^-}}}{N_\gamma^{\pi^0 tag} = \gamma^{\pi^0} \cdot \cancel{p_{conv}} \cdot \cancel{\epsilon_{e^+e^-}} \cancel{a_{e^+e^-}} \cdot \langle \epsilon_\gamma f \rangle}$$

$$\frac{\gamma^{incl}}{\gamma^{\pi^0}} = \langle \epsilon f \rangle \frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}}$$

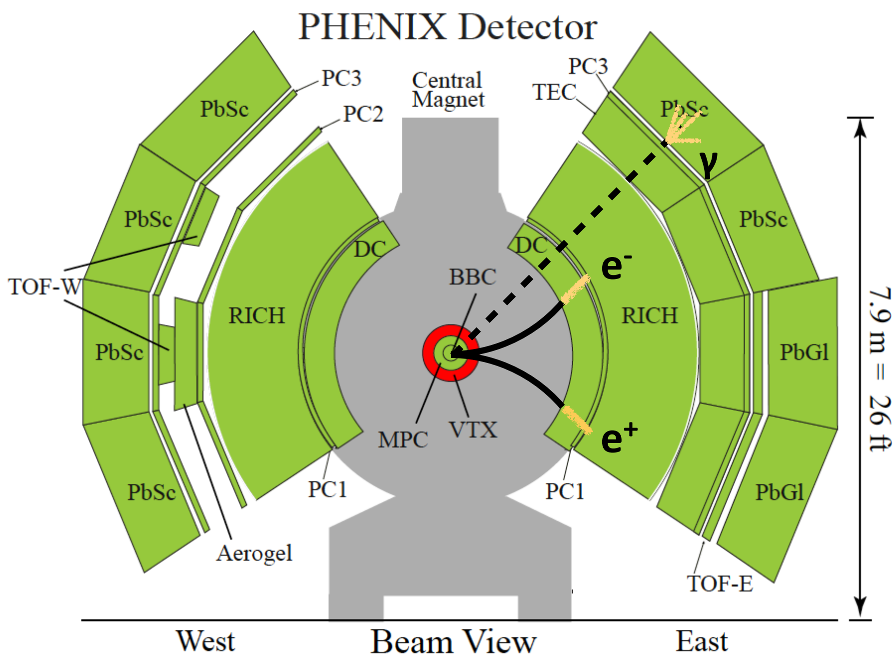
External conversion method

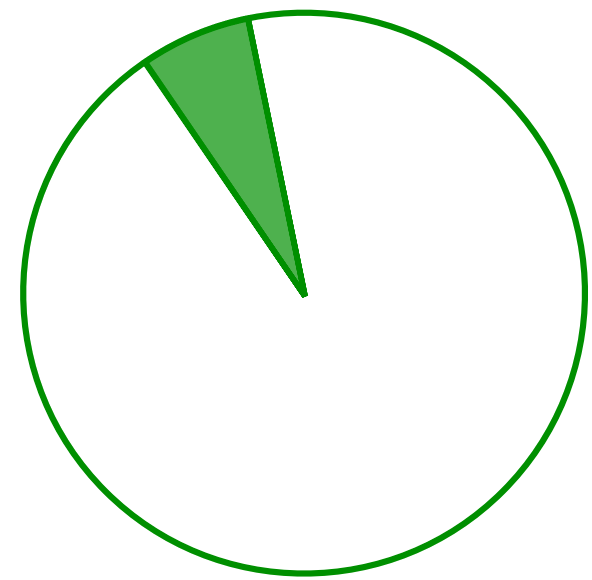
- Double ratio tagging method (R_γ>1 indicating direct photon signal)

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

Raw counts

- N^{incl}/N^{tag} from real data: # of conversion photons/# of conversion photons tagged as coming from π^0





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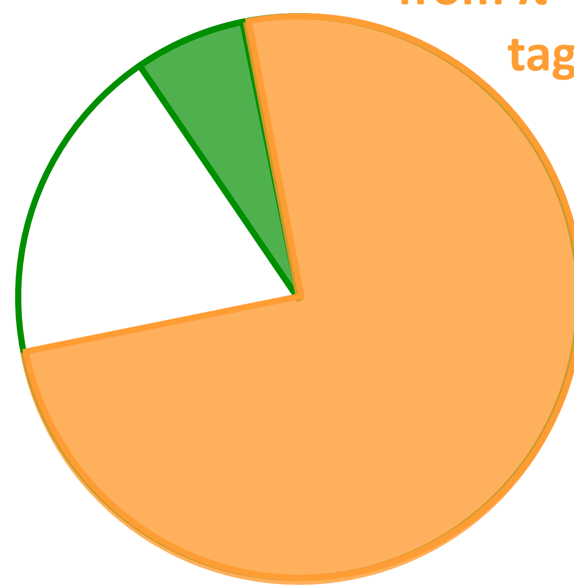
Raw counts

❖ N^{incl}/N^{tag} from real data: # of conversion photons/# of conversion photons tagged as coming from π^0

Correct for detector effects

❖ Conditional acceptance and efficiency: the acceptance for the second photon in the EMCal from π^0 decay given that we already reconstructed the first photon from a conversion pair



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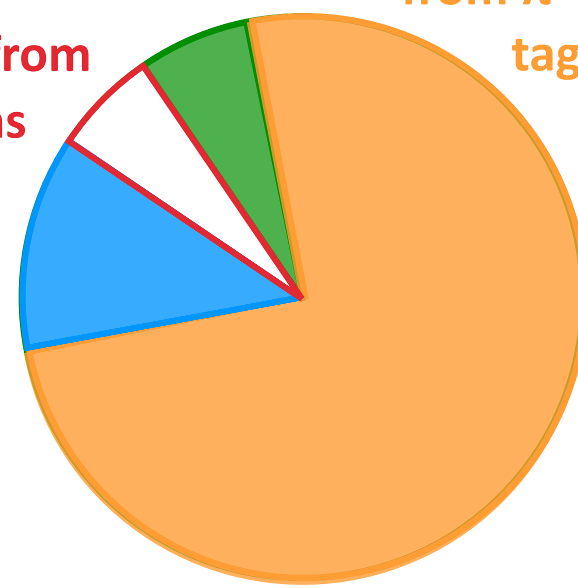
<u>Correct for other background sources</u>

❖ Cocktail ratio (other sources of decay photons)



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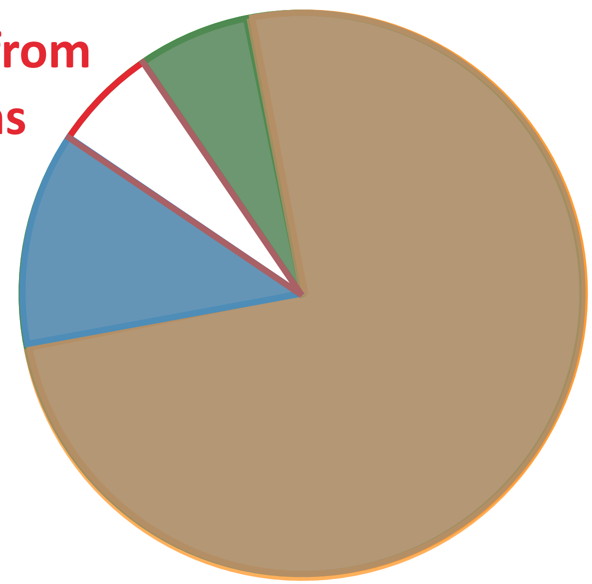

$$\langle \epsilon f \rangle \left(\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}}\right)_{Data} \left(\frac{\gamma^{hadron}}{\gamma^{\pi^0}}\right)_{Sim}$$

Experimental details — N^{incl}/N^{tag}

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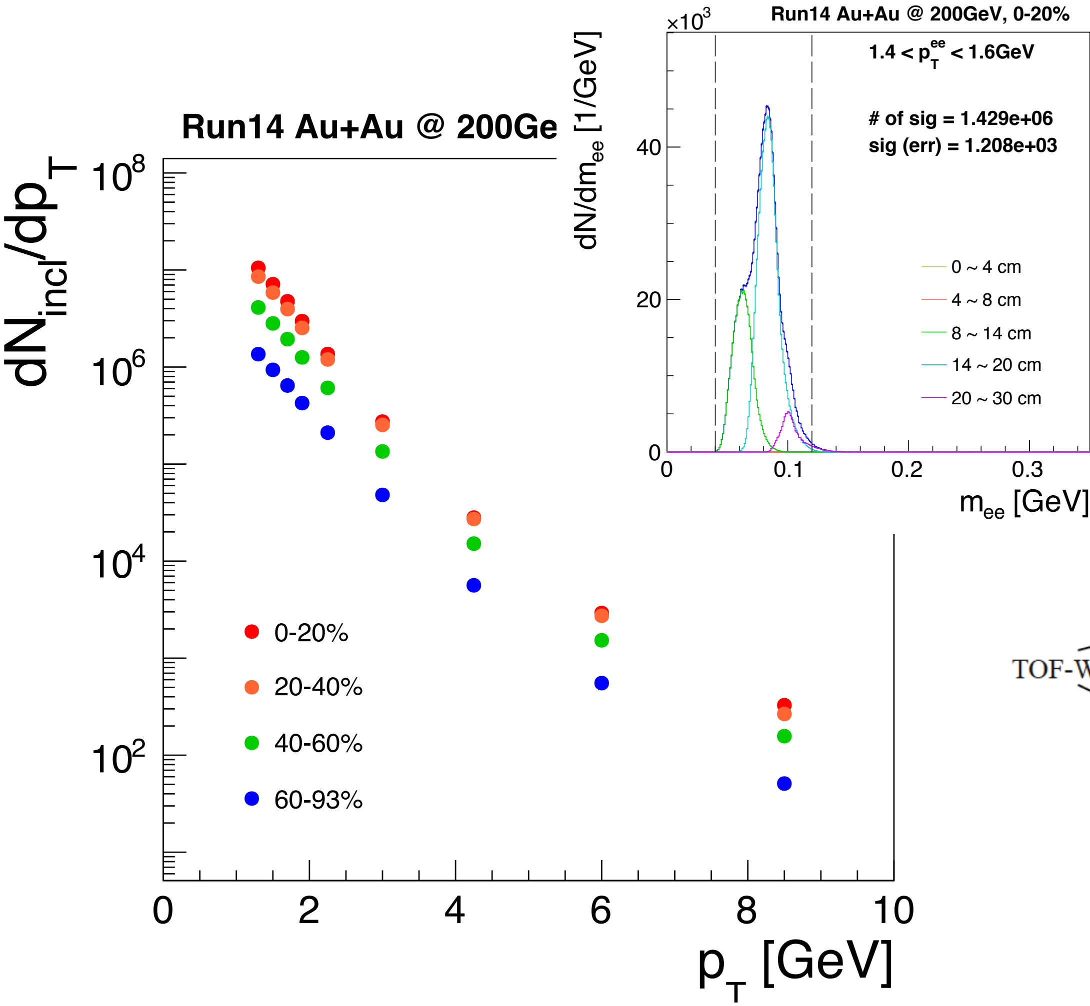

