# Results from the PHOBOS experiment at RHIC


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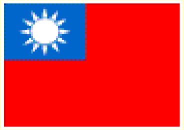
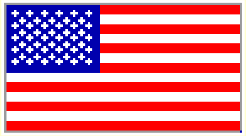
# PHOBOS Collaboration

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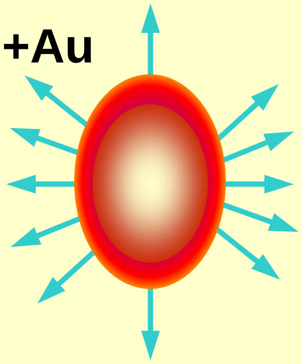
**BROOKHAVEN NATIONAL LABORATORY**
**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**
**UNIVERSITY OF ILLINOIS AT CHICAGO**
**UNIVERSITY OF ROCHESTER**

# Outline

- **PHOBOS detector**
  - *Data: p+p, d+Au, Cu+Cu, Au+Au at* $\sqrt{s_{NN}} = 20 – 200$ *GeV*
- **Charged particle multiplicities**
  - *Factorization of energy and centrality dependence in Au+Au and Cu+Cu collisions*
- **Azimuthal anisotropy of produced particles in Au+Au and Cu+Cu collisions**
  - *Participant eccentricity scaling*

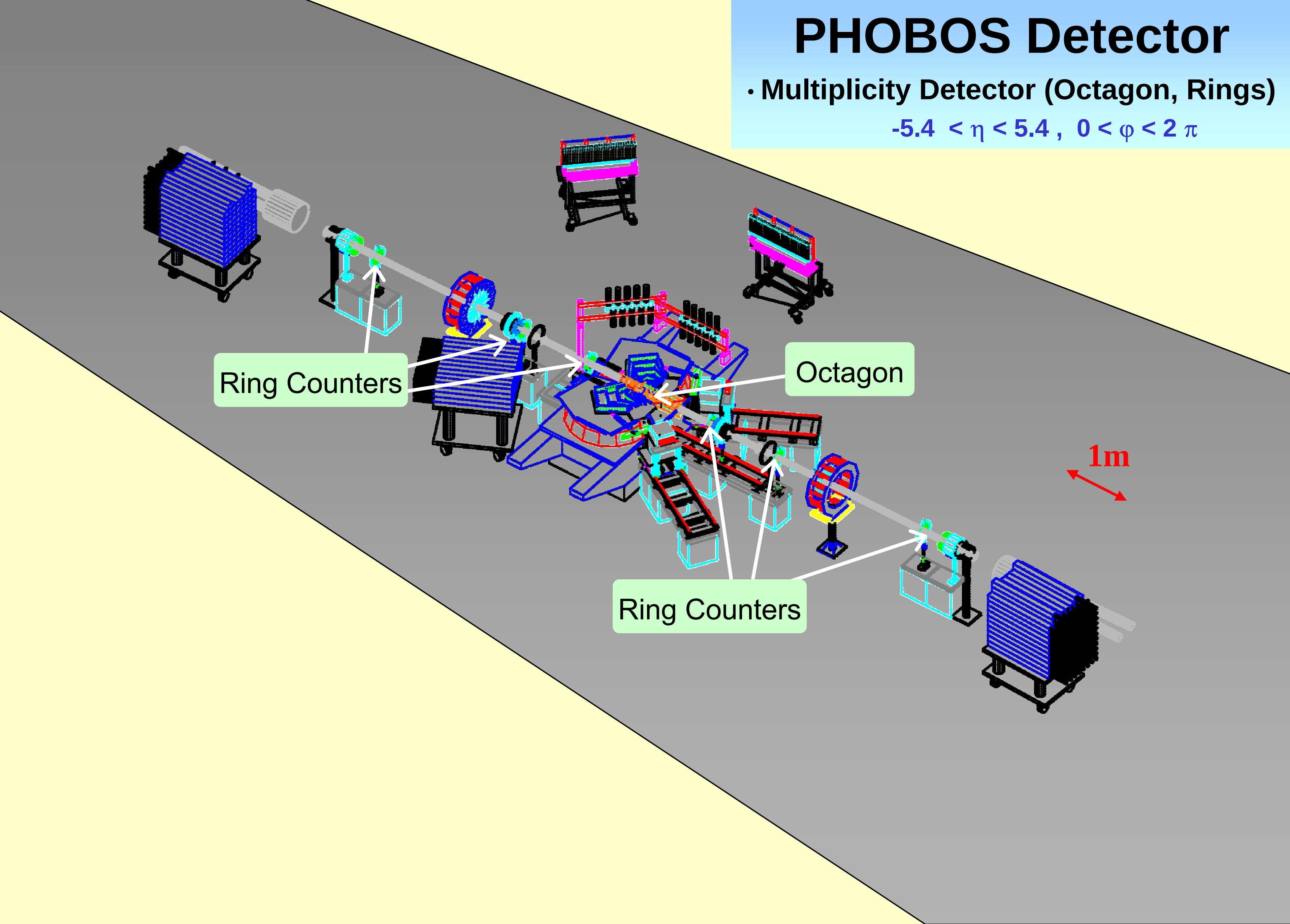


- **$p_T$ - Spectra of identified particles**
  - *Very low $p_T$ data – a handle on radial flow*
- **Summary**

# PHOBOS Detector

- **Multiplicity Detector (Octagon, Rings)**

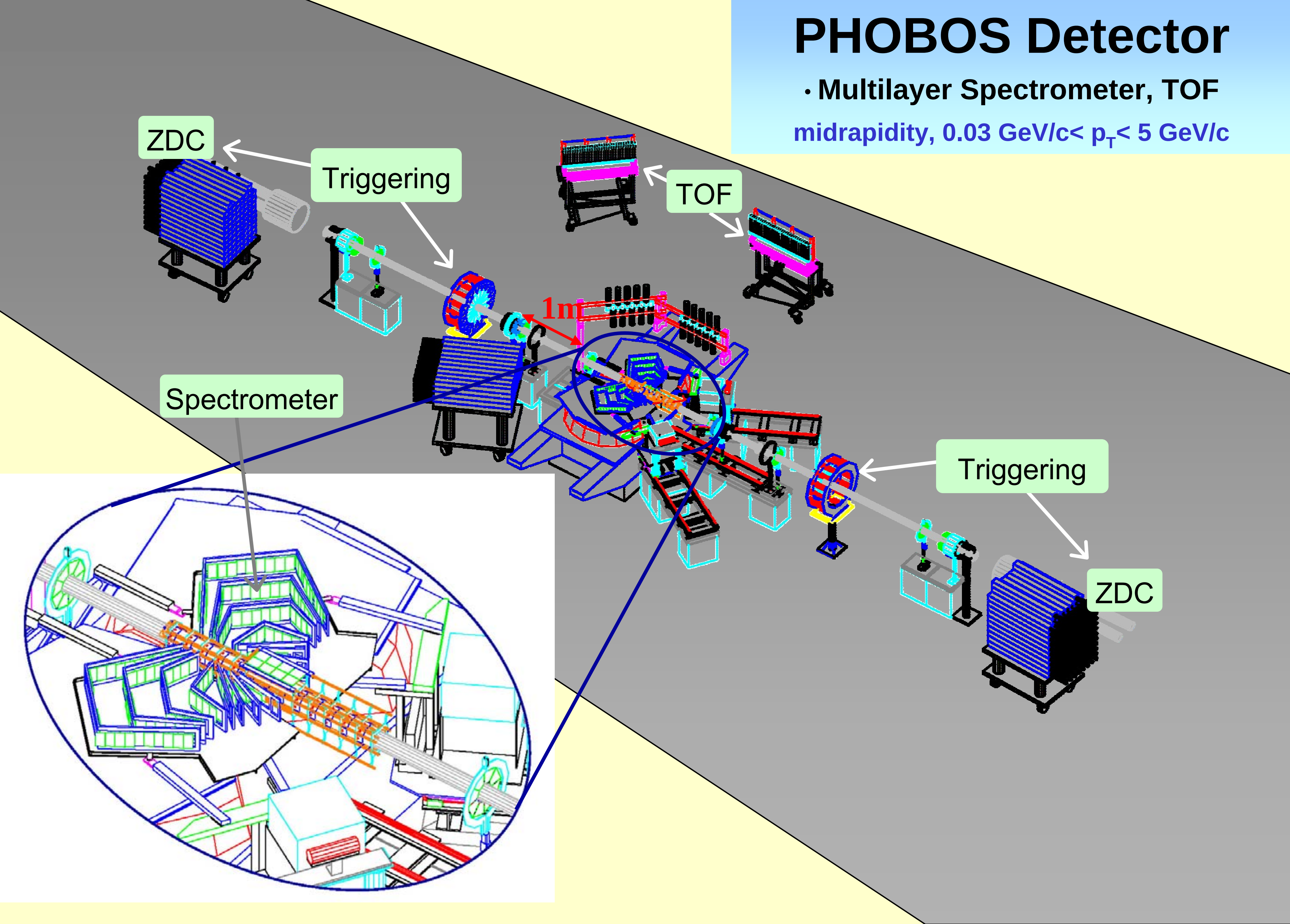
  **$-5.4 < \eta < 5.4$ , $0 < \varphi < 2\pi$**