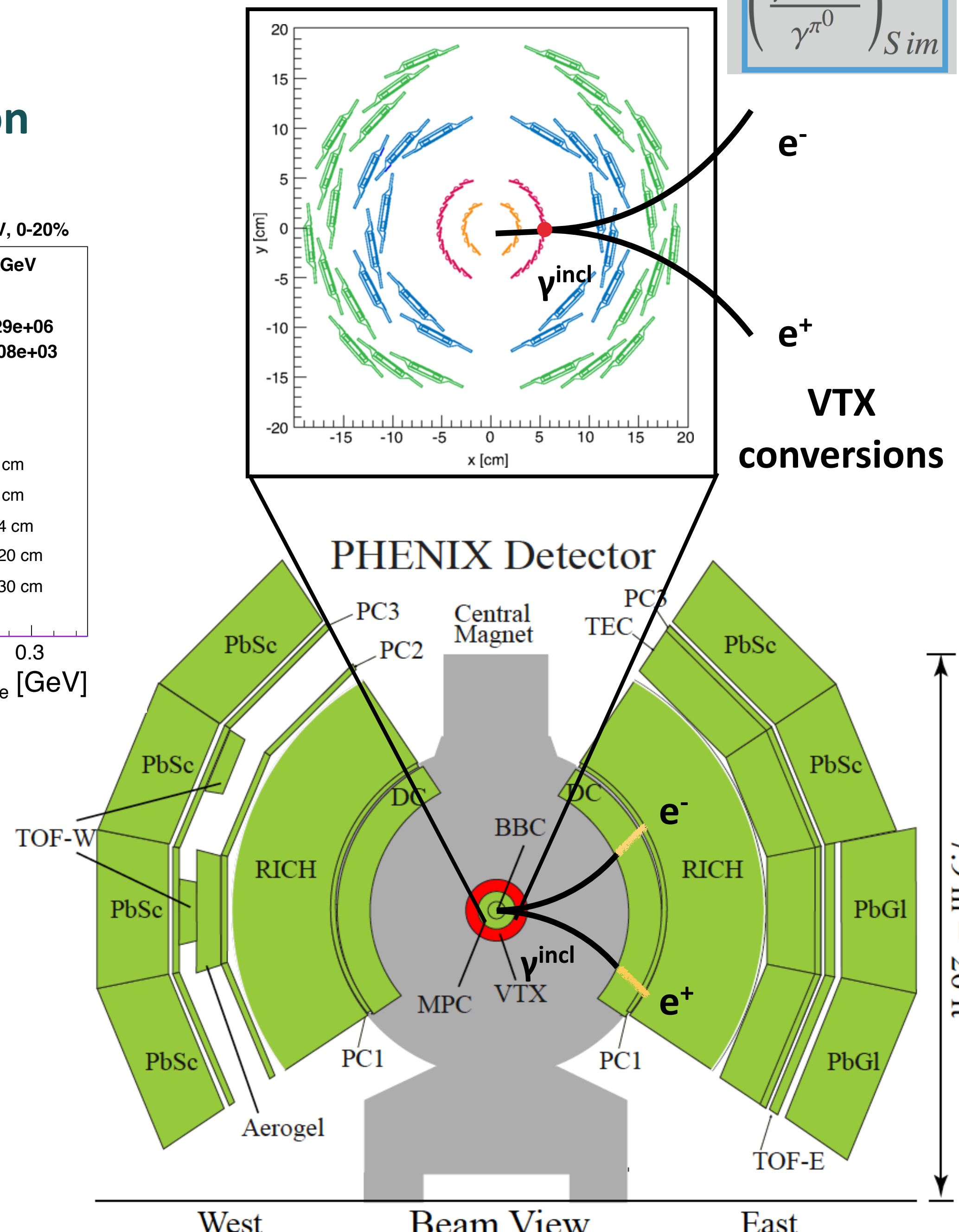

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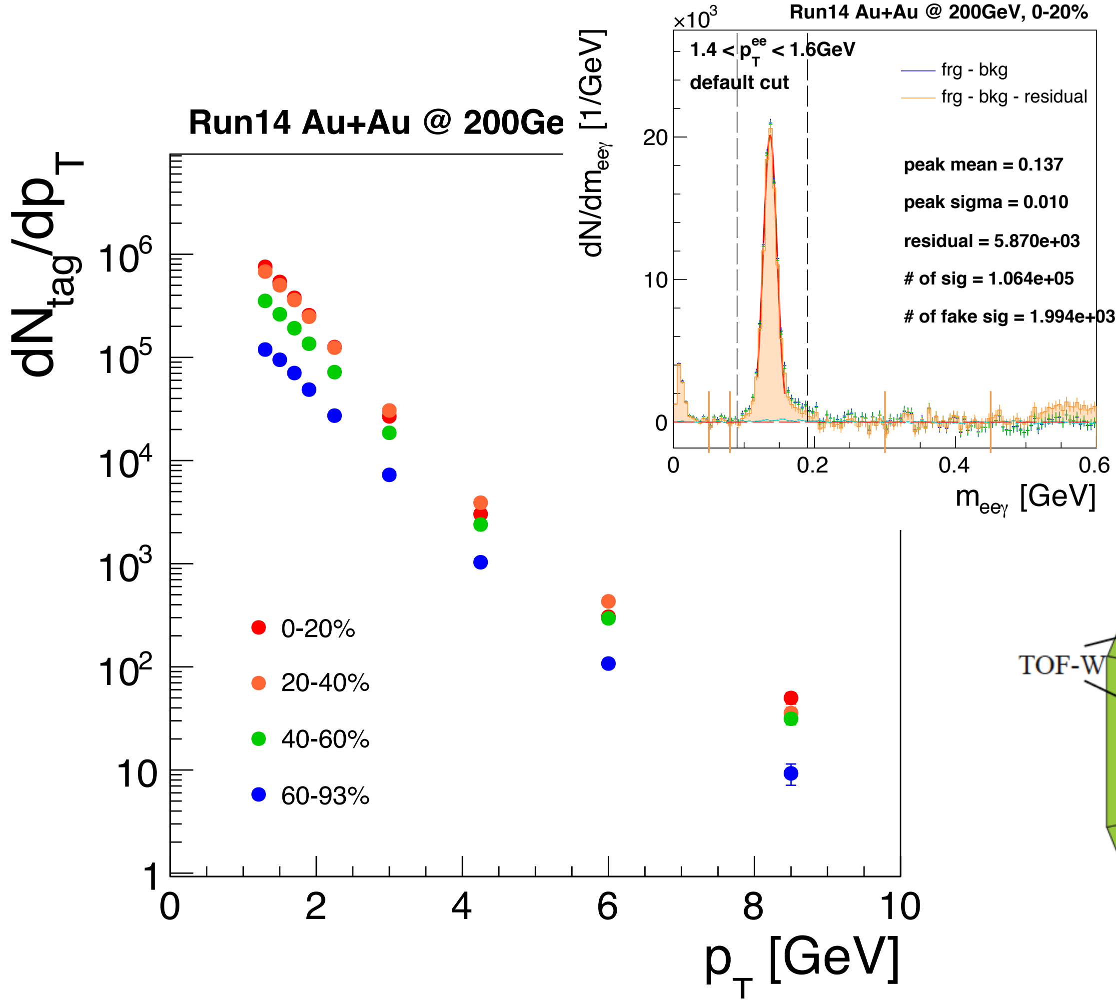
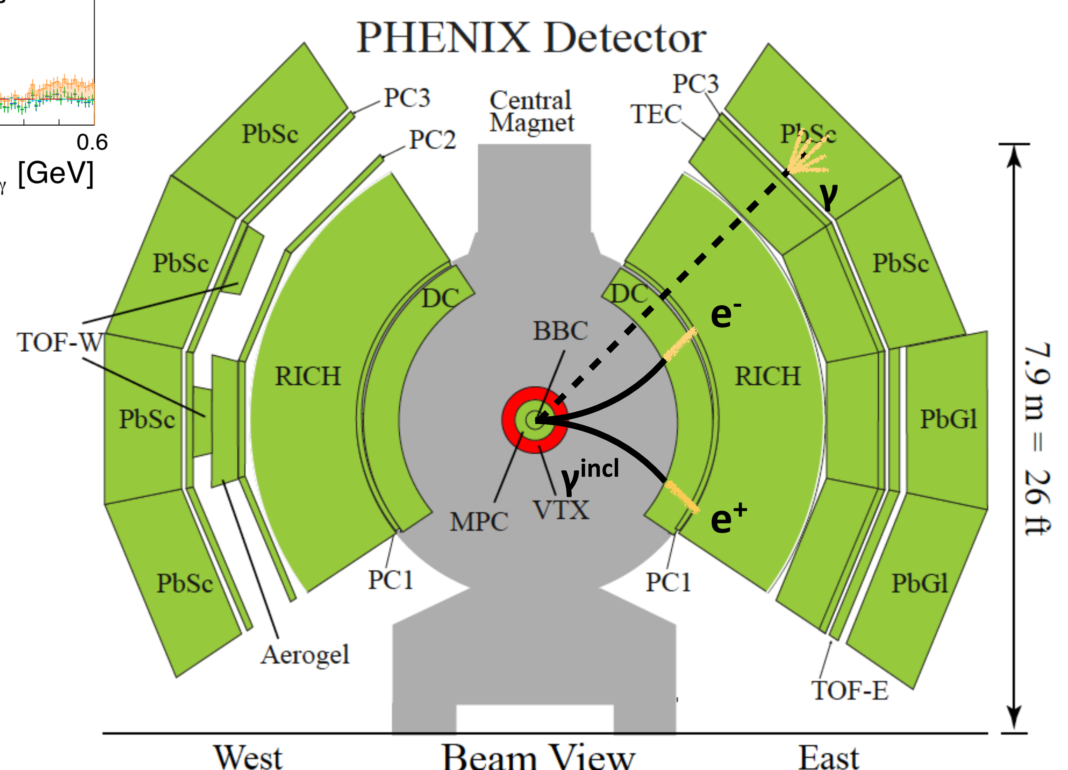
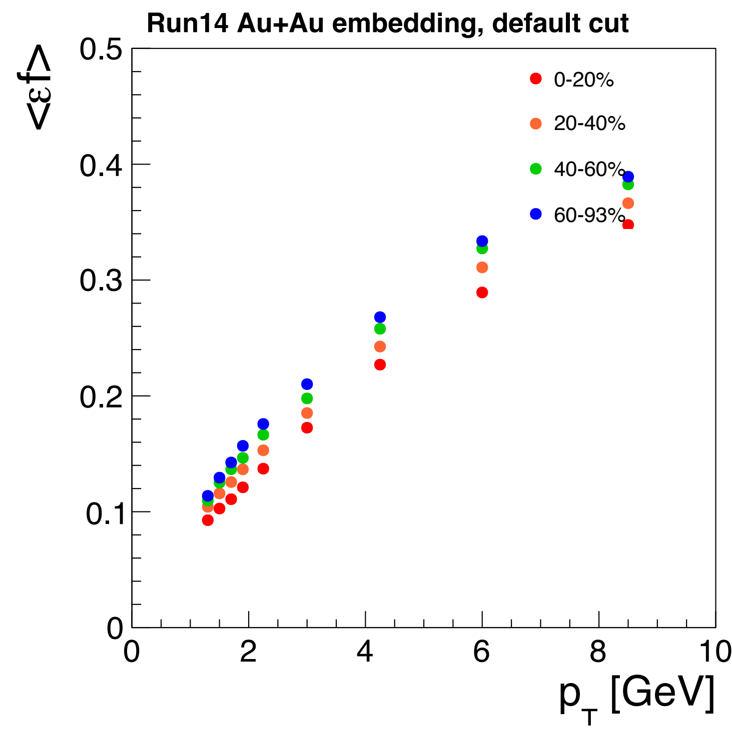




Experimental details — $\langle \varepsilon f \rangle$

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

Event generation	**single π^0 events**
Simulated detector response to input particles	**Decays, multiple scattering, bremsstrahlung, pair production (photon conversion), etc**
Detector response correction	**Scale/smear EMCal energy response** **Embed into EMCal tower signals from real data**
PHENIX Reconstruction	**Charged tracks + associated PID variables** **EMCal clusters**
Analysis module	**$e^{+/-}$ track selection** **conversion pair selection** **EMCal cluster selection (e.g. E_{min}>500MeV, shower shape)**



$$\langle \varepsilon f \rangle = \frac{N^{tag}\text{: reconstructed } \pi^0\text{s from } e^+e^-\gamma}{N^{incl}\text{: reconstructed conversion photons from } e^+e^-}$$

Experimental details — cocktail ratio

$$\langle \epsilon f \rangle \left(\frac{N_\gamma^{incl}}{N_\gamma^{\pi^0}} \right)_{Data}$$

$$\left(\frac{\gamma^{hadron}}{\gamma^{\pi^0}} \right)_{Sim}$$

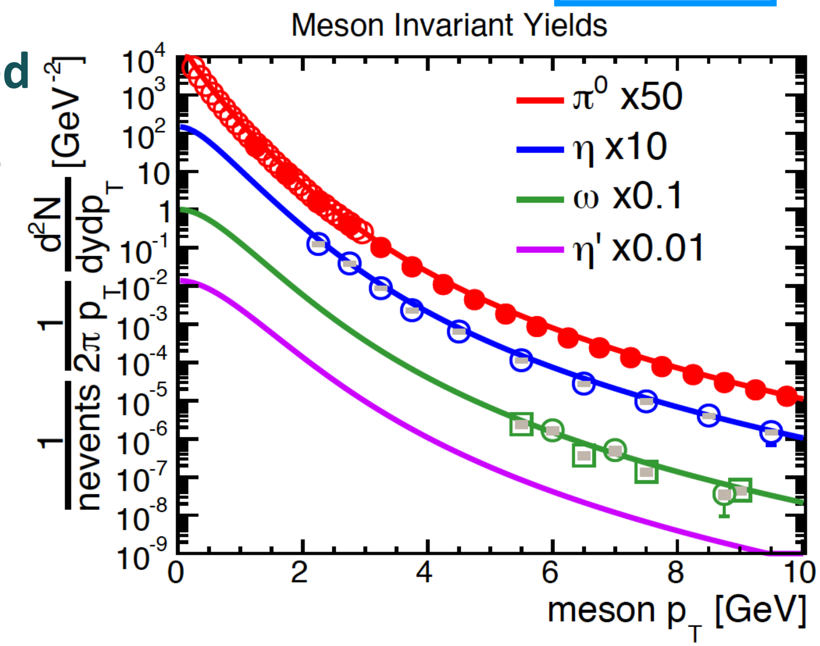
- **Cocktail ratio (other sources of decay photons)**
  - π^0 accounts for ~80% of all decay photons observed
  - Use measured spectra or m_T scaling for heavier mesons contributing to decay photons

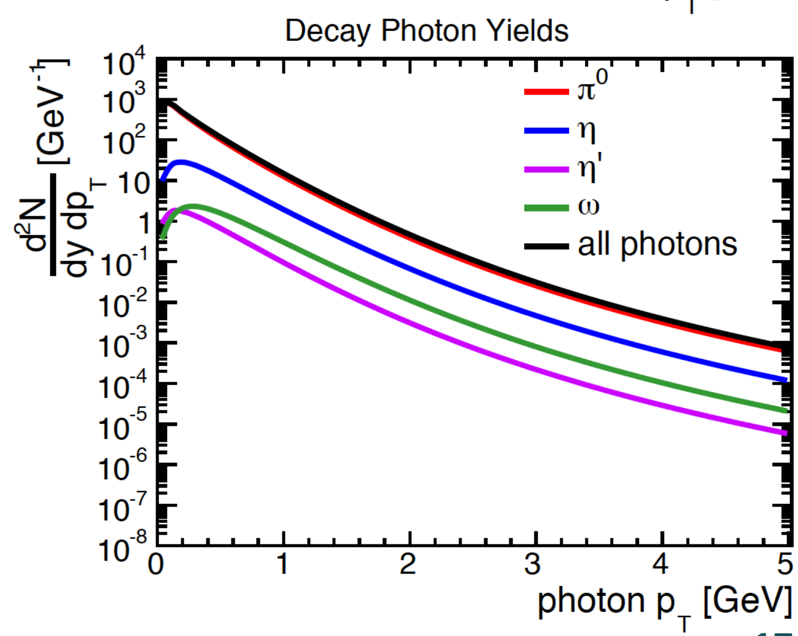
$$m_T = \sqrt{p_T^2 + m^2}$$

decay kinematics

+

parent particle	decay products	branching ratio
π^0	$\gamma\gamma$	98.8%
η	$\gamma\gamma$	39.3%
η	$\pi^+\pi^-\gamma$	4.6%
η'	$\gamma\gamma$	2.1%
η'	$\pi^+\pi^-\gamma$	23.0%
η'	$\omega\gamma$	2.8%
ω	$\pi^0\gamma$	8.3%





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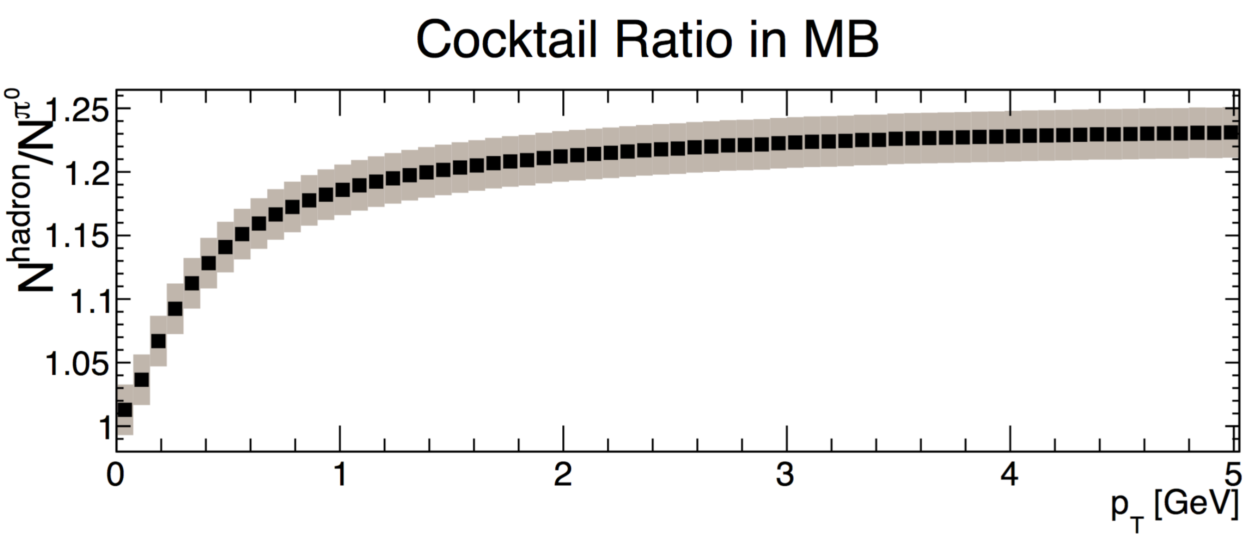

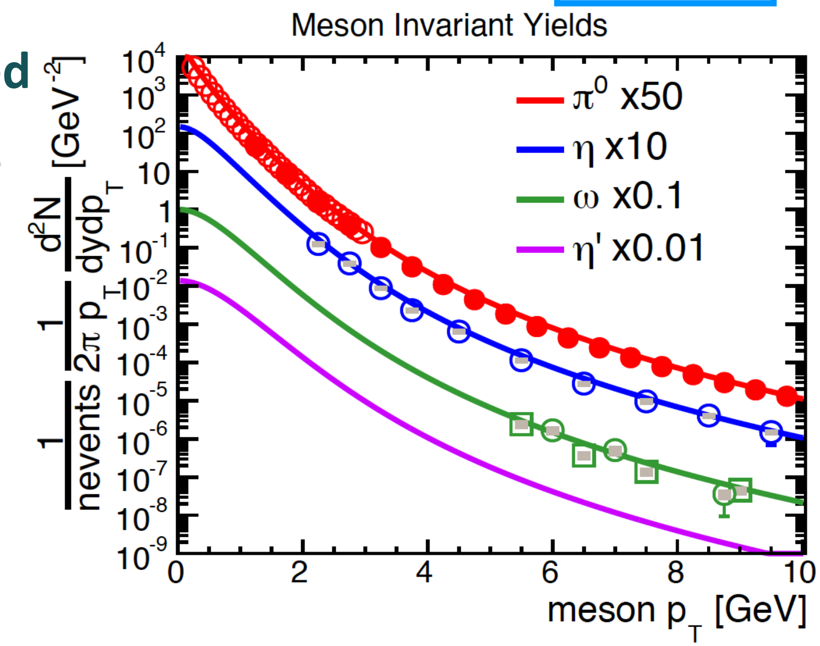

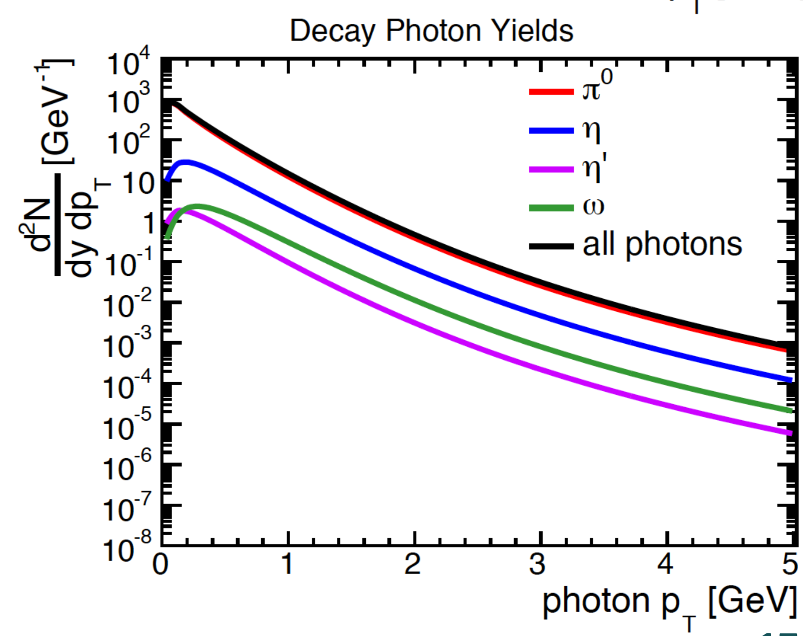

Systematic uncertainty on R_γ

- **N^{incl}/N^{tag} from real data:**
  - N^{tag} (π^0) extraction (~2%)
  - Conversion sample purity (<1%)
- **Conditional acceptance and efficiency:**
  - Energy scale and resolution (3%)
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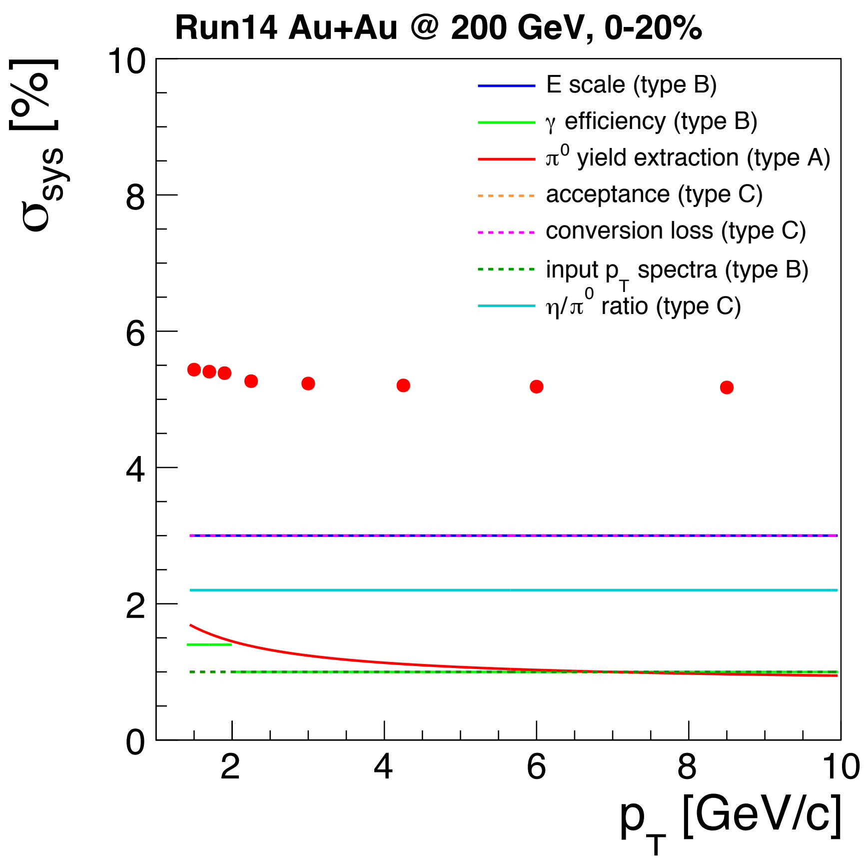

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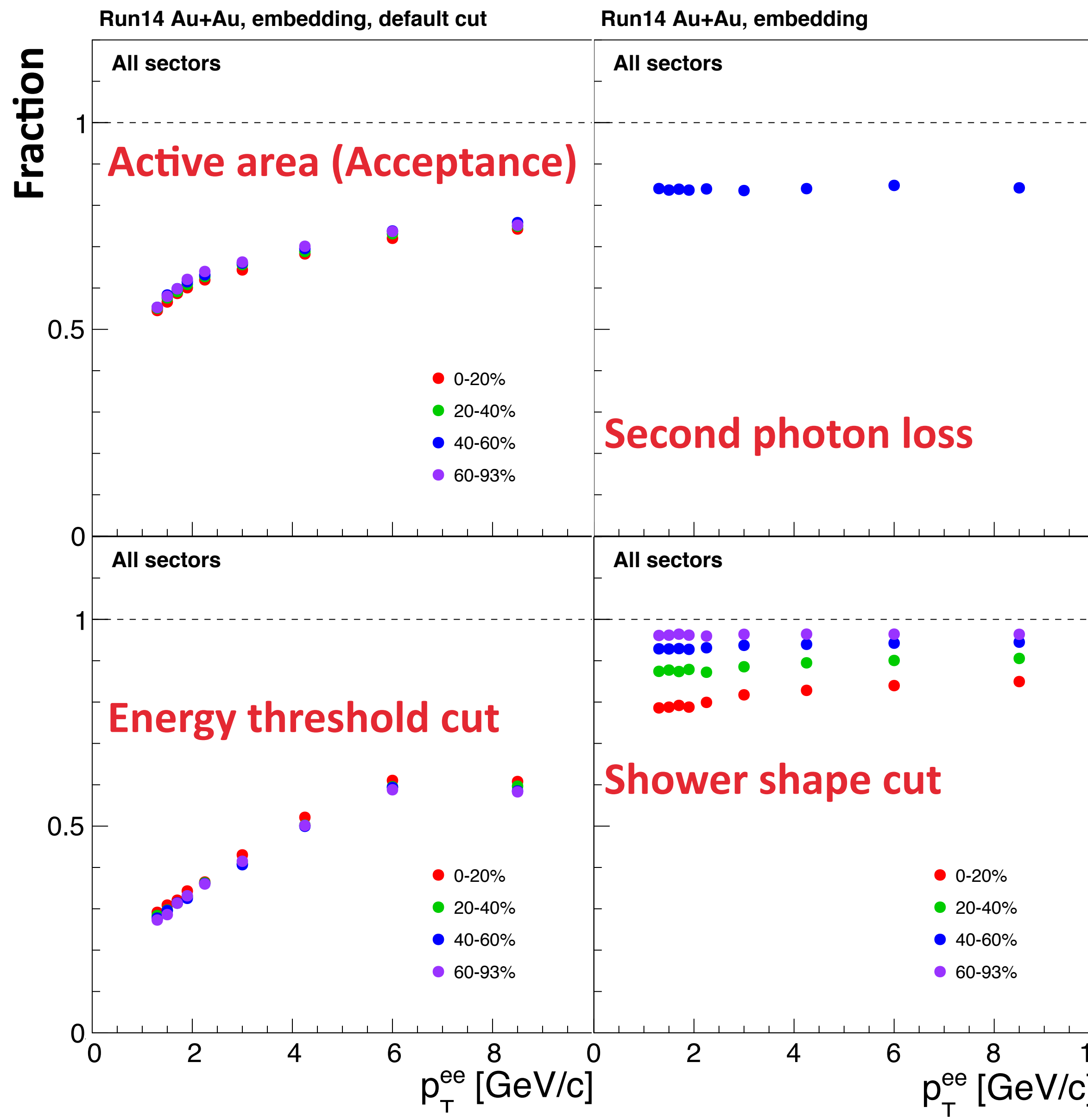

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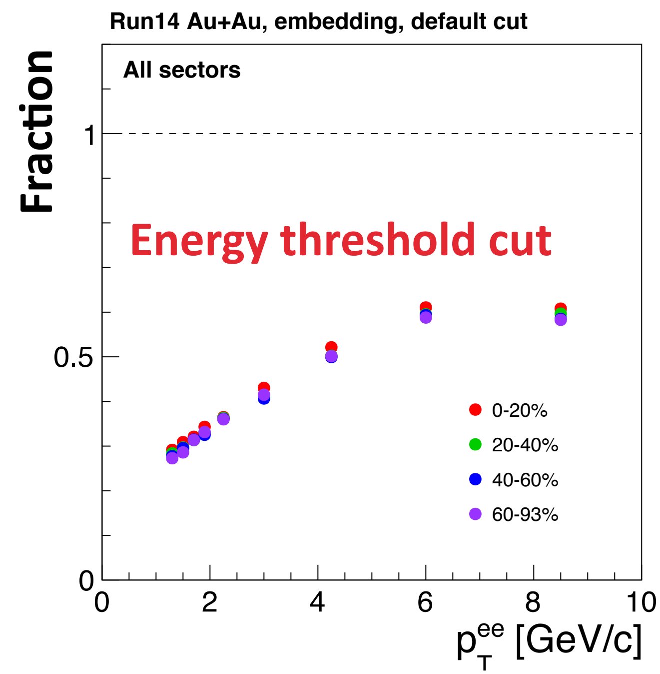

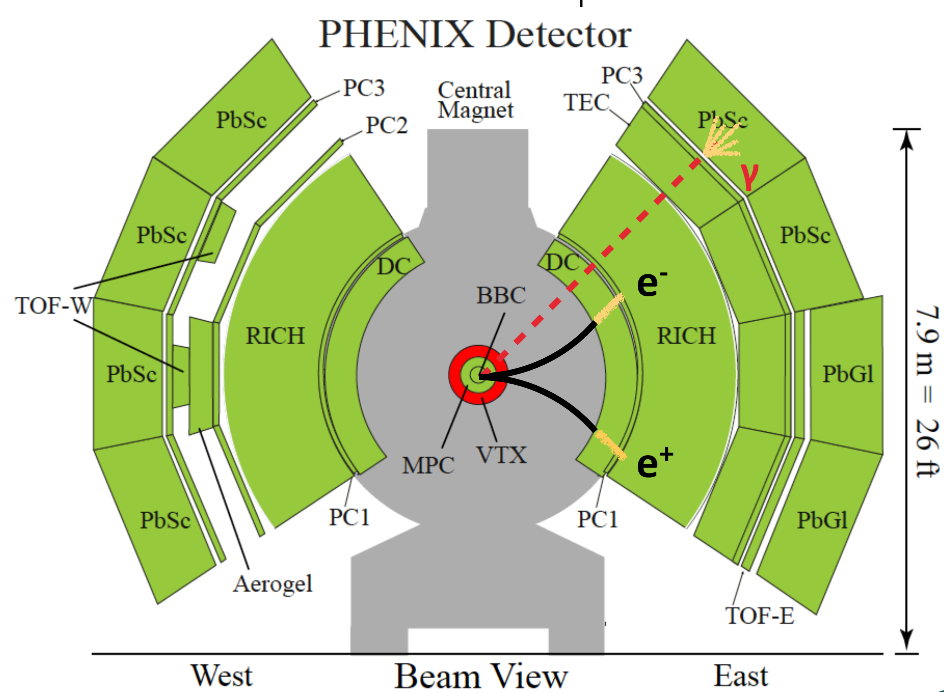

Systematic uncertainty on Rγ — energy scale

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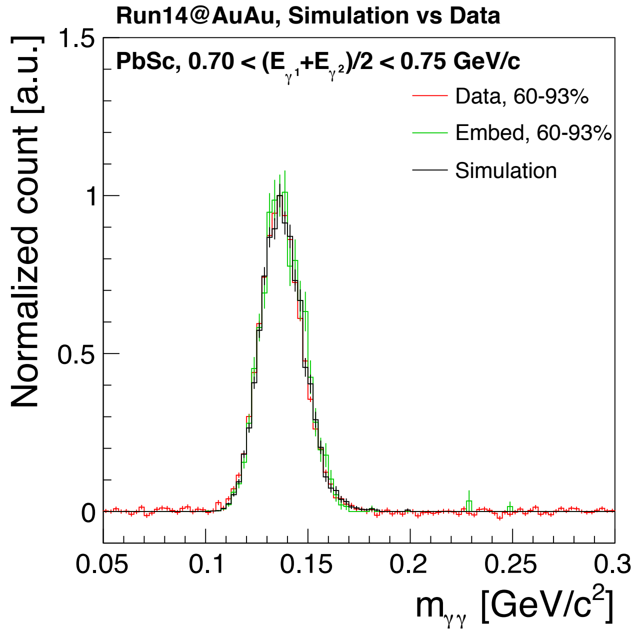