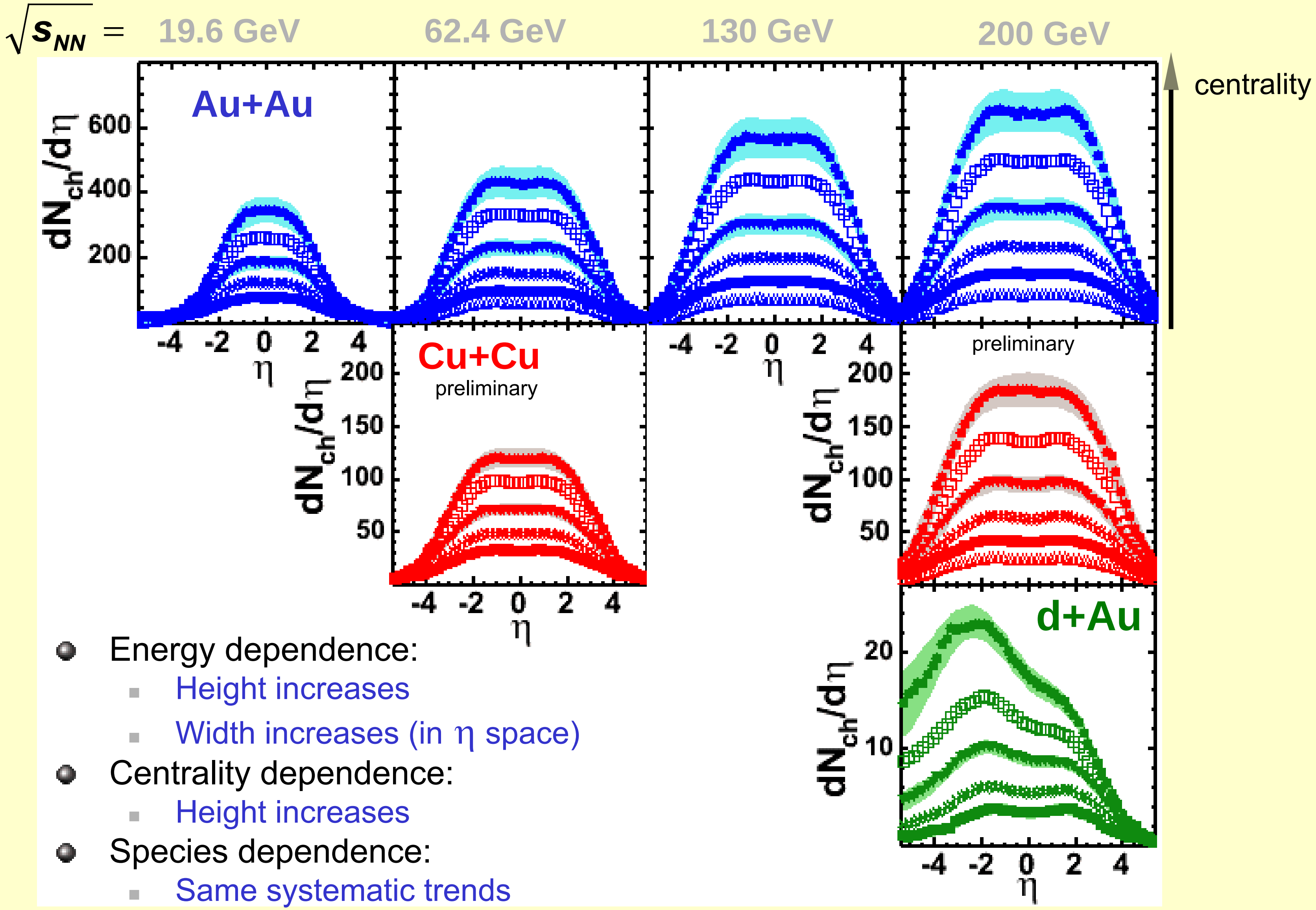
# PHOBOS Detector

- Multilayer Spectrometer, TOF

midrapidity, 0.03 GeV/c< $p_T$< 5 GeV/c



# Charged hadron $dN_{ch}/d\eta$ distribution (PHOBOS)



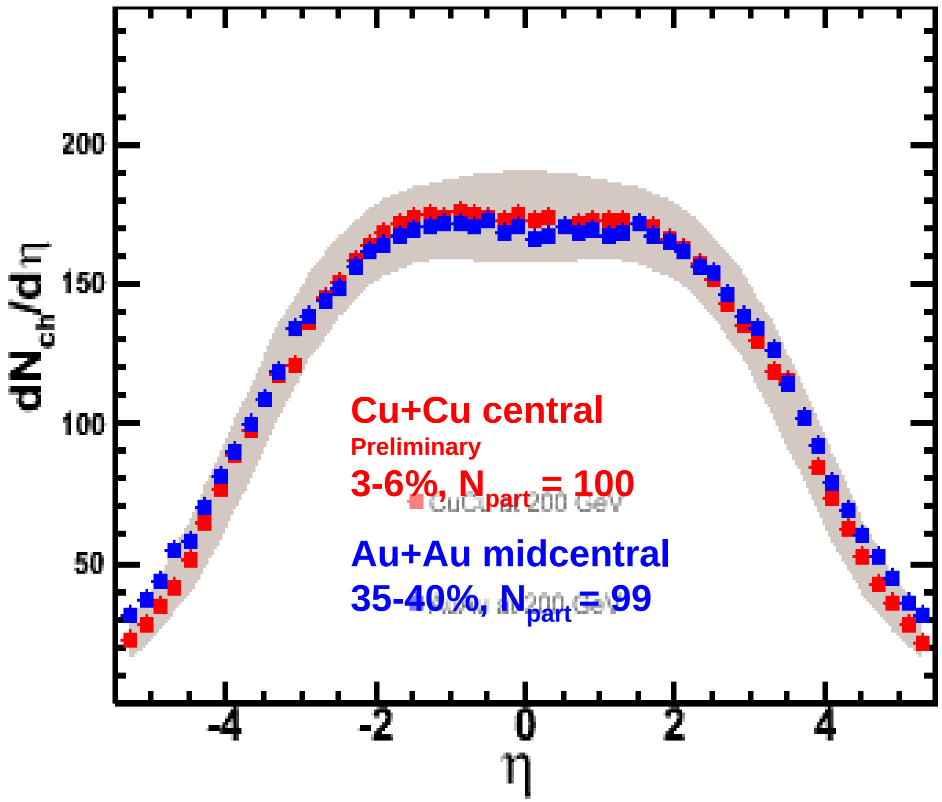

- Energy dependence:
  - Height increases
  - Width increases (in η space)
- Centrality dependence:
  - Height increases
- Species dependence:
  - Same systematic trends

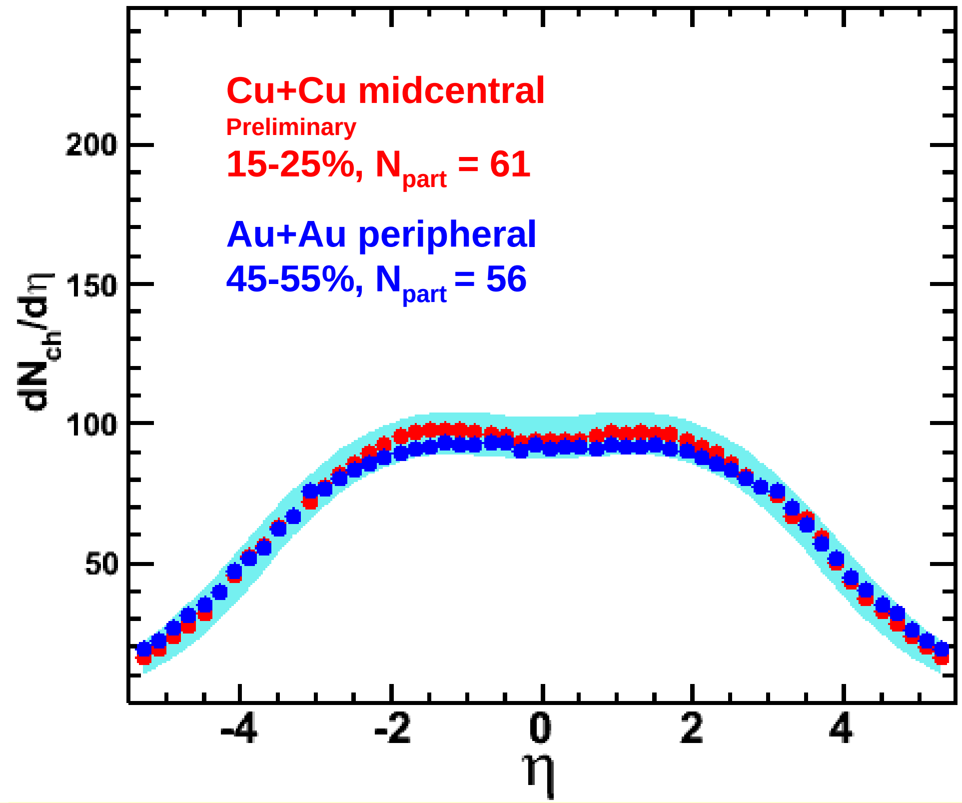
PRL 91 (2003) 052303, PRC 74 (2006) 021901, PRC 72 (2005) 031901