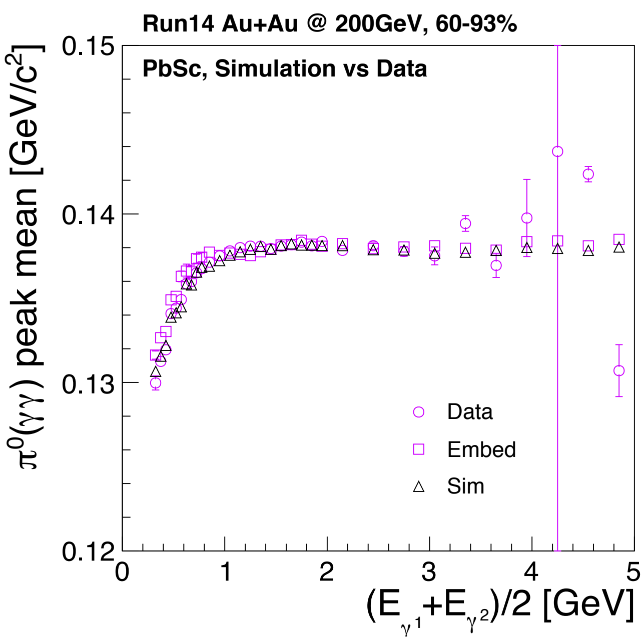

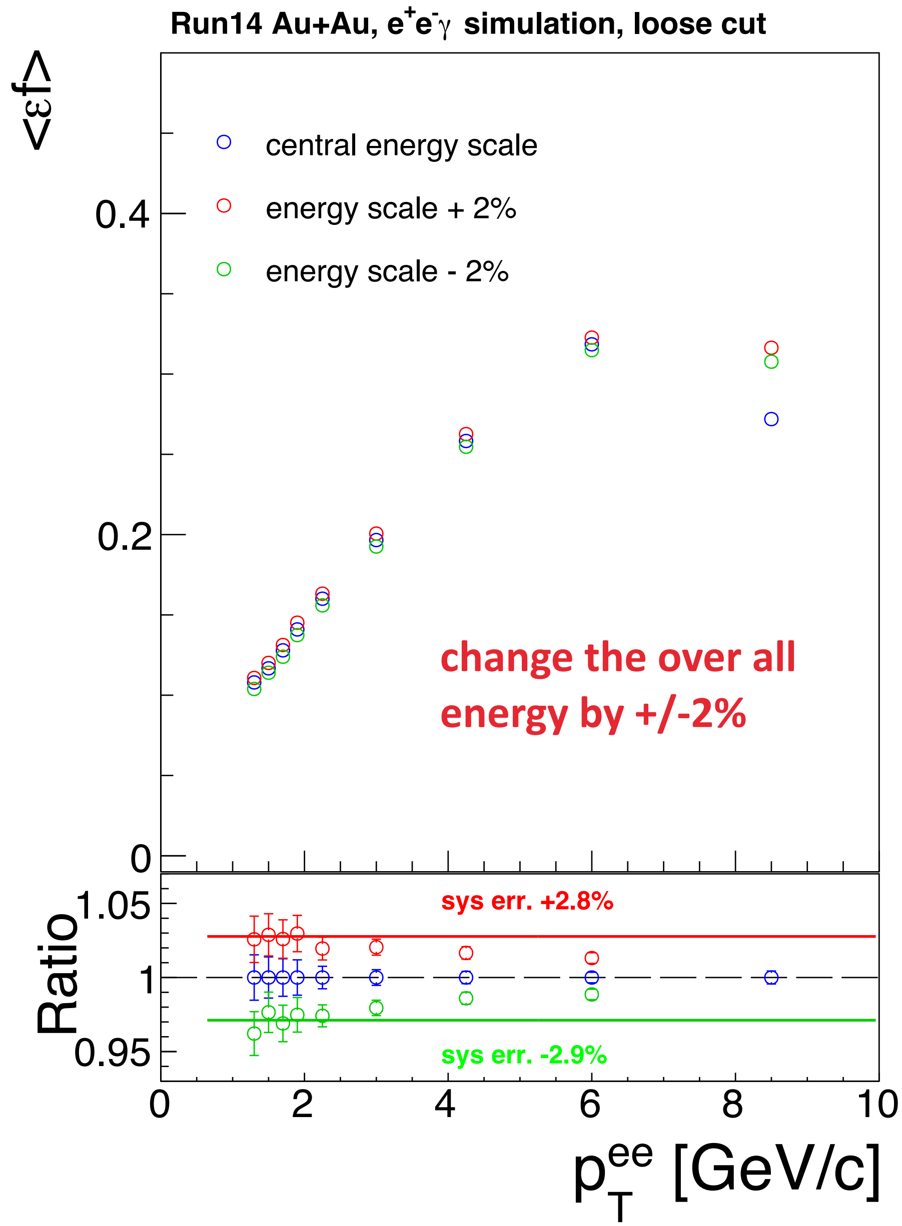

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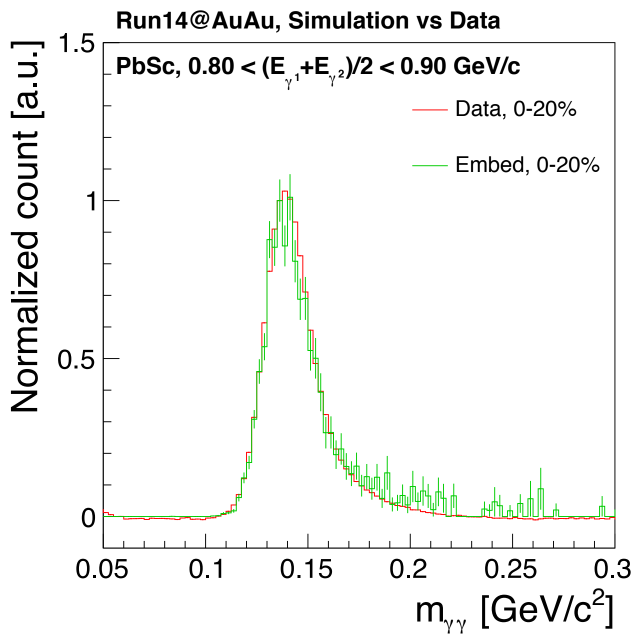

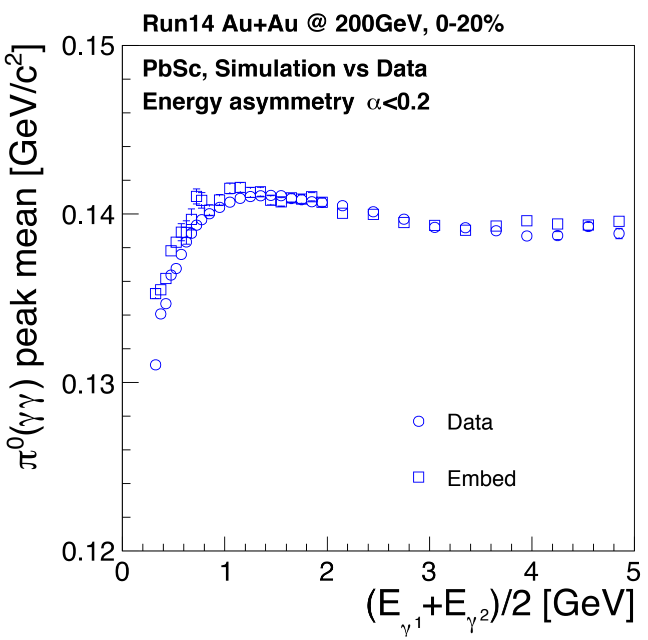

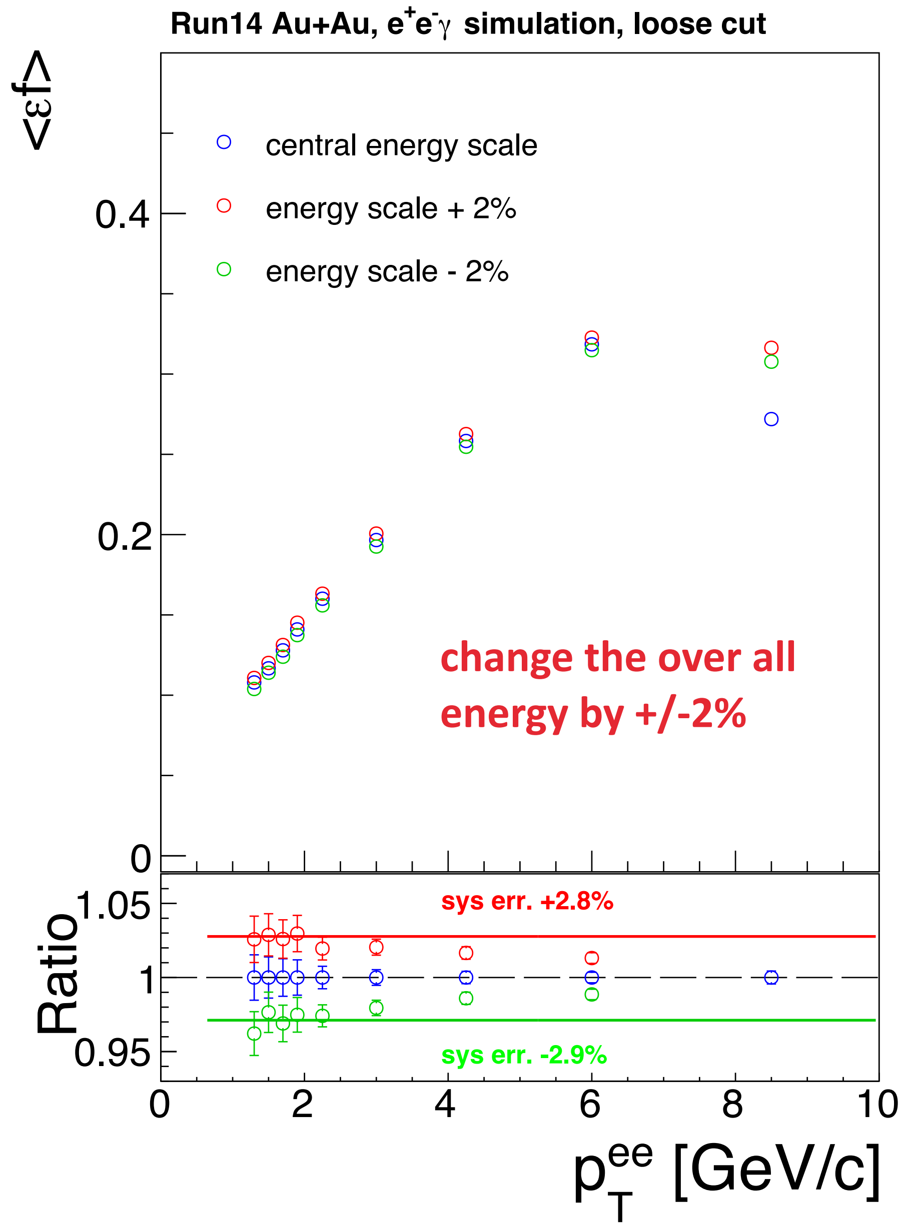

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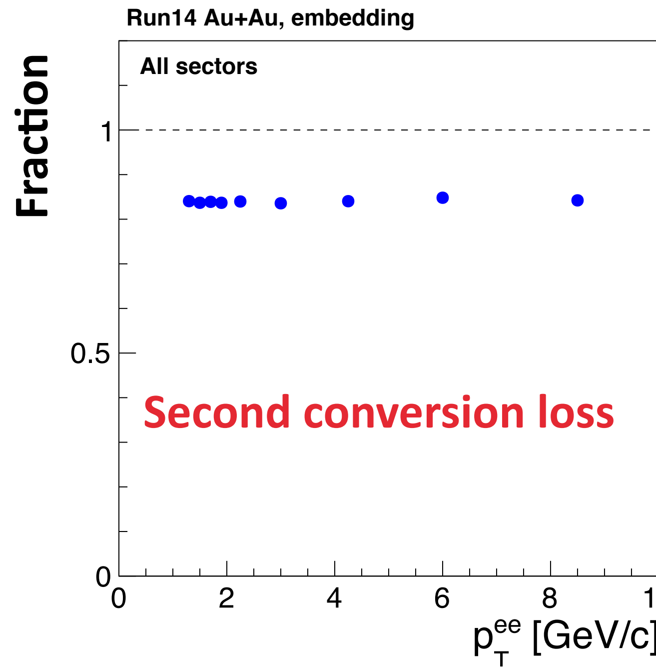

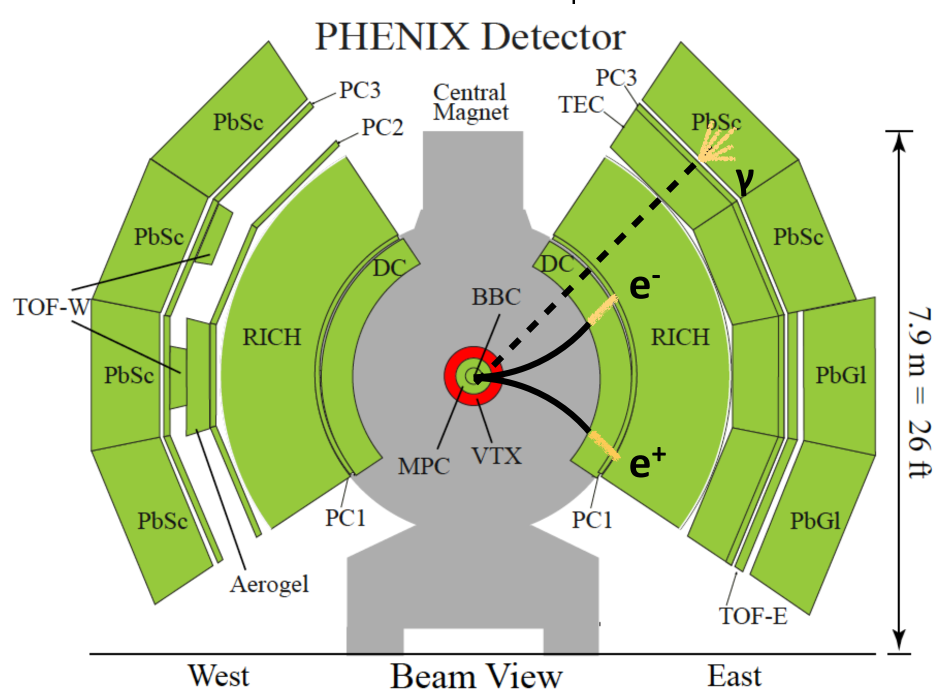

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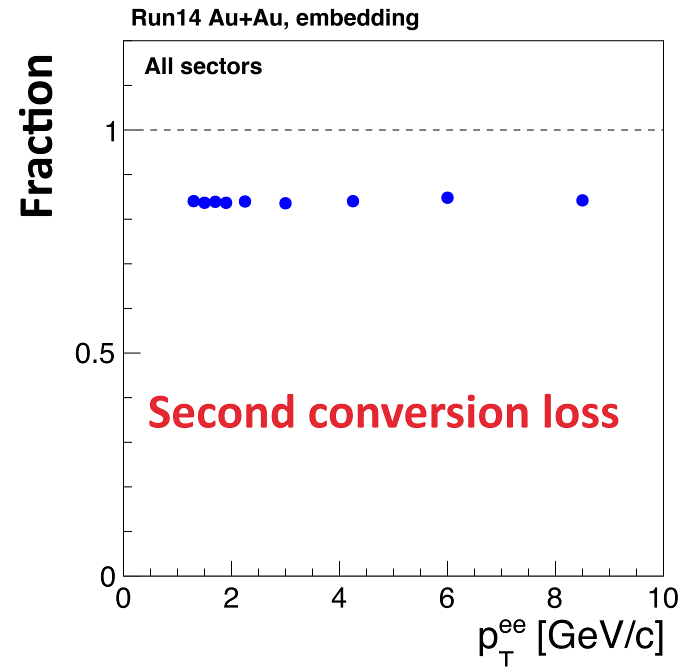