# Au+Au and Cu+Cu at the same $N_{part}$ ($\sqrt{s_{NN}}$ = 200 GeV)

$N_{part}$ - number of participating nucleons

PHOBOS: NPA 774 (2006) 113




**For the same $N_{part}$ (system size) $dN_{ch}/d\eta$ shape is very similar for Au+Au and Cu+Cu collisions**

# Charged particle yields in Au+Au and Cu+Cu at midrapidity

### Particle density per participant pair

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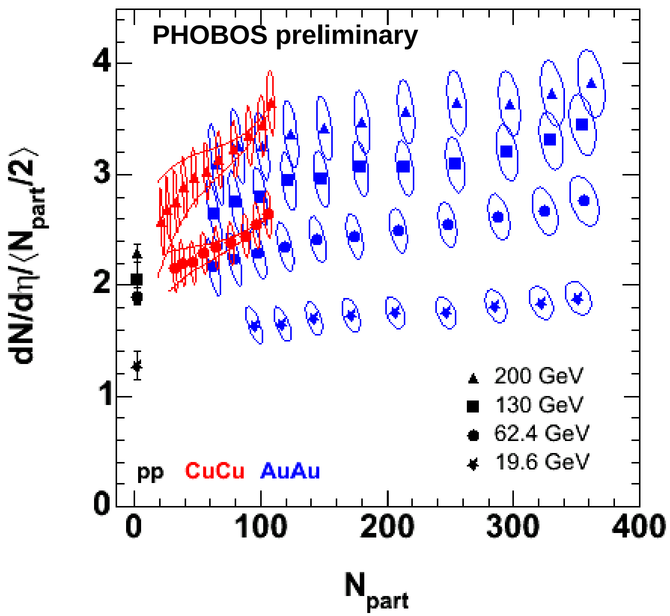
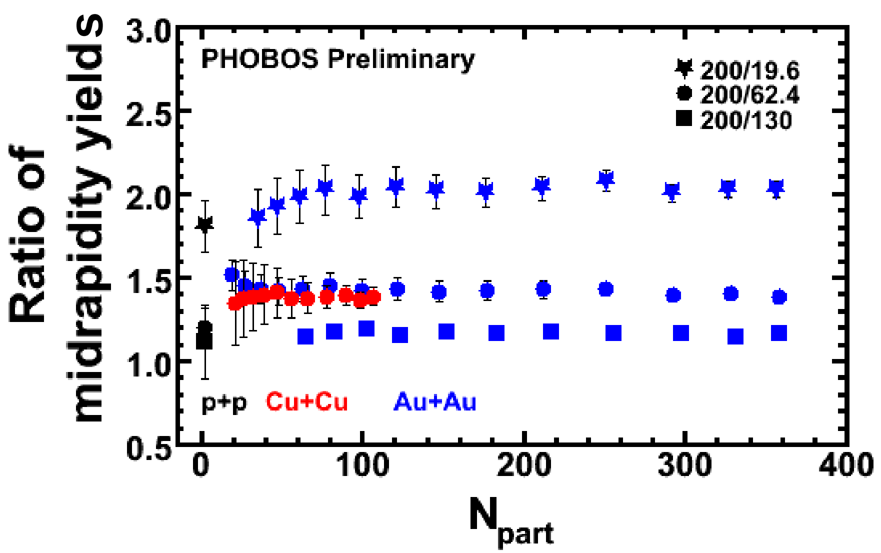



Increase in particle production per participant with $N_{part}$

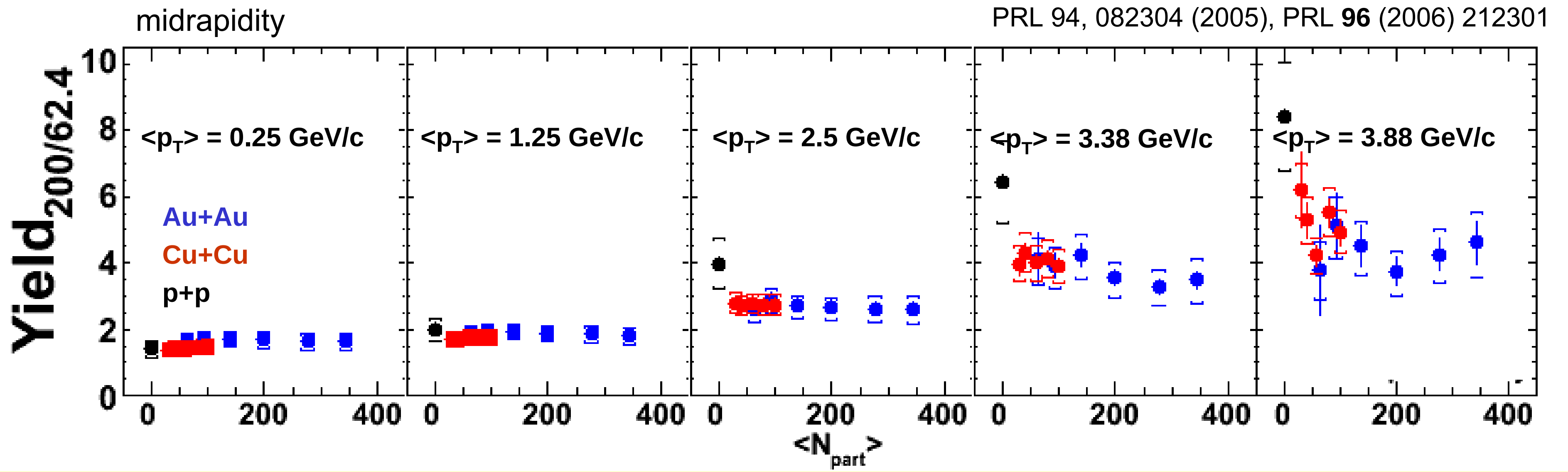
### Ratio of charged hadron yield at 200 GeV to yields at lower energies (200/X)




- No centrality dependence for $N_{part}$ > 40
- Energy and centrality dependences of charged hadron yields factorize

# Charged Particle $p_T$ Spectra

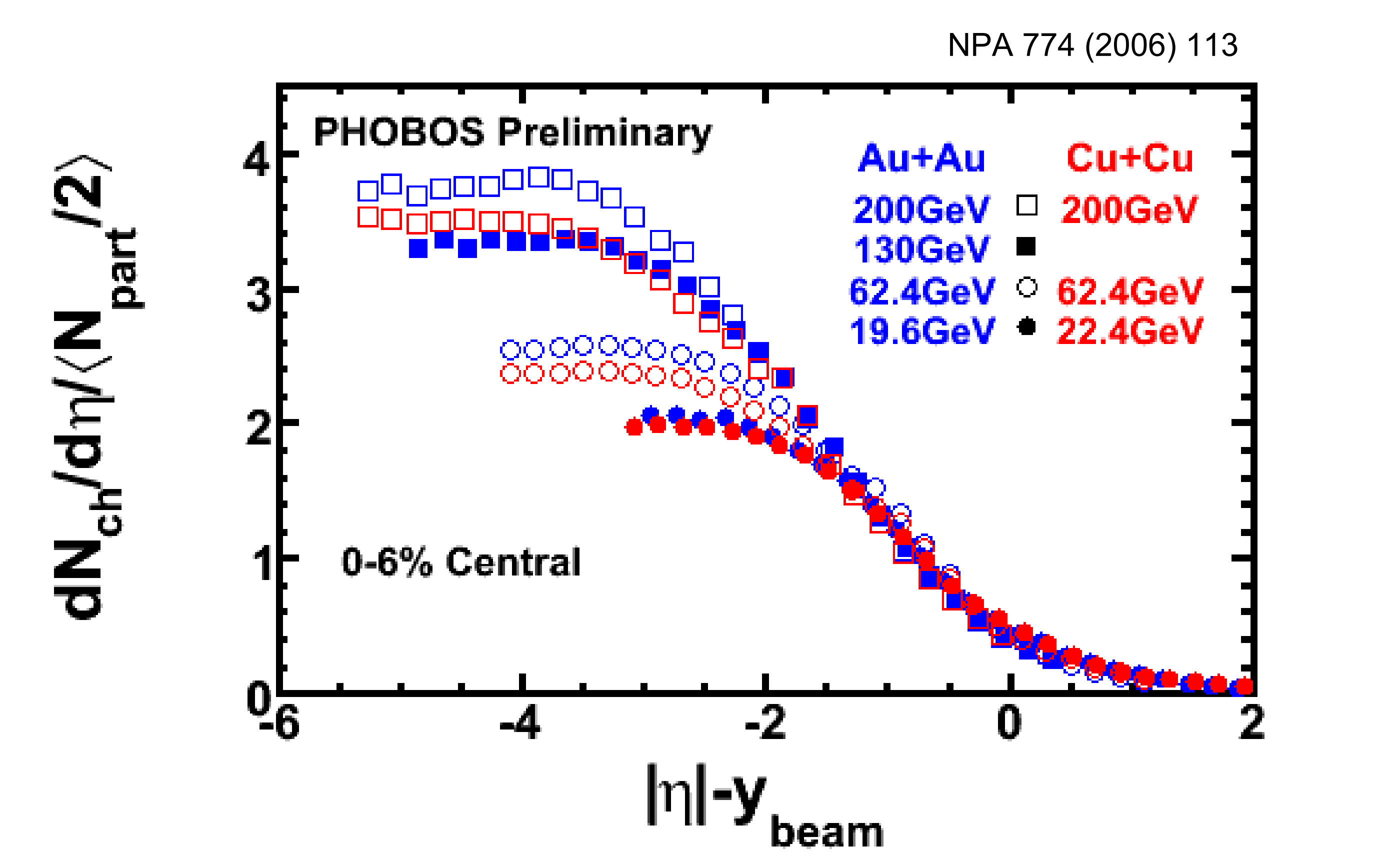
## Ratio of charged hadron yields at 200 and 62.4 GeV




**No centrality dependence for $p_T$ = 0.2 – 4 GeV/c**

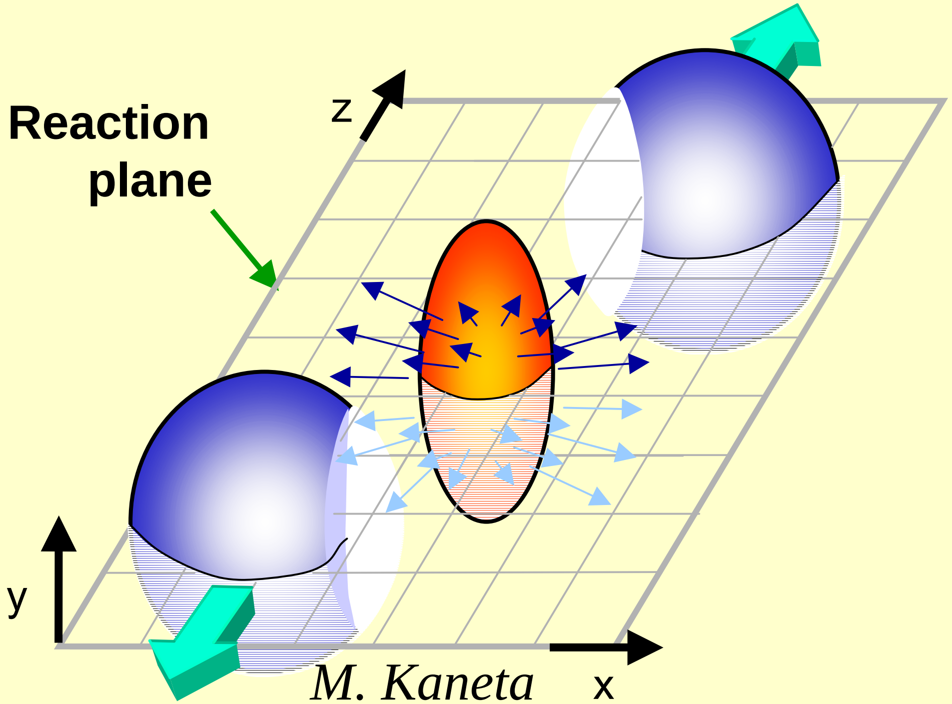
**Factorization of energy and centrality dependence is valid at different transverse momenta.**

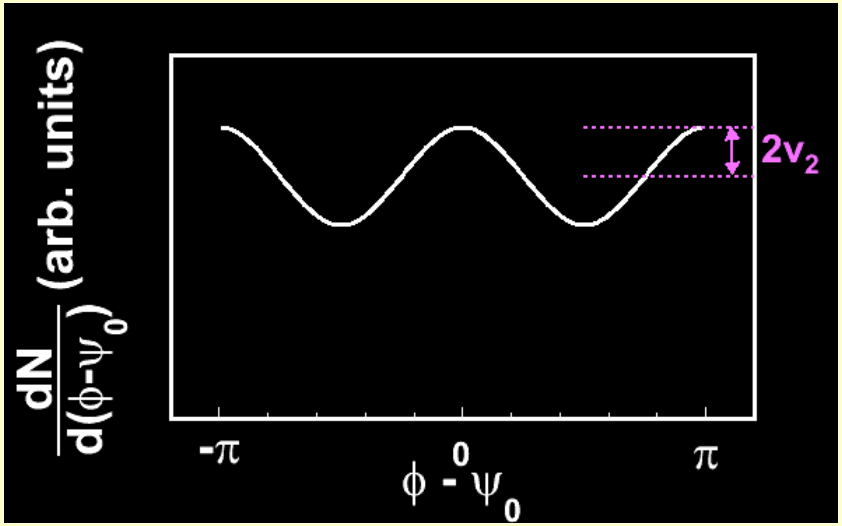
# Extended longitudinal scaling




**Energy independence of charged particle yields from moderate to high rapidities**

# Azimutal anisotropy of produced particles

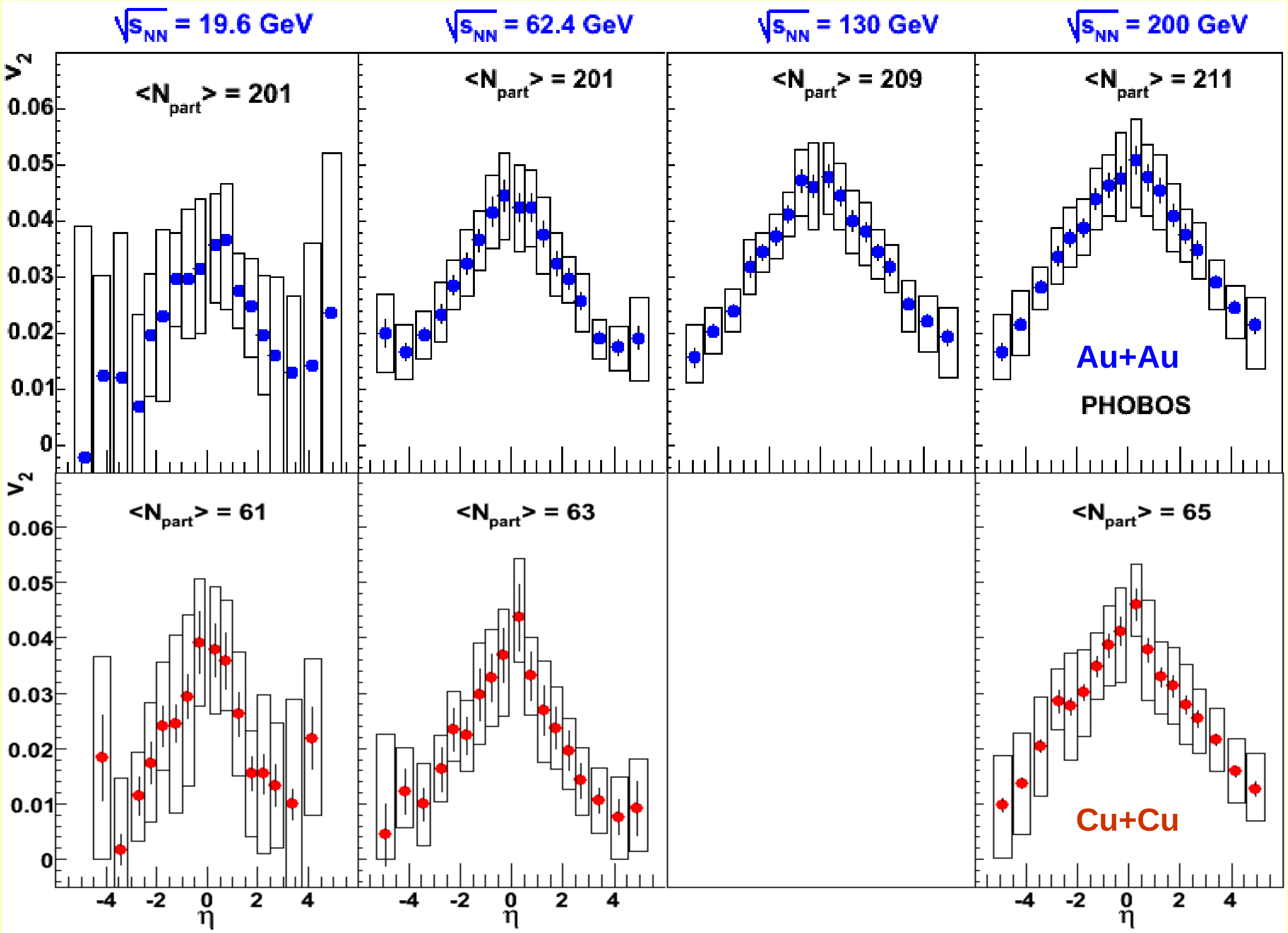



- **Pressure gradients lead to azimuthal anisotropy**
- **Elliptic flow is the second harmonic in the Fourier expansion of azimuthal particle distribution**

$$dN/d(\phi-\Psi_0) = N_0\,(1 + 2v_1\cos(\phi-\Psi_0) + 2\mathbf{v_2}\cos(2(\phi-\Psi_0)) + \ldots)$$