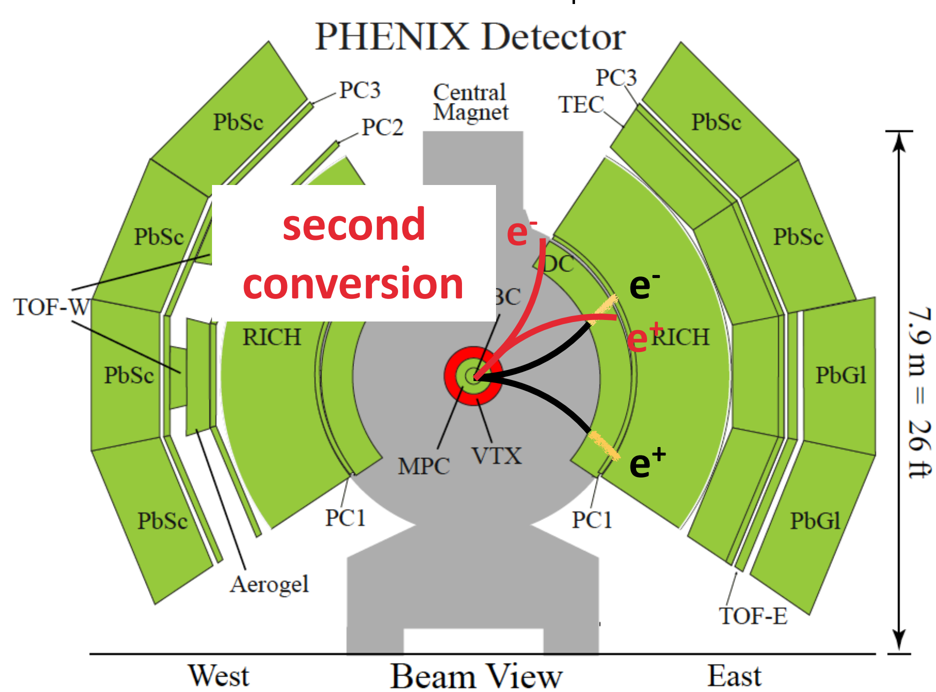

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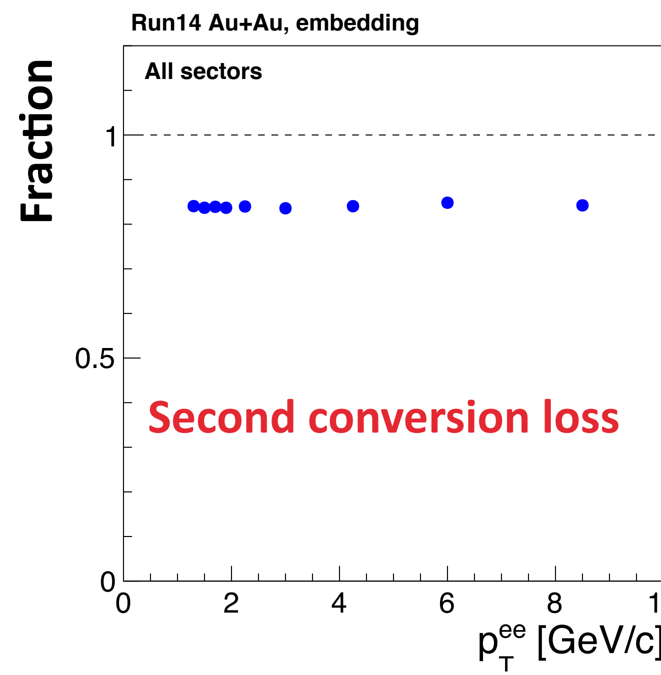

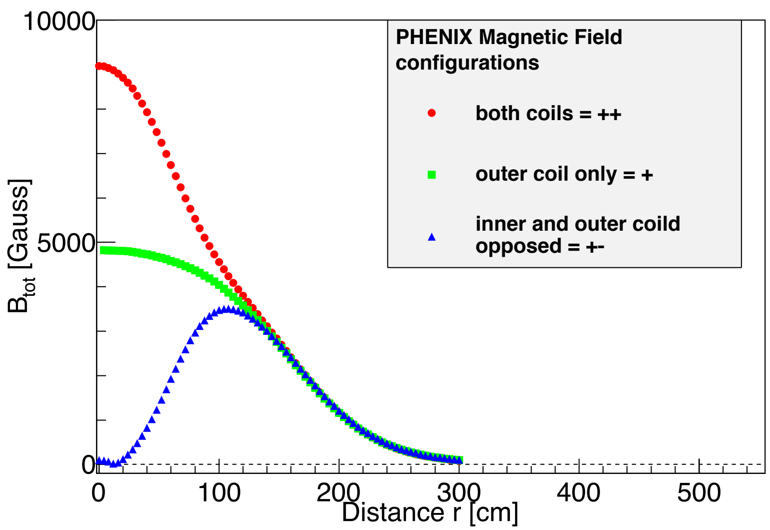

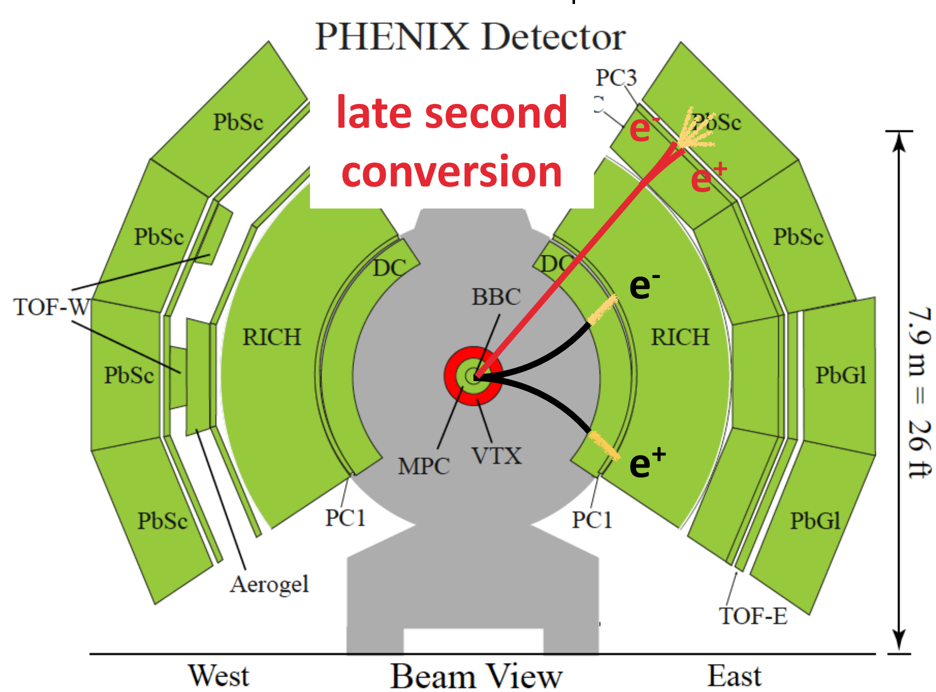

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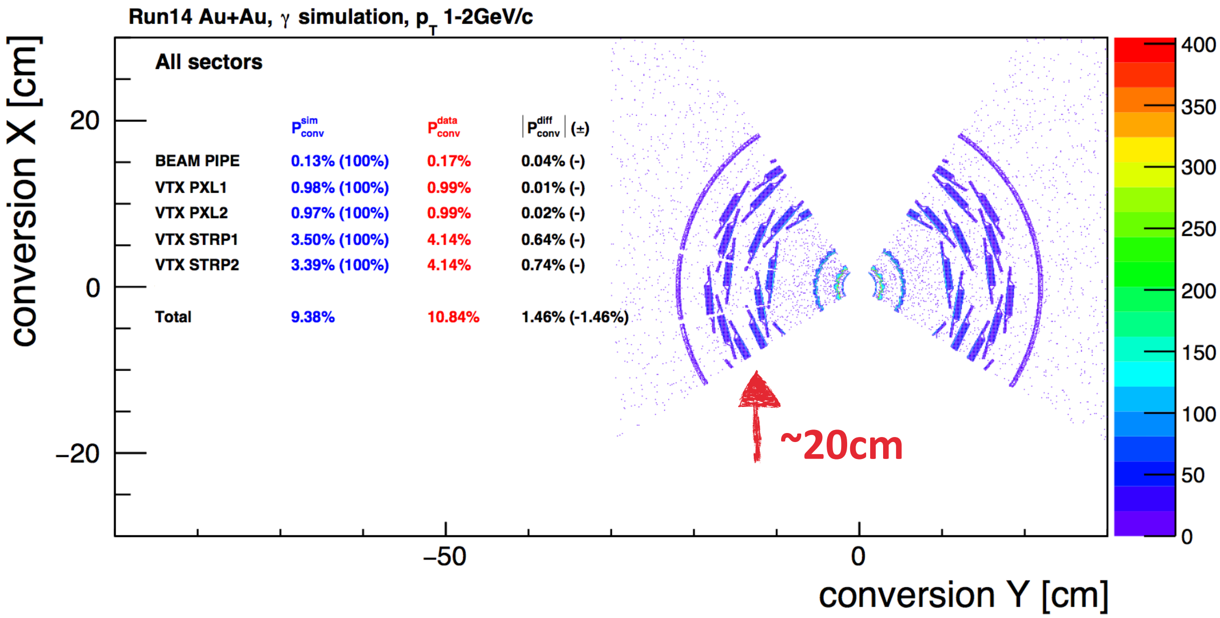
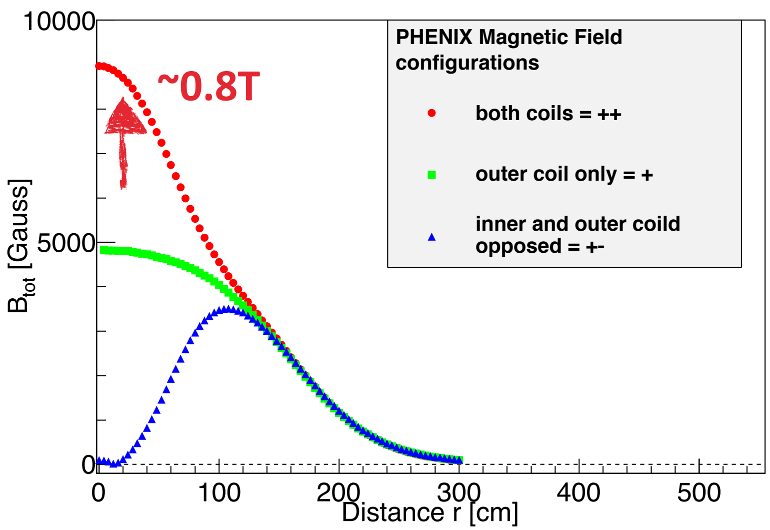
- **Use single γ simulation to check the conversion probability / radiation length**

$$p_{conv} = 1 - exp(-\frac{7}{9}X/X_0)$$





Systematic uncertainty on Rγ — material budget

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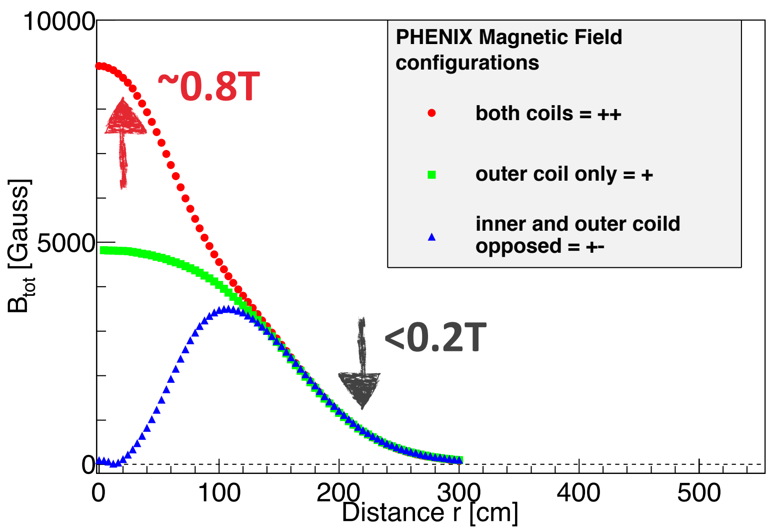
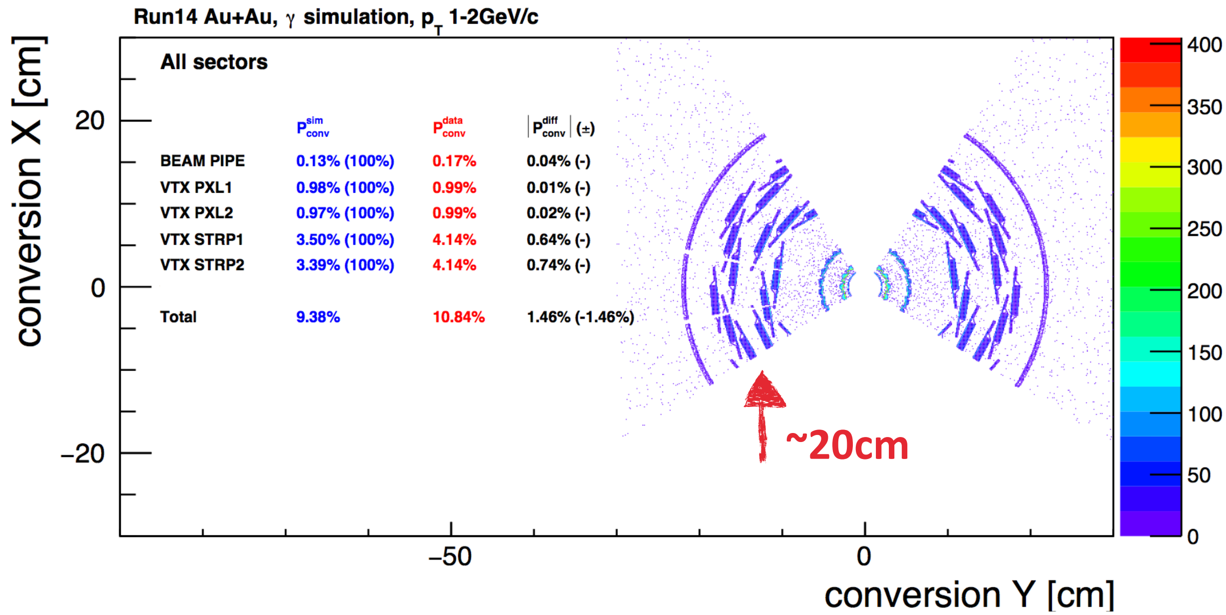
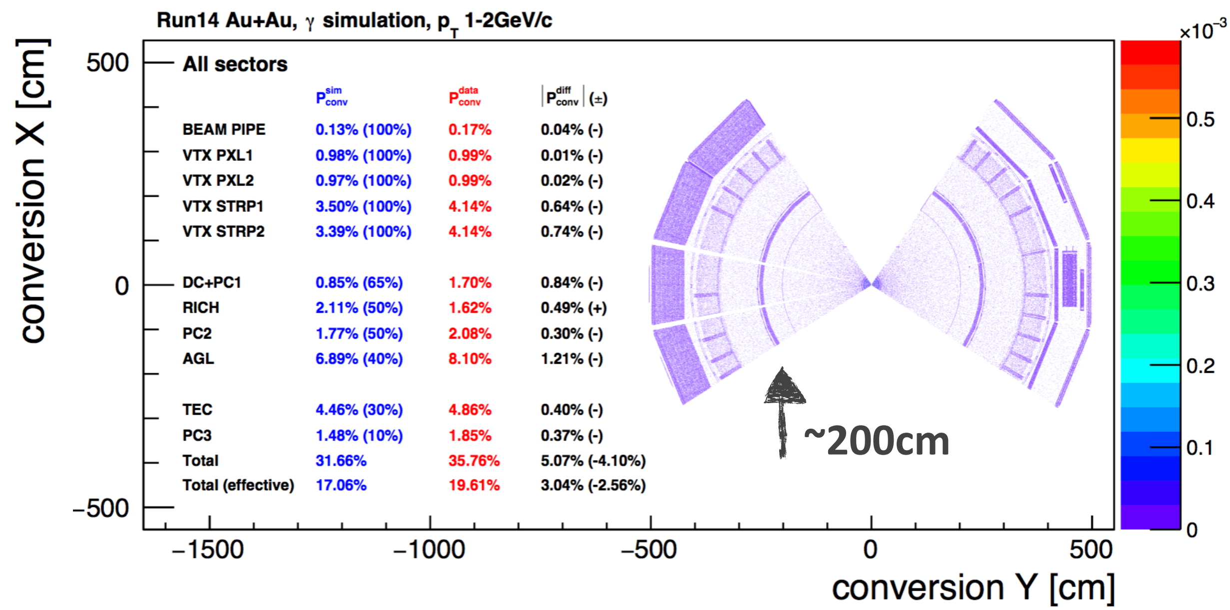
$$p_{conv} = 1 - exp(-\frac{7}{9}X/X_0)$$

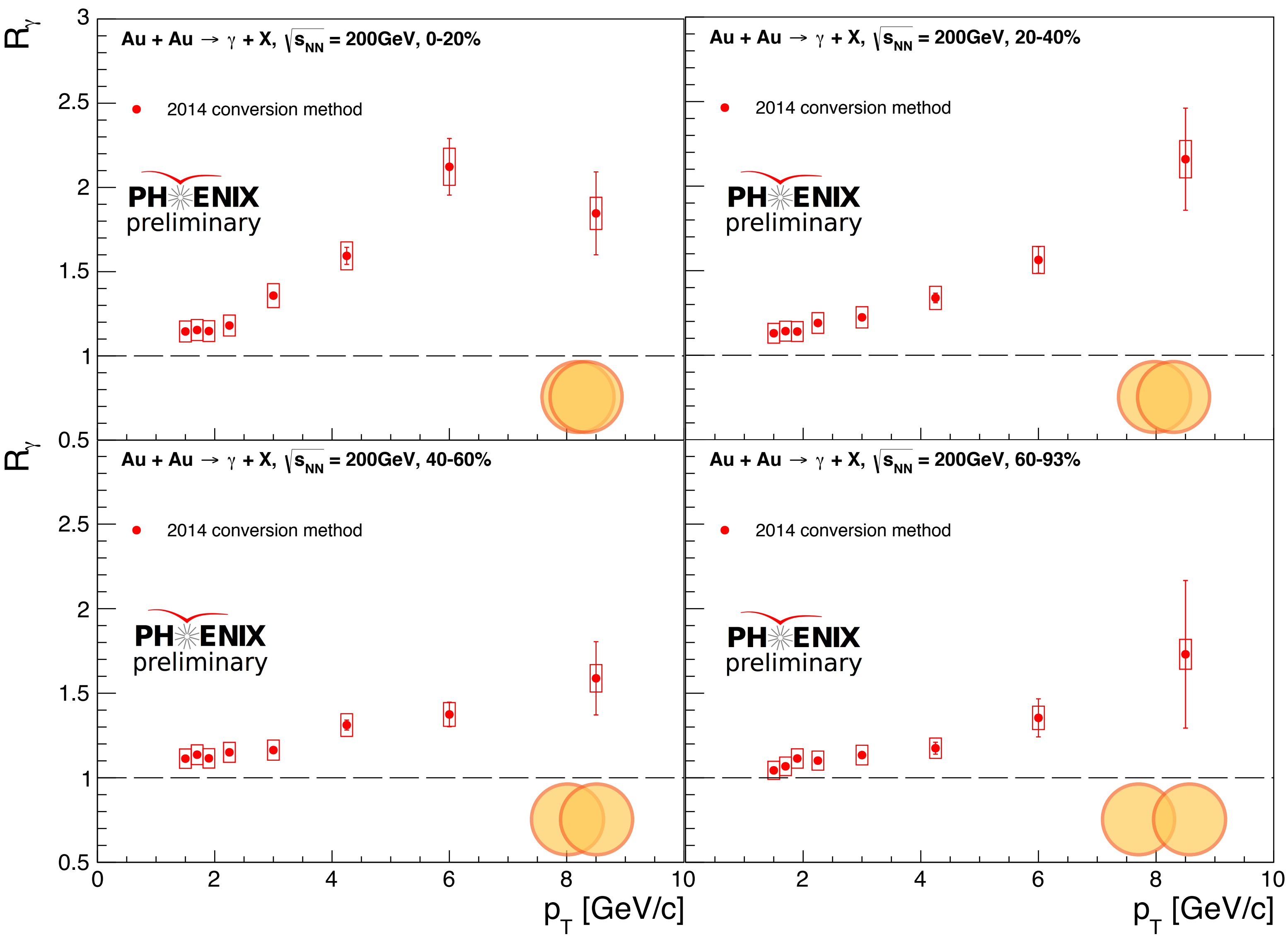
- Conversions at small magnetic field will merge into the same cluster will be reconstructed as photon





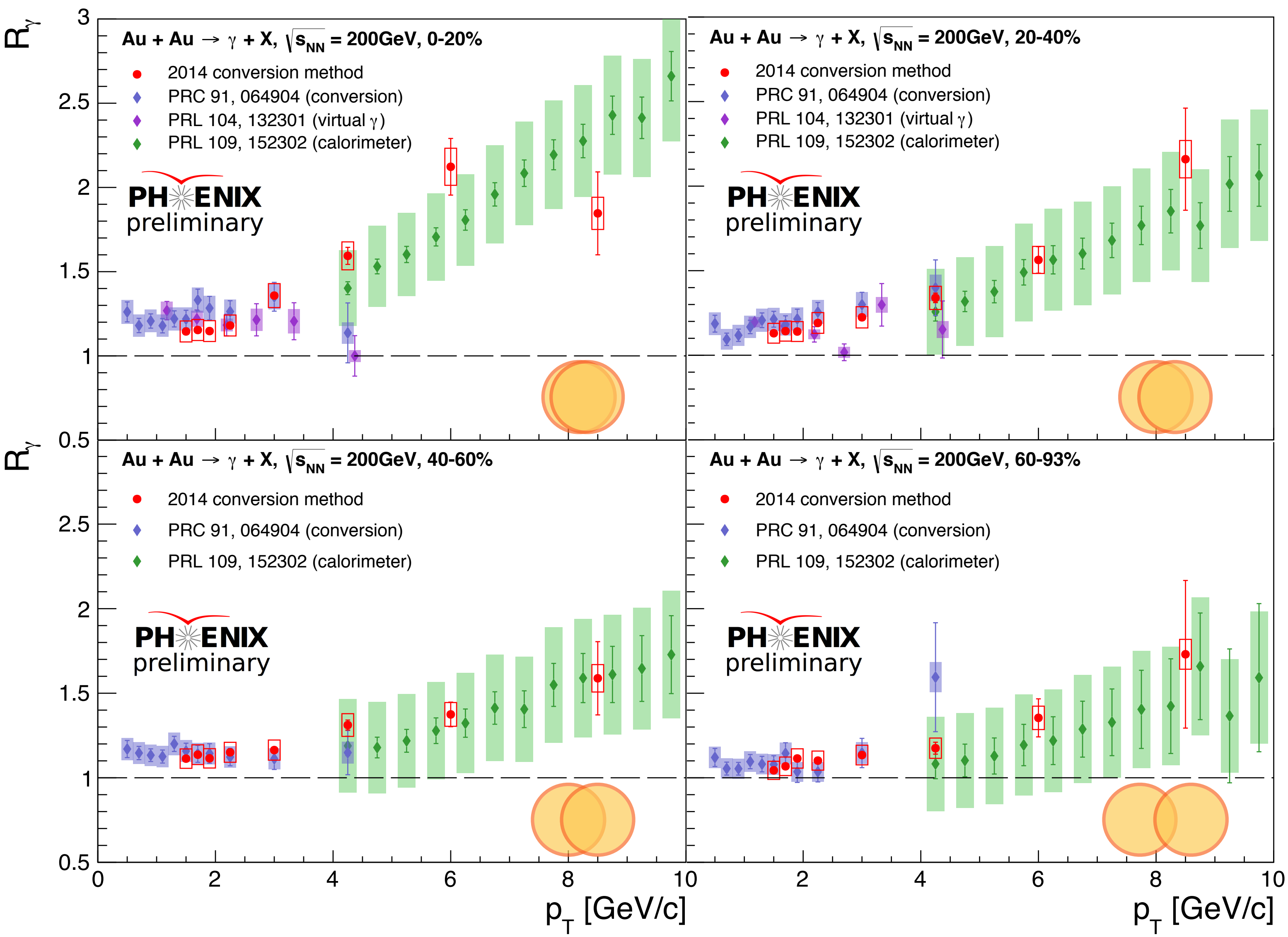


Direct photons in Au+Au collisions



A new measurement with improved statistical precision

Direct photons in Au+Au collisions



A new measurement with improved statistical precision

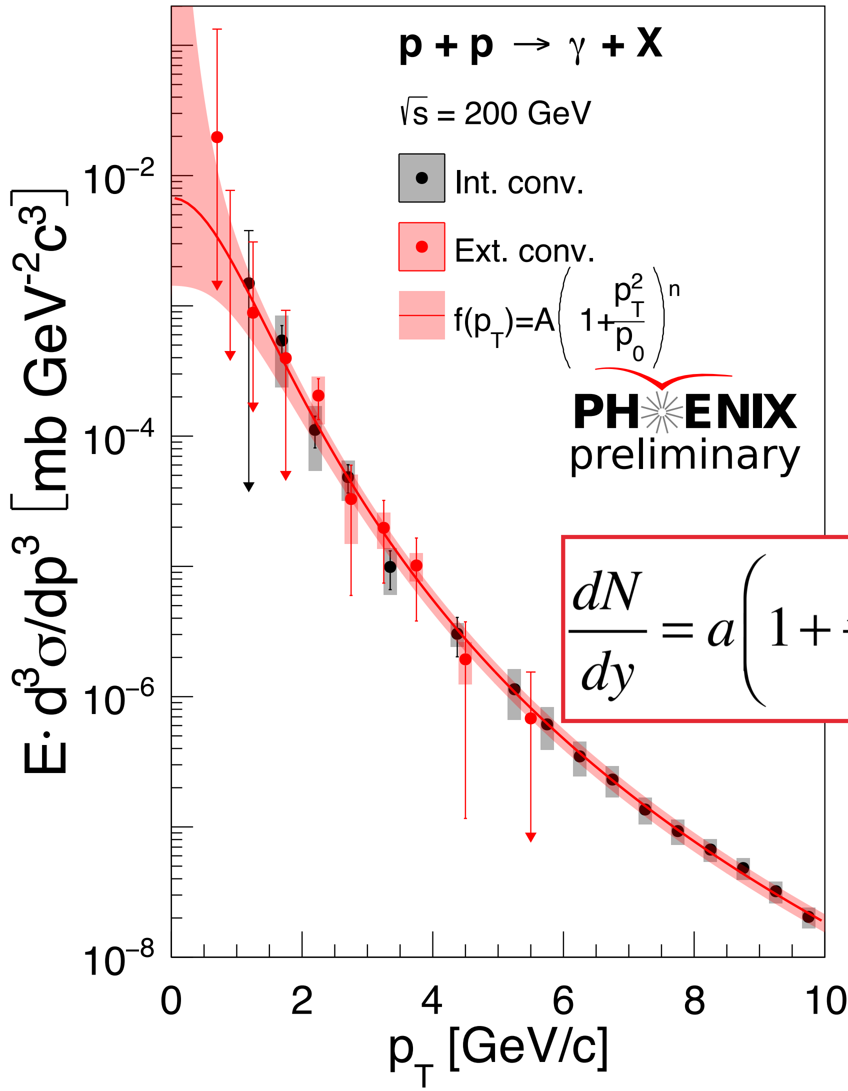
Consistent with previous published results using conversion method, virtual γ method, calorimeter method