# $v_2$ in Au+Au and Cu+Cu ($\eta$ dependence)



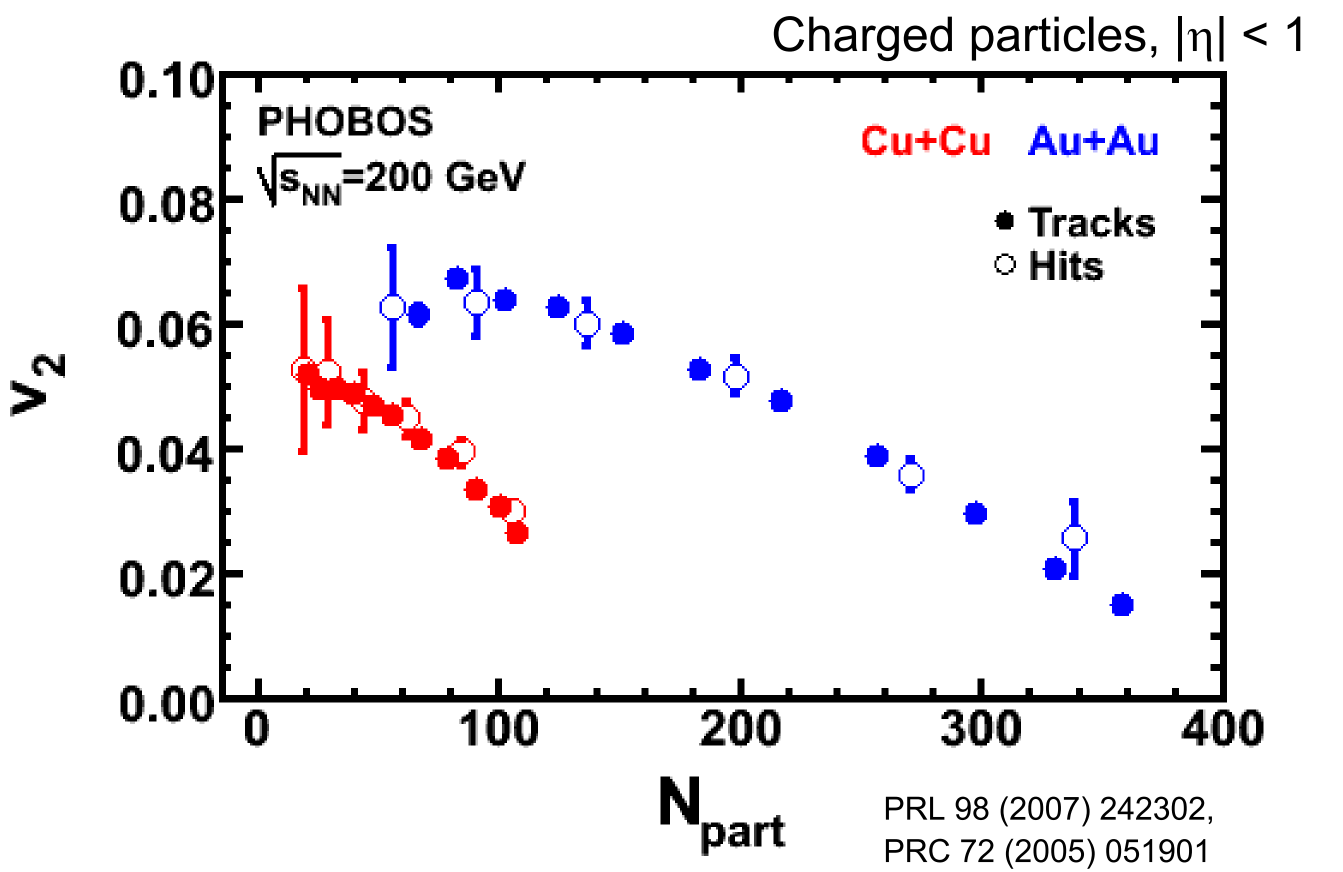

**0-40%, charged particles**

- **broad $\eta$ range**
- **several energies**

PRL 98 (2007) 242302,
PRC 72 (2005) 051901,
PRL 94 (2005) 122303

- **for Cu+Cu $v_2$ is large and grows with energy**
- **shape (in $\eta$) for Au+Au and Cu+Cu similar**

# $v_2$ in Au+Au and Cu+Cu (centrality dependence)




PRL 98 (2007) 242302,
PRC 72 (2005) 051901

- **decreases with centrality**
- **for central collisions $v_2$ is non-zero (larger in Cu+Cu)**

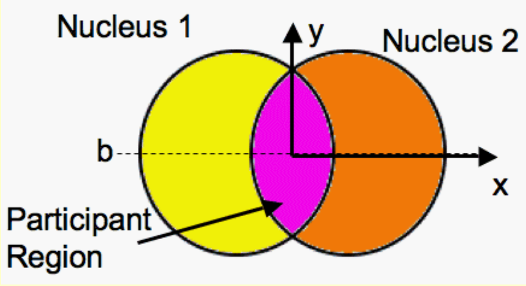
# Standard and Participant eccentricity

Initial overlap geometry → Visible in final measured particle azimuthal angular distributions

## Standard eccentricity:

$$< \varepsilon_{std} >= \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

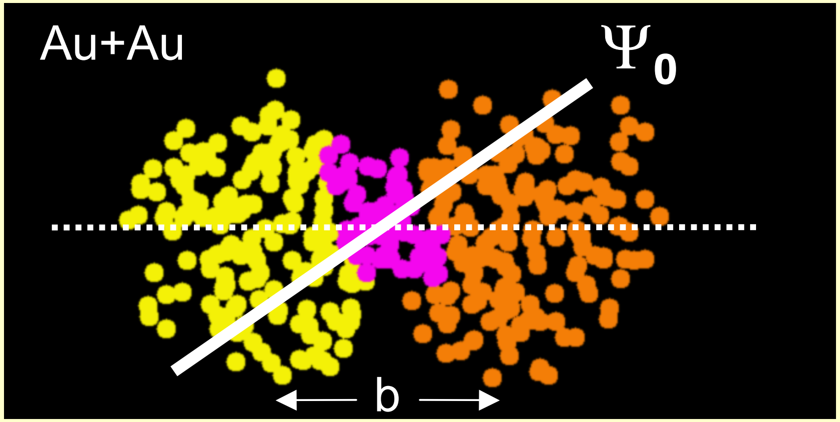
minor axis along b, (b≡x)




## Participant eccentricity:

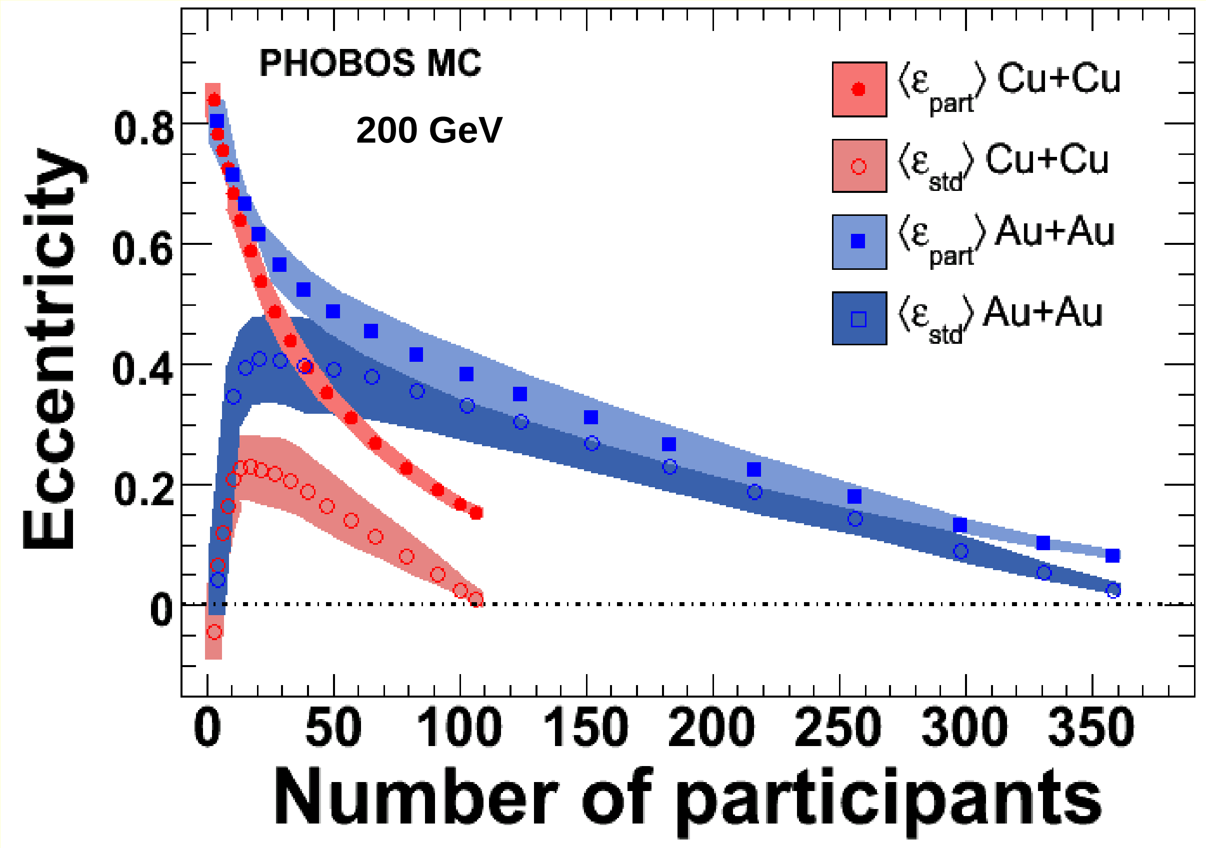
for the same b, interaction points vary from event-to-event

$$< \varepsilon_{part} >= \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$




minor axis not along b, (b≠x)

# Does using $<\varepsilon_{part}>$ make a difference? YES



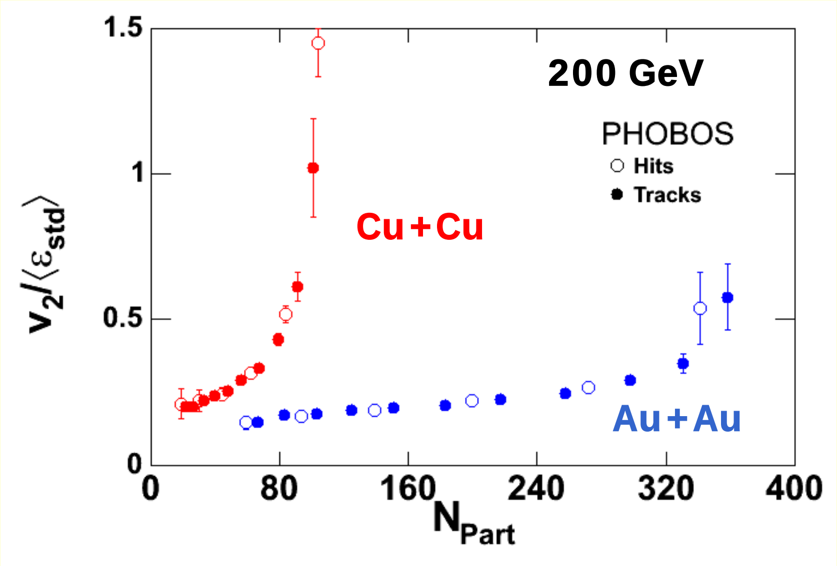

PRL 98 (2007) 242302

- $<\varepsilon_{part}>$ **increases for smaller systems**
- **For central Cu+Cu:**