Full overlap with the published low p_T and high p_T measurements

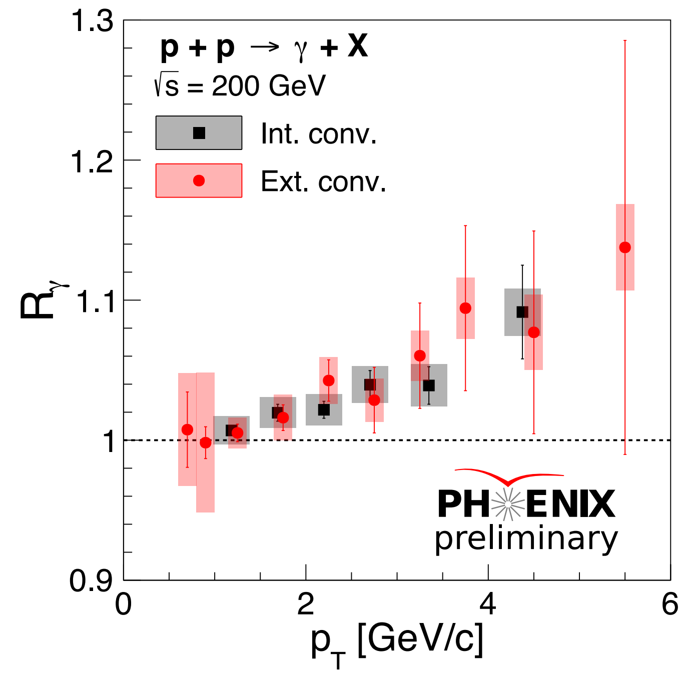
Prompt photons in p+p collisions

- New measurement of R_γ in p+p at 200GeV

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



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

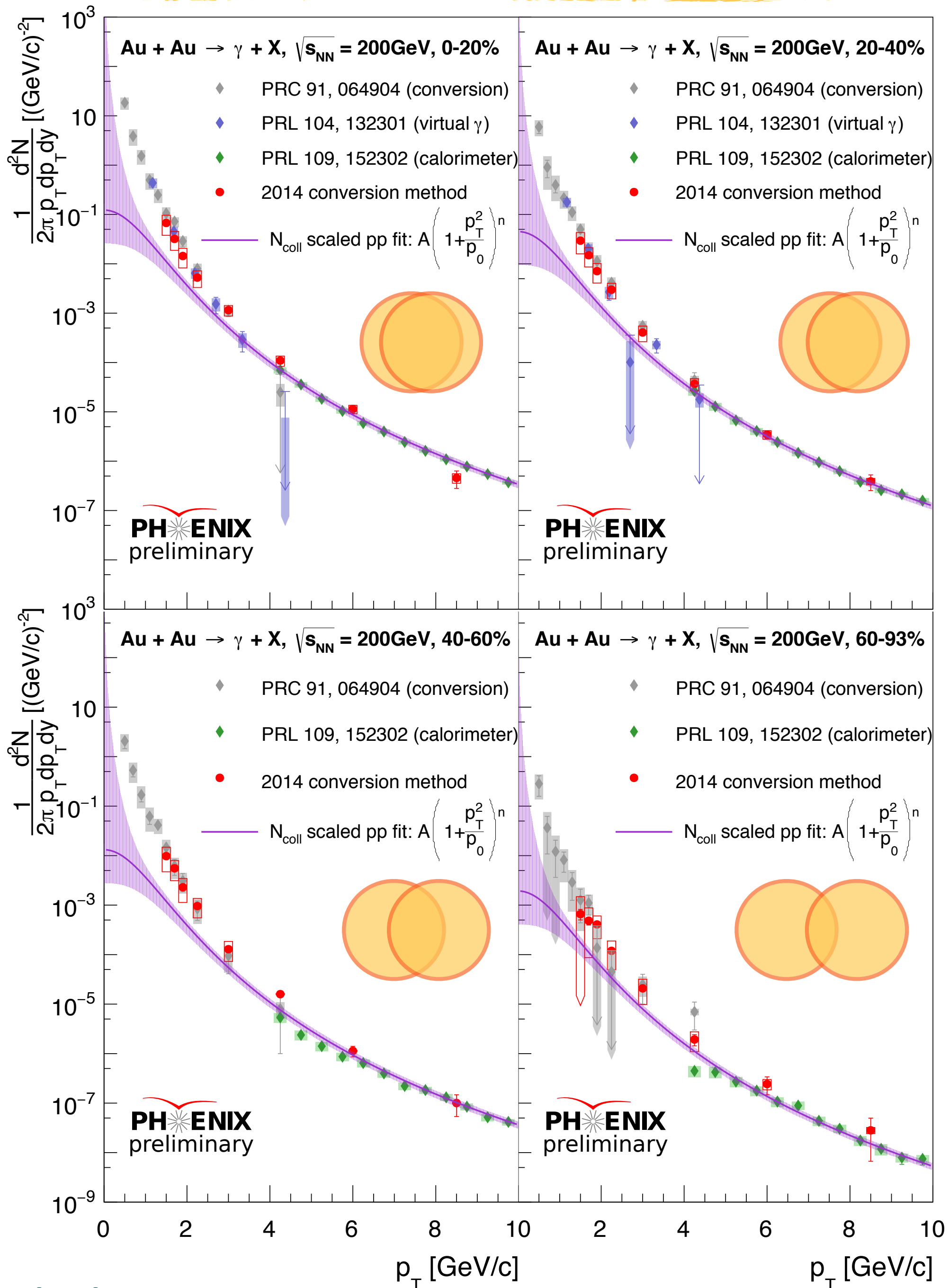


- Fitting function

a	b	c
6.74×10^3	2.10	-3.30

- pQCD inspired function
- Systematic errors include the fit errors, different functional forms

Thermal photons in Au+Au collisions



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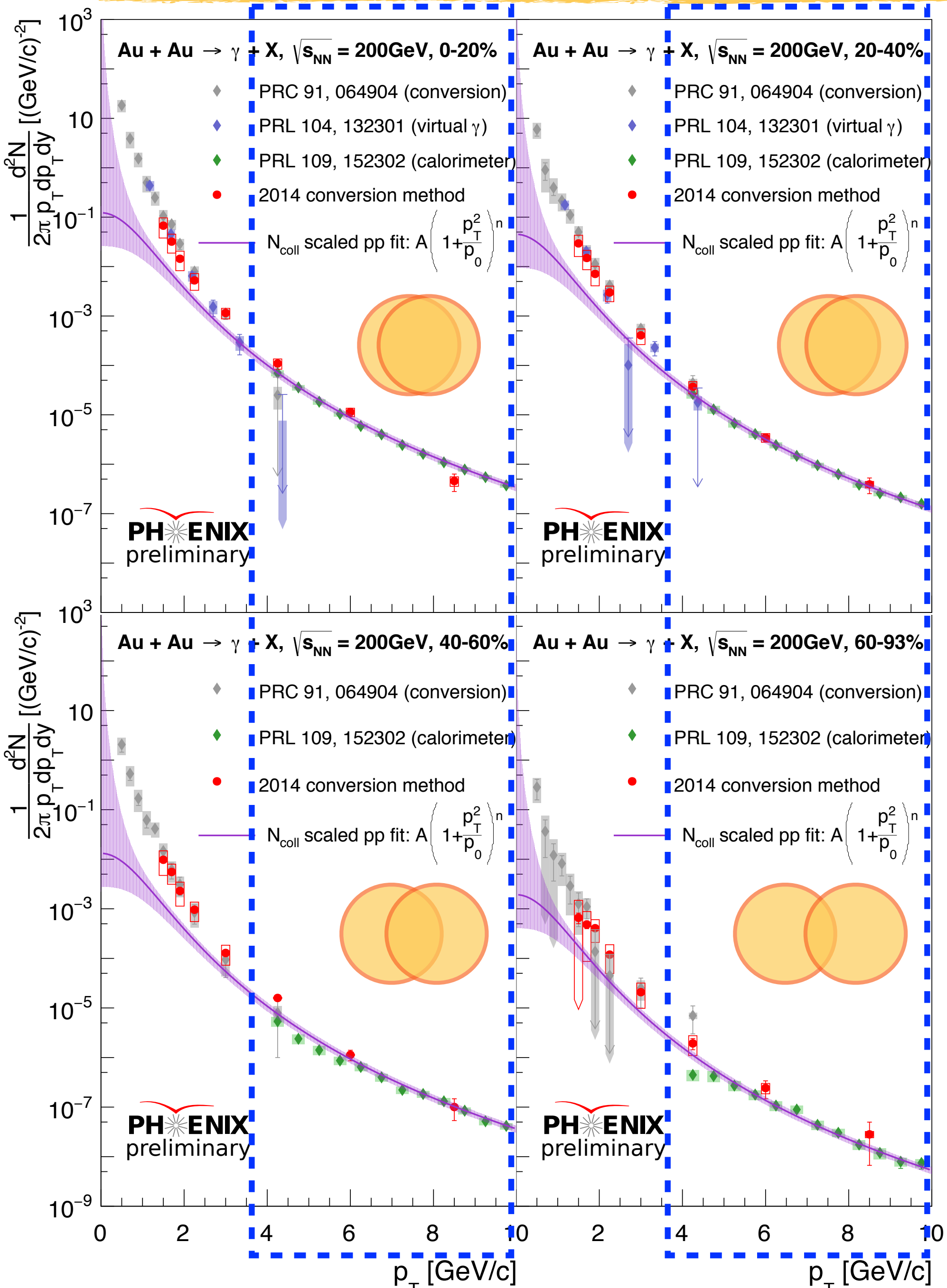

At high p_T, Au+Au data consistent with N_{coll} scaled p+p ➔ the dominant photon source is hard scattering

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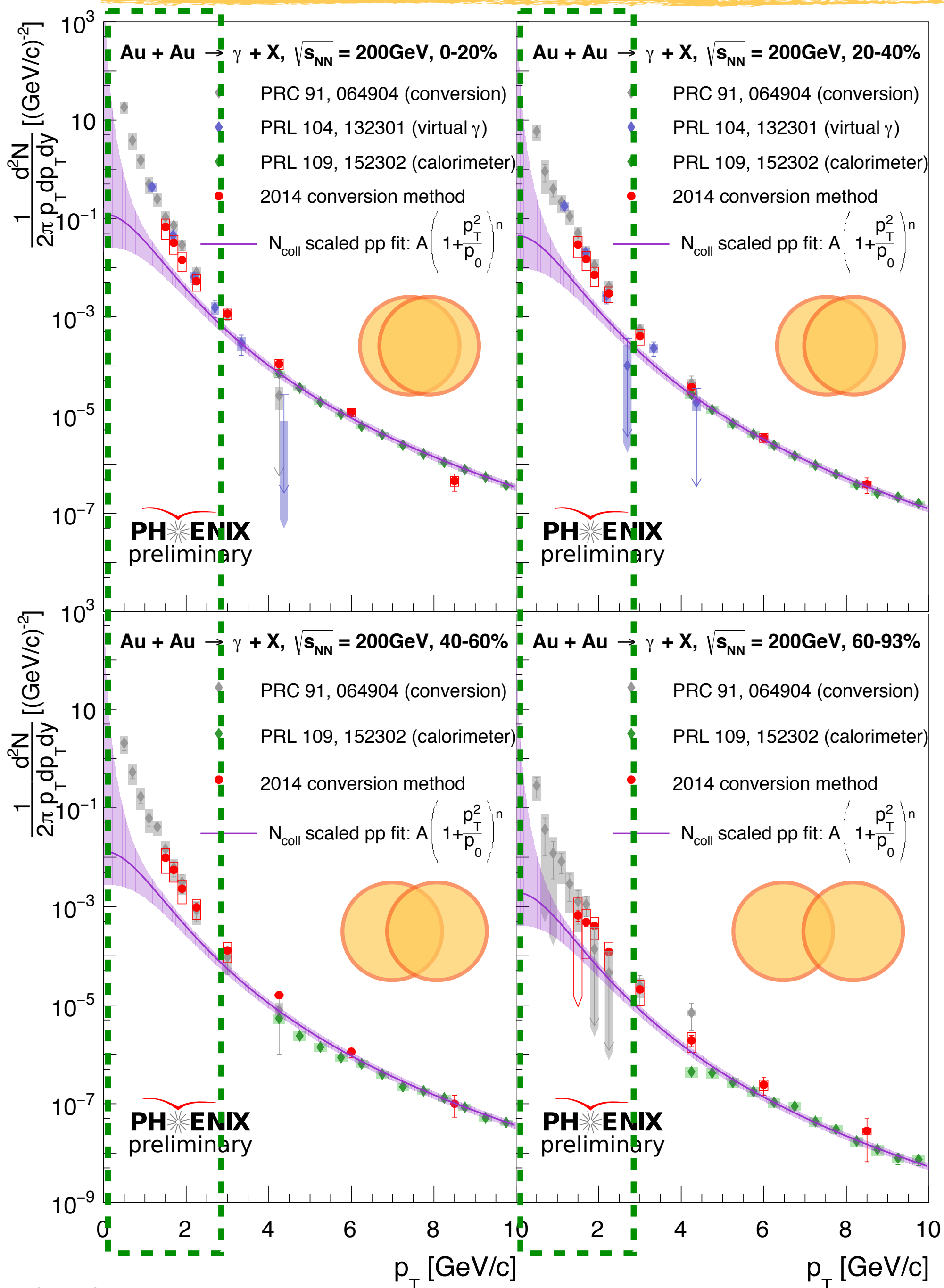
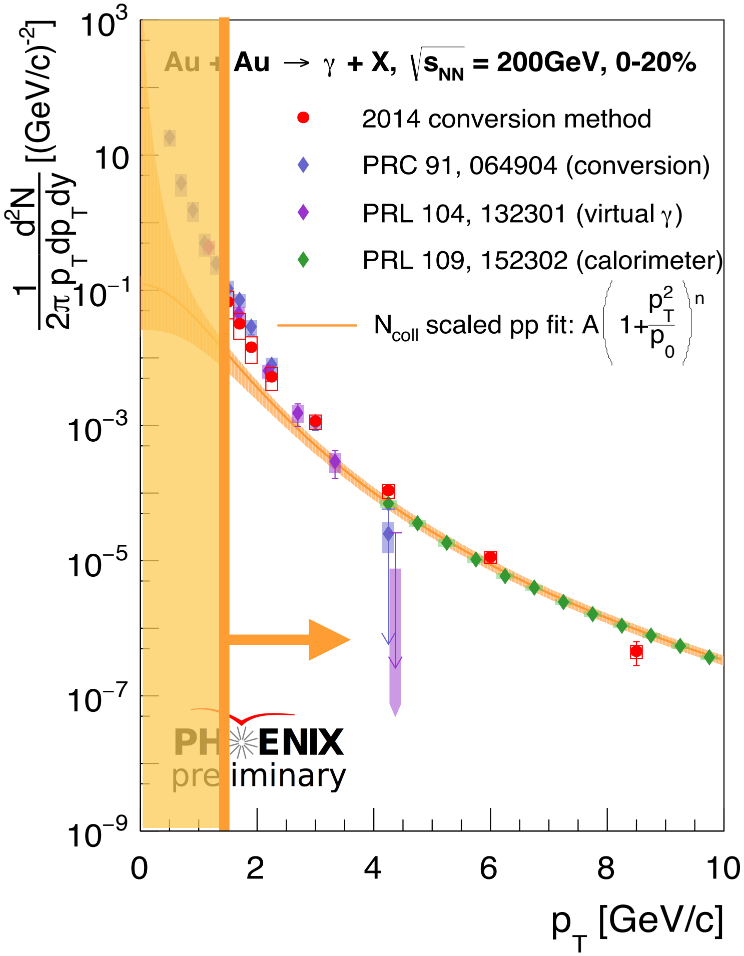