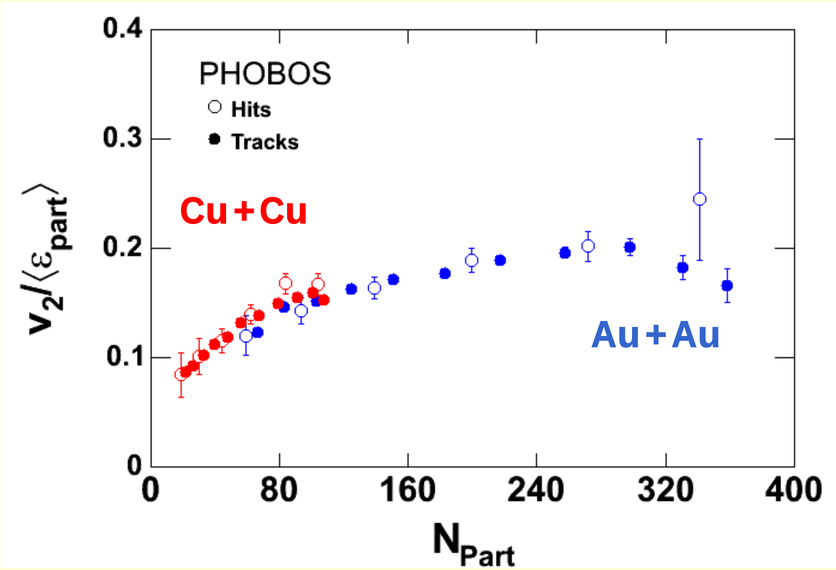
$$<\varepsilon_{part}> \gg <\varepsilon_{std}>$$

# Eccentricity scaled $v_2$ in Au+Au and Cu+Cu

## $v_2$ scaled by standard eccentricity




## $v_2$ scaled by participant eccentricity

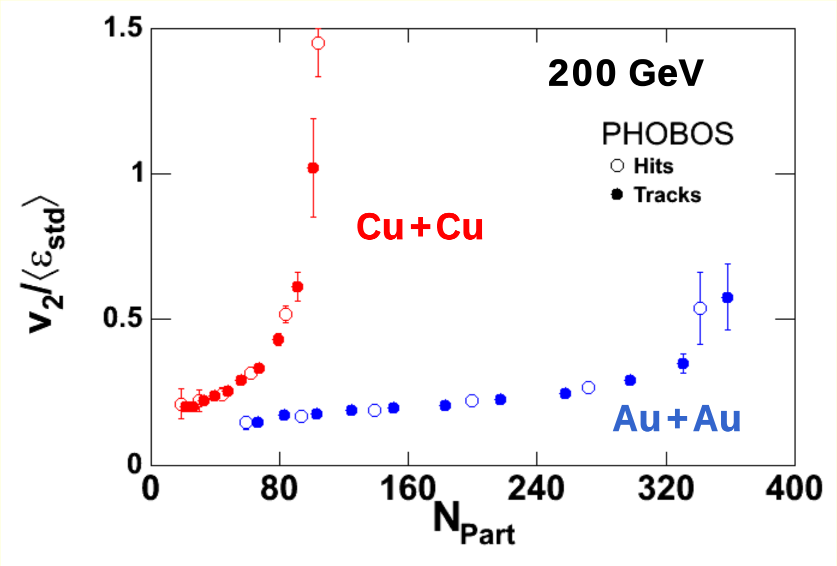



PRL 98 (2007) 242302

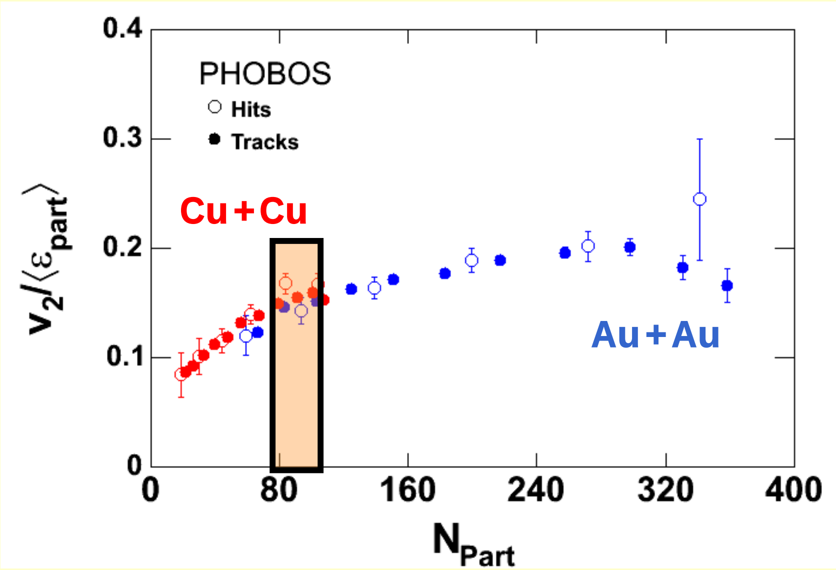
**$<\varepsilon_{part}>$ unifies average $v_2$ in Au+Au and Cu+Cu**

# Eccentricity scaled $v_2$ in Au+Au and Cu+Cu

## $v_2$ scaled by standard eccentricity




## $v_2$ scaled by participant eccentricity

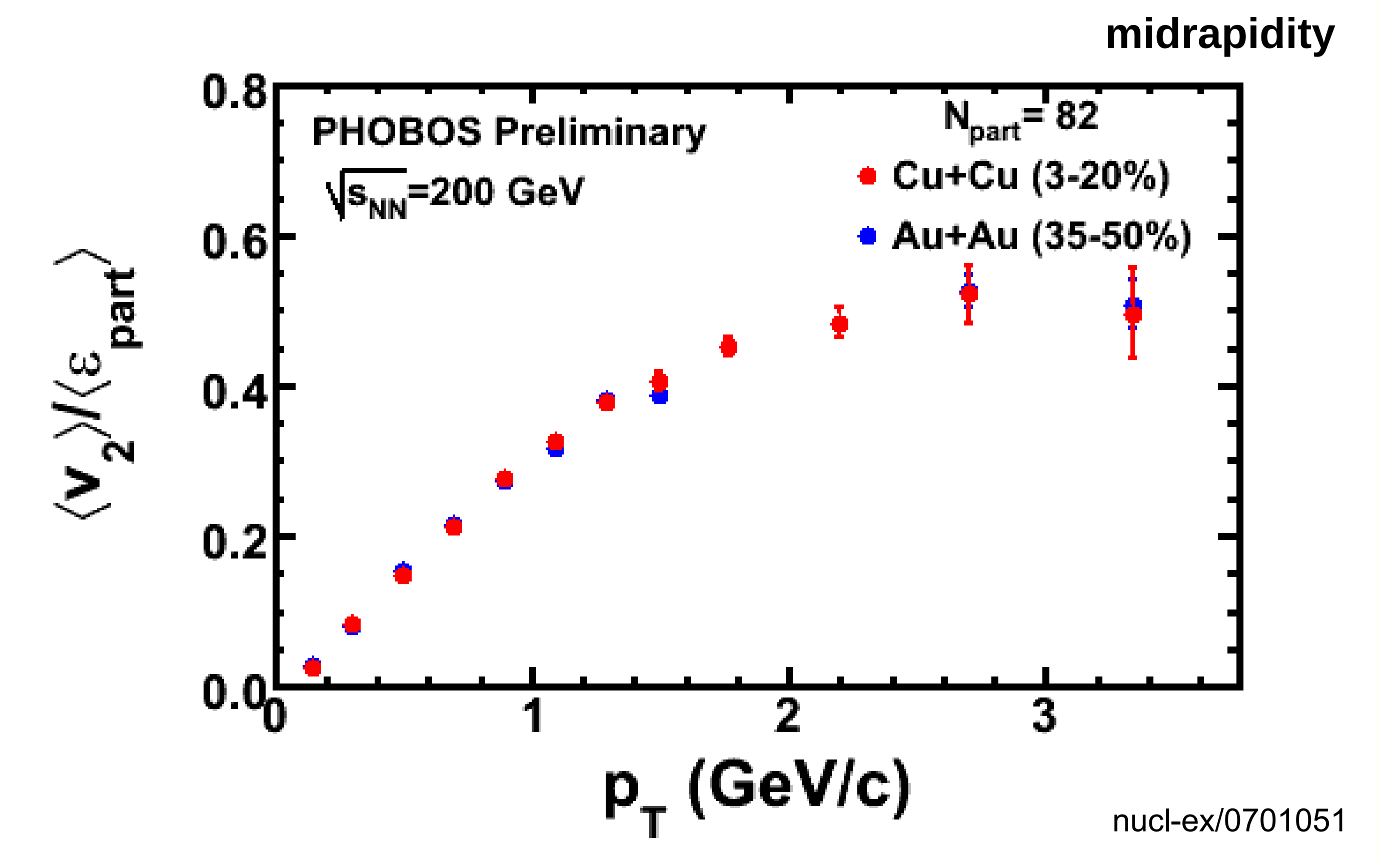



PRL 98 (2007) 242302

**$<\varepsilon_{part}>$ unifies average $v_2$ in Au+Au and Cu+Cu**

# $p_T$ dependence of $v_2 / < \varepsilon_{part} >$

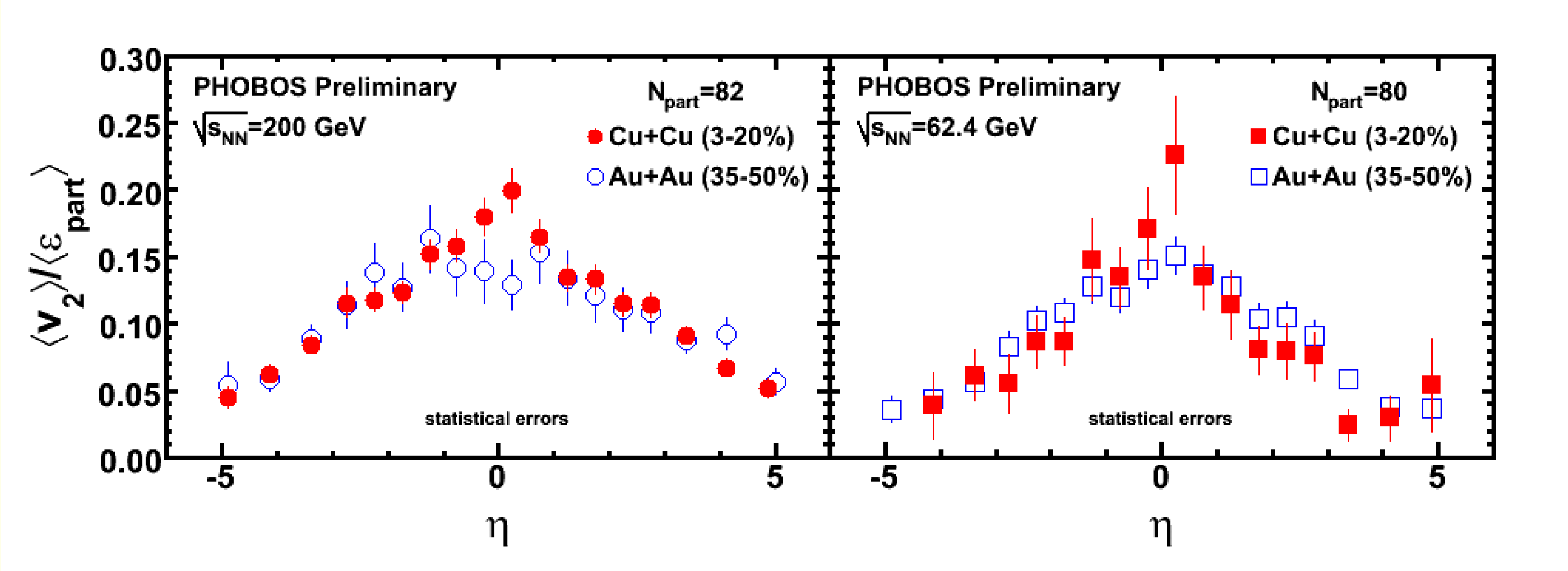
## Au+Au and Cu+Cu at matched $N_{part}$