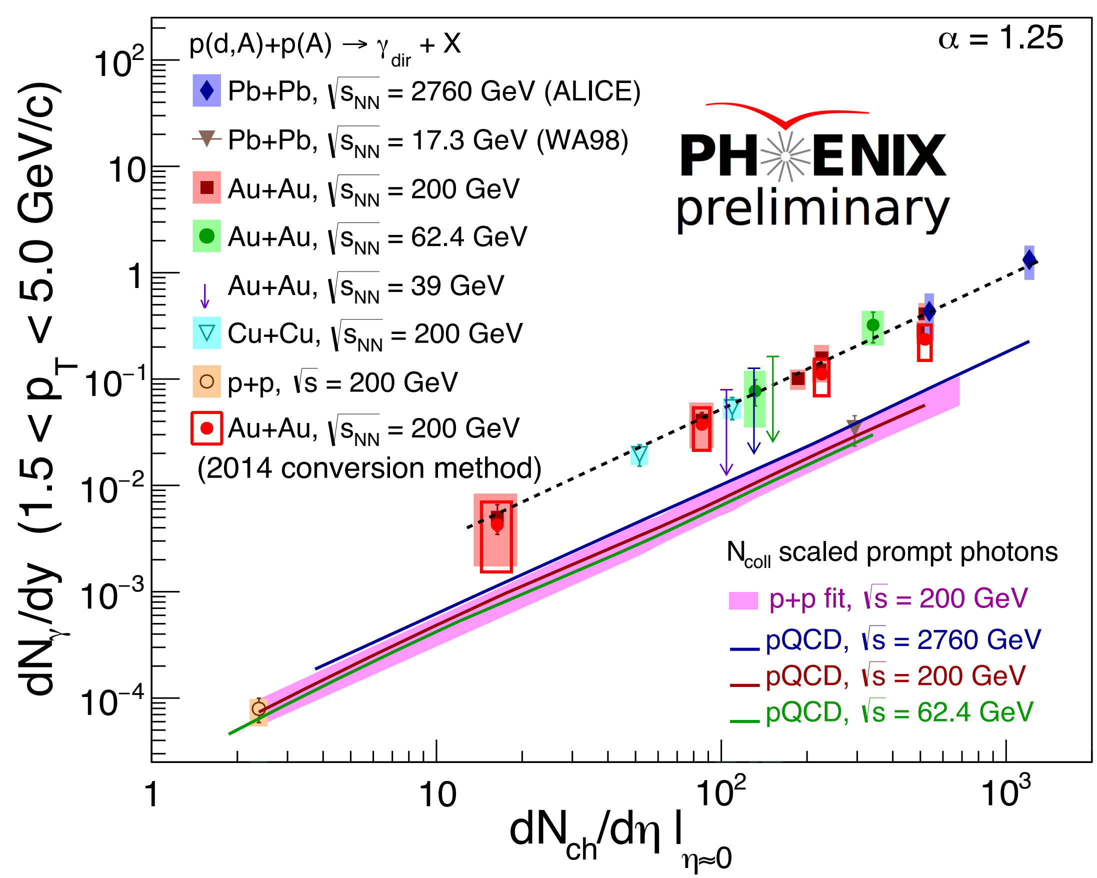
At high p_T, Au+Au data consistent with N_{coll} scaled p+p ➔ the dominant photon source is hard scattering

At low p_T, Au+Au data shows a clear enhancement wrt the prompt contribution below 3GeV

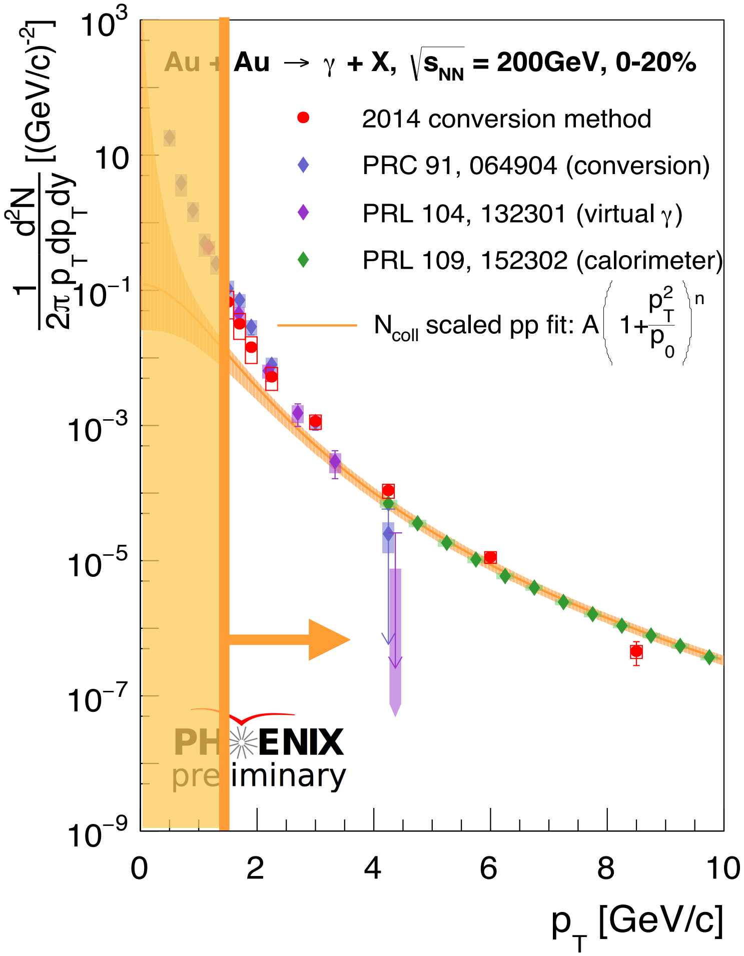
Direct photon scaling with new 2014 results



Confirms the observed scaling behavior in A+A systems



What's next — onset of QGP?



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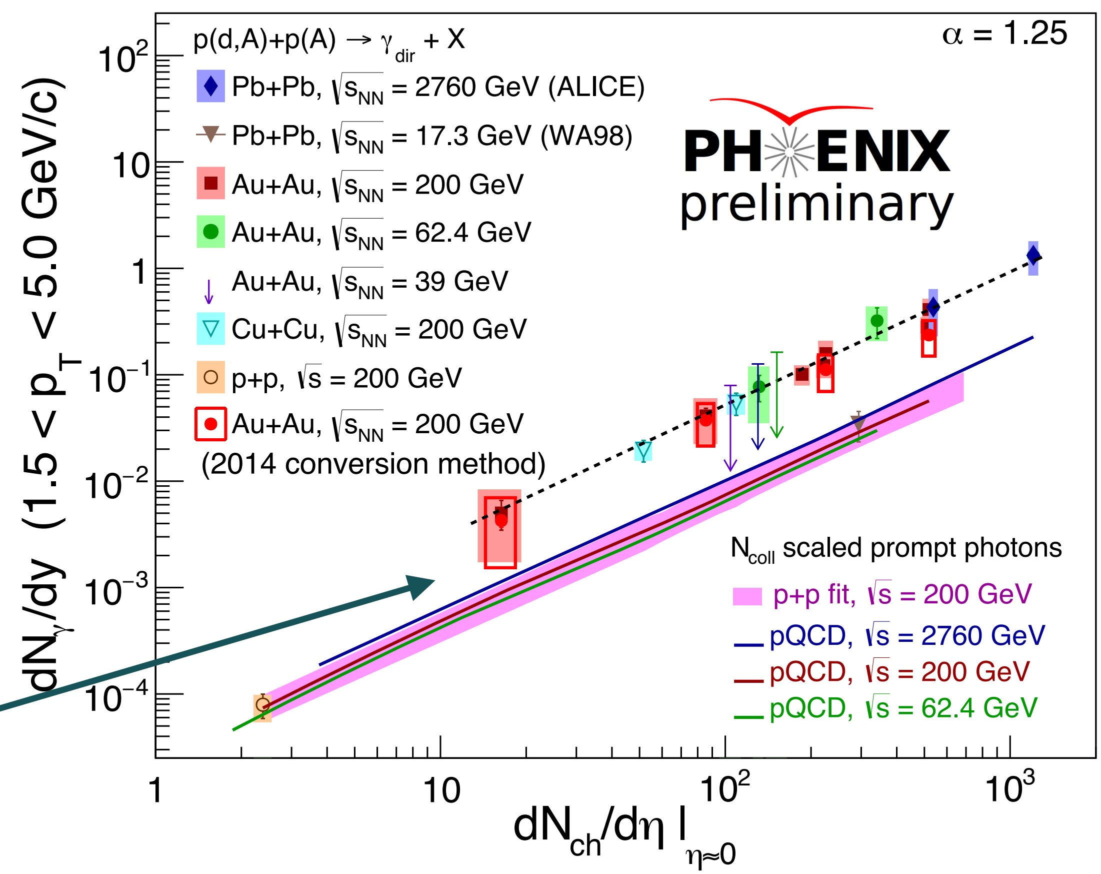
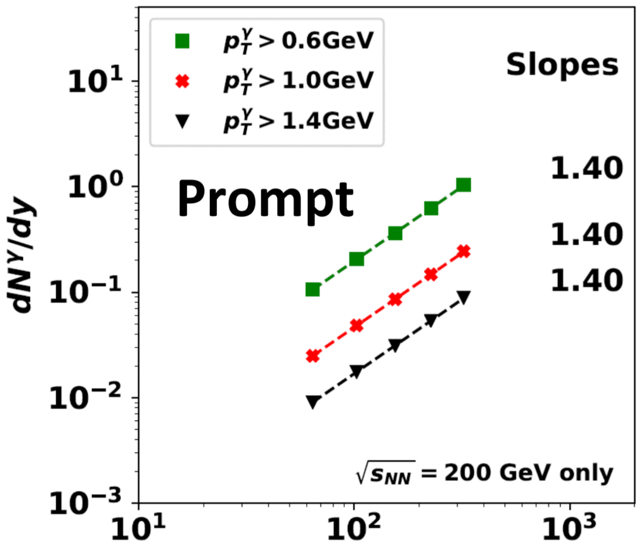


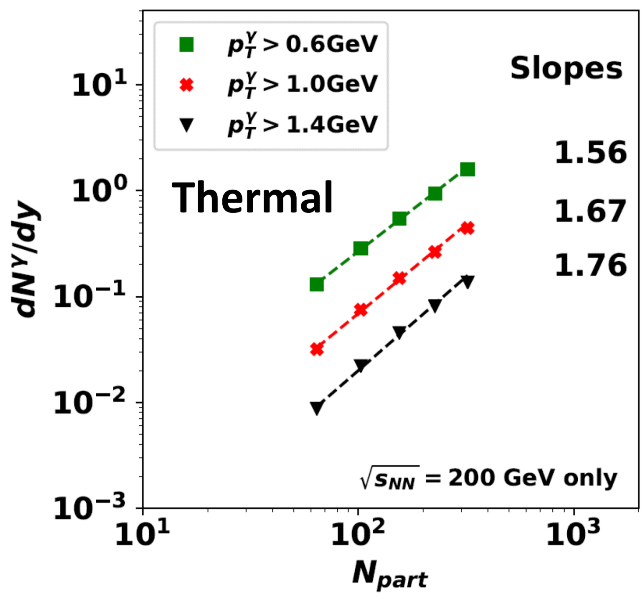
More peripheral Au+Au measurements can fill in the "transition region"

What's next — what is the source of low p_T direct photons?

- Looking into the centrality dependence of low p_T direct photons

Theory





Different slopes are predicted for prompt and thermal photons

Slopes for thermal photons show a p_T cutoff dependence

Need more precise fit from data!

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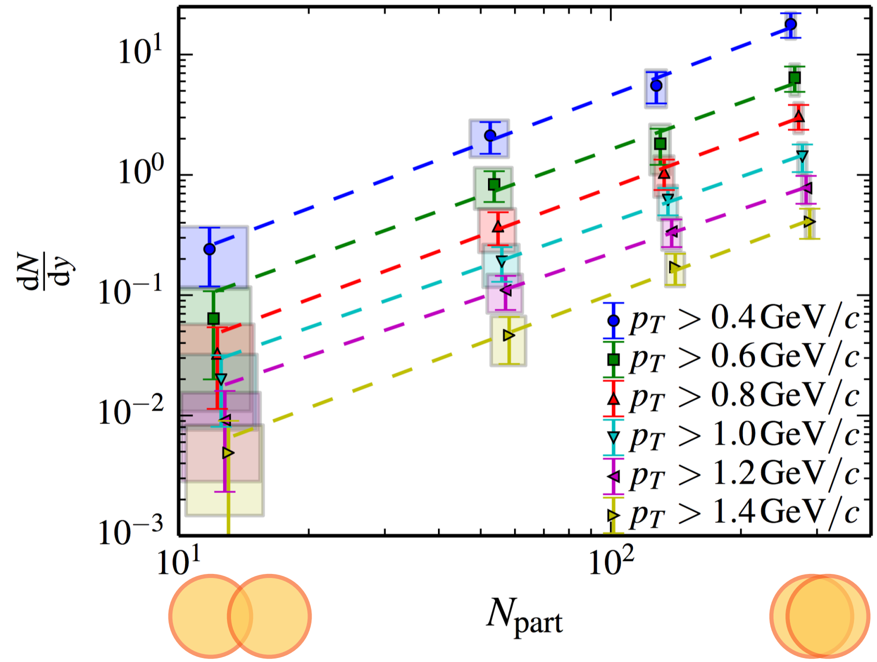
Data



p_T^{min} (GeV/c)	α
0.4	$1.36 \pm 0.08 \pm 0.08$
0.6	$1.41 \pm 0.14 \pm 0.12$
0.8	$1.42 \pm 0.07 \pm 0.11$
1.0	$1.35 \pm 0.06 \pm 0.07$
1.2	$1.36 \pm 0.09 \pm 0.07$
1.4	$1.40 \pm 0.06 \pm 0.10$

Summary

- Presented a new measurement of low p_T direct photon yields in Au+Au collisions at 200 GeV for different centrality bins with 2014 dataset
  - A new reconstruction algorithm is developed to analyze this dataset, which can also be used in all other collision systems
  - Consistent with previous published results, confirming the universal scaling behavior of direct photon multiplicity
  - Higher statistical precision, a full overlap with the published low p_T and high p_T measurements
- Ongoing analysis to measure low p_T direct photon in finer centrality classes to study the source of the photons in more detail

THANKS