**$< \varepsilon_{part} >$ unifies $v_2(p_T)$ in Au+Au and Cu+Cu**

# Pseudorapidity dependence of $v_2 / \langle \varepsilon_{part} \rangle$

## Au+Au and Cu+Cu at matched $N_{part}$



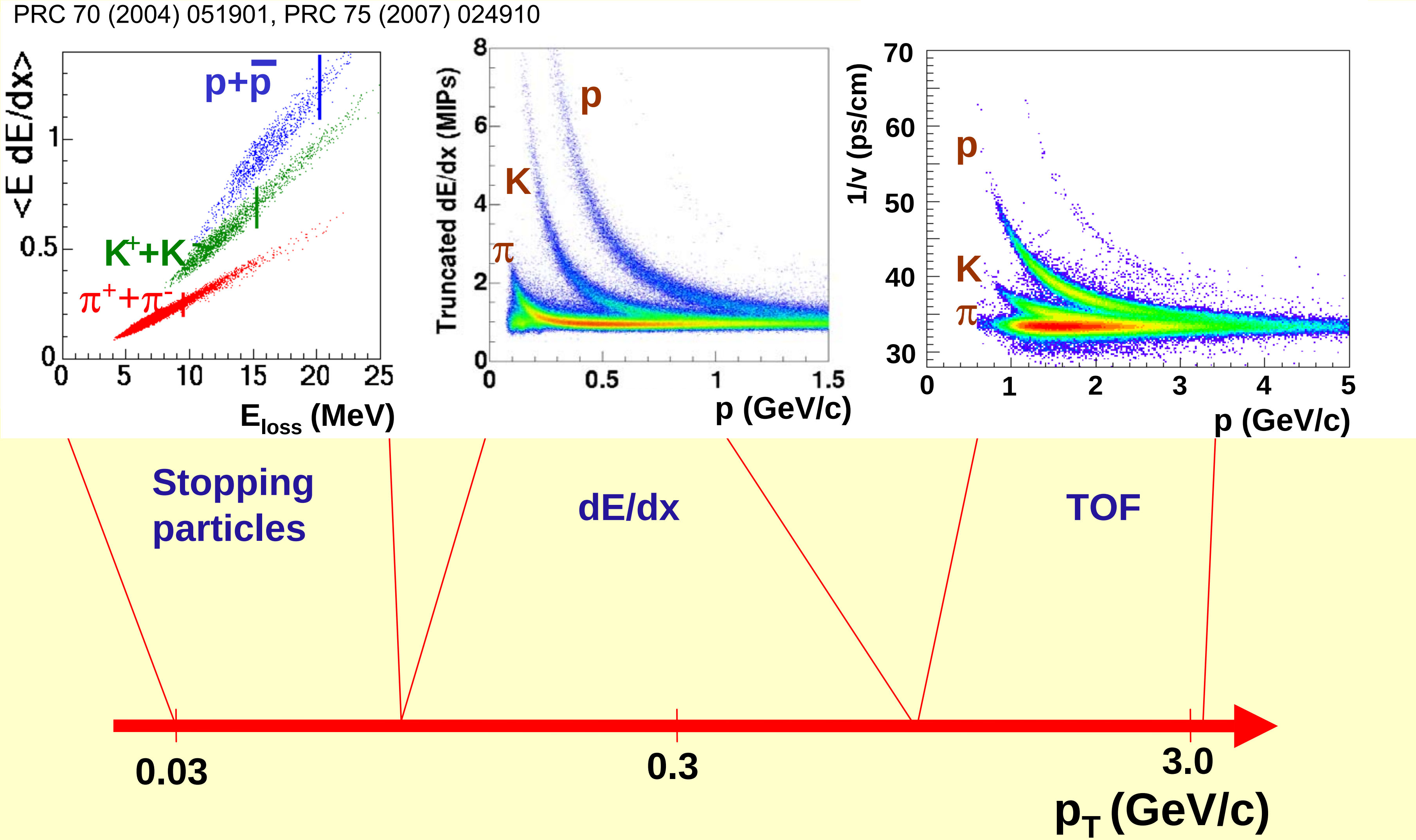

$\langle \varepsilon_{part} \rangle$ **unifies $v_2(\eta)$ in Au+Au and Cu+Cu**

**The collision geometry controls the dynamical evolution of heavy ion collisions**

**More information on the dynamical evolution can be obtained from identified particle $p_T$ spectra**

# PHOBOS Particle Identification

PRC 70 (2004) 051901, PRC 75 (2007) 024910

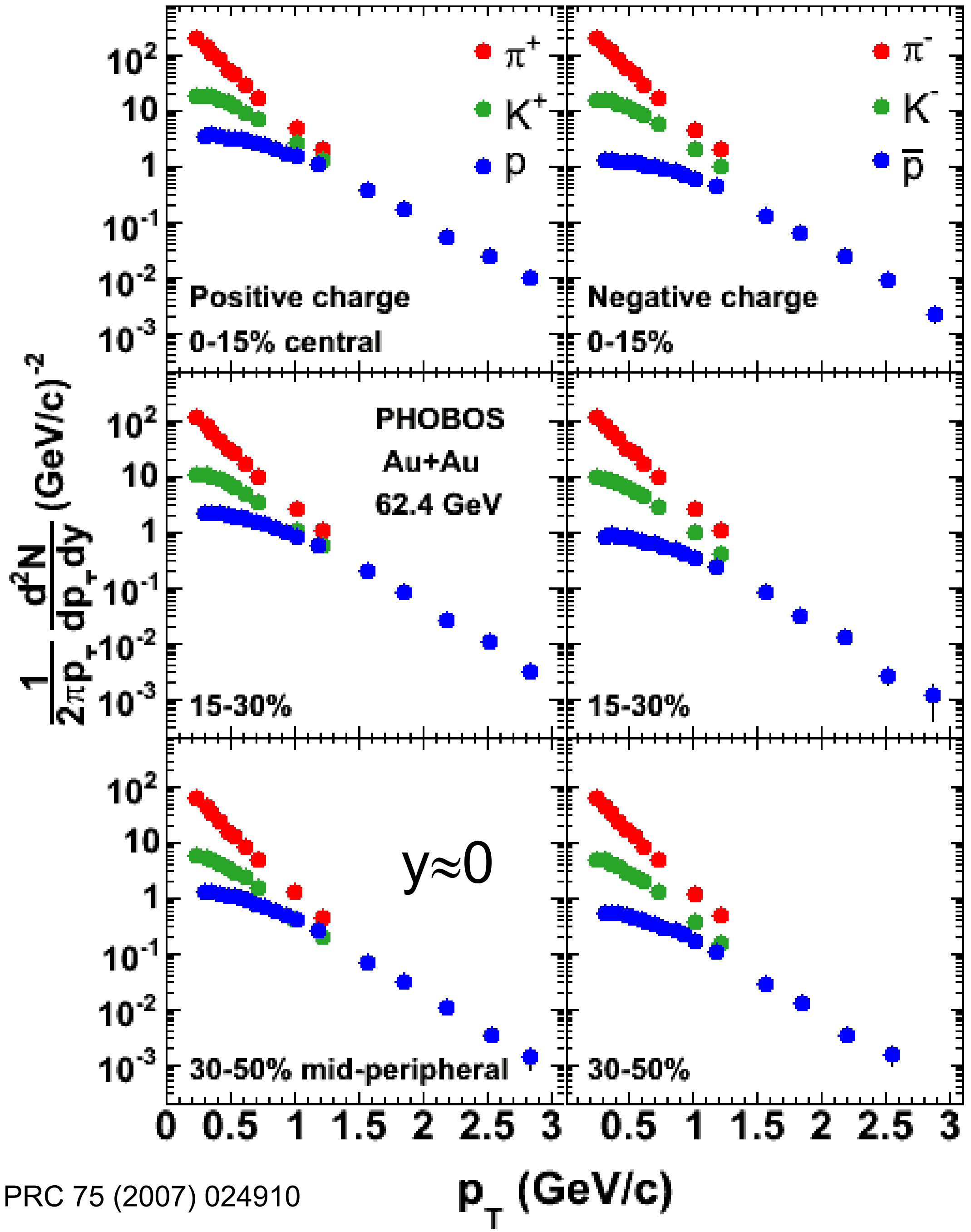



**Particle ID from low to high $p_T$**

# Identified particle $p_T$ -spectra, Au+Au at 62.4 GeV

**Time-of-Flight measurement extends $p_T$ reach to 3 GeV/c for protons**

- **Smooth evolution with centrality**
- **Proton spectra are harder than the meson spectra**

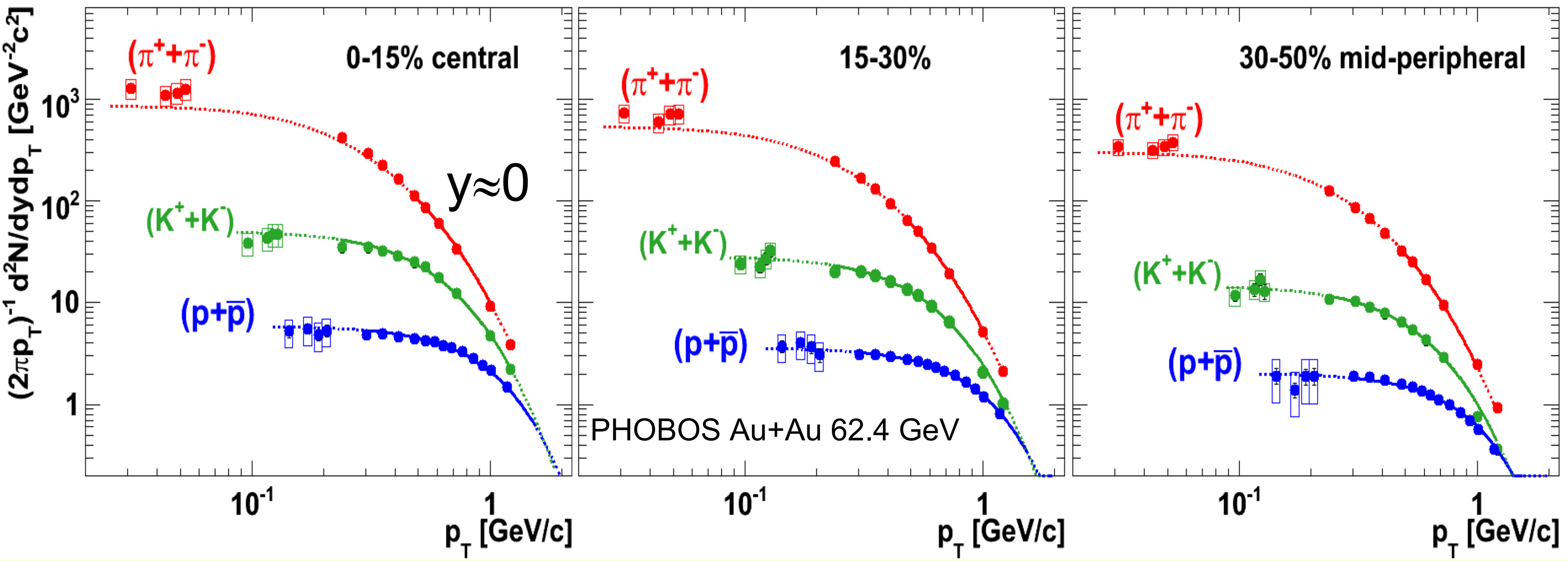



PRC 75 (2007) 024910

# Particle production at very low $p_T$

- **Unique low-$p_T$ coverage of PHOBOS**

PRC 75 (2007) 024910



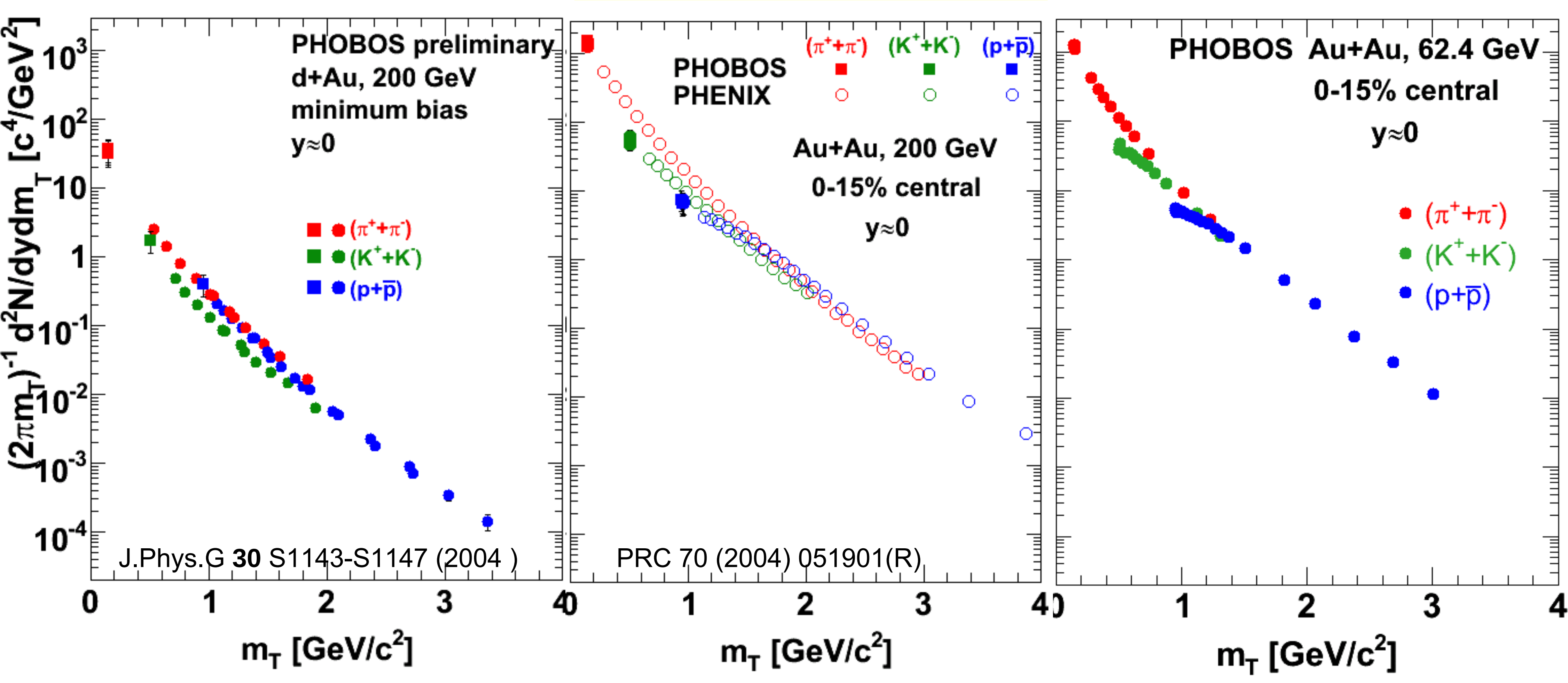

| T = 103±6 MeV | T = 102±6 MeV | T = 101±6 MeV |
|---|---|---|
| $\beta_{surface}$ = 0.78±0.02 | $\beta_{surface}$ = 0.76±0.02 | $\beta_{surface}$ = 0.72±0.02 |

- **No enhanced production at very low $p_T$**
- **$p_T$- spectra consistent with transverse expansion of the system**

# $m_T$ -scaling in d+Au vs. central Au+Au

**$m_T$ - Scaling ≡ the same slope of $m_T$ –spectra**

PRC 70 (2004) 051901, PRC 75 (2007) 024910




**Lack of $m_T$ scaling in central heavy ion collisions**

# Summary

- $dN_{ch}/d\eta$ for Au+Au and Cu+Cu
  - Similar at the same $N_{part}$
  - Factorization of centrality and energy dependence
  - Extended longitudinal scaling
- Elliptic Flow
  - $v_2$ for A+A is large and continues to grow with energy
  - Participant eccentricity is relevant for the azimuthal anisotropy
  - Scaling of $v_2/\varepsilon_{part}$ for Cu+Cu and Au+Au
- $p_T$ -Spectra of Identified Particles
  - No enhanced production at very low $p_T$ in central Au+Au collisions
  - Lack of $m_T$ scaling in central Au+Au collision consistent with transverse expansion of the system

**The collision geometry controls the dynamical evolution of heavy ion collisions**